2+1 flavor QCD simulation near the physical point on a 96^4 lattice

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Introduction

- Recent world mainstream of QCD configuration generations is those near the physical point to control extrapolations to the physical point.

- PACS-CS collaboration (2005–2012) :

  $N_f = 2+1$ Wilson clover + Iwasaki gauge,

  $32^3 \times 64$ lattice, $a^{-1} \sim 2.2$GeV, $m_\pi = 150 - 700$MeV, $m_\pi L \gtrsim 2$.

- PACS collaboration (2012–) has generated configurations near the physical point on a larger lattice,

  $N_f = 2+1$ Stout smeared Wilson clover + Iwasaki gauge,

  96^4 lattice, $a^{-1} \sim 2.3$GeV, $m_\pi \sim 147$MeV, $m_\pi L \sim 6$,

  using K computer in the Strategic Field Program 5.

- In this talk, we show our preliminary results by use of these configurations:

  quark masses, decay constants, light hadron spectrum at the physical point.

Our strategy (overview) to determine the quark masses at the physical point :

1) generate $N_f = 2 + 1$ configurations near the physical point on 96^4 lattice,

2) make new data points with the configurations using reweighting technique,

3) determine the physical point through ChPT analysis using m_π, m_K and m_Ω as the physical input,

4) determine the quark masses and the lattice cutoff at the physical point.

Contents

Setup for configuration generation

- 96^4 lattice.

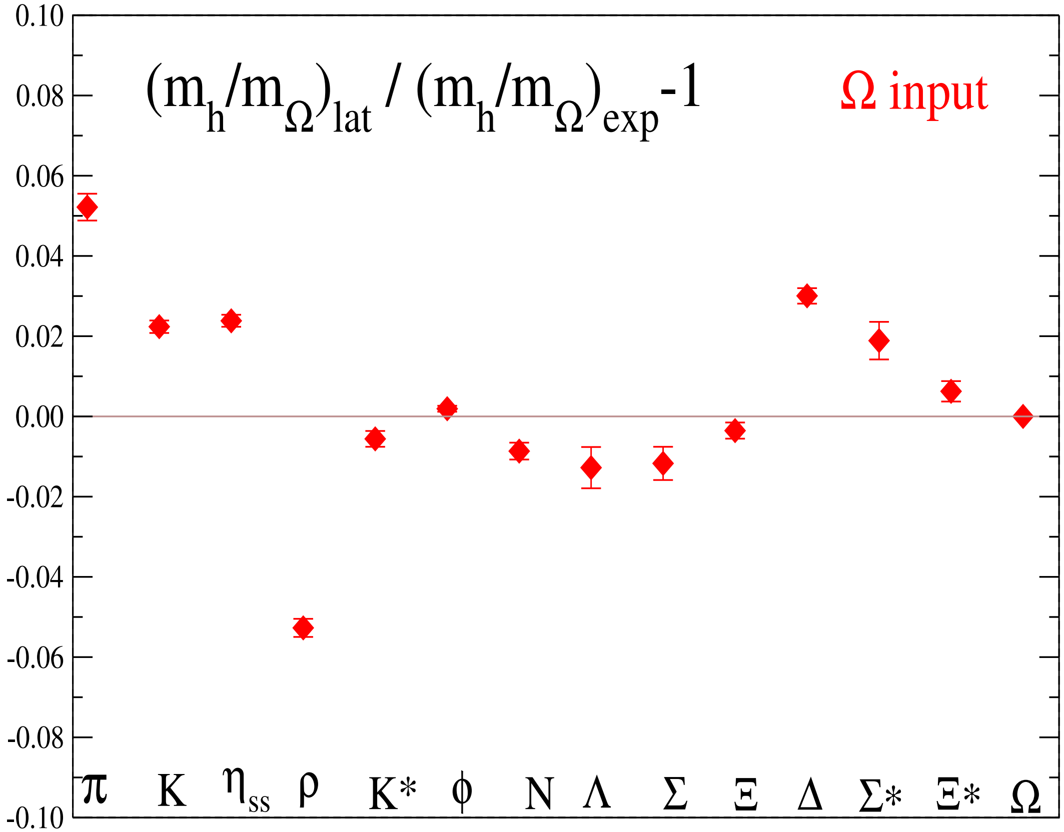
- $N_f = 2 + 1$ APE stout smeared Wilson clover action with nonperturbative c_{SW},
  $c_{\mathrm{SW}} = 1.110$ [Y. Taniguchi, lattice2012],
  $(\kappa_{\mathrm{ud}}, \kappa_{\mathrm{s}}) = (0.126117, 0.124790)$, $\alpha = 0.1$, $n_{\mathrm{stout}} = 6$.

- Iwasaki gauge action with $\beta = 1.82$, $a^{-1} \sim 2.3$GeV.

- DDHMC [Lüscher, 2003] for ud quarks + UVPHMC for strange quark,
  with even-odd preconditioning [Degrand, Rossi, 1990], mass preconditioning [Hasenbusch, 2001], multiple time scale integration [Sexton, Weingarten, 1992].

- 200 configurations (= 2000 MD time).

Spectrum compared with experiment



Ω mass input ($a^{-1} \sim 2.3$GeV).

Binsize = 5 confs. for the jackknife error analysis.

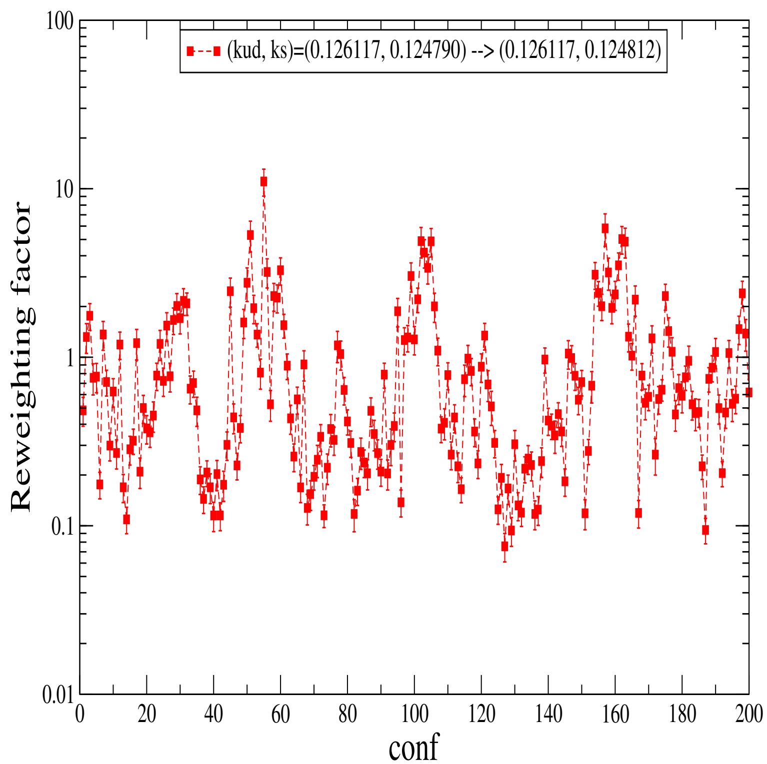
deviation from the Exp.:
$\delta m_\pi \sim +5\%$, $\delta m_K \sim +2\%$.

Using reweighting technique for this simulation point,
we make new data points with different hopping parameters
to determine the physical point with ChPT.

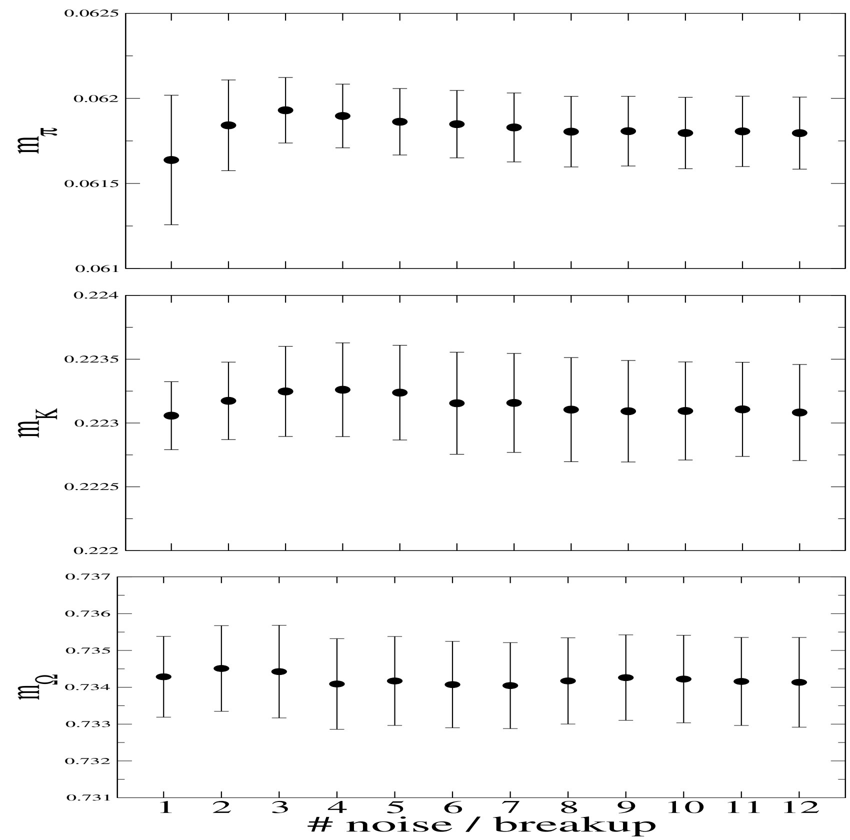
Reweighting from the simulation point to new data points

We make 6 data points with different hopping parameters using reweighting technique.

Reweighting factor : stochastic method, determinant breakups [Hasenfratz et. al, 2008],
12 noise vectors for each breakup.



$\langle W \rangle = 1.$ W fluctuates $\sim O(10^2)$.



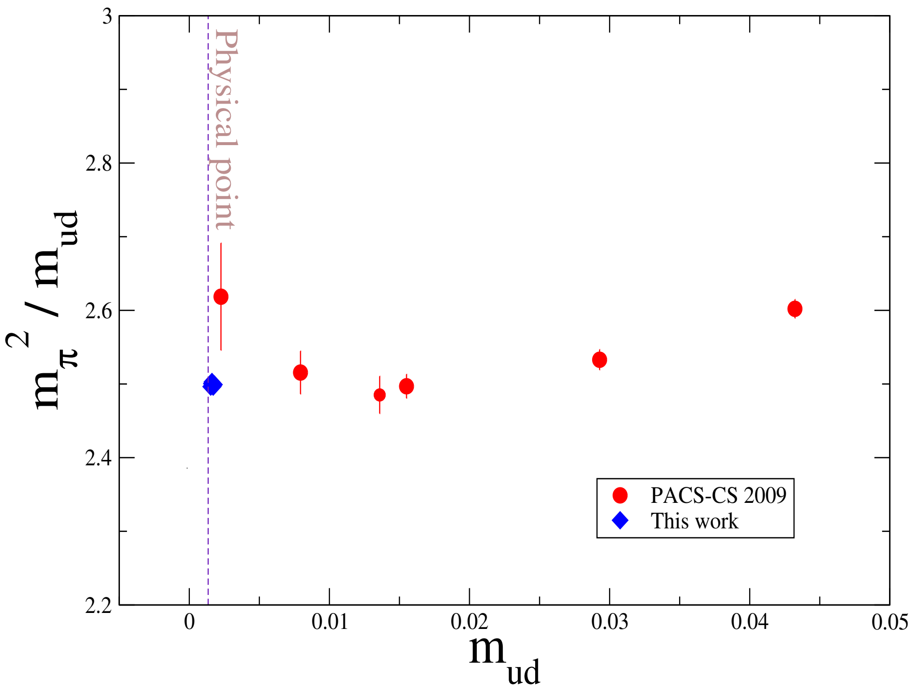
12 noises/breakup are enough for reweighting.

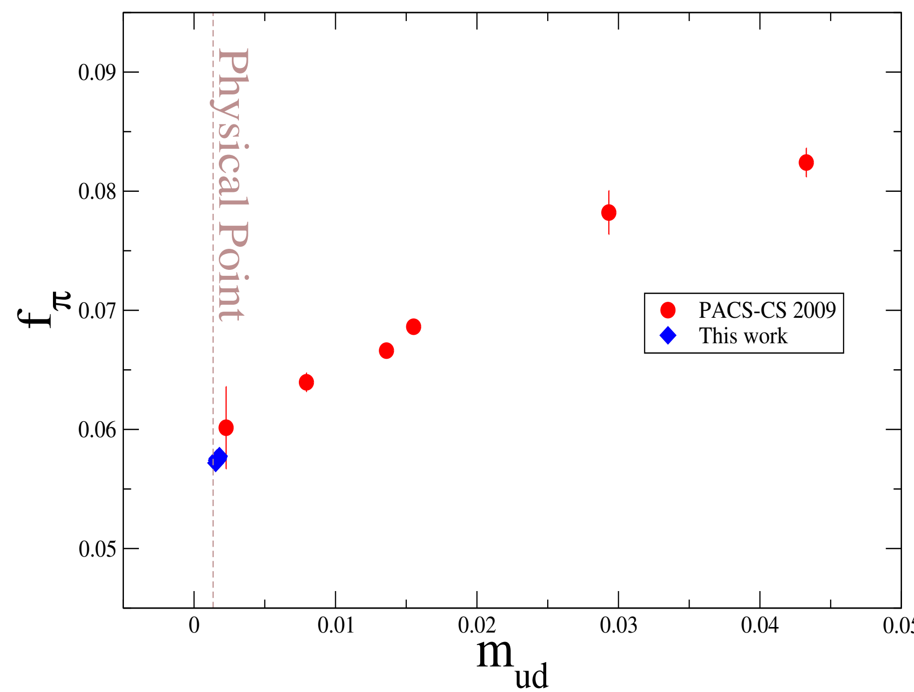
This is also the case for other hadron masses and for other reweighted points.

Data points in this work

This work (simulation point + 6 reweighted points) : $m_\pi = 144 - 156\text{MeV}$,

PACS-CS data : $m_\pi = 150 - 700\text{MeV}$, where $m_\pi \lesssim 400\text{MeV}$ was used for ChPT analysis.





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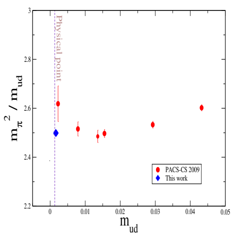
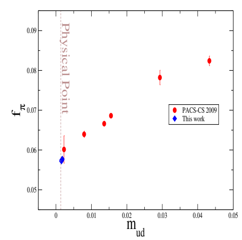
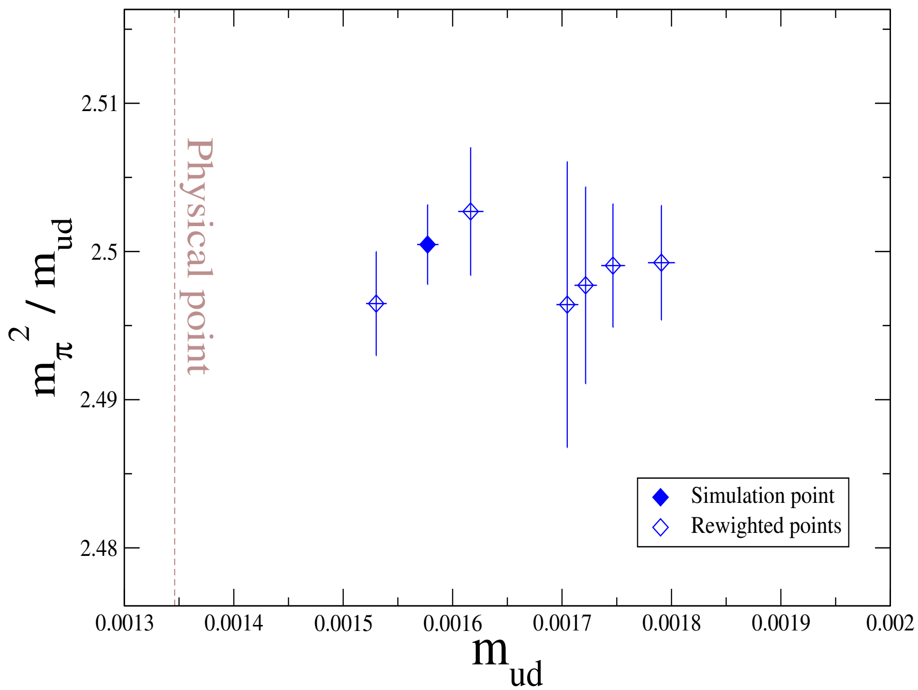
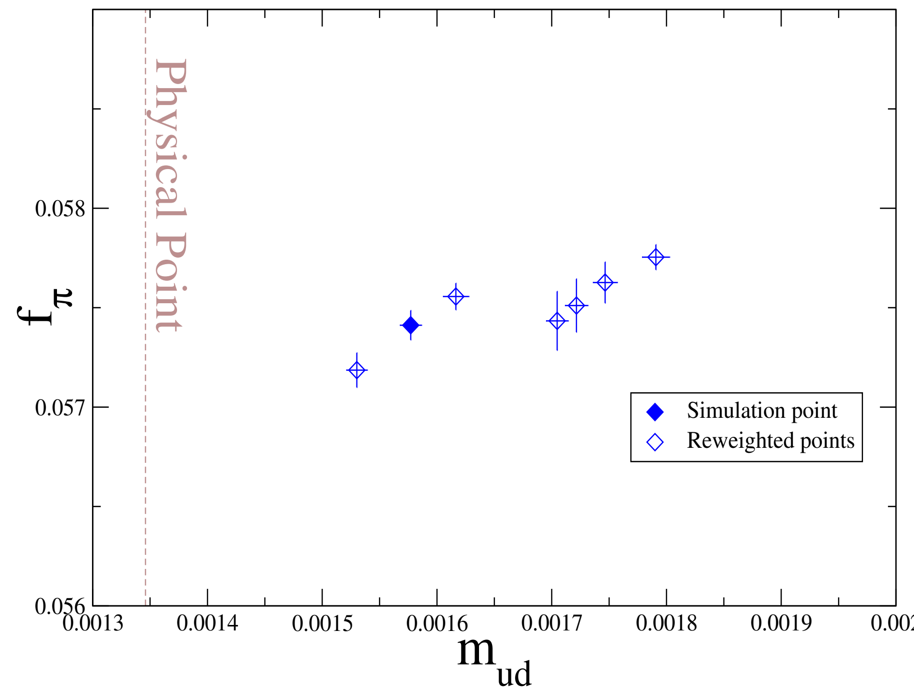




Zoom in on the data points in this work





We apply ChPT analysis for these data points to determine the physical point.

ChPT analysis

- NLO SU(2) ChPT + m_s linear fit for m_π^2/m_{ud}, f_π and f_K.

$$
\begin{aligned}
\frac{m_\pi^2}{2m_{ud}} &= B\left\{1+\frac{m_{ud}B}{8\pi^2 f^2}\ln\left(\frac{2m_{ud}B}{\mu^2}\right)+4\frac{m_{ud}B}{f^2}l_3\right\},\\
f_\pi &= f\left\{1-\frac{m_{ud}B}{4\pi^2 f^2}\ln\left(\frac{2m_{ud}B}{\mu^2}\right)+2\frac{m_{ud}B}{f^2}l_4\right\},\\
f_K &= \bar{f}\left\{1+\beta_f m_{ud}-\frac{3m_{ud}B}{32\pi^2 f^2}\ln\left(\frac{2m_{ud}B}{\mu^2}\right)\right\},
\end{aligned}
$$

where $B = B_s^{(0)} + m_s B_s^{(1)}$, $f = f_s^{(0)} + m_s f_s^{(1)}$ and $\bar{f} = \bar{f}_s^{(0)} + m_s \bar{f}_s^{(1)}$.

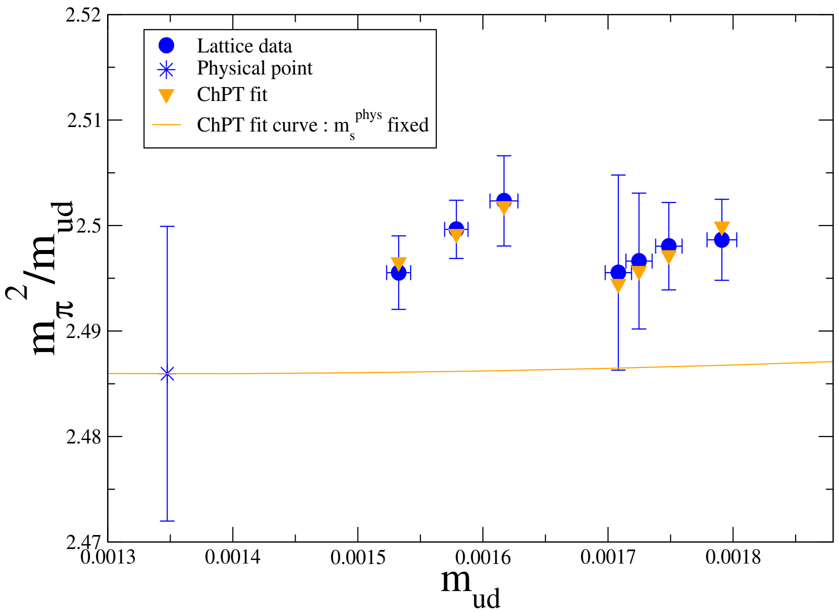
- m_{ud}, m_s linear fit for m_K^2 and m_Ω.

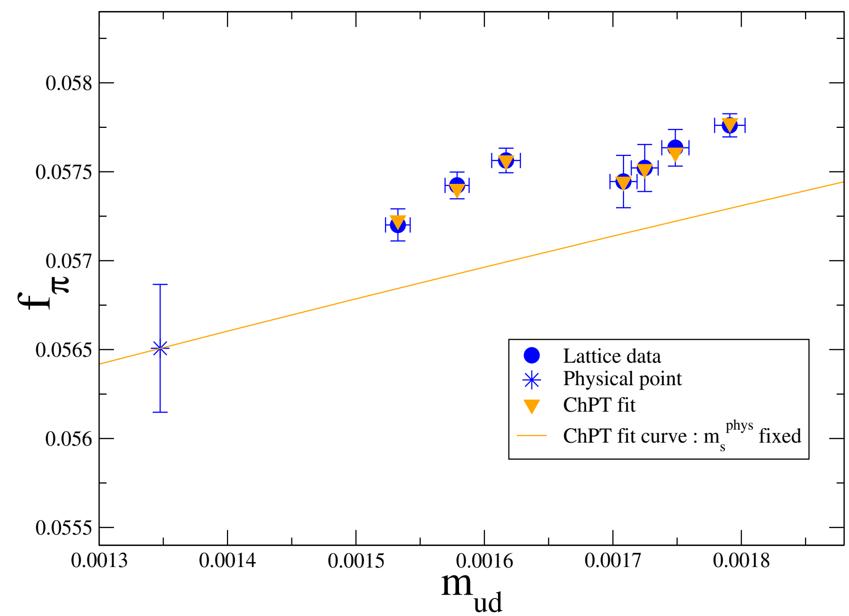
$$
\begin{aligned}
m_K^2 &= \alpha_K + \beta_K m_{ud} + \gamma_K m_s,\\
m_\Omega &= \alpha_\Omega + \beta_\Omega m_{ud} + \gamma_\Omega m_s.
\end{aligned}
$$

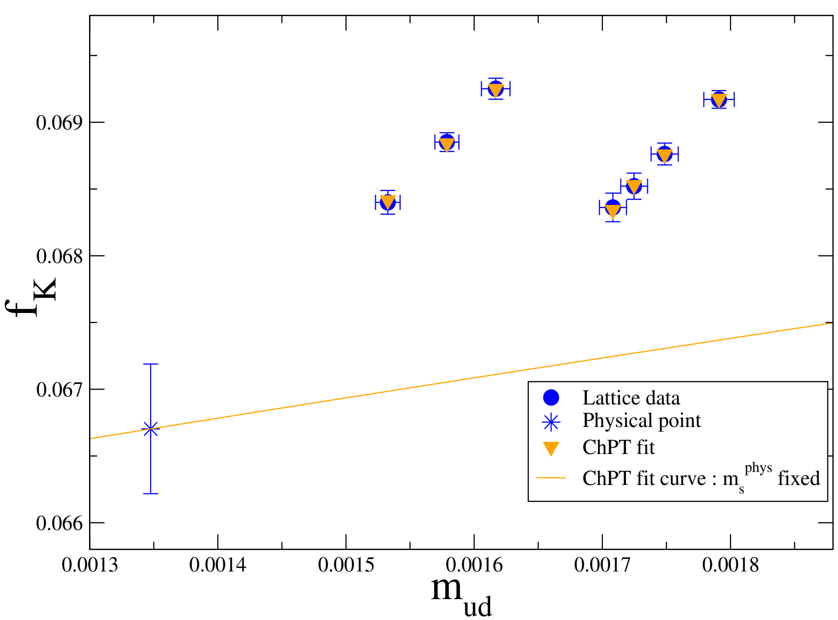
- We use m_π, m_K and m_Ω as physical inputs to determine $m_{ud}^{\rm phys}, m_s^{\rm phys}$ and a.

- We are also interested in LEC's at NLO, l_3 and l_4. It is not clear whether the data in the narrow pion mass range allows us indeed to determine these LEC's or not.

Preliminary results for ChPT







blue circle : lattice data
blue star : physical point
orange triangle : ChPT fit
orange line : ChPT fit curve with $m_s^{\rm phys}$ fixed

- $l_3 = 0.0074(14)$ in $m_\pi^2/m_{\rm ud}$.
- $l_4 = -0.0097(23)$ in f_π.
- $\chi^2/dof = 0.063(89)$.
  (uncorrelated fit)

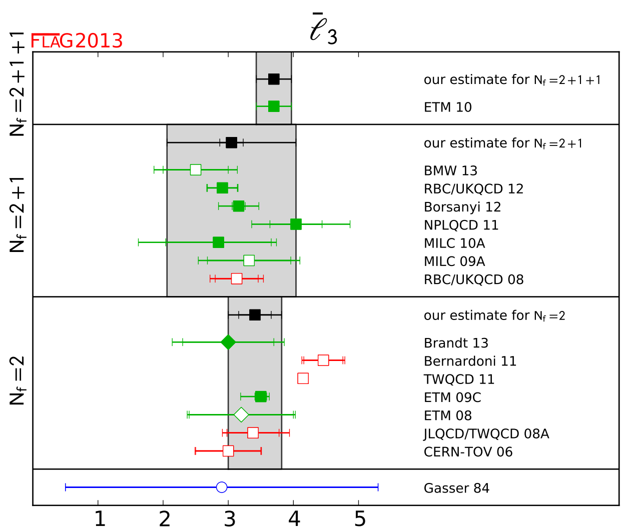
Preliminary results for $\bar{l}_3$ and $\bar{l}_4$

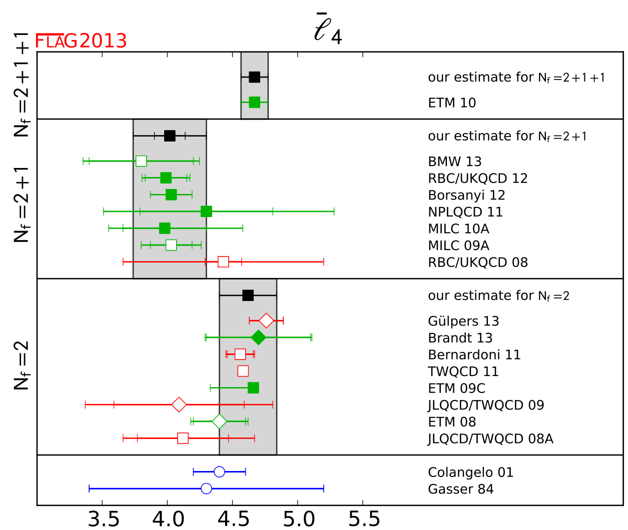
$\bar{l}_4$ is determined using phenomenological constraints [Colangelo et. al, 2001],

while the determination of $\bar{l}_3$ is difficult.

$\Rightarrow$ ChPT analysis using lattice data near the physical point imposes stronger constraints on $\bar{l}_3, \bar{l}_4$.

- $\bar{l}_4 = 4.11(36)$ which is consistent with $\bar{l}_4\big|_{N_f=2+1} = 4.02(28)$ in FLAG 2013.
- $\bar{l}_3 = 0.99(90)$ which is consistent with the phenomenological value 2.9(2.4) [Gasser, Leutwyler, 1984], but is smaller than $\bar{l}_3\big|_{N_f=2+1} = 3.05(99)$ in FLAG 2013.





Preliminary results for quark masses in $\overline{MS}$ at 2GeV

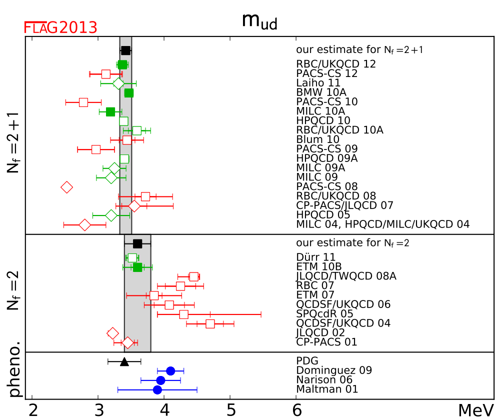
Physical inputs = m_π, m_K, m_Ω.

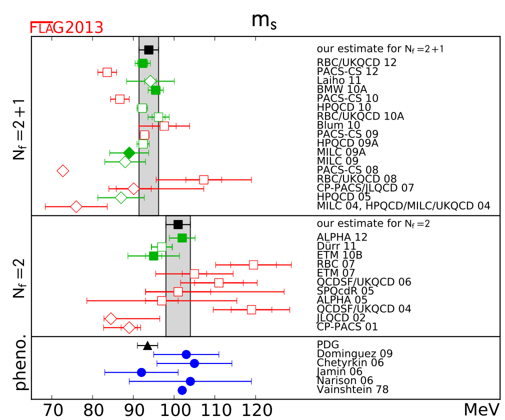
- a^{-1} = 2.332(18)[GeV].

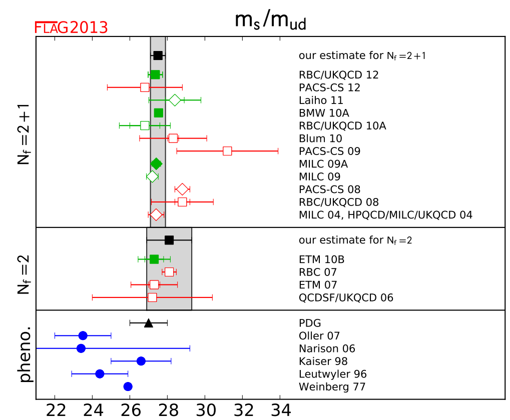
- $m_{ud}^{\rm phys}$ = 3.141(29)(35)(28)[MeV], $m_s^{\rm phys}$ = 88.59(61)(98)(79)[MeV],

  where $Z_m(\overline{MS}, 2\mathrm{GeV}) = 0.9932(111)(89)$ determined by SF scheme. [poster by K.-I. Ishikawa]
  $m_{ud}^{\rm phys}$ deviates by 3.0σ from FLAG 2013, and $m_s^{\rm phys}$ by 2.2σ possibly due to the scaling violation.

- $m_s^{\rm phys}/m_{ud}^{\rm phys}$ = 28.21(18).
  which deviates by 1.7σ including the systematic error of FLAG 2013.

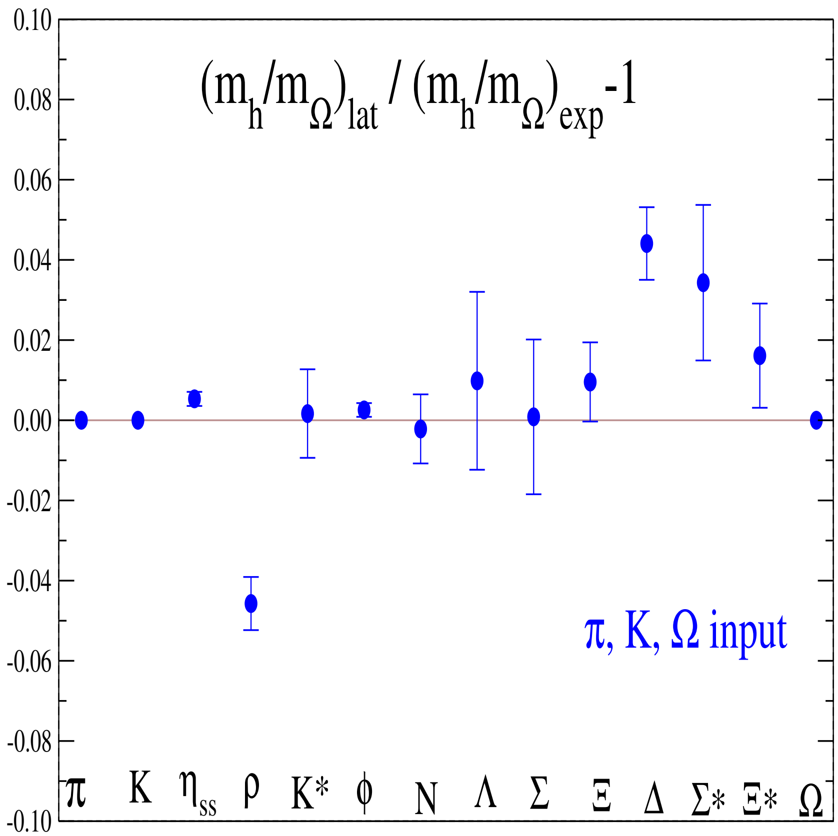






$m_{ud}^{\rm phys}$ = 3.42(6)(7)[MeV], $m_s^{\rm phys}$ = 93.8(1.5)(1.9)[MeV], $m_s^{\rm phys}/m_{ud}^{\rm phys}$ = 27.46(15)(41)
[FLAG 2013, $N_f = 2+1$].

Light hadron spectrum compared with experiment



96^4 lattice, $a^{-1} = 2.332(18)$GeV.

Physical inputs $= m_\pi,\ m_K,\ m_\Omega$.

Stable particles in QCD $(N, \Lambda, \Sigma, \Xi)$ are consistent within the errors.

For unstable particles in QCD $(\rho, \Delta, \cdots)$, we observe deviations from the experimental values.
$\rightarrow$ we need further investigations of those.

Preliminary results for pseudoscalar decay constants

$f_\pi = 131.79(80)(90)(1.25)$MeV. cf. Exp. : $f_\pi = 130.41(3)(20)$MeV,

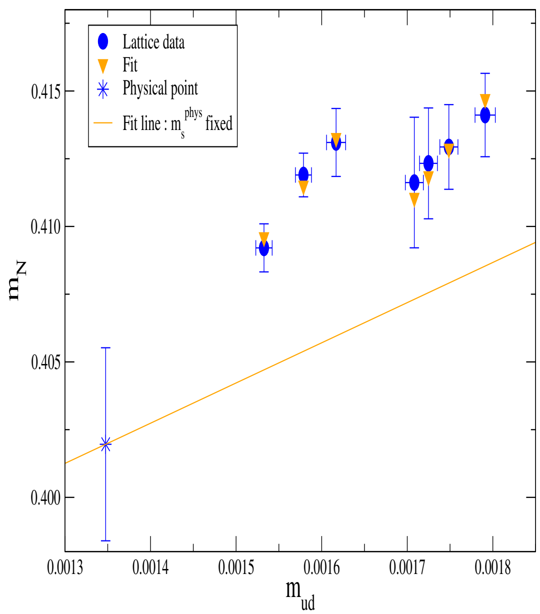
$f_K = 155.55(68)(1.06)(1.48)$MeV. cf. Exp. : $f_K = 156.1(2)(6)(3)$MeV,

where we used $Z_A = 0.9650(68)(95)$ determined by SF scheme. [poster by K.-I. Ishikawa]

$f_K/f_\pi = 1.1803(45)$. cf. Exp. : $f_K/f_\pi = 1.198(2)(5)(1)$.

We observe 3.2σ deviation including the systematic error from the experiment.
$\longrightarrow$ We are increasing source points for our final results.
Further, isospin breaking effects ignored, which should be included in the next step.

Preliminary results for Nucleon σ term



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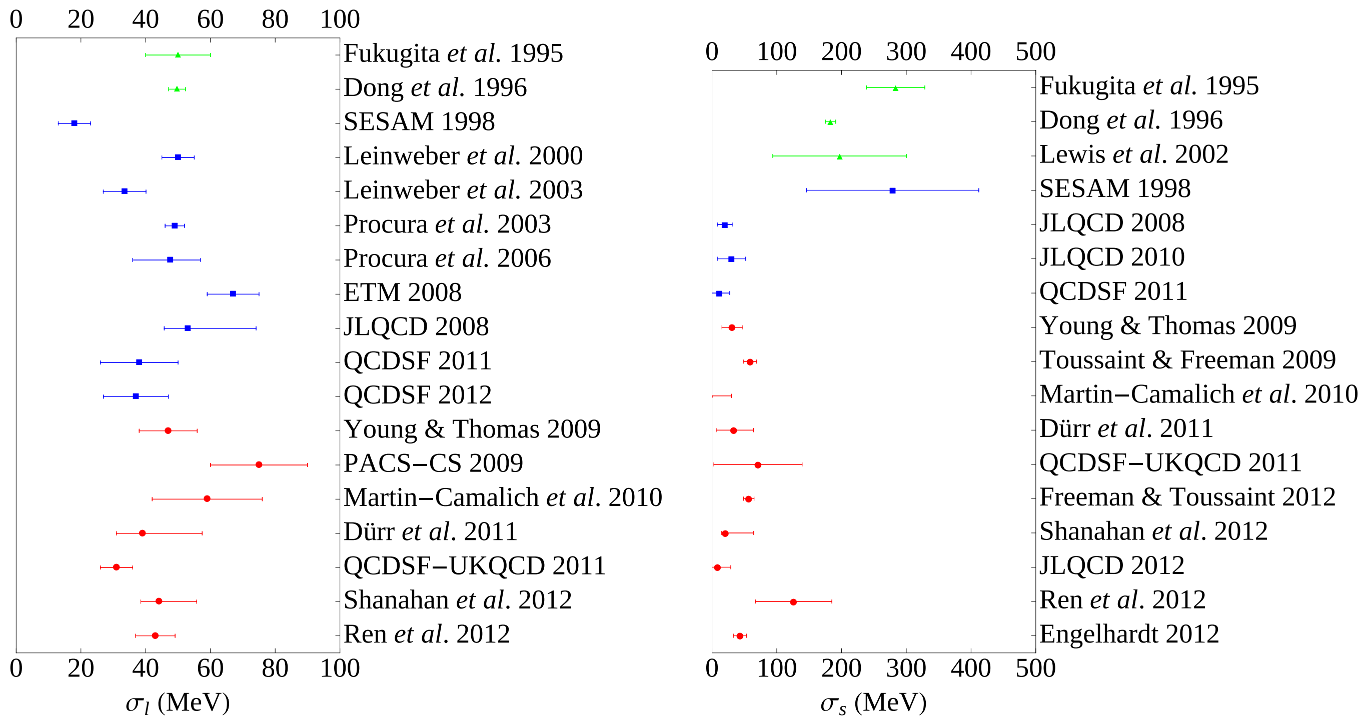

Fit : $m_N = m_0 + Cm_{ud} + Dm_s$.

$\Longrightarrow$ $\sigma_{ud} = Cm_{ud}^{\rm phys} = 47(22)$ [MeV], $\sigma_s = Dm_s^{\rm phys} = 152(87)$ [MeV].

Summary

- We generated $N_f = 2 + 1$ QCD configurations near the physical point on 96^4 lattice with $a^{-1} = 2.3$GeV.
- The physical point was determined by ChPT analysis using the simulation point and reweighted data points where $m_\pi = 144 - 156$MeV.
- We showed preliminary results: quark masses, decay constants, $\bar{l}_3$, $\bar{l}_4$ and Nucleon sigma term.
- We are increasing the number of source points for hadron measurement to conclude this work.