Lattice Flavourdynamics

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Lattice Flavourdynamics - Outline

1. Introduction
   - Introductory Remarks
   - (Partially) Twisted Boundary Conditions or *Improving the Momentum Resolution in Lattice Simulations*
2. Quark Masses
3. Kaon Phenomenology
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   - B_K
   - $K \to \pi\pi$ Decays
4. Heavy Quark Physics
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Lattice Flavourdynamics - Mission Stetement

Lattice Simulations of QCD, in partnership with Experiments and Theory, play a central rôle in

- the determination of the fundamental parameters of the Standard Model (e.g. CKM matrix elements, quark masses);
- in searches of signatures of *New Physics*
- and potentially in understanding the structure of the new physics.

The principal reason for performing lattice simulations in Flavour Physics is, of course, to quantify non-perturbative QCD effects.

- Lattice computations are performed by formulating QCD on a finite discrete Euclidean space-time lattice and performing the functional integrals by Monte-Carlo integration.
- Quantities which can be calculated include hadronic masses and matrix elements of the form $\langle 0|\mathscr{O}|H\rangle$ and $\langle H_2|\mathscr{O}|H_1\rangle$, where the $\mathscr{O}$'s are local composite operators and H, H_1 and H_2 are hadrons.
  Recently we have learned how to evaluate matrix elements with two-hadron states below the inelastic threshold.
- Until recently most results were obtained in the *quenched* approximation, in which vacuum polarization effects are neglected.

This is now largely removed.

- The emphasis now is on reducing the masses of the u and d quarks in the simulations, so as to control the chiral extrapolation.

	m_q/m_s	m_π (MeV)	m_π/m_ρ
$SU(3)$ Limit	1	690	0.68
Currently Typical	1/2	490	0.55
Impressive	1/4	340	0.42
MILC	1/8	240	0.31
Physical	1/25	140	0.18

Lattice Actions

We want to use lattice actions in which the discretization errors $\sim O(a^2)$ ($a =$ lattice spacing) which give us good control of the chiral behaviour at a *reasonable* computational cost.

The challenge has been set by the MILC collaboration (and collaborating groups using their data) using *Improved Staggered Fermions*, who have calculated many quantities with small quoted errors.

- Is the continuum limit QCD?
  Unphysical *tastes* removed by taking the fermionic Det$^{1/4}$. No proof that this is correct (but some circumstantial evidence) and no counter example. See e.g. S.Dürr, hep-lat/0509026
- Staggered Chiral Perturbation theory has to include the a-dependence and the extrapolation has many parameters (e.g. 192 for f_π).
- Renormalization is performed perturbatively.
- It would be nice if the results of the extrapolations and procedures were confirmed by other groups.

The challenge is being taken up by groups using formulations (e.g. Improved Wilson, Twisted Mass, Domain Wall, Overlap).

see e.g. M.Lüscher, `hep-lat/0509152`

There is still work to be done to be confident that the systematics are fully under control.

(Partially) Twisted Boundary Conditions

- It is conventional to define the lattice theory with periodic boundary conditions for the fields
$$\phi(x_i+L)=\phi(x_i)\,.$$
This implies that components of momenta are quantized in units of $2\pi/L$.
- Typical Example:
$$L=24a \quad \text{with} \quad a^{-1}=2\,\text{GeV} \quad \Rightarrow \quad \frac{2\pi}{L}=.52\,\text{GeV}$$
so that the available momenta for phenomenological studies (e.g. in the evaluation of form-factors) are limited.
(In addition we require pa to be small to avoid discretization errors.)
- Bedaque has advocated the use of twisted boundary conditions e.g.
$$q(x_i+L)=e^{i\theta_i}q(x_i)$$
so that the momentum spectrum is
$$p_i=n_i\frac{2\pi}{L}+\frac{\theta_i}{L}\,.$$

- For quantities which do not involve Final State Interactions (e.g. masses, decay constants, form-factors) the Finite-Volume corrections are exponentially small also with Twisted BC's. CTS & G. Villadoro (2004)
- Moreover they are also exponentially small for *partially twisted boundary conditions* in which the sea quarks satisfy periodic BC's but the valence quarks satisfy twisted BC's. CTS & G. Villadoro (2004); Bedaque & Chen (2004)

We do not need to perform new simulations for every choice of $\{\theta_i\}$.

For example:

$$\frac{\Delta f_{K^\pm}}{f_{K^\pm}} \to \begin{cases} -\frac{9}{4}\frac{m_\pi^2}{f_\pi^2}\frac{e^{-m_\pi L}}{(2\pi m_\pi L)^{3/2}} & \text{(a)} \\ -\frac{m_\pi^2}{f_\pi^2}\frac{e^{-m_\pi L}}{(2\pi m_\pi L)^{3/2}}\left(\frac{1}{2}\sum_{i=1}^3\cos\theta_i+\frac{3}{4}\right) & \text{(b)} \\ -\frac{m_\pi^2}{f_\pi^2}\frac{e^{-m_\pi L}}{(2\pi m_\pi L)^{3/2}}\left(\sum_{i=1}^3\cos\theta_i-\frac{3}{4}\right) & \text{(c)} \end{cases}$$

d and s quarks satisfy periodic boundary conditions,
u quark is (a) untwisted, (b) fully twisted (c) partially twisted.

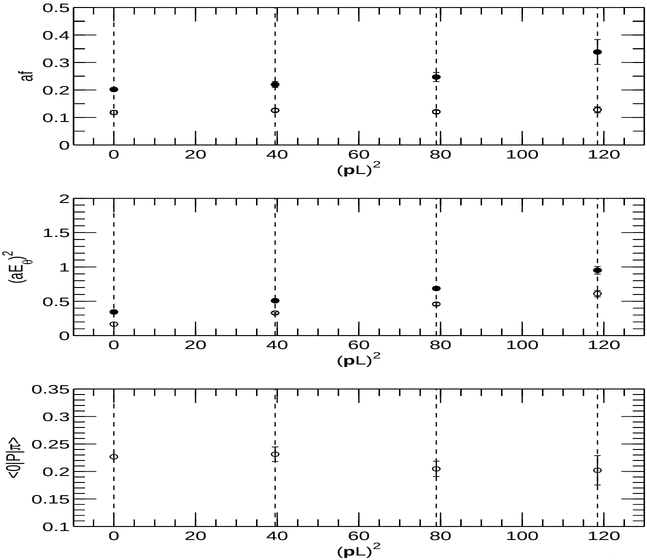
The use of partially twisted boundary conditions opens up many interesting phenomenological applications.

It also appears also to work numerically!

Tests of the dispersion relation for pseudoscalars in the quenched approximation - de Divitiis, Petronzio and Tantalo (2004)

Flynn, Juettner & CTS, using UKQCD $16^3 \times 32$, N_F=2 configurations:

$$L \simeq 1.7\,\text{fm}, \quad a \simeq 0.1\,\text{fm}, \quad \frac{m_\pi}{m_\rho} = 0.7,\ 0.57\ .$$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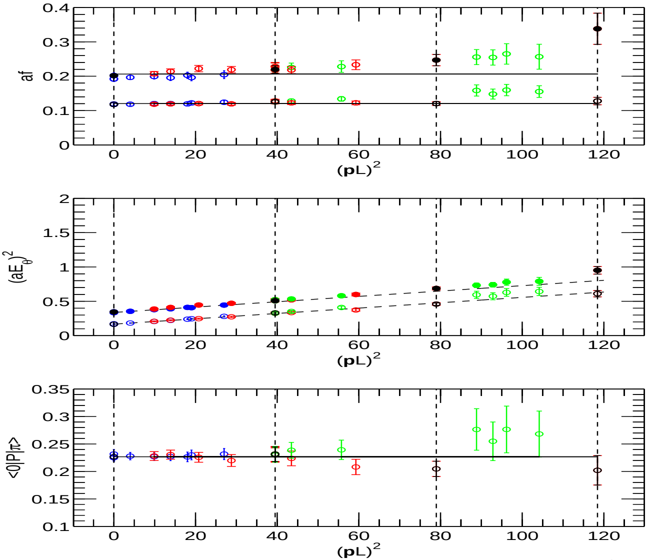
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(pL)^2

Quark Masses

Quark Masses are fundamental parameters of the Standard Model of Particle Physics

$$\mathscr{L} = \sum_{k=1}^{N_F} \bar{q}_k (i\not{D} - m_k) q_k - \frac{1}{4} G_{\mu\nu} G^{\mu\nu} \,.$$

- Unlike leptons, quarks are confined inside hadrons and are therefore not observed as physical particles $\Rightarrow$ quark masses cannot be measured directly.
- Quark masses therefore have to be obtained indirectly through their influence on hadronic quantities.
- In order to determine the quark masses we:
  - Compute a convenient and appropriate set of physical quantities (frequently a set of hadronic masses);
  - Vary the input masses until the computed values correctly reproduce the set of physical quantities being used for calibration.

  In this way we obtain the physical values of the bare quark masses, $m_k(a)$.

Recent (Unquenched) Lattice Results

Reference	$m_s^{\overline{MS}}(2\,\mathrm{GeV})$	$\frac{1}{2}(m_u^{\overline{MS}} + m_d^{\overline{MS}})(2\,\mathrm{GeV})$
HPQCD, MILC & UKQCD	$76 \pm 3 \pm 7$ MeV	$2.8 \pm .1 \pm .3$ MeV
HPQCD, MILC & UKQCD Update including 2-loop Z's	$86 \pm 3 \pm 4$ MeV	$3.2 \pm .1 \pm .2$ MeV *
CP-PACS & JLQCD (K-input)	80.4 ± 1.9 MeV	$3.05 \pm .06$ MeV
CP-PACS & JLQCD (Φ-input)	89.3 ± 2.9 MeV	$3.04 \pm .06$ MeV
SPQR (VWI)	111 ± 6 MeV	$4.8 \pm .5$ MeV
SPQR (AWI)	103 ± 9 MeV	$4.5 \pm .5$ MeV
QCDSF & UKQCD	$119 \pm 5 \pm 8$ MeV	$4.7 \pm .2 \pm .3$ MeV
Alpha	97 ± 22 MeV	—
SPQ$_{\mathrm{CD}}$R	$101 \pm 8^{+25}_{-0}$ MeV	$4.3 \pm 0.4^{+1.1}_{-0}$ MeV

* - My estimate from results for m_u and m_d.

My current summary of lattice results for the light-quark masses is:

$$\frac{1}{2}\left(m_u^{\overline{\rm MS}}(2\,{\rm GeV})+m_d^{\overline{\rm MS}}(2\,{\rm GeV})\right) = (3.8\pm0.8)\,{\rm MeV}$$
$$m_s^{\overline{\rm MS}}(2\,{\rm GeV}) = (95\pm20)\,{\rm MeV}\,.$$

In PDG(2004) these numbers are

$$\frac{1}{2}\left(m_u^{\overline{\rm MS}}(2\,{\rm GeV})+m_d^{\overline{\rm MS}}(2\,{\rm GeV})\right) = (4.2\pm1.0)\,{\rm MeV}$$
$$m_s^{\overline{\rm MS}}(2\,{\rm GeV}) = (105\pm25)\,{\rm MeV}\,.$$

- The results tend to decrease in unquenched simulations.
- Many of the unquenched simulations are new and I'm confident that the errors will decrease for the next (after 2006) PDG review.

PDG(2004), excluding lattice QCD:

$$1.5\,{\rm MeV}\le m_u^{\overline{\rm MS}}(2\,{\rm GeV})\le 5\,{\rm MeV};$$
$$5\,{\rm MeV}\le m_d^{\overline{\rm MS}}(2\,{\rm GeV})\le 9\,{\rm MeV};$$
$$80\,{\rm MeV}\le m_s^{\overline{\rm MS}}(2\,{\rm GeV})\le 155\,{\rm MeV}.$$

Mass of the Charm Quark

For the mass of the charm quark, the most detailed study has been performed by Rolf and Sint (hep-ph/0209255) who study all systematic errors in detail, except for quenching:

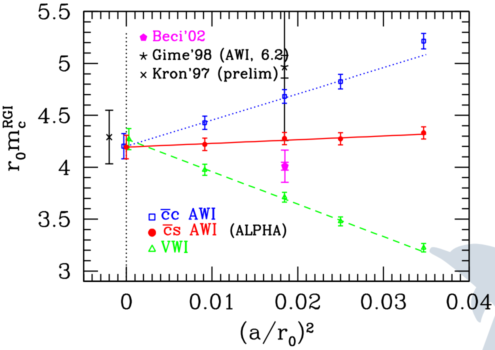
- $O(a)$ improved action $\Rightarrow$ discretization errors of $O(a^2)$,
- non-perturbative renormalization a la Alpha Collaboration $\Rightarrow$ only need to use continuum perturbation theory to get $\bar{m}_c \equiv m_c^{\overline{\rm MS}}(m_c^{\overline{\rm MS}})$,
- 5 different definitions of m_c based on Ward Identities.

They find

$$\bar{m}_c = 1.301(34)\,\text{GeV}\,,$$

where the scale has been set from f_K (setting the scale by m_p increases $\bar{m}_c$ by about 3%).

L.Lellouch – hep-ph/0211359



Continuum extrapolation of the RGI charm mass by ALPHA (Rolf and Sint).

My best estimate of the value m_c from lattice simulations is:

$$\bar{m}_c = (1.30 \pm 0.03 \pm 0.20)\,\mathrm{GeV}\,,$$

where the second error of 15% is my estimate of possible quenching effects.

- Recent preliminary unquenched results lie in the above range (1.22(9) GeV, Nobes and Trottier, `hep-lat/0509128`), and I expect that in the future the results will be dominated by unquenched simulations.

In PDG(2004) the quoted lattice result was

$$\bar{m}_c = (1.26 \pm 0.13 \pm 0.20)\,\mathrm{GeV}\,.$$

and the result excluding lattice simulations was

$$1\,\mathrm{GeV} \leq \bar{m}_c \leq 1.4\,\mathrm{GeV}\,.$$

The Mass of the b-Quark

$m_b \gg a^{-1} \gg \Lambda_{\mathrm{QCD}} \quad \Rightarrow$ Effective Theories (HQET or NRQCD) must be used.

For example we can readily compute the correlation function

$$C(t) = \sum_{\vec{x}} \langle 0 | A_0(\vec{x},t) A_0(\vec{0},0) | 0 \rangle$$

in the HQET.
(A_μ is the axial current $\bar{h}\gamma_\mu\gamma^5 q$ where h and q are heavy- and light-quark fields.)

At large t:

$$C(t) \simeq Z^2 \exp(-\xi t)$$

where from Z we obtain the value of the decay constant, f_B, in the static approximation. (E.Eichten - 1987)

From the measured value of ξ one can obtain m_b (up to $\Lambda^2_{\mathrm{QCD}}/m_b$ corrections.) (M.Crisafulli, V,Giménez, G.Martinelli, CTS - 1995)

- In order to obtain $\overline{m}_b$ from ξ, perturbative subtraction of terms proportional to $1/a$ is needed.
- This subtraction has now been performed at 3-loop order using *stochastic perturbation theory*. Di Renzo & Scorzato (2004)

Unquenched Results

- $\overline{m}_b = 4.21 \pm 0.03 \pm 0.05 \pm 0.04$ GeV
  $n_f = 2$, N^{3}LO. V.Giménez, L.Giusti, G.Martinelli and F.Rapuano (2000) + F.Di Renzo and L.Scorzato (2004)
- $\overline{m}_b = 4.25 \pm 0.02 \pm 0.11$ GeV
  $n_f = 2$, N^{2}LO . C.McNeile, C.Michael & G.Thompson (2004)
- $\overline{m}_b = 4.4 \pm 0.3$ GeV
  $n_f = 3$, one-loop perturbation theory (responsible for the relatively large error). A. Gray et al., (2005)

A strategy to renormalize the HQET non-perturbatively is being successfully developed by the DESY-Zeuthen group.

J.Heitger & R.Sommer; M.Kurth & R.Sommer; Heitger, Kurth & Sommer, $\cdots$

My current best estimate for the lattice determination of m_b is:

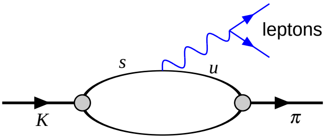
$$\bar{m}_b = (4.2 \pm 0.1 \pm 0.1)\,\mathrm{GeV}\,,$$

where the second error is a conservative 10% on $m_B - m_b$ due to the fact that the simulation was performed with $n_f = 2$.

PDG(2004):

$$\begin{array}{rcll} \bar{m}_b & = & (4.26 \pm 0.15 \pm 0.15)\,\mathrm{GeV} & \{\text{Lattice Only}\} \\ 4\,\mathrm{GeV} \leq & \bar{m}_b & \leq 4.5\,\mathrm{GeV} & \{\text{Lattice Excluded}\}\,. \end{array}$$

Kaon Physics - $K_{\ell 3}$ Decays



$\Rightarrow \quad V_{us}$

$$\langle \pi(p_\pi) | \bar{s}\gamma_\mu l | K(p_K) \rangle = f^0(q^2)\, \frac{M_K^2 - M_\pi^2}{q^2} q_\mu + f^+(q^2) \left[(p_\pi + p_K)_\mu - \frac{M_K^2 - M_\pi^2}{q^2} q_\mu \right]$$

where $q \equiv p_K - p_\pi$ and $l = u, d$.

To be useful in extracting V_{us} we require $f^0(0) = f^+(0)$ to better than about 1% precision.

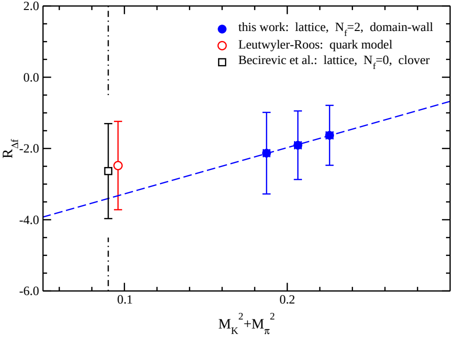
$$\chi\text{PT} \Rightarrow f^+(0) = 1 + f_2 + f_4 + \cdots \quad \text{where} \quad f_n = O(M^n_{K,\pi,\eta}).$$

Reference value $f^+(0) = 0.961 \pm 0.008$ where $f_2 = -0.023$ is relatively well known from χPT and $f_4, f_6, \cdots$ are obtained from models. Leutwyler & Roos (1984)

1% precision of $f^+(0)$ is conceivable because it is actually $1 - f^+(0)$ which is computed using *double ratios* such as: S.Hashimoto et al.

$$\frac{\langle\pi|\bar{s}\gamma_0 l|K\rangle\langle K|\bar{l}\gamma_0 s|\pi\rangle}{\langle\pi|\bar{l}\gamma_0 l|\pi\rangle\langle K|\bar{s}\gamma_0 s|K\rangle} = \left[f^0(q^2_{\max})\right]^2 \frac{(m_K + m_\pi)^2}{4 m_K m_\pi}\,.$$

q^2 and m^2 extrapolations still have to be done.



For example, the RBC collaboration show the (valence) mass behaviour of

$$R_{\Delta f} \equiv \frac{\sum_2^\infty f_{2k}}{(M_K^2 - M_\pi^2)^2}\,.$$

Results are in units of a ($a^{-1} \simeq 1.7\,$GeV).

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$$\frac{\langle\pi|\bar{s}\gamma_0 l|K\rangle\langle K|\bar{l}\gamma_0 s|\pi\rangle}{\langle\pi|\bar{l}\gamma_0 l|\pi\rangle\langle K|\bar{s}\gamma_0 s|K\rangle} = \left[f_0(q^2_{\rm max})\right]^2 \frac{(m_K+m_\pi)^2}{4m_K m_\pi}\,.$$

q^2 and m^2 extrapolations still have to be done.

Three *preliminary* new (unquenched) results for $f^+(0)$:

RBC (2005)	0.955(12)
JLQCD (2005)	0.952(6)
FNAL/MILC/HPQCD (2004)	0.962(6)(9)

in good agreement with the Leutwyler-Roos result of 0.961(8).

Systematic Errors (continuum, chiral, q^2 extrapolations) will be reduced over the next year or two.

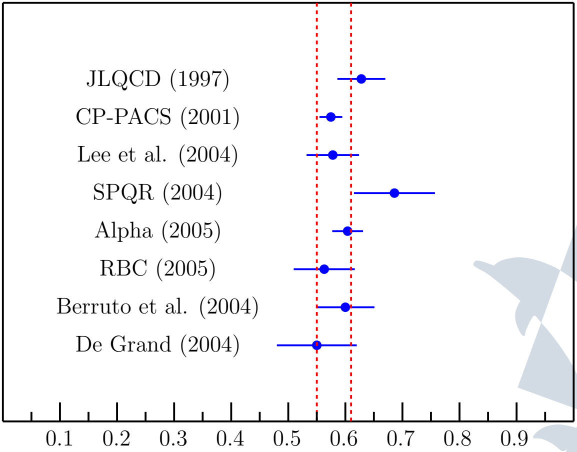
Kaon Physics - B_K

The parameter B_K contains the non-perturbative QCD effects in $K - \bar{K}$ mixing and has been computed in lattice simulations for a long time.

$$\langle \bar{K}^0 \,|\, (\bar{s}\gamma^{\mu}(1-\gamma^5)d)\,(\bar{s}\gamma_{\mu}(1-\gamma^5)d)|K^0\rangle = \frac{8}{3} M_K^2 f_K^2 B_K \,.$$

B_K depends on the renormalization scheme and scale and is conventionally given in the NDR, $\overline{\mathrm{MS}}$ scheme at $\mu = 2\,$GeV or as the RGI parameter $\hat{B}_K$ ($\hat{B}_K \simeq 1.4\, B_K^{\overline{\mathrm{MS}}}(2\,\mathrm{GeV})$.)

Selected Quenched Results for $B_K^{\overline{MS}}(2\,\mathrm{GeV})$



- Recent summaries of the quenched value of B_K include:

$$\begin{aligned} B_K^{\overline{\rm MS}}(2\,{\rm GeV}) &= 0.58(4) \qquad \text{S.Hashimoto (ICHEP 2004)} \\ B_K^{\overline{\rm MS}}(2\,{\rm GeV}) &= 0.58(3) \qquad \text{C.Dawson (Lattice 2005)}\,. \end{aligned}$$

- Dynamical computations of B_K are underway by a number of collaborations, but so far the results are very preliminary.

  C.Dawson's guesstimate (from comparison of unquenched & quenched results at similar masses and lattice spacings)

$$B_K^{\overline{\rm MS}}(2\,{\rm GeV}) = 0.58(3)(6) \qquad \text{C.Dawson (Lattice 2005)}\,.$$

  We need to wait until reliable dynamical results are available in the next year or two.

$K \to \pi\pi$ Decays

- A quantitative understanding of the non-perturbative QCD effects in $K \to \pi\pi$ decays is an important future milestone for lattice QCD, e.g.:
  - the empirical $\Delta I = 1/2$ rule, which states that amplitudes for decays with an $I = 0$ final state are enhanced by a factor of about 22 w.r.t. amplitudes for decays with an $I = 2$ final state.
  - the quantity ε'/ε, whose measurement with a non-zero value, $(17.2 \pm 1.8) \times 10^{-4}$, was the first observation of direct CP-violation.

In 2001, two collaborations published some very interesting results on these quantities:

Collaboration(s)	$\mathtt{Re}\, A_0/\mathtt{Re}\, A_2$	ε'/ε
RBC*	25.3 ± 1.8	$-(4.0 \pm 2.3) \times 10^{-4}$
CP-PACS	9÷12	(-7 ÷ -2)$\times 10^{-4}$
Experiments	22.2	$(17.2 \pm 1.8) \times 10^{-4}$

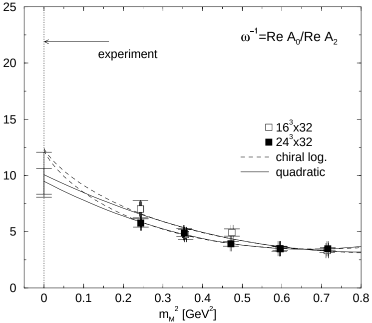
*updated results from July 2002 version of the paper.

- The lattice calculation is of the $K \to \pi\pi$ matrix elements of the $\Delta S = 1$ operators which appear in the Effective Hamiltonian.
- The two collaborations evaluated matrix elements of the form

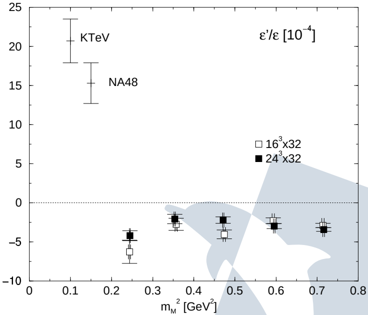
$$\langle M | \mathscr{O} | M \rangle$$

(where M is a pseudoscalar meson) and used LO χPT to determine the corresponding $K \to \pi\pi$ matrix elements.

CP-PACS



ReA_0/**Re**A_2



ε'/ε

- Is χPT applicable/reliable in the accessible range (400-800 MeV)?
- Results from RBC and CP-PACS are very interesting and will provide valuable benchmarks for future calculations.
- One suggestion for the next stage is to improve the precision to NLO in the chiral expansion. Lin, Pallante, Martinelli, CTS & Villadoro
  Laiho & Soni
- In general we need to evaluate $K \to \pi\pi$ decay amplitudes directly.
- With two hadrons in the final state the finite-volume corrections decrease only as $1/L^n$ and not exponentially.

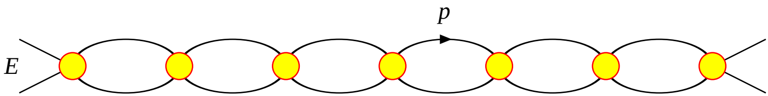
  The theory of finite-volume effects for two-hadron states in the elastic region is now fully understood $\Rightarrow$ $\pi\pi$ phase-shifts.

  Lüscher (1986-91); Lellouch and Lüscher(2000); Lin, Martinelli, CTS and Testa (2001) Rummukainen & Gottlieb (1995); Kim, CTS and Sharpe (2005);

  Christ, Kim and Yamazaki (2005)

Finite-Volume Corrections for Two-Pion States

For two-particle states the finite-volume corrections decrease as powers of the volume and not exponentially. They are numerically significant and hence need to be controlled.



where $E^2 = 4(k^2 + m^2)$.

Performing the p_0 integration by contours we obtain summations over loop-momenta of the form:

$$\frac{1}{L^3}\sum_{\vec{p}}\frac{f(p^2)}{p^2-k^2}$$

where $f(p^2)$ is non-singular.

For simplicity I am assuming here that only the s-wave $\pi\pi$ phase-shift is significant and that we are in the centre-of-mass frame.

$$\frac{1}{L^3}\sum_{\vec{p}}\frac{f(p^2)}{p^2-k^2}$$

The required relation between the FV sums and infinite-volume integrals is the **Poisson Summation Formula**, which in 1-dimension is:

$$\frac{1}{L}\sum_{p} g(p) = \sum_{l=-\infty}^{\infty}\int\frac{dp}{2\pi}e^{ilLp}g(p)$$

If $g(p)$ is non-singular then only the term with $l=0$ on the rhs contributes, up to exponentially small in L.

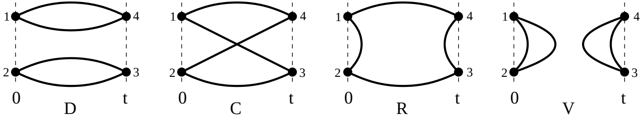
From the above it follows that this is not the case for two-hadron final states $\Rightarrow$ finite-volume corrections $\sim 1/L^n$.

In 2005 we understood these effects also in frames with $\vec{P}\neq\vec{0}$.

Similar issues and results also hold for other two-hadron states (e.g. $\pi-N$ and $N-N$).

For $I = 2$ final states, there is now no barrier to calculating the matrix elements precise, and these are underway.

For $I = 0$ $\pi\pi$ states we need to learn how to calculate the disconnected diagrams with sufficient precision.



Heavy Quark Physics

Lattice computations in heavy quark physics include:

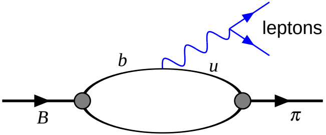
- Leptonic Decay Constants, $f_D,\ f_{D_s},\ f_B,\ f_{B_s}$;
- The B-parameters of B-$\overline{B}$ and B_s-$\overline{B}_s$ mixing. ($\Rightarrow\ V_{td}$ and V_{ts})
- Semileptonic Form Factors ($\Rightarrow\ V_{cb}$ and V_{ub});
- The $g_{BB^*\pi}$ coupling;
- Beauty Lifetimes.

In this talk I will only discuss semileptonic decays.

For QCD simulations we require $m_b \ll a^{-1}$ which is not possible at present $\Rightarrow$ we need to use effective theories (HQET, NRQCD, Fermilab formulation).

(I am concerned that the coefficients are (largely) being determined perturbatively.)

$B \to \pi$ Semileptonic Decays



$\Rightarrow \quad V_{ub}$

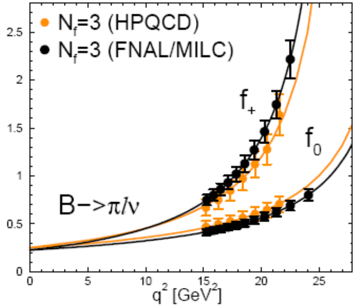
- Small lattice artefacts $\Rightarrow$ momentum of the pion must be small $\Rightarrow$ we obtain form factors at large q^2.

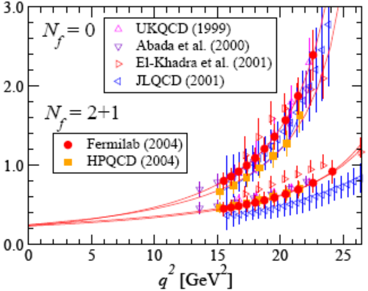
  There is a proposal to eliminate this constraint by using a formulation in which the B-meson is moving. A.Dougall et al., `hep-lat/0509108`

- Experimental results in q^2 bins together with theoretical constraints, helps one use the lattice data to obtain V_{ub} precisely.

  I.Stewart LP2005, T.Becher & R.Hill `hep-lat/0509090`

Recent Results for $B \to \pi$ Form Factors

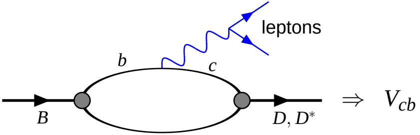




Courtesy of T.Onogi, Chamonix Flavour Dynamics Workshop, October 2005

HPQCD	Staggered Light & NRQCD Heavy	$\lvert V_{ub}\rvert = 4.04(20)(44)(53) \times 10^{-3}$
FNAL/MILC	Staggered Light & Fermilab Heavy	$\lvert V_{ub}\rvert = 3.48(29)(38)(47) \times 10^{-3}$

$B \to D^{(*)}$ Semileptonic Decays



- For $B \to D^*$ decays

$$\frac{d\Gamma}{d\omega} = \frac{G_F^2}{48\pi^3}(m_B - m_{D^*})^2 m_{D^*}^3 \sqrt{\omega^2 - 1}\,(\omega+1)^2 \times \left[1 + \frac{4\omega}{\omega+1}\frac{m_B^2 - 2\omega m_B m_{D^*} + m_{D^*}^2}{(m_B - m_{D^*})^2}\right] |V_{cb}|^2 \mathscr{F}^2(\omega)\ ,$$

  where $\mathscr{F}(\omega)$ is the IW-function combined with perturbative and power corrections. $(\omega = v_B \cdot v_{D^*})$

- $\mathscr{F}(1) = 1$ up to power corrections and calculable perturbative corrections.

- To determine the difference of $\mathscr{F}(1)$ from 1, the method of double ratios is used.
- A recent result from the FNAL/MILC/HPQCD Collaborations gives

$$|V_{cb}| = 3.9(1)(3) \times 10^{-2}\,.$$

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- Form Factors for $D \to \pi, K$ semileptonic decays are also being evaluated.

Summary and Conclusions

- Lattice Simulations of QCD, in partnership with Experiments and Theory, play a central rôle in
  - the determination of the fundamental parameters of the Standard Model (e.g. CKM matrix elements, quark masses);
  - in searches of signatures of *New Physics*
  - and potentially in understanding the structure of the new physics.
- With the advent of unquenched simulations, a major source of uncontrolled systematic uncertainty has been eliminated, and the main aim now is to control the chiral extrapolation and reduce other sources of systematic uncertainty.
- Much work continues to be done to extend the range of applicability of lattice simulations to more processes and physical quantities.
- I have given a selection of recent results and developments.

  A more complete set can be found on the web-site of the Lattice 2005 symposium, `www.maths.tcd.ie/lat05` .