Recent progress towards high-precision heavy quark physics from lattice QCD

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progress in the past five years

10-20% accuracy achieved for a wide range of masses and form factors (CKM determinations).

There are notable (PDG2002) precision determinations:

determination	total uncert.	reference
$\bar{\alpha}_s(m_Z)$	2-3%	[**hep-lat/9703010**]
$\overline{m}_b(m_b)$	2-4%	[**hep-lat/0002007**]
$h_{A_1}(1)$ in $\bar{B} \to D^* \ell \nu$	3-4%	[**hep-ph/0110253**]

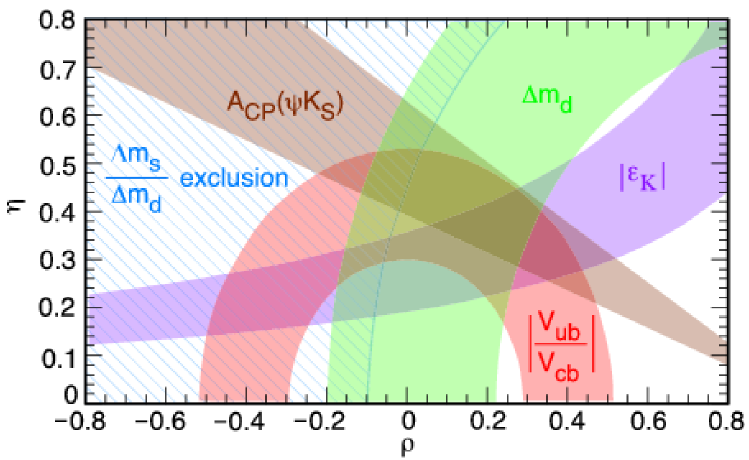
For detailed reviews of heavy quark results see:

N. Yamada	LATTICE'02 [**hep-lat/0210035**]
A. Kronfeld	Physics in Collision [**hep-ph/0209231**]
S. Ryan	LATTICE'01 [**hep-lat/0111010**]

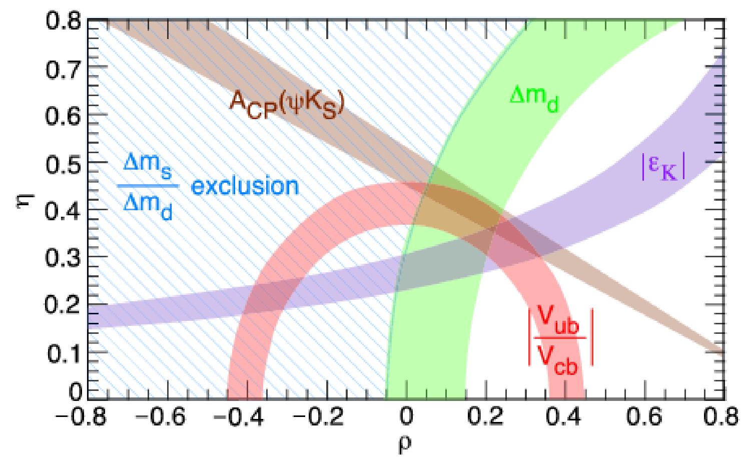
CKM physics in the B-factory era

Driving theory errors from present 10-15% level to the few percent level is absolutely crucial in the era of B factories

circa 2002 [P. Lepage]



B-factories 10% theory errors



Investments in lattice QCD and CLEO-c are crucial for leveraging the investment in B factories.

lattice QCD is predictive

Lattice QCD is not a model

- free parameters in the lattice QCD action are the bare coupling g_0 and quark masses m_f
- demanding a single computed quantity match its experimental value establishes the lattice spacing, a, hence the scale μ of the renormaized coupling: *e.g.* $m(1P\text{-}1S)$ from -onia
- match additional experimental inputs (m_π, m_K, D_s and B_s) to determine the quark masses m_u, m_d, m_s, m_c and m_b

All other caculations then serve to pre(post)dict other hadronic quantities (for example weak matrix elements)

CLEO-c

The CLEO-c program will produce abundant experimental data on charm spectroscopy and decays.

In addition to having direct impact on the B-collider programs, thes data will permit definitive precision tests of lattice QCD for charm. Such tests indirectly check lattice QCD's reliability for bottom.

system	quantity	CLEO-c goal
$\Upsilon(nS)$	spectroscopy and widths	S, P and D masses, 2-3% for $\Gamma_{ee}(nS)$
D decays	$D \to \ell\nu$	$\sim 2\%$ for f_D
	$D \to \pi\ell\nu$	$\lvert V_{cd}\rvert f_+(q^2)$ and f_+/f_D
D_s decays	$D_s \to \ell\nu$	$\sim 2\%$ for f_{D_s}
$\psi'(3686)$	spectroscopy and rates	η_s' and h_c

meeting the CLEO-c challenge

investment in computing infrastructure

collaboration

theoretical breakthroughs

refinements of existing techniques

all are important ingredients. . .

computing infrastructure

The DOE Scientific Discovery through Advanced Computing (SciDAC) program has funded the development of common software frameworks for lattice QCD, development work for QCDOC a purpose built computer at Columbia/BNL and commodity clusters at Fermilab and Jlab. **Thank You SciDAC!**

Fermilab (5/03):

128-node dual 2.4GHz Xeon

48-node dual 2.0GHz Xeon

80-node dual 0.7GHz PIII

6-node Itanium2

Myrinet Clos X-bar switches

U.S. community's goal is three multi-Teraflop national facilities at BNL, FNAL and Jlab.

SciDAC science

U.S. community is broadly organized around three goals: weak decays of hadrons, QCD thermodynamics and hadronic structure.

calculation of weak decays of strongly interacting particles:

- determination of least-well-known parameters of the Standard Model
- precision tests of the Standard Model

A collaboration of collaborations: $\mathcal{O}(35)$ physicists from 13 institutions: Cornell, DePaul, FNAL, Glasgow, IU, OSU, Simon Fraser U., U. Arizona, UCSB, UIUC, UoP, U. Utah, Wash. U.

$n_f = 2 + 1$ dynamical quarks

Neglecting vaccuum polarization ($n_f = 0$, quenched QCD) leads to 10-20% uncertainties

"Strategic" breakthrough: The MILC collaboration has created sets of gluon configurations having three flavors dynamical quarks

- "Asqtad" gluon + dynamic quark action
- uncertainties: gluon $\mathcal{O}\left(\alpha_s^2 a^2\right)$, quarks $\mathcal{O}\left(\alpha_s a^2\right)$
- one flavor m_s, two flavors m_l
- m_l "chiral" extrapolations: m_l varied from m_s to $m_s/5$ at fixed a
- numerically less expensive than common dynamical quark actions

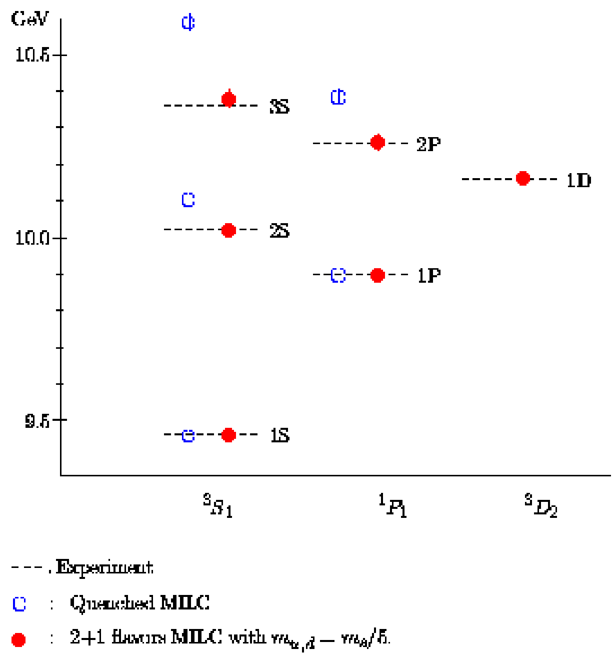
Implications:

- **no extrapolations in n_f**
- **quenching no longer dominant systematic: examine other uncertainties**

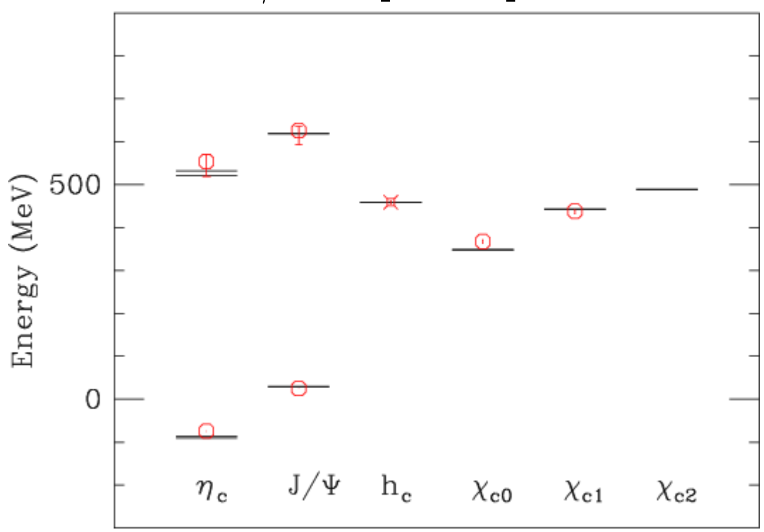
quarkonium spectra ($n_f = 2 + 1$)

Quarkonia is an ideal laboratory for testing systematic improvements

Υ [C.Davies]



ψ [FNAL]



Υ: compare quenched **(blue)** results to three flavor **(red)** results

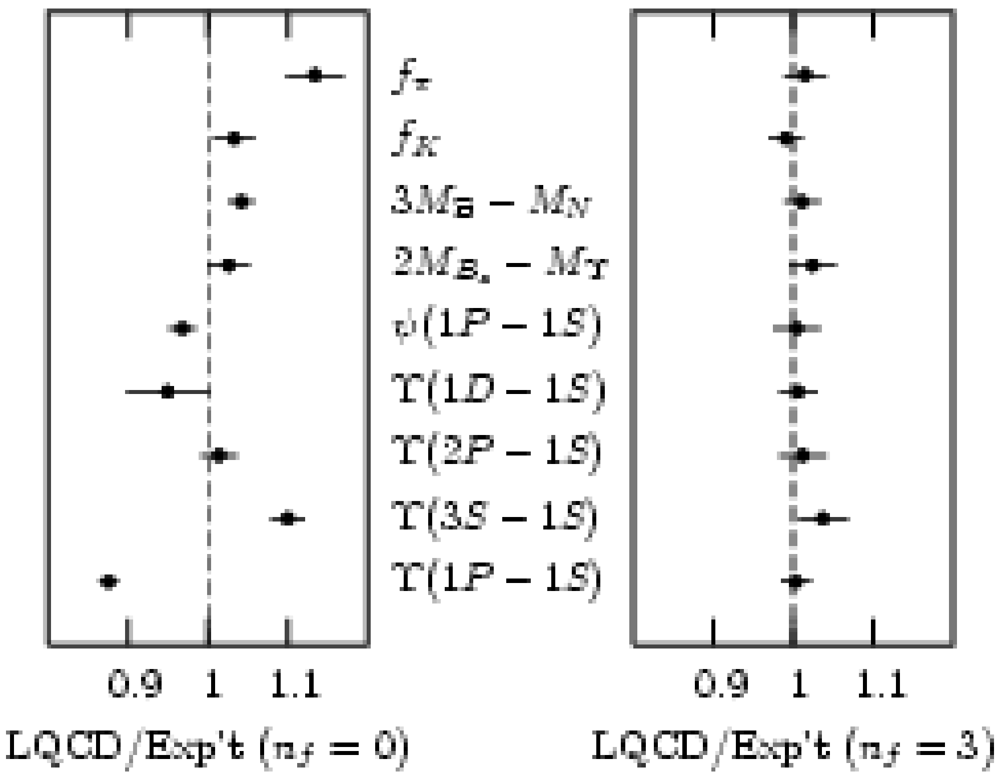
Υ: NRQCD, dominant uncertainties $\mathcal{O}(a^2, v^4)$

ψ: Fermilab quark action $\mathcal{O}(\alpha_s a\Lambda, \alpha_s a\Lambda^2/m_c)$

lattice QCD confronts experiment

Test $n_f = 2 + 1$ lattice QCD in light, heavy and heavy-light sectors

[C. Davies, *et al.*, **hep-lat/0304004**]



Figures plot

$$R_M = \frac{\left(\frac{M}{\Upsilon(2S-1S)}\right)^{\text{lqcd}}}{\left(\frac{M}{\Upsilon(2S-1S)}\right)^{\text{expt}}}$$

for each result M

Large uncertainty from quenched QCD is removed

effective field theories

With current lattice spacings, the bottom quark mass is big:

$$\Lambda_{QCD} \ll 1/a \lesssim m_b$$

The charm quark mass is also large: $am_c \lesssim 1$.

Two complimentary systematic approaches for treating heavy quarks:

NRQCD and Fermilab HQ formalism

NRQCD is computationally faster which gives it an advantage for bottom quarks.

The Fermilab formalism has the advantage for charm quarks since relativistic effects are larger.

Improvement programs underway:

NRQCD: $\mathcal{O}(\alpha_s \Lambda/m_b, \Lambda^2/m_b^2) \quad \rightarrow \quad \mathcal{O}(\alpha_s^2 \Lambda/m_b)$

FNAL: $\mathcal{O}(\alpha_s \Lambda a, \alpha_s a \Lambda^2/m_c) \quad \rightarrow \quad \mathcal{O}(\alpha_s^2 \Lambda a, \alpha_s^2 a \Lambda^2/m_c)$ **hep-lat/0209150**

Need lots of lattice perturbation theory. . .

lattice perturbation theory

Radiative corrections are need for Symanzik improvement program

$$\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{cont}} + \sum_j C_j(a, \alpha_s)\, a^{-4+dim[\mathcal{O}_j]}\, \mathcal{O}_j(a)$$

$$\mathcal{J}_\mu^{\text{cont}} = Z(a, \alpha_s)\left[\mathcal{J}_\mu^{\text{lat}}(a) + z(a, \alpha_s) a^2 \Delta \mathcal{J}_\mu + \cdots\right]$$

and for quantities such as the quark self-energy (to get $\bar{m}_c(m_c)$ and $\bar{m}_b(m_b)$)

Many expansions known to tree or first order must be done to higher orders

Automated perturbation theory [Lüscher and Weisz; Trottier, hep-lat/011005]

paths in action $\Rightarrow$ computer code $\Rightarrow$ Vegas integration

Trottier *et al.* results:

- **checks of many known first order results for variety of actions**
- α_s^3 **correction to plaquette for** $\bar{\alpha}_s(\mu)$ **determination**
- 2^{nd} **order static quark self-energy (** 3^{rd} **order from small** g_0^2 **Monte Carlo)**

“gold-plated” decay modes

These are the best choices for precision calculations:

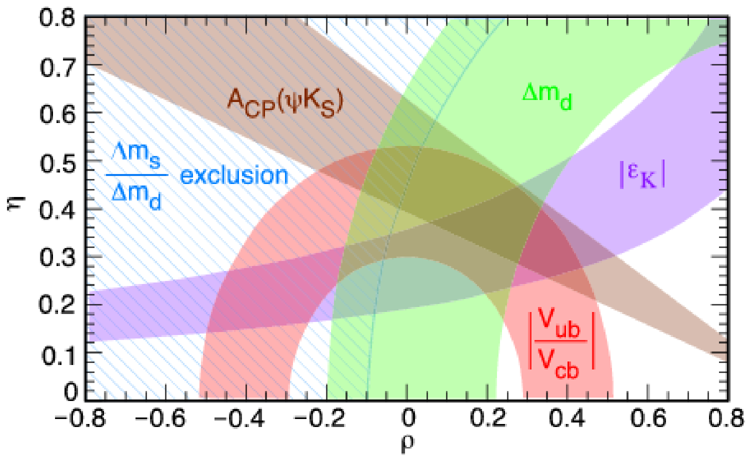
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ \pi \to \ell\nu & K \to \ell\nu; K \to \pi\ell\nu & \bar{B} \to \pi\ell\nu \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ D \to \ell\nu; D \to \pi\ell\nu & D_s \to \ell\nu; D \to K\ell\nu & \bar{B} \to D^*\ell\nu \\ |V_{td}| & |V_{ts}| & |V_{tb}| \\ B_d^0\text{-}\bar{B}_d^0 \text{ mixing} & B_s^0\text{-}\bar{B}_s^0 \text{ mixing} & \sim 1 \end{pmatrix}$$

They are theoretically and technically well understood:

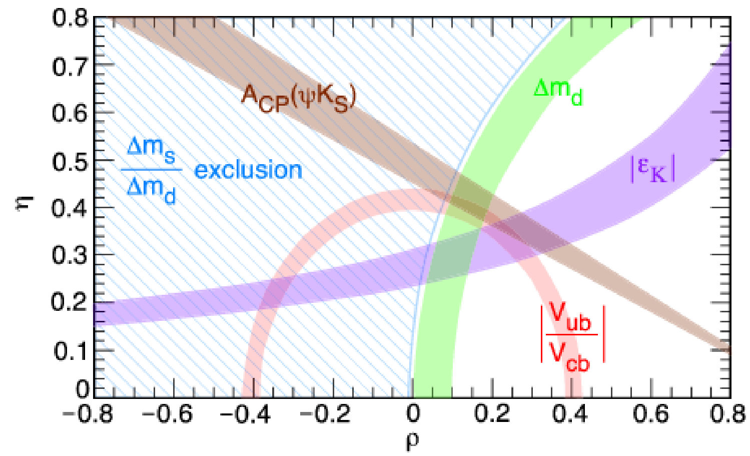
- final states are hadronically stable
- at most one hadron in initial and final states

future prospects

circa 2002 [P. Lepage]



B-factories 3% theory errors



Lattice calculations now practical with $n_f = 2 + 1$ QCD

Well understood quantities e.g. masses of stable particles, splittings in quarkonia tested at the few percent level

Expect precision determinations of Standard Model parameters $\bar{\alpha}_s(m_Z)$, $\bar{m}_b(m_b)$, $\bar{m}_c(m_c)$ and most CKM parameters from golden-plated processes

Lattice predictions will be testable to high precision using CLEO-c results