

# Heavy quark physics with light dynamical quarks (plus a lot of other stuff)

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HPQCD and UKQCD collaborations

Key aim of HPQCD collabn: accurate calcs in lattice QCD, emphasising heavy q physics. Requires a whole range of lattice systematic errors to be simultaneously minimised - critical one has been inclusion of light dynamical quarks.

- Current results on heavy quark physics,  $\alpha_s$  etc
- Developments for calculations for next 1-2 years

Japan Sept 2004

## People involved in various aspects of this work:

I. Allison, S. Collins, CD, K. Foley, E. Follana, E. Gamiz, A. Gray, E. Gulez, A. Hart, P. Lepage, Q. Mason, M. Nobes, J. Shigemitsu, H. Trotter, M. Wingate

HPQCD/UKQCD

C. Aubin, C. Bernard, T. Burch, C. DeTar, S. Gottlieb, E. Gregory, U. Heller, J. Hetrick, J. Osborn, R. Sugar, D. Toussaint,

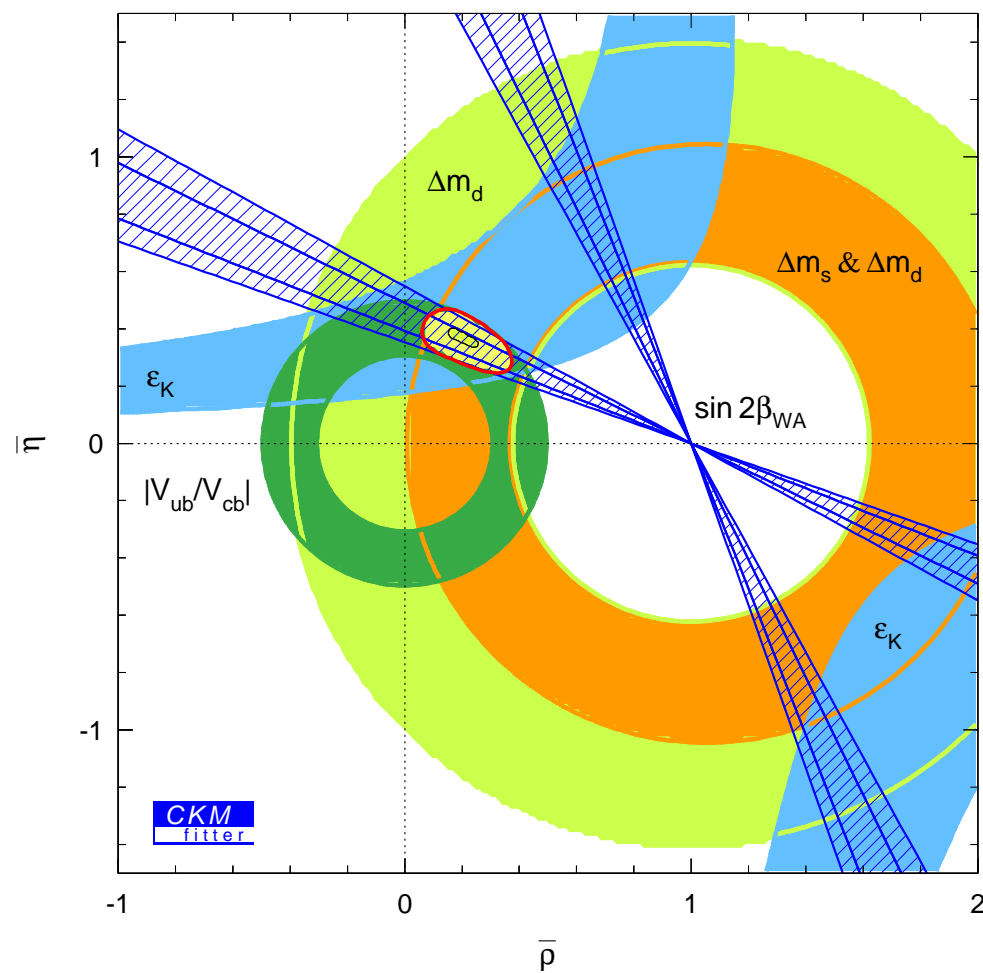
MILC

M. Di Pierro, A. El-Khadra, A. Kronfeld, P. Mackenzie, D. Menscher, M. Okamoto, J. Simone

HPQCD/Fermilab

# The Unitarity triangle

Important objective of current particle physics: accurate determination of elements of CKM matrix.



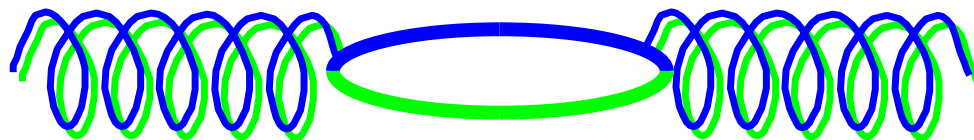
$B$  factory prog. needs small 2-3% *reliable* lattice QCD errors for  $B_{s/d}$  oscillations,  $B \rightarrow D$  or  $\pi$  decay.

CLEO-c will test lattice predictions for  $D$  physics in next 2 years.

Requires *all* systematic errors to be small simultaneously. Precise quenched calcs are no good!

## HPQCD/MILC results 2003

MILC collab. have used improved staggered quark formalism (+ highly improved gluon action) to generate ensembles of configurations which include 2+1 flavours of dynamical quarks.



2 =  $u, d$  degenerate with masses down to  $m_s/8$ .

1 =  $s$  (can ignore heavy  $c, b, t$  dynamical qs.)

3 values of lattice spacing,  $a \approx 0.087$  fm and 0.12fm and 0.18fm.

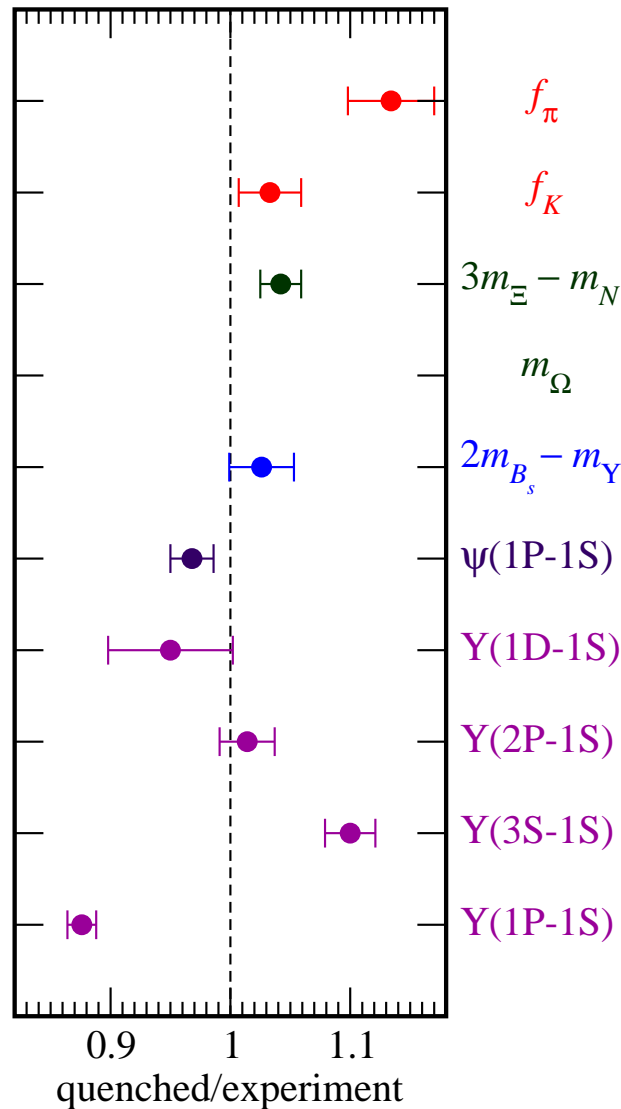
Fix 5 free parameters of QCD (bare  $m_u = m_d, m_s, m_c, m_b$ , and  $a \equiv \alpha_s$ ) using

$m_\pi, m_K, m_{D_s}, m_\Upsilon$  and  $\Delta E_\Upsilon(2S - 1S)$ . These are 'gold-plated' quantities (e.g. stable hadron masses).

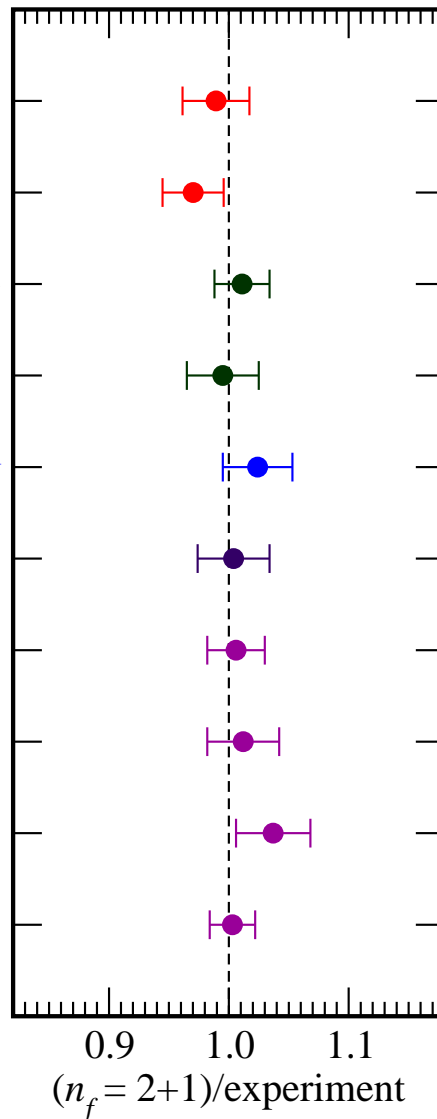
Compute other 'gold-plated' quantities as a test of (lattice) QCD.

# Lattice QCD/Experiment (no free parameters!):

Before



Now



Tests:

light mesons and baryons

heavy-light mesons

heavyonium

Find agreement with expt (at last!) when correct dyn. quark content is present.

Quenched approx. has syst. errors 10% and internal inconsistency.

Davies *et al*, hep-lat/0304004 + Toussaint, Davies, LAT04

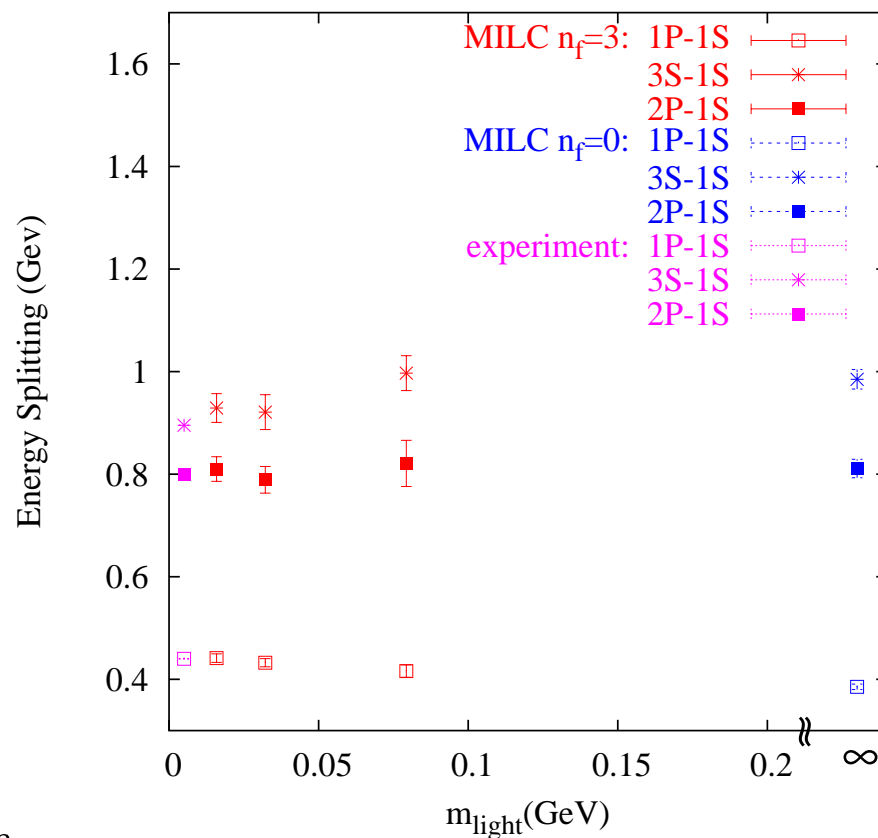
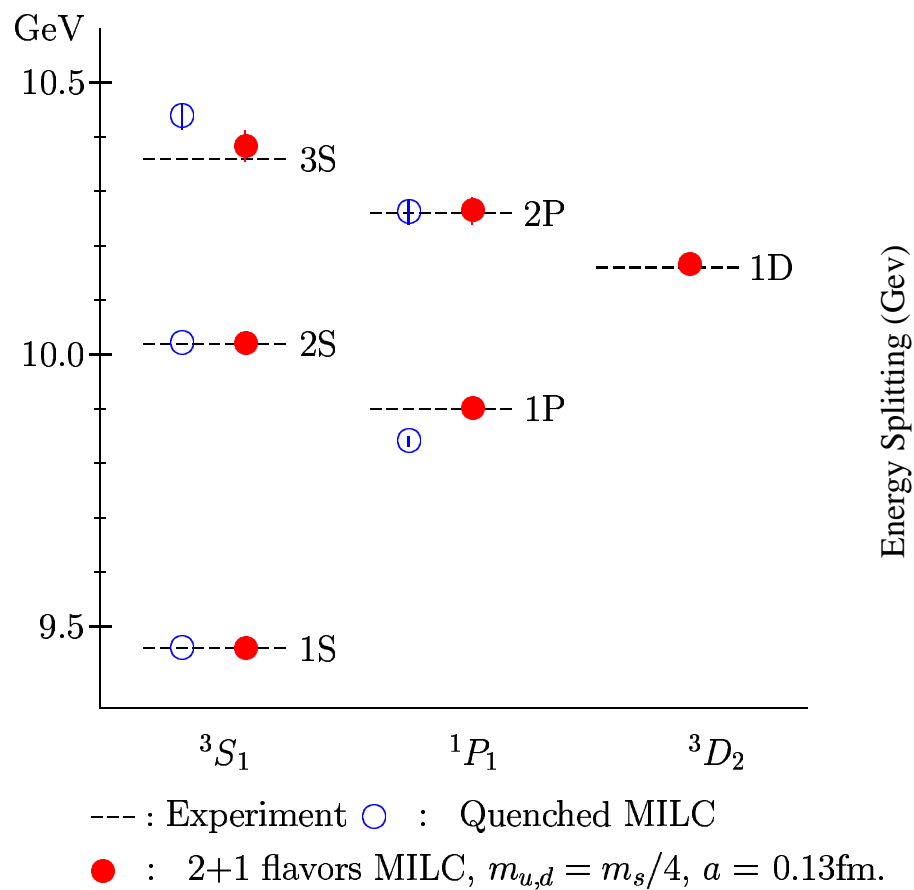
# $\Upsilon(b\bar{b})$ spectrum

Lattice NRQCD for  $bs$  on MILC configs. Tests/tunes action for  $B_s$ .

2S-1S fixes  $a$  and 1S fixes  $am_b$ .

1-loop matching gives  $m_{b,\overline{MS}}(m_{b,\overline{MS}})=4.3(3)$  GeV.

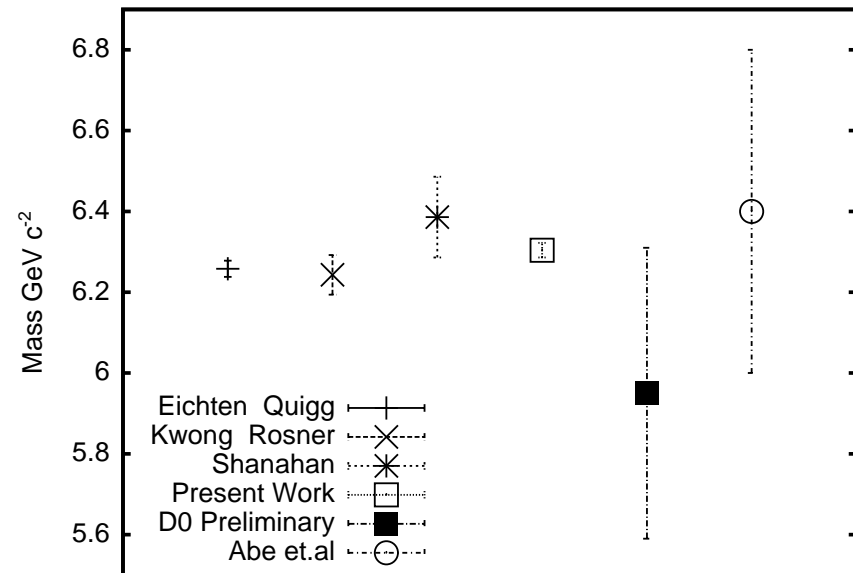
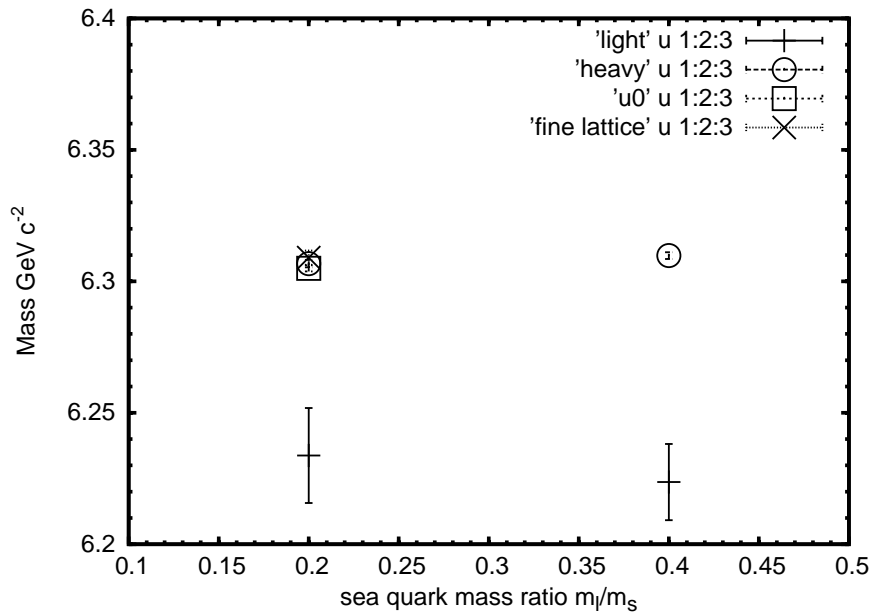
Further tests - fine structure, leptonic width, in progress.



Gray, Davies et al, HPQCD, hep-lat/0310041, Gulez, Shigemitsu, hep-lat0312017.

## Prediction of $B_c$ mass.

From difference between mass of  $B_c$  (NRQCD  $b$ , Fermilab  $c$ ) and average of  $\Upsilon$  and  $J/\psi$ , get  $6.305(20)$  GeV.



New exptl results expected from run II at FNAL.

Allison, Davies, Gray, Kronfeld, Mackenzie, Simone (HPQCD), LAT04

## Precise determination of $\alpha_s$ .

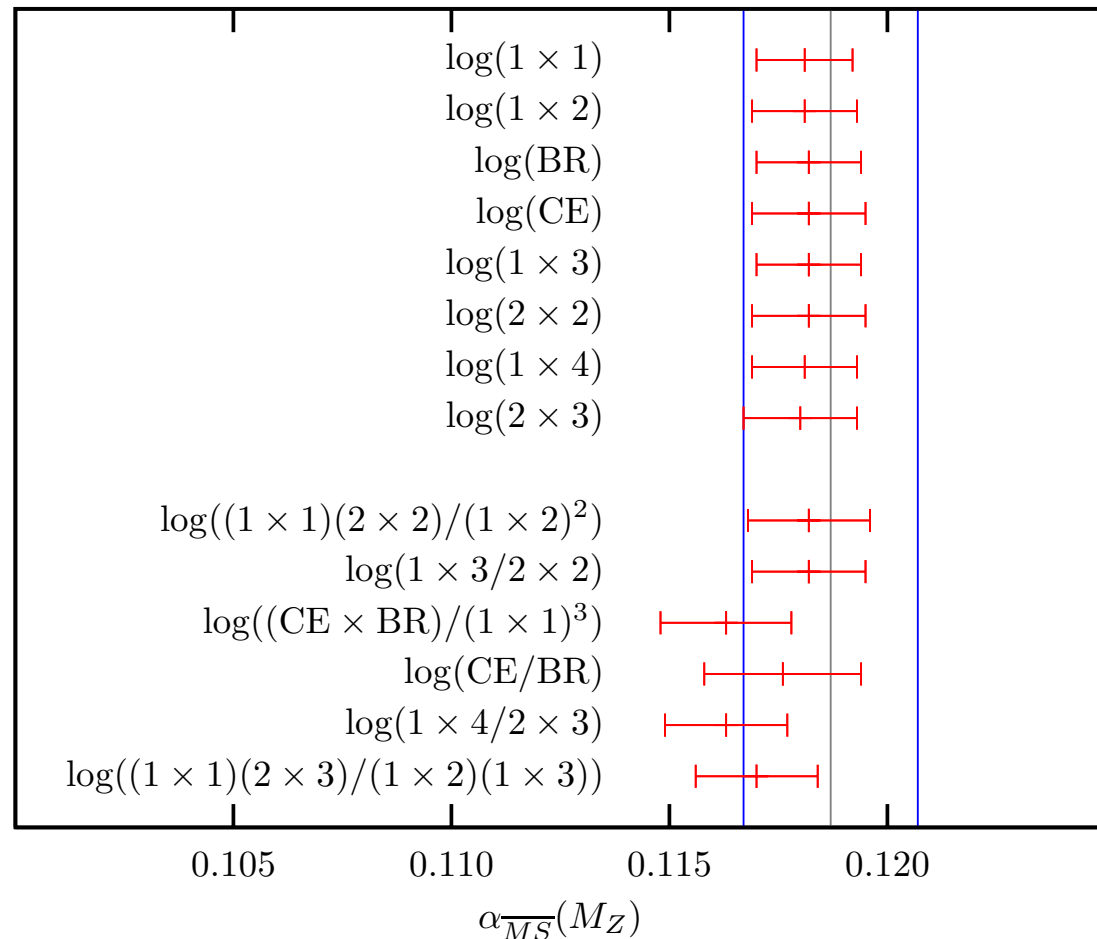
Mean value of various Wilson loops and their ratios calculated to 3rd order in lattice pert. th. and on the lattice.

Results available at 3 values of  $a$  (inc. MILC super-coarse) allows higher order terms to be estimated.

Preliminary result:  $\alpha_s(M_Z) = 0.1181(15)$ .

Improves on PDG.

Lattice Results Compared With PDG-04



Mason, Trottier, *et al* (HPQCD), LAT04

## Gold-plated quantities for the CKM matrix

Gold-plated decays (i.e. at most one hadron in final state) exist for almost every element (+  $K - \bar{K}$  mixing). Can now calculate these accurately in lattice QCD.

Important for lattice calcs to have extensive cross-checks for error calibration:  $\Upsilon$ ,  $B$ ,  $\psi$ ,  $D$ , etc.

$$\left( \begin{array}{ccc} \mathbf{V}_{ud} & \mathbf{V}_{us} & \mathbf{V}_{ub} \\ \pi \rightarrow l\nu & K \rightarrow l\nu & B \rightarrow \pi l\nu \\ & K \rightarrow \pi l\nu & \\ \mathbf{V}_{cd} & \mathbf{V}_{cs} & \mathbf{V}_{cb} \\ D \rightarrow l\nu & D_s \rightarrow l\nu & B \rightarrow D l\nu \\ D \rightarrow \pi l\nu & D \rightarrow K l\nu & \\ \mathbf{V}_{td} & \mathbf{V}_{ts} & \mathbf{V}_{tb} \\ \langle B_d | \bar{B}_d \rangle & \langle B_s | \bar{B}_s \rangle & \end{array} \right)$$

## Unquenched results for $f_{B_s}$ and $B_{B_s}$

Use MILC dynamical 2+1 configs. Make a  $B_s$  meson from an NRQCD  $b$  quark and an improved staggered  $s$  antiquark.

Gives:

$$f_{B_s} = 260 \pm 7(\text{stat}) \pm 26 \text{ (p.th.)} \pm 8 \text{ (rel)} \pm 5 \text{ (disc) MeV}$$

Major error is from matching to contnm in pert. th. (done through  $\mathcal{O}(\alpha_s/M)$ ), 2-loop calcn underway (Mason, Nobes, Trottier).

Preliminary result on  $B - \bar{B}$  mixing:

$$f_{B_s} \sqrt{B_{B_s}(m_b)} = 0.197(16)(28) \text{ GeV}$$

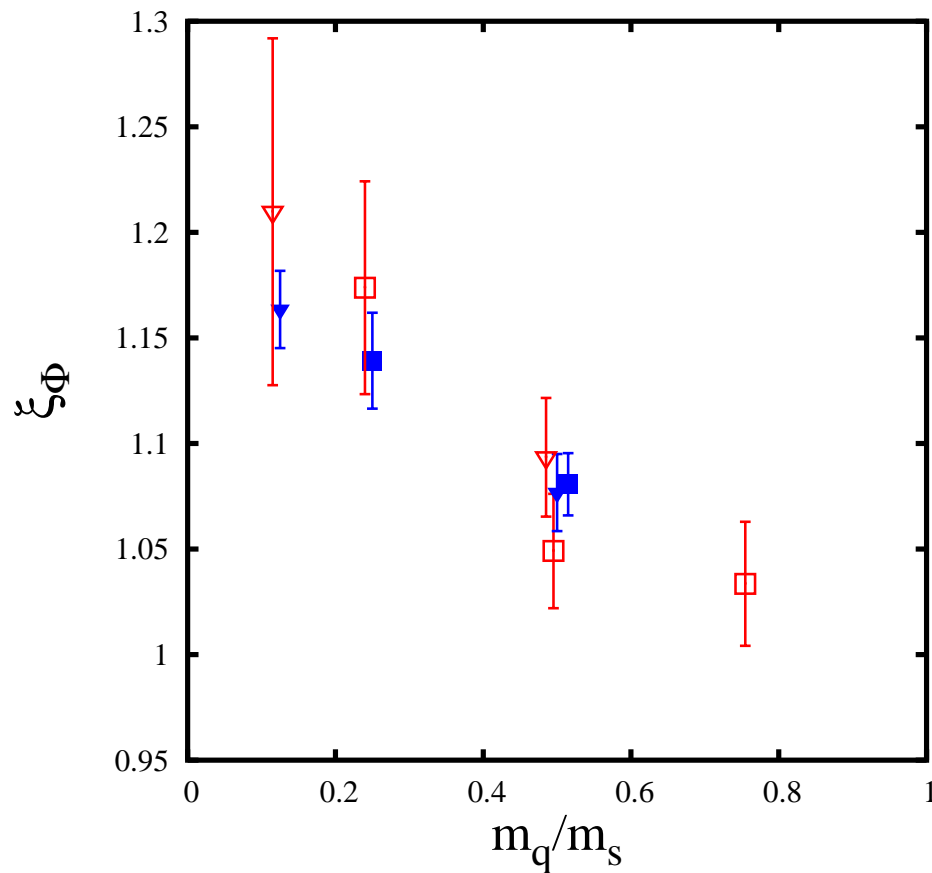
Matched to  $\mathcal{O}(\alpha_s)$ .

Wingate, Shigemitsu, HPQCD, hep-lat/0311130; Gray, Shigemitsu, LAT04

## Unquenched results for $f_B$

Calculate  $\xi = f_{B_s} \sqrt{M_{B_s}} / f_{B_d} \sqrt{M_{B_d}}$ , pert. Zs cancel.

'Hot' issue is chiral extrapoln. Expect large log term, becomes visible with light dynamical quarks.

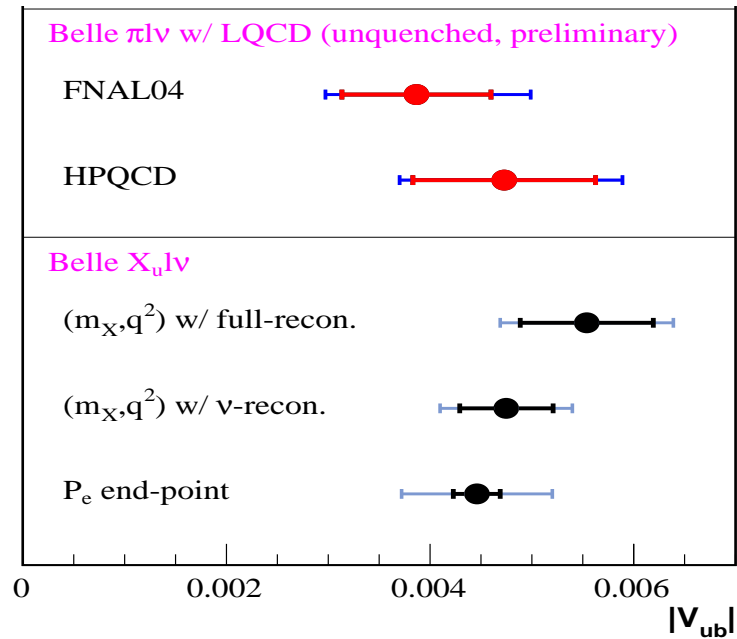
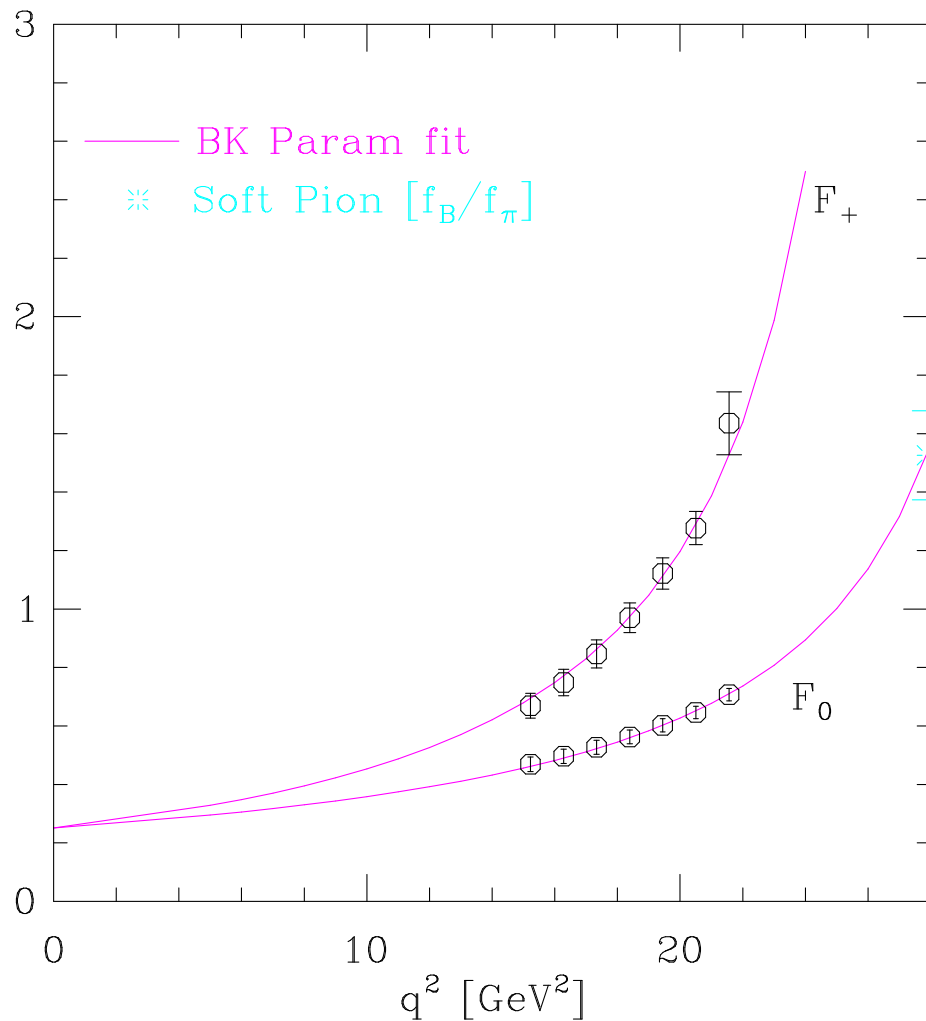


Results significantly improved on smearing - now do staggered chiral extrapolns (Aubin, Bernard).

Gray, Gulez, Shigemitsu, LAT04

# Unquenched results for $B \rightarrow \pi$ form factors

Extrapoln to physical  $m_\pi$  is done at fixed  $E_\pi$  and is not far (lightest  $m_\pi = 260$  MeV).



Used by Belle in new  $V_{ub}$  determination. (hep-ex/0408145)

Shigemitsu+Gulez, HPQCD, LAT04

## Future work on $B \rightarrow \pi$

Repeat on fine MILC lattices and renormalise current with 2-loop calcn.  
May also manage  $D$  on coarse MILC (but see later).

Will also focus on moving NRQCD.

Problem with  $B \rightarrow \pi$  is large stat. + syst. errors at large  $(pa)$  of  $\pi$ .  
Instead, give  $B$  momentum in lattice frame. Most of this is carried by  $b$  and can be treated exactly (not discretised).

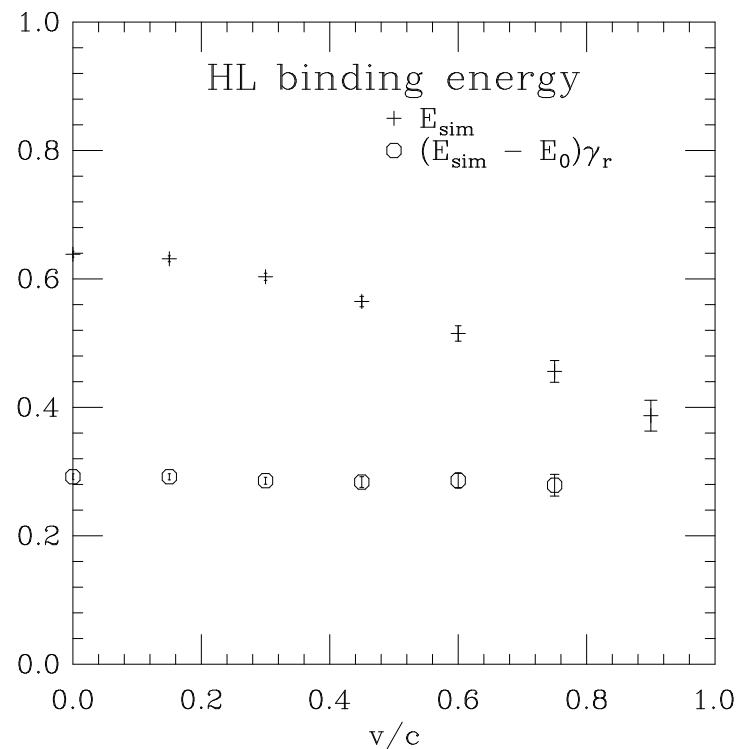
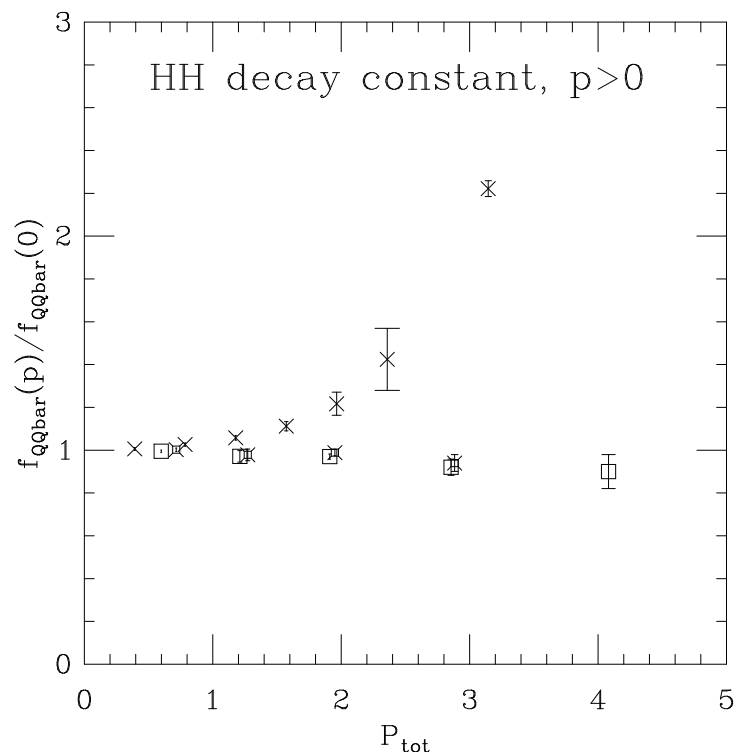
$P_b = m_b u + k$ .  $u = \gamma(1, \vec{v})$ . Remnant reparam. inv. on lattice protects  $m_b u$  from large renormln.

Can then cover whole  $q^2$  range for  $B \rightarrow \pi$ .

Early work by Hashimoto and Sloan. We have extended action, tested heavy-heavy and heavy-light and done  $\mathcal{O}(\alpha_s)$  pert. th.

# Tests of moving NRQCD

Simplest  $H$  used in quenched tests:  $(-D^2 + (v \cdot D)^2)/2m\gamma - iv \cdot D$ .



All looks good.  $v$  dependence not large and can be understood.

Now try real calcs ...

Foley, Lepage, Davies, Dougall, HPQCD, LAT04

## Current status - $B_K$

Best quenched  $B_K$  from JLQCD using unimproved staggered quarks.

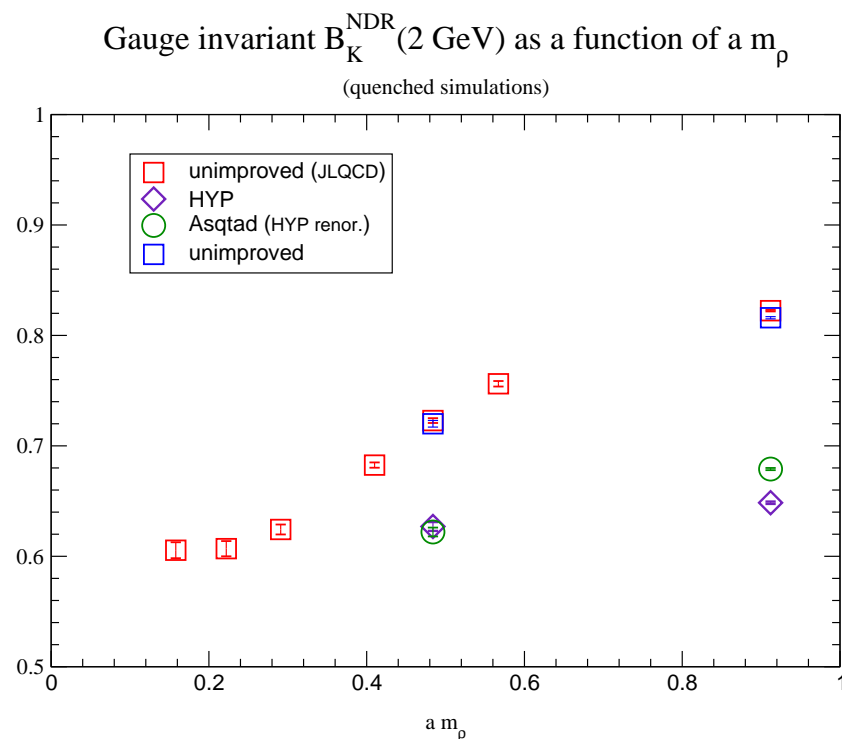
**but** these results apparently have large disc. errors.

New results with imp. staggered quarks show much better scaling.

This may be largely a renormln. effect, in fact.

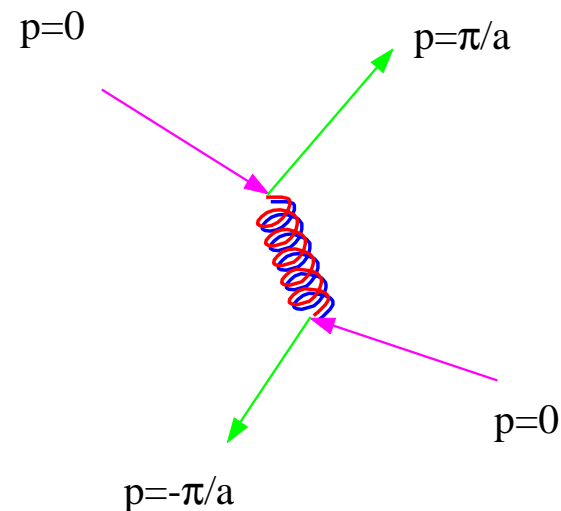
$B_K$  in dynamical QCD in progress (HPQCD).

Gamiz, Collins, Davies, HPQCD, LAT04



## Further improving the staggered formalism

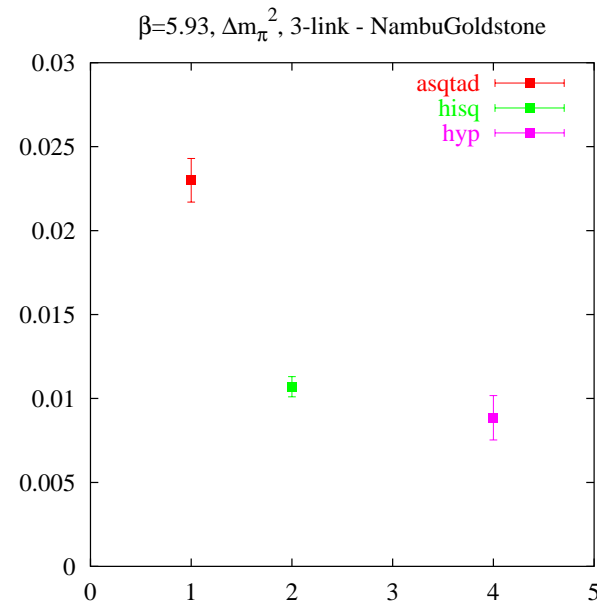
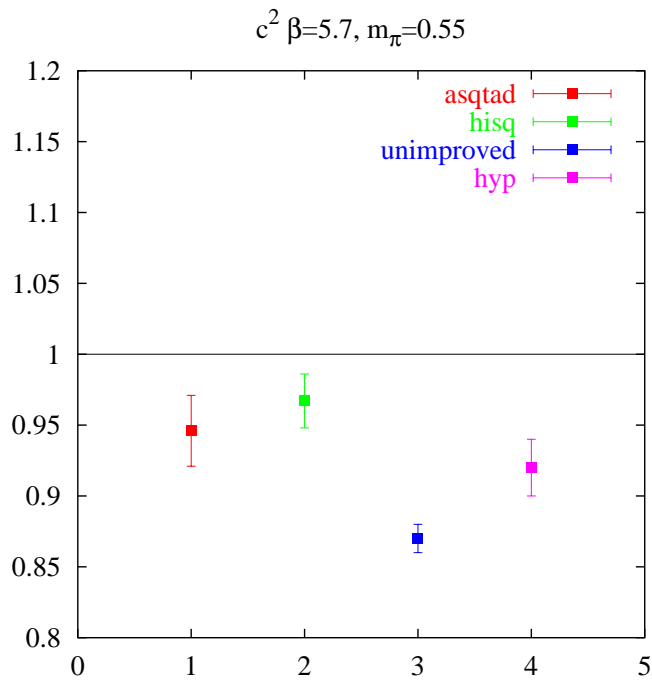
Limit to precision with asqtad improved staggered quarks is still taste-changing interactions associated with high-momentum gluon exchange.



Improve action further by repeating the 'Fat7' smearing. Add Naik and Lepage terms (x2) as before to keep an action with  $\alpha_s a^2$  errors *only*. This is the Highly Improved Staggered Quark action (HISQ).

# Discretisation errors

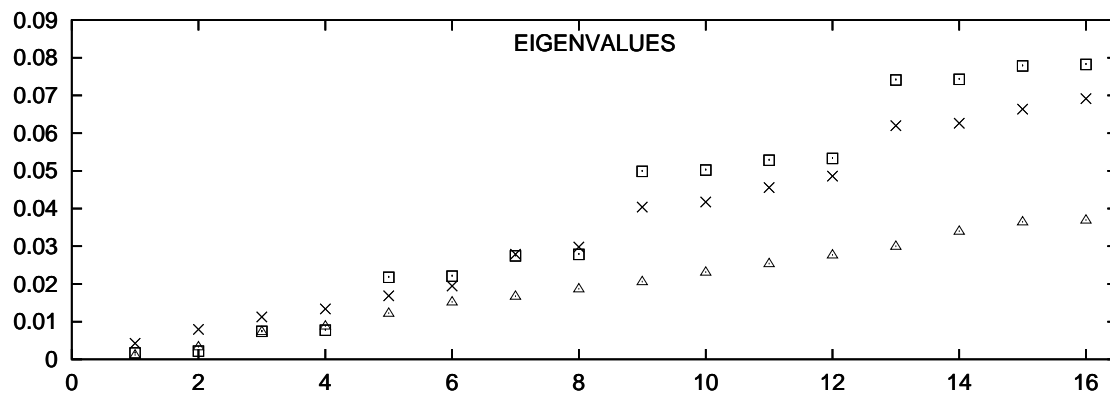
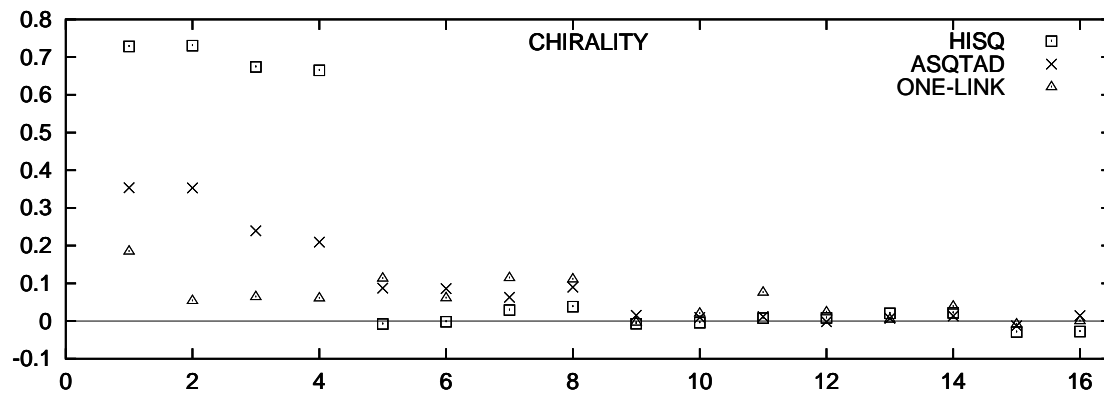
HISQ shows v. good behaviour on taste-changing and dispersion reln.



Follana, Mason, Davies, HPQCD, in preparation

## Sensitivity to topology of the staggered formalism

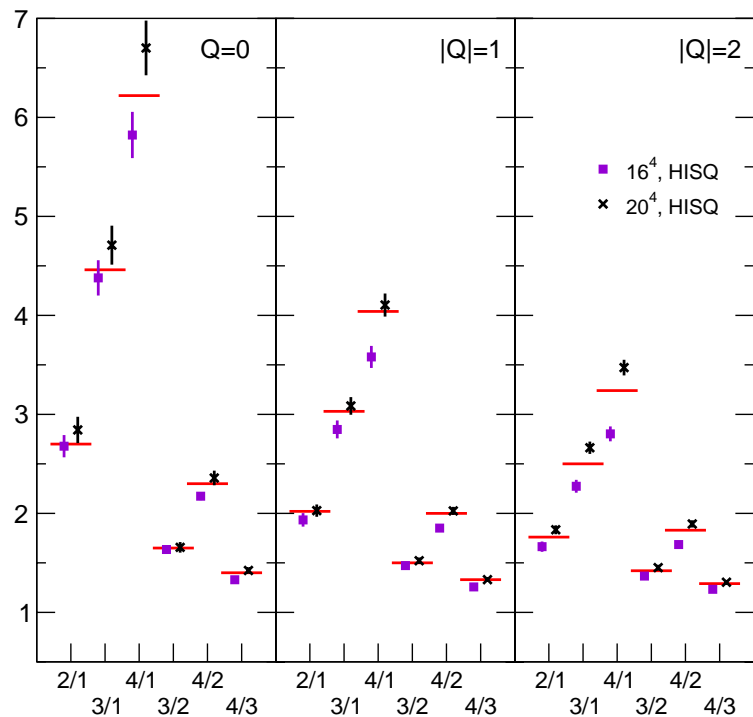
Number of 'almost-zero' eigenvalues agrees with the index theorem, ( $Q=2$  here) and they have chirality close to 1.



Also improved staggered quarks show excellent 4-fold symmetry in eigenvalue spectrum as they must in contm limit. (These tests in quenched approx. on improved glue configs.)

Follana, Hart, Davies, HPQCD, LAT04

## Sensitivity to topology of the staggered formalism



Eigs also agree with the predictions from universality/random matrix theory.

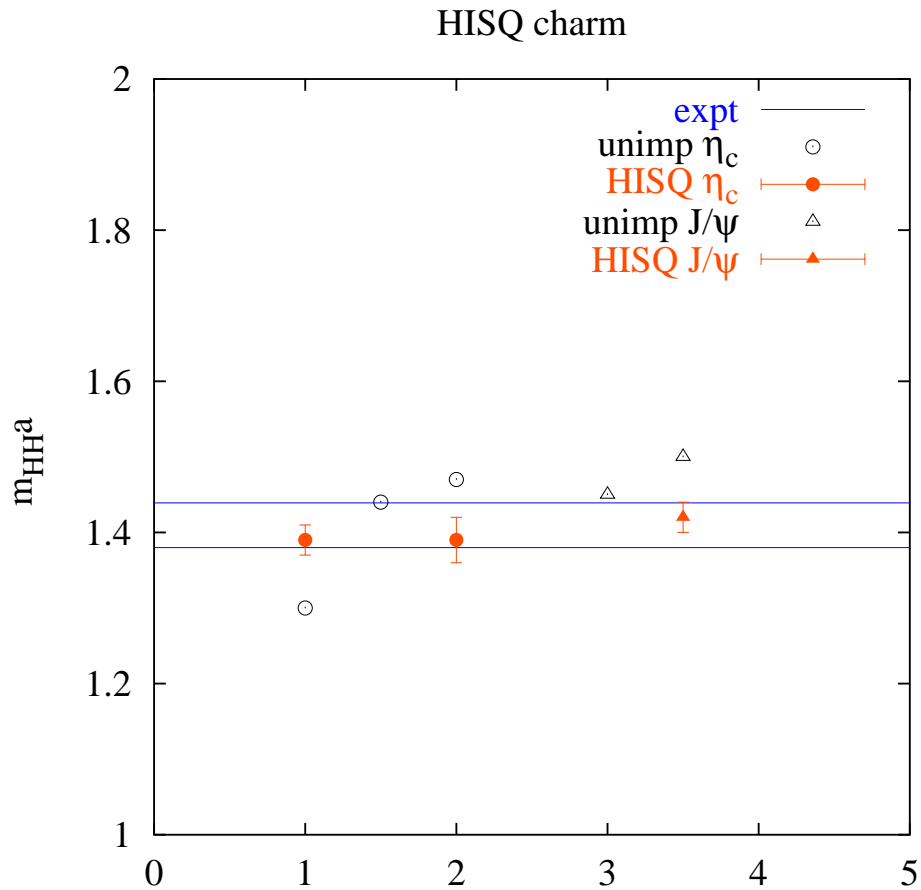
$$x/y = \langle \lambda_x \rangle / \langle \lambda_y \rangle$$

Drop 'would-be' zero modes and replace quartets by average values to obtain  $\lambda_i$ .

Undershoot visible at LAT04 is cured on bigger ( $20^4$ ) volume.

Follana, Hart, Davies, HPQCD, LAT04

## Future: Use HISQ for charm



Unimproved calcs (JLQCD hep-lat/9411012) had problems with taste-changing in  $\pi \equiv \eta_c$ .

This is much improved for HISQ.

Plan: try this on MILC fine (and planned super-fine) lattices where  $\alpha_s(m_c a)^2 =$  a few %.

## Conclusions

- Huge progress in lattice QCD recently with new calculations with 2+1 flavors of light dynamical quarks and  $m_{u/d} < m_s/2$ .
- Gold-plated matrix elements for CKM determinations are in progress, with lots of results reported this year (hear more in Paul Mackenzie's talk).
- Future work based on some new techniques which have lots of promise.