Understanding the structure and interactions of matter in QCD

Robert Edwards, for the USQCD Collaboration
Jefferson Lab: edwards@jlab.org

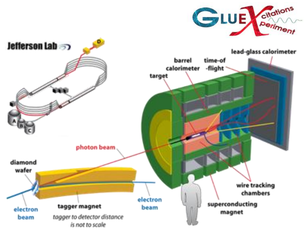
Jefferson Lab

Introduction

The structure and interactions of cold nuclear matter, and understanding the role played by Quantum Chromodynamics (QCD) is the subject of intense experimental and theoretical investigation.

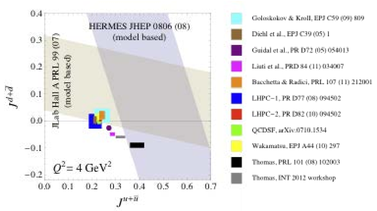
Can QCD Predict the Spectrum of Hadrons? What is the role of the Gluons?

Almost all the mass of the visible universe is composed of nucleons and nuclei. In turn, nucleons are composed of quarks and gluons. Thus, it is important to understand the role of quarks and gluons in mass generation. The self interaction of gluons predicts exotic particles such as hybrids and glue-balls. The flagship GlueX experiment at JLab @ 12 GeV will produce hybrid-mesons starting in 2015



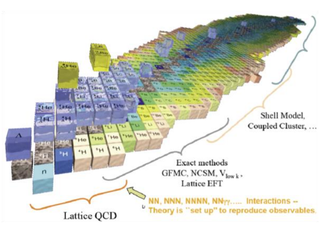
How Do Quarks and Gluons Make Nucleons? How are quarks, gluons, spin and charge distributed in the nucleon?

Understanding the distributions of quarks, gluons, spin, and charge is a major focus of the current and future JLab experimental program as well as RHIC-spin. Moments of Structure Functions and Generalized Parton Distribution functions can be directly calculated using Lattice QCD allowing for a direct link between theory and experiment.



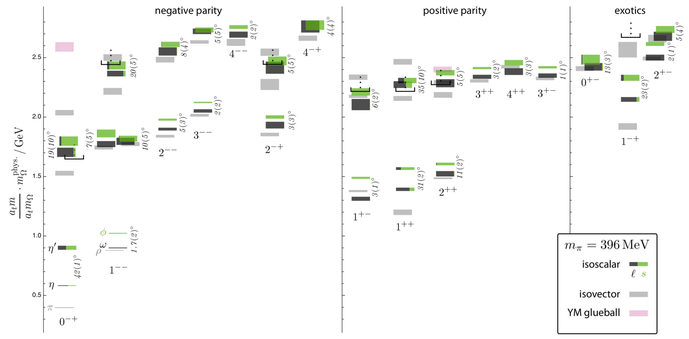
Can QCD explain nuclear interactions and the formation of light nuclei?

As the theory of the strong nuclear force, QCD must be able to predict properties of nuclei. By computing the properties of simple, light nuclei bridges can be made to more traditional effective theories and models, giving a unified picture of nuclear matter.

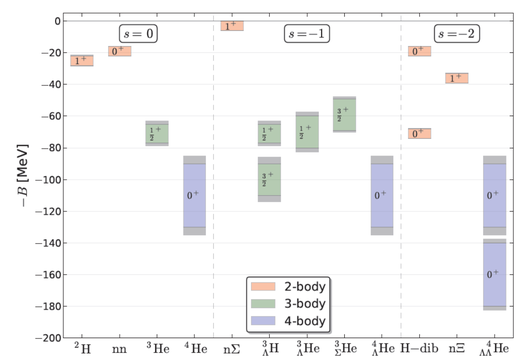


Lattice QCD calculations can give truly 'first principles' model independent answers to these questions and as such are both important in developing nuclear theory and to serve as guidance to experiment.

Recent Successes



A calculation of the spectrum of isoscalar and isovector mesons required a *new analysis algorithm (distillation)* to enable computations of the disconnected diagrams, The large number of solutions of the Dirac equation needed for the calculation was enabled by harnessing *Graphics Processing Units (GPUs)*. Data suggests exotic mesons are within the energy reach of the GlueX experiment. Figure from J. Dudek, et. al. Phys.Rev.D83:111502,2011



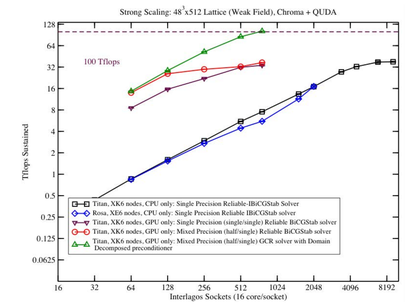
A recent calculation by the NPLQCD collaboration demonstrates that light nuclei and also hyper-nuclei properties can be determined directly from QCD. Shown are the binding energies in the SU(3) physical limit, for different atomic weight and strangeness content systems. These calculations allow for a determination of the 2, 3, and 4 body contributions. Figure from Beane et. al. arxiv:1205.5219

Software Challenges

The diversity of current HPC architectures (multi-core, many-core, and accelerated) poses a challenge for performance portability. Great advances have been made using highly optimized libraries (e.g. QUDA for GPUs), however this still leaves an Amdahl's law to overcome.

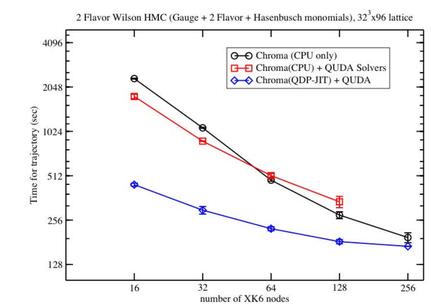
Heterogeneous Computing

GPU Computing for Capability and Capacity

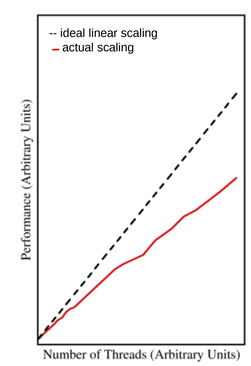


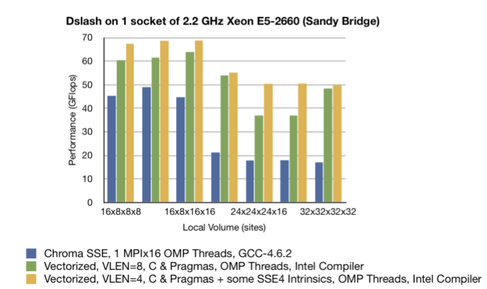
A solver with a domain-decomposed preconditioner (orignally in Babich, Clark, Joó, Shi, Brower, Gottlieb, SC11) allowed strong scaling up-to 768 GPU nodes of the Titan-Dev system. Left: Joó, Clark, Presented at ACCS'12 symposium, Washington D.C., March 2012.

Just-In-Time compilation of CUDA kernels from C++ expression templates allows QDP++ to move entirely to the GPU, significantly reducing Amdahl's law. This is necessary for gauge generation worloads where a significant fraction of time may be spent outside the library solver routines. Right: Winter, Joo, preliminary result from TitanDev



Intel Xeon and Xeon Phi





We have been working with Intel Parallel Labs and through the Intel MIC Software Development Program to tune the performance of QCD on Xeon CPUs with AVX (above) and to prepare for Intel Xeon Phi (MIC) (right).

Partnership with SUPER

Our partnership with the SUPER SciDAC Institute will focus on performance tuning and analysis on current generation hardware, with a planned development of a Domain Specific Language for QCD in later years as a solution to the problem of performance portability in preparation for the exascale.