Light Hadron Spectrum and Quark Masses in Nf=3 QCD

Dec.17 2004  ILFTN WS, T.Yoshie, CCS,Tsukuba

CP-PACS/JLQCD Collabs.


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CP-PACS Collab. @ CCS, Tsukuba

- CP-PACS: 0.6 TFlops
- SR8000/G1: 0.2 TFlops
- VPP5000: 0.8 Tflops

JLQCD Collab. @ KEK

- SR8000/F1: 1.2 TFlops
- Earth Simulator (JAMSTEC): 40 TFlops

~1.5 Tflop*Year (sustained speed) in 2 years
(20-46% efficiency depending on size and machine)

3% of ES

@ ACCC
Motivation

• Previous CP-PACS spectrum studies
  – Quenched QCD (plaquette gauge + Wilson quark)
  – Nf=2 full QCD (Iwasaki RG gauge + Clover tp Csw)
    additional quenched simulation with the same action combination
  – Continuum limit of spectrum and quark masses

• Two key observations
  – spectrum
  – quark mass
O(10%) systematic deviation of the quenched spectrum from experiment is significantly reduced by dynamical u,d quarks.
✓ Uncertainty of the strange quark mass, depending on inputs in quenched QCD, is reduced in Nf=2 QCD. Strange quark mass in Nf=2 QCD is smaller than that in quenched QCD.

Continuum extrapolations of s-quark mass
Nf=3 full QCD Simulations

- study and implement PHMC algorithm
- determine Csw non-perturbatively
- apply the project to ESC
- port and tune the PHMC program for ES

How spectrum/quark masses change if we include dynamical s-quarks

Generating configurations with no quenching effect for studies of other physics (heavy quark system ....)
Action and Simulation Parameters

• Action :
  Iwasaki RG Gauge action
  Clover quark action  \( C_{sw} \) determined non-perturbatively

• Three lattice spacings
  \( a=0.122 \) fm  \( \beta=1.83 \)
  \( a=0.10 \) fm  \( \beta=1.90 \)
  \( a=0.07 \) fm  \( \beta=2.05 \)

at regular intervals in \( a^2 \)
Simulation Parameters (Cont.)

• Quark Masses

degenerate u,d quark $5 \ K_{ud} \ (\pi/\rho = 0.78 - 0.62) \ (HMC)$
s quark with different quark mass $2 \ K_s \ (\pi/\rho \sim 0.7) \ (PHMC)$

10 combinations of $(K_{ud}, K_s)$

valence quark $K_{val,1/2} = K_{ud} / K_s$

$\Delta \tau, N_{poly}$ are tuned in a way that

$P_{HMC} \approx 85\%, P_{GMP} \approx 95\%$
Simulation Parameters (Cont.)

- Lattice Size
  2 fm in physical unit
  meson spectrum and quark masses

- \( a = 0.122 \, \text{fm} \) \( 16**3 \times 32 \) \( 6000-9000 \) traj. (almost finished)
- \( a = 0.10 \, \text{fm} \) \( 20**3 \times 40 \) \( 5000-8000 \) traj. (already finished)
- \( a = 0.07 \, \text{fm} \) \( 28**3 \times 56 \) \( 1000 \) traj \( \rightarrow 3000 \) traj. (in 1-1.5 years)

continuum extrapolation using two coarse lattices
Chiral Extrapolations

- **Quadratic polynomial functions in quark masses**
  
  $SU(3)$ symmetry in dynamical masses $m_u, m_d, m_s$
  
  exchange symmetry of $m_{val,1}, m_{val,2}$

\[
\begin{align*}
m_V(m_{ud}, m_s; m_{val,1}, m_{val,2}) &= A^V \\
&+ B_S^V(2m_{ud} + m_s) \\
&+ B_V^V(m_{val,1} + m_{val,2}) \\
&+ D_{SV}^V(2m_{ud} + m_s) \\
&\times (m_{val,1} + m_{val,2}) \\
&+ C_{S1}^V(2m_{ud}^2 + m_s^2) \\
&+ C_{S2}^V(m_{ud} + 2m_{ud}m_s) \\
&+ C_{V1}^V(m_{val,1}^2 + m_{val,2}^2) \\
&+ C_{V2}^V m_{val,1} m_{val,2}
\end{align*}
\]

Light-Light (LL), Light-Strange (LS), Strange-Strange (SS) masses are fitted simultaneously, ignoring correlation among them

- **Light:** $K_{val} = K_{ud}$
- **Strange:** $K_{val} = K_s$

26 data points 8 param.
Our chiral fit functions reproduce data well with reasonable values of $\chi^2 / \text{dof}$.
Spectrum

fix lattice spacing and quark masses

\( (m_\pi, m_\rho, m_K) \quad \text{K-input} \quad (m_\pi, m_\rho, m_\phi) \quad \phi\text{-input} \)

\[ m_h = m_0 + ca^2 \]

Meson masses extrapolate to experimental values
Comparison with Nf=0 and 2

Magnitude of scaling violation (impression)

Csw (tp) for Nf=0,2
Csw (NP) for Nf=3

larger for larger #flavors ?
for a=0.1-0.2 fm

Current error in the continuum limit for Nf=3 is 4 times larger than that we achieved for Nf=2

We plan to reduce the error to establish dynamical s-quark effect in the spectrum
Quark Masses

Determined by two methods

\[ \partial \mu A_\mu = 2m_q^{AWI} P \]

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

\( c_A \) Z-factors:

tp-improved 1-loop perturbation

Matching with MS scheme at

\( \mu = 1/a \) evolved to

\( \mu = 2 \text{ GeV} \)

4-loop perturbation theory

Though error in the continuum limit is still large,

\[ m_s^{AWI} = m_s^{VWI} \quad m_s(K) = m_s(\phi) \]
\[ m_s(N_f = 3) \approx m_s(N_f = 2) \] within large statistical error

Reduce the error to establish dynamical s-quark effect
Summary and Future Works

- Results of the spectrum and quark masses are very promising
  - control systematic errors from continuum extrapolations
  - reduce them with data at $a=0.07\text{fm}$
• Study and control other systematic errors
  1. chiral extrapolation with ChPT, WChPT
  2. non-perturbative calculation of $c_A, Z_A, Z_P$
  3. finite size effects
     1.6 fm vs. 2.0 fm study @ $a=0.1$ fm
     at most 1-2% error in $L_a=2$fm

• Study and implementation of algorithms
  recently proposed (Hasenbush, SAP) in progress