# Lattice QCD Activities at CCS

CCS at U. Tsukuba / RIKEN AICS

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# Plan of Talk

- Machines in CCS
- Introduction to Lattice QCD
- Hadron Mass Calculation
- Two Approaches for Nuclei in Lattice QCD
- Other Primary Research Subjects
- Collaborations within CCS
- Summary

# Machines in CCS

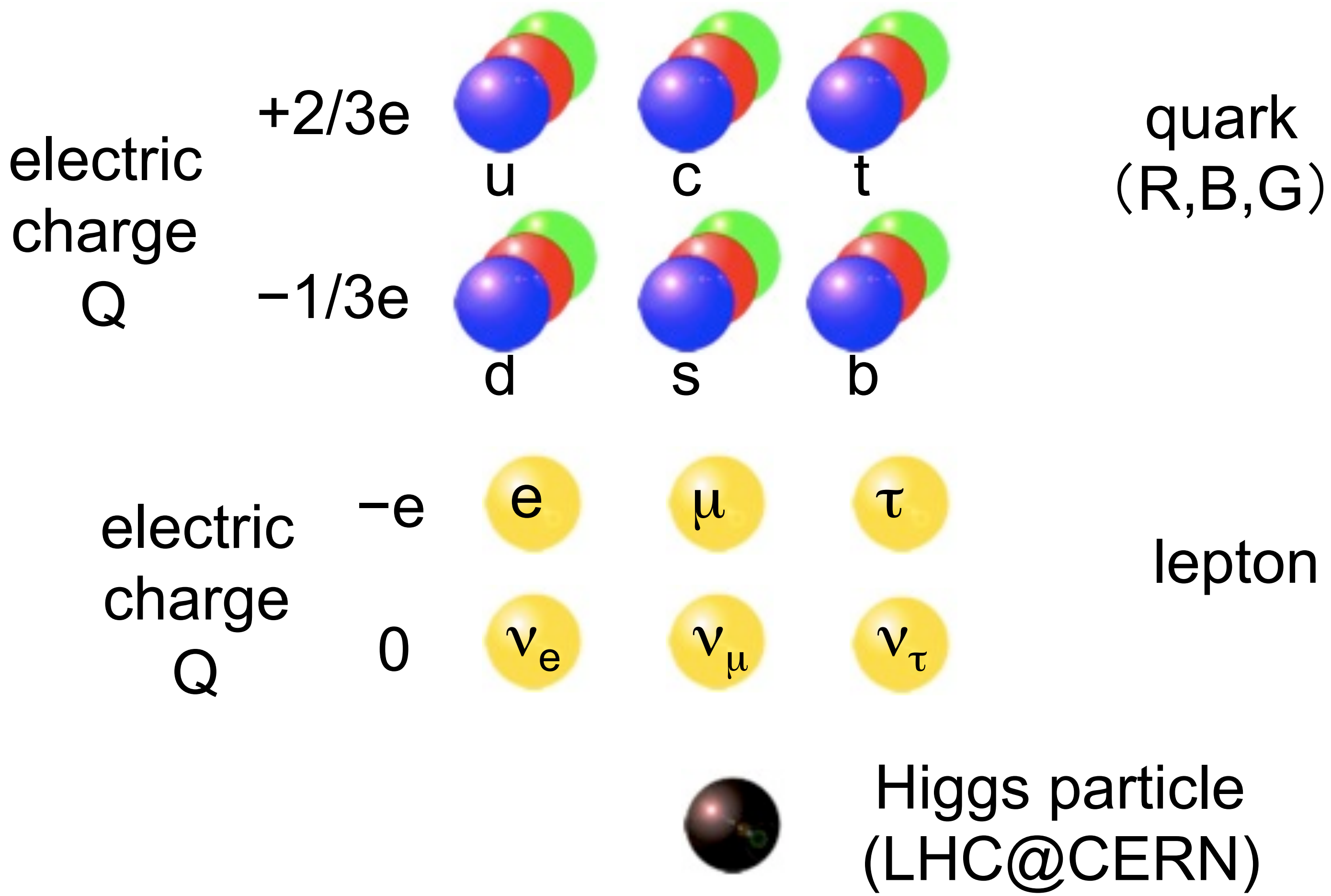
| Machine | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
|---|---|---|---|---|---|---|---|
| PACS-CS (PC-cluster, 14TF)  | Jul. 2006～ | | | | | | |
| T2K-Tsukuba (PC-cluster, 95TF)  | | | | | | ～Feb. 2014 | |
| HA-PACS (GPU-cluster, 0.8PF)  | | | | | | +364TF/TCA from fall of 2013 | |
| COMA (MIC-cluster, 1PF) No Photo | | | | | | | Apr. 2014～ |

# What is Elementary Particle Physics?

Questions in history of mankind

- What is the smallest component of matter?
- What is the most fundamental interaction?

# Elementary Particle Known to Date




**Finally discovered!!**

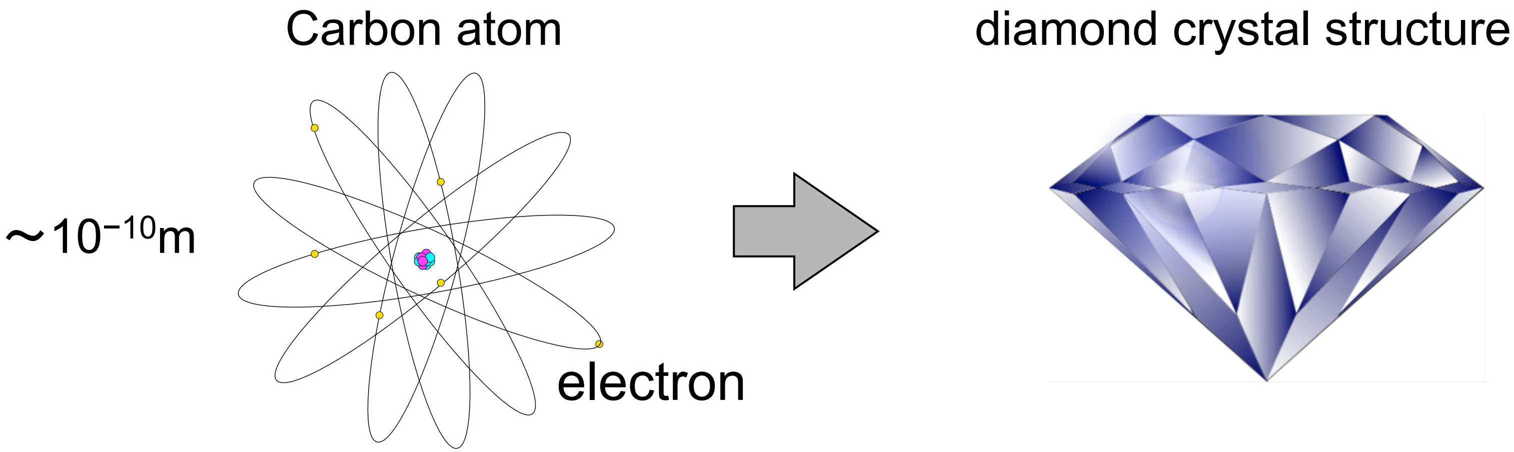
# Fundamental Interactions

| force | relative strength | gauge boson | quantum theory |
|---|---|---|---|
| Strong | 1 | Gluon | QCD |
| EM | 0.01 | Photon | QED |
| Weak | 0.00001 | Weak Boson | Weinberg-Salam |
| Gravity | $10^{-40}$ | Graviton | Superstring(?) |

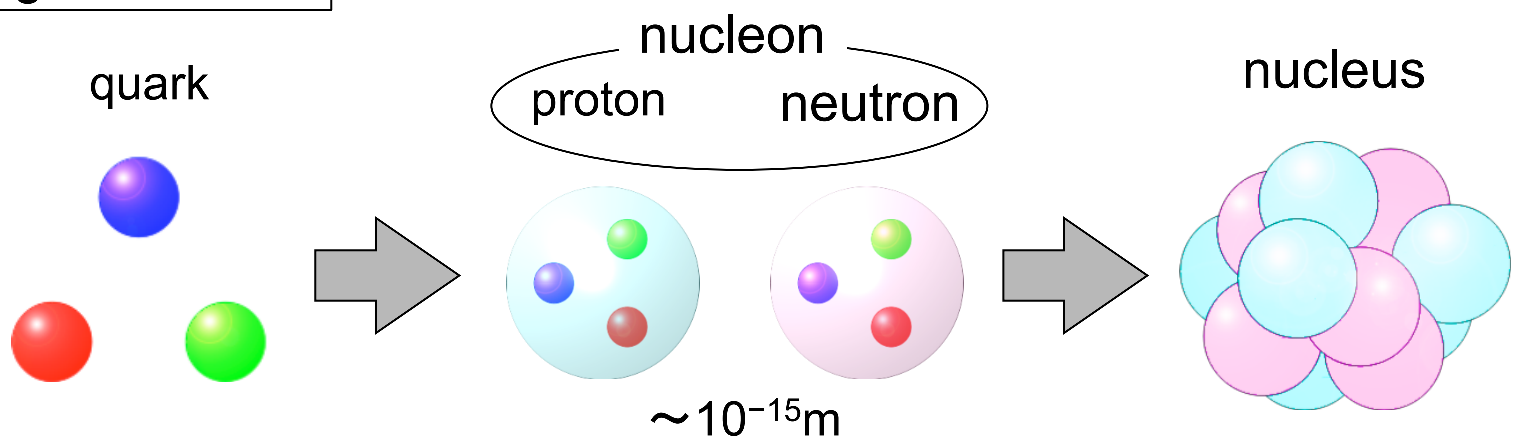
What is strong interaction?

# Strong Interaction

## Chemical bond with EM interaction




## Strong interaction

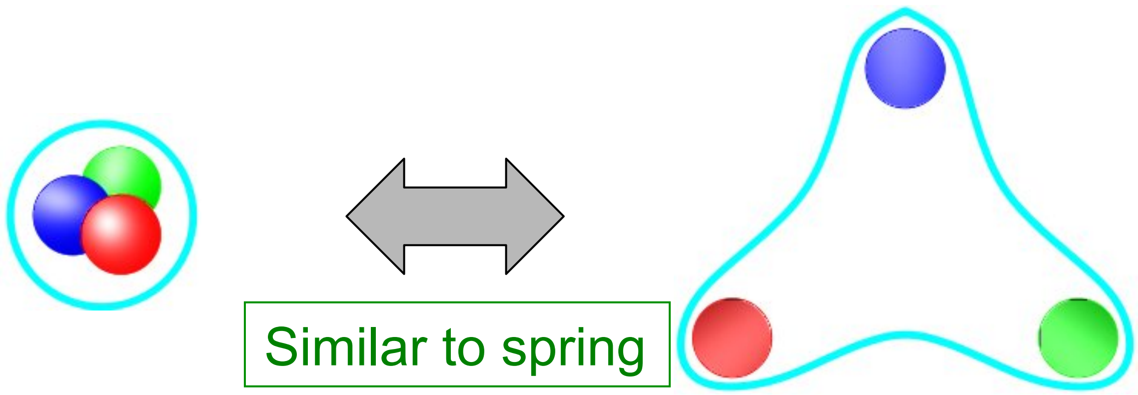


# Lattice QCD

QCD Lagrangian ＝ first principle

$$\mathcal{L} = \frac{1}{4} F_{\mu\nu} F_{\mu\nu} + \sum_{q=u,d,s,c,b,t} \bar{q} \left[ \gamma_\mu (\partial_\mu - i g A_\mu) + m_q \right] q$$

Only coupling const. g and quark masses $m_q$ are free parameters




short distance
weaker interaction
asymptotic freedom

long distance
strong attraction
confinement

Too strong to investigate with perturbative analysis

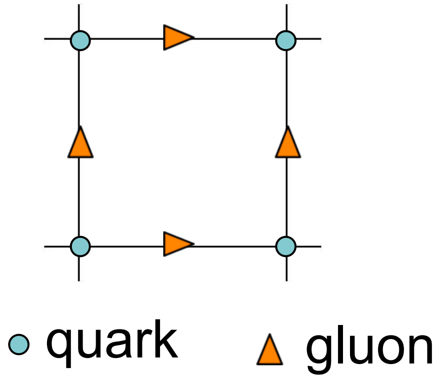
⇒ nonperturbative analysis with numerical method based on first principle

# Numerical Method

Path integral on discretized 4D（3D-space + 1D-time）lattice

$$\langle \mathcal{O}[A_\mu, q, \bar{q}] \rangle = \frac{1}{Z} \int \mathcal{D}A_\mu \mathcal{D}q \mathcal{D}\bar{q}\; \mathcal{O}[A_\mu, q, \bar{q}]\; \exp\left\{ -\int d^4x \mathcal{L}[A_\mu, q, \bar{q}] \right\}$$

Similar to partition function in stat. mechanics ⇒ Monte Carlo method




Average over configs. gives expectation value

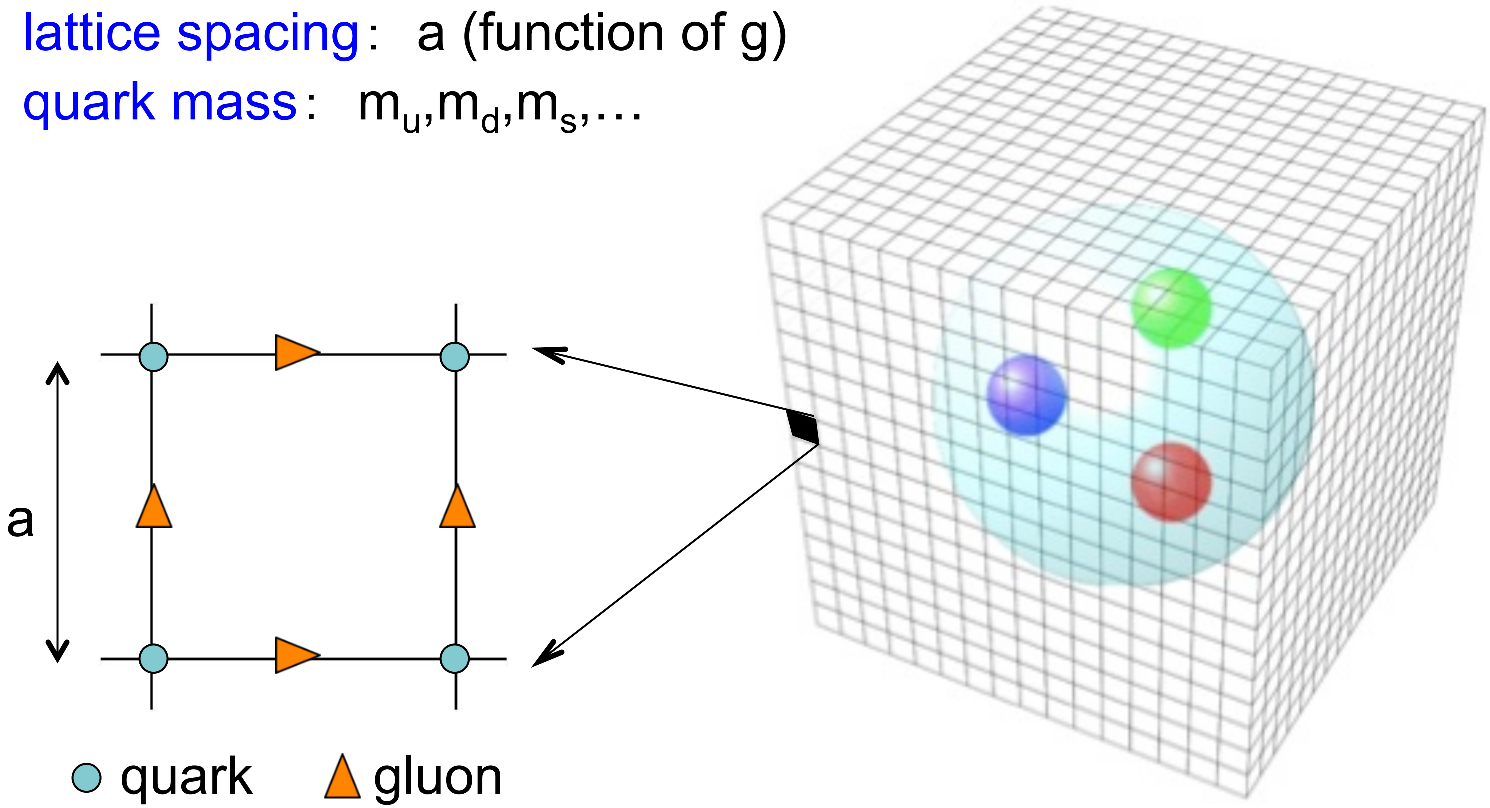
$$\langle \mathcal{O}[A_\mu, q, \bar{q}] \rangle = \frac{1}{N} \sum_{i=1}^{N} \mathcal{O}[A_\mu^{(i)}, q^{(i)}, \bar{q}^{(i)}] + O\left( \frac{1}{\sqrt{N}} \right)$$

Statistical error

# Physical Parameters

Small number of parameters

- 4D volume : V=NX･NY･NZ･NT
- lattice spacing : a (function of g)
- quark mass : $m_u, m_d, m_s, \ldots$



# Various Hadrons

Confinement : quark can never be retrieved by itself

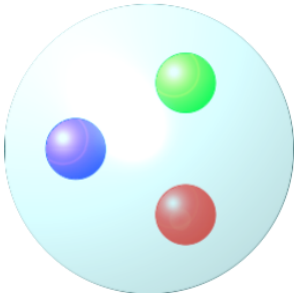
**Hadron**

Meson (quark and anti-quark)

π, K, K*, ρ, ω, η, φ, a, b, f, D, B, ...

Combinations of 6 types od quarks (u,d,s,c,b,t)

Baryon (3 quarks)



p, n, Δ, Λ, Σ, Σ*, Ξ, Ξ*, Ω, Λc, Ξc, Λc, ...

# Hadron Mass Calculation

Fundamental quantities both in physical and technical senses

## Physical side

Physical input ⇒ $m_u, m_d, m_s, \ldots$ ⇒ Reproduce all the hadron spectrum?

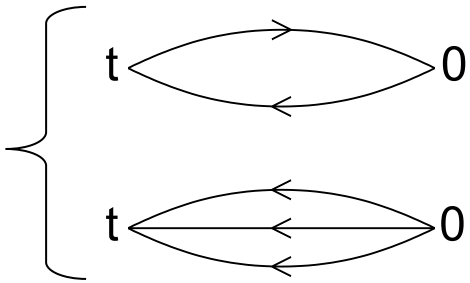
(ex. $m_\pi$, $m_K$, $m_\Omega$) validity of QCD / determination of $m_q$

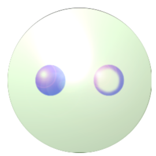
## Technical side

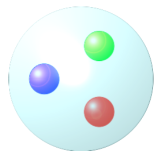
Hadron correlators in terms of quark fields

$$\langle \mathcal{O}_h(t)\mathcal{O}_h^\dagger(0)\rangle \overset{t\gg 0}{\gtrsim} C\exp\left(-m_h t\right)$$ ⇒ Extract $m_h$ by fit

Quark line diagrams
from Wick contractions



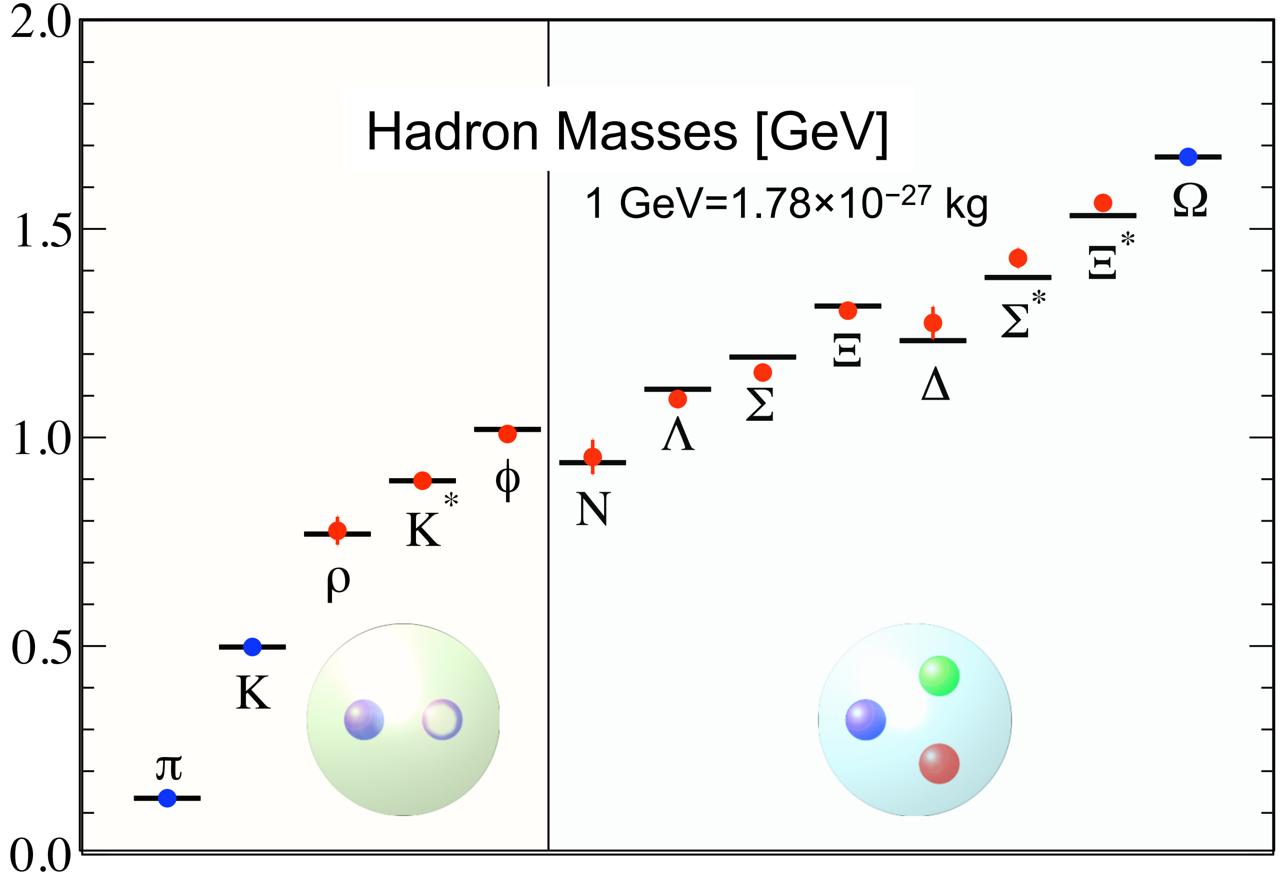

meson 

baryon 

# Hadron Masses in 2+1 Flavor QCD

PACS-CS 09

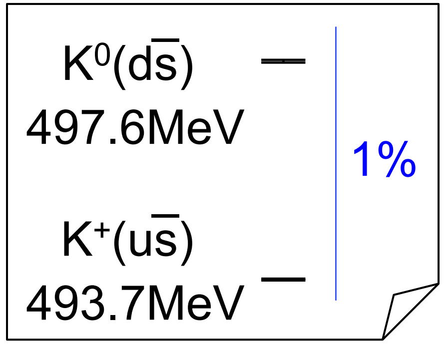
input $m_\pi$, $m_K$, $m_\Omega$ ⇒ $m_u$=$m_d$, $m_s$, a




Consistent within 2～3% error bars

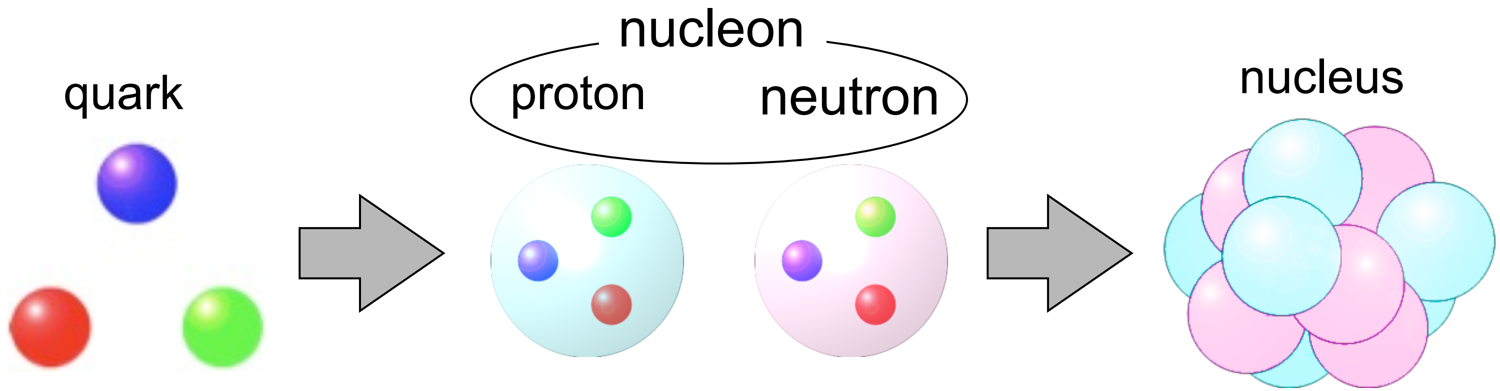
# What's Next?

- 1+1+1 ($m_u \neq m_d \neq m_s$) flavor QCD+QED simulation at physical point
  - Electromagnetic (EM) interactions
  - u-d quark mass defference




Multi-physics toward precision measurement

- Hadron-Hadron interactions




Multi-scale physics from quarks to nuclei

# 1+1+1 Flavor QCD+QED

PACS-CS 12

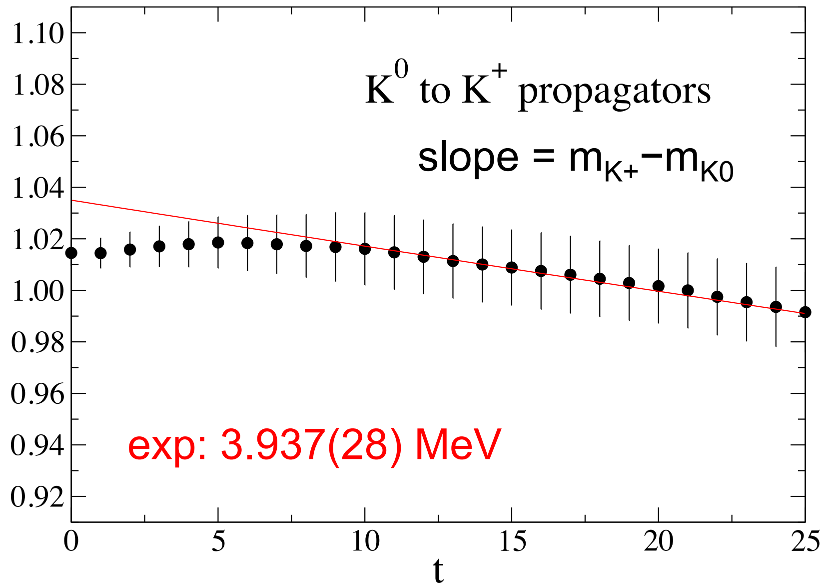
Isospin symmetry breaking

- EM interaction

  $Q_u=+2/3e$, $Q_d=Q_s=-1/3e$

- u-d quark mass difference

  $m_u=m_d\neq m_s$ (2+1 flavor) ⇒ $m_u\neq m_d\neq m_s$ (1+1+1 flavor)




lattice size = $32^3\times64$

a ∼ 0.1 fm

$$\frac{\langle K^0(t)K^0(0)\rangle}{\langle K^+(t)K^+(0)\rangle} \simeq Z\,(1-\underbrace{(m_{K^0}-m_{K^+})t}_{\text{much smaller than 1}})$$

# u, d, s Quark Masses

PACS-CS 12

Physical input:

$m_{\pi+}$(ud)=139.7(15.5) [MeV] exp: 139.6 [MeV]

$m_{K0}$(ds)=497.6(8.1) [MeV] exp: 497.6 [MeV]

$m_{K+}$(us)=492.4(8.1) [MeV] exp: 493.7 [MeV]

$m_{\Omega}$(sss) is fixed at exp. value exp: 1672.5 [MeV]

Quark masses (MSbar scheme at μ=2 GeV):

$m_u$=2.57(26)(07) [MeV]

$m_d$=3.68(29)(10) [MeV]

$m_s$=83.60(58)(2.23) [MeV]

1+1+1 flavor QCD+QED allows individual determination of $m_u$,$m_d$,$m_s$

# Two Approaches for Nuclei in Lattice QCD

- Direct construction of nuclei — Fukugita et al. 95

  Measure correlation of nucleus operators ⇔ same as hadron masses

  ex. $^4$He case

  $$\langle \mathcal{O}_{^4\mathrm{He}}(t)\mathcal{O}^\dagger_{^4\mathrm{He}}(0)\rangle \overset{t\gg 0}{\approx} C\exp\left(-m_{^4\mathrm{He}}t\right) \qquad \Delta E_{^4\mathrm{He}} = m_{^4\mathrm{He}} - 4m_N$$

  binding energy

- Potential approach — Ishii-Aoki-Hatsuda 07

  Measure wave-function of two nucleons Φ(r) ⇒ extract potential $V_C(r)$

  $$V_C(r) = E + \frac{1}{2\mu}\frac{\vec{\nabla}^2\phi(r)}{\phi(r)}$$

  Solve Schrödinger eq. with $V_C(r)$ as input

# Direct Construction of A≤4 Nuclei

Yamazaki-YK-Ukawa 12

2+1 flavor QCD, $m_\pi$=0.5 GeV (0.14 GeV in nature), $m_N$=1.32 GeV

| | $^4$He | $^3$He | NN($^3S^1$) | NN($^1S_0$) |
|---|---|---|---|---|
| Binding energy [MeV] | 43(12)(8) | 20.3(4.0)(2.0) | 11.5(1.1)(0.6) | 7.4(1.3)(0.6) |
| Exp. value [MeV] | 28.3 | 7.72 | 2.22 | 0 |

- Successful construction of light nuclei ($^4$He, $^3$He, NN(3S1))
- Larger binding energies than exp. values
- $^1S_0$ channel is also bound

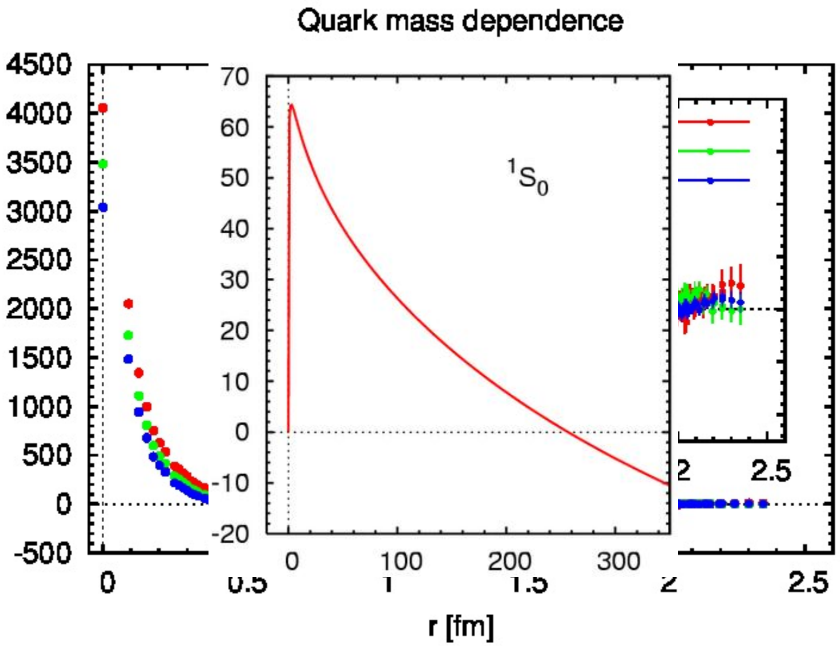
} Heavy quark effects?

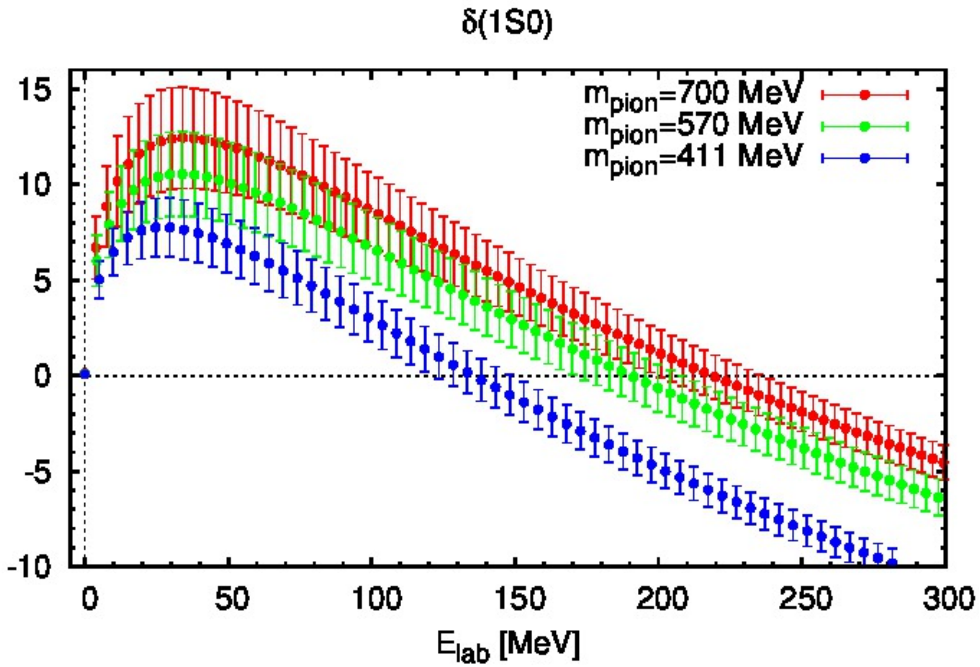
Physical point simulation is necessary

# NN Potential

HAL QCD@Lattice 2013

2+1 flavor QCD, $m_\pi$＝0.70, 0.57, 0.41 GeV (0.14 GeV in nature)




Attractive phase shift, though the magnitude is just 10% of exp. value

No bound state (He, NN) ⇔ inconsistency against the direct method

Phase shift becomes smaller, as quark mass decreases

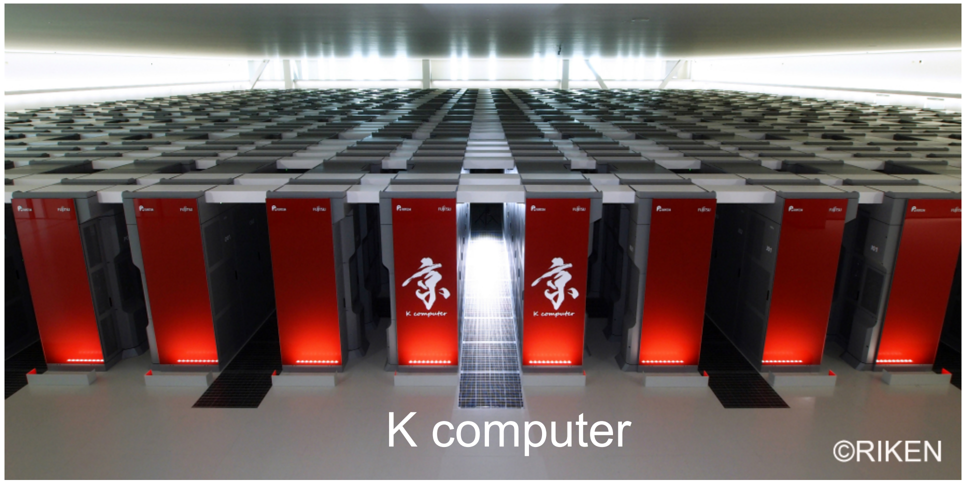
⇒ reproduce exp. values at the physical point ?

# Ongoing Project

<u>HPCI Strategic Field Program (FY2011～FY2015)</u>

- 2+1 flavor QCD ⇒ 1+1+1 flavor QCD+QED
- Direct construction of light nuclei
- Determination of baryon-baryon potentials

PACS-CS/T2K-Tsukuba ⇒ K computer
Large scale simulation on 40 times larger lattice at the physical point

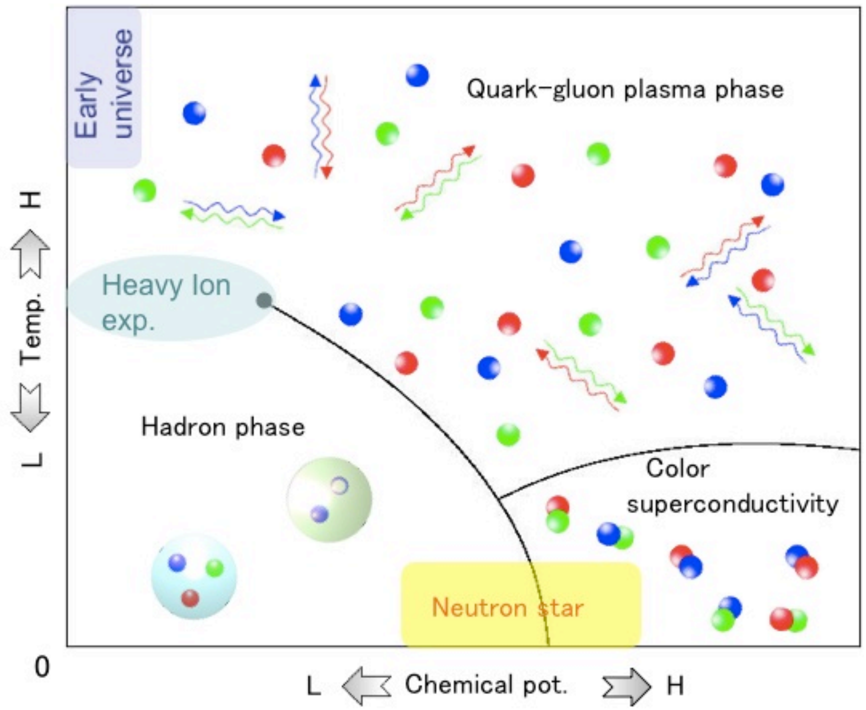



# Other Primary Research Subjects

- Dynamical properties of hadrons such as ρ→ππ resonance
  - World's first study of ρ→ππ decay width based on phase shift in 2007
  - Extended from 2 flavor to 2+1 flavor QCD at $m_\pi$=0.30, 0.41 GeV

- Lattice QCD at finite temperature and density
  - Phase structure
  - Thermodynamic properties
  - Use of Wilson-type quarks

Expected phase diagram



# Collaborations within CCS

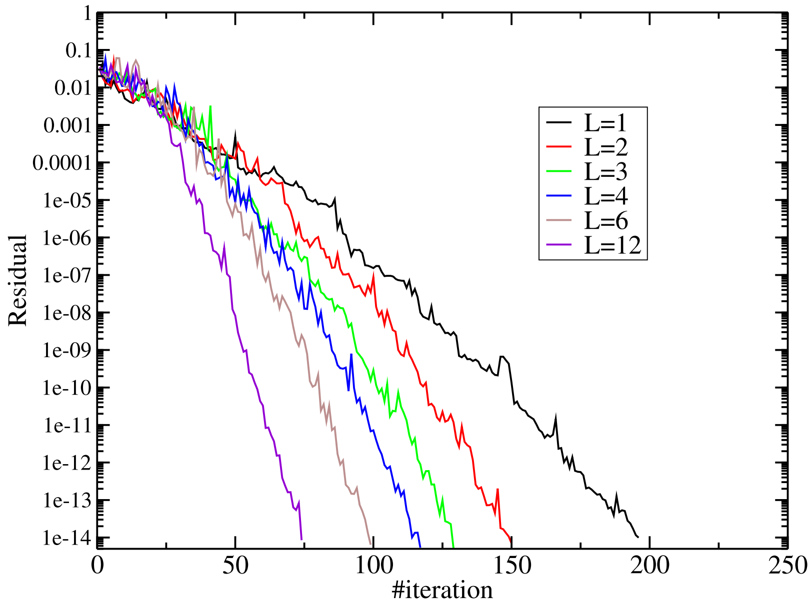
- Collaboration with applied mathematicians and computer scientists in Division of High performance Computing Systems
  - mixed precision nested BiCGStab algorithm for PACS-CS

    ⇒ Double the performance
  - block Krylov subspace algorithms with multiple right-hand sides

    ⇒ Make 1+1+1 flavor QCD+QED simulation possible

Nakamura et al. 12

2+1 flavor QCD, $32^3 \times 64$




Performance test on T2K-Tsukuba

$Dx^{(i)}=b^{(i)}$ (i=1,…,12)

#MVM(gain)=2.8

⇓

Thanks to effective use of cache

Time(gain)=5.4

# Summary

<u>Historical role of PACS-CS/T2K-Tsukuba</u>

- Achievement of physical point simulation
- Beginning of precision measurement with EM and u-d quark mass difference
- One-body study of hadron ⇒ Hadron-hadron interaction including Nuclei

| **Peak** | **Machine** | **Scientific Target** |
|---|---|---|
| <1TF class | CP-PACS | Development of 2+1 flavor QCD simulation |
| 10TFclass | PACS-CS | Physical point simulation |
| 100TFclass | T2K-Tsukuba | Development of 1+1+1flavor QCD+QED simulation<br>Construction of Nuclei with heavy $m_{ud}$ |
| 1PF class<br>10PF class | HA-PACS<br>K computer | Large scale simulation of 1+1+1 flavor QCD+QED<br>Construction of Nuclei at the physical point |