Pentaquarks in quenched lattice QCD

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Introduction

$\Theta^{+}(1540)$

- Firstly discovered by LEPS Collab. at SPring-8
- Baryon with Positive strangeness

  Minimal quark content is 5 quarks
- Very narrow width
- Mass = 1539.2 ± 1.6MeV (NK ≈ 1435MeV)
- Spin & parity are not determined
- Existence is not conclusive yet !

Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) (URL: http://pdg.lbl.gov)

$\Theta(1540)^{+}$ $I(J^P) = 0(?^?)$ Status: ∗∗∗

A POSSIBLE EXOTIC BARYON RESONANCE

Written November 2003 by G. Trilling (LBNL).

I. Introduction

The well-established baryon states can be understood as combinations of three valence quarks. In this discussion, we

Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004) and 2005 partial update for edition 2006 (URL: http://pdg.lbl.gov)

$\Theta(1540)^{+}$ $I(J^P) = 0(?^?)$ Status: ∗∗

A REVIEW GOES HERE – Check our WWW List of Reviews

$\Theta(1540)^{+}$ MASS

As is done through the *Review*, papers are listed by year, with the latest year first, and within each year they are listed alphabetically. NAKANO 03 was the earliest paper.

Since our 2004 edition, there have been several new claimed sightings of the $\Theta(1540)^{+}$ (see entries below marked with bars to the right), but there have also been several searches with negative results:

Experiments

Positive exp.

- LEPS Collab.
- DIANA Collab.
- CLAS Collab.
- SAPHIR Collab.
- ZEUS Collab.
- ITEP Collab.
- HERMES Collab.
- COSY-TOF Collab.

Negative exp.

- HERA-B Collab.
- BES Collab.
- PHENIX Collab.
- Hyper-CP Collab.
- FNAL-E690 Collab.
- CDF Collab.

No Θ^+ in high energy experiments ?

Theories

<u>Some models</u>

- Chiral soliton model (Skyrme model)
- Quark model
- ...

<u>Studies based on QCD</u>

- QCD sum rule
- Lattice QCD

many problems in QCD sum rule

- higher dim. of OPE
- assumption for Spect. func.
- etc.

T.Kojo et al. het-ph0602004

It is possible to study hadrons from first principles.

Study of properties (including existence) of unknown hadrons is one of the most important roles in Lattice QCD !!

Lattice studies

- F.Csikor et al. [JHEP0311(03)070]
  [Phys.Rev.D73(2006)034506]
- S.Sasaki [Phys.Rev.Lett.93(2004)152001]
- T.W.Chiu et al. [Phys.Rev.D.72(2005)034505]
- N.Mathur et al. [Phys.Rev.D70(2004)074508]
- N.Ishii et al. [Phys.Rev.D71(2005)034001]
- B.G.Lasscock et al. [Phys.Rev.D72(2005)014502]
- C.Alexandrou, A.Tsapalis [hep-lat/0509139]
- T.T.Takahashi et al. [Phys.Rev.D71(2005)114509]
- and some proceedings

Conclusion is not conclusive yet
→ Some reasons are explained in this talk

First principle calculation

Lattice QCD can calculate Hadron spectrum
from first principles after the following steps.

- Dynamical quark effects (N_f=2 or 2+1)
- Large physical volume simulation
- Chiral extrapolation
- Continuum limit
- etc.

However, depending on our purpose,
we can compromise some of them

First principle calculation

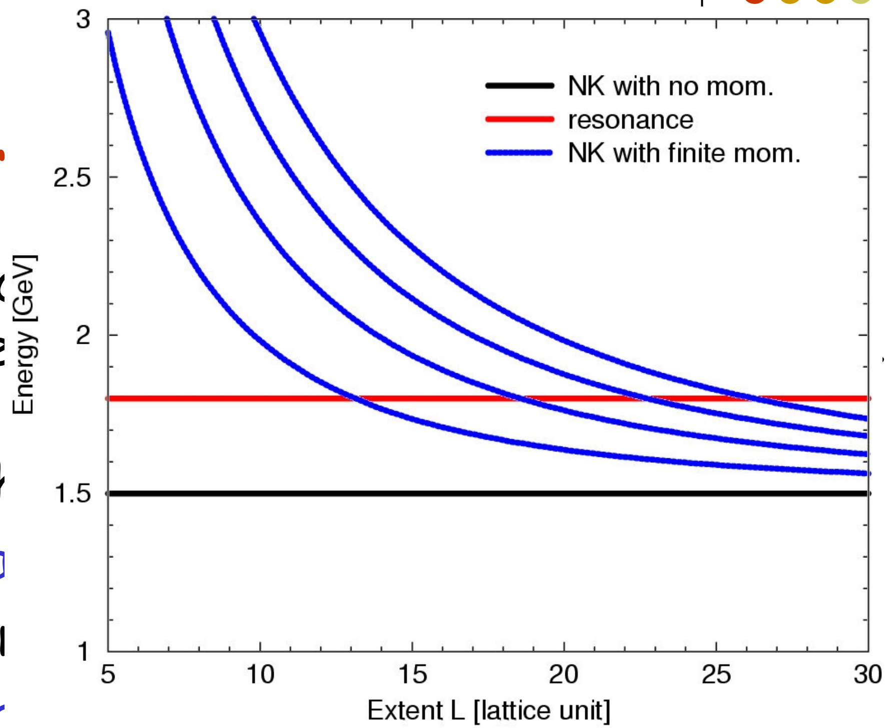
For example, hadron spectroscopy
with O(1%) systematic error

- Dynamical quark effects (N_f=2 or 2+1)
  quenched ~ O(10%) systematic errors
- Large physical volume simulation
  meson ~ L > 2fm, baryon ~ L > 3fm for O(1%) error
- Chiral extrapolation
  nonper. O(a) improved, chirally improved actions
- Continuum limit
  at least 3 betas with 1/a > 1GeV
- etc.

However, depending on our purpose,
we can compromise some of them

Difficulties for pentaquaks on lattice

Lattice QCD can calculate only
Correlation function of hadr



Most studies of lattice QCD extra
Because only lowest state dominate

- Θ^+ is not a lowest-state in th
  we have to extract 2 sta
- Θ^+ has the same quantum nu
  we have to distinguish fr
- lattice momenta are discretized in a finite box
  dilemma of spatial volume

Pentaquarks is very challenging subject in Lattice QCD !
Problem is not only # of quarks !!

Necessary steps and the order of priority

In lattice QCD, the time is not
to do quantitative study of the theta+ mass spectrum.
It is difficult to predict "1540MeV" at present

We should consider how to find pentaquark states on lattice

- Essential steps for this purpose
  - extraction of multi states (if pentaquarks is not lowest state)
  - to distinguish from KN scattering state (e.g. volume dependence)
- Not so indispensable steps
  - dynamical quarks
  - continuum limit
  - chiral extrapolation

→ In previous many lattice studies, there is no example that the existence of hadrons depends on such conditions
Of course these are very important for quantitative study of spectroscopy.

Lattice studies

	signal	Parity	diag.	V dep.
Csikor et al. (1)	Yes	negative	×	△
S.Sasaki	Yes	negative	×	×
Kentucky group	No	n/a	×	△
TITECH group	No	n/a	HB	---
Chiu & Hsieh	Yes	positive	○	×
Lasscock et al.	No	n/a	△	×
Csikor et al. (2)	No	n/a	○	○
Alexandrou et al.	Yes	negative	○	○
YITP	Yes	negative	○	○

Indispensable steps are not carried out
in some earlier studies

Our strategy

Our purpose is to investigate
whether pentaquarks exist or not on the lattice.

- Give up a quantitative study
  - △ course lattices, no continuum limit, quenched approx.
  - ○ high statistics (1K~3K configurations.)
- Extract lowest two states
  using 2x2 correlation matrices
- Distinguish pentaquark state from KN scattering states
  volume dependence ($V=8^3 \sim 16^3$)
  of mass & spectral weight

Interpolating operators

I=0, J=1/2 channel

$$\Theta^1_{wall}(t) = (\sqrt{\frac{1}{V}})^5 \sum_{\vec{x}_1 \sim \vec{x}_5} \epsilon^{abc}[u_a^T(x_1)C\gamma_5 d_b(x_2)] \times \{u_e(x_3)\bar{s}_e(x_4)(\gamma_5)d_c(x_5) - (u \leftrightarrow d)\}$$

Penta-quark like operator

$$\Theta^2_{wall}(t) = (\sqrt{\frac{1}{V}})^5 \sum_{\vec{x}_1 \sim \vec{x}_5} \epsilon^{abc}[u_a^T(x_1)C\gamma_5 d_b(x_2)] \times \{u_c(x_3)\bar{s}_e(x_4)(\gamma_5)d_e(x_5) - (u \leftrightarrow d)\}$$

Nucleon x Kaon operator

We adopt wall-type smearing operators to enhance lowest-state contribution

(operator dependence is discussed later)

Simulation parameters

Wilson quark & Plaquette gauge
beta=5.7 (a~0.17fm), quenched QCD

8^3x24 [(1.4fm)^{3}x4.0fm] 3000confs.
10^3x24 [(1.7fm)^{3}x4.0fm] 2900confs.
12^3x24 [(2.0fm)^{3}x4.0fm] 1950confs.
(14^3x24 [(2.4fm)^{3}x4.0fm] 2000confs.)
16^3x24 [(2.7fm)^{3}x4.0fm] 950conf.

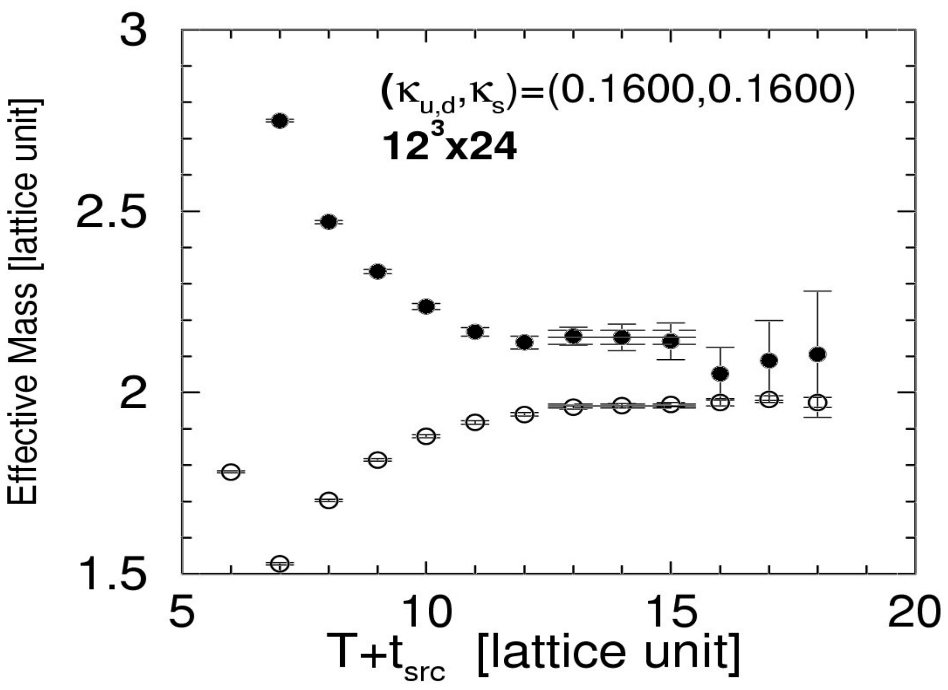
5 combinations of
quark mass = (100~240MeV)
(m_{pi}/m_{rho}=0.65~0.85)
Dirichlet boundary condition for the quark field

simulations on SX-5 @ RCNP & SR8000 @ KEK

Extraction of energies

$$C^{IJ}(T) = \sum_{\vec{x}} \langle \Theta^I(\vec{x}, T + t_{src}) \bar{\Theta}^J_{wall}(t_{src}) \rangle$$

$$\Rightarrow \quad C^{-1}_{IJ}(T+1) C_{JK}(T) = C^{-1}_{src,Ii} (\delta_{ij} e^{E_i(T)}) C_{src,jK}$$



A criterion for spectroscopy

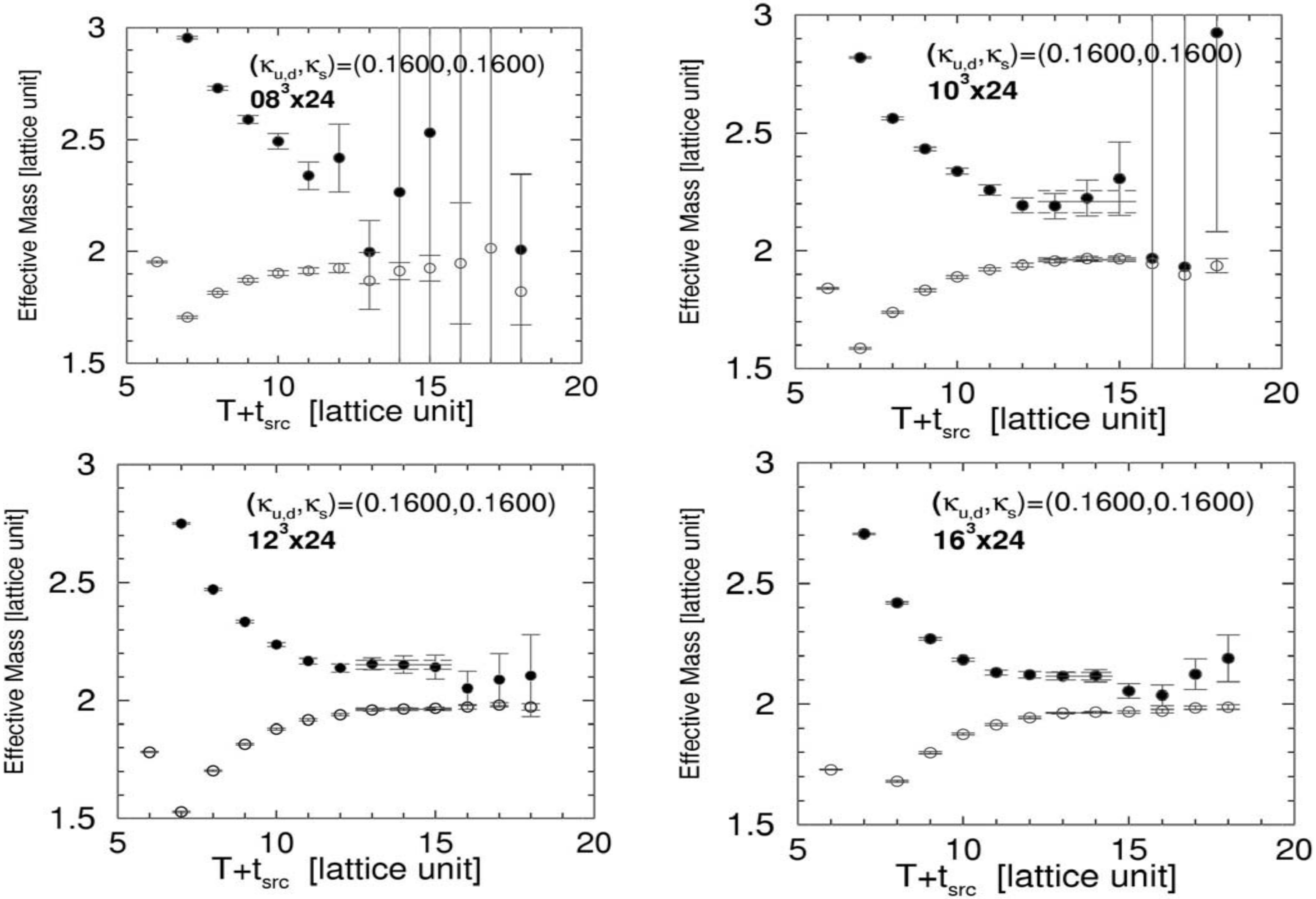
- both states have plateau with 3 points or more
- the gap is larger than errors
- both fit results are stable when $N_{fit} \rightarrow N_{fit}-1$
- lowest state energy is consistent with single exp. fit

Numerical results

$$(I, J^P) = (0, 1/2^-)$$

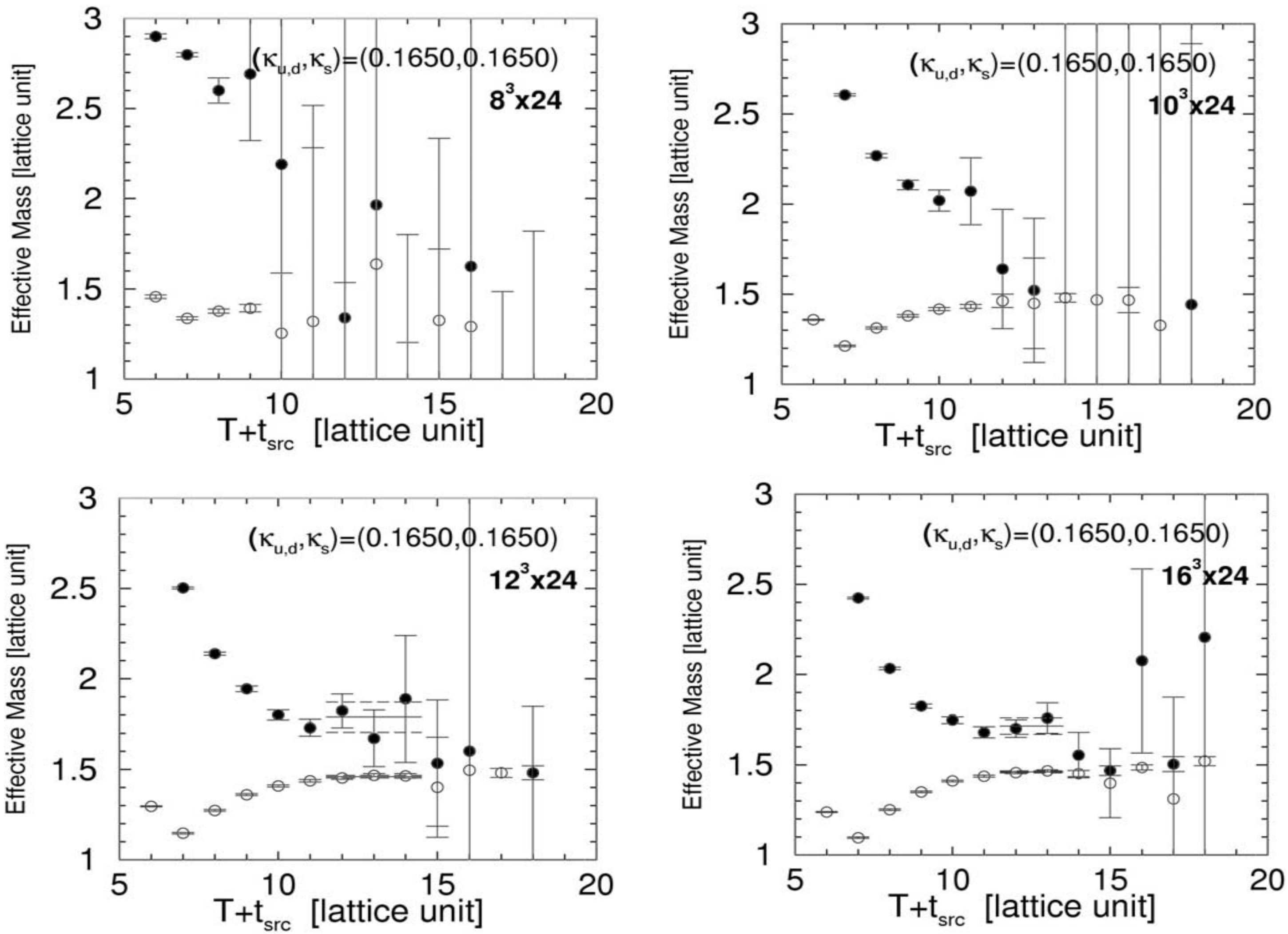
Quality of data

$(I, J^P) = (0, 1/2^-)$



Quality of data

$(I, J^P) = (0, 1/2^-)$

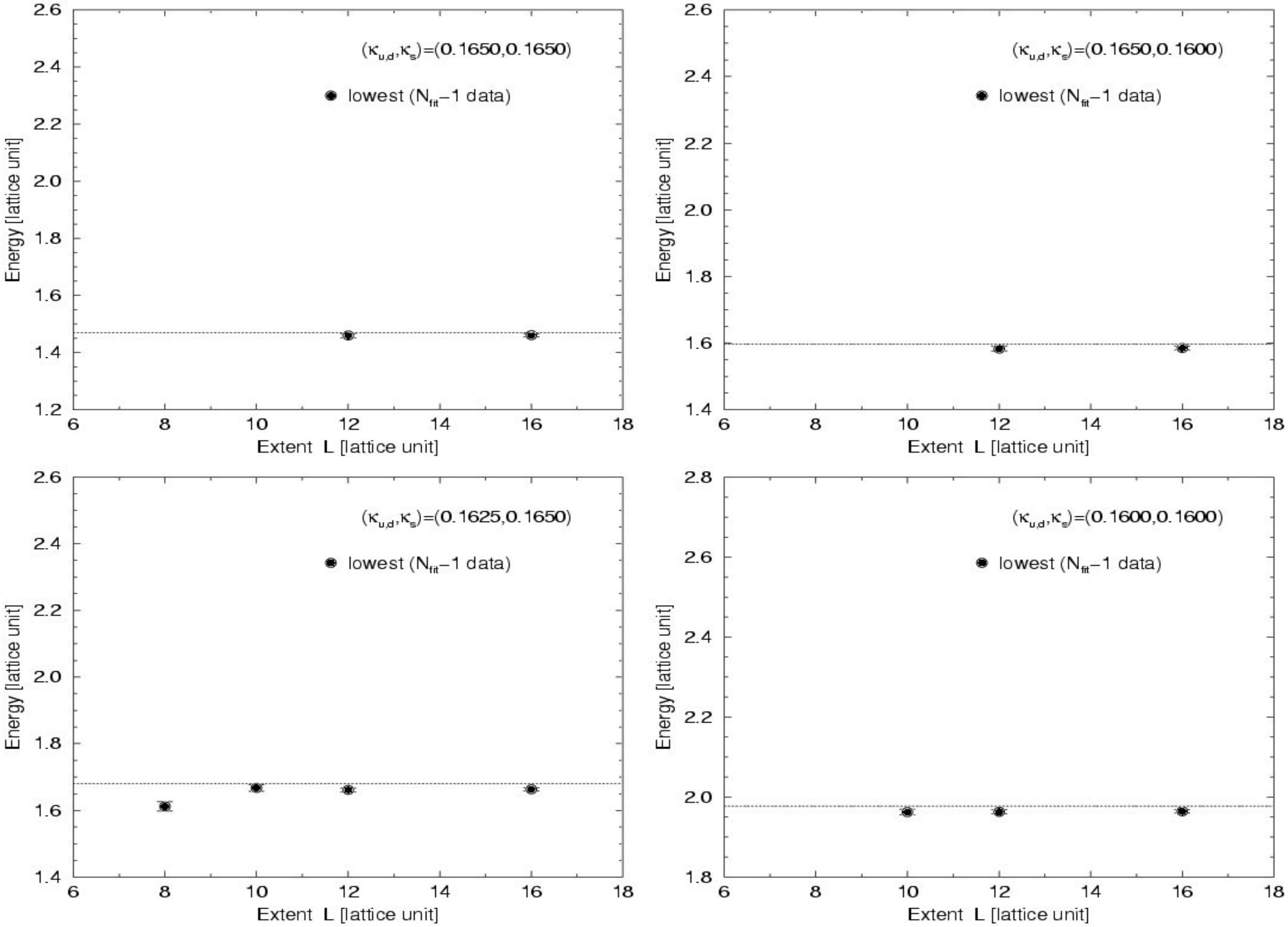


→ discussion using these results

Volume dependence

$(I, J^P) = (0, 1/2^-)$

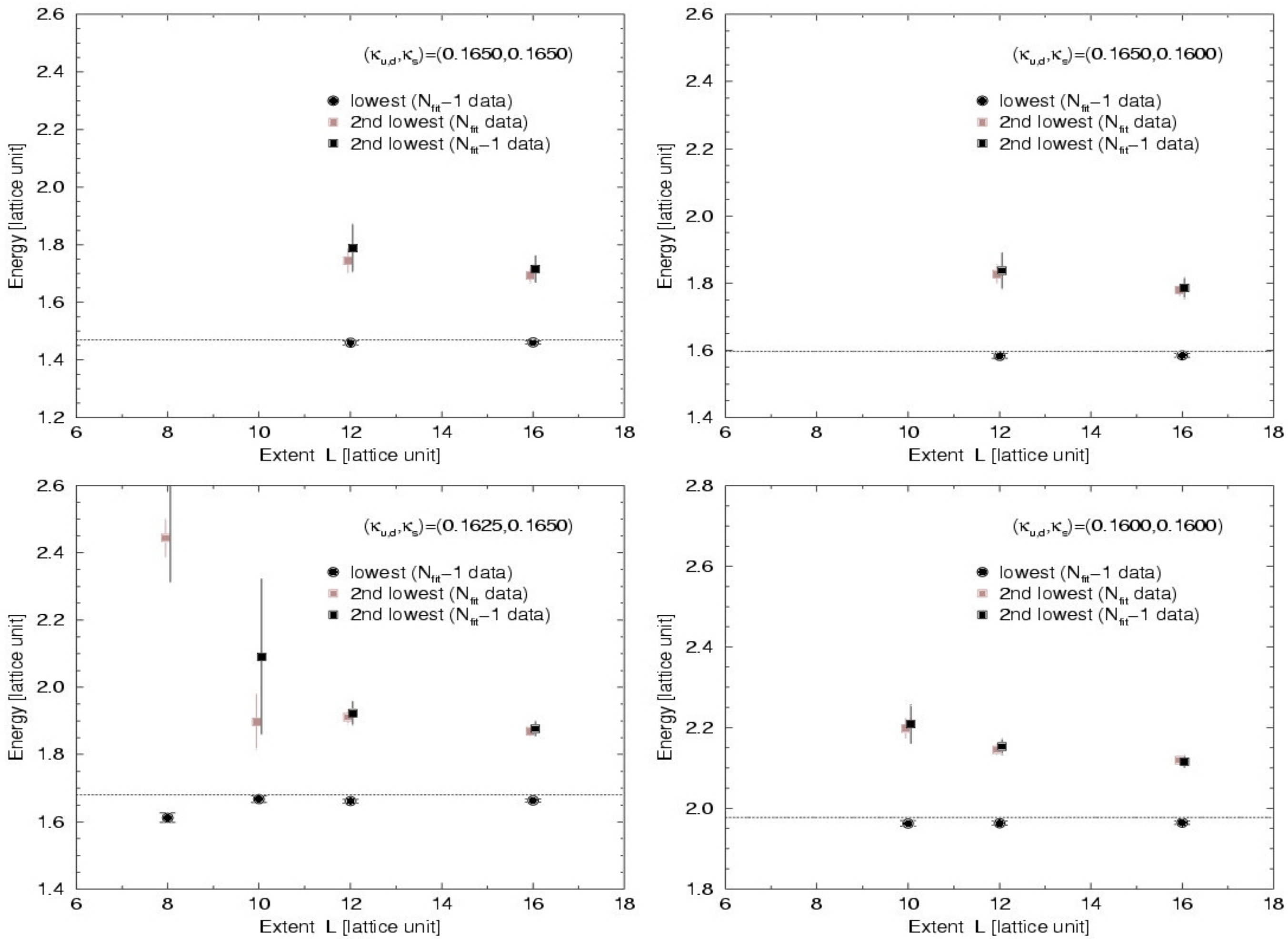
lowest state



Volume dependence

$(I, J^P) = (0, 1/2^-)$

lowest state + 2nd lowest state



→ comparison with expected NK scattering state

NK scattering state

$(I, J^P) = (0, 1/2^-)$

- Naive expectation for 2nd lowest NK state
  Nucl. & Kaon with a relative mom. $p=2\pi/L$
  small/neglegible interaction

$$E(L) = \sqrt{M_N^2 + (2\pi/L)^2} + \sqrt{M_K^2 + (2\pi/L)^2}$$

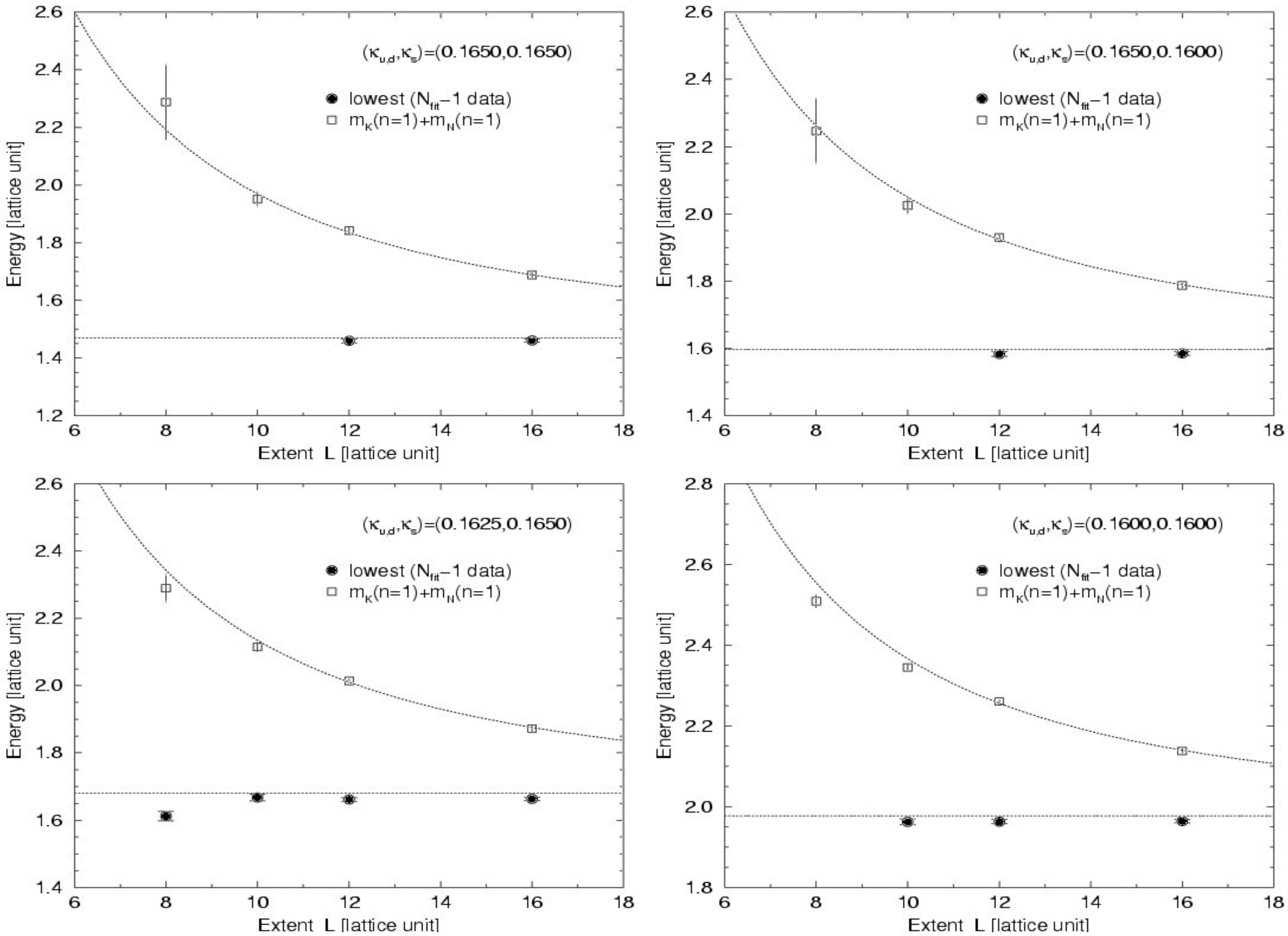
- We can calculate
  Nucleon with $p=2\pi/L$ and Kaon with $p=2\pi/L$ separetely

- Effects of interacton
  Luscher's formula + scatt. length (exp.)
  ➔ a few % deviation from simple sum of N & K

Volume dependence

$(I, J^P) = (0, 1/2^-)$

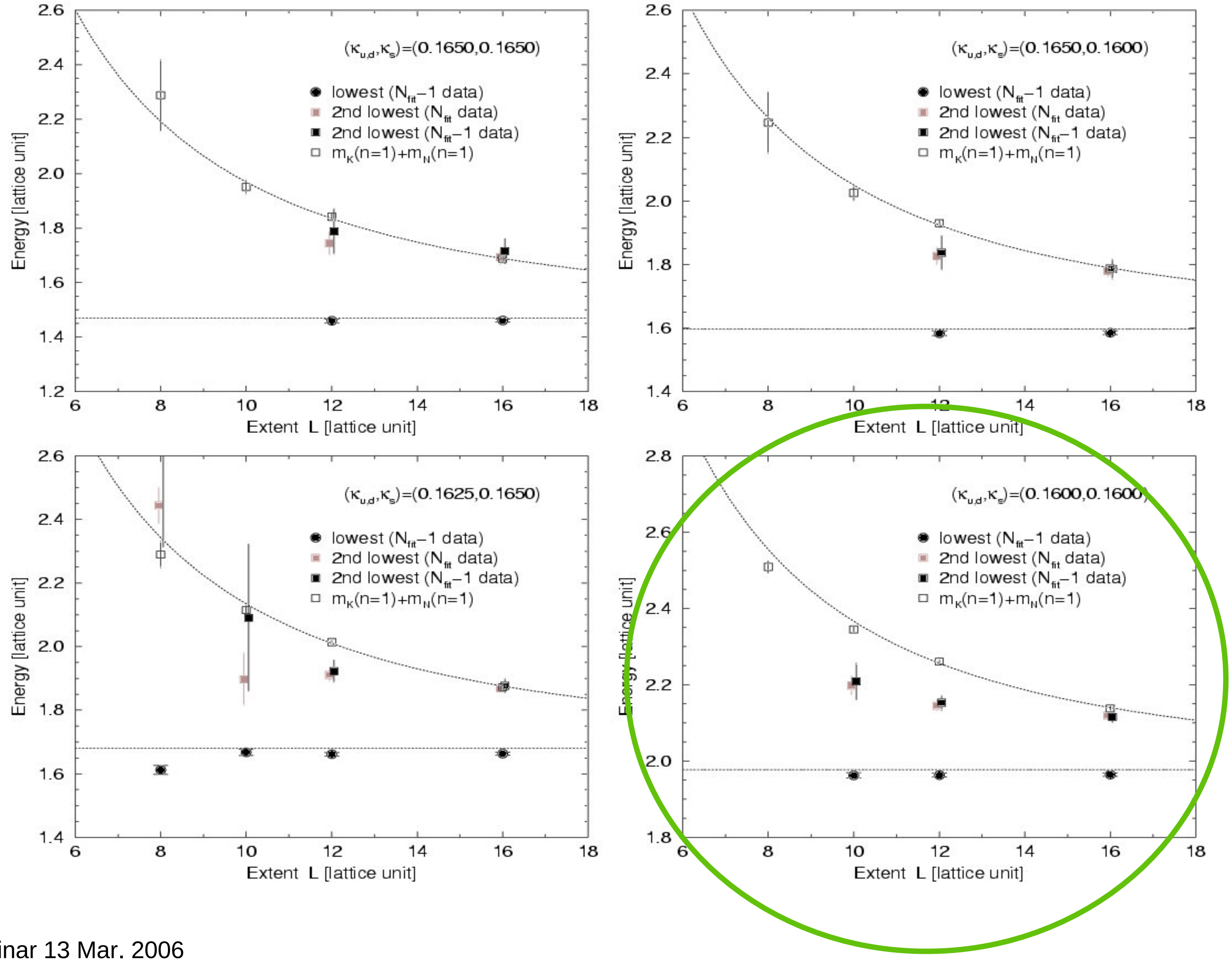
lowest state + sum of N(n=1) & K(n=1)



Volume dependence

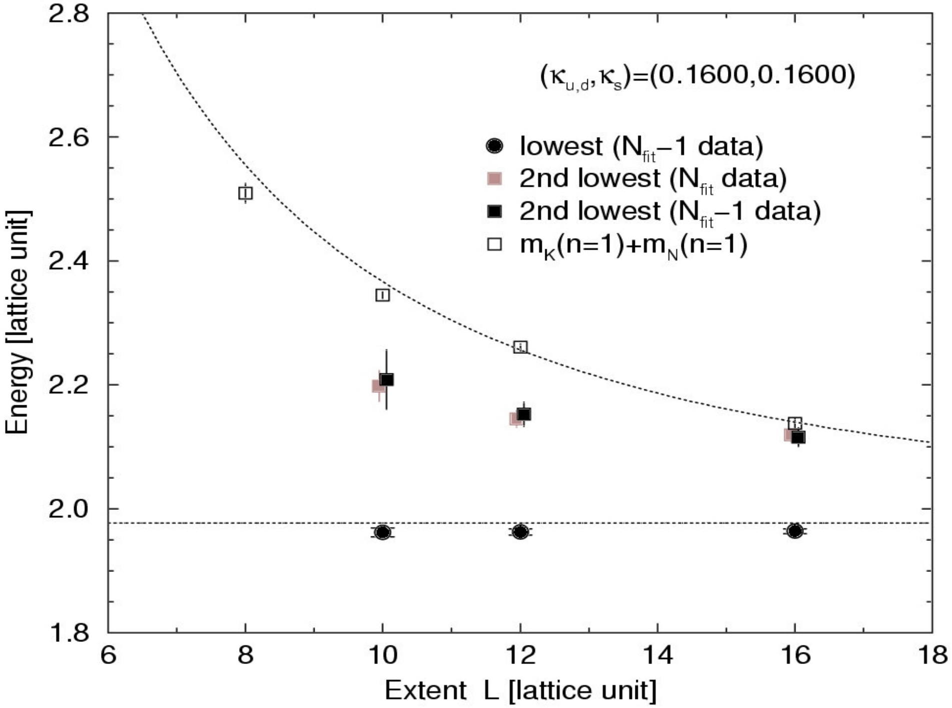
$(I, J^P) = (0, 1/2^-)$

lowest state + 2nd lowest state + sum of N(p=1) & K(p=1)



Volume dependence

$(I, J^P) = (0, 1/2^-)$



possible sources of deviation
from an expected behavior
- nontrivial finite volume effect
- interaction

hadrons become compact
at heavier quark mass
→ smaller finite volume eff.
strong volume dep. interaction
is hard to accept

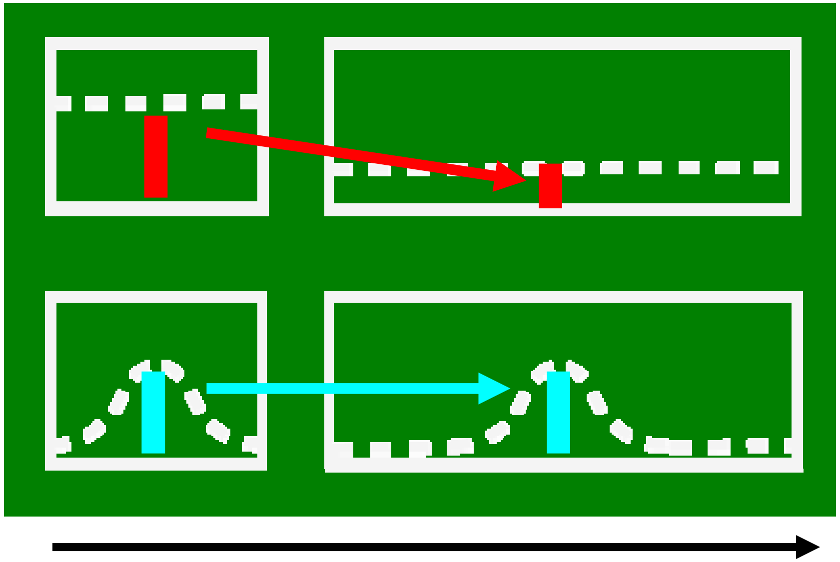
It is difficult to understand
the 2nd lowest state is NK scattering state.

Spectral weight

$(I, J^P) = (0, 1/2^-)$

Spectral weight is
overlap of local operator with each state

$$\mathcal{O}|0\rangle = c_0|0\rangle + c_1|1\rangle + \cdots$$



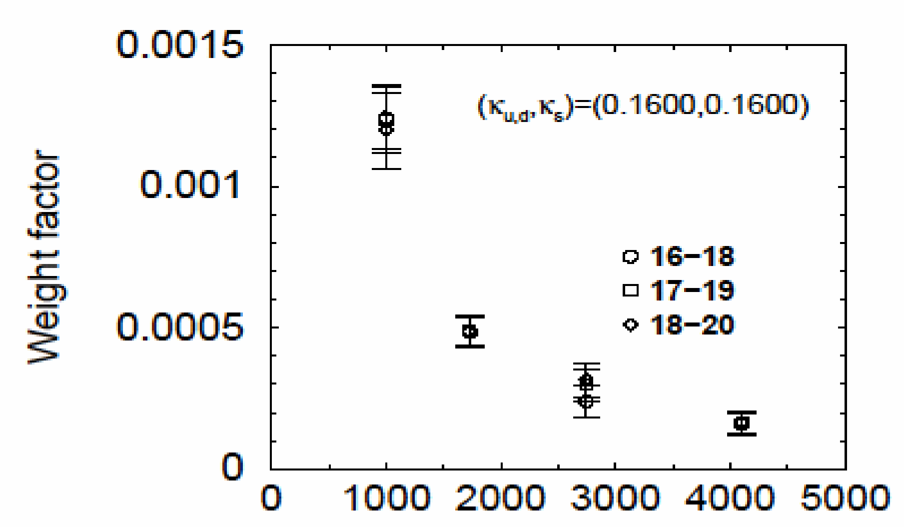
volume of the system

For scattering states
it depends on relative wavefunc.
between N and K → 1/V dep.
For resonance states
it has small volume dep. → const.

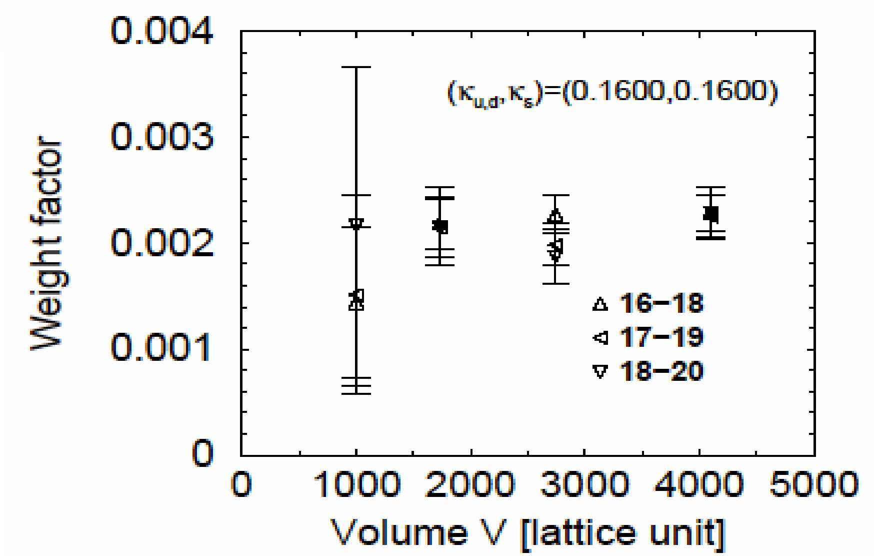
2-pole fit is unstable
using extracted masses as inputs
→ 2 params fit
we apply to heavier quark comb.
→ good signal

Spectral weight

$(I, J^P) = (0, 1/2^-)$



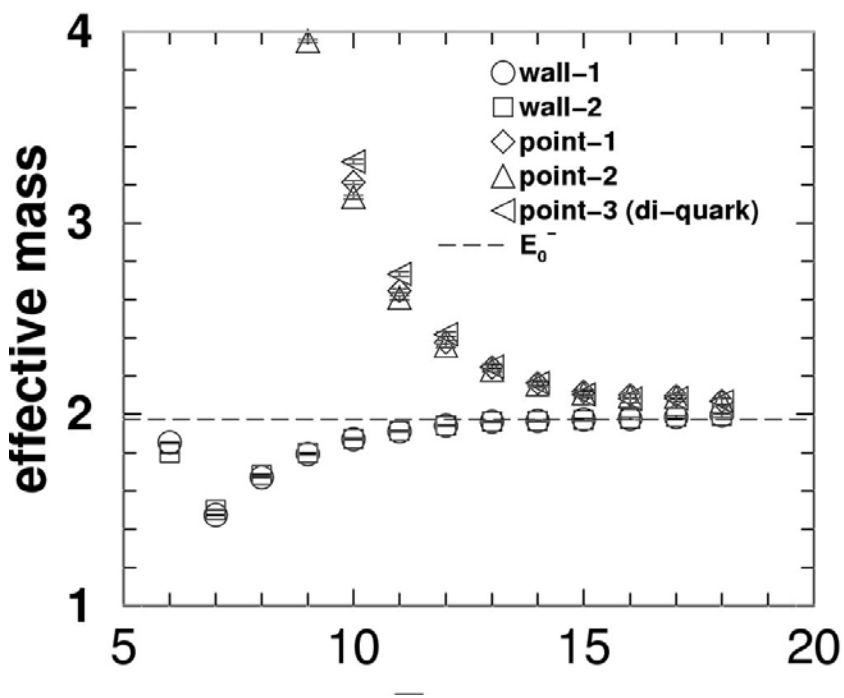
lowest-state
expected to be NK scatt.
with rela. mom. p=0
➔ 1/V dependence

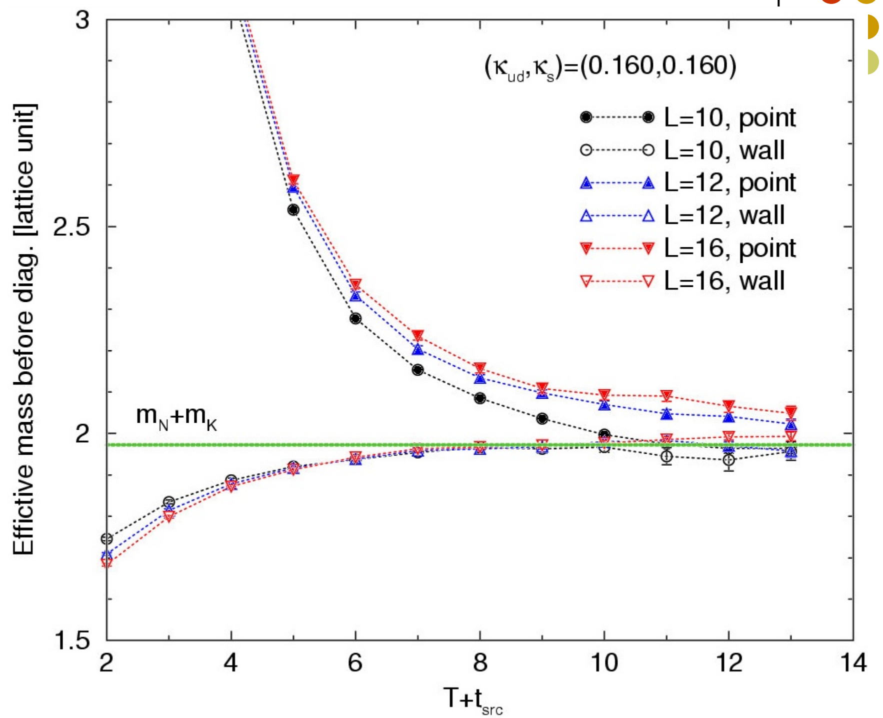


2nd lowest-state
expected to be
resonance state
➔ no V dependence

L=10,12,14 and 16 are used

Operator dependences





time to reach plateau t(point op.) >> t(wall op.)

point op. ○ NK w/o momentum
◎ pentaquark
○ NK w/ momentum

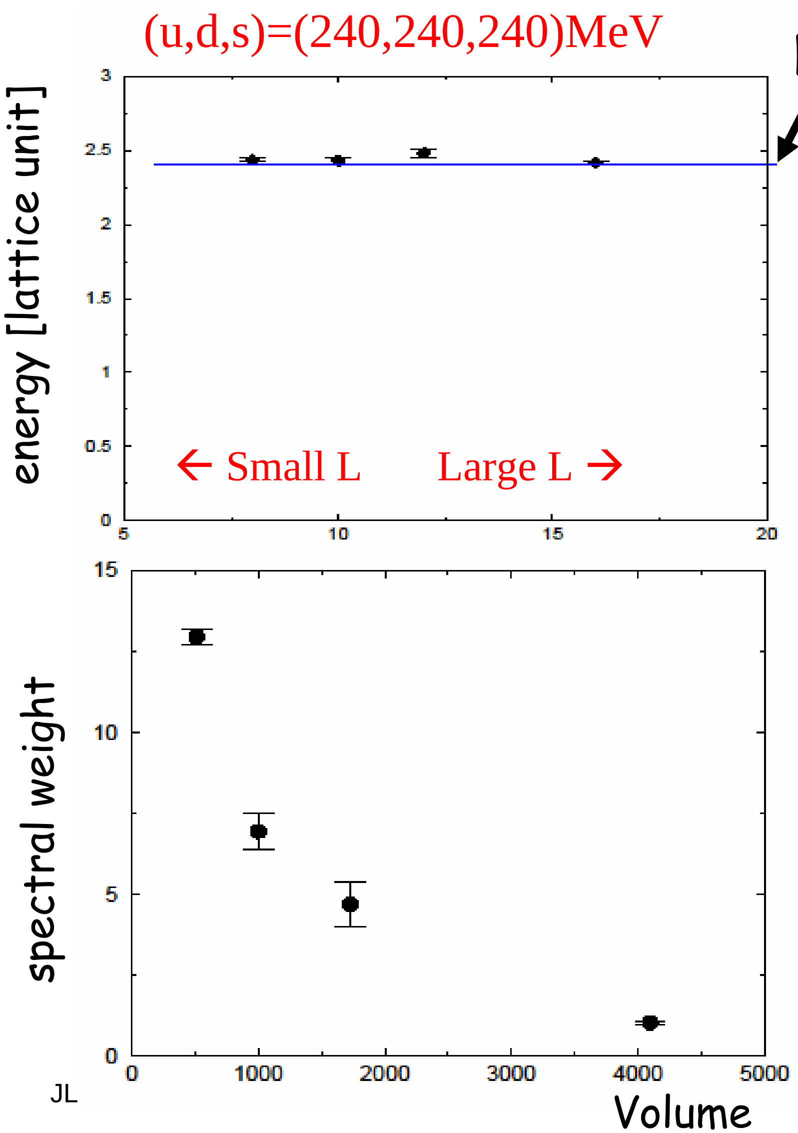
wall op. ◎ NK w/o momentum
○ pentaquark
△ NK w/ momentum

Numerical results

$$(I, J^P) = (0, \tfrac{1}{2}^+)$$

Positive parity

$(I, J^P) = (0, \frac{1}{2}^+)$



- Diagonalization is unstable
  we can extract only lowest state
  - no volume dependence
  - near the N*+K energy
  - 1/V behavior in spectral weight

  → N*K scattering state with p=0

- However NK P-wave scattering state has smaller energy than N*+K

  → wall source ops. prefer relative mom.=0 state (?)

Any resonace state is not found, but we also miss the NK P-state.

Summary & Conclusion

We study a pentaquark state with (I,J)=(0,1/2)

Our aim is whether Pentaquarks exist or not on the lattice ?

- extract lowest two states
- examine the volume dependence of mass & spectral weight

Our result supports that resonance state is likely to exist slightly above the NK threshold in $(I,J^P)=(0,1/2^-)$

But there is no systematic study in Lattice QCD up to now
"existence of theta+" is still open question in lattice QCD

Lattice studies

	signal	Parity	diag.	V dep.
Csikor et al. (1)	Yes	negative	×	△
S.Sasaki	Yes	negative	×	×
Kentuchy group	No	n/a	×	△
TITECH group	No	n/a	HB	---
Chiu & Hsieh	Yes	positive	○	×
Lasscock et al.	No	n/a	△	×
Csikor et al. (2)	No	n/a	○	○
Alexandrou et al.	Yes	negative	○	○
YITP	Yes	negative	○	○

Comparison with other studies

CSIKOR, FODOR, KATZ, KOVÁCS, AND TÓTH PHYSICAL REVIEW D **73,** 034506 (2006)

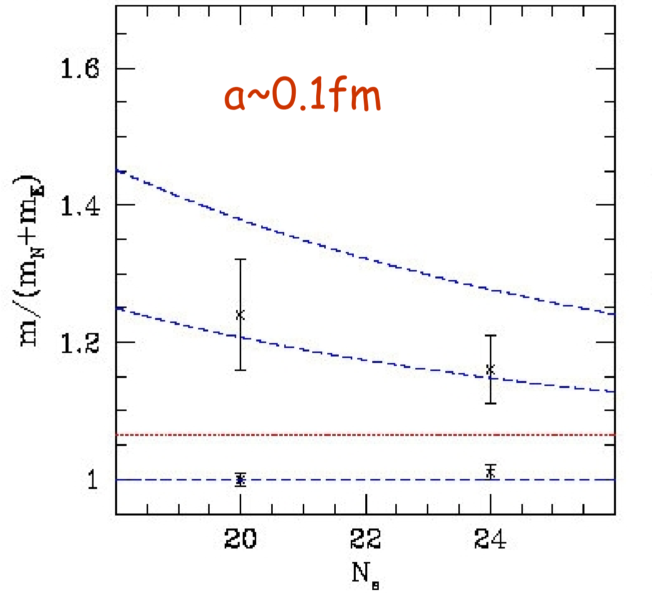
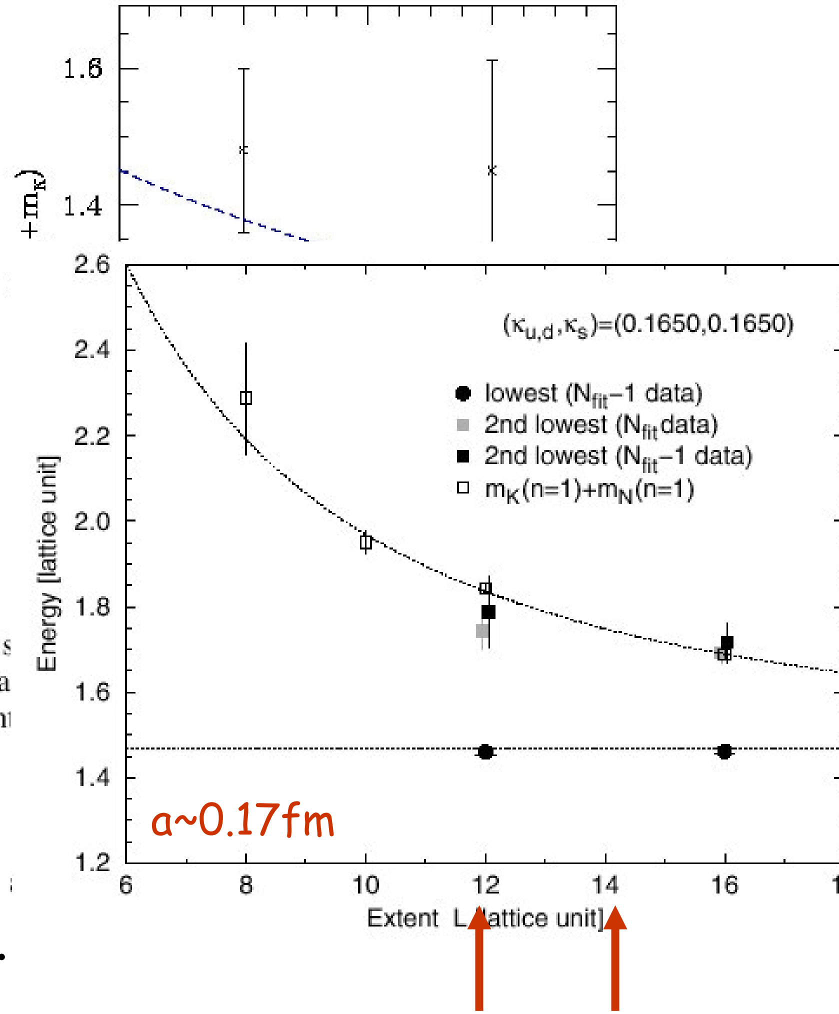


FIG. 2 (color online). The volume dependence of the two lowest s
panel: positive parity). The dashed lines indicate the expected sca
momenta. The dotted line shows the experimental value of the pen



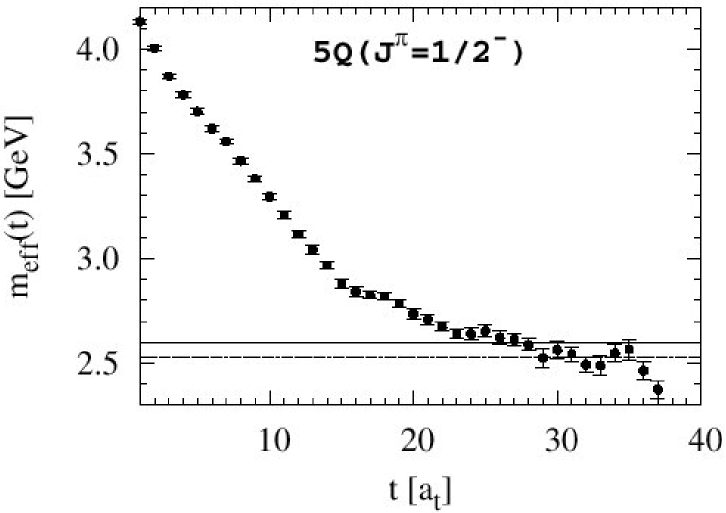
Our result:

slightly lighter quark mass

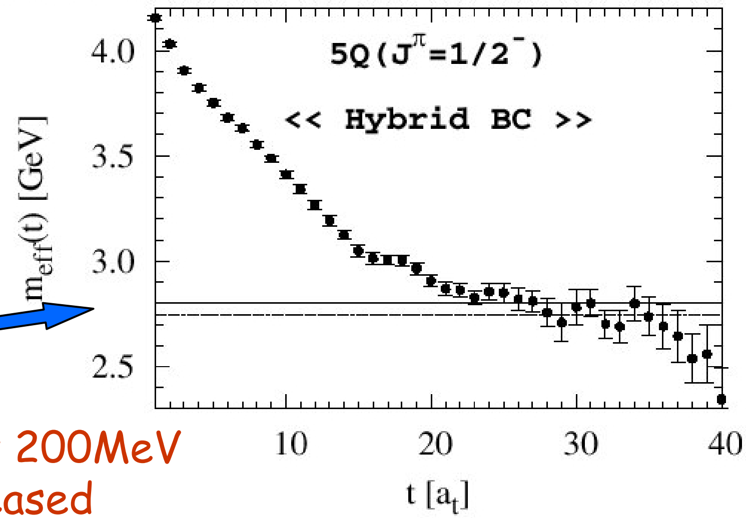
than Csikor et al.

Comparison with other studies

ISHII, DOI, IIDA, OKA, OKIHARU, AND SUGANUMA



about 200MeV increased



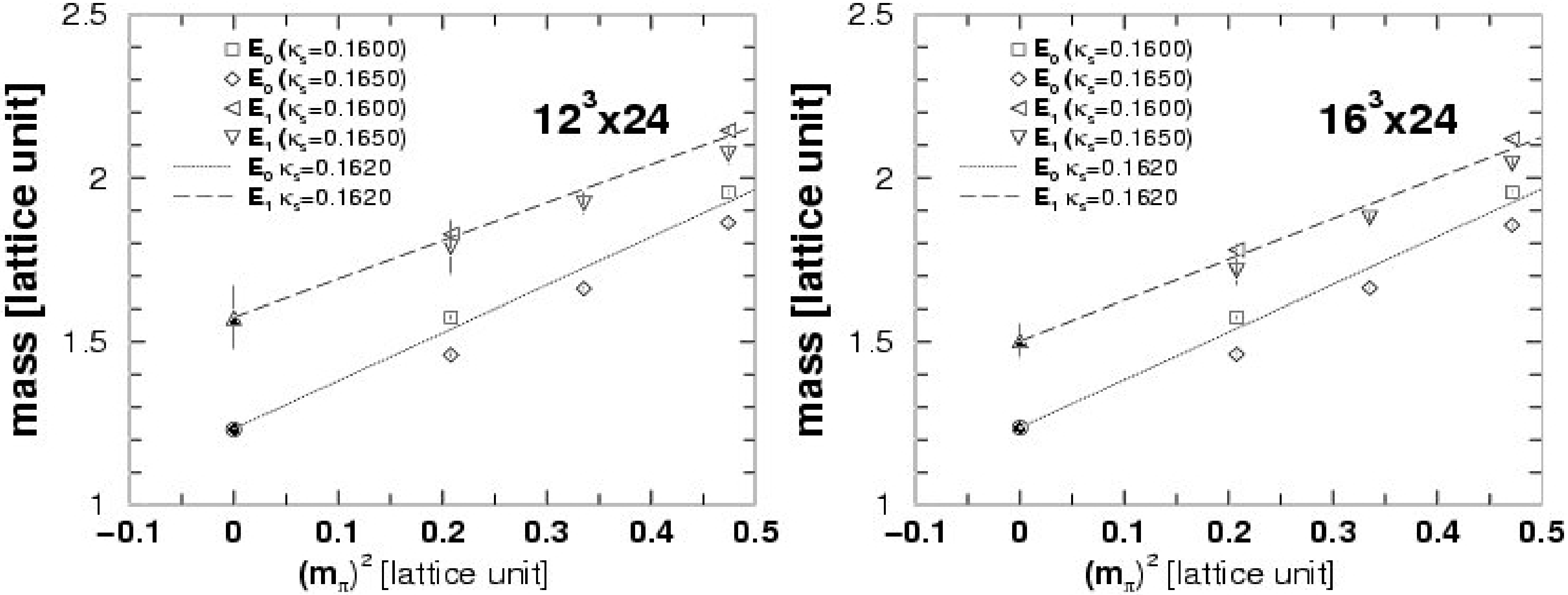
By using the HBC method, we have further investigated the negative-parity state. We have found that the plateau is raised by about 200 MeV due to the HBC, which is consistent with the shift of the NK threshold. We conclude that there is no localized resonance state below $\sqrt{m_N^2 + \vec{p}_{\rm min}^2} + \sqrt{m_K^2 + \vec{p}_{\rm min}^2}$ with $|\vec{p}_{\rm min}| = \sqrt{3}\pi/L$. It follows, in particular, that the negative-parity state observed in the standard BC *is a mere NK-scattering state.*

In this way, we have not found any relevant signals of narrow pentaquark states in both positive- and negative-parity channels even with a non-NK-type interpolating field. This result is similar to Ref. [46]. Of course, one of

From our study
($1/2^-$, heaviest quarks, L=12):
lowest energy = 2.283(6) GeV
2nd lowest energy = 2.49(2) GeV

gap ~ 200MeV

Chiral extrapolation

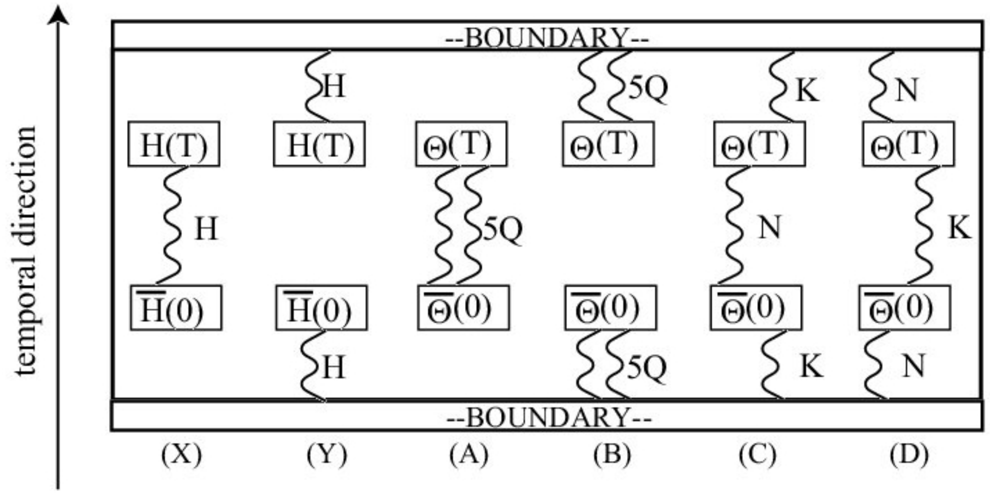


M_K=0.5001(14) GeV, M_N=0.9355(70) GeV

M_{Theta^+}=1.755(61) GeV

(16^3x24 data, 1/a by M_{rho}, m_s by Kaon)

boundary condition



- Periodic/anti-periodic boundary for quarks

$$\langle \bar{K}|\Theta(T+t_{src})|N\rangle\langle N|\bar{\Theta}(t_{src})|\bar{K}\rangle \sim e^{-E_K T+E_{\bar{K}}(T-N_t)}$$

$m_{eff} \rightarrow E_N - \bar{E}_K$

- Dirichlet boundary → no problem