Activities and Collaborations of Division of Particle Physics

CCS at U. Tsukuba / RIKEN AICS

Yoshinobu Kuramashi

Plan of Talk

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

Members

- Yoshinobu Kuramashi【P】, Leader
- Naruhito Ishizuka【AP】
- Tomoteru Yoshié【AP】
- Noriyoshi Ishii【AP】
- Hidekatsu Nemura【AP】
- Yusuke Taniguchi【L】

+ 3 postdocs

- Sinya Aoki【Visiting Professor】
- Kazuyuki Kanaya【P(Collaborative Fellow)】

Machines in CCS

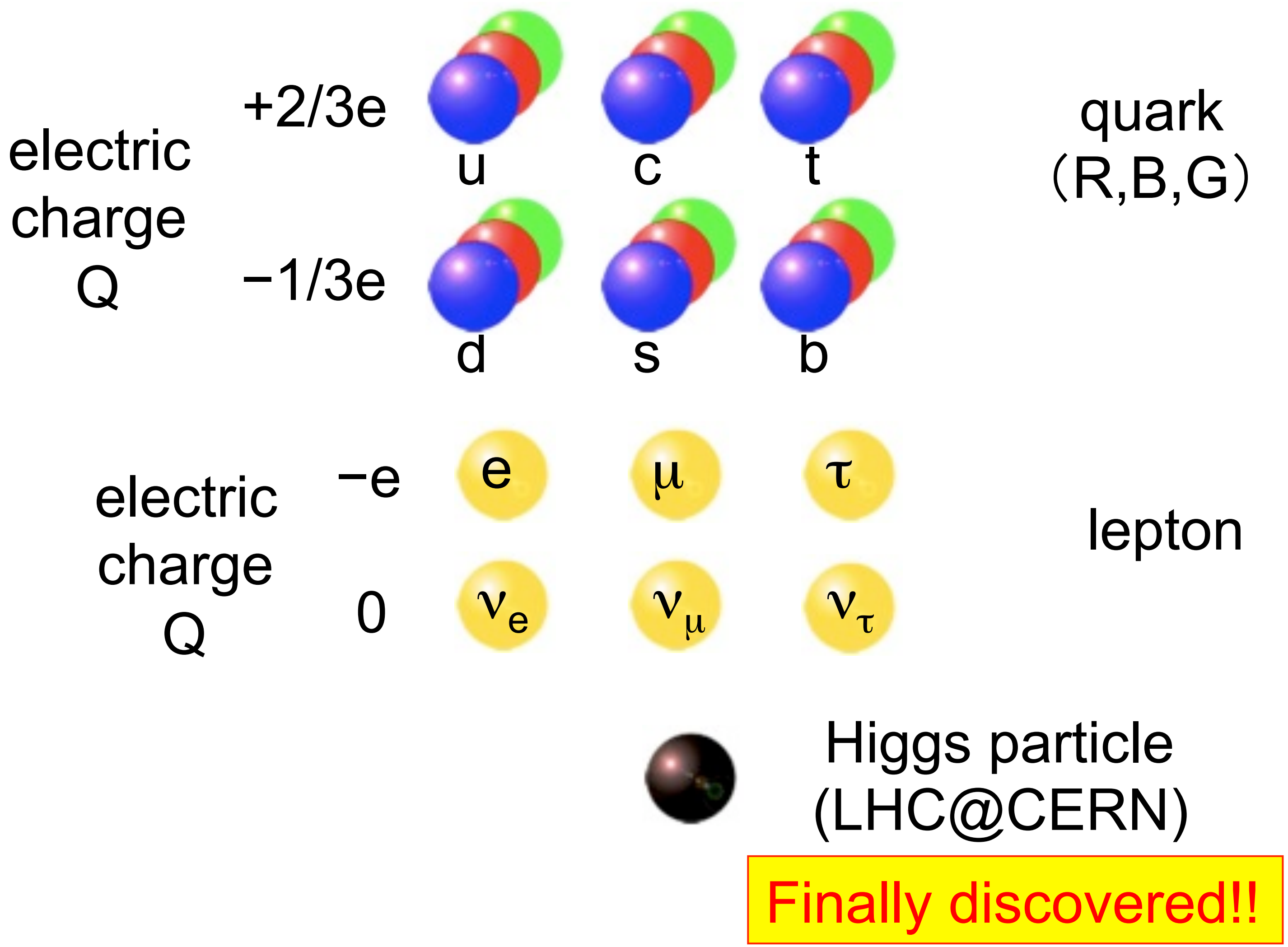
Machine	2008	2009	2010	2011	2012	2013	2014
PACS-CS (PC-cluster, 14TF) 	Jul. 2006～						
T2K-Tsukuba (PC-cluster, 95TF) 						～Feb. 2014	
HA-PACS (GPU-cluster, 0.8PF) 						+364TF/TCA from fall of 2013	
COMA (MIC-cluster, 1PF) Photo is not yet available							Apr. 2014～

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



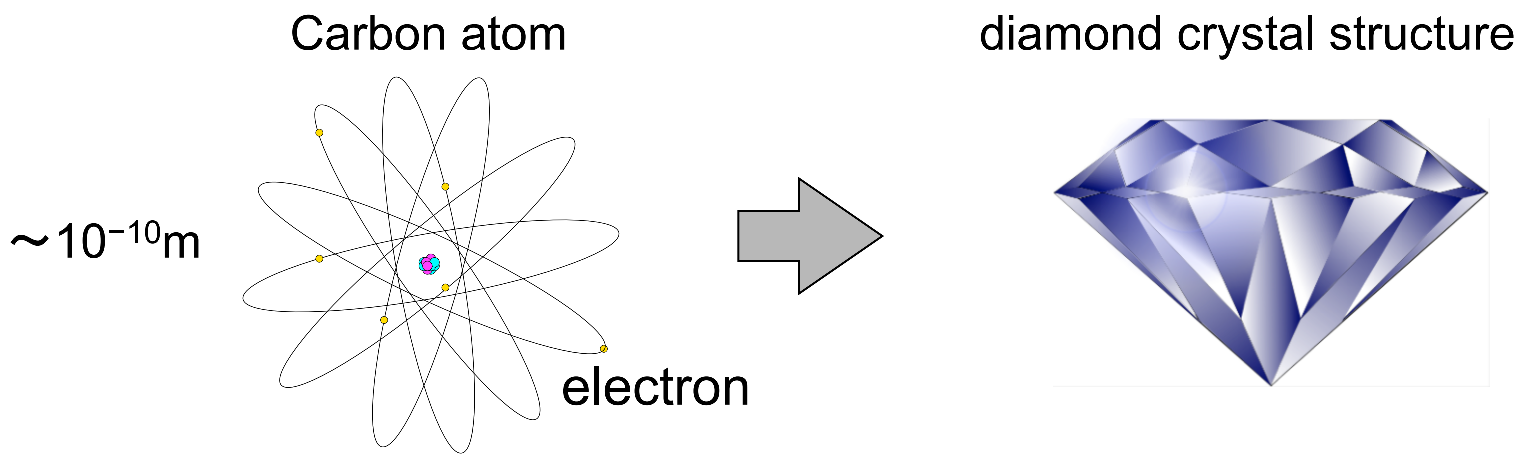
Fundamental Interactions

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(?)

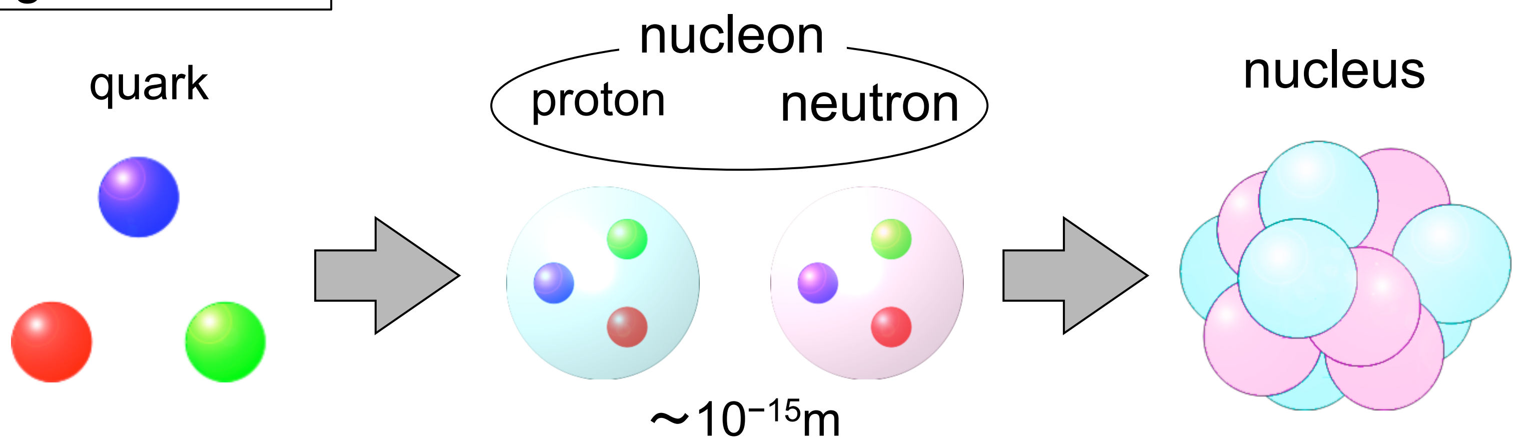
What is strong interaction?

Strong Interaction

Chemical bond with EM interaction



Strong interaction

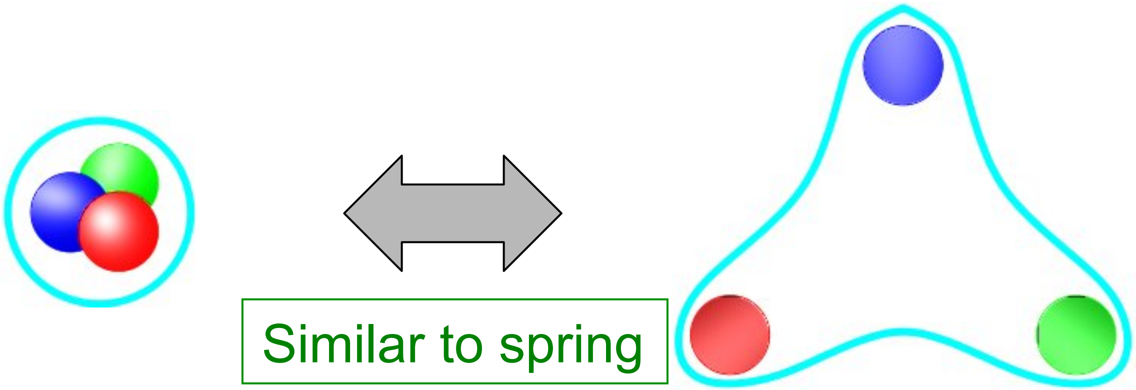


Lattice QCD

QCD Lagrangian = first principle

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

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

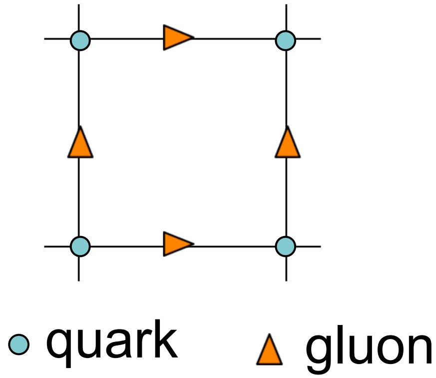
⇒ nonperturbative analysis with numerical method based on first principle

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

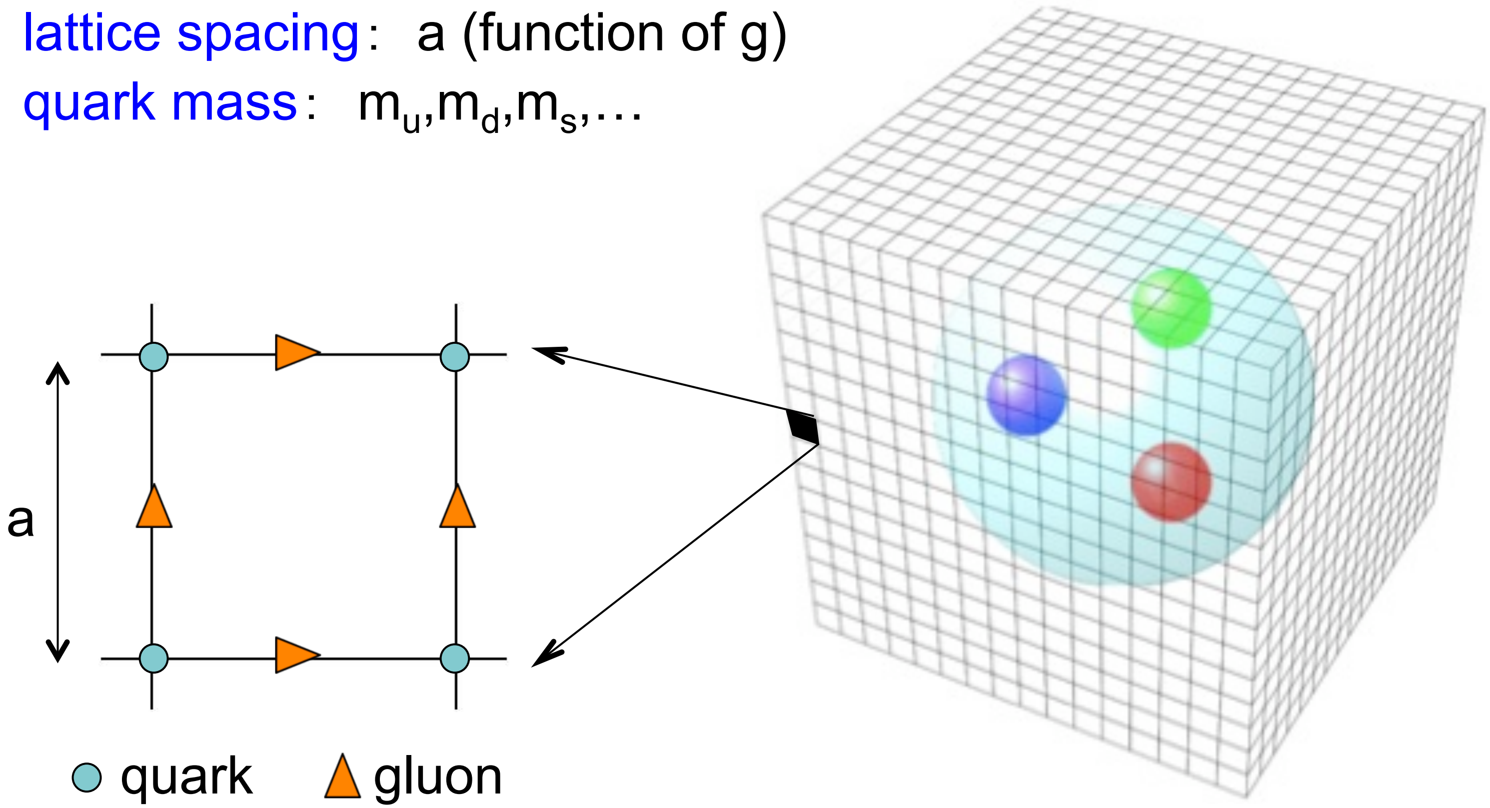
$$\langle \mathcal{O}[A_\mu, q, \bar{q}] \rangle = \frac{1}{N} \sum_{i=1}^{N} \mathcal{O}[A_\mu^{(i)}, q^{(i)}, \bar{q}^{(i)}] + O\left(\frac{1}{\sqrt{N}} \right)$$

Statistical error

Physical Parameters

Small number of parameters

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



Major Systematic Errors

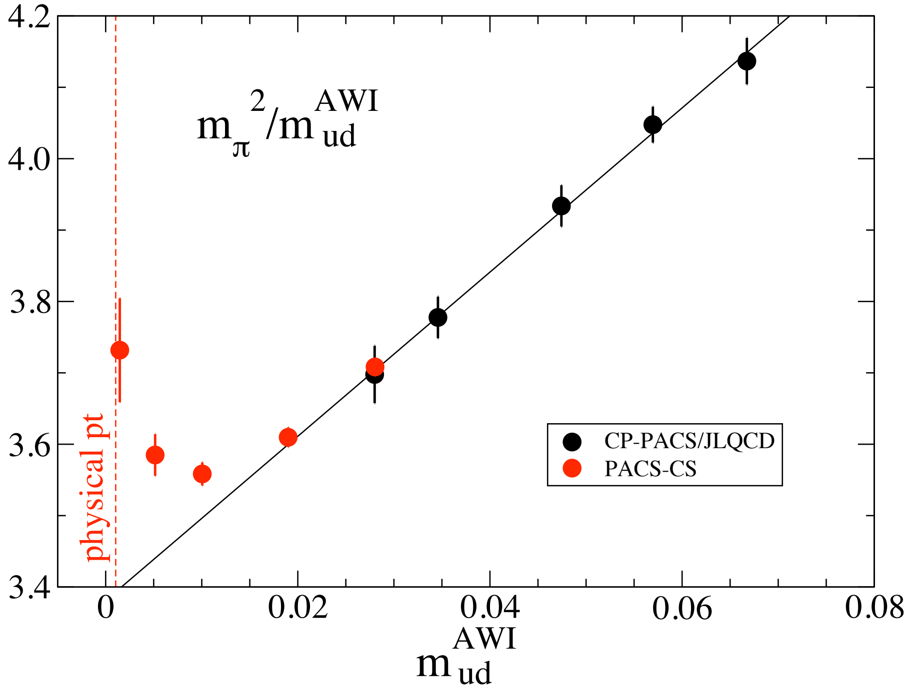
- Finite volume effects
  ⇒ Enlarge V=NX･NY･NZ･NT
- Finite lattice spacing effects
  ⇒ smaller a
- Quenched approximation (Partial inclusion of weight $\exp(-\int d^4x L_{QCD})$)
  ⇒ 2+1 ($m_u = m_d \neq m_s$) flavor QCD simulation
  CP-PACS/JLQCD project 00～05
- Chiral extrapolation with artificially heavier m_{ud} quark masses (※ Computational cost becomes cheaper for heavier m_{ud})
  ⇒ Physical point simulation
  PACS-CS project 06～

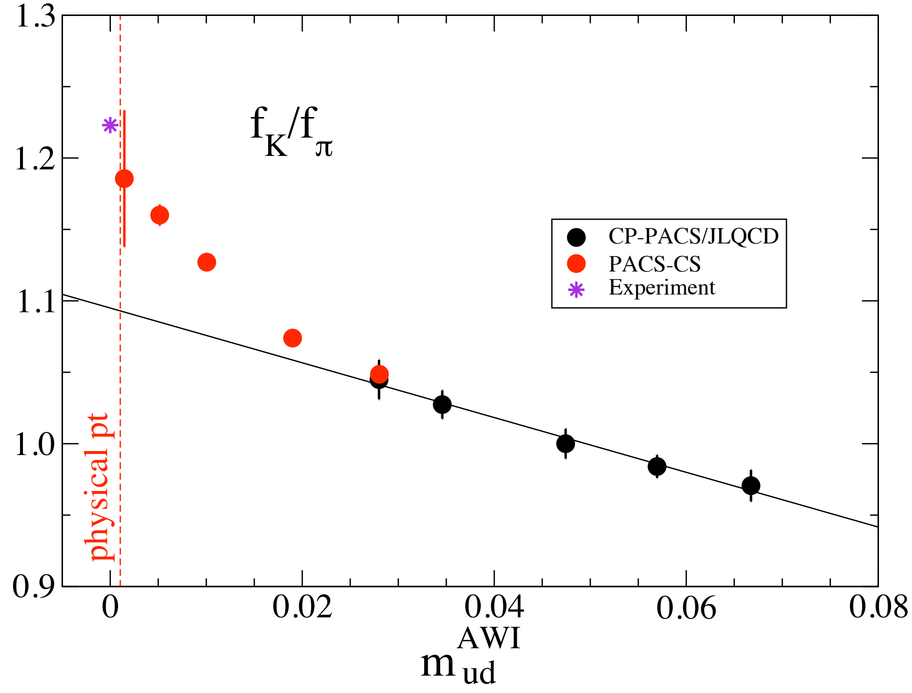
One may think of …

Chiral extrapolation with artificially heavier m_{ud} quark masses should be a good idea, because computational cost is much cheaper

Quark Mass dependence

PACS-CS 09





Non-trivial curvature toward physical point

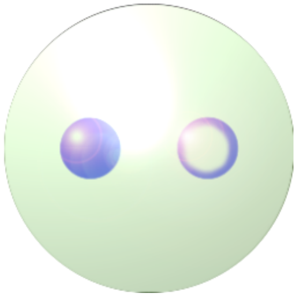
⇒ Physical point simulation is necessary

Various Hadrons

Confinement : quark can never be retrieved by itself

Hadron

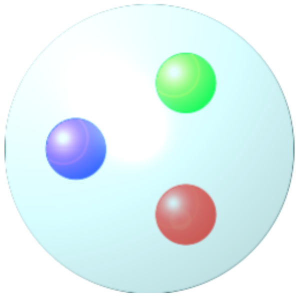
Meson (quark and anti-quark)



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

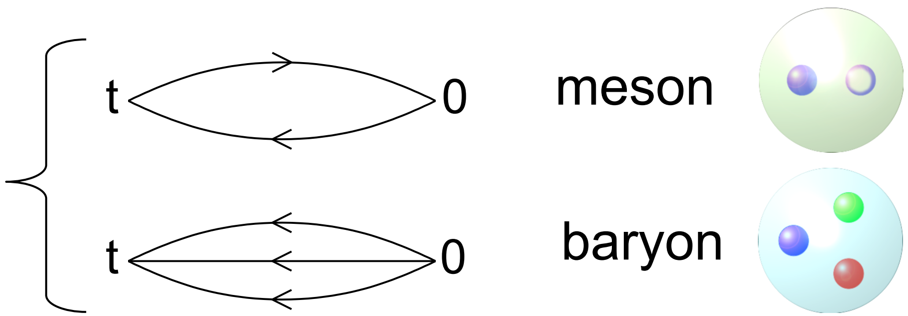
Physical input ⇒ $m_u, m_d, m_s, \ldots$ ⇒ Reproduce all the hadron spectrum?
(ex. m_π, m_K, m_Ω) validity of QCD / determination of m_q

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

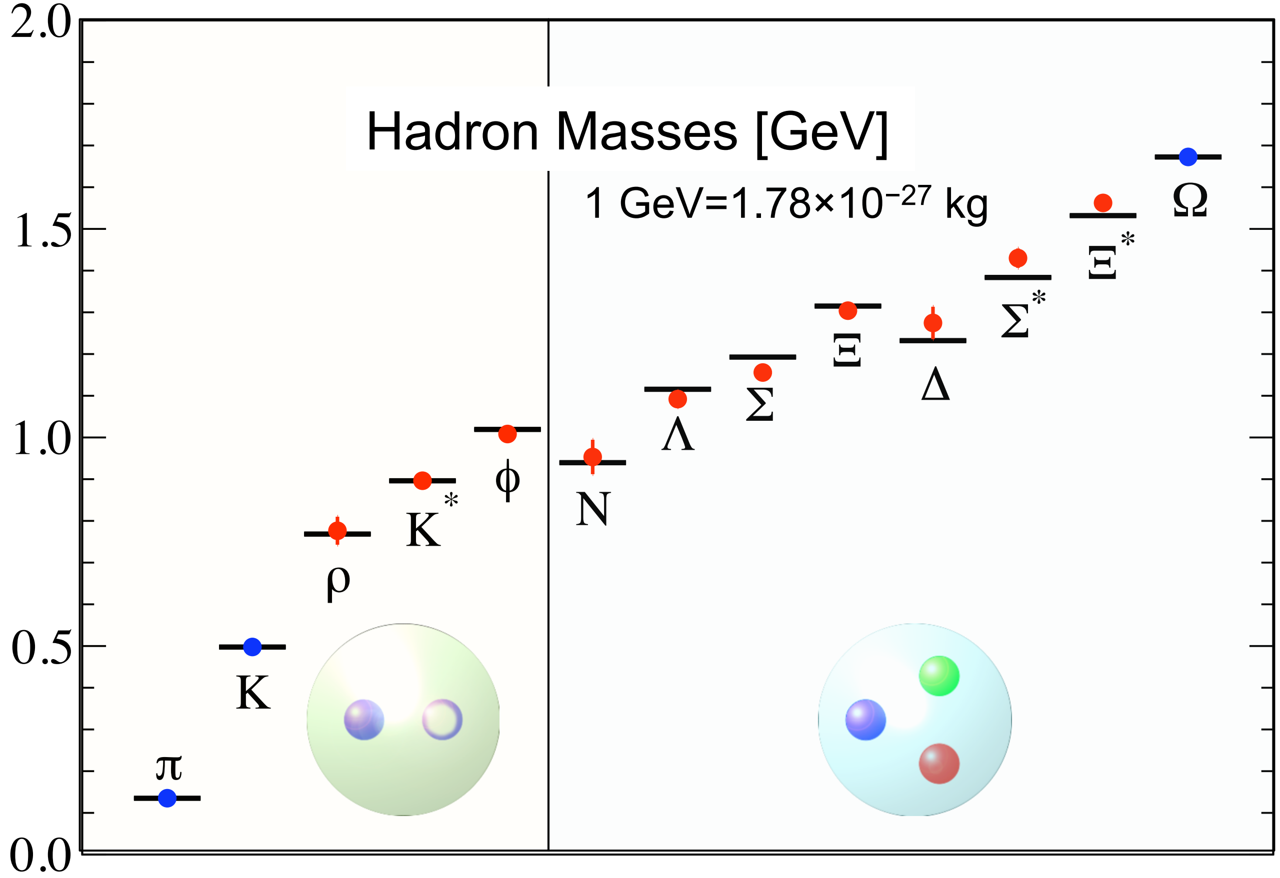
Quark line diagrams
from Wick contractions



Hadron Masses in 2+1 Flavor QCD

PACS-CS 09

input m_π, m_K, m_Ω ⇒ $m_u=m_d$, 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

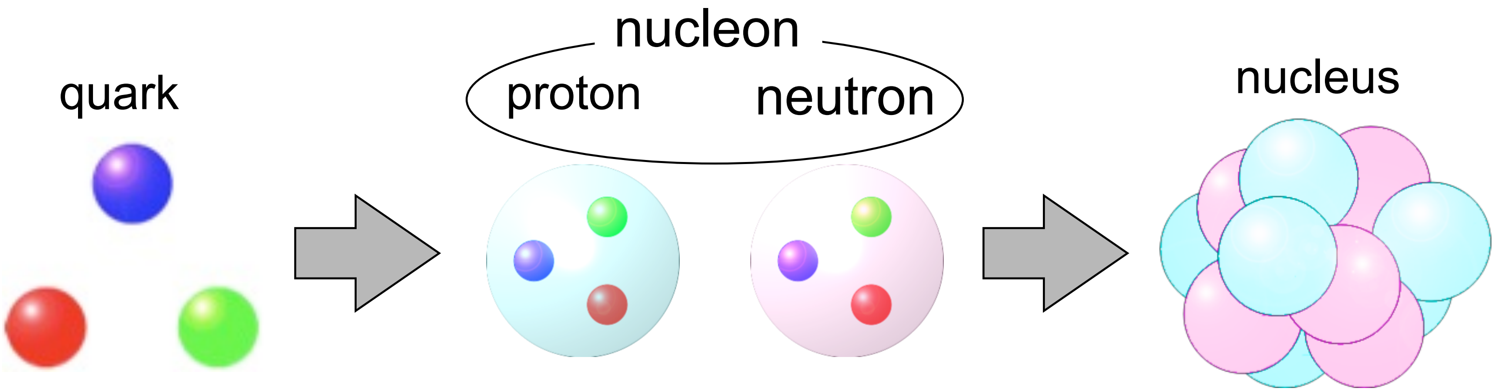
$K^0(d\bar{s})$ 497.6MeV

$K^+(u\bar{s})$ 493.7MeV

1%

Multi-physics toward precision measurement

- Hadron-Hadron interactions



Multi-scale physics from quarks to nuclei

1+1+1 Flavor QCD+QED

PACS-CS 12

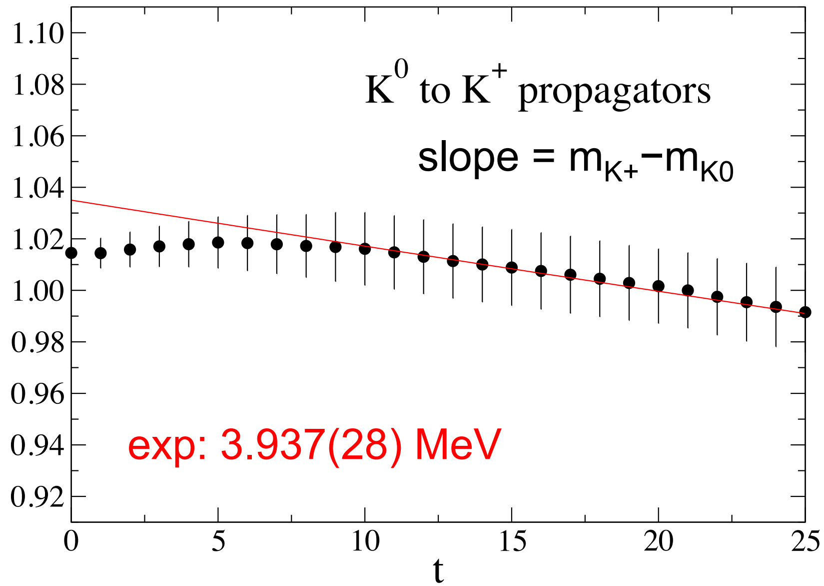
Isospin symmetry breaking

- 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) $\Rightarrow$ $m_u\neq m_d\neq m_s$ (1+1+1 flavor)



lattice size = $32^3\times 64$
a ∼ 0.1 fm

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

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_{Ω}(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_π=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

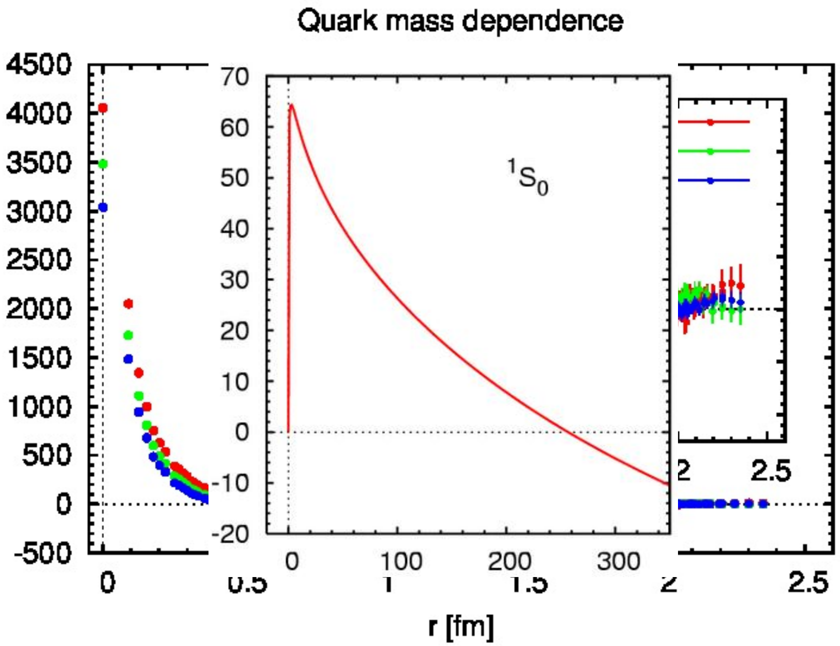
} Heavy quark effects?

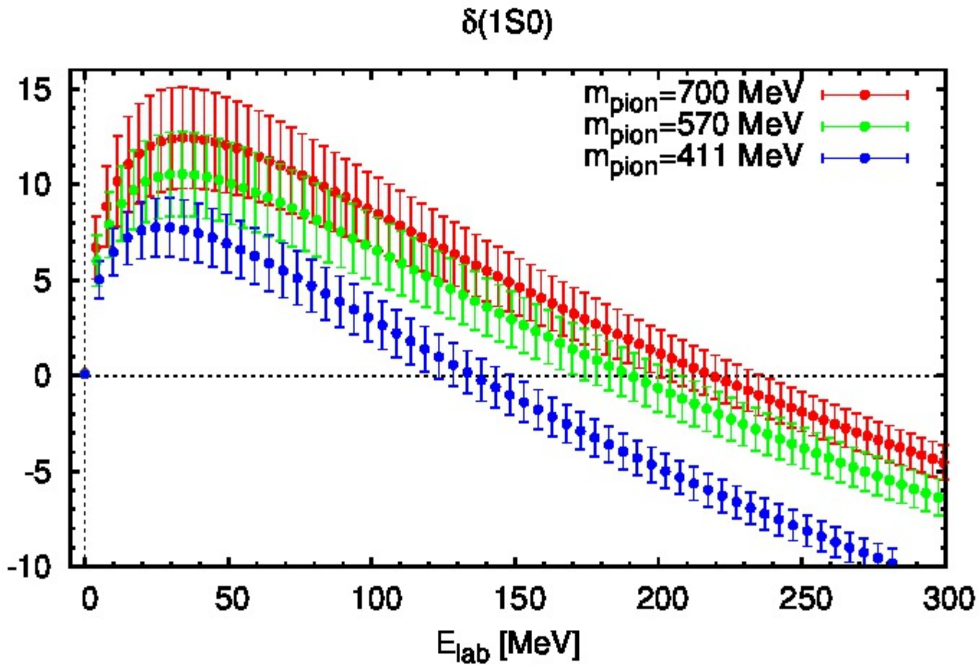
Physical point simulation is necessary

NN Potential

HAL QCD@Lattice 2013

2+1 flavor QCD, m_π = 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 ?

Other Primary Research Subjects

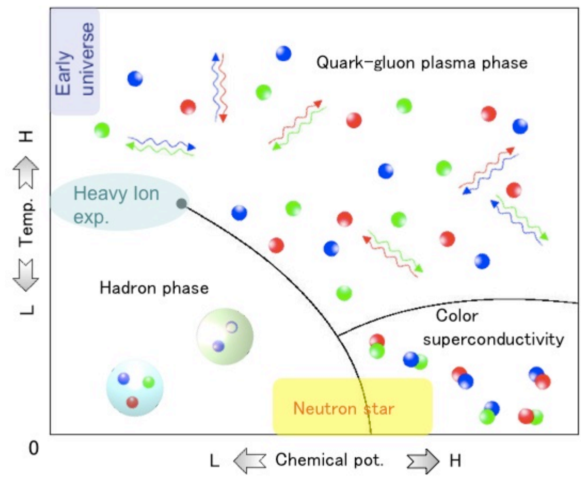
Details of research results will be explained in parallel track on Wed.

- 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_π=0.30, 0.41 GeV

- Nonperturbative renormalization with a finite volume technique
  - Running coupling constant and quark masses in 2+1 flavor QCD

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

Expected phase diagram



Collaborations

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

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

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

- International/Japan Lattice Data Grid (ILDG/JLDG)

  ⇒ Overview by Yoshié-san this morning

- Joint Institute for Computational Fundamental Science (JICFuS)

  ⇒ Future plan session on Thu.

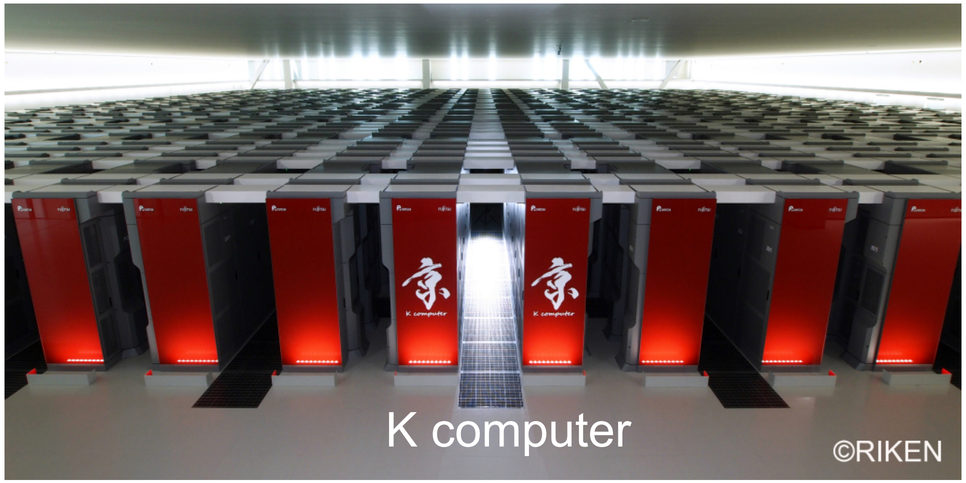
Future Plan

Future plan session on Thu.

HPCI Strategic Field Program (FY2011～FY2015)

- 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



Summary

Historical role of PACS-CS/T2K-Tsukuba

- 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 Construction of Nuclei with heavy m_{ud}
1PF class 10PF class	HA-PACS K computer	Large scale simulation of 1+1+1 flavor QCD+QED Construction of Nuclei at the physical point