LATTICE QCD : 2006 STATUS REPORT

Joint DPF2006 - JPS2006 Meeting

29th October - 3rd November, 2006

Honolulu, Hawaii

presented by :

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LATTICE QCD

GOALS

- provide reliable theoretical tools for studies of strongly coupled Quantum Field Theories
- investigate a wide range of nonperturbative phenomena from first principles
- make accurate comparisons between theory and experiment possible
- help test the Standard Model of Particle Physics and the search for Physics Beyond the SM

General Remarks

GOOD NEWS

Since a couple of years realistic unquenched Lattice QCD calculations are being carried out.

— effects of $N_f = 2 + 1$ flavors of sea quarks included

— good control over chiral limit

A significant fraction of the work to date has employed the MILC collaboration unquenched configurations based on "improved staggered" light quarks.

EVEN BETTER NEWS

Several unquenched projects underway with different light quarks

Wilson Type

huge (dramatic) algorithmic progress (Luescher)

* much faster now

* able to go down to small masses (comparable to staggered?)

$\Longrightarrow$ PACS-CS Project (Tsukuba)

Domain Wall Fermions

$\Longrightarrow$ RBC (RIKEN-Columbia-Brookhaven), UKQCD, LHPC

Overlap Fermions

$\Longrightarrow$ JLQCD Project (KEK)

! Many cross checks will become available !

Light Action (collaborations)	Cost	Main Disadvantage
Improved Staggered (MILC/Fermilab/ HPQCD)	cheap	each physical flavor comes in 4 "tastes" 4^{th} root issue *
Wilson/Clover (PACS-CS/CP-PACS/ JLQCD/QCDSF etc.)	cheaper than in past	chiral symmetry broken at $a \neq 0$
Twisted Mass (European TM)	fairly cheap	chiral symmetry, parity, flavor broken at $a \neq 0$
Domain Wall (RBC/UKQCD/LHPC)	expensive	residual mass at finite 5th dimension
Overlap (JLQCD)	most expensive	cost, topology changes

all approaches can now go down to small masses (in principle)

* see LAT06 Review Talk by S.Sharpe (hep-lat/0610094)

Outline of Talk

- General Remarks

- Criteria for judging unquenched configurations.
  — when can we call them "realistic"

- Recent results/updates from existing unquenched projects
  — light quark physics

  — CKM physics

  — other

  !! Apologies to those of you whose work could not be fitted into this talk !!

- Summary

Testing Unquenched Gauge Configurations

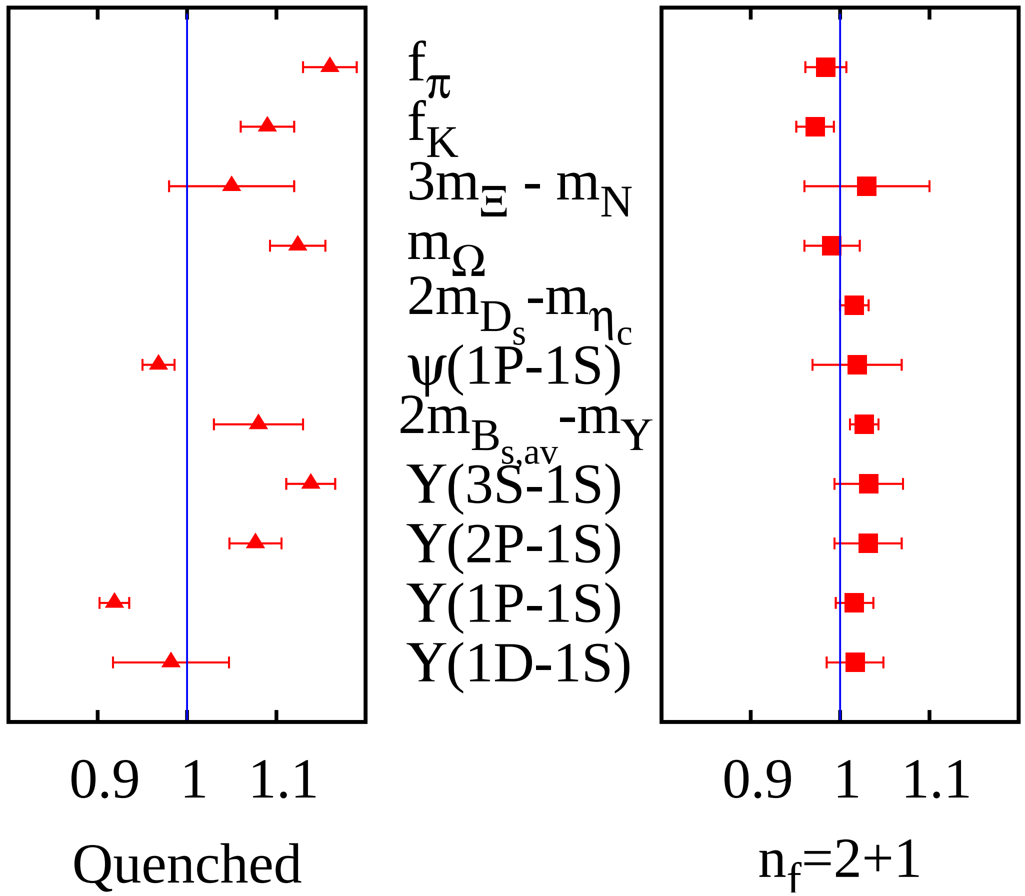
The Lattice QCD action, just as continuum QCD, includes several parameters that must be fixed by experiment before any predictions can be made. These are the bare quark masses and the scale (or coupling).

e.g. use MILC configs and fix

$$\begin{aligned}
\Upsilon(2S - 1S) \text{ splitting} &\longrightarrow a^{-1} \\
\text{pion} &\longrightarrow m_{u,d} \\
\text{kaon} &\longrightarrow m_s \\
D_s \text{ meson} &\longrightarrow m_c \\
\Upsilon\ 1^3S_1 &\longrightarrow m_b
\end{aligned}$$

After this, no adjustable parameters left. Next step is to calculate a wide range of well measured "goldplated" quantities and compare lattice results with experiment.

Ratio Plot (Lattice / Experiment)



MILC/Fermilab/HPQCD Collaborations

Testing Unquenched Gauge Configurations

(cont'd)

With the MILC unquenched configurations based on improved staggered quarks, agreement is seen within $2 \sim 3$ %. The worst discrepancy is at the $\sim 1.5\sigma$ level.

It is important that one include both light quark and heavy quark quantities in such tests.

One criterion for "realistic" unquenched configurations :

!!! a unique set of action parameters (quark masses and a^{-1})
!!! must correctly describe light quark , heavy-light (B,D)
!!! and heavy-heavy (quarkonium) physics.

Comparison with past failures of reality checks

Configs	action	N_f	L	m_l/m_s	$\frac{a(light)}{a(\Upsilon)}$
HEMCGC (∼1995)	unimproved stagg.	2	∼1.6fm (small)	~ 1	~ 1.2
UKQCD (∼1998)	clover	2	∼1.6fm	≥ 1	~ 1.14
CP-PACS (∼2001)	clover	2	∼2.5fm	> 0.5	~ 1.2
MILC	improved stagg.	$2+1$	$\sim$ 2.5fm	0.5 $\sim$ 0.1	1.00(3)

Consequence :

S.Collins et al.(HEMCGC/NRQCD) : $f_{B_s} = [215 \pm 28^{+49}_{-0}]$MeV

A.Ali Khan et al. (CP-PACS) : $f_{B_s} = [242 \pm 35^{+38}_{-0}]$MeV

Note: several unquenched ensembles exist on which Υ physics has not been studied yet.

One learns that "realistic" lattice simulations require :

- $N_f = 2+1$ (starting with $N_f = 2$ also useful)

- size $L \geq 2.5$fm

- m_l/m_s : 0.1 - 0.5
  then use chiral perturbation theory for $m_l \leq \frac{1}{2} m_s$

- improve actions (glue, light & heavy quarks)

- make sure unique action parameters, e.g. a^{-1}, exist

All the new unquenched projects listed earlier should be able to meet these criteria.
To date only MILC ensembles have generated "Ratio Plot" with light, heavy-light and heavy-heavy quantities.

Recent Results

Light quark physics (masses, f_π, f_K/f_π, V_{us}, g_A, etc.)

CKM Physics (B,D semileptonic decays, decay constants, B-mixing)

Other (g-2, ...)

Light meson Decay Constants and $|V_{us}|$

PDG

— V_{us} from $K \to \pi l \nu$ using $f_+(0) = 0.961(8)$ (Leutwyler & Roos), a value consistent with recent unquenched lattice results.

— f_K from $K^+ \to \mu^+ \nu_\mu$ using above V_{us}

Lattice (MILC)

- Use Ward identity $f_{PS} = \frac{(m_1+m_2)}{M_{PS}^2} \langle 0 | \overline{\Psi} \gamma_5 \Psi | PS \rangle$
  $\longrightarrow f_\pi,\ f_K,\ f_K/f_\pi$

- Follow Marciano and focus on $\Gamma(K^+ \to \mu^+ \nu)/\Gamma(\pi^+ \to \mu^+ \nu) \propto \left(\frac{f_K}{f_\pi}\right)^2 \frac{|V_{us}|^2}{|V_{ud}|^2}$

- V_{ud} known very accurately $\longrightarrow |V_{us}|$

K_{l3} **Form Factor** $f_+(0)$

(adapted from W.Lee review talk at LAT06)

Collaboration	$f_+(0)$	N_f	Quark Action
RBC	0.968(9)(6)	2	domain wall
RBC	0.9680(16)	2+1	domain wall
HPQCD/FNAL	0.962(6)(9)	2+1	staggered/clover
JLQCD	0.952(6)(−)	2	clover
Leutwyler&Roos	0.961(8)		

Recent unquenched lattice results consistent with popular Leutwyler&Roos value.

Light meson Decay Constants and $|V_{us}|$

(cont'd)

	MILC (2004) (PRD **70**)	MILC (2006) (LAT06 update)	PDG 2006
f_π [MeV]	$129.5 \pm 0.9 \pm 3.5$	$128.6 \pm 0.4 \pm 3.0$	$130.7 \pm 0.1 \pm 0.36$
f_K [MeV]	$156.6 \pm 1.0 \pm 3.6$	$155.3 \pm 0.4 \pm 3.1$	$159.8 \pm 0.44 \pm 1.4$
f_K/f_π	1.210(4)(13)	$1.208(2)(^{+7}_{-14})$	
$\lvert V_{us}\rvert$	0.2219(26) (V_{ud} input used)	$0.2223(^{+26}_{-14})$	0.2257(21) (from $K \to \pi l \nu$)

Note: the PDG f_K requires $|V_{us}|$.

Precision lattice calculation of f_K/f_π enables an alternate determination of $|V_{us}|$ (Marciano).

Light Quark $\overline{MS}$ Masses

All masses are $m \equiv m^{\overline{MS}}(2GeV)$, $\widehat{m} \equiv \frac{1}{2}(m_u + m_d)$

Errors in MILC/HPQCD : (stat.)(simulation)(pert.)

	$\widehat{m}$ [MeV]	m_s [MeV]	$m_s/\widehat{m}$
MILC/HPQCD (2004)	2.8(0)(1)(3)	76(0)(3)(7)	27.4(1)(4)(0)
HPQCD* (2005)	3.2(0)(2)(2)	87(0)(4)(4)	27.4(1)(4)(0)
MILC* (LAT06)	3.3(0)(2)(2)	90(0)(5)(4)	27.2(0)(4)(0)
CP-PACS/ JLQCD (LAT06)	$3.50(14)(^{+26}_{-15})$	$91.8(3.9)(^{+6.8}_{-4.1})$	

* 2-loop (Mason, Trottier & Horgan)
[nonperturbative matching underway (MILC)]
Above results for $N_f = 2+1$
Note: $N_f = 2$ calculations for m_s exist that come out > 100MeV.

Light Quark $\overline{MS}$ Masses

(cont'd)

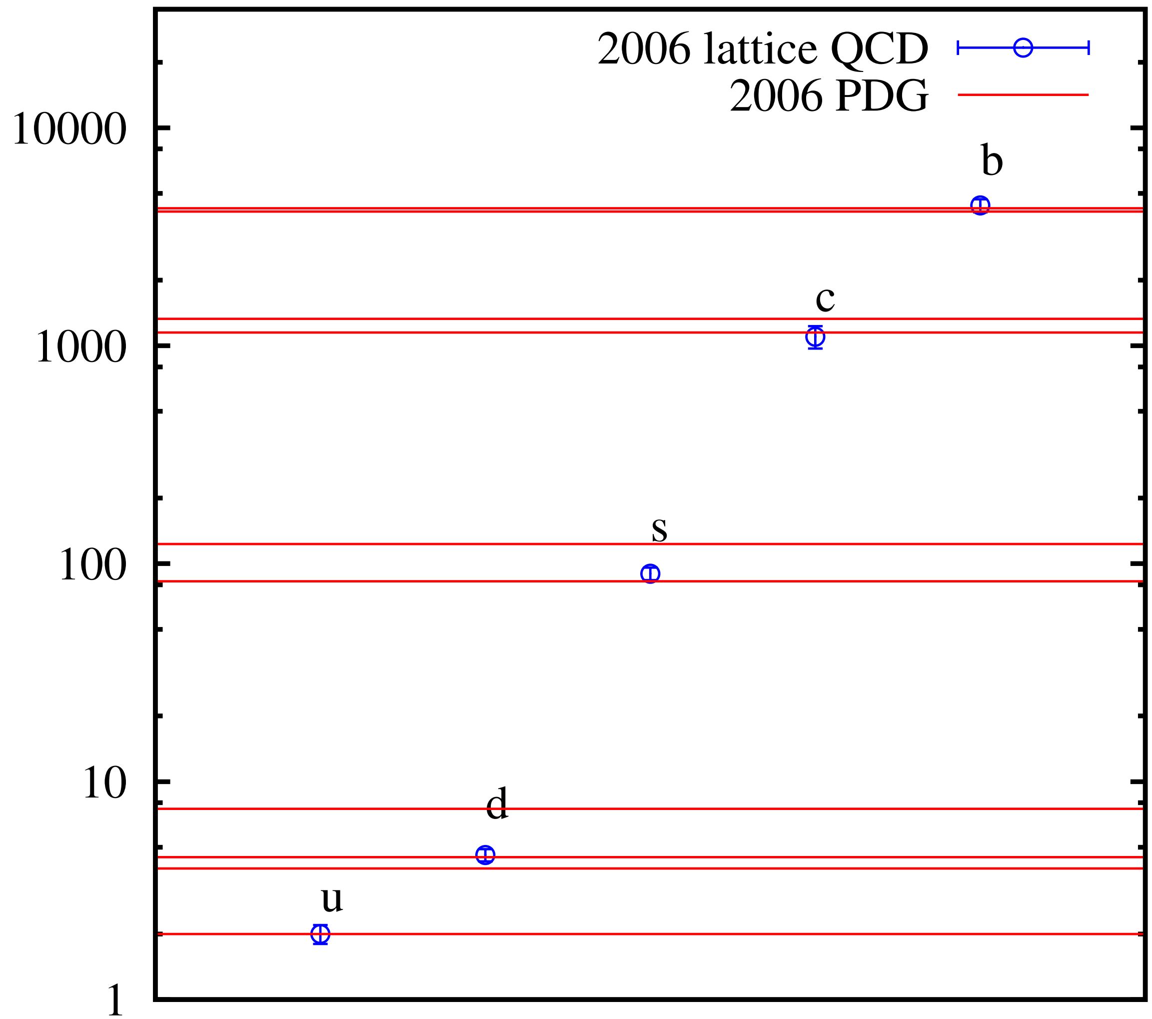
	m_u [MeV]	m_d [MeV]	m_u/m_d
MILC (2004)	1.7(0)(1)(2)(2)	3.9(0)(1)(4)(2)	0.43(0)(1)(0)(8)
HPQCD* (2005)	1.9(0)(1)(1)(2)	4.4(0)(2)(2)(2)	uses above as input
MILC* (2006)	2.0(0)(1)(1)(1)	4.6(0)(2)(2)(1)	0.42(0)(1)(0)(4)

* 2-loop

Results appear to rule out $m_u = 0$ solution to the strong CP problem.

Gasser-Leutwyler low energy constants L_i also inconsistent with having a massless m_u.

Quark masses (MeV)



Nucleon Axial Charge

LHP (Lattice Hadron Physics) Collaboration : PRL **96** (2006)
Simulations carried out on MILC configurations (improved staggered sea quarks) using domain wall valence quarks.

$$\langle N; p+q|\vec{A}_\mu|N;p\rangle = \overline{u}(p+q)\frac{\vec{\tau}}{2}[g_A(q^2)\gamma_\mu\gamma_5 + g_P(q^2)q_\mu\gamma_5]u(p)$$

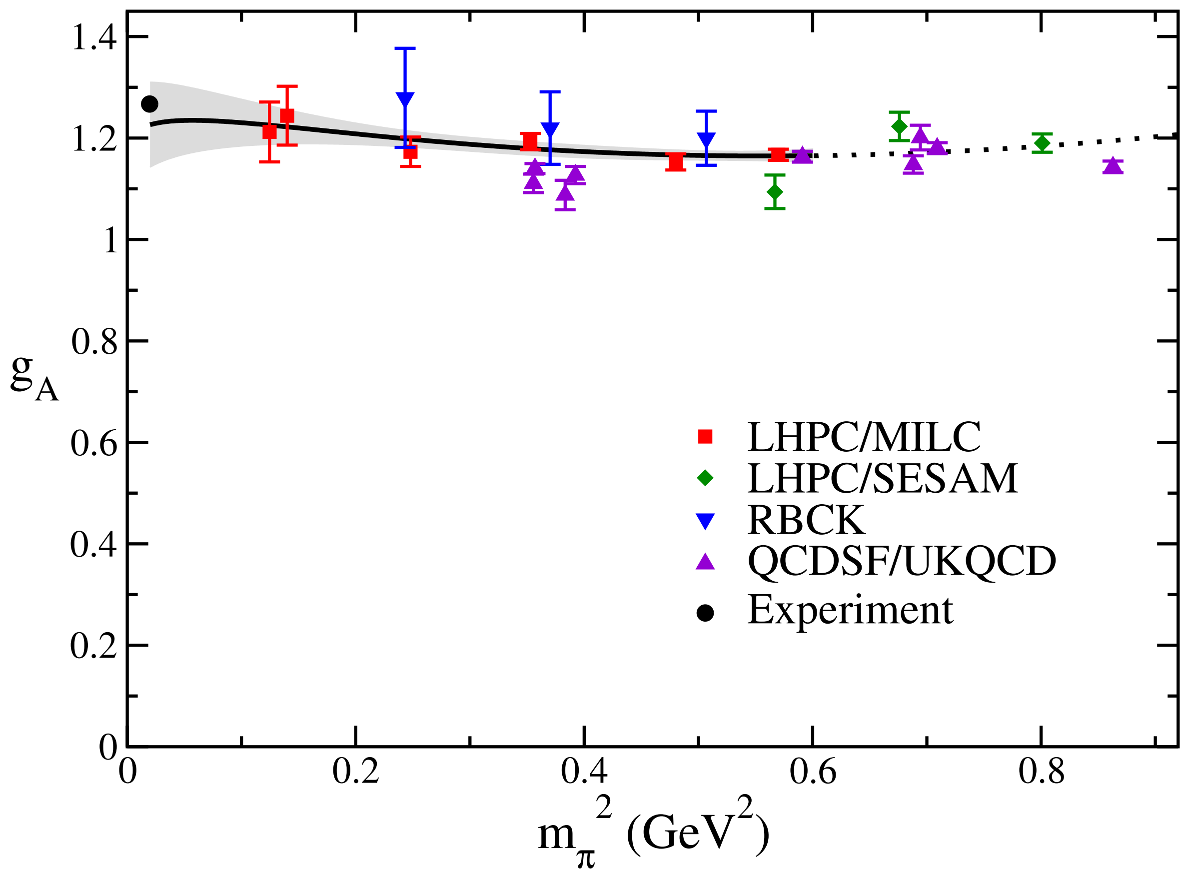
$$\vec{A}_\mu \equiv \overline{q}\gamma_\mu\gamma_5\frac{\vec{\tau}}{2}q$$

They find : $\boxed{g_A \equiv g_A(0) = 1.226 \pm 0.084}$
after extrapolating to $m_\pi = 140\text{MeV}$.

Compare with $g_A = 1.2695 \pm 0.0029$ (experiment)

Nucleon Axial Charge

(LHPC : PRL 2006)



Lattice QCD and CKM Physics

Lattice QCD is playing an important role in determinations of V_{xy}.

V_{us} $\left\{ \begin{array}{ll} K_{l3} & f_+(0) \\ K_{l2} & f_K/f_\pi \end{array} \right.$

V_{cd}, V_{cs} D semileptonic decays ($D \to \pi l \nu$, $D \to K l \nu$)

V_{ub}, V_{cb} B semileptonic decays ($B \to \pi l \nu$, $B \to D l \nu$)

V_{td}, V_{ts} $B^0_{d,s} - \overline{B^0_{d,s}}$ mixing

B Semileptonic Decays : $B \longrightarrow \pi, l\nu$

$|V_{ub}|$ determined so far mainly from inclusive B decays, with errors around $\sim 7\%$.

In recent years CLEO, BaBar and Belle have all made huge progress in measuring branching fractions $\mathcal{B}(B \to \pi, l^+\nu)$ and $\mathcal{B}(B \to \rho, l^+\nu)$. These can be used to extract $|V_{ub}|_{excl.}$ provided the relevant form factors are known.

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} p_\pi^3 \, |V_{ub}|^2 \, |f_+(q^2)|^2$$

To date two lattice groups have unquenched results for $f_+(q^2)$;

Fermilab/MILC : Okamoto *et al.* LAT04 (2004)
HPQCD : Gulez *et al.* PRD **73** (2006)

Current lattice simulations only for $q^2 \geq 16 GeV^2$

Main Results

$$\frac{1}{|V_{ub}|^2} \int_{16GeV^2}^{q^2_{max}} \frac{d\Gamma}{dq^2}\, dq^2 = \begin{cases} (1.46 \pm 0.35)\, ps^{-1} & (HPQCD) \\ (1.83 \pm 0.50)\, ps^{-1} & (Fermilab/MILC) \end{cases}$$

HFAG'06 has combined these lattice results with branching fraction averages of BABAR, Belle and CLEO data (as of ICHEP06).

$$|V_{ub}|_{exclusive} \times 10^3 = \begin{cases} 3.93 \pm 0.26^{+0.59}_{-0.41} & (HPQCD) \\ 3.54 \pm 0.23^{+0.61}_{-0.40} & (Fermilab/MILC) \end{cases}$$

PDG 2006 : $|V_{ub}| \times 10^3 = 4.31 \pm 0.30$

dominated by inclusive number

D **Semileptonic Decays :** $D \longrightarrow K(\pi), l\nu$

$N_f = 2 + 1$ results for semileptonic form factors by the Fermilab/MILC/HPQCD collaborations .

Combining these Lattice QCD results with CLEO-c branching fractions leads to (M.Artuso hep-ex/0510052) :

$\boxed{|V_{cs}| = 0.957 \pm 0.017(exp) \pm 0.093(th)}$
(value adopted by PDG 2006)

$|V_{cd}| = 0.213 \pm 0.008(exp) \pm 0.021(th)$
(to be compared with the PDG 2006 value $|V_{cd}| = 0.230 \pm 0.011$)

D Semileptonic Decays : $D \longrightarrow K(\pi), l\nu$

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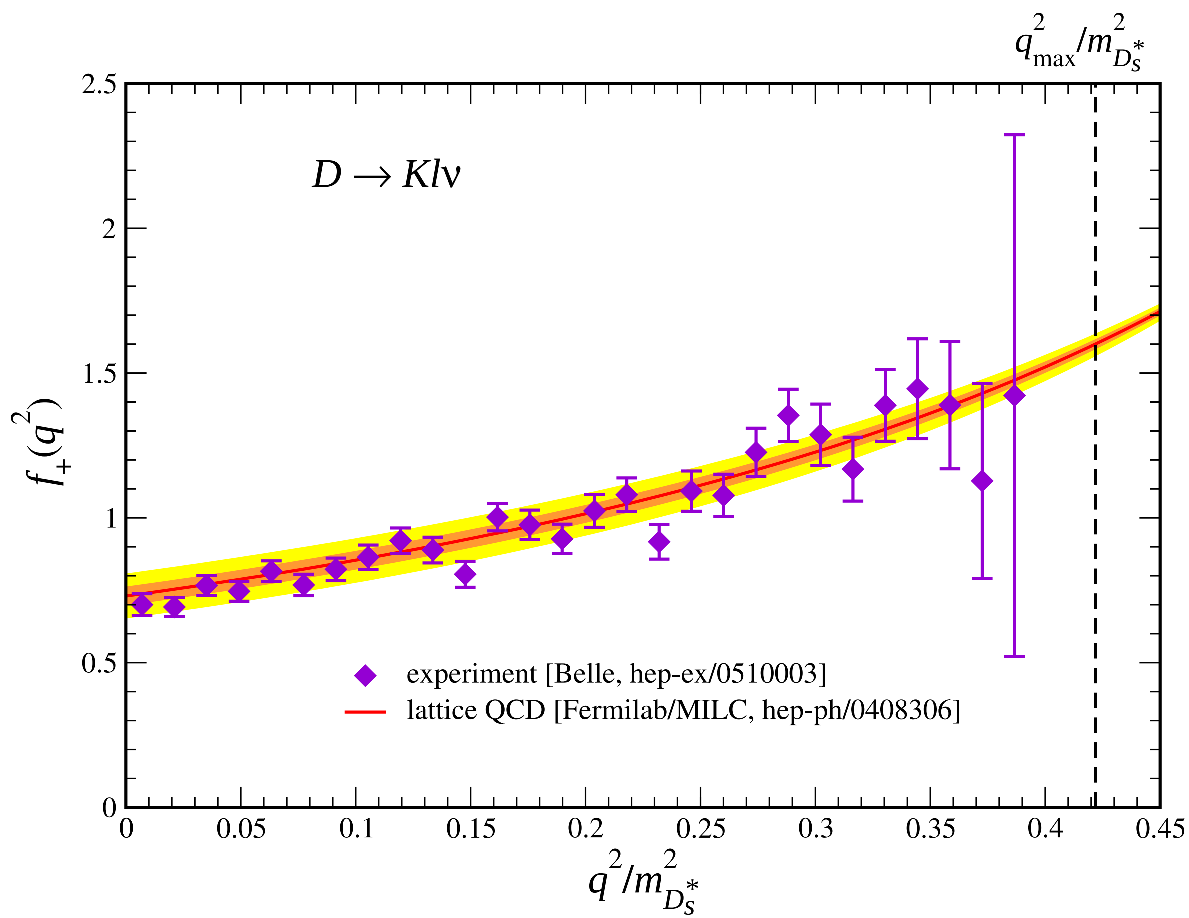


Comparison between Belle data and Lattice QCD (Fermilab/MILC/HPQCD)

D and D_s Meson Decay Constants

Now well measured by CLEO-c and BaBar.

(CLEO:PRL **95** (2005), hep-ex/0607074; BaBar: hep-ex/0605030)

uses PDG 2005 values for V_{cs}, V_{cd}

Lattice $N_f = 2 + 1$ results from MILC/Fermilab/HPQCD.

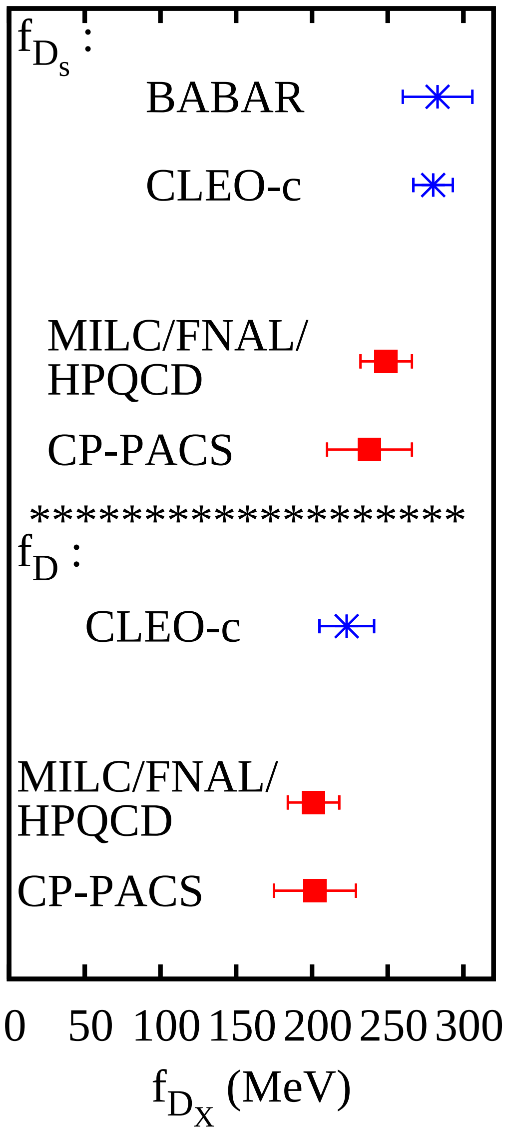
(PRL **95** (2005))

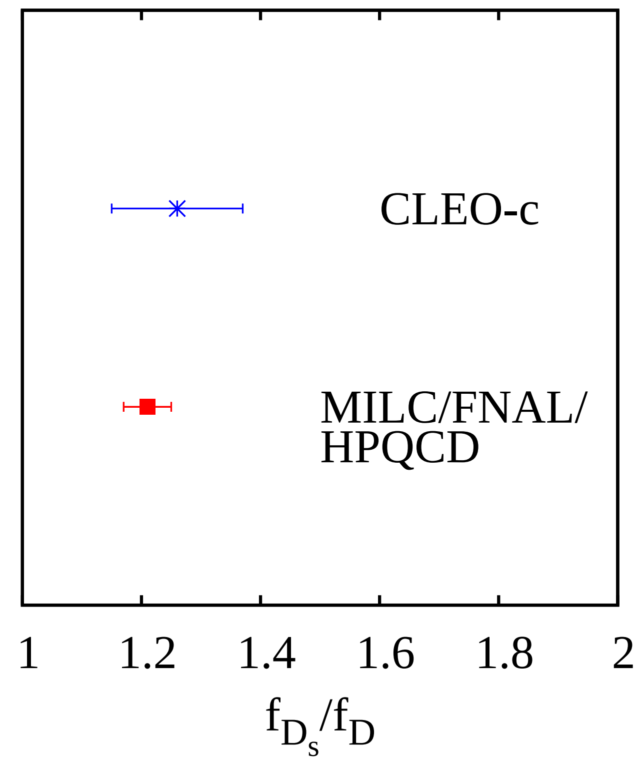
Lattice $N_f = 2$ preliminary results from CP-PACS.

(LAT05)

On lattice use : $\langle 0|A_\mu|D\rangle = ip_\mu f_D$

D & D_s Decay Constants





B and B_s Meson Decay Constants

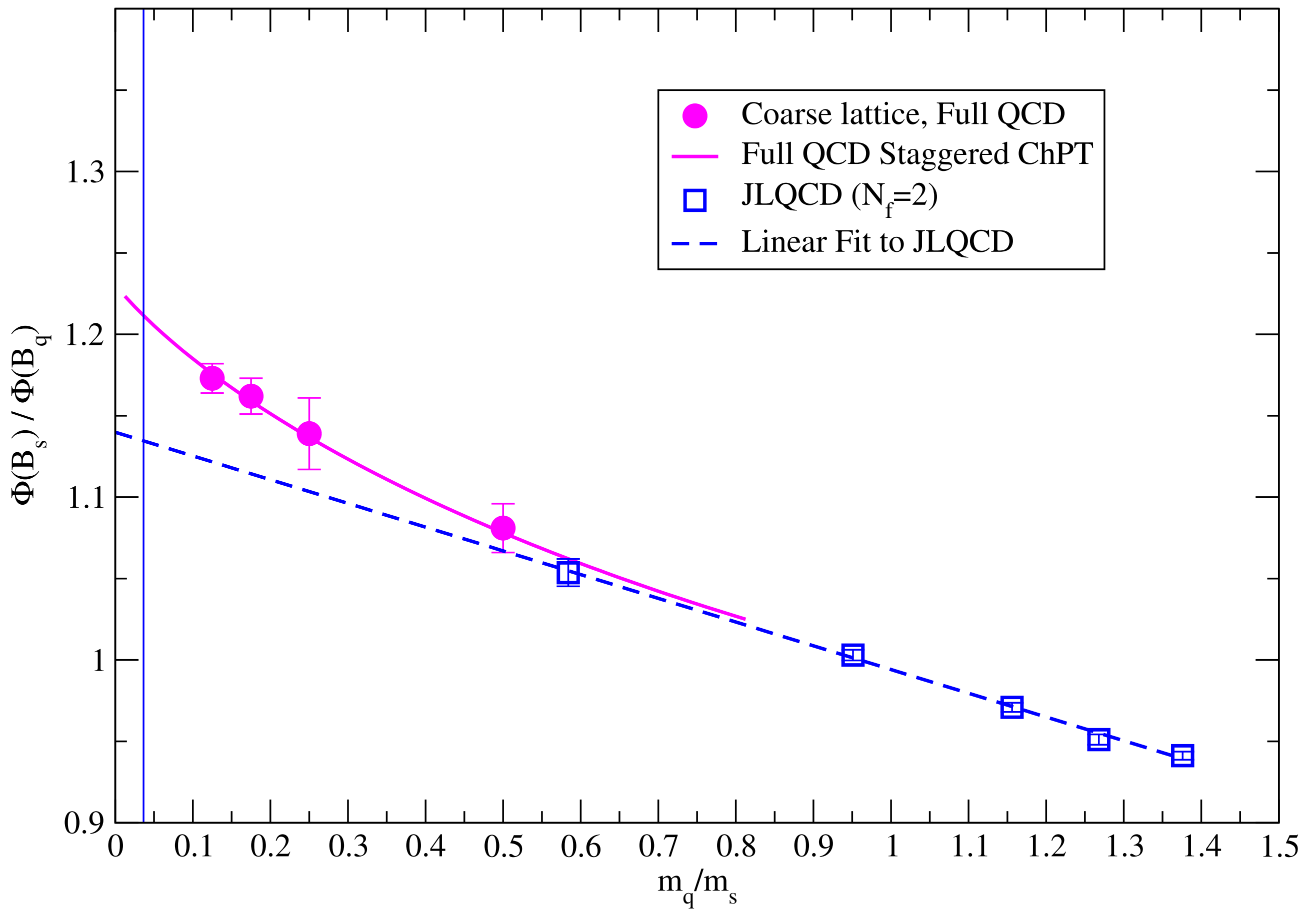
HPQCD : A.Gray *et al.* PRL **95** (2005)
MILC $N_f = 2+1$ configurations, NRQCD b quarks and improved staggered light quarks.

JLQCD : S.Aoki *et al.* PRL **91** (2003)
$N_f = 2$, NRQCD b quarks and improved Wilson (clover) light quarks.

Fermilab/MILC : J.Simone poster, LAT06
MILC $N_f = 2+1$, heavy clover b and improved staggered light quarks.

Ratio of B Meson Decay Constants

The ratio $f_{B_s}\sqrt{M_{B_s}}$ / $f_B\sqrt{M_B}$ versus the light quark mass.



HPQCD (2005) : $f_{B_s}/f_B = 1.20(3)(1)$
JLQCD (2003) : $f_{B_s}/f_B = 1.13(3)(^{+12}_{-0})(2)(^{+3}_{-0})$

B & B_s Meson Decay Constants

(cont'd)

	f_B [MeV]	f_{B_s} [MeV]	f_{B_s}/f_B
HPQCD (2005)	216(9)(20)	260(7)(28)	1.20(3)(1)
JLQCD (2003: no $\frac{a_{light}}{a_\Upsilon}$ test)	$191(10)(^{+12}_{-22})$	$215(9)(^{+14}_{-13})$	$1.13(3)((^{+13}_{-2})$
Fermilab/MILC (preliminary LAT06)	199(6)(35)	253(7)(41)	1.27(2)(6)

$f_B = 229^{+36+30}_{-31-34} MeV$ (Belle, ICHEP06) (preliminary)
using $|V_{ub}|_{incl.} = [4.39 \pm 0.33] \times 10^{-3}$ from HFAG

$B^0_{d,s} - \overline{B}^0_{d,s}$ **Mixing**

Exciting developments at the Tevatron this year with the precision measurement of ΔM_s. In the Standard Model :

$$\boxed{\Delta M_q = \frac{G_F^2 M_W^2}{6\pi^2} |V^*_{tq} V_{tb}|^2 \eta_2^B S_0(x_t) M_{B_q} f^2_{B_q} \hat{B}_{B_q}}$$

CDF Collaboration (A.Abulencia *et al.* hep-ex/0609040)

$$\boxed{|V_{td}/V_{ts}| = \xi \sqrt{\frac{\Delta M_d}{\Delta M_s}\frac{M_{B_s}}{M_{B_d}}} \Rightarrow 0.2060 \pm 0.0007^{+0.0081}_{-0.0060}} \qquad \xi = \frac{f_{B_s}}{f_B}\sqrt{\frac{B_{B_s}}{B_B}}$$

M.Okamoto (LAT05) combined f_{B_s}/f_B from HPQCD and B_{B_s}/B_B from JLQCD to obtain,

$$\boxed{\xi = 1.210^{+0.047}_{-0.035}}$$

JLQCD : $\xi = 1.14(3)(^{+13}_{-0})(2)(^{+3}_{-0})$

The HPQCD Collaboration now has $N_f = 2+1$ results for

$$\boxed{f_{B_s}\sqrt{\hat{B}_{B_s}} = 281(21)MeV}$$

Taking $|V_{ts}^* V_{tb}| \approx |V_{cs}^* V_{cb}| \approx 4.1 \times 10^{-2}$ one gets

$$\boxed{\Delta M_s(SM\ theory) = 20.3(3.0)(0.8)ps^{-1}}$$

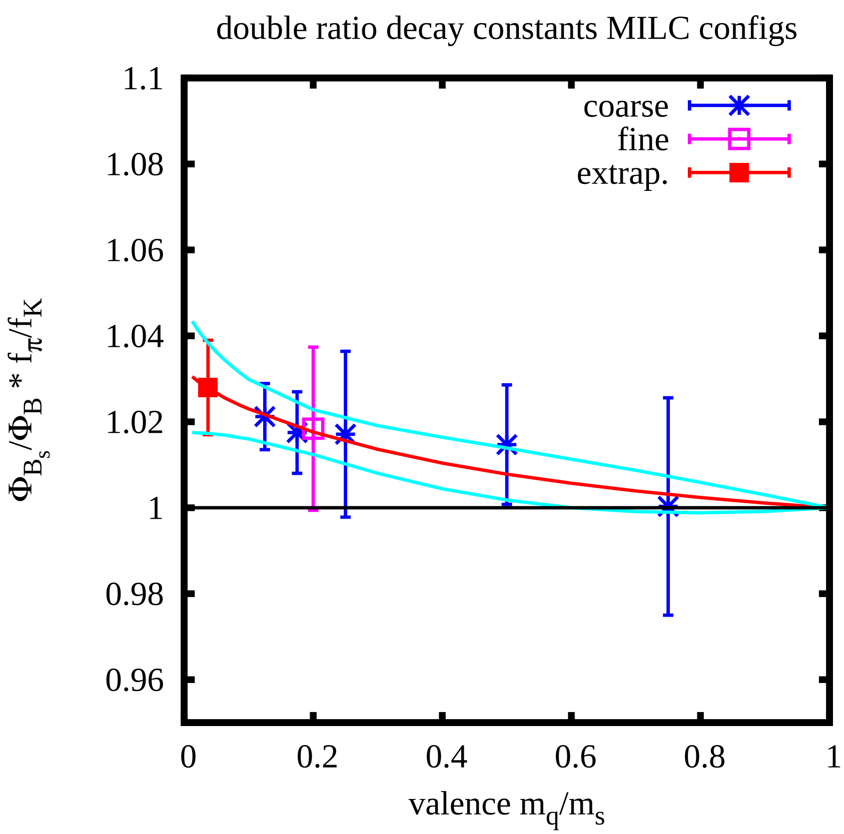
to be compared with the CDF measurement

$$\boxed{\Delta M_s = 17.77 \pm 0.10 \pm 0.07\ \ ps^{-1}}$$

Conversely, $|V_{ts}^* V_{tb}| = 3.9(3) \times 10^{-2}$.

Work underway on important ratio $\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_B\sqrt{B_B}}$

HPQCD has also calculated hadronic matrix elements relevant for $\Delta\Gamma_s$.



Reducing Errors

Recall $\sim 4\%$ error in $\xi = \frac{f_{B_s}}{f_B}\sqrt{\frac{B_{B_s}}{B_B}} = 1.210^{+0.047}_{-0.035}$

Consider double ratios : $[f_{B_s}/f_B]\,/\,[f_K/f_\pi]$ (D.Becirevic)

Smoother chiral extrapolation

Exploit more accurately known f_K/f_π.

$\Longrightarrow$ Total error in f_{B_s}/f_B reduced to $\sim 2\%$.

Hadronic Contribution to the Muon g-2

(C.Aubin & T.Blum : hep-lat/0608011)

The anomalous magnetic moment of the muon, $a_\mu = (g-2)/2$, is known very precisely, both experimentally and theoretically.

$$a_\mu^{EXP} = 116592080(5.4)(3.3) \times 10^{-11}$$

(G.Bennett *et al.* 2006)

a_μ^{TH} deviates from this by $(0.7 \sim 2.7)\sigma$.

$a_\mu^{TH} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{QCD}$ and most of the theoretical error comes from a_μ^{QCD}.

Several contributions to a_μ^{QCD}, the largest being the "hadronic contribution to the photon vacuum polarization". This is usually determined from the experimental $e^+e^- \rightarrow hadrons$ total cross-section plus dispersion relations (also $\tau \rightarrow hadrons$ decay).

Hadronic Contribution to the Muon g-2

(cont'd)

Using e^+e^- and/or τ :
$a_\mu^{HLO} = 692.4(5.9)(2.4) \times 10^{-10}$ (e^+e^-) or
$a_\mu^{HLO} = 711.0(5.0)(0.8)(2.8) \times 10^{-10}$ (τ)

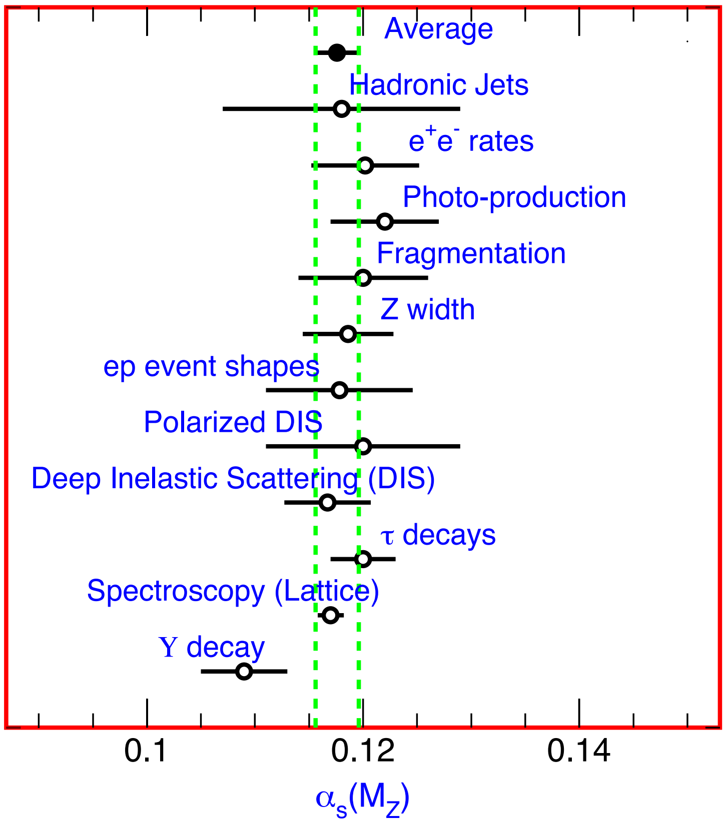
Recent unquenched lattice determination using MILC configurations

$a_\mu^{HLO} = (721 \pm 15) \times 10^{-10}$ (linear fit in m_l) or
$a_\mu^{HLO} = (748 \pm 21) \times 10^{-10}$ (quadratic fit in m_l)

Significant increase over previous quenched results.
Currently error in lattice determination larger than in other approaches
Further improvements possible (better understanding of effect of finite ρ meson width etc.)

The Strong Coupling Constant

(PDG 2006)



HPQCD value

$$\boxed{\alpha^{(5)}_{\overline{MS}}(M_Z) = 0.1170(12)}$$

to be compared with current PDG 2006 world average of

$\alpha^{(5)}_{\overline{MS}}(M_Z) = 0.1176(20)$

(central value moves to 0.1185 if lattice point omitted)

Summary

- Lattice QCD is playing an increasingly important role in Particle Physics Phenomenology and in Tests of the Standard Model.

- Much progress in recent years
  (quenching uncertainties removed, more control over chiral extrapolations)

- Many new unquenched results expected in next couple of years using a wide range of Quark Actions

K.Jansen (LAT06) : more than $\sim$ 100 TFLOPS computing power available to the lattice community in coming year.

S.Gottlieb : $\sim$ 1 TFLOPS-year was required to create existing MILC lattices (not including their super-fine).

Summary

Need to !!! REDUCE ERRORS !!!

!!! Please be patient. We are working on it !!!

— "routine" improvements through better statistics, better sources, more lattice spacings and light quark masses etc.

— New effort/ideas on operator matching

— New actions (e.g. HISQ action for charm by HPQCD)

— Exploit double ratios for smoother chiral extrapolations

It has been an exhilarating past couple of years as we have been able to overcome the quenched approximation.

We are now ready and eager to take up the challenge of delivering more and more crucial quantities with a few % accuracy.