GRADUIERTEN KOLLEG
Masse-Spektrum-Symmetrie

Nucleon Structure from Lattice QCD

DESY

Motivation

Understanding nucleon structure is one of the fundamental goals of QCD. Hoewever, quantities related to nucleon structure are in the low-energy regime and thus cannot be accessed by means of perturbative QCD. Lattice QCD, a numerical calculation from first principles, allows to compute those observables non-perturbatively. It thus provides important input and cross-checks for experiments probing the structure of the nucleon. However, there is a tension between current lattice QCD calculations and experimental results for a certain class of observables, namely moments of parton distribution functions.
Another type of nucleon structure observables are scalar condensates, the so-called scalar quark content. It has a strong influence on the cross-section of a Nucleon-WIMP interaction mediated by a scalar (Higgs) boson and is therefore important for Dark Matter searches. Such quantities however can only be computed directly in a non-perturbative way. Typically, lattice QCD calculations possess large statistical uncertainties and are thus of low relevance for phenomenological applications. A precise calculation in Lattice QCD is hence highly desirable.

Methods

Lattice QCD: Calculation of observables in the path integral formalism,

$$\left\langle \hat{\mathcal{O}}(\psi,\bar\psi,A)\right\rangle = \frac{1}{Z_{\mathrm{QCD}}}\int DA \int D\bar\psi \int D\psi\ \mathcal{O}(\psi,\bar\psi,A)\, e^{-S_{\mathrm{QCD}}[A,\bar\psi,\psi]},$$

through space-time discretization and Monte-Carlo simulation using importance sampling. We use the "$N_f = 2+1+1$ Wilson twisted mass" (one among many lattice definitions on the market) action for quarks, with dynamical up, down strange and charm quark. Advantage: Automatic $\mathcal{O}(a)$ improvement if parameters tuned properly, i.e. typically small discretization errors.

Some details

Moments of parton distribution functions

$$\langle x\rangle_{q,\mu^2} = \int_{-1}^{1} dx\ xq(x,\mu^2) = \int_0^1 dx\ x\left\{q(x,\mu^2)+\bar q(x,\mu^2)\right\}$$

can be computed in lattice QCD because OPE relates them to matrix elements of local operators. Observables:

"momentum fraction", benchmark observable $\langle x\rangle_{u-d}$ via

$$\langle N(p,s)|\underbrace{\bar q(0)\gamma^{\{\mu}iD^{\nu\}}\tau^3 q(0)}_{O^{\mu\nu}}|N(p,s)\rangle\,|_{\mu^2} = 2\,\langle x\rangle_{u-d,\mu^2}\, p^{\{\mu}p^{\nu\}}$$

nucleon axial charge/coupling ("charge pions couple to")
$g_A = \langle 1\rangle_{\Delta u-\Delta d}$ (zeroth moment of polarized PDF)
$\mapsto$ neutron beta decay, nuclear force

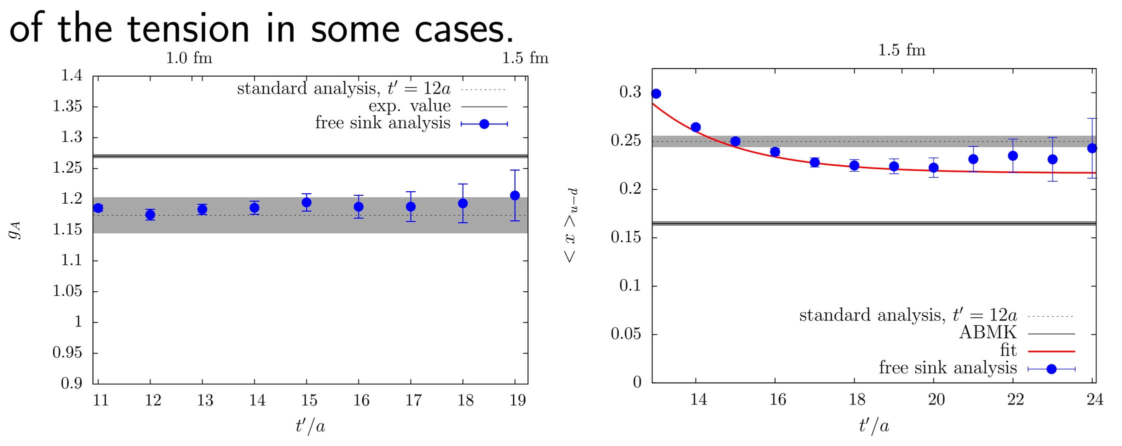
$$\langle N(p,s)|\bar q\gamma_\mu\gamma_5\tau^3 q|N(p,s)\rangle|_{\mu^2} = 2g_A|_{\mu^2}s_\mu$$

Scalar quark content of the nucleon: $\langle N|\,\bar q q\,|N\rangle = \frac{\partial m_N}{\partial m_q}$
Observables of interest are $\sigma_{\pi N}$ (sensitivity of nucleon mass to change of light quark mass) and y_N (strange quark content relative to light quark content)

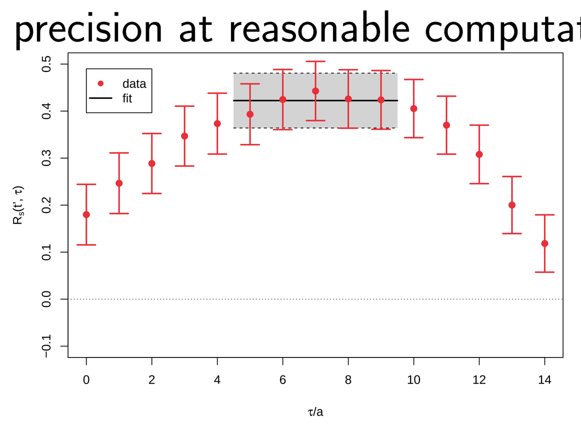
$$\sigma_{\pi N} = \langle N|\,m_{u,d}\,(\bar u u + \bar d d)\,|N\rangle\,,$$
$$y_N = \frac{2\,\langle N|\,\bar s s\,|N\rangle}{\langle N|\,(\bar u u+\bar d d)\,|N\rangle}.$$

Recent Results

(a) We have performed an analysis of systematic effects in order to explain the tension between results from lattice QCD and experiment. We found that excited state effects can explain part of the tension in some cases.

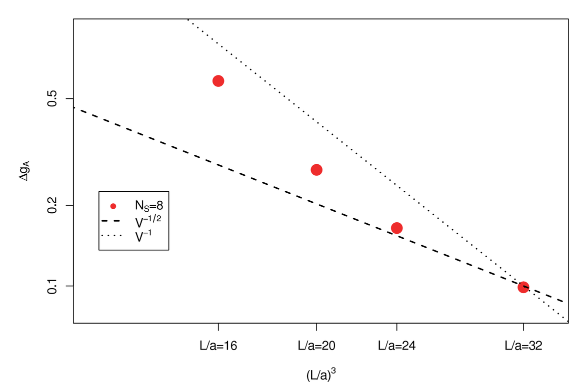


(b) We have shown in a feasibility study that using a variance reduction technique specific to the twisted mass lattice action, it is possible to compute the scalar quark content to a good precision at reasonable computational effort.



A thorough study of systematic effects is work in progress.

(c) We have tested a new stochastic method for the computation of hadron structure observables and found favourable volume scaling of the stochastic noise.



Publications

C. Alexandrou, M. Constantinou, S. Dinter, V. Drach, K. Jansen, D. B Renner *et al.*, "Nucleon matrix elements with $N_f = 2+1+1$ maximally twisted fermions," PoS LATTICE **2010** (2010) 135
S. Dinter, C. Alexandrou, M. Constantinou, V. Drach, K. Jansen and D. B. Renner, "Precision Study of Excited State Effects in Nucleon Matrix Elements," Phys. Lett. B **704** (2011) 89
S. Dinter, V. Drach and K. Jansen, "Dark matter search and the scalar quark contents of the nucleon," Int. J. Mod. Phys. Proc. Suppl. E **20** (2011) 110
S. Dinter, V. Drach and K. Jansen, "Nucleon scalar matrix elements with $N_f = 2+1+1$ twisted mass fermions," PoS LATTICE **2011** (2011) 152
C. Alexandrou, M. Constantinou, S. Dinter, V. Drach, K. Jansen, T. Leontiou and D. B. Renner, "Excited State Effects in Nucleon Matrix Element Calculations," PoS LATTICE **2011** (2011) 150
S. Dinter, V. Drach, R. Frezzotti, G. Herdoiza, K. Jansen and G. Rossi, "Sigma terms and strangeness content of the nucleon with $N_f = 2+1+1$ twisted mass fermions," JHEP **1208** (2012) 037

Selected Talks

- International Symposium on Lattice Quantum Field Theory, Villasimius, 06/2010
  "Nucleon Matrix Elements with $N_f = 2+1+1$ Maximally Twisted Fermions"
- DPG Frühjahrstagung, Karlsruhe, 03/2011
  "Nucleon Matrix Elements with $N_f = 2+1+1$ Maximally Twisted Fermions"
- International Symposium on Lattice Quantum Field Theory, Squaw Valley, 07/2011
  "Excited State Effects in Nucleon Matrix Element Calculations"
- ETMC Meeting, Rom, Italien, 10/2011
  "A Novel Method for the Computation of Nucleon Matrix Elements"
- SFB/TR9 Arbeitsgruppentreffen, Berlin, 10/2012
  "Progress in the calculation of nucleon matrix elements"

Collaborations

- European Twisted Mass Collaboration
- DFG Sonderforschungsbereich Transregio 9, Projekt B3

Profit from the GK

- valuable special topic lectures
- soft skill training at Humboldt Graduate School
- funding of travels
- enhancement of communication between PhD students

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