The Search for Beyond-the-Standard-Model Physics at the Intensity Frontier

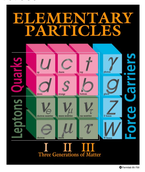
Heechang Na (ALCF, ANL) for the USQCD collaboration

Abstract

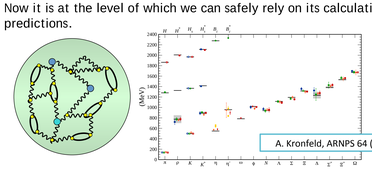
One of the most urgent tasks of particle physics experiments is the search for the suspected small effects of as yet undiscovered "beyond-the-standard-model" physics in Intensity Frontier experiments. High-precision numerical calculations are a crucial ingredient in separating known from new effects in the experiments. These calculations require the most highly optimized programs on the highest capability computers available. I will present the physics case, the role of lattice gauge theorists in designing and using the Blue Gene family of computers, and a recent installation of 48 racks of BG/Q (MIRA) at ALCF.

Introduction

- The Standard Model (SM)
  - Current theory of particle physics that explains almost everything.
  - The SM consists of a small set of particles and forces
    - 6 quarks (fermion, spin ½)
    - 6 leptons (fermion, spin ½)
    - 4 force carriers (boson, spin 1)
    - Electro-magnetic force
    - Strong force (QCD)
    - Weak force
  - The quarks bound together by the strong force, and form matter.
    - Many different combinations represent different types of matter (hadrons).



- Quantities of these quark bound states are generally very difficult to calculate.
  - Meson which consists of two quarks is the simplest bound state, but it is very difficult to calculate even its mass.
  - The bound states sound like simple system, but the reality is that the systems are very complicated
    → Need for numerical calculations with High-performance computing: Lattice QCD
- Lattice QCD has been proven to be very successful through the past decade.
  - Successfully reproduce experimental results including the hadron masses
  - Now it is at the level of which we can safely rely on its calculations as predictions.



- Weak interaction and Intensity Frontier experiments
  - Sometimes, hadrons decay via the weak force- in other words quarks change their type (flavor).
  - As the name shows, the strength of the weak force is very weak. Thus, the decays are generally very rare and are not known very well.
  - New Physics effects may hidden in these weak signals.
  - In order to investigate these rare cases, high intensity approaches are desirable: Intensity Frontier experiments and high-precision calculations
- CKM matrix elements are fundamental parameters of the SM.
  - It represents probability that quark changes its flavor via the weak force.
  - If we assume the SM is correct, then the CKM matrix should hold unitarity and there are 6 unitarity conditions, for example;

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

  - The discrepancies between experiment and theory based on the SM might lead to the physics beyond the SM.
  - Intensity Frontier experiments and high-precision calculations are key elements.

$$V = \begin{pmatrix} |V_{ud}|_{(1-\lambda^2/2)} & |V_{us}|_{(\lambda)} & |V_{ub}|_{(A\lambda^3(\rho-i\eta))} \\ 0.97425(22) & 0.2252(9) & (3.89\pm0.44)\times10^{-3} \\ \pi\to l\nu & K\to\pi l\nu,\ K\to l\nu & B\to\pi l\nu,\ B\to l\nu \\ |V_{cd}|_{(-\lambda)} & |V_{cs}|_{(1-\lambda^2/2)} & |V_{cb}|_{(A\lambda^2)} \\ 0.230(11) & 1.023(36) & (40.6\pm1.3)\times10^{-3} \\ D\to\pi l\nu,\ D\to l\nu & D\to Kl\nu,\ D_s\to l\nu & B\to Dl\nu,\ B\to D^*l\nu,\ B_c\to l\nu \\ |V_{td}|_{(A\lambda^3(1-\rho-i\eta))} & |V_{ts}|_{(-A\lambda^2)} & |V_{tb}|_{(1)} \\ (8.4\pm0.6)\times10^{-3} & (38.7\pm2.1)\times10^{-3} & 0.88\pm0.07 \\ B-\bar{B}\ \text{mixing} & B_s-\bar{B}_s\ \text{mixing} & \end{pmatrix}$$

- Not only for the CKM matrix elements, there are many quantities that Lattice QCD can calculate better than other traditional methods.

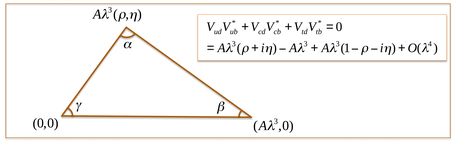
Accomplishments and future missions

1. The CKM unitarity triangle

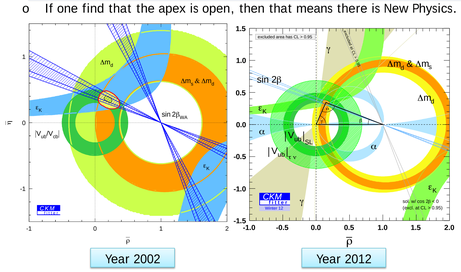
- We can search New Physics by investigating the CKM matrix in many ways.
- First row unitarity test:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999 \pm 0.0006$$

- Constraining the apex of the CKM unitarity triangle
  - The CKM matrix can be parameterized as 4 parameters: A, λ, ρ, and μ
  - In the complex plane, one can construct a triangle with an unitarity condition.



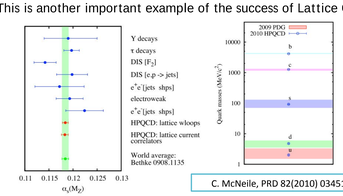
- If one find that the apex is open, then that means there is New Physics.



- Currently, there are 2~3 σ tensions at the apex.
  - If the tensions persist (~ 5σ), that means we find New Physics.
  - SUSY, extra-dimension, fourth generation, etc…
- Lattice calculations are with 1~10 % errors depend on the quantities, and the accuracy keeps improving.
- The next generation experiments (Super-B factory, Belle II) will be turned on around 2016.

2. Strong coupling constant (α_s) and quark masses

- α_s and quark masses are basic parameters on particle physics.
- The contribution from Lattice QCD is crucial to improve the accuracy.
- This is another important example of the success of Lattice QCD.



C. McNeile, PRD 82(2010) 034512

3. K→ππ decays

- K→ππ decays are technically a very challenging problem.
- The first *ab initio* calculation for the I=2 channel has been reported by the RBC collaboration using a direct method. (PRL, 108 (2012) 141601)
- This is the first calculation of a non-leptonic decay with two particle final state.

$$A(K^0 \to \pi\pi(I)) = A_I e^{i\delta_I} \quad I\ (\text{isospin}) = 2 \text{ or } 0$$
$$\mathrm{Re}(A_2) = 1.381(46)_{stat}(258)_{syst} \times 10^{-8} GeV$$
$$\mathrm{Im}(A_2) = -6.54(46)_{stat}(120)_{syst} \times 10^{-13} GeV$$

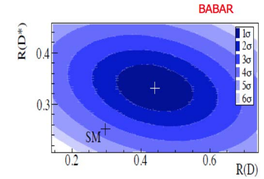
- A new method based on combining indirect and direct methods by Laiho & Van de Water is under way.
- For I=0 channel, it is much more interesting.
  - ε'/ε can be determined.
  - However, it would be much more difficult than the I=2 channel.

4. B→Dτν and B→Dμν decays

- Recently, BABAR measured

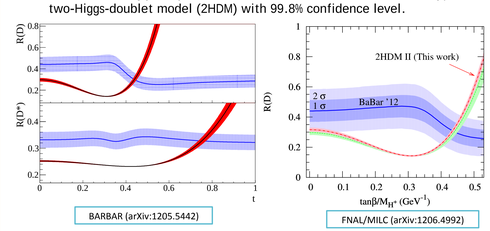
$$R(D) = \frac{Br(B\to D\tau\nu)}{Br(B\to D\mu\nu)}, \qquad R(D^*) = \frac{Br(B\to D^*\tau\nu)}{Br(B\to D^*\mu\nu)}$$

- R(D) and R(D*) are simply representing how much the decay rate changes between the heavy lepton (τ) and the light lepton (μ)
- The measurements show a 3.4σ tension between the SM.



V. Luth, FPCP 2012

- More interestingly, they claim that the measurements exclude the type II two-Higgs-doublet model (2HDM) with 99.8% confidence level.



BARBAR (arXiv:1205.5442) FNAL/MILC (arXiv:1206.4992)

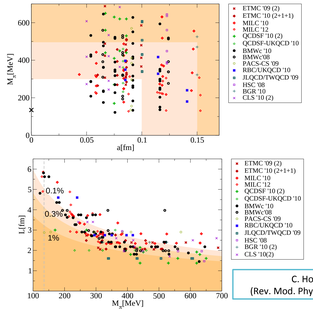
- Fermilab lattice and MILC collaborations calculate R(D) from *ab initio* full QCD.
  - It is about 1σ higher than previous model dependent calculations.
  - With R(D*) from Lattice QCD, one can confirm the exclusion from first principles.

5. Anomalous Magnetic Moment (g-2)

- Current state-of-art measurement by BNL E821 experiment
  - $a_\mu(\text{exp}) = (g-2)/2 = 116\ 592\ 080(54)(33) \times 10^{-11}$
- The best SM prediction from perturbative QED and QCD
  - $a_\mu(\text{SM}) = 116\ 591\ 802(42)(26)(02) \times 10^{-11} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had}$
- A 3.6 σ tension between the theory and experiment.
- Determination of the LO and NLO hadronic contributions from first principle is crucial.
  - LO: $O(\alpha^2)$, Hadronic Vacuum Polarization (HVP) contribution
  - NLO: $O(\alpha^3)$, Hadronic-light-by-light (HLbL) contribution
- Fermilab E989 experiment (the new muon g-2 collaboration)
  - Aiming ¼ errors of BNL E821 experiment

6. Current and future missions

- Current Lattice configuration map



C. Hoelbling (Rev. Mod. Phys. 84 (2012) 449)

- Having more lattice ensembles are very important.
  - Our understanding on the systematics will be improving, since each group uses different lattice actions and algorithms.
- Smaller lattice spacings, physical light quark masses, and larger box size are desirable for more accurate and reliable calculations.
  - Small lattice spacing: reduce the continuum extrapolation error
  - Physical light quark mass: no need for Chiral PT
  - Larger box size: reduce the finite size effects
  - However, all these cost a lot more.
    → Need more computing power and better software!!
- We are already at the physical pion mass region and smaller lattice spacings.
  - Analysis with the physical pion mass are coming up!
- Current status and outlook

Quantity	CKM element	Present expt. error	Present lattice error	2014 lattice error	2020 lattice error
f_K/f_π	$\lvert V_{us}\rvert$	0.2%	0.6%	0.3%	0.1%
$f_+^{K\pi}(0)$	$\lvert V_{us}\rvert$	0.2%	0.5%	0.2%	0.1%
D→πlν	$\lvert V_{cd}\rvert$	2.6%	5.3%	4%	1%
D→Klν	$\lvert V_{cs}\rvert$	1.1%	2.5%	2%	<1%
$B\to D^{(*)}l\nu$	$\lvert V_{cb}\rvert$	1.8%	1.8%	0.8%	<0.5%
B→πlν	$\lvert V_{ub}\rvert$	4.1%	8.7%	4%	2%
B→τν	$\lvert V_{ub}\rvert$	21%	6.4%	2%	<1%
ξ	$\lvert V_{ts}/V_{td}\rvert$	2.5%	2.5%	1.5%	<1%

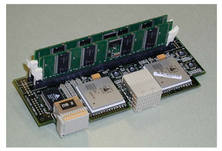
USQCD and HPC

The need to obtain the most precise possible results requires the efficient and effective use of the highest capability and capacity computing available. In the early days, this often motivated to build their own computers themselves. These early efforts were often influential in the commercial computing world.

1. QCDOC (QCD on a Chip) and Blue Gene family

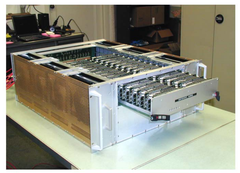
- QCDOC was created by academic lattice gauge theorists centered at Columbia University for lattice calculations.
- QCDOC is the first machine built using IBM's System-on-a-chip technology.
  - Entire node on a single chip
  - Low power and compact design
  - Collaborations between Columbia, BNL, UKQCD, RBRC, and IBM
  - Designed on optimizing performance/cost
- QCDOC architecture
  - IBM-fabricated, single-chip node
  - Processor: 32-bit PowerPC 500MHz with a 64-bit 1 Gflops FPU
  - Memory: 4 Mbyte on chip and 2 Gbyte DIMM
  - Communications
    - 6-dimension with supporting lower dimensional partitions
    - 200ns latency
    - Global sum/broadcast functionality
    - Multiple DMA engines/minimal processor overhead
  - 100 Mbit/sec Ethernet to each node
    - Booting, I/O, host control

Daughter board (2 nodes)



Mother board (64 nodes)

• Single Motherboard Cabinet.



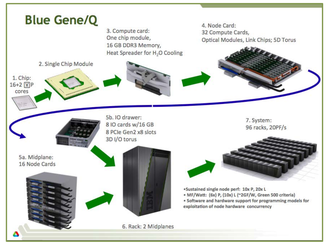
- After QCDOC, IBM developed Blue Gene/L, the first generation of the Blue Gene family.
  - IBM's key designers were Columbia "graduates"
    - Al Gara, Dong Chen, Jim Sexton, and Pavlos Vranas

Blue Gene/L Compute Card

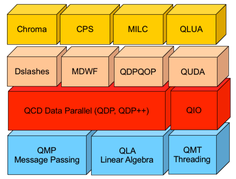
- Blue Gene family.
  - Blue Gene/L
    - Two cores per node
    - Two floating point units/core
    - 0.7 GHz, 5.6 Gflops/node, 210 Mflops/Watt
  - Blue Gene/P
    - Four cores per node
    - Two floating point units/core
    - 0.85 GHz, 13.6 Gflops/node, 357 Mflops/Watt

2. MIRA and USQCD SciDAC software

- MIRA is a 48 rack BG/Q machine at ALCF in Argonne National Lab.
  - 16 + 1 PowerPC cores 16 GB memory per node
    - 64bit, 1.6 GHz, Quad FPU, 4 physical threads
    - Additional 1 redundant processor
  - 5D torus topology + external link
    - each 1.8GB/s send and 1.8GB/s receive user bandwidth
    - DMA, remote put/get, collective operations
  - 1.99 Gflops/Watt
  - Peak performance: 204.8 Gflops @ 55 Watt
  - The Columbia lattice gauge theory group participated in the design of the BG/Q. They designed the interface between the processor core and the level-2 cache, and the look-ahead algorithms used to prefetch data from level-2 cache.



- USQCD SciDAC software modules
  - USQCD SciDAC modules are for Lattice QCD for many architectures.
  - These can be generally used at high-level Lattice codes, such as Chroma, CPS, MILC, and QLUA.



- Optimizing the USQCD SciDAC software for BG/Q
  - QMP: develop SPI communication library
    - Instead of using MPI, use low level communication (SPI) to directly handle MU (Message Unit)
    - Improve the latency by up to a factor of 8 (with small size messages)
  - QLA: use QPX intrinsics
  - QDP: threading
    - 64 threads per node
    - All 64 MPI ranks per node: not efficient enough
    - It may need application level threads: Pthreads
  - Use optimized mapping

Argonne NATIONAL LABORATORY

USQCD US Lattice Quantum Chromodynamics