Some applications in chiral effective field theory

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I. proton spin and axial charges

Phys. Rev. C 93 (2016) 045203
Chin. Phys. C (to be published)

II. u/d quark in Σ hyperons

Phys. Rev. D (2015) 034508

III. ubar-dbar asymmetry

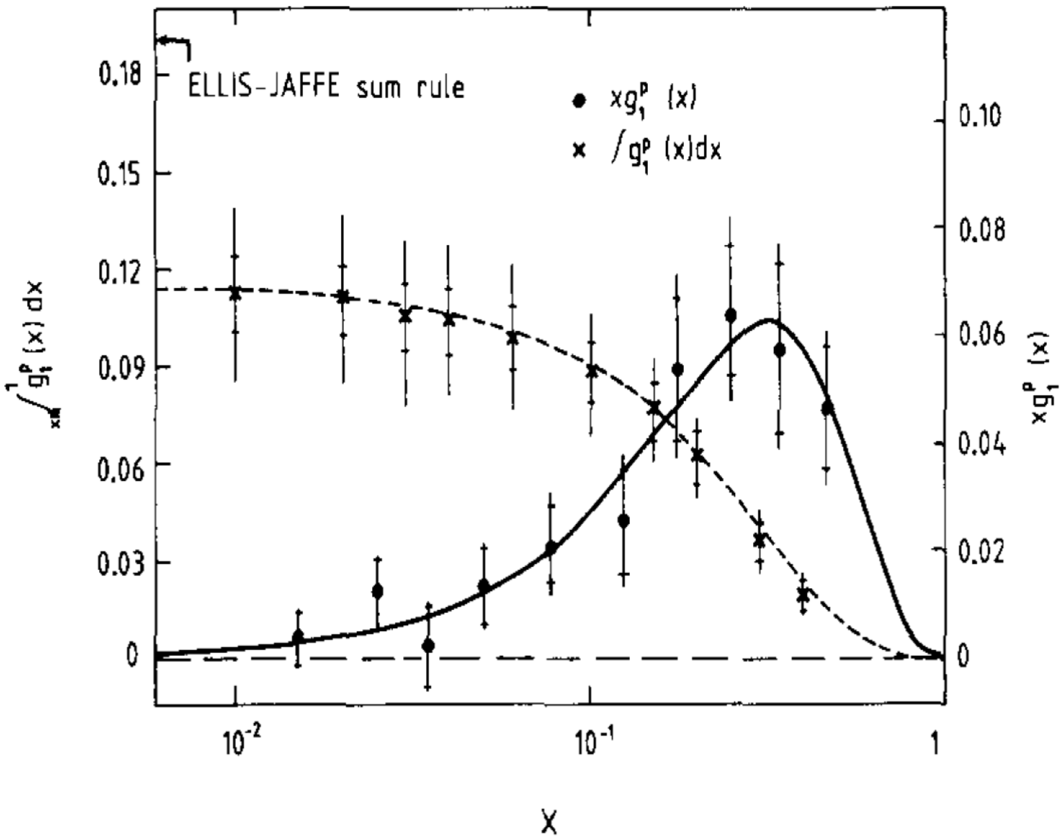
Phys. Rev. Lett. 114 (2015) 122001
Few Body Syst. 56 (2015) 355

IV. s-sbar asymmetry

Phys. Lett. B 762 (2016) 52
Phys. Rev. D (to be published)

Introduction (proton spin)

European Muon Collaboration



$$\int_{0.01}^{0.7} g_1^p(x)\,dx = 0.111 \pm 0.012\,(\text{stat.}) \pm 0.026\,(\text{syst.})$$

$$\int_0^1 g_1^p(x)\,dx = 0.114 \pm 0.012\,(\text{stat.}) \pm 0.026\,(\text{syst.})$$

Bjorken sum rule:

$$\int_0^1 dx[g_1^p(x) - g_1^n(x)] = \tfrac{1}{6}|G_A/G_V|(1 - \alpha_s/\pi)$$

$$= 0.191 \pm 0.002 \quad \text{for } \alpha_s = 0.27 \pm 0.02\,.$$

$$\int_0^1 g_1^n(x)\,dx = -0.077 \pm 0.012\,(\text{stat.}) \pm 0.026\,(\text{syst.})$$

J. Ashman et al. [European Muon Collaboration],Phys. Lett. B 206 (1988) 364.

Introduction (proton spin)

Ellis-Jaffe sum rule: SU(3) symmetry and unpolarised strange quark sea

$$\int_0^1 g_1^{p(n)}(x)\mathrm{d}x = \frac{1}{12}\left|\frac{G_A}{G_V}\right|\left(+(-)1+\frac{5}{3}\frac{3F/D-1}{F/D+1}\right) = 0.189\pm0.005$$

$$\begin{aligned}\int_0^1 dx g_1^{p(n)}(x,Q^2) &= C^{\rm ns}(1,a_s(Q^2))(\pm\frac{1}{12}|g_A|+\frac{1}{36}a_8)\\ &+C^{\rm s}(1,a_s(Q^2))\exp\left(\int_{a_s(\mu^2)}^{a_s(Q^2)} da_s'\frac{\gamma^s(a_s')}{\beta(a_s')}\right)\frac{1}{9}a_0(\mu^2)\end{aligned}$$

$$\begin{aligned}|g_A|s_\sigma &= 2\langle p,s|J_\sigma^{5,3}|p,s\rangle &= (\Delta u-\Delta d)s_\sigma,\\ a_8 s_\sigma &= 2\sqrt{3}\langle p,s|J_\sigma^{5,8}|p,s\rangle &= (\Delta u+\Delta d-2\Delta s)s_\sigma,\\ a_0(\mu^2)s_\sigma &= \langle p,s|J_\sigma^{5}|p,s\rangle &= (\Delta u+\Delta d+\Delta s)s_\sigma = \Delta\Sigma(\mu^2)s_\sigma\end{aligned}$$

$$2\int_0^1 g_1^p(x)\mathrm{d}x = \frac{3.82}{9}\Delta u + \frac{1.08}{9}\Delta d = 0.228\pm0.024\pm0.052$$

$$2\int_0^1 g_1^n(x)\mathrm{d}x = \frac{1.08}{9}\Delta u + \frac{3.82}{9}\Delta d = -0.154\pm0.024\pm0.052$$

Introduction (proton spin)

EMC results:

$$\langle S_z \rangle_{\mathrm{u}} = \tfrac{1}{2}\Delta u = 0.348 \pm 0.023 \pm 0.051$$

$$\langle S_z \rangle_{\mathrm{d}} = \tfrac{1}{2}\Delta d = -0.280 \pm 0.023 \pm 0.051$$

$$\langle S_z \rangle_{\mathrm{u+d}} = 0.068 \pm 0.047 \pm 0.103$$

$(14 \pm 9 \pm 21)\%$ of the proton spin is carried by quarks.

If assuming the discrepancy between EMC result and the Ellis-Jaffe sum rule prediction is due to the polarisation of the strange quark sea, then:

$$\langle S_z \rangle_{\mathrm{u}} = 0.373 \pm 0.019 \pm 0.039\,,$$

$$\langle S_z \rangle_{\mathrm{d}} = -0.254 \pm 0.019 \pm 0.039\,,$$

$$\langle S_z \rangle_{\mathrm{s}} = -0.113 \pm 0.019 \pm 0.039\,,$$

$$\langle S_z \rangle_{\mathrm{u+d+s}} = 0.006 \pm 0.058 \pm 0.117$$

$(1 \pm 12 \pm 24)\%$ of the proton spin is carried by quarks.

J. Ashman et al. [European Muon Collaboration],Phys. Lett. B 206 (1988) 364.

Introduction (proton spin)

TABLE I High energy spin experiments: the kinematic ranges in x and Q^2 correspond to the average kinematic values of the highest statistics measurement of each experiment, which is typically the inclusive spin asymmetry; x denotes Bjorken x unless specified.

Experiment	Year	Beam	Target	Energy (GeV)	Q^2 (GeV^2)	x
Completed experiments						
SLAC – E80, E130	1976–1983	e^-	H-butanol	$\lesssim$23	1–10	0.1–0.6
SLAC – E142/3	1992–1993	e^-	NH_3, ND_3	$\lesssim$ 30	1–10	0.03–0.8
SLAC – E154/5	1995–1999	e^-	NH_3, ^{6}LiD, ^{3}He	$\lesssim$ 50	1–35	0.01–0.8
CERN – EMC	1985	μ^+	NH_3	100, 190	1–30	0.01–0.5
CERN – SMC	1992–1996	μ^+	H/D-butanol, NH_3	100, 190	1–60	0.004–0.5
FNAL E581/E704	1988–1997	p	p	200	~ 1	$0.1 < x_F < 0.8$
Analyzing and/or Running						
DESY – HERMES	1995–2007	e^+, e^-	H, D, ^{3}He	$\sim$ 30	1–15	0.02–0.7
CERN – COMPASS	2002–2012	μ^+	NH_3, ^{6}LiD	160, 200	1–70	0.003–0.6
JLab6 – Hall A	1999–2012	e^-	^{3}He	$\lesssim 6$	1–2.5	0.1–0.6
JLab6 – Hall B	1999–2012	e^-	NH_3, ND_3	$\lesssim 6$	1.-5	0.05–0.6
RHIC – BRAHMS	2002–2006	p	p (beam)	2× (31–100)	$\sim$ 1–6	$-0.6 < x_F < 0.6$
RHIC – PHENIX, STAR	2002+	p	p (beam)	2× (31–250)	$\sim$ 1–400	$\sim$ 0.02–0.4
Approved future experiments (in preparation)						
CERN – COMPASS–II	2014+	μ^+, μ^-	unpolarized H_2	160	$\sim$ 1–15	$\sim$ 0.005–0.2
		π^-	NH_3	190		$-0.2 < x_F < 0.8$
JLab12 – HallA/B/C	2014+	e^-	HD, NH_3, ND_3, ^{3}He	$\lesssim$12	$\sim$ 1–10	$\sim$ 0.05–0.8

C. A. Aidala, S. D. Bass, D. Hasch andG. K. Mallot, Rev. Mod. Phys. 85 (2013) 655.

Introduction (proton spin)

$$\int_0^1 dx g_1^{p(n)}(x,Q^2) = \left[1 - \left(\frac{\alpha_s}{\pi}\right) - 3.5833\left(\frac{\alpha_s}{\pi}\right)^2 - 20.2153\left(\frac{\alpha_s}{\pi}\right)^3\right](\pm\frac{1}{12}|g_A| + \frac{1}{36}a_8)$$
$$+ \left[1 - 0.33333\left(\frac{\alpha_s}{\pi}\right) - 0.54959\left(\frac{\alpha_s}{\pi}\right)^2 - 4.44725\left(\frac{\alpha_s}{\pi}\right)^3\right]\frac{1}{9}\hat{a}_0$$

At NLO, $\Gamma_1^N(Q^2) = \frac{1}{9}\left(1 - \frac{\alpha_s(Q^2)}{\pi} + \mathcal{O}(\alpha_s^2)\right)\left(a_0(Q^2) + \frac{1}{4}a_8\right)$

COMPASS result:

$$\Gamma_1^N\left(Q^2 = 3(\mathrm{GeV}/c)^2\right) = 0.050 \pm 0.003\,(\text{stat.}) \pm 0.003\,(\text{evol.}) \pm 0.005\,(\text{syst.})$$

Hyperon beta decay: $a_8 = 0.585 \pm 0.025$

$$a_0\left(Q^2 = 3(\mathrm{GeV}/c)^2\right) = 0.35 \pm 0.03\,(\text{stat.}) \pm 0.05\,(\text{syst.})$$

Introduction (proton spin)

Possible explanation:

1. The singlet axial current is not conserved and it receives an additional contribution from the gluon polarization.

$$\hat{a}_0 = \Sigma - N_f \frac{\alpha_s}{2\pi} \Delta G$$

2. The large contribution to the proton spin from the strange quark

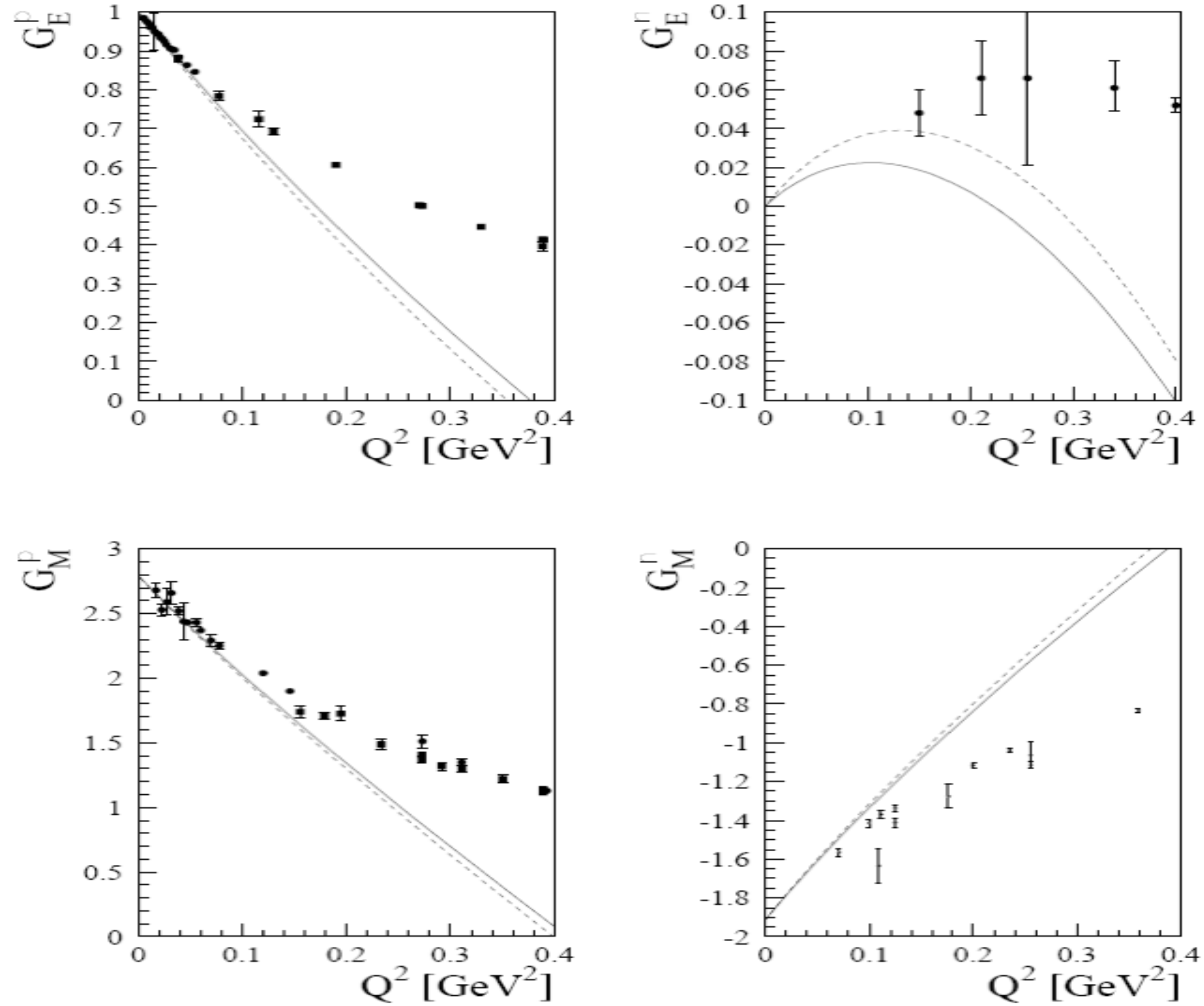
$$a_8 = \Delta u + \Delta d - 2\Delta s = 0.58 \pm 0.03 \qquad \Delta s = - \ 0.08$$

3. Relativistic effect + meson cloud contribution + one gluon exchange

$$(0.7, 0.8) \times (0.65 - 0.15) = (0.35, 0.40)$$

Finite-range-regularization

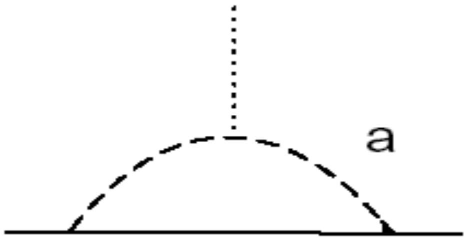
Why finite-range-regularization?



T. Fuchs, J. Gegelia, S. Scherer, J. Phys. G30 (2004) 1407

Finite-range-regularization

The contribution of diagram a:



$$G_M^{p(1a)} = \frac{m_N (D+F)^2}{8\pi^3 f_\pi^2} I_{1\pi}^{NN} + \frac{m_N (D+3F)^2 I_{1K}^{N\Lambda} + 3 m_N (D-F)^2 I_{1K}^{N\Sigma}}{48\pi^3 f_\pi^2}$$

$$G_M^{n(1a)} = -\frac{m_N (D+F)^2}{8\pi^3 f_\pi^2} I_{1\pi}^{NN} + \frac{m_N (D-F)^2}{8\pi^3 f_\pi^2} I_{1K}^{N\Sigma}.$$

$$I_{1j}^{\alpha\beta} = \int d\overrightarrow{k} \frac{k_y^2 u(\overrightarrow{k} + \overrightarrow{q}/2) u(\overrightarrow{k} - \overrightarrow{q}/2)(\omega_j(\overrightarrow{k} + \overrightarrow{q}/2) + \omega_j(\overrightarrow{k} - \overrightarrow{q}/2) + \delta^{\alpha\beta})}{A_j^{\alpha\beta}}$$

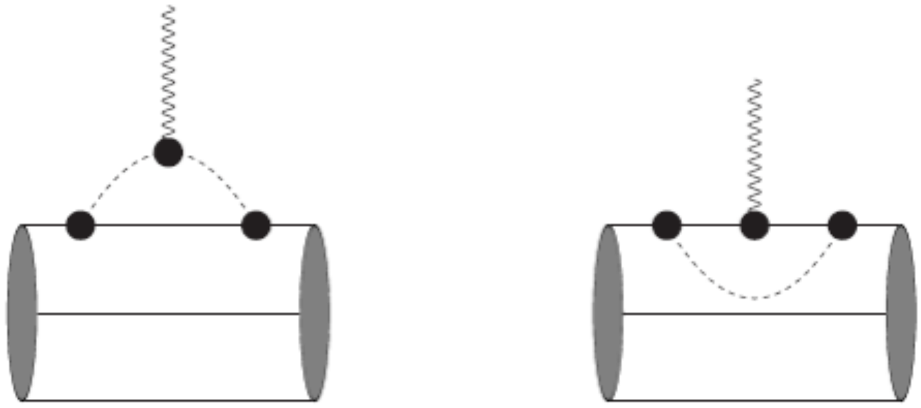
Finite-range-regularization

Perturbative chiral quark model

$$\mathcal{L}_{\rm inv}(x) = \bar{\psi}(x)[i\not\partial - \gamma^0 V(r)]\psi(x) + \frac{1}{2}[D_\mu \Phi_i(x)]^2 - S(r)\bar{\psi}(x)\exp\left[i\gamma^5 \frac{\hat{\Phi}(x)}{F}\right]\psi(x),$$

$$\mathcal{L}_{\chi SB}(x) = -\bar{\psi}(x)\mathcal{M}\psi(x) - \frac{B}{2}{\rm Tr}\left[\hat{\Phi}^2(x)\,\mathcal{M}\right],$$

$$iG_\psi(x,y) \to iG_0(x,y) \doteq u_0(\vec{x})\,\bar{u}_0(\vec{y})\,e^{-i\mathcal{E}_\alpha(x_0-y_0)}\,\theta(x_0-y_0),$$



Finite-range-regularization

$$G_E^N(Q^2)\Big|_{MC} = \frac{9}{400}\left(\frac{g_A}{\pi F}\right)^2 \int_0^\infty dp\, p^2 \int_{-1}^{1} dx (p^2 + p\sqrt{Q^2}x)$$

$$\times \mathcal{F}_{\pi NN}(p^2, Q^2, x)\, t_E^N(p^2, Q^2, x)\Big|_{MC},$$

$$t_E^p(p^2)|_{VC} = \frac{1}{2} W_\pi(p^2) - W_K(p^2) + \frac{1}{6} W_\eta(p^2), \qquad W_\Phi(p^2) = \frac{1}{w_\Phi^3(p^2)}$$

$$t_E^n(p^2)|_{VC} = W_\pi(p^2) - W_K(p^2),$$

$$\mathcal{F}_{\pi NN}(p^2, Q^2, x) = F_{\pi NN}(p^2) F_{\pi NN}(p^2 + Q^2 + 2p\sqrt{Q^2}x),$$

$$F_{\pi NN}(p^2) = \exp\left(-\frac{p^2R^2}{4}\right)\left\{1 + \frac{p^2R^2}{8}\left(1 - \frac{5}{3g_A}\right)\right\}$$

Finite-range-regularization

Non-local quark-meson coupling model

$$\mathcal{L}_{\rm int}^{\rm str}(x) = g_H H(x) \int\! dx_1 \!\int\! dx_2 F_H(x, x_1, x_2) \bar{q}_2(x_2) \Gamma_H \lambda_H q_1(x_1)$$

$$F_H(x, x_1, x_2) = \delta(x - w_{21}x_1 - w_{12}x_2) \Phi_H((x_1 - x_2)^2)$$

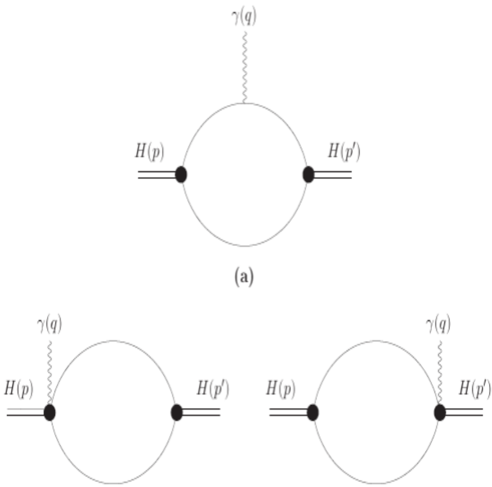
$$\begin{aligned}\mathcal{L}_{\rm int}^{\rm em(1)}(x) &= e\bar{q}(x)\, \not{A} Q\, q(x) \\ &+ ieA_\mu(x) \Big(H^-(x)\partial^\mu H^+(x) - H^+(x)\partial^\mu H^-(x) \Big) + e^2 A_\mu^2(x) H^-(x) H^+(x)\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\rm int}^{\rm str+em(2)}(x) &= g_H H(x) \int\! dx_1 \!\int\! dx_2 F_H(x, x_1, x_2) \bar{q}_2(x_2)\, e^{ie_{q_2} I(x_2, x, P)} \\ &\times \Gamma_H \lambda_H\, e^{-ie_{q_1} I(x_1, x, P)}\, q_1(x_1),\end{aligned}$$

$$I(x_i, x, P) = \int\limits_x^{x_i} dz_\mu A^\mu(z)$$

Finite-range-regularization

$$\Lambda^\mu(p,p') = \frac{q^\mu}{q^2}[\tilde{\Sigma}_\pi(p^2) - \tilde{\Sigma}_\pi(p'^{\,2})] + \Lambda^\mu_\perp(p,p')$$



(a) (b) (c)

$$\Lambda^\mu(p,p')\Big|_{p^2=p'^{\,2}=M_\pi^2} = P^\mu\, F_\pi(Q^2)$$

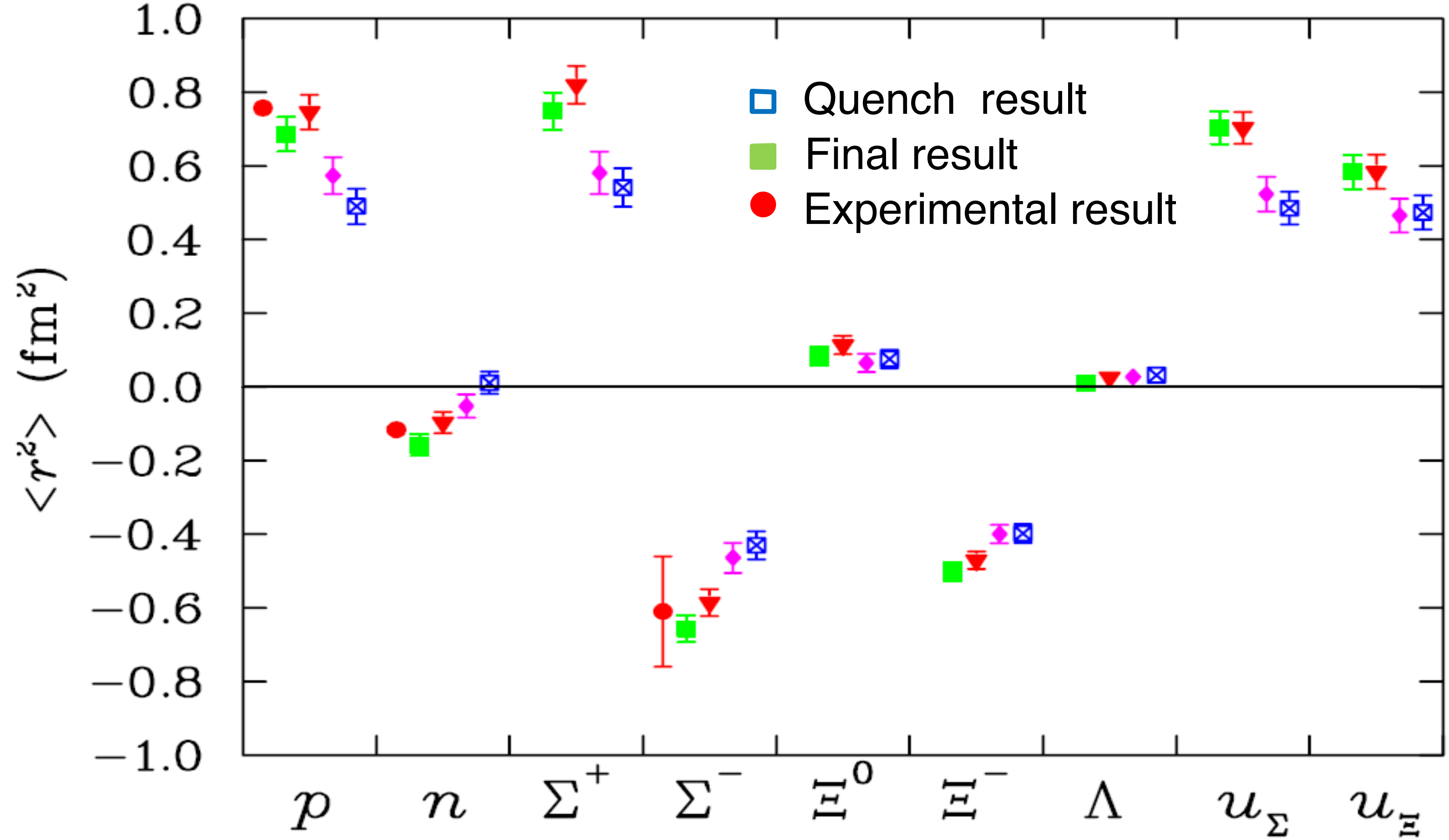
$$\Lambda^\mu_\perp(p,p') = \Lambda^\mu_{\triangle_\perp}(p,p') + \Lambda^\mu_{\mathrm{bub}_\perp}(p,p')$$

$$\Lambda^\mu_{\triangle_\perp(\mathrm{bub}_\perp)}(p,p') = \frac{3g^2}{4\pi^2}\, I^\mu_{\triangle_\perp(\mathrm{bub}_\perp)}(p,p')$$

$$I^\mu_{\triangle_\perp}(p,p') = \int \frac{d^4k}{4\pi^2 i}\,\tilde{\Phi}\left(-\left[k+\frac{p}{2}\right]^2\right)\tilde{\Phi}\left(-\left[k+\frac{p'}{2}\right]^2\right)\mathrm{tr}[\gamma^5 S(k+p')\gamma^\mu_{\perp;q} S(k+p)\gamma^5 S(k)]$$

Finite-range-regularization

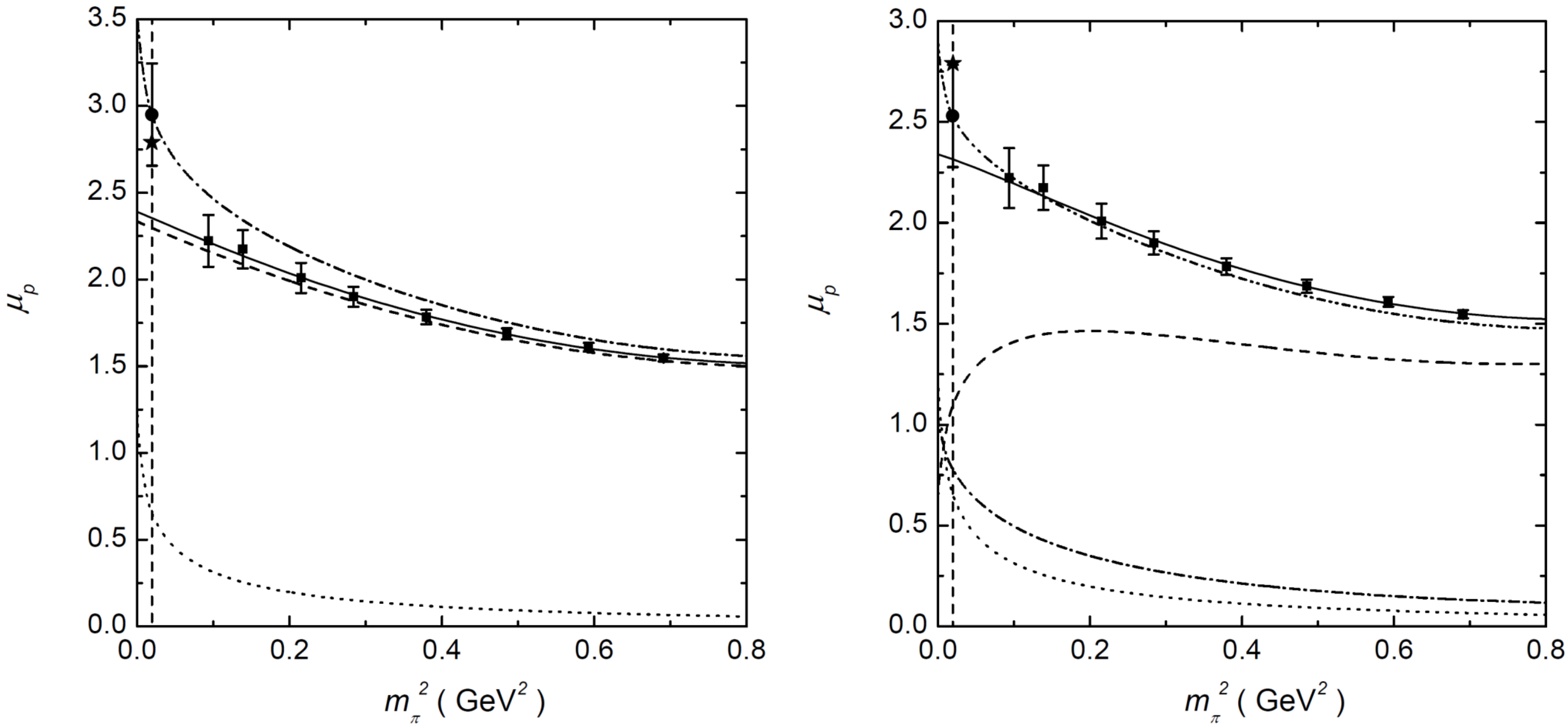
Baryon octet charge radii:



D. B. Leinweber, S. Boinepalli, A.W. Thomas, P. Wang, et at, Phys. Rev. Lett. 97 (2006) 022001
P. Wang, D. B. Leinweber, A. W. Thomas, R. Young, Phys. Rev. D 79 (2009) 094001

Finite-range-regularization

Chiral extrapolation of proton magnetic moment at LO and NLO



P. Wang, D. B. Leinweber, A. W. Thomas and R. D. Young, Phys. Rev. D 86 (2012) 94038

Axial charges

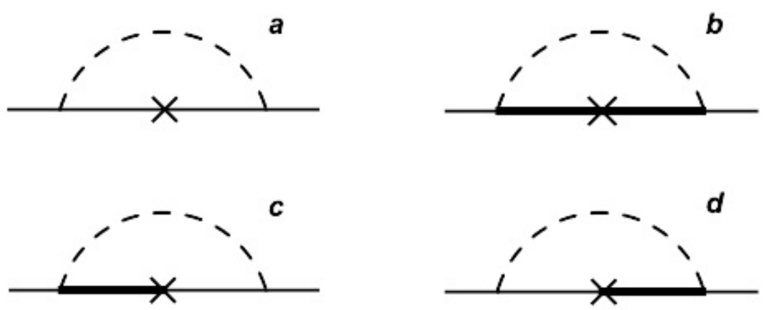
Heavy baryon chiral effective Lagrangian:

$$\begin{aligned}\mathcal{L}_v = & \; i\mathrm{Tr}\bar{B}_v(v\cdot\mathcal{D})B_v + 2D\mathrm{Tr}\bar{B}_v S_v^\mu\{A_\mu, B_v\} + 2F\mathrm{Tr}\bar{B}_v S_v^\mu[A_\mu, B_v] \\ & -i\bar{T}_v^\mu(v\cdot\mathcal{D})T_{v\mu} + \mathcal{C}(\bar{T}_v^\mu A_\mu B_v + \bar{B}_v A_\mu T_v^\mu),\end{aligned}$$

$$\begin{aligned}|g_A| s_\sigma &= 2\langle p,s|J_\sigma^{5,3}|p,s\rangle = (\Delta u - \Delta d)s_\sigma, \\ a_8 s_\sigma &= 2\sqrt{3}\langle p,s|J_\sigma^{5,8}|p,s\rangle = (\Delta u + \Delta d - 2\Delta s)s_\sigma, \\ a_0(\mu^2)s_\sigma &= \langle p,s|J_\sigma^{5}|p,s\rangle = (\Delta u + \Delta d + \Delta s)s_\sigma = \Delta\Sigma(\mu^2)s_\sigma\end{aligned}$$

$$J_{5\mu}^k = \overline{\psi}\gamma^\mu\gamma_5\frac{\lambda^k}{2}\psi$$

$$J_{5\mu} = \overline{\psi}\gamma^\mu\gamma_5\psi$$



Axial charges

Contribution from octet intermediate states:

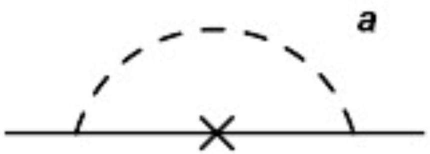
$$\Delta u^a = \left[C_{N\pi}\, I_{2\pi}^{NN} + C_{\Sigma K}\, I_{2K}^{N\Sigma} + C_{\Lambda\Sigma K}\, I_{5K}^{N\Lambda\Sigma} + C_{N\eta}\, I_{2\eta}^{NN}\right] s_u$$

$$C_{N\pi} = -\frac{(D+F)^2}{288\,\pi^3\, f_\pi^2},$$

$$C_{\Sigma K} = -\frac{5(D-F)^2}{288\,\pi^3\, f_\pi^2},$$

$$C_{\Lambda\Sigma K} = \frac{(D-F)\,(D+3F)}{288\,\pi^3\, f_\pi^2},$$

$$C_{N\eta} = -\frac{2}{3}\,\frac{(3F-D)^2}{288\,\pi^3\, f_\pi^2}.$$



$$s_p = \frac{4}{3} s_u - \frac{1}{3} s_d\,, \quad s_n = \frac{4}{3} s_d - \frac{1}{3} s_u$$

$$\Delta d^a = \left[\frac{7}{2} C_{N\pi}\, I_{2\pi}^{NN} + \frac{1}{5} C_{\Sigma K}\, I_{2K}^{N\Sigma} - C_{\Lambda\Sigma K}\, I_{5K}^{N\Lambda\Sigma} - \frac{1}{4} C_{N\eta}\, I_{2\eta}^{NN}\right] s_d$$

$$\Delta s^a = \left[-\frac{3}{10} C_{\Sigma K}\, I_{2K}^{N\Sigma} + C_{\Lambda K}\, I_{2K}^{N\Lambda}\right] s_s$$

Axial charges

Contribution from decuplet intermediate states:

$$\Delta u^b = \left[C_{\Delta\pi}\, I_{2\pi}^{N\Delta} + C_{\Sigma^* K}\, I_{2K}^{N\Sigma^*} \right] s_u$$

$$\Delta d^b = \left[\frac{2}{7} C_{\Delta\pi}\, I_{2\pi}^{N\Delta} + \frac{1}{5} C_{\Sigma^* K}\, I_{2K}^{N\Sigma^*} \right] s_d$$

$$\Delta s^b = \frac{3}{5} C_{\Sigma^* K}\, I_{2K}^{N\Sigma^*}\; s_s$$

$$s_{\Delta^+} = 2\, s_u + s_d\,, \quad s_{\Sigma^{*-}} = 2\, s_d + s_s$$

$$C_{\Delta\pi} = \frac{35\, \mathcal{C}^2}{648\, \pi^3\, f_\pi^2}\,,$$

$$C_{\Sigma^* K} = \frac{5}{28} C_{\Delta\pi}\,.$$

Axial charges

Contribution from octet-decuplet transition:

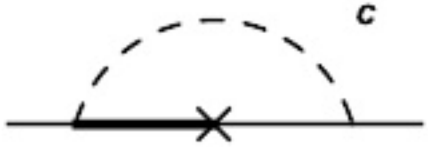
$$\Delta u^{c+d} = \left[C_{N\Delta\pi}\, I_{3\pi}^{N\Delta} + C_{\Sigma\Sigma^* K}\, I_{5K}^{N\Sigma\Sigma^*} + C_{\Lambda\Sigma^* K}\, I_{5K}^{N\Lambda\Sigma^*} \right]$$

$$C_{N\Delta\pi} = -\frac{(D+F)\,\mathcal{C}}{27\,\pi^3\, f_\pi^2},$$

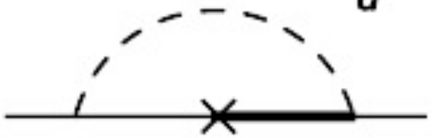
$$C_{\Sigma\Sigma^* K} = -\frac{5}{8}\,\frac{(D-F)\,\mathcal{C}}{27\,\pi^3\, f_\pi^2},$$

$$C_{\Lambda\Sigma^* K} = -\frac{1}{8}\,\frac{(D+3F)\,\mathcal{C}}{27\,\pi^3\, f_\pi^2}.$$

c



d



$$\Delta d^{c+d} = \left[-C_{N\Delta\pi}\, I_{3\pi}^{N\Delta} + \frac{1}{5}\, C_{\Sigma\Sigma^* K}\, I_{5K}^{N\Sigma\Sigma^*} - C_{\Lambda\Sigma^* K}\, I_{5K}^{N\Lambda\Sigma^*} \right] s_d$$

$$\Delta s^{c+d} = -\frac{6}{5}\, C_{\Sigma\Sigma^* K}\, I_{5K}^{N\Sigma\Sigma^*}\, s_s$$

Axial charges

The integrals are expressed as:

$$I_{2j}^{\alpha\beta} = \int d\overrightarrow{k} \frac{k^2 u(\overrightarrow{k})^2}{\omega_j(\overrightarrow{k})(\omega_j(\overrightarrow{k}) + \delta^{\alpha\beta})^2}$$

$$I_{3j}^{\alpha\beta} = \int d\overrightarrow{k} \frac{k^2 u(\overrightarrow{k})^2}{\omega_j(\overrightarrow{k})^2(\omega_j(\overrightarrow{k}) + \delta^{\alpha\beta})}$$

$$I_{5j}^{\alpha\beta\gamma} = \int d\overrightarrow{k} \frac{k^2 u(\overrightarrow{k})^2}{\omega_j(\overrightarrow{k})(\omega_j(\overrightarrow{k}) + \delta^{\alpha\beta})(\omega_j(\overrightarrow{k}) + \delta^{\alpha\gamma}))}$$

dipole regulator:

$$u(k) = \frac{1}{(1 + k^2/\Lambda^2)^2}$$

The proton spin carried by each quarks:

$$\begin{aligned}
\Delta u &= \frac{4}{3} Z s_u + \Delta u^a + \Delta u^b + \Delta u^{c+d}, \\
\Delta d &= -\frac{1}{3} Z s_d + \Delta d^a + \Delta d^b + \Delta d^{c+d}, \\
\Delta s &= \Delta s^a + \Delta s^b + \Delta s^{c+d}.
\end{aligned}$$

Axial charges

Only one parameter *Sq* (*Su* = *Sd* = *Ss* = *Sq*) determined by $g_A = 1.27$.

$$s_q = 0.79 \qquad \Delta u = 0.94\,, \quad \Delta d = -0.33\,, \quad \Delta s = -0.01$$

$$a_8 = 0.63 \text{ and } \Sigma = 0.61$$

D	F	C	Z	s_q	Δu	Δd	Δs	g_A	a_8	Σ
0.8	0.46	-1.2	0.71	0.79	0.94	-0.33	-0.009	1.27	0.63	0.61
0.8	0.46	-1.5	0.68	0.75	0.95	-0.32	-0.008	1.27	0.65	0.63
0.76	0.5	-1.2	0.71	0.79	0.94	-0.33	-0.008	1.27	0.63	0.61
0.76	0.5	-1.5	0.68	0.75	0.95	-0.32	-0.006	1.27	0.65	0.63

regulator	Λ (GeV)	Z	s_q	Δu	Δd	Δs	g_A	a_8	Σ
dipole	0.7	0.77	0.80	0.96	−0.31	−0.006	1.27	0.66	0.65
	0.8	0.71	0.79	0.94	−0.33	−0.009	1.27	0.63	0.61
	0.9	0.64	0.76	0.92	−0.35	−0.012	1.27	0.60	0.56
monopole	0.434	0.72	0.78	0.95	-0.32	-0.010	1.27	0.65	0.62
	0.496	0.65	0.76	0.93	-0.34	-0.014	1.27	0.62	0.58
	0.558	0.58	0.72	0.91	-0.36	-0.019	1.27	0.59	0.53
Gaussian	0.539	0.81	0.801	0.97	-0.30	-0.004	1.27	0.68	0.66
	0.616	0.75	0.798	0.95	-0.32	-0.006	1.27	0.64	0.63
	0.693	0.68	0.78	0.93	-0.34	-0.009	1.27	0.61	0.59
sharp cutoff	0.366	0.85	0.803	0.98	-0.29	-0.002	1.27	0.69	0.68
	0.418	0.79	0.807	0.96	-0.31	-0.003	1.27	0.66	0.65
	0.470	0.73	0.803	0.94	-0.33	-0.005	1.27	0.62	0.61

Axial charges

After the inclusion of one gluon exchange:

$$s_q = 0.82 \qquad \Delta u = 0.90\,, \qquad \Delta d = -0.38\,, \qquad \Delta s = -0.01$$

$$a_8 \;=\; 0.53 \text{ and } \Sigma = 0.51$$

D	F	C	Z	s_q	Δu	Δd	Δs	g_A	a_8	Σ
0.8	0.46	-1.2	0.71	0.82	0.90	-0.38	-0.007	1.27	0.53	0.51
0.8	0.46	-1.5	0.68	0.78	0.90	-0.37	-0.006	1.27	0.55	0.53
0.76	0.5	-1.2	0.71	0.82	0.89	-0.38	-0.007	1.27	0.53	0.51
0.76	0.5	-1.5	0.68	0.78	0.90	-0.37	-0.005	1.27	0.54	0.53

regulator	Λ (GeV)	Z	s_q	Δu	Δd	Δs	g_A	a_8	Σ
	0.7	0.77	0.83	0.91	−0.36	−0.005	1.27	0.56	0.55
dipole	0.8	0.71	0.82	0.90	−0.38	−0.007	1.27	0.53	0.51
	0.9	0.64	0.79	0.88	−0.40	−0.010	1.27	0.50	0.47
	0.434	0.72	0.81	0.90	-0.37	-0.008	1.27	0.55	0.53
monopole	0.496	0.65	0.79	0.88	-0.39	-0.012	1.27	0.52	0.49
	0.558	0.58	0.75	0.87	-0.41	-0.016	1.27	0.49	0.45
	0.539	0.81	0.831	0.92	-0.35	-0.003	1.27	0.57	0.56
Gaussian	0.616	0.75	0.828	0.90	-0.37	-0.005	1.27	0.55	0.53
	0.693	0.68	0.81	0.89	-0.39	-0.008	1.27	0.52	0.50
	0.366	0.85	0.833	0.93	-0.35	-0.001	1.27	0.59	0.58
sharp cutoff	0.418	0.79	0.837	0.91	-0.36	-0.002	1.27	0.56	0.55
	0.470	0.73	0.833	0.90	-0.38	-0.004	1.27	0.53	0.52

Axial charges

If S_q is chosen to be 0.65, then:

$$g_A = 1.00, \quad \Delta u = 0.70, \quad \Delta d = -\ 0.31, \quad \Delta s = -\ 0.01$$

$$a_8 = 0.40, \quad \Sigma = 0.38$$

D	F	C	Z	s_q	Δu	Δd	Δs	g_A	a_8	Σ
0.8	0.46	−1.2	0.71	0.65	0.70	−0.31	−0.006	1.00	0.40	0.38
0.8	0.46	−1.5	0.68	0.65	0.74	−0.31	−0.005	1.05	0.43	0.42
0.76	0.5	−1.2	0.71	0.65	0.69	−0.30	−0.005	1.00	0.40	0.38
0.76	0.5	−1.5	0.68	0.65	0.73	−0.31	−0.004	1.05	0.43	0.42

$\Lambda = 0.8 \pm 0.2$ GeV

$$\Delta u = +0.90\,^{+0.03}_{-0.04},$$

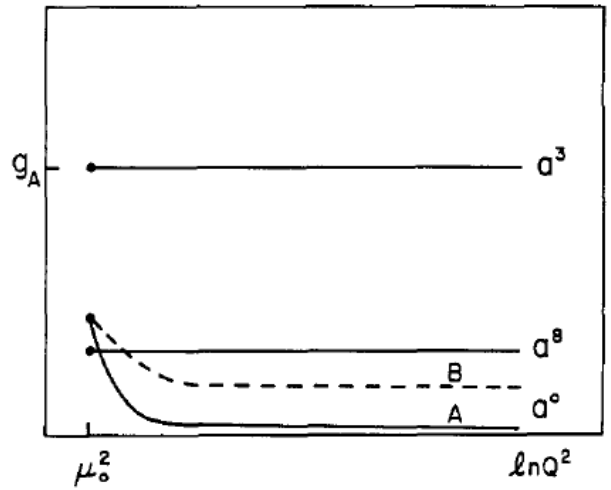
$$\Delta d = -0.38\,^{+0.03}_{-0.03},$$

$$\Delta s = -0.007\,^{+0.004}_{-0.007}.$$

$$a_0 = \Sigma = 0.51\,^{+0.07}_{-0.08}, \quad \text{and} \quad a_8 = 0.53\,^{+0.06}_{-0.06}$$

Axial charges

Q^2 evolution



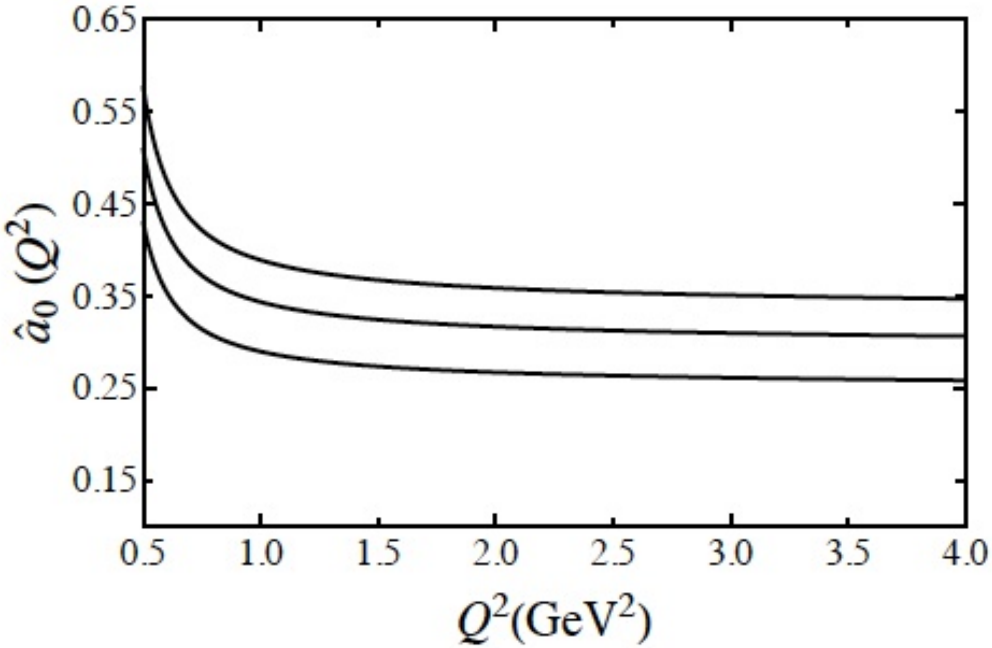
R. L. Jaffe, Phys.Lett. B 193 (1987) 101

$$\frac{d}{dt}\,\hat{a}_0(t) = -N_f\,\frac{\alpha_s}{2\pi}\,\gamma_{gq}\,\hat{a}_0(t)$$

$$\log\frac{\hat{a}_0(Q^2)}{\hat{a}_0(\mu^2)} = \frac{6N_f}{33-2N_f}\,\frac{\alpha_s(Q^2)-\alpha_s(\mu^2)}{\pi} \times\left[1+\left(\frac{83}{24}+\frac{N_f}{36}-\frac{33-2N_f}{8(153-19N_f)}\right)\times\frac{\alpha_s(Q^2)+\alpha_s(\mu^2)}{\pi}\right]$$

S. A. Larin, Phys. Lett. B 303 (1993) 113.

Axial charges



$$\hat{a}_0(3\ \mathrm{GeV}^2) = 0.31\,^{+0.04}_{-0.05}$$

TABLE I: The predictions of the meson-cloud model presented herein for proton spin structure as a function of the regulator parameter, $\Lambda = 0.8 \pm 0.2$, governing the size of the meson-cloud dressings of the proton.

Λ (GeV)	Z	s_q	Δu	Δd	Δs	g_A	a_8	Σ	$\hat{a}_0$ (3 GeV^2)
0.6	0.84	0.83	0.93	−0.35	−0.003	1.27	0.59	0.58	0.35
0.8	0.71	0.82	0.90	−0.38	−0.007	1.27	0.53	0.51	0.31
1.0	0.58	0.76	0.86	−0.41	−0.014	1.27	0.47	0.43	0.26

H. N. Li, P. Wang, D. B. Leinweber and A. W. Thomas, Phys. Rev. C 93 (2016) 045203

Summary (proton spin)

- At low energy scales the total quark spin contribution to the proton spin, $\Sigma = 0.51^{+0.07}_{-0.08}$, is of order one half in the valence quark region.

- The parameter *Sq* reflecting the role of relativistic and confinement effects and constrained by a_3 is around 0.82, smaller than 1 as expected but larger than the typical “ultra-relativistic” value 0.65.

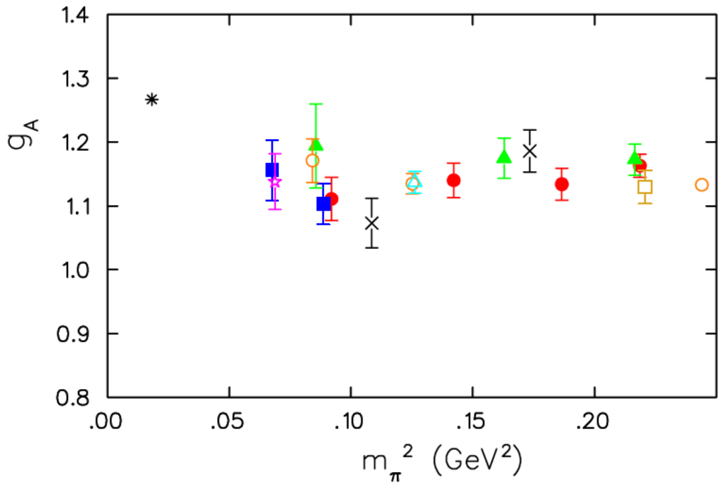
- The non-singlet axial charge $a_8 = 0.53\,^{+0.06}_{-0.06}$ lies between the value extracted from the hyperon beta decays under the assumption of SU(3) symmetry 0.58 ± 0.03 and the value 0.46 ± 0.05 obtained in the cloudy bag model.

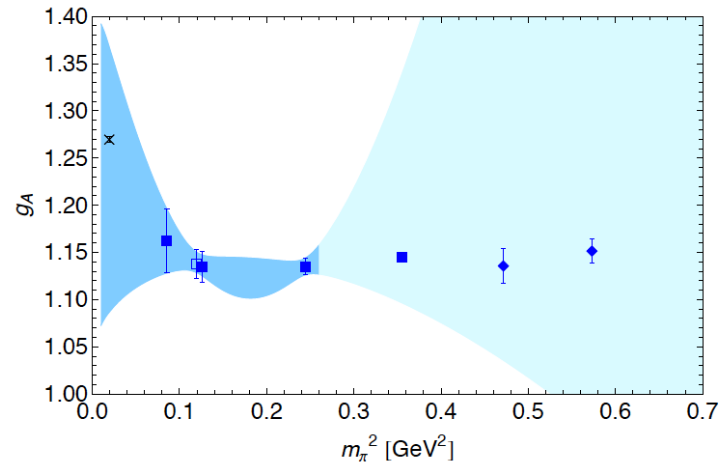
- The strange quark contribution to the proton spin is very small and negative and its absolute value is of the order 0.01.

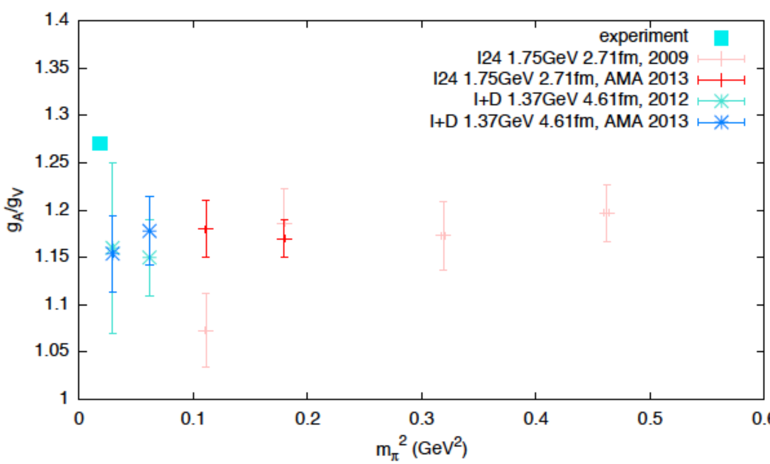
- The experimental value of a_0 at 3 GeV^2 is reproduced through a combination of the chiral correction and Q^2 evolution of Sigma from the scale of 0.5 GeV^2. We find a_0 (3 GeV^2) is $0.31^{+0.04}_{-0.05}$ which agrees with the experimental measurement $0.35 \pm 0.03(stat.) \pm 0.05(syst.)$

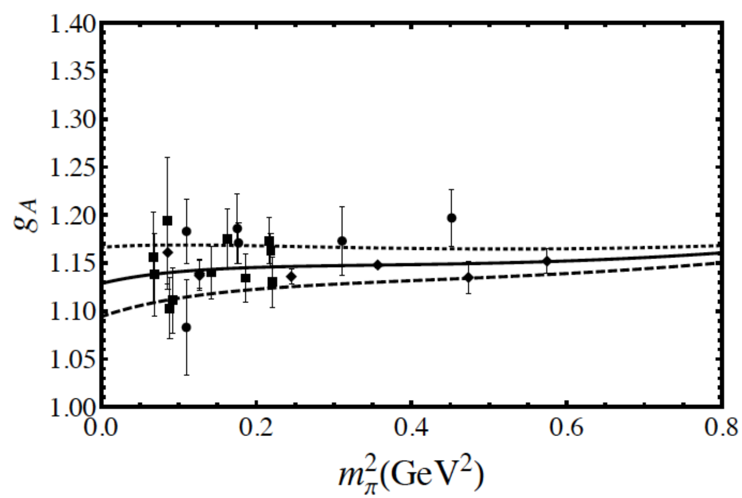
Axial charge g_A

$$
\begin{aligned}
|g_A| s_\sigma &= 2\langle p, s|J_\sigma^{5,3}|p, s\rangle = (\Delta u - \Delta d)s_\sigma, \\
a_8 s_\sigma &= 2\sqrt{3}\langle p, s|J_\sigma^{5,8}|p, s\rangle = (\Delta u + \Delta d - 2\Delta s)s_\sigma, \\
a_0(\mu^2) s_\sigma &= \langle p, s|J_\sigma^{5}|p, s\rangle = (\Delta u + \Delta d + \Delta s)s_\sigma = \Delta\Sigma(\mu^2)s_\sigma
\end{aligned}
$$









Axial charge g_A

$$g_A \equiv a_3 = \Delta u - \Delta d$$

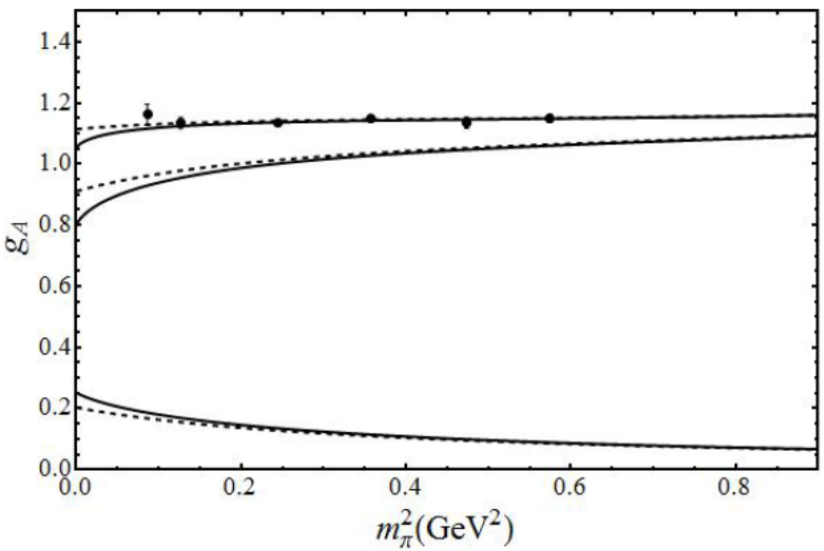
$$\begin{aligned} \Delta u &= Z[\frac{4}{3}(c_0 + c_2 m_\pi^2 + c_4 m_\pi^4) + \Delta u^a + \Delta u^b + \Delta u^{c+d}], \\ \Delta d &= Z[-\frac{1}{3}(c_0 + c_2 m_\pi^2 + c_4 m_\pi^4) + \Delta d^a + \Delta d^b + \Delta d^{c+d}] \end{aligned}$$

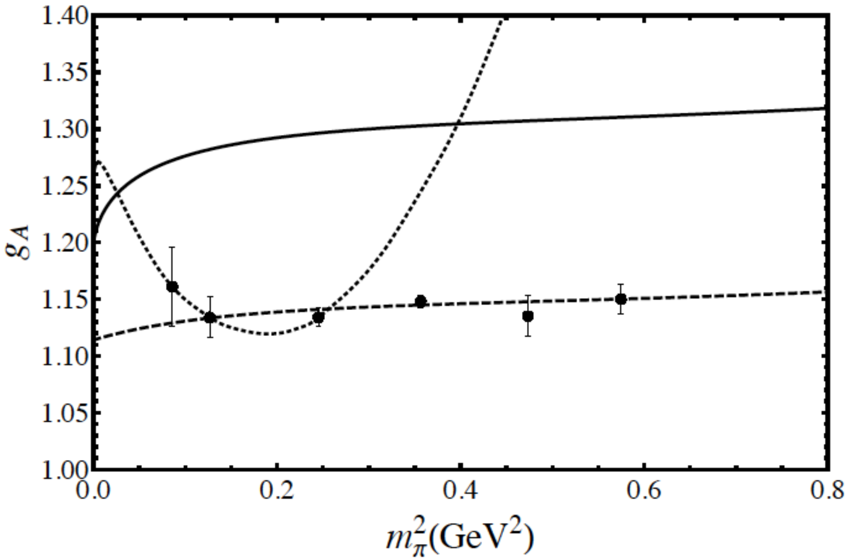
$$\int d\mathbf{k} f(\mathbf{k}) = \sum_{n_x, n_y, n_z} \left(\frac{2\pi}{L}\right)^3 f(n_x, n_y, n_z)$$

$$k_x = \frac{2\pi}{L} n_x, \quad k_y = \frac{2\pi}{L} n_y, \quad k_z = \frac{2\pi}{L} n_z$$

Λ (GeV)	c_0	c_2 (GeV^{-2})	c_4 (GeV^{-4})	Z	Δu	Δd	Δs	g_A	a_8	Σ	$\hat{a}_0$
0.6	0.73	-0.03	0.03	0.90	0.84	-0.30	-0.002	1.137	0.55	0.54	0.33
0.8	0.77	-0.08	0.06	0.77	0.82	-0.31	-0.005	1.134	0.52	0.50	0.31
1.0	0.81	-0.12	0.09	0.62	0.80	-0.33	-0.010	1.133	0.49	0.46	0.28

Axial charge g_A

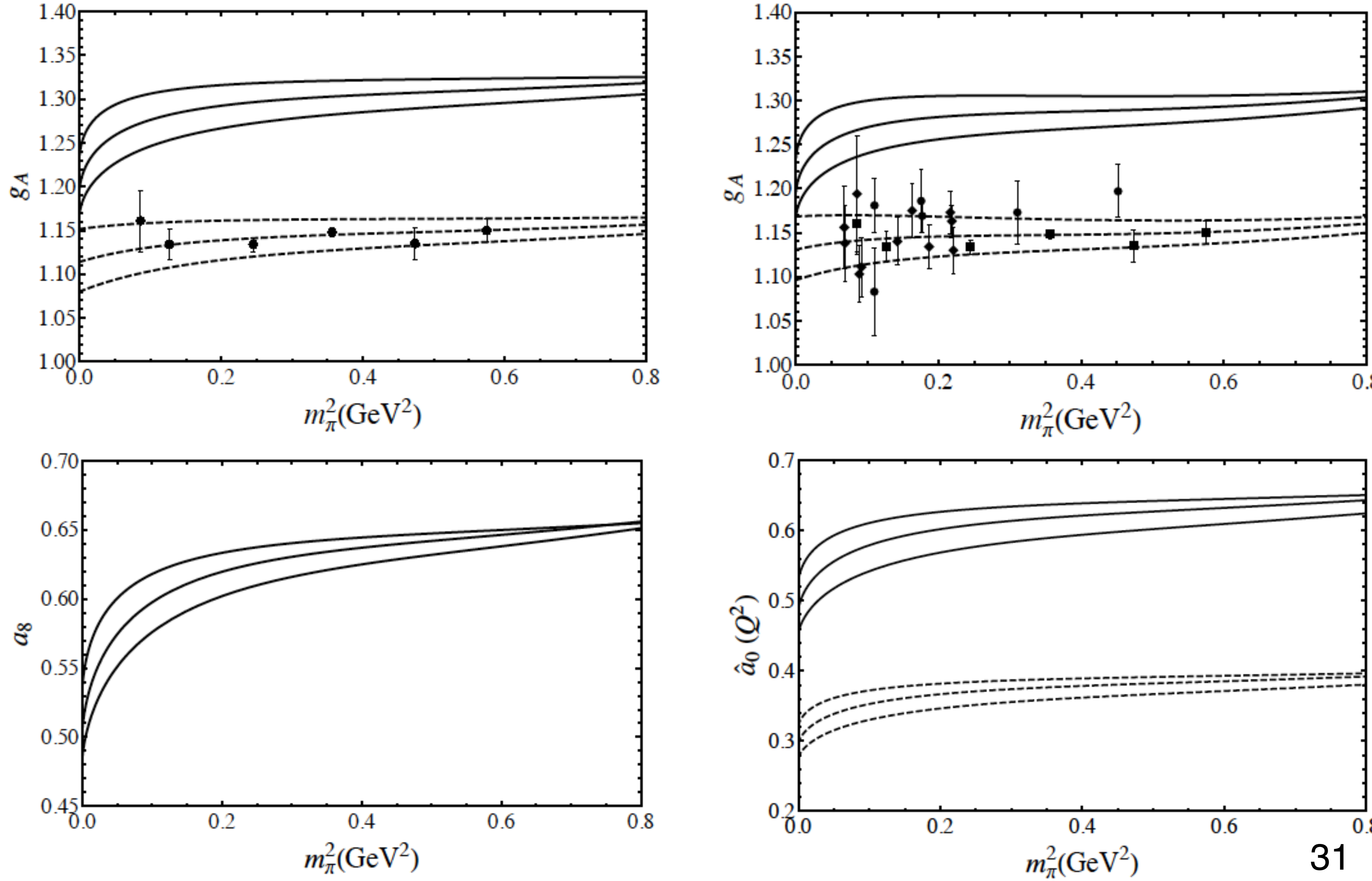




$$\frac{s_q^\infty}{s_q^L} = \frac{c_i^\infty}{c_i^L} = \frac{1.27}{g_A^L}$$

Λ (GeV)	c_0	c_2 (GeV^{-2})	c_4 (GeV^{-4})	Z	Δu	Δd	Δs	g_A	a_8	Σ	$\hat{a}_0$
0.6	0.82	-0.03	0.03	0.84	0.90	-0.33	-0.003	1.236	0.58	0.57	0.35
0.8	0.86	-0.09	0.07	0.71	0.89	-0.35	-0.006	1.236	0.55	0.53	0.32
1.0	0.90	-0.13	0.10	0.58	0.87	-0.37	-0.011	1.242	0.52	0.49	0.30

Axial charge g_A



u/d quark in Σ^-/ Σ^+

At $Q^2 = 0.1$ GeV^2

$G_M^s(0.1) = 0.37 \pm 0.20 \pm 0.26 \pm 0.07$ SAMPLE 2004

$G_M^s(0.1) = 0.23 \pm 0.36 \pm 0.40$ SAMPLE 2005

$G_E^s(0.109) + 0.09 G_M^s(0.109) = 0.007 \pm 0.011 \pm 0.006$ HAPPEX-II 2007

At $Q^2 = 0.23$ GeV^2

$G_E^s(0.23) + 0.225 G_M^s(0.23) = 0.039 \pm 0.034$ PAV4 2004

$G_E^s(0.23) + 0.26 G_M^s(0.23) = -0.12 \pm 0.11 \pm 0.11$ PAV4 2009

$G_E^s(0.23) + 0.224 G_M^s(0.23) = 0.020 \pm 0.029 \pm 0.016$ PAV4 2009

At $Q^2 = 0.477$ GeV^2

$G_E^s(0.477) + 0.392 G_M^s(0.477) = 0.014 \pm 0.020 \pm 0.010$ HAPPEX-I 2004

At $Q^2 = 0.62$ GeV^2

$G_E^s(0.62) + 0.517 G_M^s(0.62) = 0.003 \pm 0.010 \pm 0.004 \pm 0.009$ HAPPEX-III 2012

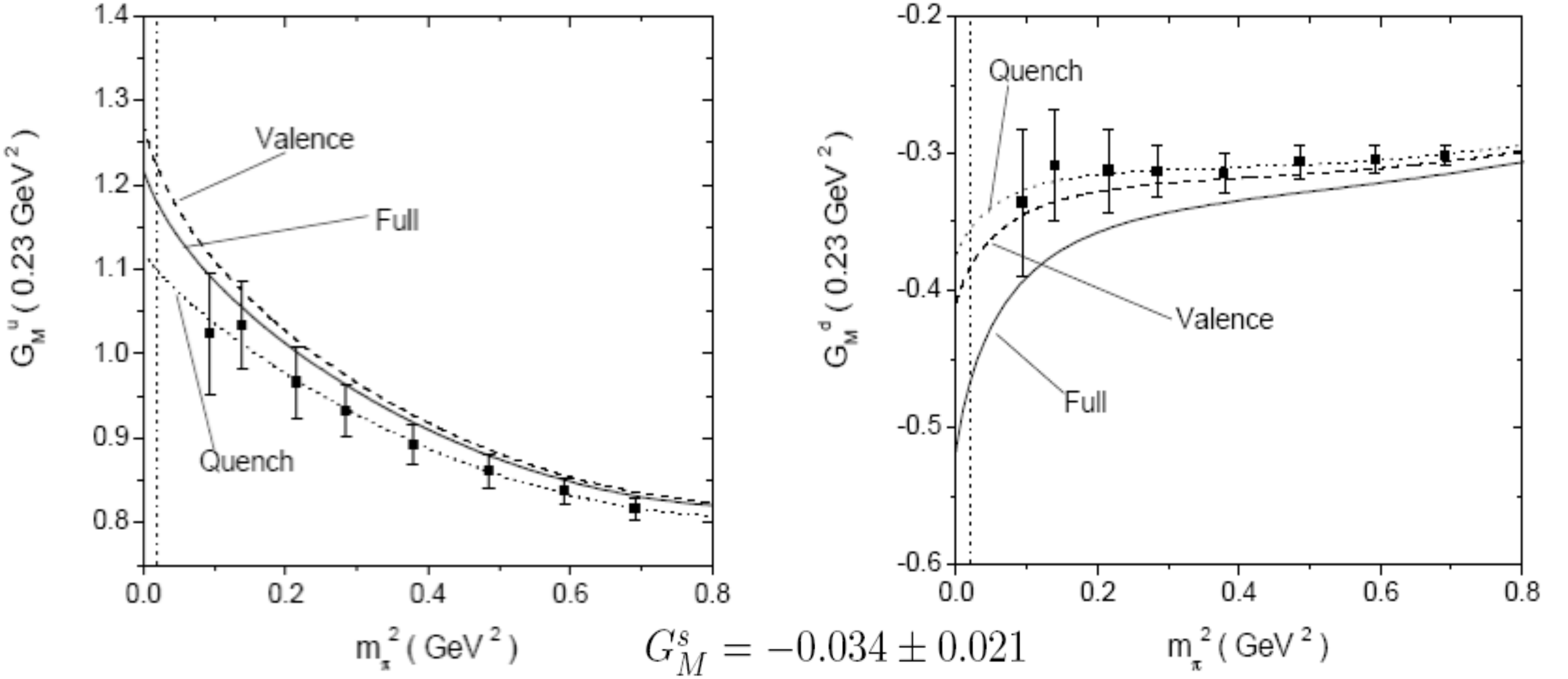
u/d quark in Σ^-/ Σ^+

Approach	μ^s (n.m.)	$< r^2 >^s_E$ (fm^2)	$< r^2 >^s_M$ (fm^2)	ρ^s	$\rho^s + \mu_p \mu^s$
QCD equalities [7]	-0.75 ± 0.30				
Lattice QCD [8]	-0.16 ± 0.18				
Lattice QCD [9]	-0.36 ± 0.20	-0.16 ± 0.06		2.02 ± 0.75	1 ± 0.75
Lattice QCD [10]	-0.28 ± 0.10				
HBChPT [12]	0.18 ± 0.34	0.05 ± 0.09	-0.14		
Poles [13]	-0.31 ± 0.09	0.14 ± 0.07		-2.1	-2.97
Poles [14]	-0.185 ± 0.075	0.14 ± 0.06		-2.93	-3.60
Poles [15]	-0.24 ± 0.03				
Kaon loop [16]	-0.355 ± 0.045	-0.0297 ± 0.0026			
Kaon loop + VMD [17]	-0.28 ± 0.04	-0.0425 ± 0.0026			
Skyrme model [19]	-0.13	-0.11		1.64	1.27
NJL soliton model [20]	0.10 ± 0.15	-0.15 ± 0.05		3.06	2.92
χQSM [21]	0.115	-0.095	0.073		
CBM [22]	0.37				
CQM [23]	~ -0.05				
CQM [24]	-0.046		~ 0.02		
PCQM	-0.048 ± 0.012	-0.011 ± 0.003	-0.024 ± 0.003	0.17 ± 0.04	0.05

V. Lyubovitskij, P. Wang, T. Gutsche, A. Faessler, Phys. Rev. C 66 (2002) 055204

u/d quark in Σ^-/Σ^+

Strange magnetic form factor:



$$G_M^s = -0.034 \pm 0.021$$

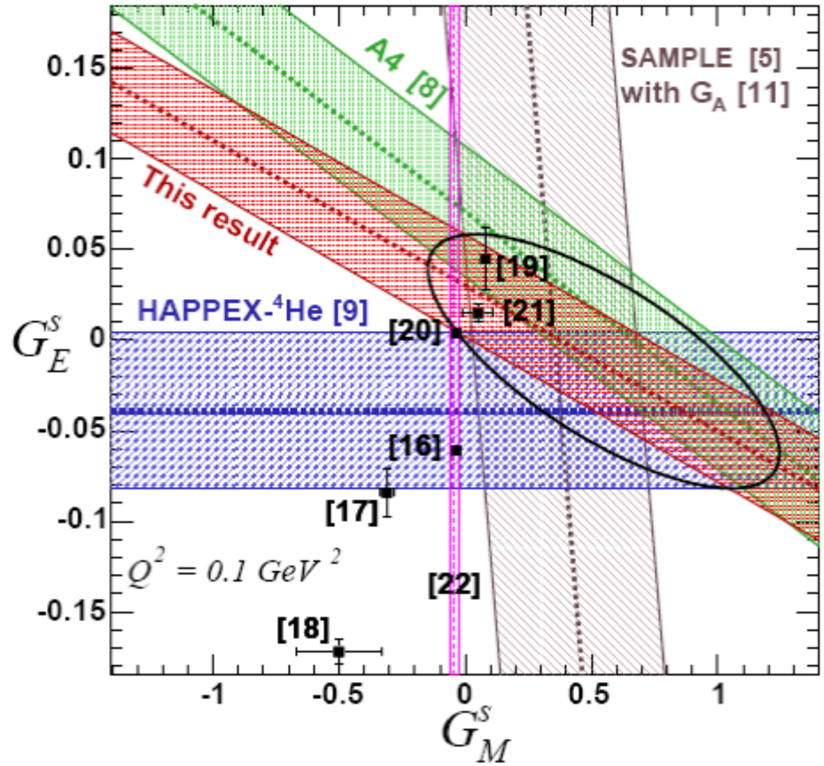
TABLE II: The strange magnetic form factor at different Q^2. Uncertainties reflect the range of Λ considered herein.

Q^2 (GeV^2)	0	0.1	0.23	0.477	0.62
$G_M^s(Q^2)$	$-0.058^{+0.034}_{-0.053}$	$-0.052^{+0.031}_{-0.051}$	$-0.046^{+0.029}_{-0.048}$	$-0.038^{+0.024}_{-0.040}$	$-0.035^{+0.023}_{-0.040}$

P. Wang, D. B. Leinweber, A. W. Thomas and R. D. Young, Phys. Rev. C 79 (2009) 065202
P. Wang, D. B. Leinweber and A. W. Thomas, Phys. Rev. D 89 (2014) 033008

u/d quark in Σ^- / Σ^+

HAPPEX Collaboration
Phys. Lett. B635 (2006) 275



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[8] F. E. Mass *et al*, Phys. Rev. Lett. 94 (2005) 152001
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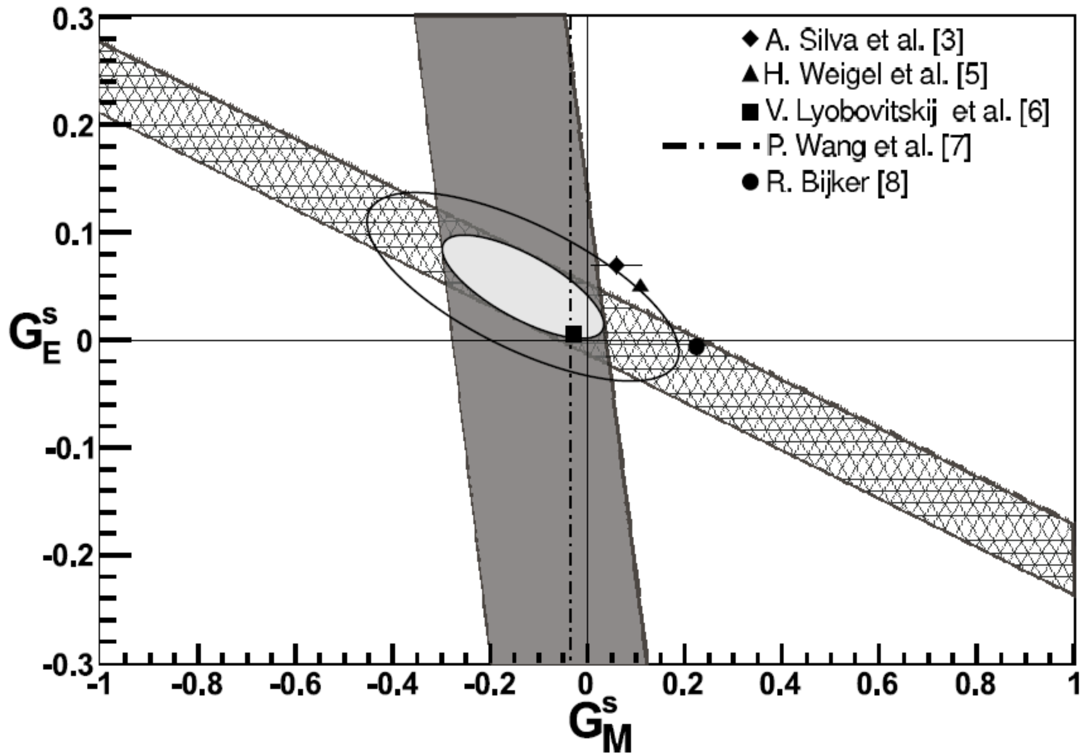
u/d quark in Σ^- / Σ^+

S. Baunack *et al.,* Phys.Rev.Lett. 102(2009)151803



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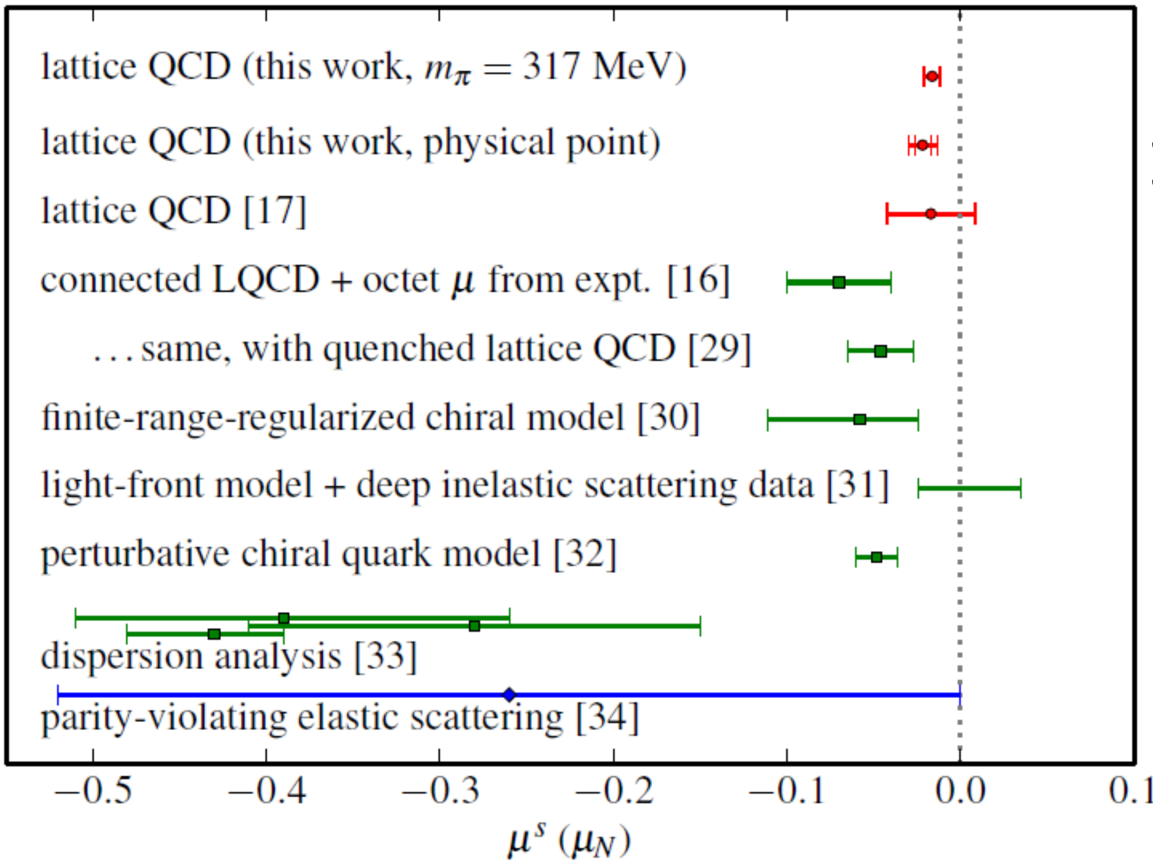
[8] R. Bijker, J. Phys. G32 (2006) L49

u/d quark in Σ^- / Σ^+



J.Green, S. Meinel, M. Engelhardt, S. Krieg, J. Laeuchli, J. Negele, K. Orginos, A. Pochinsky, S. Syritsyn, arXiV:1505.01803 [hep-lat].

$$(r_E^2)^s = -0.0067(10)(17)(15)\ \text{fm}^2,$$
$$(r_M^2)^s = -0.018(6)(5)(5)\ \text{fm}^2,$$
$$\mu^s = -0.022(4)(4)(6)\ \mu_N,$$

PCQM
-0.011 +- 0.003
-0.024 +- 0.003
-0.048 +- 0.012

[30] P. Wang, D. B. Leinweber and A. W. thomas, Phys. Rev. D 89 (2014) 033008
[32] V. Lyubovitskij, P. Wang, T. Gutsche, A. Faessler, Phys.Rev.C66 (2002) 055204

u/d quark in Σ^-/ Σ^+

$uuds$ ground state		$uuds$ $P-$state	
$[31]_{FS}[211]_F[22]_S$	(-16)	$[4]_{FS}[22]_F[22]_S$	(-28)
$[31]_{FS}[211]_F[31]_S$	(-40/3)	$[4]_{FS}[31]_F[31]_S$	(-64/3)
$[31]_{FS}[22]_F[31]_S$	(-28/3)	$[31]_{FS}[211]_F[22]_S$	(-16)
$[31]_{FS}[31]_F[22]_S$	(-8)	$[31]_{FS}[211]_F[31]_S$	(-40/3)
$[31]_{FS}[31]_F[31]_S$	(-16/3)	$[31]_{FS}[22]_F[31]_S$	(-28/3)
$[31]_{FS}[31]_F[4]_S$	(0)	$[31]_{FS}[31]_F[22]_S$	(-8)
$[31]_{FS}[4]_F[31]_S$	(+8/3)	$[4]_{FS}[4]_F[4]_S$	(-8)
		$[22]_{FS}[211]_F[31]_S$	(-16/3)
		$[31]_{FS}[31]_F[31]_S$	(-16/3)
		$[22]_{FS}[22]_F[22]_S$	(4)
		$[211]_{FS}[211]_F[22]_S$	(0)
		$[31]_{FS}[31]_F[4]_S$	(0)
		$[211]_{FS}[211]_F[31]_S$	(8/3)
		$[22]_{FS}[31]_F[31]_S$	(8/3)
		$[31]_{FS}[4]_F[31]_S$	(8/3)
		$[22]_{FS}[22]_F[4]_S$	(4)
		$[211]_{FS}[22]_F[31]_S$	(20/3)
		$[211]_{FS}[211]_F[4]_S$	(8)
		$[211]_{FS}[31]_F[22]_S$	(8)
		$[22]_{FS}[4]_F[22]_S$	(8)
		$[211]_{FS}[31]_F[31]_S$	(32/3)

negative strange magnetic moment for the configurations on the left side

positive strange magnetic moment for the configurations on the right side

positive strange magnetic moments for the diquark-diquark-antistrange quark configuration

negative strange magnetic moments for the {ud}{ussbar} configuration

B.S. Zou and D.O. Riska, PRL95(2005)072001

u/d quark in Σ^-/Σ^+

Heavy baryon chiral effective Lagrangian:

$$\begin{aligned}\mathcal{L}_v &= i\mathrm{Tr}\bar{B}_v(v\cdot\mathcal{D})B_v + 2D\mathrm{Tr}\bar{B}_v S_v^\mu\{A_\mu, B_v\} + 2F\mathrm{Tr}\bar{B}_v S_v^\mu[A_\mu, B_v] \\ &\quad -i\bar{T}_v^\mu(v\cdot\mathcal{D})T_{v\mu} + \mathcal{C}(\bar{T}_v^\mu A_\mu B_v + \bar{B}_v A_\mu T_v^\mu),\end{aligned}$$

$$\mathcal{L} = \frac{e}{4m_N}\left(\mu_D \mathrm{Tr}\bar{B}_v\sigma^{\mu\nu}\left\{F_{\mu\nu}^+, B_v\right\} + \mu_F\mathrm{Tr}\bar{B}_v\sigma^{\mu\nu}\left[F_{\mu\nu}^+, B_v\right]\right)$$

$$\mathcal{L} = -i\frac{e}{m_N}\mu_C q_{ijk}\bar{T}^\mu_{v,ikl}T^\nu_{v,jkl}F_{\mu\nu}$$

$$\mathcal{L} = i\frac{e}{2m_N}\mu_T F_{\mu\nu}\left(\epsilon_{ijk}Q^i_l\bar{B}^j_{vm}S_v^\mu T_v^{\nu,klm} + \epsilon^{ijk}Q^l_i\bar{T}^\mu_{v,klm}S^\nu_v B^m_{vj}\right)$$

$$< B(p')|J_\mu|B(p) >= \bar{u}(p')\left\{v_\mu G_E(Q^2) + \frac{i\epsilon_{\mu\nu\alpha\beta}v^\alpha S_v^\beta q^\nu}{m_N}G_M(Q^2)\right\}u(p)$$

u/d quark in Σ^-/ Σ^+

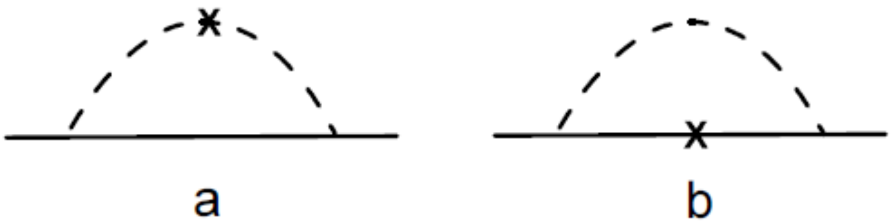


FIG. 1: Feymann diagrams for the calculation of the magnetic form factor of the Σ^+. Diagrams a and b correspond to the leading- and next-to-leading-order diagrams, respectively.

Leading order contribution: $G^{d\,(1a)}_{\Sigma^+} = P_{\pi^+\Sigma^0} + P_{\pi^+\Lambda} + P_{\pi^+\Sigma^{*0}}$

Octet intermediate state:

$$P_{\pi^+\Sigma^0} = -\frac{m_\Sigma\, F^2}{12\,\pi^3\, f_\pi^2} \int d^3k \frac{k^2\, u_1\, u_2}{\omega_1^2\, \omega_2^2} \qquad P_{\pi^+\Lambda} = \frac{D^2}{3F^2}\, P_{\pi^+\Sigma^0}$$

Decuplet intermediate state:

$$P_{\pi^+\Sigma^{*0}} = \frac{m_\Sigma\, \mathcal{C}^2}{432\,\pi^3\, f_\pi^2} \int d^3k \frac{k^2\, u_1\, u_2\, (1 + \Delta/(\omega_1 + \omega_2))}{\omega_1\, \omega_2\, (\omega_1 + \Delta)\, (\omega_2 + \Delta)}$$

u/d quark in Σ⁻/ Σ⁺

Next to Leading order contribution: $G^{d(1b)}_{\Sigma^+} = P_{\Sigma^0} \cdot \mu^d_{\Sigma^0} + P_{\Sigma^{*0}} \cdot \mu^d_{\Sigma^{*0}} + P_{\Sigma^{*0}\Sigma^0(\Lambda)} \cdot \mu^d$

Octet intermediate state: $$P_{\Sigma^0} = \frac{F^2}{16\pi^3 f_\pi^2} \int d^3k \frac{k^2 u_k^2}{\omega_k^3}$$

Decuplet intermediate state: $$P_{\Sigma^{*0}} = -\frac{5\mathcal{C}^2}{864\pi^3 f_\pi^2} \int d^3k \frac{k^2 u_k^2}{\omega_k(\omega_k + \Delta)^2}$$

Octet-decuplet transition: $$P_{\Sigma^{*0}\Sigma^0(\Lambda)} = -\frac{(D-F)\mathcal{C}}{36\pi^3 f_\pi^2} \int d^3k \frac{k^2 u_k^2}{\omega_k^2(\omega_k + \Delta)}$$

Tree level: $$\mu^d_{\Sigma^0} = \frac{2}{3}\mu^d_{\Sigma^{*0}} = \frac{2}{3}\mu_d \qquad \mu^d_{\Sigma^0\Sigma^{*0}} = \frac{\sqrt{3}}{3}\mu^d_{\Lambda\Sigma^{*0}} = \frac{\sqrt{2}}{3}\mu_d$$

u/d quark in Σ^-/Σ^+

TABLE I: d quark contributions to the magnetic moment of the Σ^+ in unit of μ_N at different Λ.

Λ (GeV)	0.6	0.7	0.8	0.9	1.0
LO	−0.21	-0.27	−0.34	−0.42	−0.49
NLO	−0.017	-0.025	−0.035	−0.045	−0.057
$G^d_{\Sigma^+}$	−0.22	−0.30	−0.38	−0.46	−0.55

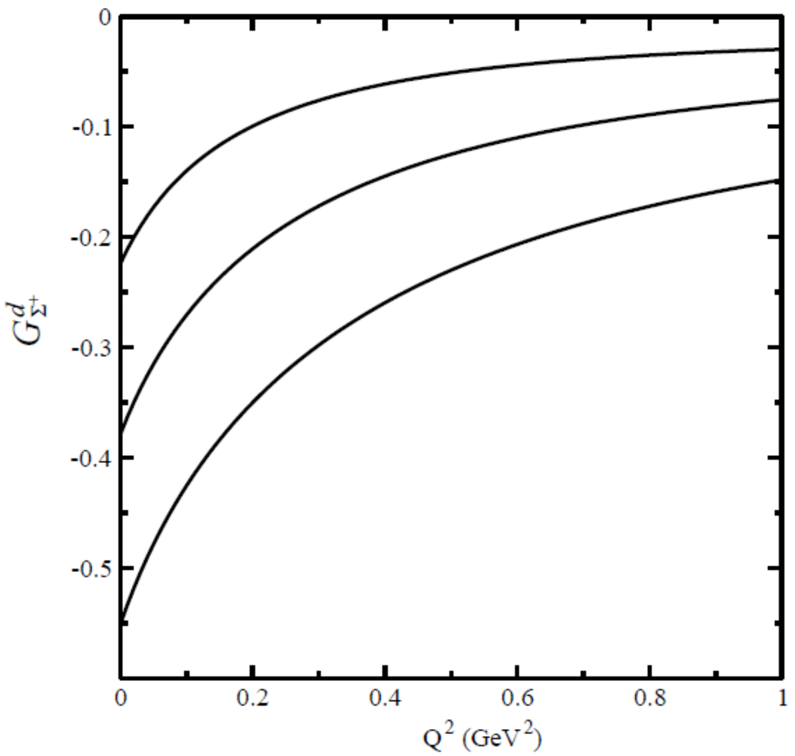
$$u_k = \frac{1}{(1+k^2/\Lambda^2)^2} \qquad \Lambda = 0.8 \pm 0.2 \ \text{GeV}$$

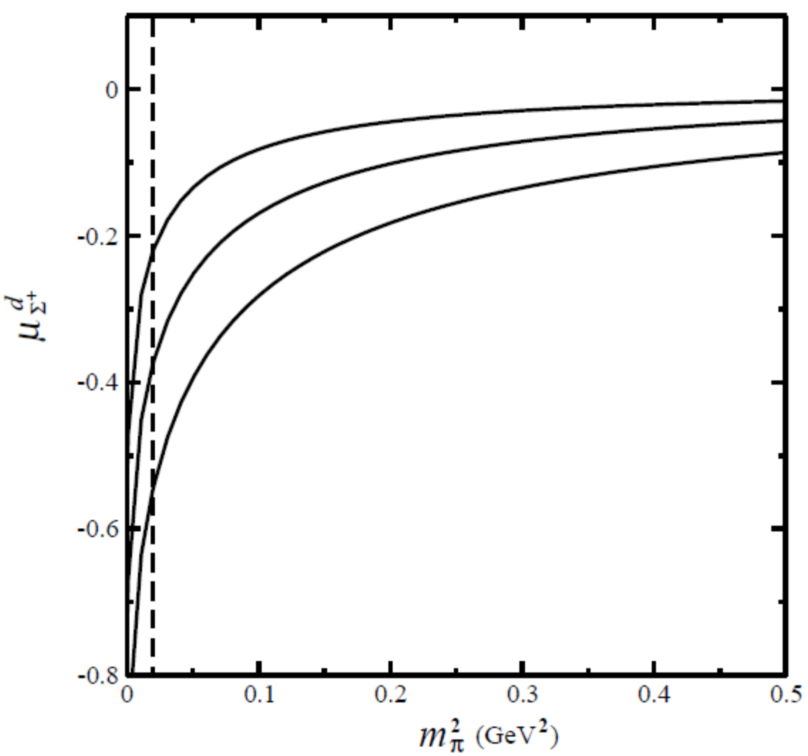
Magnetic moment : $-0.38^{+0.16}_{-0.17}\mu_N$

7 times larger than the strange magnetic moment of the nucleon.

P. Wang, D. B. Leinweber and A. W. Thomas, Phys. Rev. D92 (2015) 045203.

u/d quark in Σ⁻/ Σ⁺





Q^2 < 0.2 GeV^2
G is larger than 0.2 μN

pion mass 300-400 MeV
magnetic moment around 0.2 μN

P. Wang, D. B. Leinweber and A. W. Thomas, Phys. Rev. D92 (2015) 045203.

Summary (u/d in Sigma)

- Strange form factors of nucleon are supposed to be the best quantity to study the sea quark contributions. Current experiments are not able to precisely determine its value.

- Effective field theory with finite-range-regularization provide a successful method to study the pure sea quark contribution in baryons. No low energy constant related to the sea quark is needed in the calculation.

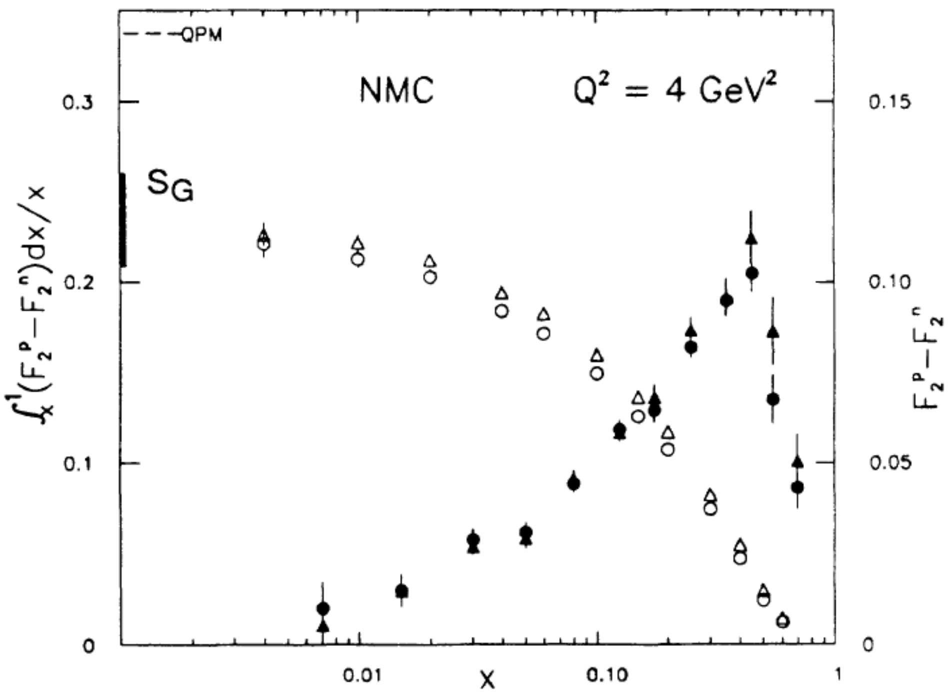
- We propose the pure sea-quark contributions to the magnetic form factors of baryons, $G^u_{\Sigma-}$ and $G^d_{\Sigma+}$ as priority observables for the examination of sea-quark contributions to baryon structure, both in present lattice QCD simulations and possible future experimental measurement.

- It is about seven times larger than the strange magnetic moment of the nucleon found in the same approach. Including quark charge factors, the u-quark contribution to the **Σ-** magnetic moment exceeds the strange quark contribution to the nucleon magnetic moment by a factor of 14.

dbar-ubar asymmetry

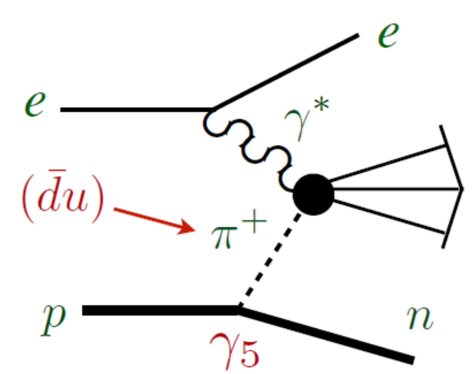
Gottifried sum rule (GSR):

$$\int_0^1 \left[F_2^p(x) - F_2^n(x)\right] \frac{dx}{x} = \frac{1}{3} - \frac{2}{3} \int_0^1 \left[\bar{d}_p(x) - \bar{u}_p(x)\right] \mathrm{d}x$$



New Muon Collaboration, PRD ***50****, 1 (1994)*

→ Sullivan process

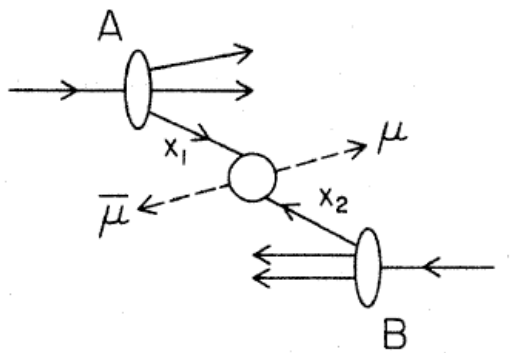


$$S_G = 0.235 \pm 0.026$$

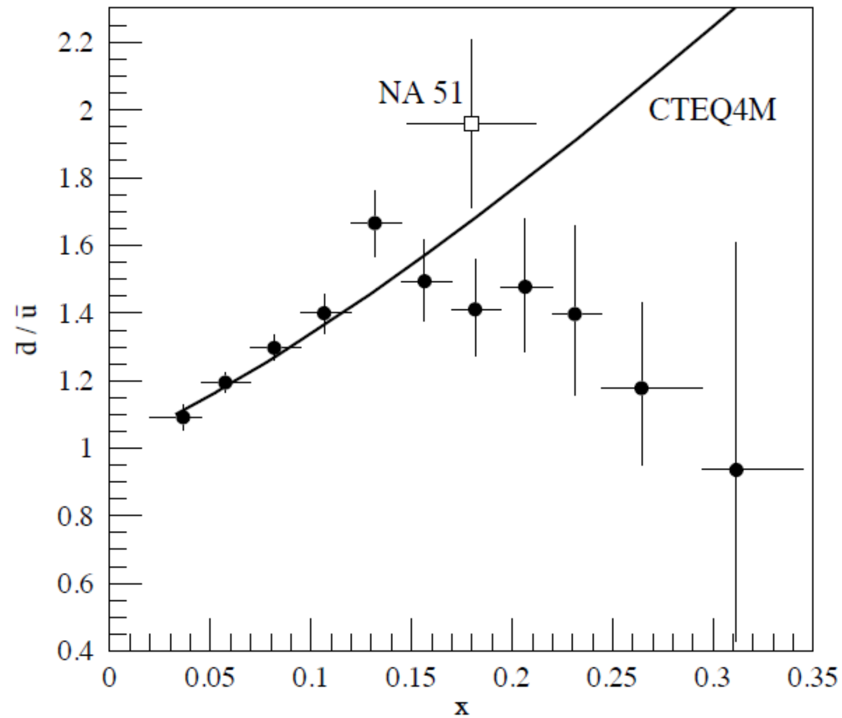
$$\int_0^1 \left[\bar{d}_p(x) - \bar{u}_p(x)\right] dx = 0.147 \pm 0.039$$

dbar-ubar asymmetry

→ Drell-Yan process



$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9Q^2} \sum_q e_q^2 \left(q(x_b)\bar{q}(x_t) + \bar{q}(x_b) q(x_t) \right)$$



*Fermilab E866, PRL **80**, 3715 (1998)*

$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right) \rightarrow \int_0^1 dx\,(\bar{d} - \bar{u}) = 0.118 \pm 0.012$$

dbar-ubar asymmetry

Generalized parton distribution function:

$$F^q = \frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-} \langle p'|\, \bar{q}(-\tfrac{1}{2}z)\, \gamma^+ q(\tfrac{1}{2}z)\, |p\rangle \Big|_{z^+=0,\, \mathbf{z}=0}$$

$$= \frac{1}{2P^+}\left[H^q(x,\xi,t)\, \bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t)\, \bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m} u(p)\right]$$

Forward limit: $H^q(x,0,0) = q(x)$

Zero-th order moments, Dirac form factor, Pauli Form factor:

$$\int_{-1}^{1} dx\, H^q(x,\xi,t) = F_1^q(t), \qquad \int_{-1}^{1} dx\, E^q(x,\xi,t) = F_2^q(t)$$

First moments:

$$\int_{-1}^{1} dx x H^q(x,\xi,t) = A_{2,0}^q(t) + (-2\xi)^2 C_{2,0}^q(t) \qquad \int_{-1}^{1} dx x E^q(x,\xi,t) = B_{2,0}^q(t) - (-2\xi)^2 C_{2,0}^q(t)$$

dbar-ubar asymmetry

Theoretical research:

Parameterization method:
M. Guidal, M.V. Polyakov, A.V. Radyushkin, M. Vanderhaegen, Phys. Rev. D72(2005)054013

Quark models:
Bag model: X. Ji, W. Melnitchouk, X. Song, Phys. Rev. D56(1997)5511
Cloudy bag mode: B. Pasquini, S.Boffi, Nucl.Phys.A782(2007)86
Constituent quark model: S. Scopetta, V. Vento, Phys. Rev. D69(2004)094004
Light-front bag model: H. Choi, C.R. Ji, L.S. Kisslinger, Phys. Rev. D64(2001)093006
Betha-Salpeter approach: B.C. Tiburzi, G.A. Miller, Phys. Rev. D65(2002)074009
NJL model: H. Mineo, S.N. Yang, C.Y. Cheung, W. Bentz, Phys. Rev. C72(2005)025202
Color glass condensate model: K. Goeke, V. Guzey, M. Siddidov, Eur. Phys. J. C56(2008)203

Experiments:

ZEUS and H1: $10^{-4} < x < 0.02$
EIC: Up to $x = 0.3$
HERMES: $0.02 < x < 0.3$
JLab 12 GeV: $0.1 < x < 0.7$
COMPASS: $0.006 < x < 0.3$

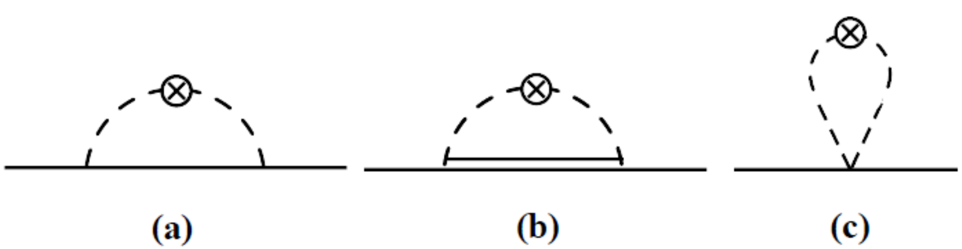
dbar-ubar asymmetry

Relativistic Lagrangian:

$$\mathcal{L}_{rel} = \mathrm{Tr}\left[\bar{B}\left(i \not{D} - M_0\right) B\right] - D\mathrm{Tr}(B\gamma^\mu\gamma^5 \{A_\mu, B\}) - F\mathrm{Tr}(B\gamma^\mu\gamma^5 [A_\mu, B])$$
$$\bar{T}_\mu \left(i\gamma^{\mu\nu\alpha} D_\alpha - M_D \gamma^{\mu\nu}\right) T_\nu + \mathcal{C}(\bar{T}_\mu \left(g^{\mu\nu} - Z\,\gamma^\mu\gamma^\nu\right) A_\mu B + h.c),$$

Heavy baryon Lagrangian:

$$\mathcal{L}_v = i\mathrm{Tr}\bar{B}_v(v\cdot\mathcal{D})B_v + 2D\mathrm{Tr}\bar{B}_v S_v^\mu\{A_\mu, B_v\} + 2F\mathrm{Tr}\bar{B}_v S_v^\mu[A_\mu, B_v]$$
$$-i\bar{T}_v^\mu(v\cdot\mathcal{D} - \Delta)T_{v\mu} + \mathcal{C}(\bar{T}_v^\mu A_\mu B_v + \bar{B}_v A_\mu T_v^\mu),$$



dbar-ubar asymmetry

The convolution form:

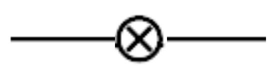
$$q(x) = Z_2\, q_0(x) + \left(f_{\rm i} \otimes q_{\rm i} \right)(x)$$

$$1 - Z_2 = \int_0^1 dy \sum_i f_i(y)$$

$$\bar{d} - \bar{u} = \left(f_{\pi^+ n} + f_{\pi^+ \Delta^0} - f_{\pi^- \Delta^{++}} + f_{\pi(\rm bub)} \right) \otimes \bar{q}_v^{\pi}$$

$$f \otimes q = \int_0^1 dy \int_0^1 dz\, \delta(x - yz)\, f(y)\, q(z), \text{ with } y = k^+/p^+$$

y is the light-cone fraction of the proton's momentum (p) carried by pion (k).

Tree level contribution is zero 

dbar-ubar asymmetry

Pion momentum distribution in nucleon:

$$f_{\pi^+n}(y) = 4M\left(\frac{g_A}{2f_\pi}\right)^2 \int \frac{d^4k}{(2\pi)^4} \bar{u}(p)\,(\not{k}\gamma_5)\frac{i(\not{p}-\not{k}+M)}{D_N}\,(\gamma_5\not{k})u(p)\frac{i}{D_\pi}\frac{i}{D_\pi}\,2k^+\delta(k^+-yp^+)$$

$$f_{\pi^+n}(y) = 2\left[f_N^{(\mathrm{on})}(y) + f_N^{(\delta)}(y)\right]$$

On-shell (nucleon pole) contribution:

$$f_N^{(\mathrm{on})}(y) = \frac{g_A^2 M^2}{(4\pi f_\pi)^2}\int dk_\perp^2\,\frac{y\,(k_\perp^2 + y^2 M^2)}{(1-y)^2 D_{\pi N}^2}$$

$$D_{\pi N} \;=\; -[k_\perp^2 + yM^2 + (1-y)m_\pi^2]/(1-y)$$

Off-shell contribution:

$$f_N^{(\delta)}(y) = \frac{g_A^2}{4(4\pi f_\pi)^2}\int dk_\perp^2\,\log\frac{\Omega_\pi}{\mu^2}\,\delta(y)$$

dbar-ubar asymmetry

Delta intermediate state:

$$f_{\pi^+\Delta^0}(y) = f_\Delta^{(\mathrm{on})}(y) + f_\Delta^{(\mathrm{end\text{-}pt})}(y) + f_\Delta^{(\delta)}(y)$$

On-shell (Delta pole) contribution:

$$f_\Delta^{(\mathrm{on})}(y) \; = \; C_\Delta \int dk_\perp^2 \, \frac{y\,(\overline{M}^2 - m_\pi^2)}{1-y} \times \Big[\frac{(\overline{M}^2 - m_\pi^2)(\Delta^2 - m_\pi^2)}{D_{\pi\Delta}^2} - \frac{3(\Delta^2 - m_\pi^2) + 4MM_\Delta}{D_{\pi\Delta}} \Big]$$

End-point singularity at y=1:

$$f_\Delta^{(\mathrm{end\text{-}pt})}(y) \; = \; C_\Delta \int dk_\perp^2 \, \delta(1-y) \times \Big\{ \Big[\Omega_\Delta - 2(\Delta^2 - m_\pi^2) - 6MM_\Delta) \Big] \log\frac{\Omega_\Delta}{\mu^2} - \Omega_\Delta \Big\}$$

dbar-ubar asymmetry

Off-shell contribution:

$$f_{\Delta}^{(\delta)}(y) \;=\; C_{\Delta} \int dk_{\perp}^2 \, \delta(y) \times \left\{ \left[3(\Omega_\pi + m_\pi^2) + \overline{M}^2 \right] \log \frac{\Omega_\pi}{\mu^2} - 3\Omega_\pi \right\}$$

Bubble diagram: $$f_{\pi(\mathrm{bub})}(y) = -\frac{2}{g_A^2} \, f_N^{(\delta)}(y)$$

In the HB limit:

$$\widetilde{f}_{\Delta}^{(\mathrm{on})}(y) = \frac{8 g_{\pi N\Delta}^2 M^2}{9(4\pi)^2} \int dk_{\perp}^2 \, \frac{y\left(\Delta^2 - m_\pi^2 - \widetilde{D}_{\pi\Delta}\right)}{\widetilde{D}_{\pi\Delta}^2}$$

$$\widetilde{f}_{\Delta}^{(\delta)}(y) = \frac{2 g_{\pi N\Delta}^2}{9(4\pi)^2} \int dk_{\perp}^2 \, \delta(y) \log \frac{\Omega_\pi}{\mu^2}$$

$f\,(y)\;\; (m << M) = \widetilde{f}\,(y)$

dbar-ubar asymmetry

LNA behavior:

$$(\overline{D}-\overline{U})_{\rm LNA} = \frac{3g_A^2+1}{2(4\pi f_\pi)^2} m_\pi^2 \log m_\pi^2 - \frac{g_{\pi N\Delta}^2}{12\pi^2} J_1$$

$$J_1 = (m_\pi^2 - 2\Delta^2)\log m_\pi^2 + 2\Delta\, r\, \log[(\Delta - r)/(\Delta + r)]$$

$$\Delta \equiv M_\Delta - M \qquad r = \sqrt{\Delta^2 - m_\pi^2}$$

Sullivan approach (on-shell component):

$$(\overline{D}-\overline{U})_{\rm LNA}^{\rm (Sul)} = \left[\frac{2g_A^2}{(4\pi f_\pi)^2} - \frac{g_{\pi N\Delta}^2}{9\pi^2}\right] m_\pi^2 \log m_\pi^2$$

dbar-ubar asymmetry

General regulator: $F(t,\ u) \equiv F[k^2,\ (p-k)^2] = \left(\frac{\Lambda_t - m^2}{\Lambda_t - t}\right) \cdot \left(\frac{\Lambda_u - M^2}{\Lambda_u - u}\right) = \frac{a}{d_N}\frac{b}{d_\pi}$

$$f_{n\pi^+}(y) = \frac{-i\cdot(F+D)^2}{4f^2} \cdot \int \frac{d^4k}{(2\pi)^4} \left(\frac{4\ (p.k)}{D_\pi^2} + \frac{8\ M^2}{D_\pi D_N} + \frac{8\ M^2\ m^2}{D_\pi^2 D_N} \right) \cdot F^2(t,\ u) \cdot y \cdot \delta\left(y - \frac{k^+}{p^+}\right)$$

$$\left(\left(-\frac{\pi\ i}{\Lambda_t} - \frac{9\ \pi\ i\ M^2}{a^2} - \frac{3\ \pi\ i}{a}\right) \ln(m^2)\right) m^4 + (-\pi\ i\ \ln(m^2))\ m^2$$

$$\left(\left(\frac{3}{2}\ \frac{\pi\ i\ M^2}{a^2} - \frac{1}{4}\ \frac{\pi\ i}{M^2}\right) \ln(m^2)\right) m^4 - \frac{1}{2}\ \frac{\pi^2\ i\ m^3}{M} + \left(\frac{1}{2}\ \pi\ i\ \ln(m^2)\right) m^2$$

$$\left(\left(\frac{3\ \pi\ i\ M^2}{a^2} + \frac{\pi\ i}{\Lambda_t} - \frac{1}{2}\ \frac{\pi\ i}{M^2}\right) \ln(m^2)\right) m^4 - \frac{3}{4}\ \frac{\pi^2\ i\ m^3}{M} + \left(\frac{1}{2}\ \pi\ i\ \ln(m^2)\right) m^2$$

dbar-ubar asymmetry

Non-analytic term with DR:

First term: $-\pi i \cdot \ln(m^2) m^2$

Second term: $\left(-\frac{1}{4}\ \frac{\pi\ i\ \ln(m^2)}{M^2}\right) m^4 - \frac{1}{2}\ \frac{\pi^2\ i\ m^3}{M} + \left(\frac{1}{2}\ \pi\ i\ \ln(m^2)\right) m^2$

Third term: $\left(-\frac{1}{2}\ \frac{\pi\ i\ \ln(m^2)}{M^2}\right) m^4 - \frac{3}{4}\ \frac{\pi^2\ i\ m^3}{M} + \left(\frac{1}{2}\ \pi\ i\ \ln(m^2)\right) m^2$

Same as that with form factor when $\Lambda_t\ \Lambda_u\ a\ b$ ==> infinity

LNA is the same as that with form factor at **finite** Λ .

dbar-ubar asymmetry

The constituent building blocks of the nucleon and the pion U and D [Gluck et at]:

$$p = UUD \qquad\qquad \pi^+ = U\bar{D}$$

$$f^p(x,Q^2) = \int_x^1 \frac{dy}{y}\left[U^p(y) + D^p(y)\right] f_c\left(\frac{x}{y}, Q^2\right)$$

$$f^\pi(x,Q^2) = \int_x^1 \frac{dy}{y}\left[U^{\pi^+}(y) + \bar{D}^{\,\pi^+}(y)\right] f_c\left(\frac{x}{y}, Q^2\right)$$

$$f = v,\, \bar{q},\, g$$

$$\frac{v^\pi(n,\mu^2)}{v^p(n,\mu^2)} = \frac{\bar{q}^{\,\pi}(n,\mu^2)}{\bar{q}^{\,p}(n,\mu^2)} = \frac{g^\pi(n,\mu^2)}{g^p(n,\mu^2)}$$

$$\int_0^1 xv^\pi(x,Q^2)dx = \int_0^1 xv^p(x,Q^2)dx$$

dbar-ubar asymmetry

Pionic parton distribution function :

$$x\, v^{\pi}(x, Q^2) = N\, x^{a}(1 + A\sqrt{x} + Bx)(1 - x)^{D}$$

$$\begin{aligned} N &= 1.212 + 0.498\, s + 0.009\, s^2 \\ a &= 0.517 - 0.020\, s \\ A &= -0.037 - 0.578\, s \\ B &= 0.241 + 0.251\, s \\ D &= 0.383 + 0.624\, s\, . \end{aligned}$$

$$s \equiv ln \frac{ln\,[Q^2/(0.204\,\mathrm{GeV})^2]}{ln\,[0.26\,/(0.204\,\mathrm{GeV})^2]}$$

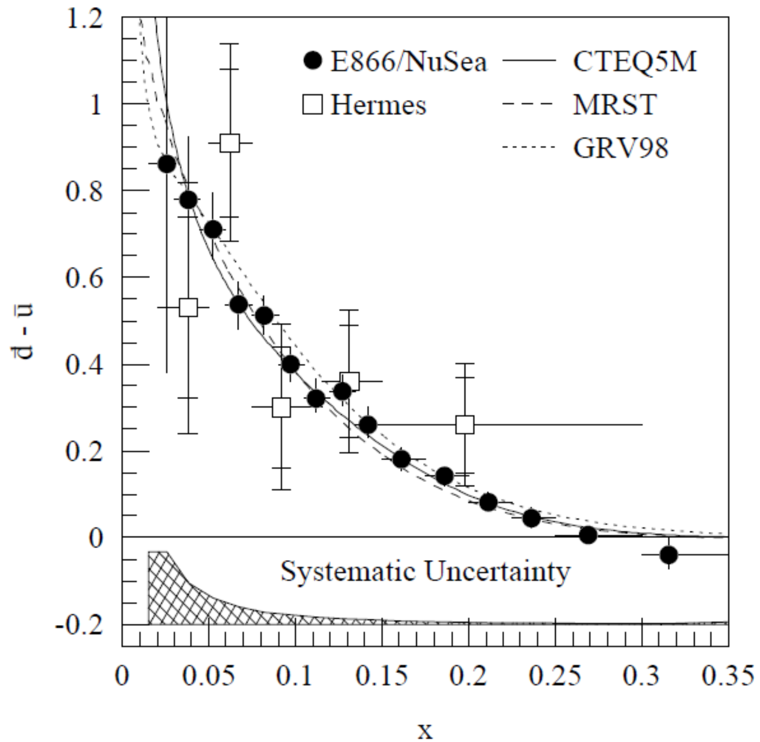
valid for $0.5 \lesssim Q^2 \lesssim 10^5\ \mathrm{GeV}^2$ and $10^{-5} \lesssim x < 1$

dbar-ubar asymmetry

Input: valence quark distribution function in pion [Gluck, 99]

$$\bar{d}_{\pi^+,v}(x, Q^2 = 1\mathrm{GeV}^2) = \frac{0.869(1-x)^{0.73}(1-0.57x^{0.5}+0.53x)}{x^{0.456}}$$

For μ ranging between 0.1 and 1 GeV, Λ is fixed by matching the dbar-ubar integral extracted from the E866 Drell-Yan data over the measured x range:

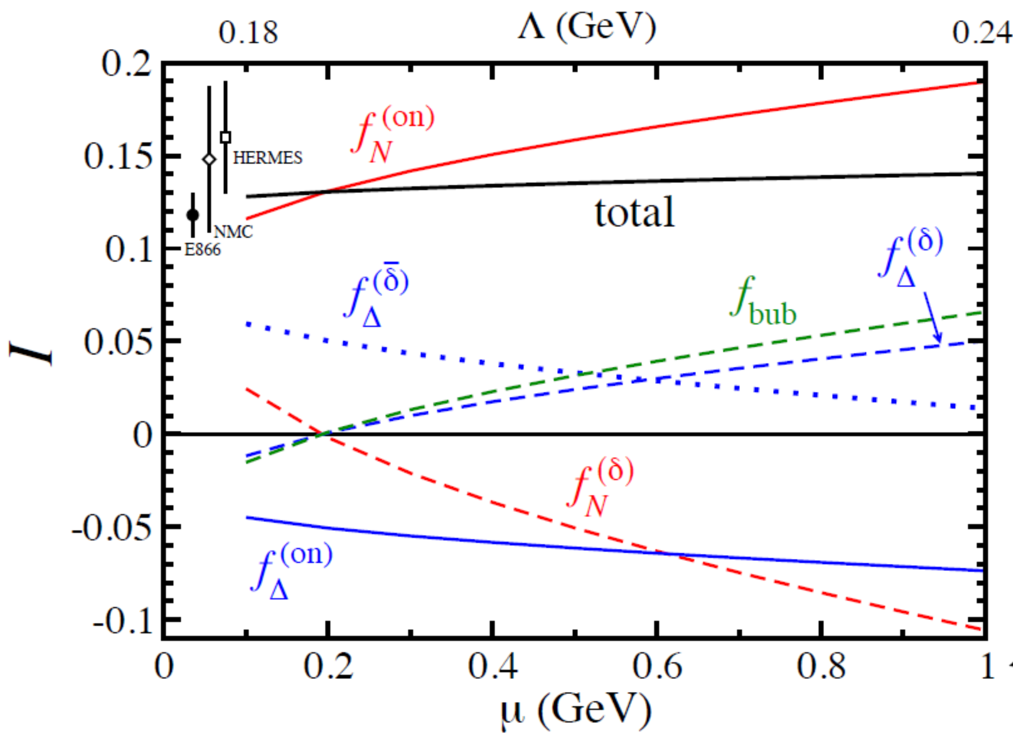


$$\int_{0.015}^{0.35} dx(\bar{d} - \bar{u}) = 0.0803(11)$$

R. S. Towell *et al.*, Phys. Rev. D **64**, 052002 (2001)

dbar-ubar asymmetry

Integrated asymmetry $I = \int_0^1 dx\,(\bar{d} - \bar{u})(x)$



$k_\perp$ cutoff

$f_N \equiv f_{\pi(N\,\text{int. state})}$

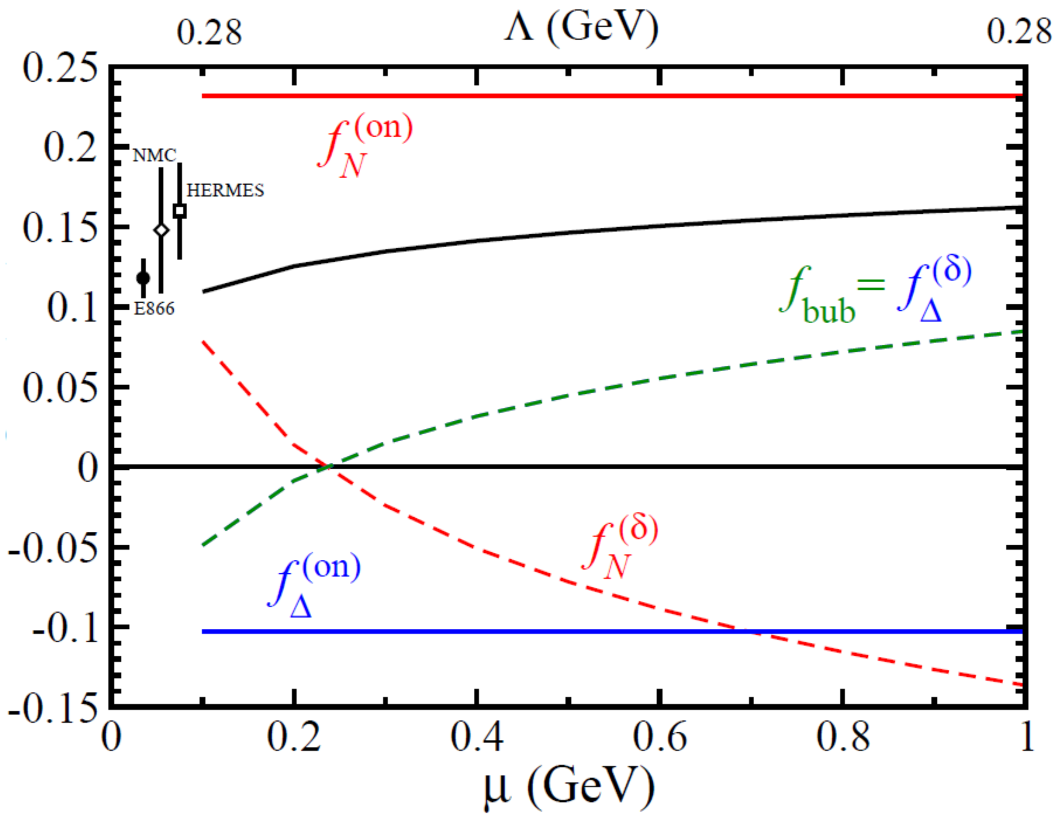
$f_\Delta \equiv f_{\pi(\Delta\,\text{int. state})}$

k^- cutoff

→ N on-shell contribution $\approx$ total!

Y.Salamu, W.Melnitchouk,C.R.Ji,P.Wang, Phys. Rev. Lett. 114 (2015) 122001

dbar-ubar asymmetry



HB limit is comparable with the relativistic case.

dbar-ubar asymmetry

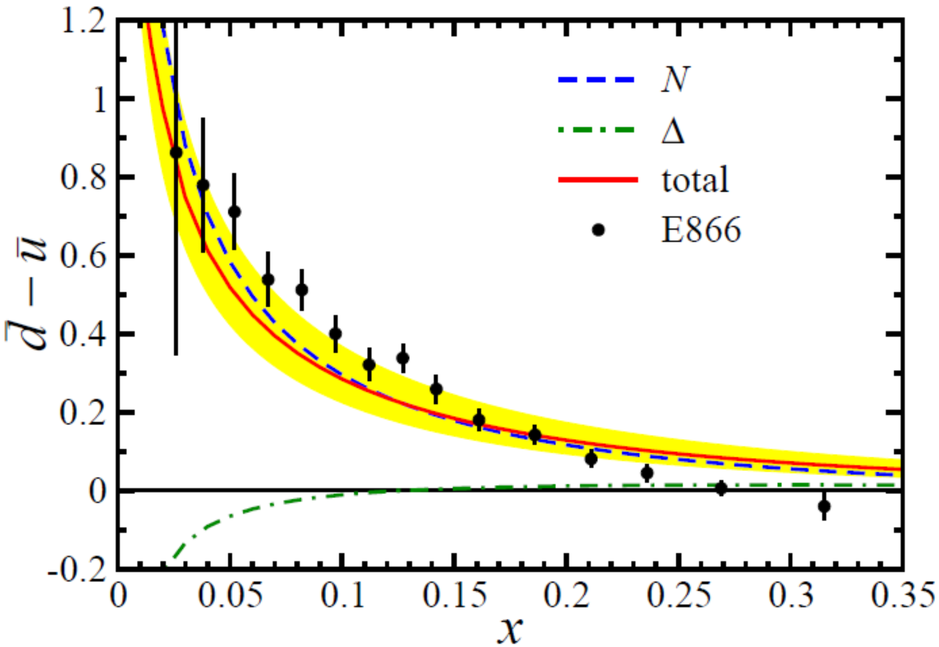


FIG. 3: Flavor asymmetry $\bar{d} - \bar{u}$ from the N and Δ intermediate states, and the total, for cutoffs $\mu = 0.3$ GeV and $\Lambda = 0.2$ GeV, compared with the asymmetry extracted at leading order from the E866 Drell-Yan data [4] at $Q^2 = 54$ GeV^2. The band indicates the uncertainty on the total distribution from the cutoff parameters (for μ between 0.1 and 1 GeV) and from the empirical $\overline{D} - \overline{U}$ normalization.

Y.Salamu, W.Melnitchouk, C.R.Ji, P.Wang, Phys. Rev. Lett. 114 (2015) 122001

Y.Salamu, W.Melnitchouk, C.R.Ji, P.Wang, Few Body Syst. 56 (2015) 355

Summary

- We compute the dbar-ubar asymmetry in the proton within relativistic and heavy baryon effective field theory Including both nucleon and baryon intermediate states.

- In addition to the distribution at nonzero x, we also estimate the correction to the integrated asymmetry arising at $x = 0$, which have not been accounted for in previous empirical analyses.

- Without attempting to fine-tune the parameters, the overall agreement between the calculation and experiment is very good.

- As with all previous pion loop calculations, the apparent trend of the E866 data towards negative dbar−ubar values for $x > 0.3$ is not reproduced in this analysis. The new SeaQuest experiment at Fermilab is expected to provide new information on the shape of dbar-ubar for $x < 0.45$.

- The analysis described here can be applied to other nonperturbative quantities in the proton, such as the flavor asymmetry of the polarized sea, the strange–antistrange asymmetry, transverse momentum dependent distributions and generalized parton distributions, etc.

s-sbar asymmetry

BEBC, CDHS and CDHSW experiments concluded that the s-quark PDF was somewhat harder than the sbar.

Beyond extractions from individual experiments, global QCD analyses of charged lepton and neutrino DIS, along with other high energy scattering data, have generally found positive values for S-.

Taking into account some of these uncertainties, the phenomenological analysis of Bentz *et al.* concluded that S- = (0 + - 2) X 0.001.

Catani et al., showed that perturbative three-loop effects can induce nonzero negative S- values ~ -0.0005, through Q2 evolution of symmetric s-sbar distributions from a low input scale Q ~ 0.5 GeV.

$$S^- \equiv \langle x(s-\bar{s})\rangle = \int_0^1 dx\, x\,(s(x)-\bar{s}(x))$$

In 2001 NuTeV collaboration, using ν DIS, measured:

- $\sin^2\theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$
- G. P. Zeller *et al.* Phys. Rev. Lett. **88**, 091802 (2002)

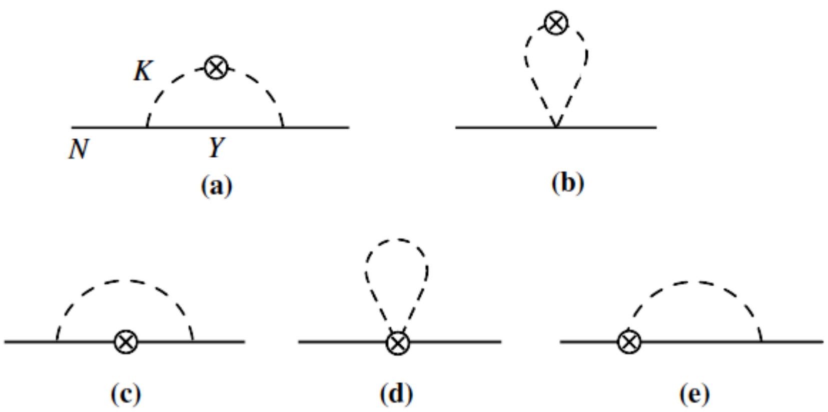
World average (not including NuTeV):

- $\sin^2\theta_W = 0.2227 \pm 0.0004$

3 σ discrepancy!!! $\Longrightarrow$ "NuTeV anomaly"

s-sbar asymmetry

$$\mathcal{L} = -\frac{D}{2}\bar{B}\gamma_\mu\gamma_5\{u^\mu, B\} - \frac{F}{2}\bar{B}\gamma_\mu\gamma_5[u^\mu, B] + i\,\bar{B}\gamma_\mu[D^\mu, B]$$



convolution form:

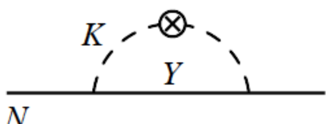
$$\bar{s}(x) = \Big(\sum_{KY} f_{KY}^{(\mathrm{rbw})} + \sum_{K} f_{K}^{(\mathrm{bub})}\Big) \otimes \bar{s}_K$$

$$s(x) = \sum_{YK}\Big(\bar{f}_{YK}^{(\mathrm{rbw})} \otimes s_Y + \bar{f}_{YK}^{(\mathrm{KR})} \otimes s_Y^{(\mathrm{KR})}\Big) + \sum_{K} \bar{f}_{K}^{(\mathrm{tad})} \otimes s_K^{(\mathrm{tad})},$$

s-sbar asymmetry

$$f_{KY}^{(\mathrm{rbw})}(y) \;=\; M C_{KY}^2 \int \frac{d^4k}{(2\pi)^4}\, \bar{u}(p)(\not{k}\gamma_5)\frac{i(\not{p}-\not{k}+M_Y)}{D_Y}(\gamma_5\not{k})u(p)\frac{i}{D_K}\frac{i}{D_K}2k^+\delta(k^+-yp^+)$$

$$f_{KY}^{(\mathrm{rbw})}(y) \;=\; -iC_{KY}^2 \int \frac{d^4k}{(2\pi)^4}\left[\frac{\overline{M}^2(p\cdot k+M\Delta)}{D_K^2 D_Y}+\frac{M\overline{M}}{D_K^2}+\frac{p\cdot k}{D_K^2}\right]2y\,\delta\left(y-\frac{k^+}{p^+}\right)$$



(a)

$$f_{KY}^{(\mathrm{rbw})}(y) \;=\; \frac{C_{KY}^2\overline{M}^2}{(4\pi f_P)^2}\left[f_Y^{(\mathrm{on})}(y)+f_K^{(\delta)}(y)\right]$$

$$f_Y^{(\mathrm{on})}(y) \;=\; y\int dk_\perp^2\, \frac{k_\perp^2+[M_Y-(1-y)M]^2}{(1-y)^2 D_{KY}^2}F^{(\mathrm{on})}$$

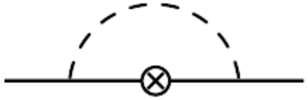
$$f_K^{(\delta)}(y) \;=\; \frac{1}{\overline{M}^2}\int dk_\perp^2\, \log\Omega_K\,\delta(y)\,F^{(\delta)}$$

s-sbar asymmetry

$$f_{YK}^{(\mathrm{rbw})}(y) = MC_{KY}^2 \int \frac{d^4k}{(2\pi)^4}\, \bar{u}(p)(\not{k}\gamma_5) \frac{i(\not{p}-\not{k}+M_Y)}{D_Y}\, \gamma^+ \frac{i(\not{p}-\not{k}+M_Y)}{D_Y} (\gamma_5 \not{k})\, u(p) \times \frac{i}{D_K} \delta(k^+ - yp^+),$$

$$f_{YK}^{(\mathrm{rbw})}(y) = -iC_{KY}^2 \int \frac{d^4k}{(2\pi)^4} \left[\frac{\overline{M}^2 (k^2 - 2y\, p\cdot k - 2yM\Delta - \Delta^2)}{D_K D_Y^2} - \frac{2M\overline{M}y + 2\overline{M}\Delta}{D_K D_Y} - \frac{1}{D_K} \right]$$

$$f_{YK}^{(\mathrm{rbw})}(y) = \frac{C_{KY}^2 \overline{M}^2}{(4\pi f_P)^2} \left[f_Y^{(\mathrm{on})}(y) + f_Y^{(\mathrm{off})}(y) - f_K^{(\delta)}(y) \right]$$



(c)

$$f_Y^{(\mathrm{off})}(y) = \frac{2}{\overline{M}} \int dk_\perp^2 \frac{[M_Y - (1-y)M]}{(1-y)D_{KY}} F^{(\mathrm{off})}$$

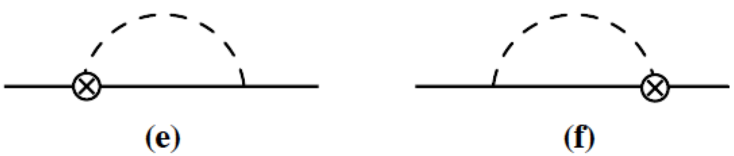
s-sbar asymmetry

$$f_{YK}^{(\mathrm{KR})}(y) \;=\; -iMC_{KY}^2 \int \frac{d^4k}{(2\pi)^4}\, \bar{u}(p) \left[\not{k}\gamma_5 \frac{i(\not{p}-\not{k}+M_Y)}{D_Y}\gamma^+\gamma_5 + \gamma^+\gamma_5 \frac{i(\not{p}-\not{k}+M_Y)}{D_Y}\not{k}\gamma_5 \right] u(p)$$

$$f_{YK}^{(\mathrm{KR})}(y) \;=\; -2iC_{KY}^2 \overline{M} \int \frac{d^4k}{(2\pi)^4} \left[\frac{My+\Delta}{D_K D_Y} + \frac{1}{M D_K} \right] \delta\left(y - \frac{k^+}{p^+} \right)$$

$$f_{YK}^{(\mathrm{KR})}(y) \;=\; \frac{C_{KY}^2 \overline{M}^2}{(4\pi f_P)^2} \left[-f_Y^{(\mathrm{off})}(y) + 2 f_K^{(\delta)}(y) \right]$$

Gauge invariance: $f_{YK}^{(\mathrm{rbw})} + f_{YK}^{(\mathrm{KR})} = f_{KY}^{(\mathrm{rbw})}$



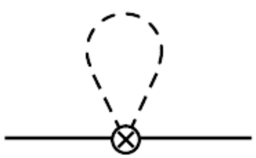
s-sbar asymmetry

(b)

$$f_{K^+}^{(\text{bub})}(y) = \frac{M}{f_\phi^2}\int \frac{d^4k}{(2\pi)^4}\,\bar{u}(p)(-i\not{k})u(p)\frac{i}{D_K}\frac{i}{D_K}2k^+\delta(k^+ - yp^+)$$

$$f_{K^+}^{(\text{bub})}(y) = \frac{i}{f_\phi^2}\int \frac{d^4k}{(2\pi)^4}\frac{p\cdot k}{D_K^2}\,2y\,\delta\left(y - \frac{k^+}{p^+}\right)$$

$$f_{K^+}^{(\text{bub})}(y) = 2f_{K^0}^{(\text{bub})}(y) = -\frac{\overline{M}^2}{(4\pi f_\phi)^2}f_K^{(\delta)}(y)$$



(d)

$$f_{K^+}^{(\text{tad})}(y) = -\frac{M}{f_\phi^2}\int \frac{d^4k}{(2\pi)^4}\,\bar{u}(p)\gamma^+u(p)\frac{i}{D_K}\delta(k^+ - yp^+)$$

$$f_{K^+}^{(\text{tad})}(y) = 2f_{K^0}^{(\text{tad})}(y) = \frac{\overline{M}^2}{(4\pi f_\phi)^2}f_K^{(\delta)}$$

$$f_K^{(\text{tad})} = f_K^{(\text{bub})}$$

s-sbar asymmetry

Input PDF, global parameterazation

$$\bar{s}_{K^+} = u_{K^+} = \bar{s}_{K^0} = u_{\pi^+} = \bar{d}_{\pi^+} = d_{\pi^-} = \bar{u}_{\pi^-}$$

$$s_\Lambda(x) = \frac{1}{3}\left[2u(x) - d(x) + 2s(x)\right]$$
$$s_{\Sigma^+}(x) = s_{\Sigma^0}(x) = d(x).$$

$$s_\Lambda^{(\mathrm{KR})}(x) = \frac{1}{D+3F}\left[2\Delta u(x) - \Delta d(x)\right],$$
$$s_{\Sigma^+}^{(\mathrm{KR})}(x) = s_{\Sigma^0}^{(\mathrm{KR})}(x) = \frac{1}{F-D}\Delta d(x).$$

$$s_{K^+}^{(\mathrm{tad})}(x) = \frac{1}{2}u(x)$$
$$s_{K^0}^{(\mathrm{tad})}(x) = d(x).$$

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s-sbar asymmetry

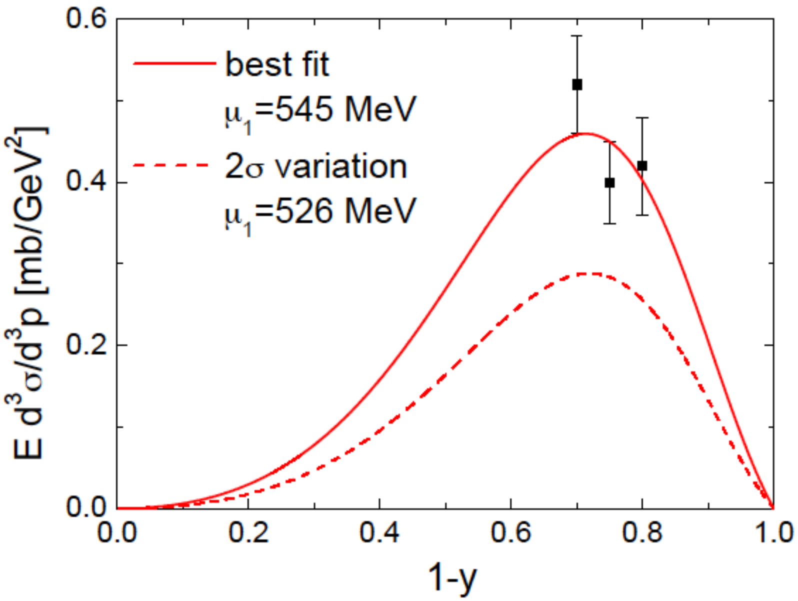

Figure 2: Differential cross section for the best fit to the $pp \to \Lambda X$ data [49] in the region $y < 0.35$ (solid curve, $\mu_1 = 545$ MeV), as a function of $1 - y$ for $k_\perp = 75$ MeV, and for a fit 2σ below the central values (dashed curve, $\mu_1 = 526$ MeV).

$$E\frac{d^3\sigma}{d^3p} = \frac{C^2_{K^+\Lambda}\overline{M}^2}{16\pi^3 f^2_\phi}\frac{y\,[k^2_\perp + (My+\Delta)^2]}{(1-y)D^2_{K^+\Lambda}}F^{(\mathrm{on})}(y,k^2_\perp)\,\sigma^{pK^+}_{\mathrm{tot}}(sy)$$

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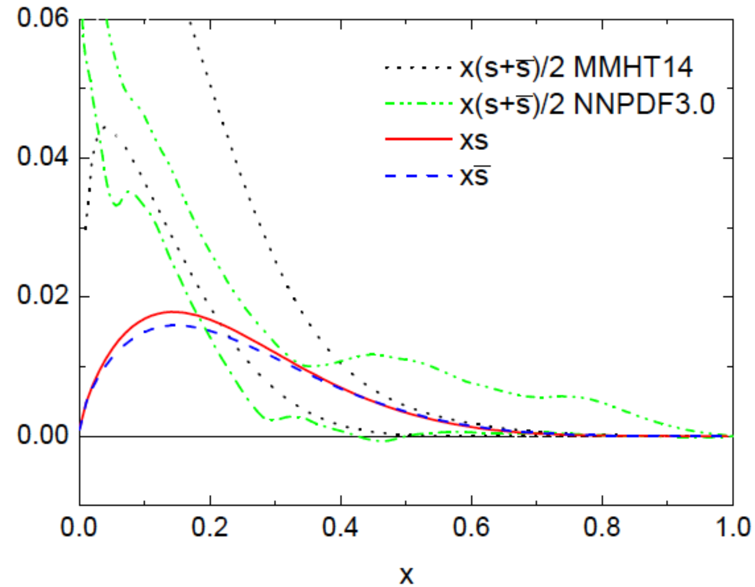
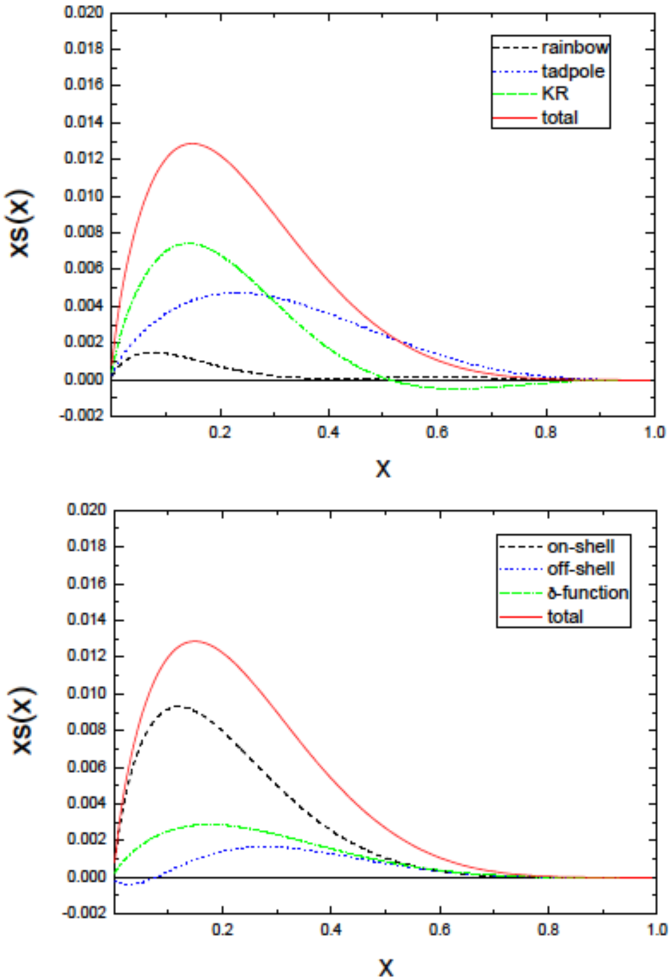


Figure 3: Comparison between the strange xs (solid red curve) and antistrange $x\bar{s}$ (dashed blue curve) PDFs from kaon loops, for the cutoff parameters ($\mu_1 =$ 545 MeV and $\mu_2 = 600$ MeV) that give the maximum total $s+\bar{s}$, with the upper and lower limits of the error bands for $x(s+\bar{s})/2$ at $Q^2 = 1$ GeV^2 from the MMHT14 [51] (black dotted) and NNPDF3.0 [52] (green dot-dashed) global fits.

s-sbar asymmetry



The distribution functions at $Q^2 = 1\text{GeV}^2$ with $\Lambda = 0.526$ GeV and $\Lambda_2 = 1.7\Lambda$.

TABLE I: The second moments of $s(x)$ and $\bar{s}(x)$ in proton at $Q^2 = 1$ GeV^2.

	$\Lambda = 0.545$ GeV		$\Lambda = 0.526$ GeV	
	$\Lambda_2 = m_K$	$\Lambda_2 = 1.1\Lambda$	$\Lambda_2 = m_K$	$\Lambda_2 = 1.7\Lambda$
$< xs >$	5.61×10^{-3}	6.10×10^{-3}	3.40×10^{-3}	4.53×10^{-3}
$< x\bar{s} >$	5.68×10^{-3}	5.68×10^{-3}	3.41×10^{-3}	3.41×10^{-3}
$< x(s+\bar{s}) >$	1.13×10^{-2}	1.18×10^{-2}	6.81×10^{-3}	7.94×10^{-3}
$< x(s-\bar{s}) >$	-7×10^{-5}	0.42×10^{-3}	-1×10^{-5}	1.12×10^{-3}

TABLE II: The second moments of $s(x)$ and $\bar{s}(x)$ in proton at $Q^2 = 1$ GeV^2.

	$\Lambda = 0.539$ GeV		$\Lambda = 0.533$ GeV	
	$\Lambda_2 = m_K$	$\Lambda_2 = 1.3\Lambda$	$\Lambda_2 = m_K$	$\Lambda_2 = 1.5\Lambda$
$< xs >$	4.91×10^{-3}	5.74×10^{-3}	4.22×10^{-3}	5.24×10^{-3}
$< x\bar{s} >$	4.96×10^{-3}	4.96×10^{-3}	4.25×10^{-3}	4.25×10^{-3}
$< x(s+\bar{s}) >$	9.87×10^{-3}	1.07×10^{-2}	8.47×10^{-3}	9.49×10^{-3}
$< x(s-\bar{s}) >$	-5×10^{-5}	0.78×10^{-3}	-3×10^{-5}	0.99×10^{-3}

$$-7 \times 10^{-5} \leq \langle x[s(x) - \bar{s}(x)] \rangle \leq 1.12 \times 10^{-3}$$

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X.G.Wang, C.R.Ji, W.Melnitchouk, Y.Salamu, A.W.Thomas, P.Wang, Phys. Rev. D (to be published)

Summary (s-sbar asymmetry)

We perform a comprehensive analysis of the strange(anti-strange) parton distribution function (PDF) asymmetry in the proton in the framework of chiral effective theory, including the full set of lowest order kaon loop diagrams with both off-shell contributions, in addition to the usual on-shell contributions previously discussed in the literature.

With the help of experimental data from inclusive production in pp scattering and results from global PDF fits we have obtained constraints on the mass parameters for the Pauli-Villars regulators used in the numerical calculation of the kaon loop contributions.

Phenomenologically important consequence of the delta-function terms is that for the s-quark distribution the corresponding splitting function is a delta function at y = 1, where y is the fraction of the nucleon momentum carried by the hyperon. This leads to a valence-like component of the strange sea, which cannot be generated from gluon radiation in perturbative QCD alone.

We find that s and sbar quarks from this source contribute up to 1% of the total momentum of the nucleon. The magnitude of the strange asymmetry, s-sbar, is about a factor of 10 smaller than the sum. Compared with other possible corrections to the NuTeV anomaly, this is a relatively minor effect, reducing the discrepancy by less than 0.5 sigma.

The End !