B and D mesons on the lattice

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Outline

1. Introduction: Lattice QCD
2. Decay constants: $P \to l\nu$
   - f_D and f_{D_s}: test of lattice QCD
   - f_B and f_{B_s}
3. Semileptonic decays
   - Exclusive $B \to D^* l\nu$: determination of $|V_{cb}|$
   - $B \to \pi l\nu$: determination of $|V_{ub}|$
4. $B^0 - \bar{B}^0$ mixing: $\Delta M_{d,s}$, $\Delta\Gamma_{d,s}$ and ξ
5. Conclusions and outlook

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Goal: control systematic errors

Quenched approximation: neglect vacuum polarization effects
→ uncontrolled and irreducible errors

Unquenched work with $N_f = 2 + 1$ flavours of sea quarks

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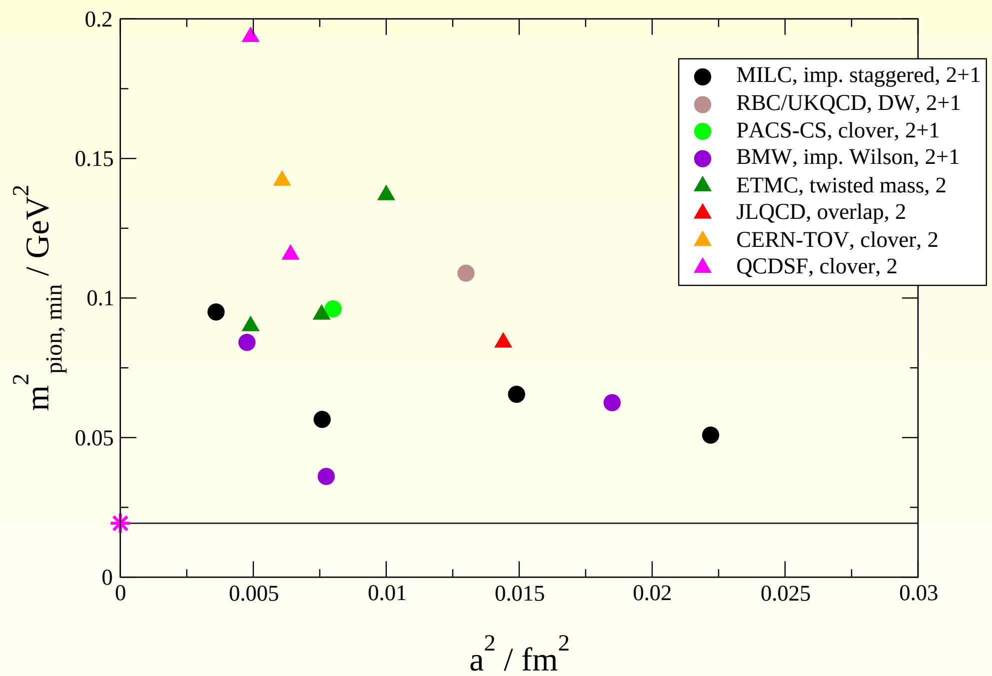
Unquenched work with $N_f = 2 + 1$ flavours of sea quarks

$N_f = 2$ and $N_f = 2 + 1$ ensembles available



\# $m_l > m_{u,d}$ in numerical simulations

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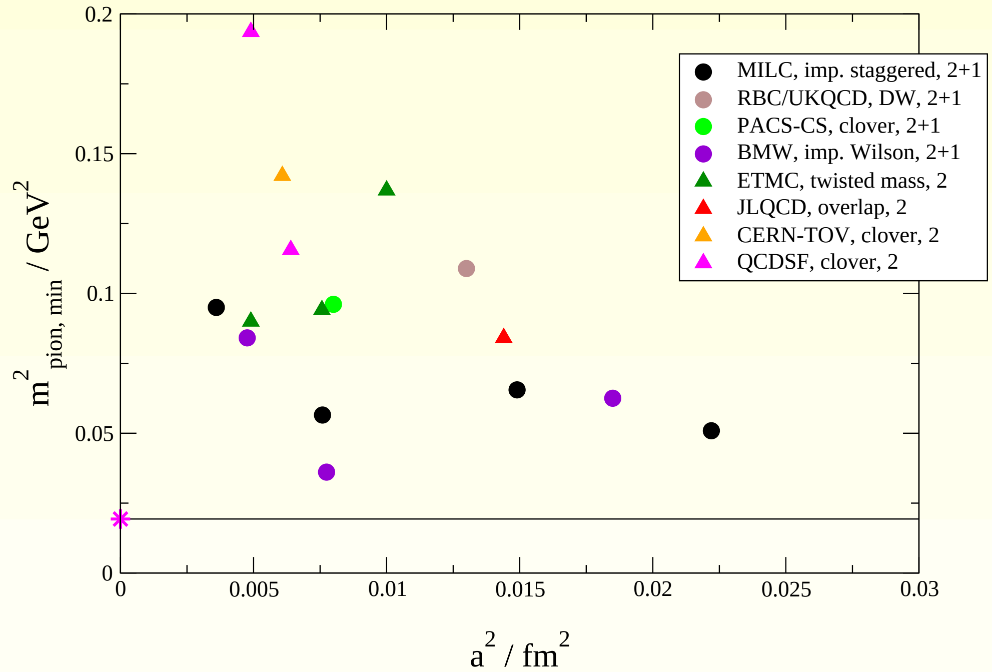

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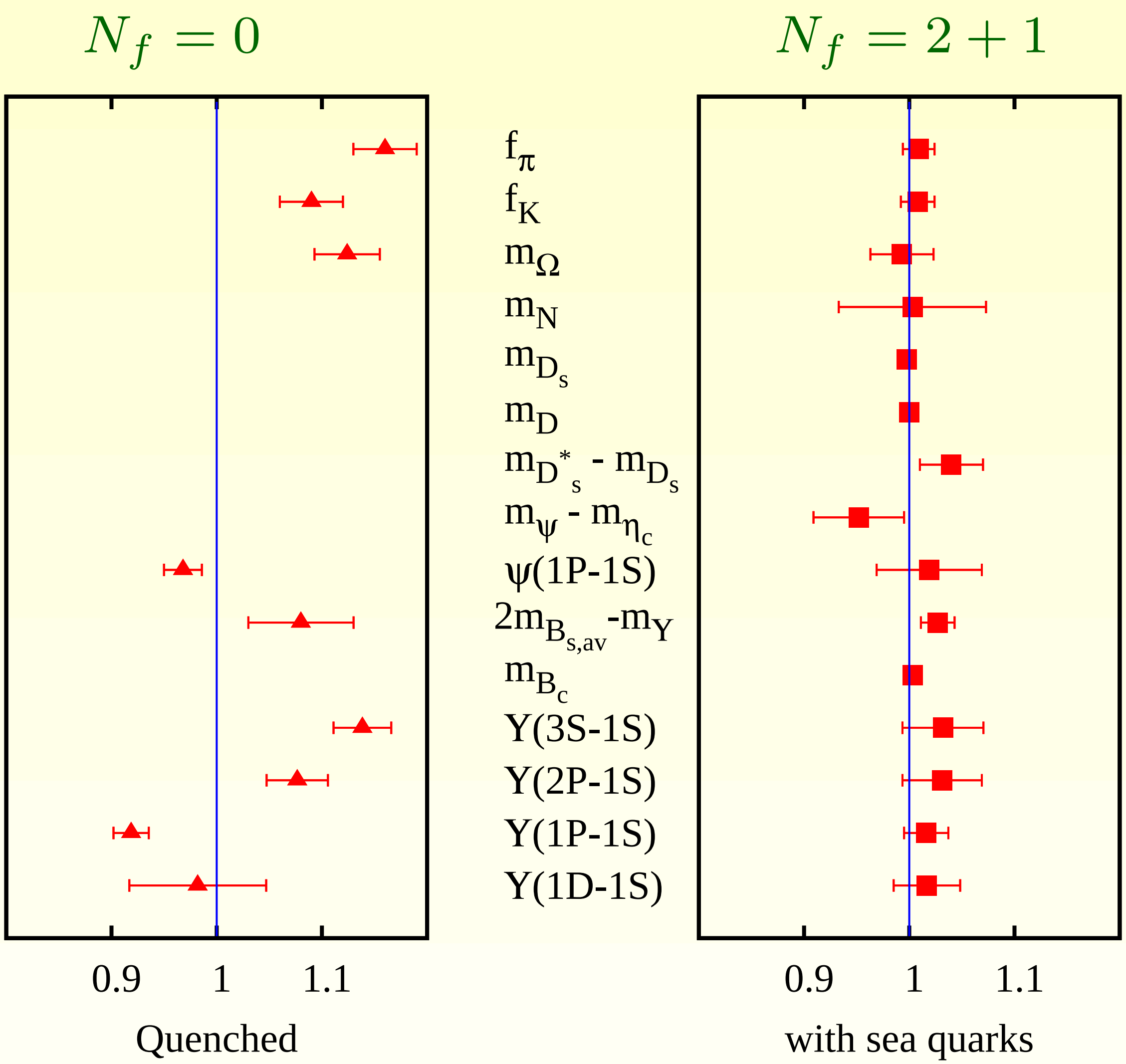
Use chiral perturbation theory to extrapolate to $m_{u,d}$

Testing Lattice QCD



$m_D^{latt.} = 1.868(7)$

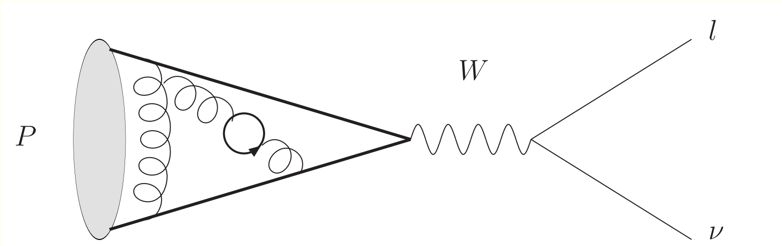
$m_D^{exp.} = 1.868$

$m_{D_s}^{latt.} = 1.962(6)$

$m_{D_s}^{exp.} = 1.968$

Experimental quantities are quite well reproduced by lattice when including realistic sea quark effects

2. Decay constants: $P \to l\nu$



Purely leptonic decays can be used to extract **CKM** matrix **elements**

$$\Gamma(P_{ab} \to l\nu) \propto f_P^2 |V_{ab}|^2$$

or testing **SM/lattice** predictions

f_D and f_{D_s}: test of lattice QCD

$$\underbrace{B(D_q \to l\nu)}_{\textbf{experiment}} \propto |V_{cq}|^2 \underbrace{f_{D_q}^2}_{\textbf{lattice}}$$

Simple matrix element $\langle 0|\bar{q}\gamma_\mu\gamma_5 c|D_q(p)\rangle = i f_{D_q} p_\mu$ → precise calculations

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Results from two groups with $N_f = 2+1$

heavy valence quarks HPQCD **HISQ**, FNAL/MILC **Fermilab action**

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Highly improved staggered quarks (**HISQ**): Reduction of $\mathcal{O}(a^2\alpha_s)$ and $\mathcal{O}((am_Q)^4)$ discretization errors $\to$ Very precise results for charm physics, charmonium and D, (m_c fixed by η_c). E. Follana et al (2007)HPQCD

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* **MILC** ensembles: 3 lattice spacings (0.09 fm ,0.12 fm, 0.15 fm)

* Renormalization partially non-pert. (FNAL/MILC, 1.5% error) and normalization via PCAC (HPQCD, no error)

* Simultaneous chiral and continuum extrapolation including all a, valence and sea quark masses:
  SChPT (FNAL/MILC) and continuum ChPT + $\mathcal{O}(a^2)$ terms (HPQCD).

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Latest Results (2007/08)

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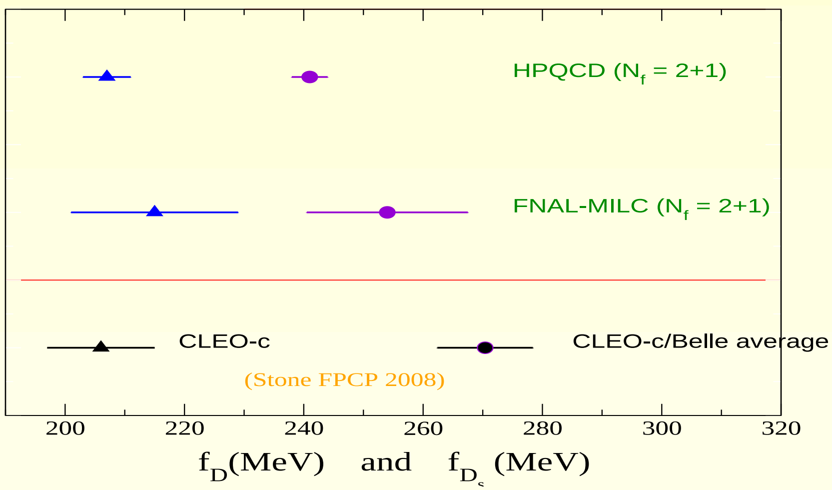

source	$f_D(MeV)$	$f_{D_s}(MeV)$
FNAL/MILC	215 ± 14	254 ± 14
HPQCD	207 ± 4	241 ± 3
exp. (see plot)	207 ± 9	270 ± 8

$> 3\sigma$ discrepancy between experiment and HPQCD lattice f_{D_s}.

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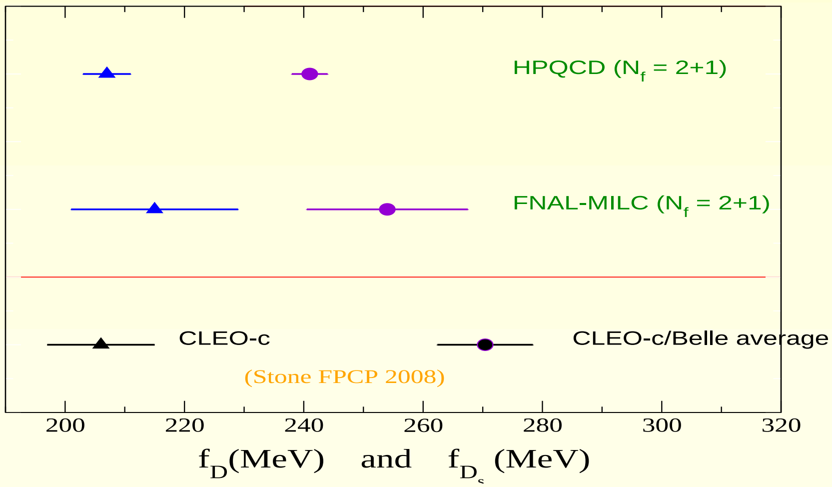

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Experiment-lattice agreement in f_K, f_π, f_D, m_D, m_{D_s}, $\frac{2m_{D_s} - m_{\eta_c}}{2m_D - m_{\eta_c}}$.

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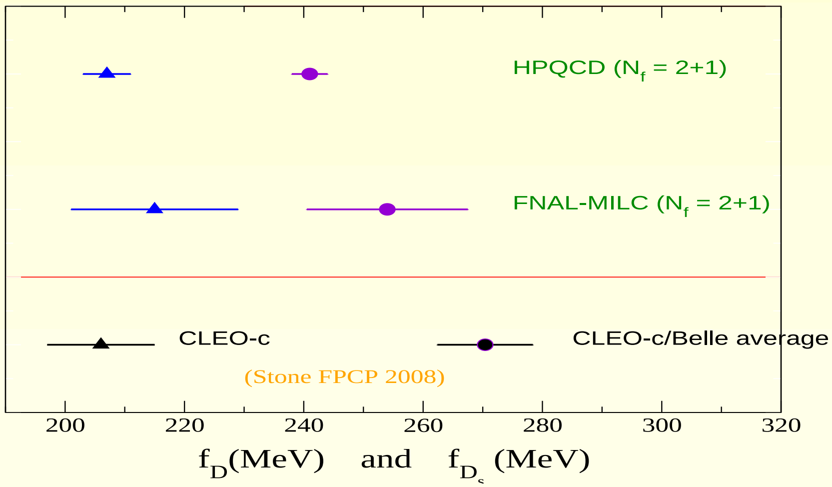

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Expected reduction of experimental errors

Experiment uses $V_{cs} = V_{ud}$.

f_B and f_{B_s}

Extraction of CKM matrix elements: $\underbrace{B(B^- \to \tau^- \bar{\nu}_\tau)}_{\text{experiment}} \propto |V_{ub}|^2 \underbrace{f_B^2}_{\text{lattice}}$

$(\langle 0|\bar{q}\gamma_\mu\gamma_5 b|B_q(p)\rangle = i f_{B_q} p_\mu)$

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\# Decay constants needed in the SM prediction for processes potentially very sensitive to BSM effects: for example, f_{B_S} for $B_s \to \mu^+\mu^-$

\# $B^- \to \tau^- \bar{\nu}_\tau$ is a sensitive probe of effects from charged Higgs bosons.

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$N_f = 2+1$ determinations

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	FNAL-MILC (LAT2007)	HPQCD (2005)		
f_B (MeV)	197 ± 13	216 ± 22		
f_{B_s} (MeV)	240 ± 12	260 ± 26		
f_{B_s}/f_B	1.22 ± 0.03	1.20 ± 0.03		

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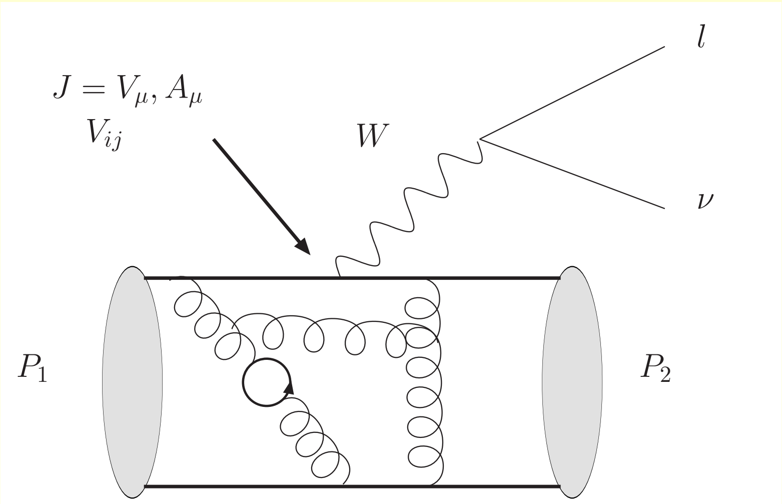
	FNAL-MILC (LAT2007)	HPQCD (2005)	errors % current	errors % in 2-5 years
f_B (MeV)	197 ± 13	216 ± 22	6.8-10.3	4.0
f_{B_s} (MeV)	240 ± 12	260 ± 26	5.1-10.1	3.5
f_{B_s}/f_B	1.22 ± 0.03	1.20 ± 0.03	2.7-2.6	2.0

J. Shigemitsu 2007

Extraction of f_{B_s}/f_B from **double ratios**: e.g. $[f_{B_s}/f_B]/[f_K/f_\pi]$

3. Semileptonic decays



Exclusive $B \to D^* l\nu$: determination of $|V_{cb}|$

$B \to D^* l\nu$ rate at zero recoil $\propto |V_{cb} h_A(1)|$

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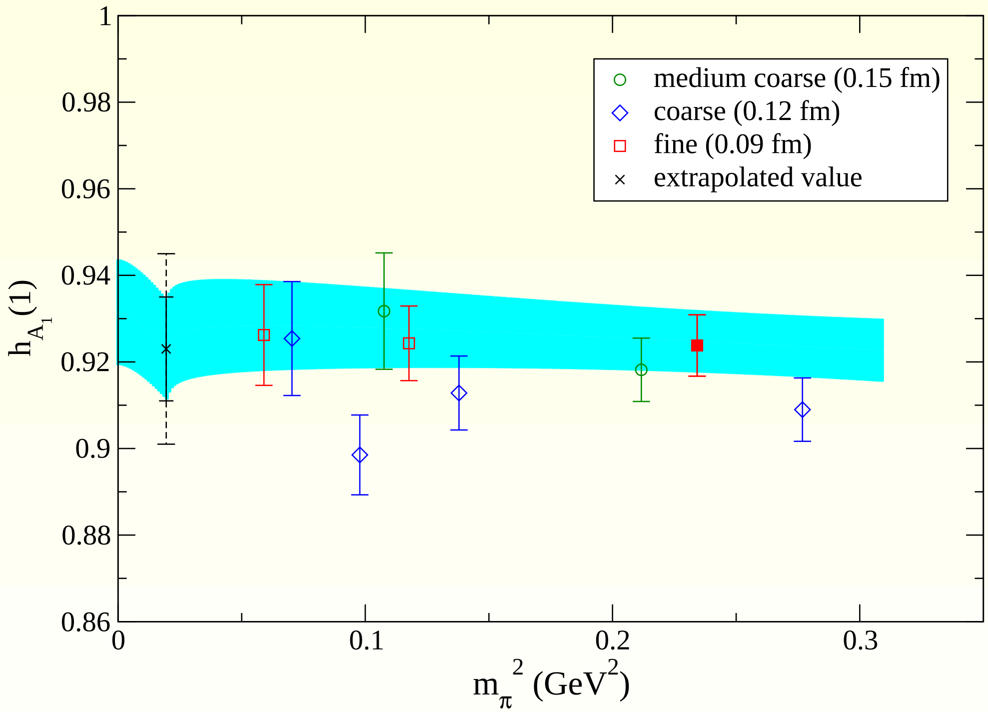

$h_{A_1}(1) = 0.921(13)_{stat.}(19)_{syst.}$

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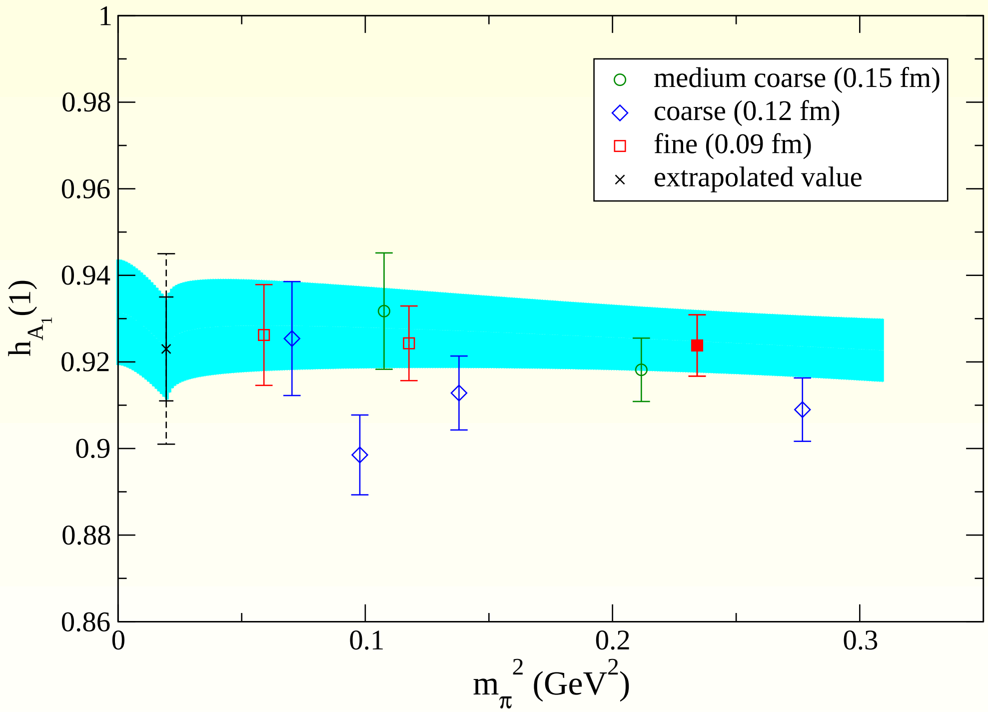

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(one year)

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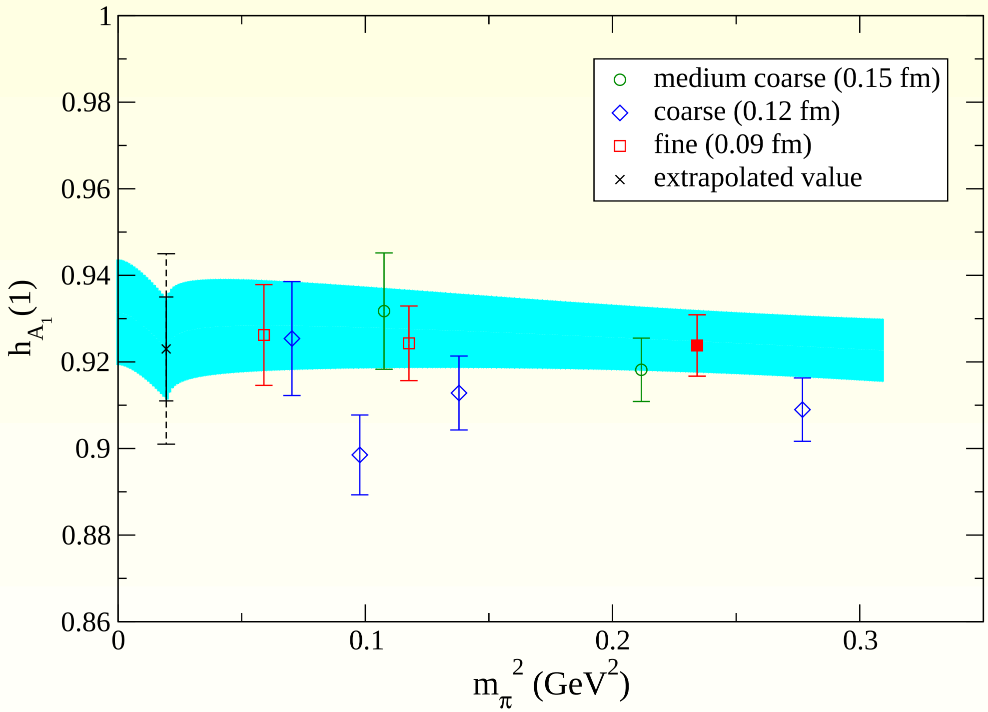

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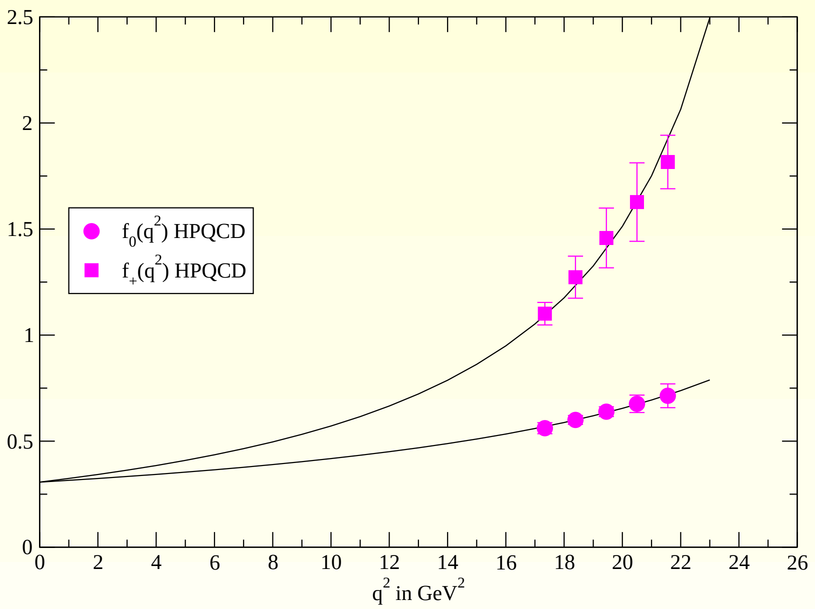
(one year)

Inclusive determination is $|V_{cb}| \times 10^3 = 41.7(0.7)$ (2σ difference)

$B \to \pi l\nu$: determination of $|V_{ub}|$

Only $N_f = 2+1$ calculation so far: staggered HPQCD PRD73/75 (2006/07)

$$Br(B \to \pi l\nu) = |V_{ub}|^2 \int_0^{q^2_{max}} dq^2 f_+^{B\to\pi}(q^2)^2 \times (\text{known factors})$$



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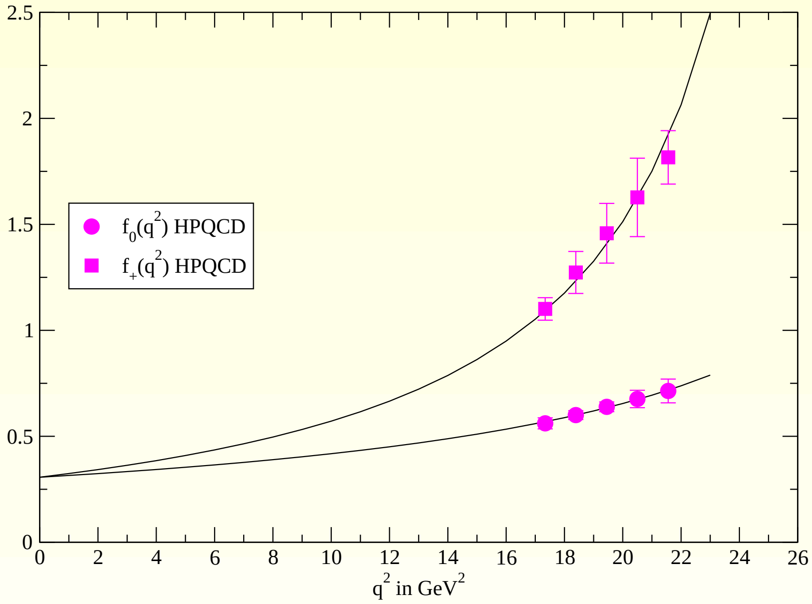

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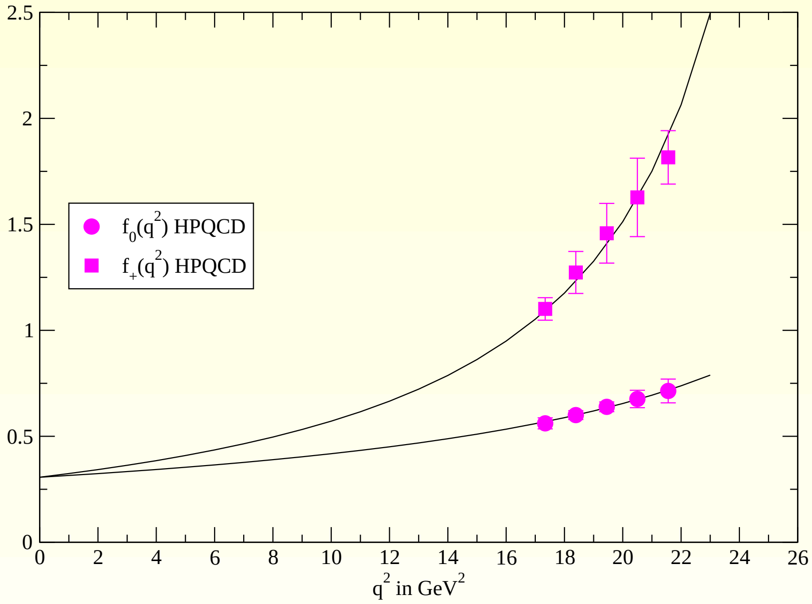

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Poor overlap in q^2 between lattice and experiment
$\longrightarrow$ increases the total error

Work in progress to reduce total error

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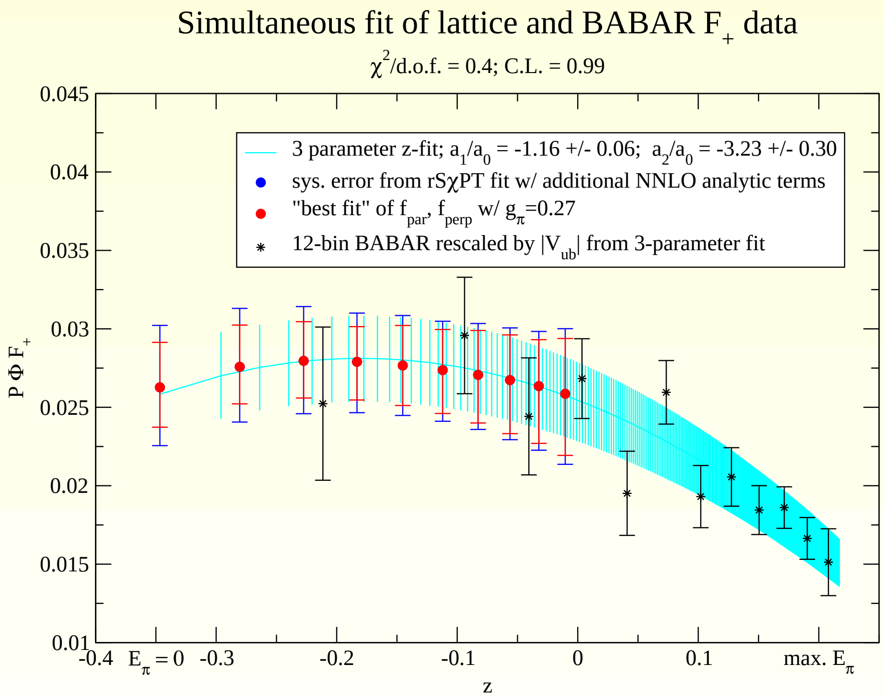

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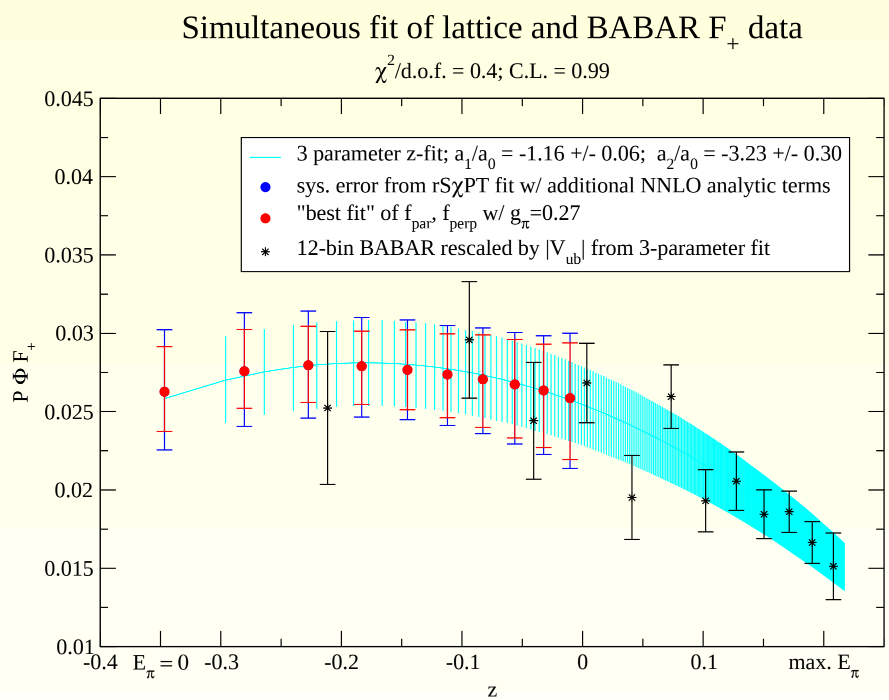

P. Mackenzie and **R. Van de Water** (2008)

Work underway to analyze systematics → FNAL-MILC (Mackenzie, LAT07)

`total error after finishing current analysis` $\sim 12\%$.

Semileptonic decays: Improvements in progress

$D \to \pi l \nu$ and $D \to K l \nu$:

FNAL-MILC working on $N_f = 2 + 1$ improvement of 2005 calculation of the form factors $f_+^{D\to\pi}(0)$ and $f_+^{D\to K}(0)$ (reduction of discr. errors)

$\longrightarrow$ V_{cd} and V_{cs}.

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* $\frac{\Gamma(D\to l\nu)}{\Gamma(D\to\pi l\nu)}$ independent of $|V_{cq}|$ $\to$ consistency check

* $\frac{\Gamma(D_s\to l\nu)}{\Gamma(D\to K l\nu)}$ CKM independent test of lattice (QCD)

$\boxed{B \to Dl\nu}$ (**alternative determination of** V_{cb}):

de Divitiis et al 2007 Quenched analysis

* Including the case of `non-vanishing lepton mass.`

** Can study $Br(B \to D\tau\nu_\tau)/Br(B \to De\nu_e)$, which is a good place to look for charged Higgs contributions to low energy observables

J.F. Kamenik and F. Mescia, arXiv:0802.3790

** Lepton-flavour universality checks on the extraction of V_{cb} are possible.

4. $B^0 - \bar{B}^0$ mixing: $\Delta M_{d,s}$, $\Delta\Gamma_{d,s}$ and ξ

Experimental measurements:

CDF

$$\Delta M_s|_{exp.} = 17.77 \pm 0.12\, ps^{-1}$$

PDG07 average

$$\Delta M_d|_{exp.} = 0.507 \pm 0.005\, ps^{-1}$$

$$\Delta\Gamma_s|^{\mathbf{D\emptyset}}_{exp.} = 0.17 \pm 0.09 \pm 0.02\, ps^{-1}$$

$$\Delta\Gamma_s|^{\mathbf{CDF}}_{exp.} = 0.076^{+0.059}_{-0.063} \pm 0.006\, ps^{-1}$$

- theoretically: In the Standard Model

$$\Delta M_q|_{theor.} \propto |V_{tq}^* V_{tb}|^2 \quad f_{B_q}^2 \hat{B}_{B_q}$$

$\Longrightarrow$ **Need accurate theoretical calculation of** $f_{B_q}^2 \hat{B}_{B_q}$

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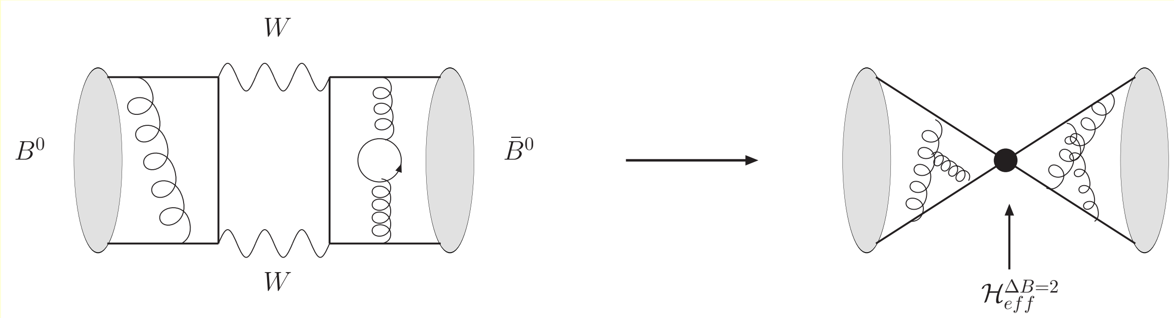
Precise determination of CKM matrix elements

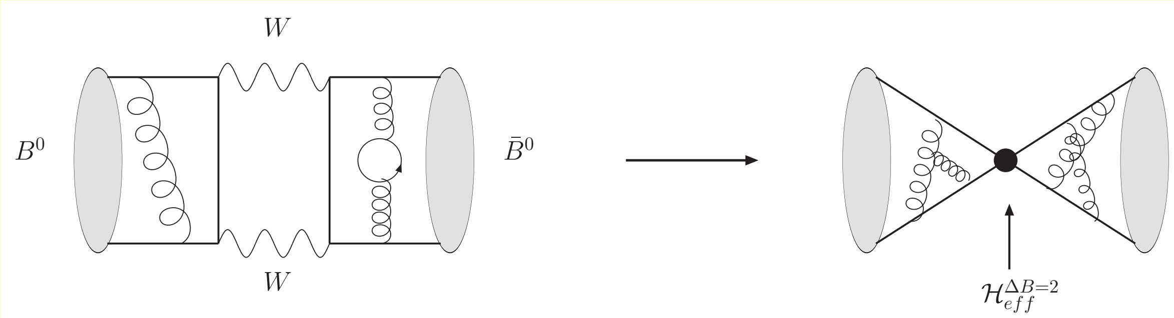
$$\left|\frac{V_{td}}{V_{ts}}\right| = \underbrace{\frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}}_{\xi} \sqrt{\frac{\Delta M_d M_{B_s}}{\Delta M_s M_{B_d}}}$$

* Many uncertainties in the theoretical (lattice) determination cancel totally or partially in the ratio



NP could enter through new particles in box diagrams.

Recent claims of NP effects in the $B_s^0 - \bar{B}_s^0$ and $B_d^0 - \bar{B}_d^0$ systems (**Bona et al. (UTfit Col.)**, arXiv:0803.0659; **Lunghi and Soni**, arXiv:0803.0512; **Buras and Guadagnoli**, arXiv:0805.3887)



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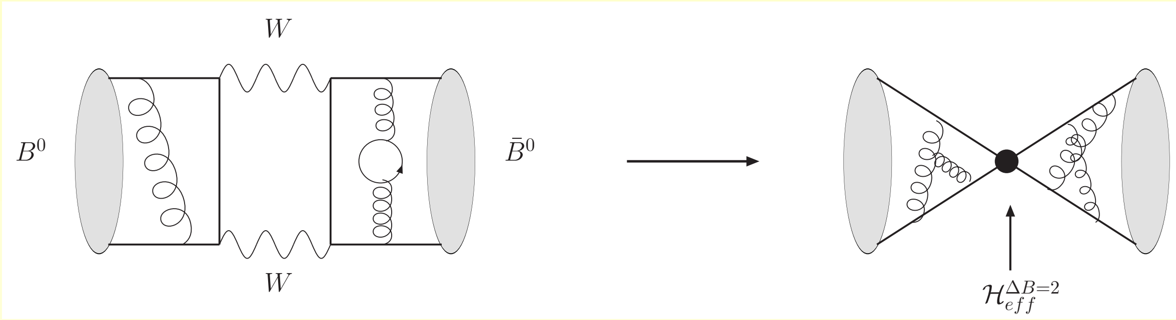
Two unquenched $N_f = 2+1$ calculations underway: HPQCD and MILC/FNAL

- Improved staggered (`Asqtad`) for light quarks and `NRQCD` (HPQCD) `Fermilab action` (MILC/FNAL)

- Calculation of all the matrix elements needed to determine $\Delta M_{d,s}$, $\Delta\Gamma_{d,s}$ and ξ.



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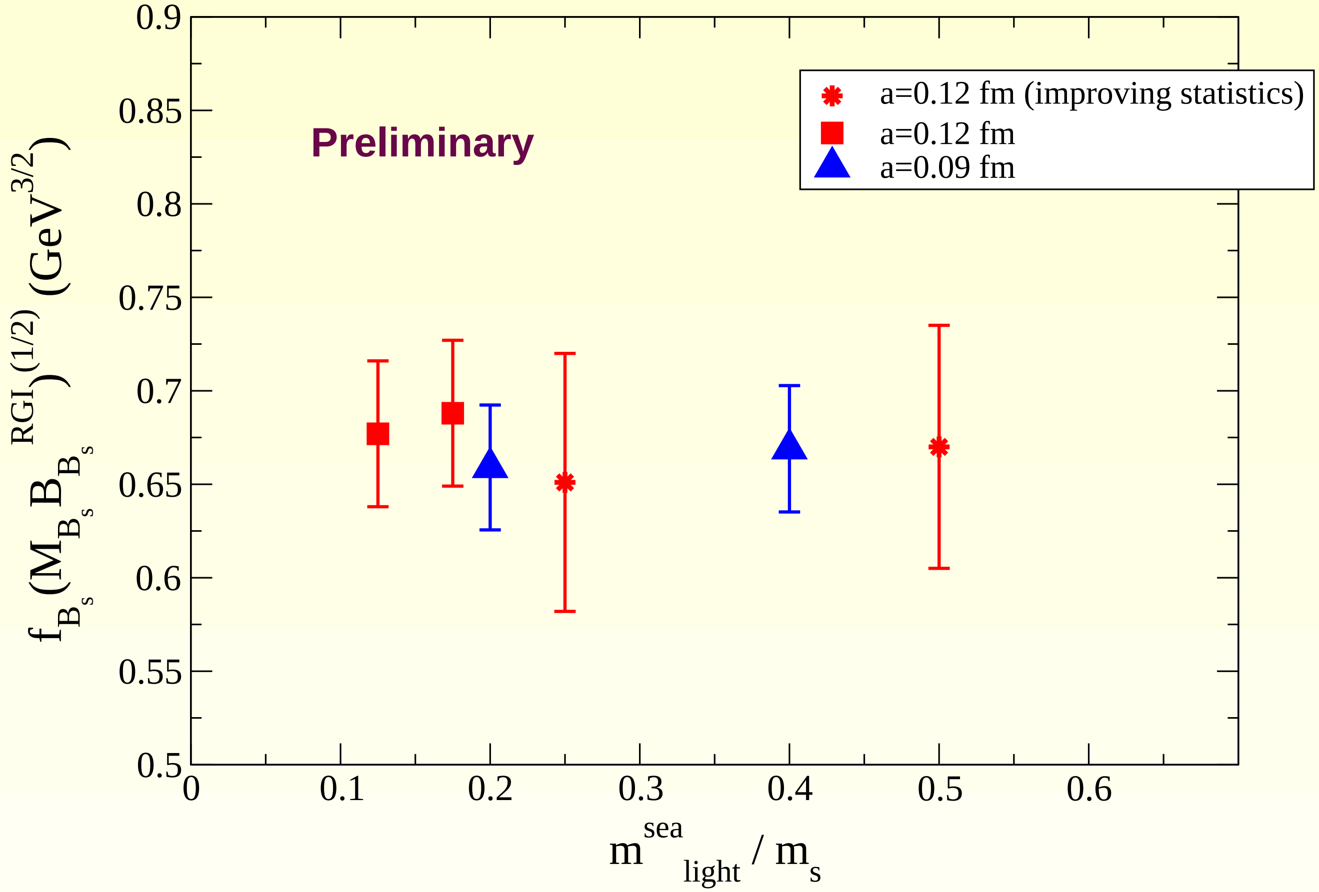
Current status: working on the chiral extrapolation
(NLO+analytic NNLO SχPT)

Preliminary results for $f_{B_q}\sqrt{M_{B_q}B_{B_q}}$

$f_{B_s}\sqrt{M_{B_s}\hat{B}_{B_s}}(GeV^{3/2})$

HPQCD



with $m_s^{valence}$ fixed to its physical value and m_s^{sea} very close to it.

statistics+fitting errors $\sim 1-2\%$

Statistics and systematic errors included

Same for $f_{B_d}\sqrt{B_{B_d}}$

Preliminary results for $f_{B_q}\sqrt{M_{B_q}\hat{B}_{B_q}}$

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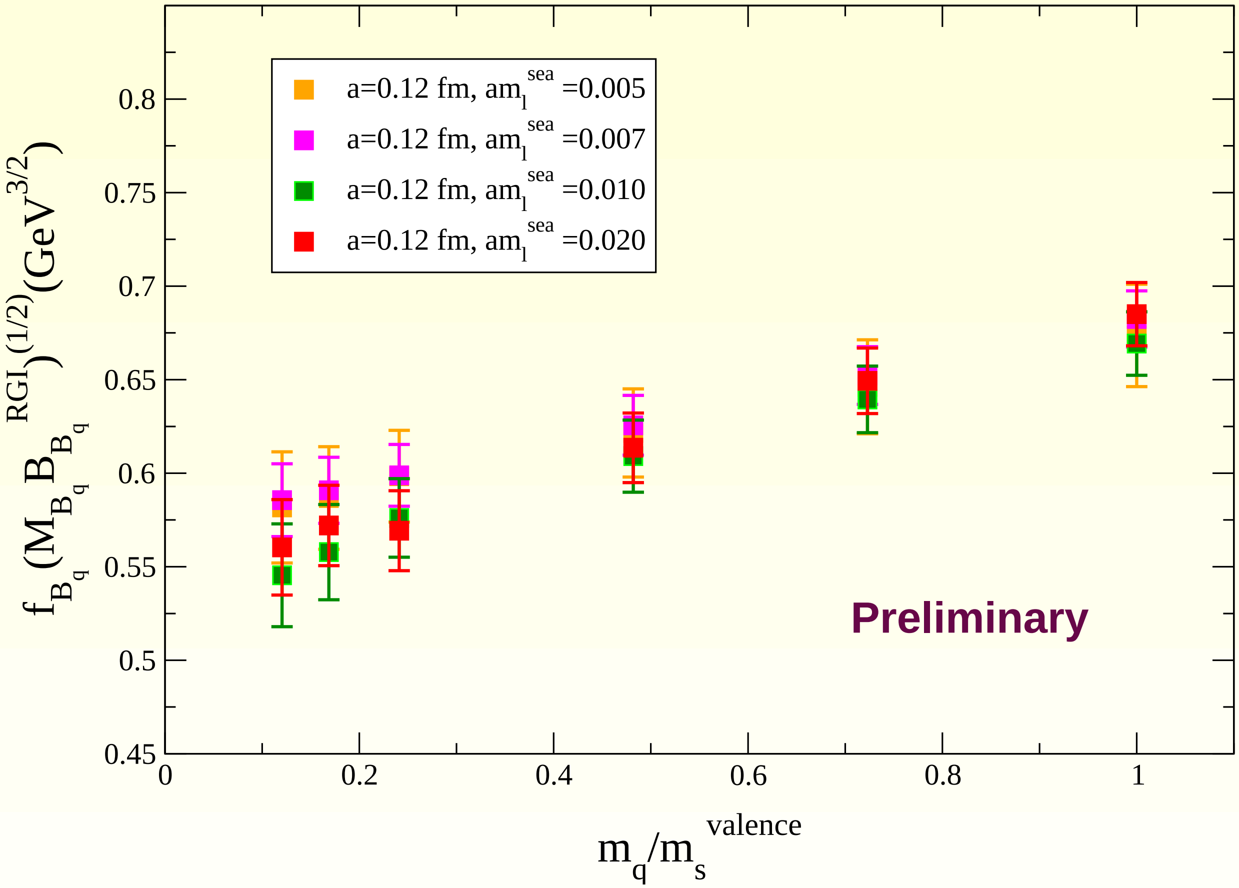
Fermilab/MILC

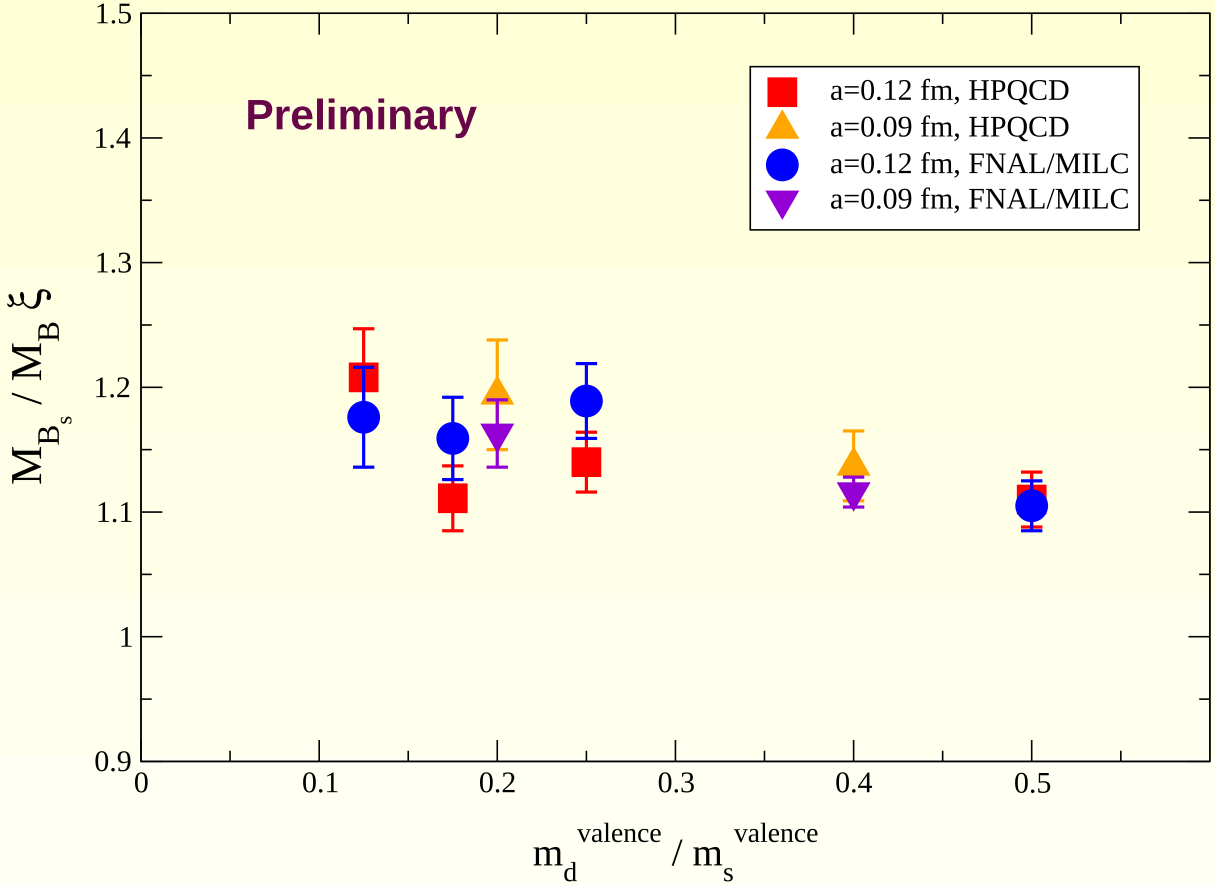


Example: Ensembles with $a = 0.12\ fm$.

Full QCD: only statistical errors included

Preliminary results for ξ: Full QCD

$$\xi\, M_{B_s}/M_{B_d} = (f_{B_s}\sqrt{M_{B_s}B_{B_s}})/(f_{B_d}\sqrt{M_{B_d}B_{B_d}})$$



Only statistical errors included.

Only full QCD points included.

Discussion of errors

	$f_{B_q}\sqrt{B_{B_q}}$	ξ
Total (estimate)	$5-7\%$	$2-3\%$

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Reduction of errors by a factor of $1.5-2$

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Underway `RBC/UKQCD`: **C. Albertus** *et al.*

* In an early stage: static limit, $m_{pion} \geq 400 MeV$,...

B^0 and D^0 mixing beyond the SM

Effects of heavy new particles seen in the form of effective operators built with **SM** degrees of freedom (`short-distance` contributions for $D^0 - \bar{D}^0$)

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$\rightarrow$ constraints on BSM physics

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\# Complete $N_f = 2+1$ analysis of $\Delta B = 2$ matrix elements expected from both **FNAL-MILC** and **HPQCD**, and $\Delta D = 2$ from **FNAL-MILC** in 1-2 years with errors$< 10\%$.

5. Conclusions and outlook

Important progress in lattice calculations including **sea quarks** ($N_f = 2 + 1$)

* Precise new results (few percent errors) in D sectors.

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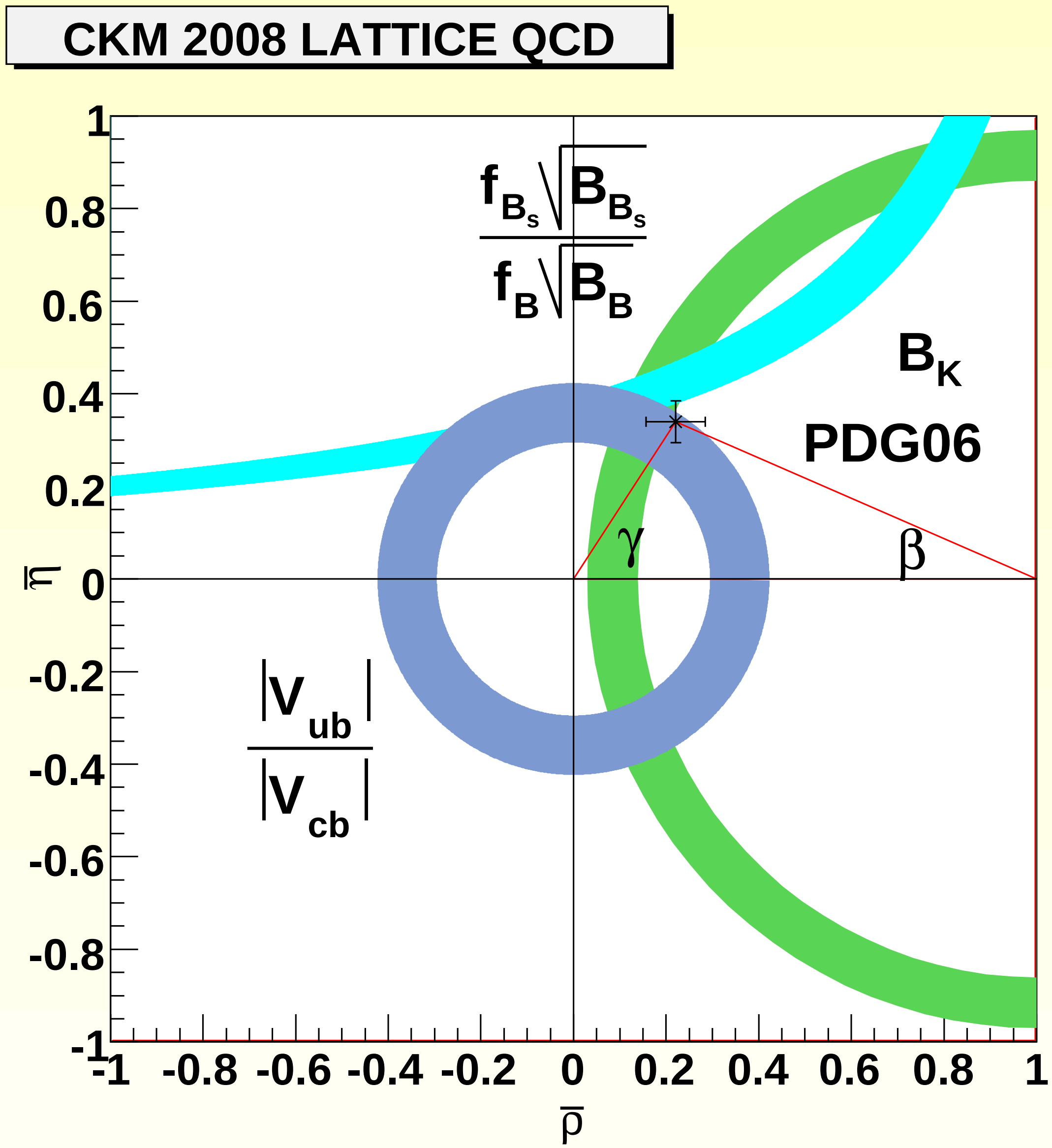
Prospects for next two years

* Reduction in uncertainties of quantities relevant for CKM physics by a factor of around 2.

* Consistency checks of lattice QCD methods by ...

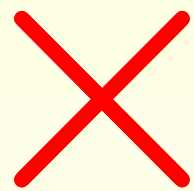
** more comparison against experiment.

** comparing lattice calculations using different fermion formulations.



* $\hat{B}_K$ from RBC/UKQCD
* $\frac{f_{B_s}\sqrt{B_{B_s}}}{f_B\sqrt{B_B}}$ **preliminary** result from FNAL/MILC
* $|V_{ub}|$ from Flynn and Nieves, 0705.3553
* $|V_{cb}|$ from Jack Laiho, LAT2007
* $|V_{us}|$ from $K_{l2}^{exp.} + \underbrace{\frac{f_K}{f_\pi}}_{\text{HPQCD}}$

C. Davies & C. McNeile



Other Heavy-light semileptonic decays

	Flavour neutral	Unstable	affordable now	in 5 years?
$B \to \eta l \nu$	$\surd$		possible but expensive	
$B \to \eta' l \nu$	$\surd$	$\surd$		$\surd$
$B \to \rho l \nu$		$\surd$		$\surd$
$B \to \omega l \nu$	$\surd$	$\surd$		$\surd$
$B \to K l l$			$\surd$	
$B \to K^* l l$		$\surd$		$\surd$
$B \to \phi l l$	$\surd$	$\surd$		$\surd$
$B \to K^* \gamma$		$\surd$		$\surd$

R. Van de Water

HISQ action

E. Follana et al, HPQCD coll.

- Highly improved staggered action.
- Much improved control of discretization errors.
  - * Highly reduce $\mathcal{O}(a^2\alpha_s)$ errors (an order of magnitude)
  - * Substantially reduce taste-changing with respect to Asqtad
  - * No tree-level $\mathcal{O}((am)^4)$ at first order in the quark velocity v/c

    $\longrightarrow$ accurate results for charm quarks

Error budget for decay constants

	f_π	f_K	f_K/f_π	f_D	f_{D_s}	f_{D_s}/f_D
r_1 uncert.	1.4	1.1	0.3	1.4	1.0	0.4
a^2 extrap.	0.2	0.2	0.2	0.6	0.5	0.4
finite volume	0.8	0.4	0.4	0.3	0.1	0.3
$m_{u/s}$ extrap.	0.4	0.3	0.2	0.4	0.3	0.2
statistical	0.5	0.4	0.2	0.7	0.6	0.5
m_s evol.	0.1	0.1	0.1	0.3	0.3	0.3
m_d, QED, etc	0.0	0.0	0.0	0.1	0.0	0.1
Total(%)	1.7	1.3	0.6	1.8	1.3	0.9

New: Determination of the charm quark mass

HPQCD coll., Chetyrkin, Kühn, Steinhauser & Sturm

m_c extracted from current-current correlators.

* **HISQ** action used to determine moments G_n of charm-quark pseudoscalar, vector and axial-vector correlators.

$$G_n \equiv \sum_t (t/a)^n G(t)$$

with

$$G(t) \equiv a^6 \sum_{\vec{x}} (am_{0c})^2 \langle 0|J(\vec{x},t)J(0,0)|0\rangle$$

* Four-loop results from continuum perturbation theory for the moments.

$\boxed{m_c(m_c) = 1.266(16) GeV}$ or equivalently $\boxed{m_c(3GeV) = 0.983(13) GeV}$

Same programme can be applied for extra operators

$$\langle \bar{B^0}_{d(s)} | Q_{i=1-5} | B^0_{d(s)} \rangle$$

- Chiral perturbation theory more complicated (extra free parameters):

$$\langle \overline{B^0_{d(s)}} | Q_{i=1-5} | B^0_{d(s)} \rangle \rightarrow_{chiral} \Gamma_i (1 + L) + \underbrace{\Gamma'_i L'}_{i \neq 1} + \text{analytic terms}$$

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Complete N_{f+1} analysis of $\Delta B = 2$ matrix elements expected from both **Fermilab lattice-MILC** and **HPQCD** collaborations in 1-2 years with `errors`$< 10\%$.

* First results: One-loop renormalization for **HPQCD** study

(**E.G,Shigemitsu,Trottier**)