1 Plenary

1.1 Status and challenges of simulations with dynamical fermions

Stefan Schaefer (CERN)

Calculations with light dynamical quarks are a longstanding problem in lattice QCD. Recent progress in simulation algorithms and methods to solve the Dirac equation as well as faster computers make it now possible to simulate at or close to physical light quark masses. An overview of the strategies employed in these computations will be given. It will be followed by a discussion of the challenges posed by fine lattices, in particular related to the slowing down of the topological charge as the continuum limit is approached.

1.2 Spectroscopy - an overview

Jozef Dudek (Jefferson Lab)

Present and near-future experiments propose a significant increase in both the quality and scope of data relevant to hadron spectroscopy. The Jefferson Lab 12 GeV experiments GlueX and CLAS12 propose photoproduction of meson systems with mass up to around 3 GeV while the same light hadron systems will be produced through charmonium decays with unprecedented statistics at BES III. States in the charmonium region with a broad set of J^{PC} quantum numbers will be mapped through $\bar{p}p$ annihilation at PANDA, building upon the renaissance in charmonium spectroscopy observed over the past decade.

Lattice QCD is increasingly able to suggest phenomenology of direct relevance to these experiments, in particular through exploring quantities that have traditionally been challenging for simple phenomenological models of QCD, such as the presence of gluonic excitations in hadrons and annihilation dynamics in isoscalar mesons.

I will present the results of recent calculations of the excited hadron spectrum, which, while currently lacking complete theoretical rigour, do reproduce many of the qualitative features of the observed hadron spectrum while also suggesting novel excited states to be explored experimentally.

1.3 Review of lattice studies of resonances

Daniel Mohler (TRIUMF)

1.4 Lattice QCD + QED — from Isospin breaking to g-2 light-by-light

Taku Izubuchi (Brookhaven National Laboratory)
T. Blum, T. Doi, M. Hayakawa, T. Ishikawa, C. Jung, T. Izubuchi, S. Uno, N. Yamada, R. Zhou

Lattice calculations using not only gluon field but also photon field will be reviewed. Results of isospin breaking studies will be presented with introductions to novel techniques developed for the studies. We will also discuss about application of lattice QCD+QED to muon's g-2 hadronic light-by-light contribution studies.

1.5 New fermion discretizations and their applications

Tatsuhiro Misumi (Brookhaven National Laboratory)
Tatsuhiro Misumi

This is a review talk on the recent progress in lattice fermion formulations. I will discuss three new types of fermion discretizations which could contribute to efficient lattice simulations in the near future: (1)Flavored-mass fermions including staggered-Wilson fermions initiated by D. Adams have possibilities of reducing notorious numerical costs in overlap fermions. (2)Central-branch Wilson fermions, in which additive mass renormalization is forbidden by a special symmetry, can enable us to perform Wilson-fermion lattice QCD without fine-tuning. (3)Flavored-chemical-potential fermions, which reduce the number of species without losing chiral symmetry, can be an alternative way to study finite-temperature and finite-density 2-flavor lattice QCD. These new formulations unveil new aspects of lattice fermions, and we can obtain deeper understanding of lattice field theory with them. It leads to further possibilities of lattice field theory as a tool to investigate elementary particle physics.

1.6 Lattice gauge theory and physics beyond the standard model

Joel Giedt (Rensselaer Polytechnic Institute)

1.7 LHC Highlights

Geoff Taylor (The University of Melbourne / CoEPP)

1.8 Calculating the two-pion decay and mixing of neutral K mesons

Norman Christ (Columbia University)

The recent calculation of the complex isospin-two decay amplitude A_2 with physical kinematics will be presented together with exploratory calculations of the isospin-zero decay amplitude A_0. Prospects for accurate calculation of A_0 as well as the mass difference between the K_L and K_S mesons will be discussed.

1.9 Nuclear Physics from Lattice simulations

Takumi Doi (RIKEN)
Takumi Doi for HAL QCD Collaboration

One of the most important objectives in lattice simulations is to understand and make predictions for various phenomena in nuclear physics. In this talk, I will review major challenges and recent developments toward this objective. In particular, nuclear forces obtained from Nambu-Bethe-Salpeter (NBS) wave functions are shown to play an important role, and the extensions to hyperon forces and multi-baryon forces are presented. Important implications on astrophysics are also discussed.

1.10 Recent results in large-N lattice gauge theories

Marco Panero (University of Helsinki)
Marco Panero

Generalizations of QCD in which the number of colors N is taken to infinity are characterized by profound mathematical properties, with far-reaching implications for fundamental problems and for phenomenological issues alike. In this talk, after a brief introduction to the theoretical motivation for studying the large-N limit, I will discuss the role of lattice computations in large-N gauge theories, and highlight a selection of interesting results obtained in recent years. Finally, I will point out some promising research directions for future studies.

1.11 Recent results form LHCb

Justine Serrano (CPPM)
Justine Serrano

1.12 Lattice Flavor Physics with an eye to SuperB

Cecilia Tarantino (University Roma Tre)

I discuss the important role of Lattice QCD in testing the Flavor sector of the Standard Model (SM) and for the indirect searches of New Physics. I will focus on beauty and charm Physics, presenting recent accurate Lattice results. The state of the art of Flavor Physics analyses, in particular of the Unitarity Triangle Analysis within and beyond the SM, is discussed, with an eye to the experimental accuracy expected for the next future thanks to experiments like LHCb and the SuperB factories.

1.13 Lattice Hadron Structure: Applications within and beyond QCD

Huey-Wen Lin (University of Washington)
Huey-Wen Lin

In this talk, I will review the latest lattice-QCD calculations of hadron structure, including nucleon isovector charges and the components of proton spin. I will also summarize progress made in exploring difficult quantities, such as large-Q^2 form factors and gluonic contributions. I will focus on the latest developments and emphasize how new lattice-QCD inputs on hadron structure are affecting the search for physics beyond the Standard Model.

1.14 Strange quark content of the nucleon and dark matter searches

Ross Young (University of Adelaide)
Ross Young

1.15 Sea Contributions to Hadron Electric Polarizabilities through Reweighting

Walter Freeman (The George Washington University)
Walter Freeman, Andrei Alexandru, Frank Lee, Mike Lujan, Craig Pelissier

As part of our ongoing lattice study of the electric polarizabilities of hadrons using the background field approach, we use reweighting to examine the effect of the field on the sea quarks. As with other reweighting studies, the chief difficulty lies in the construction of a stochastic estimate of the ratio of the fermion determinants. In contrast to the case of reweighting in the quark mass, these estimators converge extremely slowly, and are resistant to some of the more common variance-reduction techniques.

I will discuss an alternate variance-reduction approach, taking advantage of the fact that the electric fields needed are perturbatively small.

1.16 High Temperature QCD

Maria Paola Lombardo (INFN)
Maria Paola Lombardo

Recent results for high temperature lattice QCD are reviewed. Topics include the crossover temperature, the pseudocritical line in the temperature-chemical potential plane for small baryon densities, pattern of chiral symmetries, the magnetic equation of state and universalities issues. Our understanding of the quark gluon plasma is further enriched by the new results on the equation of state, meson correlators, and some transport coefficients. Different approaches to the analysis of heavy quarks in medium, and sequential dissociation of charmonium and bottomonium are compared and discussed. Domain wall fermions and overlap fermions studies are coming of age, allowing an exploration of those symmetries which are best studied with a chiral fermion formulation. At the same time, staggered studies are continuing and improved Wilson fermions calculations are steadily developing. A careful comparison among results obtained with different fermion formulations is now possible and the question as to whether thermodynamics lattice results are free from discretization errors can be addressed with increased confidence.

1.17 Complex Langevin dynamics and other approaches at finite chemical potential

Gert Aarts (Swansea University)

I will review the status of complex Langevin dynamics and other approaches to tackle the sign problem at nonzero chemical potential.

1.18 Chiral Dynamics with Wilson fermions

Kim Splittorff (The Niels Bohr Institute)

Close to the continuum the lattice spacing affects the smallest eigenvalues of the Wilson Dirac operator in a very specific manner determined by the way in which the discretization breaks chiral symmetry. These effects can be computed analytically by means of Wilson chiral perturbation theory and Wilson random matrix theory. A number of insights on chiral Dynamics with Wilson fermions can be obtained from the computation of the microscopic spectrum of the Wilson Dirac operator. For example, the unusual volume scaling of the smallest eigenvalues observed in lattice simulations has a natural explanation. The dynamics of the eigenvalues of the Wilson Dirac operator also allow us to determine the additional low energy constants of Wilson chiral perturbation theory and to understand why the Sharpe-Singleton scenario is only realized in unquenched simulations.

1.19 Monte Carlo approach to the string/M-theory

Masanori Hanada (KEK Theory Center)
Masanori Hanada

It has long been conjectured that certain supersymmetric Yang-Mills (SYM) theories provide nonperturbative formulations of the string/M-theory. Although the supersymmetry (SUSY) on lattice is notoriously difficult in general, for a class of theories important for the string/M-theory various lattice and non-lattice methods, which enable us to study them on computers, have been proposed by now.

In this talk, firstly I explain how SYM and string/M-theory are related. Then I explain why the lattice SUSY is difficult in general, and how the difficulties are solved in theories related to the string/M-theory. Then I review the status of the simulation of the simulations. It is explained that some stringy effects are correctly incorporated in SYM. Furthermore, concrete values can be obtained from the SYM side, even when a direct calculation in the string side is impossible by the state-of-the-art techniques. We also comment on other recent developments, including the membrane mini-revolution in 2008 and simulation of the matrix model formulation of the string theory.

1.20 The BlueGene/Q supercomputer

Peter Boyle (University of Edinburgh)
Peter Boyle

1.21 FLAG phase 2: status and prospects

Gilberto Colangelo (University of Bern)
Gilberto Colangelo

1.22 Hadronic contributions to the muon g-2

Tom Blum (University of Connecticut)
T. Blum, M. Hayakawa, T. Izubuchi

Status and prospects for lattice calculations of the hadronic contributions to the muon anomalous magnetic moment are presented, with particular attention payed to the light-by-light amplitude.

2 Algorithms and machines

2.1 Gauge field generation on large-scale GPU-enabled systems

Frank Winter (The University of Edinburgh)

While GPUs have been successfully applied to the post-Monte Carlo "analysis" phase they have not entered the domain of the initial Monte Carlo "gauge field generation" phase. Entering this domain represents a software challenge since it requires significantly more functionality than an accelerated linear solver running on the GPU. This contribution introduces QDP-JIT, the migration of SciDAC QDP++ to GPU-enabled parallel systems. QDP-JIT automatically off-loads calculations to GPUs using dynamic code generation, just-in-time compilation, and automated memory management. USQCD SciDAC software runs unaltered on parallel GPU machines achieving orders of magnitude of speedup on routines typically not subject to manual optimization. We show initial results for gauge field generation with Wilson fermions on large-scale GPU-enabled systems using Chroma LQCD software application built on top of QDP-JIT.

2.2 Adventures in single precision on the GTX 580

Waseem Kamleh (University of Adelaide)
Waseem Kamleh

General purpose computing on GPUs provides a cost-effective means of performing lattice QCD calculations. When calculating quark propagators, the desired accuracy is such that single precision arithmetic should be sufficient to obtain a solution. By avoiding extensive double precision calculations one can make use of inexpensive consumer-level graphics hardware. However, performing matrix inversions in single precision presents certain challenges. I will describe the techniques used to obtain quark propagators on large lattices at light quark mass using the NVIDIA GTX 580.

2.3 Gauge fixing using overrelaxation and simulated annealing on GPUs

Mario Schröck (Universität Graz)
Mario Schröck and Hannes Vogt

We adopt CUDA-capable Graphic Processing Units (GPUs) for Coulomb, Landau and maximally Abelian gauge fixing in 3+1 dimensional SU(3) lattice gauge field theories. The local overrelaxation algorithm is perfectly suited for highly parallel architectures. Simulated annealing preconditioning strongly increases the probability to reach the global maximum of the gauge functional. We give performance results for single and double precision. To obtain our maximum performance of 250 GFlops on NVIDIA's GTX 580 a very fine grained degree of parallelism is required due to the register limits of NVIDIA's Fermi GPUs: we use eight cores per lattice site, i.e., one core per SU(3) matrix that is involved in the computation of a site update. Our code will be publicly available.

2.4 Multi-block/multi-core SSOR preconditioner for the QCD quark solver for K computer

Ken-Ichi Ishikawa (Hiroshima University)
Taisuke Boku, Ken-Ichi Ishikawa, Yoshinobu Kuramashi, Kazuo Minami, Yoshifumi Nakamura, Fumiyoshi Shoji, Daisuke Takahashi, Masaaki Terai, Akira Ukawa, Tomoteru Yoshie

Recent High-Performance computing requires combinations of several layer or kind of parallelisms to extract the high performance of the target machine. The K computer developed by Fujitsu and RIKEN

took the world's fastest record of TOP500 ranking. To boost the scientific computing with 10PFlops machine power the system consists of about 80,000 computational nodes connected by Tofu (3D-Torus) networks, and each node has single 8-core CPU named Sparc64TM VIII Fx with efficient number of SIMD enabled register files capable for scientific computing. Lattice QCD should be one of science target promoted in HPC field and is suitable to develop parallel algorithms and programs as a test bench. In this talk we show some algorithmic development on the efficient usage of the multi-core, SIMD, and communication pattern targeted to the K computer using LQCD Hopping matrix kernel program. We implement Lüscher's SAP preconditioner with sub-blocking in which the lattice block in a node is further divided to several sub-blocks and each sub-block is mapped to each CPU-core. To obtain a better convergence property the sub-blocks are SSOR ordered in the SAP preconditioner. The code is written and ordered to make use of full functionality of SIMD performance of the Sparc64TM VIII Fx. The communication hiding within the SAP preconditioner is also considered.

2.5 Autocorrelation studies in two-flavour Wilson Lattice QCD using DD-HMC algorithm

Santanu Mondal (Saha Institute of Nuclear Physics, Kolkata, India)
Abhishek Chowdhury, Asit De, Sangita De Sarkar, A. Harindranath, Jyotirmoy Maiti, Santanu Mondal, Anwesa Sarkar

We perform an extensive study of autocorrelation of several observables in lattice QCD with two degenerate flavours of naive Wilson fermions and unimproved Wilson gauge action, using DD-HMC algorithm and show that (1) autocorrelations of topological charge and susceptibility substantially increase with decreasing lattice spacing but topological charge density correlator shows only mild increase, (2) at a given lattice spacing, autocorrelations of topological charge and susceptibility both decrease with decreasing quark mass, and (3) autocorrelations of pion and nucleon propagators with wall source decrease with decreasing quark mass. We have also shown the effect of smearing on autocorrelation. We also studied autocorrelations for plaquette and Wilson loop for different quark masses and lattice spacings.

2.6 Application of Domain Decomposition to the Evaluation of Fermion Determinant Ratios

Jacob Finkenrath (Bergische Universität Wuppertal)
Jacob Finkenrath, Francesco Knechtli, Björn Leder

It is a well-known challenge to include the fermion determinant into the Boltzmann factor of the desired ensemble. Many applications like algorithms with Metropolis acceptance-rejection steps or reweighting methods require the ratio of such determinants. The main problem are the fluctuations of the ratio due to the stochastic and the ensemble noise. The idea is to factorize the fluctuations into UV- and IR-dominated terms. We will show the effectiveness of a factorization based on domain decomposition of the lattice in the case of Monte-Carlo algorithms and reweighting in the quarkmass.

2.7 Exploring QCD Thermodynamics Using Möbius Fermions

Hantao Yin (Department of Physics, Columbia University)
Hantao Yin

We discuss the implementation of the HMC and RHMC evolution algorithms for 2+1 flavors of Möbius fermions and present comparisons between Möbius fermions and DWF for QCD at zero and non-zero temperature. We discuss how quantities such as the residual mass, topological charge and chiral condensate behave using the Möbius action and compare the results with the standard domain wall fermions that we have previously used. The immediate benefit comes from a smaller size being used in the 5th dimension. With appropriately chosen Möbius parameters we argue that the same physics can be achieved more efficiently.

2.8 Lattice QCD performances on Aurora

Francesco Di Renzo (University of Parma and INFN)
F. Di Renzo, M. Brambilla

We present our most recent results for Lattice QCD performances on the Aurora parallel architecture. Aurora is based on Intel multicore CPUs and benefits from both standard (IB) and custom (3D torus) networks. Performances for LQCD are shown to effectively meet the expectations. We discuss applications that take advantage of both networks.

2.9 Playing with the kinetic term in the HMC

Alberto Ramos (NIC, DESY)
Alberto Ramos

The HMC algorithm, combining the advantages of molecular dynamics and Monte-Carlo methods is the most efficient algorithm to simulate QCD including the effects of sea quarks. In the standard approach momentum fields are generated with a Gaussian probability density. In this talk I will explore other possibilities. Although the dynamics of systems with different kinetic terms can be very different all of them share the same equilibrium properties. I will present some preliminary results for a Lorentzian choice of the kinetic term and explain its possible benefits.

2.10 New algorithms and new results for Strong Coupling Lattice QCD

Wolfgang Unger (ETH Zürich)
Philippe de Forcrand, Wolfgang Unger

We present and compare new types of algorithms for lattice QCD with staggered fermions in the limit of infinite gauge coupling. These algorithms are formulated on a discrete spatial lattice but with continuous Euclidean time. They make use of the exact Hamiltonian, with the inverse temperature beta as the only input parameter. This formulation turns out to be analogous to that of a quantum spin system. The sign problem is completely absent.

We compare the performance of a continuous-time worm algorithm and of a stochastic series expansion algorithm (SSE), which operates on equivalence classes of time-ordered interactions.

Finally, we apply the SSE algorithm to a first exploratory study of two-flavor SC-LQCD, which is manageable in the Hamiltonian formulation because the sign problem can be controlled.

2.11 Benefits of peer to peer transfers between remote GPUs using QuonG platfrom with APENet+ network.

Roberto Ammendola (INFN)
R. Ammendola, A. Biagioni, O. Frezza, P. Incardona, F. Locicero, A. Lonardo, P. Paolucci, D. Rossetti, F. Simula, L. Tosoratto, P. Vicini

QuonG (lattice Quantum Chromodynamics on GPUs) is an INFN deployment initiative aimed to provide a hybrid, GPU-accelerated x86_64 cluster with a custom 3D-torus network. The interconnect fabric is based on APENet+, an FPGA PCIe board with 6 bidirectional off-board links with 34 Gbps of raw bandwidth per direction, that leverages upon peer-to-peer capabilities of Fermi-class NVIDIA GPUs to obtain real zero-copy, GPU-to-GPU low latency transfers. Latency and bandwidth benchmarks are given at current state of development, showing a performance benefit of using inter-node peer-to-peer communication for message size up to 128kB and increasing. We discuss the status of system deployment,

the results of the synthetic benchmarks and the ongoing development of QuonG-optimized computational kernels (e.g. staggered Dirac operator).

3 Applications beyond QCD

3.1 Four fermion operators and the search for BSM physics

Simon Catterall (Syracuse University)
Simon Catterall, Aarti Vernaala

We describe the use of reduced staggered fermions in the construction of chirally invariant theories with four fermion operators. In particular we show results from simulations of the gauged NJL model in four dimensions. We highlight the advantages of the reduced formalism for constructing theories of BSM physics.

3.2 The sextet gauge model and the composite Higgs mechanism

Julius Kuti (University of California, San Diego)
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chris Schroeder, Chik Him Wong

We present new results for two massless fermions in the sextet representation of the SU(3) color gauge group. Chiral symmetry breaking in the model is consistent with the simplest realization of the composite Higgs mechanism. The composite spectrum and the anomalous dimension of the fermion mass are discussed.

3.3 Confining force and running coupling with twelve fundamental and two sextet fermions

Kieran Holland (University of the Pacific)
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chris Schroeder, Chik Him Wong

We report new simulation results on the static quark potential in two important gauge theories: twelve fermion flavors in the fundamental SU(3) representation and two fermions in the sextet representation. We find a confining force in both models at finite fermion masses. Based on the potential, we investigate the renormalized coupling at scales set by the separation of the static sources. The interpretation of the confining force away from the critical surface is discussed.

3.4 QCD with colour-sextet quarks

D. K. Sinclair (Argonne National Laboratory)
D. K. Sinclair and J. B. Kogut

We study the thermodynamics of QCD with massless colour-sextet quarks. The position of the chiral-symmetry restoration transition as a function of N_t is used to determine the evolution of the lattice running coupling. For $N_f = 2$, which is a candidate walking Technicolor theory, this can be used to determine if this transition is a finite-temperature transition controlled by asymptotic freedom, in which case the theory is QCD-like and walks, or a bulk transition, in which case it is a conformal field theory.

3.5 Conformal finite size scaling of twelve fermion flavors

Chik Him Wong (UC San Diego)
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chris Schroeder

We report extended simulation results and their new analysis for twelve fermion flavors in the fundamental SU(3) representation. We probe the model with respect to conformal behavior using mass deformed finite

size scaling theory based on the anomalous dimension of the fermion mass. Our results at fixed gauge coupling show problems with the expected form of conformal finite size scaling driven by one relevant operator.

3.6 Bulk and finite-temperature transitions in SU(3) gauge theories with many light fermions

David Schaich (University of Colorado at Boulder)
Anqi Cheng, Anna Hasenfratz, Gregory Petropoulos, David Schaich

The scaling behavior of finite-temperature transitions is a possible means to distinguish IR-conformal systems from those exhibiting confinement and spontaneous chiral symmetry breaking. In the past year, our studies of SU(3) gauge theories with Nf=8 and 12 light fermions in the fundamental representation have identified and characterized a novel lattice phase that complicates this approach. At strong coupling and light fermion mass, we find that the single-site shift symmetry of staggered fermions is spontaneously broken in this phase, which is bordered by first-order bulk transitions. In this talk I will summarize our investigations of this phenomenon and its implications for studies of the finite-temperature transitions.

3.7 Low energy spectra in many flavor QCD with Nf=12 and 16

Hiroshi Ohki (KMI, Nagoya University)
Yasumichi Aoki, Tatsumi Aoyama, Masafumi Kurachi, Toshihide Maskawa, Kei-ichi Nagai, Hiroshi Ohki, Akihiro Shibata, Koichi Yamawaki, Takeshi Yamazaki

We present our result of the LatKMI collaboration on the many flavor QCD. Information of the phase structure of many flavor SU(3) gauge theory is of great interest, since the gauge theories with the walking behavior near the infrared fixed point are candidates of new physics for the origin of the dynamical electroweak symmetry breaking. We study the SU(3) gauge theory with Nf=12 and 16 fundamental fermions. From the perturbative analysis, both two models reside in the conformal phase. We try to determine the phase structure of each model non-perturbatively with lattice simulation. HISQ type staggered fermions are used to reduce the discretization error which is useful to study the continuum physics. We study low energy quantities such as meson masses and decay constants at various fermion masses and several lattice spacings to find a characteristic behavior of physical quantities in the phase. The finite size scaling test in conformal hypothesis is also performed, from which we discuss the possible value of the mass anomalous dimension.

3.8 Exploring many flavor QCD with Wilson fermion

N. Yamada (KEK)
N. Yamada, M. Hayakawa, K.-I. Ishikawa, S. Takeda

Progress report on the study on Many flavor QCD is presented aiming at clarifying the conformal window in N_f space. We take the Wilson fermion to examine the phase structure of many flavor QCD, as it enables us to study any number of fermions.

3.9 Lattice artefacts in the Schrödinger Functional coupling for Strongly Interacting theories

Pol Vilaseca (Trinity College Dublin)
Stefan Sint, Pol Vilaseca

Models of Dynamical Electroweak Symmetry Breaking must display a quasi-conformal scaling behaviour in order to accomodate experimental constraints. The scaling properties of a theory can be studied

using finite volume renormalization schemes. Among these, the most practical ones are based on the Schrodinger Functional (SF). However, SF schemes suffer from potentially large O(a) effects and special care has to be taken to remove these effets.

Here we will compare the standard setup of the SF with Wilson quarks to a setup with chirally rotated boundary conditions. We study the step scaling function for SU(2) and SU(3) gauge groups in the funsamental, 2-index symmetric and adjoint representations. We perform the O(a)-improvement of both setups at 1-loop in perturbation theory, and we describe a way of minimizing higher order cutoff effects by an appropiate definition of the renormalised coupling.

3.10 Effect of the Schrödinger functional boundary conditions on the convergence of step scaling

Tuomas Karavirta (University of Jyväskylä)
Tuomas Karavirta, Kari Rummukainen, Kimmo Tuominen

A well established method to measure the running of the coupling is the Schrödinger functional (i.e. background field) method. Recently several lattice measurements of the evolution of the coupling in theories with different gauge groups and fermion representations have appeared. Motivated with these results, we investigate the convergence of the perturbative step scaling to its continuum limit in SU(2) and SU(3) gauge theories with fermions in fundamental, adjoint or two-index symmetric representation of the gauge group. We demonstrate that the improved Wilson action, when properly implemented, indeed removes the contributions linear in lattice spacing. However, the convergence is still extremely slow. We show how this can be further optimized by a careful choice of the boundary values of the background field.

3.11 Recent results for SU(3) Yang-Mills with ten flavors

George T. Fleming (Yale University)
LSD Collaboration

We summarize the recent results of the LSD Collaboration on the study of SU(3) Yang-Mills gauge theory with ten flavors of light domain wall fermions. Fits to the fermion mass dependence of various observables are found to be globally consistent with the hypothesis that this theory is within or just outside the strongly-coupled edge of the conformal window. We discuss important systematic effects, including finite-volume corrections, and consider directions for future improvement.

3.12 Mass anomalous dimension from Dirac eigenmode scaling in conformal and confining systems

Anna Hasenfratz (University of Colorado)
Anqi Cheng, Anna Hasenfratz, Greg Petropoulos, David Schaich

We study the scaling of the individual eigenmodes of the lattice Dirac operator. In a conformal system the relation between the expectation value of the nth eigenmode and the node number predicts the anomalous mass dimension with high precision especially when different volumes are combined. In confining systems the scaling of the eigenmodes on a single volume predicts the running anomalous mass dimension at the given lattice scale.

We apply these principles to study the SU(3) gauge model with 12 and 8 fundamental flavors.

3.13 Exploring walking behavior in SU(3) gauge theory with 4 and 8 HISQ quarks

Kei-ichi Nagai (KMI, Nagoya University)
LatKMI Collaboration: Yasumichi Aoki, Tatsumi Aoyama, Masafumi Kurachi, Toshihide Maskawa, Kei-ichi Nagai, Hiroshi Ohki, Akihiro Shibata, Koichi Yamawaki, Takeshi Yamazaki

We present the report of the LatKMI collaboration on the lattice QCD simulation for the cases of 4 and 8 flavors. The $N_f = 8$ in particular is interesting from the model-building point of view: The typical walking technicolor model with the large anomalous dimension is the so-called one-family model (Farhi-Susskind model). Thus we explore the walking behavior in LQCD with 8 HISQ quarks by comparing with the 4-flavor case (in which the chiral symmetry is spontaneously broken). We report preliminary results on the spectrum, analyzed through the chiral perturbation theory and the finite-size hyperscaling, and we discuss the availability of the $N_f = 8$ QCD to the phenomenology.

3.14 Infrared Fixed Point of SU(3) gauge theory with 12 flavor staggered fermions

Kenji Ogawa (National Chiao-Tung University)

We present our study to identify the location of the fixed point of SU(3) gauge theory with 12 flavors. We show a method to extract the renormalization group beta function from the data of lattice renormalized coupling using a simultaneous fit with respect to bare coupling and lattice size. We show some examples of application of this method to available data from step scaling study, and compare the location of infrared fixed point.

3.15 Mapping the Conformal Window: SU2 with 4, 6 and 10 flavors of fermions

Jarno Rantaharju (University of Helsinki)
Tuomas Karavirta, Jarno Rantaharju, Kari Rummukainen and Kimmo Tuominen

We present studies of the SU(2) gauge theory with 4, 6 and 10 fermion flavors. These models are expected to lie on both sides of the edge of the conformal window, where the theory has an infrared fixed point. We observe that the coupling grows with the lenght scale at four flavors, implying QCD-like behaviour. At ten flavors the results are compatible with a Bank-Zaks type fixed point. The results at six flavors remain inconclusive, the running is slow towards the infrared but the range and accuracy of the study are insufficient for determining the existance of a fixed point.

3.16 Light scalar spectrum in extra-dimensional gauge theories

Enrico Rinaldi (University of Edinburgh)
Luigi Del Debbio, Alistair Hart, Enrico Rinaldi

The phase diagram of five-dimensional SU(2) gauge theories with one compactified dimension on anisotropic lattices has a rich structure. In this talk I will show how to control non-perturbatively the scale hierarchy between the cutoff and the compactification scale in the bare parameter space. There exists a set of strong bare couplings where the the five-dimensional lattice theory can be described by an effective four-dimensional theory with a scalar field in the adjoint representation. I will present a detailed study of the light scalar spectrum as it arises from the non-perturbative dynamics of the full lattice theory. Cutoff effects and finite-size effects are studied and the results are favourably compared to perturbative results.

3.17 Lattice Study of the Extent of the Conformal Window in Two-Color Yang-Mills Theory

Gennady Voronov (Yale University)
Gennady Voronov

We perform a lattice calculation of the Schrödinger functional running coupling in $SU(2)$ Yang-Mills theory with six massless stout-smeared Wilson fermions in the fundamental representation. The aim of this work is to determine whether the above theory has an infrared fixed point. We will present out latest results.

3.18 Lattice study on two-color QCD with six flavors of dynamical quarks

Masashi Hayakawa (Nagoya University)
M.Hayakawa, K.-I.Ishikawa, Y. Osaki, S. Takeda and N. Yamada

We focus on two-color QCD with six Dirac fermions, and report the result of the dynamical properties which have been found from Wilson fermion simulation on mesonic spectrum, heavy quark potential, scale-dependence of effective gauge coupling constant.

3.19 Walking near a conformal fixed point

Michele Pepe (INFN - Milan Bicocca)
P. de Forcrand, M. Pepe, U.-J. Wiese

Slowly walking technicolor models provide a natural mechanism for electroweak symmetry breaking with no need for a scalar particle. The non-perturbative lattice investigation of this phenomenon is rather challenging. Here we demonstrate walking near a conformal fixed point considering the 2-d lattice O(3) model with a vacuum angle θ. An efficient algorithm allows us to perform an accurate investigation of the mechanism of electroweak symmetry breaking of slowly walking technicolor models. We show results for the running coupling and the β-function and we perform a finite-size scaling analysis of the mass gap close to the conformal fixed point.

3.20 The gluino-glue particle and relevant scales for the simulations of supersymmetric Yang-Mills theory

Georg Bergner (University of Münster)
G. Bergner, I. Montvay, G. Münster, D. Sandbrink, U. D. Özugurel

Supersymmetric Yang-Mills theory is in several respects different from QCD and pure Yang-Mills theory. Therefore, a reinvestigation of the scales, at which finite size effects and lattice artifacts become relevant, is necessary. Both, finite size effects and lattice artifacts, induce a breaking of supersymmetry. In view of the unexpected mass gap between bosonic and fermionic particles an estimation of these effects is essential.

3.21 Spontaneous supersymmetry breaking in the two-dimensional Wess-Zumino model

Urs Wenger (Institute for Theoretical Physics, University of Bern)
David Baumgartner, Kyle Steinhauer and Urs Wenger

We study the phase diagram of the two-dimensional Wess-Zumino model using Wilson fermions and the

fermion loop formulation. In particular we give a complete non-perturbative determination of the ground state structure and the particle spectrum, including the Goldstino, both in the continuum and infinite volume limit and across the supersymmetry breaking phase transition. We also present the very first computation of a non-perturbatively renormalised critical coupling.

3.22 Mass Anomalous Dimension at large N

Liam Keegan (IFT UAM/CSIC)
Liam Keegan

We study the SU(N) gauge theory with 2 adjoint Dirac fermions at large N on a small volume, and investigate the possibility of measuring the mass anomalous dimension for this theory using the mode number of the Dirac operator, as was done recently in arXiv:1204.4432 for the SU(2) case.

3.23 Large-N reduction with adjoint Wilson fermions

Mateusz Koren (Jagiellonian University, Krakow, Poland)
Barak Bringoltz, Mateusz Koren, Stephen R. Sharpe

We study SU(N) gauge theory with $N_f = 1$ and $N_f = 2$ adjoint Wilson-Dirac fermions on a single-site lattice. Using values of N up to 53 we show that in both cases the region of the unbroken center symmetry persists when extrapolated to the large-N limit, containing both light and heavy fermions. Using large-N reduction we attempt to calculate physical quantities such as the string tension and meson masses. We compare the single-site results to 2^4 lattice to study effective L(N) dependence.

3.24 Twisted reduction in large N QCD with two adjoint Wilson fermions

Masanori Okawa (Hiroshima University)
Antonio Gonzalez-Arroyo and Masanori Okawa

The twisted reduced model of large N QCD with two adjoint Wilson fermions is studied numerically using the Hybrid Monte Carlo method. This is the one-site model, whose large N limit (large volume limit) is expected to be conformal or nearly conformal. The symmetric twist boundary condition with flux k is used. $k = 0$ corresponds to periodic boundary conditions. It is shown that the phase structure and N dependence of the model with non-vanishing k differ significantly from those of $k = 0$ model. A preliminary result for the string tension calculated at $N = 289$ is also presented.

3.25 Large N_c volume reduction and chiral random matrix theory

Jong-Wan Lee (KEK Theory Center, IPNS)
Masanori Hanada, Jong-Wan Lee, Norikazu Yamada

Motivated by recent progress on the understanding of the Eguchi-Kawai equivalence and growing interest in conformal window, we simultaneously use the large N_c volume reduction and Chiral Random Matrix Theory (ChRMT) to study the conformal window of four dimensional SU(N_c) gauge theory with adjoint fermions in the large N_c limit. As a first step, we mainly focus on the quenched approximation to establish the methodology. We first confirm that heavy adjoint fermions play a role in leaving center symmetry unbroken in the reduced model and thus the volume reduction holds. Using massless overlap fermion as a probe, we then calculate the low-lying Dirac spectrum for fermion in the adjoint representation to compare to that of ChRMT, and find that chiral symmetry is indeed broken in the quenched theory.

3.26 Precision Electroweak Constraints on Near-Conformal Dynamical EWSB

Eoin Kerrane (Universidad Autonoma de Madrid)

Early attempts to construct models of Dynamical Electro-Weak Symmetry Breaking (DEWSB), assuming familiar dynamics for the technisector, failed to overcome strict constraints from the oblique correction parameter S. More recently it has been suggested that models involving a technisector with near-conformal dynamics might be more successful in avoiding these constraints. In such theories the reduced strength of chiral symmetry breaking is expected to suppress the splitting between the vector and axial channels, leading to a reduced contribution to S. We describe an ongoing attempt to measure the contribution to the S parameter from a technisector involving the SU(2) theory with two flavours of adjoint Dirac fermions, which is the main component of the minimal walking-technicolor (MWT) model. The dynamics of this theory have been extensively studied and it has been shown to be consistent with the presence of an infra-red conformal fixed point. We study the S parameter in this theory using a mixed-action lattice simulation, using Wilson sea fermions and Domain-Wall fermions in the valence sector. We describe the steps involved in the computation, explore important systematic effects, and present current results.

3.27 Lattice simulation of ultracold atomic Bose-Fermi mixtures

Arata Yamamoto (RIKEN)
Arata Yamamoto

Recently, Bose-Fermi mixtures have been realized and invesitigated in ultracold atomic experiments. We formulate quantum Monte Carlo simulation of nonrelativistic Bose-Fermi systems on the (3+1)-dimensional lattice. As its first application, we analyze the phase structure at finite temperature.

3.28 The Yang-Mills gradient flow in finite volume

Daniel Nogradi (Eotvos University Budapest)

3.29 MCRG study of 8 and 12 fundamental flavors with mixed fundamental-adjoint gauge action in strong coupling

Gregory Petropoulos (University of Colorado Boulder)
Anna Hasenfratz, Gregory Petropoulos

We study the phase diagram of the fundamental-adjoint action in SU(3) with 8 and 12 flavors of fundamental fermions. This is done using Monte Carlo Renormalization Group (MCRG) techniques to analyze the critical behavior of the theory.

3.30 The Strong coupling regime of twelve flavours QCD

Tiago Nunes (University of Groningen)
Tiago Nunes and Elisabetta Pallante

We report on our study on the strong coupling regime of the SU(3) gauge theory with $N_f = 12$ flavors in the fundamental representation. We show evidence that there is a first order chiral symmetry breaking bulk transition separating a region at weak coupling where chiral symmetry is restored from a region at strong coupling where chiral symmetry is broken. We also discuss a possible interpretation of a second crossover observed with Kogut-Susskind fermions at weaker coupling and for sufficiently light fermion

masses. The results agree with restoration of conformality in non abelian gauge theories as the number of flavors is increased.

3.31 A surprise with many-flavor staggered fermions in the strong coupling limit

Wolfgang Unger (ETH Zürich)
Philippe de Forcrand, Seyong Kim, Wolfgang Unger

Using staggered fermions, we search in the strong coupling limit for a remnant of the conformal window, where chiral symmetry is restored at zero temperature, by varying the number N_f of fundamental flavors. The mean-field approximation predicts that the quark condensate is independent of N_f, and that the chiral transition occurs at a finite, non-zero temperature for arbitrarily large N_f. This goes against naive expectations from the loop expansion of the determinant, according to which fermions have an ordering effect which is approximately accounted for by a shift in β proportional to N_f.

To resolve this puzzle, we carry simulations at $\beta = 0$ with several values of N_f, and uncover a zero-temperature first-order transition to a chirally restored phase. We explore the (N_f, β) zero-temperature phase diagram.

3.32 Higgs Boson mass bounds in presence of a hervy fourth quark family

Attila Nagy (Humboldt University, Berlin)
John Bulava, Philipp Gerhold, Karl Jansen, Jim Kallarackal, Attila Nagy

We investigate Higgs boson mass bounds in a chirally invariant Higgs-Yukawa model using the Overlap operator. We show results for the upper and lower mass bounds in the presence of a heavy mass degenerate quark doublet with various masses up to 700 GeV. We perform infinite volume extrapolations in all cases, and examine several values of the lattice cutoff. Furthermore, we argue that the lower bound is stable with respect to the addition of higher dimensional operators to the scalar field potential. Our results have severe consequences for the phenomenology of a fourth generation of quarks if a light Higgs boson is discovered at the LHC.

3.33 The sphaleron rate at the electroweak crossover with 126GeV Higgs mass

Michela D'Onofrio (Helsinki University)
Michela D'Onofrio, Kari Rummukainen, Anders Tranberg

We investigate the scenario of Baryogenesis through Leptogenesis in the Standard Model. Baryon number is violated by sphaleron transitions at the electroweak crossover temperature (100 GeV). The electroweak crossover marks the limit below which the sphaleron rate becomes exponentially suppressed. Estimates and lattice calculations have been previously performed, but we calculate the sphaleron rate for the first time for the whole crossover range and with a plausible Higgs mass of 126 GeV. In order to do this, we make use of an effective electroweak theory on the lattice and multicanonical and real-time simulation methods.

3.34 Gauge-Higgs Unification on the Lattice

Nikos Irges (National Technical University of Athens)
Nikos Irges, Francesco Knechtli, Kyoko Yoneyama

Fluctuations around a mean-field background are computed for a five-dimensional SU(2) lattice gauge theory where the fifth dimension is taken to be an interval. The gauge symmetry breaks down to U(1) at the two ends of the interval due to the orbifold boundary conditions. We examine the phase diagram and compute the Wilson Loop, the scalar and the vector observables. We show that contrary to conclusions reached in the perturbative expansion in the continuum, spontaneous symmetry breaking of the U(1) symmetry is realized at a generic point of the phase diagram already in the pure gauge theory, and that near the bulk phase transition the scalar constructed from the extra dimensional components of the gauge field can be as heavy or sometimes heavier than the vector boson. Thus, this approach can be viewed as the non-perturbative version of the Gauge-Higgs Unification scenario, however where several serious drawbacks of its continuum version are avoided.

3.35 Thermodynamics of the unitary Fermi gas

Olga Goulko (Ludwig-Maximilians-University, Munich)
Olga Goulko, Matthew Wingate

Lattice field theory has become an increasingly popular method to study problems in the field of cold atoms. For strongly interacting systems, such as the unitary Fermi gas, a numerical simulation is often the only reliable tool to give quantitative predictions. In this talk we build upon our previous calculation of the critical temperature of the unitary Fermi gas with the determinant diagrammatic Monte Carlo method. Now we generalise our approach to temperatures above and below the critical point and present results for the equation of state and the temperature dependence of the contact density. Our values show good agreement with recent experimental data.

3.36 Universal four-component Fermi gas on the lattice

Michael G. Endres (RIKEN)
Michael G. Endres

I present a lattice theory for a universal four-component Fermi gas in one spatial dimension. The canonical and grand-canonical partition functions for the theory are formulated in terms of path-integrals over fermion world-lines, and are free of the sign problem for arbitrary mass- and polarization- imbalances, external potentials, and sign of the four-body interaction strength. The model exhibits a wide range of interesting nonperturbative phenomena in common with a two-component three-dimensional unitary Fermi gas, including an analog of the BCS-BEC crossover regime, and universal few- and many-body physics. Unlike its three-dimensional counterpart, much of these phenomena are numerically accessible using the lattice formulation presented here, due to positivity of the path integration measure. Here, I present the lattice formulation, as well as some preliminary numerical results from canonical ensemble simulations of few-body systems.

3.37 Study of the conformal hyperscaling relation through the Schwinger-Dyson equation

Masafumi Kurachi (KMI, Nagoya University)
Yasumichi Aoki, Tatsumi Aoyama, Masafumi Kurachi, Toshihide Maskawa, Kei-ichi Nagai, Hiroshi Ohki, Akihiro Shibata, Koichi Yamawaki, Takeshi Yamazaki

We study corrections to the conformal hyperscaling relation in the conformal window of the large Nf QCD by using the ladder Schwinger-Dyson (SD) equation as a concrete dynamical model. From the analytical expression of the solution of the ladder SD equation, we identify the form of the leading mass correction to the hyperscaling relation. We find that the anomalous dimension, when identified through the hyperscaling relation neglecting these corrections, yields a value substantially lower than the one at the fixed point γ_m^* for large mass region. We further study finite-volume effects on the hyperscaling relation, based on the ladder SD equation in a finite space-time with the periodic boundary condition.

We find that the finite-volume corrections on the hyperscaling relation are negligible compared with the mass correction. The anomalous dimension, when identified through the finite-size hyperscaling relation neglecting the mass corrections as is often done in the lattice analyses, yields almost the same value as that in the case of the infinite space-time neglecting the mass correction, i.e., a substantially lower value than γ_m^* for large mass. We also apply the finite-volume SD equation to the chiral-symmetry-breaking phase and find that when the theory is close to the critical point such that the dynamically generated mass is much smaller than the explicit breaking mass, the finite-size hyperscaling relation is still operative. We also suggest a concrete form of the modification of the finite-size hyperscaling relation by including the mass correction, which may be useful to analyze the lattice data. (ref: Phys.Rev. D85 (2012) 074502 (arXiv:1201.4157 [hep-lat])

3.38 Screening in two-dimensional gauge theories.

Mateusz Koren (Jagiellonian University, Krakow, Poland)
Piotr Korcyl, Mateusz Koren

We analyze the problem of screening in 1+1 dimensional gauge theories. Using QED_2 as a warm-up for the non-abelian models we show the mechanism of the string breaking, in particular the vanishing overlap of the Wilson loops to the broken-string ground state that has been conjectured in higher-dimensional analyses. We attempt to extend our analysis to non-integer charges in pursuit of the numerical check of a renowned result for the string tension between arbitrarily-charged fermions (Coleman, Jackiw, Susskind).

3.39 Radial Quantization for Conformal Field Theories on the Lattice

Richard C. Brower (Boston University)
Richard C. Brower, George T. Fleming and Herbert Neuberger

We consider radial quantization for conformal quantum field theory with a lattice regulator. For a D dimensional field theory on $R \times S^{D-1}$, the radial transfer matrix or dilatation operator is conjugate to a lattice spacing constant in the logarithmic of the radial distance and orthogonal to D-1 angles on the S^{D-1} sphere. To test the approach, we apply this to the 3D Ising model and compute η for the Z_2 odd primary operator and its descendants. Possible applications to an IR conformal fixed points for gauge theories are being explored.

3.40 Chiral symmetry breaking in lattice QED model with fermion brane

Eigo Shintani (RIKEN-BNL)
Eigo Shintani, Testuya Onogi

We present the numerical results of chiral symmetry breaking in lattice QED with 2+1 dimensional fermion using Hybrid Monte-Carlo simulation. We check the consistency of chiral symmetry breaking in this system with Banks-Casher relation and Nambu-Goldstone theorem near critical point we found in chiral susceptibility. We also discuss the comparison with Graphene model.

3.41 Simulation of graphene on the graphene lattice

Claudio Rebbi (Boston University)
Richard Brower, Michael Cheng, Claudio Rebbi

Strongly coupled electrons on a hexagonal lattice have a dispersion formula which in the low energy limit reduces to the dispersion formula of relativistic massless fermions. This has prompted the use of lattice simulations of 2-dimensional Dirac fermions on square lattices for investigating the properties of graphene. While this approach can be quite powerful, it has limitations due to the mismatch between the original

lattice and the one used in the simulations. In earlier work (done in collaboration with David Schaich) we developed a path integral description of graphene formulated directly on the graphene lattice. By taking advantage of the symmetry of the system, the hybrid Monte Carlo technique can then be used to simulate the Coulomb interaction among the electrons. In this talk I will recapitulate the main features of our formulation. I will then illustrate recent results, including comparison with the exact numerical diagonalization of an 8-site system (with dimensionality 65,536) and discuss challenges which our method may face.

3.42 One dimensional supersymmetric Yang-Mills theory with 16 supercharges

Daisuke Kadoh (RIKEN)
Daisuke Kadoh, Syo Kamata

We report on numerical simulations of the one-dimensional supersymmetric Yang-Mills theory(Quantum mechanics) with sixteen supercharges, by using the Sugino's supersymmetric lattice action (dimensionally reduced version to one dimension). The model is a simple one to verify gauge/gravity duality and its behaviour in the large Nc limit is predicted by the duality. We discuss the validity of the prediction from our numerical results.

3.43 Simulations of SO(4) gauge theory with two fundamental Wilson fermions

Ari Hietanen (CP3-Origins, SDU)
Ari Hietanen, Claudio Pica, Francesco Sannino, Ulrik Søndergaard

We present preliminary results for simulations of SO(4) gauge theory with two fundamental Wilson fermions. We map out the phase diagram including the strong coupling bulk phase transition line as well as the zero PCAC-mass line. In addition, we measure the pseudo scalar and vector meson masses, and investigate the chiral symmetry breaking.

4 Chiral symmetry

4.1 Chiral symmetry restoration and eigenvalue densities of Dirac operators at finite temperature

Sinya Aoki (University of Tsukuba)
Sinya Aoki, Hidenori Fukaya, Yusuke Taniguchi

In the chiral symmetric phase of QCD at finite temperature, we reconsider the constraints on the eigenvalue density of the Dirac operator. To make our arguments more precise, we employ the lattice Dirac operators which satisfy the Ginsparg-Wilson relation. By carefully studying the multi-point correlation functions in various channels, we obtain stronger constraints than those found in the previous studies. We show, in particular, that susceptibilities of the pion and eta meson should be identical in the chiral symmetric phase, which means that the axial U(1) anomaly is invisible, at least, in these channels.

4.2 Quark disconnected diagrams in chiral perturbation theory - the scalar form factor

Andreas Jüttner (University of Southampton, UK)
Andreas Jüttner

The computation of the quark-connected and the quark-disconnected Wick contractions contributing to the pion's scalar form factor in the two and in the three flavour chiral effective theory at next-to-leading order will be presented.

While the quark-disconnected contribution to the form factor itself turns out to be power-counting suppressed its contribution to the scalar radius is of the same order of magnitude as the one of the quark-connected contribution. This result underlines that neglecting quark-disconnected contributions in simulations of lattice QCD can cause significant systematic effects. The technique used to derive these predictions can be applied to a large class of observables relevant for QCD-phenomenology.

4.3 Axial symmetry at the phase transition - An update

Guido Cossu (KEK High Energy Physics Organization)
S. Hashimoto, S. Aoki, T. Kaneko, H .Matsufuru, J. Noaki, E. Shintani

We will discuss our simulations of finite temperature two flavors QCD at the phase transition with overlap fermions, looking for possible signals of axial symmetry restoration. After some details on the control of systematic errors in simulations with fixed topolgy I will present some evidences of suppression of the axial anomaly by looking at the 4 different meson channels that are supposed to be degenerate if the full chiral symmetry is restored.

4.4 Pion form factors in the epsilon regime

Hidenori Fukaya (Osaka University)
JLQCD collaboration : H. Fukaya, S. Aoki, S. Hashimoto, T. Kaneko, H. Matsufuru, J. Noaki, T. Onogi, N. Yamada

We calculate the pion form factors in the epsilon regime. By using the correlators with non-zero momenta and taking an appropriate ratio of them, we can eliminate the dominant finite volume effect from the zero-momentum pion mode. Our preliminary lattice result for the pion charge radius is consistent with the experiment.

4.5 Staggered Chiral Perturbation Theory for all-staggered heavy-light mesons

J. Komijani (Washington University in St. Louis)
J. Komijani and C. Bernard (for the Fermilab Lattice/MILC Collaborations)

In HISQ simulations by the MILC and Fermilab lattice collaborations, both the light quarks and the charm quark are staggered. We extend staggered chiral perturbation theory (SχPT) to include all-staggered heavy-light mesons. We assume that the charm quark action is sufficiently improved that we may take $am_c \ll 1$, but $m_c \gg \Lambda_{QCD}$ so that a continuum heavy quark expansion is appropriate. Using this heavy-light SχPT, the D meson leptonic decay constant is derived at next-to-leading-order. The taste splittings in the heavy-light meson masses are also worked out.

4.6 Topological charge density correlator in Lattice QCD with two flavours of naive Wilson fermions

Santanu Mondal (Saha Institute of Nuclear Physics, Kolkata, India)
Abhishek Chowdhury, Asit K. De, A. Harindranath, Jyotirmoy Maiti, Santanu Mondal

The verification of continuum and chiral properties of QCD is particularly important for lattice QCD with naive Wilson fermion because of the lack of chiral symmetry and O(a) lattice artifacts. We study the topological charge density correlator in lattice QCD with two degenerate flavours of naive Wilson fermions and unimproved Wilson gauge action at two values of lattice spacings and different volumes, for a range of quark masses. Configurations are generated with DDHMC algorithm and smoothed with HYP smearing. The continuum limit of the correlator complies with the requirement of non-positivity at nonzero distances. The dependences of the size of the positive core and the contact term in topological charge density correlator are studied as a function of quark mass and lattice spacing. The effects of smearing on the short and long distance properties of topological charge density correlator are also studied.

4.7 Staggered Chiral Perturbation Theory for Neutral B Mixing

Claude Bernard (Washington University, Saint Louis, USA)
(for the Fermilab Lattice/MILC collaborations)

I describe a calculation of B meson mixing at one-loop in staggered chiral perturbation theory, for the complete set of Standard Model and BSM operators. The particular lattice representation of the continuum operators used by the Fermilab Lattice/MILC collaborations (and earlier by the HPQCD collaboration) turns out to be important, and results in the presence of "wrong-spin" operators, whose contributions however vanish in the continuum limit. The relation between staggered and naive fermions also plays a key role.

4.8 Taste non-Goldstone pion decay constants in staggered chiral perturbation theory

Boram Yoon (Seoul National University)
Jon A. Bailey, Boram Yoon, Weonjong Lee

We calculate the decay constants of taste non-Goldstone pions and kaons in staggered chiral perturbation theory through next-to-leading order. This calculation is an extension of that of the taste Goldstone decay constants. The results can be used for precise determinations of the decay constants and Gasser-Leutwyler parameters. We present the results in quenched, partially quenched and fully dynamical cases.

4.9 Strong coupling analysis of Aoki phase in Staggered-Wilson fermions

Takashi Z. Nakano (Kyoto University/YITP)
Takashi Z. Nakano, Tatsuhiro Misumi, Taro Kimura, Akira Ohnishi

We study Aoki phase with new lattice fermions (staggered-Wilson fermions) in the strong-coupling lattice QCD. Especially, we investigate the existance of parity-broken phase and the possibility of taking a chiral limit. Following two main results are obtained by performing the hopping parameter expansion and the effective potential analysis in the strong-coupling limit. In some range of the fermion mass parameter, the parity- broken phase exists because the pion condensate is nonzero. It is possible to take a chiral limit because the pions become massless Nambu-Goldstone bosons on the phase boundary. These results strongly suggest that it is possible to perform lattice Monte-Carlo simulations with staggered-Wilson fermions by tuning the mass parameter to take a chiral limit as in the Wilson fermion.

4.10 $Nf = 2$ chiral dynamics in the mixed-regime

Gregory Vulvert (IFIC Valencia)
Gregory Vulvert

Lattice QCD benefits nowadays from numerous progess thanks to algorithmic enhancements to push down the quark masses to reach the physical masses and to increase the lattice geometry to avoid finite volume effects. However using fermions which do not break the chiral symmetry both in valence and sea sector is still a challenge. An alternative is to consider mixed action simulations, where one uses for example Ginsparg-Wilson respecting chiral symmetry to describe the valence quark whereas the sea is described by Wilson fermions, which breaks chiral symmetry and which are numerically cheaper but even in this case, using large volumes do avoid finite-volume effects is rather expensive. Chiral perturbation theory (ChPT) can be done in finite-volume so that it can take into account the finite-volume effects. But we can use quarks that do not belong to the same chiral regime : some quarks can be in the so-called epsilon regime of ChPT which allows to compute large finite-size effects while other quarks are in the usual p regime. We thus consider a theory with N_v quarks in the epsilon regime and N_s quarks in the p-regime. These results can be used to match lattice QCD and the chiral effective theory in a large but finite box in which the Compton wavelength of the lightest pions is of the order of the box size. This approach allows us to test the chiral regime. I will present some results obtained in the case of the PP correlator.

4.11 Lattice QCD with optimal domain-wall fermion on the $20^3 \times 40$ lattice

Ting-Wai Chiu (Physics Department, National Taiwan University)
Ting-Wai Chiu, Tung-Han Hsieh (for the TWQCD collaboration)

We perform hybrid Monte Carlo simulations of 2 flavors lattice QCD with optimal domain-wall fermion on the $20^3 \times 40$ lattice, with plaquette gauge action at $\beta = 5.95$, for 6 sea-quark masses corresponding to pion masses in the range 230-450 MeV. For each sea quark mass, 5000 trajectories are generated after thermalization, and one configuration is sampled every 10 trajectories. For each configuration, quark propagators are computed with the point source at the origin, and the zero modes plus 180 pairs of low-lying eigenmodes of the overlap Dirac operator are computed with the adaptive thick-restart Lanczos algorithm. In this talk, we present our preliminary results of the pseudoscalar mass and decay constant, and also the spectra of low-lying mesons and baryons.

4.12 A study of one-flavor algorithms for HMC simulation with the optimal domain-wall

Yu-Chih Chen (National Taiwan University)
Yu-Chih Chen, Ting-Wai Chiu (for the TWQCD collaboration)

In 2009, TWQCD collaboration proposed a new algorithm for HMC simulation of one flavor of optimal domain wall fermion, without taking square root in the action of the pseudo fermions. In this talk, we outline the salient features of this new algorithm, and also compare its efficiency with RHMC.

4.13 Physical observables from the low-lying eigenmodes of the lattice Dirac operator

Tung-Han Hsieh (Research Center for Applied Sciences, Academia Sinica)
Ting-Wai Chiu, Tung-Han Hsieh (for the TWQCD Collaboration)

For the unquenched gauge ensembles (8 sea quark masses, each quark mass of 5000 trajectories after thermalization) generated by lattice simulations of two flavors QCD with the optimal domain-wall fermion, we project the low-lying eigenmodes of the overlap Dirac operator with the adaptive thick-restart Lanczos algorithm. For each configuration (sampled every 10 trajectories), we compute the zero modes plus 80 conjugate pairs of the low-lying eigenmodes of the overlap Dirac operator. Using the zero modes and low-lying modes, we measure the topological susceptibility, the eigenvalue spectrum, and the time-correlation function of the pseudoscalar meson (for the flavor singlet, and non-singlet). With these observables, we study the chiral symmetry breaking at zero temperature, and its restoration at high temperatures.

4.14 Low lying hadron spectrum and chiral condensate with two flavours of naive Wilson fermions

Asit De (Saha Institute of Nuclear Physics, Kolkata, India)
Abhishek Chowdhury, Asit De, Sangita De Sarkar, A. Harindranath, Jyotirmoy Maiti, Santanu Mondal, Anwesa Sarkar

We study pion and rho masses and decay constants, nucleon and delta masses with two degenerate flavours of naive Wilson fermions and unimproved Wilson gauge action using DDHMC algorithm as a function of PCAC quark mass at two different lattice spacings and different volumes. Infinite volume extrapolation is performed wherever possible. The scaling violations of the pionic observables are found to be negligible. The chiral behaviour of different observables are compared with NLO chiral perturbation theory predictions. Using the extracted pion mass, quark mass and pion decay constant we calculate chiral condensate and it is found to be compatible with NLO chiral perturbation theory prediction.

4.15 Random Matrix Models for the Hermitian Wilson-Dirac operator of QCD-like theories

Savvas Zafeiropoulos (Stony Brook University)
Mario Kieburg,Jacobus Verbaarschot,Savvas Zafeiropoulos

We propose and discuss Random Matrix Models for the Hermitian Wilson-Dirac operator of QCD-like theories. We show that they are equivalent to the ϵ limit of the chiral Lagrangian for Wilson chiral perturbation theory. Results are obtained for two-color QCD with quarks in the fundamental representation of the color

group as well as any-color QCD with quarks in the adjoint representation. For $N_c = 2$ we also have obtained the lattice spacing dependence of the quenched average spectral density for a fixed value of the index of the Dirac operator . Comparisons with direct numerical simulations of the random matrix ensemble are shown.

5 Hadron spectroscopy and interactions

5.1 Omega Baryon Interactions with Lattice QCD

Joseph Wasem (Lawrence Livermore National Laboratory)
Joseph Wasem, Michael I. Buchoff, Thomas Luu

We discuss the interactions of the two-Ω^- baryon system in multiple spin channels with lattice QCD. In addition to being an interesting hyperonic system in its own right, the two-Ω^- system also provides an ideal laboratory for exploring the interactions of multi-baryon systems with minimal dependence on light quark masses. Previous model calculations of the two-Ω^- system have obtained conflicting results, which can be resolved by the lattice calculation. The calculations are performed using two different volumes with $L \sim 2.5$ and 3.9 fm at $m_\pi \sim 390$ MeV with a lattice spacing of $a_s \sim 0.123$ fm. Using multiple interpolating operators from a non-displaced source, we present scattering information for two ground state Ω^- baryons in both the S=0 and S=2 channels. For S=0, $k \cot \delta$ is extracted at two volumes, which leads to an extrapolated scattering length of $a_{S=0}^{\Omega\Omega} = 0.16 \pm 0.22$ fm, indicating a weakly repulsive interaction. Additionally, for S=2, two separate highly repulsive states are observed.

5.2 High-precision scale setting in lattice QCD

Thorsten Kurth (Bergische Universität Wuppertal)
Szabolcs Borsanyi, Stephan Durr, Zoltan Fodor, Christian Hoelbling, Sandor D. Katz, Stefan Krieg, Thorsten Kurth, Laurent Lellouch, Thomas Lippert, Craig McNeile and Kalman K. Szabo

Scale setting is of central importance in lattice QCD. It is required to predict dimensional quantities in physical units. Moreover, it determines the relative lattice spac- ings of computations performed at different values of the bare coupling, and this is needed for extrapolating results into the continuum. Thus, we propose here a new method for setting the scale in lattice QCD calculations. It is cheap and straightforward to implement and compute. In particular, it does not involve the delicate fitting of correlation functions at asymptotic times. It typically can be determined on the few per-mil level. We compute its continuum extrapolated value in 2 + 1-flavor QCD for physical and non-physical pion and kaon masses, to allow for mass-independent scale setting even away from the physical mass point. We demonstrate its robustness by computing it with two very different actions (one of them with staggered, the other with Wilson fermions) and by showing that the results agree for physical quark masses in the continuum limit.

5.3 Isospin breaking in octet baryon mass splittings

Roger Horsley (University of Edinburgh)
R. Horsley, J. Najjar, Y. Nakamura, H. Perlt, D. Pleiter, P.E.L. Rakow, G. Schierholz, A. Schiller, J.M. Zanotti (QCDSF-UKQCD collaborations)

Using an SU(3) flavour symmetry breaking expansion in the quark mass, we determine the QCD component of the neutron-proton, Sigma and Xi mass splittings of the baryon octet due to up-down (and strange) quark mass differences. Provided the average quark mass is kept constant, the expansion coefficients in our procedure can be determined from computationally cheaper simulations with mass degenerate sea quarks and partially quenched valence quarks. We find the QCD contribution to the neutron-proton mass difference to be about 3 MeV.

5.4 Isospin violation in the light hadron spectrum

André Walker-Loud (Lawrence Berkeley National Laboratory)

I will discuss both electromagnetic and strong contributions to isospin breaking in the light hadron spectrum.

5.5 Status of the MILC calculation of electromagnetic contributions to pseudoscalar masses

Ludmila Levkova (University of Utah)
S. Basak, A. Bazavov, C. Bernard, C. DeTar, E. Freeland, W. Freeman, J. Foley, Steven Gottlieb, U.M. Heller, J.E. Hetrick, J. Laiho, L. Levkova, M. Oktay, J. Osborn, R.L. Sugar, A. Torok, D. Toussaint, R.S. Van de Water, R. Zhou

We find pseudoscalar masses from calculations with asqtad dynamical quarks plus quenched photons at lattice spacings varying from 0.15 to 0.06 fm. The masses are fit with staggered perturbation theory with NLO electromagnetic terms. We attempt to extract the fit parameters for the electromagnetic contributions, while taking into account the finite volume effects, and extrapolate them to the physical limit.

5.6 Excited and exotic charmonium spectroscopy from lattice QCD

Liuming Liu (Trinity College Dublin)
Liuming Liu, Graham Moir, Mike Peardon, Sinead M. Ryan, Christopher E. Thomas, Pol Vilasecaa, Jozef J. Dudek, Robert G. Edwards, Balint Joo and David G. Richards

We present a spectrum of highly excited charmonium mesons up to ~ 4.5 GeV calculated using dynamical lattice QCD. Employing novel computational techniques and the variational method with a large basis of carefully constructed operators, we extract and reliably identify the continuum spin of an extensive set of excited states, states with exotic quantum numbers (0^{+-}, 1^{-+}, 2^{+-}) and states with high spin. Calculations are performed on two lattice volumes with pion mass ≈ 400 MeV and the mass determinations have high statistical precision even for excited states. We discuss the results in light of experimental observations, identify the lightest 'supermultiplet' of hybrid mesons and comment on the phenomenological implications of the spectrum of exotic mesons.

5.7 Charmed baryon spectroscopy on the physical point in 2+1 flavor lattice QCD

Yusuke Namekawa (University of Tsukuba)
PACS-CS Collaboration

We investigate the charmed baryon spectrum using the relativistic heavy quark action on 2+1 flavor PACS-CS configurations previously generated on $32^3 \times 64$ lattice. The dynamical up-down and strange quark masses are set to the physical values by using the reweighting technique to shift the quark hopping parameters from the values employed in the configuration generation. At the physical point, the lattice spacing equals $a^{-1} = 2.194(10)$ GeV and the spatial extent $L = 2.88(1)$ fm. Our results for the charmed baryon masses are consistent with experiments except for Ξ_{cc}, which has a weak experimental evidence yet. We also predict mass values for other doubly and triply charmed baryons.

5.8 Heavy quarkonium spectroscopy in pNRQCD with lattice QCD input

Yoshiaki Koma (Numazu College of Technology)
Yoshiaki Koma and Miho Koma

We present the heavy quarkonium mass spectra obtained by using our lattice results of the heavy quark potential in an effective field theory called potential nonrelativistic QCD (pNRQCD), which contains spin

and velocity-dependent relativistic corrections up to $O(1/m^2)$ with the heavy quark mass m. We discuss the effect of nonperturbative contribution to the relativistic corrections on the mass spectra.

5.9 Charm and strange hadron spectra from overlap fermions on HISQ gauge configurations

Nilmani Mathur (Tata Institute of Fundamental Research, India)
S. Basak, S. Datta, Padmanath M, P. Majumdar, N. Mathur

We report results on charm and strange hadron spectra and leptonic decay constants. We use overlap fermions for valence quarks, generated on a background of 2+1+1 flavor HISQ gauge configurations. Two lattice spacings (0.09 fm and 0.06 fm) are used. The dispersion relation, as well as hyperfine splitting of 1S charmonia, suggest that at these lattice spacings, cutoff effects are small and charm quark can be treated relativistically.

5.10 Quark mass dependence of s-wave meson-baryon interactions in strangeness sector

Yoichi Ikeda (Tokyo Institute of Technology)
HAL QCD Collaboration

We investigate the s-wave $I = 2$ $\pi\Sigma$ and $I = 1$ KN interactions from 2+1 flavor full lattice QCD simulation for relatively heavy quark mass corresponding to $m_\pi = 570$ and 700 MeV. The s-wave meson-baryon potentials are obtained from the Nambu-Bethe-Salpeter amplitudes. Potentials in both channels reveal short range repulsions, which suggest the importance of the Pauli blocking effect. The scattering phase shifts are calculated by solving the Schroedinger equation with the potentials obtained from our LQCD simulation and compared with the existing experimental data. In this contribution, we discuss quark mass dependence of the meson-baryon potentials and the scattering phase shifts.

5.11 Bound states of multi-nucleon channels in $N_f = 2 + 1$ lattice QCD

Takeshi Yamazaki (KMI, Nagoya University)
T. Yamazaki, Y. Kuramashi and A. Ukawa

We present our results of bound states in multi-nucleon channels where the nuclear mass numbers are from two to four. The simulations are performed in $N_f = 2 + 1$ QCD with Iwasaki and non-perturbative improved Wilson fermion actions at the lattice spacing of $a = 0.09$ fm with relatively heavy pion mass of $m_\pi = 0.5$ GeV. The strange quark mass is chosen to be close to the physical one. To distinguish a bound state from an attractive scattering state, we investigate the volume dependence of the energy difference between the ground state and the free nucleons by changing the spatial extent of the lattice from 2.9 fm to 5.8 fm. From the investigations we conclude that the ground states in all the channels are bound states.

5.12 Study of H-dibaryon Mass in Lattice QCD

Takashi Inoue (Nihon University , College of Bioresource Sciences)
Takashi Inoue for HAL QCD Collaboration

We will report our recent study on H-dibaryon mass in lattice QCD. We utilize the Nambu-Bethe-Salpeter wave function and corresponding potential.

At the last lattice conference, we reported discovery of H-dibaryon in the flavor SU(3) limit of QCD with a degenerate quark mass corresponding to pseudo-scalar meson mass of 469 – 1171 MeV, and found that

the H-dibaryon binding energy decrease as the quark mass decrease.

In order to see the quark mass dependence near the physical point, we have carried out this calculation at one more lighter quark, by generating 3-flavor full-QCD gauge configurations at $m_\pi \simeq 350$ MeV. In addition to the previous method utilizing two gauge-invariant baryon operators for H-dibaryon, we have tested an alternative interpolating operator for H-dibaryon, which is a gauge-invariant product of two colored 3-quark operators.

5.13 Baryon resonances in a finite volume: improved phase shift extraction

Jonathan Hall (CSSM,CoEPP)
Jonathan Hall, Chi-Pin Hsu, Derek Leinweber, Anthony Thomas, Ross Young

In a finite volume, resonances and multi-hadron states are identified by discrete energy levels. When comparing the results of lattice QCD calculations to scattering experiments, it is important to have a way of associating the energy spectra of the finite-volume lattice with the asymptotic behaviour of the S-matrix. Luescher's formula suggests a fixed, geometric relationship between each energy level and the phase shift of elastic scattering. The formula is tested in the context of a finite-volume matrix Hamiltonian model of Delta to nucleon-pion decay. The eigenvalues of the matrix Hamiltonian can be solved exactly, and the phase shift reconstructed using Luescher's formula. By independently calculating the phase shift from the Lippmann-Schwinger equation, it is found that Luescher's formula suffers from errors proportional to 1/L, and extremely large box sizes ¿ 20 fm are required before an accurate extrapolation to the continuum results can be accomplished. A new method is proposed to obtain a phase shift using effective field theory, which is able to reproduce the correct resonance position within a few MeV, even at box sizes of 3 fm- comparable to current feasible lattice sizes.

5.14 2+1 flavor QCD results of nuclear forces

Noriyoshi Ishii (Kobe-branch, Center for Computational Sciences, University of Tsukuba)
Noriyoshi Ishii for HAL QCD Collaboration

We present 2+1 flavor QCD results for the nuclear potentials (central and tensor forces in even parity sectors) together with the scattering phases obtained by using these potentials. We use 2+1 flavor dynamical QCD gauge configurations generated by PACS-CS collaboration on the $32^3 \times 64$ lattice with the RG improved Iwasaki gauge action at $\beta = 1.9$ and the non-perturbatively O(a) improved Wilson quark action with $C_{SW} = 1.715$ ($1/a = 2.176(31)$ GeV ($a = 0.091$ fm) and $L = 32a = 2.9fm$) [1].

The nuclear potentials are constructed from the Nambu-Bethe-Salpeter (NBS) wave functions based on the method proposed by HAL QCD Collaboration [2,3]. Note that the resulting potential is faithful to the scattering phase, because the asymptotic long distance behavior of NBS wave functions is exactly the same as the scattering wave functions of non-relativistic quantum mechanics.

A special attention is paid on the contamination of excited states in Euclidean two-nucleon correlators, which poses the more severe problem when the spacial volume becomes the larger. To avoid, we use time-dependent Shroedinger-like equation [4], which allows us to construct the energy-independent potentials defined in Ref.[3] even in the presence of contamination of excited states.

We construct the central and the tensor potentials in the even parity sectors in the pion mass region $m_\pi = 410 - 700$ MeV, and use these potentials to obtain the scattering phases by solving Schroedinger equation.

Reference: [1] S. Aoki et al., (PACS-CS Coll.), Phys. Rev. 79, 034503 (2009). [2] N. Ishii, S. Aoki, T. Hatsuda, Phys. Rev. Lett. 99, 022001 (2007). [3] S. Aoki, T. Hatsuda, N. Ishii, Prog. Theor. Phys. 123, 89 (2010). [4] N. Ishii et al., (HAL QCD Coll.), Phys. Lett. B in press, arXiv:1203.3642[hep-lat].

5.15 Multi-baryon systems

Kostas Orginos (College of William and Mary)
Kostas Orginos, William Detmold

In this talk I review the challenges related to calculations of properties of interacting baryons on the lattice. I report on the progress made addressing these challenges over the last year and discuss the open questions for the future of such calculations. Results from recent lattice QCD calculations will be presented.

5.16 First calculation of the spin-orbit force in the parity odd sector in NN system from Lattice QCD

K. Murano for HALQCD Collaboration (RIKEN)

The nucleon-nucleon (NN) interaction is a basis for nuclear physics. Once the NN interaction is determined from QCD, one can study properties of various atomic nuclei, by solving Shrödinger equations for many body systems. Recently, a new method to extract the NN interaction from Lattice QCD has been proposed and the first result has been reported (N.Ishii, et.al., Phys. Rev. Lett 99 2007). In the method, NN potentials are constructed from Nambu-Bethe-Salpeter (NBS) wave functions through Schrödinger equations. Potentials obtained so far in this method are limited to central and tensor potentials in the parity even sector. Therefore, for a complete determination of NN potentials, central and tensor potentials in the parity odd sector as well as the spin-orbit force (LS potential) are needed to be determined. In this talk, we report a first attempt to determine NN potential in the parity odd sector including the spin-orbit force in Lattice QCD. Calculation is performed on University of Tsukuba Supercomputer system (T2K), using $N_f = 2$ CP-PACS gauge configurations on a $16^3 \times 32$ lattice at $a = 0.16$ fm and $m_\pi = 1.1$ GeV.

5.17 Quark-quark interaction in baryons from Nambu-Bethe-Salpeter amplitudes on lattice

Hideaki Iida (Department of Physics, Kyoto University)
Hideaki Iida and Yoichi Ikeda

Quark-quark interactions in baryons are studied from the Nambu-Bethe-Salpeter (NBS) amplitudes on lattice. Effective two-quark NBS wavefunction is obtained by integrating out a spectator particle in three-quark NBS wave function, and the effective two-quark potentials are calculated through an effective Schroedigner equation. The obtained potential shows Cornel-type potential, i.e., Coulomb + linear form. The string tension of the potential is comparable with that of q-qbar potential, and the Coulomb coefficient is considerably smaller than that of q-qbar. The method would be useful for constructing a constituent quark model for baryons from lattice QCD.

5.18 Phase shifts in I=2 $\pi\pi$ heavy-pion-scattering from two approaches

Thorsten Kurth (Bergische Universität Wuppertal)
Thorsten Kurth, Sinya, Aoki, Takumi Doi, Stephan Durr, Zoltan Fodor, Tetsuo Hatsuda, Christian Hoelbling, Noriyoshi Ishii, Sandor Katz,Stefan Krieg, Kalman Szabo

A recent approach to address scattering problems in nuclear physics uses the nucleon-potential computed from the Nambu-Bethe-Salpeter (NBS) wave function obtained in lattice calculations. From this potential, the infinite volume multi-nucleon wave functions are obtained by solving a Schroedinger equation. In this talk, I will present a high-precision case study of this method in a quenched 2-pion framework using

a large volume and very high statistics. The results are compared to the well known method introduced by Lüscher for treating scattering problems.

5.19 Properties of Pseudoscalar Flavor-Singlet Mesons from 2+1+1 Twisted Mass Lattice QCD

Konstantin Ottnad (University of Bonn (HISKP))
Konstantin Ottnad, Chris Michael, Carsten Urbach

We use simulations in Wilson twisted mass lattice QCD with 2+1+1 dynamic quark flavors to study properties of η and η' mesons. Results are presented for three values of the lattice spacing and for charged pion masses in a range of 230 MeV to 500 MeV. This allows us to investigate the light quark mass dependence of the η-mass and to obtain some insight into the scaling behavior. Furthermore, we perform simulations with different strange quark mass in order to estimate its impact on the η-mass. We also determine mixing angles for η and η'. The charm quark contribution to both of these states turns out to be negligible within errors.

5.20 η, η' meson masses from a mixed action approach in 2+1+1 twisted mass lattice QCD

Falk Zimmermann (Helmholtz-Institut für Strahlen- und Kernphysik, University of Bonn)
Krzysztof Cichy, Vincent Drach, Konstantin Ottnad, Elena Garcia Ramos, Carsten Urbach, Falk Zimmermann

We extract η, η' mesons masses from Wilson twisted mass lattice configurations with 2+1+1 dynamical quark flavours within the Osterwalder-Seiler framework. In contrast to the unitary approach, this mixed action approximations implicates a different regularisation of the valence and sea quark sector, which provides a striking tool to study the strange quark mass dependence of η, η' states. Furthermore, we capable to employ the powerful, so-called vv-variance reduction method of unitary light disconnected quark loops to heavy Osterwalder-Seiler quarks, too. Features and drawbacks of the Osterwalder-Seiler ansatz are discussed and we present first results.

5.21 Nucleon Eigenstates in Full QCD

Selim Mahbub (University of Adelaide)
M. S. Mahbub, W. Kamleh, D. B. Leinweber, P. J. Moran, A. G. Williams

The nucleon mass spectrum in the positive- and negative-parity channels is examined in full 2+1 flavour dynamical-fermion QCD using the correlation-matrix approach. Of particular interest is the identification and flow of the eigenstates from one quark mass to the next. Using the PACS-CS gauge-field configurations made available via the ILDG, we find it is essential to use the orthogonal eigenvectors obtained from a symmetric construction of the generalized eigenvalue equation in order to unambiguously track the states. The method is particularly useful when the energy states are nearly degenerate.

5.22 Radiative improvement of spin and Darwin terms in the NRQCD action

Georg von Hippel (University of Mainz)
T.C. Hammant, A.G. Hart, G.M. von Hippel, R.R. Horgan, C.J. Monahan

We present updated results for the radiative improvement of the lattice NRQCD action. Besides the $\sigma \cdot B$ term and the spin-dependent four-fermion interactions for both $O(v^4)$ and $O(v^6)$ NRQCD actions, also the Darwin term is radiatively improved. Including the radiative improvements has significant effects, in particular bringing the lattice prediction for the $2S$ hyperfine splitting into line with experiment.

5.23 Progress with applications of the stochastic LapH method to excited states

Jimmy Juge (University of the Pacific)
Colin Morningstar, Justin Foley, John Bulava, Ricky Wong, David Lenkner, You-Cyuan Jhang, Brendan Fahy

Progress in computing the hadron spectrum including multi-hadron states in lattice QCD is described. The stochastic LapH algorithm is used to estimate the propagation of the low modes of the quark fields on 2+1 dynamical, anisotropic lattices with 240 MeV pions.

5.24 Some continuum physics results from the the lattice V-A correlator

Kim Maltman (York University)

5.25 Quark mass dependence of hyperonic interactions from lattice QCD

Kenji Sasaki (Center for Computational Sciences, University of Tsukuba)
for HAL QCD Collaboration

We discuss quark mass dependence of hyperonic interactions by lattice QCD simulation. Derivation of baryon-baryon interactions from lattice QCD is highly awaited to investigate hypernuclear system, neutron star structure and mechanism of supernova explosions since their experimental data are scarce. Our approach to baryon-baryon interactions is deriving a potential from inverting coupled channel Schroedinger equation which is supplemented by Nambu-Behte-Salpeter wave function simulated on lattice. Our numerical results are obtained from three ensembles of 2+1 flavor QCD gauge configurations, which corresponds to $m_\pi \sim 410, 570, 700$MeV, provided by the PACS-CS Collaboration. The quark mass dependence and flavor SU(3) breaking effects of the potential matrix is discussed by comparing the results of three different ensembles of gauge configurations.

5.26 Two-point correlator fits on HISQ ensembles

Jongjeong Kim (University of Arizona)
[MILC and Fermilab Lattice Collaborations] A. Bazavov, C. Bernard, C. Bouchard, C. DeTar, D. Du, A.X. El-Khadra, E.D. Freeland, E. Gamiz, J. Foley, Steven Gottlieb, U.M. Heller, J.E. Hetrick, R. Jain, J. Kim, A.S. Kronfeld, J. Laiho, L. Levkova, M. Lightman, P.B. Mackenzie, E.T. Neil, M. B. Oktay, J. N. Simone, R. Sugar, D. Toussaint, R.S. Van de Water and R. Zhou.

We present the heavy-light and light-light two-point correlator fits for the decay constants of the π, K, D, and D_s mesons on the Highly Improved Staggered Quark (HISQ) ensembles. We perform the correlator fits on a variety of the HISQ ensembles. The lattice spacing ranges from 0.15 fm down to 0.06 fm. The light sea quark mass ranges from 0.2 times the strange quark mass down to the physical light quark mass. The HISQ ensembles also include lattices with different volumes and with unphysical values of the strange quark mass. The results from this work are used to extrapolate to the physical values of the decay constants with good control of systematic uncertainties.

5.27 Pseudoscalar meson physics with four dynamical quarks

Doug Toussaint (University of Arizona)
[MILC and Fermilab Lattice Collaborations] Jon A. Bailey, A. Bazavov, C. Bernard, C. Bouchard, C. DeTar, D. Du, A.X. El-Khadra, E.D. Freeland, E. Gamiz, J. Foley, Steven Gottlieb, U.M. Heller, J.E.

Hetrick, R. Jain, J. Kim, A.S. Kronfeld, J. Laiho, L. Levkova, M. Lightman, P.B. Mackenzie, E.T. Neil, M. B. Oktay, J. N. Simone, R. Sugar, D. Toussaint, R.S. Van de Water and R. Zhou.

We present preliminary results for light, strange and charmed pseudoscalar meson physics from simulations using four flavors of dynamical quarks with the Highly Improved Staggered Quark (HISQ) action. These simulations include lattice spacings ranging from 0.15 to 0.06 fm, and sea quark masses both above and at their physical value. The major results are ratios of quark masses and ratios of meson decay constants f_K/f_π, f_D/f_K and f_Ds/f_K. This talk will focus on valence and sea quark mass adjustments, the continuum extrapolation, and estimates of systematic error.

5.28 Lattice study of J/ψ-ϕ scattering at low energies to search for narrow resonance

Sho Ozaki (Riken)
Sho Ozaki, Shoichi Sasaki, Tetsuo Hatsuda

We investigate low energy J/ψ-ϕ scattering and search for narrow resonances. The J/ψ-ϕ channel is considered to be an interesting system, since three narrow resonances have been reported in recent experiments, namely, $Y(4140)$ and $Y(4274)$ by CDF collaboration, and $X(4350)$ by Belle collaboration. These resonances seem to be relatively stable despite being above open charm thresholds, since their upper bounds of the widths are less then 10-30 MeV. In particular, $Y(4140)$ is located close to the J/ψ-ϕ threshold.

We study the J/ψ-ϕ interaction at low energies by using extended Lüscher formula with partially twisted boundary conditions, which allows us to calculate the phase shift at any small value of the scattering momentum even in a single finite volume. We perform our simulations with the relativistic heavy quark action for charm quarks in 2+1 flavor dynamical lattice QCD using the PACS-CS gauge configurations with a lattice cut-off of $1/a = 2.2$ GeV.

5.29 Lattice investigation of the tetraquark candidates $a_0(980)$ and κ

Jan Daldrop (University of Bonn (HISKP))
Jan Daldrop, Constantia Alexandrou, Marco Cristoforetti, Mattia Dalla Brida, Mario Gravina, Luigi Scorzato, Carsten Urbach, Marc Wagner

It is a long discussed issue whether light scalar mesons have sizeable four-quark components. We present an exploratory study of this question using $N_f = 2 + 1 + 1$ twisted mass lattice QCD. A mixed action approach neglecting disconnected contributions is used to calculate correlator matrices consisting of mesonic molecule, diquark anti-diquark and two-meson interpolating operators with quantum numbers of the scalar mesons a_0 $(1^-(0^{++}))$ and κ $(1/2\,(0^+))$. The correlation matrices are analyzed by solving the generalized eigenvalue problem. The theoretically expected free two-particle scattering states are identified, while no additional low lying states are observed. The result indicates that no bound tetraquark states exist in the channels investigated.

5.30 Gradient flow and scale setting for twisted mass fermions

Albert Deuzeman (University of Bern)
Albert Deuzeman and Urs Wenger, for the ETM Collaboration

The recently introduced gradient flow suggests a way to obtain renormalised gauge field quantities from lattice QCD. It is not only useful to calculate quantities like the renormalised topological susceptibility, but in particular allows a very precise scale setting using the renormalised energy density. We will use this approach to investigate these quantities in detail on gauge field ensembles produced with dynamical Wilson twisted mass fermions. Attention will be paid to the impact of lattice artefacts, quark mass, finite volume effects and the number of sea quarks on the determination of the scale.

6 Hadron structure

6.1 Sigma terms and strangeness content of the nucleon with $Nf = 2 + 1 + 1$ twisted mass fermions.

V. Drach (DESY, NIC)
C. Alexandrou, S. Dinter, V. Drach, G. Koutsou, K. Jansen, A. Vaquero

We study the nucleon matrix elements of the quark scalar-density operator using maximally twisted mass fermions with dynamical light (u,d), strange and charm degrees of freedom. Using an efficient stochastic evaluation of disconnected contributions, we investigate systematic effects. In particular, we perform a dedicated study of the excited states contamination.

6.2 Nucleon mass and strange content from (2+1)-flavor Domain Wall Fermion

Chulwoo Jung (Brookhaven National Laboratory)
Chulwoo Jung (For RBC collaboration)

We report on the ongoing study of nucleon mass and strange quark content on (2+1)-flavor Iwasaki ($1/a \sim 1.7, 2.3$ Gev) and DSDR ($1/a \sim 1.4$ Gev) Domain Wall Fermion ensembles. Scalar matrix element for light quarks are also discussed.

6.3 Sigma terms from an SU(3) chiral extrapolation

Phiala Shanahan (CoEPP and CSSM, The University of Adelaide)
P. E. Shanahan, A. W. Thomas, R. D. Young

We report a new analysis of lattice simulation results for octet baryon masses in 2+1-flavor QCD, with an emphasis on a precise determination of the strangeness nucleon sigma term. A controlled chiral extrapolation of a recent PACS-CS Collaboration data set yields baryon masses which exhibit remarkable agreement both with experimental values at the physical point and with the results of independent lattice QCD simulations at unphysical meson masses. Using the Feynman-Hellmann relation, we evaluate sigma commutators for all octet baryons. The small statistical uncertainty, and considerably smaller model-dependence, allows a significantly more precise determination of the pion-nucleon sigma commutator and the strangeness sigma term than hitherto possible.

6.4 Strange nucleon form factors on $N_f = 2 + 1$ anisotropic wilson clover lattices

Michael Cheng (Boston University)
Michael Cheng, Ron Babich, Richard C. Brower, Michael A. Clark, Saul D. Cohen, George T. Fleming, Joel Giedt, James Osborn, Claudio Rebbi, David Schaich, Oliver Witzel

We present an update of our calculation of the strange quark contribution to the electromagnetic, axial, and scalar nucleon form factors. These calculations are performed on 2+1 flavor, $24^3 \times 128$ anisotropic wilson clover lattices with spatial lattice spacing $a_s \approx 0.12$ fm and anisotropy $\xi = 3.5$. We use two different ensembles with light sea quark masses corresponding to $m_\pi = 220, 360$ MeV.

6.5 Strangeness matrix elements of the nucleon from overlap fermions

Ming Gong (University of Kentucky)
Ming Gong, Anyi Li, Andrei Alexandru, Terrence Draper, Keh-Fei Liu

We present an update on the strangeness matrix elements of the nucleon. We adopt overlap fermion action on 2 + 1 flavor domain-wall fermion configurations. The low mode substitution technique on nucleon two-point functions and the low mode averaging technique on quark loops with the stochastic grid sources are used to improve the signals.

6.6 Axial couplings and strong decay widths of heavy hadrons

William Detmold (College of William & Mary / JLab)
William Detmold, David Lin, Stefan Meinel

We present results from a calculation of the axial couplings of mesons and baryons containing a single heavy quark using domain wall light quarks and static heavy quarks. These couplings determine the leading interactions in heavy hadron chiral perturbation theory and are central quantities in heavy quark physics on the lattice as they control the light-quark mass dependence of heavy hadron observables. The couplings we extract enable us to make predictions for the strong decay widths of various heavy baryons. Flavour SU(3) breaking effects in the axial couplings will also be discussed.

6.7 Transverse momentum-dependent parton distribution functions from lattice QCD

Michael Engelhardt (New Mexico State University)
B.Musch, Ph.Hägler, M.Engelhardt, J.Negele and A.Schäfer

Transverse momentum-dependent parton distributions (TMDs) relevant for semi-inclusive deep inelastic scattering (SIDIS) and the Drell-Yan process can be defined in terms of matrix elements of a quark bilocal operator containing a staple-shaped Wilson connection. Starting from such a definition, a scheme to determine TMDs in lattice QCD is developed and explored. Parametrizing the aforementioned matrix elements in terms of invariant amplitudes permits a simple transformation of the problem to a Lorentz frame suited for the lattice calculation. Results for the Sivers and Boer-Mulders transverse momentum shifts are obtained using ensembles at the pion masses 369 MeV and 518 MeV, focusing in particular on the dependence of these shifts on the staple extent and a Collins-Soper-type evolution parameter quantifying proximity of the staples to the light cone.

6.8 Nucleon structure with pion mass down to 150 MeV

Jeremy Green (Center for Theoretical Physics, Massachusetts Institute of Technology)
Jeremy Green, Michael Engelhardt, Stefan Krieg, John Negele, Andrew Pochinsky, Sergey Syritsyn

We present isovector nucleon observables including axial, tensor and scalar charges, and the Dirac radius. Using the BMW clover-improved Wilson action and pion masses as low as 150 MeV, we achieve good control over chiral extrapolation to the physical point. Our analysis is done using three different source-sink separations in order to have some control over excited-state contamination.

6.9 Finite-size scaling in nucleon axial charge from 2+1-flavor DWF lattice QCD

Shigemi Ohta (Institute of Particle and Nuclear Physics, KEK)
Shigemi Ohta for the RBC and UKQCD Collaborations

We report the current status of the on-going lattice-QCD calculations of nucleon isovector axial charge, g_A, using the RBC/UKQCD 2+1-flavor dynamical domain-wall fermion ensembles at lattice cutoff of about $a^{-1} = 1.4$ GeV in spatial volume $(L = 4.6\text{fm})^3$. The result from the ensemble with $m_\pi = 250$ MeV pion mass, corresponding to the finite-size scaling parameter $m_\pi L \sim 5.8$, agrees well with an earlier result

at $a^{-1} = 1.7$ GeV, $L = 2.8$ fm, and $m_\pi = 420$ MeV, with similar $m_\pi L$. This suggests the systematic error from excited-state contamination is small in both ensembles and about 10-% deficit in g_A we are observing is likely a finite-size effect that scales with $m_\pi L$. We also report the result from the lighter, $m_\pi = 170$ MeV ensemble.

6.10 Status of nucleon structure calculations with 2+1 flavors of domain wall fermions

Meifeng Lin (Yale University)
Yasumichi Aoki, Tom Blum, Taku Izubuchi, Chulwoo Jung, Meifeng Lin, Shigemi Ohta, Eigo Shintani, Shoichi Sasaki, Takeshi Yamazaki

We report the status of our nucleon structure calculations with 2+1 flavors of domain wall fermions on the RBC-UKQCD $32^3 \times 64$ gauge ensembles with the Iwasaki+DSDR action. These ensembles have a fixed lattice scale of approximately 1.4 GeV, and two pion masses of about 170 and 250 MeV. Preliminary results for nucleon form factors will be presented.

6.11 Correlation matrix methods for the pion and rho meson form factors in Full QCD

Benjamin Owen (University of Adelaide)
B. J. Owen, W. Kamleh, D. B. Leinweber, M. S. Mahbub, B. J. Menadue, P. J. Moran

We present a calculation of pion and rho meson form factors in full QCD with the inclusion of variational analysis techniques. Using correlation matrix techniques we are able to calculate the magnetic and quadrupole form factors of the rho meson and are able to extract charge form factors for the first excited states of both the pion and rho mesons.

6.12 Leading order hadronic contributions to a_μ and $\alpha_{\rm QED}$ from $N_f = 2+1+1$ twisted mass fermions

Grit Hotzel (Humboldt University Berlin)
X. Feng, G. Hotzel, K. Jansen, M. Petschlies, D. Renner

We present results for the leading QCD corrections of the magnetic moment of the muon and the running of the QED coupling constant for the complete first two generations of quarks. In the heavy sector a mixed-action setup is employed. Here, the bare masses are determined from matching the kaon and D-meson masses with their physical values. Several light quark masses are used in order to yield a controlled extrapolation to the physical pion mass utilising a recently designed improved method. We analyse ensembles of different lattice spacings and volumes in order to estimate the systematic uncertainties.

6.13 Lattice calculations of the leading hadronic contribution to g-2

Benjamin Jäger (Helmholtz Institut Mainz)
M. Della Morte, B. Jäger, A. Jüttner, H. Wittig

We present an update on the ongoing computation of the leading hadronic contribution to the anomalous magnetic moment of the muon using non-perturbatively O(a) improved Wilson fermions. Partially twisted boundary conditions have been successfully applied to improve the momentum resolution in the relevant dispersion integral. Several ensembles allow a study of systematic uncertainties, such as lattice artefacts and the chiral behaviour towards the physical pion mass.

6.14 Padé approximants and g-2 for the muon

Maarten Golterman (San Francisco State University)
Christopher Aubin, Thomas Blum, Maarten Golterman, Santiago Peris

The leading hadronic contribution to the muon anomalous magnetic moment is given by a weighted euclidean momentum integral of the hadronic vacuum polarization. This integral is dominated by momenta of order the muon mass. Since the finite volume in lattice QCD makes it difficult to compute the vacuum polarization at a large number of low momenta with high statistics, a parametrization of the vacuum polarization is required to extrapolate the data. A much used functional form is based on vector meson dominance, which introduces model dependence into the lattice computation of the magnetic moment. Here we introduce a model-independent extrapolation method, and present a few first tests of this new method.

6.15 Excited state systematics in extracting nucleon electromagnetic form factors

Thomas Rae (University of Mainz)
S. Capitani, M. Della Morte, G. von Hippel, B. Jaeger, B. Knippschild, H.B. Meyer, T. Rae, H. Wittig

We present updated results for the nucleon electromagnetic form factors for $\mathcal{O}(a)$ improved Wilson fermions in $N_f = 2$ QCD measured on the CLS ensembles. The use of the summed operator insertion method allows us to suppress the influence of excited states on three-point functions. A study of the excited state contamination on the q^2 dependence of the form factors may then be made through comparisons of the summation method to standard plateau fits, as well as to excited-state fits.

6.16 Electromagnetic Form-Factors of the $\Lambda(1405)$ in (2 + 1)-flavour Lattice QCD

Ben Menadue (CSSM, The University of Adelaide)
Benjamin J. Menadue, Waseem Kamleh, Derek B. Leinweber, M. Selim Mahbub, Benjamin J. Owen

The $\Lambda(1405)$ is unusual in that it lies surprisingly low in mass. At 1405.1MeV, it lies lower than the lowest-lying odd-parity state of the nucleon, even though it contains a valence strange quark. We build on our recent success in isolating this otherwise elusive state in lattice QCD using correlation matrix techniques coupled with source and sink smearing, and present first results from our world-first calculation of the electromagnetic form factors of this unusual state. We use the PACS-CS (2+1)-flavour full-QCD ensembles, available through the ILDG.

6.17 Neutron Electric Dipole Moment from Beyond the Standard Model

Tanmoy Bhattacharya (Los Alamos National Laboratory)
Tanmoy Bhattacharya, Vincenzo Cirigliano, Rajan Gupta, Anosh Joseph

I will discuss the phenomenology of neutron Electric Dipole Moment (nEDM) from the Standard Model and beyond, and identify the matrix elements most necessary to connect the current and forthcoming nEDM experiments with phenomenology. I will then describe issues with operator mixing and renormalization and the lattice simulations necessary to fix these and evaluate the matrix elements.

6.18 The Two-Photon Decay of the Neutral Pion from Lattice QCD

Xu Feng (KEK)
X. Feng, S. Aoki, H. Fukaya, S. Hashimoto, T. Kaneko, J. Noaki and E. Shintani

We present a reliable nonperturbative calculation of the $\pi^0 \to \gamma\gamma$ transition form factor and the pion radiative decay width using 2+1 flavors of lattice QCD. We use multiple momentum insertions, multiple volumes, multiple topological charge sectors and a broad range of quark masses to control the systematic effects. We examine the impact of the commonly ignored disconnected diagrams. We obtain $\Gamma_{\pi^0\gamma\gamma} = 7.93(29)(43)$ eV for the pion decay width, which is accurate to a few percent and consistent with the experimental measurement.

6.19 The scalar pion form factor with Wilson fermions

Vera Guelpers (Helmholtz-Institut Mainz)
V. Guelpers, G. von Hippel, H. Wittig

We calculate the scalar form factor of the Pion in $N_f = 2$ QCD with $O(a)$ improved Wilson fermions including both the connected and the disconnected contributions. The latter is estimated using stochastic sources and a generalized hopping parameter expansion to reduce the noise. To investigate the stability of the method we compare results from conventional plateau fits to those obtained using summed operator insertions.

6.20 Hyperon-Nucleon Interactions and the Composition of Dense Nuclear Matter

Martin Savage (University of Washington)
S. R. Beane, E. Chang, S. D. Cohen, W. Detmold, H.-W. Lin, T. C. Luu, K. Orginos, A. Parreno, M. J. Savage, A. Walker-Loud

Low-energy neutron-Sigma- interactions determine, in part, the role of the strange quark in dense matter, such as that found in astrophysical environments. The scattering phase shifts for this system are obtained from Lattice QCD calculations, performed at a pion mass of ∼389 MeV in two large lattice volumes and at one lattice spacing. and are extrapolated to the physical pion mass using effective field theory. The interactions determined from QCD are consistent with those extracted from hyperon-nucleon experimental data within uncertainties, and strengthen theoretical arguments that the strange quark is a crucial component of dense nuclear matter.

6.21 Magnetic properties of the neutron in a uniform background field

Thomas Primer (CSSM, University of Adelaide)
Thomas Primer, Waseem Kamleh, Derek Leinweber and Matthias Burkardt

We present calculations of the magnetic moment and magnetic polarisability of the neutron from the background field method. The calculations are performed on a $32^3 \times 64$ dynamical lattice with a quantised magnetic field. We consider different approaches for improving the quality of the fits used in the results. Also included are initial results for the magnetic moment of the negative parity neutron.

6.22 Disconnected contributions from GPU's

Alejandro Vaquero (The Cyprus Institute)
Constantia Alexandrou, Giannis Koutsou, Alexei Strelchenko and Alejandro Vaquero

We calculate the disconnected diagrams associated with the nucleon form factors and moments of generalized parton distributions using $N_f = 2+1+1$ twisted mass gauge configurations on GPUs. We employ the truncated solver method (TSM) for estimating the all-to-all propagators. Due to the fact that the TSM involves many low precision stochastic estimators, usage of GPUs is essential to perform efficiently the contractions and the inversions.

7 Nonzero temperature and density

7.1 Finite size scaling for 4-flavor QCD with finite chemical potential

Shinji Takeda (Kanazawa University)
X-Y. Jin, Y. Kuramashi, Y. Nakamura, S. Takeda and A. Ukawa

We present a finite size scaling study for 4-flavor QCD with nonzero quark chemical potential by the grand canonical approach. We adopt the phase reweighting method and the reweighting factor is computed exactly up to numerical precision. We employ the Wilson-clover fermion action and investigate the parameter region which was previously explored by the Kenctucky group using the canonical approach. We discuss the location and order of the transition by examining the volume dependence of higher moments of quark number density and other observables.

7.2 Two-flavor QCD at finite quark or isospin density

Leonardo Cosmai (INFN)
Paolo Cea, Leonardo Cosmai, Massimo D'Elia, Alessandro Papa, Francesco Sanfilippo

We exploit analytic continuation to prolongate to the region of real chemical potentials the (pseudo)critical lines of QCD with two degenerate staggered fermions at nonzero temperature and quark or isospin density obtained in the region of imaginary chemical potentials. We determine the curvatures at zero chemical potential and quantify the deviation between the case of finite quark and of finite isospin chemical potential. In both cases deviations from a quadratic dependence of the pseudocritical lines on the chemical potential are clearly seen. We try different extrapolations and, for the case of nonzero isospin chemical potential, confront them with the results of direct Monte Carlo simulations. We also find that, as for the finite quark density case, an imaginary isospin chemical potential can strengthen the transition till turning it into strong first order.

7.3 Equation of state from $N_f = 2$ twisted mass lattice QCD

Florian Burger (Humboldt University Berlin)
F. Burger, E.-M. Ilgenfritz, M. P. Lombardo, M. Müller-Preußker, O. Philipsen, C. Pinke, C. Urbach

We present an update of our ongoing investigation of the finite temperature QCD phase transition with two flavours of maximally twisted mass fermions focussing mostly on the determination of T_c and the evaluation of the thermodynamic equation of state for two values of the pion mass.

7.4 Equation of state in 2+1 flavor QCD

Peter Petreczky (BNL)
for HotQCD

I will present a new HotQCD calculation of the equation of state in (2+1)- flavor QCD using a combination of a tree-level improved gauge action and the highly improved staggered quark (HISQ) action. Calculations have been performed on lattices with temporal extent $N_t = 6$, 8, 10 and 12 and aspect ratio $N_s/N_t = 4$. I will discuss the dependence of the results on the lattice spacing and the scale-setting procedure.

7.5 Thermodynamics with overlap fermions and update on the charmed EOS

Stefan Krieg (Wuppertal University/Forschungszentrum Jülich)
S. Borsanyi, Y. Delgado, S. Durr, Z. Fodor, S.D. Katz, S. Krieg, T. Lippert, D. Nogradi, C. Ratti, C. Schroeder, K.K. Szabo

I will discuss an effort to cross-check thermodynamics results obtained with the staggered formulation with results from overlap fermions using the same quark masses and give an update on the charmed EOS.

7.6 Towards a QCD equation of state with 2+1+1 flavors using the HISQ action

Urs M. Heller (American Physical Society)
A. Bazavov, C. Bernard, C. DeTar, J. Foley, Steven Gottlieb, U.M. Heller, J.E. Hetrick, J. Laiho, L. Levkova, J. Osborn, R. Sugar, D. Toussaint, R.S. Van de Water, and R. Zhou (MILC collaboration)

We present first, preliminary results for the QCD equation of state with 2+1+1 flavors of highly improved staggered quarks (HISQ), that is, including the effects of a dynamical charm quark. This first study uses a line of constant physics (LCP) with the light quark mass at $m_l = m_s/5$ and physical strange and charm quark masses. With increasing temperature, the effects of the charm quark, as in earlier partially quenched studies, start to be visible at temperatures where the equation of state is becoming insensitive to the value of the light (up/down) quark mass.

7.7 Phase quenching in finite-density QCD: models, holography, and lattice

Masanori Hanada (KEK Theory Center)
Masanori Hanada, Yoshinori Matsuo, Naoki Yamamoto

The effect of the complex phase of the fermion determinant is a key question related to the sign problem in finite-density QCD. Recently it has been shown that ignoring the complex phase – the phase quenching – does not change the expectation values of a class of observables in a certain region of the phase diagram when a number of colors N_c is large. In this talk we show the same equivalence holds in effective models and holographic models. We show, in a unified manner, that the phase quenching gives exact results for a class of fermionic observables (e.g., chiral condensate) in the mean-field approximation and for gauge-invariant gluonic observables (e.g., Polyakov loop) up to one-meson-loop corrections beyond mean field. We also discuss implications for the lattice simulations and confirm good quantitative agreement between our prediction and existing lattice QCD results. Therefore the phase quenching provides rather accurate answer already at $N_c = 3$ with small $1/N_c$ corrections which can be taken into account by the phase reweighting.

7.8 QCD thermodynamics with two flavours of Wilson fermions on large lattices

Bastian B. Brandt (Institute for nuclear physics, University of Mainz)
Bastian B. Brandt, Anthony Francis, Harvey B. Meyer, Owe Philipsen, Hartmut Wittig

We explore the phase diagram of two-flavour QCD at vanishing chemical potential using dynamical $O(a)$-improved Wilson quarks. In the approach to the chiral limit we use lattices with a temporal extent of $N_t = 16$ and spatial extent $L = 32, 48$ and 64 to enable an analysis close to the continuum with small discretisation effects. Keeping κ fixed and varying β our scans currently cover pion masses ranging from 600 MeV down to $m_\pi = 300$ MeV at the transition points. In addition, we present first results from scans along lines of constant physics. We probe the transition using the Polyakov loop and the chiral condensate, as well as spectroscopic observables such as screening masses. Furthermore, we present first

results on temporal correlation functions in the confined and deconfined phases evaluated on lattices with pion masses going down to the physical value $m_\pi = 140$ MeV.

7.9 Thermodynamics in 2+1 flavor QCD with improved Wilson quarks by the fixed scale approach

Takashi Umeda (Hiroshima University)
T. Umeda for the WHOT-QCD Collaboration

We present our result on thermodynamics in 2+1 flavor QCD by the fixed scale approach. The calculation is performed with non-perturbatively improved Wilson quarks coupled with the RG improved glue. In the approach we study the QCD equation of state by the T-integration method, and the renormalized Polyakov loop. We also show the results in quenched QCD and discuss prospects of the approach to study QCD thermodynamics.

7.10 QCD thermodynamics with continuum extrapolated Wilson fermions

Daniel Nogradi (Eotvos University Budapest)
S. Borsanyi, S. Durr, Z. Fodor, C. Hoelbling, S.D. Katz, S. Krieg, D. Nogradi, B.C. Toth, N. Trombitas, K.K. Szabo

The temperature dependence of the renormalized chiral condensate, strange quark number susceptibility and the renormalized Polyakov loop is measured in the fixed scale approach using Wilson fermions. The strange quark mass is set to its physical value while the light quark masses correspond to a 545 MeV pion. The simulations are performed at 4 lattice spacings and are extrapolated to the continuum. Simulations with staggered fermions are also performed and are also extrapolated to the continuum. Nice agreement is found between the two continuum results.

7.11 Model approach to the sign problem on lattice QCD with theta vacuum

Takahiro Sasaki (Kyushu University)
Takahiro Sasaki, Yuji Sakai, Junichi Takahashi, Hiroaki Kouno, and Masanobu Yahiro

The existence of instanton solution in QCD requires the QCD Lagrangian to have the topological term proportional to $\epsilon_{\mu\nu\sigma\rho}F^a_{\mu\nu}F^a_{\sigma\rho}$. Theoretically the coefficient θ can take any arbitrary value but experiments indicate $\theta < 3 \times 10^{-10}$. The fundamental reason for this suppression is not clear. This long-standing puzzle is called the strong CP problem. Finite θ causes the sign problem to LQCD simulations. We then propose a way of circumventing this sign problem by using the Polyakov-loop extended Nambu-Jona-Lasinio (PNJL) model.

For this purpose, we investigate theta-vacuum effects on the QCD phase diagram for the realistic 2+1 flavor system, using the three-flavor PNJL model and the entanglement PNJL model as an extension of the PNJL model. The theta-vacuum effects make the chiral transition sharper. For large theta-vacuum angle the chiral transition becomes first order even if the quark number chemical potential is zero, when the entanglement coupling between the chiral condensate and the Polyakov loop is taken into account.

The theta vacuum term can be eliminated by the $\mathrm{SU_A}(N_\mathrm{f}) \times \mathrm{U_A}(1)$ transformation, but the quark mass term is changed in the parity-even and -odd terms. The parity-odd term that induces the sign problem yields only small effects on the QCD phase diagram. Using this property, we propose a new version of the reweighting method. This talk is based on the paper: T. Sasaki, J. Takahashi, Y. Sakai, H. Kouno, and M. Yahiro, Phys. Rev. D**85**, 056009 (2012).

7.12 θ-dependence of the deconfinement temperature in Yang-Mills theories.

Francesco Negro (Universit degli studi di Genova - INFN sezione di Genova)
Massimo D'Elia e Francesco Negro

We determine the θ dependence of the deconfinement temperature in SU(3) pure gauge theory, showing that it decreases in presence of a topological theta term. Results are obtained by lattice simulations at imaginary theta, to go around the sign problem, then exploiting analytic continuation to determine the dependence of T_c up to the quadratic term in theta. We also present an estimate of such dependence in the limit of a large number of colors N, showing that the quadratic term in theta vanishes as $1/N^2$, and compare this estimate with our numerical results.

7.13 Is there a gap in the QCD Dirac spectrum above T_c?

Tamas G. Kovacs (Institute for Nuclear Research, Debrecen)
Tamas G. Kovacs and Ferenc Pittler

Previously we found that above T_c there is a transition in the QCD Dirac spectrum from the lowest modes that are localized to delocalized modes higher up in the spectrum. In the present work we use $N_f = 2+1$ flavor simulations with physical quark masses to study how the transition point in the spectrum (λ_c) depends on the temperature and how it scales in the continuum limit. We find that in the continuum limit all eigenmodes below a finite physical scale in the spectrum are localized on the length scale of the inverse temperature. Due to their localized nature eigenmodes below λ_c cannot contribute to long distance spatial correlators. For long distance quark propagation the system effectively has a spectral gap λ_c. We show that in the temperature range $1.5T_c < T \leq 5T_c$ the gap depends linearly on the temperature and extrapolates to zero at T_c. This could provide an explanation for the temperature dependence of hadron screening masses above T_c

7.14 QCD Phase Diagram with Two-Flavor Fermion Discretizations

Taro Kimura (RIKEN)
Taro Kimura, Tatsuhiro Misumi, Akira Ohnishi

We propose a new framework for investigating the two-flavor QCD phase structure with finite temperature and chemical potential. We show that Karsten-Wilczeck minimally-doubled fermion is useful for study on the QCD phase diagram since it possesses spatial cubic symmetry, CT and P symmetries, which are symmetries possessed by hypercubic-symmetric lattice fermions (e.g. staggered fermions) with complex chemical potential. To show usefulness of this formulation for the purpose, we study strong-coupling lattice QCD with introducing temperature and complex chemical potential. We derive the effective potential of the chiral condensate and elucidate the critical line of the chiral phase transition, which is qualitatively consistent with that of staggered fermions. We also find that the effective imaginary chemical potential can be controlled by varying parameters in the minimally doubled fermion.

7.15 G_2-QCD - The phase diagram of a QCD-like theory without sign problem

Axel Maas (Friedrich-Schiller-University Jena)
Julia Danzer, Christof Gattringer, Ernst-Michael Ilgenfritz, Lorenz von Smekal, Bjoern Wellegehausen, Andreas Wipf

The sign problem is the bane of lattice calculations of the QCD phase diagram. Therefore, alternatives are desirable which have no sign problem, but share as many features with QCD as possible. One suitable candidate is obtained by replacing the gauge group SU(3) with G_2, G_2-QCD. It will be shown that this theory h as many similarities with QCD, like fermionic baryons, a coincident chiral and deconfinement

transition in the quenched case, and topologically similar properties. The phase diagram will thus contain effects of fermionic hadrons, which supposedly dominate the physics of neutron stars. The first calculation of the full phase diagram in the temperature-baryo-chemical-potential plane will be presented. Detailed features of this phase diagram will then be discussed in a second talk.

7.16 The phase diagram of G_2-QCD

Björn Wellegehausen (Friedrich-Schiller-University Jena)
Axel Maas, Lorenz von Smekal, Björn Wellegehausen, Andreas Wipf

QCD based on the exceptional gauge group G_2 does not suffer from a fermion sign problem and therefore its phase diagram can be investigated at low temperatures and high baryon densities employing standard Monte-Carlo techniques. It turns out that G_2-QCD shares many features with QCD, e.g. fermionic baryons and the silver blaze property. First simulations results of the full phase diagram are presented and different features, e.g. the silver blaze property, are discussed in detail.

7.17 Charmonium Spectral Functions and Potentials

Chris Allton (Swansea University)
Wynne Evans, Chris Allton, Jon-Ivar Skullerud

The charmonium states at non-zero temperature are studied on anisotropic lattices with 2 dynamical quark flavours. Non-local (point-split) operators are used to determine the Bethe-Salpeter (BS) wavefunction via both conventional fitting methods and the Maximum Entropy Method. The inter-quark potential is determined from the solution of the Schrodinger equation, given the BS wavefunction as input.

7.18 Finite density phase transition of 3 flavor QCD

Yoshifumi Nakanura (RIKEN AICS)
X-Y. Jin, Y. Kuramashi, Y. Nakamura, S. Takeda and A. Ukawa

We present the results on QCD with three degenerate flavors at finite temperature and non-vanishing baryon number density. Calculations are carried out with phase quenched full QCD gauge configurations generated with the nonperturbatively $O(a)$-improved Wilson quark action and the Iwasaki gauge action at $\beta = 1.77$ on $10^3 \times 6$, $8^3 \times 6$ and $6^3 \times 6$ lattices. We discuss the finite density phase transition by using higher moments of quark number density reweighted by the exact phase.

7.19 QCD phase transition and the distribution of low-lying eigenvalues with 2+1 flavors of DWF

Zhongjie Lin (Columbia University)
Zhongjie Lin

Progress is reported from seven finite temperature ensembles in the temperature range $T = 139 - 195$ MeV with $2 + 1$ flavors of domain wall fermions and the DSDR gauge action, which all lie on a line of constant physics with a pion mass of 200 MeV and a lattice volume of $32^3 \times 8$. We compare preliminary results for the chiral susceptibility and other observables with a previous study at smaller volume and discuss the effects of finite volume. Low-lying eigenvalues of the Dirac operator are computed and related to the breaking of the chiral and anomalous $U(1)_A$ symmetries in the region of the QCD phase transition.

7.20 Confinement in high-temperature lattice gauge theories

Michael Ogilvie (Washington University)
Michael Ogilvie

There has been substantial progress in understanding a class of SU(N) gauge theories that are confining at high temperatures. This class includes theories with center-symmetric Polyakov loop deformations or with periodic adjoint fermions. The crucial role of monopoles in lattice gauge theories of this type can be understood analytically. The basic mechanisms occur in the two-dimensional O(3) spin model, deformed by appropriate mass term to give an XY model. Vortices of the XY model are constituents of O(3) instantons just as SU(N) magnetic monopoles are constituents of KvBLL instantons. Similar methods applied to an SU(2) lattice gauge theory yield an effective U(1) description in which monopoles are responsible for confinement.

7.21 Two topics from lattice NRQCD at non-zero temperature: heavy quark mass dependence and S-wave bottomonium states moving in a thermal bath

Seyong Kim (Sejong University)
G. Aarts, C. Allton, S. Kim, M.P. Lombardo, M.B. Oktay, S.M Ryan,D.K. Sinclair, J.I. Skullerud

Using Non-Relativistic QCD (NRQCD) on anisotropic lattices generated with two dynamical quark flavors, we study heavy quark mass dependence of S-wave and P-wave bottomonium correlators for $0.42T_c \leq T \leq 2.09T_c$. By comparing S-wave and P-wave correlators at non-zero temperature from different heavy quarks masses, temperature effect in bottomonium is investigated.

Also, we study behaviors of S-wave bottomonium states moving in a thermal bath at the temperature above the deconfinement but still below the melting temperature. Maximum Entropy Method with NRQCD kernel is employed to study the spectral functions for each momentum dependent Upsilon and η_b correlators. For the momentum range studied, we find that the energy of moving states shows quadratic momentum-dependence and that the width of moving states does not change significantly as the momentum of bottomonium is increased.

7.22 Singular values of the Dirac operator at nonzero density

Tilo Wettig (University of Regensburg)
Takuya Kanazawa, Tilo Wettig, Naoki Yamamoto

At nonzero density the eigenvalues of the Dirac operator move into the complex plane, while its singular values remain real. In QCD-like theories, the singular-value spectrum carries information on the diquark condensate. We have constructed low-energy effective theories in different density regimes and derived a number of exact results for the Dirac singular values, including Banks-Casher-type relations for the diquark condensate, Smilga-Stern-type relations for the slope of the singular-value density, and Leutwyler-Smilga-type sum rules for the inverse singular values. We also present a rigorous index theorem for non-Hermitian Dirac operators.

7.23 Auxiliary field Monte-Carlo study of the QCD phase diagram at strong coupling

Akira Ohnishi (Yukawa Institute for Theoretical Physics, Kyoto University)
Akira Ohnishi, Terukazu Ichihara, Takashi Z. Nakano

We study the QCD phase diagram at strong coupling by using a newly developed method, auxiliary field Monte-Carlo (AFMC). In the strong coupling lattice QCD, we obtain the effective action at a given order

of $1/g^2$. In many of previous works, mean-field approximation has been applied to obtain the phase diagram. There are several exceptions which invoke the monomer-dimer-polymer (MDP) simulation and include fluctuation effects in the strong coupling limit [1], but it is not straightforward to extend of the MDP simulation to take account of finite coupling effects. In AFMC, we integrate out the auxiliary field exactly by using the Monte-Carlo technique. Since effective actions with finite coupling effects $(1/g^2, 1/g^2, 1/g^{2N_\tau})$ have been obtained and their bosonized versions have been known to work well under the mean field approximation [2], it would be straightforward to include fluctuation effects in those auxiliary field effective actions. While we have the sign problem in AFMC, we find that there is a cancellation mechanism of the phase for low momentum auxiliary field and the average sign factor is around $\cos\theta \sim 0.9$ for a small lattice (4^4). In the presentation, we discuss how we can obtain the effective action in the strong coupling lattice QCD, and present some of our recent results on the QCD phase diagram.

Refs. [1] F. Karsch, K.-H. Mutter, Nucl. Phys. B313(1989)541; P. de Forcrand, M. Fromm, Phys. Rev. Lett. 104 (2010) 112005. [2] T. Z. Nakano, K. Miura, A. Ohnishi, Phys.Rev. D83 (2011) 016014; K. Miura, T.Z. Nakano, A. Ohnishi, N. Kawamoto, Phys.Rev. D80 (2009) 074034.

7.24 Probability distribution functions in the finite density lattice QCD

Shinji Ejiri (Niigata University)
S. Ejiri, S. Aoki, T. Hatsuda, K. Kanaya, Y. Nakagawa, H. Ohno, H. Saito, T. Umeda (WHOT-QCD Collaboration)

We study the phase structure of QCD at high temperature and density by lattice QCD simulations adopting a histogram method. Because the quark determinant is complex at finite density, the Monte-Carlo method cannot be applied directly. We use the reweighting method measuring the probability distribution function (histogram), and try to solve the problems which arise in the reweighting method, i.e. the sign problem and the overlap problem. As a first step, we investigate the chemical potential dependence of the probability distribution function in terms of the plaquette and Polyakov loop when all quark masses are sufficiently large, and study the properties of the distribution function. The critical surface which separates the first order transition and crossover regions in the heavy quark region is determined for the 2+1-flavor case. We moreover discuss the applicability of this approach in the light quark region.

7.25 Reweighting and Lee-Yang Zero

Xiao-Yong Jin (RIKEN Advanced Institute for Computational Science)
X-Y. Jin, Y. Kuramashi, Y. Nakamura, S. Takeda and A. Ukawa

We report on studies of reweighting on our phase quenched ensembles with 3 and 4 degenerate quark flavors at finite temperature and density. We have explored reweighting techniques in either the lattice gauge coupling or the chemical potential direction on some of our ensembles. In the context of reweighting, Lee-Yang zero of the partition function at imaginary lattice gauge coupling values has been studied. We introduce a different way of examining Lee-Yang zero with ensembles at finite density, and discuss its implications.

7.26 Phase structure of QC_2D at high temperature and density

Jon-Ivar Skullerud (NUI Maynooth)
Seamus Cotter, Pietro Giudice, Simon Hands, Seyong Kim, Jon-Ivar Skullerud

We investigate two-colour QCD (QC_2D) with two flavours of Wilson fermion as a function of quark chemical potential μ and temperature T. We find evidence of a superfluid phase at intermediate μ and low T where the quark number density and diquark condensate are both very well described by a

Fermi sphere of nearly-free quarks disrupted by a BCS condensate. We also find evidence that chiral symmetry is approximately restored in this region. At higher temperature this phase gives way to a normal quark-gluon plasma characterised by a vanishing diquark condensate and nonvanishing Polyakov loop L. The deconfinement temperature signalled by L is found to decrease only very slowly with increasing μ, but is lower than the BCS $\rightarrow$ normal transition temperature at large μ. However, the quark number susceptibility does not exhibit any rapid variation in the region where L increases from zero, suggesting that a full understanding of deconfinement at high density remains elusive.

7.27 Phase structure of finite density QCD with a histogram method

Yoshiyuki Nakagawa (Niigata University)
S. Aoki, S. Ejiri, T. Hatsuda, K. Kanaya, Y. Nakagawa, H. Ohno, H. Saito, T. Umeda (WHOT-QCD Collaboration)

We study the phase structure of QCD in the T-μ plane using a histogram method and the reweighting technique by performing phase quenched simulations of two-flavor QCD with RG-improved gluon action and a non-perturbatively $O(a)$ improved Wilson quark action. We calculate the probability distribution function of the plaquette and the phase-quenched determinant. The complex phase of the quark determinant is handled with the cumulant expansion, which makes the complex phase factor real and positive. In this talk, we discuss the order of the QCD phase transition through the T and μ dependence of the shapes of the probability distribution function and the phase factor.

7.28 An estimate of heavy quark momentum diffusion coefficient in gluon plasma

Saumen Datta (Tata Institute of Fundamental Research)
Debasish Banerjee, Saumen Datta, Rajiv V. Gavai and Pushan Majumdar

We calculate the momentum diffusion coefficient for heavy quarks in SU(3) gluon plasma at temperatures 1-2 times the deconfinement temperature. The momentum diffusion coefficient is extracted from a Monte Carlo calculation of the correlation function of color electric fields, in the leading order of expansion in heavy quark mass. Various systematics of the calculation will be examined, and compared with perturbtion theory and other estimates.

7.29 Low temperature limit of lattice QCD

Keitaro Nagata (RIISE, Hiroshima University)
Shinji Motoki, Keitaro Nagata, Atsushi Nakamura

We study the low temperature limit of lattice QCD by using a reduction formula for a fermion determinant. The reduction formula, which is obtained by performing the temporal part of the fermion matrix, has been often used in finite density lattice simulations.

In this talk, we first focus on a reduced matrix, where we discuss spectral properties and physical interpretation of the reduced matrix. Using the spectral properties, we obtain two kinds of the low temperature limit; one is for small chemical potential, and the other is for large chemical potential.

7.30 $U_A(1)$ breaking at finite temperature from the Dirac spectrum with the dynamical HISQ action

Hiroshi Ohno (Bielefeld University)
H. Ohno, U. M. Heller, F. Karsch and S. Mukherjee

We investigate $U_A(1)$ breaking above T_c in terms of the Dirac spectrum on configurations with (2+1)-flavors, using the HISQ action. The strange quark mass is at its physical value. We use several light quark masses corresponding to pion masses in the range of about 115 – 230 MeV on lattices of size $32^3\times 8$ and $48^3\times 8$. We calculate the 100 lowest-lying Dirac eigenvalues at temperatures below and above T_c. Even around $2T_c$, we find a volume independent tail of the spectrum approaching the origin, i.e., no clear evidence of a gap. This suggests that the $U_A(1)$ symmetry remains broken. Moreover we find a linear quark mass dependence of the spectral density at zero at temperatures just above T_c, which is expected if the chiral symmetry is restored while the $U_A(1)$ symmetry still remains broken in the chiral limit.

7.31 Baryon Number Correlation Signals in Heavy Ion Collisions

Apoorva Patel (Indian Institute of Science, Bangalore, India)
Apoorva Patel

The flux tube model offers a pictorial description of what happens during the deconfinement phase transition in QCD. The 3-point vertices of a flux tube network lead to formation of baryons upon hadronisation. Therefore, correlations in the baryon number distribution at the last scattering surface are related to the preceding pattern of the flux tube vertices, and provide a signature of the nearby deconfinement phase transition. The distribution of vertices has a simple topological feature, which suggests a two-point baryon number correlation signal that should be observable in heavy ion collisions at RHIC and LHC. Numerical simulations provide an estimate of the size of the signal.

7.32 Critical couplings and string tensions from two-lattice matching of RG decimations

Terry Tomboulis (Dept. of Physics and Astronomy, UCLA, Los Angeles, CA 90095, USA)
Xi Cheng and E. T. Tomboulis

We calculate critical couplings and string tensions in $SU(2)$ and $SU(3)$ lattice gauge theory by a simple technique of two-lattice matching of RG block transformations. The transformations are of the potential moving type generating plaquette actions with large number of group characters - we typically retain fifty in our computations - and exhibit rapid approach to a unique renormalized trajectory. Fixing the critical coupling $\beta_c(N_\tau)$ at one value of temporal lattice extent N_τ by MC simulation, the critical couplings for any other value of N_τ are then obtained by lattice matching of the decimations. We obtain $\beta_c(N_\tau)$ values for the range $N_\tau = 3 - 32$ and find agreement with MC simulation results to within a few percent in all cases. A similar procedure allows the calculation of string tensions $\hat{\sigma}(\beta)$ for a range of β values with similarly excellent agreement with MC data. Both for $SU(3)$ and $SU(2)$ then the technique seems to provide a cheap method for rapid and rather accurate determination of critical couplings and string tensions with no intrinsic lattice size limitations.

7.33 Monte Carlo simulation of abelian Gauge-Higgs lattice models using dual representations

Alexander Schmidt (University of Graz)
Christof Gattringer, Alexander Schmidt

We explore representations of abelian Gauge-Higgs lattice field theories in terms of dual variables, i.e., fluxes and surfaces and their use in Monte Carlo simulations. In particular we study the U(1) Gauge-Higgs model and the Z(3) Gauge-Higgs Model with chemical potential. The latter has a complex phase problem and we show that this can be overcome by using the dual variables as new degrees of freedom. We discuss suitable algorithms for a Monte Carlo simulation and assess advantages and disadvantages of a dual approach.

7.34 A simple model with the Z_N symmetry

Masanobu Yahiro (Kyushu University)
H. Kouno, Y. Sakai, T. Makiyama, K. Tokunaga, T. Sasaki and M. Yahiro

We propose a simple model with the Z_N symmetry. The flavor-dependent twisted boundary condition (TBC) is imposed on N degenerate flavor quarks in the SU(N) gauge theory. The model is useful to understand the mechanism of color confinement.

Dynamics of the model is studied by imposing the TBC on the Polyakov-loop extended Nambu-Jona-Lasinio (PNJL) model. The TBC model is applied to systems with finite temperature T and chemical potential μ. When T is finite and $\mu = 0$, the Z_N symmetry is preserved below some temperature T_c, but spontaneously broken above T_c. The color confinement below T_c preserves the flavor symmetry. Particularly at low temperature, dynamics of the TBC model is similar to that of the PNJL model. This may indicate that the Z_N symmetry is a good approximate concept in QCD, even if the current quark mass is small.

We also investigate the interplay between the Z_N symmetry and the emergence of the quarkyonic phase. In the TBC model with the Z_N symmetry, the quarkyonic phase in which the Polyakov loop is zero but the quark-number density is finite exists at small T and large μ. In the PNJL model without the symmetry, the region at small T and large μ is dominated by the quarkyonic-like phase in which the Polyakov loop is non-zero but small.

This talk is based on two papers: arXiv:1202.5584 [hep-ph] and arXiv:1204.0228 [hep-ph].

7.35 Improved Maximum Entropy Method with Extended Search Space

Alexander Rothkopf (Institute for Theoretical Physics, University of Bern)
A. Rothkopf, T.Hatsuda, S.Sasaki

We report on an improvement to the implementation of the Maximum Entropy Method (MEM) by departing from the standard (Bryan's) singular (SVD) search space. Both mathematical arguments as well as numerical evidence show that the MEM spectrum, i.e. the global maximum ρ^{MEM} of the underlying functional $\mathcal{Q}(\rho, D, I)$ does not in general lie in the SVD subspace. Systematically extending the search basis will thus eventually recover the full search space and the correct extremum. Hence our method is consistent with the proof of existence and uniqueness for the extremum that applies to the complete search space. Scenarios where the extended search space offers an improvement over the standard implementation in practice are discussed.

8 Standard model parameters and renormalization

8.1 Perturbative subtraction of lattice artefacts in the computation of renormalization constants

8.2 HQET Flavor Currents Using Automated Lattice Perturbation Theory

Dirk Hesse (University of Parma)
Dirk Hesse, Rainer Sommer

We present a next-to-leading order lattice perturbation theory calculation involving correlators of the axial vector and vector currents. The quantities we consider are candidates for observables to be used in the matching process of heavy quark effective theory to QCD. We will demonstrate that they exhibit beneficial features for this task. Using the power of the pastor package for automated lattice perturbation theory calculations in the Schrdinger functional, the computations could be performed timely and with moderate numerical effort, proving that our software generator is ready to produce production code. The results we obtained will be helpful input for future non-perturbative studies.

8.3 Preliminary calculations for matching factor in B_K using automatized lattice perturbation

Kwangwoo Kim (Seoul National University)
Kwangwoo Kim, Weonjong Lee

We present preliminary results on automatized lattice perturbation calculation. In B_K parameter calculation, one of the dominant errors comes from matching factor, which was calculated recently in one-loop order. To further reduce error in matching factor, one needs to go more than one loop order, which is practically impossible to calculate by hand. Therefore, we are using automatized lattice perturbation to calculate matching factor in B_K parameter calculation. As a first step, we implement a program that generates Feynman rules automatically and performs integrals. To check this code, we perform quark mass renormalization with Wilson gauge action and unimproved staggered fermion action.

8.4 The SU(3) beta-function to 20 loops

Gerrit Schierholz (DESY)
For the QCDSF Collaboration

The beta-function of the SU(3) Yang-Mills theory is computed to 20 loops in numerical stochastic perturbation theory. That enables us to map out the renormalization group flow of the running coupling constant over a wide range of scales from the ultraviolet to the infrared. It is argued that the theory has two phases, like the supersymmetric Yang-Mills theory, one which is asymptotically free and another which is strongly coupled in the infrared. No sign of a conformal window is found. As a by-product the static potential is computed.

8.5 Non-perturbative evaluation of $c_{\rm SW}$ for smeared link clover fermion with Iwasaki gauge action

Yusuke Taniguchi (University of Tsukuba)

We evaluate the improvement factor $c_{\rm SW}$ non-pertubatively for the clover fermion with the stout smeared gauge link. We use the Iwasaki gauge action at $a^{-1} \sim 2.5$ GeV. We adopted several number of smearings

and observed that $c_{\rm SW}$ approaches to unity as increasing the number.

8.6 The QCD strong coupling from the lattice three gluon vertex using 2+1 flavor domain wall fermions

Renwick Hudspith (University of Edinburgh)
Renwick Hudspith, Peter Boyle We present the first measurement of the QCD strong coupling constant (α_s) using 2+1 Flavor Domain Wall Fermion (DWF) configurations generated by the RBC and UKQCD collaborations. Measurements of the non-perturbative momentum-space triple gluon vertex in the exceptional and non-exceptional schemes are discussed, along with their matching to perturbation theory.

8.7 Strong coupling constant with 2+1+1 flavours

Konstantin Petrov (LAL/IN2P3/Orsay)
ETMC Collaboration

I present our results on strong coupling constant extracted from ghost-gluon coupling with 4 non-degenerate flavours of dynamical quarks within twisted mass formulation

Holger Perlt (Institute for Theoretical Physics, Leipzig University)
M. Constantinou, M. Costa, M. Göckeler, R. Horsley, H. Panagopoulos, H. Perlt, P.E.L. Rakow, G. Schierholz, A. Schiller

In order to compare lattice results with continuum observables we need to know the corresponding renormalization constants as accurately as possible. One widely used method for their computation is the non-perturbative RI-MOM scheme. In order to eliminate the scheme and scale dependence we transform the Z^{RI-MOM} factors into the so-called renormalization group invariant (RGI) scheme. Ideally, the Z^{RGI} depend on the lattice constant a only, but not on the renormalization scale M. However, they suffer from discretization errors proportional to $(aM)^n$ which make their computation difficult. We propose a method how to use one-loop perturbation theory up to order $(aM)^2$ to subtract a part of those lattice artefacts. Parametrizing the remaining artefacts by suitable (hypercubic) structures we are able to determine Z^{RGI} with good precision. We demonstrate our procedure for local and one-link operators.

8.8 Three loops renormalization constants in Numerical Stochastic Perturbation Theory

Masayasu Hasegawa (University of Parma)
Masayasu Hasegawa , Michele Brambilla, Francesco Di Renzo

We present three loops renormalization constants for Wilson fermion bilinears (vector, scalar, axial, pseudoscalar currents). Two gluonic regularizations are considered: tree level Symanzik improved action (with $n_f = 2$) and Iwasaki action (with $n_f = 4$). Both cases are amenable for comparisons with non-perturbative results. We discuss the issue of taming both finite lattice spacing and finite volume artifacts. As a byproduct, we discuss two loops matching of lattice and continuum couplings.

8.9 Non-perturbative Renormalization(NPR) for Improved Staggered Fermions

Jangho Kim (Seoul National University)
Jango Kim, Weonjong Lee, Stephen R. Sharpe

We calculate the renormalization factor using Non-perturbative renormalization(NPR) for improved staggered fermions on the MILC asqtad lattices. The perturbative renormalization is to calculate renormalization factors up to a given order. On the other hand non-perturbative renormalization is to calculate

renormalization factors up to the infinite order in g^2 directly on the lattice. We calucalte mass renormalization factor and wave function renormalization factor from self-energy diagrams. And we obtain the renomalization and mixing matrix of composite operators using RI-SMOM scheme.

8.10 NPR of Improved Staggered Bilinears

Andrew Lytle (University of Southampton)
Andrew Lytle, Stephen Sharpe

We present results for general improved staggered bilinears on both fine and coarse MILC lattices. Comparisons to perturbation theory take an especially simple form when studying ratios of Z-factors corresponding to the same spin but different tastes. These ratios provide a non-perturbative check on the degree to which the NPR "window" condition is satisfied.

8.11 Determination of Λ_{MS} from the gluon and ghost propagators in Landau gauge

Andre Sternbeck (University of Regensburg)
Andre Sternbeck, Kim Maltman, Michael Müller-Preußker, Lorenz von Smekal

We give an update on our lattice calculation of the QCD Lambda parameter using the minimal MOM scheme in Landau gauge. We discuss the treatment of involved systematic uncertainties and give estimates for $N_f = 0$ and 2 fermion flavors. First preliminary data for $N_f = 2 + 1$ will be shown, too.

9 Theoretical developments

9.1 Volume dependence in 2+1 Yang-Mills theory

Margarita Garcia Perez (Instituto de Fisica Teorica UAM/CSIC)
Margarita Garcia Perez, Antonio Gonzalez-Arroyo and Masanori Okawa

We present the results of an analysis of 2+1 pure Yang-Mills theory formulated on a 2-dimensional spatial torus with non-trivial magnetic flux. We have focused on investigating the dependence of the energy spectrum, extracted from Polyakov loop correlators, with the spatial size, the rank of the group N, and the magnetic flux m. The size of the torus acts a parameter that allows to control the onset of non-perturbative effects. In the small volume regime, where perturbation theory holds, we have derived the one-loop self-energy correction to the single-gluon spectrum, for arbitrary N and m. We will discuss the transition from small to large volumes which has been investigated by means of Monte-Carlo simulations.

9.2 Large-N string tension from rectangular Wilson loops

Robert Lohmayer (Rutgers University)
Robert Lohmayer, Herbert Neuberger

In pure SU(N) gauge theory in four dimensions, we determine the string tension at large N from smeared rectangular Wilson loops on the lattice. We learn how well loops of sizes barely on the strong coupling side of the large-N transition in their eigenvalue distribution can be described by effective string theory.

9.3 The string tension for large N gauge theory from smeared Wilson loops

Antonio Gonzalez-Arroyo (Instituto de Fisica Teorica UAM/CSIC)
Antonio Gonzalez-Arroyo and Masanori Okawa

We present our results of a high statistics study of smeared Wilson loops for SU(N) Yang-Mills theory. We study both the ordinary Lattice Gauge Theory with $N = 3$, 5, 6 and 8, and the twisted reduced model with $N = 841$. The results are consistent with a $1/N^2$ dependence and allow a determination of the large N string tension. Results for the string fluctuation parameters are also obtained.

9.4 Integrable field theories and their application to gauge theories

Peter Orland (Baruch College, CUNY)
Peter Orland

Lattice gauge theories may be viewed as systems of coupled integrable $SU(N) \times SU(N)$ principal chiral sigma models. It is possible to understand confinement some weak coupling regimes, using the exact S-matrices and/or exact form factors of the sigma model. New results for form factors have been obtained in the large-N (planar) limit.

9.5 Phase transitions in a gas of anyons

Manu Paranjape (Groupe de physique des particules, Université de Montréal)
F. Nebia-Rahal, R. B. MacKenzie, M. B. Paranjape

We present our numerical Monte Carlo simulation of a gas of closed loops on a 3 dimensional lattice, however now in the presence of a topological term added to the action corresponding to the total linking number between the loops. Adding the topological term converts the particles into anyons. Interpreting

the model as an effective theory that describes the 2+1-dimensional Abelian Higgs model in the asymptotic strong-coupling regime, the topological linking number simply corresponds to the addition to the action of the Chern-Simons term. We find that the Chern-Simons term has no effect on the Wilson loop. We find the unexpected result that both the Wilson loop and the t Hooft loop exhibit a perimeter law even though there are no massless particles in the theory, in both phases of the theory.

9.6 Fermion Bag Solutions to Sign Problems

Shailesh Chandrasekharan (Duke University)
Shailesh Chandrasekharan

The fermion bag approach solves many sign problems that have remained unsolved with conventional methods until now. We give specific examples from four-fermion field theories and Yukawa models. This theoretical progress should allow one to solve many interesting lattice field theories from first principles using the Monte Carlo method.

9.7 Fermion bag solutions to some sign problems in four-fermion field theories

Anyi Li (Institute for Nuclear Theory, University of Washington)
Shailesh Chandrasekharan, Anyi Li

Lattice four-fermion models containing N flavors of staggered fermions, that are invariant under Z_2 and $U(1)$ chiral symmetries, are known to suffer from sign problems when formulated using the auxiliary field approach. Although these problems have been ignored in previous studies, they can be severe. Here I will show that the sign problems disappear when the models are formulated in the fermion bag approach.

9.8 Monte Carlo simulations of a supersymmetric matrix model of dynamical compactification in non perturbative string theory

Konstantinos Anagnostopoulos (National Technical University of Athens)
Konstantinos Anagnostopoulos, Takehiro Azuma and Jun Nishimura

Certain supersymmetric matrix models have been proposed as nonperturbative approaches to string theory. The IIB matrix model has been postulated to be a nonperturbative definition of string theory and has the interesting feature that space time is generated dynamically from the eigenvalues of the bosonic degrees of freedom. The exciting possibility that the extra dimensions are dynamically compactified is studied in a supersymmetric 6 dimensional euclidean matrix model using Monte Carlo simulations. We present results that are consistent with previous calculations using the Gaussian Expansion Method which state that the SO(6) rotationally invariant spacetime is broken down to SO(3). Monte Carlo simulations are hindered by a severe complex action problem, and the factorization method is used successfully in order to overcome the strong sign fluctuations and the overlap problem.

9.9 A perturbative test of the chirally rotated SF

Stefan Sint (Trinity College Dublin)
Stefan Sint

I present some one-loop results for correlation functions in the chirally rotated Schrödinger functional. Besides providing perturbative estimates of action parameters, this study allows to address some questions regarding the continuum limit and how it is approached in this framework.

9.10 Non-trivial θ-Vacuum Effects in the 2-d O(3) Model

Michael Bögli (Institute for Theoretical Physics, University of Bern)
Michael Bögli, Ferenc Niedermayer, Michele Pepe, Uwe-Jens Wiese

Our study of θ-vacua in the 2-d lattice O(3) Model confirms for the first time the conjectured exact S-matrix at $\theta = \pi$. We use the standard action and an optimized constraint action with very small cut-off effects, combined with the geometric topological charge. The 2-d O(3) model shares many features with 4-d non-Abelian Yang-Mills theories: it is asymptotically free, has a non-perturbatively generated massgap, instantons, as well as non-trivial θ-vacua. We demonstrate with high accuracy, that θ is actually a relevant parameter and that each value $0 \leq \theta \leq \pi$ is associated with a different continuum theory. Remarkably, dislocation lattice artifacts do not spoil the non-trivial continuum limit at $\theta \neq 0$.

9.11 Fisher zeros and conformality in lattice models

Yannick Meurice (University of Iowa)
A. Bazavov, B. Berg, A. Denbleyker, Daping Du, Yuzhi Liu, Y. Meurice, D. Sinclair, J. Unmuth-Yockey, Haiyuan Zou

Fisher zeros are the zeros of the partition function in the $\beta = 2N_c/g^2$ complex plane. When they pinch the real axis, finite size scaling allows to distinguish between first and second order transition and to estimate exponents. On the other hand, a gap signals confinement and the method can be used to explore the boundary of the conformal window. We present recent numerical results for $O(N)$ sigma models, $U(1)$ and $SU(2)$ pure gauge and $SU(3)$ with $N_f \geq 4$ flavors. We discuss attempts to understand some of these results using analytical methods.

9.12 Monte Carlo study on the birth of our universe by a Lorentzian matrix model for superstring theory

Sang-Woo Kim (Osaka University)
Sang-Woo Kim, Jun Nishimura, Asato Tsuchiya

In this talk, I will explain how Monte Carlo method can be used to answer questions in cosmology such as why we are living in (3+1) spacetime dimension. To study real time evolution in cosmology, we introduce two IR cutoffs instead of the usual Wick rotation to regularize the 0-dimensional matrix model for superstring theory. Monte Carlo study reveals that 3d expanding space emerges from 9 spatial dimension after some critical time. I will also report our recent study on a simplified model which shares many important features like the emergence of 3d expanding space.

9.13 Leibniz rule, locality and supersymmetry on lattice

Hiroto So (Ehime University/ Dept. of Phys.)
M.Kato, M.Sakamoto and H.So

We clarify problems of Leibniz rule and locality on lattice. In addition to a single flavor case in an infinite system, we investigate multi-flavor cases and finite volume cases. The relation to its supersymmetrical application is discussed.

9.14 Exact Lattice Supersymmry at the Quantum Level for N=2 Wess-Zumino Models in Lower Dimensions

Noboru Kawamoto (Hokkaido University)
K. Asaka, A. D'Adda, N. Kawamoto and Y. Kondo

We summarize the current status of recently proposed exact lattice super symmetry formulation. We show that super symmetry is exactly kept at the quantum level by deriving exactly super symmetric Ward-Takahashi identities for $N = 2$ Wess-Zumino models in one and two dimensions.

9.15 Monte Carlo studies of 3d $\mathcal{N} = 6$ superconformal Chern-Simons gauge theory via localization method

Masazumi Honda (SOKENDAI & KEK)
Masanori Hanada, Masazumi Honda, Yoshinori Honma, Jun Nishimura, Shotaro Shiba, Yutaka Yoshida

We perform Monte Carlo studies of the 3d $\mathcal{N} = 6$ superconformal $U(N) \times U(N)$ Chern-Simons gauge theory, which is conjectured to be dual to M-theory or type IIA superstring theory on certain AdS backgrounds. Our approach is based on a localization method, which reduces the problem to Monte Carlo calculations in a simple matrix model. This enables us to circumvent the difficulties in the original theory such as the sign problem and the SUSY breaking on a lattice. The new approach opens up the possibility of probing the quantum aspects of M-theory and testing the AdS_4/CFT_3 duality at the quantum level. Here we calculate the free energy, and confirm the $N^{3/2}$ scaling in the M-theory limit predicted from the gravity side. We also find that our results nicely interpolate the analytical formulae proposed previously in the M-theory and type IIA regimes.

10 Vacuum structure and confinement

10.1 Chiral Polarization Scale at Finite Temperature

Andrei Alexandru (The George Washington University)
Andrei Alexandru and Ivan Horvath

We study the chiral polarization properties of low-lying Dirac eigenmodes at finite temperature. Results in quenched Wilson theory on both sides of deconfinement phase transition are presented.

10.2 Stringy excitation and role of IR/UV gluons in lattice QCD

Hiroshi Ueda (Kyoto University)
H.Ueda, T.Doi, S.Fujibayashi, S.Tsutsui, T.Iritani and H.Suganuma

Using SU(3) lattice QCD, we investigate ground-state (GS) and low-lying excited-state (ES) potentials of quark-antiquark systems in terms of the gluon momentum component in the Coulomb gauge. By introducing IR/UV cuts in the gluon-momentum space, we investigate the sensitivity of the GS and ES potentials, and the stringy excitation to the IR/UV gluons quantitatively.

10.3 Analytical derivation of gauge fields from link variables in SU(3) lattice QCD and its application in maximally Abelian gauge

Shinya Gongyo (Kyoto University)
Shinya Gongyo, Takumi Iritani, Hideo Suganuma

In SU(3) lattice QCD, we improve a method to extract gauge fields from link variables analytically. With this method, we study effective mass generation of off-diagonal gluons and infrared Abelian dominance in the maximally Abelian (MA) gauge in the SU(3) case. Using SU(3) lattice QCD, we investigate the propagator and the effective mass of the gluon field in the MA gauge with $U(1)_3 \times U(1)_8$ Landau gauge fixing. The off-diagonal gluon component behaves as a massive vector boson with the approximate effective mass $M_{off} = 1.2$GeV in the region of $r = 0.2 - 0.8$fm, and its propagation is limited within short range. In this way, infrared Abelian dominance is shown in terms of short-range propagation of off-diagonal gluons. Furthermore, we investigate the functional form of the off-diagonal gluon propagator. The functional form is well described by the Yukawa-type function e^{-mr}/r with $m = 1.6$GeV for $r = 0.2 - 0.8$fm. This also indicates that the spectral function has a negative region.

10.4 String tension from gauge invariant Magnetic Monopoles

Nigel Cundy (Seoul National University)
Nigel Cundy, Yongmin Cho, Weonjong Lee, Jaehoon Leem

Recent claims have been made that the confining string is caused primarily by Monopole condensation. We investigate these claims using an exact, gauge invariant, Abelian decomposition of the SU(N) gauge field originally formulated by Cho, and expanded by Faddeev and Niemi, Shabanov, and, recently, by Kondo and his collaborators. Using this decomposition, it is possible to extract both an Abelian field from the gauge field and a monopole contribution from the Abelian field. We study this decomposition on quenched lattice configurations. By comparing observables, including the string tension, calculated from the extracted monopole field with those from the original gauge field and with theoretical expectations, we study whether the phenomenon of monopole condensation contributes to confinement.

10.5 Glueball spectral densities from the lattice

Orlando Oliveira (University of Coimbra)
D. Dudal, O. Oliveira, P. J. Silva

The propagator of a physical degree of freedom ought to obey a Källén-Lehmann (KL) spectral representation, with positive spectral density. The latter quantity is directly related to a cross section based on the optical theorem. The spectral density is a crucial ingredient of a quantum field theory with elementary and bound states, with a direct experimental connection as the masses of the excitations reflect themselves into δ-singularities.

In usual lattice simulational approaches to the QCD spectrum the spectral density itself is not accessed. The (bound state) masses are extracted from the asymptotic exponential decay of the two-point function. Given the importance of the spectral density, each nonperturbative continuum approach to QCD should be able to adequately describe it or to take into proper account. In this work, we wish to present a first trial in extracting an estimate for the scalar glueball spectral density in SU(3) gluodynamics using lattice gauge theory.

10.6 Gluon propagators in the deep IR region and non-Abelian dual superconductivity for SU(3) Yang-Mills theory

Akihiro Shibata (Conputing Research Center, High Energy Accelerator Research Organization (KEK))
Akihiro Shibata, Kei-Ichi Kondo, Seiko Kato and Toru Shinohara

We have presented non-Abelian dual superconductivity picture in the SU(3) Yang-Mills(YM) theory, and evidences such as the restricted U(2)-field dominance and the non-Abelian magnetic monopole dominance in the string tension, and also non-Abelian dual Meissner effect in the last lattice conferences.

In this talk, we study the non-Abelian dual superconductivity picture for SU(3) YM theory through propagators on a large lattice. Applying the minimal option of our new formulation, we measure correlation functions of restricted U(2)-field, so called "Abelian" part, as well as the original YM field, and examine that whether the propagator in the momentum space is the Gribov-Stingl type or not.

10.7 The Landau gauge gluon propagator at zero and finite temperature: accounting for the combined finite lattice spacing and finite volume effects

Paulo Silva (University of Coimbra)
O. Oliveira, P. J. Silva

In the past years a good comprehension of the infrared gluon propagator has been achieved. Indeed, the lattice results are in good agreement with the so-called decoupling solution of the Dyson-Schwinger equations and the prediction of the non-perturbative quantization of the Yang-Mills theories. However, lattice simulations have been performed at physical volumes which are close to 20 fm but using a large lattice spacing. The interplay between volume effects and lattice spacing effects has not been investigated. In this talk, we aim to fill this gap and address how the two effects change the gluon propagator in the infrared region. Furthermore, we provide infinite volume extrapolations which take into account the finite volume and finite lattice spacing.

The results of the simulations at finite T near the confinement-deconfinement transition are not fully understood. We look at the electric and magnetic propagators and try to disentangle the finite size effects.

10.8 Dirac-mode expansion for confinement and chiral symmetry breaking

Hideo Suganuma (Kyoto University)
H.Suganuma, S.Gongyo and T.Iritani

With the Dirac-mode expansion, we analyze the correspondence between confinement and chiral symmetry breaking in SU(3) lattice QCD. Notably, the confinement force is almost unchanged even after removing the low-lying Dirac modes, which are responsible to chiral symmetry breaking. This indicates that one-to-one correspondence does not hold for between confinement and chiral symmetry breaking in QCD.

10.9 Dirac-mode expansion analysis for Polyakov loop

Takumi Iritani (Kyoto University)
Takumi Iritani, Shinya Gongyo, Hideo Suganuma

In order to investigate the correspondence between chiral symmetry breaking and confinement, we analyze the Dirac-mode dependence of the Polyakov loop at finite temperature using SU(3) lattice QCD. Using the Dirac-mode expansion method, we investigate low/high Dirac-mode contribution to the Polyakov loop, and discuss the role of the Dirac-mode in deconfinement transition.

11 Weak decays and matrix elements

11.1 B and D meson decay constants from 2+1 flavor QCD with improved staggered fermions

Ethan T. Neil (Fermilab)
E. T. Neil, C. Bernard, J. N. Simone for the Fermilab Lattice and MILC collaborations

We report on new results for the decay constants f_B, f_{B_s}, f_D, and f_{D_s} based on the MILC (2+1)-flavor asqtad ensembles. The clover action with the Fermilab method is used for the heavy quarks. This work extends a previous result with increased statistics and additional ensembles, with lattice spacings ranging from a = 0.045 fm to 0.12 fm and light sea quark masses down to 1/20 of the strange quark mass. Partially quenched, staggered chiral perturbation theory is used to extrapolate to the physical point.

11.2 Precise determinations for the decay constants of B and D mesons

Heechang Na (Argonne National Lab.)
Heechang Na, Chris Monahan, Christine Davies, Eduardo Follana, Ron Hogan, Peter Lepage, Junko Shigemitsu

Recently we study B, B_s, D and D_s meson decay constants using various treatments for the heavy quark. We get f_{B_s}/f_B using the NRQCD bottom quark. We then combine the ratio and a very precise determination result for f_{B_s} using heavy HISQ quark, and extract f_B with total 2% errors. We also calculate f_D, f_{D_s}, and f_{D_s}/f_D using HISQ charm quark. The results that we will show are the most updated results from the HPQCD collaboration.

11.3 Calculating B-meson decay constants using domain-wall light quarks and nonperturbatively tuned relativistic b-quarks

Oliver Witzel (Boston University, Center for Computational Science)

We calculate B-physics quantities using the RBC/UKQCD 2+1 flavor domain-wall-Iwasaki lattices and the relativistic heavy quark (RHQ) action developed by Christ, Li and Lin. After tuning these parameters nonperturbatively, we present our preliminary results for the calculation of the decay constants f_B and f_{B_s} analyzing data at two lattice spacings of $a \approx 0.11$ fm and $a \approx 0.08$ fm. Moreover we describe our future plans to compute e.g. B-meson mixing matrix elements using this framework.

11.4 B-physics from the ratio method with Wilson twisted mass fermions

Andrea Shindler (Humboldt University)
B. Blossier, N. Carrasco Vela, P. Dimopoulos, R. Frezzotti, V. Gimenez Gomez, G. Herdoiza, V. Lubicz, C. Michael, D. Palao, G.C. Rossi, F. Sanfilippo, S. Simula, C. Tarantino

Leptonic B decays and neutral B-mesons oscillations play an important role in CKM physics. I present a precise lattice QCD determination of the b quark mass, of the B and B_s decay constants and results for the B-meson bag parameter. Simulations are performed with $N_f = 2$ Wilson twisted mass fermions at three values of the lattice spacing and the results are extrapolated to the continuum limit.

Our calculation benefits from the use of improved interpolating operators for the B-mesons and employs the so-called ratio method. The latter allows a controlled interpolation at the b-quark mass between the relativistic data around the charm quark mass and the exactly known static limit.

The impact of these improvements in the final error budget is discussed together with the application of the ratio-method to the bag parameters.

11.5 Neutral meson oscillations in the Standard Model and Beyond from $N_f = 2$ tmQCD

Nuria Carrasco Vela (Universitat Valencia - IFIC)
B.Blossier, P.Dimopoulos, R.Frezzotti, V.Giménez, G.Herdoiza, V.Lubicz, D.Palao, G.Rossi, F.Sanfilippo, A. Shindler, S.Simula and C.Tarantino

The matrix elements of the relevant four-fermion operators are determined from unquenched lattice QCD simulations with $N_f = 2$ maximally twisted sea quarks and Osterwalder-Seiler valence quarks at three values of the lattice spacing and extrapolated to the continuum limit. With our mixed-action setup we achieve both O(a)-improvement and a continuum-like renormalization pattern for the four-fermion operators. The computation of the renormalization constants is performed non-perturbatively in the RI-MOM scheme.

In the case of $B^0_{d/s} - B^{\bar{0}}_{d/s}$ oscillations, in order to avoid large discretization errors, we compute ratios of the bag parameters with exactly known static limit and then interpolate them to the physical b-quark mass.

Phenomenological implications of our results will be discussed.The accuracy of our results for the kaon mixing allows us to improve previous Unitarity Triangle analysis and provide new model independent bounds on New Physics.

11.6 Chiral extrapolation of matrix elements of BSM kaon operators

Stephen R. Sharpe (University of Washington)
Jon Bailey, Hyung-Jin Kim, Weonjong Lee and Stephen R. Sharpe

Models of new physics induce $K - \overline{K}$ mixing operators having Dirac structures other than the "left-left" form of the Standard Model. We have calculate the functional form of the corresponding B-parameters in the partially quenched (PQ) theory at next-to-leading order in both SU(3) and SU(2) staggered chiral perturbation theory (SChPT). The SU(3) SChPT results turn out to be much simpler than that for the Standard Model B_K operators, due to the absence of chiral suppression for the new operators. The SU(2) SChPT result turns out to be closely related to that for B_K. Our results are also useful for fermions with chiral symmetry as they provide, in the continuum limit, the PQ generalization of existing continuum results. We also investigate the numerical size of the NLO corrections compared to those for B_K.

11.7 Data Analysis for BSM corrections to Kaon B-parameters

Hyung-Jin Kim (Brookhaven National Laboratory)
Jon A. Bailey, Hyung-Jin Kim, Weonjong Lee, Stephen R. Sharpe

Beyond Standard Model(BSM) gives new Dirac structures to the $K - \bar{K}$ mixing operators. Functional forms of corresponding B-parameters were calculated at the next-to-leading order in SU(3) and SU(2) staggered chiral perturbation theory(SChPT) in the previous research. In this time, we analyzed the BSM corrections to Kaon B-parameters with the SChPT. We will give the one-loop level data analysis results using the improved staggered fermion.

11.8 Neutral kaon mixing beyond the standard model from $n_f = 2+1$ Domain-Wall fermions

Nicolas Garron (University of Edinburgh)
RBC-UKQCD

We report on a computation of the hadronic matrix elements of the four-quark operators needed for the study of $K^0 - \bar{K}^0$ mixing beyond the Standard Model. We use $n_f = 2+1$ flavours of domain-wall fermions and a lattice spacing $a \sim 0.085$ fm. We consider partially quenched and unitary data, with lightest pion mass 290 MeV.

11.9 The $B \to \pi$ form factor from domain-wall light quarks and relativistic b-quarks

Taichi Kawanai (Brookhaven National Laboratory)
Taichi Kawanai, Oliver Witzel and Ruth S. Van de Water

We study the $B \to \pi\ell\nu$ semileptonic decay process using lattice QCD with domain-wall light quarks and relativistic b-quarks. The $B \to \pi\ell\nu$ form factor is needed to obtain the CKM matrix element $|V_{ub}|$ from experimental measurements of the branching fraction. We use the 2+1 flavor domain-wall Iwasaki gauge configurations generated by the RBC and UKQCD collaborations at two lattice spacings and several sea-quark masses, and compute the form factors $f_0(q^2)$ and $f_+(q^2)$ with several partially-quenched valence quark masses. For the bottom quark, we use the relativistic heavy-quark action developed by Christ, Li, and Lin and tune the parameters of the anistotropic clover action nonperturbatively. We present preliminary results for the $B \to \pi\ell\nu$ from factor at $a \approx 0.11$ fm.

11.10 $B \to \pi$ form factor with $Nf = 2$ $O(a)$ improved Wilson quarks

Fabio Bernardoni (DESY, Zeuthen)
Felix Bahr, Fabio Bernardoni, John Bulava, Alberto Ramos, Hubert Simma, Rainer Sommer

At present there is a tension at the level of 3σ between two exclusive determinations of $|V_{ub}|$. They are obtained combining the experimental branching ratios of $B \to \tau\nu$ and $B \to \pi l\nu$ (respectively) with a theoretical computation of the hadronic matrix elements f_B and the B to π form factor $f_+(q^2)$. To understand the tension, improved precision and a careful analysis of the systematics involved are necessary.

We present preliminary results of the ALPHA collaboration for the B to π form factor $f_+(q^2)$ with $N_f = 2$ $O(a)$ improved Wilson fermions. We employ HQET in the static limit, with pion masses ranging down to ~ 250 MeV, volumes such that $M_\pi L > 4$, three lattice spacings, and non-perturbative renormalization. We discuss the impact of the techniques adopted to reduce the statistical noise (stochastic all-to-all with full time dilution) and the contamination from excited states (smearing for the B and the pion). We estimate the size of the chiral and continuum extrapolations. We compare with the results from other collaborations and discuss the impact our result could have to solve the above mentioned discrepancy in the determination of $|V_{ub}|$.

11.11 Chiral behavior of kaon semileptonic form factors from lattice QCD with dynamical overlap quarks

Takashi Kaneko (KEK)
T.Kaneko, S.Aoki, G.Cossu, X.Feng, H.Fukaya, S.Hashimoto, J.Noaki, K.Takeda, T.Onogi (JLQCD collaboration)

We calculate the kaon semileptonic form factors in lattice QCD with three flavors of dynamical overlap

quarks. Gauge ensembles are generated at pion masses as low as 300 MeV and at a strange quark mass near its physical value. We precisely calculate relevant meson correlators using the all-to-all quark propagator. Twisted boundary conditions and the reweighting technique are employed to vary the momentum transfer and the strange quark mass. We discuss the chiral behavior of the form factors by comparing with chiral perturbation theory and experiments.

11.12 Determination of Vus from semi-leptonic K to pi decays

Karthee Sivalingam (University Of Edinburgh)
A. Jüttner , P.A. Boyle , J.M. Flynn , C.T. Sachrajda , K. Sivalingam and J.M. Zanotti

The $K \to \pi$ semi-leptonic form factor can be calculated using Lattice QCD. This value is then combined with results from experimental decay rates to estimate CKM matrix element $|V_{us}|$. New methods like twisted boundary conditions have improved the precision of this Lattice calculation by completely removing systematic errors due to interpolation. We present the latest results from the RBC/UKQCD collaboration for $N_f = 2 + 1$ domain wall fermions and lightest pion mass of about 180 MeV

11.13 Kaon semileptonic decay form factors with HISQ valence quarks

Elvira Gamiz (Universidad de Granada/CAFPE)
E. Gamiz, C. Bernard, C. DeTar, A.X. El-Khadra, A.S. Kronfeld, J. Laiho, P.B. Mackenzie, J.N. Simone, D. Toussaint, R. Van de Water

We report on the status of the Fermilab-MILC semileptonic form factor program using the HISQ action for the valence fermions. We present results for the form factor $f_+^{K\pi}(0)$ on a subset of the MILC collaboration's $N_f = 2 + 1$ asqtad ensembles. We discuss the chiral and continuum extrapolation, and give a preliminary error budget for this quantity. We also present a more preliminary set of results for the same form factor calculated on the MILC collaboration's ensembles with $N_f = 2 + 1 + 1$ HISQ sea quarks. These results include data at the physical light quark masses. The improvements that we expect to achieve with the use of the HISQ configurations and with the inclusion of ensembles at the physical light quark masses are discussed.

11.14 Probing novel TeV physics through precision calculations of scalar and tensor charges of the nucleon

Rajan Gupta (Los Alamos National Lab)
PNDME Collaboration

This talk will present results from the ongoing calculations of matrix elements of iso-vector quark bilinear operators between a neutron and proton state by the PNDME collaboration. These matrix elements are needed to connect precision measurements of decays of neutrons to possible scalar and tensor interactions at the TeV scale. Key results on existing bounds from other low and high energy experiments will also be summarized.

11.15 The effects of flavour symmetry breaking on hadron matrix elements I

Paul Rakow (University of Liverpool)
P. E. L. Rakow (for the QCDSF-UKQCD collaborations)

We have previously used SU(3) symmetry to analyse the effects of the strange - light quark mass difference on hadron masses. We extend our analysis to the case of hadron matrix elements concentrating here on the octet baryons.

As is well known, with unbroken SU(3) constraints are very strong - all matrix elements of a non-singlet operator are given by 2 parameters, F and D. Once the strange quark is given different mass from the up and down, matrix elements "fan out" from their symmetric values in a characteristic way. We use an SU(3) symmetry analysis to describe the pattern of symmetry breaking in the matrix elements.

11.16 The Effects of flavour symmetry breaking on hadron matrix elements II

Ashley Cooke (University of Edinburgh)
QCDSF-UKQCD Collaboration

We discuss the techniques involved in calculating octet baryon diagonal and transition matrix elements, including those relevant to semi-leptonic decays. We present results of hyperon semi-leptonic form factors from simulations of $2+1$ flavours of dynamical $O(a)$-improved Wilson (Clover) fermions. The effects of $SU(3)$ flavour symmetry breaking in these transitions are examined by varying the strange-light quark mass difference while keeping the singlet quark mass fixed. We use 5 individual choice of quark masses on $24^3 \times 48$ lattices with a lattice spacing of ~ 0.078fm.

11.17 $B \to V$ form factors at low recoil

Matthew Wingate (University of Cambridge)
R R Horgan, Z Liu, S Meinel, M Wingate

We present results for the form factors describing B meson decays to light vector mesons. These results are obtained using the NRQCD heavy quark action and the AsqTad staggered action on a subset of MILC lattices. The $B \to K^*$ and $B_s \to \phi$ form factors contribute to some observables in rare $b \to s$ decays. Together with the $B \to \rho$ and $B_s \to K^*$ form factors, we fit the form factors as functions of the quark masses and the kinematic variable $z(q^2)$, allowing for discretization errors.

11.18 Form factors for B and B_s semileptonic decays with NRQCD/HISQ quarks

C. M. Bouchard (The Ohio State University)
C. M. Bouchard, G. P. Lepage, C. J. Monahan, H. Na, and J. Shigemitsu

We discuss preliminaries of a calculation of the form factors for the semileptonic decays $B \to \pi l \nu$ and $B_s \to K l \nu$. We simulate with NRQCD heavy and HISQ light valence quarks on the MILC $2+1$ dynamical asqtad configurations. The form factors are calculated over a range of momentum transfer to allow determination of their shape and the extraction of $|V_{ub}|$. In addition, we are calculating ratios of these form factors to those for the unphysical decay $B_s \to \eta_s l \nu$. We are studying the possibility of combining these precisely determined ratios with future calculations of $B_s \to \eta_s l \nu$ using HISQ b-quarks to generate form factors with significantly reduced errors.

11.19 Semileptonic B to D decays at nonzero recoil with 2+1 flavors of improved staggered quarks

Si-Wei Qiu (University of Utah)
Si-Wei Qiu, C. DeTar, Daping Du, A.S. Kronfeld, J. Laiho, R. S. Van de Water (Fermilab Lattice and MILC Collaborations)

The Fermilab Lattice and MILC collaborations are completing a comprehensive program of heavy-light physics on MILC (2+1)-flavor asqtad ensembles with lattice spacings as small as 0.045 fm and light-to-strange-quark mass ratios as low as 1/20. We use the Fermilab interpretation of the clover action for

heavy valence quarks and the asqtad action for the light valence quarks. The central goal of the program is to provide ever more exacting tests of the unitarity of the CKM matrix. We present preliminary results for one part of the program, namely the analysis of the semileptonic decay $B \to D$ at both zero and nonzero recoil and a determination of the CKM matrix element $|V_{cb}|$.

11.20 Form factors for several semi-leptonic and radiative B decays

Steven Gottlieb (Indiana University)
Ran Zhou, Steven Gottlieb, Jon Bailey, Daping Du, Aida X. El-Khadra, Rajendra D. Jain, Andreas S. Kronfeld, Yuzhi Liu, Yannick Meurice, Ruth S. Van de Water

We report on form factors for the semi-leptonic $B \to K l^+ l^-$ and radiative $B \to K\gamma$ rare decay processes. We use three lattice spacings from $a = 0.12$ fm down to 0.06 fm and a variety of dynamical quark masses with 2+1 flavors of asqtad quarks provided by the MILC Collaboration. These ensembles allow good control of chiral and continuum extrapolations. The b-quark is treated as a clover quark with the Fermilab interpretation. We update prior results for $f_\parallel$ and $f_\perp$, or, equivalently, f_+ and f_0. In addition, we present new results for the tensor form factor f_T. Model independent results are obtained based upon the z-expansion. We also discuss the extension of these techniques to $B \to \pi l \nu$ and $B_s \to K l \nu$.

11.21 Looking Beyond the Standard Model with B Meson Form Factors

Andreas S. Kronfeld (Fermilab)
Daping Du, Jack Laiho, Andreas S. Kronfeld, Ruth S. Van de Water

We discuss two applications of lattice-QCD calculations of B meson semileptonic form factors to physics beyond the Standard Model. First, we compute a ratio of form factors for the $B \to D$ and $B_s \to D_s$ transitions that aids the normalization of measurements of $\mathrm{BR}(B_s \to \mu\mu)$ at hadron colliders. In many extensions of the Standard Model, this branching ratio is enhanced. Second, we use these form factors to compute the ratio of branching fractions $R(D) = \mathrm{BR}(B \to D\tau\nu)/\mathrm{BR}(B \to D\ell nu)$, where $\ell = \{\mu, e\}$. This quantity is also enhanced in many extensions of the Standard Model because of the large τ mass. Recently BaBar reported on the first observation of the decay process $B \to D\tau\nu$, finding an approximately 2σ excess in $R(D)$ above the estimate of the Standard-Model rate. Current Standard-Model predictions for $R(D)$, however, are based on based on estimates of the the form factors from HQET; we provide a more reliable estimate of this ratio using *ab initio* lattice QCD.

11.22 Continuum Light Hadronic Observables from 2+1 flavor DWF QCD

Robert Mawhinney (Columbia University)
Robert Mawhinney (For the RBC and UKQCD Collaborations)

The RBC and UKQCD Collaborations have decreased the errors on continuum light hadronic observables from 2+1 flavor DWF QCD through the inclusion of simulations with $m_\pi \sim 170$ and 250 MeV. These simulations were carried out using the Iwasaki plus Dislocation Suppressing Determinant Ratio (DSDR) gauge action and have been combined, in a global fit to the the data, with earlier results from DWF with the Iwasaki gauge action. Including these simulations with lighter pion masses has markedly reduced the chiral extrapolation errors. Results for quark masses, pion and kaon decay constants, and B_K will be presented.

11.23 Form factors for $\Lambda_b \to \Lambda$ transitions from lattice QCD

Stefan Meinel (College of William and Mary)
William Detmold, C.-J. David Lin, Stefan Meinel, Matthew Wingate

Compared to mesonic $b \to s$ decays, the rare baryonic decays $\Lambda_b \to \Lambda\gamma$ and $\Lambda_b \to \Lambda\ell^+\ell^-$ provide additional sensitivity to the helicity structure of the effective weak Hamiltonian. Here we present results from a lattice calculation of $\Lambda_b \to \Lambda$ transition form factors, using static heavy quarks and domain-wall light quarks.

11.24 Matrix elements for B-Bbar Mixing from 2+1 flavor lattice QCD

Elizabeth D. Freeland (Benedictine University)
E.D. Freeland, C.M. Bouchard, C. Bernard, A.X. El-Khadra, E. Gmiz, A.S. Kronfeld, J. Laiho, R.S. Van de Water

We present an update of the Fermilab-MILC collaboration's calculation of hadronic matrix elements for B-$\bar{B}$ mixing. We use the asqtad staggered action for light valence quarks in combination with the Fermilab interpretation of the Sheikoleslami-Wohlert action for heavy quarks. The calculations use MILC's 2+1 flavor asqtad ensembles. Ensembles include four lattice spacings from 0.125 – 0.045 fm and up/down to strange quark mass ratios as low as 0.05. Our calculation covers the complete set of five operators needed to describe B mixing in the Standard Model and Beyond. In addition to an update including a fuller set of analyzed data, we comment on the form of the staggered ChiPT extrapolation function.

11.25 Matching heavy-light currents with NRQCD and HISQ quarks

Chris Monahan (College of William and Mary)
Chris Monahan, Christine Davies, Ron Horgan, G. Peter Lepage, Heechang Na, Junko Shigemitsu (HPQCD Collaboration)

We present new matching calculations for heavy-light currents using NRQCD heavy quarks and both massless and massive HISQ light quarks as part of the HPQCD collaborations determination of the B and B_s decay constants. These results extend the HPQCD's earlier work with NRQCD bottom quarks by replacing AsqTad with HISQ valence quarks. We include details of the perturbative renormalisation of the heavy HISQ action. This work is the first step in a perturbative matching programme that will ultimately include NRQCD bottom with HISQ charm currents and NRQCD-HISQ four fermion operators.

11.26 Automated lattice perturbation theory and relativistic heavy quarks in the Columbia formulation

Christoph Lehner (RBRC)

I introduce a new computer algebra system (CAS) optimized for use in lattice perturbation theory (LPT) as well as continuum perturbation theory and a new framework to perform automated LPT calculations on top of said CAS. The new framework is then used to tune the relativistic heavy quark action in the Columbia formulation at one loop in meanfield-improved LPT. I give an outlook of future applications of the CAS/LPT framework.

11.27 Multiple-channel generalization of Lellouch-Lüscher formula

Maxwell T Hansen (University of Washington)
Maxwell T. Hansen and Stephen R. Sharpe

We generalize the Lellouch-Lüscher formula, relating weak matrix elements in finite and infinite volumes, to the case of multiple strongly-coupled decay channels into two scalar particles. This is a necessary first step on the way to a lattice QCD calculation of weak decay rates for processes such as $D \to \pi\pi$ and

$D \to KK$. We also present a field theoretic derivation of the generalization of Lüscher's finite volume quantization condition to multiple two-particle channels. Our results hold for arbitrary total momentum.

11.28 Neutron Oscillations on the Lattice

Michael I. Buchoff (Lawrence Livermore National Laboratory)
Michael I. Buchoff, Joseph Wasem

One intriguing low-energy process due to beyond-the-Standard-Model (BSM) physics is the neutron-antineutron transition, where baryon number changes by two units. In addition to providing a source of baryon number violation in the early universe, interactions of this kind are natural in grand-unified-theories (GUTs) with Majorana neutrinos that violate lepton number. For these reasons, bounds on these oscillations can greatly restrict a variety of GUTs, while a non-zero signal would be a smoking gun for new physics. However, to make a reliable prediction, the dimension-six nucleon-antinucleon matrix elements must first be calculated non-perturbatively via lattice QCD. In this talk, I will review the current understanding of this quantity, describe the lattice formalism, and present preliminary results from $32^3 \times 256$ clover-Wilson lattices at ~ 390 MeV pion masses.

11.29 Lattice Calculation of the $K_L K_S$ mass difference

Jianglei Yu (Columbia University)
Jianglei Yu

We report progress on calculating the K_L-K_S mass difference in lattice QCD. The calculation is performed on a 2+1 flavor, domain wall fermion, $16^3 \times 32$ ensemble with a 421 MeV pion mass. We include only current-current operators and drop all disconnected and double penguin diagrams in the calculation. The calculation is made finite through the GIM mechanism by introducing a valence charm quark. The long distance effects are discussed separately for each of the two parity channels. While we find a clear long distance contribution from the parity odd channel, the signal to noise ratio in the parity even channel is exponentially decreasing and the two-pion state can be seen in only a subclass of amplitudes. We obtain the mass difference ΔM_K in a range from $5.52(24) \times 10^{-12}$ to $9.93(65) \times 10^{12}$ MeV for kaon masses between 563 and 839 MeV.

11.30 Progress Towards $\Delta I = 1/2 K \to \pi\pi$ Decays with G-parity Boundary Conditions

Christopher Kelly (Columbia University)
Christopher Kelly, Norman Christ

We will discuss the RBC & UKQCD collaboration's efforts to calculate the $K \to \pi\pi$ decay amplitude with an Isospin-zero final state on the lattice using domain wall fermions. The discussion will be centered upon the use of G-parity boundary conditions for obtaining physical kinematics; we will present our progress towards their implementation and show some preliminary results.

11.31 Variance reduction techniques for a quantitative understanding of the $\Delta I = 1/2$ rule

Eric Endreß (Instituto de Física Teórica , Madrid University)
E. Endreß, C. Pena

The role of the charm quark in the dynamics underlying the $\Delta I = 1/2$ rule for kaon decays can be understood by studying the dependence of kaon decay amplitudes on the charm quark mass, using an effective $\Delta S = 1$ weak Hamiltonian in which the charm is kept as an active degree of freedom. Overlap

fermions are employed in order to avoid renormalization problems, as well as to allow access to the deep chiral regime. Quenched results in the GIM limit have shown that a significant part of the enhancement is purely due to low-energy QCD effects; variance reduction techniques based on low-mode averaging were instrumental in determining the relevant weak effective low-energy couplings in this case. Moving away from the GIM limit requires the computation of diagrams containing closed quark loops. We report on our progress to employ a combination of low-mode averaging and stochastic volume sources in order to control these contributions. Results showing a significant improvement in the statistical signal will be presented.

11.32 X(3872) , η_{c2} or χ'_{c1} ?

Yibo Yang (Institute of Theoretical Physics, Chinese Academy of Sciences)
Yi-Bo Yang , Ying Chen , Long-Cheng Gui

The very recent analysis of BABAR Collaboration indicates that the X(3872) may favor the quantum number $J^{PC} = 2^{-+}$ rather then the previously 1^{++}. We compute, for the first time using lattice QCD methods, radiative transition rates involving X(3872) candidate η_{c2} and find a small partial width $\eta_{c2} \to J/\psi\gamma \sim 4$ keV. Besides, research for candidate χ'_{c1} is in preceeding, we try to find a new method to pickup χ'_{c1} beyond smearing or variation.

12 Posters

12.1 Landau gauge fixing on GPU's

Paulo Silva (University of Coimbra)
N. Cardoso , P. Bicudo , P. J. Silva and O. Oliveira

We discuss how the steepest descent method with Fourier acceleration for Laudau gauge fixing in lattice SU(3) simulations can be implemented using CUDA. The scaling of the gauge fixing code was investigated using a GPU with a Tesla C2070 Fermi architecture, and compared with a parallel CPU gauge fixing code. Our code is available together with a code to generate configurations both for $T = 0$ and for finite temperature lattice configurations.

12.2 Local gauge symmetry on optical lattices?

Yuzhi Liu (University of Iowa)
Yuzhi Liu, Yannick Meurice and Shan-Wen Tsai

The versatile technology of cold atoms confined in optical lattices allows the creation of a vast number of lattice geometries and interactions, providing a promising platform for emulating various lattice models. This opens the possibility of letting nature take care of sign problems and real time evolution in carefully prepared situations. Up to now, experimentalists have succeeded to implement several types of Hubbard models considered by condensed matter theorists. In this poster, we discuss the possibility of extending this effort to lattice gauge theory. We report recent efforts to establish the strong coupling equivalence between the Fermi Hubbard model and SU(2) pure gauge theory in 2+1 dimensions by standard determinantal methods developed by Bob Sugar and collaborators. We discuss the possibility of using dipolar molecules and external fields to build models where the equivalence holds beyond the leading order in the strong coupling expansion.

12.3 The Influence of Instantons on the Quark Propagator

Daniel Trewartha (CSSM, University of Adelaide)
Waseem Kamleh, Derek Leinweber, Daniel Trewartha

The non-Abelian nature of quantum chromodynamics means the vacuum cannot be treated as devoid of structure. The presence of (anti-)instantons is one mechanism by which the vacuum can acquire a non-trivial topology, leading to chiral symmetry breaking and dynamical mass generation. We wish to discern the presence and import of instantons on the lattice, first by using the technique of smearing to create lattice configurations which consist solely of instanton-like objects, then calculating the quark propagator on such configurations. This will reveal the role of instantons in the dynamical generation of quark mass by the gluon field.

12.4 Geometrical representation of the 2D Antiferromagnetic Ising Model with topological term $\theta = \pi$

Gennaro Cortese (UAM/CSIC, DFT Universidad de Zaragoza)
V. Azcoiti, G. Cortese, E. Follana, M. Giordano

In this preliminary work, we propose a study of the 2D Antiferromagnetic Ising Model with an imaginary magnetic field $i\theta$. Using a new geometrical algorithm and with the choice of the topological term $\theta = \pi$, this model becomes free from the sign problem and allows us to perform numerical simulations.

12.5 Performance Improvement of lattice QCD calculation with SIMD programming

Hwancheol Jeong (Seoul National University)
Hwancheol Jeong, Weonjong Lee

In many numerical simulations of lattice QCD, solving the Dirac equation dominates the computing time. Regardless of the solving method, the procedure is composed of linear algebraic operations of gauge link matrices and vectors. The performance of such linear algebraic subroutines can be significantly improved by adapting the SIMD programming technology, such as SSE and AVX. They allow parallel calculations of arithmetic operations, so that one can sum or multiply multiple data simultaneously. In addition, they also offer controlling methods for registers and cache memories to store or prefetch the data. Using this method, we improved the performance of our CG(Conjugate Gradient) solver.

12.6 Multi-Particle Baryon Spectroscopy

Adrian Kiratidis (CSSM, University of Adelaide)
Waseem Kamleh, Adrian Kiratidis, Derek Leinweber

In Nature the excited states of the hadron spectrum appear as resonances. Consequently, there has been significant interest in studying the excited baryon spectrum using lattice QCD. With this in mind we perform spectroscopic calculations with five-quark interpolating fields. Stochastic estimation techniques are used in order to calculate the loop propagators, with dilution in spin, colour and time implemented as a means of variance reduction. We present effective mass plots extracted from these five-quark interpolators, and examine the contributions from fully-connected and loop-containing pieces of the correlation function.

12.7 Softly broken N=1 supersymmetric Yang-Mills theory on the lattice

G. Münster (University of Münster)
G. Bergner, I. Montvay, G. Münster, D. Sandbrink, U. D. Özugurel

$N = 1$ supersymmetric Yang-Mills theory describes interacting gauge fields and their superpartners, the spin 1/2 gluinos. A gluino mass term breaks supersymmetry softly. In the supersymmetric limit, the physical particles are expected to form supermultiplets. Past numerical simulations on the lattice were afflicted by significant systematic errors and did not show a clear picture of degenerate multiplets. We report about progress in the study of systematic effects and about the present status of the results.

12.8 Scaling properties of SU(2) gauge theory with mixed fundamental-adjoint action.

Enrico Rinaldi (University of Edinburgh)
Giuseppe Lacagnina, Biagio Lucini, Agostino Patella, Antonio Rago, Enrico Rinaldi

We study the phase diagram of the SU(2) lattice gauge theory with fundamental-adjoint Wilson plaquette action. We confirm the presence of a first order bulk phase transition and we estimate the location of its end point in the bare parameter space. If this point is second order, the theory is one of the simplest realization of a gauge theory with a non-trivial second order fixed point at finite bare couplings. All the relevant gauge observables are monitored in the vicinity of the fixed point with very good control over finite-size effects. The scaling properties of the low-lying glueball spectrum are studied while approaching the end point in a controlled manner.

12.9 Investigation of the phase structure of a chirally-invariant Higgs-Yukawa model

Attila Nagy (Humbolt University, Berlin)
John Bulava, Phillip Gerhold, Karl Jansen, Bastian Knippschild, David Lin, Attila Nagy

We discuss investigations of a chirally-invariant Higgs-Yukawa model which employs the overlap formulation for a mass degenerate fermion doublet. We discuss both the finite temperature phase transition at moderate values of the Yukawa coupling (y) as well as the bulk phase transition at large values of y. While it remains second order, modification of the finite temperature transition may become non-perturbative, leading to implications for electroweak baryogenisis. We examine the transition temperature for several values of the mass of the fermion doublet. At large values of y, we investigate a bulk second order phase transition at several volumes. We report on results for the critical exponents of the transition which are required to determine the universality class.

12.10 Light Meson Transition Form Factors on the Lattice

Benjamin Owen (CSSM, University of Adelaide)
Benjamin Owen, Ahmed Bakry, Waseem Kamleh, Derek Leinweber, Peter Moran

We present a calculation of the light meson transition form factors over a wide range of quark masses in the context of quenched QCD. In our calculation, by varying choice of momentum insertion between the states, we are able to extract the transition form factor at multiple Q^2. The data is then fitted using a monopole form to extract the transition form factors at $Q^2 = 0$. This allows for direct comparison to quark model predictions.

12.11 Locality of the overlap-Dirac operator on topology-fixed gauge configurations

Yong-Gwi Cho (University of Tsukuba)
Yong-GWi Cho, Shoji Hashimoto

We investigate the locality property of the overlap-Dirac operator on gauge configurations generated with extra Wilson fermions. By such extra terms we expect that the structure of the Aoki phase would change drastically. In particular, we study the possibility of defining the overlap-Dirac operator in the strong coupling regime keeping its exponential locality.

12.12 Instanton contributions to the low-lying hadronic mass spectrum

Sam Thomas (CSSM, University of Adelaide)
Sam Thomas, Waseem Kamleh, Derek Leinweber

The applicability of instanton-based models to the real QCD vacuum is studied by analysis of the light-hadron mass spectrum. The masses of the light hadrons are calculated on a partially-quenched dynamical FLIC lattice at various stages of stout-link smearing. The smearing method preserves instanton-like objects, creating vacuum configurations similar to those used in instanton liquid models.

12.13 Charmonium mass splittings at the continuum physical point with Fermilab heavy quarks and 2+1 flavors of improved staggered sea quarks

Carleton DeTar (University of Utah)
J.A. Bailey, A. Bazavov, C. Bernard, C. Bouchard, C. DeTar, A. X. El-Khadra, J. Foley, E.D. Freeland,

E. Gamiz, Steven Gottlieb, M. Heller, J.E. Hetrick, J. Kim, A.S. Kronfeld, J. Laiho, L. Levkova, M. Lightman, P.B. Mackenzie, D. Mohler, E. Neil, M. Oktay, J.N. Simone, R. Sugar, D. Toussaint, R.S. Van de Water, and R. Zhou (Fermilab Lattice-MILC collaboration)

We present results from an ongoing study of mass splittings of the lowest lying states in the charmonium system. We use clover valence charm quarks in the Fermilab interpretation, an improved staggered (asqtad) action for sea quarks, and the one-loop, tadpole-improved gauge action for gluons. This study includes five lattice spacings, 0.15, 0.12, 0.09, 0.06, and 0.045 fm, with two sets of degenerate up and down quark masses for most spacings. We use an enlarged set of interpolation operators and a variational analysis that permits study of various low-lying excited states. The strange sea quark mass and charm valence quark mass are tuned to their physical values. This large set of gauge configurations allows us to extrapolate results to the continuum physical point and test the methodology.

12.14 Pion-pion interaction in the $I = 1$ channel

Bruno Charron (University of Tokyo)
Bruno Charron for HAL QCD Collaboration

To unravel the physics of the rho-resonance in QCD, we study the pion-pion interaction in the isospin $I = 1$ channel from full lattice QCD simulations. To extract the phase shifts in this channel, we adopt the HAL QCD method and compute the pion-pion interaction-kernel localized in space from the Nambu-Bethe-Salpeter wave function. This approach enables us to treat the rho-meson as a bound state for heavy quark masses and that as a resonance for light quark masses simultaneously. After presenting the basic formulation of this approach, we show some preliminary results simulated in the lattice frame with the two pion mass heavier than the rho-meson mass, so that the rho meson is the ground state. The structure of the interaction-kernel (or the potential in short) in presence of a tightly bound ground state is thoroughly examined.

12.15 Stochastic Laplacian-Heaviside(LapH) algorithm and its applications in Hadron Spectroscopy

Chik Him Wong (UC San Diego)
John Bulava, Brendan Fahy, Justin Foley, You-Cyuan Jhang, Keisuke Juge, David Lenkner, Colin Morningstar

Recently a novel algorithm of computing all-to-all quark propagators known as the Stochastic Laplacian-Heaviside(LapH) method has been developed. Due to its high efficiency and robustness, it acquires significant potential in accurately evaluating multi-hadronic states and hadron-hadron scattering. The technology and its latest applications will be presented.

12.16 Improved interpolating fields for hadrons at non-zero momentum

B. Jäger and T. Rae (University of Mainz)
M. Della Morte, B. Jäger, T. Rae, H. Wittig

We present initial results for two-point correlation functions of hadrons at non-zero momentum, calculated using non-spherical wavefunctions through a generalized Gaussian smearing. The results demonstrate a reduction in the noise-to-signal ratio, whilst, at the same time, preserving a good projection on the ground state.

12.17 The Wave Function of the Roper Resonance

Dale Roberts (CSSM, University of Adelaide)
Waseem Kamleh, Derek Leinweber, Dale Roberts

We apply the eigenvectors from a variational analysis to successfully extract the wave function of the Roper state, and the next P_{11} state of the nucleon, associated with the $N^*(1710)$. We find that both states exhibit a structure consistent with a constituent quark model, the Roper d-quark wave function containing a single node consistent with a $2S$ state, and the $N^*(1710)$ containing two, consistent with a $3S$ state. As a result, a detailed comparison with constituent quark model wave functions is carried out, obtained from a Coulomb + Ramp potential. These results validate the approach of accessing these states by constructing a variational basis composed of different levels of fermion source-sink smearing. Furthermore, significant finite volume effects are obvious fore these excited states, likely driving their masses artificially high.

12.18 Error reduction technique using covariant approximation and application to nucleon form factor

Eigo Shintani (RIKEN-BNL)
T. Izubuchi and E. Shintani (for RBC/UKQCD collaborations)

We report new error reduction techniques using covariant approximation analogy to lowmode averaging. In our poster we show some preliminary results of nucleon propagator and electromagnetic form factor of CP-even and odd components at several momenta with this technique. We also compare with lowmode averaging.

12.19 First and second moments of quark distribution in proton from $2+1$ flavor DWF

Mingyang Sun (University of Kentucky)
Mingyang Sun, Ming Gong, Keh-Fei Liu

We calculate $\langle x \rangle$ and $\langle x^2 \rangle$ of proton. We adopt overlap fermion action on 2 + 1 flavor domain-wall fermion configurations. Stochastic grid sources with finite momenta, as well as low mode substitution technique on nucleon two-point functions and low mode averaging technique on quark loops are used to improve the signals.

12.20 Finite volume corrections to LECs in Wilson and staggered χPT

Pucci Fabrizio (Bielefeld University)
Gernot Akemann, Pucci Fabrizio

We study the simultaneous effect of finite volume and finite lattice spacing corrections in the framework of chiral perturbation theory (χPT) in the epsilon regime, for both the Wilson and staggered formulations. In particular the finite volume corrections to the low energy constants (LECs) in the presence of order $O(a^2)$ corrections in Wilson and staggered χPT are computed to next-to-leading order (NLO) in the ϵ expansion. For Wilson with $N_f = 2$ flavours and staggered with generic N_f the partition function at NLO can be rewritten as the LO partition function with renormalised effective LECs. As applications we compute the scalar and pseudo-scalar two-point functions in Wilson χPT as well as the taste splittings in staggered χPT to that order.

12.21 Taste symmetry violation at finite temperature

Pucci Fabrizio (Bielefeld University)
Edwin Laermann, Pucci Fabrizio

Symmetries play a distinctive role at the high temperature phase transition in QCD. Therefore the spectrum of screening masses has been investigated with emphasis on taste breaking. Altough taste violation is an UV effect the relevant operators could be temperature dependent. We have studied the meson screening masses in the temperature range between 140 MeV to 550 MeV. The computation has been performed using dynamical $N_f = 2+1$ gauge field configurations generated with the p4 staggered action. For temperature below the transition an agreement with the prediction of staggered chiral perturbation theory has been found and no temperature effect can be observed on the taste violation. Above the transition the taste splitting still shows an $O(a^2)$ behavior but with a temperature dependent slope.

12.22 Study of the low temperature and high density states by using lattice QCD simulations

Shinji Motoki (KEK (High Energy Accelerator Research Organization))
Shinji Motoki, Keitaro Nagata, Atsushi Nakamura

We study the further of QCD at low temperature and finite density, using lattice QCD simulations with imaginary chemical potential approach. There are expectations of the existence of sign free regions at low temperatures. We will discuss the behavior of observable in this regions.

12.23 Resonant phase shifts from finite volume interactions

Chi-Pin Hsu (CSSM, University of Adelaide)
Chi-Pin Hsu, Jonathan Hall, Anthony Thomas, Ross Young

12.24 Lattice QCD at non-zero isospin chemical potential

William Detmold (College of William and Mary)
William Detmold, Kostas Orginos, Zhifeng Shi

We present a study of quantum chromodynamics (QCD) at non-zero isospin chemical potential through a canonical approach of analyzing systems of fixed isospin number density. We develop a range of new algorithms for performing the factorially large numbers of Wick contractions required in multi-meson systems. We make use of these methods to study systems of up to 72 π^+'s on three ensembles of gauge configurations with spatial extents, L= 2.0, 2.5 and 3.0 fm, at a pion mass of 390 MeV. The ground state energies of these systems are extracted and the volume dependence of these energies is utilized to determine the two- and three- body interactions amongst pions. We explore high isospin densities of up to $\rho_I \sim 9$ fm^{-3} and probe isospin chemical potentials, μ_I, in the range $m_\pi < \mu_I < 4.5\ m_\pi$, allowing us to investigate aspects of the QCD phase diagram at low temperature and for varying isospin chemical potential. From the behaviour of the energy density of the system as a function of the isospin chemical potential, we provide numerical evidence for the conjectured transition of the system to a Bose-Einstein condensed phase at $\mu_I > m_\pi$.

12.25 Current tension on the CP violation

Yong-Chull Jang (Seoul National University)
Yong-Chull Jang, Weonjong Lee

In the Standard Model, the CP violation can be predicted through CKM mechanism. The neutral kaon mixing is one of the most precise channels to test how the theoretical framework accurately fitted with the experiment data. To see the current status of standard model, the bag parameter B_K and the mixing parameter ϵ_K are obtained by direct substitution of the various lattice and experiment inputs. Some input parameters, e.g., V_{cb}, have a multiple choice which makes a tension among the various measurements. The effect of these tensions into the size of the indirect CP violation and the CKM unitarity has checked. The 3σ tension between the unitarity of the CKM matrix and the measurement of inclusive and exclusive V_{cb} is observed. The tension in mixing parameter ϵ_K between experimental value and the theoretical value also reveals. In this analysis, the error budget of the input parameters is estimated by the standard error propagation method.

12.26 BKT phase transitions in strongly coupled 3D Z(N) LGT at finite temperature

Gennaro Cortese (UAM/CSIC, DFT Universidad de Zaragoza)
O. Borisenko, V. Chelnokov, G. Cortese, R. Fiore, M. Gravina, A. Papa, I. Surzhikov

We perform both analytical and numerical analysis to investigate the phase diagram of the three dimensional Z(N) lattice gauge theories at finite temperature for $N > 4$. These models, in the strong coupling limit, are equivalent to a generalized version of vector Potts models in two dimension, with Polyakov loops playing the role of Z(N) spins. It is argued that the effective spin models have two phase transitions of infinite order (i.e. BKT). Using a cluster algorithm we confirm this conjecture, locate the position of the critical points and extract various critical indices.

12.27 Gluonic fields as unraveled with Polyakov loops and predicted by Bosonic strings

Ahmed Bakry (CSSM, University of Adelaide)
Ahmed S. Bakry, Derek B. Leinweber, Anthony G. Williams

12.28 Charm semileptonic decays and the CKM matrix elements $|V_{cs(d)}|$ from heavy clover charm quarks and 2+1 flavor asqtad staggered ensembles

Jon A. Bailey (Fermilab/Seoul National University)
Jon A. Bailey, A. Bazavov, D. Du, A. X. El-Khadra, Steven Gottlieb, R. D. Jain, A. S. Kronfeld, R. S. Van de Water, and R. Zhou for the Fermilab Lattice and MILC Collaborations

When combined with experimentally measured partial fractions for $D \to K\ell\nu$ and $D \to \pi\ell\nu$, lattice calculations of the form factors provide direct access to $|V_{cs}|$ and $|V_{cd}|$. Tests of second row and column unitarity are dominated by the uncertainty in $|V_{cs}|$, while assuming three generation unitarity leads to very precise values for $|V_{cs(d)}|$ that can be used to validate appropriately designed lattice calculations of the form factors for $B \to \pi\ell\nu$ and $B \to K\ell\bar{\ell}$. We are calculating the form factors using Fermilab heavy quarks and asqtad staggered light quarks on 2+1 flavor MILC asqtad staggered gauge ensembles. The analyses include ensembles with light quark masses from $0.4m_s$ to $0.05m_s$ and lattice spacings from ≈ 0.12 fm to ≈ 0.045 fm. We extrapolate results for the charm form factors to the physical light quark masses and the continuum limit using staggered heavy-light meson chiral perturbation theory and compare to experiment.

12.29 B-physics from HQET in two-flavour lattice QCD

Fabio Bernardoni (DESY)
Fabio Bernardoni, Benoit Blossier, John Bulava, Michele Della Morte, Patrick Fritzsch, Nicolas Garron,

Antoine Gérardin, Jochen Heitger, Georg M. von Hippel, Hubert Simma, Rainer Sommer

We update the results of the ALPHA Collaboration's lattice B-physics programme based on $N_{\mathrm{f}} = 2$ O(a) improved Wilson fermions and Heavy Quark Effective Theory (HQET), including all effects of order $1/m_{\mathrm{h}}$ and non-perturbative renormalization and matching to fix the parameters of the effective theory. Our simulations in large physical volume cover three lattice spacings ($a \sim 0.08, 0.07, 0.05$ fm) and pion masses ranging down to ~ 250 MeV in order to control continuum and chiral extrapolations. In particular, we present improved results for the b-quark mass and the decay constant f_{B} (entering the current $\sim 3\sigma$ tension between two exclusive determinations of $|V_{\mathrm{ub}}|$) as well as an analysis of $f_{\mathrm{B_s}}$ and the associated ratio $f_{\mathrm{B_s}}/f_{\mathrm{B}}$.

12.30 Recent progress in B_K calculation uisng staggered fermions

Weonjong Lee (Seoul National University)
Weonjong Lee, SWME Collaboration

Here, we review a recent progress in B_K determination using improved staggered fermions. We have accumulated significantly higher statistics in MILC superfine and fine ensembles, which leads to a better determination of B_K. We report the results of this new analysis.

12.31 Continuum results for the QCD EOS at order μ^2

Stefan Krieg (Wuppertal University/Forschungszentrum Jülich)
S. Borsanyi, G. Endrodi, Z. Fodor, S.D. Katz, S. Krieg, C. Ratti, K.K. Szabo

We present continuum results for the QCD EOS with finite chemical potential, computed with physical quark masses at order μ^2.

12.32 Analysis of the scalar mesons on the Lattice

Masayuki Wakayama (Nagoya University)
Chiho Nonaka, Masayuki Wakayama

We study the possibility that the scalar mesons exist as four-quark states. The energy shift of two pseudoscalar mesons as a function of spatial lattice size makes a distinction between the bound and the scattering states of four-quark states. We calculate the four-quark state in the quenched approximation, ignoring the two-quark annihilation diagram and the vacuum channels. We perform a calculation of pseudo scalar meson scattering amplitudes, using $N_f = 2$ Wilson fermions and plaquette/Iwasaki gauge actions with pion masses in the range of 368-738 MeV. We obtain the indication that the four-quark states in the non-exotic ($I = 2$) and the exotic ($I = 0$) channels are no bound states.