Elementary Particle Physics at Syracuse
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Contents

1 PI Reports

Supersymmetry and Technicolor on the Lattice

Simon Catterall

Supersymmetric lattice actions and $\mathcal{N} = 4$ SYM

Over the grant period Catterall and his collaborators and students have been using these ideas to push forward a program to conduct a non-perturbative study $\mathcal{N} = 4$ super Yang-Mills theory on the lattice. The lattice formulation that is being studied corresponds to a discretization of a topologically twisted form of the $\mathcal{N} = 4$ action. The existence of a supersymmetric lattice formulation dramatically reduces the usual fine tuning problem associated with supersymmetric lattice theories. The availability of a supersymmetric lattice construction for this theory is clearly very exciting from the point of view of exploring the possible holographic connections between gauge theories and string/gravitational theories.

One of the prime goals of the current program is to refine our understanding of these new lattice constructions so as to allow for a serious numerical investigation of this theory using the same tools and techniques that are used for lattice QCD. A suitable C++ simulation code was developed to aid in these studies and this has been made publically available in the hope of stimulating further work by members of the lattice community. Using a GPU accelerated version of this code Catterall and collaborators have been studying the zero temperature phase diagram of the $\mathcal{N} = 4$ theory as the 't Hooft coupling varies on lattices of size $8^3 \times 16$ (equivalent to $16^3 \times 32$ staggered lattices). Initial results point to the existence of a single phase corresponding to a deconfined conformal field theory in the infrared for any value of the bare gauge coupling. A full parallelized code based on the MILC software suite has now been developed which should allow further precision work on much larger lattices.

In addition to the development of simulation code, Catterall and collaborators have been focused on the question of how much fine tuning will be needed to recover full supersymmetry as the lattice spacing is sent to zero. Substantial analytic progress on this question has been obtained recently. A perturbative calculation has been completed and published which contains several remarkable results. The first of these is that the effective potential of the lattice theory vanishes to all orders in perturbation theory in complete analogy to the continuum theory.

In addition, a study has recently been completed on the question of whether the lattice theory exhibits a sign problem. The Pfaffian representing the effect of the fermion loops is generically complex in Euclidean space rendering the use of Monte Carlo methods potentially problematic. Catterall and collaborators have been examining this issue in some detail in the dimensional reduction of this model to two dimensions. The initial results are encouraging; the observed fluctuations in the Pfaffian phase as measured in the phase quenched Monte Carlo ensembles used for simulation are actually rather small allowing for the possibility of the use of reweighting techniques to be employed to compute expectation values.

Minimal walking technicolor

There are many ways to arrive at a composite Higgs scenario. One popular idea is afforded by technicolor models. In these models electroweak symmetry can be broken by the formation of a condensate of fermions carrying the quantum numbers of the SM Higgs. Such theories conjecture the existence of new fermionic degrees of freedom - techniquarks and a new *technicolor* gauge force which becomes strong at electroweak scales causing the condensate to form. One specific idea for finding viable technicolor models requires that the theory lie close in theory space to a conformal field theory. The resultant theory would presumably possess a small beta function with the consequence that the coupling would only evolve slowly or *walk* over a wide range of scales. It is hoped that by changing the number of colors, flavors and representation of the techniquarks we can find such a walking theory.

In this context Catterall and collaborators pioneered the lattice study of a particularly interesting gauge theory which has been dubbed *Minimal Walking Technicolor*. It consists of two Dirac flavors of adjoint fermions in a theory with $SU(2)$ gauge symmetry. Evidence has been presented that the theory enjoys a two phase structure with a confining phase at strong coupling separated by a first order phase transition from a phase whose properties are consistent with a would-be conformal field theory in the infinite volume continuum limit. Furthermore, lattice simulations have indeed found that the gauge coupling runs very slowly as expected - although distinguishing between confor- mal and near conformal behavior is an inherently difficult task.

Models with four fermion interactions

The technicolor models all share a common feature that they use strong gauge dynamics to drive a chiral symmetry breaking condensate. If we embed the technicolor theory in an extended technicolor scheme then at low energies the resultant model will acquire additional four fermion interactions. We have studied one such model using a lattice action employing reduced staggered fermions that maintains a discrete chiral symmetry at non zero lattice spacing. Our results indicate that the four fermion term can strongly enhance any chiral condensate already present due to strong gauge dynamics but no new fixed points are found in the phase diagram of the lattice and hence no new continuum limits or universality classes. This has been confirmed in more recent simulations which we performed last year with an improved lattice fermion action.

Graduate students and postdocs

Two students have worked on these projects: Richard Galvez and Aarti Veernala. Both are likely to graduate with PhDs within two years.
One postdoc Dhagash Mehta has been employed under the grant and has contributed to many of these papers.

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TeV Scale Dynamics and the LHC
Jay Hubisz

Model Building in the LHC Era

Over the time period of this grant, Hubisz and his collaborators have been exploring a number of different solutions to persistent problems associated with the Standard Model (SM) of particle physics. These include the Higgs hierarchy problem, the dark matter puzzle, the strong CP problem, and flavor. Hubisz is also currently working on possible solutions to the cosmological constant problem.

Naturalness in the electroweak symmetry breaking sector is one of the largest puzzles facing the SM, with quantum corrections favoring a Higgs mass and vacuum expectation value of order the cutoff of the field theory. Direct and indirect searches indicate that this cutoff (the scale of potential new physics) is well above the observed electroweak scale, in conflicft with expectations from effective field theory.

Some solutions to this problem involve promoting the fundamental Higgs scalar to a composite particle, or to enforce supersymmetry. Hubisz has conducted research during this grant involving the composite Higgs hypothesis [1, 4, 5]. In particular, the idea of top quark condensation is an interesting possibility for the origin of the Higgs, in which top quarks form a scalar bound state due to 4-fermion operators generated at a high scale. Hubisz studied such phenomena in the context of extra dimensions in [5] in which many aspects of renormalization in extra dimensional theories were clarified, and it was shown that boundary interactions in compactified theories can drive the formation of chiral condensates. Hubisz also studied such models non-perturbatively on the lattice. Of interest in this result is the evidence that such interactions can greatly enhance chiral condensates already present due to strong dynamics. In addition, no evidence was found in support of various claims in the literature of new fixed points in the phase diagram for these models.

Hubisz has also completed two papers considering dark matter. Firstly, Hubisz considered with collaborators the possibility that light (keV or greater) dark matter particles might arise due to a new extra-dimensional gauge symmetry broken in such a way as to generate a very light A_5 scalar field (via the Hosotani mechanism) [12] which is odd under KK-parity. Such a light particle has phenomenology similar to an axino or gravitino, as might arise from particular supersymmetric theories. Additionally, we considered an MSSM extension that introduces a new global symmetry which, when broken, produces a dark matter candidate which is generically not in tension with existing direct search bounds [6].

Hubisz' newest work focuses on the question of whether the resonance near 126 GeV could in fact be a dilaton, the Goldstone boson associated with the spontaneous breakdown of a strongly coupled conformally invariant theory [1]. It was shown in our work that this is indeed possible, although there are tensions associated with this hypothesis involving its mass, flavor, electroweak precision, and the data on the resonance itself.

Ongoing work connected to dilatons begun during the grant time period (not necessarily associated with the Higgs like resonance) explores the possibility that such particles may play a role in ameliorating the cosmological constant problem. That is, the dilaton could erase the contributions of QCD and/or the Higgs vacuum expectation value to the value of the cosmological constant, arguably the most problematic part of the cosmological constant problem.

Collider Phenomenology at the LHC

Hubisz has also completed numerous projects considering various aspects of LHC collider phenomenology during the grant period. Topics in this genre include mass measurement in decay chains with missing energy [9], probing non-standard hadronic Higgs decay channels via jet substructure [8], limits on top-quark partners [3], and composite Higgs models [2].

The question of mass measurement is crucial should it prove to be the case that there is a new symmetry at the TeV scale that stabilizes some electroweak scale neutral particle. Such degrees of freedom may prove to be at least partial contributors to the cosmological abundance of dark matter, and may manifest at collider experiments like the LHC as decay chains which involve large amounts of missing energy. With Jing Shao, we showed that certain kinematic limits of such decay chains allow for relatively precise determination of the masses of exotica.

In addition, the Higgs itself may have non-standard decay channels. In [8], we showed that the context of such Higgses , which have large branching fractions to purely hadronic final states via an intermediate decay to two light pseudo-scalar particles, in the context of supersymmetry models may be studied via jet substructure techniques. For sizable branching fractions to these exotic states, SUSY decay chains produce boosted Higgs bosons which will be separable from backgrounds using substructure techniques.

Naturalness is a key component of the research goals of numerous theory projects. Along these lines, models with fermionic top-quark partners, which may serve to cancel the most problematic part of Higgs naturalness issues (which arise from the large top-quark Yukawa coupling), have been a part of Hubisz' research during the project. Hubisz has studied the limits on such models with collaborators in [3] from the standpoint of direct LHC bounds (re-interpreted in our work from various non-optimized searches), and from electroweak precision and flavor constraints.

Finally, the possibility that the scalar resonance at 126 GeV does not fully unitarize electroweak gauge boson scattering was considered in [2]. In this work, a triplet of vector bosons is introduced to and the couplings of the scalar resonance are reduced compared with SM Higgs couplings to SM fields. The phenomenology of such models was considered in detail, looking at electroweak precision, direct bounds, and unitarity constraints. This study may be crucially important should the 126 GeV resonance turn out to have the properties expected of a composite state.

Finally, work on the Higgs phenomenology of gauge extensions of the standard model was initiated during the time period of this grant. This work aims to characterize the effect of new vector states on Higgs di-boson decays (with focus on both $H \to \gamma\gamma$ and on $H \to \gamma Z$).

Graduate students and postdocs

Two students have worked on these projects: Don Bunk and Bithika Jain. Don Bunk is likely to graduate with a PhD in spring 2013. Bithika Jain is likely to graduate in approximately 2 years.

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Joseph Schechter

Perturbed S_3 neutrinos

by Renata Jora, Joseph Schechter, M. Naeem Shahid
Phys. Rev. D **80**, 093007 (2009); arXiv:0909.4414

We study the effects of the perturbation which violates the permutation symmetry of three Majorana neutrinos but preserves the well known (23) interchange symmetry. This is done in the presence of an arbitrary Majorana phase ψ which serves to insure the degeneracy of the three neutrinos at the unperturbed level.

Light Scalar Puzzle in QCD

by Amir H. Fariborz, Renata Jora, and Joseph Schechter (speaker)
AIP Conf.Proc.1361:127-131,2011

An approach to understanding the light scalar meson spectroscopy is briefly reviewed

Doubly Perturbed S_3 neutrinos and the s_{13} mixing parameter

by Renata Jora, Joseph Schechter, M. Naeem Shahid
Phys. Rev. D **82**, 053006 (2010); arXiv:1006.3307

We further study a predictive model for the masses and mixing matrix of three Majorana neutrinos. At zeroth order the model yielded degenerate neutrinos and a generalized "tribimaximal" mixing matrix. At first order the mass splitting was incorporated and the tribimaximal mixing matrix emerged with very small corrections but with a zero value for the parameter s_{13}. In the present paper a different, assumed weaker, perturbation is included which gives a non zero value for s_{13} and further corrections to other quantities. These corrections are worked out and their consequences discussed under the simplifying assumption that the conventional CP violation phase vanishes. It is shown that the existing measurements of the parameter s_{23} provide strong bounds on s_{13} in this model.

Nonperturbative Results for Yang-Mills Theories

by Francesco Sannino and Joseph Schechter
Phys. Rev. D **82**, 096008 (2010); arXiv:1009.0265

Some non perturbative aspects of the pure SU(3) Yang-Mills theory are investigated assuming a specific form of the beta function, based on a recent modification by Ryttov and Sannino of the known one for supersymmetric gauge theories. The characteristic feature is a pole at a particular value of the coupling constant, g. First it is noted, using dimensional analysis, that physical quantities behave smoothly as one travels from one side of the pole to the other. Then it is argued that the form of the integrated beta function $g(\mu)$, where μ is the mass scale, determines the mass gap of the theory. Assuming the usual QCD value one finds it to be 1.67 GeV, which is in surprisingly good agreement with a quenched lattice calculation. A similar calculation is made for the supersymmetric Yang-Mills theory where the corresponding beta function is considered to be exact.

Are three flavors special?

by Amir H. Fariborz, Renata Jora, Joseph Schechter, M. Naeem Shahid
Phys. Rev. D **83**, 034018 (2011); arXiv:1012.4868

It has become clearer recently that the regular pattern of three flavor nonets describing the low spin meson multiplets seems to require some modification for the case of the spin 0 scalar mesons. One picture which has had some success, treats the scalars in a chiral Lagrangian framework and considers them to populate two nonets. These are, in turn, taken to result from the mixing of two "bare" nonets, one of which is of quark- antiquark type and the other of two quark- two antiquark type. Here we show that such a mixing is, before chiral symmetry breaking terms are included, only possible for three flavors. In other cases, the two types of structure can not have the same chiral symmetry transformation property. Specifically, our criterion would lead one to believe that scalar and pseudoscalar states containing charm would not have "four quark" admixtures. This work is of potential interest for constructing chiral Lagrangians based on exact chiral symmetry which is then broken by well known specific terms. It may also be of interest in studying some kinds of technicolor theories.

Chiral Nonet Mixing in $\pi\pi$ Scattering

Amir H. Fariborz, Renata Jora, Joseph Schechter, M. Naeem Shahid
Phys. Rev. D **84**, 113004 (2011); arXiv:1106.4538

Pion pion scattering is studied in a generalized linear sigma model which contains two scalar nonets (one of quark-antiquark type and the other of diquark-antidiquark type) and two corresponding pseudoscalar nonets. An interesting feature concerns the mixing of the four isosinglet scalar mesons which yield poles in the scattering amplitude. Some realism is introduced by enforcing exact unitarity via the K-matrix method. It is shown that a reasonable agreement with experimental data is obtained up to about 1 GeV. The poles in the unitarized scattering amplitude are studied in some detail. The lowest pole clearly represents the sigma meson (or $f_0(600)$) with a mass and decay width around 500 MeV. The second pole invites comparison with the $f_0(980)$ which has a mass around 1 GeV and decay width around 100 MeV. The third and fourth poles, resemble some of the isosinglet state in the complicated 1-2 GeV region. Some comparison is made to the situation in the usual SU(3) linear sigma model with a single scalar nonet.

Semi-leptonic $D_s^+(1968)$ decays as a scalar meson probe

by Amir H. Fariborz, Renata Jora, Joseph Schechter, M. Naeem Shahid
Phys.Rev. D84 (2011) 094024; arXiv:1108.3581

The unusual multiplet structures associated with the light spin zero mesons have recently attracted a good deal of theoretical attention. Here we discuss some aspects associated with the possibility of getting new experimental information on this topic from semi-leptonic decays of heavy charged mesons into an isosinglet scalar or pseudoscalar plus leptons.

Neutrinos with velocities greater than c ?

by Joseph Schechter, M. Naeem Shahid
Phys.Rev. D85 (2012) 093008; arXiv:1201.4374

A possible explanation of the results of the OPERA experiment is presented. Assuming that the usual value of c should be interpreted as the velocity of light in dark matter, we call the "true" velocity of light in vacuum, c_t. Then the OPERA neutrinos can be faster than c but slower than c_t. We also discuss the relationship between c_t and neutrino masses.

Testing a model for the puzzling spin 0 mesons

by Joseph Schechter
Prog.Theor.Phys.Suppl. 197 (2012) 64-75; arXiv:1202.3176

After a brief historical discussion of meson quantum numbers, we examine the possibility of additional internal meson structure. Experimental tests of this structure using the semi-leptonic decays of the $D_s^+(1968)$ meson are discussed.

Absolute neutrino masses

by Joseph Schechter, M. Naeem Shahid
Mod.Phys.Lett. A27 (2012) 1250152; arXiv:1204.0582

We discuss the possibility of using experiments timing the propagation of neutrino beams over large distances to help determine the absolute masses of the three neutrinos.

Naturally perturbed S$_3$ neutrinos

by Renata Jora, Joseph Schechter, M. Naeem Shahid
Accepted for publication; arXiv:1210.6755

We simplify and extend our previous model for the masses and mixing matrix of three Majorana neutrinos based on permutation symmetry S_3 and the perturbations which violate this symmetry. The perturbations are arranged such that we get the smaller solar neutrinos mass difference at second order. We work out the corrections to the tribimaximal mixing matrix with the non-zero value for s_{13} and the conventional CP-violating phase. It is shown that the results of the model are comparable with the global analysis of neutrino oscillation data.

Naturalness in a simple two Higgs doublet model

by Renata Jora, Salah Nasri, Joseph Schechter
Accepted for publication; arXiv:1302.6344

We study the implications of a criterion of naturalness for a simple two Higgs doublet model in the context of the discovery of a Higgs like particle with a mass at 125 GeV. This condition which measures the amount of fine-tuning further limits the parameter space of this particular model and together with other phenomenological constraints leads to an allowed range of masses for the other neutral or charged Higgs bosons: H, $a^{\pm}$, a^{0}.

Co-Authors

Prof. Amir Fariborz is on the faculty at the nearby State University of New York in Utica; he had a postdoctoral appointment at Syracuse about ten years ago. Prof. Renata Jora has a faculty position at the National Institute of Physics in Bucharest, Romania. She obtained her PhD at Syracuse about five years ago. Prof. Salah Nasri has a faculty position at United Emirates University; he obtained his PhD at Syracuse about eight years ago. Prof. Francesco Sannino is a group leader at the University of Southern Denmark in Odense. He obtained his PhD at Syracuse about 12 years ago. Dr. M. Naeem Shahid obtained his PhD at Syracuse last summer. He is presently visiting Fermilab.

Studies in non-commutative geometry
A. P. Balachandran

Balachandran and his collaborators were engaged in the study of noncommutative space times and their applications to CMB radiation and Lorentz and Pauli principle violations . As regards CMB , they reexamined the one inflaton model and reforrmulatd it on a noncommutative universe . A fit was made to available data. The data were not accurate enough to give good information on the noncommutative theta parameter. Similarly scattering theory was formulated on Moyal spacetimes and it was proved that there were unique characteristics in Lorentz violation in noncommutative geometry. Finally using the fact that Moyal plane leads to twisted statistics, careful calculations on atomic transitions forbidden by Pauli principle were made and compared with the available bounds on such transitions. They suggested that scale of noncommutativity exceeded the Planck scale , at least as they affected these processes. Pedagogical reviews of physics on the Moyal plane and how they lead to twisted Poincare' group and statistics were also published.

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2 Brief history of the Syracuse High Energy Theory Grant

- The Syracuse High Energy theory group was started around 1963 by E.C.G. Sudarshan. He was well known for being one of the co-discoverers of the "V-A" theory of the weak interactions. He also had strong interests in Quantum Optics and the structure of Classical Mechanics. The early faculty members included A.P. Balachandran, L. O' Raifeartaigh, Alan Macfarlane and Arno Bohm. There were also a fair number of visiting scientists. Two younger scientists on the faculty were N. Mukunda and Austin Gleason.

- By Fall 1967 the faculty included A.P. Balachandran, A. Bohm, A. Gleason, J. Schechter and E.C.G. Sudarshan. There were also about 6 post docs and two students- Bill Meggs and Pierre Ramond (both working with A.P. Balachandran). Balachandran was developing an innovative approach to the study of partial wave dispersion relations.

- Around Fall 1969, Sudarshan with Bohm and Gleason left for the University of Texas at Austin. Sudarshan helped recruit Kamesh Wali, from Argonne Lab, to be the new group leader. Kamesh brought along Maurice Blackmon as a new assistant professor.

- Two visiting assistant professors around that time (1969-1972) were Paul Frampton and Yoshiaki Ueda . Ueda and Schechter wrote the first paper on the then new Weinberg electroweak theory; they introduced a new U(1) gauge field to try to solve the problem of strangeness changing neutral currents.

- After a few years, Maurice Blackmon switched his interest to meteorology and took up a position in Colorado. He was replaced around 1975 by Carl Rosenzweig, who had been at Berkeley working with G. Chew.

- Around 1985 Mark Bowick was hired to give the group some breadth in the rapidly developing field of string theory.

- In 1993 Simon Catterall was hired in part to support a University wide effort in computational physics associated with the newly created Northeast Parallel Architectures Center (NPAC). Catterall's interest at the time embraced efforts in both string theory, quantum gravity and lattice gauge theory.

- By the early 2000's Mark Bowick's interests had shifted to condensed matter physics and he left the high energy group. For a brief time he was replaced in 1995 by Kaustubh Agashe before he moved to Maryland. In his place the group hired Jay Hubisz in 1998. Hubisz's research in model building and LHC phenomenology were seen as giving new strength in these crucial areas. He was added to the DOE grant in 2010.

- Balachandran retired in the summer of 2012 and was replaced by Catterall as PI in 2011. Joe Schechter will retire in January 2013. These retirements have already led to two new hires in theoretical particle physics. Jack Laiho, a lattice gauge theorist, who joined the faculty in January 2013 and JiJi Fan, a phenomenologist who will start at Syracuse in Fall 2013. The group has also broadended its interests to include cosmology with Scott Watson who was funded with Catterall and Hubisz on a new DOE grant in 2013.