Nucleon axial, tensor, and scalar charges and σ-terms in lattice QCD

16th European Research Conference on Electromagnetic Interactions with Nucleons and Nuclei

Constantia Alexandrou[a,b], Simone Bacchio[b], Jacob Finkenrath[c], Christos Iona[a,b], Giannis Koutsou[b], Yan Li[a], Gregoris Spanoudes[a]

[a]Department of Physics, University of Cyprus, Nicosia, Cyprus
[b]Computation-based Science and Technology Research Center, The Cyprus Institute, Nicosia, Cyprus
[c]Theoretische Teilchenphysik, Bergische Universität Wuppertal, Germany

Introduction

We present our calculation for the nucleon axial, scalar and tensor charges at the continuum limit using Lattice Quantum Chromodynamics simulations.

- We analyze three $N_f = 2+1+1$ twisted mass fermion ensembles with all quark masses tuned to approximately their physical values.
- We also include preliminary results for the isovector quantities with a fourth, finer lattice spacing ensemble.

Motivation

- The nucleon axial, tensor, and scalar charges, together with the σ-terms, are fundamental quantities that reveal the internal structure of the nucleon within the Standard Model.
- The axial charge, g_A^{u-d}, governs neutron β-decay and probes chiral symmetry breaking, CKM unitarity, and neutrinoless double-β decay.
- Flavor-diagonal axial charges, g_A^f, describe the intrinsic quark spin contribution to the nucleon spin, measured in polarized deep inelastic scattering experiments and planned for further study at the Electron-Ion Collider (EIC).
- The isovector scalar charge g_S^{u-d} links the neutron–proton mass difference to quark mass splitting, while the tensor charge g_T encodes the first moment of the transversity PDF.
- Flavor-diagonal tensor charges connect quark electric dipole moments to the neutron EDM, probing CP violation.
- The tensor and scalar charges are important for constraining possible Beyond Standard Model interactions and interpreting results from neutrino and dark matter experiments.
- The nucleon σ-terms quantify the contribution of quark masses to the nucleon mass and are essential for predicting dark matter–nucleon scattering cross sections.

Methodology

- The nucleon charges for each quark flavor f, denoted as $g^f_{\mathrm{A,T,S}}$, are extracted from the matrix elements of the corresponding axial, tensor, and scalar operators at zero momentum transfer:

$$\langle N|\bar{\psi}^f\Gamma_{\mathrm{A,S,T}}\psi^f|N\rangle = g^f_{\mathrm{A,T,S}}\bar{u}_N\Gamma_{\mathrm{A,S,T}}u_N\,, \qquad (1)$$

- The renormalization group invariant σ^f-term is given by

$$\sigma^f = m_f\langle\, N|\bar{\psi}^f\psi^f|N\rangle, \qquad (2)$$

with m_f the mass of the quark with flavor f.
- Nucleon charges are extracted by combining two- and three-point nucleon correlation functions.
- There are both connected and disconnected contributions to the nucleon three-point function. These are illustrated in Fig.1.

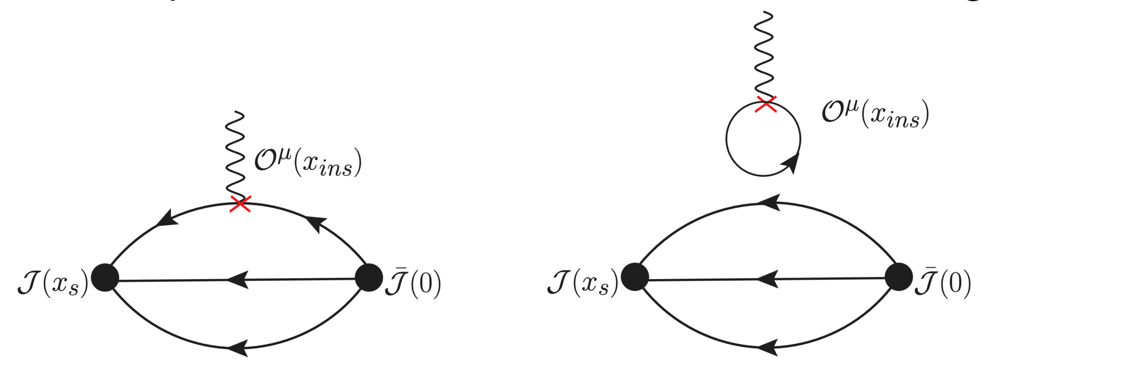

Figure 1: Connected (left) and disconnected (right) contributions of a baryon three-point function.

- The axial case, for example, is given as the ratio of the axial current three- to two-point function for $\vec{p} = \vec{q} = 0$:

$$R^A_\mu(t_s, t_{ins}) = \frac{C^{3pt}_\mu(\Gamma_k; t_s, t_{ins})}{C^{2pt}(t_s)} \xrightarrow[t_{ins}\to\infty]{t_s - t_{ins}\to\infty} g_A. \qquad (3)$$

- In the large time separation limit, the ratio converges to the corresponding charge, e.g., g_A.
- All quantities are computed at the physical point, eliminating the need for chiral extrapolation.

Reference

C. Alexandrou, S. Bacchio, J. Finkenrath, C. Iona, G. Koutsou, Y. Li, and G. Spanoudes, *Nucleon charges and σ-terms in lattice QCD, Phys. Rev. D 111, 054505 (2025), arXiv:2412.01535 [hep-lat].*

Results

- The calculated nucleon matrix elements are renormalized nonperturbatively by employing the RI′/MOM scheme followed by perturbative conversion to the $\overline{\mathrm{MS}}$ scheme at the reference scale of 2 GeV.
- We obtain final results via a model-averaged continuum extrapolation ($a \to 0$), combining linear and constant fits in a^2 with weights reflecting lattice spacing dependence. For the isovector quantities, we perform a continuum limit extrapolation using four ensembles. The extrapolation for g_A^{u-d} is shown in Fig. 2.
- In Fig. 3 we compare our preliminary results for the isovector charges with other lattice QCD determinations, observing good overall agreement.

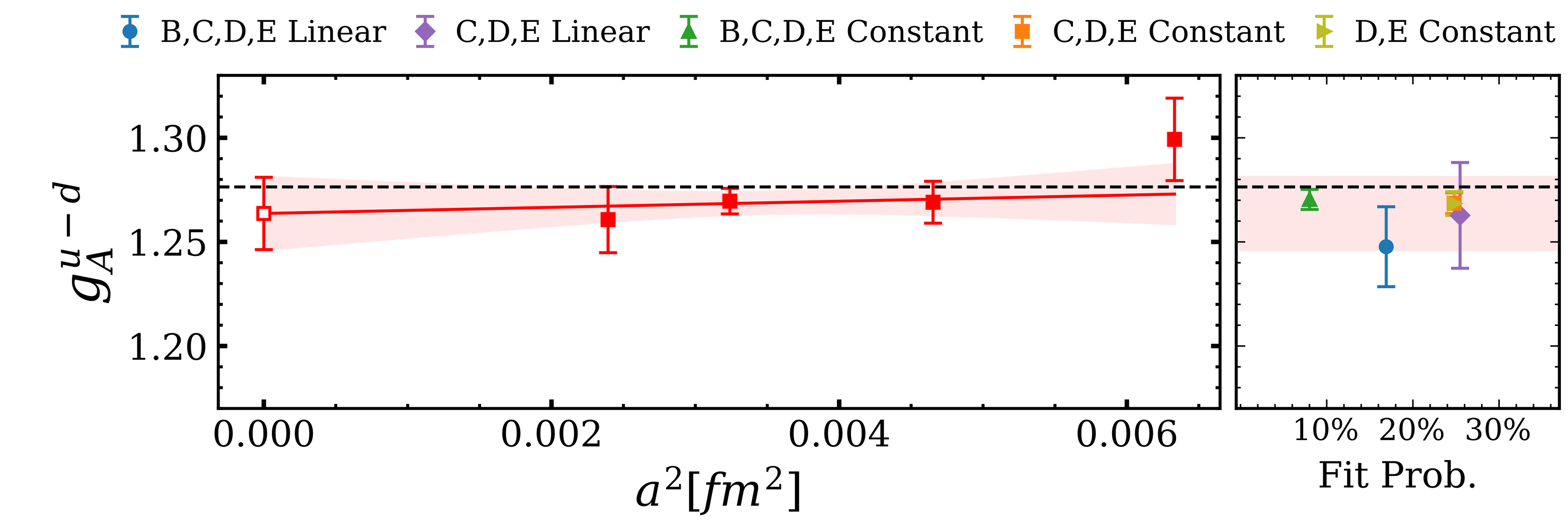

Figure 2: Continuum limit extrapolation of the nucleon isovector axial charge using four ensembles (left) and the corresponding fit weights (right). The dashed line represents the experimental value.

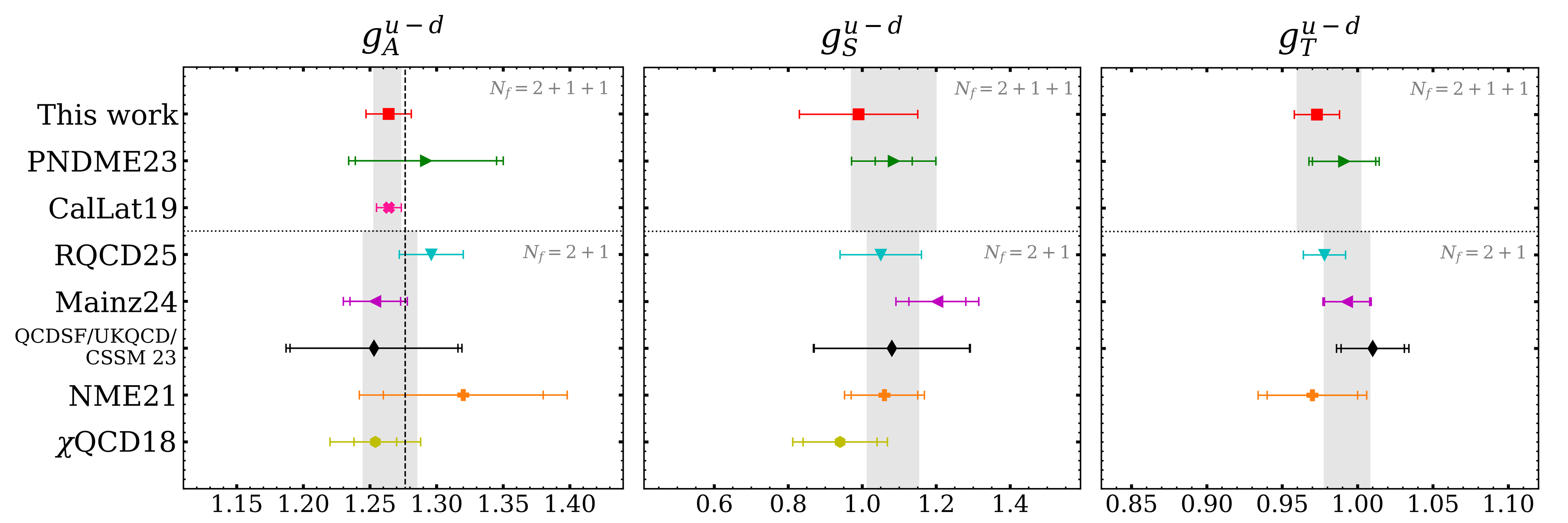

Figure 3: Comparison of our results with other lattice QCD works for the isovector charges. Our results are shown with the red squares. The gray bands show the FLAG24 averages for $N_f = 2+1+1$ and $N_f = 2+1$. The dashed line in g_A^{u-d} represents the experimental value.

- In this work, we also calculate the nucleon σ-terms, using the three coarser ensembles. The value of σ^{u+d}, also referred to as $\sigma^{\pi N}$, is determined from phenomenological analyses using experimental inputs.
- In Fig. 4, we compare our results for the nucleon σ-terms with other lattice and phenomenological determinations. Most lattice results show good agreement, while our values, like others, remain lower than phenomenological estimates, which tend to give larger values.

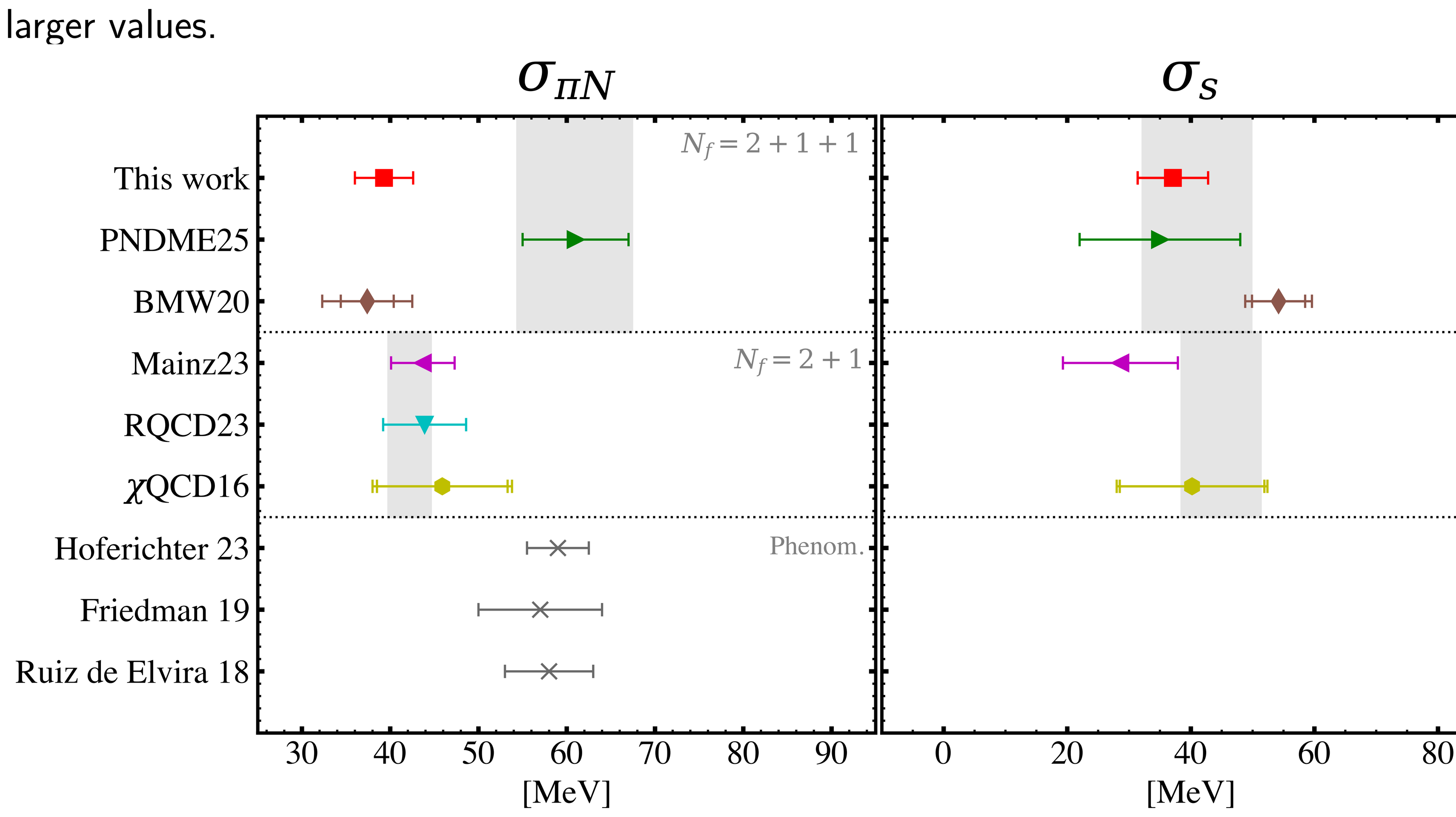

Figure 4: Comparison of our results for the nucleon σ-terms with other lattice calculations and phenomenological estimates for $\sigma_{\pi N}$. Our results are shown with red squares. The gray bands show the FLAG24 averages. Results from phenomenology are shown with gray crosses.

Conclusions and Future outlook

- In this work we calculate the nucleon axial, scalar and tensor charges, as well as the nucleon σ-terms at the continuum limit using only physical point ensembles, thus avoiding chiral extrapolations.
- Our results are in agreement with results by other collaborations. The value we get for the isovector axial charge also agrees with the experimental value.
- Our value for $\sigma_{\pi N}$ is in agreement with most lattice results, but phenomenological results tend to give larger values.
- These results provide benchmark values for nucleon structure parameters directly at the physical point.
- Our future goal is to include the fourth ensemble with a finer lattice spacing of $a \approx 0.05$ fm at full statistics, for all quantities in the analysis.
- This finer ensemble will further refine our continuum limit extrapolations and increase the accuracy of our final values.

Co-funded by the European Union
Republic of Cyprus
Research & Innovation Foundation

This work was supported by the projects **DeNuTra** and **PulseQCD** co-funded by the EU within the framework of the Cohesion Policy Programme "THALIA 2021-2027". Support is also acknowledged by the University of Cyprus through the project "Nucleon generalized parton distributions within lattice QCD (Nucleon-GPDs)."