Tensor Chargers and their Impact on Physics Beyond the Standard Model

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Motivation

- Nuclear and neutron beta decays have played an important role in determining the vector-axial (V-A) structure of weak interactions and in shaping the Standard Model
- Recently neutron decay can be used to probe the existence of BSM interactions
- Next generation of neutron beta decay experiments increasing sensitivity to BSM tensor interactions by an order of magnitude
- In order to assess the impact of these future experiments, constraints need to be put on the tensor charge, g_T.

b-Fierz interference term

- For a beam of polarized neutrons the differential decay rate is described by:

$$dW \propto \frac{1}{\tau_n} F(E_e)\left[1 + a\frac{\mathbf{p}_e.\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + A\frac{\boldsymbol{\sigma}_n.\mathbf{p}_e}{E_e} + B\frac{\boldsymbol{\sigma}_n.\mathbf{p}_\nu}{E_\nu}\right]$$

$$\begin{aligned} b^{\text{BSM}} &\approx 0.34 g_S \epsilon_S - 5.22 g_T \epsilon_T \\ b_v^{\text{BSM}} &\approx 0.44 g_S \epsilon_S - 4.85 g_T \epsilon_T \end{aligned}$$

- b_v^{BSM} correction term to the correlation coefficient B
- Extracting bounds on new-physics effective couplings ϵ_T and ϵ_S requires knowledge of $g_T,\ g_S$
- Improved measurements of neutrino asymmetry parameter B and the Fierz interference term b

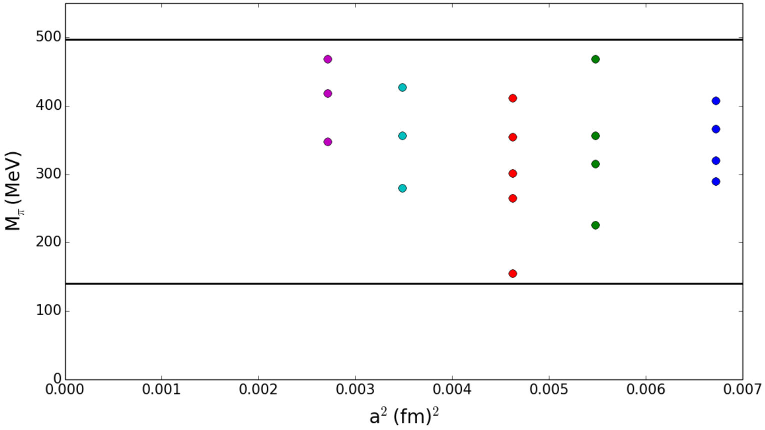
Quark Electric Dipole Moment

- The quark EDM contributions to the neutron EDM, d_n, are given by:

$$d_n = d_u g_T^d + d_d g_T^u + d_s g_T^s$$

- g_T^s consistent with 0
- d_u, d_d, d_s contain new CP violating interactions at the TeV scale
- knowing g_T^q put bound on d_n, constrain d_q and BSM theories

Analysis



500
400
300
200
100
0
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0.007
M_π (MeV)
a^2 (fm)^2

Calculating Matrix Elements using The Feynman-Hellmann Theorem

- Relates the derivative of the total energy to the expectation value of the derivative of the action

$$\frac{\partial E_{X,\lambda}(\vec{k})}{\partial \lambda} = \frac{1}{2E_{X,\lambda}(\vec{k})} \langle X, \vec{k}| \frac{\partial S}{\partial \lambda} |X, \vec{k}\rangle_\lambda \, ,$$

- In lattice calculations, modify the action

$$S \to S + \lambda \mathcal{O}$$

- Examine the behaviour of hadron energies as λ changes
- Extract the matrix element
- Hadron energies are extracted from two-point functions
- Control of excited state contamination more simple than standard three-point analyses

Calculating Matrix Elements using The Feynman- Hellmann Theorem

- To calculate the tensor charge we have the modified action:

$$S \to S + \lambda \int d^4x \bar{q}(x)\gamma_5\sigma_{\mu\nu}q(x),$$

- Applying the Feynman- Hellmann Theorem we get:

Spin-up	Spin-down
$\frac{\partial E_\lambda}{\partial \lambda}\Big\|_{\lambda=0} = \delta q$	$\frac{\partial E_\lambda}{\partial \lambda}\Big\|_{\lambda=0} = -\delta q$

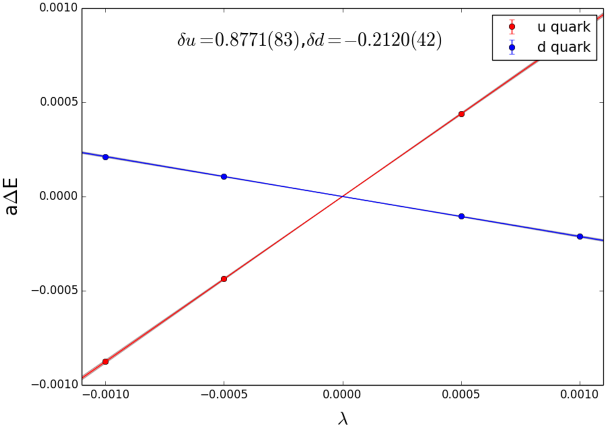
- The energy as a function of λ is therefore given by

$$E(\lambda) = E(0) + \lambda\delta q + \mathcal{O}(\lambda^2).$$

- Tensor charge is then:

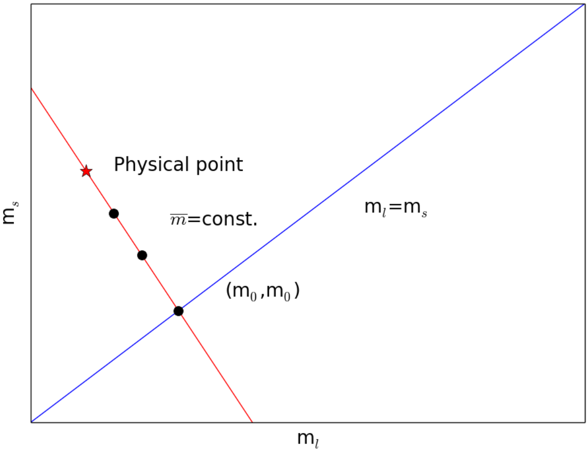
$$g_T = \delta u - \delta d,$$

Results



Calculated at $a = 0.074fm$, $(\kappa_l, \kappa_s) = (0.120900, 0.120900)$

Flavour Symmetry Breaking



Flavour Symmetry Breaking

- $SU(3)$ unbroken $\Rightarrow$ operator octet expressed as two couplings (f, d)
- $SU(3)$ broken $\Rightarrow$ construct quantities (D_i, F_i) Example:

$$\begin{aligned} D_1 &= -(A_{\bar{N}\eta N} + A_{\bar{\Xi}\eta\Xi}) \\ &= -(\frac{1}{\sqrt{6}}\delta_u^p + \delta_d^p) + \frac{1}{\sqrt{6}}(\delta_u^{\Xi} - 2\delta_s^{\Xi})) \end{aligned}$$

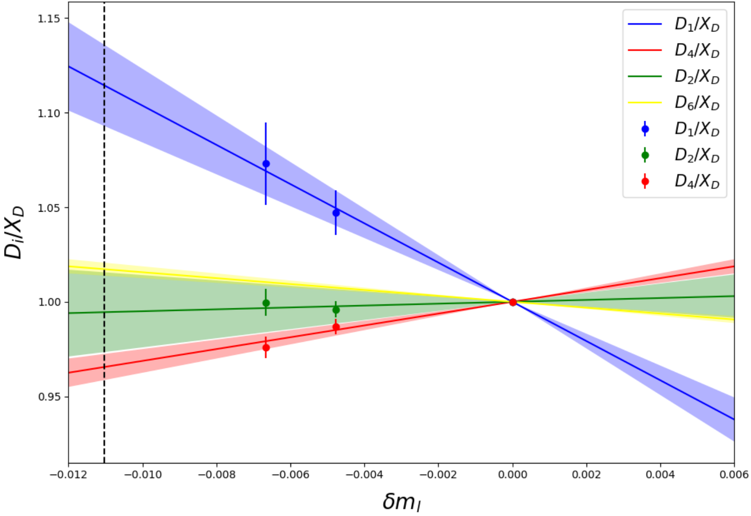
- Fan plots with slope parameters (r_i, s_i) constraining them
- Calculate each quantity (D_i, F_i) for each quark mass calculated on the lattice

$$\begin{aligned} D_1 &= 2d - 2r_1\delta m_l \\ D_2 &= 2d + (r_1 + 2\sqrt{3}r_3)\delta m_l \\ \text{where } \delta m_l &= m_l - \bar{m} \end{aligned}$$

Flavour Symmetry Breaking

- Roger Horsley: Patterns of flavour symmetry breaking in hadron matrix elements involving u, d and s quarks. 26th July, 13:15 ET
- PRD(2019) arXiv:1909.02521

Fan plots



$a = 0.074 fm$ using first 3 pion masses

Flavour Symmetry Breaking

- Calculate Flavour diagonal matrix elements and hence the tensor charge through:

$$\langle p|\,\bar{u}\Gamma u\,|p\rangle \;= 2\sqrt{2}f + \Big(\sqrt{\frac{3}{2}}r_1 - \sqrt{2}r_3 + \sqrt{2}s_1 - \sqrt{\frac{3}{2}}s_2\Big)\delta m_l^*$$
$$\langle p|\,\bar{d}\Gamma d\,|p\rangle \;= \sqrt{2}(f - \sqrt{3}d) + \Big(\sqrt{\frac{3}{2}}r_1 - \sqrt{2}r_3 - \sqrt{2}s_1 - \sqrt{\frac{3}{2}}s_2\Big)\delta m_l^*$$

Where r_1, r_3 , s_1 and s_2 are the slopes of the fan plots, and:

$$g_T = \langle p|\,\bar{u}\Gamma u\,|p\rangle - \langle p|\,\bar{d}\Gamma d\,|p\rangle\,.$$

and using δm_l^* at physical point

Systematics

- Quark Mass
  - Simulate mass degenerate u, d quarks, separate heavier s quark
  - Mass of the quarks is varied keeping the average masses of the quarks the same
  - Flavour symmetry breaking to extrapolate towards the physical point
- Finite Spacing and Volume
  - Require a exploration to the continuum limit, $a = 0$
  - Using lattice spacings $a = 0.082,\ 0.074,\ 0.068,\ 0.059,\ 0.052$ fm
  - lattice volumes $32^3 \times 64$, $48^3 \times 96$, $64^3 \times 96$

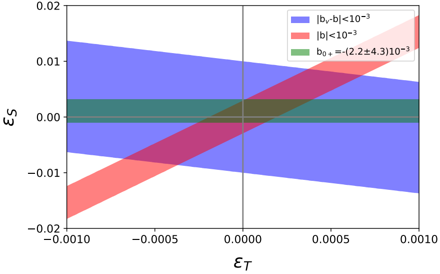
Preliminary Results

$a(fm)$	g_T
0.082	1.008(6)
0.074	0.989(5)
0.068	0.992(4)

- Error purely statistical

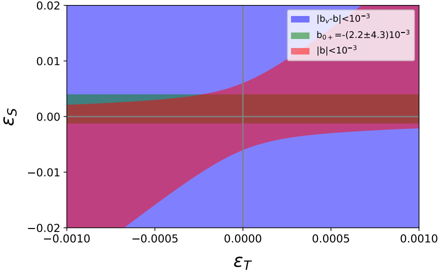
Impact on Phenomenology

- $g_T = g_S = 1$
- No uncertainty



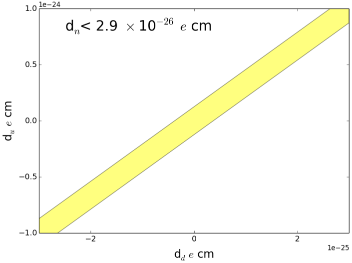
- Tensor and scalar charges taken from lattice QCD:
  $g_S = 0.8(4)$
  $g_T = 1.05(35)$

arXiv:1110.6448



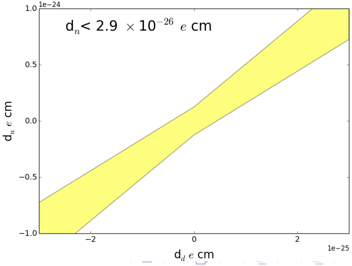
Impact on Phenomenology

- g_T^u andg_T^d with no uncertainty



- g_T^u andg_T^d taken from lattice QCD: $g_T^u = 0.774(66)$ $g_T^d = -0.233(28)$

arXiv:1506.06411



Conclusion

- Current uncertainties in g_T weaken the significance of new 10^{-3} and further 10^{-4} level experiments
- Experimental progress cannot lead to competitive constraints on new tensor couplings without theoretical progress
- Method presented we have:
    - Control of excited state contamination from FH method
    - Quark mass- Flavour symmetry breaking to extrapolate towards the physical point
    - Exploration to the continuum limit, $a = 0$, using 5 lattice spaces