NORMAL SPIN ASYMMETRIES IN ELASTIC ELECTRON-PROTON SCATTERING

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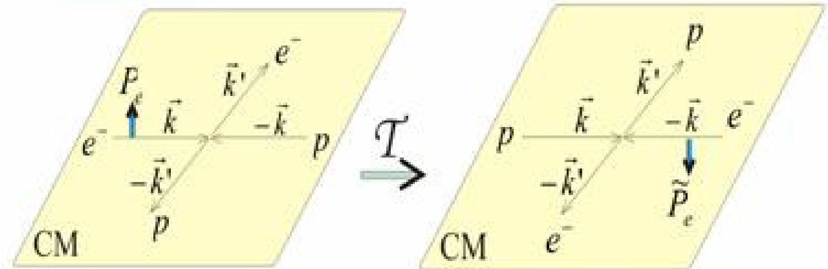
- T-odd effects and absorptive part of T-matrix
- Elastic electron-proton scattering beyond one-photon exchange
- Experimental probes of two-photon exchange effects
- Two-photon kinematics
- Hard collinear photons and quasi-RCS approximation
- Conclusions and Outlook

International Workshop on "Precision Electroweak Interactions", August 15-17 2005, College of William and Mary, Williamsburg, VA

$\mathcal{T}$-odd effects and absorptive part of T-matrix

$\uparrow \equiv (\hat{k} \times \hat{k}')$

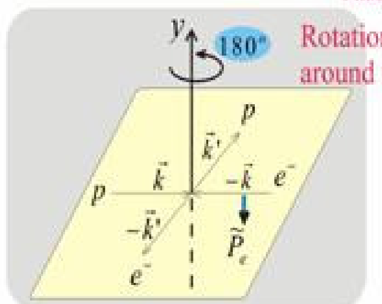
Consider elastic scattering with transverse spin



Transition between time-reversed states

$$T_{fi} = T_{\Uparrow}(\vec{k},\vec{k}') \xrightarrow{\mathcal{T}} T_{\tilde{f}\tilde{i}} = T_{\Downarrow}(-\vec{k},-\vec{k}') = \eta T_{\Downarrow}(\vec{k},\vec{k}')$$

Phase



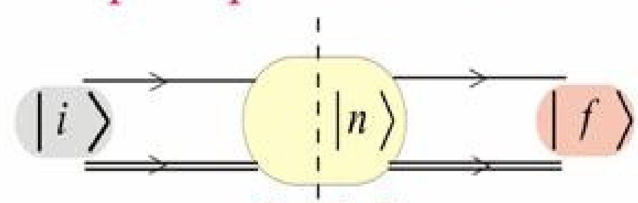
$\Downarrow$

$$A_{\perp} = \frac{|T_{\Uparrow}|^2 - |T_{\Downarrow}|^2}{|T_{\Uparrow}|^2 + |T_{\Downarrow}|^2} = \frac{|T_{fi}|^2 - |T_{\tilde{f}\tilde{i}}|^2}{|T_{fi}|^2 + |T_{\tilde{f}\tilde{i}}|^2} \propto \mathcal{T}\text{-odd effects}$$

- <u>Unitarity</u> $S\,S^{+} = S^{+}S = \mathbb{1}$ $\quad with\ S_{fi} = \delta_{fi} - iT_{fi}$

$$i(T_{fi} - T^{+}_{fi}) = \sum_{n} T^{+}_{fn} T_{ni} \equiv AbsT_{fi}$$

Absorptive part of the T-matrix



Time reversal invariance:
(Identical initial and final states)

$$|T_{fi}|^2 = |T_{\tilde{i}\tilde{f}}|^2$$

$$\Downarrow$$

$$\begin{cases} |AbsT_{fi}|^2 = |T_{fi}|^2 + |T_{\tilde{f}\tilde{i}}|^2 - 2\,\mathrm{Re}(T_{fi} \cdot T_{if}) \\ 2\,\mathrm{Im}(T^{*}_{fi} \cdot AbsT_{fi}) = 2|T_{fi}|^2 - 2\,\mathrm{Re}(T^{*}_{fi} \cdot T^{*}_{if}) \end{cases}$$

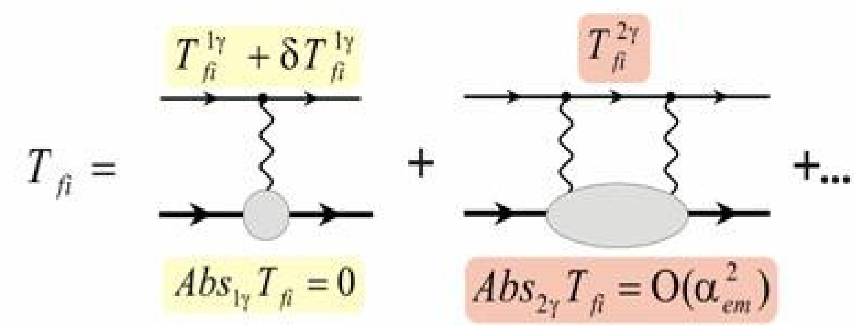
$$\Downarrow$$

$$2\,\mathrm{Im}(T^{*}_{fi} \cdot AbsT_{fi}) - |AbsT_{fi}|^2 = |T_{fi}|^2 - |T_{\tilde{f}\tilde{i}}|^2 \propto A_{\perp}$$

<u>The T-odd effects measure the absorptive part of T-matrix</u>

De Rújula et al., NP B35 (1971) 365-389

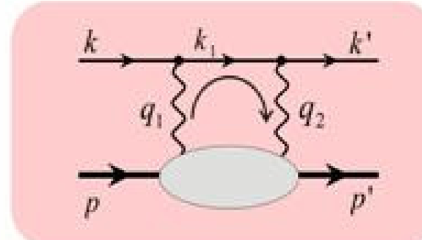
- Elastic e-p scattering amplitude



$\Rightarrow$ To leading order in α_{em}

$$|T_{fi}|^2 - |T_{\tilde{f}\tilde{i}}|^2 = 2\,\mathrm{Im}\,(T_{fi}^{1\gamma\,*} \cdot Abs\,T_{fi}^{2\gamma})$$

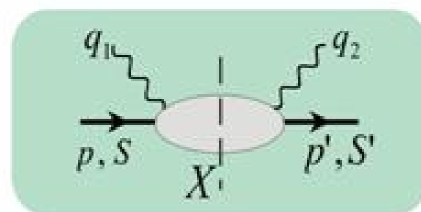
- Absorptive part of the 2γ-exchange amplitude



$$Abs T_{fi}^{2\gamma} = e^4 \int \frac{d^3\vec{k}_1}{(2\pi)^3 2E_1} \bar{u}(k',s')\gamma_\mu(\not{k}_1 + m_e)\gamma_\nu u(k,s) \cdot \frac{1}{Q_1^2 Q_2^2} \cdot W^{\mu\nu}(p',S';p,S)$$

- Hadronic tensor

  Doubly VCS

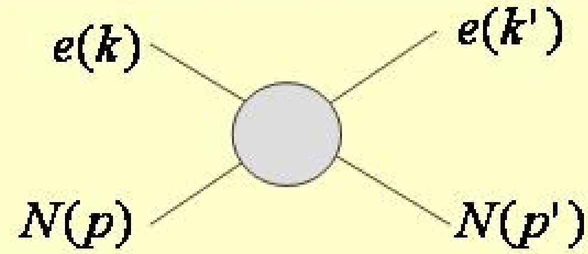


$$W^{\mu\nu} = \sum_X (2\pi)^4 \delta^4(p+q_1-P_X) \langle p' S' | J^\mu(0) | X \rangle \langle X | J^\nu(0) | p, S \rangle$$

Elastic electron-proton scattering beyond one-photon exchange

$$P=\frac{1}{2}(p+p'),\quad K=\frac{1}{2}(k+k'),\quad \mathbf{q}=\mathbf{k}-\mathbf{k}'=\mathbf{p}'-\mathbf{p}$$

$$Q^2=-q^2,\quad \nu=\frac{PK}{M}\ \leftrightarrow\ \tau=\frac{Q^2}{4M^2},\quad \varepsilon=\frac{\nu^2-M^2\tau(1+\tau)}{\nu^2+M^2\tau(1+\tau)}$$



$$T=T_{no-flip}+T_{flip}$$

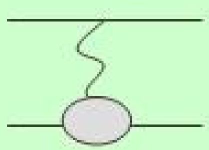
$$T_{no-flip}=\frac{e^2}{Q^2}\bar{u}'\gamma_\mu u\cdot\bar{N}'\left(\tilde{G}_M\gamma^\mu-\tilde{F}_2\frac{P^\mu}{M}+\tilde{F}_3\frac{P^\mu K\!\!\!/}{M^2}\right)N$$

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

$$T_{flip}=\frac{m}{M}\frac{e^2}{Q^2}\left[\bar{u}'u\cdot\bar{N}'\left(\tilde{F}_4+\tilde{F}_5\frac{K\!\!\!/}{M}\right)N+\tilde{F}_6\bar{u}'\gamma_5 u\cdot\bar{N}'\gamma_5 N\right]$$

M. G., P.A.M. Guichon, M. Vanderhaeghen, NP A741 (2004) 234

One-photon exchange (Born):



$$\tilde{G}_M^{Born}(\nu,Q^2)=G_M(Q^2)$$

$$\tilde{F}_2^{Born}(\nu,Q^2)=F_2(Q^2)$$

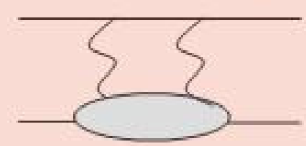
$$\tilde{F}_{3,4,5,6}^{Born}=0$$

Two- and more- photon exchange

$$\tilde{G}_M=G_M+\delta\tilde{G}_M$$

$$\tilde{F}_2=F_2+\delta\tilde{F}_2$$

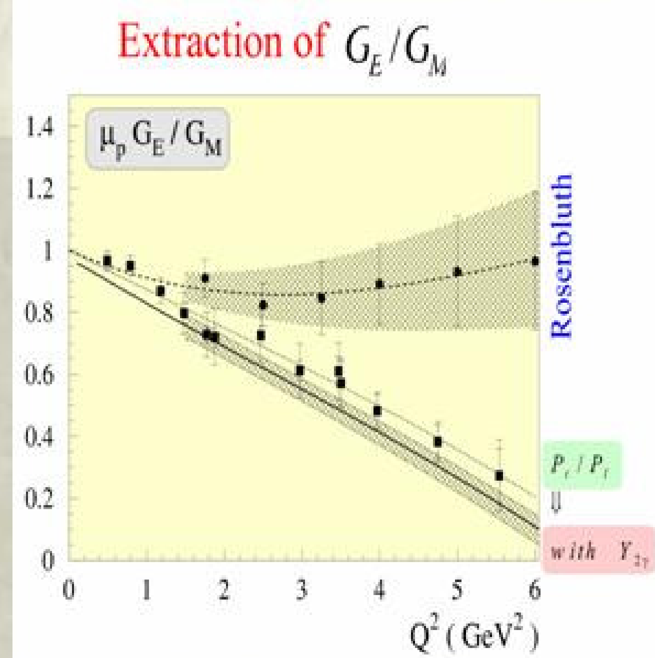
$$\delta\tilde{G}_M,\ \delta\tilde{F}_2,\ \tilde{F}_{3,4,5,6}\sim e^2$$



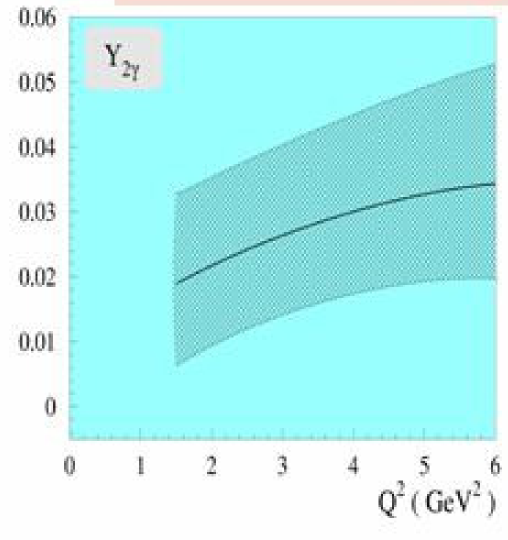
Rosenbluth separation vs. polarization transfer method

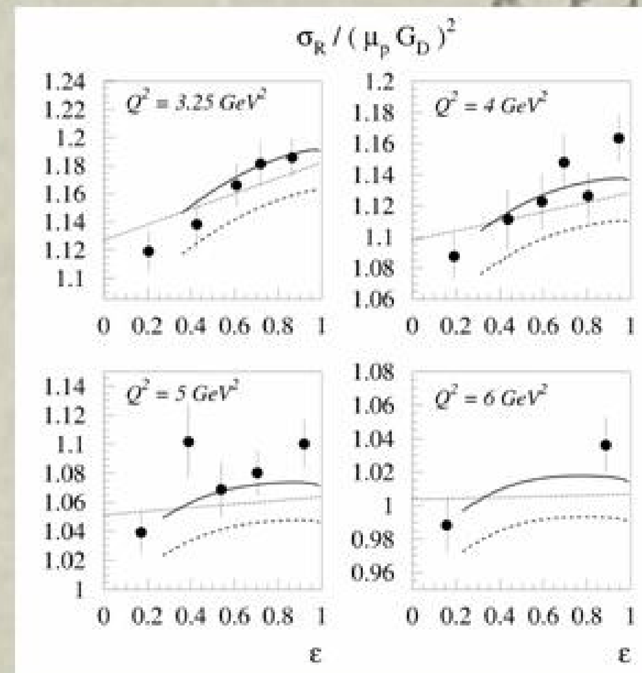
$$\sigma_R = G_M^2 + \frac{\varepsilon}{\tau} G_E^2 + 2G_M \,\mathrm{Re}\,\delta\widetilde{G}_M + 2\frac{\varepsilon}{\tau} G_E \,\mathrm{Re}\,\delta\widetilde{G}_E + 2\varepsilon\left(G_M + \frac{1}{\tau} G_E\right)\frac{\nu}{M}\,\mathrm{Re}\,\widetilde{F}_3$$

$$\frac{P_t}{P_l} = -\sqrt{\frac{2\varepsilon}{\tau(1+\varepsilon)}}\left(\frac{G_E}{G_M} + \left[1 - \frac{2\varepsilon}{1+\varepsilon}\frac{G_E}{G_M}\right]\frac{\nu}{M}\,\mathrm{Re}\,\frac{\widetilde{F}_3}{G_M}\right)$$



$$Y_{2\gamma} = \frac{\nu}{M}\,\mathrm{Re}\left(\frac{\widetilde{F}_3}{G_M}\right)$$





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

P.G. Blunden et al., PRL 91 (2003) 142304

Y.-C. Chen et al., PRL 93 (2004) 122301

Charge asymmetry

$$\frac{\sigma^{e^+p} - \sigma^{e^-p}}{\sigma^{e^+p} + \sigma^{e^-p}} \sim Y_{2\gamma}$$

Beam normal spin asymmetry

$$B_n = -\frac{2m}{Q}\sqrt{2\varepsilon(1-\varepsilon)}\sqrt{1+\frac{1}{\tau}}\left(G_M^2 + \frac{\varepsilon}{\tau}G_E^2\right)^{-1} \cdot \left\{\tau G_M \operatorname{Im}\tilde{F}_3 + G_E \operatorname{Im}\tilde{F}_4 + F_1 \frac{\nu}{M}\operatorname{Im}\tilde{F}_5\right\}$$

$$B_n \sim \alpha_{em} \cdot \frac{m}{E} \sim 10^{-6}$$

Theory:

- A.O. Barut and C. Fronsdal, PR 120 (1960) 1871 — $e\mu$ – scattering
- A.Afanasev et al., hep-ph/0208260 — $ep;\ X = N$
- B. Pasquini and M. VdH, PR C70 (2004) 0450206 — $ep;\ X = \pi N, \Delta, N^*$
- L.Diaconescu and M.J.Ramsey-Musolf, PR C70 (2004) 054003 — $ep;\ X = N$ (EFT)
- M.G. et al., NP A 741 (2004) 234 — ep; GPD's
- A.Afanasev and M.Merenkov, Phys.Lett.B599:48,2004, Phys.Rev.D70:073002,2004 — Regge regime
- M.G., hep-ph/0505022

Experiment:

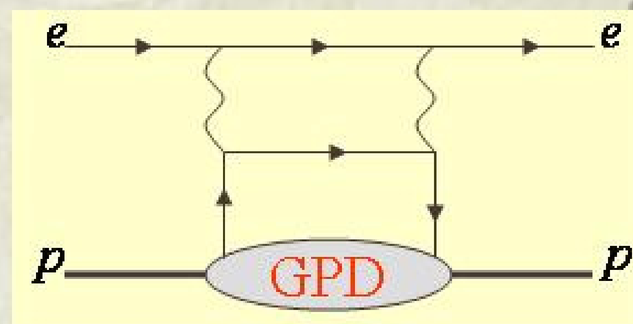
- S.P. Wells et al. (SAMPLE), PR C 63 (2001) 06401
- F. Maas et al. (MAMI/A4) nucl-ex/0410013
- K. Kumar, contact person of SLAC E158 experiment
- G. Cates, K. Kumar, D. Lhuillier, HAPPEX-2 (Jlab E-99-115)
- D. Beck, spokesperson Jlab/ G0 Exp. (Jlab E-00-06, E-01-116)

At large momentum transfer $s, Q^2 >> M^2$

$$P^+ >>, \quad q^+ = 0, \quad \xi = 0$$

$$x = \frac{p_q^+}{P^+} = \frac{p_q'^+}{P^+}, \quad \eta = \frac{K^+}{P^+}$$

$$n^\mu = \frac{2}{\sqrt{M^4 - su}}\left(K^\mu - \eta P^\mu\right)$$



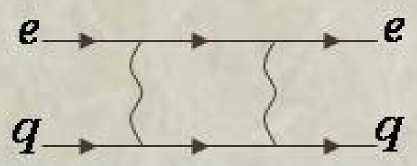
A.V. Radyushkin, PR D 58 (1998) 114008

M. Diehl et al., PL B 460 (1999) 204

$$T^{hard}_{h'H',hH} = \int_{-1}^{1}\frac{dx}{x}\sum_q \frac{1}{2}\left[H^{hard}_{h'h,+1/2} + H^{hard}_{h'h,-1/2}\right]\cdot\left\{\frac{1}{2}\left(H^q + E^q\right)\overline{N}'_{H'}\, \not{n} N_H - \frac{E^q}{2M}\overline{N}'_{H'} N_H\right\}$$
$$+ \int_{-1}^{1}\frac{dx}{x}\sum_q \frac{1}{2}\left[H^{hard}_{h'h,+1/2} - H^{hard}_{h'h,-1/2}\right]\cdot \mathrm{sgn}(x)\widetilde{H}^q \frac{1}{2}\overline{N}'_{H'}\, \not{n}\gamma_5 N_H$$

GPD's $H^q = H^q(x,0,q^2)$ $E^q = E^q(x,0,q^2)$ $\widetilde{H}^q = \widetilde{H}^q(x,0,q^2)$ $q = u,d,s$

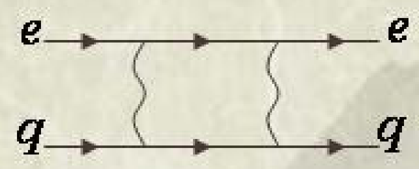
Hard amplitude



$$H^{hard}_{h'h,\lambda} = \frac{e^2 e_q^2}{Q^2}\left\{\overline{u}'_{h'}\gamma_\mu u_h \cdot \overline{q}'_\lambda\left[\widetilde{f}_1\gamma^\mu + \widetilde{f}_3 P_q^\mu \not{K}\right]q_\lambda + m\widetilde{f}_5 \overline{u}'_{h'} u_h \cdot \overline{q}'_\lambda \not{K} q_\lambda\right\}$$

$e_q = 2/3(u), -1/3(d,s)$

Hard amplitude



$$\begin{cases} \hat{s} = (p_q + k)^2 = \dfrac{(x+\eta)^2}{4x\eta} Q^2 \\ \hat{u} = (p_q - k')^2 = -\dfrac{(x-\eta)^2}{4x\eta} Q^2 \\ \hat{Q}^2 = -(p_q' - p_q)^2 = -(k-k')^2 = Q^2 \end{cases}$$

$$\mathrm{Im}\, \tilde{f}_1^{soft} = -\frac{e^2}{4\pi} \ln\left(\frac{\lambda^2}{\hat{s}}\right)$$ ~ coulomb phase to lowest order

$$\mathrm{Im}_{2\gamma}\, \tilde{f}_1^{hard} = -\frac{e^2}{4\pi}\left\{\frac{Q^2}{2\hat{u}} \ln\left(\frac{\hat{s}}{Q^2}\right) + \frac{1}{2}\right\}$$

$$\tilde{f}_1 = \tilde{f}_1^{soft} + \tilde{f}_1^{hard}$$

Y.-C. Chen et al., hep-ph/0403058

$$\mathrm{Im}\, \tilde{f}_3 = -\frac{e^2}{4\pi}\frac{1}{\hat{u}}\left\{\frac{\hat{s}-\hat{u}}{\hat{u}} \ln\left(\frac{\hat{s}}{Q^2}\right) + 1\right\}$$

$$\mathrm{Im}\, \tilde{f}_5 = -\frac{e^2}{4\pi}\frac{Q^2}{\hat{u}}\left\{-\frac{1}{\hat{u}} \ln\left(\frac{\hat{s}}{Q^2}\right) - \frac{1}{\hat{s}}\right\}$$

M.G. et al., NP A 741 (2004) 234

Beam normal spin asymmetry on quark

$$B_n = -\frac{m_e}{Q}\sqrt{2\varepsilon(1-\varepsilon)}\,\frac{1}{2}\left[Q^2\, \mathrm{Im}_{2\gamma}\, \tilde{f}_3 + (\hat{s}-\hat{u})\,\mathrm{Im}_{2\gamma}\, \tilde{f}_5\right] = \frac{e^2}{4\pi}\sqrt{-\frac{\hat{u}}{\hat{s}}}\,\frac{m_e Q^3}{\hat{s}^2 + \hat{u}^2}$$

A.O. Barut and C. Fronsdal, PR 120 (1960) 1871

Results for the beam normal spin asymmetry

$$B_n = \frac{2m}{Q}\frac{\sqrt{1-\varepsilon^2}}{\left(G_M^2+\frac{\varepsilon}{\tau}G_E^2\right)}\left\{G_M\left[\frac{\sqrt{2\varepsilon\tau}}{\sqrt{1+\varepsilon}\sqrt{1+\tau}+\sqrt{1-\varepsilon}\sqrt{\tau}}\,\mathrm{Im}\,A-\sqrt{\frac{\tau}{1+\tau}}\,\mathrm{Im}\,A'\right]\right.$$
$$\left.+\frac{1}{\tau}G_E\left[\frac{\sqrt{1+\varepsilon}\sqrt{\tau}+\sqrt{1-\varepsilon}\sqrt{1+\tau}}{\sqrt{1+\varepsilon}\sqrt{1+\tau}+\sqrt{1-\varepsilon}\sqrt{\tau}}\,\mathrm{Im}\,B-\sqrt{\frac{\tau}{1+\tau}}\sqrt{\frac{2\varepsilon}{1+\varepsilon}}\,\mathrm{Im}\,B'\right]\right\}$$

"Magnetic GPD"

$$A \equiv \int_{-1}^{1}\frac{dx}{x}\frac{(\hat{s}-\hat{u})\tilde{f}_1^{hard}-\hat{s}\hat{u}\tilde{f}_3}{s-u}\sum_q e_q^2(H^q+E^q)$$

$$A' \equiv \int_{-1}^{1}\frac{dx}{x}\frac{\sqrt{-\hat{s}\hat{u}}}{2}\left[\frac{2}{\hat{s}}\tilde{f}_1^{hard}+\tilde{f}_3+\tilde{f}_5\right]\sum_q e_q^2(H^q+E^q)$$

"Electric GPD"

$$B \equiv \int_{-1}^{1}\frac{dx}{x}\frac{(\hat{s}-\hat{u})\tilde{f}_1^{hard}-\hat{s}\hat{u}\tilde{f}_3}{s-u}\sum_q e_q^2(H^q-\tau E^q)$$

$$B' \equiv \int_{-1}^{1}\frac{dx}{x}\frac{\sqrt{-\hat{s}\hat{u}}}{2}\left[\frac{2}{\hat{s}}\tilde{f}_1^{hard}+\tilde{f}_3+\tilde{f}_5\right]\sum_q e_q^2(H^q-\tau E^q)$$

Parametrization for the GPDs

$$H^q(x,0,q^2) = q_v(x)\exp\left(-\frac{(1-x)Q^2}{4x\sigma}\right)$$

A.V. Radyushkin, PR D 58 (1998) 11408

$$E^q(x,0,q^2) = \frac{\kappa_q}{N_q}(1-x)^2 q_v(x)\exp\left(-\frac{(1-x)Q^2}{4x\sigma}\right)$$

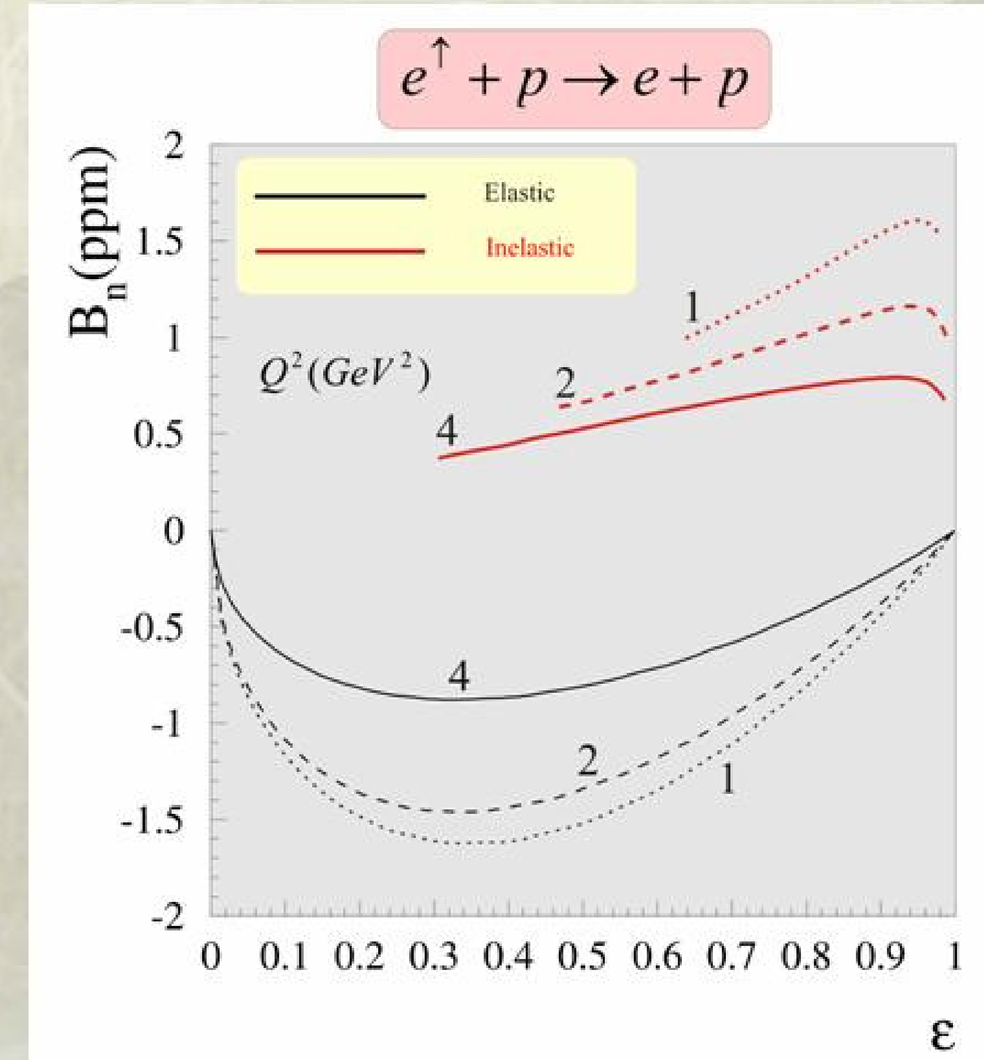
Feng Yuan, PR D 69 (2004) 051501

Valence quark distribution: MRST2002 global fit

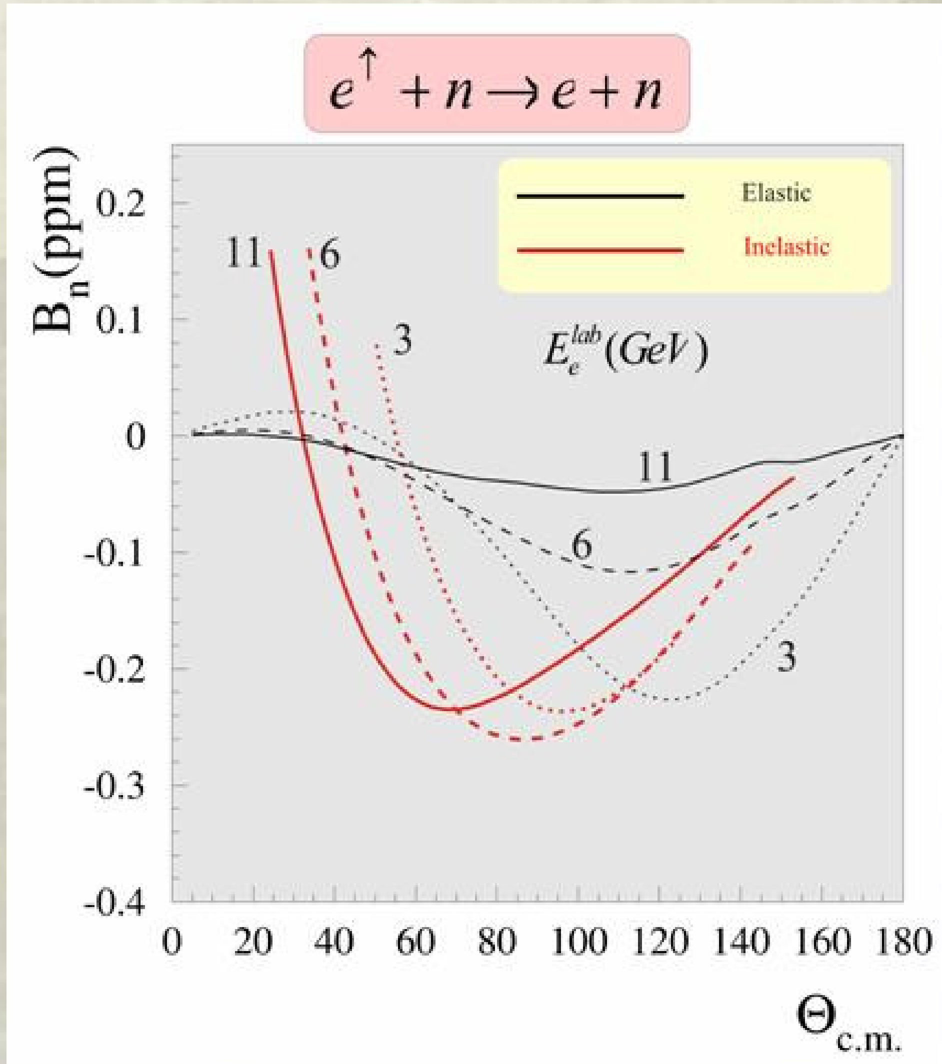
A.D. Martin et al., PL B 531 (2002) 216

$$u_v = 0.262x^{-0.69}(1-x)^{3.50}(1+3.83\sqrt{x}+37.65x)$$
$$d_v = 0.0061x^{-0.65}(1-x)^{4.03}(1+49.05\sqrt{x}+8.65x)$$

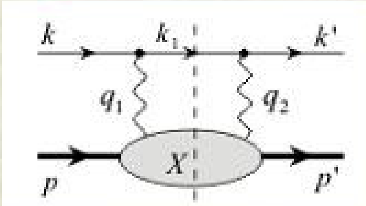
Results for B_n on the proton target



Results for B_n on the neutron target



Kinematics of two-photon exchange



$s = (p+k)^2$

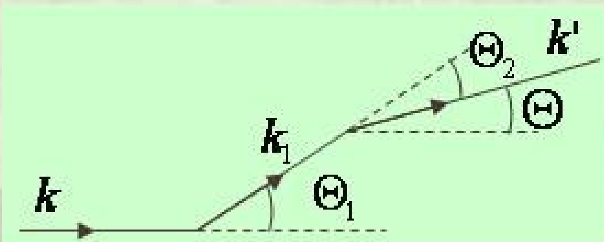
$Q^2 = -(k-k')^2$

$P_X^2 = W^2$

CM

$|\vec{k}| = |\vec{k}'| = \frac{s-M^2}{2\sqrt{s}}$

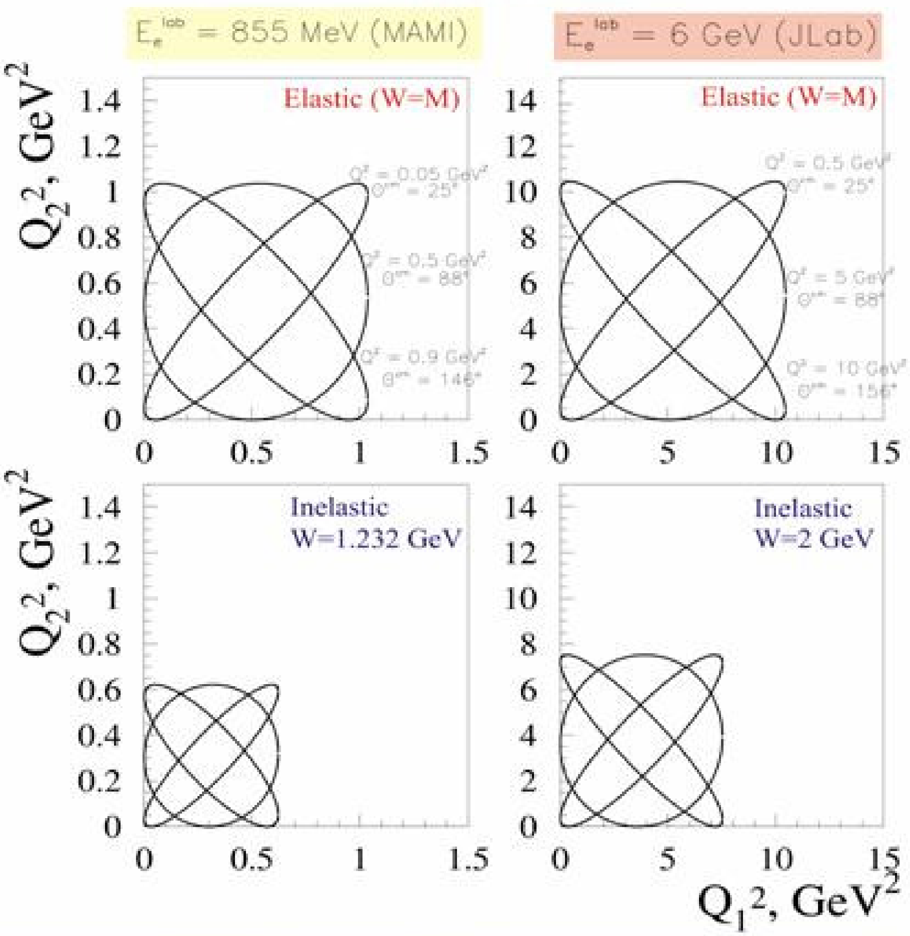
$|\vec{k}_1| = \frac{s-W^2}{2\sqrt{s}}$



$$Q^2 = \frac{(s-M^2)^2}{2s}(1-\cos\Theta)$$

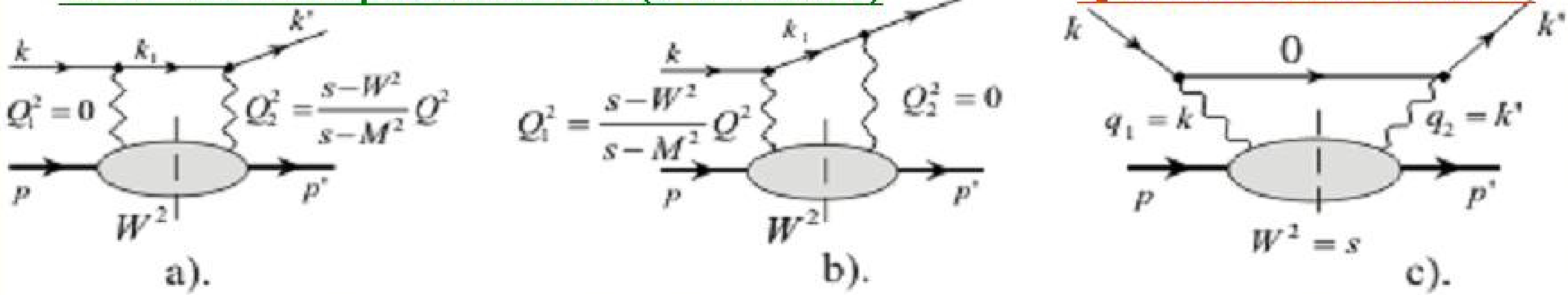
$$Q^2_{1,2} \approx \frac{(s-W^2)(s-M^2)}{2s}(1-\cos\Theta_{1,2})$$

Kinematical bounds for Q_1^2, Q_2^2



VCS: one of the photons is real (soft or hard)

Quasi-RCS: soft electron



Quasi-RCS limit for the 2γ exchange

$$B_n = -\frac{e^2 Q^2}{D(s,Q^2)}\frac{1}{(2\pi)^3}\int_{M^2}^{s} dW^2 \underbrace{\frac{k_1^2}{4\sqrt{s}E_1}\int \frac{d\Omega_{k_1}}{Q_1^2 Q_2^2}\,\mathrm{Im}\left[L_{\alpha\mu\nu}H^{\alpha\mu\nu}\right]}_{\text{Integrand}}$$

$$L_{\alpha\mu\nu} = \sum_{spins} l_{\mu\nu}\cdot(\bar{u}'\gamma_\alpha u)^* \qquad H^{\alpha\mu\nu} = \sum_{spins} W_{\mu\nu}\cdot(\bar{N}'\Gamma^\alpha(Q^2)N)^*$$

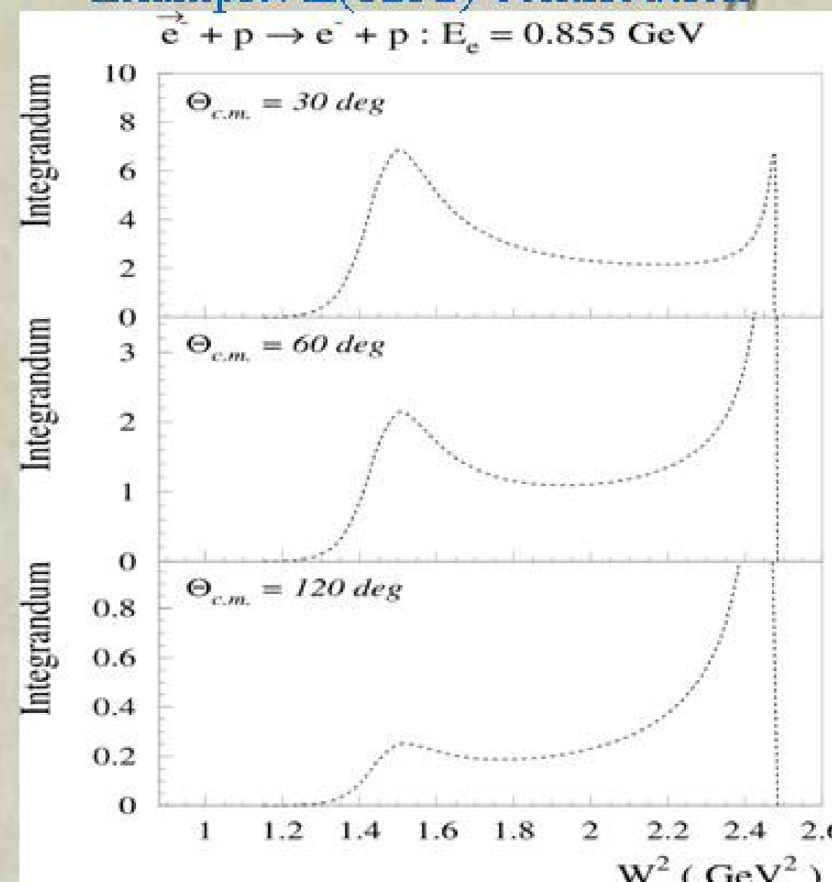
QRCS limit: $W^2 \to s$

$$\frac{k_1^2}{E_1 Q_1^2 Q_2^2} \to \frac{1}{m_e}\frac{1}{2Q^2}\frac{1-\cos\Theta}{(1-\cos\Theta_1)(1-\cos\Theta_2)}$$

Quasi-RCS: two hard collinear photons!

QRCS peak strongly pronounced at backward scattering angles

Example: Δ(1232) contribution



QRCS approximation

$$\mathrm{Im} M_{2\gamma} = e^2 \int \frac{d^3\vec{k}_1}{2E_1(2\pi)^3} \frac{1}{Q_1^2 Q_2^2} l_{\mu\nu} W^{\mu\nu}$$

$$Q_{1,2}^2 \sim \frac{s-w^2}{s-M^2} Q^2 \sim 10^{-3} Q^2 \approx 0 \text{ at the peak position}$$

Leptonic tensor: take exact

$$l_{\mu\nu} = \bar{u}'\gamma_\nu (\not{k}_1 + m)\gamma_\mu u$$

Hadronic tensor: rewrite identically

$$W^{\mu\nu}(w^2, t, Q_1^2, Q_2^2) \equiv W_{RCS}^{\mu\nu}(s,t,0,0) + \left(W^{\mu\nu}(w^2, t, Q_1^2, Q_2^2) - W_{RCS}^{\mu\nu}(s,t,0,0)\right)$$

independent of k1

- smooth function of energy?

High energies, forward angles (Regge regime) - YES

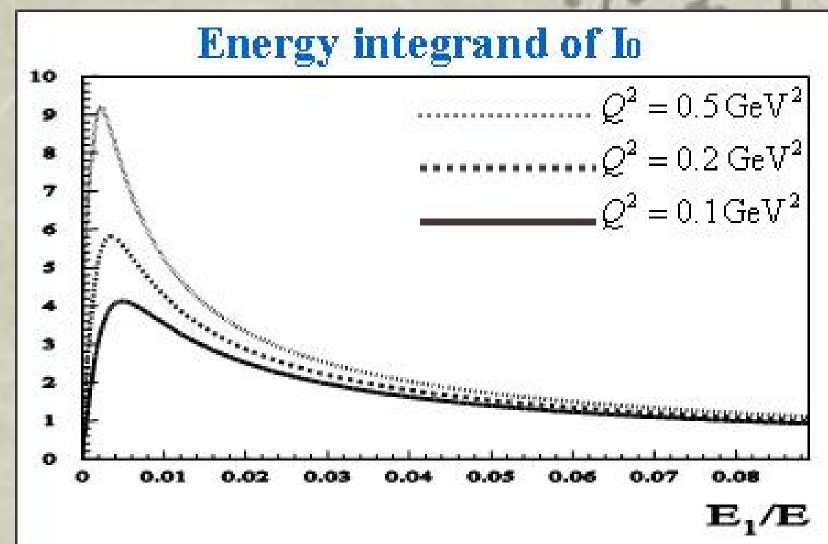
$$\mathrm{Im} M_{2\gamma} = e^2 W_{RCS}^{\mu\nu}(s,t)\left[m\bar{u}'\gamma_\nu\gamma_\mu u \cdot I_0 + \bar{u}'\gamma_\nu\gamma_\alpha\gamma_\mu u \cdot I_1^\alpha\right]$$
$$+ e^2 \int \frac{d^3\vec{k}_1}{2E_1(2\pi)^3} \frac{\bar{u}'\gamma_\nu(\not{k}_1 + m)\gamma_\mu u}{Q_1^2 Q_2^2}\left(W^{\mu\nu}(w^2, t, Q_1^2, Q_2^2) - W_{RCS}^{\mu\nu}(s,t,0,0)\right)$$

The second term can only lead to simple logarithms!

$$I_0 = \int \frac{d^3 k_1}{2E_1(2\pi)^3} \frac{1}{Q_1^2 Q_2^2} \sim \ln^2\left(\frac{Q^2}{m^2}\right) \sim 200$$

$$I_1^\mu = \int \frac{d^3 k_1}{2E_1(2\pi)^3} \frac{k_1^\mu}{Q_1^2 Q_2^2} \sim \ln\left(\frac{E}{m}\right) \sim 10 \div 15$$

Expansion in powers of $\ln(m)$



RCS tensor: use the basis of Prange

$$\tilde{K} = \frac{1}{2}(q_1 + q_2) \qquad P = \frac{1}{2}(p + p')$$

$$P' = P - \frac{(P\tilde{K})}{\tilde{K}^2}\tilde{K} \qquad N^\mu = \varepsilon^{\mu\nu\alpha\beta} P_\nu \tilde{K}_\alpha q_\beta$$

$$(P'\tilde{K}) = (N\tilde{K}) = (P'N) = 0$$

$$W^{\mu\nu} = e^2 \bar{N}' \left\{ \frac{P'^\mu P'^\nu}{P'^2}(B_1 + B_2\tilde{K}) + \frac{N^\mu N^\nu}{N^2}(B_3 + B_4\tilde{K}) + \frac{P'^\mu N^\nu - P'^\nu N^\mu}{P'^2 N^2} B_5 i\gamma_5 + \frac{P'^\mu N^\nu + P'^\nu N^\mu}{P'^2 N^2} B_6 \mathcal{N} \right\} N$$

$$\mathrm{Im}\, M_{2\gamma}^{QRCS} = e^2 \bar{u}' \gamma_\nu (\gamma \cdot I_1 + m I_0) \gamma_\mu u \cdot \mathrm{Im}\, W_{RCS}^{\mu\nu}$$

$$I_0 = \frac{1}{(2\pi)^3} \int \frac{d^3\vec{k}_1}{2E_1 Q_1^2 Q_2^2} = \frac{1}{32\pi^2 Q^2} \left(\ln^2\left(\frac{Q^2}{m^2}\right) + \frac{4\pi^2}{3} \right)$$

$$I_1^\mu = I_{1K} K^\mu + I_{1P} P^\mu$$

$$I_{1P} = \frac{1}{16\pi^2} \frac{s - M^2}{M^4 - su} \ln\left(\frac{4E^2}{Q^2}\right)$$

$$I_{1K} = \frac{1}{4\pi^2 Q^2} \ln\left(\frac{2E}{m}\right) - \frac{4PK}{Q^2} I_{1P}$$

$$\mathrm{Im}\,\tilde{G}_M^{QRCS} = 2Q^2 I_{1P}\,\mathrm{Im}\,B_6$$

$$\mathrm{Im}\,\tilde{F}_2^{QRCS} = MQ^2 I_{1P}\,\mathrm{Im}\left[B_1 - B_3 + \frac{2MQ^2}{M^4 - su}B_6\right]$$

$$\mathrm{Im}\,\tilde{F}_3^{QRCS} = M^2Q^2 I_{1P}\,\mathrm{Im}\left[B_2 - B_4 - \frac{8M\nu}{M^4 - su}B_6\right]$$

$$\mathrm{Im}\,\tilde{F}_4^{QRCS} = MQ^2 (I_0 - I_{1K}^0)\,\mathrm{Im}(B_1 + B_3) - 4M^2\nu I_{1P}\,\mathrm{Im}\left[B_1 - B_3 + \frac{2MQ^2}{M^4 - su}B_6\right]$$

$$\mathrm{Im}\,\tilde{F}_4^{QRCS} = M^2Q^2 (I_0 - I_{1K}^0)\,\mathrm{Im}(B_2 + B_4) - 4M^3\nu I_{1P}\,\mathrm{Im}[B_2 - B_4] + \frac{8M^4Q^2(1+\tau)}{M^4 - su} I_{1P}\,\mathrm{Im}\,B_6$$

Use forward kinematics $Q^2 << s$

$$B_n^{QRCS} = \frac{m}{M}\frac{Q}{\nu}\frac{F_1}{F_1^2 + \tau F_2^2}\left\{-MQ^2\left(I_0 - I_{1K}^0\right)\mathrm{Im}\left[B_1 + B_3 + \nu\left(B_2 + B_4\right)\right] + 4M^2\nu I_{1P}\,\mathrm{Im}\left[B_1 - B_3 + \nu\left(B_2 - B_4\right)\right]\right\}$$

M.G., hep-ph/0505022

Combinations of Bi:

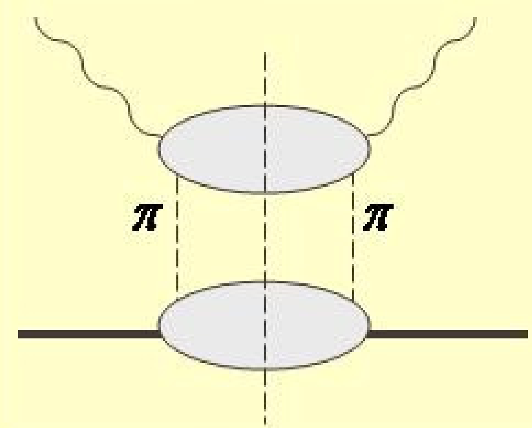
$\mathrm{Re}\left[B_1 + B_3 + \nu\left(B_2 + B_4\right)\right] \sim (\alpha - \beta)$ Backward polarizability

$\mathrm{Re}\left[B_1 - B_3 + \nu\left(B_2 - B_4\right)\right] \sim (\alpha + \beta)$ Forward polarizability

From analysis of RCS: *A.Lvov et al., PR C 55 (1997) 359.*

$$\mathrm{Im}\left[B_1 - B_3 + \nu\left(B_2 - B_4\right)\right] = 2\nu \cdot \sigma_{\gamma p}^{tot}$$ optical theorem

$$\frac{1}{t}\left[B_1 + B_3 + \nu\left(B_2 + B_4\right)\right] \sim T_{1\frac{1}{2},-1\frac{1}{2}}, T_{1-\frac{1}{2},-1\frac{1}{2}}, T_{-1-\frac{1}{2},1\frac{1}{2}} \sim t\text{-channel } \sigma(\pi\pi)\text{-exchange}$$



Estimate: πN and ρN contributions

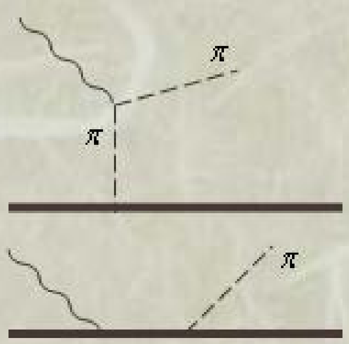
"Minimal" Regge model for π and ρ photoproduction

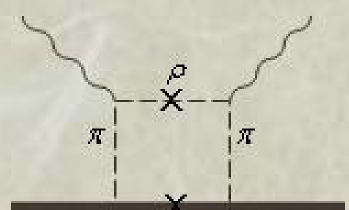
$$\frac{1}{t - m_\pi^2} \to \mathcal{P}_\pi^R(\alpha_\pi(t)) = \left(\frac{s}{s_0}\right)^{\alpha_\pi(t)} \frac{\pi\alpha'_\pi}{\sin \pi\alpha_\pi(t)} \frac{1}{\Gamma(1 + \alpha_\pi(t))}$$

$\alpha_\pi(t) = \alpha'_\pi\,(t - m_\pi^2)$, with $\alpha'_\pi = 0.7\,\mathrm{GeV}^{-2}$ and $s_0 = 1\,\mathrm{GeV}$

Explicit gauge invariance + Regge behavior

M.Guidal, J.-M.Laget, M.VdH, NP A 627 (1997) 645



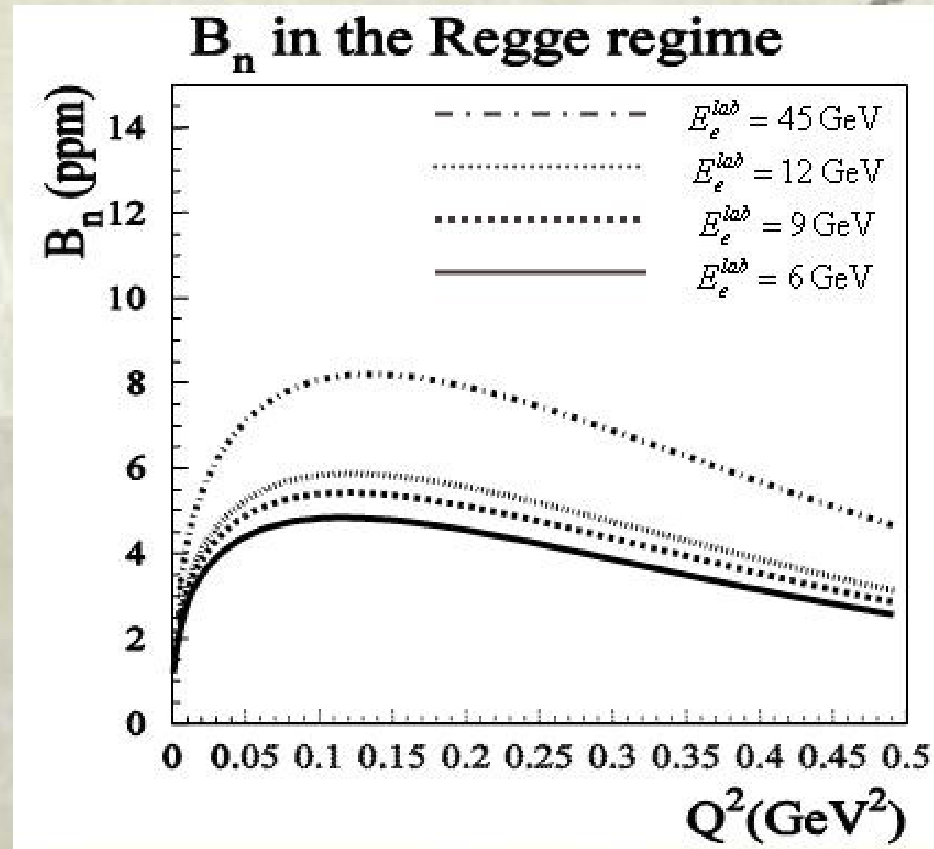


Estimates for B_n in Regge regime

Helicity-flip amplitudes:

- suppressed through $m^2_{\pi,\rho}/(s-M^2)$
- suppressed by Regge pion trajectory
- numerically are ~ 1-2%

Resulting asymmetry increases with energy logarithmically



Quadratic logarithm terms are irrelevant in forward kinematics!

Is in accordance with the observations for resonance region contributions!

Higher order terms are not negligible and final result may be even smaller than 4-8 ppm!

Conclusions

Normal spin asymmetries measure T-odd effects and are related to the imaginary part of the two-photon exchange amplitude

Provide a unique way to measure doubly VCS with two space-like photons

Serve as a cross-check for two-photon effects for a form factor

Handbag model: beam normal spin asymmetry ~ 1.5 ppm in the hard regime

Beam normal spin asymmetry: hard collinear photons kinematics is present and may be dominant at certain kinematical conditions

Both forward and backward RCS amplitudes enter the expression of B_n at forward angles

In hard regime, amplitudes with the photon helicity flipped by 2 units are enhanced through hard collinear kinematics, which may give a hint to “see” the gluon double helicity flip GPD’s.