Unquenched QCD project by CP-PACS and JLQCD collaboration

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Introduction

- Light hadron spectrum
  - Direct test of QCD at low energy scale
  - Determination of fundamental parameters
    quark masses, etc.
- Systematic studies by CP-PACS and JLQCD collab.
  - quenched QCD
    - plaquette gauge + Wilson quark (CP-PACS, 2003)
    - RG-improved gauge + clover quark (tad.imp. c_{SW}) (CP-PACS, 2001)

    ⇨ systematic deviation from experiment
  - $N_f = 2$ QCD
    - RG-improved gauge + clover quark (tad.imp. c_{SW}) (CP-PACS, 2001)
    - plaquette gauge + clover quark (NP c_{SW}) (JLQCD, 2003)

    ⇨ deviation is reduced
  - Next (and final) step : $N_f = 3$ QCD

Computing facilities





machines	GF/ node	total		for LQCD	
		# Node	GFlops	# Node	GFlops
SR8000/F1 @KEK	12	100	1200	~ 64	~ 768
CP-PACS @CCP, U.Tsukuba	0.3	2048	614	2048	614
SR8000/G1 @CCP, U.Tsukuba	14.4	12	173	12	173
VPP5000 @SIPC, U.Tsukuba	9.6	80	768	~ 24	~ 230
Earth Simulator @JAMSTEC	64	640	40960	~ 10	~ 640

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Simulation parameters

- with degenerate up and down quarks and strange quark
- Algorithm
  - dynamical u, d, s quarks ⇦ odd flavor algorithm is needed.
    - HMC for ud quarks
    - PHMC for strange quark
- Lattice action
  - gauge : RG improved action
  - quark : non-perturbatively $\mathcal{O}(a)$ improved Wilson action
- $\beta = 1.9$, $c_{SW} = 1.715$, ($a^{-1} \sim 2GeV$)
- Lattice size : $20^3 \times 40$ ($La \simeq 2.0 fm$)

  small for baryons ⇨ concentrate on meson sector

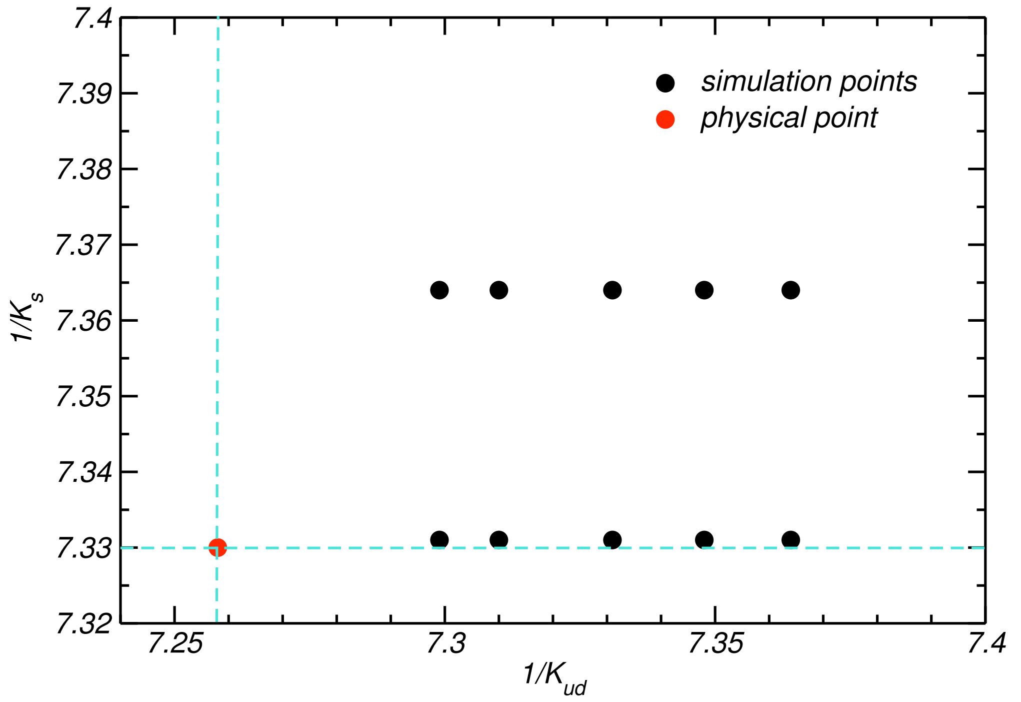
κ parameters

- **5 ud quark masses**

$$m_{PS,LL}/m_{V,LL} \sim 0.62 - 0.77$$
$$(m_\pi/m_\rho = 0.18)$$

- **2 strange quark masses**

$$m_{PS,SS}/m_{V,SS} \sim 0.71, 0.77$$
$$(m_{\eta_s}/m_\phi = 0.68 \ \ : \mathrm{ChPT})$$



Statics

- **5000 traj at each simulation point**
- **measure hadron masses every 10 trajectories**
- **statistical error ⇐ jack-knife with bin size of 100 traj**

Analysis

- **chiral extrapolation**
  - fitting functions (VWI)

$$
\begin{aligned}
&m_{PS}(K_{ud}, K_s; K_{val,1}, K_{val,2})^2 \\
&\quad = B_S^{PS}(2m_{ud}^{VWI} + m_s^{VWI}) + B_V^{PS}(m_{val,1}^{VWI} + m_{val,2}^{VWI}) \\
&\quad +D_{VS}^{PS}(2m_{ud}^{VWI} + m_s^{VWI})(m_{val,1}^{VWI} + m_{val,2}^{VWI}) \\
&\quad +C_V^{PS}((m_{val,1}^{VWI})^2 + (m_{val,2}^{VWI})^2) + 2D_{VV}^{PS} m_{val,1}^{VWI} m_{val,2}^{VWI}
\end{aligned}
$$

$$
\begin{aligned}
&m_V(K_{ud}, K_s; K_{val,1}, K_{val,2}) \\
&\quad = A^{VK} + B_S^{VK}(2m_{ud}^{VWI} + m_s^{VWI}) + B_V^{VK}(m_{val,1}^{VWI} + m_{val,2}^{VWI}) \\
&\quad +D_{VS}^{VK}(2m_{ud}^{VWI} + m_s^{VWI})(m_{val,1}^{VWI} + m_{val,2}^{VWI}) \\
&\quad +C_V^{VK}((m_{val,1}^{VWI})^2 + (m_{val,2}^{VWI})^2)
\end{aligned}
$$

$$
m_{ud}^{VWI} = \frac{1}{2}\left(\frac{1}{K_{ud}} - \frac{1}{K_c}\right), \quad m_s^{VWI} = \frac{1}{2}\left(\frac{1}{K_s} - \frac{1}{K_c}\right), \quad m_{val,i}^{VWI} = \frac{1}{2}\left(\frac{1}{K_{val,i}} - \frac{1}{K_c}\right)
$$

- **fitting functions (AWI)**

$$m_{PS}(K_{ud},K_s;K_{val,1},K_{val,2})^2 = B_V^{PS}(m_{val,1}^{AWI}+m_{val,2}^{AWI}) + D_{VS}^{PS}(2m_{ud}^{AWI}+m_s^{AWI})(m_{val,1}^{AWI}+m_{val,2}^{AWI}) + C_V^{PS}((m_{val,1}^{AWI})^2+(m_{val,2}^{AWI})^2)$$

$$m_V(K_{ud},K_s;K_{val,1},K_{val,2}) = A^{VK} + B_V^{VK}(2m_{ud}^{AWI}+m_s^{AWI}) + D_{VS}^{VK}(2m_{ud}^{AWI}+m_s^{AWI})(m_{val,1}^{AWI}+m_{val,2}^{AWI}) + C_V^{VK}((m_{val,1}^{AWI})^2+(m_{val,2}^{AWI})^2)$$

$$m^{AWI} = \frac{\langle 0|\nabla_4 A_4|PS\rangle}{2\langle 0|P|PS\rangle}$$

Input to fix m_{ud} and m_s

- K-input

$$\frac{m_{PS,LL}(K_{ud},K_s)}{m_{V,LL}(K_{ud},K_s)} = \frac{m_\pi}{m_\rho}, \quad \frac{m_{PS,LS}(K_{ud},K_s)}{m_{V,LL}(K_{ud},K_s)} = \frac{m_K}{m_\rho}$$

- ϕ-input

$$\frac{m_{PS,LL}(K_{ud},K_s)}{m_{V,LL}(K_{ud},K_s)} = \frac{m_\pi}{m_\rho}, \quad \frac{m_{V,SS}(K_{ud},K_s)}{m_{V,LL}(K_{ud},K_s)} = \frac{m_\phi}{m_\rho}$$

Input to fix a^{-1} —— m_ρ

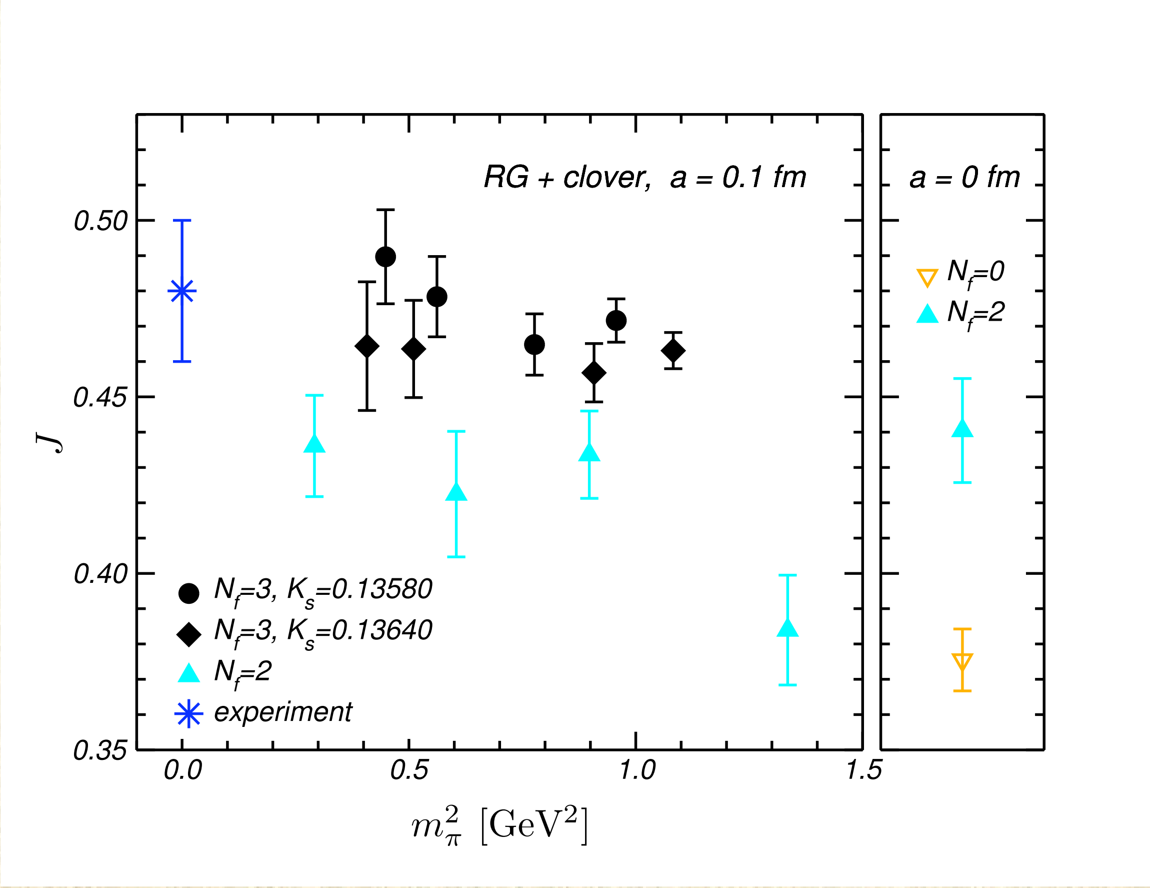
$$a^{-1} = \begin{cases} 1.98(4)\ \ GeV & (K\text{-input}) \\ 1.98(4)\ \ GeV & (\phi\text{-input}) \end{cases}$$

Meson spectrum

- **J parameter**

$$J = m_V \frac{dm_V}{dm_{PS}^2} \quad \left(\text{at} \quad \frac{m_{PS}}{m_V} = \frac{m_K}{m_{K^*}}\right) \simeq m_{K^*} \frac{m_{K^*} - m_\rho}{m_K^2 - m_\pi^2} = 0.48(2)$$

- **quenched**
  smaller than experiment
- **2-flavor**
  deviation is reduced
- **3-flavor**
  consistent with experiment

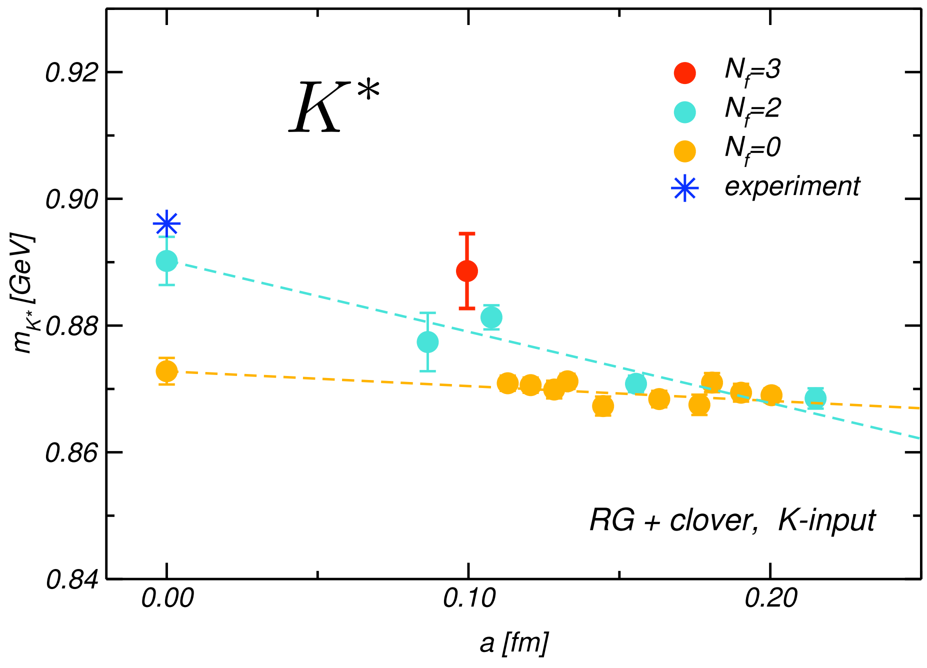


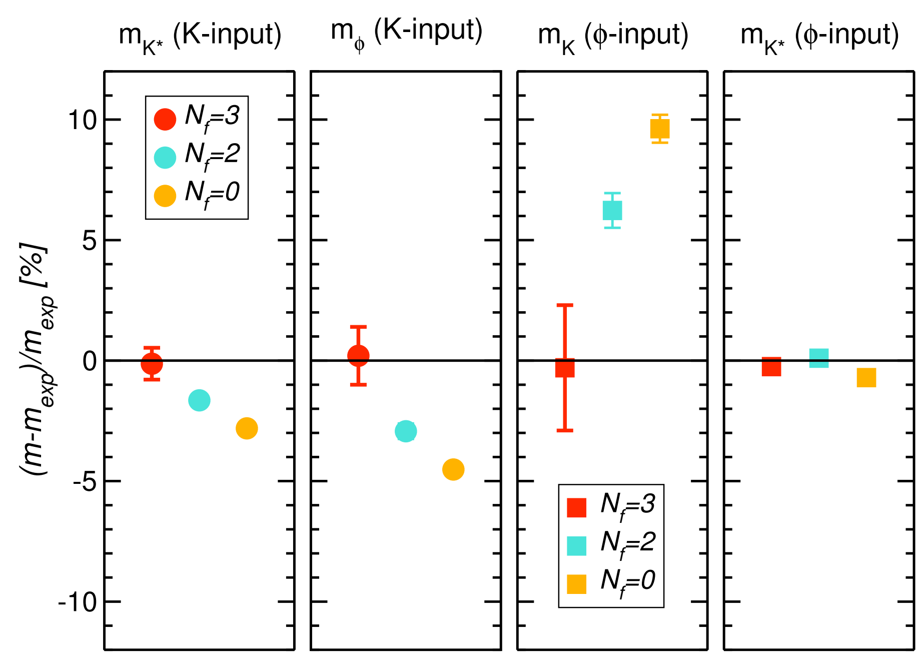
Light meson masses

- At $a \sim 0.1$ fm
  - consistent with experiment
  - K-input and ϕ-input agree
- NP c_{SW}
  - small scaling violation (?)

⇩

The consistency with experiment maintains even in the continuum limit.





Quark masses

- **VWI quark masses**
  - define $K_{c,L}(K_s)$ ⇦ $m_{PS,LL}(K_{c,L}, K_s) = 0$
  - $K_{c,L}(K_s) > K_c$ (due to lack of chiral symmetry)

    ⇨ $K_{ud,phys} > K_c$ ⇨ negative m_{ud}^{VWI}
  - define m_q^{VWI} as

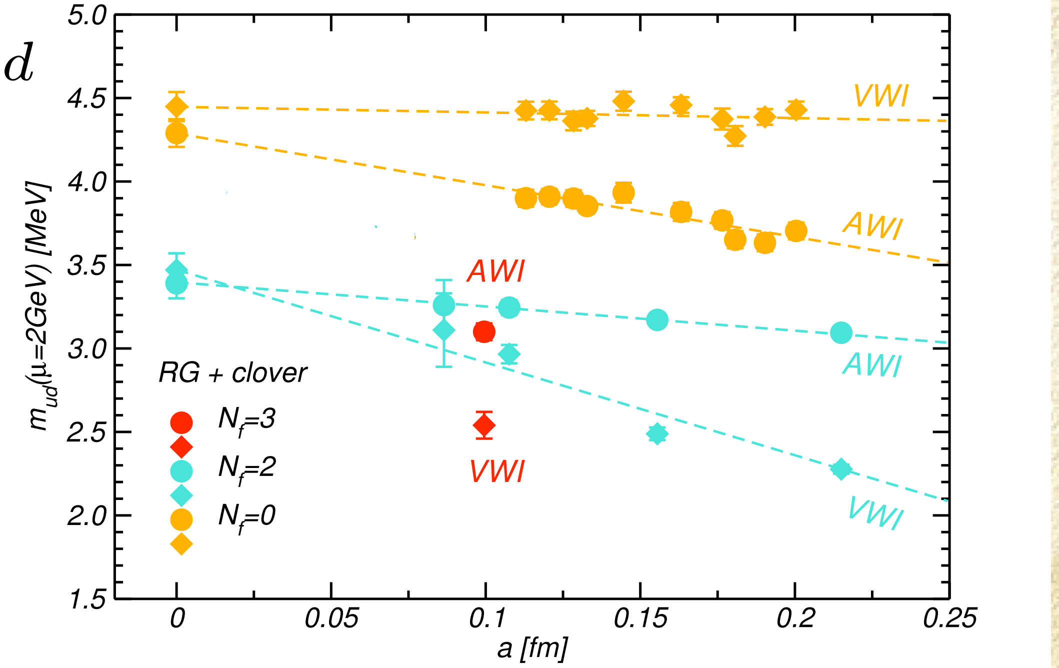
$$m_q^{VWI} = \frac{1}{2}\left(\frac{1}{K_q} - \frac{1}{K_{c,L}(K_{s,phys})}\right) > 0$$

- **AWI quark masses**
  - no such problems as in VWI quark masses
- **renormalization**
  - MF-improved 1-loop matching with $\overline{\text{MS}}$ at $\mu = a^{-1}$
  - 4-loop running to $\mu = 2\ GeV$

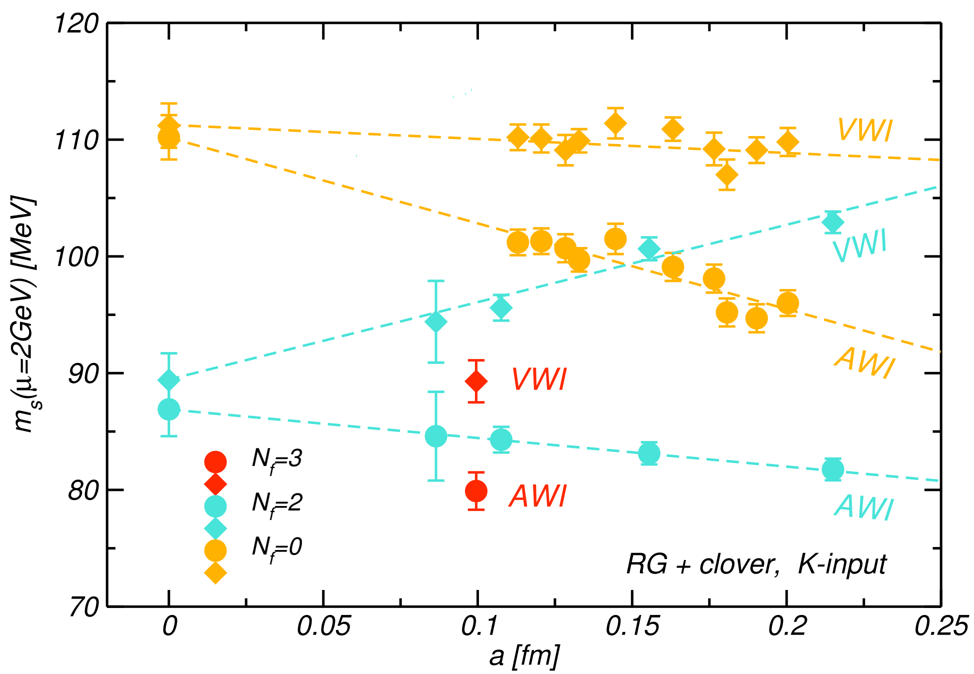
Results

- significant deviation between AWI and VWI masses

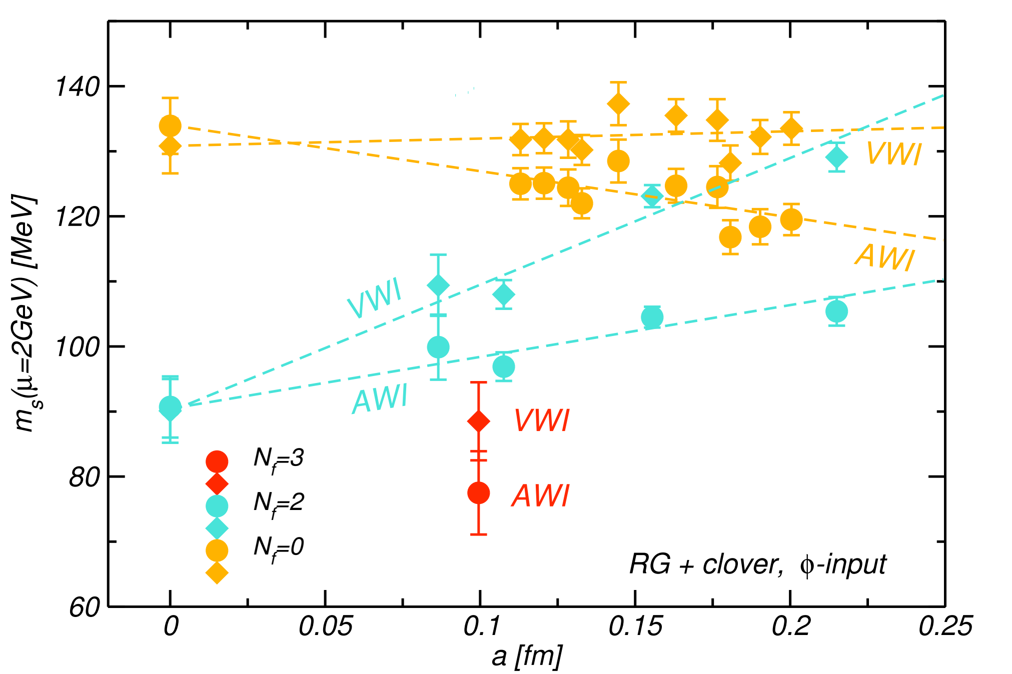
m_{ud}



$m_s(K - \mathrm{input})$



$m_s(\phi - \mathrm{input})$



Assuming small scaling violation in m_q^{AWI},

in the $\overline{\text{MS}}$ scheme at $\mu = 2\ GeV$

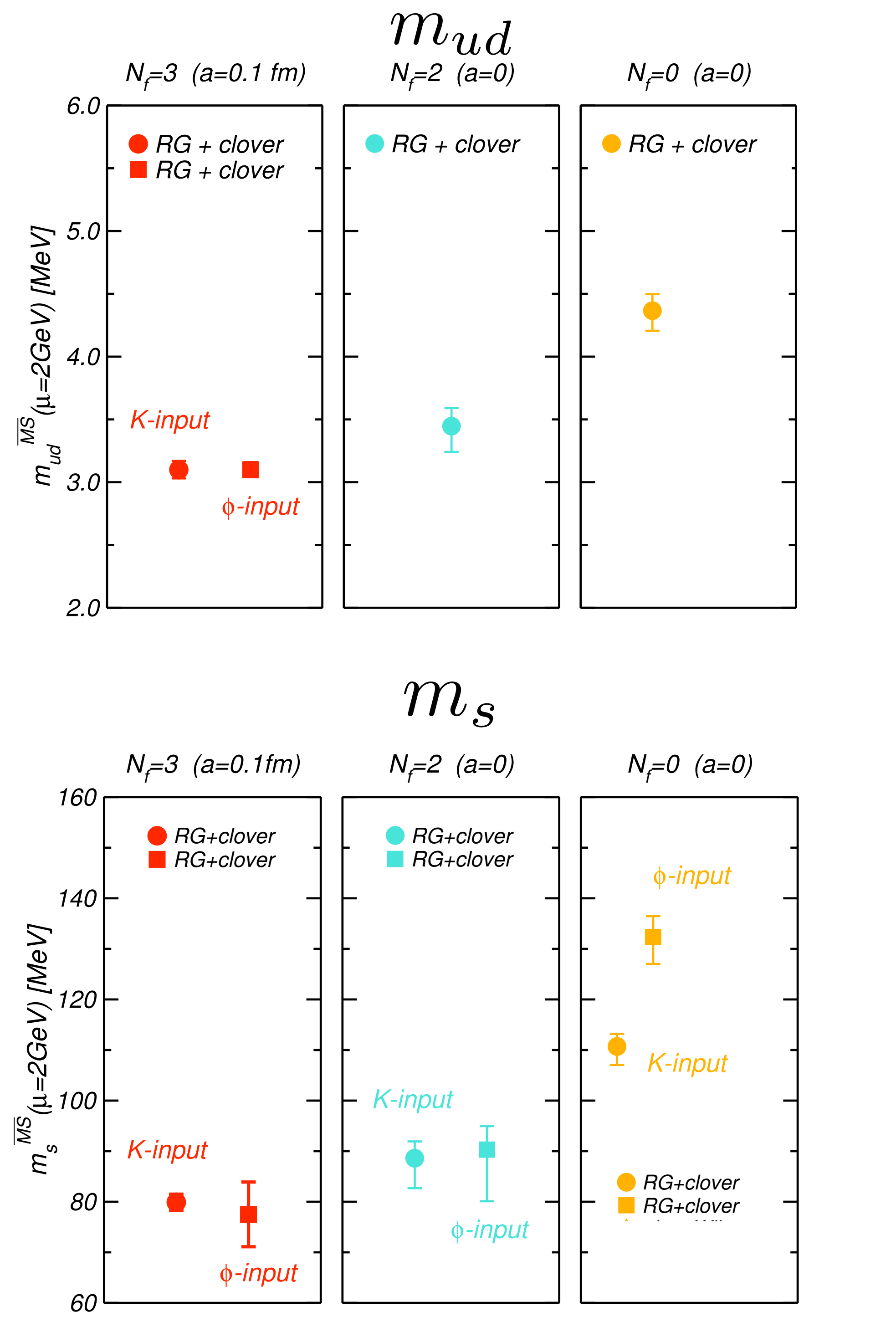
$$m_{ud} = 3.10(7)\ MeV$$
$$m_s = 78.7(3.3)\ MeV$$
$$m_s/m_{ud} = 25.4(1.2)$$

- $m_{ud},\ m_s$:

  10-15% smaller than in $N_f = 2$

- m_s/m_{ud} :

  consistent with 1-loop ChPT, 24.4(1.5)



Finite size effect

- **Comparison with $16^3 \times 32$ result**
  - $16^3 \times 32$ **lattice,** $\beta = 1.9$**, 3000 traj (T.Kaneko et al., Lat 03)**
  - **results on $20^3 \times 40$ lattice**

    m_{ud} **: 10% larger than on $16^3 \times 32$ lattice**

    m_s **: 4% larger than on $16^3 \times 32$ lattice**

	$20^3 \times 40$	$16^3 \times 32$
m_{ud}	3.10(7)	2.89(6)
m_s	78.7(3.3)	75.6(3.4)
m_s/m_{ud}	25.4(1.2)	26.2(1.0)

More analysis of the finite size effect is needed.

Conclusions and future plans

- $N_f = 3$ QCD project of CP-PACS+JLQCD
  - $20^3 \times 40$ lattice, $a \sim 0.1$ fm
  - RG-improved gauge action + NP improved clover quark
- Light meson spectrum
  - consistent with experiment already at $a \sim 0.1$ fm
- Quark mass
  - 10-15% smaller than in $N_f = 2$
- Next
  - other lattice spacing (⇦ investigation of scaling violation)
  - finite size effect