Scalar & Pseudoscalar Higgs Couplings with Nucleons

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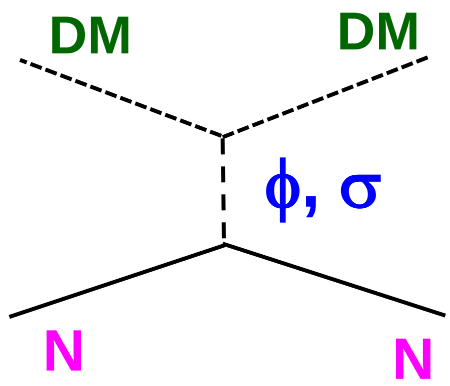


$DM = (\phi, \chi, B_\mu)$

Interactions of dark matter with nucleons mediated by scalar Higgs ϕ or pseudoscalar σ can be probed by studying spin-independent & spin-dependent cross sections

History

- **Shifman, Vainstein, Zakharov ('78) were the first to study Higgs-nucleon couplings $g_{\phi NN}$ and showed that it is dominated by heavy quarks**
- **T. P. Cheng ('88), HYC ('89) $\Rightarrow$ $g_{\phi NN}$ dominated by s quark**
- **HYC ('89) $\Rightarrow$ pseudoscalar Higgs coupling with nucleons studied in chiral & large N_c limits**
- **Calculations of higher order terms in ChPT available in 90's Gasser, Leutwyler, Sainio ('91); Jenkins, Manohar ('92); Borasoy, Meissner ('96,'97)**
- **Intense lattice studies after 2008 on various sigma terms and strange quark fraction in the nucleon**
- **Many new determinations of pion-nucleon sigma terms from π-N scattering data since 2000**
- **Study of SU(3) breaking effect on the determination of g_A^8 & Δs in recent years**

Scalar Higgs

$$g_{\phi NN} = (\sqrt{2}G_F)^{1/2} \sum \langle N | \varsigma_q m_q \bar{q} q | N \rangle$$

ζ_q=1 in SM, but not necessarily so in BSM. Relevant nucleon matrix elements are related to the trace of energy-momentum tensor $\Theta^\mu{}_\mu$
Under heavy quark expansion $m_h \bar{q}_h q_h \rightarrow -(2\alpha_s/8\pi)GG$ **SVZ ('78)**

$$\Theta^\mu{}_\mu = m_u \bar{u}u + m_d \bar{d}d + m_s \bar{s}s + \sum m_h \bar{q}_h q_h + (\beta / 4\alpha_s)GG$$
$$\rightarrow m_u \bar{u}u + m_d \bar{d}d + m_s \bar{s}s - (9\alpha_s / 8\pi)GG$$

Under light quark expansion, baryon mass is given by

$$m_{\mathcal{B}} = m_0 + \sum_q b_q m_q + \sum_q c_q m_q^{3/2} + \sum_q d_q m_q^2 \ln \frac{m_q}{m_0} + \sum_q e_q m_q^2 + \mathcal{O}(m_q^3)$$

To first order, baryon masses can be expressed in terms of $B_u = \langle p|\bar{u}u|p\rangle$, $B_d = \langle p|\bar{d}d|p\rangle$, $B_s = \langle p|\bar{s}s|p\rangle$ with SU(3) symmetry

$$B_u - B_s = \frac{2(m_\Xi - m_N)}{2m_s - m_u - m_d} = 3.94 \qquad B_d - B_s = \frac{2(m_\Sigma - m_N)}{2m_s - m_u - m_d} = 2.64$$

To determine B_u, B_d, B_s, we define several quantities:

- **strange quark content of the proton:** $y=2B_s/(B_u+B_d)$
- **pion-nucleon sigma term:** $\sigma_{\pi N} \equiv \hat{m}\langle N|\bar{u}u+\bar{d}d|N\rangle, \quad \hat{m}=(m_u+m_d)/2$
- **sigma term σ_0:** $\sigma_0 \equiv \hat{m}\langle N|\bar{u}u+\bar{d}d-2\bar{s}s|N\rangle$
- **quark sigma term:** $\sigma_q = m_q \langle p|\bar{q}q|p\rangle$

$\sigma_{\pi N}$ & σ_0 are related by $\sigma_{\pi N}=\sigma_0/(1-y)$ and σ_0 can be fixed by baryon masses to be ~ 24 MeV.

In 80's $\sigma_{\pi N}$ = 55 ~ 60 MeV $\Rightarrow$ large strange quark content y ~ 0.5-0.6 and σ_u ~ 20 MeV, σ_d ~ 33 MeV, σ_s ~ 390 MeV

Strange quark content y and sigma terms $\sigma_{\pi N}$ and σ_s are reduced in 90's:

1. **higher order expansion terms in $m_q^{3/2}$ and m_q^2**

   $\sigma_0 \sim 36$ **MeV** — Borasoy, Missner ('97); Jenskin, Manohar ('92); Gasser, Leutwyler, Saino ('91)

2. $\Sigma_{\pi N} = 64 \pm 8$ **MeV extracted from πN scattering data** — Koch ('82)

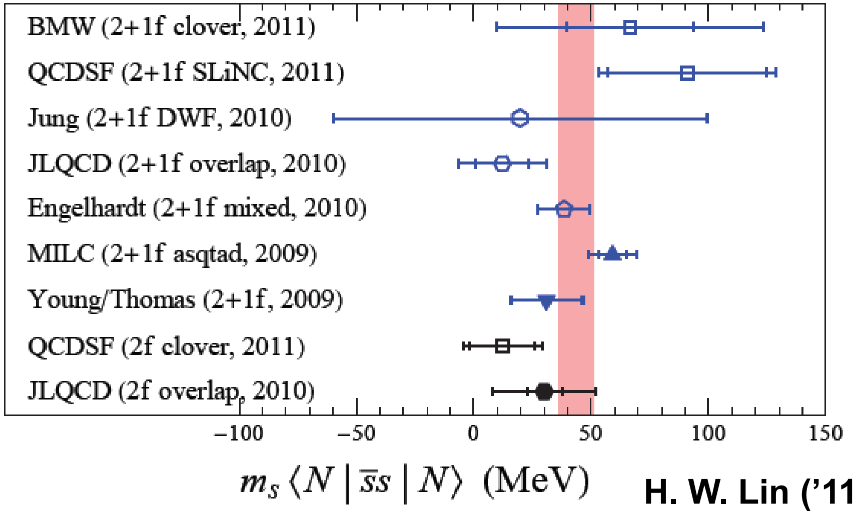
   $\Rightarrow \sigma_{\pi N} = \Sigma_{\pi N} - \Delta_\sigma - \Delta_R \sim 45$ **MeV**

2. $y = \sigma_0/\sigma_{\pi N} \sim 0.2 \Rightarrow \sigma_s \sim 130$ **MeV**

Sigma terms and strange quark content in 90's:

$\sigma_{\pi N} \sim 45$ **MeV**, $\sigma_0 \sim 36$ **MeV**, $\sigma_s \sim 130$ **MeV**, $y \sim 0.2$

Intense lattice studies of σ_s in past few years



H. W. Lin ('11)

$\sigma_s = 43 \pm 8$ MeV (2011)

~ 20 – 60 MeV circa 2012

y lies in the range 0.05 ~0.20

$\sigma_{\pi N} = 37 \pm 10$ QCDSF ('12)

$39 \pm 4^{+18}_{-7}$ Durr et al ('11)

For $\sigma_s = 50$ MeV as an example, ⇒ $\sigma_{\pi N} - \sigma_0 = 4$ MeV & y ~ 0.1

$$g_{\phi NN} = (\sqrt{2} G_F)^{1/2} \left(\sigma_u + \sigma_d + \sigma_s + \frac{2}{27} (m_N - \sigma_u - \sigma_d - \sigma_s) \right)$$

for $\zeta_q = 1$ & three heavy quarks

dominated by heavy quark contributions

σ_s	σ_u	σ_d	$\sigma_{\pi N}$	$\langle p \| \frac{\alpha_s}{4\pi} GG \| p \rangle$	y	$g_{\phi NN}$
60	15.9	22.3	40.5	−187	0.11	1.2×10^{-3}
50	15.6	21.8	39.8	−189	0.09	1.1×10^{-3}
40	15.4	21.3	39.0	−191	0.08	1.1×10^{-3}

$\sigma_{\pi N}$ from πN scattering data

Consider $\pi N \to \pi N$ scattering amplitude & define

$$\Sigma_{\pi N} \equiv F_\pi^2 \underline{D}^+ \text{ at Cheng-Dashen point, } s = u = m_N^2,\ t = 2m_\pi^2$$

$$\Sigma_{\pi N} = \sigma_{\pi N}(2m_\pi^2) + \Delta_R = \sigma_{\pi N}(0) + \Delta_\sigma + \Delta_R \quad \text{with } \Delta_\sigma = 15 \text{ MeV},\ \Delta_R = 2 \text{ MeV}$$

Since Cheng-Dashen point is outside of physical region, one relies on dispersion relation to extract Σ from the data

- Koch ('82) : $\Sigma = 64 \pm 8$ $\Rightarrow$ $\sigma_{\pi N} \sim$ 45 MeV, benchmark in 90's
- Olsson ('00): $\Sigma = 73 \pm 9$
- Pavan et al. ('02): $\Sigma = 79 \pm 7$
- Hite et al. ('05): $\Sigma = 81 \pm 6$
- Alarcon et al. ('11): $\Sigma = 76 \pm 7$ (a different approach)

(Olsson through Alarcon) $\Rightarrow$ $\sigma_{\pi N} \sim$ 60-65 MeV after 2000

- A conflict between lattice and expt'l results for $\sigma_{\pi N}$?
- Decouplets will enhance $\sigma_{u,d}$, and hence $\sigma_{\pi N}$, σ_0 and suppress y ?

Alarcon et al.
1209.2870

Pseudoscalar Higgs

$$g_{\sigma NN} = (\sqrt{2}G_F)^{1/2} \sum \langle N | \xi_q m_q \bar{q} i\gamma_5 q | N \rangle$$

Heavy quark expansion: $m_h \bar{q}_h i\gamma_5 q_h \to -\frac{\alpha_s}{8\pi} G\tilde{G}$ $\quad G\tilde{G} \equiv \frac{1}{2}\epsilon_{\mu\nu\alpha\beta} G^{a\mu\nu} G^{a\alpha\beta}$

$E_q \equiv \langle N|\underline{q} i\gamma_5 q|N\rangle$ are related to nucleon m.e. of axial-vector currents

$$\begin{cases} A_\mu^3 &= \bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d \ , \\ A_\mu^8 &= \bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d - 2\bar{s}\gamma_\mu\gamma_5 s \\ A_\mu^0 &= \bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d + \bar{s}\gamma_\mu\gamma_5 s \ , \end{cases} \xrightarrow{\text{EOM}} \begin{cases} g_A^3 m_N &= m_u E_u - m_d E_d \ , \\ g_A^8 m_N &= m_u E_u + m_d E_d - 2m_s E_s \ , \\ g_A^0 m_N &= m_u E_u + m_d E_d + m_s E_s + 3\left\langle N \left| \frac{\alpha_s}{8\pi} G\tilde{G} \right| N \right\rangle \end{cases}$$

Axial-vector couplings g_A^3, g_A^8 determined from neutron and hyperon β decays, g_A^0 from polarized DIS experiment

$$\int_0^1 g_1^p(x, Q^2)dx = C_{\rm NS}(Q^2)\left(\frac{1}{12}g_A^3 + \frac{1}{36}g_A^8\right) + \frac{1}{9}C_{\rm S}(Q^2)g_A^0(Q^2)$$

$$\begin{aligned} g_A^3(Q^2) &= \Delta u(Q^2) - \Delta d(Q^2) \ , \\ g_A^8(Q^2) &= \Delta u(Q^2) + \Delta d(Q^2) - 2\Delta s(Q^2) \\ g_A^0(Q^2) &= \Delta u(Q^2) + \Delta d(Q^2) + \Delta s(Q^2) \ , \end{aligned}$$

Δq: net quark helicity component

Need one more relation to determine $\langle N|\bar{q}i\gamma_5 q|N\rangle$

Some proposals before:

- Large-N_c and chiral limits $\Rightarrow E_u + E_d + E_s = 0$ — **HYC ('89)**
- $\langle p|G\tilde{G}|p\rangle$ is related to gluon spin component

$$2m_N \Delta G\, \bar{u}i\gamma_5 u = \langle p|G\tilde{G}|p\rangle$$

Cheng, Li ('89); Geng, Ng ('90)

However, (i) there is no twist-2 local operator definition for ΔG in OPE, (ii) $\langle N|G\tilde{G}|N\rangle$ violates isospin symmetry

Gross, Treiman, Wilczek ('79)

- Strong CP-odd operator replaced by quark operator

$$-(g^2/32\pi^2)\theta G\tilde{G} \to \theta\,\overline{m}(\bar{u}i\gamma_5 u + \bar{d}i\gamma_5 d + \bar{s}i\gamma_5 d), \qquad \overline{m} = (1/m_u + 1/m_d + 1/m_s)^{-1}$$

Baluni ('79)

$$\overline{m}(E_u + E_d + E_s) = -\langle N|\frac{\alpha_s}{8\pi}G\tilde{G}|N\rangle$$

No solutions for E_u, E_d, E_s !

- U(1) Goldberger-Treiman relation

$$g_A^0 = \frac{\sqrt{3}f_\pi}{2m_N}g_{\eta_0 NN} + \cdots$$ in chiral limit $\Rightarrow$ $$\left\langle N\left|\frac{\alpha_s}{8\pi}G\tilde{G}\right|N\right\rangle = \frac{f_\pi}{2\sqrt{3}}g_{\eta_0 NN} + \cdots .$$

Large-N_c and chiral relation $\langle p|\underline{u}i\gamma_5 u+\underline{d}i\gamma_5 d+\underline{s}i\gamma_5 s|p\rangle=0$

$$E_u = \frac{1}{2}\frac{m_N}{m_d m_s(1+z+w)}\left[(m_d+2m_s)g_A^3 + m_d\, g_A^8\right],$$

$$E_d = \frac{1}{2}\frac{m_N}{m_d m_s(1+z+w)}\left[-(m_u+2m_s)g_A^3 + m_u g_A^8\right],$$

$$E_s = \frac{1}{2}\frac{m_N}{m_d m_s(1+z+w)}\left[(m_u-m_d)g_A^3 - (m_u+m_d)g_A^8\right],$$

$$\left\langle N\left|\frac{\alpha_s}{8\pi}G\tilde{G}\right|N\right\rangle = \frac{1}{2}\frac{m_N}{m_d m_s(1+z+w)}\left\{\frac{2}{3}m_d m_s(1+z+w)g_A^0 + m_s(m_d-m_u)g_A^3 + \frac{1}{3}[m_s(m_u+m_d)-2m_u m_d]g_A^8\right\}$$

$z=m_u/m_d$, $w=m_u/m_s$

Pseudoscalar-nucleon coupling:

$$g_{\sigma NN} = (\sqrt{2}G_F)^{1/2}m_N\left\{\left[\xi_u - \frac{\bar{m}}{m_u}\sum_q \xi_q\right]\Delta u + \left[\xi_d - \frac{\bar{m}}{m_d}\sum_q \xi_q\right]\Delta d + \left[\xi_s - \frac{\bar{m}}{m_s}\sum_q \xi_q\right]\Delta s\right\}$$

This is precisely the general axion-nucleon coupling. Note that physical axion is free of anomalous $G\tilde{G}$ interaction

Light quark contributions to scalar-nucleon coupling vanish in chiral limit. By contrast, $g_{\sigma NN}$ receives significant light quark contributions even in chiral limit because pseuodscalar Higgs has admixture with π^0, η_8, η_0 which couple strongly with nucleon

Zero anomalous dimension for A_μ^3, A_μ^8 $\Rightarrow$ g_A^3 & g_A^8 can be determined from low-energy neutron & hyperon β decays.

SU(3) symmetry implies g_A^8 = 3F-D = 0.585 while g_A^3= F+D = 1.2701

$$\int_0^1 g_1^p(x,Q^2)dx = C_{\rm NS}(Q^2)\left(\frac{1}{12}g_A^3 + \frac{1}{36}g_A^8\right) + \frac{1}{9}C_{\rm S}(Q^2)g_A^0(Q^2)$$

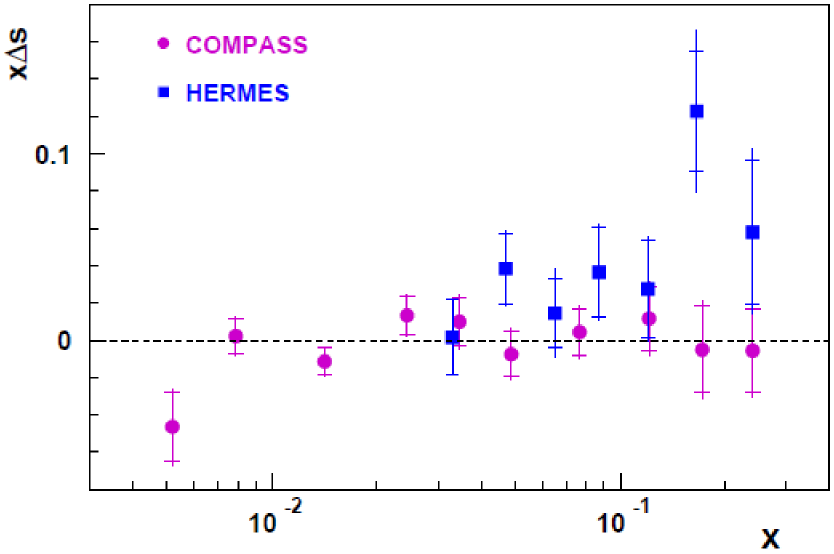
Using g_A^8=0.585, COMPASS ('07) & HERMES ('07) obtained

$g_A^0(3\ \text{GeV}^2) = 0.35\pm0.03\pm0.05$ (COMPASS)

$g_A^0(5\ \text{GeV}^2) = 0.330\pm0.0011\pm0.025\pm0.028$ (HERMES)

$\Rightarrow$ $\Delta u = 0.85$, $\Delta d = -0.42$, $\Delta s = -0.08$ at $Q^2 \sim 4\ \text{GeV}^2$

Semi-inclusive DIS data of COMPASS & HERMES show no evidence of large negative Δs: Δs = -0.02±0.03 by COMPASS



Also ΔG/G is small from RHIC, COMPASS, HERMES

$$\Delta q_{GI}(Q^2) - \Delta q_{CI}(Q^2) = -\frac{1}{2\pi}\alpha_s(Q^2)\Delta G(Q^2)$$

Sea polarization should be small due to smallness of ΔG

Three lattice calculations in 2012 :

1.QCDSF Δs = - 0.020±0.010±0.004 at Q = 2.7 GeV

2.Engelhardt Δs = - 0.031±0.017 at Q = 2 GeV

3.Babich et al Δs = $G_A^s(0)$ = - 0.019±0.017 not renormalized yet

When SU(3) symmtry is broken, g_A^8 may be reduced. For example, $g_A^8 = 0.46\pm0.05$ in cloudy bag model **Bass, Thomas ('10)**

$$\int_0^1 g_1^p(x,Q^2)dx = C_{\rm NS}(Q^2)\left(\frac{1}{12}g_A^3 + \frac{1}{36}g_A^8\right) + \frac{1}{9}C_{\rm S}(Q^2)g_A^0(Q^2)$$

$g_A^8 \downarrow \Rightarrow g_A^0 \uparrow \Rightarrow -\Delta s = 1/3\,(g_A^8 - g_A^0) \downarrow$

For $g_A^8 = 0.46$, $\Delta s = -0.03$ sensitive to SU(3) breaking

$(g_A^3)_n = -(g_A^3)_p \Rightarrow$ large isospin violation

N	$m_u E_u$	$m_d E_d$	$m_s E_s$	$\langle N \vert \frac{\alpha_s}{8\pi} G\tilde{G} \vert N\rangle$	Δu	Δd	Δs	$g_{\sigma NN}$
p	405	−787	−466	389	0.85	−0.42	−0.08	-8.2×10^{-3}
n	−396	796	−75	−2	−0.42	0.85	−0.08	1.3×10^{-3}
p	404	−788	−408	380	0.84	−0.44	−0.03	-7.8×10^{-3}
n	−397	795	−17	−11	−0.44	0.84	−0.03	1.7×10^{-3}

Comparison with other works

$$f_{T_q} \equiv \frac{\langle N \,|\, m_q \bar{q} q \,|\, N \rangle}{m_N} = \frac{\sigma_q}{m_N}$$

	DarkSUSY	Ellis et al	Our
$f_{Tu}^{(p)}$	0.023	0.020	0.017
$f_{Tu}^{(n)}$	0.019	0.014	0.012
$f_{Td}^{(p)}$	0.034	0.026	0.023
$f_{Td}^{(n)}$	0.041	0.036	0.033
$f_{Ts}^{(p)}$	0.14	0.118	0.053
$f_{Ts}^{(n)}$	0.14	0.118	0.053
Δu	0.77	0.78	0.84
Δd	-0.40	-0.48	-0.44
Δs	-0.12	-0.15	-0.03

Conclusions

- **Intensive lattice calculations of sigma terms of strange quark content in the nucleon $\Rightarrow$ scalar-nucleon coupling dominated by heavy quarks**

- **A conflict between lattice and expt'l results for $\sigma_{\pi N}$?**

- **Due to axial anomaly, additional assumption is needed to solve the nucleon matrix elements of pseudoscalar densities. We rely on chiral and large-N_c limits to derive the extra constraint. Chiral and $1/N_c$ corrections need to be studied.**