presented by:

Junko Shigemitsu
The Ohio State University
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?)

⇒ PACS-CS Project (Tsukuba)

**Domain Wall Fermions**

⇒ RBC (RIKEN-Columbia-Brookhaven), UKQCD, LHPC

**Overlap Fermions**

⇒ JLQCD Project (KEK)

! Many cross checks will become available!
<table>
<thead>
<tr>
<th>Light Action (collaborations)</th>
<th>Cost</th>
<th>Main Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved Staggered (MILC/Fermilab/HPQCD)</td>
<td>cheap</td>
<td>each physical flavor comes in 4 “tastes” 4\textsuperscript{th} root issue *</td>
</tr>
<tr>
<td>Wilson/Clover (PACS-CS/CP-PACS/JLQCD/QCDSF etc.)</td>
<td>cheaper than in past</td>
<td>chiral symmetry broken at $a \neq 0$</td>
</tr>
<tr>
<td>Twisted Mass (European TM)</td>
<td>fairly cheap</td>
<td>chiral symmetry, parity, flavor broken at $a \neq 0$</td>
</tr>
<tr>
<td>Domain Wall (RBC/UKQCD/LHPC)</td>
<td>expensive</td>
<td>residual mass at finite 5\textsuperscript{th} dimension</td>
</tr>
<tr>
<td>Overlap (JLQCD)</td>
<td>most expensive</td>
<td>cost, topology changes</td>
</tr>
</tbody>
</table>

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

\[
\begin{align*}
\Upsilon(2S - 1S) \text{ splitting} & \quad \rightarrow \quad a^{-1} \\
pion & \quad \rightarrow \quad m_{u,d} \\
\text{kaon} & \quad \rightarrow \quad m_s \\
D_s \text{ meson} & \quad \rightarrow \quad m_c \\
\Upsilon(1^3S_1) & \quad \rightarrow \quad m_b
\end{align*}
\]

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)

Quenched

nf=2+1

\[
\begin{align*}
\frac{f_\pi}{f_K} \\
3m_\Xi - m_N \\
m_\Omega \\
2m_{\Omega} - m_\eta_c \\
\psi(1P-1S) \\
2m_{\psi(1S)} - m_Y \\
Y(3S-1S) \\
Y(2P-1S) \\
Y(1P-1S) \\
Y(1D-1S)
\end{align*}
\]

MILC/Fermilab/HPQCD Collaborations
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

<table>
<thead>
<tr>
<th>Configs</th>
<th>action</th>
<th>$N_f$</th>
<th>L</th>
<th>$m_l/m_s$</th>
<th>$a(\text{light})/a(\Upsilon)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEMCGC (~1995)</td>
<td>unimproved stagg.</td>
<td>2</td>
<td>$\sim 1.6\text{fm}$ (small)</td>
<td>$\sim 1$</td>
<td>$\sim 1.2$</td>
</tr>
<tr>
<td>UKQCD (~1998)</td>
<td>clover</td>
<td>2</td>
<td>$\sim 1.6\text{fm}$</td>
<td>$\geq 1$</td>
<td>$\sim 1.14$</td>
</tr>
<tr>
<td>CP-PACS (~2001)</td>
<td>clover</td>
<td>2</td>
<td>$\sim 2.5\text{fm}$</td>
<td>$&gt; 0.5$</td>
<td>$\sim 1.2$</td>
</tr>
<tr>
<td>MILC</td>
<td>improved stagg.</td>
<td>2 + 1</td>
<td>$\sim 2.5\text{fm}$</td>
<td>$0.5 \sim 0.1$</td>
<td>1.00(3)</td>
</tr>
</tbody>
</table>

Consequence:

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

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

Note: several unquenched ensembles exist on which $\Upsilon$ 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 $L \geq 2.5\text{fm}$
- $m_l/m_s : 0.1 - 0.5$
  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, $f_\pi$, $f_K/f_\pi$, $V_{us}$, $g_A$, 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 \(K \rightarrow \pi l \nu\) using \(f_+(0) = 0.961(8)\) (Leutwyler & Roos), a value consistent with recent unquenched lattice results.

— \(f_K\) from \(K^+ \rightarrow \mu^+ \nu\mu\) using above \(V_{us}\)

**Lattice (MILC)**

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

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

- \(V_{ud}\) known very accurately \(\rightarrow |V_{us}|\)
**$K_{l3}$ Form Factor $f_+(0)$**

(adapted from W. Lee review talk at LAT06)

<table>
<thead>
<tr>
<th>Collaboration</th>
<th>$f_+(0)$</th>
<th>$N_f$</th>
<th>Quark Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBC</td>
<td>0.968(9)(6)</td>
<td>2</td>
<td>domain wall</td>
</tr>
<tr>
<td>RBC</td>
<td>0.9680(16)</td>
<td>2+1</td>
<td>domain wall</td>
</tr>
<tr>
<td>HPQCD/FNAL</td>
<td>0.962(6)(9)</td>
<td>2+1</td>
<td>staggered/clover</td>
</tr>
<tr>
<td>JLQCD</td>
<td>0.952(6)(-)</td>
<td>2</td>
<td>clover</td>
</tr>
<tr>
<td>Leutwyler&amp;Roos</td>
<td>0.961(8)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Recent unquenched lattice results consistent with popular Leutwyler&Roos value.
**Light meson Decay Constants and $|V_{us}|$**  
(cont’d)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_\pi$ [MeV]</td>
<td>$129.5 \pm 0.9 \pm 3.5$</td>
<td>$128.6 \pm 0.4 \pm 3.0$</td>
<td>$130.7 \pm 0.1 \pm 0.36$</td>
</tr>
<tr>
<td>$f_K$ [MeV]</td>
<td>$156.6 \pm 1.0 \pm 3.6$</td>
<td>$155.3 \pm 0.4 \pm 3.1$</td>
<td>$159.8 \pm 0.44 \pm 1.4$</td>
</tr>
<tr>
<td>$f_K/f_\pi$</td>
<td>1.210(4)(13)</td>
<td>1.208(2)(+714)</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>V_{us}</td>
<td>$</td>
<td>0.2219(26) (V_{ud} input used)</td>
</tr>
</tbody>
</table>

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

Precision lattice calculation of $f_K/f_\pi$ enables an alternate determination of $|V_{us}|$ (Marciano).
## Light Quark $\overline{MS}$ Masses

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

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

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

* 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 $> 100\text{MeV}$.
**Light Quark $\overline{MS}$ Masses**

(cont’d)

<table>
<thead>
<tr>
<th></th>
<th>$m_u$ [MeV]</th>
<th>$m_d$ [MeV]</th>
<th>$m_u/m_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MILC (2004)</td>
<td>1.7(0)(1)(2)(2)</td>
<td>3.9(0)(1)(4)(2)</td>
<td>0.43(0)(1)(0)(8)</td>
</tr>
<tr>
<td>HPQCD* (2005)</td>
<td>1.9(0)(1)(1)(2)</td>
<td>4.4(0)(2)(2)(2)</td>
<td>uses above as input</td>
</tr>
<tr>
<td>MILC* (2006)</td>
<td>2.0(0)(1)(1)(1)</td>
<td>4.6(0)(2)(2)(1)</td>
<td>0.42(0)(1)(0)(4)</td>
</tr>
</tbody>
</table>

* 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)

2006 lattice QCD
2006 PDG
Simulations carried out on MILC configurations (improved staggered sea quarks) using domain wall valence quarks.

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

\[
\vec{A}_\mu \equiv \overline{q} \gamma_\mu \gamma_5 \frac{\bar{\tau}}{2} q
\]

They find: \[ g_A \equiv g_A(0) = 1.226 \pm 0.084 \]
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 is playing an important role in determinations of $V_{xy}$.

\[ V_{us} \left\{ \begin{array}{c} K_{l3} \ f_+(0) \\ K_{l2} \ f_K/f_\pi \end{array} \right. \]

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

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

$V_{td}, V_{ts}$ $B^0_{d,s} - \bar{B}^0_{d,s}$ mixing
Semileptonic Decays: $B \rightarrow \pi, l\nu$

$|V_{ub}|$ 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 $\mathcal{B}(B \rightarrow \pi, l^+\nu)$ and $\mathcal{B}(B \rightarrow \rho, l^+\nu)$. These can be used to extract $|V_{ub}|_{excl.}$ provided the relevant form factors are known.

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

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 $q^2 \geq 16GeV^2$
Main Results

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

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

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

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

dominated by inclusive number
**D Semileptonic Decays: $D \rightarrow K(\pi), l\nu$**

$N_f = 2 + 1$ 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):

\[
|V_{cs}| = 0.957 \pm 0.017(exp) \pm 0.093(th)
\]

(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 $|V_{cd}| = 0.230 \pm 0.011$)
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: $\langle 0|A_{\mu}|D\rangle = i p_\mu f_D$
$f_{D_s}$:
- BABAR
- CLEO-c
- MILC/FNAL/HPQCD
- CP-PACS

$D$ and $D_s$ Decay Constants

$C_p$:
- CLEO-c
- MILC/FNAL/HPQCD

$0$ $50$ $100$ $150$ $200$ $250$ $300$

$f_{D_x}$ (MeV)
$B$ 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.

$N_f = 2$, 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.
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)

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

$f_B = 229^{+36+30}_{-31-34} \text{MeV (Belle, ICHEP06) (preliminary)}$

using $|V_{ub}|_{incl.} = [4.39 \pm 0.33] \times 10^{-3}$ from HFAG
Exciting developments at the Tevatron this year with the precision measurement of $\Delta M_s$. In the Standard Model:

$$\Delta M_q = \frac{G_F^2 M_W^2}{6\pi^2} |V_{tq}^* V_{tb}|^2 \eta B S_0(x_t) M_B f_B^2 \tilde{B}_B$$

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

$$|V_{td}/V_{ts}| = \xi \sqrt{\frac{\Delta M_d M_{Bs}}{\Delta M_s M_{B_d}}} \Rightarrow 0.2060 \pm 0.0007^{+0.0081}_{-0.0060}$$

$$\xi = \frac{f_{Bs}}{f_B} \sqrt{\frac{B_{Bs}}{B_B}}$$

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

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

JLQCD: $\xi = 1.14(3)^{+13}_{-0} (2)^{+3}_{-0}$
The HPQCD Collaboration now has \( N_f = 2 + 1 \) results for

\[
f_{B_s} \sqrt{B_{B_s}} = 281(21) \text{MeV}
\]

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

\[
\Delta M_s (\text{SM theory}) = 20.3(3.0)(0.8) \text{ps}^{-1}
\]

to be compared with the CDF measurement

\[
\Delta M_s = 17.77 \pm 0.10 \pm 0.07 \ \text{ps}^{-1}
\]

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 \( \Delta \Gamma_s \).
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:

$$\left[ \frac{f_{B_s}}{f_B} \right] / \left[ \frac{f_K}{f_\pi} \right]$$

D.Becirevic

Smoother chiral extrapolation

Exploit more accurately known $f_K/f_\pi$.

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

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

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

(G. Bennett et al. 2006)

\( a_\mu^{TH} \) 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 \( a_\mu^{QCD} \).

Several contributions to \( a_\mu^{QCD} \), the largest being the “hadronic contribution to the photon vacuum polarization”. This is usually determined from the experimental \( e^+e^- \rightarrow \text{hadrons} \) total cross-section plus dispersion relations (also \( \tau \rightarrow \text{hadrons} \) decay).
Hadronic Contribution to the Muon g-2
(cont’d)

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

Recent unquenched lattice determination using MILC configurations

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

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 $\rho$ meson width etc.)
The Strong Coupling Constant
(PDG 2006)

HPQCD value

$$\alpha_{MS}(M_Z) = 0.1170(12)$$

to be compared with current PDG 2006 world average of

$$\alpha_{MS}(M_Z) = 0.1176(20)$$

(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 ~ 100 TFLOPS computing power available to the lattice community in coming year.

S.Gottlieb: ~ 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.