Calculations using PACS10 configuration

Takeshi Yamazaki

University of Tsukuba

Center for Computational Sciences

Large-scale lattice QCD simulation and application of machine learning

November 23-25 2023

Outline

- PACS10 project
- Calculations with PACS10 configuration
- Preliminary results
  - Hadron spectrum
  - Kaon semileptonic decay form factor
- Summary

PACS10 project

history of Collaboration name

CP-PACS (∼2006) → PACS-CS (∼2014) → PACS (2015∼)

name of supercomputer at CCS

PACS Collaboration

Tsukuba Univ.

N. Ishizuka, Y. Kuramashi, K. Sato, E. Shintani,

T. Taniguchi, N. Ukita, T. Yamazaki, T. Yoshié

Hiroshima Univ.

K.-I. Ishikawa, N. Namekawa

Kyoto Univ.

H. Watanabe

Riken-CCS

Y. Aoki, Y. Nakamura

Tohoku Univ.

S. Sasaki, R. Tsuji

PACS10 project

PACS Collaboration

Tsukuba	N. Ishizuka, Y. Kuramashi, K. Sato, E. Shintani, T. Taniguchi, N. Ukita, T. Yamazaki, T. Yoshié
Hiroshima	K.-I. Ishikawa, N. Namekawa
Kyoto	H. Watanabe
Riken-CCS	Y. Aoki, Y. Nakamura
Tohoku	S. Sasaki, R. Tsuji

Larger than (10 fm)^4 volume

PACS10 project

PACS Collaboration

Tsukuba	N. Ishizuka, Y. Kuramashi, K. Sato, E. Shintani, T. Taniguchi, N. Ukita, T. Yamazaki, T. Yoshié
Hiroshima	K.-I. Ishikawa, N. Namekawa
Kyoto	H. Watanabe
Riken-CCS	Y. Aoki, Y. Nakamura
Tohoku	S. Sasaki, R. Tsuji

Larger than (10 fm)^4 volume

Purpose of PACS10 project

Removing main systematic uncertainties in lattice QCD

three $N_f = 2 + 1$ ensembles at physical m_π on (10 fm)^4 volume

PACS10 project since 2016

	PACS10 configuration		
$L^3 \cdot T$	128^4	160^4	256^4
L [fm]	10.9	10.2	10.5
a [fm]	0.08	0.06	0.04
m_π [GeV]	0.135	0.138	0.141
m_K [GeV]	0.497	0.505	0.514
Machine	OFP	OFP	OFP→Fugaku
Node	512	512	2048→16384

OFP: Oakforest-PACS (KNL machine); Fugaku: since 2020

PACS10 configuration: More than (10 fm)^4 at the physical point

$N_f = 2+1$ nonperturbatively $O(a)$ improved Wilson clover quark action with 6-stout smeared link + Iwasaki gauge action

same actions as HPCI Field 5 project using K computer [PoS LATTICE2015 (2016) 075]

a^{-1} determined from Ξ baryon mass

Fugaku co-design outcome: [Ishikawa *et al.*:CPC(2023)]

QCD Wide SIMD (QWS) Library for Fugaku

→ Ken-ichi Ishikawa's talk

Resources: Fugaku in HPCI System Research Project
(hp200062, hp200167, hp210112, hp220079, hp230199)

Purpose of PACS10 project

precise determination of physical quantity
w/o main systematic uncertainties in lattice QCD

I. quantitatively understand property of hadrons
reproduce experimental values in high accuracy

- Hadron spectrum
- Light meson electromagnetic form factor — Kohei Sato's talk
- Nucleon form factor — Ryutaro Tsuji's talk

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

- Nucleon charge — Ryutaro Tsuji's talk
- Proton decay matrix element
- Hadron vacuum polarization
- Kaon semileptonic decay form factor

Purpose of PACS10 project

precise determination of physical quantity
w/o main systematic uncertainties in lattice QCD

I. quantitatively understand property of hadrons
reproduce experimental values in high accuracy

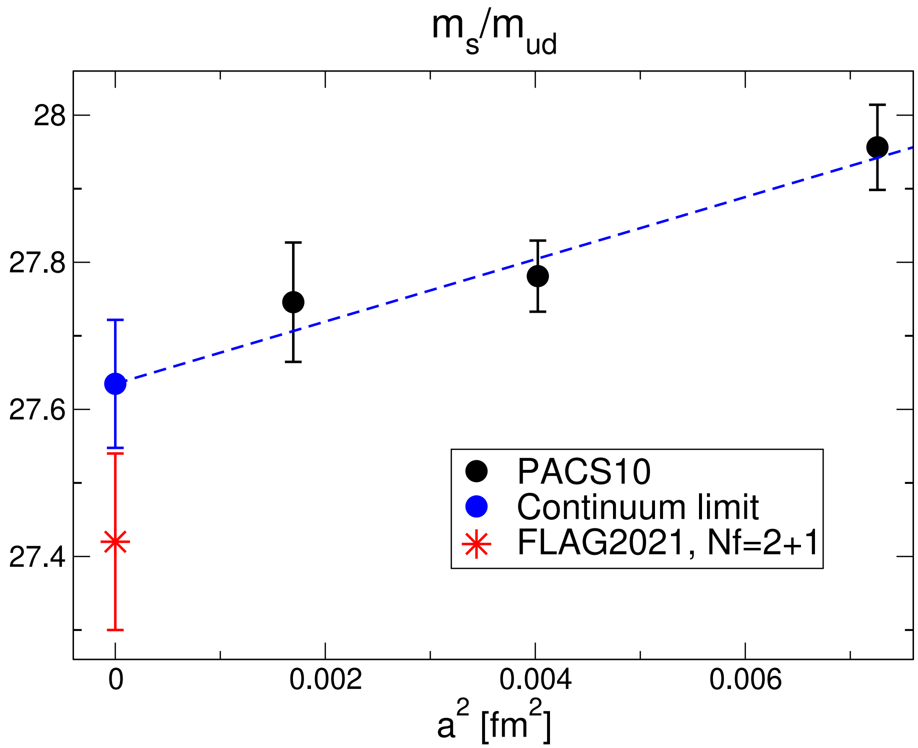
- Hadron spectrum
- Light meson electromagnetic form factor — Kohei Sato's talk
- Nucleon form factor — Ryutaro Tsuji's talk

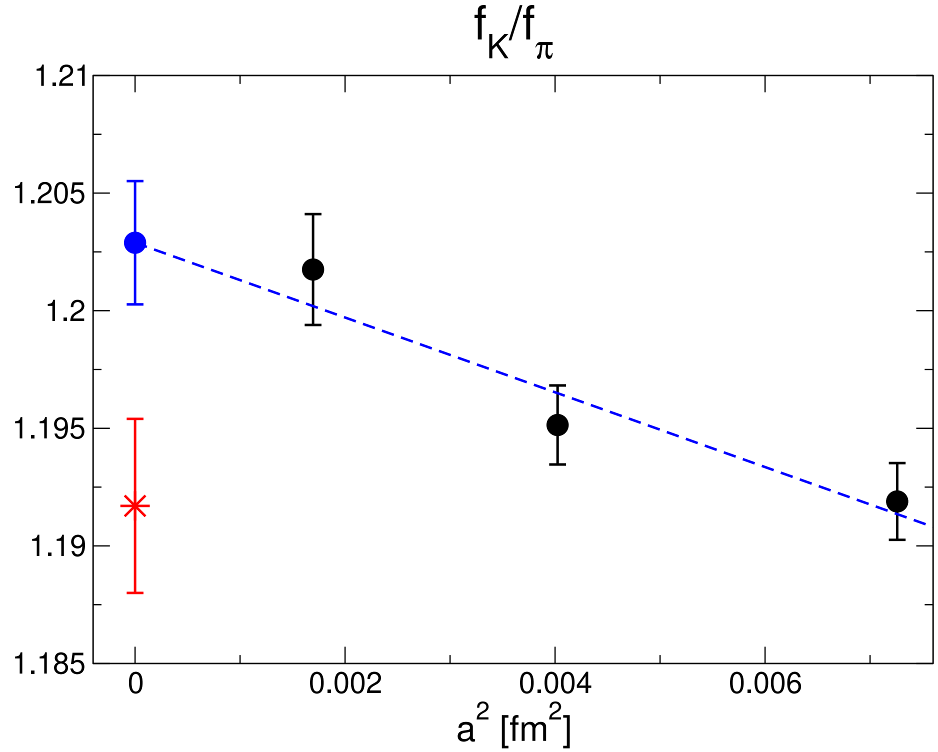
II. search for new physics beyond the standard model
discrepancy between theoretical calculation and experiment

- Nucleon charge — Ryutaro Tsuji's talk
- Proton decay matrix element
- Hadron vacuum polarization
- Kaon semileptonic decay form factor

Hadron spectrum

Ratios for quark mass and decay constant [Preliminary result]



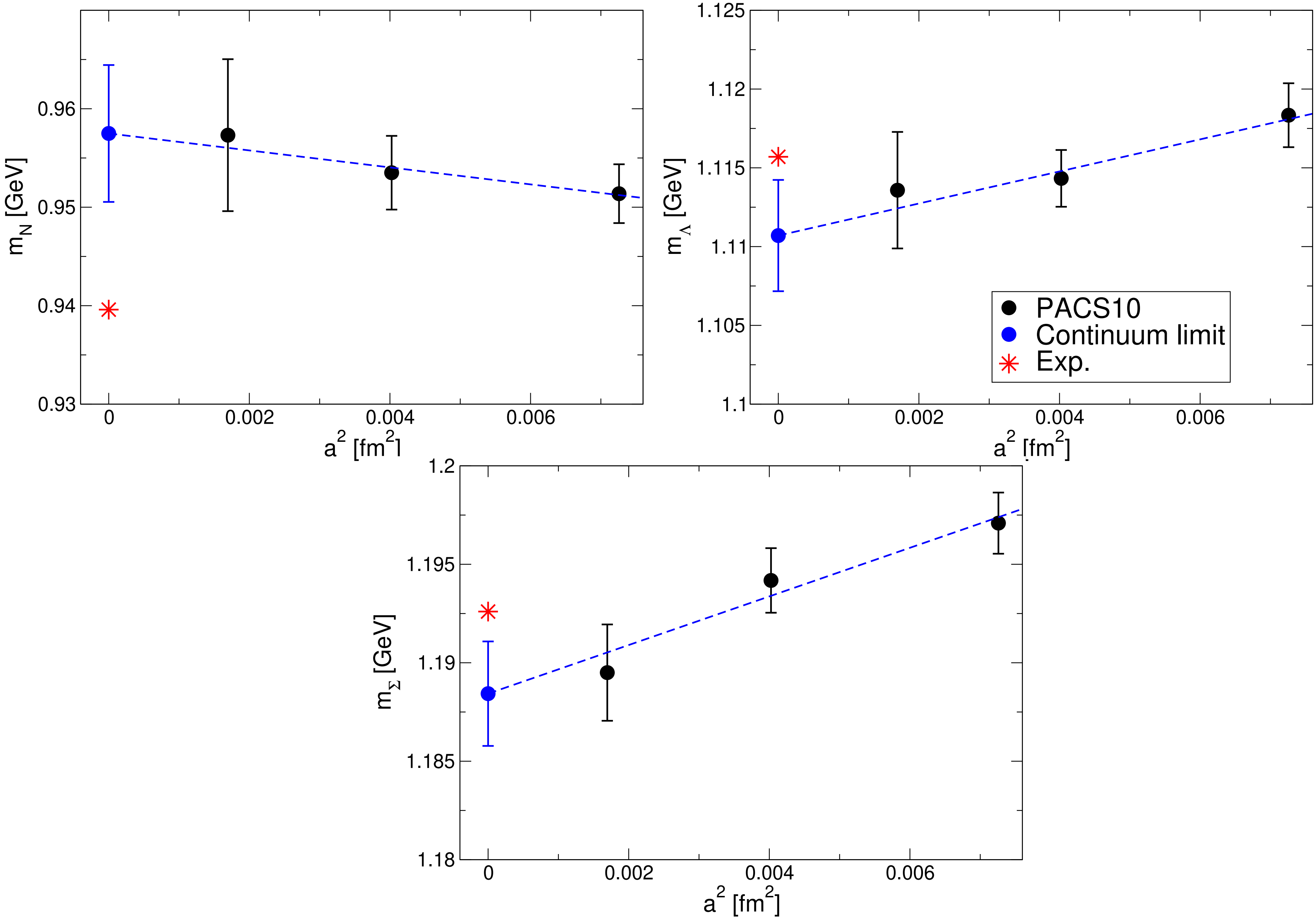


	PACS10 configuration			
$L^3 \cdot T$	128^4	160^4	256^4	64^4
L [fm]	10.9	10.2	10.5	5.5
a [fm]	0.08	0.06	0.04	0.08
m_π [GeV]	0.135	0.138	0.141	0.138
m_K [GeV]	0.497	0.505	0.514	0.496

Short m_π and m_K extrapolation to physical point

using m_π and m_K dependences determined from 64^4 reweigted data

Octet baryon masses [Preliminary result]



Kaon semileptonic ($K_{\ell 3}$) decay form factor

Introduction

Urgent task: search for signal beyond standard model (BSM)

Muon $g-2$ @ FNAL 2023 : 5σ away from SM(?)

$|V_{us}|$: a candidate of BSM signal

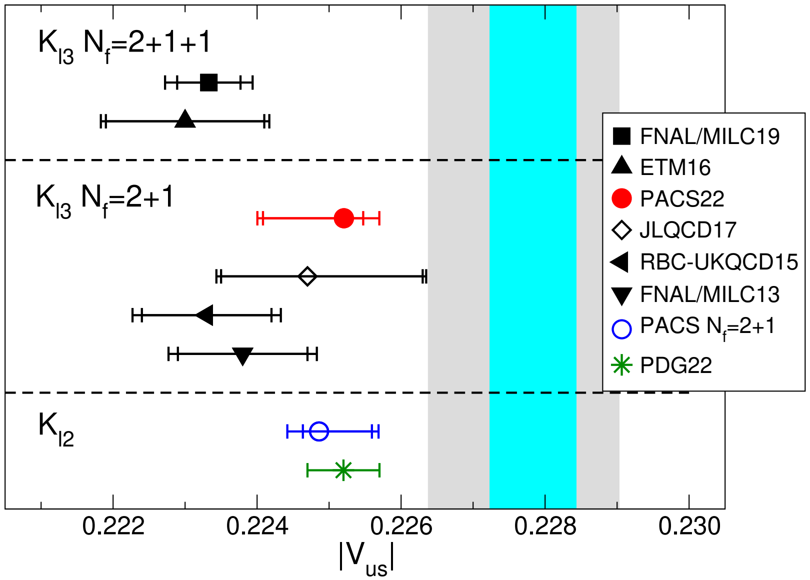
Most accurate $|V_{us}|$ from $K_{\ell 3}$ decay
['19 FNAL/MILC]

$\sim 5\sigma$ from CKM unitarity (cyan band)

$|V_{us}| \approx \sqrt{1-|V_{ud}|^2}$ w/ $|V_{ud}|$ ['18 Seng *et al.*]

$\sim 3\sigma$ (grey band) w/ $|V_{ud}|$ ['20 Hardy, Towner]

$\sim 2\sigma$ from $K_{\ell 2}$ decay [PDG22]



Important to confirm by several independent calculations

$K_{\ell 3}$ form factors with two PACS10 configurations ['20 PACS, '22 PACS]

$L \gtrsim 10$[fm] at physical point

Negligible finite L effect, tiny q^2 region, without chiral extrapolation

Largest uncertainty form finite a effect

This talk: preliminary result with 3rd PACS10 configuration

Simulation parameters

PACS10 configurations: $L \gtrsim 10$[fm] at physical point

$N_f = 2+1$ six-stout-smeared non-perturbative $O(a)$ Wilson action
+ Iwasaki gauge action

β	$L^3 \cdot T$	L[fm]	a[fm]	a^{-1}[GeV]	M_π[MeV]	M_K[MeV]	$N_{\rm conf}$	$t_{\rm sep}$[fm]
2.20	256^4	10.5	0.041	4.792	142	514	20	3.5, 4.0
2.00	160^4	10.2	0.063	3.111	137	501	20	2.3–4.1
1.82	128^4	10.9	0.085	2.316	135	497	20	3.4–3.9

(1000–2500 measurements in each $t_{\rm sep}$)

All the results on 256^4 are preliminary.

$K_{\ell 3}$ form factors $f_+(q^2), f_0(q^2)$ from 3-point function

w/ $Z(2) \otimes Z(2)$ random source spread in L^3, color, spin ['08 RBC-UKQCD]

$$C_{V_\mu}(t,p) = \langle 0 | O_K(t_{\rm sep}, \mathbf{0}) V_\mu(t,\mathbf{p}) O_\pi^\dagger(0,\mathbf{p}) | 0 \rangle$$

V_μ: Local vector current renormalized by Z_V
Conserved vector current

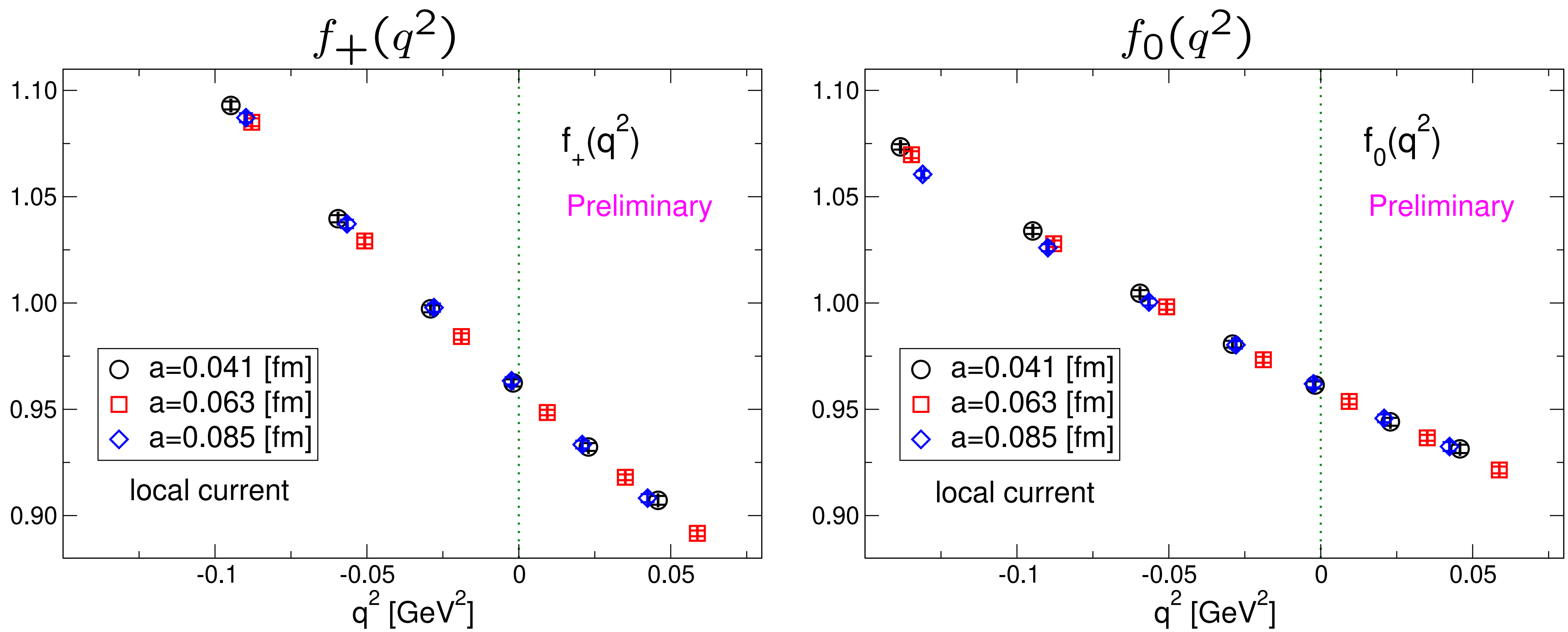
$$\langle \pi(p) | V_\mu | K(0) \rangle = (p_K + p_\pi)_\mu f_+(q^2) + (p_K - p_\pi)_\mu f_-(q^2)$$

$$f_0(q^2) = f_+(q^2) - \frac{q^2}{M_K^2 - M_\pi^2} f_-(q^2)$$

$p_K = (M_K, \mathbf{0}), p_\pi = (E_\pi, \vec{p})$
$q^2 = -(M_K - E_\pi)^2 + p^2$

Resources: Fugaku in HPCI System Research Project
(hp200062, hp200167, hp210112, hp220079, hp230199)

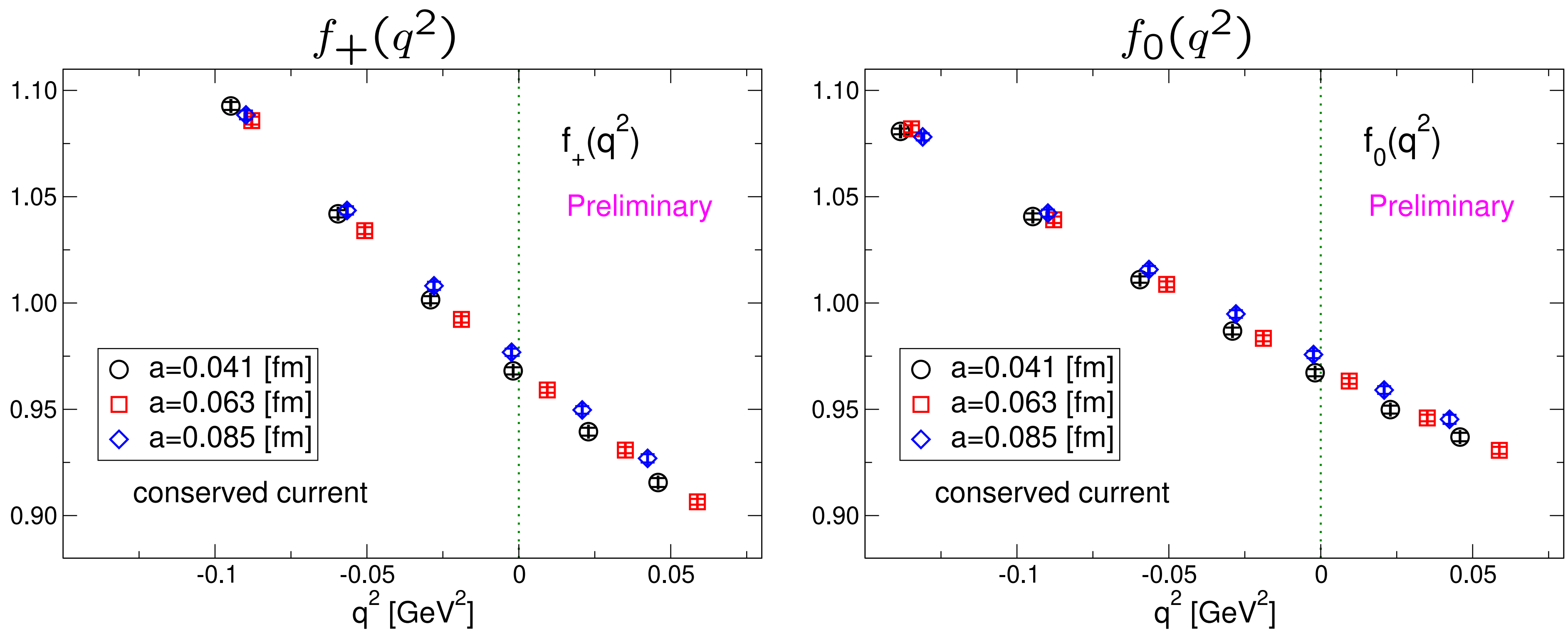
$f_+(q^2)$ and $f_0(q^2)$ at three lattice spacings (local current)



local : Little a dependence in small and large q^2 region

$\rightarrow$ Small a effect in $q^2 \sim 0$

$f_+(q^2)$ and $f_0(q^2)$ at three lattice spacings (conserved current)



local : Little a dependence in small and large q^2 region

$\to$ Small a effect in $q^2 \sim 0$

conserved : Relatively larger difference in all q^2 region

$f_+(q^2)$ and $f_0(q^2)$ decrease with a.

$\to$ expect to converge to local current data toward $a \to 0$

q^2 interpolation + tiny chiral extrapolation

$|V_{us}|f_+(0) = 0.21654(41)$ ['17 Moulson]

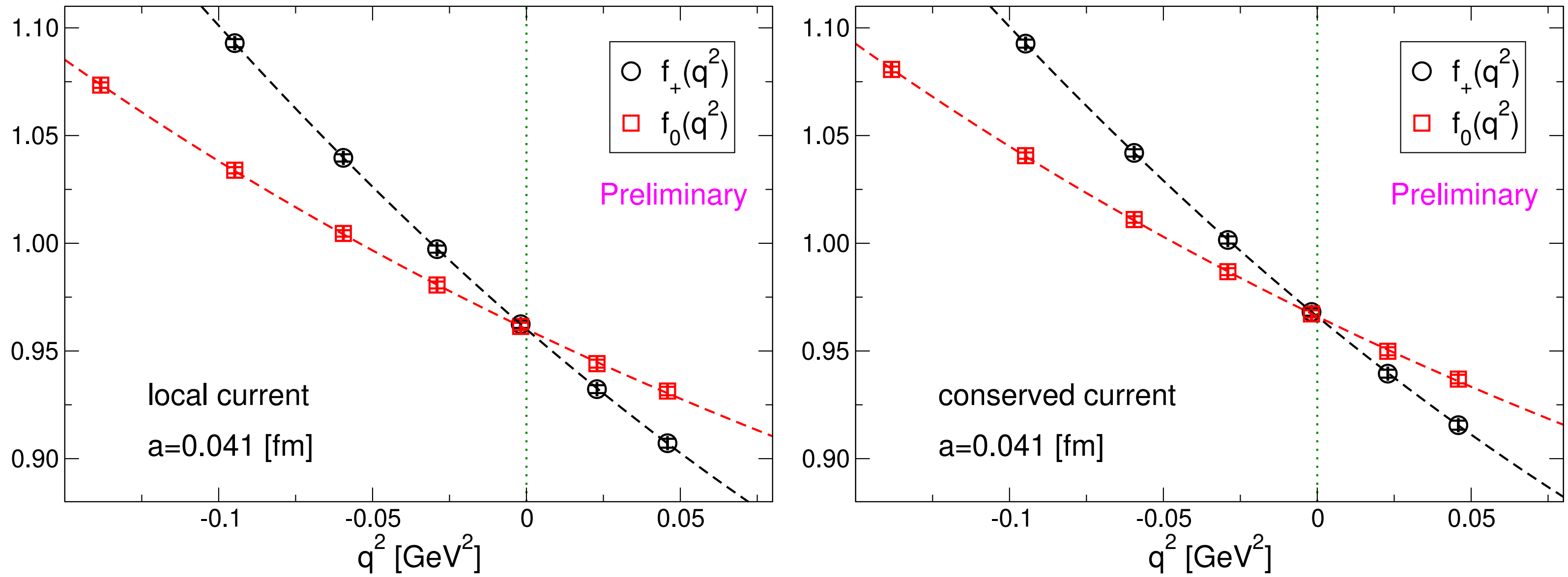
Fit based on SU(3) NLO ChPT with $f_+(0) = f_0(0)$ [PACS, PRD101,9,094504(2020)]

$$f_+(q^2) = 1 - \frac{4}{F_0^2}L_9(\mu)q^2 + K_+(q^2, M_\pi^2, M_K^2, F_0, \mu) + c_0 + c_2^+ q^4$$

$$f_0(q^2) = 1 - \frac{8}{F_0^2}L_5(\mu)q^2 + K_0(q^2, M_\pi^2, M_K^2, F_0, \mu) + c_0 + c_2^0 q^4$$

Fit parameters : $L_9(\mu), L_5(\mu), c_0, c_2^+, c_2^0$; Known functions : K_+, K_0 ['85 Gasser, Leutwyler]

using $\mu = 0.77$ GeV, $F_0 = 0.11205$ GeV (estimated from FLAG $F^{\text{SU(2)}}/F_0$ w/ $F^{\text{SU(2)}} = 0.129$ GeV)

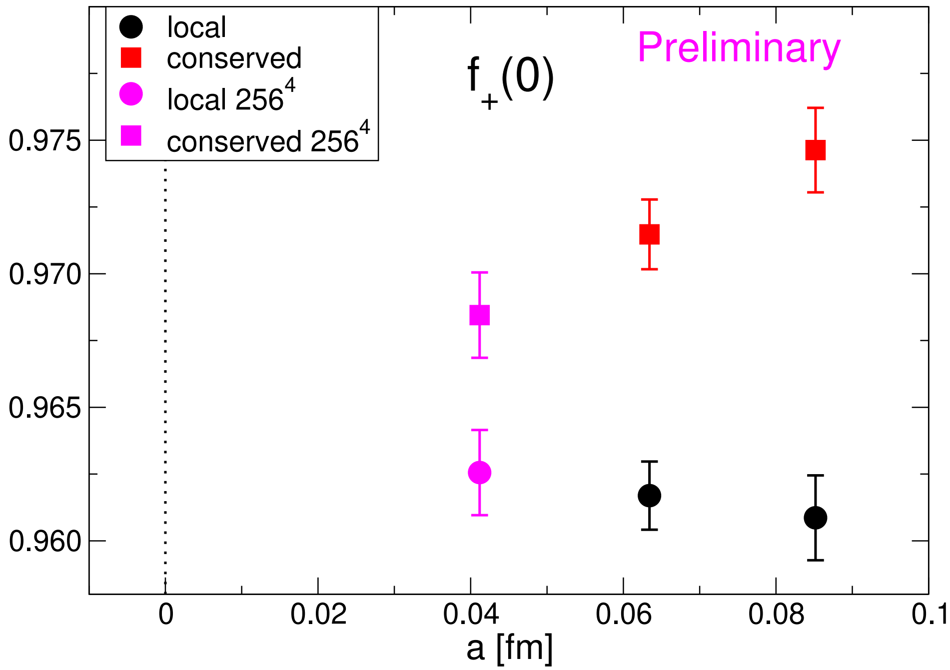


q^2 fits for (f_+, f_0) in each (local,conserved) work well.

Tiny extrapolation to physical M_{π^-} and M_{K^0} using same formulas

$M_\pi - M_{\pi^-}^{\text{phys}} \sim 2$ MeV, $M_K - M_{K^0}^{\text{phys}} \sim 16$ MeV

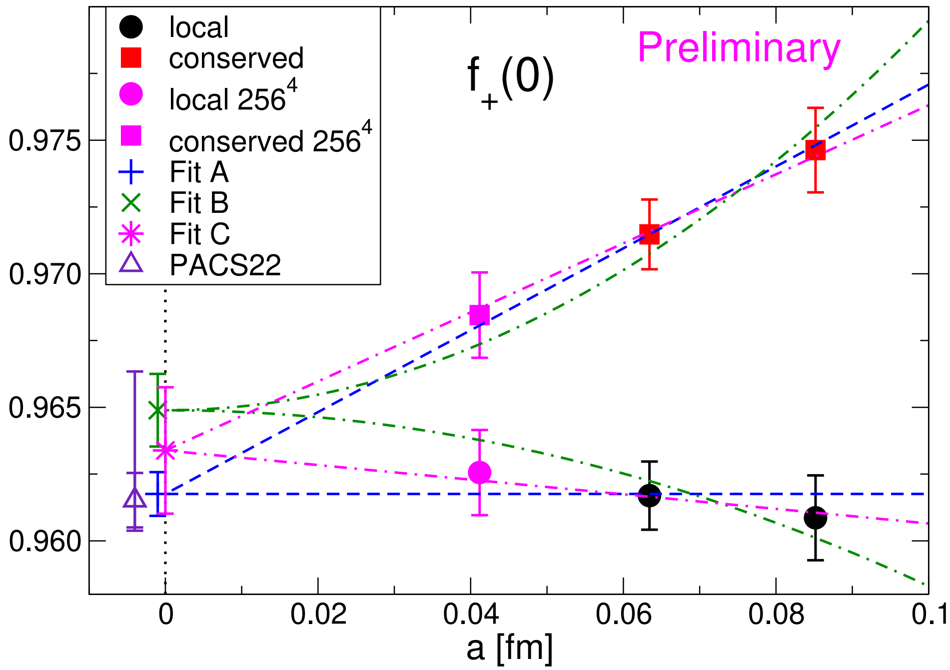
Continuum extrapolation of $f_+(0)$



local current: little a dependence after tiny chiral extrapolation

conserved current: clear a dependence

Continuum extrapolation of $f_+(0)$



local current: little a dependence after tiny chiral extrapolation

conserved current: clear a dependence

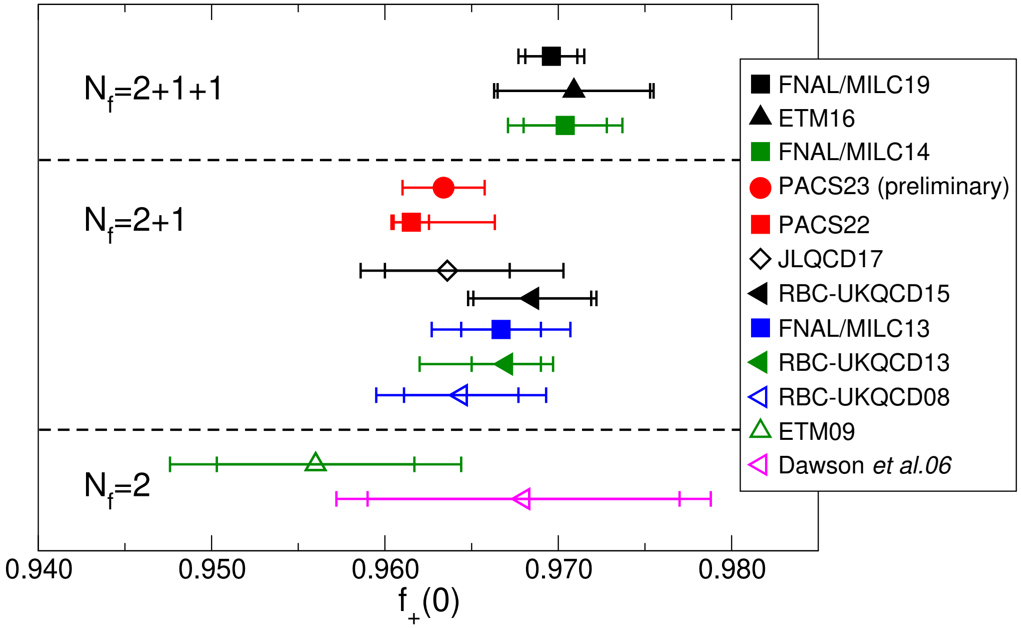
fit form	Fit A	Fit B	Fit C
local	C_0	$C_0 + C_2 a^2$	$C_0 + C_1 a$
conserved	$C_0 + C_1' a$	$C_0 + C_2' a^2$	$C_0 + C_1' a$

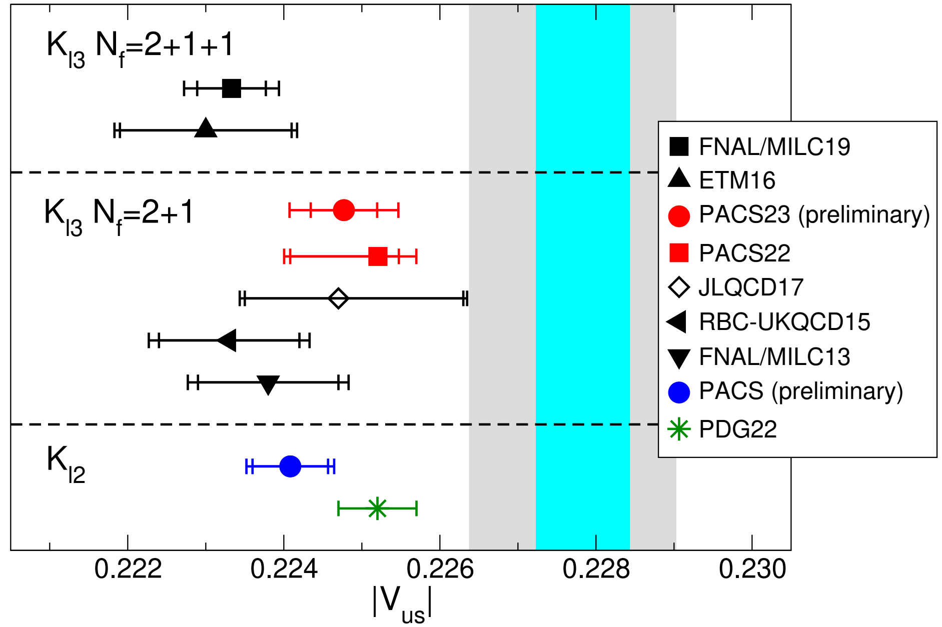
Result of Fit C covers other two fit results within the error.

Fit C adopted as our preliminary result

Consistent with PACS22 result

$f_+(0)$ and $|V_{us}|$





inner, outer = statistical, total(stat.+sys.)

inner, outer = lattice, total(lat.+exp.)

Standard model (SM) prediction using $|V_{us}| \approx \sqrt{1 - |V_{ud}|^2}$

cyan band: ['18 Seng *et al.*]; grey band: ['20 Hardy, Towner]

$f_+(0)$: Reasonably agree with previous lattice calculations $\lesssim 2\sigma$

Systematic error not estimated yet

$|V_{us}|$ using $|V_{us}|f_+(0) = 0.21654(41)$ ['17 Moulson]

agree with $|V_{us}|$ from K_{l2} using f_K/f_π $\quad \dfrac{|V_{us}|}{|V_{ud}|}\dfrac{f_K}{f_\pi} = 0.27683(35)$ ['19 Di Carlo *et al.*]

$2 \sim 3\sigma$ difference from CKM unitarity (grey and cyan bands)

Future work: Continue 256^4 calculation + IB correction

Summary

PACS10 Project

calculation w/o three main systematic uncertainties in lattice QCD

PACS10 configuration:

$V \gtrsim (10\text{fm})^4$ in physical point at three lattice spacings

various calculations

– Hadron spectrum
– Nucleon charge and form factor
– Light meson electromagnetic form factor
– Proton decay matrix element
– Hadron vacuum polarization
– Kaon semileptonic decay form factor

Future works

Continue calculations with 3rd PACS10 configuration

Reliable $a \to 0$ extrapolations

Estimate systematic uncertainties *e.g.*, isospin breaking, c quark effect