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Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines

November 12-13, 2004

Organizers:

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

The RBRC has both a theory and experimental component. At present the theoretical group has 4 Fellows and 3 Research Associates as well as 11 RHIC Physics/University Fellows (academic year 2003-2004). To date there are approximately 30 graduates from the program of which 13 have attained tenure positions at major institutions worldwide. The experimental group is smaller and has 2 Fellows and 3 RHIC Physics/University Fellows and 3 Research Associates, and historically 6 individuals have attained permanent positions.

Beginning in 2001 a new RIKEN Spin Program (RSP) category was implemented at RBRC. These appointments are joint positions of RBRC and RIKEN and include the following positions in theory and experiment: RSP Researchers, RSP Research Associates, and Young Researchers, who are mentored by senior RBRC Scientists. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time. To date there are sixty-eight proceeding volumes available.

The construction of a 0.6 teraflops parallel processor, dedicated to lattice QCD, begun at the Center on February 19, 1998, was completed on August 28, 1998 and is still operational. A 10 teraflops QCDOC computer in under construction and expected to be completed this year.

N. P. Samios, Director
November 2004

*Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.

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Physics Programs of the RBRC and UKQCD QCDOC Computers
Introduction

N.H. Christ, R.D. Kenway, R.D. Mawhinney, S. Ohta

The second intercollaborational workshop of RIKEN-BNL-Columbia (RBC) and UKQCD collaborations was organized as the ??th RIKEN-BNL Research Center Workshop entitled "Physics Programs of the RBRC and UKQCD QCDOC Computers" and held at Brookhaven National Laboratory on November 12th and 13th, 2004.

At the time of the meeting, two 12K-node QCDOC configurations, one in Edinburgh and the other at the RIKEN-BNL Research Center in Brookhaven were soon to become available for lattice QCD numerical calculations. Indeed the Edinburgh configuration had been successfully assembled and verified in Brookhaven during the preceding months, and was just shipped from Brookhaven and then received in Edinburgh. The RIKEN configuration was being assembled. As of this writing (January ??th, 2005), the two configurations are now complete and ready to start physics calculations.

Since the first intercollaborational workshop held in Edinburgh in December, 2003, some members of the two collaborations had been discussing possible advantages of jointly producing gauge configurations with dynamical domain-wall fermion quark and improved gauge actions. As is summarized in this volume, many interesting presentations and discussions in the workshop helped to identify areas where such a collaboration would be helpful. Following these discussions, the RBC and UKQCD collaborations agreed, in January 2005, to jointly generate such ensembles of gauge configurations with the so-called (2+1) flavors (degenerate up and down plus heavier strange) dynamical domain-wall fermion quarks and "DBW2"-like improved gauge actions. At first a set of production parameters with lattice spacing as coarse as about 0.11 fm (or its inverse about 1.8 GeV) is aimed at. This will allow the entire calculation be completed within a year with the up and down quark mass as light as possible and the lattice volume as large as possible.

We would like to thank Dr. Nicholas Samios and RIKEN-BNL Research Center for providing the opportunity and support to organize this workshop. We thank Ms. Pamela Esposito for her invaluable help in organizing and running the workshop.

Current status of QCDOC runs

Michael Clark

Current Status of QCDOC runs

Michael Clark
The University of Edinburgh

The initial runs performed on the QCDOC supercomputer prototypes is discussed. The parameters intended for the light ASQTAD run are discussed, as are the problems holding back running with these parameters. The results from an initial domain-wall fermion eigenvalue bounds study are discussed.

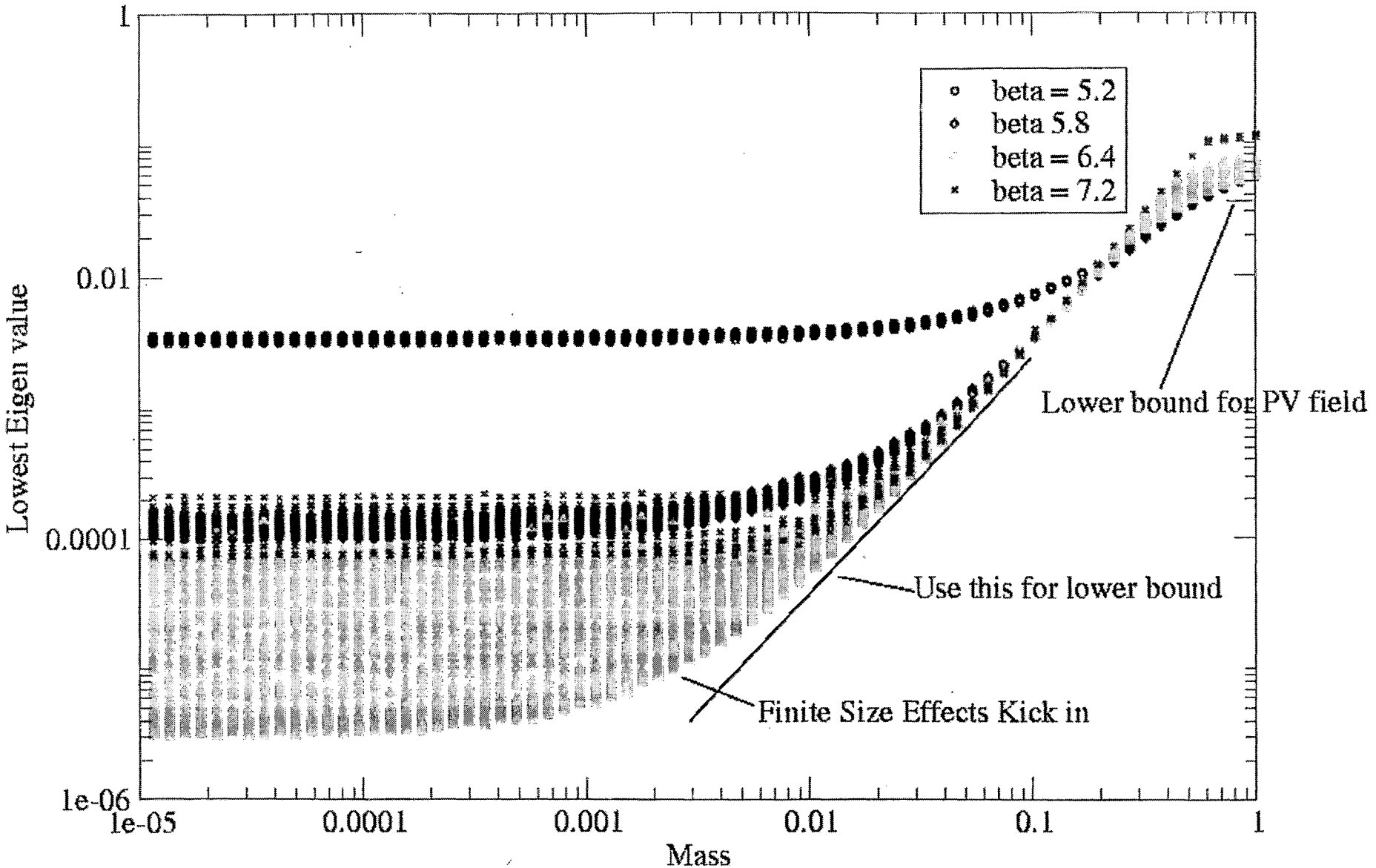
ASQTAD 2+1 runs

- Running on 1024 nodes
- Intended parameters
  - 24^3x64 lattice
  - m=0.0079, 0.038
  - dt = 0.05
  - Symanzik improved gauge action
- RHMC algorithm
- Successfully run above parameters but 16^3x64

  PLB-SCU error holding back the runRunning on 1024 nodes

DWF eigenvalue study

- Not obvious what DWF e-value bounds are
- Require this to efficiently perform RHMC
- Empirical study of DWF e-value bounds
- Performed on quenched ensembles
- Proof of concept test successfully completed


beta = 5.2
beta 5.8
beta = 6.4
beta = 7.2
Lower bound for PV field
Use this for lower bound
Finite Size Effects Kick in
Lowest Eigen value
Mass
1
0.01
0.0001
1e-06
1e-05
0.0001
0.001
0.01
0.1
1

DWF Simulations on QCDOC

Meifeng Lin (Columbia University)

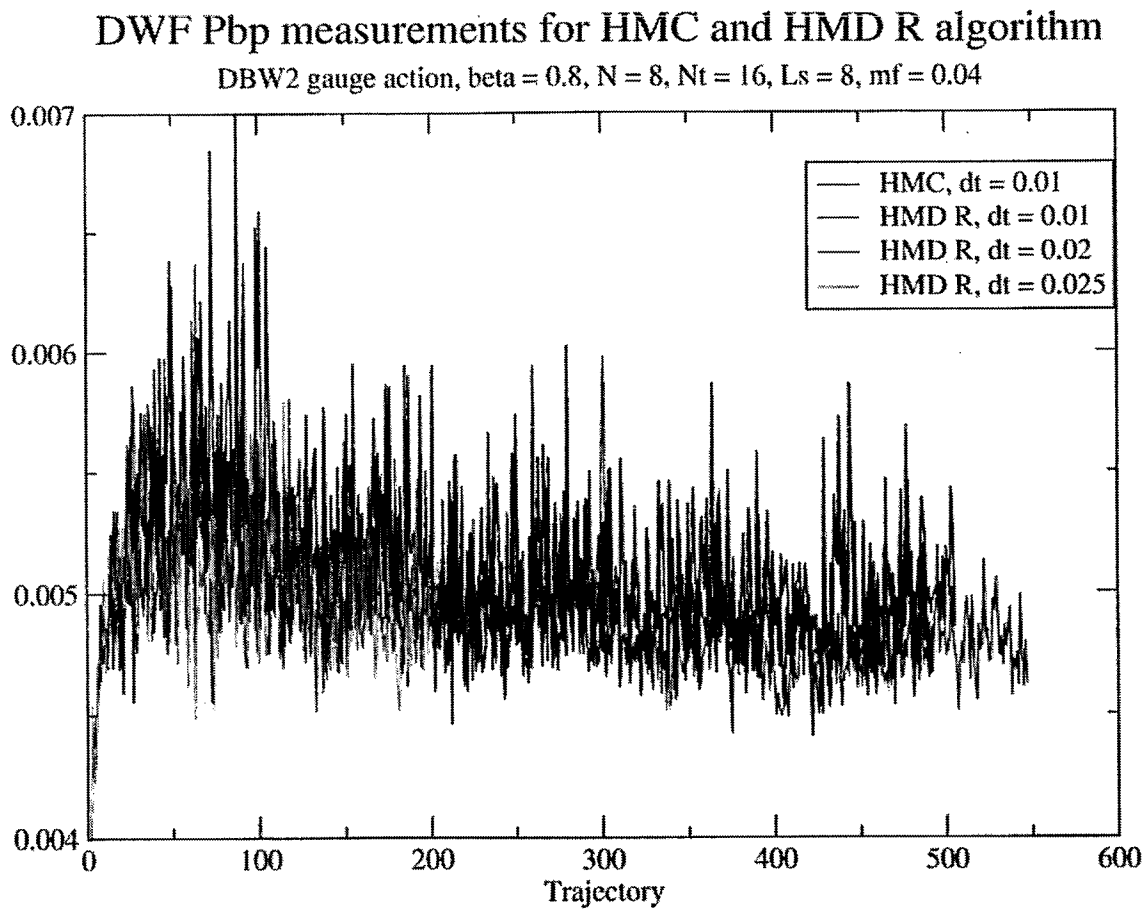
11/12/04

I report recent progress on DWF simulations on QCDOC with Columbia Physics System (cps++). $N_f = 2$ DWF HMC evolution is compared with QCDSP data. Preliminary tests for R algorithm are also being done on a smaller volume.

Plans (tentative)

- reproduce $N_f = 3$ QCDSP data on QCDOC
- study the effects of various rectangle coefficients in DBW2 action.
- $N_f = 2 + 1$ production runs with RHMC?

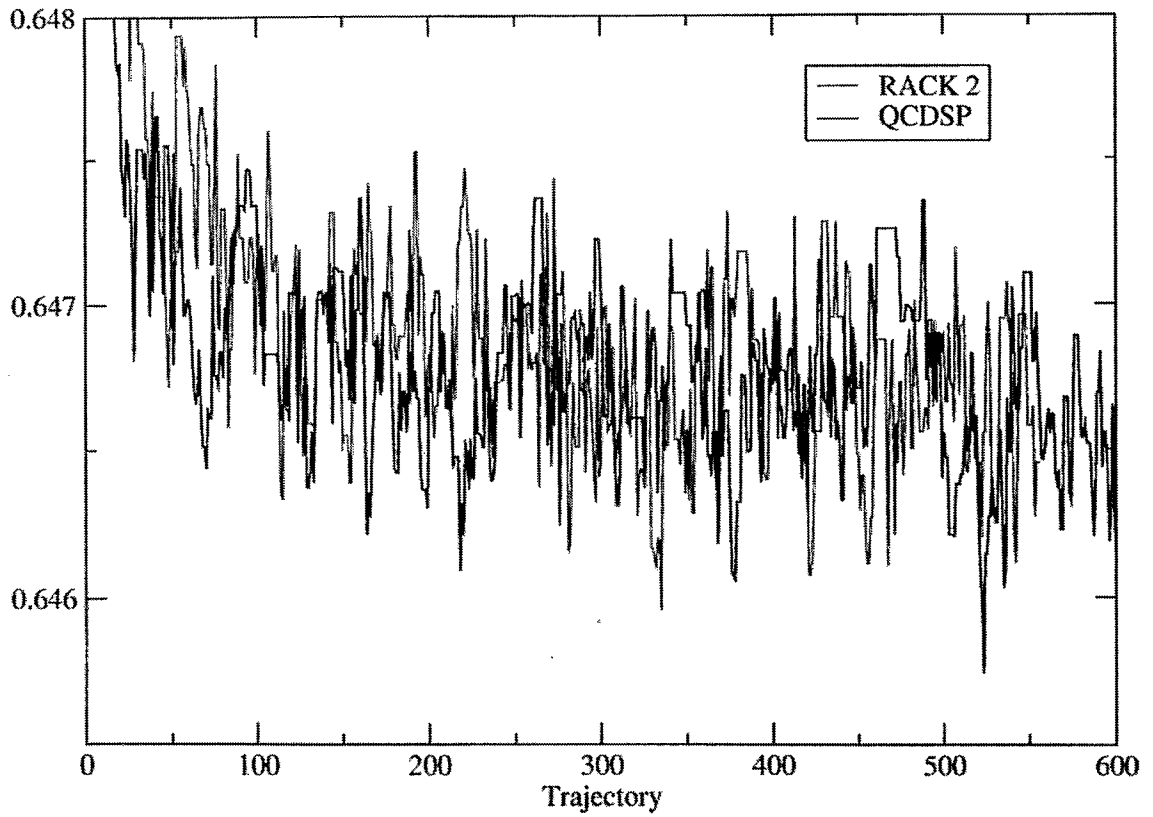
$\bar{\psi}\psi$ evolution



$N_f = 2$ DWF HMC evolution

- Parameters:
  $16^3 \times 32$, $L_s = 12$, $M_5 = 1.8$, $\beta = 0.8$, $m_f = 0.04$; stepsize = 0.01, trajectory length = 0.5
  $\Rightarrow$ acceptance rate $\sim$ 70%
- Performance (assuming no hardware problems):
  5 trajectories / 45 mins $\rightarrow$ 160 trajectories / day
  + 100% reproducibility tests every 5 trajectories
  $\Rightarrow$ 80 new trajectories / day

Plaquette evolution



R algorithm evolution

- Parameters:
  $8^3 \times 16$, $L_s = 8$, $M_5 = 1.8$, $\beta = 0.8$, $m_f = 0.04$; stepsize = 0.01,0.02,0.025,0.05,0.1, trajectory length = 0.5.
- HMC evolution for comparison:
  $8^3 \times 16$, $L_s = 8$, $M_5 = 1.8$, $\beta = 0.8$, $m_f = 0.04$; stepsize = 0.01, trajectory length = 0.5.

Improved Staggered Fermions, Mixed Actions, and all that.

Chris Maynard

UKQCD

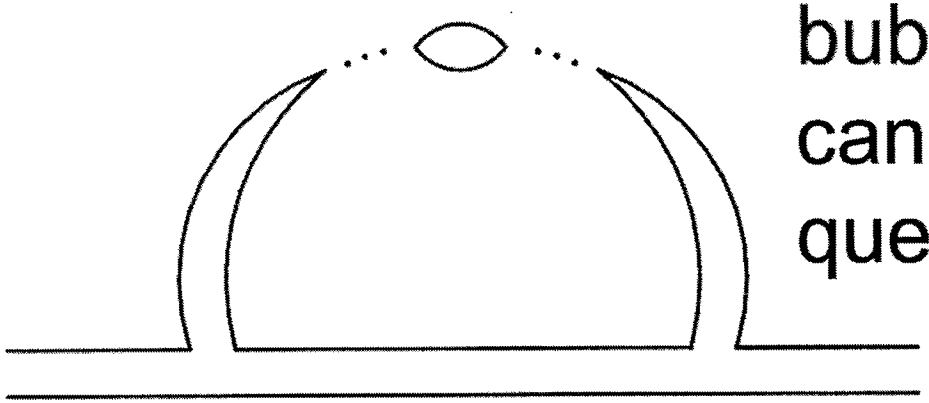
Proposed runs – UKQCD machine

- Integrated run-time 1 Tflop-year
  - am_s=0.039
    - (physical value estimated by MILC)

a (fm)	V	m_l/m_s	#Traj	Tflop/yr
0.125	$24^3\times64$	1/5	30000	21%
0.09	$32^3\times64$	1/5	4000	11%
0.06	$48^3\times64$	1/5	3000	47%
0.125	$32^3\times64$	1/8	4000	10%
0.125	$32^3\times64$	1/10	4000	17%

Sea Sickness

- Negative double pole



No vacuum bubbles to cancel hairpin in quenched

- Same pathology occurs in PQ model
  Contributions of bubbles $\propto m_{\rm sea}$
- Cancelation depends on $m_{\rm val}/m_{\rm sea}$
- Sickness only present when $m_{\rm val} < m_{\rm sea}$

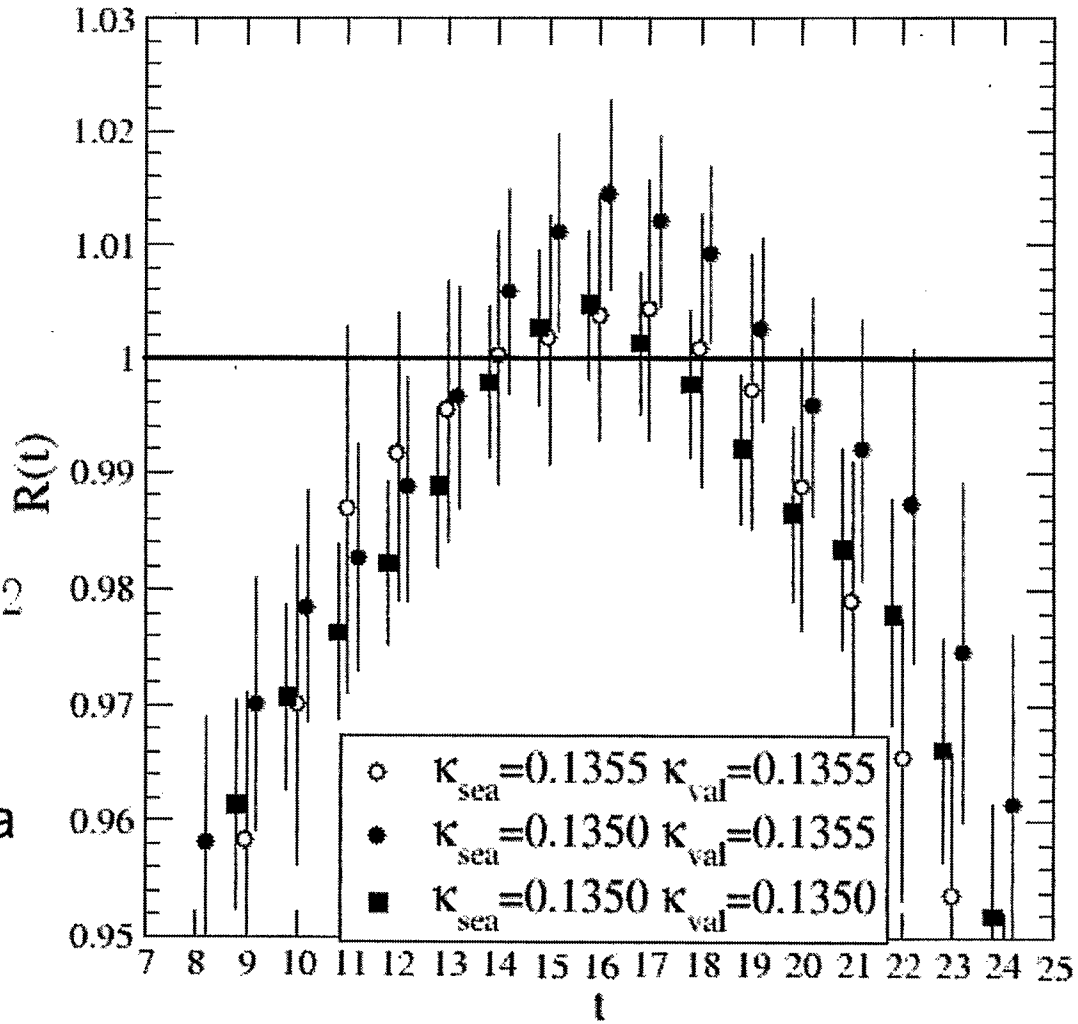
Matching Sea and Valence

- UKQCD N_f=2 Clover data

$$R(t) = \frac{C_{PP}(t) - C_{SS}(t)}{C_{PP}(t)}$$

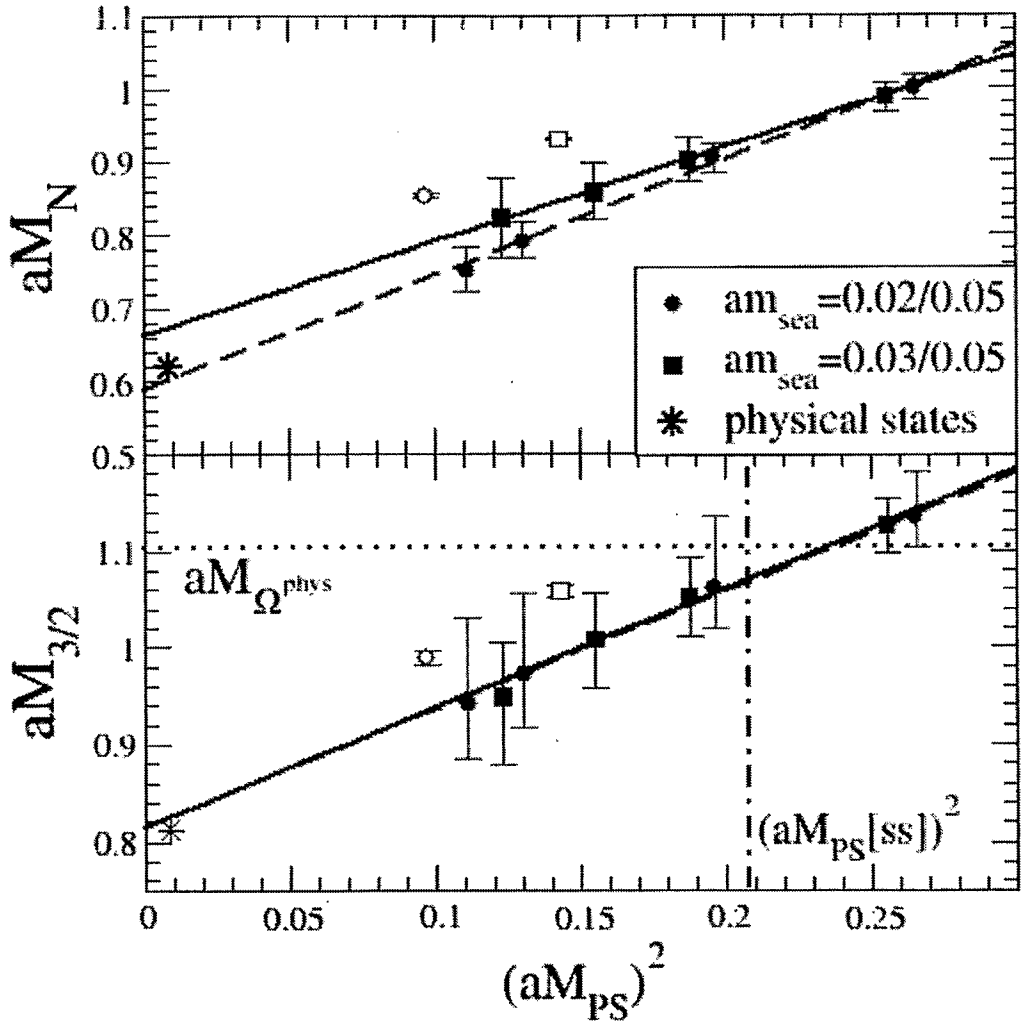
$$R(T/2) = 1 - \frac{A_{SS}}{A_{PP}} e^{-\Delta M T/2}$$

- R>1 → $m_{val} < m_{sea}$



Nucleon and decuplet masses

- Improved staggered valence baryons suffer significant lattice artefacts
- Overlap valence seems to do better



Summary

- VOIDSS has potential despite obvious drawbacks
- Relatively computationally cheap
- Chiral symmetry
  - Operator mixing under control
- Light hadron spectrum, matrix elements
  - Mesons, baryons, excitations
  - Decay constants, nucleon decay, Kaon ME
- Charm meson spectrum and decay contants

Understanding the staggered Dirac operator

Alistair Hart

University of Edinburgh

In collaboration with E. Follana and C. Davies (University of Glasgow).

- We study the spectrum of the staggered Dirac operator on improved gauge backgrounds for lattice spacings between 0.08 and 0.13 fm.
- Using a highly improved formulation of staggered, Kogut-Susskind quarks, we find the modes to clearly divide into zero modes of high chirality and non-zero modes whose chirality is uniformly close to zero.
- Very few modes of intermediate chirality are seen, giving us a clear Index Theorem.
- We compare the fluctuations in the distributions of the non-zero modes to the predictions of a random matrix theory with the continuum symmetries of QCD.
- Provided the zero modes are subtracted from the spectrum, and the remaining modes are grouped as near-degenerate quartets, good agreement is found.
- In particular, the distribution of modes clearly changes as we move between sectors of different topological charge.
- Improved staggered quarks therefore show restoration of continuum chiral symmetries for lattice spacings below 0.1 fm.

Continuum global symmetries

- $SU(N_f) \times SU(N_f)$:
  - Spont. broken to $SU(N_f) \times SU(N_f) / SU(N_f)$
  - Pions as Goldstone bosons
  - Order param = chiral cond. $\Sigma = -\langle\bar{\psi}\psi\rangle$
- $U_A(1)$:
  - Anomalous
  - Atiyah-Singer Index Theorem

Symmetries in the spectrum

- eigenvalues $D f_s = i \lambda_s f_s$
- anti-Herm: $D^\dagger = -D \quad \Rightarrow \quad \lambda_s$ real
- chirality: $\chi_s = f_s^\dagger \gamma_5 f_s$
- $SU(N_f) \Rightarrow N_f$-fold mode degeneracy
- Classify modes
  - Zero modes: $\lambda_s = 0$
  - Non-zero modes: $\lambda_s \neq 0$

Two sets of modes:

- Non-zero modes:
  - occur in ± pairs, chirality zero
- Zero modes:
  - Chirality $\chi_s = \pm 1$ ($n_\pm$ of each)
  - Atiyah-Singer index theorem
  - gluonic top. ch.: $Q = n_- - n_+$
  - Usually n_+ and/or $n_- = 0$.

Kogut-Susskind fermions

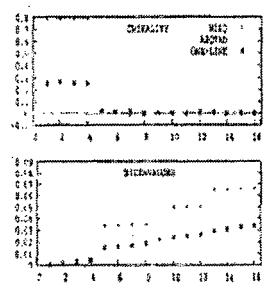
- Global symmetry: $U(1) \times U(1) / U(1)$
  - No N_f-fold mode degeneracy
  - No exact zero modes or Index Theorem
- Full symmetry group restored as $a \to 0$.
  - N_f-fold degeneracy important in understanding reduced flavour KS sea *and valence* quarks.
  - How small does a need to be?
  - Is ASQtad #1 or should we try harder?

Measurement parameters

- Quenched gauge action:
  - 1x1 + 1x2: tree level Sym. + tadpole imp.
- KS actions: One-link and improved:
  - ASQtad, HYP
  - HISQ = $FAT7_R \times ASQ$
- a = 0.125, 0.09, 0.077 fm
- L = 1.1, 1.5, 1.8 fm

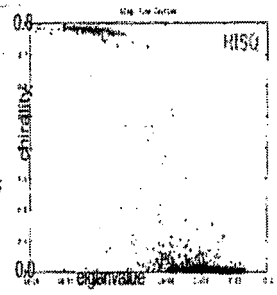
Eigenvalues: a=0.077 fm

- Zero modes + gap.
- Non-zero modes in quartets: near degenerate
- Zero modes chiral, other modes not
- Index Theorem for Q=−2.



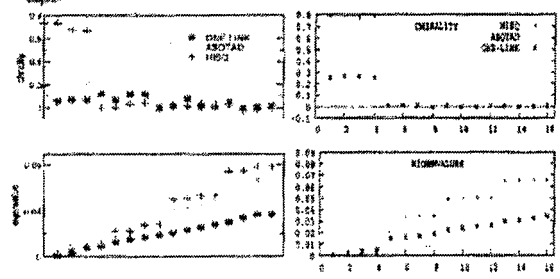
Chirality gap: a=0.077 fm

- Previously, one typical config.
- Scatter plot for an ensemble
- Almost no intermediate modes



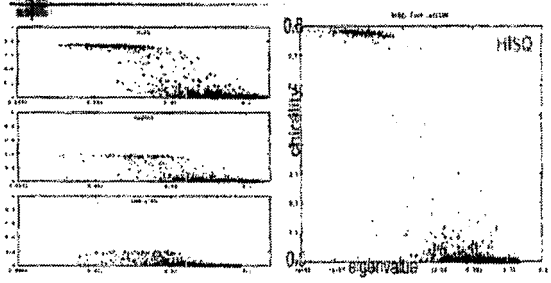
Coarser lattices:

a=0.09 fm a=0.077 fm



Coarser lattices:

a=0.09 fm a=0.077 fm



Non-zero modes revisited

- Chiral condensate: $\Sigma = -\langle\bar{\psi}\psi\rangle$
- Banks-Casher: $\Sigma = \lim \pi\langle\rho(0)\rangle/V$
- Fluctuations about this are universal: depend only on symmetries of theory.
- Good way of probing symmetries
- e.g. (chiral) random matrix theory

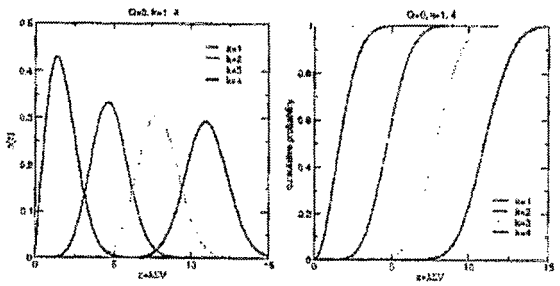
chiral Random Matrix Theory

- Replace QCD partition function by
  - $\int dW \det(D+m) \exp -[N\beta_D/4 \mathrm{Tr}\, V(W^\dagger W)]$
- W n x m matrix: $Q = |n-m|$, $N = n+m$
  - $D = \begin{pmatrix} 0 & iW \\ iW^\dagger & 0 \end{pmatrix}$
- $\beta_D=2$: W_{ij} complex, Unitary Ensemble
- $N\to\infty$: Random number distrib. irrel.

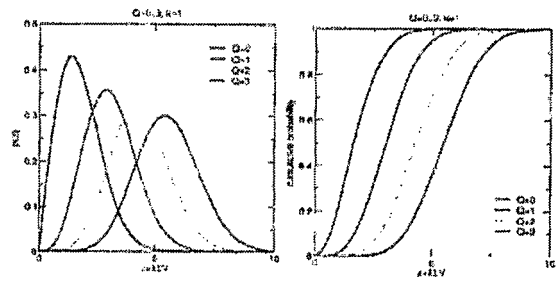
chRMT symmetries

- All continuum symmetries of Dirac op.
  - Axial symmetry $U_A(1)$: $\lambda = 0$ or $\pm$ pairs
  - Exactly $Q = |n-m|$ zero modes
  - Flavour symmetry: $SU(N_f) \times SU(N_f)$
  - Chiral S.B. pattern same as QCD
- Comparing lattice to chRMT tells us how well continuum symmetries are restored

chRMT predictions: Eigenvalues 1 to 4, for Q=0



chRMT predictions: Eigenvalue 1 for Q=0 to 3

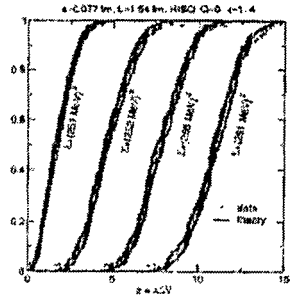


Comparison procedure

- Spectrum has clear zero modes:
  - Remove these from spectrum
- Spectrum has clear quartets
  - Average each quartet
  - Compare quartet averages with chRMT
- In the past: no removal or grouping
  - No dependence on Q: all agree with Q=0

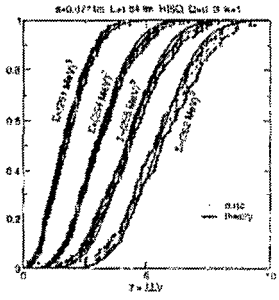
HISQ, a=0.077, Q=0, k=1..4

- agrees well
- no quartet grouping: k'=2..4 lie on top of k=1.
- Only consistent with SU(4) symmetry

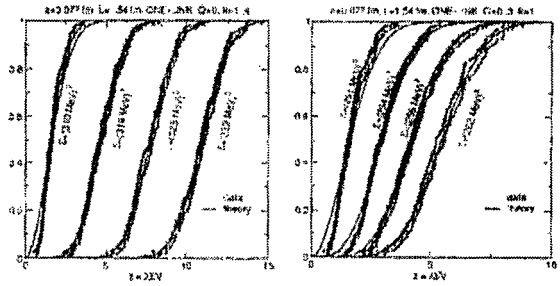


HISQ, a=0.077, Q=0..3, k=1

- Clear dependence on Q
- Axial anomaly well reproduced, implying Dirac index.

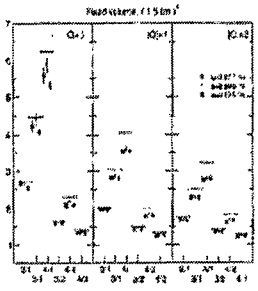


One-link staggered: only OK



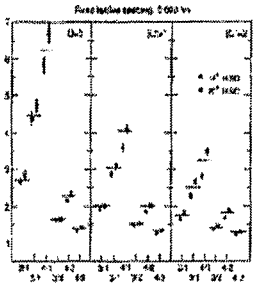
HISQ: various a

- Clear differences between the Q's.
- Small deviations from RMT
- Finite volume effect...



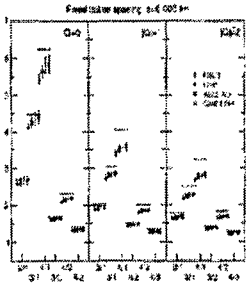
a=0.09 fm: vol. dependence

- L=1.5 fm has finite volume deviations from RMT
- As per overlap (Giusti et al. hep-lat/0309189)



Eigenvalue ratios and action

- All actions give consistent results
- One-link shows largest deviations
- HYP and HISQ very similar
- ASQtad performs well



Conclusions

- ASQtad good, HISQ is better
- Continuum chiral symmetries well restored for a ≤ 0.1 fm, provided...
- We are using improved glue
- Important for understanding reduced flavour sea and valence quarks
- How does HISQ compare to GW ? (Duerr)

First results from Dynamical Domain Wall Fermions

Chris Dawson

To finally make predictions which bear direct relevance to the real world, it is vital that lattice calculations move away from the quenched approximation. Within this approximation, the domain wall fermion formulation of lattice QCD – which preserves both flavour and chiral symmetries at finite lattice spacing – has been extremely successful. In this talk i discuss results from the first large scale simulations using dynamical domain wall fermions. While only including two dynamical relatively heavy flavours of quark, these results are encouraging: the lattice spacing from three different determinations (using the mass of the rho-meson, the string tension, and the pion decay constant). I also show results for the mass of the pseudo-scalar meson, the nucleon mass, and the pion and kaon decay constants. In the latter case we find that NLO chiral perturbation theory does not describe our data, although the reason for this requires further investigation.

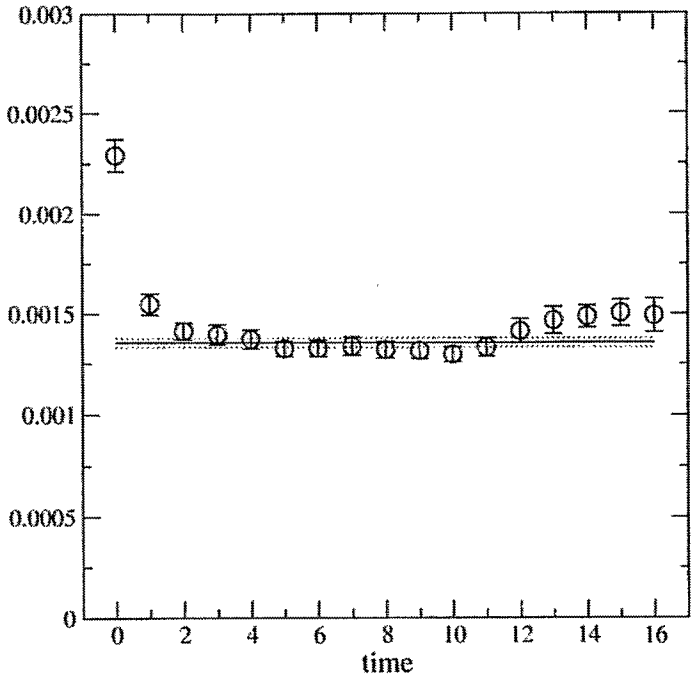
Run Details

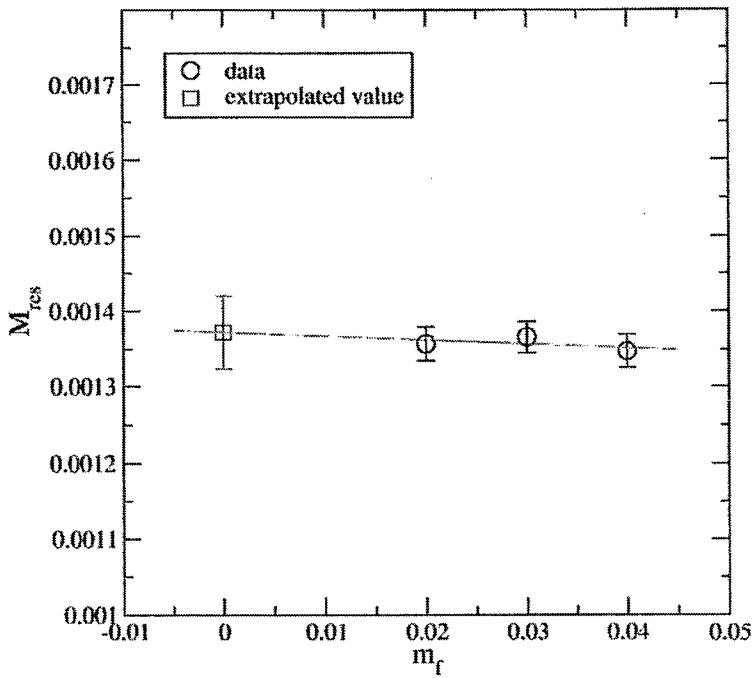
- We are using
  - DBW2 gauge action with $\beta = 0.80$ (Educated guess + hard work : aiming for $a^{-1} \approx 2$GeV).
  - $16^3 \times 32$ lattices
  - Standard domain wall fermion action with $L_s = 12$
  - $N_f = 2$ m Bare dynamical masses of $m_f = 0.02$, 0.03 and 0.04 .

- Lattice are generated using the HMC algorithm. Each trajectory is of length 0.5 in HMC time split up into 50 leapfrog integration steps for mass of 0.02 and 0.03 , and 40 integration steps for 0.04
  Total number of trajectories collected:
  - $am_f = 0.02$ - 5361 trajectories (8 months on 200GF)
  - $am_f = 0.03$ - 6195 trajectories
  - $am_f = 0.04$ - 5605 trajectories

  The acceptance is $\approx 78\%$ for $m_f = 0.02, 0.03$ and 68% for $m_f = 0.04$.

am_{res} results





- Extract am_{res} by averaging between $t = 6$ and 16 .
- Dynamical extrapolation gives $am_{\text{res}} = 0.001372(49)$; a few MeV.

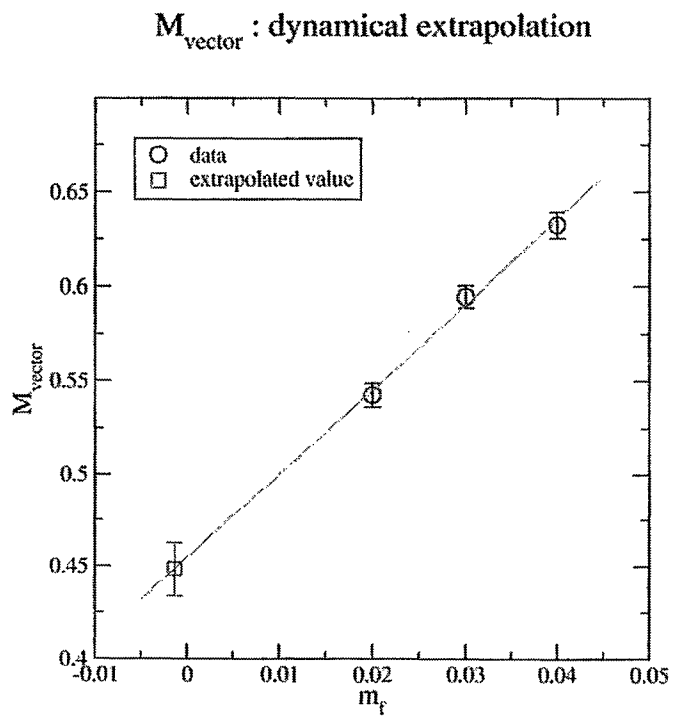
Lattice Scale

- We need to set the lattice spacing using some physical input. We use the rho mass:

$$a_\rho^{-1} = 1.691(53)\ \text{GeV}\,.$$

We could also use the static quark potential (the Sommer scale):

$$a_{r_0}^{-1} = 1.688(21)\ \text{GeV}\,.$$



- We could also have used the Pseudo-scalar decay constant. Taking the scale from the rho mass, a simple linear extrapolation gives:

$$f_\pi = 134.0(42)\ \text{MeV}\,.$$

[Note: NLO fit problematic]

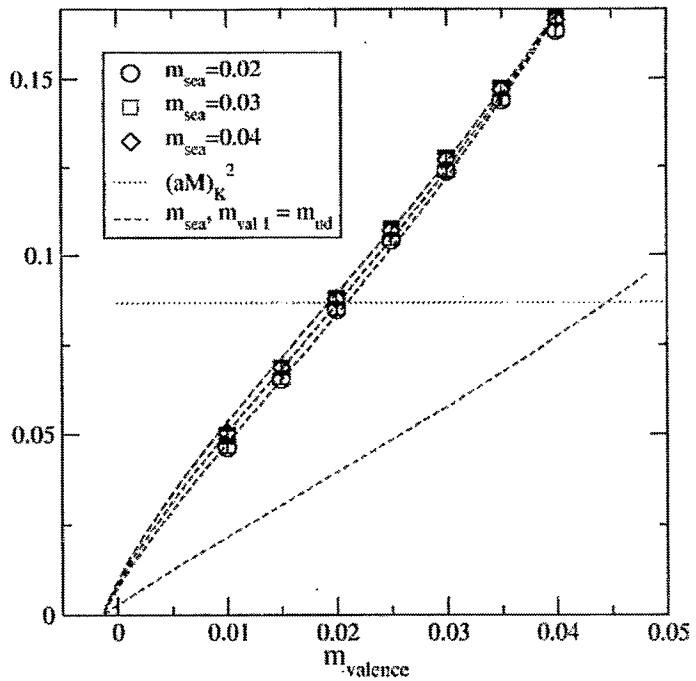
Fixing the strange quark mass : NLO

- At NLO the dynamical mass enters.
- dashed line is limit:

$$am_{\text{valence},1} \equiv am_{\text{sea}} \longrightarrow a\bar{m}$$

plotted versus the second valence quark mass

- This leads to a strange quark mass that is $\approx 10\%$ higher than the leading order fit.



- For a consistancy check, we may take our values for the quark masses and lattice spacing, and use the results for the vector meson to predict the Φ meson mass:

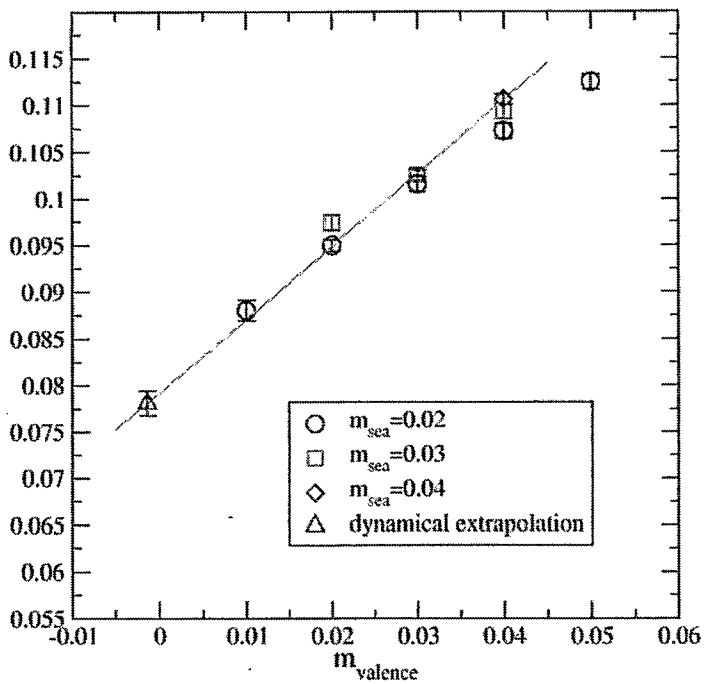
$$M_\Phi = 978(12) \text{ MeV}$$

$\approx 4\%$ off experiment [1020 MeV].

Decay Constant..

What to do:

- could try semi NNLO fit (not enough data)
- drop log term (this is what we did)
- use lighter masses/more data (next machine)



- Results:
  - $f_\pi = 134.0(42)$ MeV [130.7]
  - $f_K = 157.4(38)$ MeV [160]

Excited Nucleons.

Chris Maynard
UKQCD

Nstars and Lattice QCD

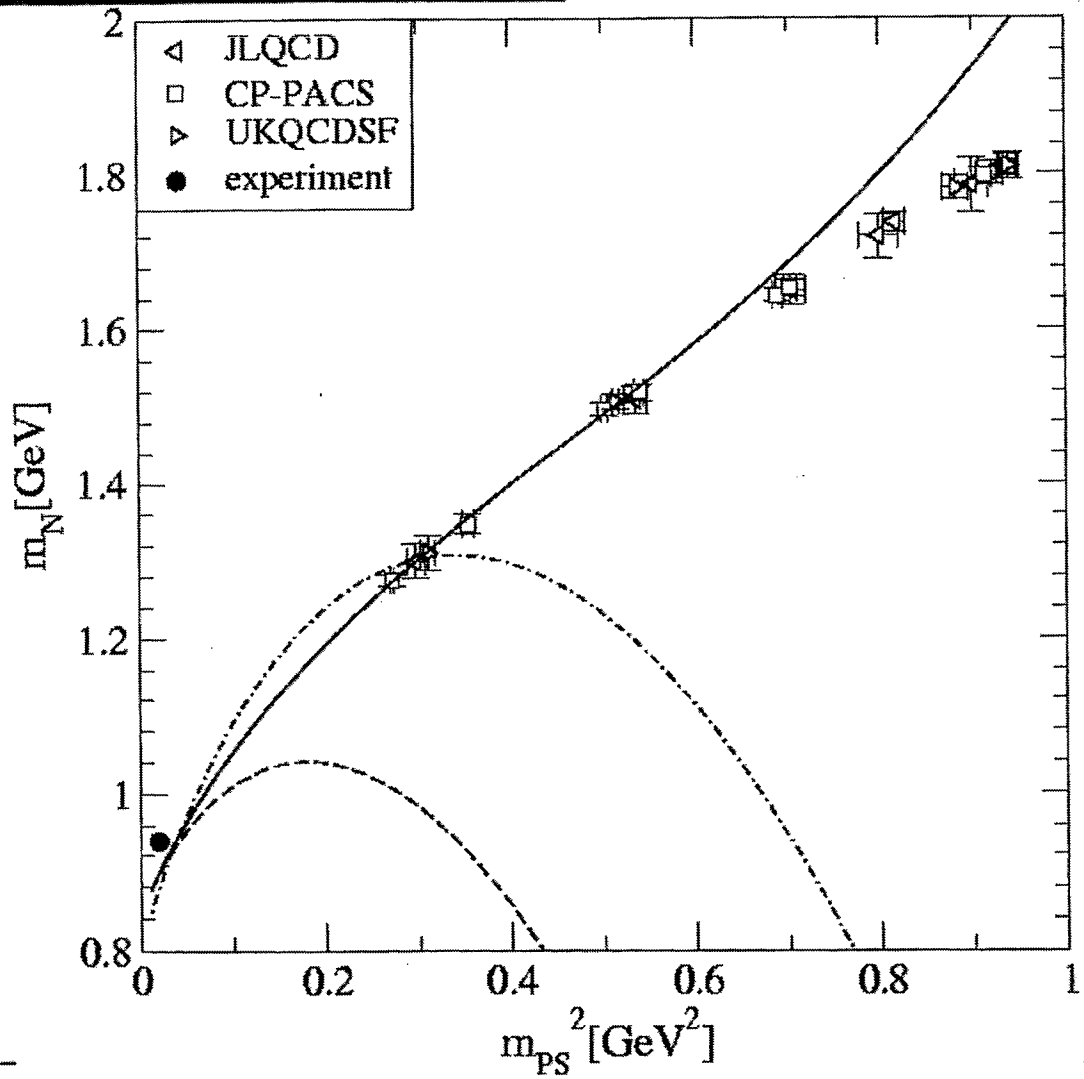
- Lattice QCD can resolve some old questions
  - Nature of some excited states
    - Roper resonance N*(1440)
    - Does not fit *naturally* into quark model
- Computationally hard
  - Noisy → large ensembles
  - Large objects → large volumes
  - Quantitative → continuum and chiral limits

Chiral behaviour

QCDSF

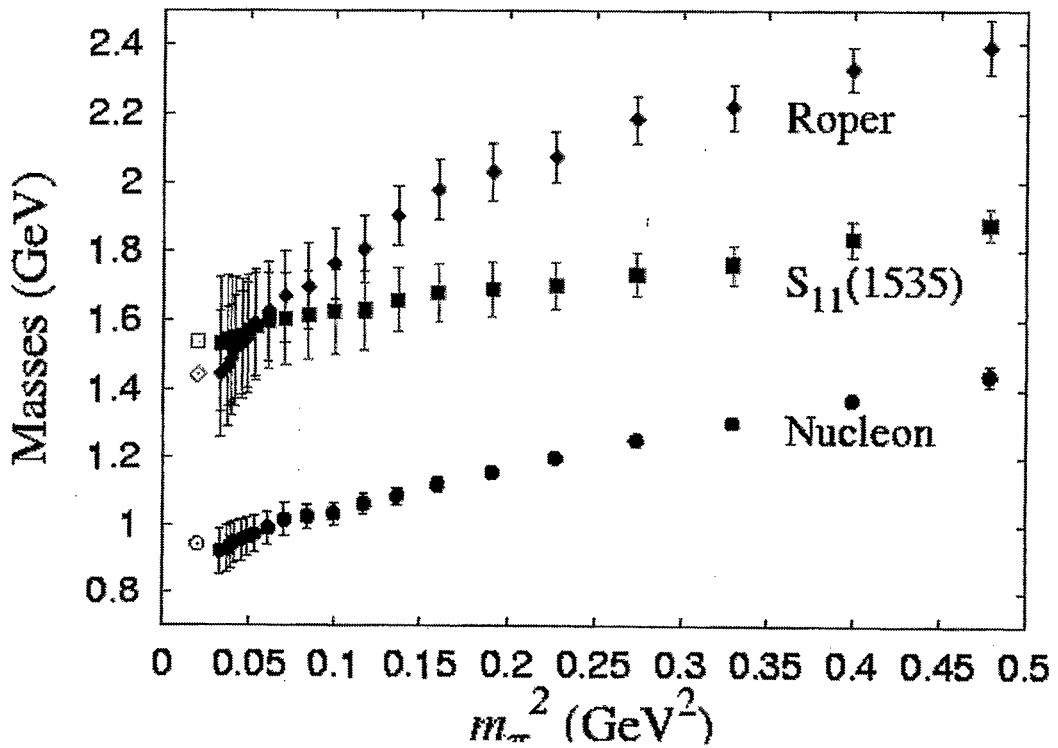
Hep-lap/0309133

How far out can trust chiral perturbation theory?



Quenched Overlap

Dong *et al* hep-lat/0306199



Kentucky Group. See N* cross over. Is mixing with Quenched ghost state really under control?

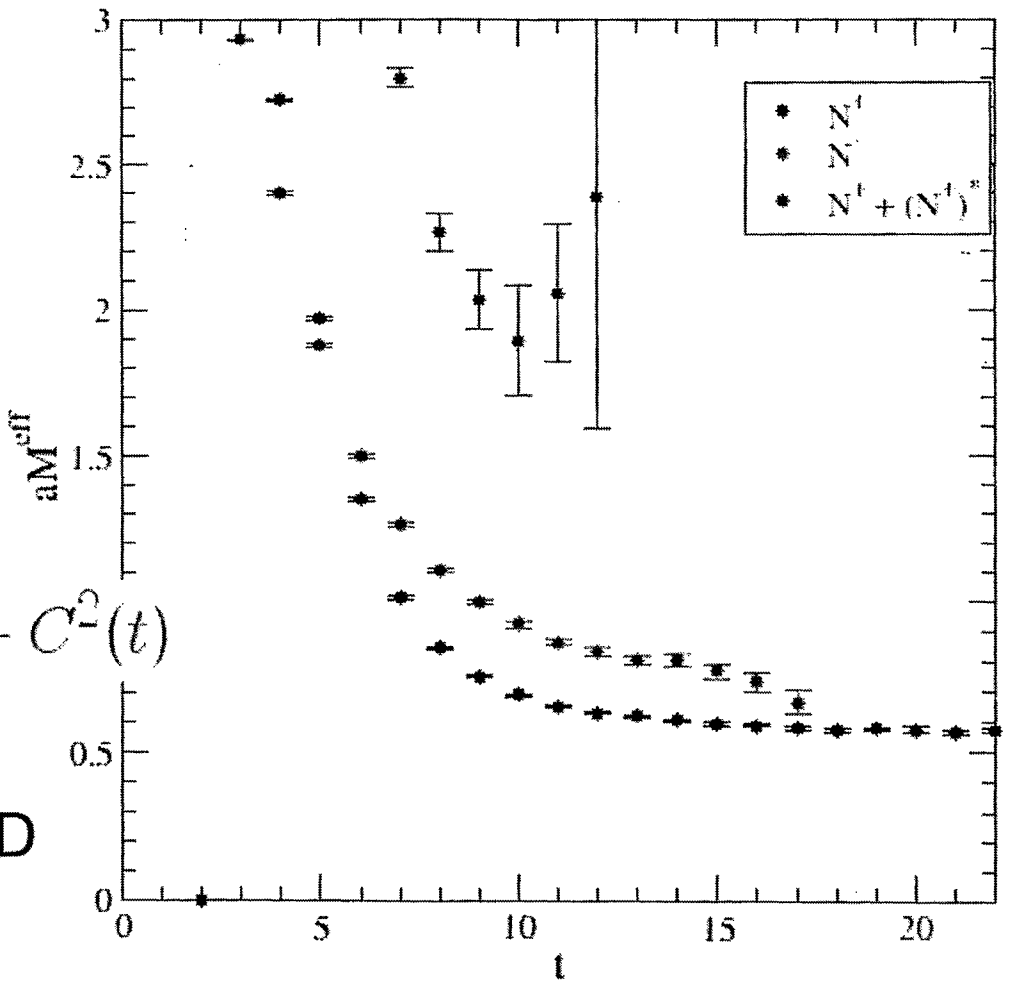
Excited states - Methodology

- Many calculations
  - Folk in this room
- Bayesian techniques
  - Constrained fitting, MEM
- D. Guadagnoli *et al* hep-lat/0409011

$$\hat{C}(t) \equiv C(t+1)C(t-1) - C^2(t)$$

$$\hat{C}(t) = Z_+^2 e^{-(M_+ + M_+^*)t}$$

Effective mass on UKQCD Quenched data



Pentaquark from Lattice QCD

Takumi Doi (RBRC)

In the calculation of pentaquark(5Q) from lattice QCD, the separation of 5Q from NK state has been a difficult issue. In this talk, we propose the new method imposing hybrid boundary condition (HBC), which artificially raise the energy of NK states without affecting 5Q states. The results with HBC shows that the negative-parity state on the lattice is not 5Q state but a NK state.

The Discovery of Θ^+

- B = +1, S= +1 → definitely exotic ($uudd\bar{s}$)
- M ~1540 MeV, Γ < ~10 MeV
- Confirmed by many experiments
  (Parity and spin are not known yet)
- Negative experiments also exist

→ Real need for Lattice QCD

- *Does exotic Θ^+ really exist ?*
- *If exists, what is the quantum number ?*
- *Any other exotics ?*

The difficulty: Separation Θ^+ from NK state

- **Lattice QCD can extract only ground state**
- **Volume dependence is helpful**

Θ^+ (exp):	1540MeV
N+K:	1440MeV

  - **Positive Parity channel**

    ➔ NK state is **P-wave** with discretized momentum

$$E(NK) \simeq \sqrt{m_K^2 + p^2} + \sqrt{m_K^2 + p^2}, \quad (\vec{p} = 2\pi\vec{n}/L)$$

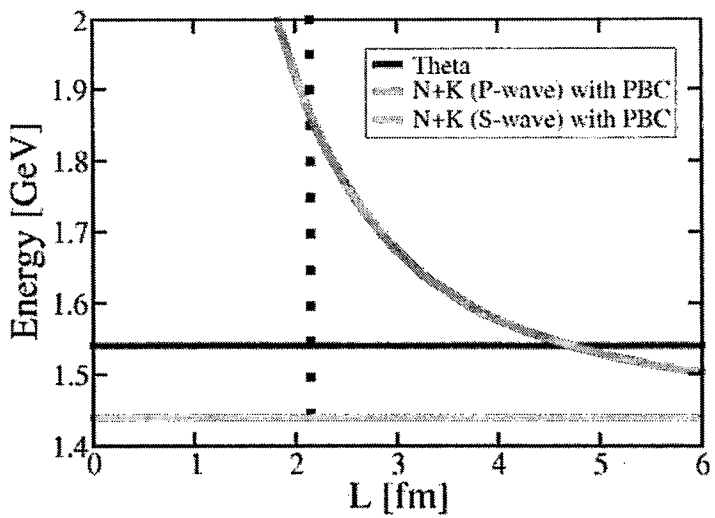
$$\rightarrow E(\Theta^+) < E(NK)$$

  - **Negative Parity channel**

    ➔ **No such advantage**

    (NK state is **S-wave**)

    ➔ ***difficulty still remains***

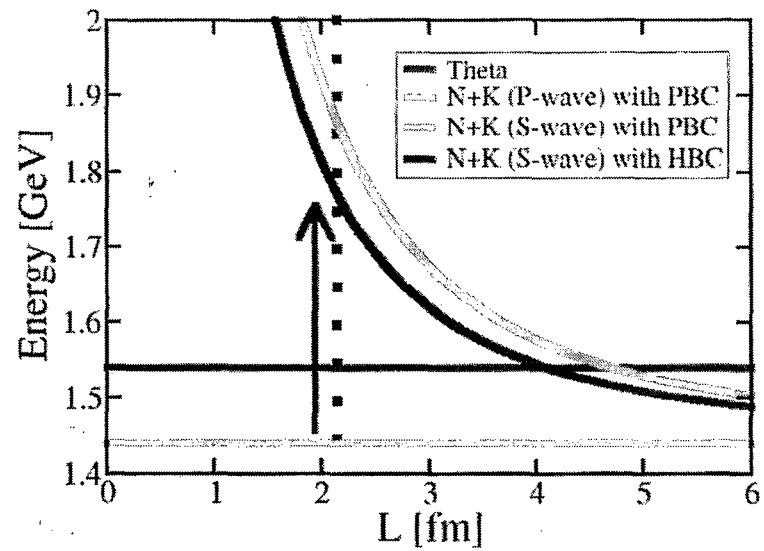


New method to separate Θ+ from NK

- **Hybrid Boundary Condition (HBC)**
  - **Effective even when negative parity channel**

Hybrid Boundary Condition

u quark	spatially **anti-periodic BC**
d quark	spatially **anti-periodic BC**
s quark	spatially **periodic BC**



N	uud, udd	**anti-periodic BC**
K	$u\bar{s}$, $d\bar{s}$	**anti-periodic BC**
Θ+	$uudd\bar{s}$	**periodic BC**

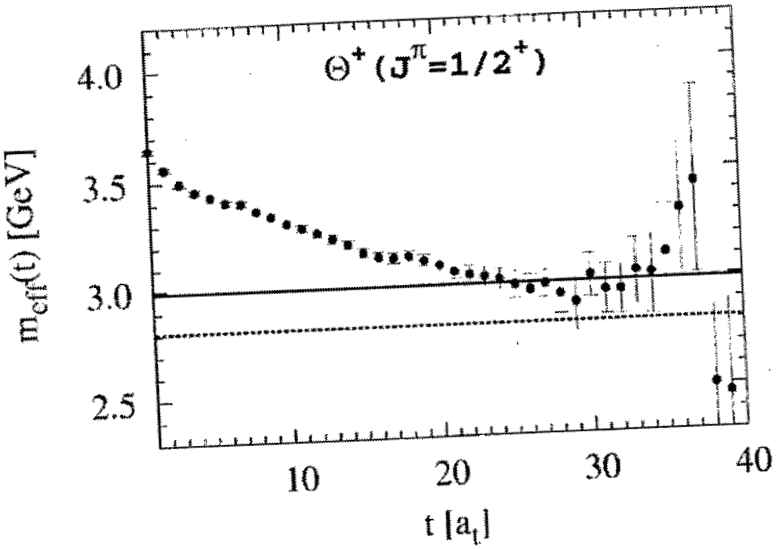
$$\Rightarrow \vec{p}_{min} = \pi\vec{n}/L$$

$$\Rightarrow \vec{p}_{min} = \pi\vec{n}/L$$

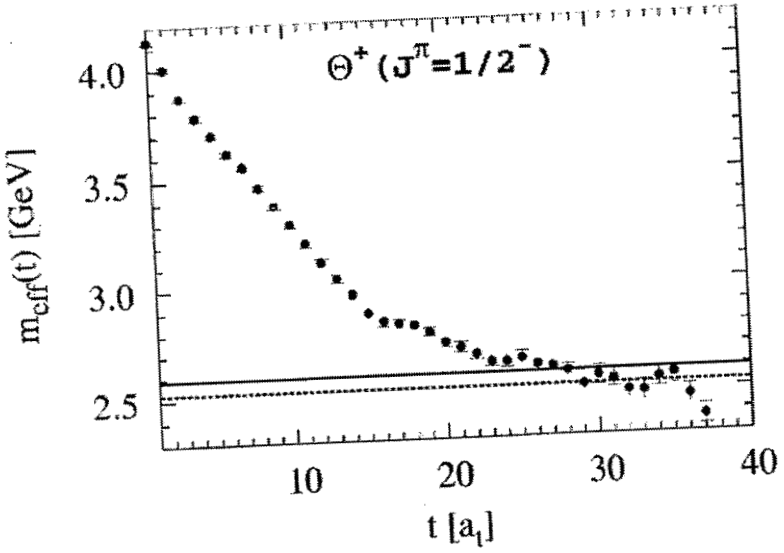
$$\Rightarrow \vec{p}_{min} = \vec{0}$$

The Results of Effective mass for each parity

Positive parity



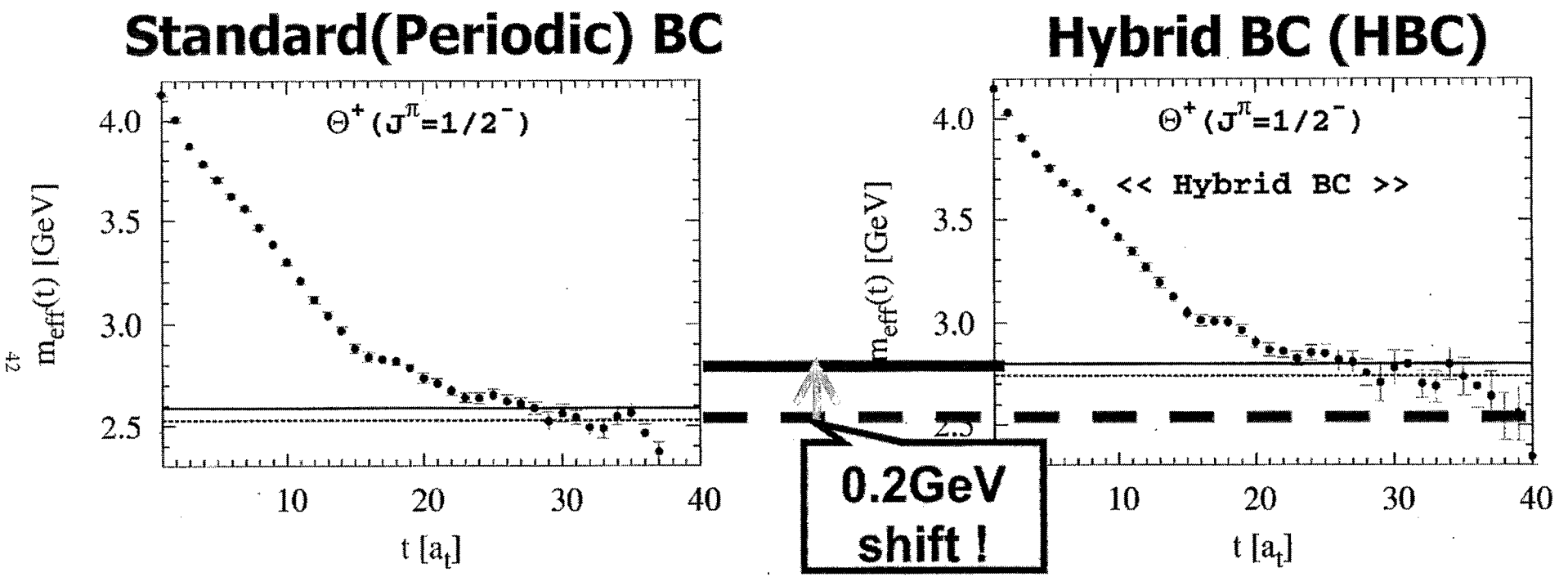
Negative parity



- Low-lying state is negative parity.
- Positive parity is too massive for Θ^+.

➔ *Is the plateau in negative parity Θ^+ or N+K ?*

The Results from HBC



The plateau shifts as much as the NK state shifts.

※Such shift will not occur if the plateau is Θ^+※

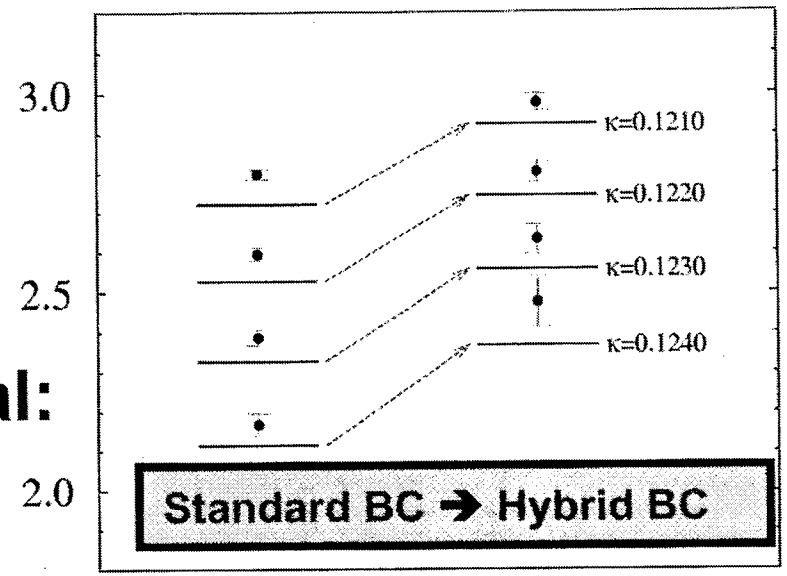
Conclusions

◎ The observed plateau is a NK scattering state from the analysis of energy shift.

◎ We do not see signal for pentaquark state in the interval:

$$m_N + m_K \leq m(\Theta^+) \leq \sqrt{m_N^2 + \vec{p}_{min}^2} + \sqrt{m_K^2 + \vec{p}_{min}^2}$$

Shift for each quark mass



N.Ishii, T.Doi, H.Iida, M.Oka, F.Okiharu, H.Suganuma, **hep-lat/0408030**

Future:
Other operator/other quantum number etc.
Light quark mass/Full QCD → DWF@QCDOC
Multi-quark state physics, Other exotics

Nucleon structure with domain wall fermions

Shigemi Ohta*
and
Kostas Orginos†

Abstract

RBC calculations of the ratio of the isovector axial and vector charges, g_A/g_V, and the moments of structure functions $\langle x\rangle_q$, $\langle x\rangle_{\Delta u-\Delta d}$, and $\langle 1\rangle_{\delta q}$ with domain wall fermions (DWF) quark and DBW2 gauge actions are described. Those on the 1.3 GeV cutoff quenched lattices are complete with non perturbative renormalization (NPR): all the quantities show only mild linear dependence on quark mass. The dynamical results with two degenerate dynamical quark flavors from 1.7 GeV cutoff lattices are without NPR while the axial charge result is naturally renormalized and in agreement with the quenched results.

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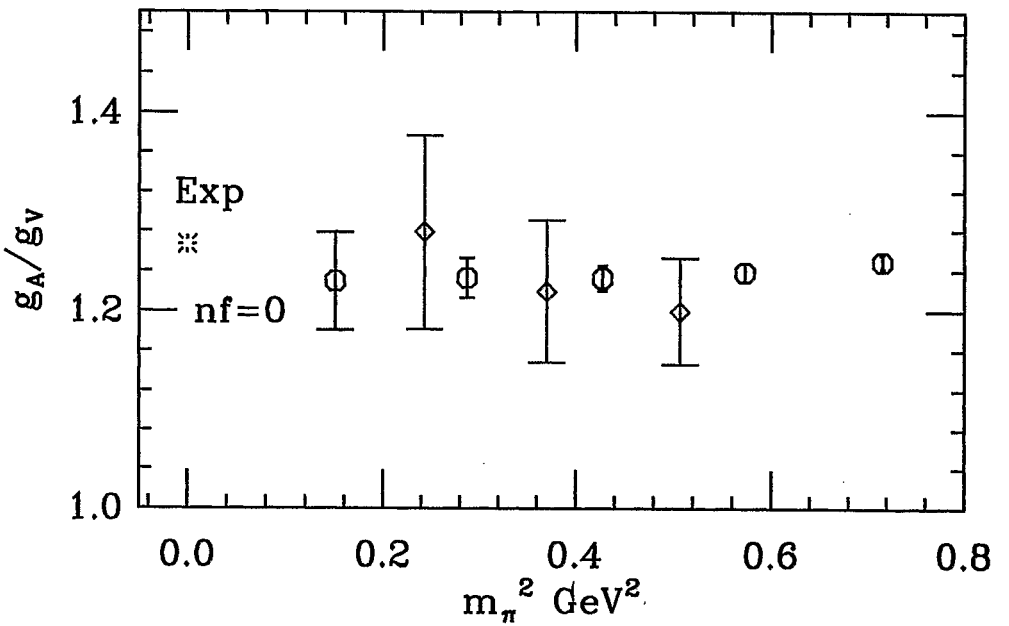
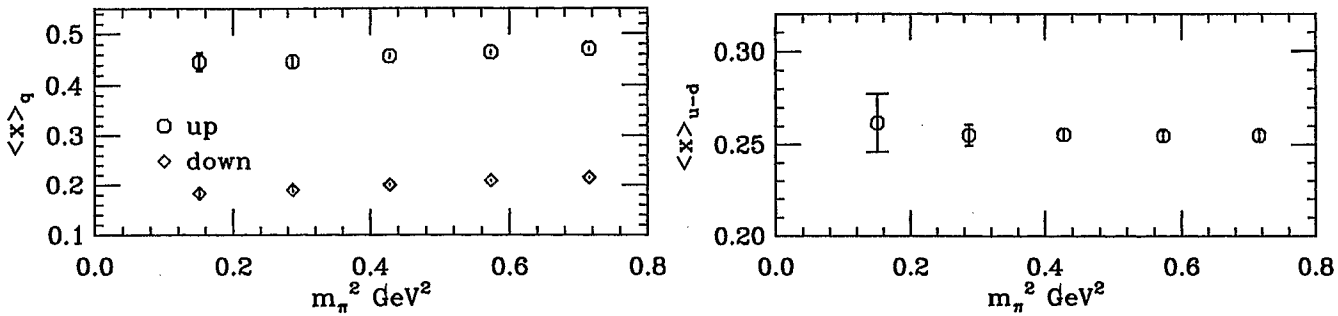
New, this year, of axial charge: dynamical result seems to follow the quenched [6].



[6]Note the lattice scales obtained from m_ρ and Sommer scale agree, with $a^{-1} \sim 1.7$ GeV.

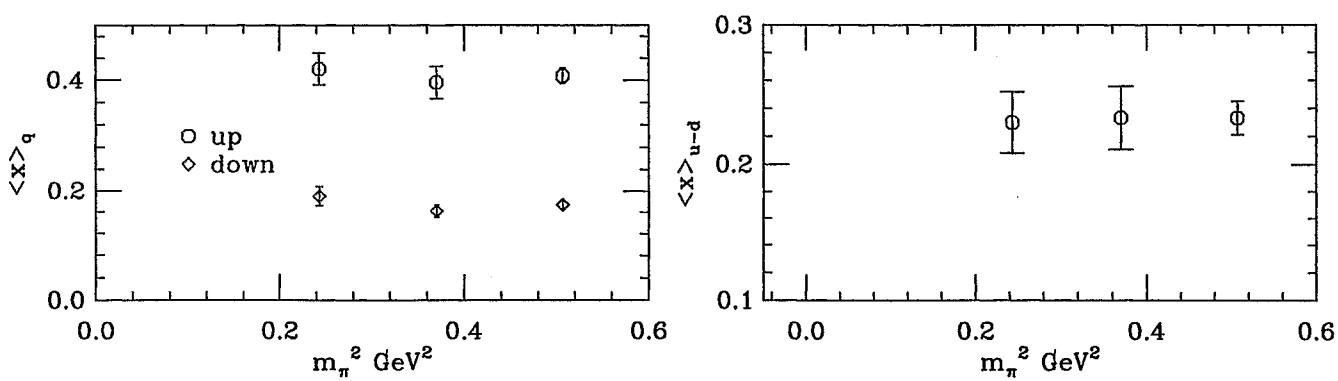
Quark density $\langle x \rangle_{u-d}$, calculated with $\mathcal{O}^q_{44} = \bar{q}\left[\gamma_4 \overleftrightarrow{D}_4 - \frac{1}{3}\sum_{k=1}^{3} \gamma_k \overleftrightarrow{D}_k\right] q$.

- Quenched calculation complete with NPR,



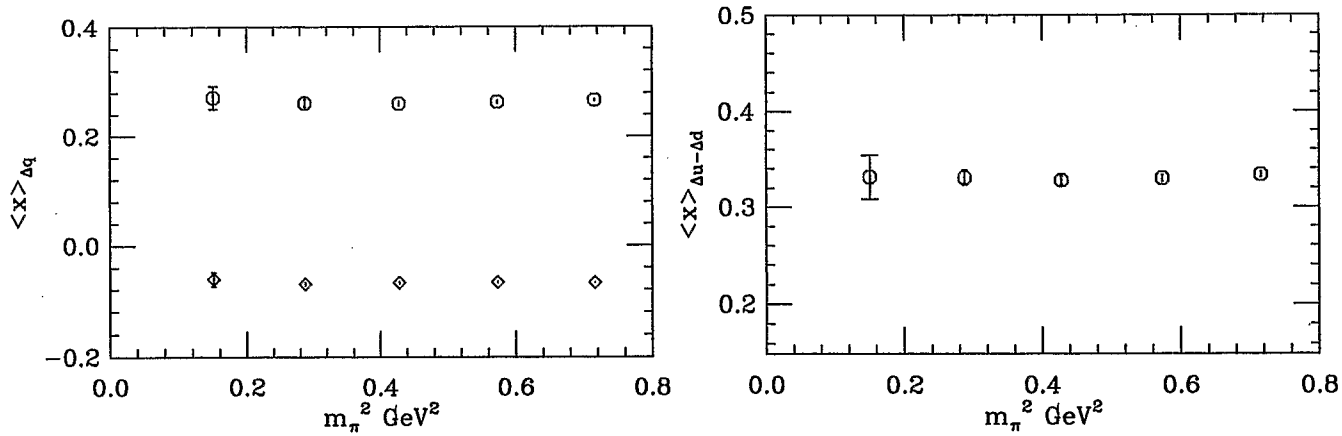
  - $Z = 1.02(10)$, with $\overline{\text{MS}}$ 2 GeV, 2-loop running,
  - no curvature seen in the chiral limit,
  - $\langle x \rangle_u / \langle x \rangle_d = 2.41(4)$ at the chiral limit.

- Dynamical calculation ongoing, lacks NPR,



Polarization, $\langle x \rangle_{\Delta u - \Delta d}$, calculated with $\mathcal{O}_{34}^{5q} = \frac{1}{4}\bar{q}\gamma_5 \left[\gamma_3 \overleftrightarrow{D}_4 + \gamma_4 \overleftrightarrow{D}_3\right] q$.

- Quenched calculation complete with NPR,

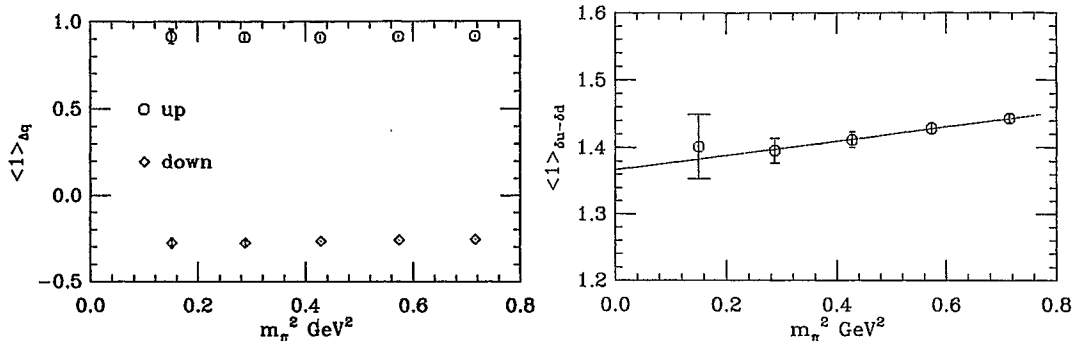


  - $Z = 1.02(9)$, with $\overline{\text{MS}}$ 2 GeV, 2-loop running,
  - no curvature seen in the chiral limit.

- Dynamical calculation ongoing.

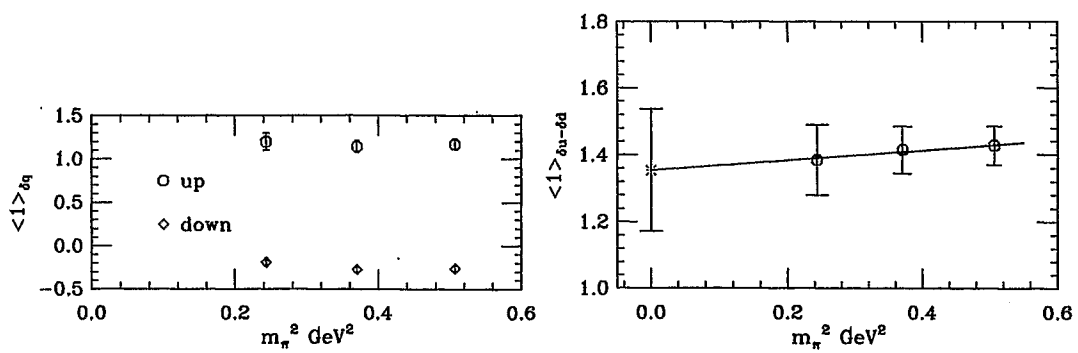
Transversity, $\langle 1 \rangle_{\delta u - \delta d}$, calculated with $\mathcal{O}_{34}^{\sigma q} = \bar{q}\gamma_5\sigma_{34}q$.

- Quenched calculation complete with NPR,



  - $\langle 1 \rangle_{\delta u - \delta d} = 1.193(30)$, $\overline{\text{MS}}$ (2 GeV) 2-loop running,
  - QCDSF (quenched continuum): $\langle 1 \rangle_{\delta u - \delta d} = 1.214(40)$, $\overline{\text{MS}}$ (1 GeV) 1-loop perturbative.

- Dynamical calculation ongoing, lacks NPR,



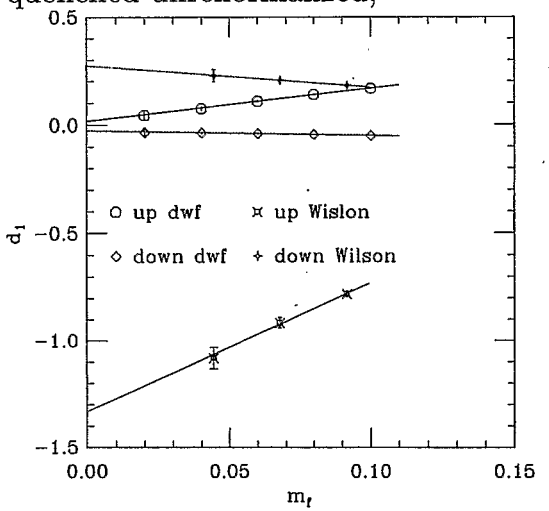
d_1: twist-3 part of g_2 ($\langle x\rangle_{\Delta q}$ is twist-2),

$$2\int_0^1 dx x^n g_2(x,Q^2) = \frac{1}{2}\frac{n}{n+1}\sum_{q=u,d}\left[e^q_{2,n}(\mu^2/Q^2, g(\mu))\, d^q_n(\mu) - 2e^q_{1,n}(\mu^2/Q^2, g(\mu))\,\langle x^n\rangle_{\Delta q}(\mu)\right],$$

calculated with $\mathcal{O}^{[5]q}_{[\sigma\mu_1]\mu_2\cdots\mu_n} = \bar{q}\left[\left(\frac{i}{2}\right)^n \gamma_5\gamma_{[\sigma}\overleftrightarrow{D}_{\mu_1]}\cdots\overleftrightarrow{D}_{\mu_n} - \text{traces}\right] q.$

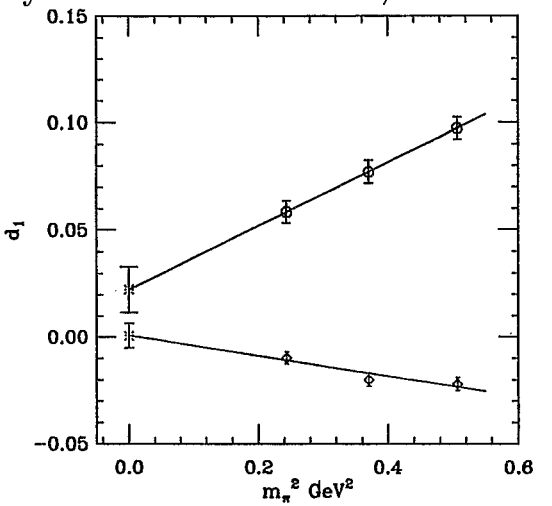
- negligible in Wandzura-Wilczek relation, $g_2(x) = -g_1(x) + \int_x^1 \frac{dy}{y} g_1(y)$,
- but need not be small in a confining theory (Jaffe and Ji, Phys. Rev. D43, 91),

quenched unrenormalized,



- small in the chiral limit (no power divergent mixing),
- disagree with Wilson fermion results (which suffer from power divergent mixing)?

dynamical unrenormalized,



- small in the chiral limit.

Abstract:
We present preliminary results for nucleon dipole moments computed with domain wall fermions. Our main target is the electric dipole moment of the neutron arising from the θ term in the gauge part of the QCD lagrangian. The calculated magnetic dipole moments of the proton and neutron are in rough accord with experimental values.

Lattice calculation of the Neutron Electric Dipole Moment

(hep-lat/0411003)

F. Berruto, T. Blum*, K. Orginos, A. Soni

November 12, 2004

*Presenter

Introduction

T and P-odd term (violates CP!) allowed in QCD Lagrangian: θ term which gives rise to neutron electric dipole moment, d_N

$$S_{QCD,\theta} = i\theta \int d^4x \, \frac{g^2}{32\pi^2} \mathrm{tr}\left[G(x)\tilde{G}(x)\right] = i\theta Q. \qquad (1)$$

where Q is the topological charge of the QCD vacuum.

Weak interactions: CKM mechanism: $d_N \leq 10^{-30}\, e$-cm (vanishes at one-loop), many orders of magnitude below the experimental bound [1], $|\vec{d}_N| < 6.3 \times 10^{-26}\, e$-cm.

Computational strategy

Two important elements:

(1) Compute the matrix elements of the electromagnetic current between nucleon states, $\langle p', s|J^\mu|p, s\rangle_\theta = \bar{u}(p', s)\Gamma_\mu(q^2)u(p, s)$, where

$$\begin{aligned}\Gamma_\mu(q^2) &= \gamma_\mu F_1(q^2) + i\,\sigma_{\mu\nu}q^\nu \frac{F_2(q^2)}{2m} \\ &\quad + \left(\gamma_\mu \gamma_5 q^2 - 2m\gamma_5 q_\mu\right) F_A(q^2) \\ &\quad + \sigma_{\mu\nu}q^\nu \gamma_5 \frac{F_3(q^2)}{2m},\end{aligned} \tag{3}$$

and use projectors to obtain linear combinations of F_1 and F_2,

Numerical Results

In Table 1 we summarize results for the ratios of neutron and proton magnetic to proton electric form factors which become the dipole moment in question in the limit $q^2 \to 0$.

Computed on 280 $N_f = 2$, $m_{sea} = 0.02$, domain wall fermion configurations (separated by 10-15 trajectories) with $m_{val} = 0.04$ and 0.08 [10].

Lattice: $16^3 \times 32$, $L_s = 12$, and the inverse lattice spacing in the $m_{sea} = 0$ limit is $a^{-1} \approx 1.7$ GeV.

We have averaged over time slices 14-17 and (equivalent) permutations of the momenta $\vec{p} = (1,0,0)$, (1,1,0), and (1,1,1).

Approximating the $q^2 \to 0$ value of each with the smallest value of $\vec{p}^2$ $(= (2\pi/16)^2)$, taking $m_f = 0.04$ as the physical value of the light quark mass, and $aM_N = aM_P = 0.8989(77)$ at this quark mass, we obtain

$$\begin{aligned} a_\mu^P &\approx 1.45(10) \\ a_\mu^N &\approx -1.50(7) \\ d_N/(e\,a\,\theta) &\approx -0.06(15). \end{aligned}$$

Considering the crude extrapolations just described, these are roughly consistent with the experimental values $a_\mu^P = 1.79$ and $a_\mu^N = -1.91$ (and of course $d_N \sim 0$).The error estimates are statistical uncertainties only.

In physical units, $d_N = -7.4(18.0) \times 10^{-16}\,\theta\,e$-cm, consistent with the model calculations mentioned above.

Outlook

In the near future, we will strive to reduce the statistical error on our determination of d_N which has already yielded an interesting first-principles bound on the magnitude of d_N.

Do this by measuring d_N on all available $N_f = 2$ lattices ($\sim 1000/m_{sea}$) and measuring more than once on each lattice.

We have begun new calculations with *smeared sources*.

Compute the m_{sea} dependence as well.

Compute electromagnetic effects in the magnetic dipole moments.

Nucleon Decay Matrix Elements on the Lattice

Robert Tweedie
University of Edinburgh

The motivation for calculating nucleon decay matrix elements on the lattice is discussed and in particular their role in GUT and SUSY GUT models. The form of the nucleon decay matrix elements is discussed. A recent code check calculation is presented and there is some discussion of code available for future calculations of these matrix elements. Finally there is discussion of a possible future calculation of these matrix elements using two-point functions and a mixed action where the sea and valence quark actions are not the same.

Motivation

Many BSMMs predict nucleon decay

- GUTs, SUSY GUTs

Hadronic matrix element dominates theoretical uncertainty in decay lifetime

- Accurate knowledge of HME can discriminate between models

Most previous lattice calculations are quenched

To progress from qualitative to quantitative calculations requires light dynamical sea quarks

- Continuum limit, large volume, chiral limit
- Computationally challenging

Matrix Elements for Nucleon Decay

- Chiral lagrangian approach in the soft pion limit allows all decays of the form $(p/n \to \bar{l} + PS)$ to be related to the matrix element of just two local operators:

$$\langle 0 | (O^{\not{B}}_{R;L}) | p; \vec{k} = 0 \rangle \equiv \alpha \; P_L u_p$$

$$\langle 0 | (O^{\not{B}}_{L;L}) | p; \vec{k} = 0 \rangle \equiv \beta \; P_L u_p$$

- where $O^{\not{B}}_{R/L;L} = \varepsilon^{ijk} (u^{iT} C P_{R/L} d^j) P_L u^k$

Matrix Elements

- Can calculate matrix elements as ratios of three to two point functions or as ratios of two point functions
- Code exists in chroma for calculating the two-point functions
  - has been verified by comparison with a JLQCD calculation
  - some additional smearing code may be required
    - e.g. Boyling…
- Code also exists in chroma for three point functions

Mixing and Chiral Symmetry

- Chiral symmetry breaking in the Wilson quark action causes mixing between operators
- Mixing structures under perturbative renormalisation up to one-loop level looks like

$$O^{cont}_{RL/LL}(\mu) = Z(\alpha_s, \mu a) O^{latt}_{RL/LL}(a) + \frac{\alpha_s}{4\pi} Z_{mix} O^{latt}_{LL/RL}(a) \mp \frac{\alpha_s}{4\pi} Z'_{mix} O^{latt}_{\gamma_\mu L}(a)$$

- This requires the evaluation of additional matrix elements which may not be small $O_{\gamma_\mu;L} = \varepsilon^{ijk} (u^{iT} C \gamma_\mu \gamma_5 d^j) P_L \gamma_\mu u^k$
- and the evaluation of several different mixing coefficients

Mixed Action Calculations

- Can do calculations with light dynamical improved staggered sea quarks and overlap valence quarks
  - Advantage: overlap valence quarks have correct chiral/flavour symmetries (simplify operator mixing)
  - Advantage: quarks in the sea are light and computationally relatively cheap to produce (important for chiral and continuum limit)
  - Advantage: get a remarkably good signal on low number of configurations
  - Disadvantage: we have a mixed action - not clear how to match sea and valence quark masses
    - Now have a prescription (See C. Maynard's talk!)
- Aim would be be to calculate nucleon matrix elements with two-point functions

Nucleon Decay on the Lattice with Domain Wall Fermions

Shigemi Ohta*

Abstract

RBC calculations of the nucleon decay matrix element with domain wall fermion (DWF) quark and DBW2 gauge actions are described. These calculations are driven by Yasumichi Aoki who is now in Wuppertal. Both direct and indirect calculations have been carried out on quenched 1.3 GeV cutoff lattices, complete with non-perturbative renormalization (NPR). The two methods disagrees. Indirect method calculations have been carried out on two-flavor dynamical DWF 1.7 GeV cutoff lattices leads to the same chiral limit as in the quenched calculations. Dyn.amical calculations with the direct method are well under way

*Inst. Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki 305-0801, Japan and RIKEN BNL Research Center, Upton, NY 11973, USA

Issues:

- direct method is about 10 times more expensive,
- indirect and direct results disagree (Gavela et al (1989)),
- |indirect| = |direct|+ $\sim$ 50 % (JLQCD (2000)).

Direct method:

$$\langle \pi^0 | i\epsilon_{ijk}(u^{iT} C P_{L/R} d^j) P_L u^k | p \rangle = P_L[W_0(q^2) - W_q(q^2) i(\gamma q)] u_p,$$

where q is the momentum transfer of $p \to \pi^0$.

- as $i(\gamma q)v_e \sim m_e v_e$ is negligible, we need to extract W_0,
- yet the mixing of W_q is inevitable because we also need to project to positive parity proton,

$$\mathrm{tr}\left(P_L[W_0 - W_q i(\gamma q)]\frac{1+\gamma_4}{2}\right) = W_0 - iq_4 W_q,$$

- we go around this by injecting finite momentum (JLQCD, PRD 62, 014506 (2000)),

$$\mathrm{tr}\left(P_L[W_0 - W_q i(\gamma q)]\frac{1+\gamma_4}{2} i\gamma_j\right) = q_j W_q.$$

Slightly different sequential propagators are used.

Remaining problems:

- chiral symmetry,
  - previous studies used Wilson fermions which explicitly break chiral symmetry,

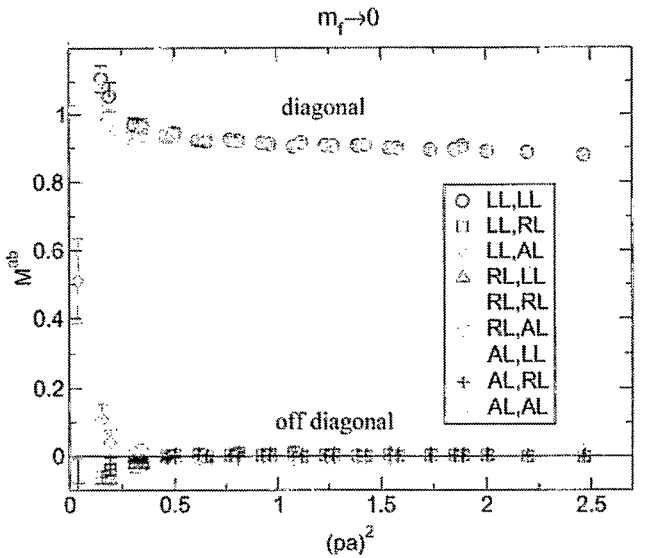
$$O_{RL}^{\text{cont}} = ZO_{RL}^{\text{latt}} + Z_{\text{mix}}O_{LL}^{\text{latt}} + Z'_{\text{mix}}O_{\gamma_\mu L}^{\text{latt}}$$

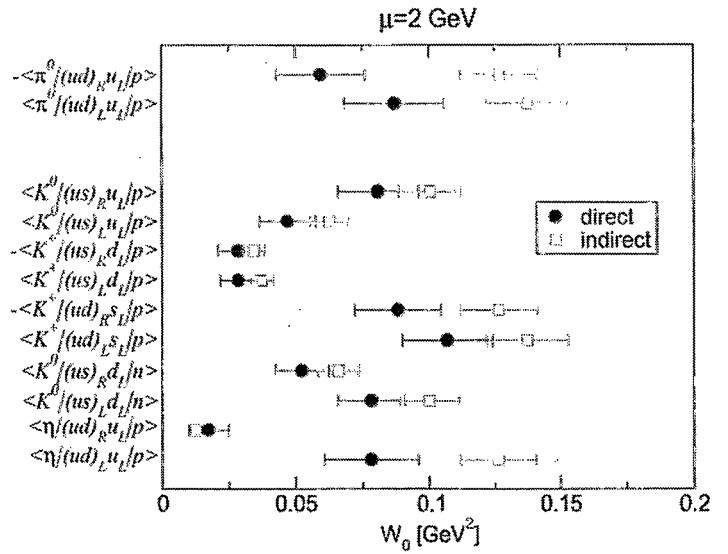
  - so the results need not match the chiral perturbation,
  - with DWF better chiral symmetry, the indirect method may work.
- $\mathcal{O}(a)$ scaling violation,
- quenched approximation.

DWF:

- good chiral symmetry, $O_{RL}^{\text{cont}} = ZO_{RL}^{\text{latt}}$,
  - should match the chiral perturbation at finite a,
  - if the low-energy coefficients are calculated on the lattice,
  - note f_π and g_A $(=D+F)$ are consistent with experiment within a few % even at finite a,
- scaling violation starts at $\mathcal{O}(a^2)$,

Renormalization: NPR works well, one-loop matching from MOM to $\overline{\text{MS}}$(NDR), two-loop running to 2 GeV.

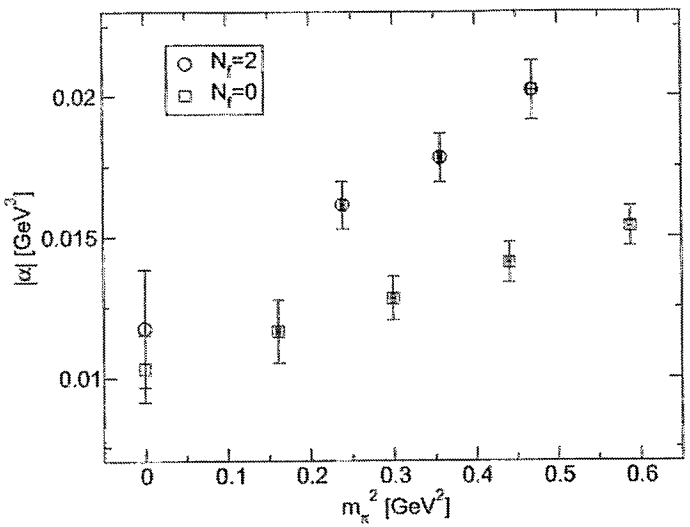




Quenched results: the direct and indirect methods disagree with each other. We have to

- follow through the direct method, or
- work out higher order chiral pertubation.

Quenching error: estimated in the indirect method, appear small from $\frac{1}{2}m_s \leq m_{\rm sea} \leq m_s$.



The dynamical result shows stronger dependence on m_π, but the extrapolation to the chiral limit is consistent with that of the quenched within ~ 20 % error.

Summary of the low energy parameter of nucleon decay at the renormalization scale $\mu = 2$ GeV. Quoted errors for DWF are statistical only. $\alpha + \beta = 0$ within the error.

Fermion	Wilson[a]	DWF	
N_f	0	0	2
a [fm]	0	0.15	0.12
$\lvert\alpha\rvert$ [GeV^3]	$0.0090(09)(^{+5}_{-19})$	0.010(1)	0.012(2)
$\lvert\beta\rvert$ [GeV^3]	$0.0096(09)(^{+6}_{-20})$	0.011(1)	0.012(2)

[a] Tsutsui *et al.*, [CP-PACS Collaboration], arXiv:hep-lat/0402026.

Need to explore much lighter quark mass with dynamical flavors. The direct method is favored.

New, this year, are

- quenched calculation complete with NPR, in favor of the direct method,
- dynamical calculations well under way (essentially done.)

Immediate future

- Publish quenched results.
- Complete dynamical calculations (QCDSP/QCDOC).
- Explore lighter quark mass and (2+1)-flavor dynamical (QCDOC).
- Turn on observables with finite momentum: some form factors, e.g. F_1, F_2, g_P and electric dipole and higher moments of the structure functions.

Testing 5D Chiral Operators

R. G. Edwards, B. Joó, A. D. Kennedy, K. Orginos, U. Wenger

November 13, 2004

In this talk we have demonstrated that all current 5D Chiral Operators are different representations of the Overlap operator. The Overlap Operator in with zero mass, satisfies the Ginsparg-Wilson relation, which guarantees a lattice version of chiral symmetry at non-zero lattice spacing. Unfortunately a numerical implementation of the Overlap operator: $D = \frac{1}{2}(1 + \mu + (1 - \mu)\gamma_5 \mathrm{sgn}(\mathrm{H}))$ for some bare quark mass μ and kernel H incurs the application of the matrix sign function of the kernel. This has to be approximated in some way. All current 5D chiral operators approximate $\mathrm{sgn}(\mathrm{H})$ with a rational approximation.

The rational approximation is commonly represented in three ways: partial fraction form, Cayley transformed form and continued fraction form. These three different representations result in different styles of 5D operator: the partial fraction form results in Neuberger and Narayanan's "Alternative to Domain Wall" operator and the Truncated Overlap operator of Boriçi. The Cayley transformed representation results in the traditional Domain Wall operators due to Shamir, Boriçi and in the Möbius operator of Brower, Orginos and Neff. The continued fraction representation results in the Continued Fration operator of Kennedy, Pendleton and Wenger.

Apart from the represantation, one has the choice of rational approximation which determines the coefficients of the 5D operator and the Overlap kernel which determines the discretisation effects in the operator. The most common approximations are the tanh representation of Higham (also known as the Polar Approximation of Neuberger) and the Optimal Rational approximation whose coefficients are known in closed form in terms of Elliptic functions due to Zolotarev. The Zolotarev approximation is optimal in the minimax sense over a given approximation range. The tanh approximation is nonuniform. The usual Domain Wall operators make use of the tanh approximation, whereas the Zolotarev approximation is commonly used in the Continued Fracition operator and in the Optimal Domain Wall formulation of Chiu. However each kind of operator is entirely capable of using both kinds of approximations.

Finally common choices for the kernel are $H_T = H_w$ where H_w is the Hermitian Wilson operator (used in Boriçi and its variants) and $H_T = \frac{H_w}{2+\gamma_5 H_w}$. Recently Brower, Orginos and Neff proposed $H_T = \frac{(b_5+c_5)H_w}{2+\gamma_5(b_5-c_5)H_w}$ which is the Möbius formalism. Here $b_5 - c_5$ chooses the operator ($b_5 = 1, c_5 = 0$ is the usual Shamir operator, and $b_5 = c_5 = 1$ is the Boriçi operator), and $b_5 + c_5$ correspond to a scale factor for H_T which can be used to scale the spectrum of H_T to a more convenient region of the tanh approximation.

The key point is that one should separate considerations of the representation of the rational approximation which determine the 5D operator, the approximation itself be it tanh or Zolotarev which determine coefficients and the kernel in the sign function.

We tested the efficiencies of various versions of the operator and we show them on the attached transparencies. Our chief findings are, that: numerically the ensemble averaged pion agrees between all Boriçi like formulations and approximations. The cost of all approaches is roughly the same for high values of m_{res} whereas at smaller m_{res} the clear winner is the continued fraction operator with the runner up being the Scaled Shamir-like Möbius operator. Further m_{res} seems in some cases to be insensitive to the sign function being badly approximated for small eigenvalues of H_T while at other times it seems more sensitive to this.

Our chief recommendation from this study is to use the Continued Fraction operator if one desires a small m_{res}. In the case of larger m_{res} there is little difference in cost betwen the approaches. In this case using formulation where $H_T = H_w$ offers several tempting options: since in this case the effective 4D operator is the Overlap it is possible to use Overlap valence quarks and make these calculations more efficient through the use of multi mass solvers. Secondly the eigenvalues of H_w are better behaved than those of the Shamir variant, resulting in the possibility of easier projection techniques in the Boriçi like case should one wish to achieve exact chiral symmetry. The option would also be left open to perform HMC simulations with 4D pseudofermions potentially reducing noise from the bulk Pauli-Villars fields in 5D formulations, which is more problematic to do with the Shamir H_T.

Summary of 5D Chiral Operators

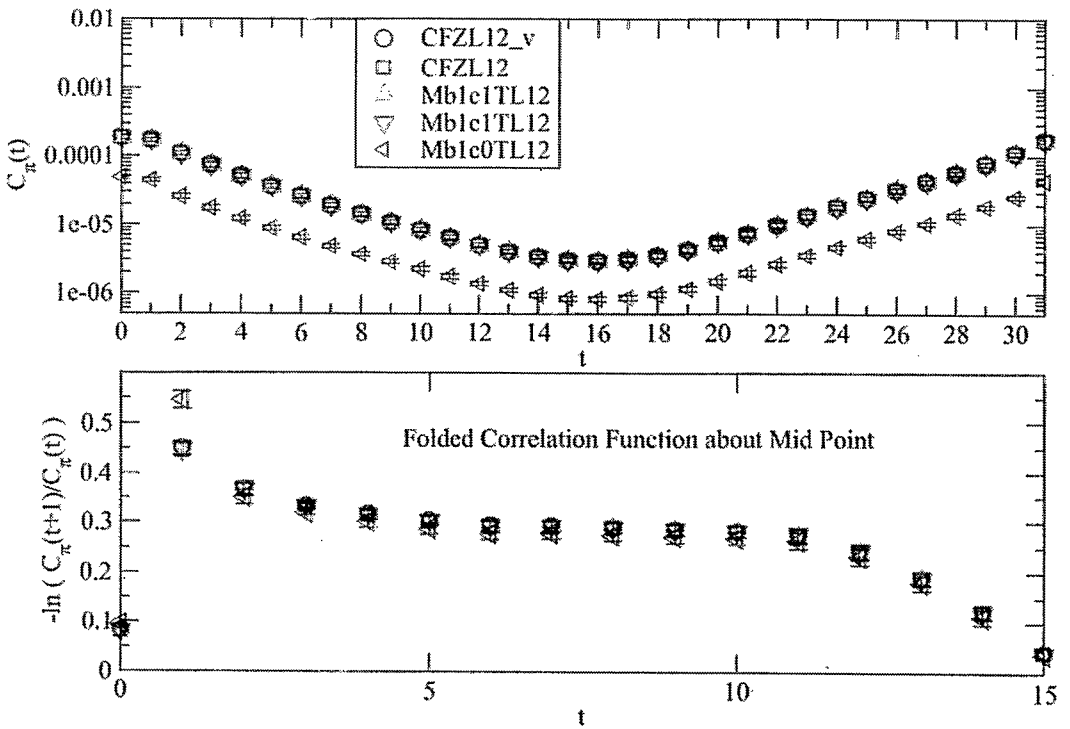
- One should separate the issues of the
  - Rational Function Representation: eg Cayley – DWF, Continued Fraction, Partial Fraction, others...
  - Approximation: eg: Higham-Tanh, Zolotarev, possible others...
  - Auxiliary Kernel: Shamir, Boriçi, Möbius, possible others (eg Jansen)
- One can mix and match these as one chooses.

Operators

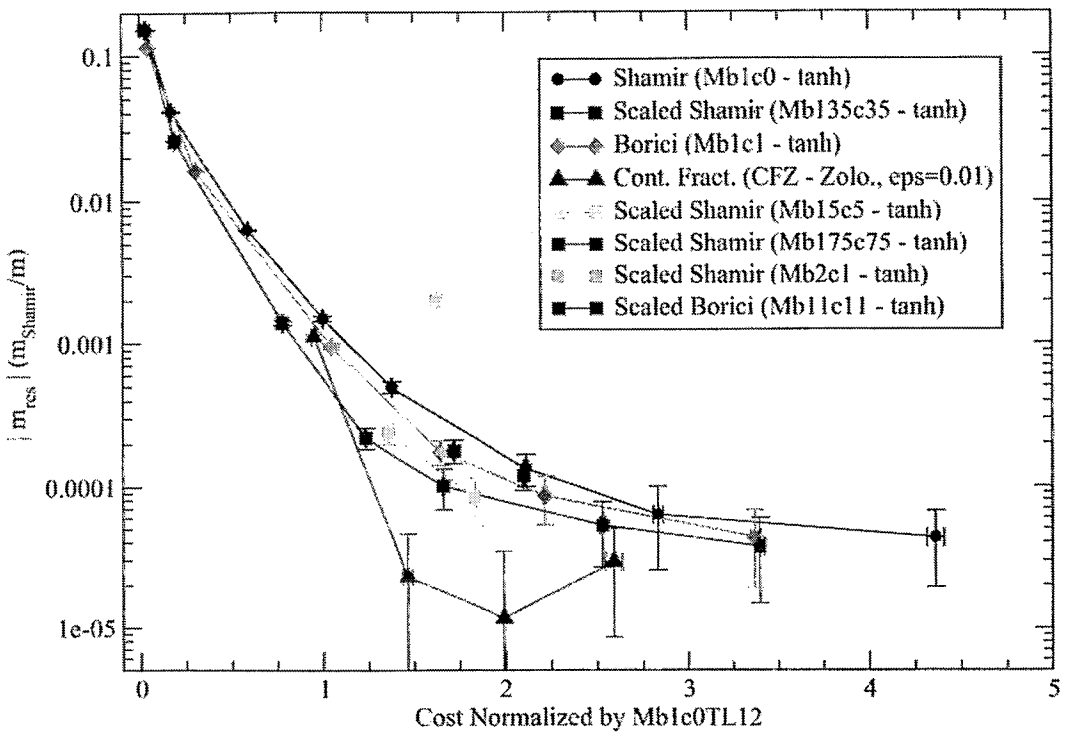
Name	Operator	b_5	c_5	Ls	m_q	Approx	Fixed ϵ	# Conf	Moniker
Shamir	Möbius	1	0	12	0.02	Tanh	–	15	Mb1c0TL12
Boriçi	Möbius	1	1	12	0.0115	Tanh	–	15	Mb1c1TL12
	Möbius	1.35	.35	12	0.02	Tanh	–	15	Mb135c35TL12
Boriçi	Cont. Frac.	–	–	12	0.0115	Tanh	–	15	CFTL12
	Cont. Frac.	–	–	12	0.0115	Zolo	0.01	15	CFZL12
	Cont. Frac.	–	–	12	0.0115	Zolo	–	15	CFZL12_v
	Cont. Frac.	–	–	12	0.0115	Zolo	0.069	1	CFZL12_e
Boriçi	Möbius	1	1	12	0.02	Zolo	0.01	1	Mb1c1ZL12
Shamir	Möbius	1	0	12	0.02	Zolo	0.01	1	Mb1c0ZL12
	Möbius	1.35	.35	24	0.02	Tanh	–	15	Mb135c35TL24
Boriçi	Möbius	1	1	24	0.0115	Tanh	–	15	Mb1c1TL24
	Cont. Frac.	–	–	24	0.0115	Zolo	–	1	CFZL24_v

'CF' = Cont frac. 'M' = Möbius 'Z'=Zolotarev, 'T'=tanh,

Pion Correlators



Cost measurements 2: m_{res} vs. Cost



Which one to choose (Recommendations)?

- Personal view: Continued Fraction ... but if that is not possible:
- Staying with DWF, our group prefers $H_T = H_w$ (Boriçi like) variants as
  - Eigenvalues of H_w are better behaved than for Shamir H_T
  - Future implementation of H_T eigenmode projection easier
- Effective 4D operator is Overlap Operator $\Rightarrow$
  - Leave open option for HMC with 4D pseudofermions...
  - Option to use overlap for valence (MultiMass solver)
  - Eigenvalue projection in valence $\Rightarrow m_{\text{res}} = 0$ to machine precision
  - May be easier to satisfy Shamir-Golterman valence m_{res} criterion.

$\Delta I = 1/2$ rule from $K \to \pi$ matrix element in domain-wall QCD

Jun-Ichi Noaki [1] for the RBC Collaboration

We report our numerical calculation of $\Delta I = 1/2$ rule in $K \to \pi\pi$ decay. $K \to \pi\pi$ matrix elements are computed from $K \to \pi$ matrix elements on the lattice using the chiral perturbation theory at the leading order. In order to control two sources of systematic error in this kind of calculation,*i.e.* charmed quark effect on the lattice and quenched error, we performed quenched calculation which can accommodate charmed quark and dynamical calculation. In this talk, we present our preliminary results.

[1]Present address: School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ UK
email: noaki@phys.soton.ac.uk

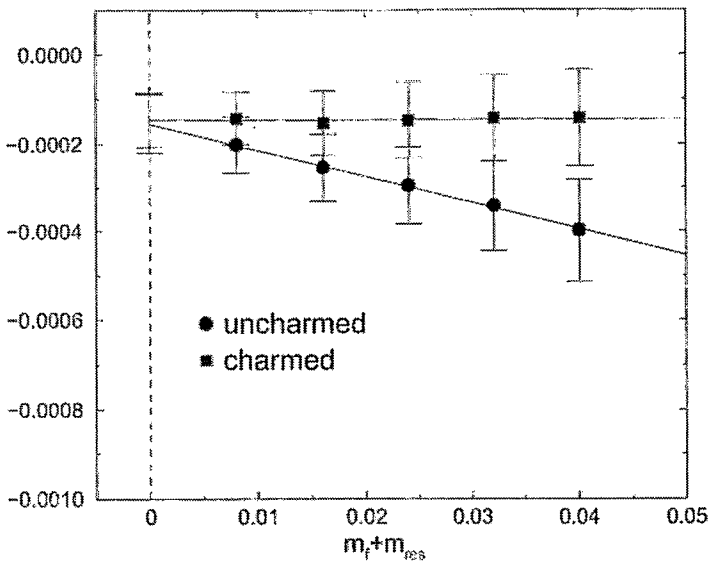
Simulation paprameters

QUENCHED		$N_f = 2$ DYNAMICAL
	$\beta = 1.22$	$\beta = 0.80$
size	$24^3 \times 48$	$16^3 \times 32$
L_s	10	12
M_5	1.65	1.80
wall-source	$t = 7,\ 41$	$t = 4,\ 28$
statistics for ME	106	94
NPR	53	40
m_f	$0.008 \times 1, 2, 3, 4, 5$	$0.01 \times 1, 2, 3, 4, 5$
$m_s/2$	0.01495(78)	0.0214
m_{res}	$0.9722(27) \cdot 10^{-4}$	$1.399(55) \cdot 10^{-3}$
$a^{-1}(m_\rho)$	2.914(54) GeV	1.689(21) GeV
Phys. volume	1.65 fm	1.89 fm

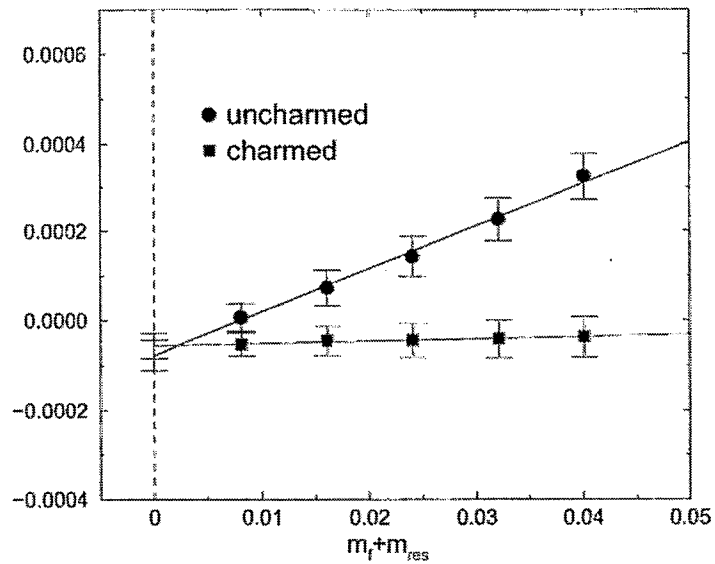
$m_{\text{sea}} = 0.02, 0.03, 0.04$

Quenched result

Q_1 , $\Delta I = 1/2$



Q_2 , $\Delta I = 1/2$

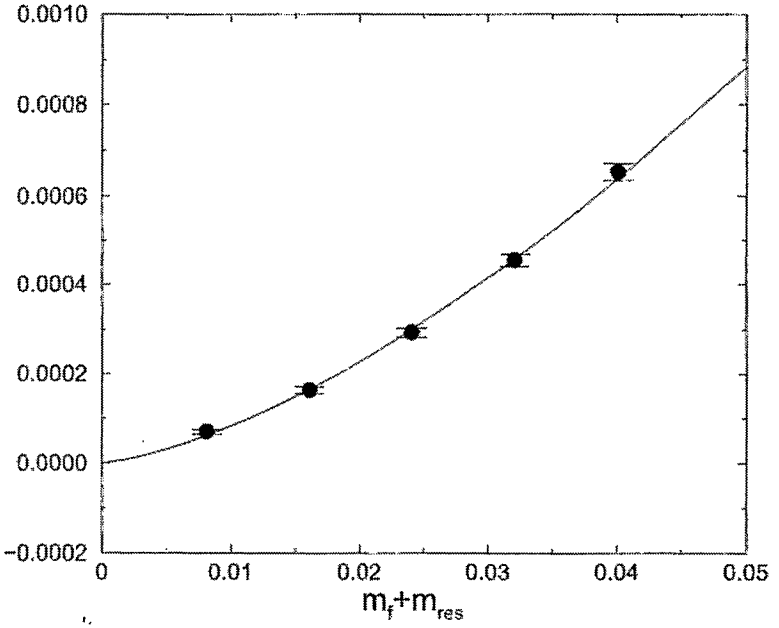


Chamed effects are negligiblly small. $W_i(\mu)$ only make difference.

$$\frac{Amp(\Delta I = 1/2)}{Amp(\Delta I = 3/2)} \simeq 17.5 \pm 15\% \quad (\mu > m_c)$$
$$\simeq 20.1 \pm 15\% \quad (\mu < m_c)$$

A rough estimation, NPR and RG-running ongoing.

$Q_1 = Q_2\ ,\ \Delta I = 3/2$

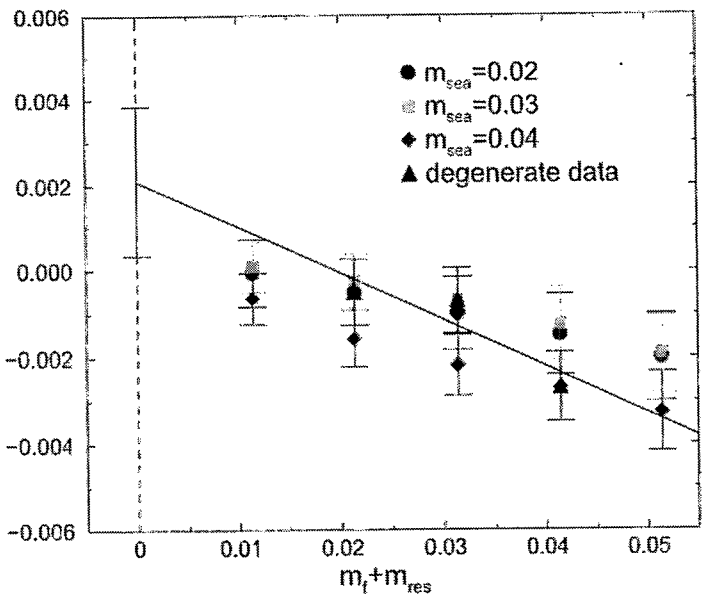


chiral expansion: $\langle \pi^+ | Q | K^+ \rangle = \xi_1^{(0)} m_f \left[1 - \frac{6 m_f}{(4\pi f)^2} \ln m_f \right] + \zeta m_f^2$

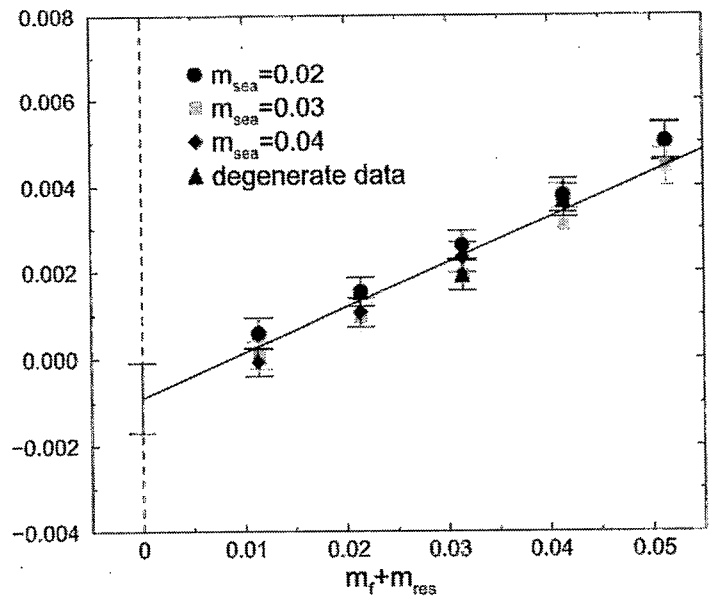
$\overline{\mathrm{MS}}$, NDR, $\mu = 2$ GeV : $\mathrm{Re}Amp(\Delta I = 3/2) = 1.70 \cdot 10^{-8}\mathrm{GeV} \pm 12\%$

$N_f = 2$ dynamical result

Q_1 , $\Delta I = 1/2$



Q_2 , $\Delta I = 1/2$

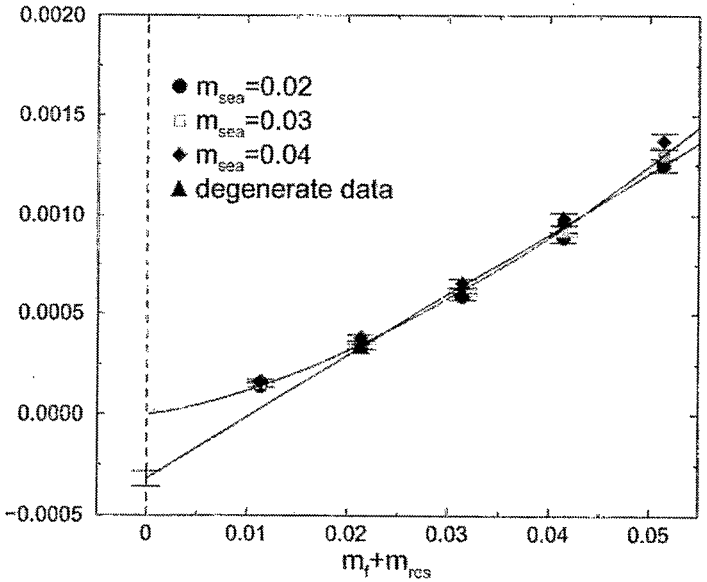


Degenerate data are used for now.

$$\frac{Amp(\Delta I = 1/2)}{Amp(\Delta I = 3/2)} \simeq 25.4 \pm 50\% \quad \text{(fit + statistics)}$$

NPR and RG-running ongoing.

$Q_1 = Q_2$, $\Delta I = 3/2$



Using only degenerate masses: $\langle \pi^+ | Q | K^+ \rangle = \xi_1^{(0)} m_f \left[1 - \frac{6 m_f}{(4\pi f)^2} \ln m_f \right] + \zeta m_f^2$

$\overline{\text{MS}}$, NDR, $\mu = 2$ GeV : $\mathrm{Re}Amp(\Delta I = 3/2) = 1.89 \cdot 10^{-8}$ GeV $\pm 20\%$

I=2 S-wave pion scattering phase shift with two-flavor full QCD

Takeshi Yamazaki
RIKEN BNL Research Center
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Ultimate goal of this study is to expand our understanding of hadron dynamics based on lattice QCD. So far many lattice calculations, however, have focused on static physical quantities, e.g., hadron spectrum. Hence we attempt to investigate the isospin $I = 2$ S-wave pion scattering which is one of simple hadron scatterings. This work is also a first step to study decays of hadrons.

We present a lattice QCD calculation of the pion scattering phase shift with two-flavor dynamical quark effect. The calculation uses two-flavor full QCD configurations previously generated with a renormalization group improved gauge action and clover quark action with a tadpole improved clover coefficient. We employ three different lattice spacings $a \approx 0.22, 0.16$ and 0.11 fm for the continuum extrapolation, and four pion masses $m_\pi \approx 0.5, 0.75, 0.9$ and 1.1 GeV for the chiral extrapolation. This is the first calculation for the scattering phase including the two flavor dynamical quark effect and taken to the continuum limit.

The scattering phase is obtained through the finite volume method in the center of mass system, and its extension to the non-rest system. While the inclusion of the non-rest system requires little extra computational cost, the use of the system allows significantly more dense sampling of the scattering phase. We observe a reasonable fit with the results obtained from the calculations in the different systems. We also find that the pion mass and the lattice spacing dependences for the scattering phase are large. These dependences cause large systematic errors at the physical pion mass and in the continuum limit. The result for the scattering phase in the continuum limit agrees with the experimental result.

I=2 S-wave pion scattering phase shift with two-flavor full QCD

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(for CP-PACS Collaboration:
S. Aoki, M. Fukugita, K-I. Ishikawa, N. Ishizuka, Y. Iwasaki, K. Kanaya, T. Kaneko, Y. Kuramashi, M. Okawa, A. Ukawa, T. Yoshié)

Reference CP-PACS Collaboration, hep-lat/0402025

UKQCD/RBC workshop November 12 & 13, 2004

1. Introduction

Motivation

- Understanding of hadron dynamics based on (lattice) QCD

Strict test of Standard model requires comparison of theory and experiment. But one of main theoretical uncertainties is hadronic effect.
To calculate hadron scattering ($\pi\pi$ scattering) based on QCD, non-perturbative method, e.g. lattice QCD, is required.

- 'Dynamical' physical quantity beyond hadron mass

Isospin $I = 2$ S-wave $\pi\pi$ scattering phase shift $\delta_0(p)$

$$T(p) = \frac{16\pi E}{p}\sum_l (2l+1)P_l(\cos\theta)\frac{1}{2i}\left(e^{2i\delta_l(p)} - 1\right), \quad E = 2\sqrt{m_\pi^2 + p^2}$$

Most of the lattice studies have focused on 'static' physical quantities, e.g. hadron spectrum.

- First step toward calculation of decays of hadrons

$$\rho \to \pi\pi,\ \sigma \to \pi\pi$$

$$K \to \pi\pi \text{ direct calculation}$$

(Traditional calculation method is $K \to 0$ and $K \to \pi$ relate to $K \to \pi\pi$ with ChPT.)

3. Parameters

$N_f = 2$ full QCD configuration (CP-PACS Collaboration)

- Improved action

gauge : Iwasaki action
fermion : clover action

- Simulation parameters $La \sim 2.5$[fm]

β	c_{SW}	a^{-1}[GeV]	a[fm]	$L^3 \cdot T$
1.80	1.60	0.9176(93)	0.2250(22)	$12^3 \cdot 24$
1.95	1.53	1.268(13)	0.1555(17)	$16^3 \cdot 32$
2.10	1.47	1.833(22)	0.1076(13)	$24^3 \cdot 48$

a is determined by m_ρ

- Pion mass and number of configurations

$\beta = 1.80$				
m_π [GeV]	1.06	0.90	0.76	0.49
# of conf.	645	520	725	405
$\beta = 1.95$				
m_π [GeV]	1.13	0.93	0.76	0.54
# of conf.	595	690	685	495
$\beta = 2.10$				
m_π [GeV]	1.15	0.95	0.78	0.54
# of conf.	395	390	380	640

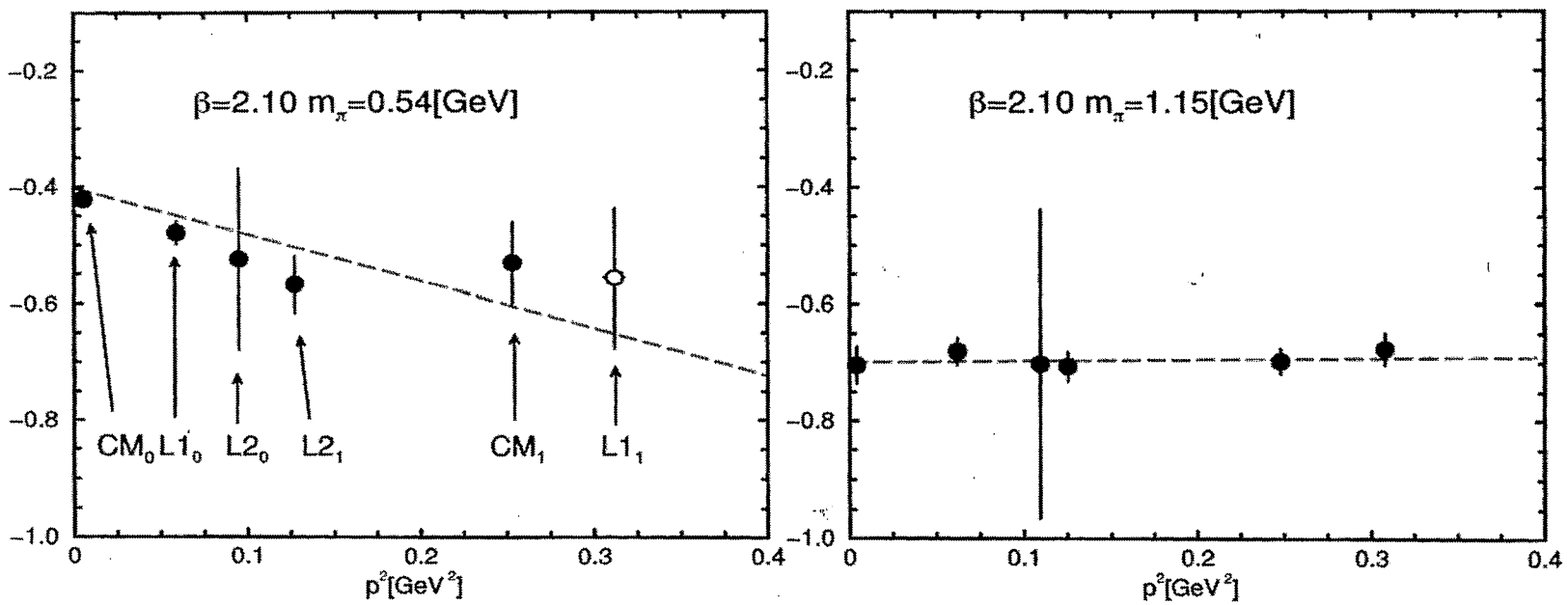
4 Result of scattering phase shift $\delta(\overline{p})$

4.1 Chiral extrapolations

'Scattering amplitude' $A(\overline{p}, m_\pi) = \dfrac{\tan\delta(\overline{p})}{\overline{p}} \cdot \dfrac{\overline{E}}{2}$, $\lim_{\overline{p}\to 0} A(\overline{p}, m_\pi) = a_0 m_\pi$

global fit for m_π^2 and $\overline{p}^2$ at each β

$$A(\overline{p}, m_\pi) = A_{10} m_\pi^2 + A_{20} m_\pi^4 + A_{30} m_\pi^6 + A_{01}\overline{p}^2 + A_{11} m_\pi^2 \overline{p}^2 + A_{21} m_\pi^4 \overline{p}^2$$



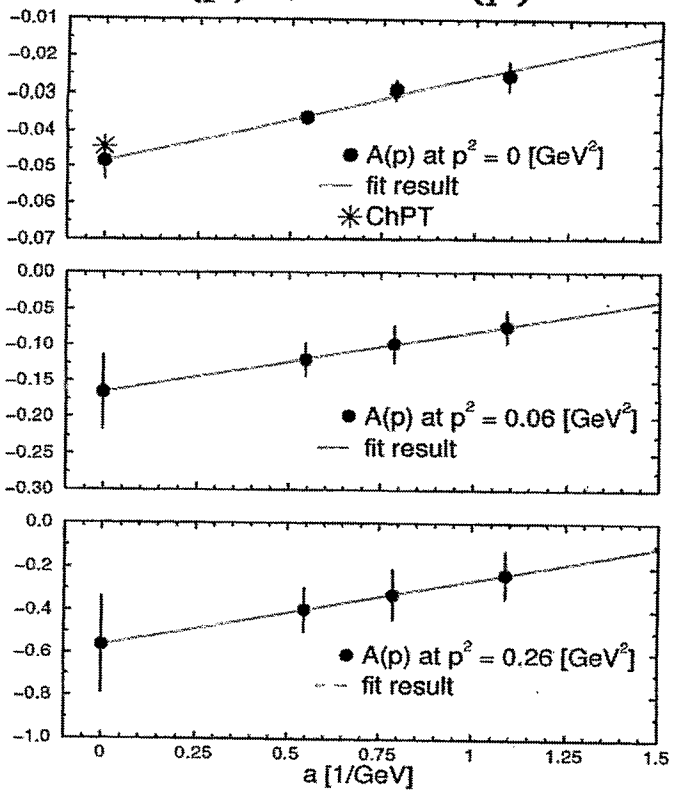
Reasonable fittings are possible with the amplitudes obtained from different systems.

β	1.80	1.95	2.10
χ^2/d.o.f.	0.90	0.64	1.33

4.2 Continuum extrapolations at $m_\pi = 0.14$[GeV]

linear fit at fixed $\overline{p}$

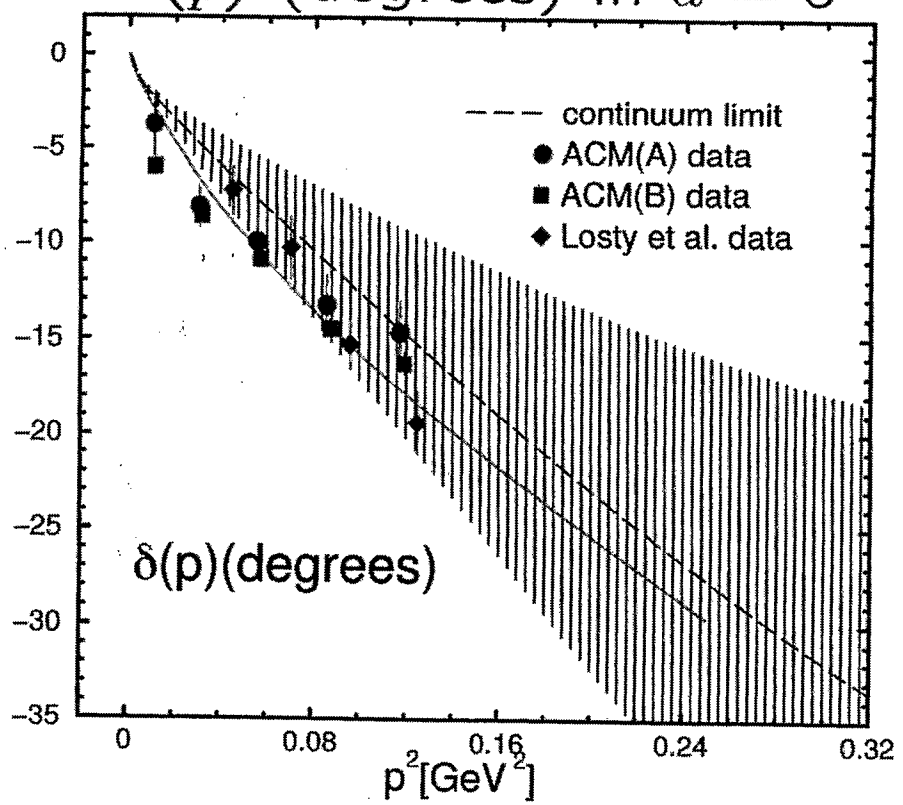
$$A(\overline{p}) + aA^{(a)}(\overline{p})$$



Large $O(a)$ effect exists.

$$A(0) = -0.0484(49)$$
$$a_0 m_\pi(\text{ChPT}) = -0.0444(10)$$

$\delta(p)$ (degrees) in $a = 0$



Symbols are the experimental data.

(Hoogland *et al.*, Losty*et al.*)

Solid line is fitting of experimental.

(Colangelo *et al.*)

Result is consistent with experimental data.

On-Shell $K \to \pi\pi$ Decay

Norman H. Christ
Columbia University

UKQCD - RBC Workshop
November 12, 2004

Both of our collaborations have begun serious work on direct calculation of K meson decay into two final-state pions. In this presentation I will describe the RBC side of these efforts. This research, carried out primarily by Changhoan Kim, makes up his now completed Ph.D. thesis and should appear as a paper within the next few months. Our basic strategy is to impose boundary conditions on the quarks that appear in the final-state pions so that those pions must also obey non-trivial boundary conditions and therefore must carry non-zero momenta, typically $p \propto \pi/L$. This circumvents the Maiani-Testa theorem and allows an "on-shell" final state whose energy equals that of the decaying K meson. Finally, the recent formula of Lellouch and Lüscher can be used to convert the finite volume matrix element into the infinite volume matrix element of interest.

As was shown some time ago, if G-parity boundary conditions are imposed on the underlying u and d quarks, this method can be used to determine decay amplitudes into both the $I = 0$ and $I = 2$ final states. In the work I will describe, simpler H-parity boundary conditions are imposed which allows the treatment of only the $I = 2$ final state.

In the first slide below, these two sets of boundary conditions are defined. The second slide provides the parameters for the somewhat coarse lattice spacing, quenched simulation with domain-wall quarks that Changhoan carried out. The third slide shows the $I = 2$, $\pi - \pi$ phase shifts that were obtained from the finite-volume, two-pion energy using Lüscher's formalism and imposing H-parity boundary conditions in a number of spatial directions varying between zero and three. While good agreement with experiment is likely not to be expected given the unphysically heavy quarks, it is interesting that we find the non-resonant behavior, increasing and then decreasing with energy that is seen experimentally.

In the fourth slide an "effective mass" computed from the time dependence of the matrix element of the weak operator $O^{(27,1)}$ is shown. If the Kaon and $\pi - \pi$ masses are the same this effective mass should be zero. A reasonable plateau is seen between $t = 4$ and 20. Here the K meson is created at $t = 22$ and the final two pions absorbed at $t = 0$. In the final slide the actual lattice matrix element is shown as a function of Kaon mass. The vertical lines indicate that region in which the Kaon mass equals the finite-volume $\pi - \pi$ energy determined by the H-parity boundary conditions, here imposed in only one direction.

The good plateaus and relative small errors seen in these figures indicate that this method is quite successful, allowing the calculation of $K \to \pi\pi$ decay without the resort to chiral perturbation theory. We plan to extend these calculations studying more physical parameter values and properly including the effects of quark loops.

Anti-Periodic Boundary Conditions for Pions?

- **G-parity boundary conditions:**

$$G|\pi^{\pm}> \; = \; -|\pi^{\pm}>$$
$$G|\pi^{0}> \; = \; -|\pi^{0}>$$

  - **G-parity operation on the quark fields:**

$$G\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix} = \begin{pmatrix} -\mathbf{d}^C \\ \mathbf{u}^C \end{pmatrix}$$

  - **Required charge-conjugation boundary conditions for the gauge fields too.**

- **H-parity Boundary Conditions:**

$$H|\pi^{\pm}> \; = \; -|\pi^{\pm}>$$
$$H|\pi^{0}> \; = \; +|\pi^{0}>$$

  - **H-parity operation on the quark fields (definition):**

$$H\begin{pmatrix} \mathbf{u} \\ \mathbf{d} \end{pmatrix} = \begin{pmatrix} \mathbf{u} \\ -\mathbf{d} \end{pmatrix}$$

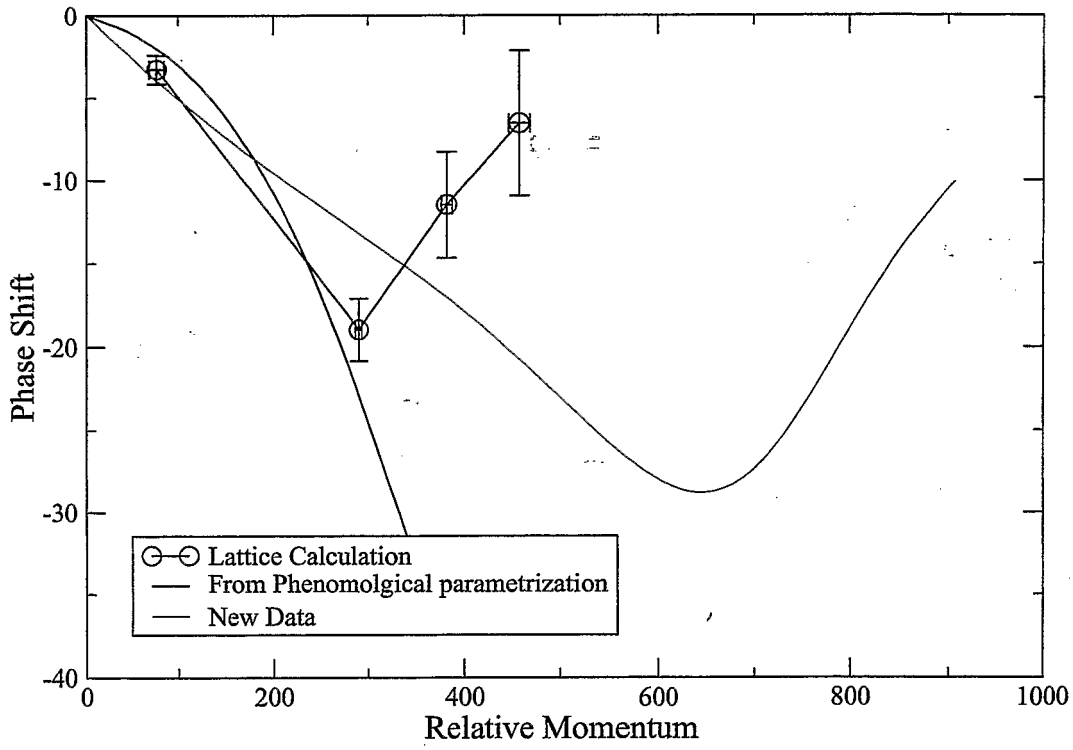
  - **$\mathbf{I_z = 2}$, $\pi^+\pi^+$ state contains anti-symmetric pions with non-zero momenta.**

$K \to (\pi\pi)_{I=2}$ Simulation Parameters

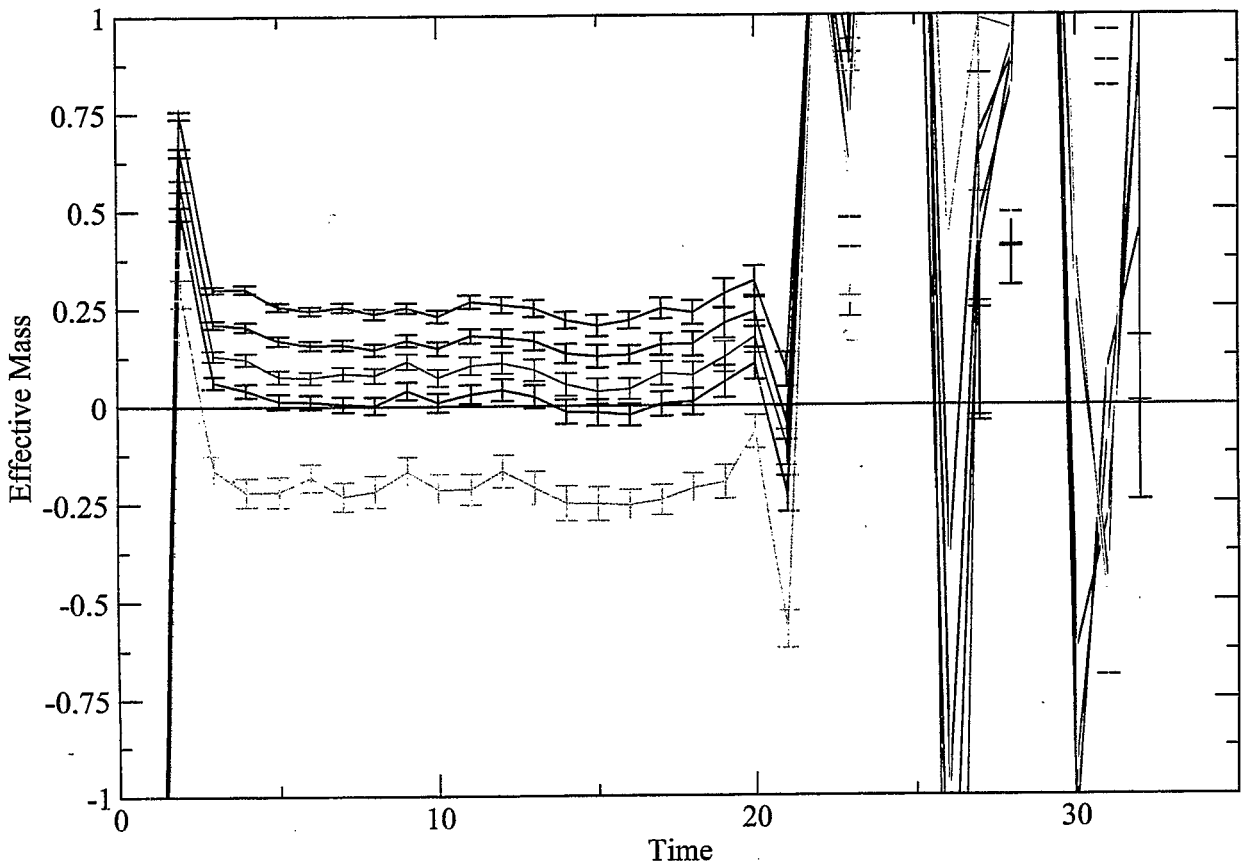
- **Lattice size:** $16^3 \times 32$
- **Pion mass:** **352**MeV
- **Kaon mass:** **712**MeV **- 1290**MeV
- **Lattice spacing:** a^{-1}**=1.3**GeV
- **Action: DBW2**
- **Number of Configurations: 129**
- **Domain Wall Fermions:** M_5**=1.8,** L_s**=12**
- **Resulting kinematics:**

	m_K	m_π	p_π
Simulation	**910 MeV**	**352 MeV**	**290 MeV**
Nature	**496 MeV**	**138 MeV**	**206 MeV**

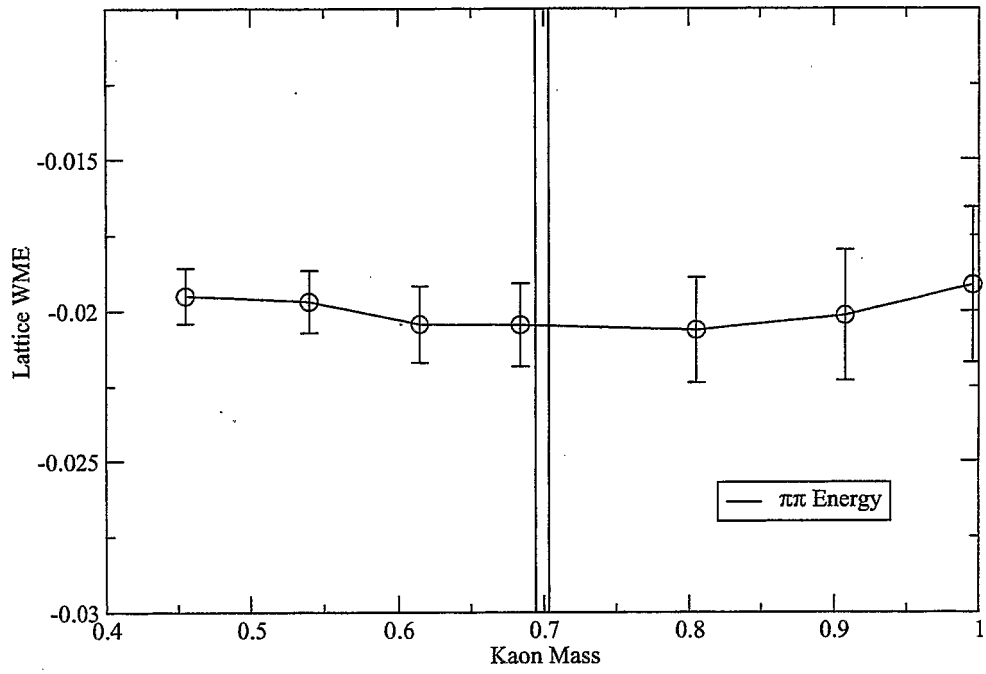
Numerical $\delta_{\pi\pi}(I=0)$ results compared with higher energy data

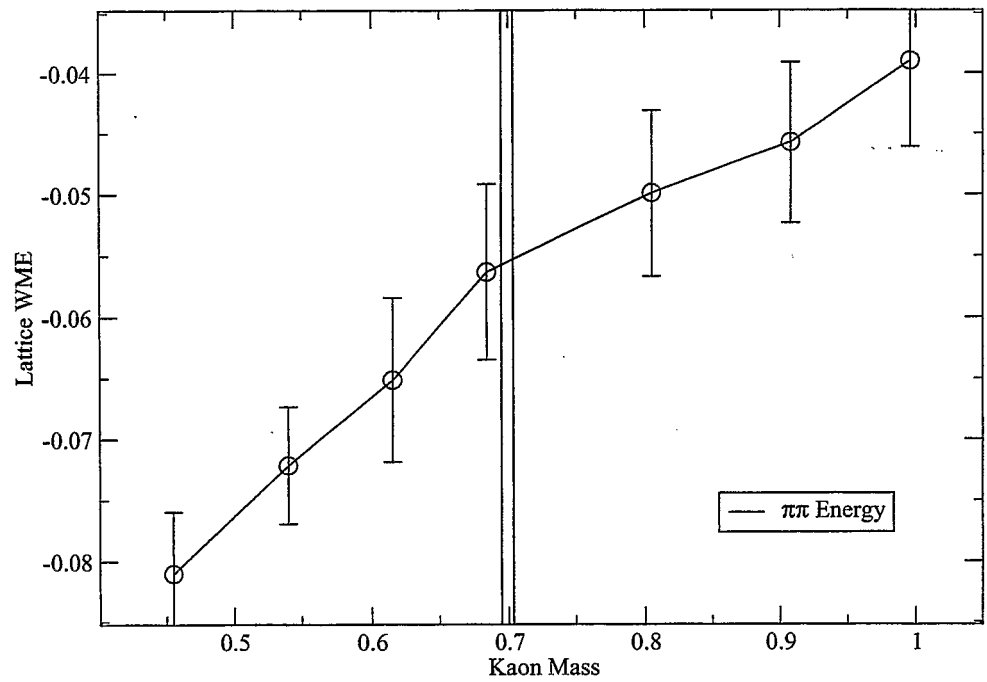


Effective mass difference from $G_{\pi\pi O27K}$



O^{27} and $O^{(8,8)}$ matrix element versus Kaon mass





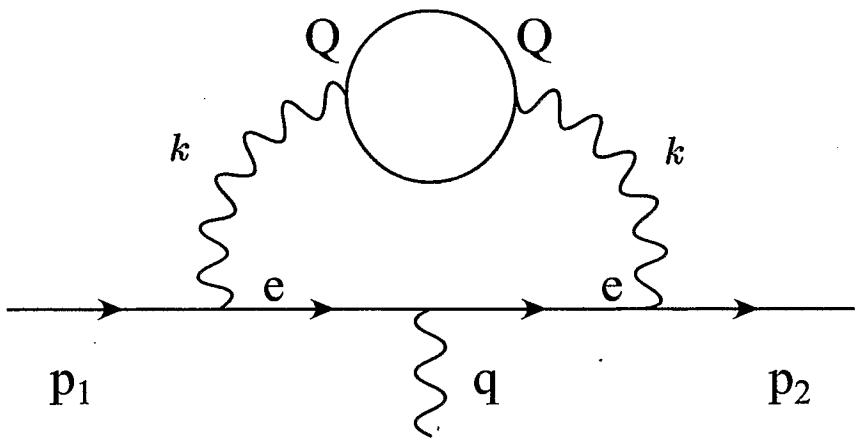
Lattice calculation of the lowest-order hadronic contribution to the muon anomalous magnetic moment

Tom Blum

University of Connecticut and RIKEN BNL Research Center

UKQCD-RBC Workshop

$\mathcal{O}(\alpha^2)$ hadronic contribution comes from the hadronic vacuum polarization: $(\Pi(k^2))$



The blob, which represents all possible intermediate hadronic states, is not calculable in perturbation theory

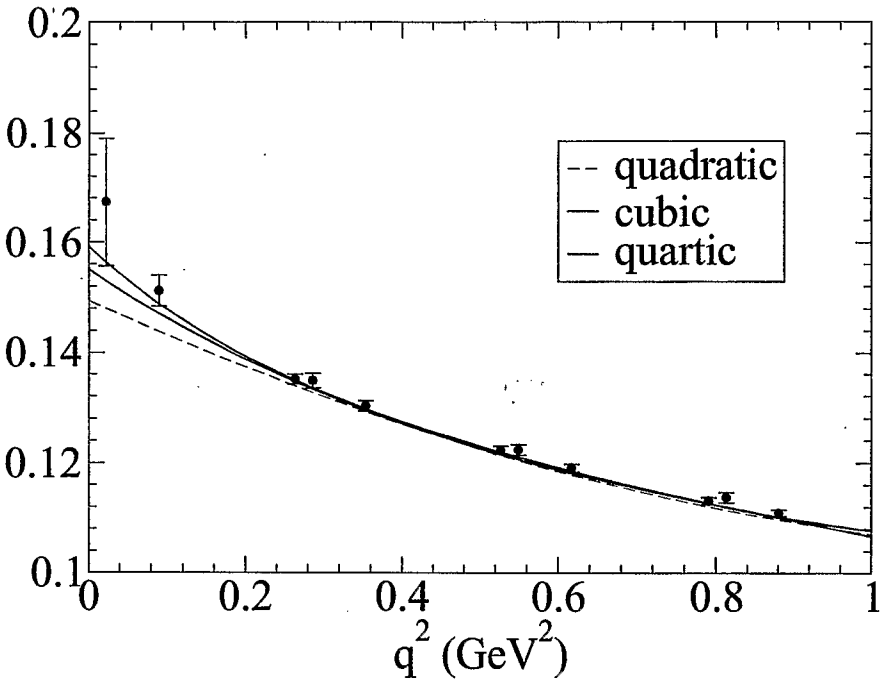
Calculation of the vacuum polarization with Improved-Kogut-Susskind fermions on the The MILC 2+1 Flavor Lattices:

a (fm)	size	m_l	m_s	m_{val}	#
0.121(3)	$20^3 \times 64$	0.01	0.05	0.05	
0.121(3)	$20^3 \times 64$	0.01	0.05	0.01	
0.120(3)	$24^3 \times 64$	0.005	0.05	0.005	
0.086(2)	$28^3 \times 96$	0.0062	0.031	0.031	
0.086(2)	$28^3 \times 96$	0.0062	0.031	0.0062	
0.086(2)	$40^3 \times 96$	0.0031	0.031	0.0031	
0.085(2)	$28^3 \times 96$	quenched		0.031	
0.085(2)	$28^3 \times 96$	quenched		0.0062	
MILC proposal on QCDOC		m_l/m_s	$m_\pi L$	trajecs	
0.086	$48^3 \times 96$	0.1	4.2	$\sim$ 2000	
0.06	$48^3 \times 144$	0.2	5.8	3750	
0.06	$48^3 \times 144$	0.4	7.0	3000	

In the 2+1 flavor case, knowing $\mathrm{Im}\Pi(-q^2)$ is, of course, a cheat

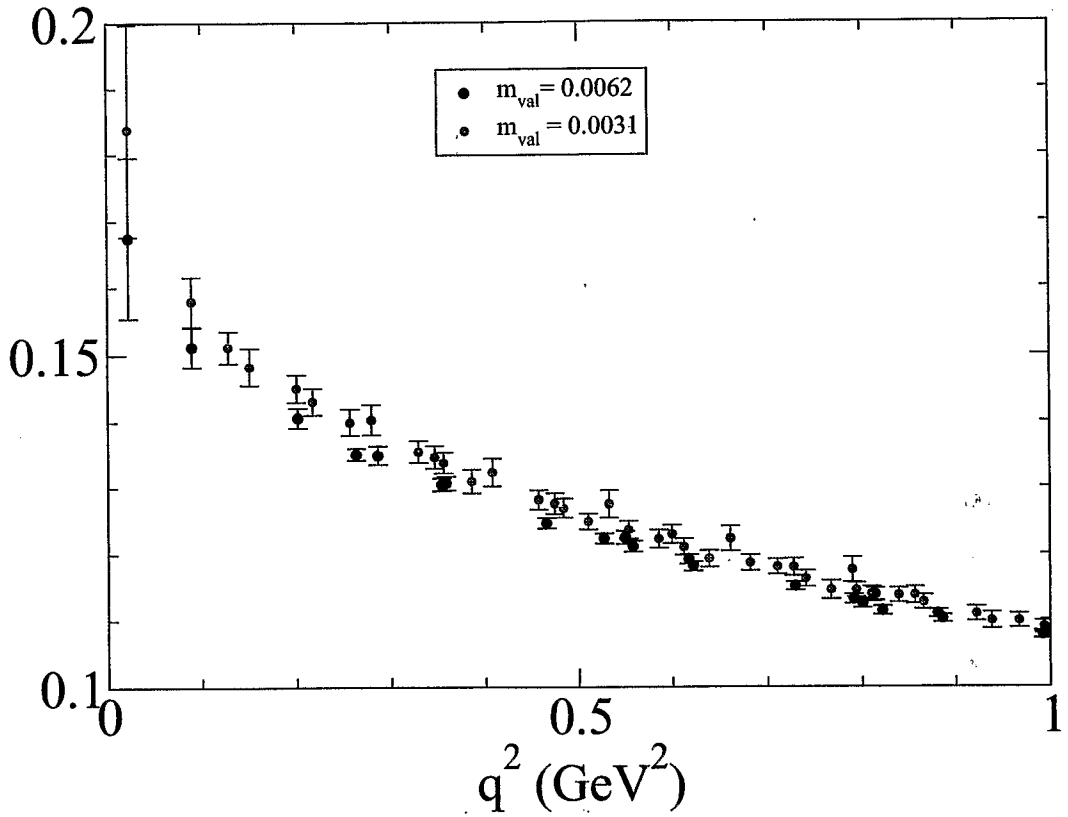
Polynomial in q^2

- $\chi^2/\mathrm{dof} = 4.9,\ 1.6,\ 1.2$
- underestimates data



Quartic fit: $903(117)\times10^{-10}$, $\approx 85\%$ of the physical contribution (may'be more)

$m_l \approx \frac{m_s}{10}$ and lattice size $= 40^3 \times 96$



Discussion/Outlook

1. Need better fit function for low q^2, small $m_q \rightarrow$ chiral PT. Continuum: 1-loop is just vacuum polarization of two pions. Staggered, $a \neq 0$: same with (different mass) non-Goldstone pions in the loop.

2. Complete large lattice, small quark mass, staggered caclulations.

3. 1% accuracy from 1 and 2? Recall f_K/f_π...

4. Repeat for 2+1 flavor DWF lattices

THE ELECTROMAGNETIC SPLITTING AND $g_\mu - 2$ LIGHT-BY-LIGHT CONTRIBUTION

TAKU IZUBUCHI

ABSTRACT. We report our ongoing calculation for the electromagnetic splitting for hadron mass and decay constants, which may serve as an input for the precision check of the standard model. The calculations are being carried out on the ensemble of $N_F = 2$ dynamical domain wall fermion lattices. Preliminary results of the mass splittings for the pseudoscalar meson mass following a calculation done with Wilson fermion in [1] are shown. We also present a new formalism for the perturbative QED correction applied to the non-perturbative QCD quantities, which will be an essential step to resolve the theoretical uncertainty in the muon anomalous magnetic moment[2], the light-by-light contribution[3].

REFERENCES

[1] A. Duncan, E. Eichten, and H. Thacker. Electromagnetic splittings and light quark masses in lattice qcd. *Phys. Rev. Lett.*, 76:3894–3897, 1996.

[2] T. Blum. Lattice calculation of the lowest order hadronic contribution to the muon anomalous magnetic moment: An update with kogut-susskind fermions. 2003.

[3] M. Hayakawa and T. Kinoshita. Pseudoscalar pole terms in the hadronic light-by-light scattering contribution to muon g-2. *Phys. Rev.*, D57:465–477, 1998.

(Taku Izubuchi) RIKEN BNL RESEARCH CENTER, KANAZAWA UNIVERSITY

Motivations

- The first principle calculations of isospin breaking effects due to electromagnetic (EM) and the up, down quark mass difference are necessary for accurate hadron spectrum, quark mass determination.

- From $\Gamma(\pi^+ \to \mu^+\nu_\mu, \mu^+\nu_\mu\gamma)$ + V_{ud}(exp)

$$f_{\pi^+} = 130.7 \pm 0.1 \pm 0.36\text{MeV} \quad \text{PDG 2004}$$

the last error is due to the uncertainty in the part of $\mathcal{O}(\alpha)$ radiative corrections that depends on the hadronic structure of the π meson.

$$\Gamma(PS^+ \to \mu^+\nu_\mu, \mu^+\nu_\mu\gamma) \propto [1 + C_{\text{PS}}\ \alpha]_{\text{had. struc.}}$$

$$C_\pi \sim 0 \pm 0.24, \quad C_\pi - C_K = 3.0 \pm 1.5$$

c.f. Marciano 2004 : V_{us} from f_π/f_K (MILC) + $\Gamma(\pi_{l2})/\Gamma(K_{l2})$.
Also the radiative correction to the baryon sector might be worth considering.

EM splitting

- Dashen's theorem : meson made from two quarks with charges q_1, q_2:

$$M_{ps}^2(q_1, q_2) - M_{ps}^2(0,0) \propto A^{(1)} \times (q_1 - q_2)^2 + B^{(1)} \times [q_1^2, q_2^2](m_1 + m_2) + \cdots$$

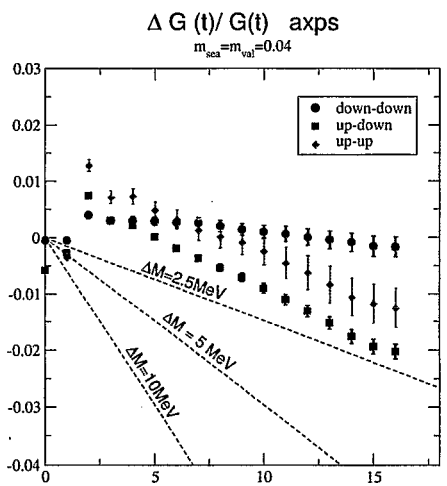
- 1996 Duncan, Eichten, Thacker used SU(3)×U(1) simulation to do the EM splitting for the hadron spectroscopy using quenched Wilson fermion. Using DynDWF would have advantages such as better scaling and smaller systematic errors due to the the quark massless limit, $m_f \to -m_{res}(q_i)$, has smaller q_i dependence than that of Wilson, $K \to K_c(q_i)$.

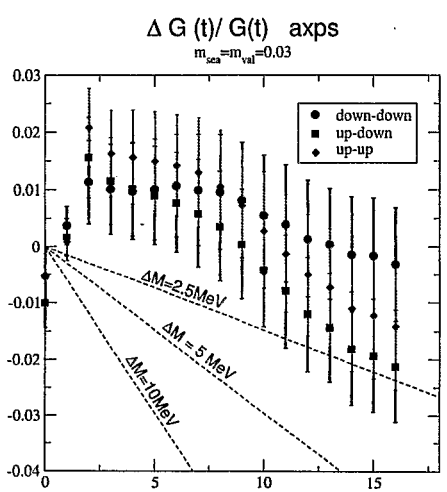
- Generate Coulomb gauge fixed (quenched) non-compact U(1) gauge action with $\beta_{QED} = 1$. $U_{U(1),\mu} = \exp[-iA_\mu(x)]$.

- Charge $q_i e$ quark propagator, with Coulomb gauge fixed wall source with physical $e = 0.3029, q_{up} = 2/3, q_{down} = -1/3$:

$$D\Big[(U_{U(1)})^{q_i e} \times U_{SU(3)}\Big] S_{q_i}(x) = b, \qquad (i = up, down)$$

preliminary results





- Dynamical DWF configuration $m_{val} = m_{sea} = (0.02), 0.03, 0.04$ $a = 0.0013$ or a few MeV.
- The correlator of the temporal competent of the axial vector, $G(t) = \langle A_4(0) A_4(t) \rangle$

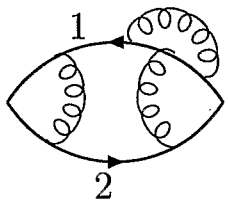
$$\frac{\Delta G(t; q_1, q_2)}{G(t; 0, 0)} \approx \frac{\Delta C(q_1, q_2)}{C(0, 0)} - \Delta M(q_1, q_2) t,$$

- ~ 40 configurations (an U(1) configuration per a SU(3)).
- Error bars might be underestimated.
- Fluctuations due to SU(3) are larger than that from U(1).
- EM effects seem to be visible, but only after taking the ratio.
- The sign and the magnitude of the slope, $-\Delta M(q_1, q_2)$, is in the ballpark.

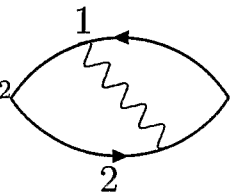
Direct calculation of the each QED diagram

- The perturbative expansion in QED coupling, α, converges rapidly. Each of the perturbative pieces could be obtained by a *direct calculation of QED diagram* treating QCD non-perturbatively. This method may have the following advantages:
  - Could obtain the contribution from each QED diagram separately, and/or order by order in α.
  - The charge, e and q_i, could be input later than simulation.
  - Would help or avoid the subtractions, for example in the light-by-light calculation.
- An example for meson EM splittings :

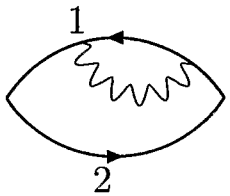
$G(t; q_1, q_2) =$



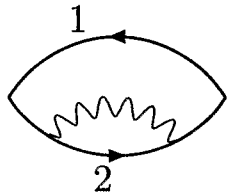
e^2 : $q_1 q_2$



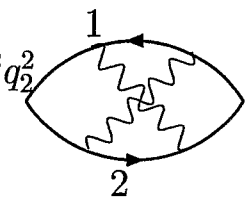
q_1^2



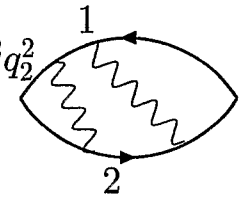
q_2^2



e^4 : $q_1^2 q_2^2$



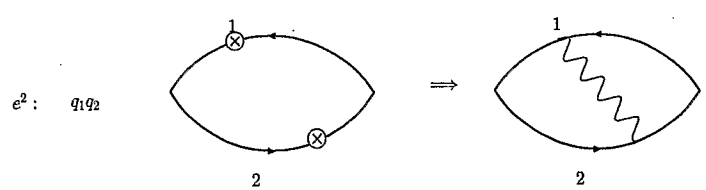
$q_1^2 q_2^2$



Direct calculation ...

- Prepare a $U_{SU(3)\mu}$, and an A_μ.
- 1. Solve
$$D\Big[U_{SU(3)}\Big]\, S_q^{(1)}(x) = b,$$
- 2. multiply $-iA_\mu(x)K_\mu$ or $-ieq_iA_\mu(x)K_\mu$ to the first solution vector, $S_q^{(1)}(x)$, where K_μ is the kernel of the conserved vector current: $V_\mu^{con}(x) == \bar{\psi}K_\mu\psi$.
- 3. Sequentially solve
$$D\Big[U_{SU(3)}\Big]\, S_q^{(2)}(x) = -iA_\mu(x)\gamma_\mu S_q^{(1)}(x),$$
- (4. Repeat 2, 3. $(n-1)$ times for $S_q^{(n)}$)
- Then Tr$[S_q^{(2)}\Gamma\gamma_5[S_q^{(2)}]^\dagger\gamma_5\Gamma]$ is the $e^2q_1q_2$ diagram of the $G(t;q_1,q_2)$ in the background fields,

$$\frac{1}{e^2}\frac{\partial^2}{\partial q_1 q_2}G(t;q_1,q_2) =$$



Charm Physics

- Charm physics very interesting
  - Light dynamical quarks required
  - Coarse lattice spacing
    - Challenge for charm
  - Continuum limit of two HQ methods
    - Control of systematic uncertainty
- Ds meson spectrum
- fDs/fD

Chris Maynard

UKQCD

Light quarks in heavy-light mesons

- Kronfeld and Ryan hep-ph/0206058
  - Analyse chiral logs in B^0-$\bar{B}^0$ mixing

$$\frac{\Delta m_s}{\Delta m_d} = \left|\frac{V_{\rm ts}}{V_{\rm td}}\right|^2 \frac{m_{B_s}}{m_{B_d}} \xi^2$$

Δm is oscillation frequency

$$\xi^2 = \frac{f_{B_s}^2 \mathcal{B}_s}{f_{B_d}^2 \mathcal{B}_d}$$

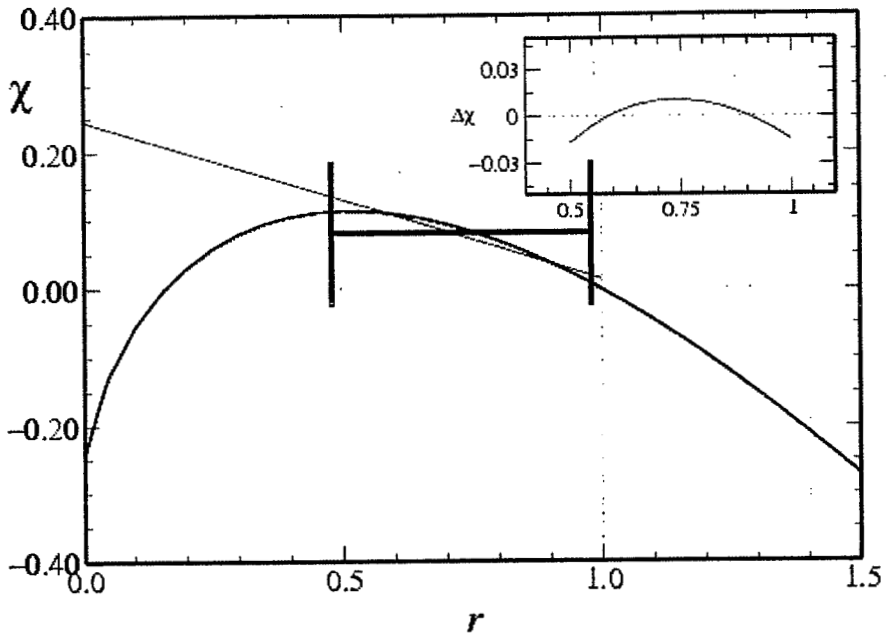
f pseudoscalar decay constant and ***B*** is bag parameter

Chiral perturbation theory for *f* and ***B***, collect the chiral logs in $\chi(r)$

$$r = \frac{m_{PS}^2(q)}{m_{PS}^2(s)} = \frac{m_q}{m_s}$$

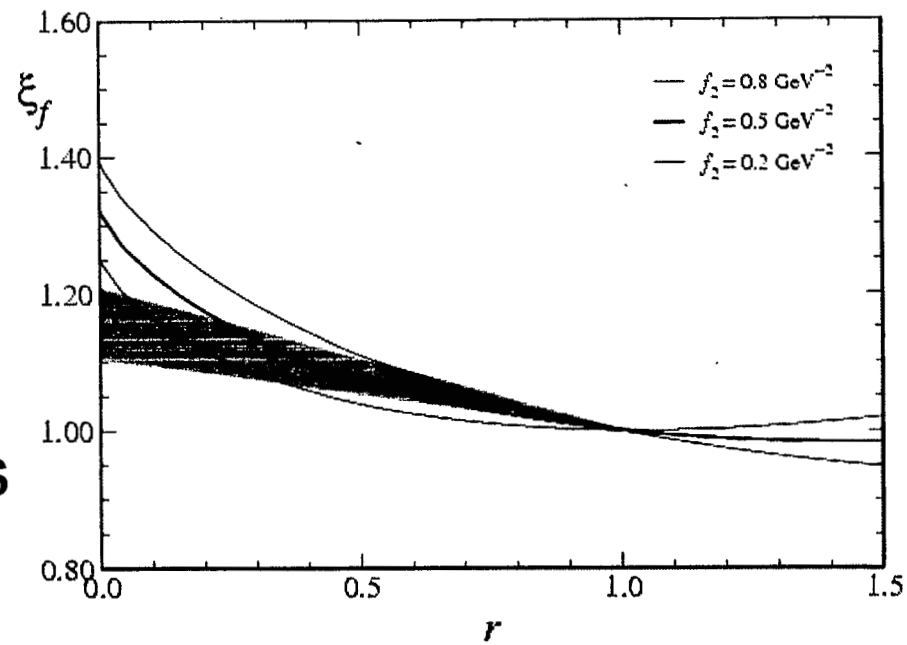
Large uncertainty in SU(3) flavour breaking quantities

Chiral logs



Extrapolate lattice data from 0.5<r<1

Cannot determine true chiral limit



Implies large systematic uncertainty

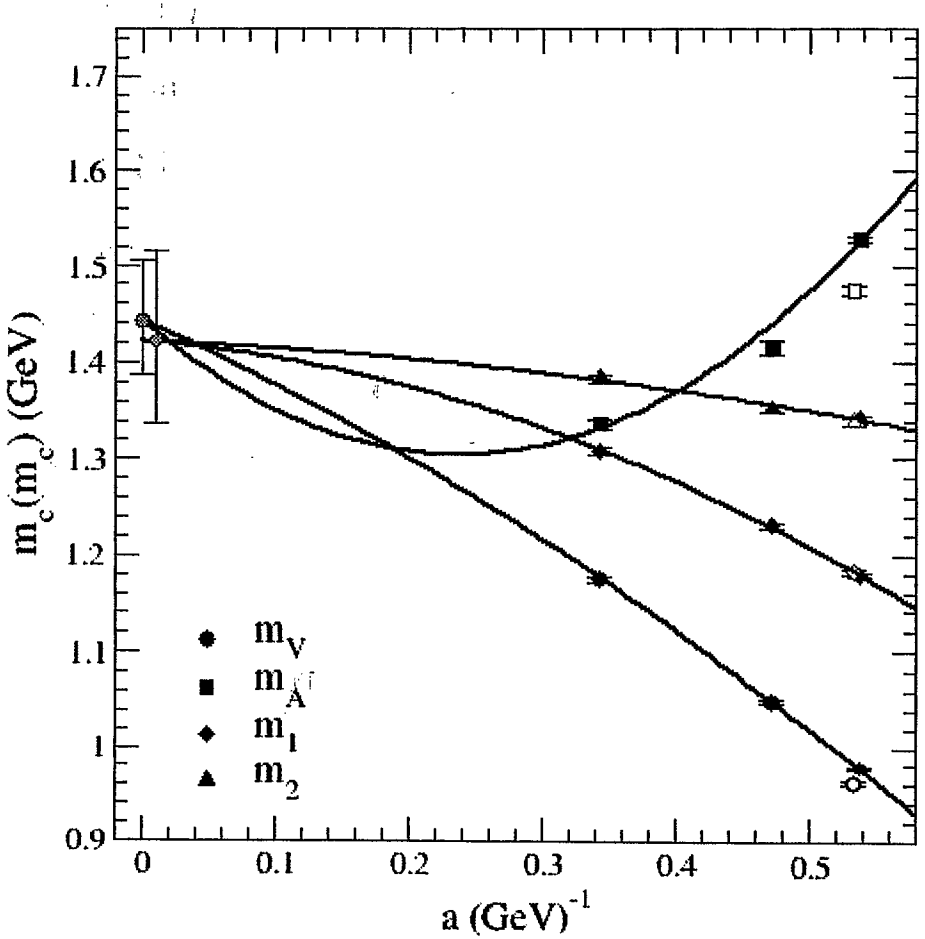
→ Light dynamical quarks

Continuum limits of charm mass

ALPHA-esque red and black combined continuum limit

FNAL blue and green combined continuum limit

Agreement → control of lattice artefacts at coarse *a*



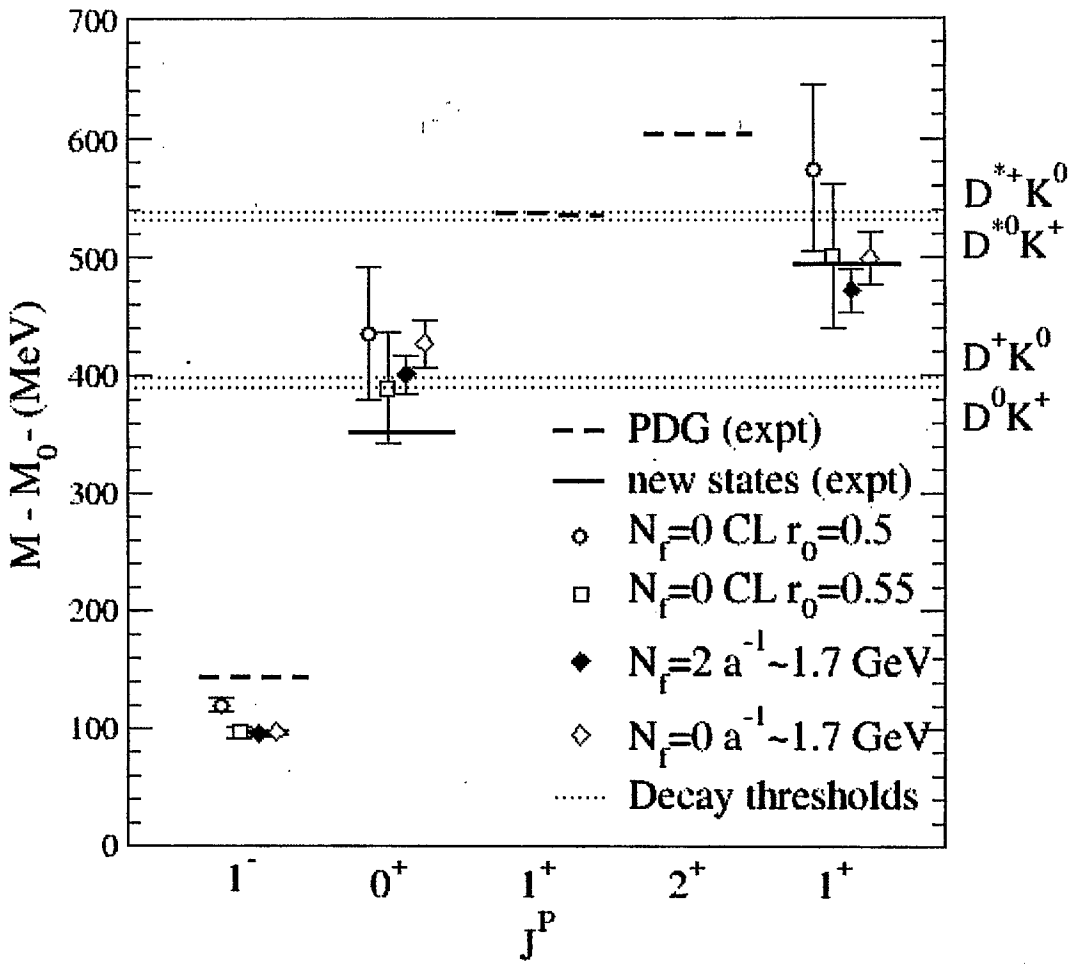
New states in D_s spectrum

- B. Aubert *et al.* (BaBar) Phys.Rev.Lett 242001 Cited 162 times!
- Discovery of new narrow state
  - Mass ~ 2.32 GeV
  - Decays to $D^+_s \pi^0$ $J^P=0^+(?)$
  - Is it $c\bar{s}$ meson?
- Confirmed by Belle and CLEO
  - Other narrow states discovered

Ds Spectrum

Results *consistent* with mesonic interpretation

Narrow width as state is below threshold and decay to pion channel is isospin suppressed



SU(3) flavor breaking ratio in hadronic matrix elements

Oleg Loktik
Columbia University

Summary

We reported on an attempt to calculate the ratio $\xi^2 = \frac{f_{B_s}^2 B_{B_s}}{f_{B_d}^2 B_{B_d}}$, which is relevant to CKM triangle fit, using a static formulation for heavy quarks and DWF formulation for light quarks. In particular, we are looking for any evidence of chiral log in the chiral limit. The preserved chirality, thanks to the use of DWF formulation, significantly simplifies the renormalization procedure. Moreover, the ratio itself is very stable against any variation in renormalization constants. An explaratory study was performed on a coarse $1/a = 1.3GeV$,and small $8^3 \times 24$ quenched lattice. The calculation on finer and larger, unquenched lattices is in progress.

Motivation

SM prediction for $B_q^0 - \bar{B}_q^0$ oscillation frequency $(q \in \{d, s\})$

$$\Delta m_q = \left(\frac{G_F^2 m_W^2 S_0}{16\pi^2 m_{B_q}} \right) |V_{tq}^* V_{tb}|^2 \eta_B \mathcal{M}_q$$

Experiment: $\Delta m_d = 0.502 \pm 0.007 ps^{-1}, \ \Delta m_s > 14.5 ps^{-1}$

$$\mathcal{M}_q = \langle \bar{B}_q^0 | [\bar{b}\gamma^\mu (1-\gamma^5) q][\bar{b}\gamma_\mu (1-\gamma^5) q] | B_q^0 \rangle = \frac{8}{3} m_{B_q}^2 f_{B_q}^2 B_{B_q}$$

We can constrain V_{td} with the following ratio

$$\frac{\Delta m_s}{\Delta m_d} = \left| \frac{V_{ts}}{V_{td}} \right|^2 \frac{m_{B_s}}{m_{B_d}} \xi^2$$

where

$$\xi^2 = \frac{f_{B_s}^2 B_{B_s}}{f_{B_d}^2 B_{B_d}}$$

Our Calculation

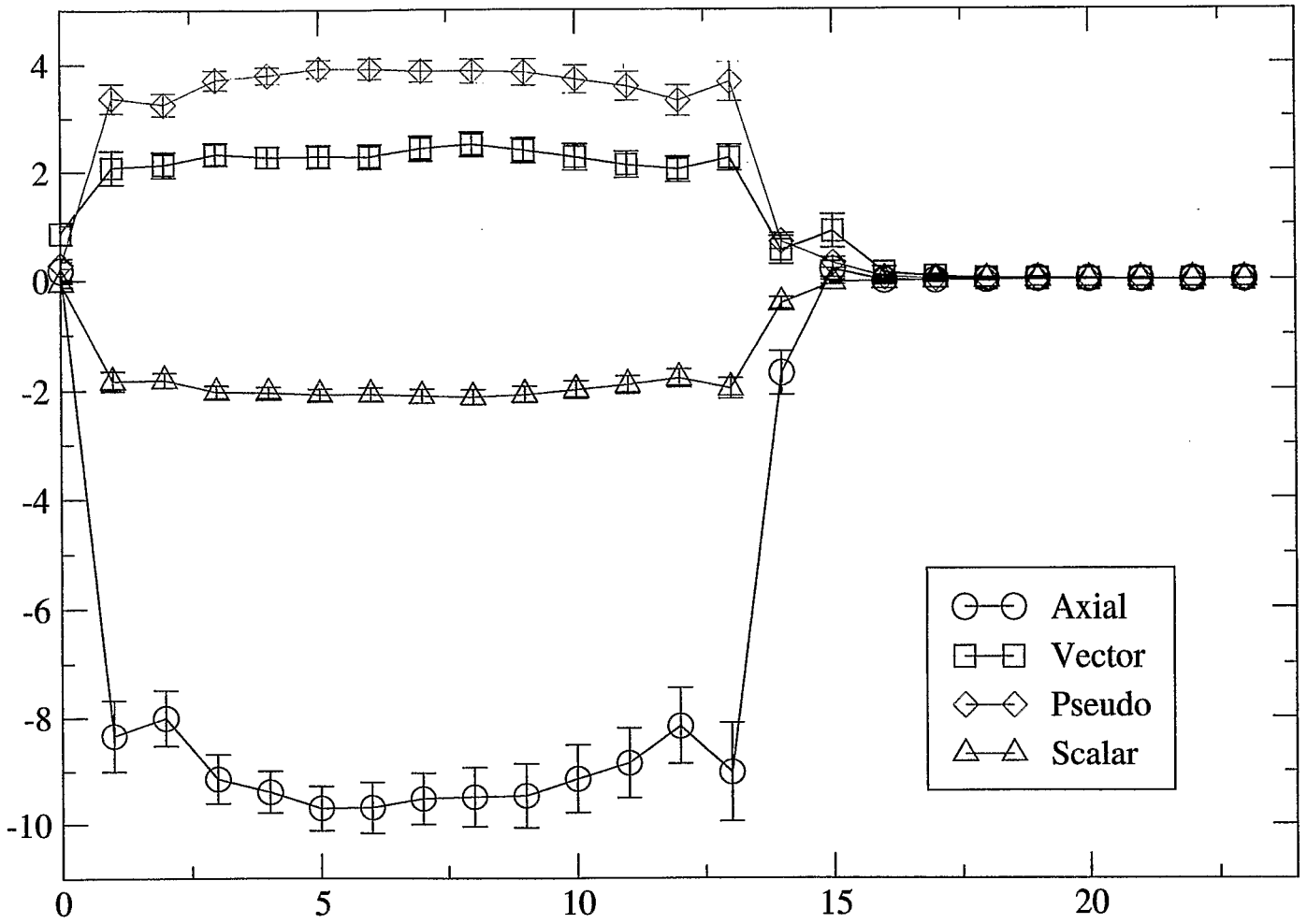
- Use DWF formulation for light quark
  - ➛ Allows to work at low quark masses
  - ➛ Preserved chirality significantly simplifies renormalization

For heavy quarks since $m_b a > 1$ we are forced to use some effective theory. HQET integrates out analytically heavy degrees of freedom. Full QCD Lagrangian is expanded in powers of $1/m_b$. Take leading order.

- Static approximation for heavy quark ($m_B \to \infty$)
  - ➛ Easy to implement
  - ➛ Well-understood limit of QCD

B-BBar three-point correlators with static(staple) and DWF

8^3x24 lattice; 200 conf; 1.3GeV; m= 0.025



Symmetry Constrains

Chiral symmetry, heavy quark spin symmetry simplify operator mixing:

$$O_L^{con}(\mu) = Z_L^{lat}(\mu) O_L^{lat}(\mu)$$

$$O_S^{con} = -\frac{1}{4}\left[Z_L^{lat}(\mu) - Z_S^{lat}(\mu)\right] O_L^{lat}(\mu) + Z_S^{lat}(\mu) O_S^{lat}(\mu)$$

$$O_L^{QCD}(\mu_B) = Z_L(\mu_B,\mu) O_L^{lat}(\mu) + Z_S(\mu_B,\mu) O_S^{lat}(\mu)$$

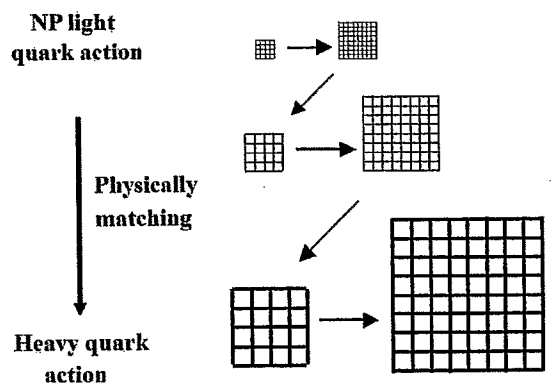
$$Z_L(\mu_B,\mu) = Z_L^{con}(\mu_B,\mu)\left[1 + \frac{\alpha_s^L(\mu_B)}{4\pi}\right]\left(4\, ln(a^2\mu^2) + D_L\right)$$

$$Z_S(\mu_B,\mu) = Z_S^{con}(\mu_B,\mu)$$

Relativistic Heavy Quark Actions

Huey-Wen Lin
Columbia University

We propose to determine the other non-trivial coefficients in the Fermilab heavy quark action by matching the finite-volume, on-shell heavy-heavy and heavy-light spectrum with those determined in the exact, relativistic theory. The matching relativistic amplitudes may be determined from finite-volume step-scaling recursion.



Relativistic heavy quark action - review

- The relativistic heavy quark action can be written down as

$$S = \sum_n \bar{\psi}_n (D_{RHQ} + m)\psi_n \quad (1)$$

$$D_{RHQ} + m = m + \gamma_0 D_0 + \zeta\vec{\gamma}\cdot\vec{D} - r_t a D_0^2 - r_s a\zeta(\vec{\gamma}\cdot\vec{D})^2 + \sum_i \frac{i}{2} c_E a\zeta\sigma_{0i}F_{0i} + \sum_{i,j}\frac{i}{4}c_B a\zeta\sigma_{ij}F_{ij} \quad (2)$$

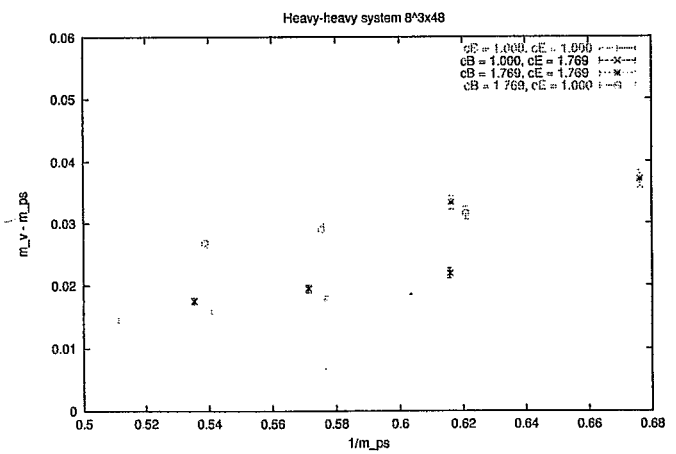
where $\zeta = \kappa_s/\kappa_t$.

- 4 parameters in the action to be tuned: ζ, r_s, c_E and c_B, as a function of ma (set redundant parameter $r_t = 1$).
- Fermilab approach:
  For on-shell quantities, $r_s = 1$. Tune ζ NP and use tadpole improved clover coefficients for c_E and c_B.
- Aoki approach:
  Determine these 4 parameters from one-loop calculations via quark propagator and quark-quark scattering diagram.

NP determined Fermilab coefficients

- ζ will be easily to determined from dispersion relation
- The question is: can we determine both c_E and c_B?

- c_B:



Heavy-heavy hyperfine splitting is dominated by c_B!!!!!!!

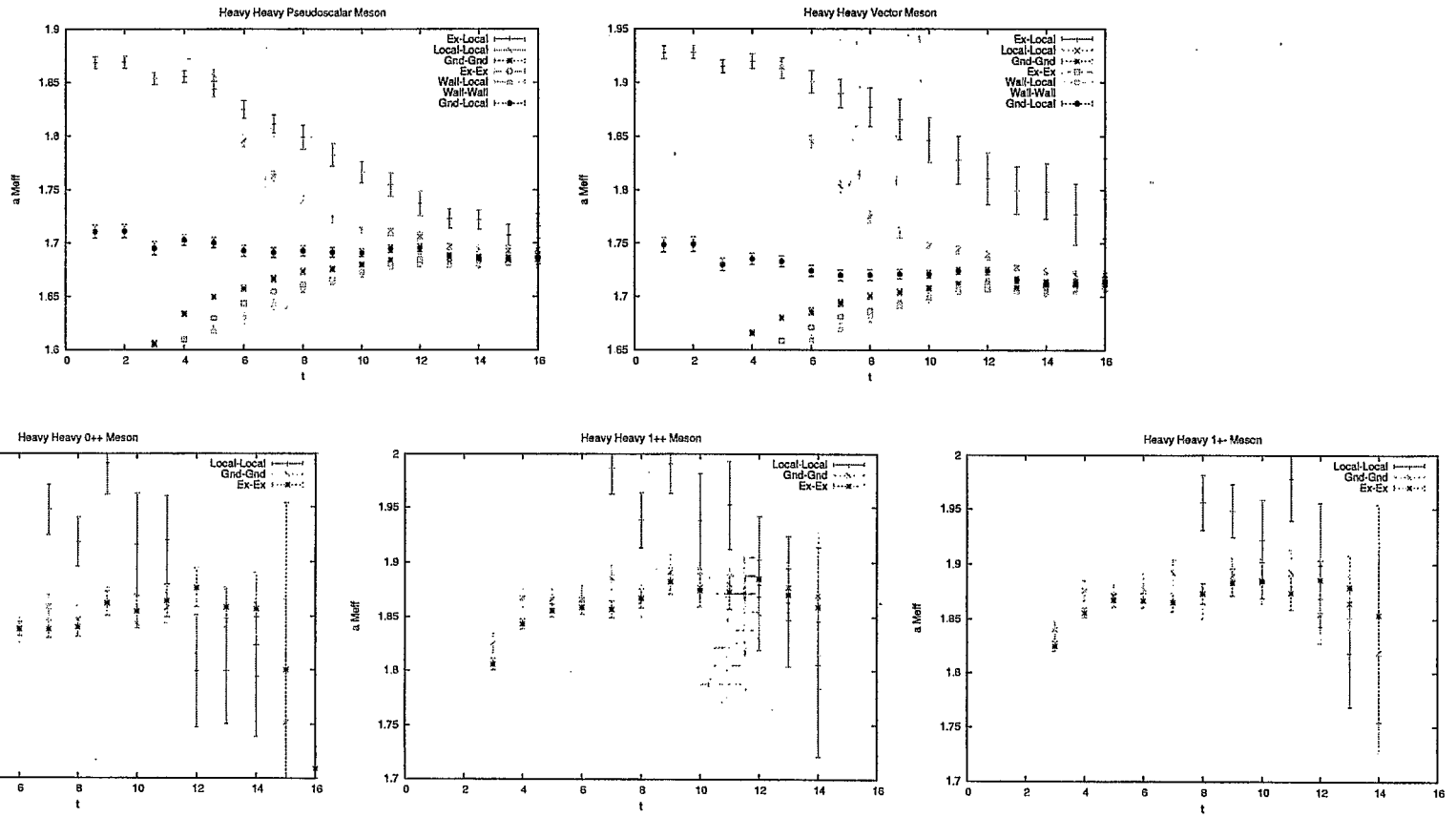
- c_E:
  Look at the energy in heavy-heavy and heavy-light system.
- Check the Jacobian:

$$\begin{pmatrix} \frac{dE^{HH}}{dm} & \frac{dE^{HH}}{dc_E} \\ \frac{dE^{HL}}{dm} & \frac{dE^{HL}}{dc_E} \end{pmatrix}$$

- Result on $16^3 \times 32$ lattice with 153 configurations with zero momentum:
  t=11-16: 5.203793e-03 +/- 7.638558e-04
- More statistics or smearing to extract the number with better accuracy. On-going project!!!

Gauge fixed hydrogenic source smearing

- 2 orthogonal smearing functions: $\Psi_{gnd}(r) = e^{-r/r_0}$ and $\Psi_{ex}(r) = (1-r/2r_0)e^{-r/2r_0}$
- Effective mass plot from heavy quark action with parameters of $c_E = c_B = 1.769, \kappa = 0.113636$ with 39 configurations.



Summary and outlook

On-going project for relativistic heavy quarks

- Fixing the Fermilab parameters non-perturbatively.
- Investigating on-shell step scaling approach - high statistics needed
- Brief study with the one-loop Aoki coefficients with physics quantities being pursued
  $\rightarrow$ would be a foundation for tuning the NP coefficients.
  $\rightarrow$ develop measurement system with perturbative coefficients
- Preliminary results show good qualities from spectrum data.
- D, B meson spectrum (S-states, P-states, radial excitations) with relativistic heavy quark actions combined with DWF light quark on quenched and dynamical DWF configurations.
- J/ψ, Υ meson spectrum (S, P, radial excitations) with relativistic heavy quark actions combined with DWF light quark on quenched and dynamical configurations.
- Heavy light decay constants

D and D_s on the Lattice with Domain Wall Fermions

Shigemi Ohta*

Abstract

RBC calculations of the D_s and D meson mass pectrum with domain wall fermion (DWF) quark and DBW2 gauge actions are described. These calculations are driven by Norikazu Yamada who is now in KEK. The calculations have been carried out on quenched 3 GeV cutoff lattices. At the statistics with 64 gauge configurations, splitting between parity partners with total spin $J = 0$ and 1, Δ_0 and $Delta_1$ appear degenerate when the heavy quark mass is set at charm quark mass or heavier. They seem to grow as we set the lighter quark mass lighter, $\Delta_{ud} > \Delta_s$. This is an on-going calculation with a tentative goal of 100 gauge configuration.

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Many lattice numerical calculations exist, with

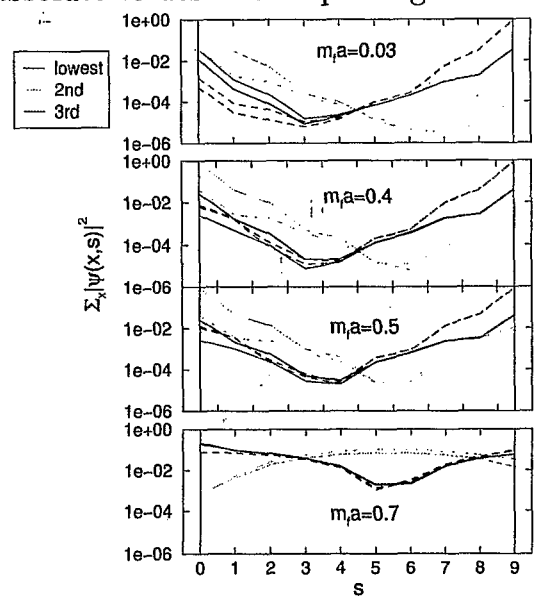
- clover/NRQCD/static heavy quarks and
- Wilson/clover light quarks.

But no systematic study seems available for

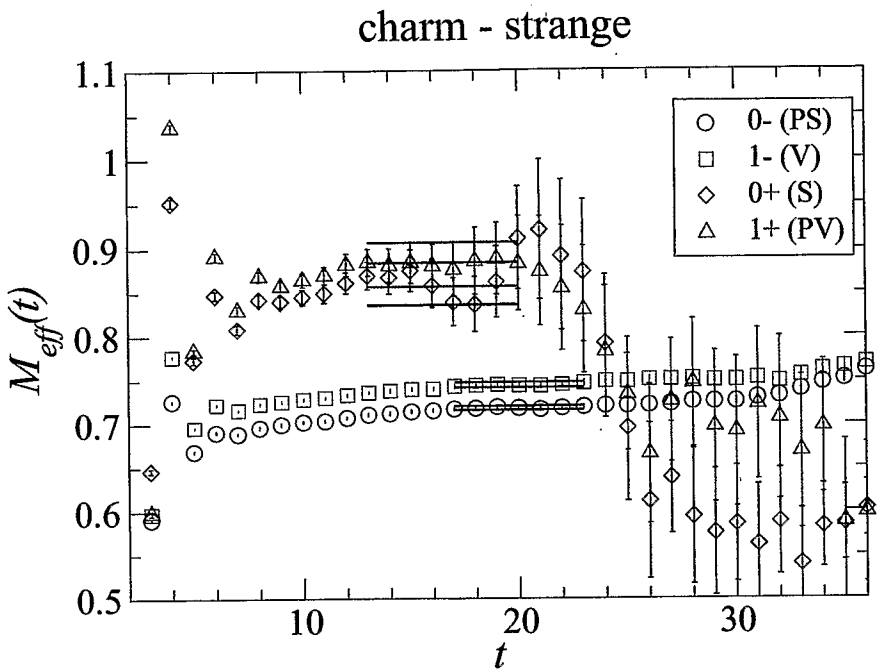
- dependence on m_{light},
- $\Delta_{s,0}$ and $\Delta_{s,1}$ degeneracy.

This work, with DWF, we'd like to address these issues, as well as the absolute values of the splittings.

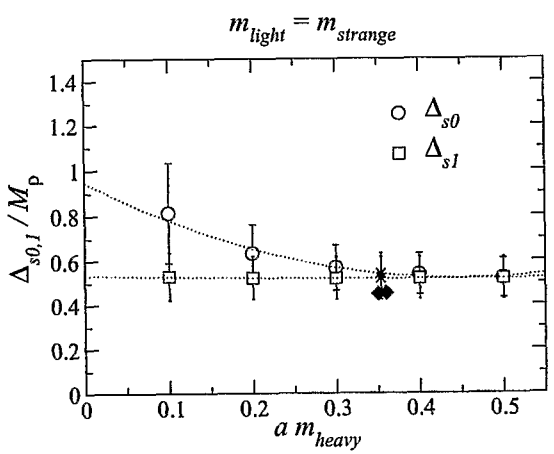
- Why DWF? For this particular system,
  - $O(a)$ error exponentially suppressed for up to $m_{\text{heavy}}a \leq 0.5$,
    - for the current lattice parameter, $a^{-1}\sim 3$ GeV and $L_s = 10$,
  - well-controlled chiral extrapolation for m_{light}.
- More generally,
  - more data expected from both B factories, and τ/charm factories,
  - comparison with heavy-quark effective models,
  - why not?



Effective mass: reasonable plateaux for all mesons

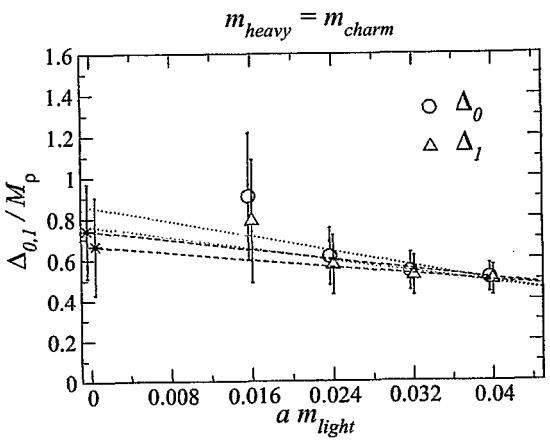


Dependence on heavy quark mass:



- $\Delta_{s,0}$: 417(70) MeV,
  - constant for $m_{\text{heavy}} \geq m_{\text{charm}}$,
  - larger for lighter m_{heavy}.
- $\Delta_{s,1}$: 401(74) MeV,
  - constant for all m_{heavy}.
- $\Delta_{s,0}$ and $\Delta_{s,1}$ are degenerate for $m_{\text{heavy}} \geq m_{\text{charm}}$.
- $\Delta_{s,J}$ consistent with experiment, albeit with large statistical errors.
- $K_1(1270) - K^*(892)$ splitting seems to support $\Delta_{s,1}$=constant.

Dependence on light quark mass:



- Δ_0: 571(177) MeV with three heavier m_{light} points,
- Δ_1: 515(183) MeV with three heavier m_{light} points,
- Both seem consistent with experiments,
  - especiallly the moderate slope,
  - albeit with large statistical error.

In summary: lattice calculations with DWF/DBW2 at 3 GeV show

- Splittings between different parities consistent with experiment, albeit with large statistical errors.
- $\Delta_{s,0}$ and $\Delta_{s,1}$ are degenerate for $m_{\text{heavy}} \geq m_{\text{charm}}$.
- $\Delta_s < \Delta_{ud}$ is likely reproduced.
- We need more statistics, 100 is planned and on-going.

Future: extend to decay constants and beyond?

Twisted Boundary Conditions and Application to Semileptonic Heavy-to-light Decays

Jonathan Flynn
University of Southampton

This is a short note on using twisted boundary conditions for lattice quark fields in order to access a continuous range of momentum values, with application to calculating form factors for heavy-to-light semileptonic meson decays, in particular D to pi plus leptons.

Twisted Boundary Conditions

- $\psi(x + e_i L) = e^{i\theta_i}\psi(x)$
- allowed momenta: $p_i = \frac{2\pi n_i}{L} + \frac{\theta_i}{L}$
- change variable: $\tilde{\psi}(x) = e^{-i\theta\cdot x}\psi(x)$ $(\theta_0 = 0)$
- $\tilde{\psi}$ satisfies PBC, propagator encodes shift: $S(x, y) \to S(x, y; \theta)$
- hadron momentum shifted by sum of quark shifts

Quenched study by de Divitiis, Petronzio and Tantalo (hep-lat/0405002)

Partial Twisting

Chiral PT analysis by Sachrajda, Villadoro, ...

- Exponential suppression for quantities without FSI (masses, decay constants, semileptonic FF's)
- Remains true for 'partial twisting': θ-BC for valence, PBC for sea

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Application to heavy-to-light semileptonic decays (eg: $D \to \pi l \nu$)

- at fixed quark masses: map out full q^2 range
- chiral extrapolation: generate points at fixed $E = v \cdot p_\pi$ for different light quarks and avoid fitting to a model FF

Summary and Look to the Future

Richard Kenway
School of Physics, The University of Edinburgh, Edinburgh, UK

QCDOC offers 10-100 times more computer power than ever before to generate ensembles with any particular lattice action. The current state-of-the-art is the MILC improved staggered ensemble, and so our goal should be to make a significant step forward from this data set. In the context of staggered quarks, we could make incremental improvements by generating bigger ensembles, with larger volumes, smaller lattice spacings, and/or smaller quark masses. MILC is planning to do this. But, to make a real impact, we need to extend the range of physics. The question is whether the technical challenges in controlling taste violation, applying partially quenched staggered perturbation theory and, possibly, dealing with non-locality, are too great. There is no prize for proving staggered quarks wrong! UKQCD also plans to carry out such an incremental improvement in the ensemble, and to extend the range of physics through using a variety of valence quark actions, such as DWF, HISQ and NRQCD. We estimate the resource required to be 6-8 months on 4 racks.

The alternative is to employ a formulation with exact chiral symmetry. Since this costs much more, we must be sure we can really exploit the advantages of chiral symmetry by running with light enough quarks on big enough volumes. This demands a coarse lattice and, hence, a gauge action that gives smooth enough gauge fields to avoid non-localities. Thus, an essential first step is to find suitable values of the rectangle coefficients in the DBW2 action for 2+1 flavours. It is also necessary to focus on physics that needs good chiral symmetry, eg to control operator mixing and power divergences, so that, although the computer costs are high, the human time to physics is reduced.

The computational costs will be an order of magnitude higher than staggered, even if we keep the u and d quark masses larger than 1/5 of the strange quark mass. We need around 20 QCDOC racks to do this within 12-24 months. These can only be found by pooling the resources available to both collaborations, and so we need to agree on the action. If we are happy with the residual mass being around 1/10 of the u and d quark masses, then there is little to choose between the different formulations and we might as well use DWF that we know scales well for quenched QCD. If we need the valence residual mass to be much smaller, we can reduce both valence and sea residual masses by a factor of 100 at no more than 40% increased cost using the continued fraction Zolotarev formulation. Jointly, we are well placed to aim for a range of big targets, such as nucleon structure and kaon physics, nucleon decays and the neutron edm that might constrain physics beyond the SM, the existence of exotics like pentaquarks, the CLEO-c challenge to compute charm leptonic and semileptonic decays to high precision, and $SU(3)$ flavour breaking in heavy-quark matrix elements needed for unitarity triangle tests at B factories.

In the future, we must look to petascale machines. The physics impact of QCDOC in the next 12-24 months will be critical in making the scientific case for this next big step.

summary and look to the future

- **starting point**
  - MILC 2+1 flavour improved staggered ensembles are the state of the art
- **QCDOC → 10-100× increase in computer power per action**
  - we must achieve a significant step forward
- **staggered quarks**
  - 10× ensemble sizes, lighter *ud* quarks, bigger volumes, continuum limit
    - these represent incremental improvements
  - for impact we need to extend the range of physics
    - but are the theoretical challenges too great?
    - control of taste violations, staggered PQχPT, possible non-locality
  - there is no prize for proving staggered quarks are wrong
- **(improved) DWF**
  - can we reach the chiral regime?
  - take the continuum limit?
  - we must use the chiral symmetry to reduce the (human) time to physics
    - eg by controlling operator mixing and power divergences

first steps

- **reproducibility tests**
  - 1024-node machines run for ~24 hours without even correctable errors
    - asqtad RHMC $16^3 \times 64$ reproducible for ~100 trajectories on rack 1
    - DWF HMC $16^3 \times 32$, $L_s = 12$, reproducible over 5 trajectories on rack 2
  - incorporate tests (translate lattice relative to hardware) into production schedule
- **production runs**
  - start on 1024-node machines as each passes basic tests
    - R algorithm study to optimise DBW2 rectangle coefficients for gauge field smoothness with 2+1 flavour DWF
    - start RHMC DWF $16^3 \times 32$, 2+1 flavour ensemble generation
  - phase in 2048 and 4096 node configurations
    - start asqtad $24^3 \times 64$, 2+1 flavour ensemble generation (held back by SCU-PLB problem)
- **increase clock speed to 450 MHz**
  - may help SCU link error rate

asqtad staggered quark physics beyond MILC

UKQCD + RBC

- **improvements relative to MILC ensemble**
  - incremental
    - ? tuned Lüscher-Weisz gluon action
    - one high statistics ensemble, better control of continuum and chiral limits
  - more physics
    - flavour singlets, various valence actions for light and heavy quarks
  - 6-8 months on 4 UKQCD racks

a (fm)	V	m_l/m_s	# traj	Tflop/s × yr
0.06	$48^3\times64$	1/5	3000	47%
0.09	$32^3\times64$	1/5	4000	11%
0.125	$24^3\times64$	1/5	30000	21%
0.125	$32^3\times64$	1/8	4000	10%
0.125	$32^3\times64$	1/10	4000	17%

continuum limit at fixed volume & quark mass

flavour singlets

chiral limit at fixed lattice spacing $m_{PS}L > 4$

towards full chiral symmetry

- **(improved) domain wall programme**
  - roughly 10-20 × cost of staggered ensembles even for $m_{ud}/m_s > 1/5$
- **coordinate ensemble generation across QCDOC machines**
  - fermion action
    - cost of all variants is similar if $m_{res} \sim m_{ud}/10$ … DWF has good scaling
    - if we need valence $m_{res} << $ sea m_{res}, can reduce both by 1/100 for ~ 40% extra cost using continued fraction Zolotarev formulation
  - gauge action
    - light quarks → big lattices → coarse lattices → highly-improved gauge action
    - 2+1 flavours coarser than 2 → optimise DBW2 for smoothness
  - 12-24 months on 20 racks
    - we can't afford to take longer!
- **we pay a lot for chiral symmetry, so use it and aim for some big targets**
    - m_{ud}, m_s, K physics and hadron structure → full chiral symmetry
    - excited and exotic hadron spectrum, eg pentaquarks
    - rare decays, N decay, neutron edm → beyond SM physics
    - charm leptonic and semileptonic decays → CLEO-c challenge
    - unitarity triangle heavy-quark matrix elements → B Factories

future machines

- **is there a future for purpose-built QCD machines?**
  - do we need them?
  - can we achieve better price/performance and/or better single-system performance than for any other architecture?
  - can we get funding?
- **actions**
  - make the science case
  - begin a design study aiming for $10M/sustained Pflops or better
  - target UK call for proposals in May 05, decision in May 06 → start now!
- **science case**
  - QCDOC must make an impact in 12-24 months
  - what are the physics objectives of a Pflops machine?
  - should the next machine must be optimised for (improved) DWF?
- **some results in Lat05, domination in Lat06/07**

Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines

Brookhaven National Laboratory, November 12-13, 2004

Participants

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Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines

Physics Department, Small Seminar Room

November 12 -13, 2004

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Friday, November 12:

8:30 - 9:00	**Visit BNL Housing Office, Bldg. 179B) to pay for accommodations (Not possible Thursday, BNL closed for Veterans' Day Holiday)
9:00 -10:30	Machine/Code Status, Reproducibility Tests, Production Runs [Mawhinney] (Boyle, Dawson, Jung, Clark, Kenway, M.Lin, Mawhinney)
10:30 -11:00	***Coffee***
11:00 -12:00	Physics on Improved Staggered Ensembles [Maynard]
	11:00 - 11:30 Mixed Actions (Maynard)
	11:30 - 12:00 RMT (Hart)
12:00 - 1:00	***Lunch***
1:00 - 1:30	**Visit Human Resources, if necessary, to complete security procedures (see your folder)
1:30 - 3:30	Physics on DWF Ensembles (A) [Ohta and Maynard]:
	1:30 - 1:45 Ordinary Hadron Mass Spectrum and Decay Constants (Dawson)
	1:45 - 2:15 Excited and Exotic Hadron Mass Spectrum (Maynard and Doi)
	2:15 - 2:30 Nucleon Axial Charge and Structure Function Moments (Orginos)
	2:30 - 3:00 Nucleon EM Form Factors and Neutron edm (Yamaguchi and Blum)
	3:00 - 3:30 Nucleon Decay (Tweedie and Ohta)
3:30 - 4:00	***Coffee***
4:00 - 5:30	On-Shell Chiral Fermion Algorithms [Kennedy]
	4:00 - 4:45 Testing 5D Chiral Operators (Joo)
	5:00 - 5:20 Moebius Fermions (Orginos)
6:30	***Dinner***

Saturday, November 13:

9:00 - 10:30 Physics on DWF ensembles (B) Kaon Matrix Elements, em Effects [Christ]:

9:00 - 9:15	Delta I = 1/2 Rule and CP Violation using Chiral Perturbation Theory with and without Active Charm (Noaki)
9:20 - 9:35	K->pi-pi Decays (Yamazaki)
9:40 - 9:50	K->pi-pi Decays (Christ)
9:55 - 10:10	g-2 and Electromagnetic Splittings (Blum)
10:15 - 10:30	g-2 light-by-light Scattering & Electromagnetic Splitting (Izubuchi)

10:30 - 11:00 ***Coffee***

11:00 - 12:30 Physics on DWF Ensembles (C) [Flynn]:

11:00 - 11:20	SU(3) Flavor Breaking in Hadronic Matrix Elements (Loktik)
11:30 - 11:50	Relativistic Heavy Quark Actions (H.Lin)
12:00 - 12:20	D-meson Spectroscopy with DWF (Ohta)

12:30 - 1:00 Summary and Look to the Future (Kenway)

1:00 - 2:00 *****Lunch** (beware, serving of lunch stops at 1:30 pm; only snacks from 1:30-2:00)*

2:00 - 4:00 Informal Meetings

Additional RIKEN BNL Research Center Proceedings:

Volume 68 – Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines – BNL-
Volume 67 – High Performance Computing with BlueGene/L and QCDOC Architectures – BNL-
Volume 66 – RHIC Spin Collaboration Meeting XXIX, October 8-9, 2004, Torino Italy – BNL-73534-2004
Volume 65 – RHIC Spin Collaboration Meetings XXVII (July 22, 2004), XXVIII (September 2, 2004), XXX (December 6, 2004) - BNL-73506-2004
Volume 64 – Theory Summer Program on RHIC Physics – BNL-73263-2004
Volume 63 – RHIC Spin Collaboration Meetings XXIV (May 21, 2004), XXV (May 27, 2004), XXVI (June 1, 2004) – BNL-72397-2004
Volume 62 – New Discoveries at RHIC, May 14-15, 2004 – BNL- 72391-2004
Volume 61 – RIKEN-TODAI Mini Workshop on "Topics in Hadron Physics at RHIC", March 23-24, 2004 – BNL-72336-2004
Volume 60 – Lattice QCD at Finite Temperature and Density – BNL–72083-2004
Volume 59 – RHIC Spin Collaboration Meeting XXI (January 22, 2004), XXII (February 27, 2004), XXIII (March 19, 2004)– BNL-72382-2004
Volume 58 – RHIC Spin Collaboration Meeting XX – BNL-71900-2004
Volume 57 – High pt Physics at RHIC, December 2-6, 2003 – BNL-72069-2004
Volume 56 – RBRC Scientific Review Committee Meeting – BNL-71899-2003
Volume 55 – Collective Flow and QGP Properties – BNL-71898-2003
Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX – BNL-71751-2003
Volume 53 – Theory Studies for Polarized *pp* Scattering – BNL-71747-2003
Volume 52 – RIKEN School on QCD "Topics on the Proton" – BNL-71694-2003
Volume 51 – RHIC Spin Collaboration Meetings XV, XVI – BNL-71539-2003
Volume 50 – High Performance Computing with QCDOC and BlueGene – BNL-71147-2003
Volume 49 – RBRC Scientific Review Committee Meeting – BNL-52679
Volume 48 – RHIC Spin Collaboration Meeting XIV – BNL-71300-2003
Volume 47 – RHIC Spin Collaboration Meetings XII, XIII – BNL-71118-2003
Volume 46 – Large-Scale Computations in Nuclear Physics using the QCDOC – BNL-52678
Volume 45 – Summer Program: Current and Future Directions at RHIC – BNL-71035
Volume 44 – RHIC Spin Collaboration Meetings VIII, IX, X, XI – BNL-71117-2003
Volume 43 – RIKEN Winter School – Quark-Gluon Structure of the Nucleon and QCD – BNL-52672
Volume 42 – Baryon Dynamics at RHIC – BNL-52669
Volume 41 – Hadron Structure from Lattice QCD – BNL-52674
Volume 40 – Theory Studies for RHIC-Spin – BNL-52662
Volume 39 – RHIC Spin Collaboration Meeting VII – BNL-52659
Volume 38 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 37 – RHIC Spin Collaboration Meeting VI (Part 2) – BNL-52660
Volume 36 – RHIC Spin Collaboration Meeting VI – BNL-52642
Volume 35 – RIKEN Winter School – Quarks, Hadrons and Nuclei – QCD Hard Processes and the Nucleon Spin – BNL-52643
Volume 34 – High Energy QCD: Beyond the Pomeron – BNL-52641

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Volume 33 – Spin Physics at RHIC in Year-1 and Beyond – BNL-52635
Volume 32 – RHIC Spin Physics V – BNL-52628
Volume 31 – RHIC Spin Physics III & IV Polarized Partons at High Q^2 Region – BNL-52617
Volume 30 – RBRC Scientific Review Committee Meeting – BNL-52603
Volume 29 – Future Transversity Measurements – BNL-52612
Volume 28 – Equilibrium & Non-Equilibrium Aspects of Hot, Dense QCD – BNL-52613
Volume 27 – Predictions and Uncertainties for RHIC Spin Physics & Event Generator for RHIC Spin Physics III – Towards Precision Spin Physics at RHIC – BNL-52596
Volume 26 – Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics – BNL-52588
Volume 25 – RHIC Spin – BNL-52581
Volume 24 – Physics Society of Japan Biannual Meeting Symposium on QCD Physics at RIKEN BNL Research Center – BNL-52578
Volume 23 – Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies – BNL-52589
Volume 22 – OSCAR II: Predictions for RHIC – BNL-52591
Volume 21 – RBRC Scientific Review Committee Meeting – BNL-52568
Volume 20 – Gauge-Invariant Variables in Gauge Theories – BNL-52590
Volume 19 – Numerical Algorithms at Non-Zero Chemical Potential – BNL-52573
Volume 18 – Event Generator for RHIC Spin Physics – BNL-52571
Volume 17 – Hard Parton Physics in High-Energy Nuclear Collisions – BNL-52574
Volume 16 – RIKEN Winter School - Structure of Hadrons - Introduction to QCD Hard Processes – BNL-52569
Volume 15 – QCD Phase Transitions – BNL-52561
Volume 14 – Quantum Fields In and Out of Equilibrium – BNL-52560
Volume 13 – Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration – BNL-66299
Volume 12 – Quarkonium Production in Relativistic Nuclear Collisions – BNL-52559
Volume 11 – Event Generator for RHIC Spin Physics – BNL-66116
Volume 10 – Physics of Polarimetry at RHIC – BNL-65926
Volume 9 – High Density Matter in AGS, SPS and RHIC Collisions – BNL-65762
Volume 8 – Fermion Frontiers in Vector Lattice Gauge Theories – BNL-65634
Volume 7 – RHIC Spin Physics – BNL-65615
Volume 6 – Quarks and Gluons in the Nucleon – BNL-65234
Volume 5 – Color Superconductivity, Instantons and Parity (Non?)-Conservation at High Baryon Density – BNL-65105
Volume 4 – Inauguration Ceremony, September 22 and Non -Equilibrium Many Body Dynamics –BNL-64912
Volume 3 – Hadron Spin-Flip at RHIC Energies – BNL-64724
Volume 2 – Perturbative QCD as a Probe of Hadron Structure – BNL-64723
Volume 1 – Open Standards for Cascade Models for RHIC – BNL-64722

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RIKEN BNL RESEARCH CENTER

Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines

November 12-13, 2004

Li Keran

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

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Speakers:

Thomas Blum	Norman Christ	Michael Clark	Chris Dawson	Takumi Doi
Jonathan Flynn	Alistair Hart	Taku Izubuchi	Balint Joo	Richard Kenway
HueyWen Lin	Meifeng Lin	Oleg Loktik	Robert Mawhinney	Chris Maynard
Jun-Ichi Noaki	Shigemi Ohta	Robert Tweedie	Azusa Yamaguchi	Takeshi Yamazaki

Organizers: N. Christ, R. Kenway, R. Mawhinney, and S. Ohta