# Nucleon axial, tensor, and scalar charges and $\sigma$-terms from lattice QCD

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# Contents

# Methodology

- To extract the nucleon charges we use three- and two-point correlation functions:

$$C^{\mu}(x_s; x_{ins}) = \langle \mathcal{J}(x_s) \mathcal{O}^{\mu}(x_{ins}) \bar{\mathcal{J}}(0) \rangle$$

$$C(x_s) = \langle \mathcal{J}(x_s) \bar{\mathcal{J}}(0) \rangle$$

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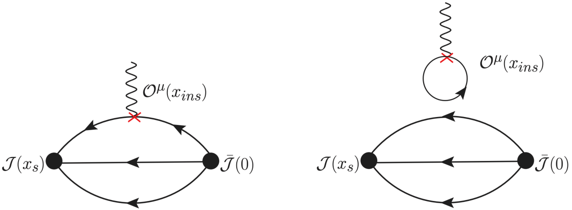


Connected (left) and disconnected (right) contributions of a baryon three-point function.

# Methodology

- We can manipulate the three-point function and at the limit of large time, where $(t_s - t_{ins}) \to \infty$ and $t_{ins} \to \infty$ write it as:

$$C^{\mu}(\vec{p'}, t_s; \vec{p}_1, t_{ins}) \to \langle \mathcal{J} | H(\vec{p'}) \rangle \langle H(\vec{p}_1) | \bar{\mathcal{J}} \rangle \times \langle H(\vec{p'}) | \mathcal{O}^{\mu} | H(\vec{p'} - \vec{p}_1) \rangle \, e^{-E(\vec{p'})(t_s - t_{ins})} e^{-E(\vec{p}_1) t_{ins}}$$

- Similarly, the two-point function can be written as:

$$C(\vec{p}, t_s) \to \langle \mathcal{J} | H(\vec{p}) \rangle \langle H(\vec{p}) | \bar{\mathcal{J}} \rangle \, e^{-E(\vec{p}) t_s}$$

- To isolate the matrix element from the overlap terms and the exponentials, we take the ratio of the three-point function with two-point functions:

$$R^{\mu}(\vec{p'}, t_s; \vec{p}_1, t_{ins}) = \frac{C^{\mu}(\vec{p'}, t_s; \vec{p}_1, t_{ins})}{C(\vec{p'}, t_s)} \times \sqrt{\frac{C(\vec{p}_1, t_s - t_{ins}) C(\vec{p'}, t_{ins}) C(\vec{p'}, t_s)}{C(\vec{p'}, t_s - t_{ins}) C(\vec{p}_1, t_{ins}) C(\vec{p}_1, t_s)}}$$

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- The spectral decomposition of the two- and three-point functions are given respectively by:

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$$C^{\mu}(\Gamma_k, \vec{q}; t_s, t_{ins}) = \sum_{i,j}^{\infty} A_{\mu}^{i,j}(\Gamma_k, \vec{q}) e^{-E_i(\vec{0})(t_s - t_{ins}) - E_j(\vec{q}) t_{ins}}$$

- The nucleon charges are obtained at zero momentum transfer and the ratio at large times gives:

$$R^{\mu}_{A,S,T}(t_s, t_{ins}) = \frac{C^{\mu}(t_s, t_{ins})}{C(t_s)} \rightarrow g_{A,S,T}$$

- To extract the charge from the data we use:

$$g_{A,S,T} = \frac{A_{\mu}^{0,0}(\vec{0})_{A,S,T}}{c_0(\vec{0})}$$

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- From each combination of the varied parameters, we obtain a different result. We average the results using the Akaike Information Criterion (AIC).
- For each fit $i$, we associate a weight $w_i$, which we define as:

$$\log(w_i) = -\frac{\chi_i^2}{2} + N_{\text{dof},i}$$

- We use the weights to define the probability:

$$p_i = \frac{w_i}{Z} \quad \text{with} \quad Z = \sum_i w_i$$

- We define the *Model Average (MA)* value of an observable $\mathcal{O}$ as:

$$\langle \mathcal{O} \rangle_{MA} = \sum_i \bar{\mathcal{O}}_i p_i \quad \text{with} \quad \sigma_{MA}^2 = \sum_i (\sigma_i^2 + \bar{\mathcal{O}}_i^2) p_i - \langle \mathcal{O} \rangle_{MA}^2$$

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# The Data

- Our data consists of two- and three-point functions from three $N_f = 2+1+1$ twisted mass fermion ensembles at the physical point, generated by the *Extended Twisted Mass Collaboration (ETMC)*.

| **cB211.072.64** 749 configurations | | |
|---|---|---|
| $t_s/a$ | $t_s$ [fm] | $n_{src}$ |
| 8 | 0.64 | 1 |
| 10 | 0.80 | 2 |
| 12 | 0.96 | 5 |
| 14 | 1.12 | 10 |
| 16 | 1.28 | 32 |
| 18 | 1.44 | 112 |
| 20 | 1.60 | 128 |
| Nucleon 2pt 477 | | |

| **cC211.060.80** 400 configurations | | |
|---|---|---|
| $t_s/a$ | $t_s$ [fm] | $n_{src}$ |
| 6 | 0.41 | 1 |
| 8 | 0.55 | 2 |
| 10 | 0.69 | 4 |
| 12 | 0.82 | 10 |
| 14 | 0.96 | 22 |
| 16 | 1.10 | 48 |
| 18 | 1.24 | 45 |
| 20 | 1.37 | 116 |
| 22 | 1.51 | 246 |
| Nucleon 2pt 650 | | |

| **cD211.054.96** 496 configurations | | |
|---|---|---|
| $t_s/a$ | $t_s$ [fm] | $n_{src}$ |
| 8 | 0.46 | 1 |
| 10 | 0.57 | 2 |
| 12 | 0.68 | 4 |
| 14 | 0.80 | 8 |
| 16 | 0.91 | 16 |
| 18 | 1.03 | 32 |
| 20 | 1.14 | 64 |
| 22 | 1.25 | 16 |
| 24 | 1.37 | 32 |
| 26 | 1.48 | 64 |
| Nucleon 2pt 480 | | |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flavour | $N_{defl}$ | $N_r$ | $N_{Had}$ | $N_{vect}$ | $N_{defl}$ | $N_r$ | $N_{Had}$ | $N_{vect}$ | $N_{defl}$ | $N_r$ | $N_{Had}$ | $N_{vect}$ |
| Light | 200 | 1 | 512 | 6144 | 450 | 1 | 512 | 6144 | 0 | 8 | 512 | 49152 |
| Strange | 0 | 2 | 512 | 12288 | 0 | 4 | 512 | 24576 | 0 | 4 | 512 | 24576 |
| Charm | 0 | 12 | 32 | 4608 | 0 | 1 | 512 | 6144 | 0 | 1 | 512 | 6144 |

Statistics used for the connected two- and three-point functions (top) and disconnected loops (bottom)

# Axial Charge

- The nucleon isovector axial charge, $g_A^{u-d}$, governs the rate of weak decay of neutrons into protons.

- The flavor diagonal $g_A^f$, are related to the intrinsic spin carried by the quarks in the nucleon.

- The isovector axial-vector operator is given by:

$$\mathcal{O}_A^{u-d} \equiv A_\mu = \bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d$$

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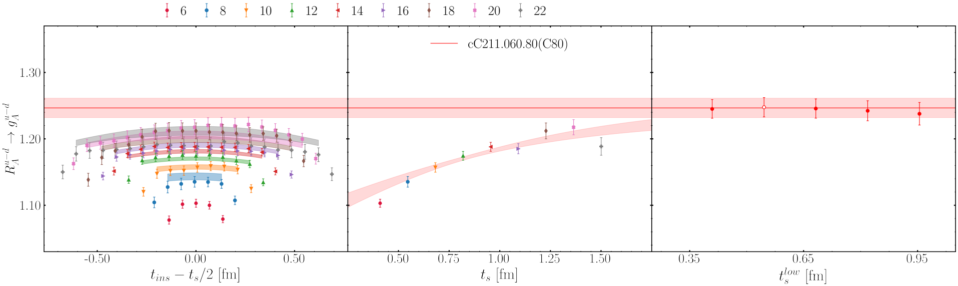
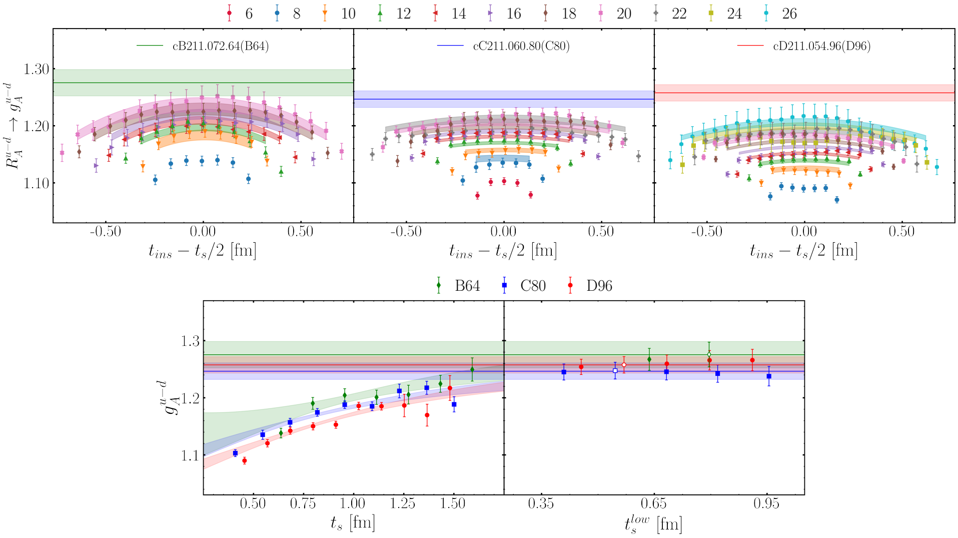
# Axial Charge

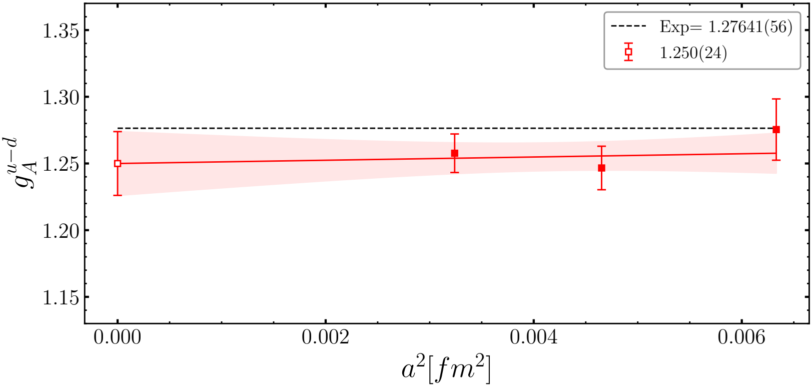



See G. Koutsou, after the lunch break for more details.




Analysis of the isovector axial charge $g_A^{u-d}$ for all three ensembles.

# Axial Charge - Preliminary Results




The continuum limit of the isovector axial charge $g_A^{u-d}$.

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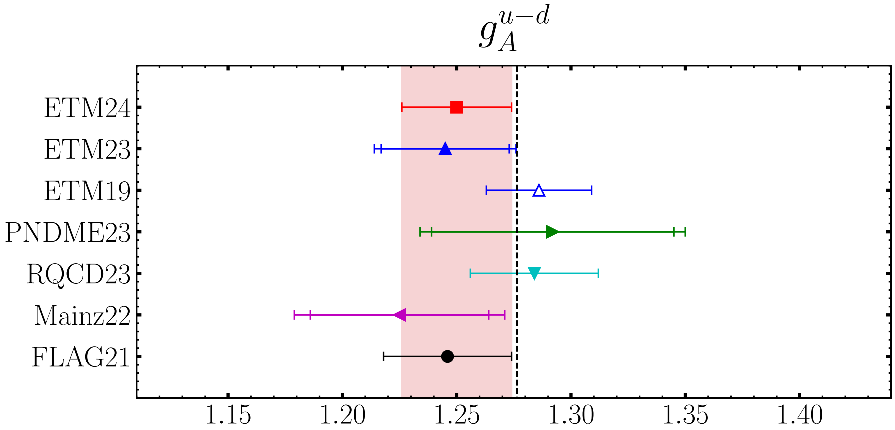


Comparison of the results of this work (ETM24) with previous ETMC results and other lattice works.

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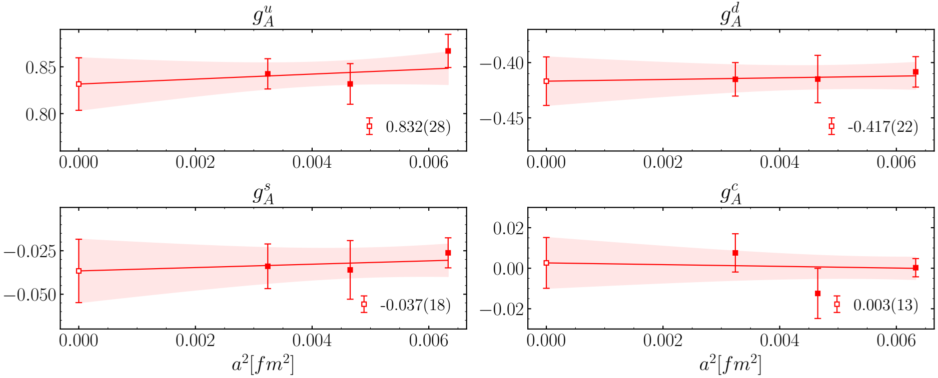


Continuum limit extrapolations for single flavor axial charges.

# Scalar Charge

- Scalar charges are only known poorly from phenomenology.
- They can put limits on the existence of BSM interactions and are relevant in dark matter searches.
- The isovector scalar charge $g_S^{u-d}$ measures the proportionality constant between the neutron-proton mass splitting and the up and down quark mass splitting.
- The nucleon matrix element of the single-flavor scalar operator $g_S^f$ is directly connected to the quark content of the nucleon.
- We define the nucleon $\sigma$-terms as

$$\sigma^f = m_f \langle N|\bar{q}_f q_f|N\rangle \ , \quad \sigma^{u+d} = m_{ud} \langle N|\bar{u}u + \bar{d}d|N\rangle$$

for a given quark $q_f$ of flavor $f$, or for the isoscalar combination.

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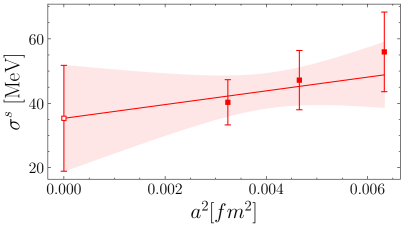
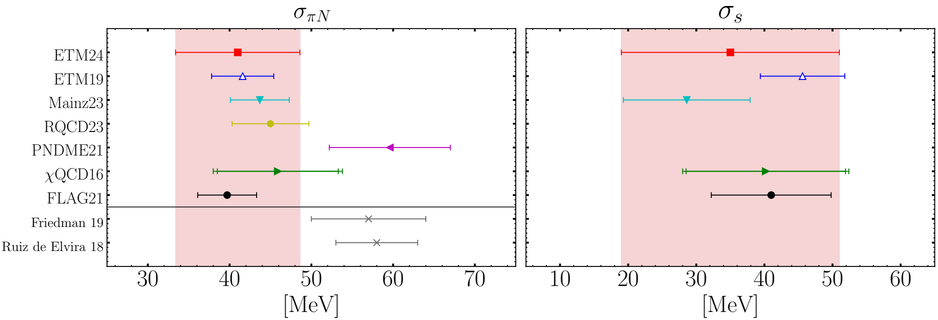
# $\sigma$-terms - Preliminary Results

$$\sigma_{\pi N} = 41.0(7.6) MeV$$

$$\sigma_s = 35(16) MeV$$

$$\sigma_c = 82(29) MeV$$




Comparison of the $\pi N$ and strange sigma term results of this work (ETM24) with previous ETMC results and other lattice works.

# Tensor Charge

- The tensor charge is the first Mellin moment of the transversity parton distribution function (PDF).

- The flavor-diagonal tensor charge plays a crucial role in determining the contribution of quark electric dipole moments to the neutron electric dipole moment, which indicates CP violation.

- Like the scalar charges, tensor charges are only known poorly from phenomenology.

- They can put limits on the existence of BSM interactions with tensor structures and are also relevant in dark matter searches.

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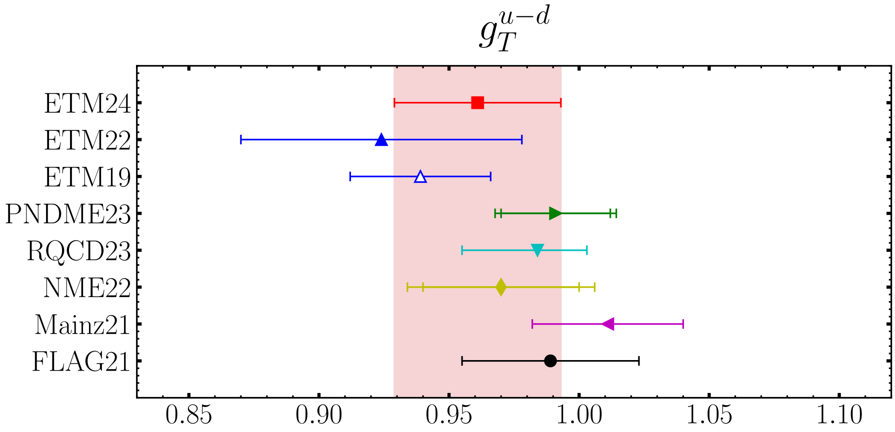


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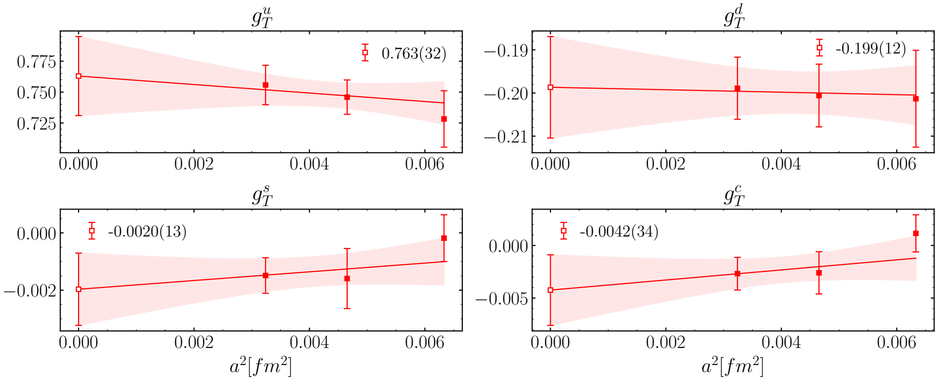


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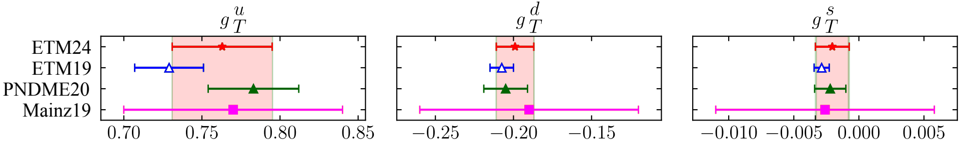


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# Summary and Outlook

- In this work we used three $N_f = 2+1+1$ physical point ensembles to calculate the nucleon axial, scalar and tensor charges as well as the nucleon $\sigma$-terms.

- Our results are in agreement with other lattice works and with the experimental value the case of $g_A^{u-d}$.

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# Thank you for your attention!

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