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A strange contribution to the neutron EDM

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Outline

- Lattice results on the neutron EDM from quark EDMs
- (Opposing) theoretical arguments
  - NDA
  - Chiral perturbation theory
  - Constituent quark model
  - Lage N_c
- QCD sum rules
- Conclusions

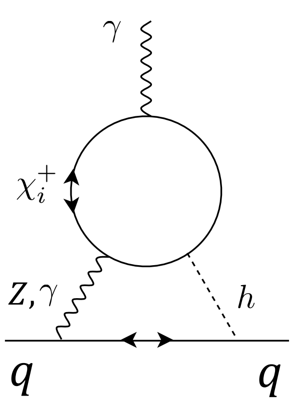
Quark EDMs from BSM

Quark EDMs from the SM are tiny, while CP-violating BSM at $1\sim100$ TeV scale can give rise to sizable quark EDMs near the current experimental sensitivity.

$$\sum_q d_q\, \bar{q} i\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu}$$

Experimental bound (from neutron EDM) $\quad d_{u,d} \lesssim 10^{-26}\, e\, cm$

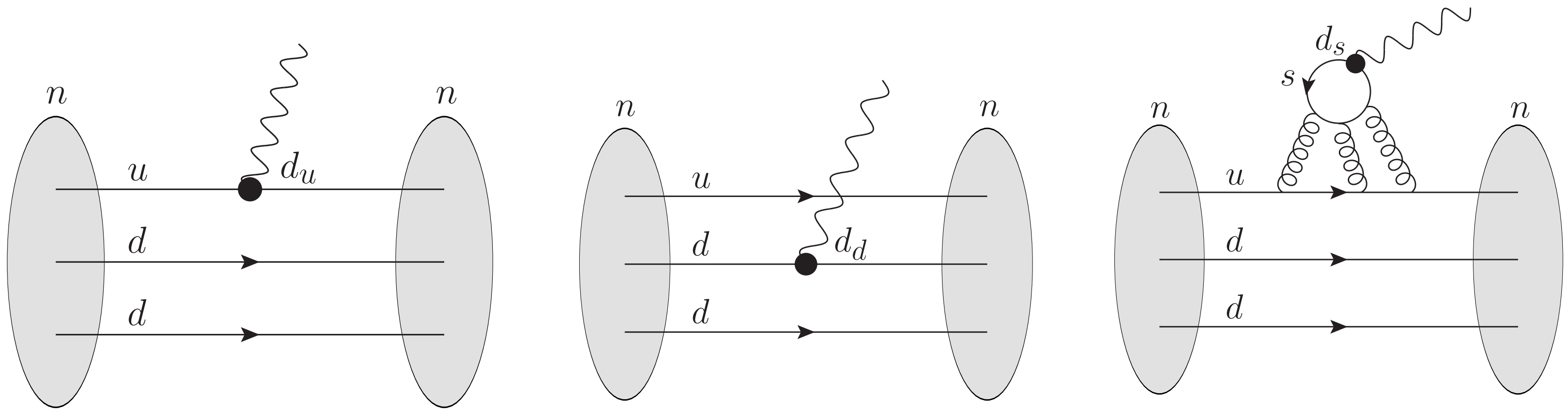
$$d_q^{\rm SM} \sim \frac{m_q}{5\ \rm MeV}\left(10^{-34}\sin\delta_{\rm KM} + 10^{-16}\,\bar{\theta}\right) e\, cm$$



$$d_q^{\rm BSM} \sim \frac{m_q}{5\ \rm MeV}\left(\frac{1\ \rm TeV}{\Lambda_{\rm BSM}}\right)^2\left(\frac{g^2}{16\pi^2}\right)^n 10^{-22}\, e\, cm$$

Neutron EDM from quark EDMs

$$d_n \, \bar{n} i \sigma^{\mu\nu} \gamma_5 n \, F_{\mu\nu} \;\Longleftarrow\; \sum_{q=u,\,d,\,s} d_q \, \bar{q} i \sigma^{\mu\nu} \gamma_5 q \, F_{\mu\nu}$$



$$d_n = g_{Tn}^u d_u + g_{Tn}^d d_d + g_{Tn}^s d_s$$

g_{Tn}^q: quark tensor charge of the neutron

$$g_{Tp}^u = g_{Tn}^d, \;\; g_{Tp}^d = g_{Tn}^u, \;\; g_{Tp}^s = g_{Tn}^s$$

Lattice QCD results on the tensor charges

$$d_n = g_{Tn}^{u} d_u + g_{Tn}^{d} d_d + g_{Tn}^{s} d_s \quad \text{at } \mu = 2 \text{ GeV}$$

$$g_{Tn}^{u} = -0.195(16),\ g_{Tn}^{d} = 0.782(28),\ g_{Tn}^{s} = -0.0016(12)$$

S. Park et al [PNDME collaboration] '25

$$g_{Tn}^{u} = -0.196(12),\ g_{Tn}^{d} = 0.756(29),\ g_{Tn}^{s} = -0.0009(11)$$

C. Alexandrou et al [ETM collaboration] '24

➡ $g_T^{u,d} \sim O(1),\ g_T^{s} \sim O(10^{-3})$ $\quad \frac{g_{Tn}^{d}}{g_{Tn}^{u}} \simeq -4,$

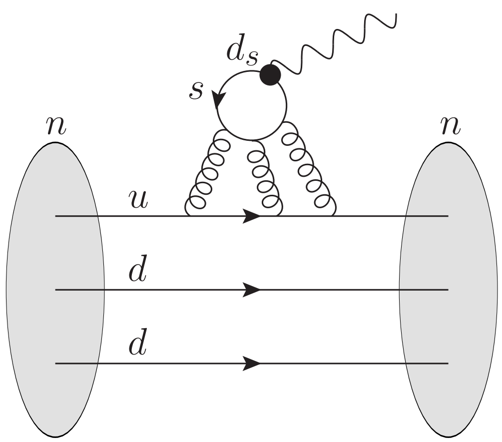
Naïve Dimensional Analysis (NDA)

$$d_n = g_{Tn}^u d_u + g_{Tn}^d d_d + g_{Tn}^s d_s$$

Since $m_s \ll \Lambda_h$ (hadronization scale), NDA tells us

$$\boxed{g_{Tn}^{u,d,s} \sim O(1)}$$

i) Sea quark-loop diagrams

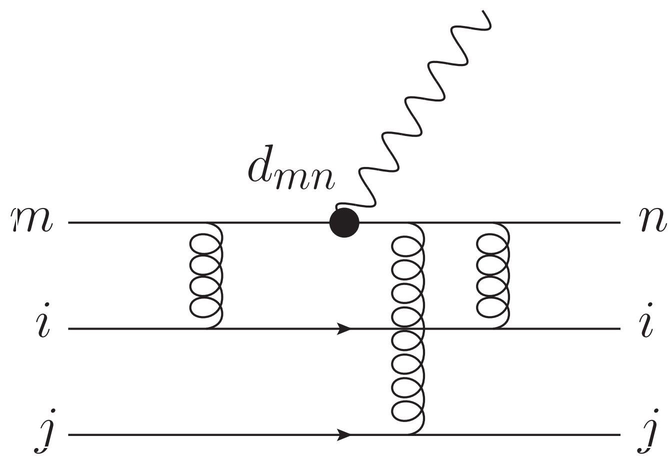


$$SU(3)_L \times SU(3)_R : d \to L d R^\dagger, m \to L m R^\dagger$$

$$\Delta d_u \sim \left(\frac{g^2}{16\pi^2}\right)^{\ell \geq 3} \frac{\mathrm{Tr}\left[d m^\dagger\right]}{\Lambda_h} \sim \frac{m_s}{\Lambda_h} d_s \sim 0.1 d_s$$

$(g \sim 4\pi)$

ii) Diagrams with external quark condensates



$$\sim \frac{g^4}{\Lambda_h^6}\left(\frac{g^2}{16\pi^2}\right)^{\ell\geq 1} [d_{mn}\bar{q}_m P_R q_n][\bar{q}_j P_L q_i][\bar{q}_i i\sigma^{\mu\nu} P_R q_j]F_{\mu\nu} + \mathrm{h.c.}$$

$$\Rightarrow \quad O(1)\ \mathrm{Tr}[d]\ [\bar{q}_i i\sigma^{\mu\nu}\gamma_5 q_i]\ F_{\mu\nu}$$

$g \sim 4\pi$

$\langle \bar{q}_i q_j \rangle \sim \delta_{ij}\frac{\Lambda_h^3}{16\pi^2}$

i.e. $\Delta d_{u,d} \sim O(1) d_s$

Importance of quantifying g_T^s

From BSM, usually $d_q \sim \frac{m_q}{\Lambda_{BSM}^2}$

So if $g_T^s \gtrsim \frac{m_d}{m_s} \fallingdotseq 0.05$, the strange quark EDM contribution to the nucleon EDMs dominates over the up and down quark EDMs.

Lattice simulations tell us $g_T^s \sim 10^{-3}$, and so actually strange EDM would be negligible. On the other hand, here we are discussing why it is hard to be understood theoretically.

For correct BSM interpretation of nucleon EDM data, this issue has to be resolved.

Chiral perturbation theory

The heavy baryon EFT invariant under $SU(3)_L \times SU(3)_R$

$$\mathcal{L}_0 = \frac{f_\pi^2}{4}\mathrm{Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right] - B\mathrm{Tr}\left[mU^\dagger + m^\dagger U\right]$$
$$+ \mathrm{Tr}\left[\overline{\Psi} v^\mu i \nabla_\mu \Psi\right] + (D+F)\mathrm{Tr}\left[\overline{\Psi}\gamma^\mu\gamma_5 A_\mu \Psi\right] + (D-F)\mathrm{Tr}\left[\overline{\Psi}\gamma^\mu\gamma_5 \Psi A_\mu\right]$$

where $U = \xi^2 = e^{i\Pi^a\lambda^a}$ Meson octet field

$$\Psi = \begin{pmatrix} \frac{\Sigma_0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma_+ & p \\ \Sigma_- & -\frac{\Sigma_0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi_- & \Xi_0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

Baryon octet field

$$\nabla_\mu \psi = (D_\mu + V_\mu)\psi \qquad V_\mu = \frac{1}{2}\left(\xi\partial_\mu\xi^\dagger + \xi^\dagger\partial_\mu\xi\right)$$
$$A_\mu = \frac{i}{2}\left(\xi\partial_\mu\xi^\dagger - \xi^\dagger\partial_\mu\xi\right)$$

Baryon EDM operators invariant under $SU(3)_L \times SU(3)_R$

$$\mathcal{L}_{\rm dip} = -\frac{i}{2}\left\{\kappa_1 {\rm Tr}[\hat{d}\overline{\Psi}\sigma^{\mu\nu}\gamma_5\Psi] + \kappa_2 {\rm Tr}[\overline{\Psi}\sigma^{\mu\nu}\gamma_5\hat{d}\Psi] + \kappa_3 {\rm Tr}[\hat{d}]{\rm Tr}[\overline{\Psi}\sigma^{\mu\nu}\gamma_5\Psi]\right\} F_{\mu\nu}$$

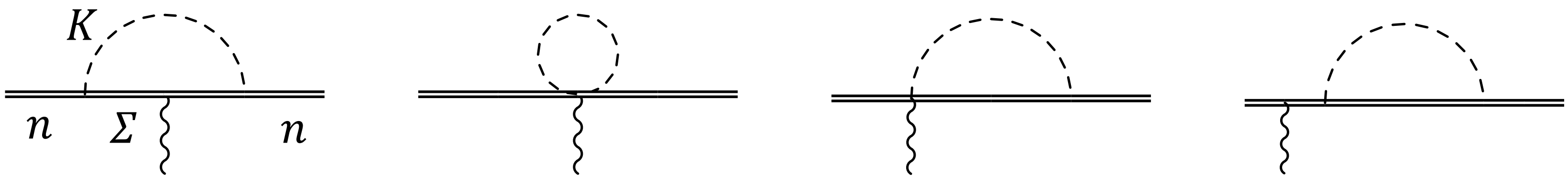
$$\hat{d} = \frac{1}{2}\left(\xi^\dagger d\xi^\dagger + \xi d^\dagger \xi\right) = d - \Pi d \Pi - \frac{1}{2}\left(\Pi^2 d + d\Pi^2\right) + \cdots$$

Setting $\langle \xi \rangle = 1$, $\quad d_n^{\rm LO} = \kappa_1 d_s + \kappa_2 d_d + \kappa_3 (d_u + d_d + d_s)$

$$g^u_{Tn,{\rm LO}} = \kappa_3$$
$$g^d_{Tn,{\rm LO}} = \kappa_2 + \kappa_3$$
$$g^s_{Tn,{\rm LO}} = \kappa_1 + \kappa_3$$

NDA gives $\kappa_1 \sim \kappa_2 \sim \kappa_3 \sim O(1)$.

NLO corrections from baryon-meson loops



$$g^s_{Tn,\mathrm{NLO}} = 0.14\, g^u_{Tn,\mathrm{LO}} + 0.048\, g^d_{Tn,\mathrm{LO}} + 1.7\, g^s_{Tn,\mathrm{LO}} + 0.18\, B^K_{nn,s}$$

from

$$g^s_{Tn,\mathrm{NLO}} = \frac{M_K^2}{16\pi^2 f_\pi^2} \ln \frac{M_n^2}{M_K^2} \left(\frac{1}{2} - \frac{13}{18}D^2 + \frac{15}{9}DF - \frac{1}{2}F^2\right) g^u_{Tn,\mathrm{LO}}$$
$$+ \frac{M_K^2}{16\pi^2 f_\pi^2} \ln \frac{M_n^2}{M_K^2} \left(\frac{1}{2} - \frac{1}{18}(D+3F)^2\right) g^d_{Tn,\mathrm{LO}}$$
$$+ \left\{1 + \frac{M_K^2}{16\pi^2 f_\pi^2} \ln \frac{M_n^2}{M_K^2} \left(1 + \frac{22}{9}D^2 - \frac{10}{3}DF + 4F^2\right)\right.$$
$$\left. + \frac{M_\eta^2}{16\pi^2 f_\pi^2} \ln \frac{M_n^2}{M_\eta^2} \left(\frac{2}{3} + \frac{1}{6}(D-3F)^2\right)\right\} g^s_{Tn,\mathrm{LO}}$$
$$+ B^K_{nn,s} \frac{M_K^2}{16\pi^2 f_\pi^2}.$$

$M_K = 494$ MeV

$M_\eta = 548$ MeV

$D \sim 0.8$, $F \sim 0.5$

$$g^s_{Tn,\mathrm{NLO}} = 0.14\, g^u_{Tn,\mathrm{LO}} + 0.048\, g^d_{Tn,\mathrm{LO}} + 1.7\, g^s_{Tn,\mathrm{LO}} + 0.18\, B^K_{nn,s}$$

Barring unnatural cancellations between the leading order m_s-independent value $g^s_{Tn,\mathrm{LO}}$ and the m_s-dependent chiral corrections,

$$\frac{|g^s_{Tn}|}{|g^{u,d}_{Tn}|} \gtrsim 0.1$$

Constituent quark model

- Often called non-relativistic quark model (NRQM)
- Nucleons = bound states of weakly-interacting QCD-dressed quarks ψ of mass m_ψ larger than the fundamental quark mass

Neutron state with spin up

$$|n;\mathrm{NR}\rangle = \frac{1}{3\sqrt{2}}\left[|ddu\rangle\left(2|++-\rangle - |+-+\rangle - |-++\rangle\right)\right.$$
$$+\ |dud\rangle\left(2|+-+\rangle - |-++\rangle - |++-\rangle\right)$$
$$\left.+\ |udd\rangle\left(2|-++\rangle - |++-\rangle - |+-+\rangle\right)\right]$$

Constituent quark flavor ⊗ spin of the corresponding flavor

$$d_n|_{\mathrm{NRQM}} = \langle n;\mathrm{NR}|d_\psi \otimes \sigma_3|n;\mathrm{NR}\rangle = -\frac{1}{3}d_\psi^u + \frac{4}{3}d_\psi^d$$

Surprisingly close to the lattice results!

However, the constituent quark EDM $d_\psi \neq$ the fundamental quark EDM d
What's the relation between them?

Let's take the chiral quark model by Georgi and Manohar '84 as an EFT of the constituent quarks.

EFT invariant under $SU(3)_L \times SU(3)_R$ with the UV cutoff $M_\chi = 4\pi f_\pi/\sqrt{N_c}$

$$
\begin{aligned}
\mathcal{L}_{\chi\mathrm{QM}} = & -\frac{1}{4} G^A_{\mu\nu} G^{A\,\mu\nu} + \overline{\psi} i \gamma^\mu \nabla_\mu \psi - m_\psi \overline{\psi}\psi \\
& + \frac{f_\pi^2}{4} \mathrm{Tr}[\partial_\mu U \partial^\mu U^\dagger] + b M_\chi f_\pi^2 \mathrm{Tr}[m U^\dagger + \mathrm{hc}] + g_A \overline{\psi} \gamma^\mu \gamma_5 A_\mu \psi \\
& + \cdots ,
\end{aligned}
$$

where ψ Constituent quark fields (triplet of $SU(3)_V$)

$U = \xi^2 = e^{i\Pi^a \lambda^a}$ Meson octet field

$$\nabla_\mu \psi = (D_\mu + V_\mu)\psi \qquad V_\mu = \frac{1}{2}\left(\xi \partial_\mu \xi^\dagger + \xi^\dagger \partial_\mu \xi\right)$$

$$A_\mu = \frac{i}{2}\left(\xi \partial_\mu \xi^\dagger - \xi^\dagger \partial_\mu \xi\right)$$

EDM operator of the constituent quarks

$$\mathcal{L}_{\chi\mathrm{QM}} \supset -\frac{i}{2}\,\overline{\psi}\hat{d}_\psi \sigma^{\mu\nu}\gamma_5\psi\, F_{\mu\nu}$$

$$[\hat{d}_\psi]_{ij} = c_1[\hat{d}]_{ij} + c_2 \mathrm{Tr}[\hat{d}]\,\delta_{ij}$$ dictated by the chiral symmetry

$$\hat{d} = \frac{1}{2}\left(\xi^\dagger d \xi^\dagger + \xi d^\dagger \xi\right) = d - \Pi d \Pi - \frac{1}{2}\left(\Pi^2 d + d\Pi^2\right) + \cdots$$

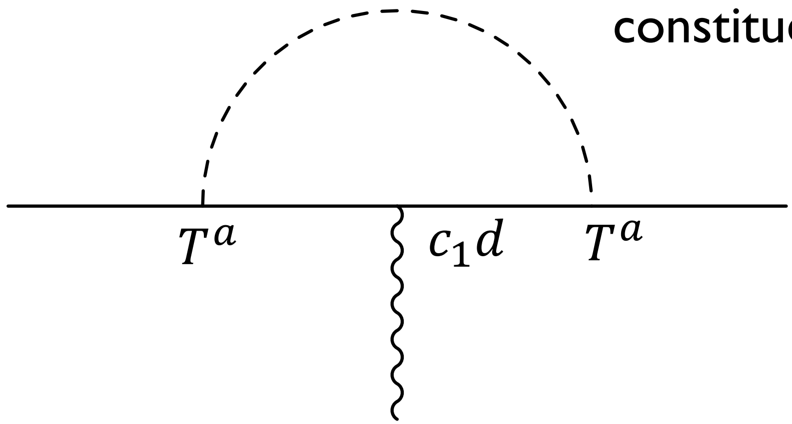
Setting $\langle \xi \rangle = 1$ and using $d_n = -\frac{1}{3} d_\psi^u + \frac{4}{3} d_\psi^d$,

$$g_{Tn}^u = -\frac{1}{3}c_1 + c_2, \qquad g_{Tn}^d = \frac{4}{3}c_1 + c_2, \qquad g_{Tn}^s = c_2$$

The constituent quark EDMs have a contribution from the strange quark EDM.

Natural size of c_2?

constituent quark-meson loop



$$(T^a d T^a)_{ij} = \frac{1}{2}\mathrm{Tr}[d]\delta_{ij} - \frac{1}{6} d_{ij}$$

$$\delta c_2|_{\mathrm{LL}} = c_1 \frac{g_A^2}{16\pi^2 f_\pi^2}\left[\frac{7}{12} m_{\psi_s}^2 \ln\frac{\mu^2}{m_{\psi_s}^2} + \frac{1}{2} M_K^2 \ln\frac{\mu^2}{M_K^2}\right]$$

$m_{\psi_s} \approx 540$ MeV
$M_K \approx 494$ MeV

$\Rightarrow$ $\delta c_2|_{\mathrm{LL}} \sim 0.2\, c_1$

Therefore, barring unnatural cancellations

$$\frac{|g_{Tn}^s|}{|g_{Tn}^{u,d}|} \gtrsim 0.1$$

Large N_c counting

- Neutron as a state composed of $O(N_c)$ up and down quarks with strangeness $|S| \ll O(N_c)$

$$d_n|_{\mathrm{LO}} = c_0 \left(n\right| \{d_a \lambda_a J_3\} \left|n\right)$$
$$= c_0 \left[\left(-\frac{N_c+1}{6}\right) d_u + \left(\frac{N_c+3}{6}\right) d_d + \left(-\frac{1}{3}\right) d_s\right]$$

For $N_c = 3$, $\frac{g_{Tn}^d}{g_{Tn}^u} = -\frac{3}{2}, \quad \frac{g_{Tn}^s}{g_{Tn}^u} = \frac{1}{2}$

For large N_c, $\frac{g_{Tn}^d}{g_{Tn}^u} = -1 + \mathcal{O}(1/N_c), \quad \frac{g_{Tn}^s}{g_{Tn}^u} = \mathcal{O}(1/N_c)$

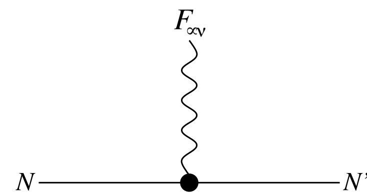
The lattice results are not reproduced in large N_c.

QCD sum rules

Compute the two point correlation function of the neutron interpolating fields

$$\eta_n = 2\epsilon_{abc}(d_a^T C\gamma_5 u_b)d_c + 2\beta\epsilon_{abc}(d^T C u_b)\gamma_5 d_c$$

$$i\int d^4x e^{iq\cdot x}\langle\Omega_{\rm CPV}|T\{\eta_n(x)\bar{\eta}_n(0)\}|\Omega_{\rm CPV}\rangle$$

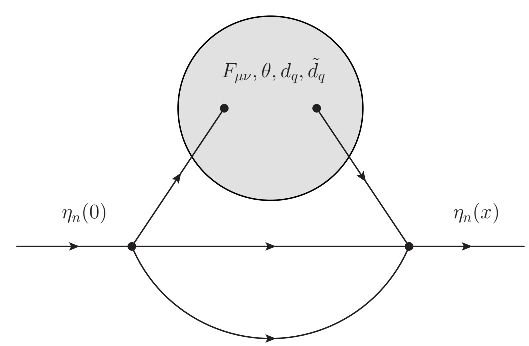


Pheno side

$$= \frac{\{\tilde{F}\sigma, \not{q}\}}{2}\left[\frac{\lambda_n^2 d_n m_n}{(q^2 - m_n^2)^2} + \sum_i \frac{f_i}{(q^2 - m_n^2)(q^2 - m_i^2)} + \sum_{i,j} \frac{f_{ij}}{(q^2 - m_i^2)(q^2 - m_j^2)}\right] + \cdots$$

OPE side $(q(x) \; = q(0) + x^\mu D_\mu q(0) + \cdots, \; x\sim 1/Q)$

$$= \frac{1}{16\pi^2}\langle\bar{q}q\rangle \log\left(\frac{-q^2}{\Lambda^2}\right)\{\tilde{F}\cdot\sigma, \not{q}\}\big[(4e_d m_d \rho_d - e_u m_u \rho_u)\chi\bar{\theta}$$
$$+ (4d_d - d_u) + (\kappa - \frac{1}{2}\xi)(4e_d\tilde{d}_d - e_u\tilde{d}_u)\big] \; .$$



To single out the neutron EDM part, $q^2 \approx m_n^2$ for which $\frac{\alpha_s}{4\pi}\sim 0.1$

Conclusions

- Two independent lattice QCD groups have shown quite precisely

$$g_{Tn}^{u} = -0.2,\ \ g_{Tn}^{d} = 0.8,\ \ g_{Tn}^{s} = -O(10^{-3})$$

- Determining g_T^s at the level of $m_d/m_s \fallingdotseq 0.05$ is very important to interpret EDM data in terms of BSM scenarios.

- Chiral perturbation theory and constituent quark model support $g_T^s \gtrsim O(0.1)$ assuming there are no cancellations among LO, NLO, and higher order contributions. Still the bad convergence of the perturbation theory has to be kept in mind.

- QCD sum rules yet give tensor charges in agreement with the lattice results.