PACS10 project in lattice QCD

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10th symposium on Discovery, Fusion, Creation of New Knowledge by Multidisciplinary Computational Sciences @ University of Tsukuba, October 15-16 2018

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Not PACS-X project

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PACS10 project

PACS = PACS Collaboration

Tsukuba	N. Ishizuka, J. Kakazu, Y. Kuramashi, N. Namekawa, T. Taniguchi, N. Ukita, T. Yamazaki, T. Yoshié
Riken-CCS	Y. Nakamura, E. Shintani
Hiroshima	K.-I. Ishikawa
Tohoku	N. Tsukamoto, S. Sasaki

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10 = spatial extent of 10 fm

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Purpose of PACS10 project

Removing all main systematic uncertainties in lattice QCD

using three ensembles at physical m_π on (10 fm)^3 volume

Outline

- PACS10 project
  - Lattice QCD
  - pre-PACS10 project
  - PACS10 project
  - PACS10 configuration
- Result of PACS10 project
  - Light meson form factors
  - Nucleon form factors
  - Kaon semileptonic decay
  - Muon anomalous magnetic moment
- Summary

Lattice QCD

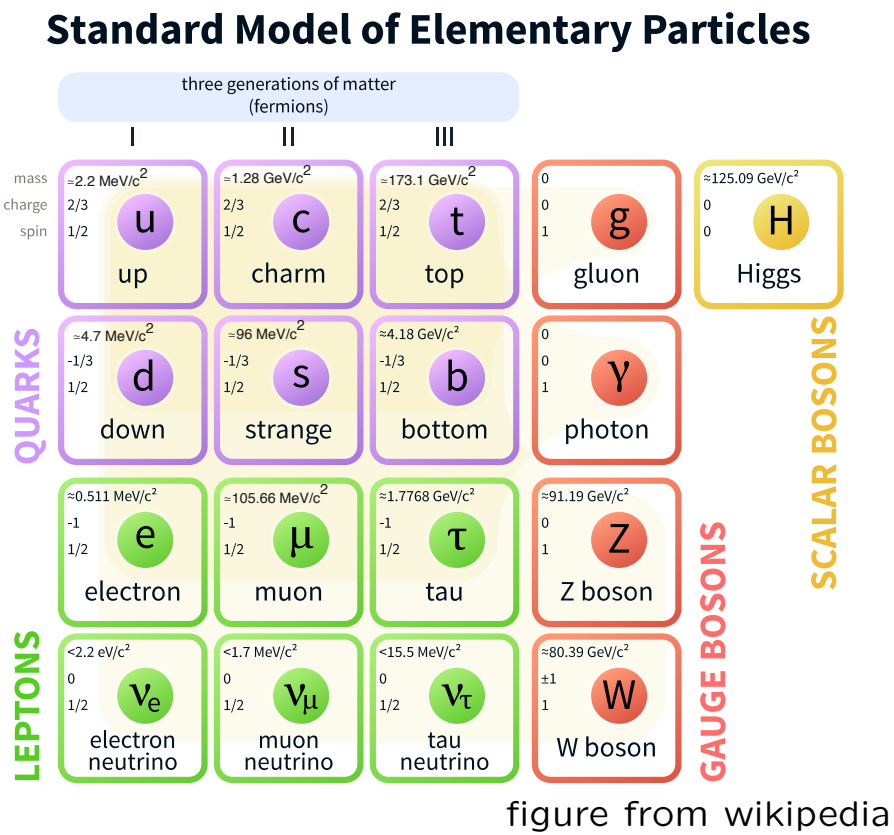


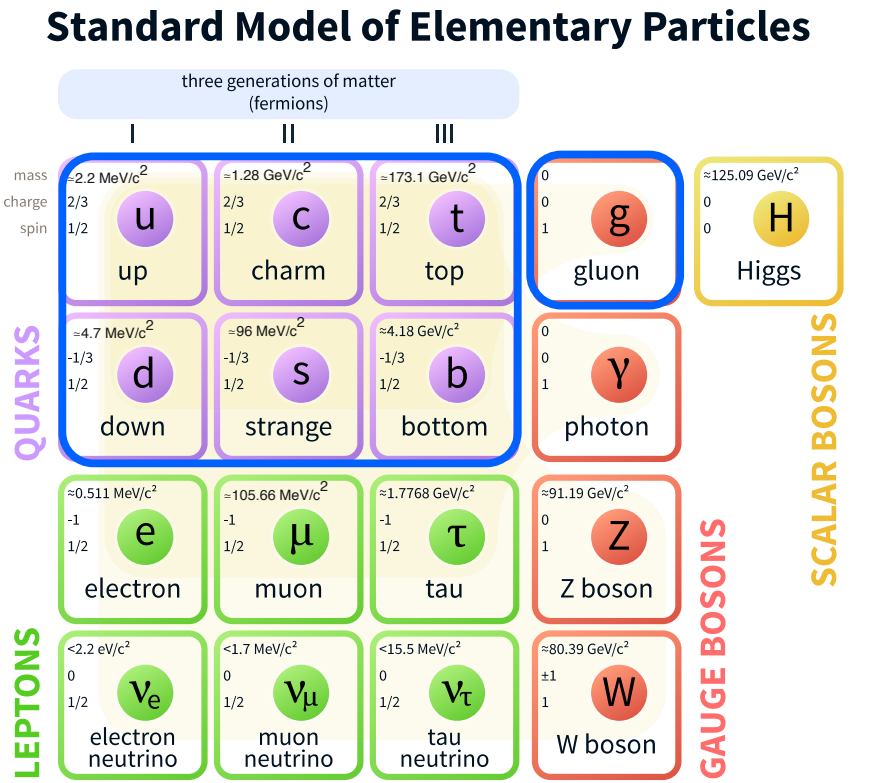
figure from wikipedia

Lattice QCD

QCD =

Quantum Chromodynamics

theory of strong interaction for quarks and gluons



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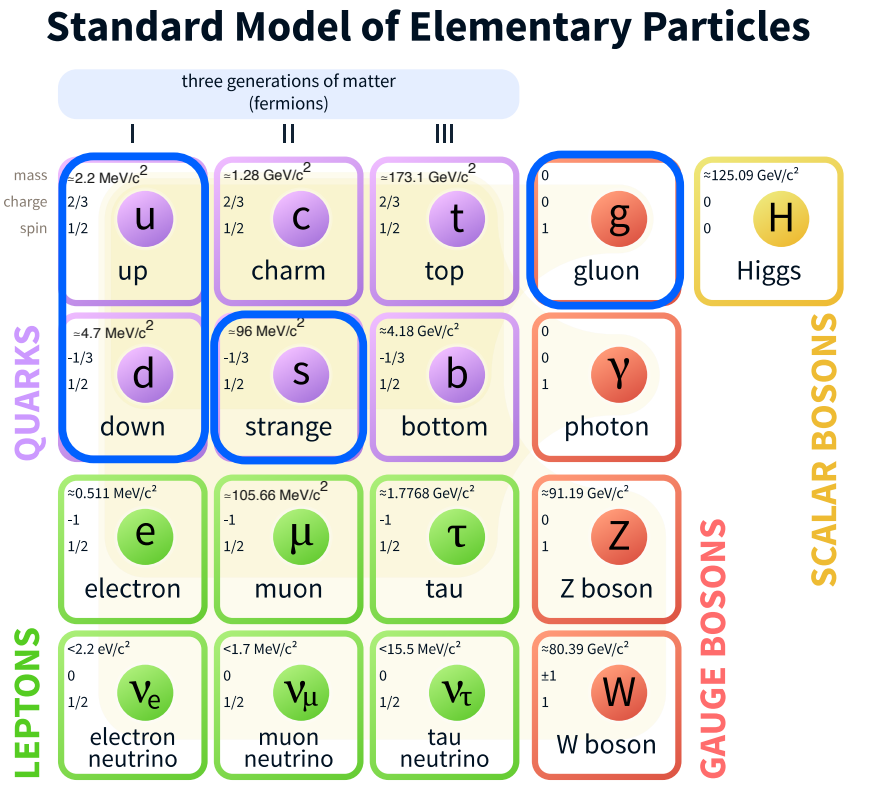
theory of strong interaction for quarks and gluons

dynamical u, d, s quark effect in low energy physics

$N_f = 2+1$ QCD $(m_u = m_d \ll m_s)$

what we want to calculate



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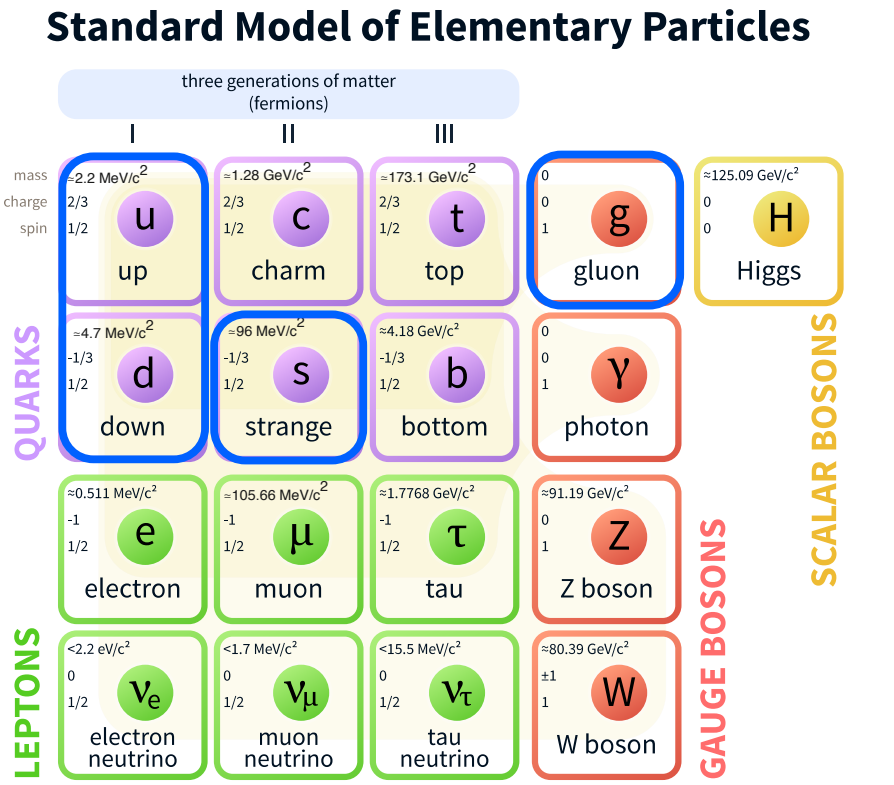
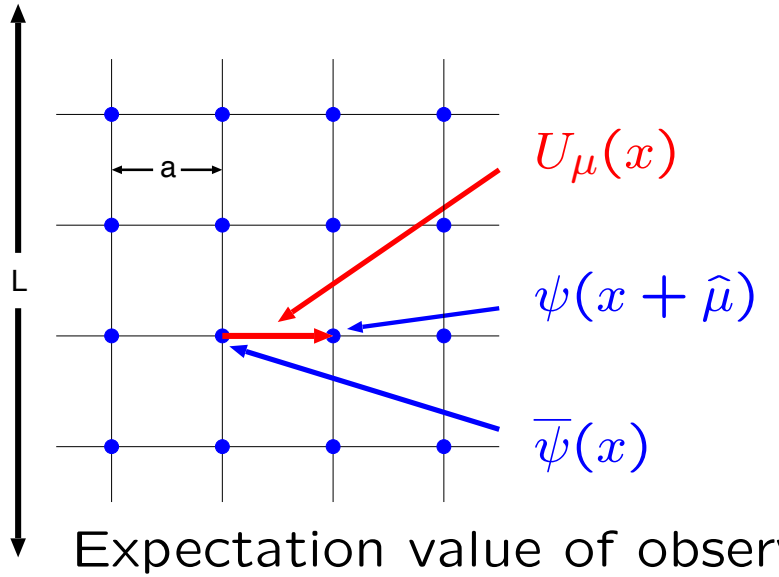


figure from wikipedia

non-perturbative calculation method is necessary for QCD.

Lattice QCD: non-perturbative calculation using supercomputer

Lattice QCD non-perturbative calculation using supercomputer



finite lattice spacing a (regularization)

momentum cut-off : $|p| \leq \pi/a$

4d finite spacetime $= L^3 \times T$

quarks $\psi(x)$: on site

gluons $U_\mu(x)$: link between sites

Expectation value of observable $\mathcal{O}(\overline{\psi}, \psi, U)$

$$\langle \mathcal{O}(\overline{\psi}, \psi, U) \rangle = \frac{1}{N} \sum_{i=1}^{N} \mathcal{O}(D^{-1}, U_i) + O(1/\sqrt{N})$$

quark propagator $D^{-1}[U, m_q]$, quark mass m_q

Monte Carlo simulation

gauge configuration U_i generated with proper probability

each U_i generation needs $O(10^4)$ $D^{-1}[U, m_q]$

$D[U, m_q] = O(10^9) \times O(10^9)$ matrix when $L = T = 10^2$

$m_q \to$ small $\Rightarrow$ computational time $\to$ long

Large computational resource necessary

Lattice QCD

Simulation parameters: $m_\pi(m_{u,d,s})$, $L^3 \times T$, a

m_π: pion mass (pion = lightest composite particle of quarks in QCD)

Lattice QCD→QCD need $m_\pi = m_\pi^{\rm phys}$, $L \gtrsim 6/m_\pi$, $a \to 0$

unphysical m_π ($m_\pi^{\rm phys} = 0.135$ GeV): cost $\propto m_\pi^{-(2\sim9)}$

(depend on solver algorithm of $D^{-1}[U, m_q]$)

traditionally extrapolate to $m_\pi^{\rm phys}$ with several data at larger m_π

finite L: cost $\propto L^3 T$

finite L effect is negligible in $L \gtrsim 6/m_\pi$

finite a: cost $\propto a^{-(2\sim6)}$ (depend on Monte Carlo algorithm)

need several data in small a for $a \to 0$

main systematic uncertainty in lattice QCD

pre-PACS10 project

History of lattice QCD Collaboration in University of Tsukuba

Collaboration	CP-PACS		CP-PACS+JLQCD	PACS-CS	PACS
Main resource	CP-PACS		Earth Simulator	PACS-CS, T2K	K[†]
N_f	0	2	2+1	2+1	2+1
m_π [GeV]	> 0.3	> 0.5	> 0.6	> 0.156	0.146
L [fm]	3.0	2.5	2.0	2.9	8.1
a [fm]	> 0.05	> 0.1	> 0.07	0.09	0.08
$a \to 0$	○	○	○		
year	∼2002		∼2006	∼2009	∼2015

$N_f = 0$ no dynamical quark effect
$N_f = 2$ dynamical quark effect for u, d
$N_f = 2 + 1$ dynamical quark effect for u, d, s

$m_\pi^{\text{phys}} = 0.135$ GeV

[†]MEXT SPIRE Field 5 Subject 1

pioneering study in each period

PACS10 project since 2016

Project	PACS10			pre-PACS10
Resource	OFP			K
N_f	2+1			2+1
m_π [GeV]	0.135			0.146
L [fm]	10			8.1
$L^3 \cdot T$	128^4	160^4	256^4	96^4
a [fm]	0.08	0.06	0.04	0.08
$a \to 0$	◯			
OFP node	256	512	2048	—
status	done	almost done	running	—
Name	PACS10-1	PACS10-2	PACS10-3	K conf

Purpose

Removing all main systematic uncertainties in lattice QCD

using three ensembles at physical m_π on (10 fm)^4 volume

Results of PACS10 project

precise determination of physical quantity from lattice QCD

I. quantitatively understand property of hadrons (mass, size, etc.)
reproduce experimental values with high accuracy

hadron = composite particles of quarks, e.g. mesons ($\pi, K, \cdots$) and nucleon (proton, neutron)

II. search for new physics beyond the standard model
discrepancy between theoretical calculation and experiment

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1. Light meson electromagnetic form factors
2. Nucleon form factors

Finite volume effect PACS10-1 and $(5.4\ \mathrm{fm})^3$: [arXiv:1807.06237]

II. search for new physics beyond the standard model
discrepancy between theoretical calculation and experiment

3. Kaon semileptonic decay
4. Muon anomalous magnetic moment

Results from PACS10-1 and PACS10-2 configurations

All results are preliminary.

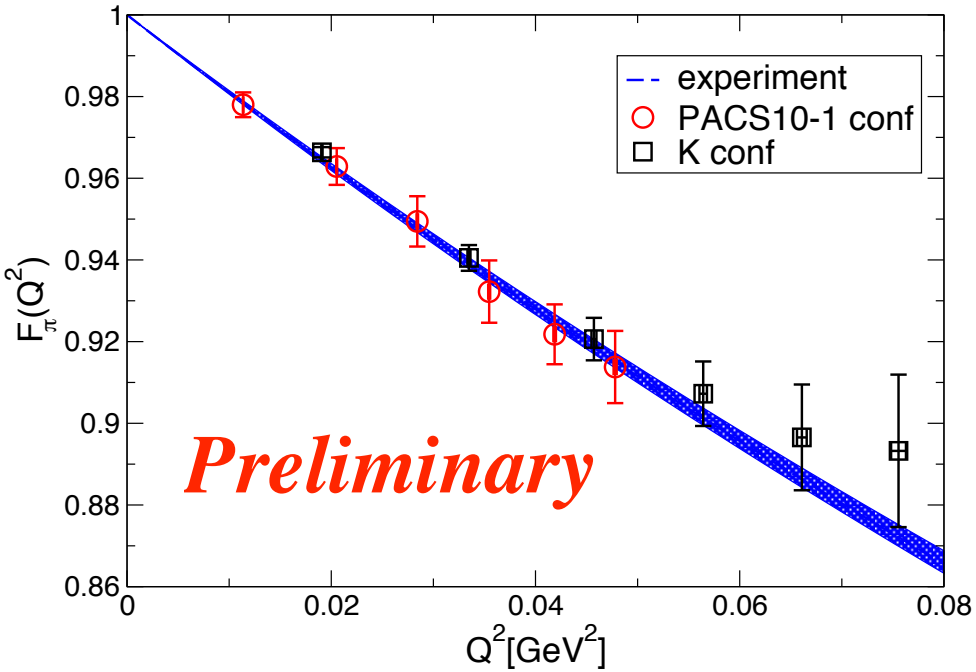
1. Light meson form factors by J. Kakazu

Electromagnetic form factor $F(Q^2) = 1 - \frac{1}{6}Q^2\langle r^2\rangle + \cdots$

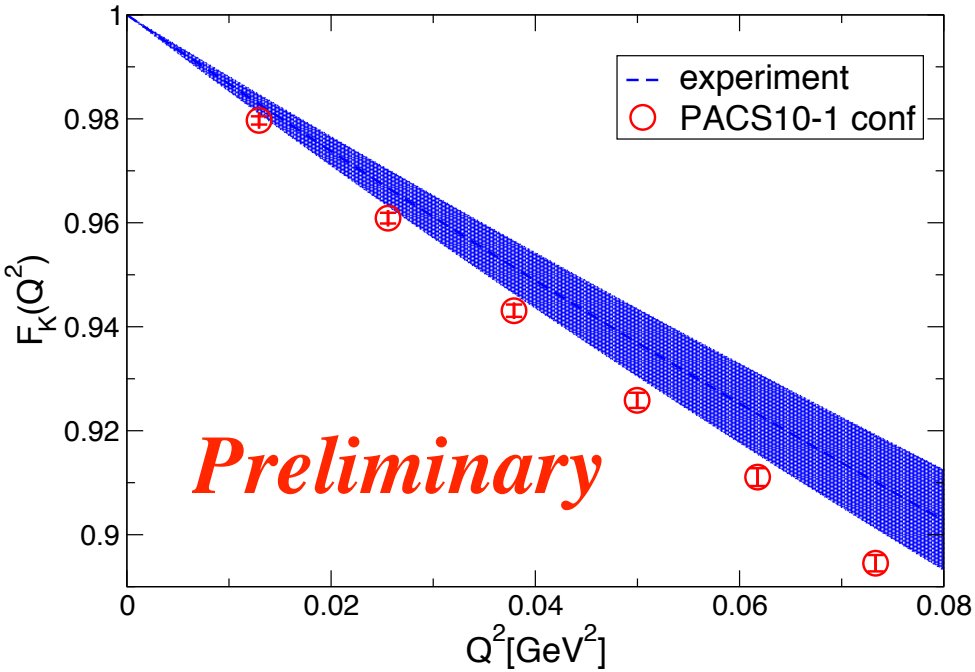
$\langle r^2\rangle$ mean square charge radius, Q^2 momentum transfer

$F(Q^2) \neq 1 \rightarrow$ hadron has internal structure.

pion



kaon



advantage of PACS10: smaller q^2 due to large L

[experiment from PDG18]

pion: agree with the experiment

kaon: agree with experiment within 1.5σ

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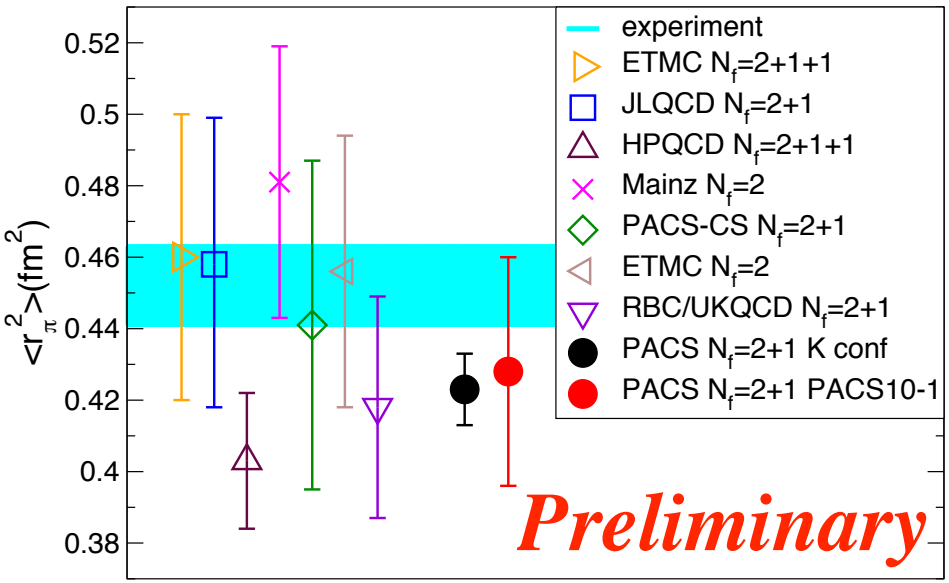
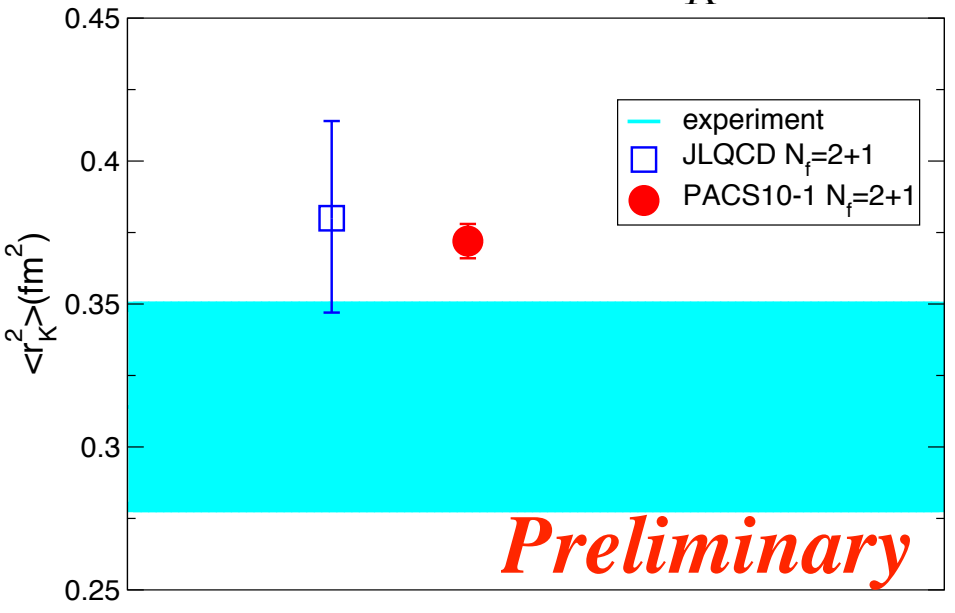
comparison of $\langle r_\pi^2\rangle$



comparison of $\langle r_K^2\rangle$



[experiment from PDG18]

pion: agree with the experiment and other lattice results

kaon: agree with experiment and closer to another lattice result

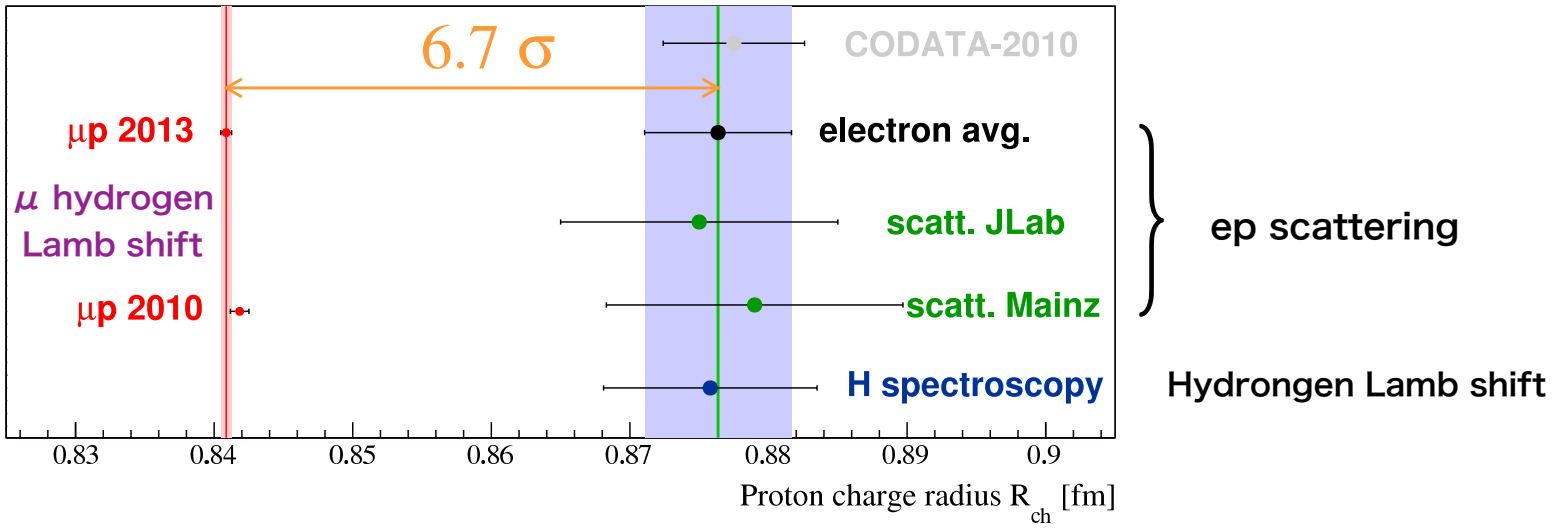
will investigate systematic errors

2. Nucleon form factors

Nucleon: proton p and neutron n

Proton size puzzle

Proton charge radius : $G_E(q^2) = 1 - \frac{q^2}{6}\langle r^2 \rangle_E + \mathcal{O}(q^4)$



[Arrington, arXiv:1506.00873]

Slide from S. Sasaki in QCDdownunder2017

$\langle r^2 \rangle_E$ differs in μ-proton and e-proton experiments.

Several experiments proposed to resolve this puzzle

3. Kaon semileptonic decay

Standard model predicts

$$\Delta_{\mathrm{CKM}} = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = 0$$

V_{ij}: Cabbibo-Kobayashi-Maskawa matrix element

if $\Delta_{\mathrm{CKM}} \neq 0$, signal of new physics

$|V_{ud}| = 0.97420(21)$ nuclear β decay [PoS(CKM2016):028]

$|V_{ub}| = O(10^{-3})$ B meson decay

Determination of $|V_{us}|$ using lattice QCD

Experimental result of $K \to \pi l \nu$ decay (l: lepton, ν: neutrino)

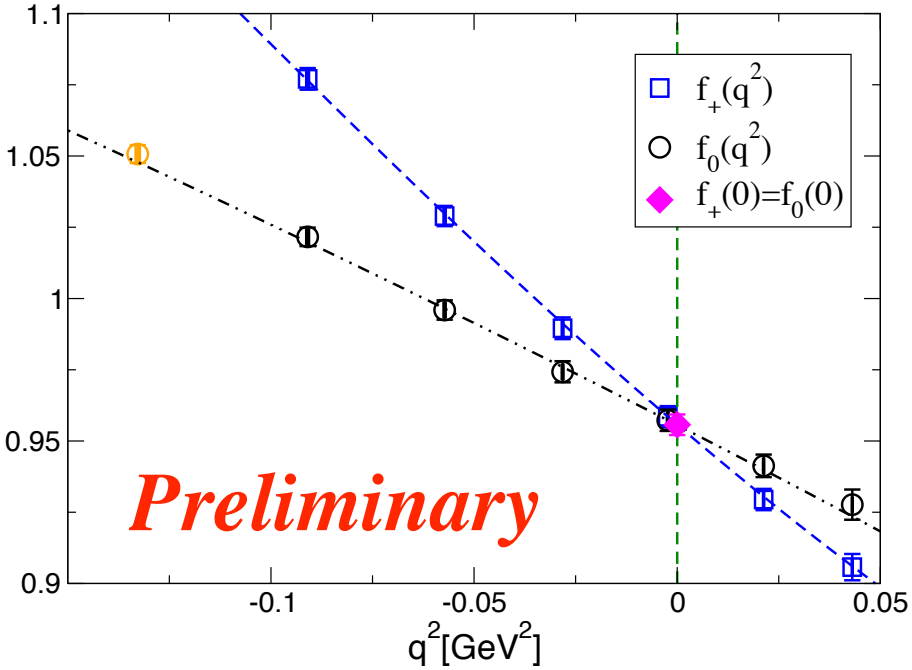
$$|V_{us}| f_+(0) = 0.21654(41)$$ [PoS(CKM2016):032]

$Kl3$ form factor $f_+(0)$ from lattice QCD calculation $\to |V_{us}|$

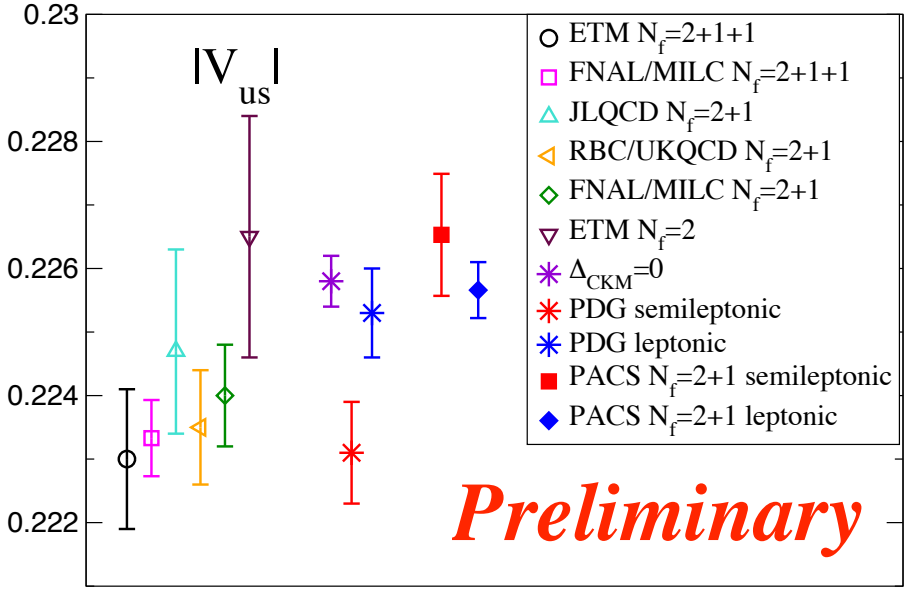
3. Kaon semileptonic decay (PACS10-1) by J. Kakazu

$Kl3$ form factors: $f_+(q^2)$ and $f_0(q^2)$, $f_+(0) = f_0(0)$

$f_+(q^2)$ and $f_0(q^2)$



comparison of $|V_{us}|$



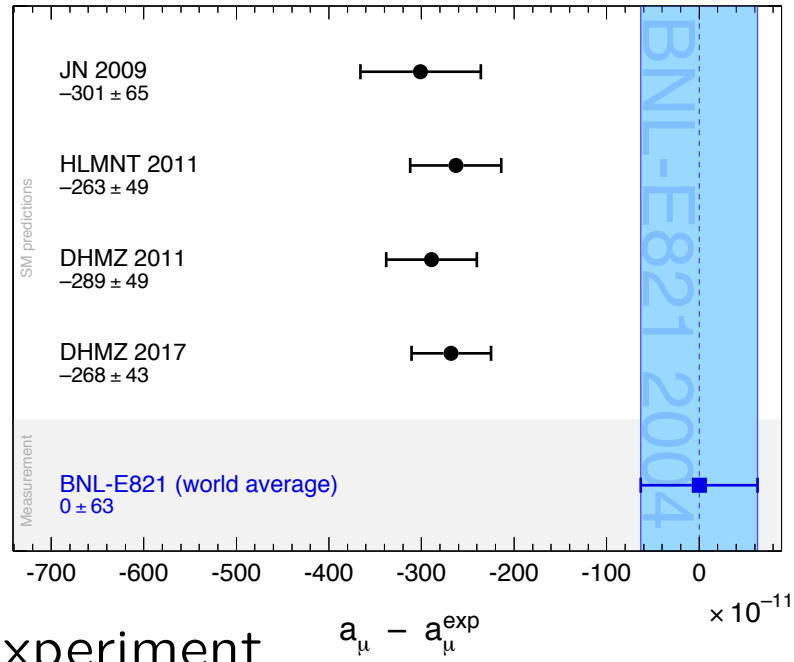
Our $|V_{us}|$ agrees with $\Delta_{\mathrm{CKM}} = 0$

and another determination of $|V_{us}|$ (leptonic decay $K \to l\nu$).

will investigate systematic errors for final result

4. Muon anomalous magnetic moment

figure and values from PDG18



$$a_\mu^{\rm exp} = 116592091(63)\times 10^{-11}$$

$$a_\mu^{\rm SM} = 116591823(43)\times 10^{-11}$$

$$\longleftarrow \quad a_\mu^{\rm exp} - a_\mu^{\rm SM} = 268(76)\times 10^{-11}$$

SM: Standard Model

3.5σ difference = New physics?

Need to check more precisely

Experiment

FNAL(US) and J-PARC(Japan): $\frac{1}{2} \sim \frac{1}{4}$ error in ∼2020

Theory

Main uncertainty from leading order Hadronic Vacuum Polarization

$a_\mu^{\rm hvp} = 6931(34) \times 10^{-11}$ by phenomenology

desired Lattice QCD calculation for new physics search

Summary

PACS10 project

Removing all main uncertainties in lattice QCD

$$m_\pi = 0.135 \text{ GeV},\ L = 10 \text{ fm},\ a = 0.8, 0.6, 0.4 \text{ for } a \to 0$$

Encouraging results obtained from PACS10 configuration

- charge radius for π, K, N
- new physics search from $|V_{us}|$ and a_μ

Future works

- finish PACS10-3 generation
- precise physical quantity for stable hadrons [arXiv:1807.06237]
  mass, decay constant, charge radius, $\cdots$
- multi-hadron systems
  scattering, strong and weak decays, nucleus, $\cdots$