Field Theory Simulation towards Fugaku

Yasumichi Aoki (Field Theory Research Team)

17, February 2020
2nd R-CCS International Symposium
Quantum Field Theory

• Quantum mechanics: physics framework for microscopic world
• Special Relativity: physics framework of fast moving particle

• Quantum Field Theory (QFT)

• Standard Model of Particle Physics: most successful application of QFT
Quantum Field Theory

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• Standard Model of Particle Physics: most successful application of QFT

Standard Model
• Electromagnetism
• Weak Interaction
• QCD
Quantum Field Theory

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- Electromagnetism
- Weak Interaction
- QCD

- Test of the Standard Model
- Seeking physics beyond the Standard Model for “New” Physics are central targets of particle physics
Quantum Field Theory

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Standard Model
- Electromagnetism
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Test of the Standard Model
Seeking physics beyond the Standard Model for “New” Physics are central targets of particle physics

- QCD has most complex dynamics → numerical simulation is most powerful tool
Fermilab / J-Parc

$\mu$

(g-2)$_\mu$

QCD

Standard Model

heavy flavor

KEK
(g-2)μ

QCD

Standard Model

New Physics

Fermilab / J-Parc

KEK

heavy flavor

3
Compute $\neq$ Measure

KEK

QCD

Standard Model
Compute \((V_{ij})\) = Measure

Constrains parameters in Standard Model

Kobayashi-Maskawa matrix elements \(V_{ij}\)

Q: consistency btw many different processes?
proton decay

Fermilab / J-Parc

$(g-2)_\mu$

heavy flavor

KEK

Kamioka

QCD

Standard Model

New Physics
QCD for the tool to bridge new physics

proton decay matrix element as an example

• bridge between new theories and experiments
  (GUTs) (SuperKamiokande etc)
non-chiral fermions used for a test
• chiral extrapolation: largest systematic uncertainty
• physical point simulation will solve this completely
• small mass, large volume ($64^4$, $96^4$) required
• All mode averaging (AMA) with many sloppy linear solve
  • correlation: $r=0.9994$ OK: $N_G=256$

\[ \text{err}_{\text{imp}} \approx \text{err} \sqrt{2(1-r) + \frac{1}{N_G}}, \]

• old: long distance extrapolation

\[ \frac{1}{\text{Proton Lifetime}} \propto [\text{QCD param.}] \times [\text{NewPhys. param}] \]

• new: on physical point simulation

Aoki, Kuramashi, Shintani, Tsukamoto @ Lattice 2019
QCD for the tool to bridge new physics

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QCD for the tool to bridge new physics

- proton decay matrix element as an example
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Achievements with K

Hokusai BW and other HPCI resources

- new: on physical point simulation

1/Proton Lifetime \( \propto [\text{QCD param.}] \times [\text{NewPhys. param}] \)
QCD for the tool to bridge new physics

proton decay form factors
- more demanding comp.
- directly related to proton lifetime
- obtaining promising results

on-shell lepton: $-q^2 = m_l^2 = 0$

operator renormalization
- RI/SMOM non-perturbative renormalization
- application: proton decay, nucleon charges
- improved Wilson fermions with 6 stout-link smeared
  - admixture from chiral symmetry breaking is as small as 1%

old (after long extrpl.)
new (on physical mass)

$M_{a,b}^{\phi,\eta}$ for nucleon decay
$Nf=2+1$, PACS, 64*, 99 configurations

poster: Aoki, Kuramashi, Tsukamoto, Shintani @ Lattice 2019
QCD for the tool to bridge new physics

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\[ \langle \pi^0 (ud)_R u_L | p \rangle \]

**on-shell lepton:** \[-q^2 = m_l^2 = 0\]

\[ W_0 (GeV^2) \]

Extending this to all possible final state mesons

old (after long extrpl.)

\[ q^2 \text{ GeV}^2 \]

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Proton decay

$\mu$

Fermilab / J-Parc

(g-2)$_\mu$

KEK

Heavy flavor

CERN

Kamioka

New Physics

QCD

Standard Model

QCD like

Proton decay

Composite Higgs
Revealing the history of Universe

BNL / CERN

QCD

Dark Matter

QCD phase

Standard Model
QCD phase: Post-K priority issues #9

Scientific motivation

• fundamental understanding of QCD phase transition
• Through the use of methods with no compromise
• spontaneous breakdown of chiral symmetry
• use of chiral fermion algorithm
• in-depth study
  • role of the symmetry
  • role of the anomaly: $U(1)_A$ symmetry
• will give most precise description of the QCD at finite temperature
  ➡ experiment / early universe
QCD phase: Post-K priority issues #9

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BNL / CERN

QCD phase: 2nd order transition

BNL / CERN

QCD phase: 1st order transition

Dark Matter

New Physics

Standard Model

Columbia plot

$\infty$

$m_s$

physical pt. cross over

1st order transition

$\infty$

$0$

$m_{ud}$

$\infty$

$0$

$m_{ud}$

physicists
QCD phase: Post-K priority issues #9

Columbia plot (phase diagram for $N_f=2+1$ as function of quark mass)

- spontaneous breakdown of **chiral symmetry**
- use of **chiral fermion** algorithm
  - essential: interplay of symmetry and quantum anomaly
- demanding comp.
- $N_f=2$ ($m_s \to \infty$) phase: yet to be conclusive
  - knowledges being acquired
- interesting development of fate of $U(1)_A$
- around physical point $\to$ Fugaku
QCD phase: Post-K priority issues #9

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Achievements w/o K
KEK Blue Gene/Q
Oakforest PACS

[Volcano]
plans for QCD phase

direct access to physical point and surrounding area

degenerate 3 quark system: simpler

Planned to be explored on Fugaku

Started using HPCI resources and Hokusai-BW
ongoing projects and plans

1) QCD code packaging and tuning for Fugaku
   - lowest revel taken from co-design activity
   - higher level, packaging, tuning

2) algorithms for chiral fermions for big volume
   - mostly for linear solvers
   - AMA, multigrid, etc

3) new algorithms / developments
   - AI: may be used for optimizing implicit parameters / initial guess
     - integration path (start, end fixed)
     - MD parameters
   - tensor network

4) collaborations for developments and science
   - priority issue #9 and successors
   - international

Post-K/Fugaku development in the team

QCD codes for Fugaku and future machines

[25+] x K

QCD wide simd library for fugaku

BQCD

FS 2020

Bridge ++

Iroiro++

Priority issue #9 co-design

Priority issue #9/ JLDCD

Grid

BNL/ Edinburgh/ Regensburg
Use of Fugaku w/ our developments extends the reach of simulation

• with Domain-wall Fermions (chiral)

• QCD phase
  \* N_t=16 for N_f=2+1 (dynamical u,d,s quarks)
    ‣ real chiral simulation for phase transition

• Heavy flavor
  \* M_B a \approx 1
    ‣ to control discretization error
    ‣ B→πlν, etc
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Previously, $N_f = 2$ (only u,d quarks) or $N_t = 8$

$\to$ lattice spacing $a_{\text{new}}/a_{\text{old}} = 1/2$
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$\to$ lattice spacing $a_{\text{new}}/a_{\text{old}} = 1/2$

Previously $M_B a \approx 2$

$\to$ lattice spacing $a_{\text{new}}/a_{\text{old}} \leq 1/2$