Light hadron spectrum in 2+1 flavor full QCD by CP-PACS and JLQCD collaboration

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Introduction

- Lattice QCD
  - One of the regularization of QCD
  - The only systematic way to calculate non-perturbative property of QCD from its first principles.
  - Numerical simulation can be applied.
  - Various application :
    - Hadron spectrum, Weak matrix elements, Finite-temperature and finite-density system, Confinement, Topology ...
- Light hadron spectrum
  - Direct test of QCD at low energy scale
  - Determination of fundamental parameters
    quark masses, QCD coupling, ...

Systematic studies by CP-PACS and JLQCD collab.

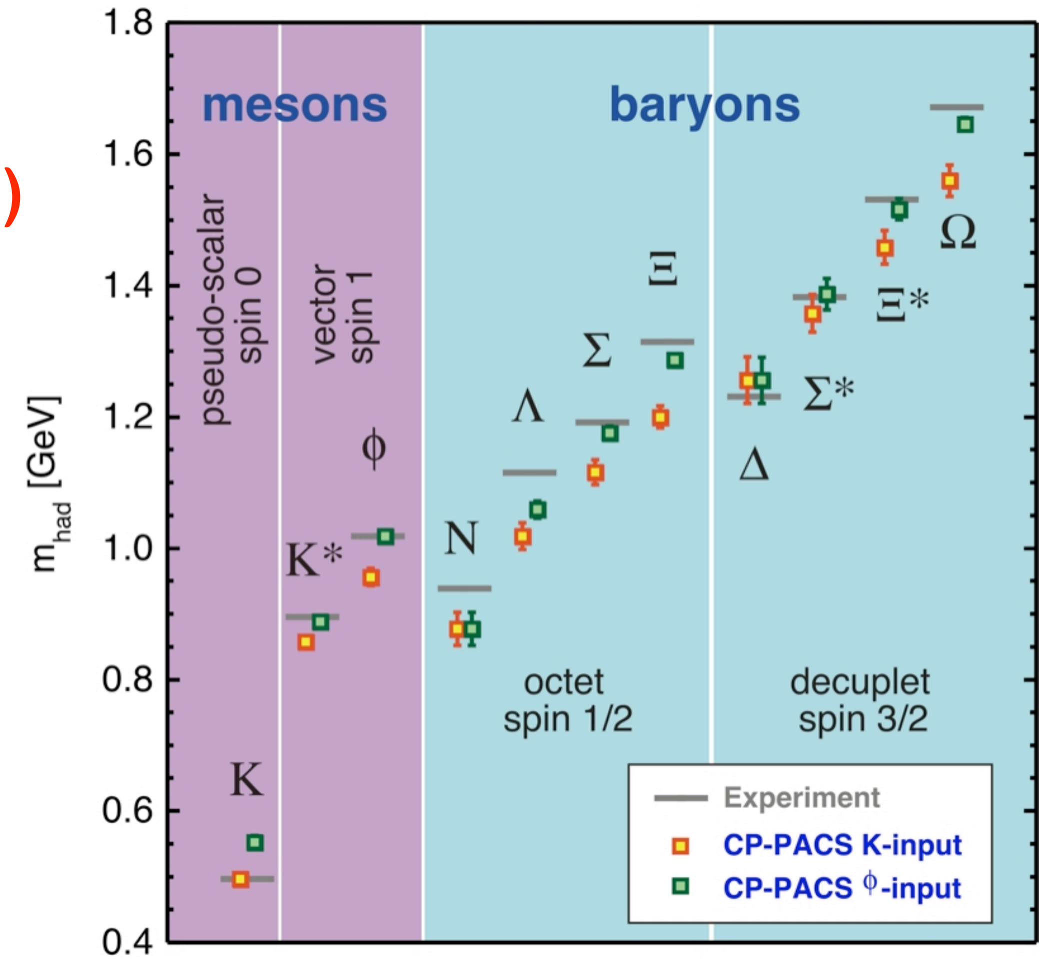
quenched QCD (continuum limit)

- RG-improved gauge + clover quark (tad.imp. c_{SW}) (CP-PACS, 2001)
- plaquette + Wilson (CP-PACS, 2001)

Systematic deviation from experiment (5-10%)

⇩

artifact due to the quenched approx.

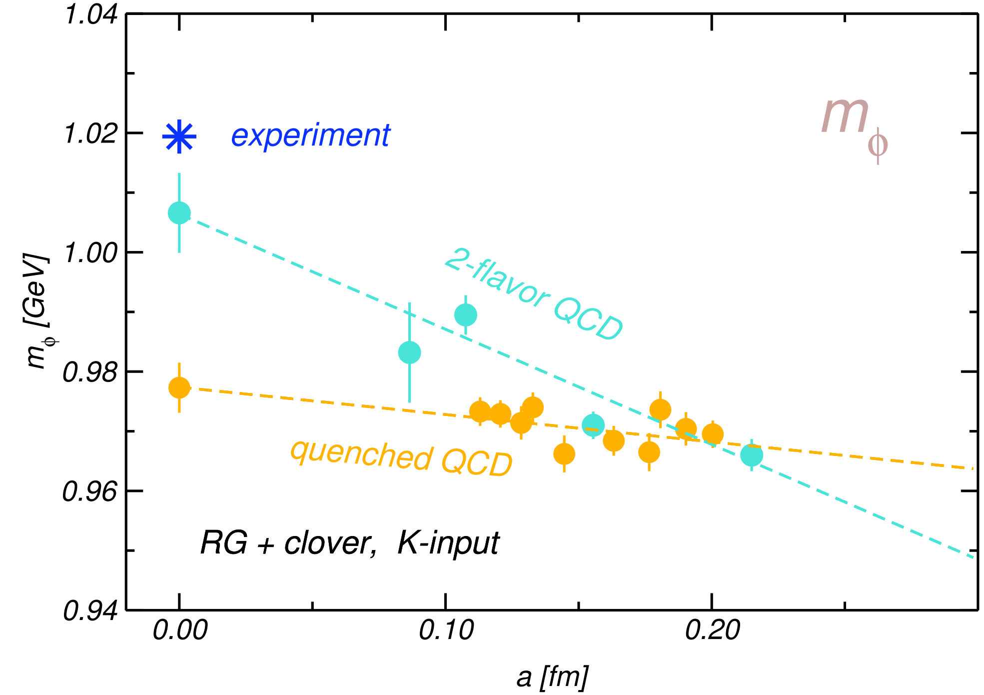


2-flavor QCD (continuum limit)

ud : dynamical
s : quenched

- RG-improved gauge
  + clover quark (tad.imp. c_{SW})
  (CP-PACS, 2001)

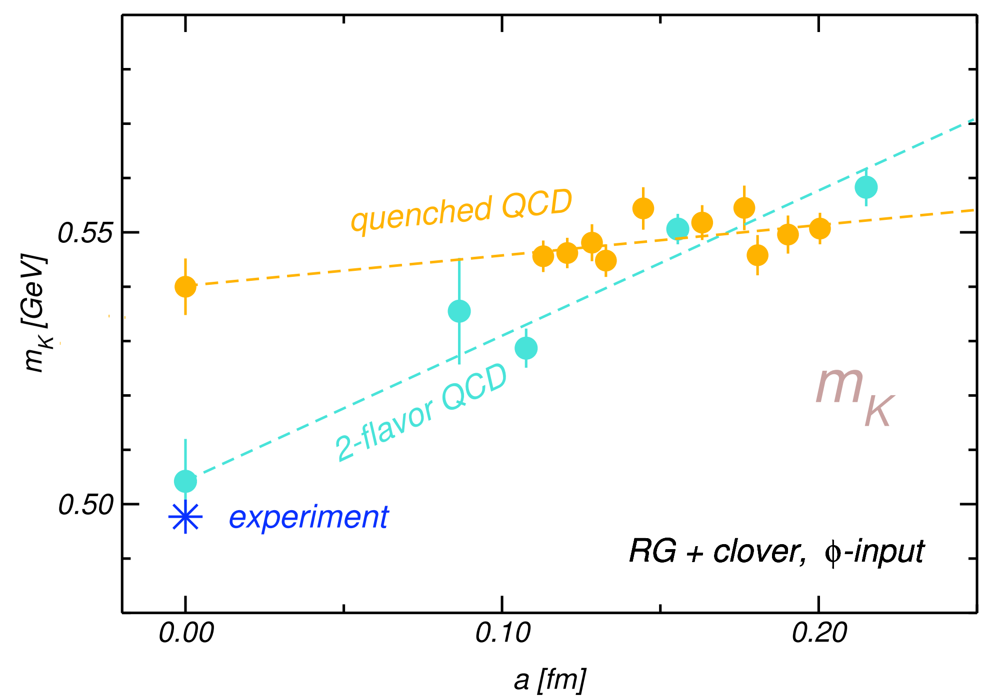
deviation is reduced



Next Step :

3-flavor full QCD

ud : dynamical
s : dynamical



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Algorithm

- with degenerate up and down quarks and strange quark
- Algorithm (odd flavor algorithm)
  - **Pseudo-fermion method**

$$Z = \int \mathcal{D}U \det[D]^{N_f} \exp[-S_g] = \int \mathcal{D}U \mathcal{D}\phi^\dagger \mathcal{D}\phi \exp[-S_g - \phi^\dagger D^{-N_f} \phi]$$

U : link valiable, D : Dirac matrix, ; ϕ : complex scalar

- $N_f = \text{even}$: $\phi^\dagger D^{-N_f}\phi = |D^{-N_f/2}\phi|^2 \longleftarrow$ real positive
- $N_f = \text{odd}$: $\phi^\dagger D^{-N_f}\phi \longleftarrow$ complex **(?)**

  - **Polynomial HMC** (Forcrand and Takaishi, 1997, K-I.Ishikawa et.al., 2002)

- **Polynomial approx. of D^{-1}:** $D^{-1} \sim P_{2N_{poly}}[D] = \bar{T}[D]T[D]$
- **Metropolis test for correction factor** $\det[P_{2N_{poly}}[D]D]$

⟹ **exact algorithm**

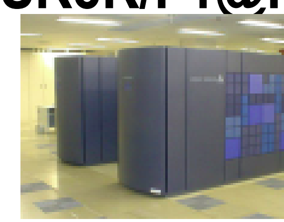
We employ PHMC algorithm for strange quark.

Simulation parameters

- Lattice action
  - gauge : RG improved action
  - quark : non-perturbatively $\mathcal{O}(a)$ improved Wilson action
- $\beta = 1.9$, $c_{SW} = 1.715$, (lattice spacing a ~ 0.1 fm)
- Lattice size : $20^3 \times 40 (La \sim 2.0\mathrm{fm})$
  $16^3 \times 32 (La \sim 1.6\mathrm{fm})$

  small for baryons ⟹ concentrate on meson sector
- Computing facilities

  Earth Simulator@JAMSTEC, SR8K/F1@KEK,



CP-PACS, VPP-5000, SR8K/G1@Univ. of Tsukuba

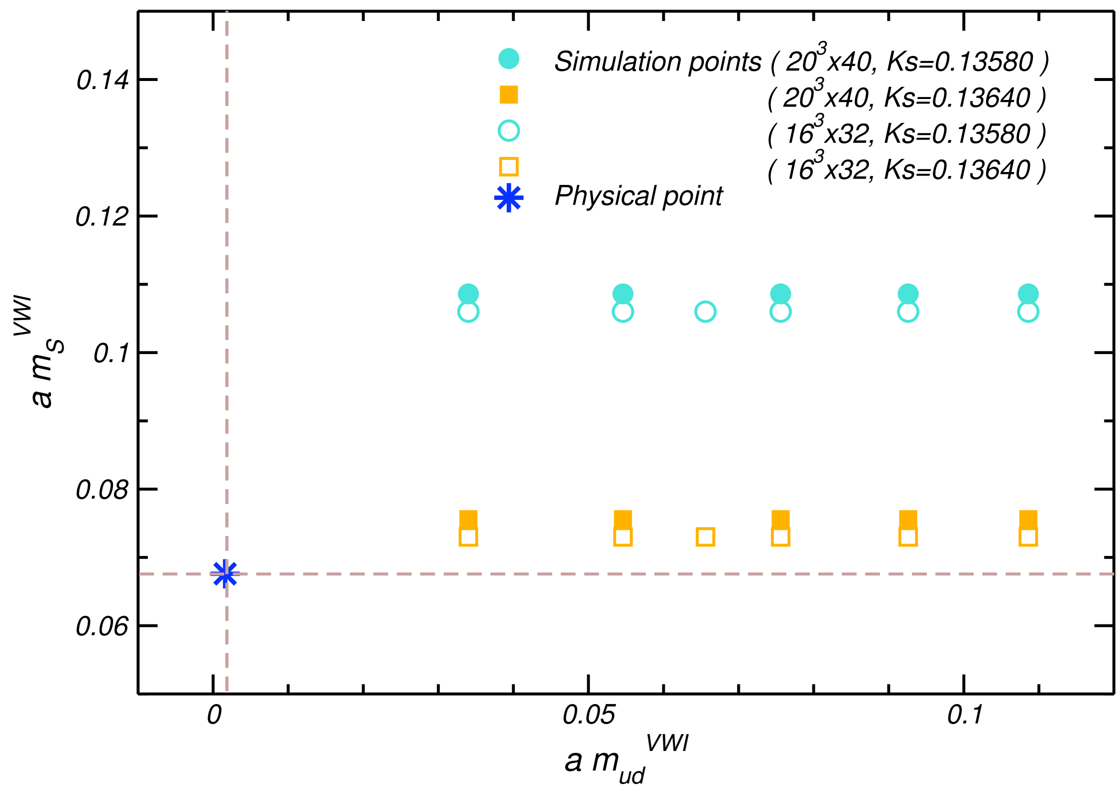
κ parameters

- **5 ud for $20^3 \times 40$ and 6 ud for $16^3 \times 32$**

  $$m_\pi / m_\rho \sim 0.62 - 0.77$$
  $$(0.18 : \text{experiment})$$

- **2 strange**

  $$m_{\eta_s} / m_\phi \sim 0.71, 0.77$$
  $$(0.68 : \text{1-loop ChPT})$$

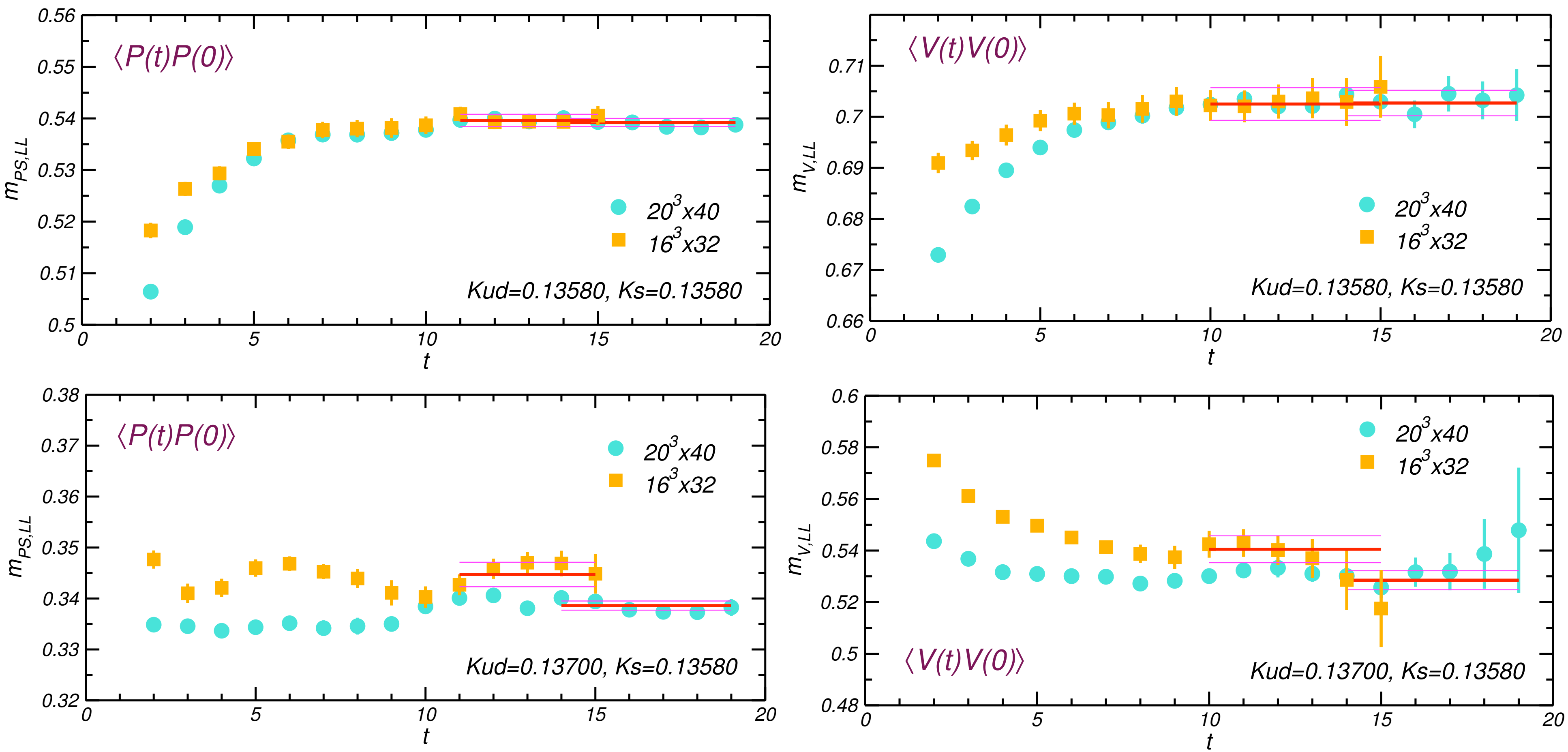


Statistics

- **5000~8000 traj at each simulation point for $20^3 \times 40$**
  3000 traj at each simulation point for $16^3 \times 32$
- **measure meson masses every 10 trajectories**
- **statistical error ⟸ jack-knife with bin size of 100 traj**

Finite size effect

- effective mass plot



- **FSE is observed at the simulation point where quark masses are small.**

measured meson mass

- diff. between L=16 and 20

  ~ 2 %

- assumption

$$\frac{m(L) - m(\infty)}{m(\infty)} \sim \frac{c}{L^3}$$

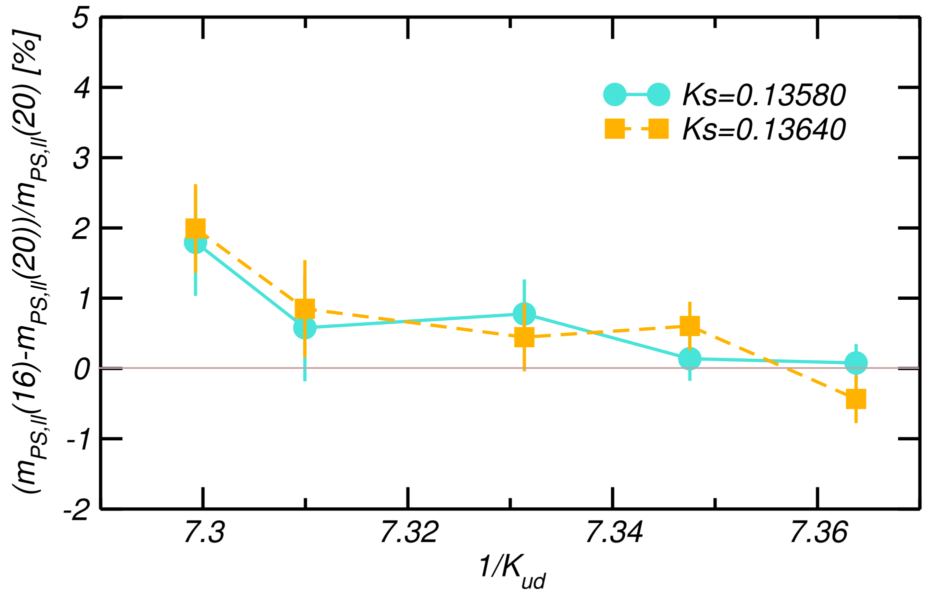
(Fukugita et al., 1992)

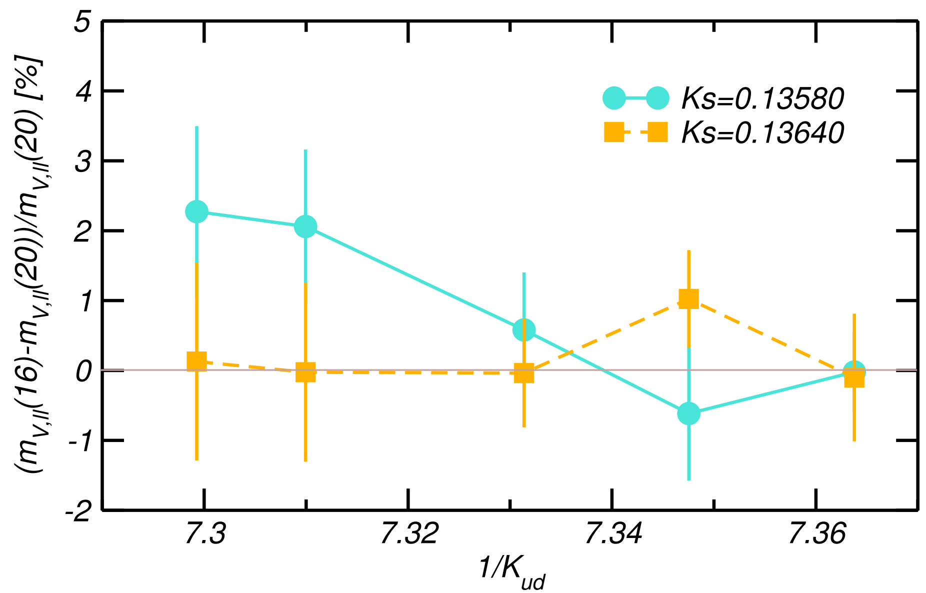
diff. between L=20 and ∞

~ 2 %

FSE is comparable to or slightly larger than statistical error of spectrum at physical points.

It does not change conclusions below.





Chiral extrapolation

- fit function ——— polynomial in quark masses
- Ambiguity of fit forms
  - linear in $m_{\rm sea}$ and $m_{\rm valence}$

$$f(m_q) = A + B_S m_{\rm sea} + B_V m_{\rm val} + D_{SV} m_{\rm sea} m_{\rm val}$$

$$m_{\rm sea} = 2m_{ud} + m_s, \quad m_{\rm val} = m_{val1} + m_{val2}$$

  - general quadratic polynomial

$$\begin{aligned} f(m_q) &= A + B_S m_{\rm sea} + B_V m_{\rm val} \\ &+ D_{SV} m_{\rm sea} m_{\rm val} \\ &+ C_S m_{\rm sea}^2 + C_V m_{\rm val}^2 \end{aligned}$$

Naive fitting yields large contribution of quadratic part.

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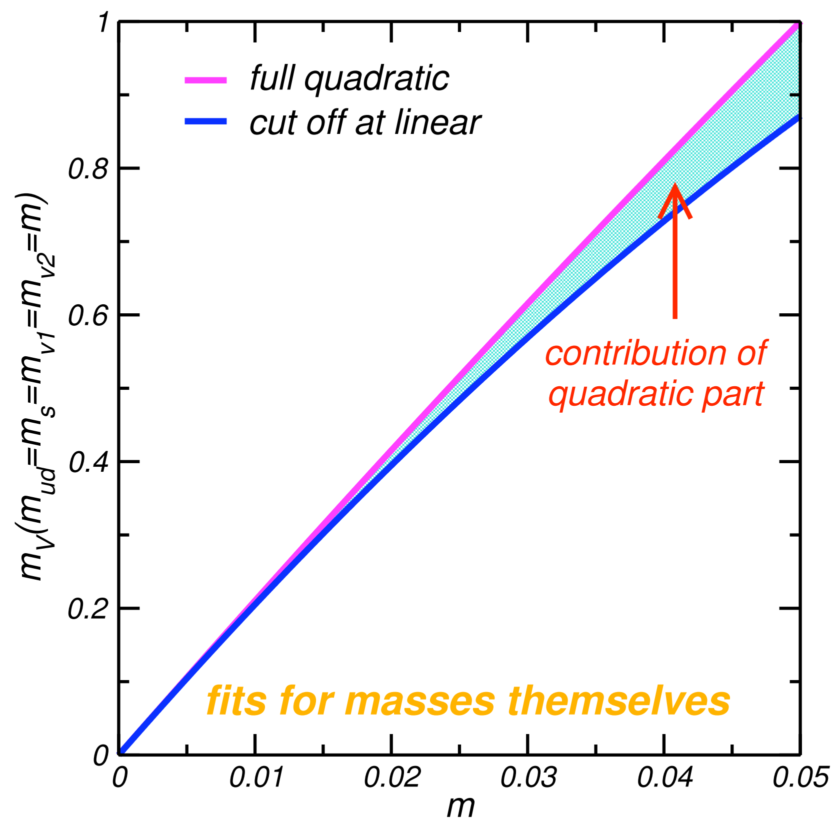
Convergency is not well.



Fits for masses normalized by r_0

- Sommer scale $r_0(m_{\rm sea})$

$$r^2 \frac{dV(r)}{dr}\bigg|_{r=r_0} = 1.65$$

- Masses normalized by r_0

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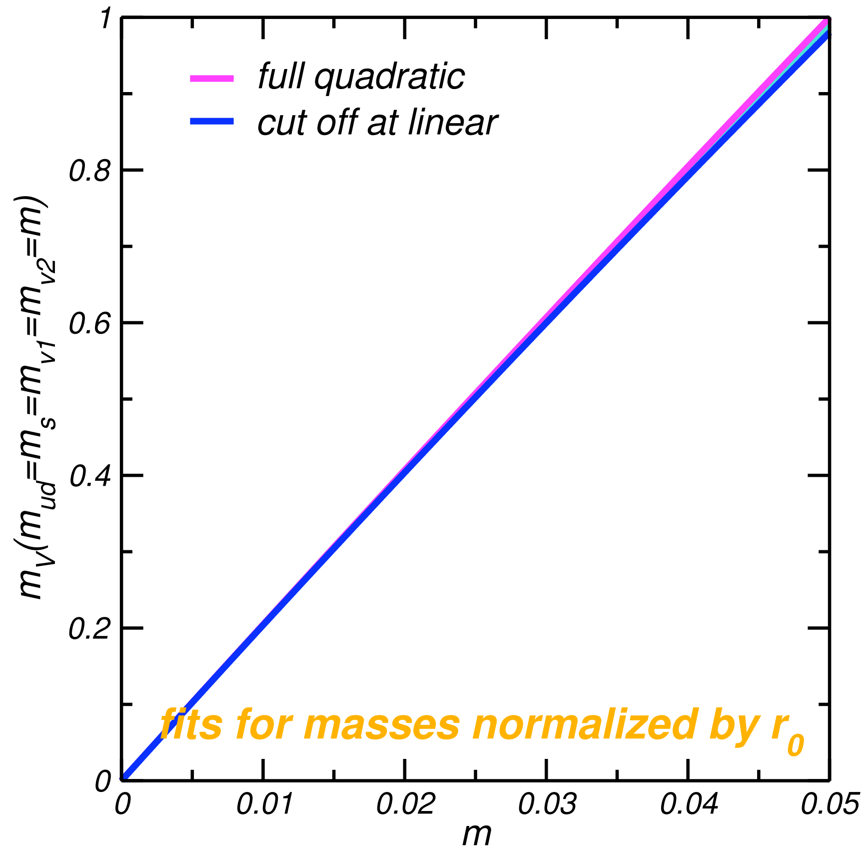
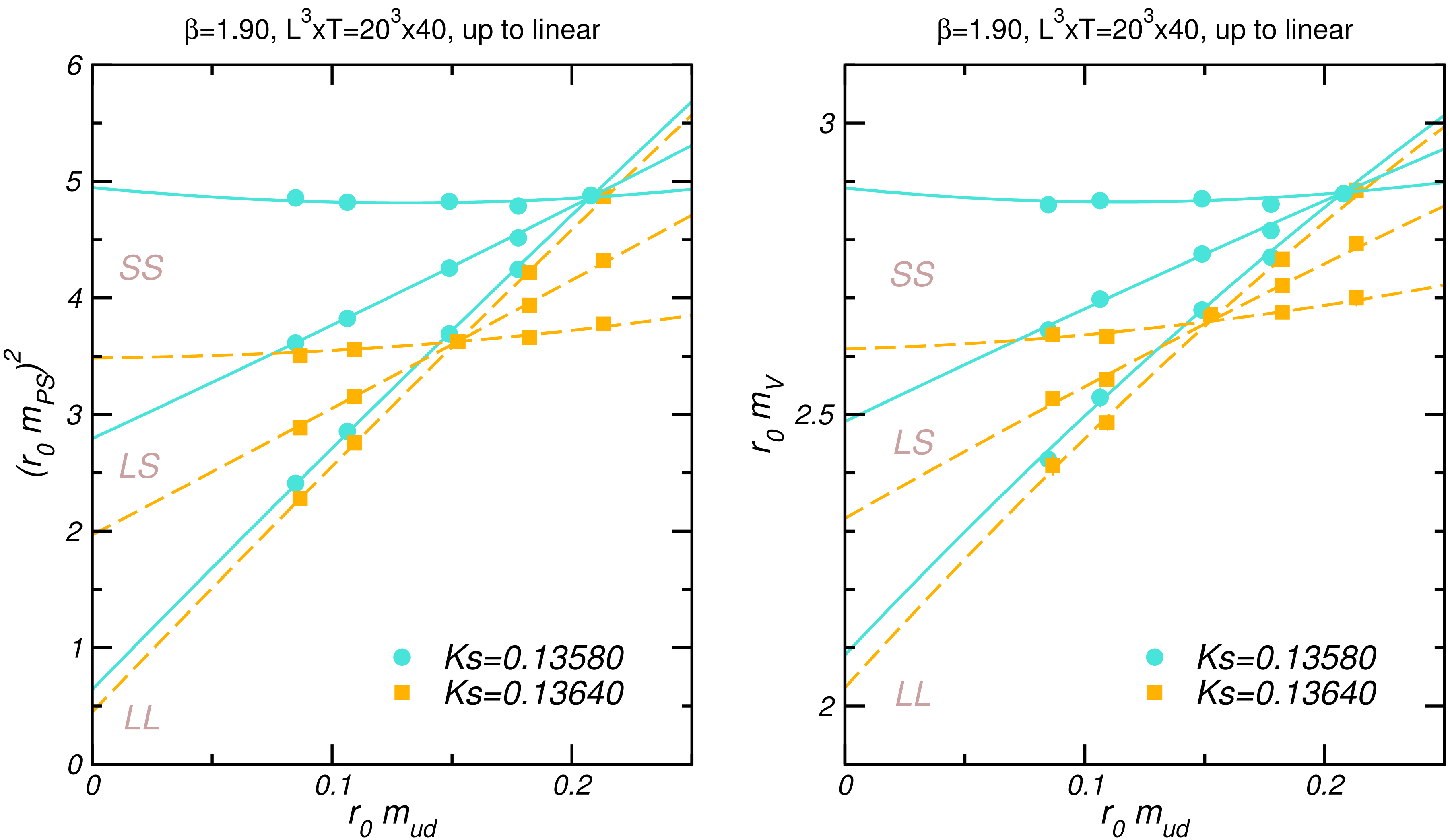
absorption of $m_{\rm sea}$ dependences of the effective lattice spacing

This fits are well reproduced by linear function.

⇨ our best estimation of central value and statistical error



- Others: used to estimate the systematic uncertainty of chiral fits



L : light quarks (up, down),   S : strange quark

Light meson spectrum (preliminary)

- Inputs to fix the quark masses

$$m_{ud} \longleftarrow \frac{m_{PS}(m_{ud},m_{ud})}{m_V(m_{ud},m_{ud})} = \frac{m_\pi}{m_\rho}$$

$$m_s(K\text{-input}) \longleftarrow \frac{m_{PS}(m_{ud},m_s)}{m_V(m_{ud},m_{ud})} = \frac{m_K}{m_\rho}$$

$$m_s(\phi\text{-input}) \longleftarrow \frac{m_V(m_s,m_s)}{m_V(m_{ud},m_{ud})} = \frac{m_\phi}{m_\rho}$$

- Input to fix the lattice spacing

$$a \leftarrow m_\rho$$

$$a = \begin{cases} 0.0948(34)\ \text{fm} & (K\text{-input}) \\ 0.0954(35)\ \text{fm} & (\phi\text{-input}) \end{cases}$$

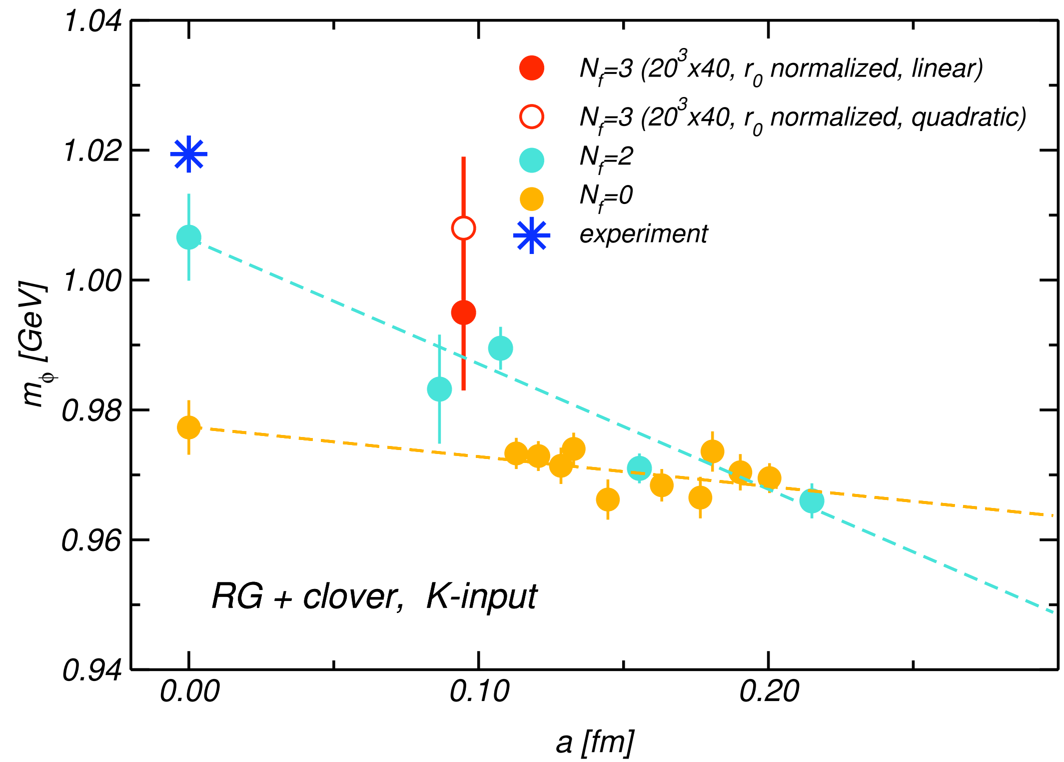
At a ~ 0.1 fm

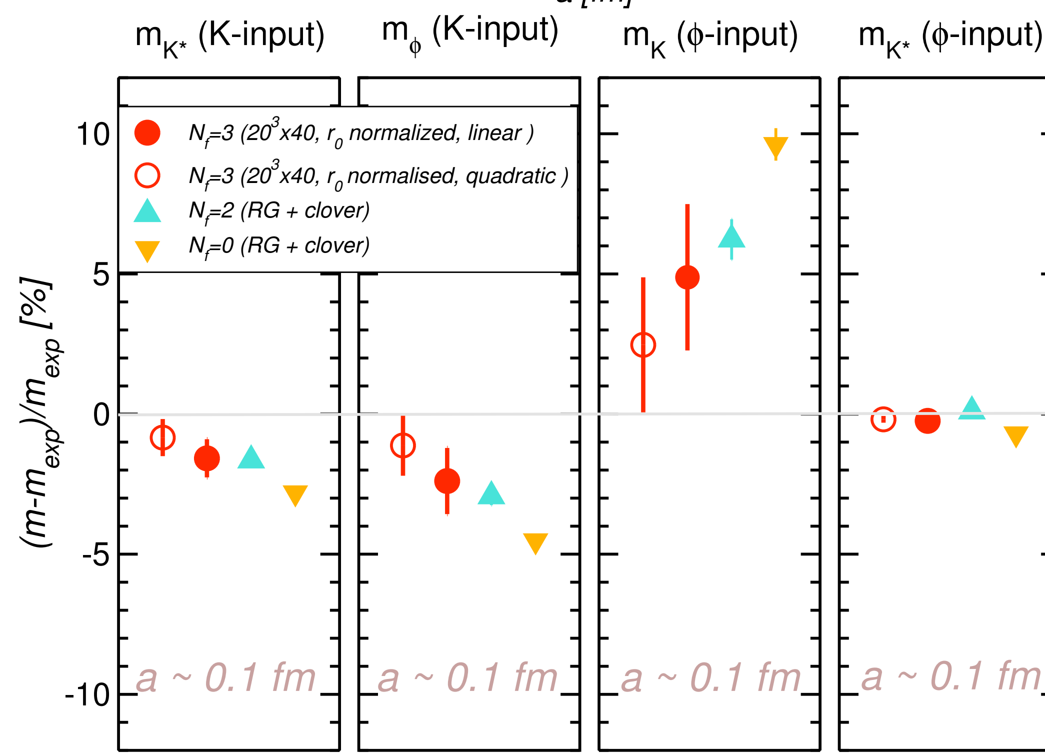
We observe that masses in Nf=3 are closer to experiment than in Nf=2 and Nf=0 at a ~ 0.1 fm.

We may expect that

our obsevation is unchanged in the continuum limit.

This point should be checked in the future study.





Quark masses (preliminary)

- **VWI quark mass**

$$m_q = \frac{1}{2}\left(\frac{1}{K} - \frac{1}{K_c}\right)$$

  - **VWI ud quark mass has negative value.**

    ← due to the chiral symmetry breaking

- **AWI quark mass (We use.)**

$$m_q = \frac{\langle \Delta_4 A_4(t) P(0) \rangle}{2\langle P(t) P(0) \rangle}$$

  - **no such problem as in the VWI quark mass**
  - **The scaling violation is small in $N_f = 2$ case.**

- **renormalization**
  - **MF-improved 1-loop matching with $\overline{\text{MS}}$ at $\mu = a^{-1}$**
  - **4-loop running to $\mu = 2\ GeV$**

- **Non-perturbatively $\mathcal{O}(a)$ improved Wilson quark action**

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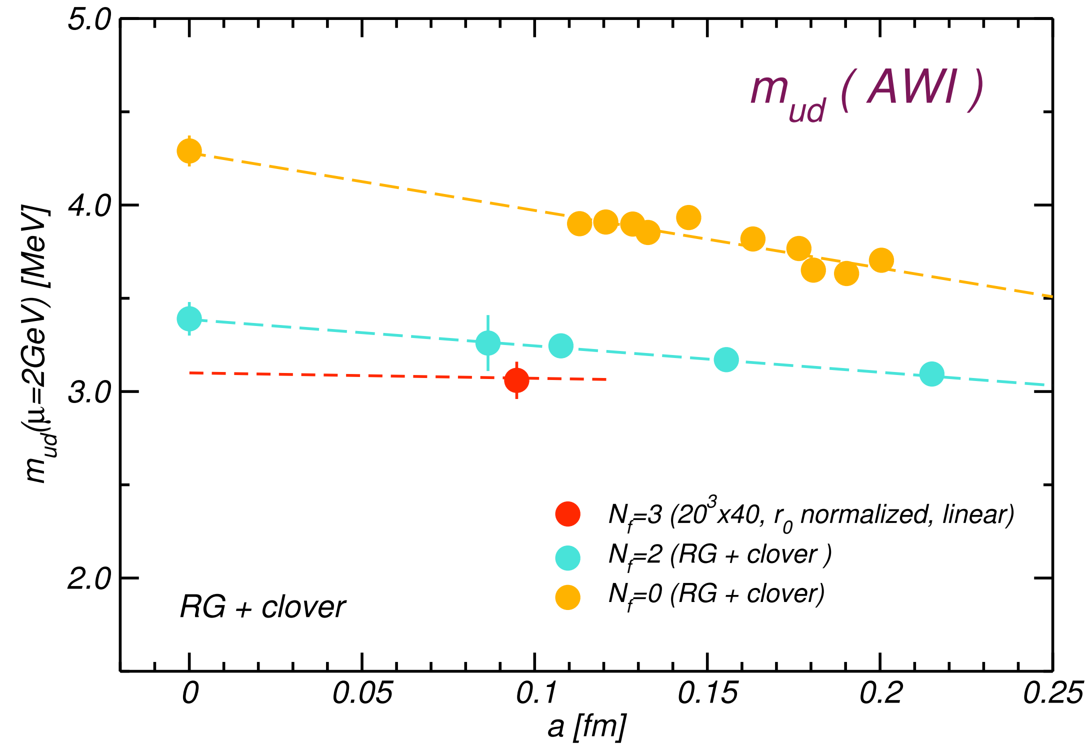
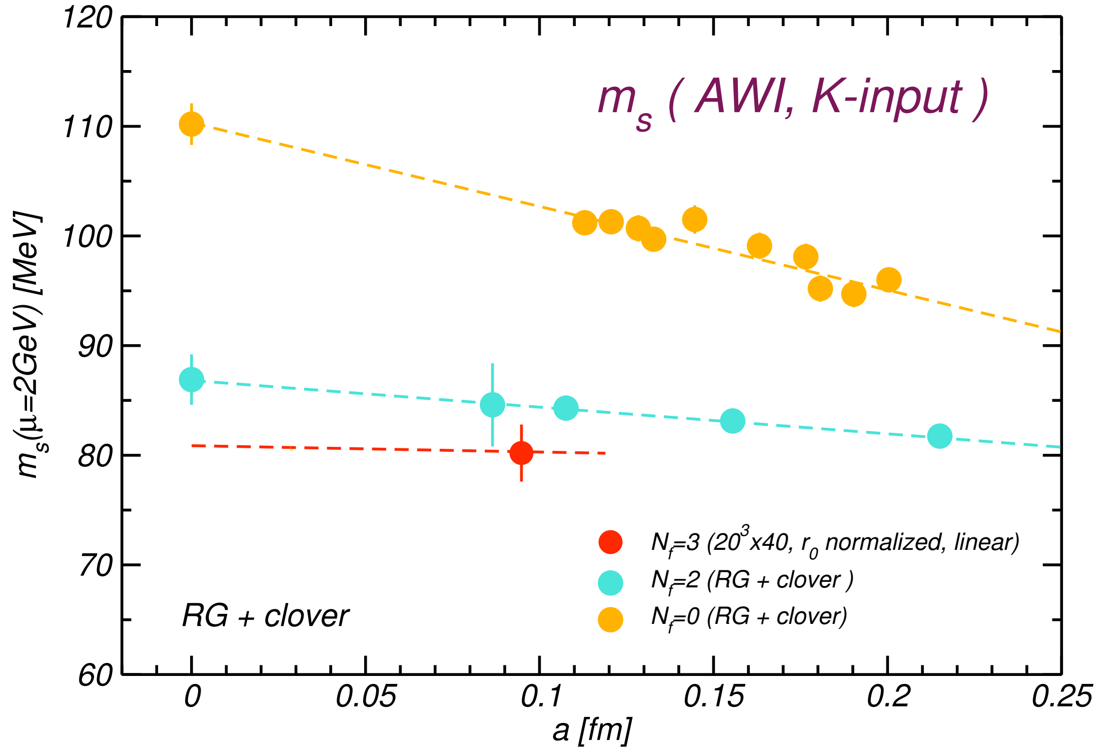
small scaling violation

Assuming that the results at a ~ 0.1 fm are the same as in the continuum limit, ...





- **Dynamical quarks reduce quark masses.**

- m_{ud}, m_s **:**

  10 % smaller than in $N_f = 2$

  Note: Finite size effect is not observed in quark masses.

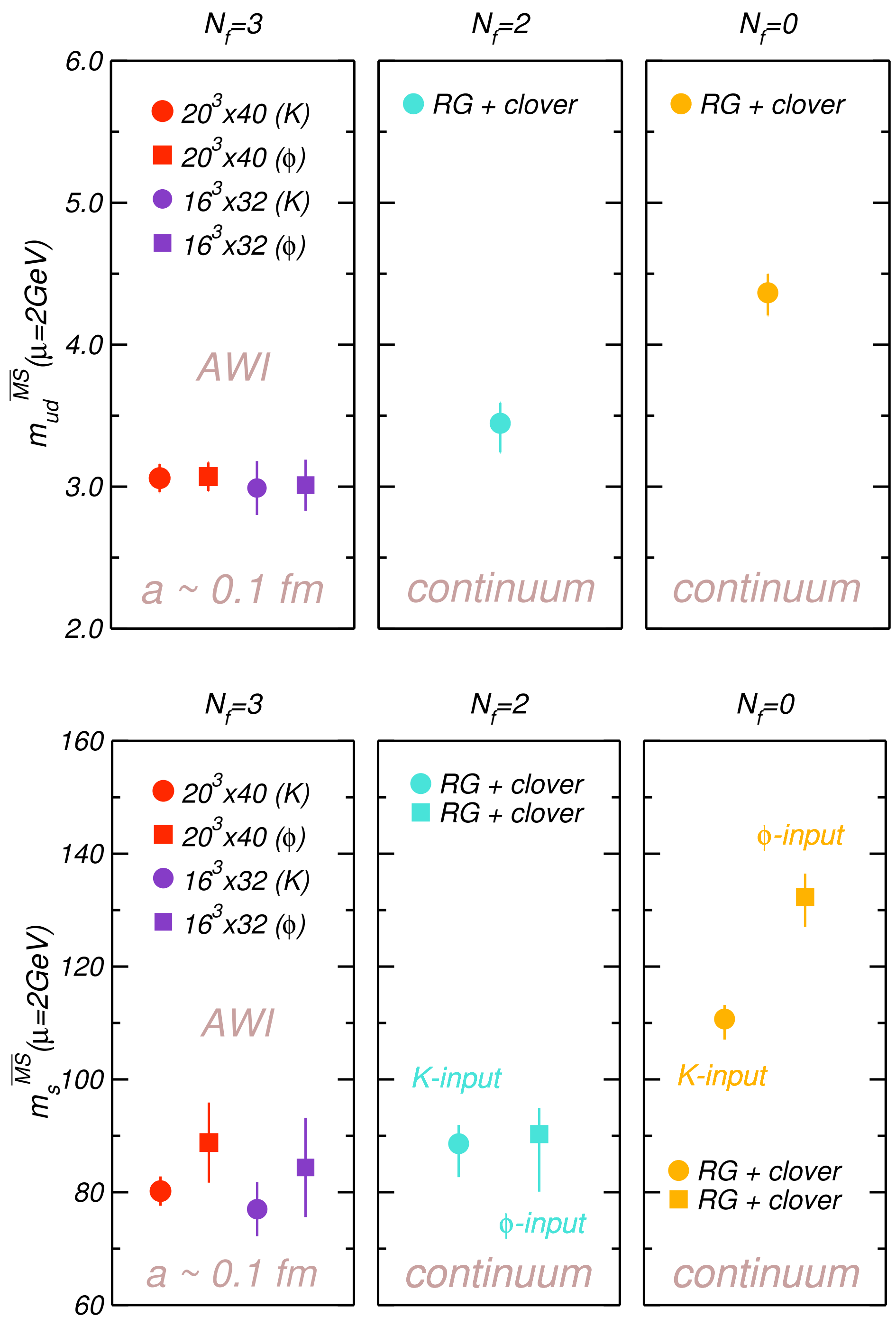
- $\overline{\textbf{MS}}$ **scheme at** $\mu = 2\ GeV$

$$m_{ud} = 3.06(10)^{+0.03}_{-0.53}\ [\mathrm{MeV}]$$

$$m_s = 80.2(2.6)^{+8.6}_{-0.5}\ [\mathrm{MeV}]$$

$$m_s/m_{ud} = 26.2(1.2)$$

(central value: K-input)



Summary and future work

- Although our simulation is performed only at one lattice spacing, our result is consistent with the following picture :
  - Light meson spectrum
    - The result of meson spectrum in $N_f = 3$ is closer to experiment than in $N_f = 2$.
  - Quark mass
    - Dynamical quarks (u,d,s) reduce the quark masses.
    - Quark masses in $N_f = 3$ is about 10% smaller than in $N_f = 2$.
- Simulations are on-going at two other lattice spacings (⇨ continuum extrapolation)

$$a \sim 0.0707[\text{fm}], \quad L^3 \times T = 28^3 \times 56, \qquad (\text{finer lattice})$$

$$a \sim 0.1225[\text{fm}], \quad L^3 \times T = 16^3 \times 32, \qquad (\text{coarser lattice})$$