Final Report

Title:	**Non-Perturbative Aspects of Thermal QCD**
Principal Investigators:	Jeffrey P. Greensite Maarten F. L. Golterman
Address:	Physics and Astronomy Department San Francisco State University San Francisco, CA 94132
e-mail:	greensit@sfsu.edu maarten@sfsu.edu
telephone:	415 338-1600 (Greensite) 415 405-0903 (Golterman) 415 338-2178 Fax
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The principal investigator of grant DE-SC0007864, "Non-Perturbative Aspects of Thermal QCD," was originally Mithat Ünsal, who was a member of our department from 2011 to 2013. Dr. Ünsal then left San Francisco State to take up a position at North Carolina State University. At that point the grant was taken over by Jeff Greensite and Maarten Golterman.

The personnel supported by this grant were Mithat Ünsal, originally a professor at SF State and now at North Carolina State, Jeff Greensite and Maarten Golterman, both professors at San Francisco State University, and a number of graduate students.

Ünsal's research, carried out under grant support in the 2012-2013 period, centered on the application of a mathematical insight known as "resurgence theory" to quantum field theory, and specifically opens the door to a non-perturbative definition of quantum field theories via perturbative expansions. The results of this research are reported in ten articles listed below.

Greensite's research, carried out under grant support in the 2013-2015 period, has focused mainly on dealing with the sign problem, encountered when dealing with gauge theories at non-zero baryon density, via a method known as "relative weights." Aspects of the quark confinement problem in Coulomb gauge have also been considered, along with a critique of various confinement methods from the perspective of multiple-winding Wilson loops. The results are published in fifteen articles listed below.

Golterman's research, carried out under grant support in the 2013-2015 period, has focused mainly on the lattice computation of the anomalous magnetic moment of the muon, lattice aspects of composite Higgs models, the determination of the strong coupling from hadronic tau decays, and various applications of chiral perturbation theory. The results have been published in twenty-three articles listed below.

Publication List for Mithat Ünsal, 2012-2013

1. Deconfinement in Yang-Mills theory through toroidal compactification with deformation, Phys. Rev. D **85**, 105027 (2012) doi:10.1103/PhysRevD.85.105027 [arXiv:1010.5515 [hep-th]], with D. Simic.

2. Theta dependence, sign problems and topological interference, Phys. Rev. D **86**, 105012 (2012) doi:10.1103/PhysRevD.86.105012 [arXiv:1201.6426 [hep-th]].

3. A semiclassical realization of infrared renormalons, Phys. Rev. Lett. **109**, 121601 (2012) doi:10.1103/PhysRevLett.109.121601 [arXiv:1204.1661 [hep-th]], P. Argyres.

4. Continuity, Deconfinement, and (Super) Yang-Mills Theory, JHEP **1210**, 115 (2012) doi:10.1007/JHEP10(2012)115 [arXiv:1205.0290 [hep-th]], with E. Poppitz, T. Schfer.

5. The semi-classical expansion and resurgence in gauge theories: new perturbative, instanton, bion, and renormalon effects, JHEP **1208**, 063 (2012) doi:10.1007/JHEP08(2012)063 [arXiv:1206.1890 [hep-th]], with P. C. Argyres.

6. Resurgence and Trans-series in Quantum Field Theory: The CP(N-1) Model, JHEP **1211**, 170 (2012) doi:10.1007/JHEP11(2012)170 [arXiv:1210.2423 [hep-th]], with G. V. Dunne.

7. Continuity and Resurgence: towards a continuum definition of the CP(N-1) model, Phys. Rev. D **87**, 025015 (2013) doi:10.1103/PhysRevD.87.025015 [arXiv:1210.3646 [hep-th]], with G. V. Dunne.

8. Universal mechanism of (semi-classical) deconfinement and theta-dependence for all simple groups, JHEP **1303**, 087 (2013) doi:10.1007/JHEP03(2013)087 [arXiv:1212.1238 [hep-th]], with E. Poppitz, and T. Schfer.

9. Volume Independence in the Large N Limit and an Emergent Fermionic Symmetry, Phys. Rev. Lett. **111**, no. 12, 121601 (2013) doi:10.1103/PhysRevLett.111.121601 [arXiv:1306.2960 [hep-th]], with G. Basar, A. Cherman, and D. Dorigoni.

10. Resurgence theory, ghost-instantons, and analytic continuation of path integrals, JHEP **1310**, 041 (2013) doi:10.1007/JHEP10(2013)041 [arXiv:1308.1108 [hep-th]], and G. Basar, G. V. Dunne.

Publication List for Jeff Greensite, 2013-2015

1. Effective Polyakov line action from the relative weights method, Phys.Rev. D87 (2013) 094501, arXiv:1301.4977 [hep-lat], with Kurt Langfeld.
2. Effective Polyakov line action from strong lattice couplings to the deconfinement transition, Phys.Rev. D88 (2013) 074503, arXiv:1305.0048, with Kurt Langfeld
3. QCD sign problem as a total derivative, Phys.Rev. D88 (2013) 3, 031502, arXiv:1306.3085 [hep-lat] , with J. C. Myers and K. Splittorff.
4. The density in the density of states method, JHEP 1310 (2013) 192, arXiv:1308.6712 [hep-lat], with J. C. Myers and K. Splittorff.
5. Numerical study of the Yang-Mills vacuum wave functional in D= 3 + 1 dimensions, Phys.Rev. D89 (2014) 3, 034504, arXiv:1310.6706 [hep-lat], with S. Olejnik.
6. Investigating corrections to a Gaussian distribution of the complex phase, PoS LATTICE2013 (2014) 023, arXiv:1311.4568 [hep-lat], with J. C. Myers and K. Splittorff.
7. Extracting the effective Polyakov line action from SU(2) and SU(3) lattice gauge theories, PoS QCD-TNT-III (2013) 017, arXiv:1312.0143 [hep-lat] , with Kurt Langfeld.
8. Finding the effective Polyakov line action for SU(3) gauge theories at finite chemical potential, Phys.Rev. D90 (2014) 1, 014507, arXiv:1403.5844 , with Kurt Langfeld.
9. Comparison of complex Langevin and mean field methods applied to effective Polyakov line models, Phys.Rev. D90 (2014) 11, 114507, arXiv:1406.4558 [hep-lat].
10. Coulomb string tension, asymptotic string tension, and the gluon chain, Phys.Rev. D91 (2015) 3, 034503, arXiv:1410.3525 [hep-lat], with Adam Szczepaniak.
11. Effective Polyakov line actions, and their solutions at finite chemical potential, PoS LATTICE2014 (2015) 233, arXiv:1411.0607 [hep-lat].
12. Double-winding Wilson loops and monopole confinement mechanisms, Phys.Rev. D91 (2015) 5, 054509, arXiv:1411.5091 [hep-lat], with R. Höllwieser.
13. Center Vortex Versus Abelian Models of the QCD Vacuum, Acta Phys. Polon. Supp. **8**, no. 2, 509 (2015), with M. Faber, and R. Höllwieser.
14. Constituent gluons and the static quark potential," arXiv:1505.05104 [hep-lat], with A. P. Szczepaniak.
15. Polyakov line actions from $SU(3)$ lattice gauge theory with dynamical fermions: first results via relative weights," arXiv:1510.03824 [hep-lat], with R. Höllwieser.

Publication List for Maarten Golterman, 2013-2015

1. Two-pion excited state contribution to pseudo-scalar correlators, arXiv:1301.5151, with O. Bär, contribution to the proceedings of Chiral Dynamics 2012.

2. On the foundations of partially quenched chiral perturbation theory, Phys. Rev. D88 (2013) 014004, with C. Bernard.

3. The hadronic vacuum polarization with twisted boundary conditions, Phys. Rev. D88 (2013) 074505, with C. Aubin, T. Blum, and S. Peris.

4. Tests of hadronic vacuum polarization fits for the muon anomalous magnetic moment, Phys. Rev. D88 (2013) 114508, with K. Maltman and S. Peris.

5. A possible new phase in non-perturbatively gauge-fixed Yang-Mills theory, arXiv:1310.5301, with Y. Shamir, contribution to the proceedings of Lattice 2013, July/Aug. 2013, Mainz, Germany.

6. Tests of hadronic vacuum polarization fits for the muon anomalous magnetic moment, arXiv:1310.5928, with K. Maltman and S. Peris, contribution to the proceedings of Lattice 2013, July/Aug. 2013, Mainz, Germany.

7. The hadronic vacuum polarization with twisted boundary conditions, arXiv:1311.1078, with C. Aubin, T. Blum and S. Peris, contribution to the proceedings of Lattice 2013, July/Aug. 2013, Mainz, Germany.

8. The muon anomalous magnetic moment, a view from the lattice, arXiv:1311.5504, with C. Aubin, T. Blum, K. Maltman and S. Peris, contribution to the proceedings of PhiPsi13, Sept. 2013, Rome, Italy.

9. Low-energy constants and condensates from the V-A spectrum, arXiv:1311.6679, with D. Boito, M. Jamin, K. Maltman and S. Peris, contribution to the proceedings of PhiPsi13, Sept. 2013, Rome, Italy.

10. Chiral perturbation theory for gradient flow observables, Phys. Rev. D89 (2014) 034505, with O. Bär.

11. Vacuum alignment and lattice artifacts: Wilson fermions, Phys. Rev. D89 (2014) 054501, with Y. Shamir.

12. Vacuum alignment and lattice artifacts: staggered fermions, Phys. Rev. D89 (2014) 074502, with Y. Shamir.

13. NNLO low-energy constants from flavor-breaking chiral sum rules based on hadronic tau-decay data, Phys. Rev. D89 (2014) 054036, with K. Maltman and S. Peris.

14. Dimensional transmutation in the longitudinal sector of equivariantly gauge-fixed Yang–Mills theory, Phys. Rev. D90 (2014) 034504, with Y. Shamir.

15. A new strategy for the lattice evaluation of the leading order hadronic contribution to $(g-2)_\mu$, Phys. Rev. D90 (2014) 074508, with K. Maltman and S. Peris.

16. Functional-analysis based tool for testing quark-hadron duality, Phys. Rev. D90 (2014) 033008, with I. Caprini and S. Peris.

17. The strong coupling from the revised ALEPH data for hadronic τ decays, Phys. Rev. D91 (2015) 034003, with D. Boito, K. Maltman, J. Osborne and S. Peris.

18. A new strategy for evaluating the LO HVP contribution to $(g-2)_\mu$ on the lattice, arXiv:1410.7068, with K. Maltman and S. Peris, contribution to the proceedings of Lattice 2014, June 2014, New York, USA.

19. Vacuum alignment and lattice artifacts, arXiv:1410.7992, with Y. Shamir, contribution to the proceedings of Lattice 2014, June 2014, New York, USA.

20. A Hybrid Strategy for the Lattice Evaluation of the Leading Order Hadronic Contribution to $(g-2)_\mu$, arXiv:1410.8405, with K. Maltman and S. Peris, contribution to the proceedings of the 37th International Conference on High Energy Physics, July 2014, Valencia, Spain.

21. α_s from the (revised) ALEPH data for τ decay, arXiv:1410.8415, with K. Maltman and S. Peris, contribution to the 13th International Workshop on Tau Lepton Physics, Sept. 2014, Aachen, Germany.

22. Top quark induced effective potential in a composite Higgs model, Phys. Rev. D91 (2015) 094506, with Y. Shamir.

23. Low-energy constants and condensates from ALEPH hadronic τ decay data, Phys. Rev. D92 (2015) 114501, with D. Boito, A. Francis, R. Hudspith, R. Lewis, K. Maltman and S. Peris.