Unquenched spectroscopy with dynamical up, down and strange quarks

CP-PACS and JLQCD Collaborations

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Nf=2+1 full QCD project members (CP-PACS and JLQCD)

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Nf=2+1 full QCD project

- CP-PACS and JLQCD joint project
- Wilson quark formalism
  - Chiral symmetry is violated at finite lattice spacing.
  - Computational cost is large.
  - Theoretical ambiguity is less.
- Dynamical up, down and strange quark

Up and down are degenerate.
Strange has a distinct mass.

Large scaled simulations in Nf=0 and Nf=2 QCD by CP-PACS and JLQCD

Quenched (Nf=0)

- CP-PACS : Plaquette gauge + Wilson quarks, continuum limit

  Phys.Rev.D67(2003)034503, Phys.Rev.Lett.84(2000)238.

- CP-PACS : RG improved gauge + clover quarks with PT c_{SW} , continuum limit

  Phys.Rev.D65(2002)054505.

Dynamical up and down quarks (Nf=2)

strange : quenched

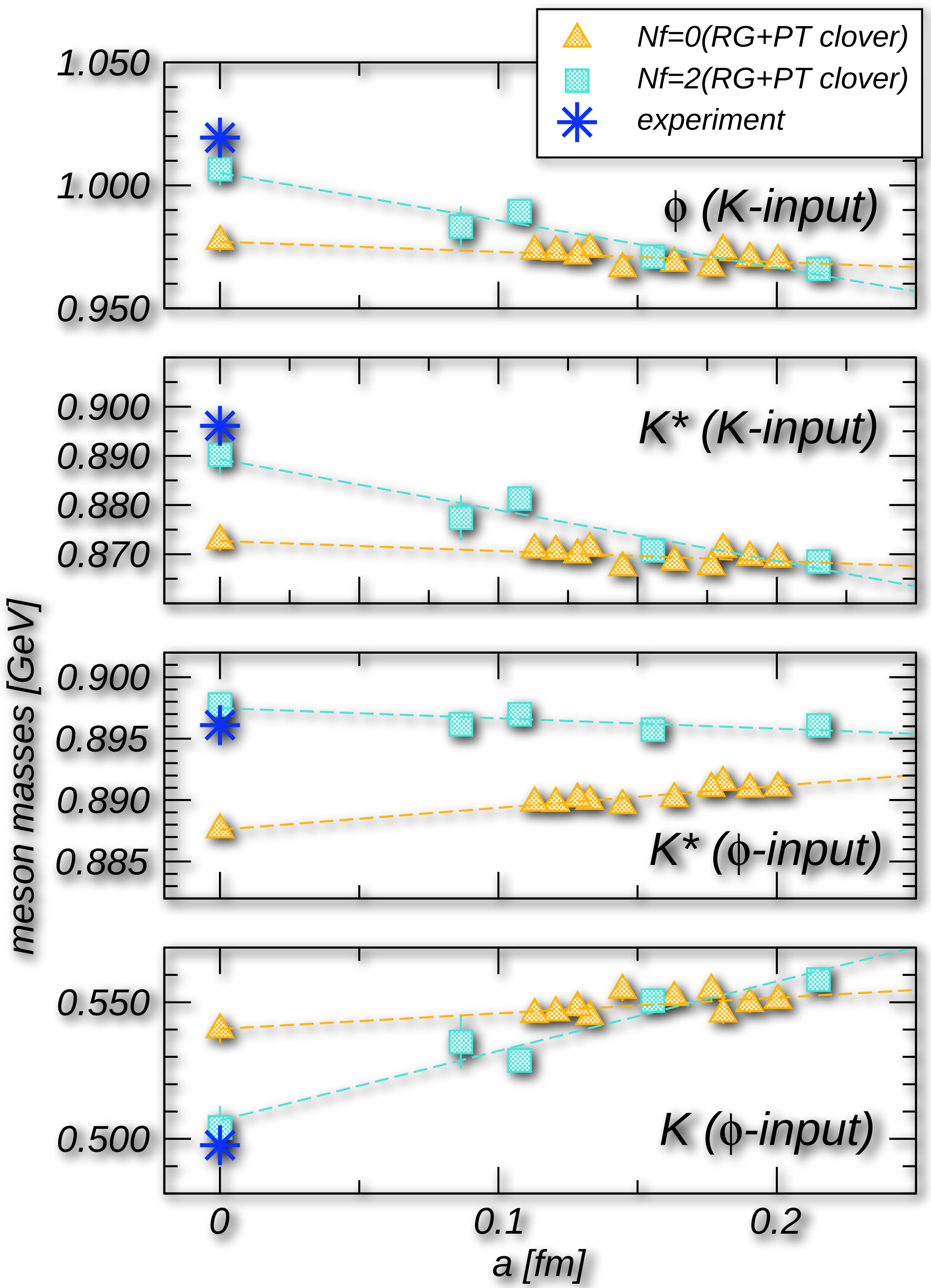
- JLQCD : Plaquette gauge + clover quarks with NPT c_{SW}

  Phys.Rev.D68(2003)054502.

- CP-PACS : RG improved gauge + clover quarks with PT c_{SW} , continuum limit

  Phys.Rev.D65(2002)054505, Phys.Rev.Lett.85(2000)4674.

Nf=0 and Nf=2 results



meson spectrum

- Nf=0
  - Systematic deviation from experiment is O(5-10%).
- Nf=2
  - The deviation is considerably reduced.

the effect of dynamical up and down quarks

RG+clover (Phys.Rev.D65(2002)054505)

c_{SW} : perturbation

$N_f = 0: \quad a = 0.11 - 0.2 \text{ fm}, \quad La = 2.7 - 3.2 \text{ fm}$

$N_f = 2: \quad a = 0.086 - 0.215 \text{ fm}, \quad La = 2.0 - 2.5 \text{ fm}$

Baryon spectrum

- Nf=0
  - large volume

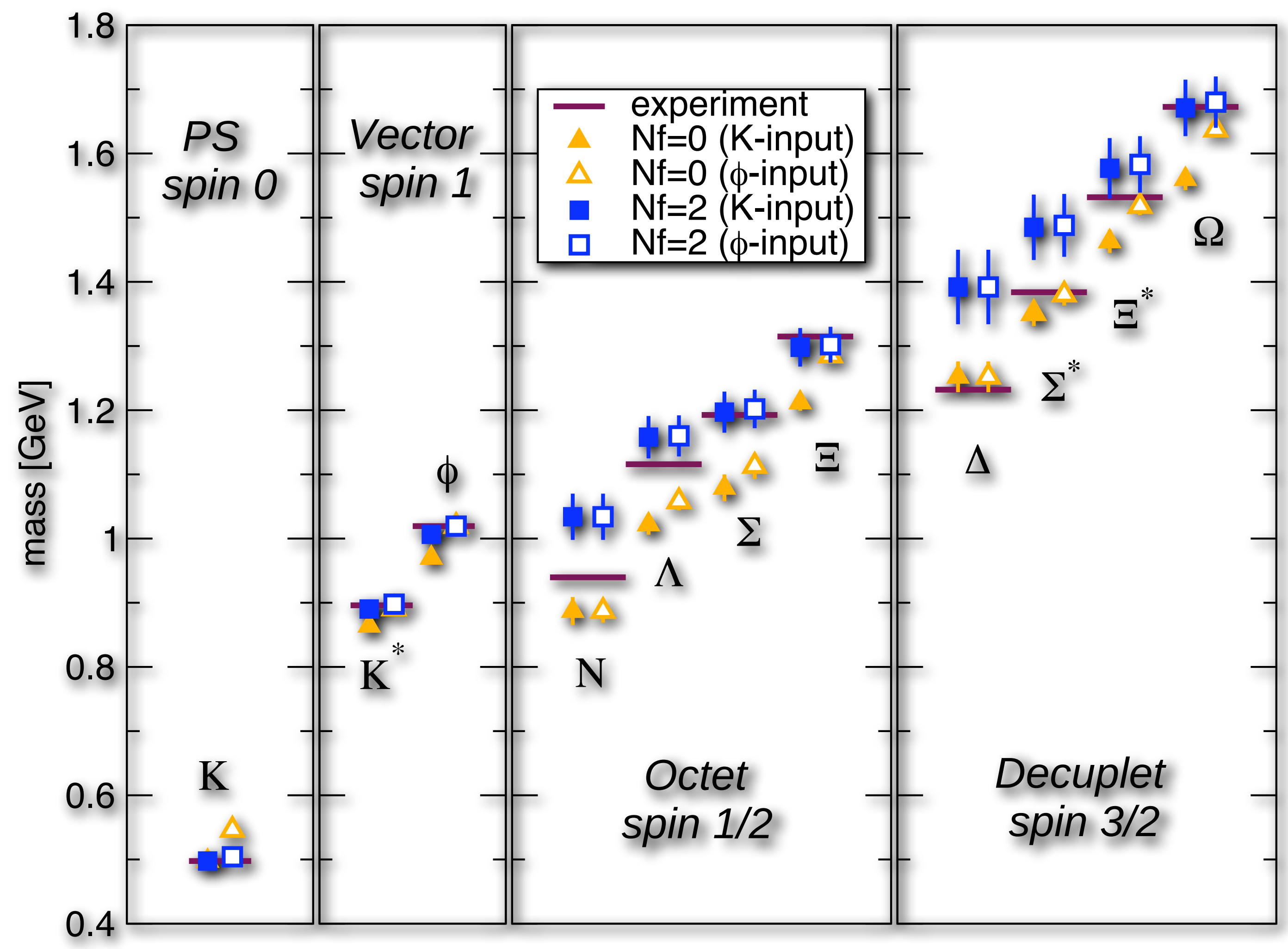
    small Finite Size Effect (FSE)
  - systematic deviation from experiment (5-10%)
- Nf=2
  - small volume
  - for heavier baryons

    good agreement with exp.

    ⟵ dynamical ud quark effect
  - for lighter baryons

    large discrepancy from exp.

    ⟵ FSE



PLQ+Wilson (Phys.Rev.D67(2003)034503)

$$N_f = 0: \quad a = 0.05 - 0.10 \text{ fm}, \quad La = 3.08 - 3.26 \text{ fm}$$

RG+clover (Phys.Rev.D65(2002)054505)

$$c_{SW} : \text{perturbation}$$

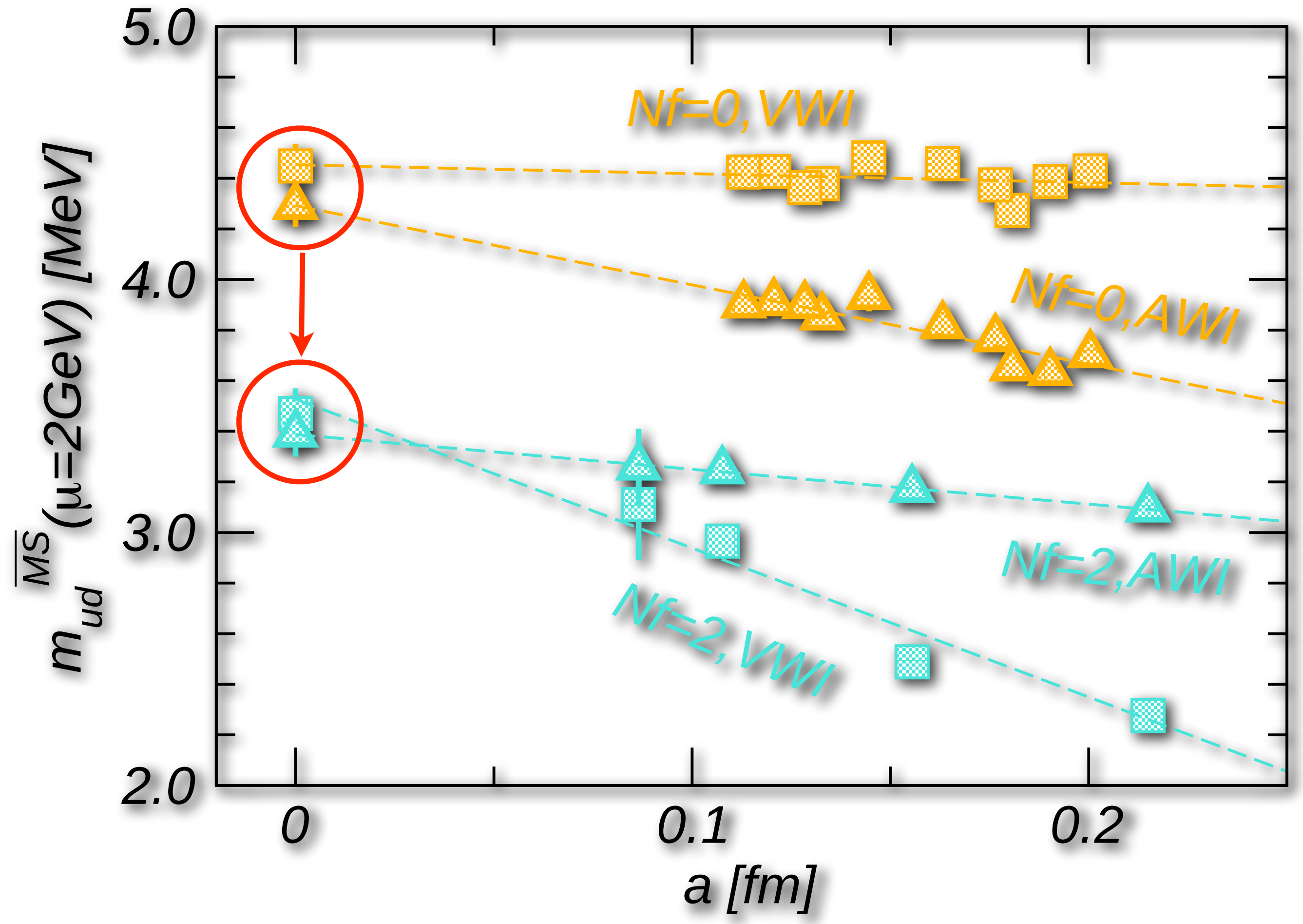
$$N_f = 2: \quad a = 0.086 - 0.215 \text{ fm}, \quad La = 2.0 - 2.5 \text{ fm}$$

ud quark masses

◆ Nf=0 ⟶ Nf=2 :

ud quark mass is reduced.

dynamical ud quark effects



RG+clover (Phys.Rev.D65(2002)054505)

s quark masses

- Nf=0 ⟶ Nf=2 :

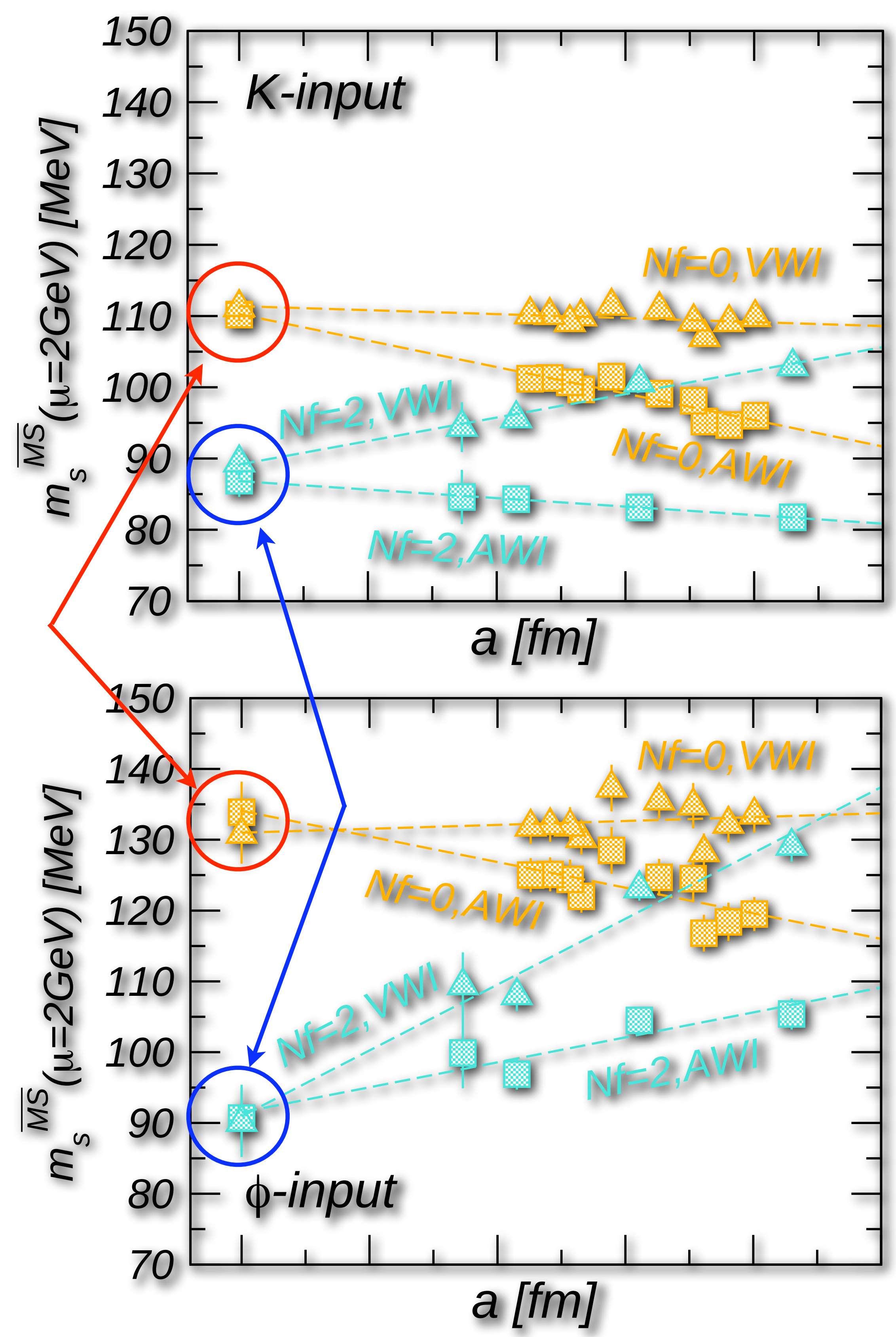
strange quark mass is largely reduced.

discrepancy between K- and ϕ-input vanish.

dynamical ud quark effects

How is the results in the fully unquenched QCD (Nf=2+1)?

RG+clover (Phys.Rev.D65(2002)054505)



Strategy for Nf=2+1

Lattice action

- gauge : RG improved action (Iwasaki,1985)
- quark : non-perturbatively $O(a)$ improved Wilson action
  - c_{SW} is non-perturbatively determined. (Nucl.Phys.Proc.Suppl.129(2004)444, Phys.Rev.D73(2006)034501)

Algorithm

- standard HMC algorithm for up and down quarks
  - usual pseudo-fermion method
- Polynomial HMC (PHMC) algorithm for strange quark
  - odd flavor algorithm
  - exact algorithm (Phys.Rev.D65(2002)094507)

- $\delta\tau, \quad N_{poly}$

$$\delta\tau, \quad N_{poly} \quad \longleftarrow P_{HMC} \simeq 85\%, \quad P_{GMP} \simeq 90\%$$

$\beta = 1.83$

κ_{ud}	κ_s	$d\tau$	N_{poly}	κ_{ud}	κ_s	$d\tau$	N_{poly}
0.13655		1/80	80	0.13655		1/90	110
0.13710		1/85	80	0.13710		1/100	110
0.13760	0.13710	1/100	100	0.13760	0.13760	1/110	120
0.13800		1/120	110	0.13800		1/120	130
0.13825		1/140	120	0.13825		1/150	150

$\beta = 1.90$

κ_{ud}	κ_s	$d\tau$	N_{poly}	κ_{ud}	κ_s	$d\tau$	N_{poly}
0.13580		1/125	110	0.13580		1/125	140
0.13610		1/125	110	0.13610		1/125	140
0.13640	0.13580	1/140	110	0.13640	0.13640	1/140	140
0.13680		1/160	110	0.13680		1/160	140
0.13700		1/180	110	0.13700		1/180	140

$\beta = 2.05$

κ_{ud}	κ_s	$d\tau$	N_{poly}	κ_{ud}	κ_s	$d\tau$	N_{poly}
0.13470		1/175	200	0.13470		1/175	250
0.13510		1/195	200	0.13510		1/195	250
0.13540	0.13510	1/225	200	0.13540	0.13540	1/225	250
0.13550		1/235	200	0.13550		1/235	250
0.13560		1/250	200	0.13560		1/250	250

Simulation parameters

Lattice spacing, size, etc.

$\beta = 2.05$	$\beta = 1.90$	$\beta = 1.83$
$(a \sim 0.070 \text{ fm})$	$(a \sim 0.100 \text{ fm})$	$(a \sim 0.122 \text{ fm})$
$c_{SW} = 1.628$	$c_{SW} = 1.715$	$c_{SW} = 1.761$
$L^3 \times T = 28^3 \times 56$	$L^3 \times T = 20^3 \times 40$	$L^3 \times T = 16^3 \times 32$
HMC traj. $= 6000 - 6500$	HMC traj. $= 5000 - 9000$	HMC traj. $= 7000 - 8600$

fixed physical volume $\sim (2 \text{ fm})^3$

Quark mass parameters

5 ud quark parameters

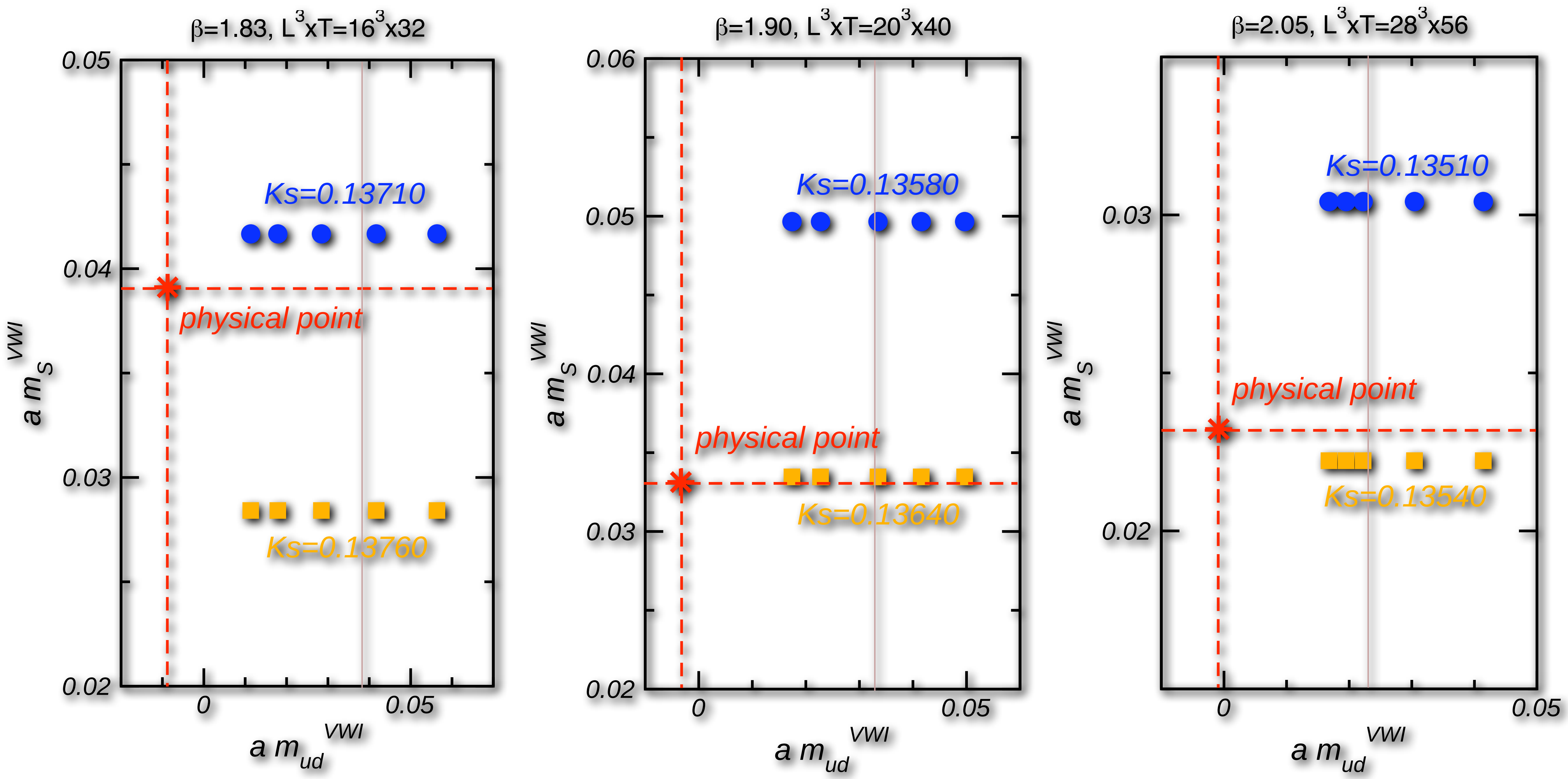
$m_{ps}/m_V \sim 0.60 - 0.78$

(0.18 : exprriment)

2 s quark parameters

$m_{ps}/m_V \sim 0.7$

(0.68 : 1-loop ChPT)



Gauge configuration generation

Earth Simulator @JAMSTEC

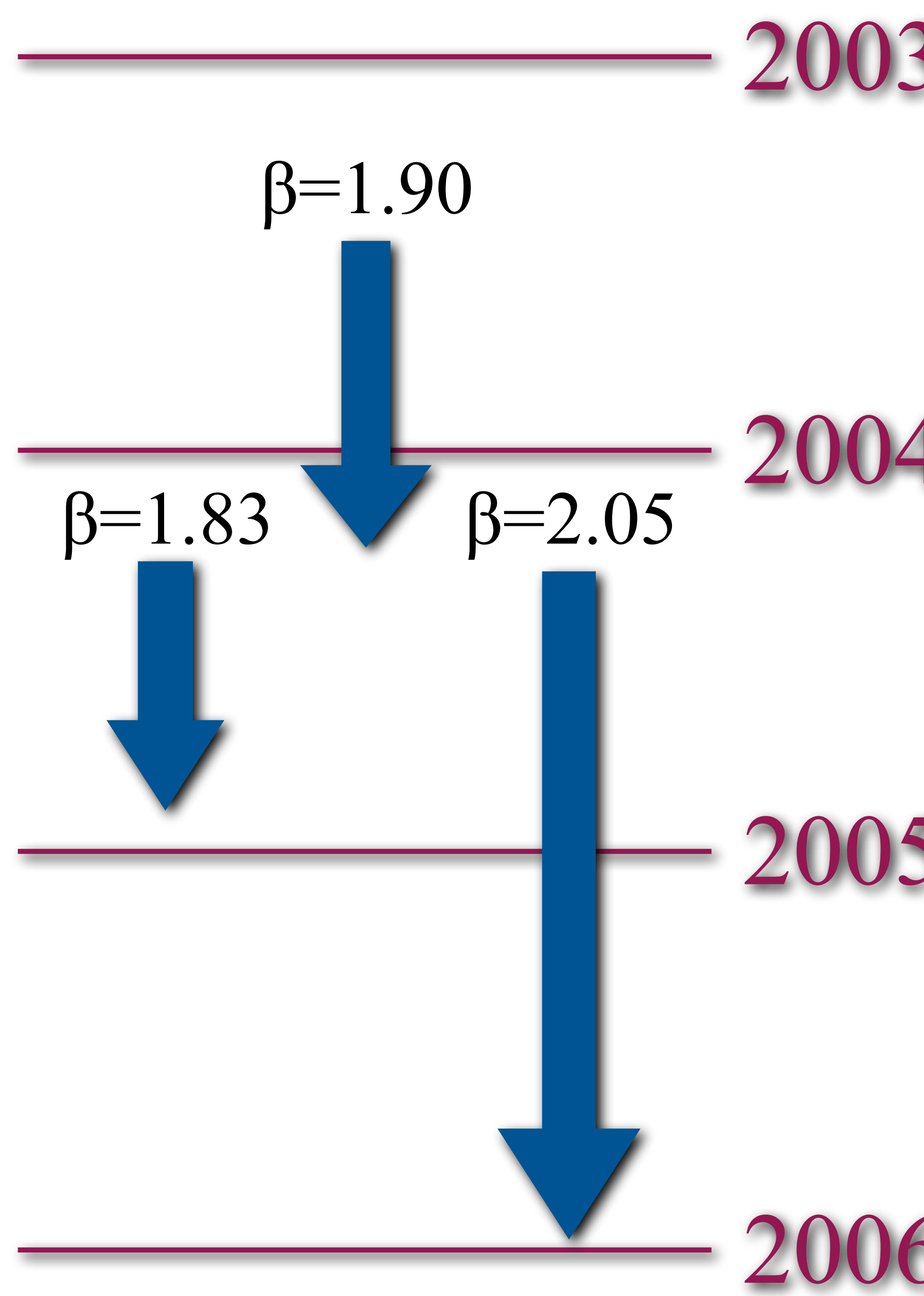
SR8000/F1 @KEK

CP-PACS @CCS, Univ. of Tsukuba

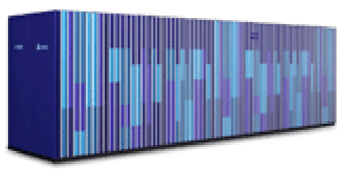
SR8000/G1 @CCS, Univ. of Tsukuba

VPP5000 @ACCC, Univ. of Tsukuba

Production runs



Computing facilities for Nf=2+1



machines	GF/node	total		for Nf=2+1 QCD		use
		# of node	GFlops	# of node	GFlops	
SR11000/J1 @ISSP, Univ. of Tokyo	60.8	88	5350	~2	~122	measurement
SR8000/G1 @CCS, Univ. of Tsukuba	14.4	12	173	12	173	production (β=1.83, 1.90), measurement
VPP5000 @ACCC, Univ. of Tsukuba	9.6	80	768	~24	~230	production (β=1.83, 1.90)
CP-PACS @CCS, Univ. of Tsukuba	0.3	2048	614	2048	614	production (β=1.83, 1.90)
SR8000/F1 @KEK	12	100	1200	~64	~768	production (β=1.90, 2.05), measurement
Earth Simulator @JAMSTEC	64	640	40960	~14	~896	production (β=1.90, 2.05)

total ~2.8TFlops

Measurement of the meson masses

Procedure

- We perform the measurements at only unitarity points.

$$m_{valence} = m_{sea}$$

- Physical volume $\sim (2\ \mathrm{fm})^3$ is not large to calculate baryon masses.

  $\longrightarrow$ We mainly focus on the meson sector.

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

  $\longrightarrow$ It does not change conclusions.

- Measurements are performed at every 10 HMC trajectories.

- 2 source points

- Smearing: Doubly (exponentialy) smeared source - point sink

Statistics for the measurement

β=1.83

κ_{ud}	κ_s	traj.	m_π/m_ρ	m_{η_s}/m_ϕ	κ_{ud}	κ_s	traj.	m_π/m_ρ	m_{η_s}/m_ϕ
0.13655		7000	0.7772(13)	0.7521(15)	0.13655		7000	0.7769(14)	0.7235(19)
0.13710		7000	0.7524(21)	0.7524(21)	0.13710		8600	0.7447(14)	0.7128(16)
0.13760	0.13710	7000	0.7076(18)	0.7414(17)	0.13760	0.13760	8000	0.7033(18)	0.7033(18)
0.13800		8000	0.6628(22)	0.7365(16)	0.13800		8100	0.6524(23)	0.6941(20)
0.13825		8000	0.6212(24)	0.7343(15)	0.13825		8100	0.6083(32)	0.6884(21)

β=1.90

κ_{ud}	κ_s	traj.	m_π/m_ρ	m_{η_s}/m_ϕ	κ_{ud}	κ_s	traj.	m_π/m_ρ	m_{η_s}/m_ϕ
0.13580		5000	0.7673(15)	0.7673(15)	0.13580		5200	0.7667(16)	0.7210(21)
0.13610		6000	0.7435(18)	0.7647(17)	0.13610		8000	0.7443(15)	0.7182(17)
0.13640	0.13580	7600	0.7204(19)	0.7687(15)	0.13640	0.13640	9000	0.7145(16)	0.7145(16)
0.13680		8000	0.6701(27)	0.7673(17)	0.13680		9200	0.6630(21)	0.7127(17)
0.13700		8000	0.6389(21)	0.7693(15)	0.13700		8000	0.6241(28)	0.7101(20)

β=2.05

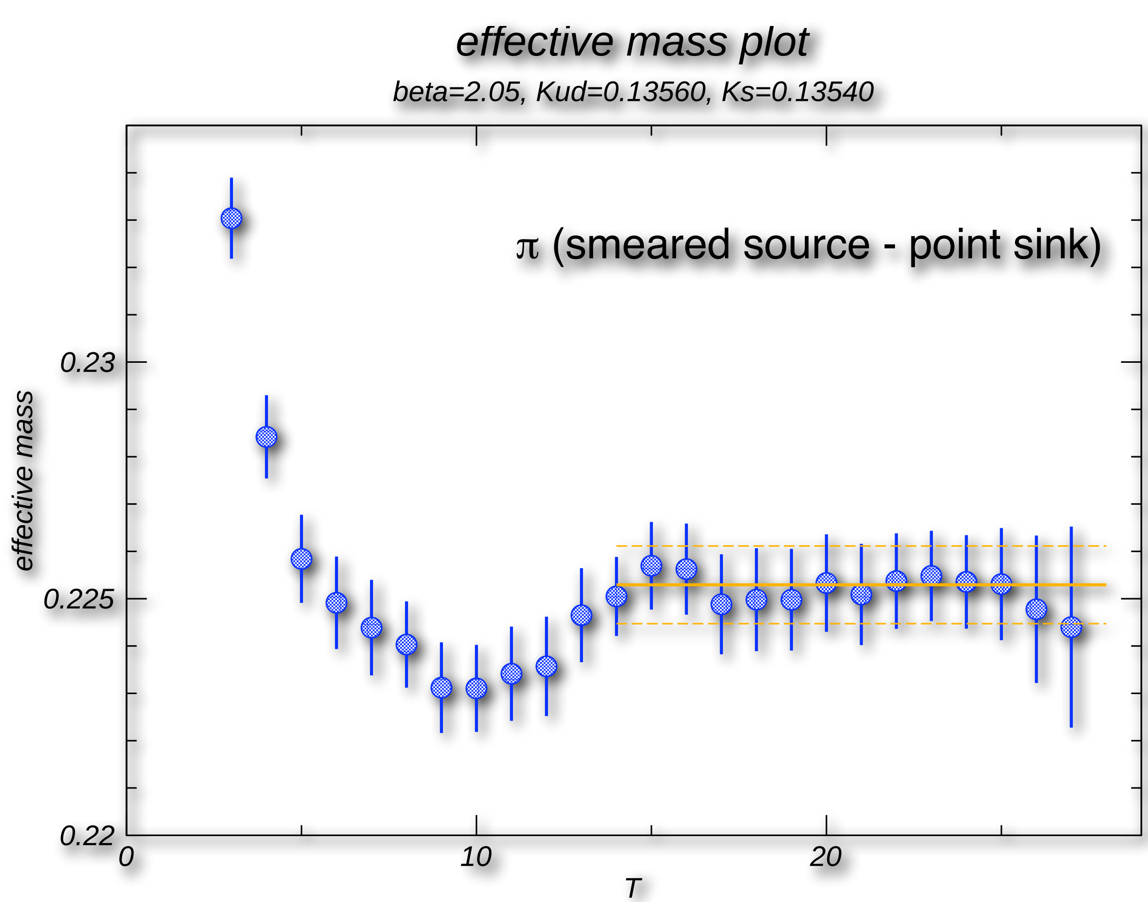
κ_{ud}	κ_s	traj.	m_π/m_ρ	m_{η_s}/m_ϕ	κ_{ud}	κ_s	traj.	m_π/m_ρ	m_{η_s}/m_ϕ
0.13470		6000	0.7757(26)	0.7274(29)	0.13470		6000	0.7790(23)	0.6821(32)
0.13510		6000	0.7316(23)	0.7316(23)	0.13510		6000	0.7341(29)	0.6820(39)
0.13540	0.13510	6000	0.6874(30)	0.7395(23)	0.13540	0.13540	6000	0.6899(34)	0.6899(34)
0.13550		6500	0.6611(34)	0.7361(25)	0.13550		6500	0.6679(45)	0.6899(43)
0.13560		6500	0.6337(38)	0.7377(28)	0.13560		6500	0.6360(47)	0.6852(46)

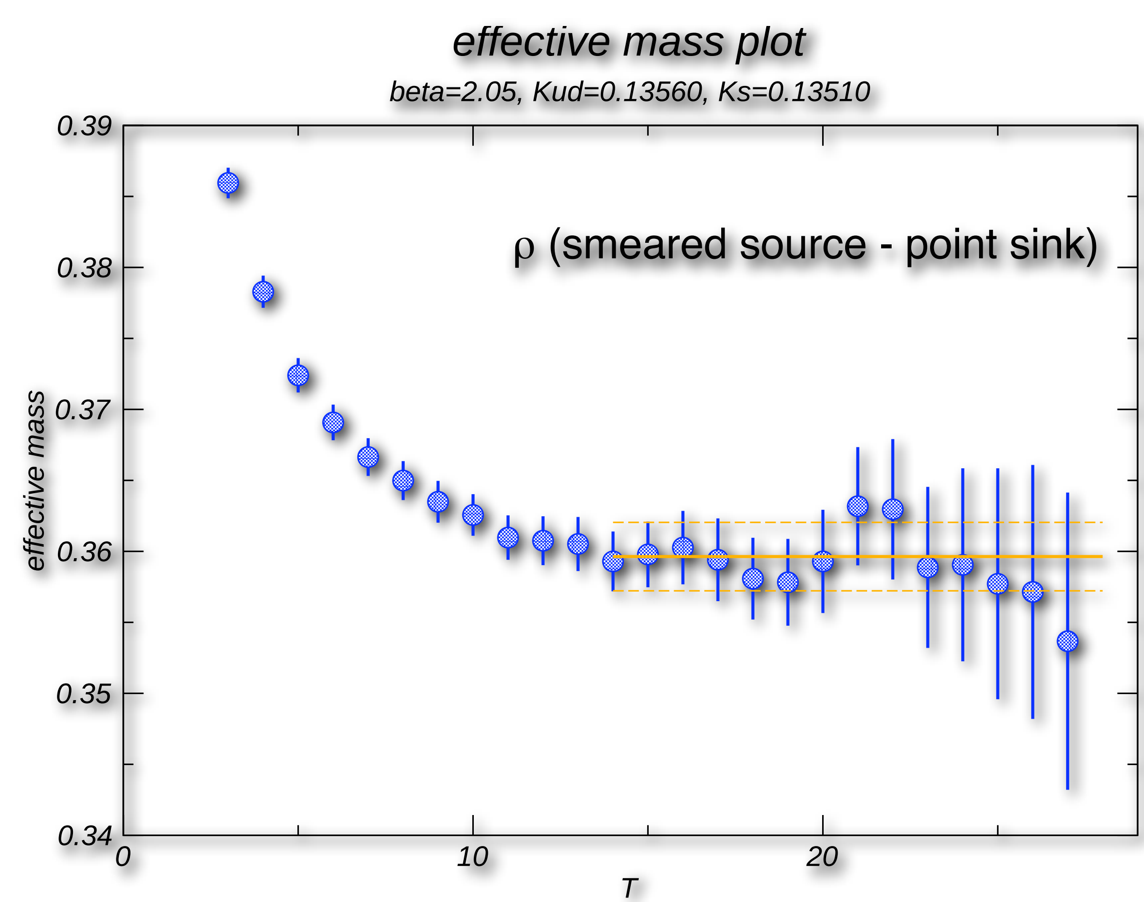
jackknife bin size = 100 HMC traj.

Effective mass plot

$$am_{eff}(t) = -\ln\frac{G(t+1)}{G(t)}$$

$$G(t)\ :\ \text{correlation function}$$





Chiral extrapolation

Fitting procedure

- Polynomial fit functions in quark masses are used.
  - include up to quadratic terms
  - interchanging symmetry among 3 sea quarks

    among 2 valence quarks
- Chiral fits are made to
  - light-light (LL), light-strange (LS) and strange-strange (SS) meson simultaneously.
  - ignoring correlations among LL, LS and SS

- Polynomial fit forms using the VWI quark mass definition

$$
\begin{aligned}
m_{PS}^2 = \quad & B_S^{PS}(2m_{ud}+m_s) + B_V^{PS}(m_{val1}+m_{val2}) \\
+ \quad & D_{SV}^{PS}(2m_{ud}+m_s)(m_{val1}+m_{val2}) \\
+ \quad & C_{S1}^{PS}(2m_{ud}^2+m_s^2) + C_{S2}^{PS}(m_{ud}^2+2m_{ud}m_s) \\
+ \quad & C_{V1}^{PS}(m_{val1}^2+m_{val2}^2) + C_{V2}^{PS}m_{val1}m_{val2}
\end{aligned}
$$

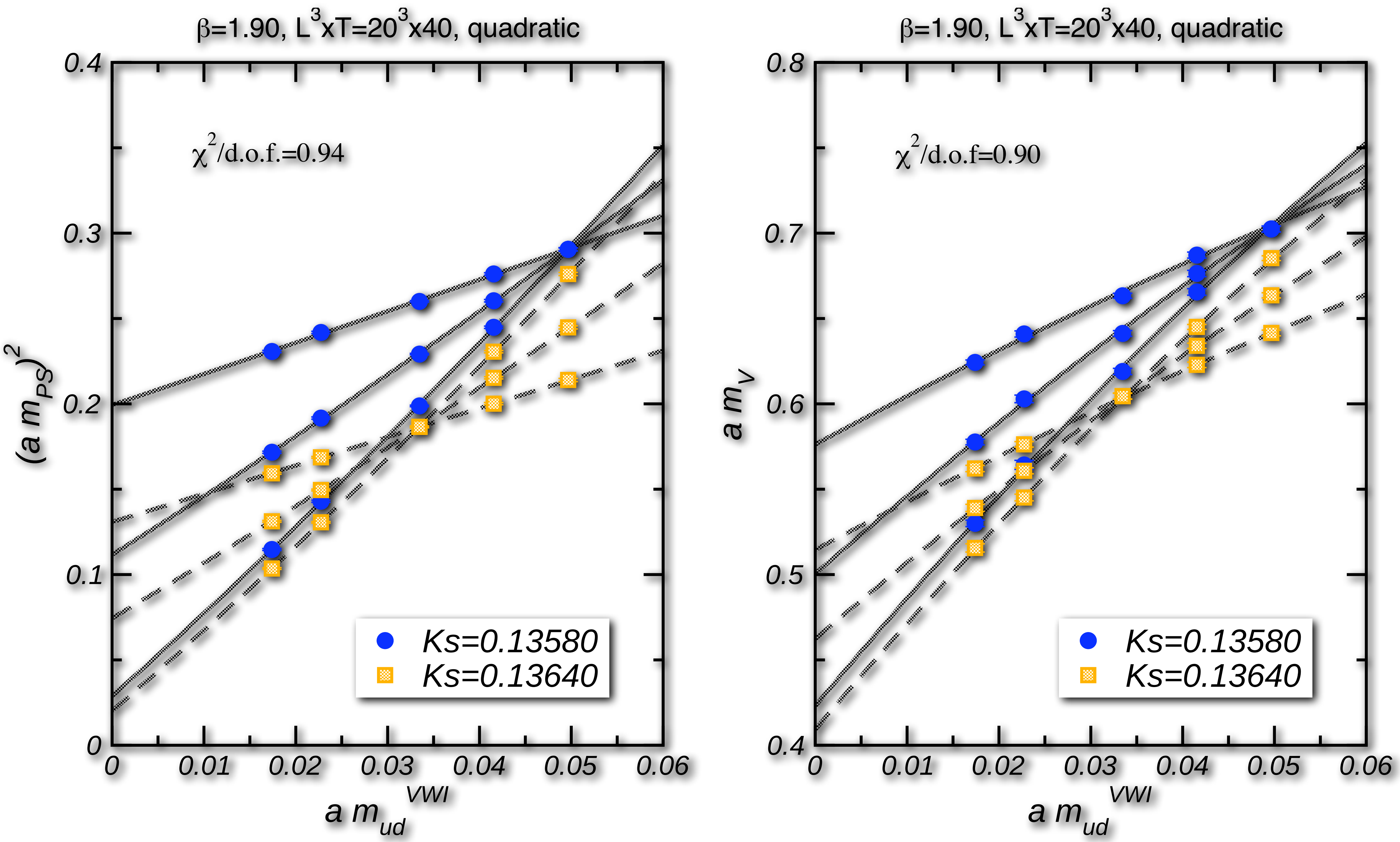
$$
\begin{aligned}
m_V = \quad & A^V + B_S^V(2m_{ud}+m_s) + B_V^V(m_{val1}+m_{val2}) \\
+ \quad & D_{SV}^V(2m_{ud}+m_s)(m_{val1}+m_{val2}) \\
+ \quad & C_{S1}^V(2m_{ud}^2+m_s^2) + C_{S2}^V(m_{ud}^2+2m_{ud}m_s) \\
+ \quad & C_{V1}^V(m_{val1}^2+m_{val2}^2) + C_{V2}^V m_{val1}m_{val2}
\end{aligned}
$$

$$
m_q = \frac{1}{2}\left(\frac{1}{K_q} - \frac{1}{K_C}\right)
$$

m_{ud}, m_s : sea quarks

m_{val1}, m_{val2} : valence quarks

# of fit parameters = 16


β=1.90, L3xT=203x40, quadratic
χ2/d.o.f.=0.94
(a mPS)2
a mudVWI
Ks=0.13580
Ks=0.13640
β=1.90, L3xT=203x40, quadratic
χ2/d.o.f=0.90
a mV
a mudVWI
Ks=0.13580
Ks=0.13640

Fitting form from Wilson ChPT (WChPT)

- chiral log behavior $m_\pi^2 \ln m_\pi^2$
- Wilson ChPT (WChPT) (Sharpe et al. '98, Lee et al. '99)
  - include explicit chiral symmetry breaking effect of Wilson quark
  - Nf=2+1 version (Phys.Rev.D73(2006)014511), hep-lat/0601019

- for π and ρ (O(a) improved theory)

$$m_\pi^2 = x + 2y + \frac{1}{f^2}\Big[L_\pi(\frac{x}{2} + y + 5C) + L_K \cdot 4C + L_\eta(-\frac{x}{6} - \frac{y}{3} + C) - (D_x x + 2D_y y + E_{xx}x^2 + E_{yy}^\pi y^2 + 2Exy)\Big]$$

$$m_\rho = m_O + \lambda_x x + 2\lambda_y y - \frac{2}{3\pi f^2}\Big[(g_1^2 + \frac{2}{3}g^2)(x+2y)^{3/2} + 2g_2^2(x-y)^{3/2} + \frac{2}{3}g_2^2(x-2y)^{3/2}\Big]$$

$$L_\psi = \frac{\tilde{m}_\psi^2}{16\pi^2}\ln\tilde{m}_\psi^2, \quad \tilde{m}_\pi^2 = x + 2y,\ \tilde{m}_K^2 = x - y,\ \tilde{m}_\eta^2 = x - 2y$$

$$x = \frac{2B}{3}(2m_{ud} + m_s), \quad y = \frac{B}{3}(m_{ud} - m_s)$$

# of fit parameters = 16

fitting is very difficult due to highly non-linear form (in progress)

Physical point and lattice spacing

- Inputs to fix the quark masses and the lattice spacing

K-input $\longleftarrow$ $m_\pi,\ m_\rho,\ m_K$

ϕ-input $\longleftarrow$ $m_\pi,\ m_\rho,\ m_\phi$

to set s quark mass

- lattice spacings $\longleftarrow$ m_ρ

	K-input		ϕ-input	
β	a^{-1}[GeV]	a[fm]	a^{-1}[GeV]	a[fm]
1.83	1.612(22)	0.1222(17)	1.598(26)	0.1233(20)
1.90	1.983(38)	0.0993(19)	1.980(37)	0.0995(19)
2.05	2.84(11)	0.0693(26)	2.84(10)	0.0695(26)

K-input and ϕ-input give consistent results.

Light meson spectrum

Prediction

$$K\text{-input} \quad \rightarrow \quad m_{K^*}, m_\phi$$

$$\phi\text{-input} \quad \rightarrow \quad m_K, m_{K^*}$$

The calculation of $m_\eta, m_{\eta'}$ is in progress.

disconnected diagram is needed.

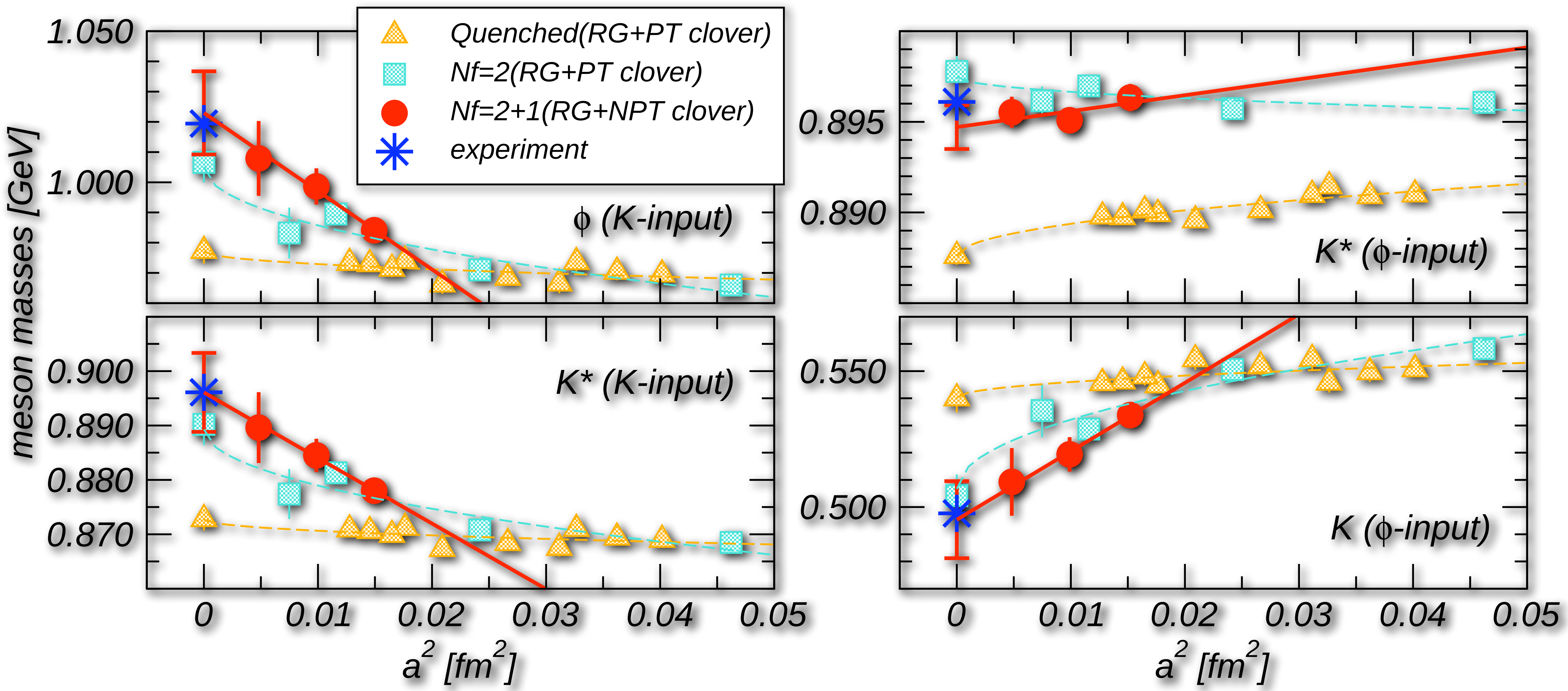
Continuum extrapolation

- We use the non-perturbatively $\mathcal{O}(a)$ improved Wilson quark, thus meson spectrum should scale as a^2.

$$m(a) = A + Ba^2$$

Results

- In the continuum, meson spectrum is consistent with experiment.
- The statistical error in the continuum limit is large.

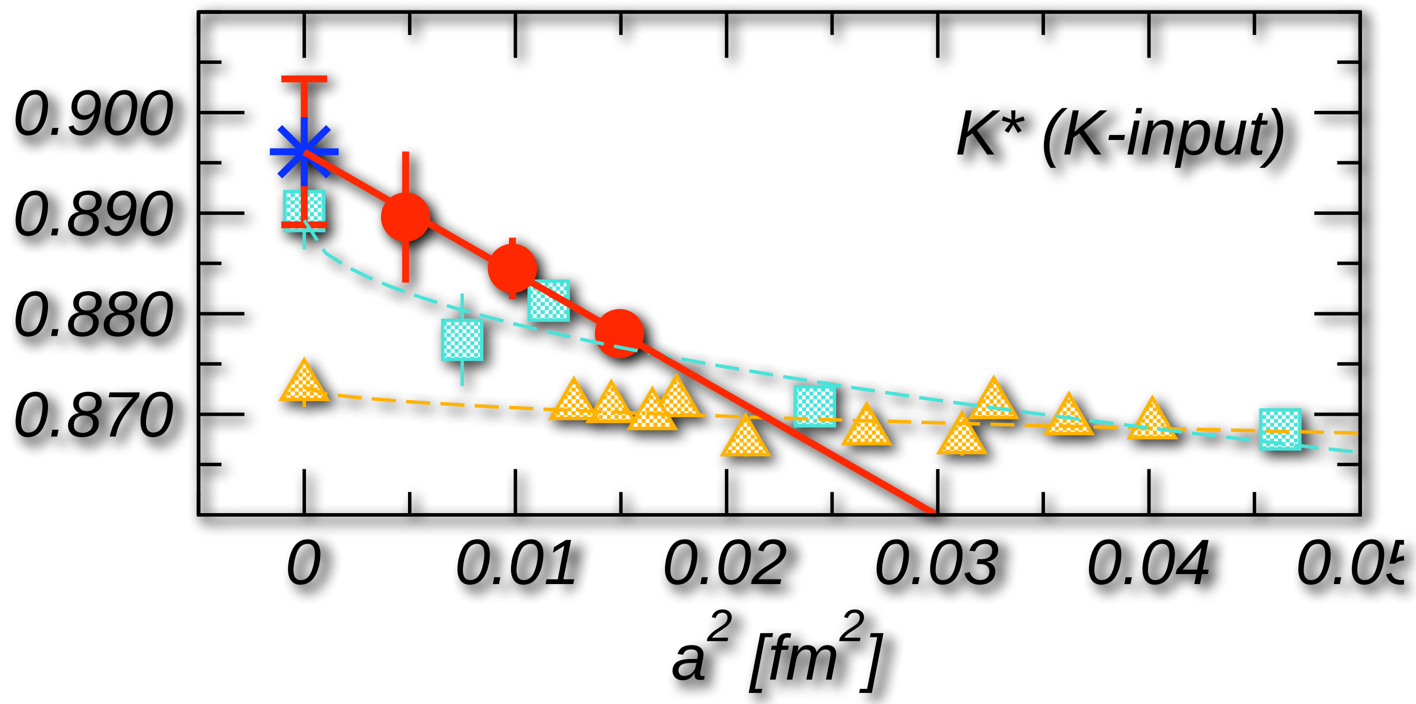


In the Nf=2,0 case, extrapolation function is m(a)=A+Ba, because clover action is perturbatively O(a) improved.

Scaling violations

- Is the scaling violations in Nf=2+1 larger than that in Nf=2 and Nf=0 ?

$$N_f = 2+1 \; : \; \mathrm{NPT}\; c_{SW}, \qquad N_f = 2, 0 \; : \; \mathrm{PT}\; c_{SW}$$



$$m_{K^*}(a) = m_{K^*}(0)(1 + c(\Lambda a)^2), \quad \Lambda \sim 300\ \mathrm{MeV}$$

$$\longrightarrow c \sim O(1)$$

The scaling violation in Nf=2+1 is reasonable.
The small scaling violation in Nf=2 and 0 is accidental.

Light quark masses

VWI quark mass

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

$$K_c \longleftarrow m_\pi(K_{ud}, K_s)|_{K_{ud}=K_s=K_c} = 0$$

- VWI quark mass can be negative due to lack of chiral symmetry of the Wilson quark.

AWI quark mass

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

- The scaling violation is smaller than that of VWI in Nf=2 case.

Renormalization $m_q^{LAT}(a^{-1}) \longrightarrow m_q^{\overline{MS}}(\mu = 2\ \mathrm{GeV})$

- tad-pole improved 1-loop matching with $\overline{\mathrm{MS}}$ at $\mu = a^{-1}$
- 4-loop running to $\mu = 2\ \mathrm{GeV}$

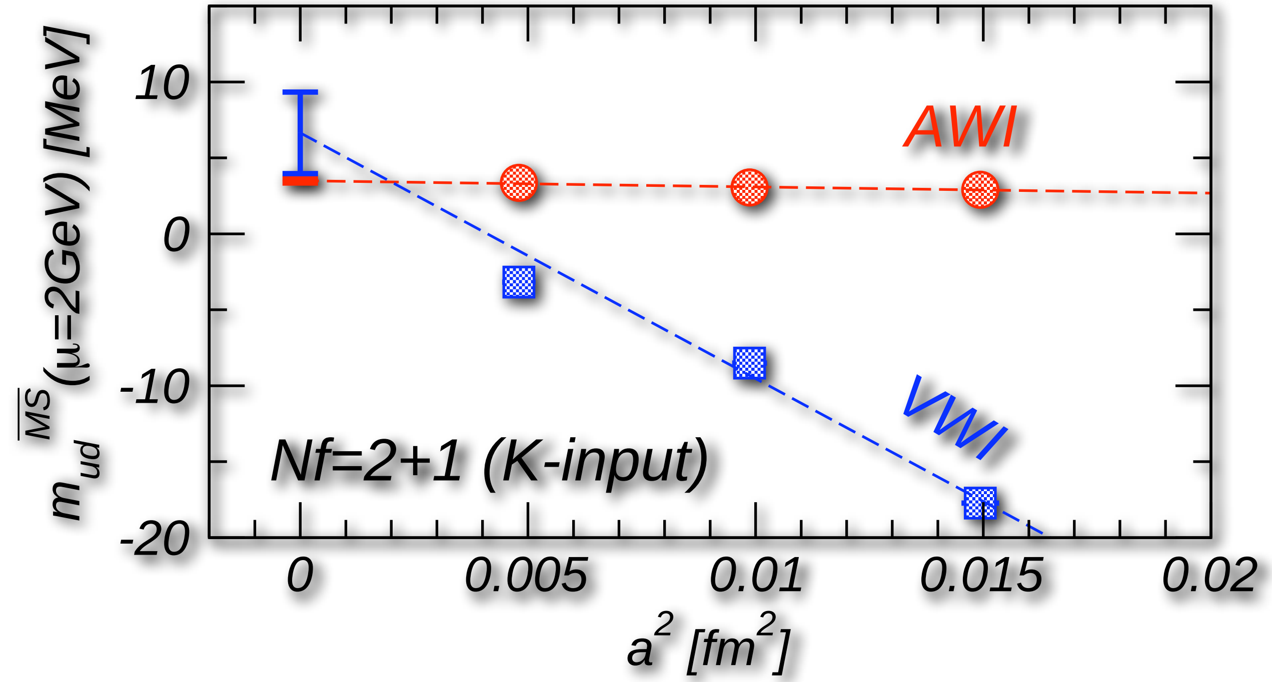
up and down quarks

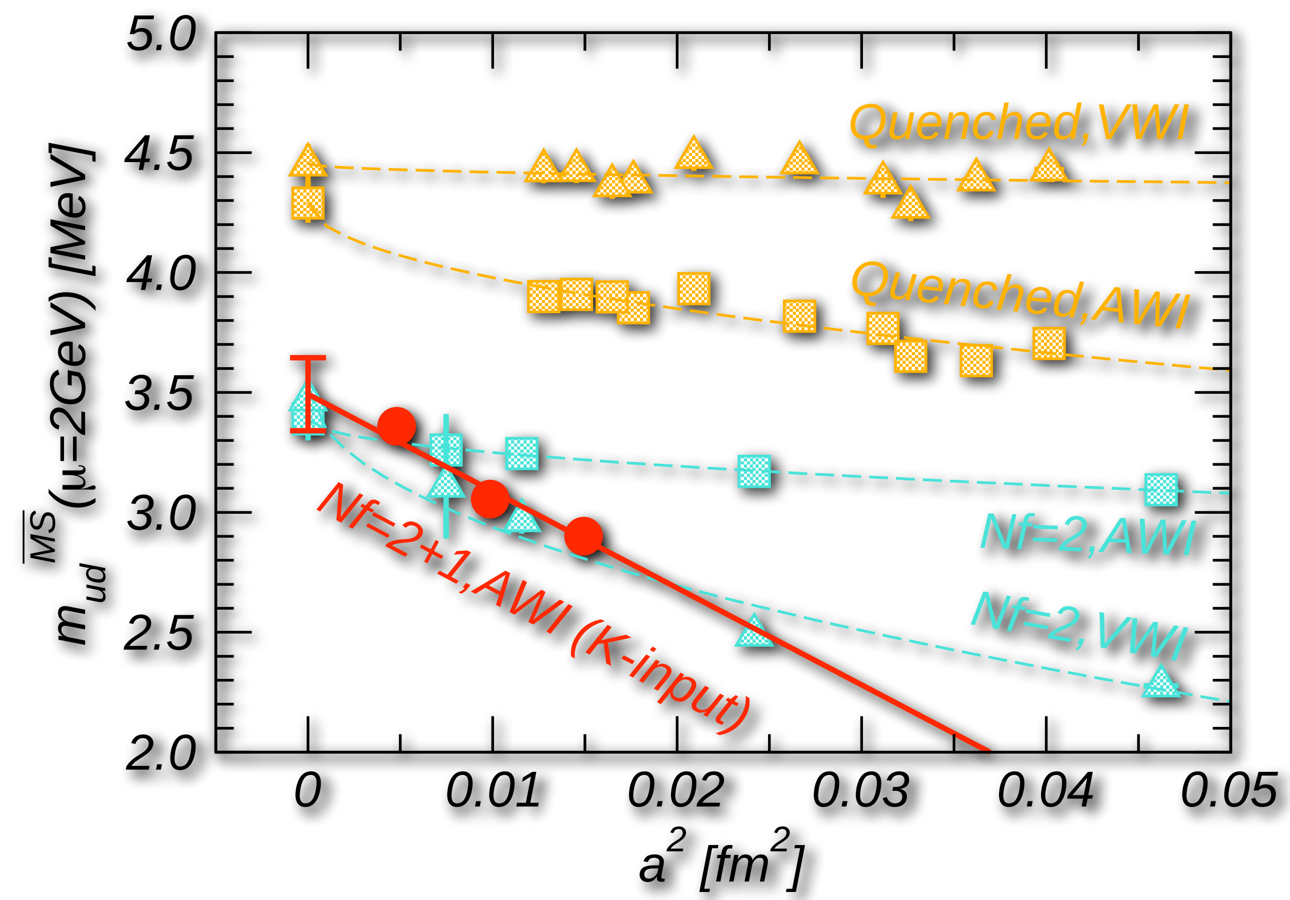
- We assume that the $O(a)$ contribution is small and use the extrapolation function which is same as in the meson spectrum (linear in a^2).

- In the continuum limit, the VWI definition gives a positive value.

$$m_{ud}^{\overline{MS}}(\mu = 2\text{GeV}) = 3.49(15)\ \text{MeV}$$

(AWI, combined K with ϕ-input)





(Nf=2, 0 : RG+clover(PT))

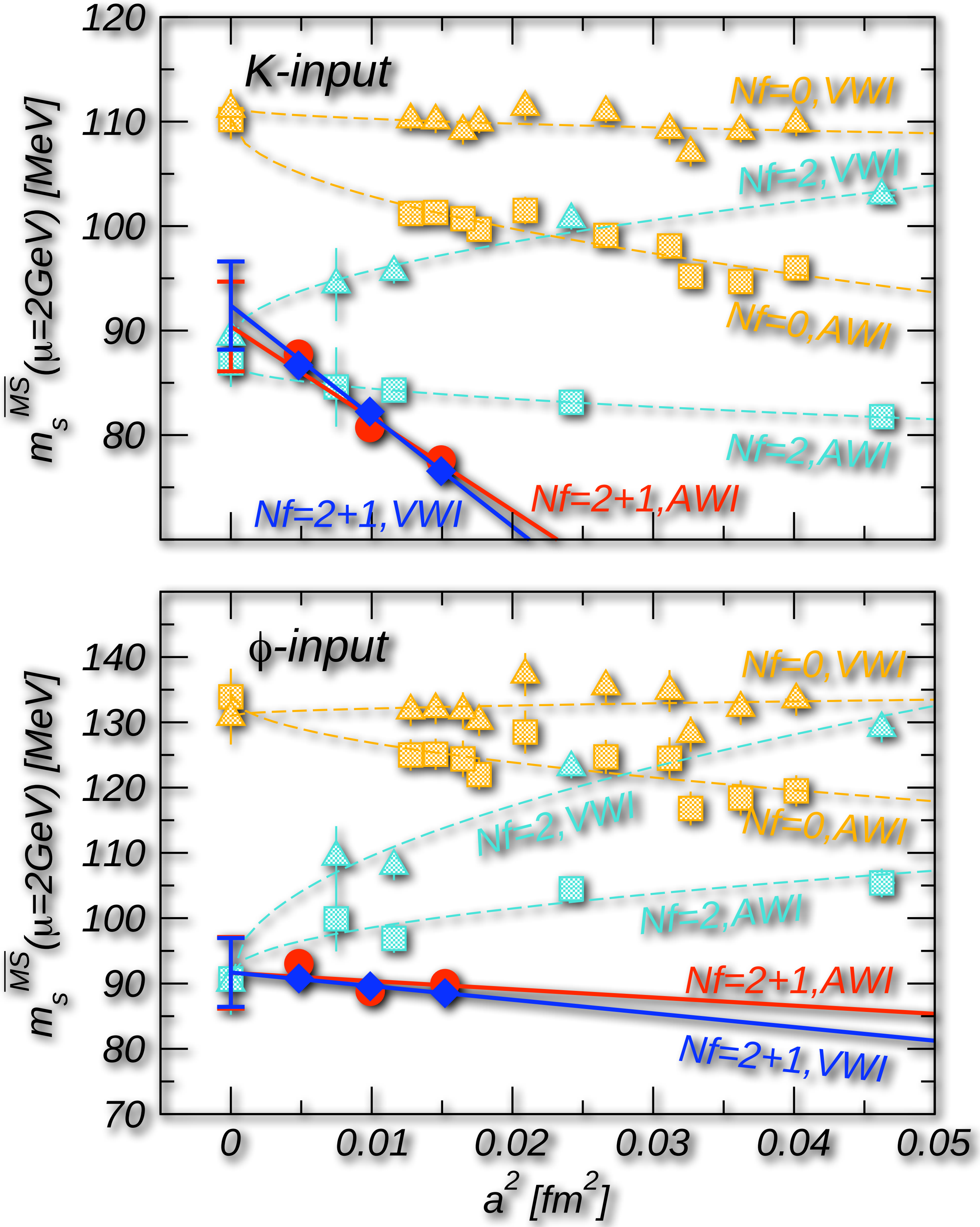
strange quark

- All definitions of strange quark mass gives consistent results in the continuum limit.

- The difference between Nf=2+1 and Nf=2 is invisible in the continuum limit as in the ud quark.

$$m_s^{\overline{MS}}(\mu = 2\mathrm{GeV}) = 90.9(3.7)\ \mathrm{MeV}$$

(AWI, combined K with ϕ-input)



(Nf=2, 0 : RG+clover(PT))

Comment : PT and NPT renormalization factor

In Nf=2 we can see systematic deviation of strange quark mass between PT and NPT renormalization factor.

NPT renormalization factor is very important.

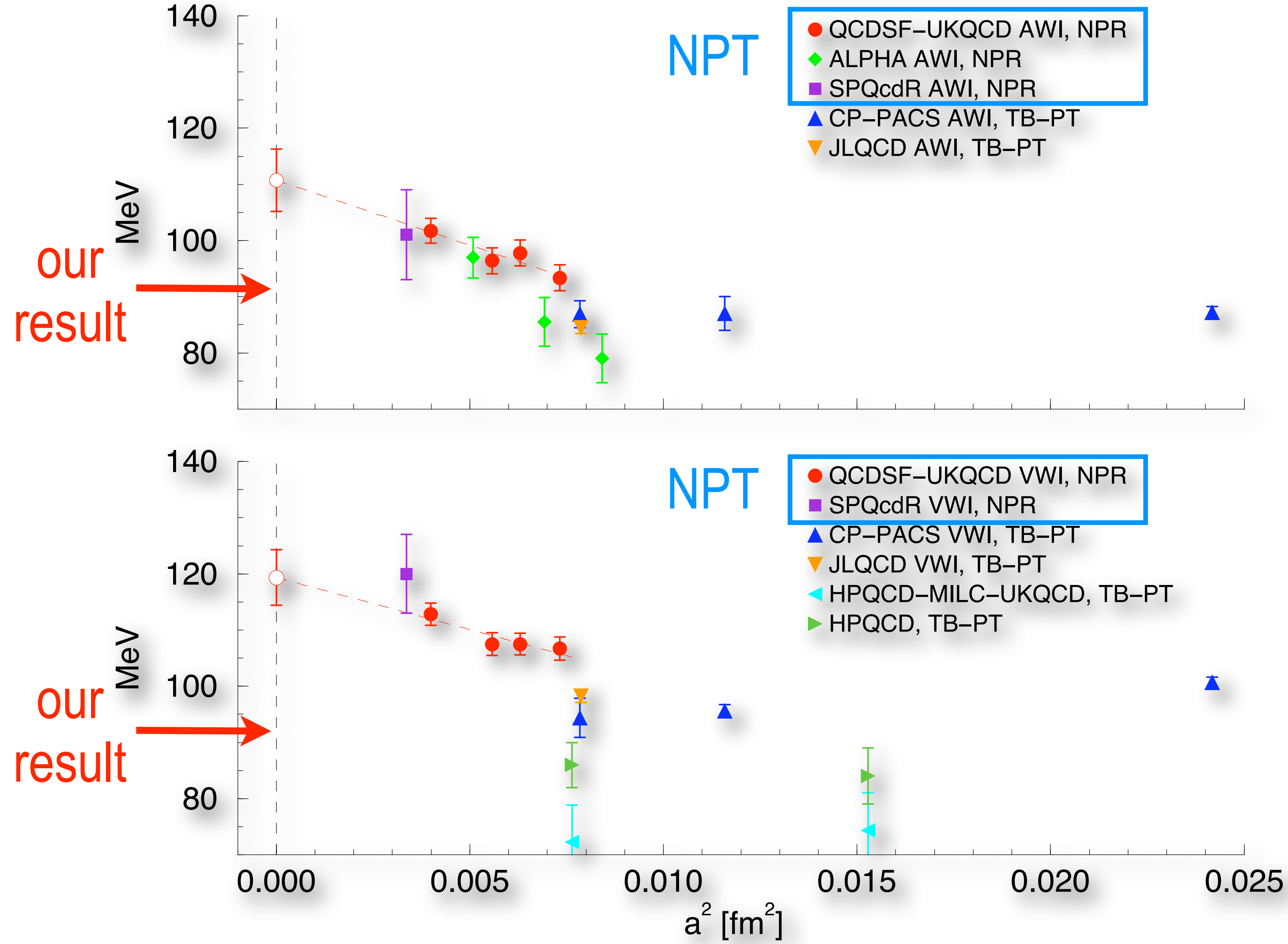


figure from hep-lat/0601004 (QCDSF-UKQCD)

PS meson decay constants

PS decay constant f_π, f_K

$$\langle 0|A_4|\pi\rangle = f_\pi m_\pi$$

renormalization

- tad-pole improved one-loop renormalization factor

definitions for the calculation

- We test two different definitions.

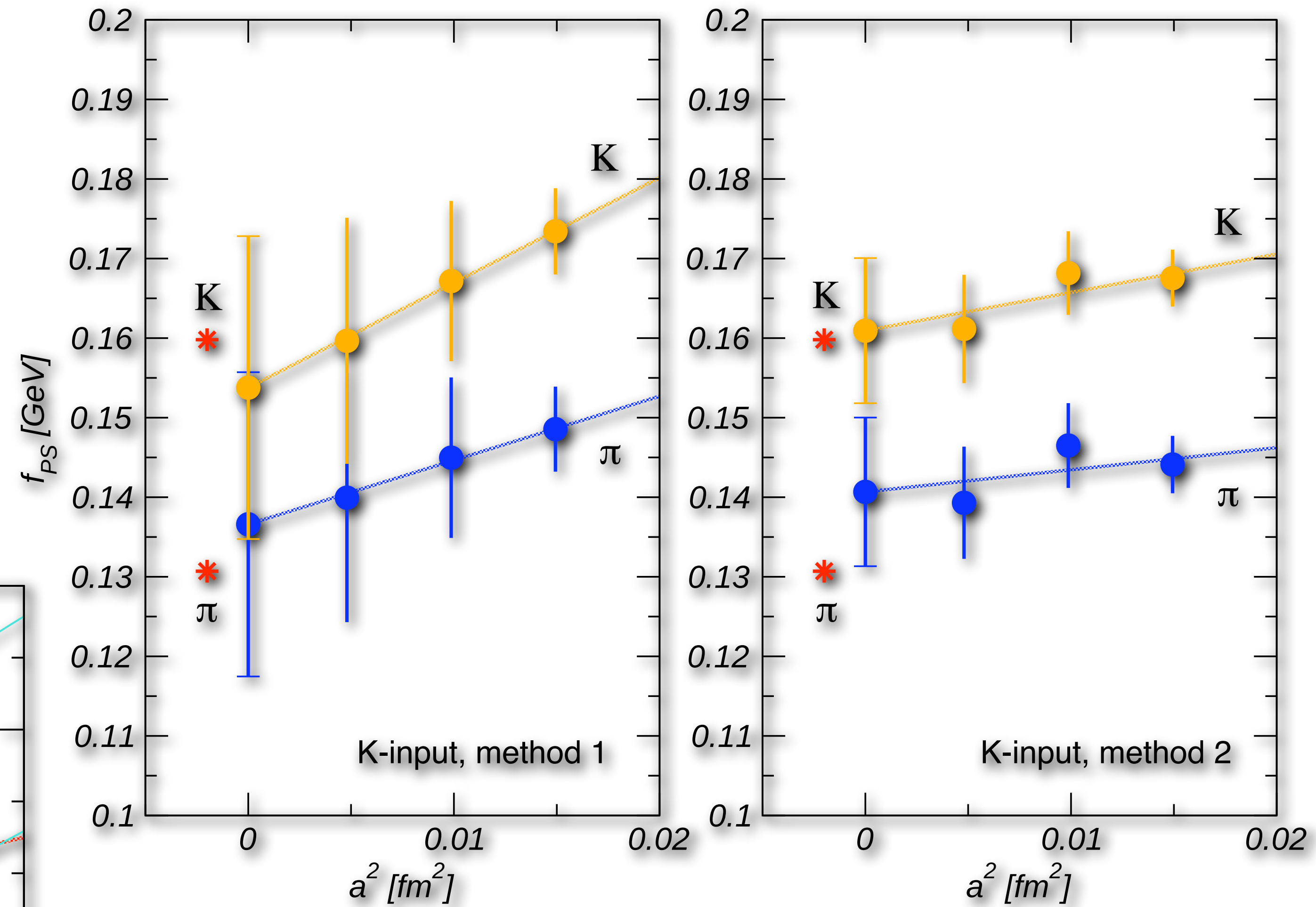
$$\begin{aligned}
\langle P^P(t)P^P(0)\rangle &\sim C_P^{PP} e^{-m_\pi t} \\
\langle P^P(t)P^S(0)\rangle &\sim C_P^{PS} e^{-m_\pi t} \\
\langle P^S(t)P^S(0)\rangle &\sim C_P^{SS} e^{-m_\pi t} \\
\langle A_4^P(t)P^S(0)\rangle &\sim C_A^{PS} e^{-m_\pi t}
\end{aligned}$$

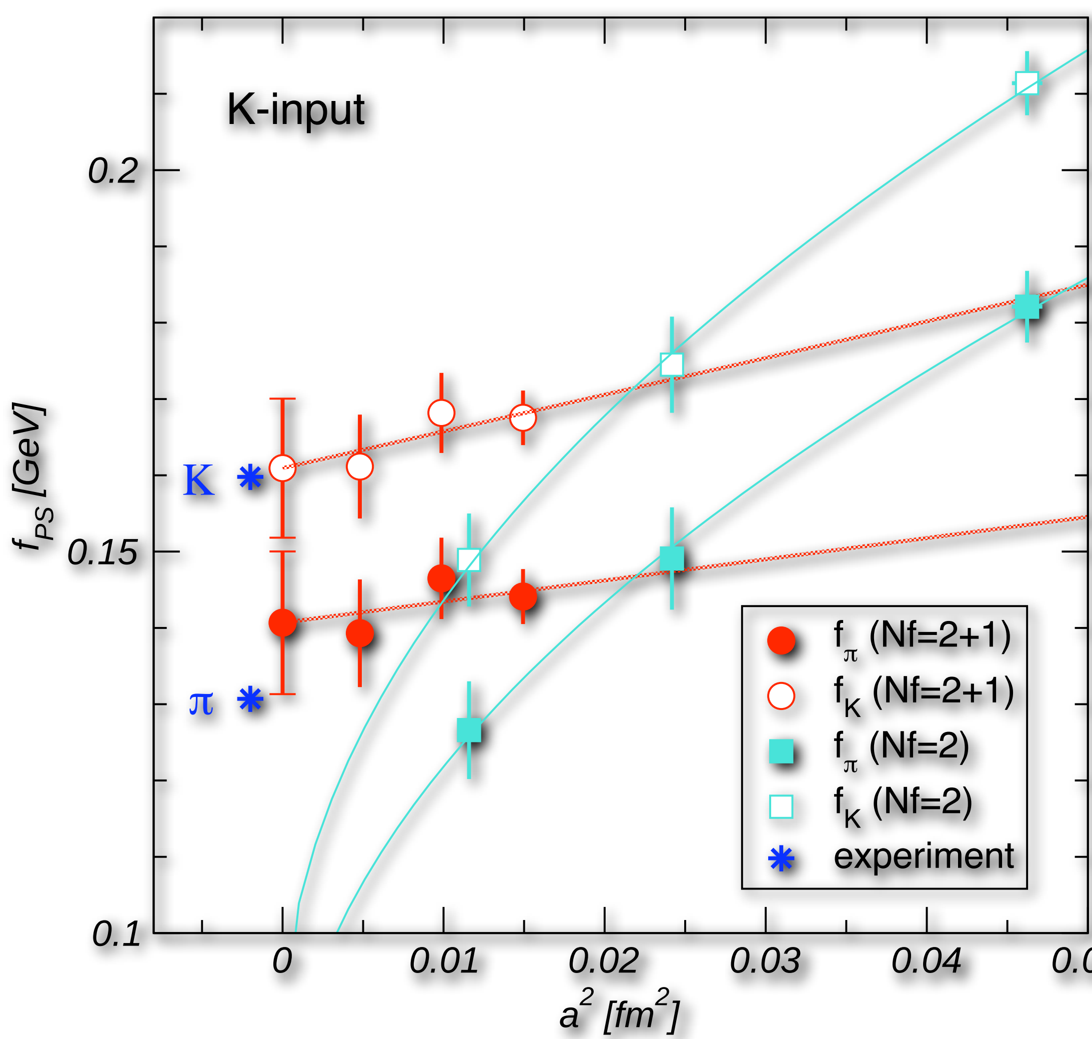
$$P \ : \ \text{point}, \quad S \ : \ \text{exponential}$$

$$f_\pi = \frac{C_A^{PS}}{C_P^{PS}} \sqrt{\frac{2C_P^{PP}}{m_\pi}} \qquad \text{(method 1)}$$

$$f_\pi = C_A^{PS} \sqrt{\frac{2}{m_\pi C_P^{SS}}} \qquad \text{(method 2)}$$

Two methods are consistent each other within the large statistical error.





(Nf=2 : RG+clover(PT))

- The continuum limit values are consistent with experiment.

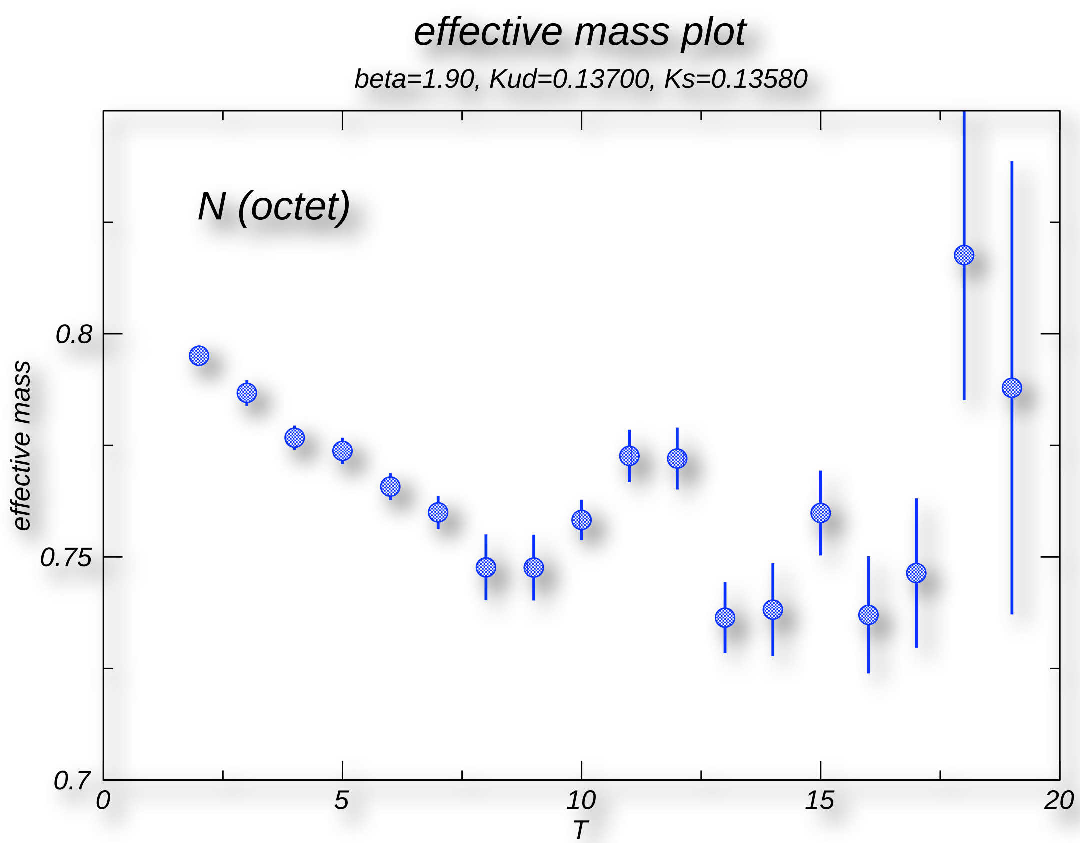
$$f_\pi = 140.7(9.3)\ \mathrm{MeV}$$
$$f_K = 160.9(9.1)\ \mathrm{MeV}$$

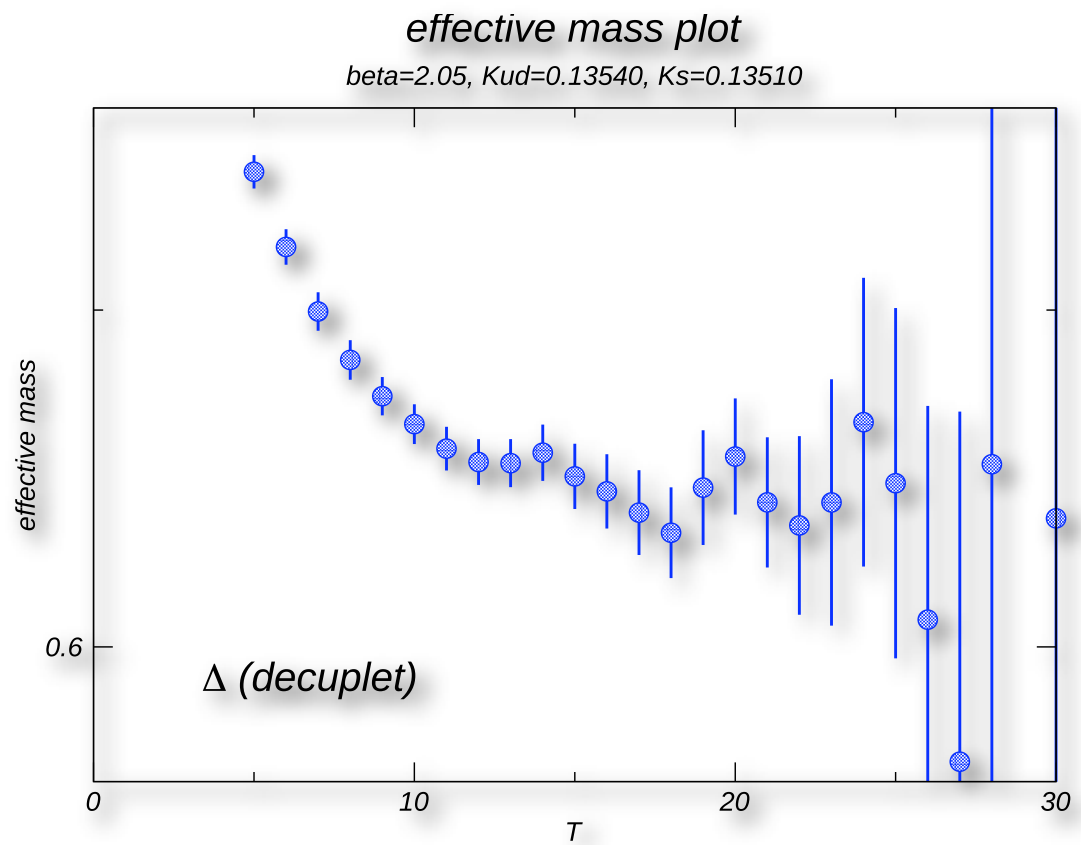
(method 2, K-input)

(preliminary)

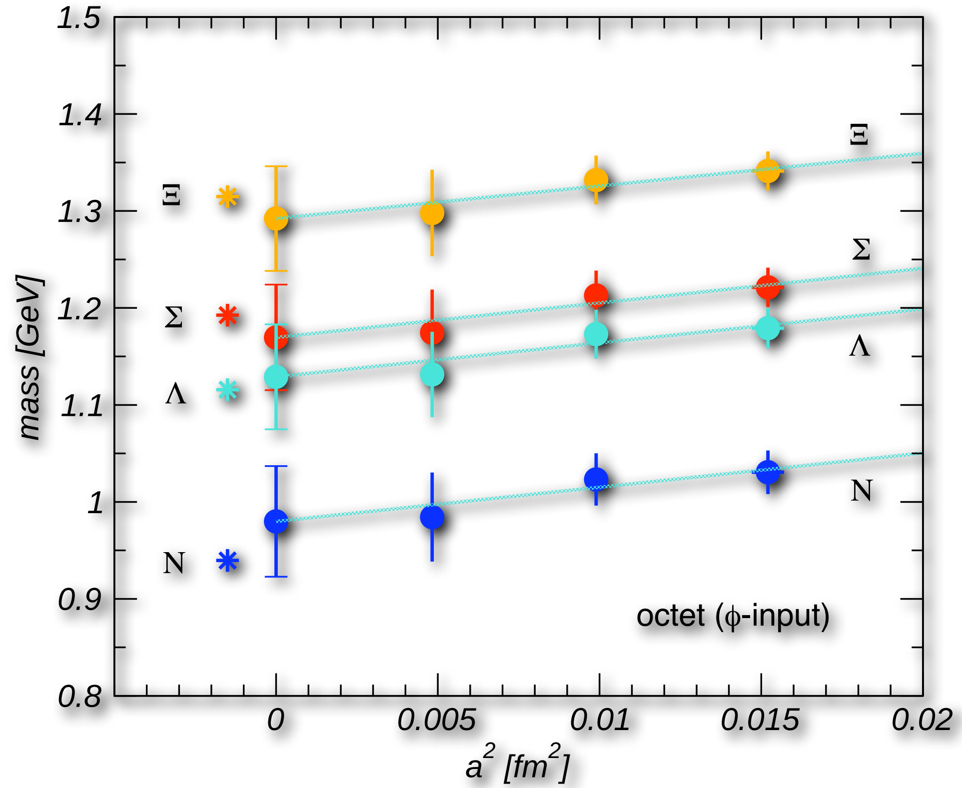
Baryon spectrum

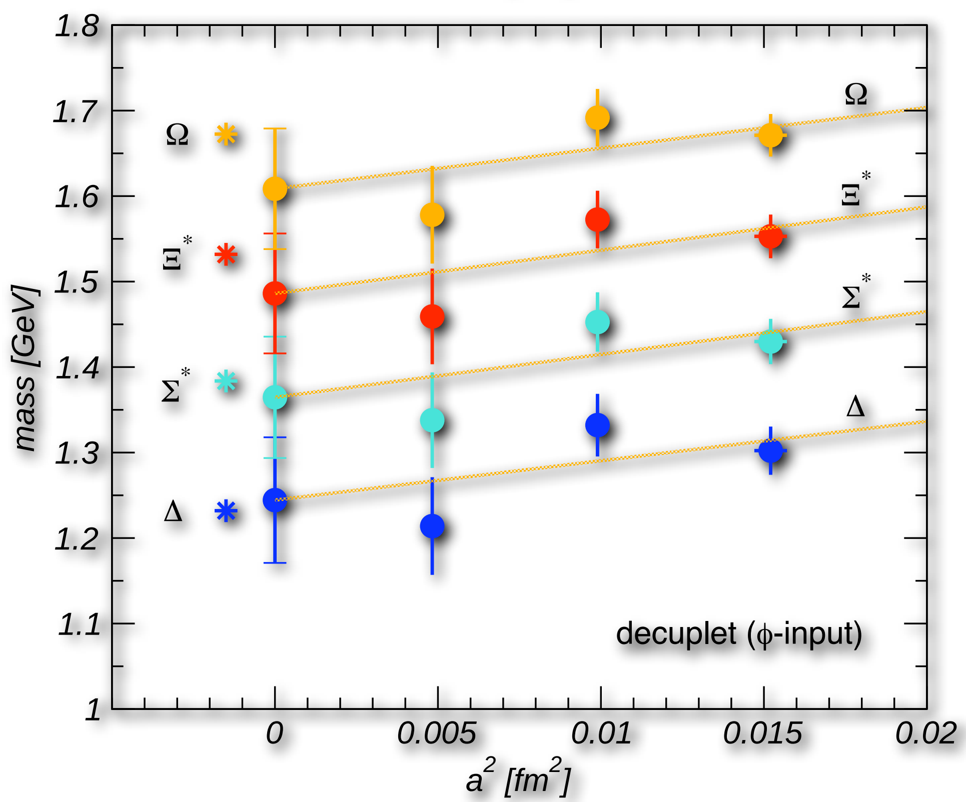
- Effective mass plot



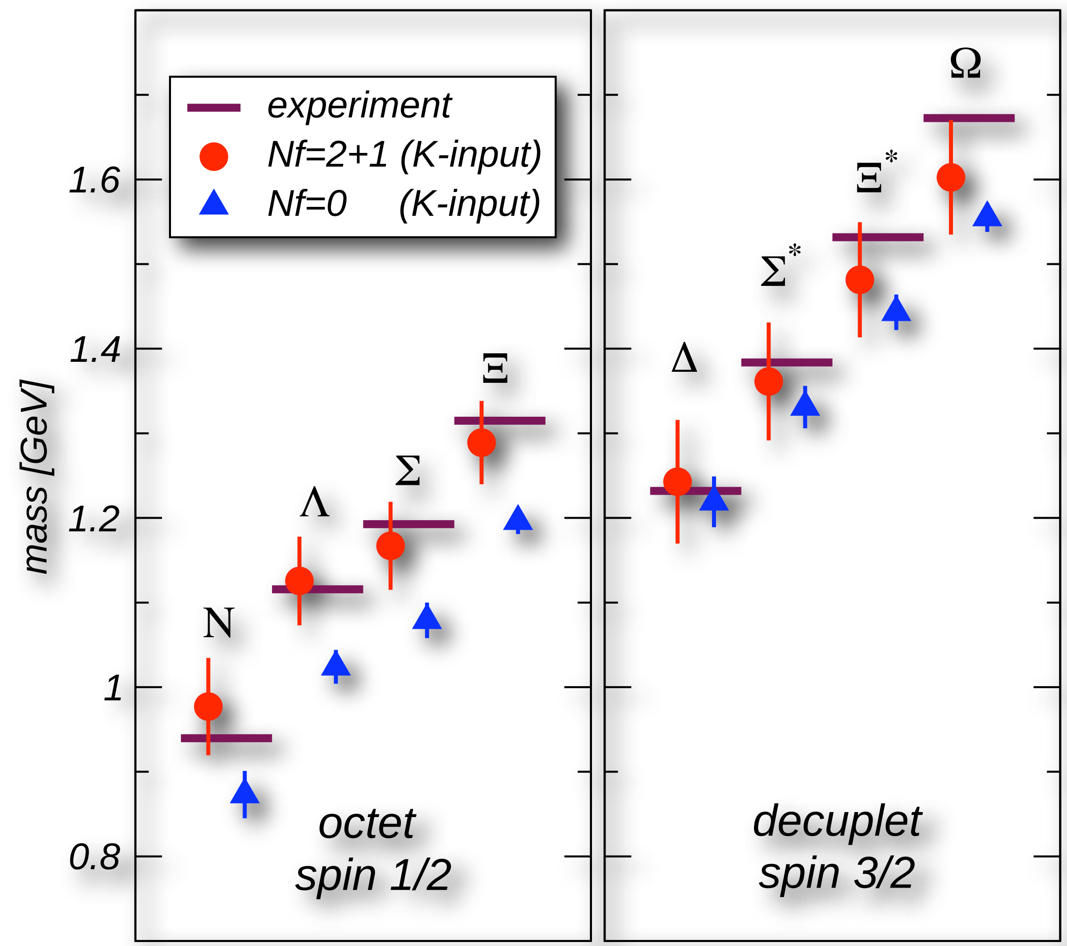


Signal is not good.
Volume $(2.0\ \mathrm{fm})^3$ is too small (?)





The data points rampage widely.



(preliminary)

Pattern of the spectrum is reproduced. But the precise spectrum and FSE are unclear.

Sommer scale

- **Static quark potential**

$$V(r) = V_0 - \frac{\alpha}{r} + \sigma r$$

- **Sommer scale r_0**

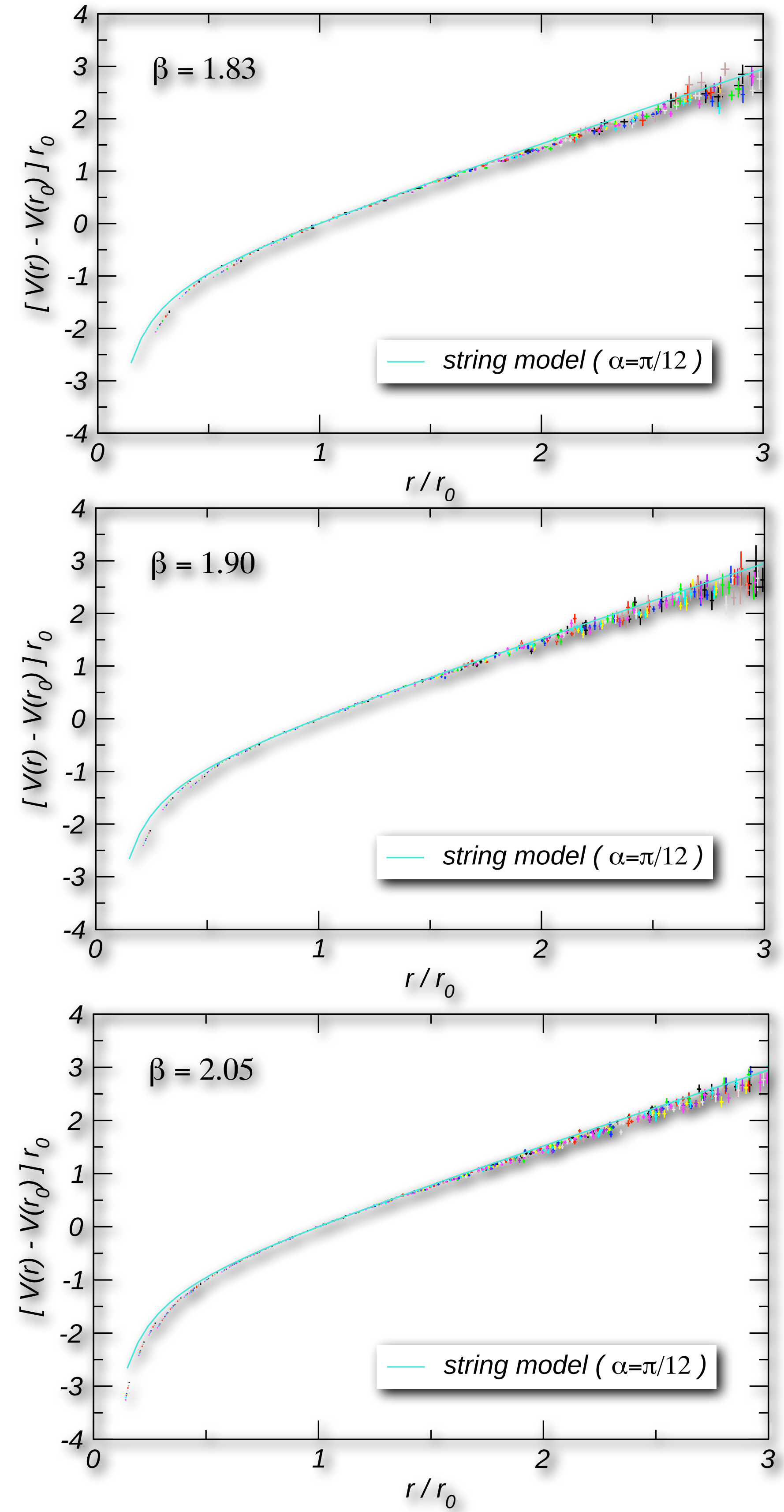
$$r^2 \left. \frac{dV(r)}{dr} \right|_{r=r_0} = 1.65$$

$$R_0 = a r_0 \simeq 0.5 \text{ fm}$$

⟵ phenomenological model

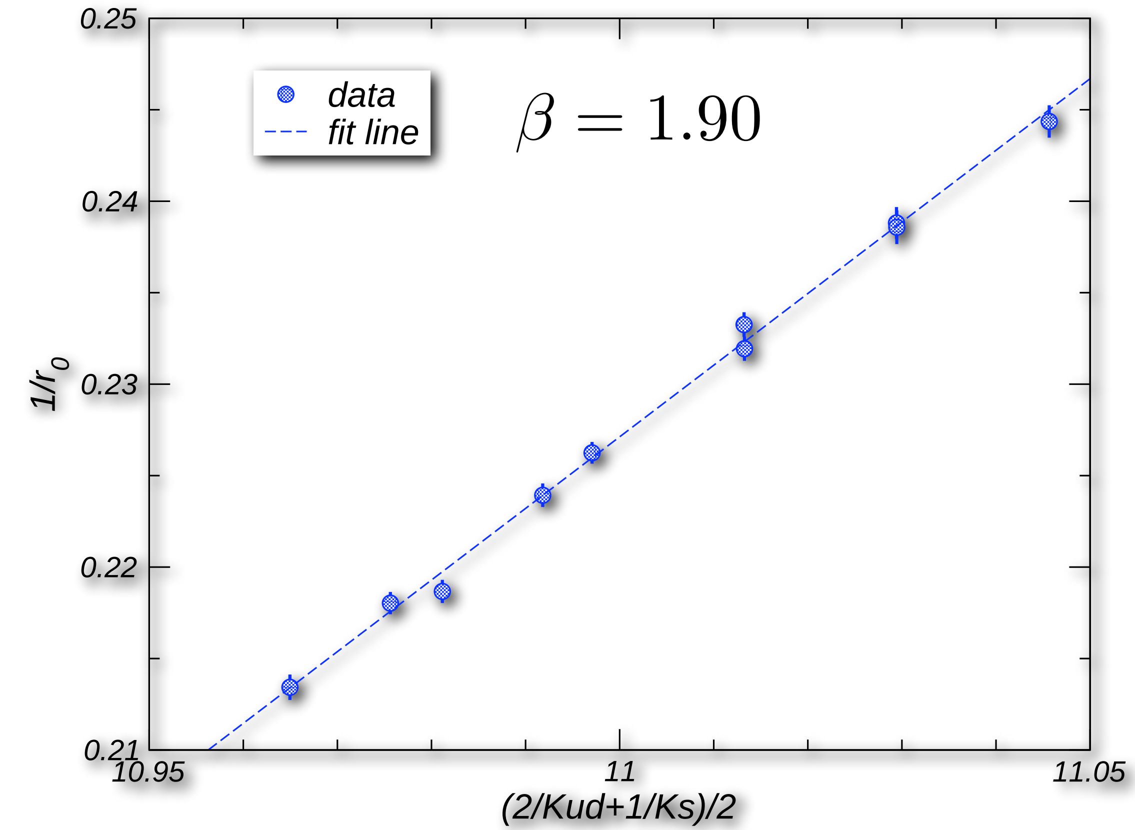
In our calculation r_0 is obtained through

$$r_0 = \sqrt{\frac{1.65 - \alpha}{\sigma}}$$



Chiral extrapolation

$$\frac{1}{r_0} = A + B\left(\frac{2}{\kappa_{ud}} + \frac{1}{\kappa_s}\right)$$



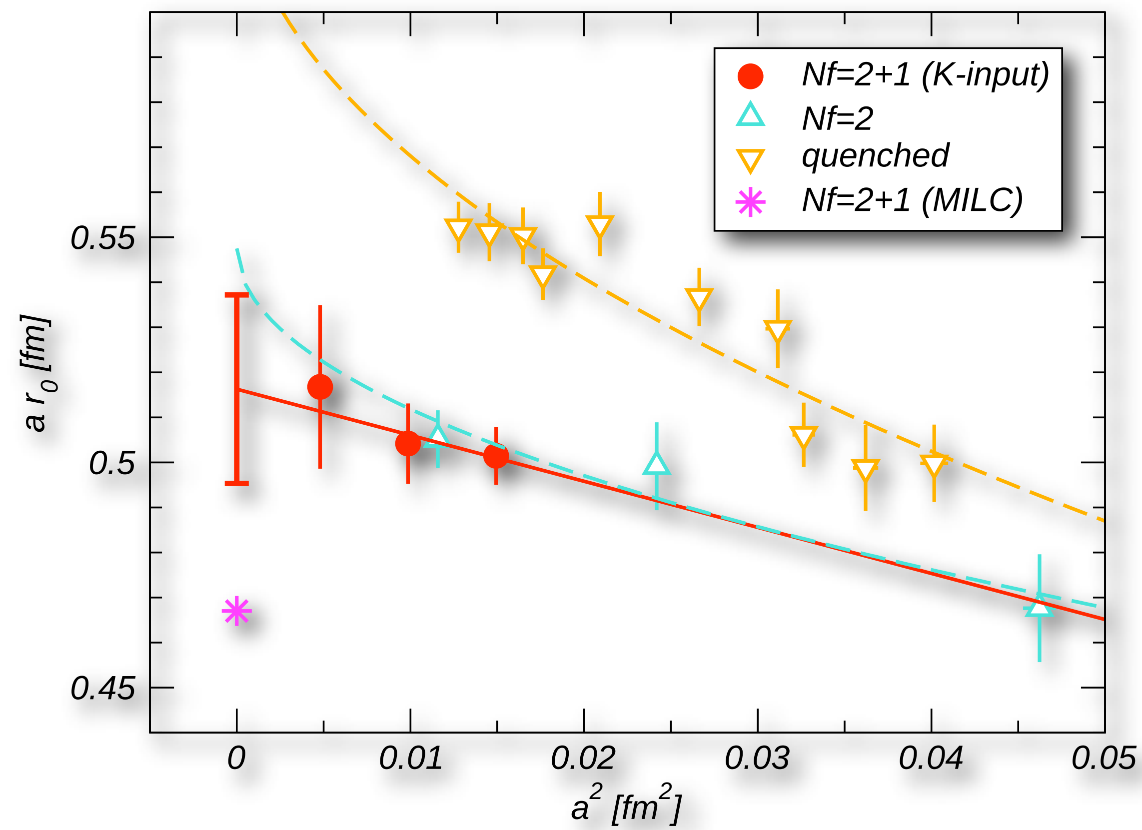
Continuum limit of R_0 using the lattice spacing from m_ρ

$$R_0 = 0.516(21)\ \text{fm}$$

consistent with 0.5 fm

(preliminary)

$$\left(\begin{array}{r} R_0 = 0.467\ \text{fm (MILC)} \\ \longleftarrow \Upsilon\ \text{spectrum} \end{array}\right)$$



(Nf=2, 0 : RG+clover(PT))

Summary

CP-PACS/JLQCD Nf=2+1 project

- RG-gauge + non-PT clover (Wilson quark formalism)
- Gauge configuration generation has been already finished.

Analysis of spectrum and quark masses

- Encouraging results in the continuum limit are obtained.
- Assuming that the scaling is a^2 ,
  - Meson spectrum is consistent with experiment.
  - All definitions and inputs of quark masses gives consistent results.
  - Quark masses in the continuum :

$$m_{ud}^{\overline{MS}}(\mu = 2\text{GeV}) = 3.49(15)\ \text{MeV}$$
$$m_s^{\overline{MS}}(\mu = 2\text{GeV}) = 90.9(3.7)\ \text{MeV}$$

- Baryon spectrum
  signal is not so good(?), large statistical error

Required task

- Non-perturbative determination of renormalization factor

Calcurations in progress

- η’ meson mass
- Heavy meson quantities using a relativistic heavy quark action

(Aoki,Kuramashi,Tominaga,2001)

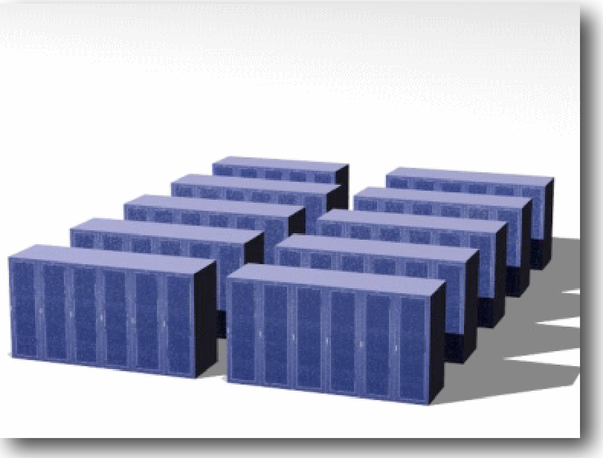
Next direction - lighter quark mass -

PACS-CS collaboration

- clover quark with domain decomposed HMC
- PACS-CS (CCS, Univ. of Tsukuba)

  to be installed in June 2006

  cluster, 2560 nodes, 14.3 TFLOPS



JLQCD collaboration

- dynamical overlap fermion
- IBM Blue Gene (KEK)

  10 rack (10240 node), 57.3 TFLOPS

ambiguity in the chiral extrapolation will be removed