Studies with Improved Renormalization Group Techniques

by

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Dedication

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1.1 The original 6x6 lattice on the left possesses a discrete scaling symmetry of $s = 2$ and $s = 3$. The shaded orange square is a $s = 2$ block variable. The resulting orange 3×3 blocked lattice in the bottom right formed by replacing each block variable with a single site in the upper left corner of the block. The cyan shaded region shows a $b = 3$ block variable. Performing a block transformation that replaces each block with a point in the upper left of the block produces the 2×2 blocked lattice shown in the upper right. 14

1.2 This figure shows how links are blocked on the lattice. Two adjacent links in the same direction are block transformed to form one link of twice the lattice spacing. We perform all possible block transformation shown on the left as the red, blue, green, and orange block tilings of the unblocked lattice. We then store the links of the blocked lattice as shown on the right hand side of the figure. 14

1.3 Here I show coupling space for a system with one relevant direction K_0. All irrelevant directions are collected in K'. We simulate at a point P in parameter. As we block the system it the effective couplings will change. In the diagram here the couplings reach the renormalized trajectory after 3 blocking steps. Further blocking steps move the couplnigs along the renormalized trajectory. 15

1.4 For matching we pick two points in coupling space P_1 and P_2. After 3 blocking steps, shown as circles the effective action of P_2 has reached the renormalized trajectory. P_1 requires 4 blocking steps shown as stars but reahes the same point on the renormalized trajectory. Because P_2 took one less blockign step its correlation length ξ is a factor of s smaller than the correlation length of the first ensemble that started at P_1. By choosing pairs of points in coupling space that block to the same point on the renormalized trajectory in coupling space, we can construct a discrete step scaling function. 15

1.5 The RG flow of a confining theory on the $m = 0$ critical surface. β is the relevant gauge coupling, β' are irrelevant couplings. 16

1.6 The RG flow of a conformal theory on the $m = 0$ critical surface. β is the relevant gauge coupling, β' are irrelevant couplings. 16

1.7 Optimization of the HYP-smearing parameter α in the RG blocking transformation, for $\beta_F = 5.0$. The uncertainties on the data points are dominated by averaging over the different observables as described in the text. 17

1.8 Results for the bare step-scaling function s_b from traditional MCRG two-lattice matching with $24^3\times48$, $12^3\times24$ and $6^3\times12$ lattice volumes for $N_f = 8$. The blue dashed lines are perturbative predictions for asymptotically weak coupling. 17

1.9 Results for the bare step-scaling function s_b from traditional MCRG two-lattice matching with $24^3\times48$, $12^3\times24$ and $6^3\times12$ lattice volumes for $N_f = 12$. The blue dashed lines are perturbative predictions for asymptotically weak coupling. 18

1.10 An illustration of how optimizing the block transformation can result in difficulties locating an IRFP, β is the relevant gauge coupling and β' are irrelevant couplings. The upper figure shows the renormalized trajectory in red, green, and blue found by optimizing the RG transformation at $\beta_1, \beta_2, \text{and} \beta_3$ respectively. The location of the IRFP changes in each renormalized trajectory, in this picture the IRFP is moved to the coupling we perform MCRG at. The resulting s_b is consistent with zero across a wide range of couplings. 19

Chapter 1

Conclusion

Truly it is an exciting time in particle physics. For almost two decades since the discovery of the top quark no new fundamental particles were discovered in collider experiments. After a long wait the Higgs particle has been discovered, completing the standard model. Although the standard model is complete we know it must be an effective theory and our knowledge of the Higgs mass puts constraints on beyond standard model physics.

Many proposals for beyond standard model physics, including technicolor, are strongly coupled theories and thus inherently nonperturbative. Since the lattice offers the only controlled means of studying non perturbative field theories in a controlled manner, it is natural that strongly coupled beyond standard model is an active area of lattice research. Studying BSM physics on the lattices has created many new challenges for the lattice community to solve. Unlike QCD, we don't know the answer to most questions beforehand, and there are no experimental results to compare lattice results with. Furthermore just because a technique is successful when studying QCD does not mean that it will work just as well in systems that are very different from QCD. Accordingly it is important to approach each theory we study carefully and with an open mind. Only when several methods converge on the same result can that result be trusted. Additionally since there is more than one way to put a continuum theory on the lattice, it is important to understand the effect of the lattice action and lattice artifacts.

The lattice search for viable technicolor theories has focused on exploring gauge theories with $SU(N_C)$ colors and N_f fermions in some representation R. Changing these parameters generates theories with dramatically different behavior. Theories with a small number of fermionic flavors in a lower representation behave similarly to QCD. If more fermionic degrees of freedom are added, the theory develops an infrared fixed point. If enough degrees of freedom are added the theory will lose asymptotic freedom. The location of the conformal window in the parameter space N_C, N_f, and R is fundamentally a question of strong dynamics. Perturbative and quasi perturbative calculations exist for the bounds of the conformal window but they can only serve as a guide to locate interesting theories for numerical studies.

Ultimately we are interested in the behavior of theories that may exhibit a slowly running coupling. This behavior, also called walking, may exist just below the conformal window. In a walking theory, γ_m must be $\mathcal{O}(1)$ for the theory to be phenomenologically successful.. Walking is widely believed to be necessary for any technicolor model to fit current experimental bounds on flavor changing neutral currents. To date a viable walking theory has not yet been found.

Many groups, including our own have explored the conformal window with several goals in mind. First understand the extent of the conformal window. Second improve lattice techniques in conformal systems. Third explore the bottom of the conformal window for walking behavior.

In this thesis I have discussed three methods that can be used to understand the β function. These methods are general and work for confining and conformal systems, they have the benefit that distinguishing between the two is straight forward. I first discussed MCRG and presented results for $SU(3)$ gauge theory with $N_f = 8$ and $N_f = 12$. Our results were consistent with the 12 flavor theory exhibiting an IRFP. The 8 flavor theory did not show a fixed point and appeared to be chirally broken and confining.

Next I introduced the gradient flow step scaling and showed results for $SU(3)$ gauge theory with $N_f = 4$ and N_f=12. The 4 flavor results were simply to show that our improvement works in a theory we know to be chirally broken. They also serve as a contrast to the 12 flavor results which clearly indicate an IRFP. Another group has recently applied this technique, with our improvement, to $SU(3)$ gauge theory with 8 flavors [72] their results show that while the theory runs slower than perturbation theory predicts, they can not locate an IRFP.

Finally I introduced an improvement to MCRG that uses the Wilson flow as an optimization. We call this technique Wilson Flow MCRG or WMCRG. WMCRG is like MCRG in that we are calculating the discrete step scaling function. By using the Wilson Flow as an optimization we are able to probe a single renormalized trajectory. Results from WMCRG for $SU(3)$ gauge theory of 12 flavors of fermions in the fundamental representation shows very clear evidence of a fixed point.

One of the benefits of these three techniques is that they are computationally inexpensive and do not require specific lattice dimensions or special boundary conditions. That is the lattices that we use for these step scaling studies are able to be used in other studies as well. Our group has been involved with several other analysis. We studied finite temperature phase transitions [107], finding a bulk phase transition in the 12 flavor theory and no such transition in the 8 flavor theory. We also used the Dirac eigenmodes to calculate γ_m over several length scales [26, 27]. Results from both of these studies are consistent with an IR conformal 12 flavor theory. For several years the IR physics of $SU(3)$ gauge theory with 12 flavors of fermions in the fundamental representation was a topic of debate. Several early papers drew different conclusions from their analysis. A consensus has emerged that the theory is indeed conformal. This consensus is a result of improvements in our understanding of quantum field theories as well as implements in lattice techniques used to study those quantum field theories.

In contrast to the 12 flavor theory, the results for 8 flavors show no sign of an IRFP. The fact that 8 flavors is chirally broken is not controversial. However, peculiar behavior in the eigenmode study seems to suggest that the running of the coupling is slow over a wide range of energy scales. These results seem to be confirmed by recent studies using our improved Wilson Flow step scaling function. It is still not clear if the running is simply slower than expected or is the long sought for walking scenario. Clearly $SU(3)$ gauge theory with 8 flavors of fermions in the fundamental representation is an interesting theory that should be studied further.

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