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Author(s):

R. Gupta and T. Bhattacharya, T-8
P. Tamayo, CIC-ACL
J. Grandy, Lawrence Livermore National Laboratory
G. Kilcup, Ohio State U.
S. Sharpe, U. of Washington, Seattle

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Nonperturbative Estimates of the Standard Model Parameters

Rajan Gupta*, T. Bhattacharya and P. Tamayo
Los Alamos National Laboratory

T. Grandy
Lawrence Livermore National Laboratory

G. Kilcup
Ohio State University

S. Sharpe
University of Washington, Seattle

Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The project objectives were (1) to develop highly optimized codes for the simulation of lattice Quantum Chromodynamics (QCD) on the Connection Machine CM-5, (2) to use these codes to carry out a comprehensive analysis of Standard Model phenomenology on large lattices using a large statistical sample, and (3) to combine the results of numerical simulations with experimental data to estimate the unknown parameters of the Standard Model. We were successful in achieving all these goals. Our highly optimized codes were used to debug both the hardware and software of the CM-5. We carried out a comprehensive study of the hadron spectrum, decay constants for mesons, semi-leptonic form factors, form-factors for the rare decay $B \rightarrow K^* \gamma$, $\pi\text{-}\pi$ scattering amplitude, and matrix elements of a variety of 4-fermion weak operators. From these observables we were able to predict the masses of light quarks, $m_u + m_d$ and m_s , matrix elements of the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix, and the CP violating parameters ϵ and ϵ' . Our new estimates light-quark masses are roughly half of commonly believed values, and we predict a much larger value for ϵ'/ϵ , which will be tested experimentally over the next few years.

1. Background and Research Objectives

The Standard Model is a highly successful theory describing the strong, weak and electromagnetic interactions. All present experimental data are consistent with this theory. Yet there are strong reasons to think that the SM is not the fundamental theory. There are too many arbitrary parameters, and certain questions are left completely unanswered. An

*Principal Investigator, E-mail: rg@lanl.gov

example of the former shortcoming is that the masses of the six types of quarks (up, down, strange, charm, bottom and top) are not predictions of the theory, but rather parameters extracted from experiment. One unanswered question is why, in the SM, particles appear to come in "families" (up+down+electron, strange+charm+muon, bottom+top+tau) that are repetitions of one another. To establish the SM it must be subjected to as many *quantitative* tests as possible. The goals are to determine precise values for the unknown parameters as well as look for deviations from the SM that will yield clues to the structure of a new theory.

A serious limitation to obtaining accurate values for these parameters is the large correction due to the strong interactions (described by quantum chromodynamics—QCD), so it is very difficult to deduce quantitative predictions of the full SM using analytical techniques. Thus an enormous body of experimental information cannot be used effectively. One example is the weak decay amplitudes of mesons containing bottom quarks. The rate of the decay $B \rightarrow \rho \nu$ will be measured in the next few years. This should allow one to extract a fundamental parameter of the SM, namely the Cabibbo-Kobayashi-Maskawa (CKM) matrix element V_{bu} .

Without the knowledge of the strong interaction corrections, encapsulated in the so called semi-leptonic form factors, however, this extraction is not possible.

Solving QCD will enhance our understanding of the fundamental forces of nature and allow us to test the Standard Model of particle interactions. In the last few years there has been a significant development in numerical methods such that a number of phenomenologically interesting questions can be answered with an accuracy far exceeding that obtainable from approximate analytical methods. We believe that over the next five years systematic errors can be made smaller than 5%. Furthermore, for some quantities analytic results can be used to roughly correct for these errors. The one area which is still in an exploratory stage, both in terms of algorithms and in terms of the computer power available, is including the effects of quark loops, i.e., the theory with dynamical fermions. The approximate theory that neglects the effect of quark loops (called quenched QCD) is simpler to simulate by a factor of 1000–10000. Since the effects of this approximation are expected to be at the level of 10% for a number of observables, and as the results described below show, it has been opportune to carry out a statistics study of these quantities using a large statistical sample.

To simulate Lattice QCD we use stochastic methods based on Monte Carlo integration that include Metropolis, overrelaxed and cluster update algorithms as well as Molecular Dynamics and Langevin evolution. The most computer intensive part of the QCD calculation is a matrix inversion necessary to calculate the quark propagator. We solve the

corresponding linear system using conjugate-gradient, overrelaxed, preconditioned, minimal residue methods.

2. Importance to LANL's Science and Technology Base and National R&D Needs

The problems in Standard Model phenomenology under investigation have a direct impact on a number of experiments being done at the Stanford Linear Accelerator Center (SLAC), Fermilab and Cornell. These centers are all part of DOE's mission to enhance our understanding of the basic properties of matter. Theoretical investigations of the properties of QCD at finite temperature and the possible transition to the quark-gluon plasma complement the heavy-ion experiments being done by members of the Physics Division at Los Alamos, and also provide an understanding of the properties of hot dense matter in neutron stars and the evolution of the early universe.

Simulations of quantum field theories face some of the most challenging problems in numerical analysis. Our research focuses on algorithm development for (1) fast matrix inversion, (2) efficient Monte Carlo and molecular dynamics algorithms to include dynamical fermions in simulations, (3) overcoming critical slowing down and (4) making optimal use of supercomputers. These same algorithms are used extensively by many groups at the Laboratory. Problems in QCD and statistical mechanics are also ideal test beds for new emerging architectures as they are extremely CPU intensive. This provides an ideal combination—the drive to solve challenging problems in basic sciences coupled with the Laboratory's mission to be the largest and most innovative computer center for the use and development of massively parallel supercomputers. Over these three years we have made significant contributions to helping debug the CM-5 at Los Alamos and to making it a stable production environment.

3. Scientific Approach and Accomplishments

We developed highly optimized codes for the simulation of lattice QCD and physics analysis on the CM-5. The computationally intensive parts of all our codes were optimized by developing low level assembly language routines in CDPEAC. Using these codes we have finished the generation and analysis of $170 \times 32^3 \times 64$ quenched lattices. These lattices represent the largest physical volume that has been simulated by anyone, and as a result we

have obtained very accurate results for a number of physical observables as described below.

Hadron Spectrum. Our analysis of the two-point correlation functions made up of quark propagators provide results with 1%–10% errors for a number of hadron masses. Using these and chiral perturbation theory we are able to make accurate estimates of the nucleon-to-rho mass ratio and the mass splittings within the baryon multiplets. Our results are also accurate enough to analyze some of the pathologies of quenching that are predicted to show up at small quark masses. A major consequence of our analysis is the prediction of the light and strange quark masses. Our results, $m_u + m_d = 5.4 \pm 1.0$ MeV and $m_s = 90 \pm 15$ MeV, are almost half of conventionally accepted values and have significant impact on the CP violating parameters ϵ'/ϵ .

Decay Constants. The second quantity that can be extracted from two-point correlation functions is decay constants of pseudoscalar and vector mesons. We have obtained results for f_π , f_K , f_D , and f_{D^*} with errors that are 5% or smaller. Our estimates of f_D and f_{D^*} provide input to phenomenology as reliable experimental numbers do not exist. Furthermore, in the future we are all set to extend this calculation to the very important case of f_B by combining our light quarks with heavy quarks generated using a lattice version of non-relativistic QCD.

Semi-leptonic form factors. We have paid special attention to the extraction of semi-leptonic form factors in current calculations. Knowing these quantities will allow us to extract elements of the Cabibbo-Kobayashi-Maskawa mixing matrix and address fundamental questions like the number of quark families and the origin of CP violation. Comparing our present results to known experimental data indicate that the two sources of systematic errors remaining in our calculations, $O(a)$ discretization errors and those due to quenching, may be small. With the present data we are able to match experimental data for the decays $D \rightarrow K \ell \nu$, $D \rightarrow K^* \ell \nu$, and $D \rightarrow K^* \gamma$, and make predictions for the decay $D_s \rightarrow \phi \ell \nu$, for which experimental data is still not reliable. With this expertise in hand we are now developing the machinery to calculate the form-factors for the decay $B \rightarrow \pi(\rho) \ell \nu$, from which the CKM element V_{bu} can be evaluated.

Kaon B parameters. Over the last year we have produced very precise results for QCD corrections to CP violating weak processes. A large part of the success was due to our understanding and quantification of the various sources of systematic errors in the B parameters B_K , B_7 and B_8 . Combining these results with our predictions of light quark masses changes the Standard Model estimate of ϵ'/ϵ from 3.6 times 10^{-4} to 14–20 times

10^{-4} . Current experiments give the values 7.5(5.9) times 10^{-4} (Fermilab) and 23 (7) times 10^{-4} (CERN). Future experiments will decrease the errors to 10^{-4} , thus testing the enhanced value we predict.

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