NPQCD

Exploring the non-perturbative properties of fundamental interactions under extreme conditions

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Main Research Topic within the NPQCD collaboration

- Non-perturbative properties of the QCD vacuum and color confinement
- Topological properties, θ-dependence in QCD and QCD-like theories, axion cosmology
- QCD at finite temperature and baryon density. Phase diagram of QCD and QCD-like theories
- Properties of strong interactions in external background fields
- Non-perturbative numerical approaches to Quantum Gravity: Causal Dynamical Triangulations
- Development of new codes and algorithms for HPC architectures

PEOPLE

- **BARI** Paolo Cea, Leonardo Cosmai
- **COSENZA & LNGS** Alessandro Papa, Volodymyr CHELNOKOV, Giuseppe Di Carlo and master students
- **PISA** Bartolome Alles, Claudio Bonanno, Claudio Bonati, Giuseppe Clemente, Massimo D'Elia, Adriano Di Giacomo, Enrico Meggiolaro, Francesco Negro, Giampiero Paffuti, Andrea Rucci, Davide Vadacchino and master students

Team work with other INFN collaborations:

- **FERRARA** Enrico Calore, Fabio Schifano, Raffaele Tripiccione
  Development of LQCD codes on frontier HPC architecture, application on problems for QCD at finite temperature and density
- **ROMA** Guido Martinelli, Francesco Sanfilippo
  LQCD and Axion Cosmology, various issues on the QCD phase diagram
- **TORINO** Michele Caselle, Alessandro Nada, Marco Panero
  Statistical Mechanics techniques for the QCD phase diagram

LIST OF RECENT PAPERS (last 3 years)

1. V. Azcoiti, G. Di Carlo, E. Follana and E. Royo-Amondarain, Phys. Rev. E 96, no. 3, 032114 (2017) [arXiv:1612.08598 [hep-lat]].
2. V. Azcoiti, G. Di Carlo, E. Follana and A. Vaquero, Phys. Lett. B 744, 303 (2015) [arXiv:1410.5733 [hep-lat]].
3. C. Bonati, M. D'Elia, M. Mariti, M. Mesiti, F. Negro, A. Rucci and F. Sanfilippo, Phys. Rev. D 95, no. 7, 074515 (2017) [arXiv:1703.00842 [hep-lat]].
4. C. Bonati *et al.*, Int. J. Mod. Phys. C 28, no. 05, 1750063 (2017) [arXiv:1701.00426 [hep-lat]].
5. C. Bonati, M. D'Elia, M. Mariti, M. Mesiti, F. Negro, A. Rucci and F. Sanfilippo, Phys. Rev. D 94, no. 9, 094007 (2016) [arXiv:1607.08160 [hep-lat]].
6. C. Bonati, M. D'Elia, P. Rossi and E. Vicari, Phys. Rev. D 94, no. 8, 085017 (2016) [arXiv:1607.06360 [hep-lat]].
7. C. Bonati, M. D'Elia, M. Mariti, M. Mesiti, F. Negro and F. Sanfilippo, Phys. Rev. D 93, no. 7, 074504 (2016) [arXiv:1602.01426 [hep-lat]].
8. C. Bonati, M. D'Elia, M. Mariti, G. Martinelli, M. Mesiti, F. Negro, F. Sanfilippo and G. Villadoro, JHEP 1603, 155 (2016) [arXiv:1512.06746 [hep-lat]].
9. C. Bonati, M. D'Elia and A. Scapellato, Phys. Rev. D 93, no. 2, 025028 (2016) [arXiv:1512.01544 [hep-lat]].
10. C. Bonati, M. D'Elia, M. Mariti, M. Mesiti, F. Negro and F. Sanfilippo, Phys. Rev. D 92, no. 5, 054503 (2015) [arXiv:1507.03571 [hep-lat]].
11. C. Bonati, M. D'Elia and A. Rucci, Phys. Rev. D 92, no. 5, 054014 (2015) [arXiv:1506.07890 [hep-ph]].

12. O. Borisenko, V. Chelnokov, F. Cuteri and A. Papa, Phys. Rev. E 94, no. 1, 012108 (2016) [arXiv:1512.05737 [hep-lat]].

13. O. Borisenko, V. Chelnokov, M. Gravina and A. Papa, JHEP 1509, 062 (2015) [arXiv:1507.00833 [hep-lat]].

14. P. Cea, L. Cosmai, F. Cuteri and A. Papa, Phys. Rev. D 95, no. 11, 114511 (2017) [arXiv:1702.06437 [hep-lat]].

15. P. Cea, L. Cosmai, F. Cuteri and A. Papa, JHEP 1606, 033 (2016) [arXiv:1511.01783 [hep-lat]].

16. P. Cea and L. Cosmai, JHEP 1512, 058 (2015) [arXiv:1509.01982 [hep-lat]].

17. P. Cea, L. Cosmai and A. Papa, Phys. Rev. D 93, no. 1, 014507 (2016) [arXiv:1508.07599 [hep-lat]].

18. A. Di Giacomo and M. Hasegawa, Phys. Rev. D 91, no. 5, 054512 (2015) [arXiv:1501.06517 [hep-lat]].

19. M. D'Elia and M. Mariti, Phys. Rev. Lett. 118, no. 17, 172001 (2017) [arXiv:1612.07752 [hep-lat]].

20. M. D'Elia, G. Gagliardi and F. Sanfilippo, Phys. Rev. D 95, no. 9, 094503 (2017) [arXiv:1611.08285 [hep-lat]].

21. M. D'Elia, E. Meggiolaro, M. Mesiti and F. Negro, Phys. Rev. D 93, 054017 (2016) [arXiv:1510.07012 [hep-lat]].

22. M. Giordano, E. Meggiolaro and P. V. R. G. Silva, Phys. Rev. D 96, no. 3, 034015 (2017) [arXiv:1703.00244 [hep-ph]].

23. M. Giordano and E. Meggiolaro, Phys. Rev. D 92, no. 9, 096007 (2015) [arXiv:1507.07215 [hep-ph]].

24. M. Giordano and E. Meggiolaro, Phys. Lett. B 744, 263 (2015) [arXiv:1411.0553 [hep-ph]].

TALKS AT SM&FT 2017

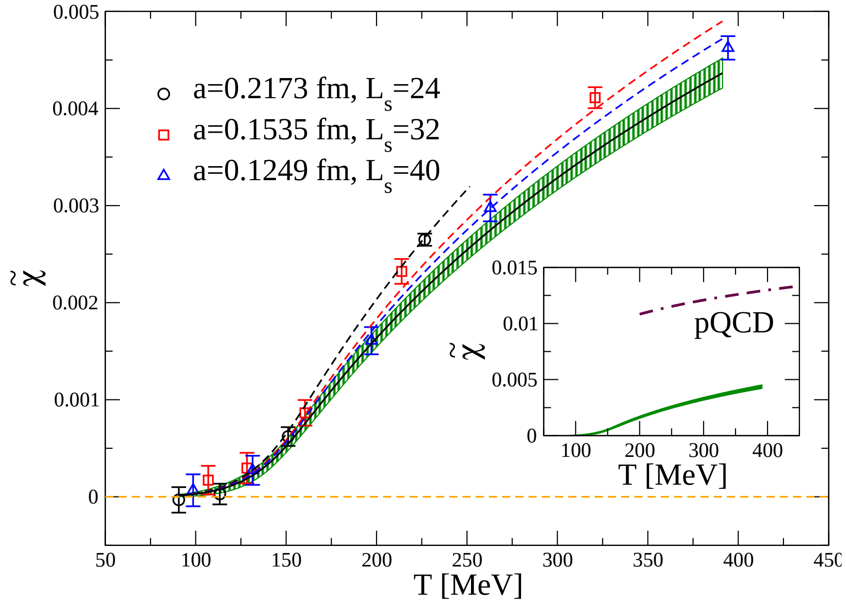
- A. Di Giacomo monopoles and color confinement in QCD
- C. Bonanno θ-dependence in 2d CP^{N-1} models
- E. Calore portable OpenACC code for multi-GPU architectures
- G. Clemente spectral methods in Causal Dynamical Triangulations
- F. Negro curvature of the pseudocritical line in the QCD phase diagram
- A. Rucci confining properties of QCD in strong magnetic fields
- D. Vadacchino machine learning algorithms for statistical mechanics

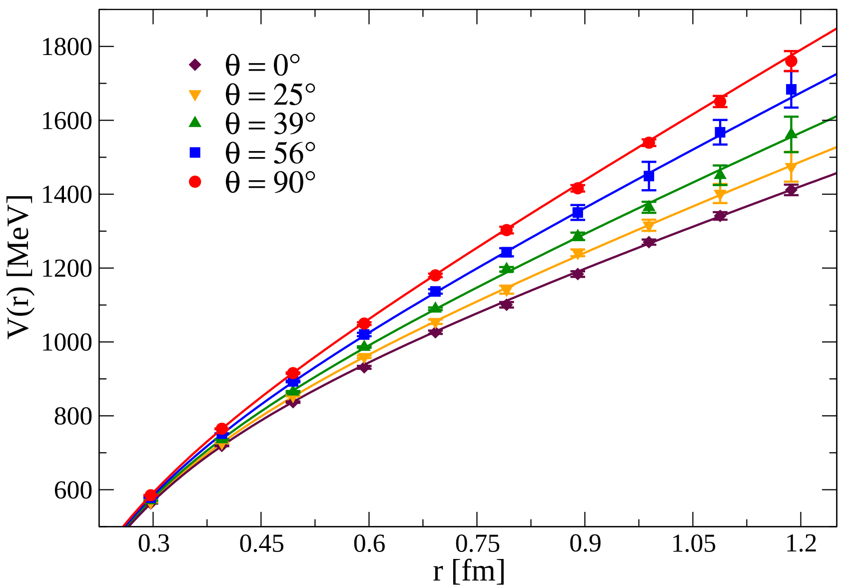
In the remaining part of this talk I will highlight a selection of our results and future projects which are particularly demanding in terms of computational power, thus representing an HPC challenge

They are conceivable only thanks to the availability of adequate computing resources. Our present and past resources

- Computer time available through the INFN-CINECA agreement on FERMI, GALILEO and MARCONI
- GPU farms in Pisa, Ferrara (COKA) and Rome (QUONG)
- CSN4 ZEFIRO cluster in Pisa
- 2 PRACE projects at CINECA
- 7 ISCRA B projects at CINECA

Properties of QCD in strong magnetic fields





We have determined the magnetic susceptibility of the Quark-Gluon Plasma (left)

C. Bonati et al., arXiv:1307.8063, arXiv:1310.8656

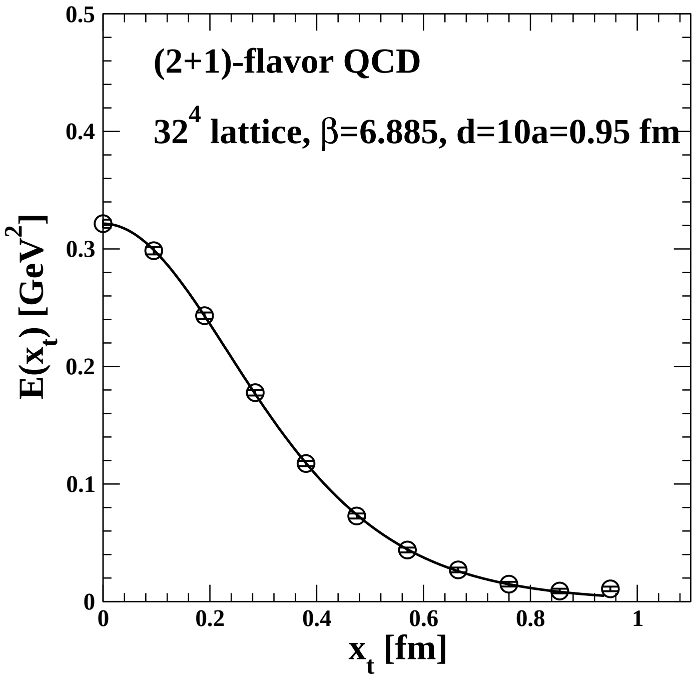
and shown that the confining potential between static quark-antiquark pairs is strongly affected by the presence of a background field (right)

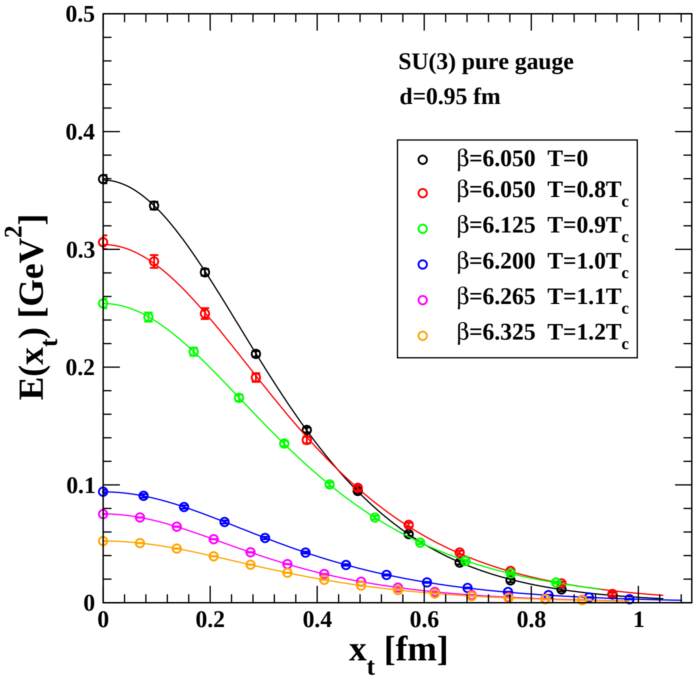
C. Bonati et al., arXiv:1403.6094, arXiv:1403.6094, arXiv:1703.00842

In both cases for QCD with physical quark masses.

PERSPECTIVE: understanding the dependence of the critical temperature on B

Flux tube properties in full QCD





We have determined the structure of the flux tube between static quark-antiquark pairs both in full QCD at zero temperature (left)

P. Cea, L. Cosmai, F. Cuteri, A. Papa, arXiv:1702.06437

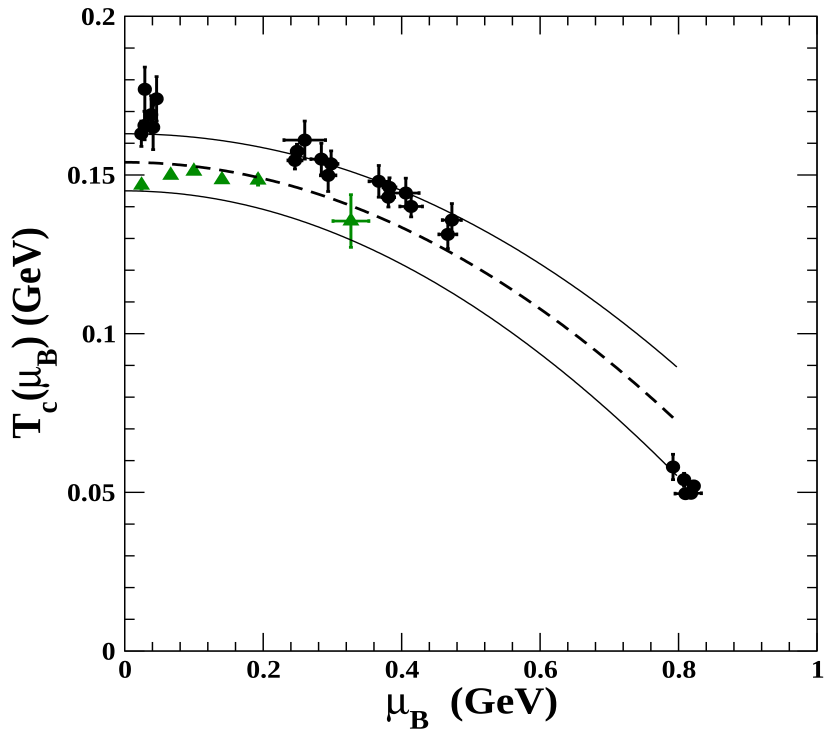
and in the quenched case across the deconfinement temperature (right)

P. Cea, L. Cosmai, F. Cuteri, A. Papa, arXiv:1511.01783, arXiv:1710.01963

PERSPECTIVE: extend full QCD results to finite T, measure also transverse fields, study flux tube modifications under the action of external fields.

Curvature of the pseudocritical line of QCD in the T-μ_B plane

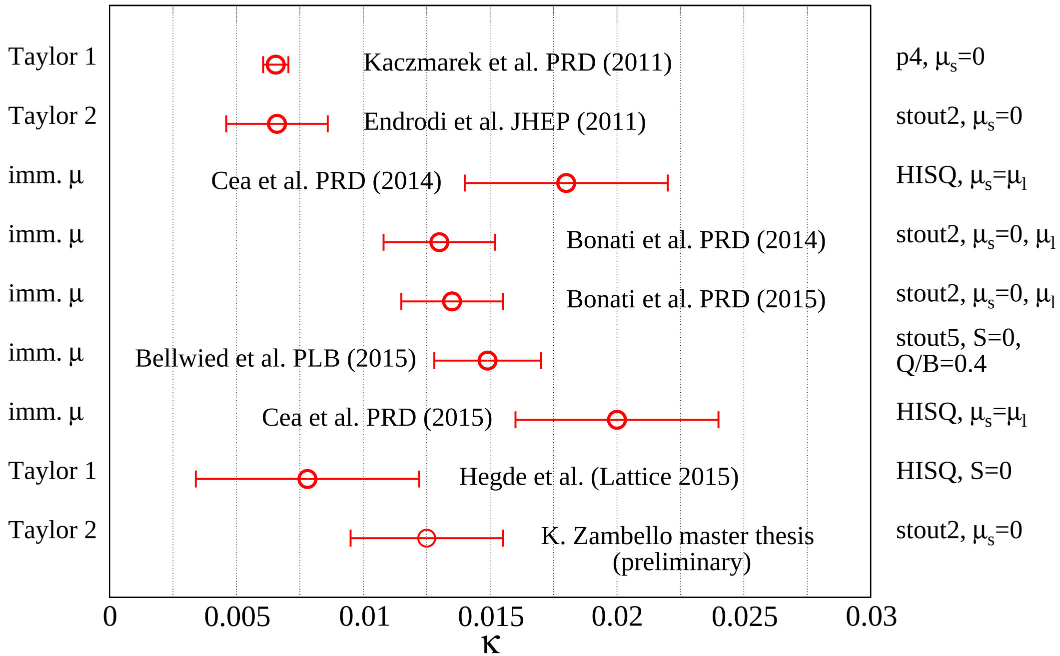
$$\frac{T(\mu_B)}{T_c} = 1 - \kappa \left(\frac{\mu_B}{T(\mu_B)}\right)^2 + O(\mu_B^4)$$

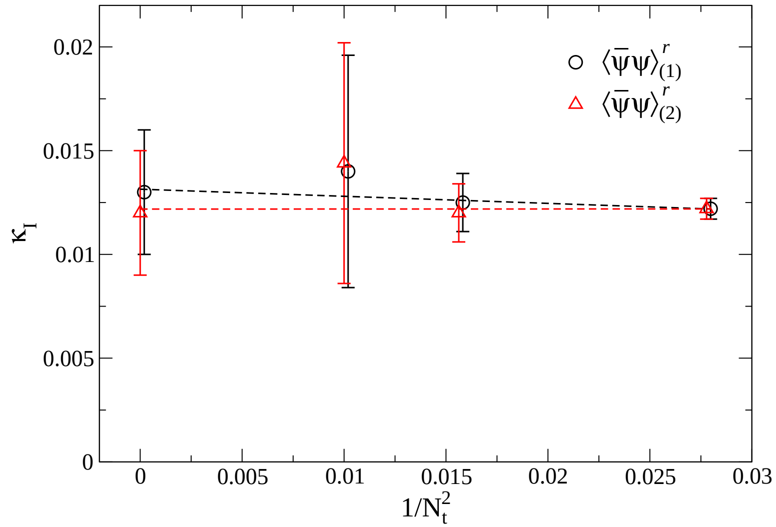


from P. Cea, L. Cosmai, A. Papa, arXiv:1508.07599

Recent years have seen large efforts by our groups, with two different discretizations of QCD with physical quark masses (stout staggered fermions in Pisa, HISQ fermions in Bari and Cosenza) to determine the curvature of the line by analytic continuation from imaginary chemical potentials

Curvature of the pseudocritical line of QCD in the T-μ_B plane

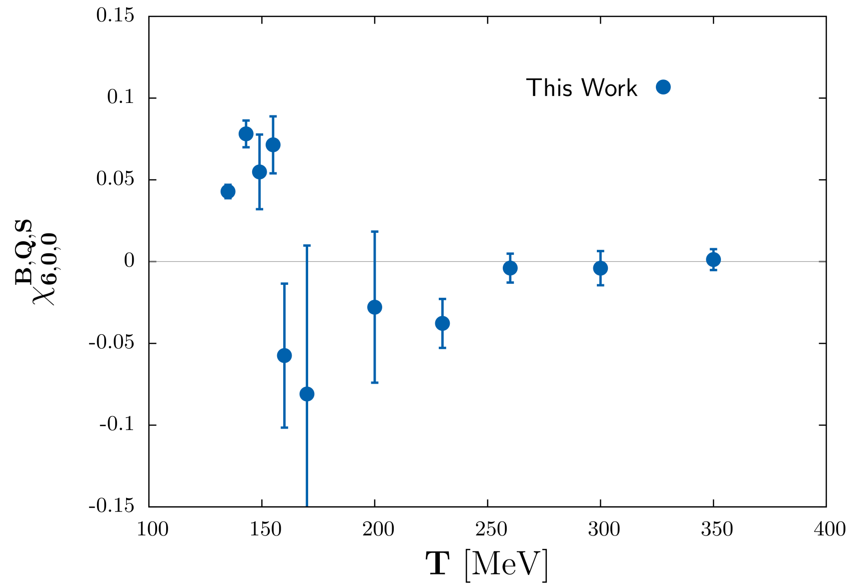


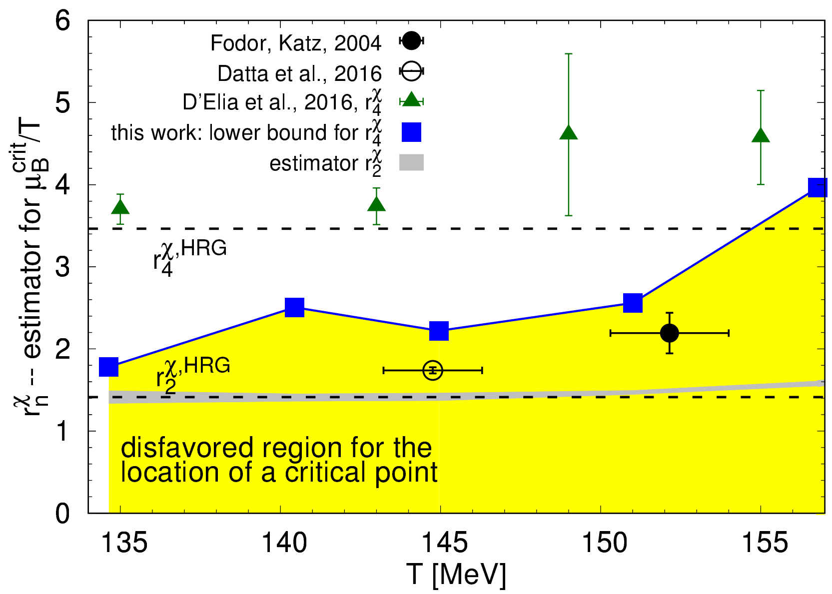


Our results have changed previous knowledge on the curvature, moving κ to larger values.

PERSPECTIVE: will Taylor expansion and analytic continuation results eventually converge? Our preliminary results go towards a positive answer

Fluctuations of conserved charges in finite T QCD





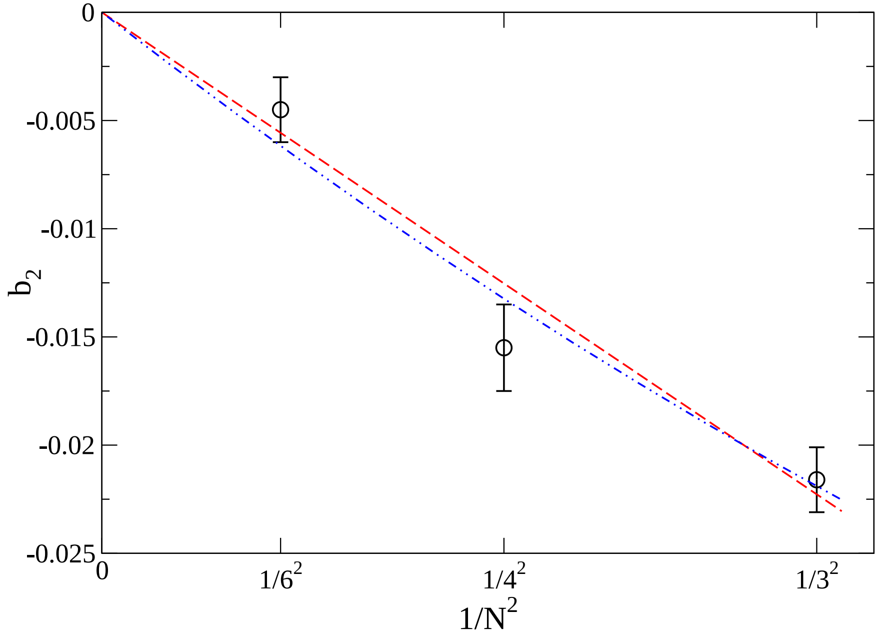
We have determined, exploiting analytic continuation from simulations with imaginary chemical potentials, the fluctuations of conserved charges (baryon, electric, strangeness, up to eight order cumulants

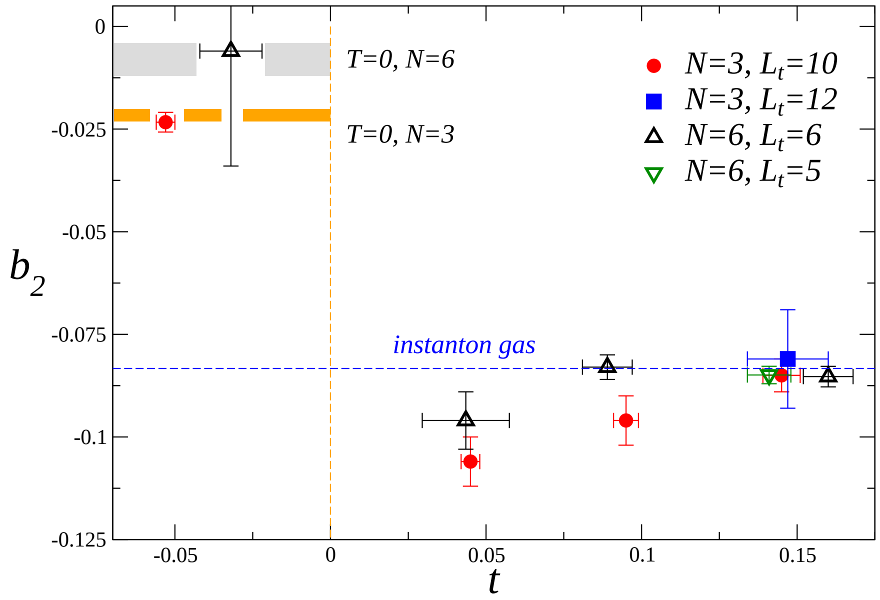
M.D., G. Gagliardi, F. Sanfilippo arXiv:1702.06437

Such susceptibilities can be used to set lower bounds on the possible location of the critical endpoint in the T - μ_B plane (right, from A. Bazavov et al., arXiv:1701.04325)

PERSPECTIVE: Our present results are only for one set of lattice spacings, continuum extrapolation is an expensive task for the future

θ-dependence in pure gauge theories





Large-N computations set clear predictions for the low-T and high-T dependence of the free energy of $SU(N)$ Yang-Mills on the topological θ-parameter.

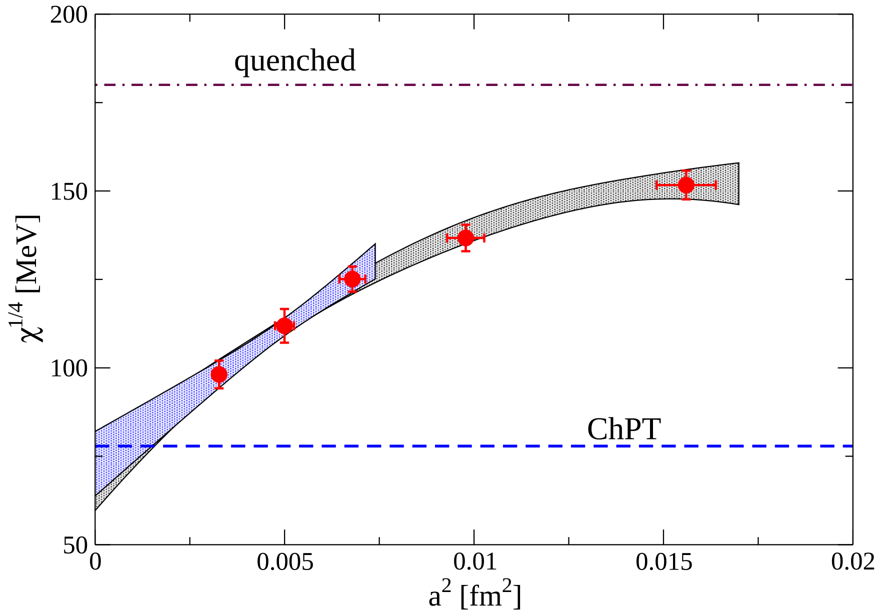
We have verified the correct scaling for the fourth order cumulant of the topological charge ($\propto$ b$_2$) at $T = 0$ (left)

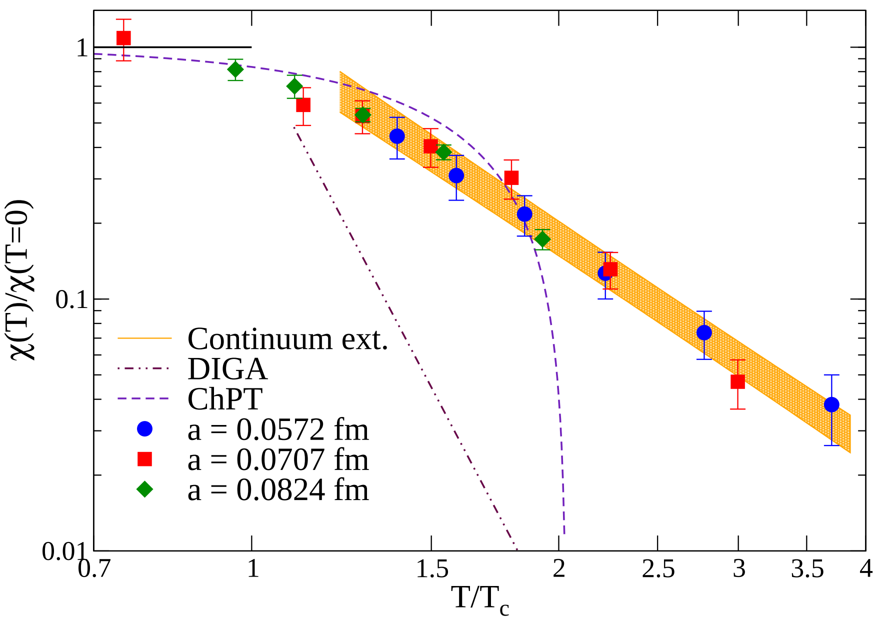
C. Bonati, M.D., P. Rossi, E. Vicari arXiv:1607.06360

The high-T prediction (instanton gas) sets in soon after T_c in the large-N limit.

C. Bonati, M.D., H. Panagopoulos, E. Vicari arXiv:1301.7640

θ-dependence in full QCD and axion phenomenology





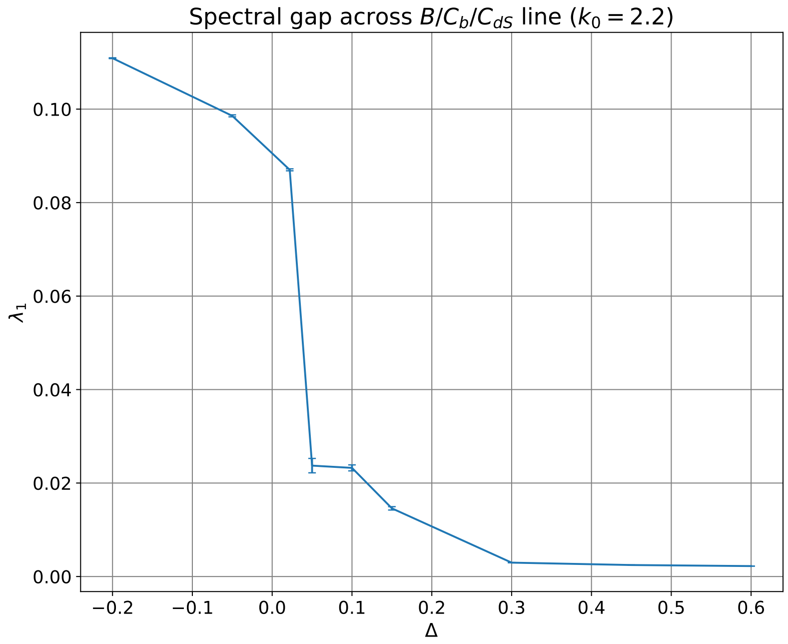
We have provided a continuum extrapolated determination for the topological susceptibility at $T = 0$ which is consistent with chiral perturbation theory predictions (left) and obtained results for χ at finite T (right).

C. Bonati et al. arXiv:1512.06746

The latter quantity is interesting for predicting the mass of the QCD axion (if it exists) at present days.

PERSPECTIVES: fight the freezing of topological modes in the continuum limit to improve accuracy temperatures interesting for axion cosmology

Spectral methods in Causal Dynamical Triangulations



Computing the path integral of (regularized) Einstein-Hilbert gravity by dynamical triangulations is a challenging HPC task comparable to LQCD.

We have achieved a better definition of observables in the theory by looking at the spectrum of the Laplacian operator (talk by Giuseppe Clemente)

PERSPECTIVES: The development of algorithms in this field is still at the initial stage and there is much room for improvement