Flavor Phenomenology from Lattice QCD

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· Kibbutz Maale Hachamisha, Israel, 27 May 2011 ·

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2. Light quark matrix elements
    - 2.1. f_K/f_π: Determination of $|V_{us}|$ and test of unitarity
    - 2.2. $K \to \pi l \nu$: Determination of $|V_{us}|$ and test of unitarity
    - 2.3. $K^0 - \bar{K}^0$ mixing
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    - 3.4. D semileptonic decays
    - 3.5. Neutral B-`meson` mixing
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1. Introduction

Lattice QCD can be used to

- * Determine fundamental parameters of the SM: quark masses, CKM matrix elements (tensions in inclus.-exclus. determinations of $|V_{ub}|$, $|V_{cb}|$).
- * Provide the non-perturbative input for the study of some theory-experiment discrepancies in UT analyses ($\hat{B}_K$, f_B, $f_B\sqrt{B_B}$, ξ ...), processes involving $B^0_{d,s} - \bar{B}^0_{d,s}$ mixing (like-sign dimuon charge asymmetry), heavy-light decay constants ...

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Goal: Precise calculations ($\sim 5\%$ error)

Gold-platted quantities: For stable (or almost stable) hadron, masses and amplitudes with no more then one initial (final) state hadron.

`Dificult to study on the lattice:` scattering processes, including charmoniun production, inclusive processes, and multihadronic decays

Control over systematic errors: including chiral extrapolation, discretization (continuum limit), renormalization, finite volume ...

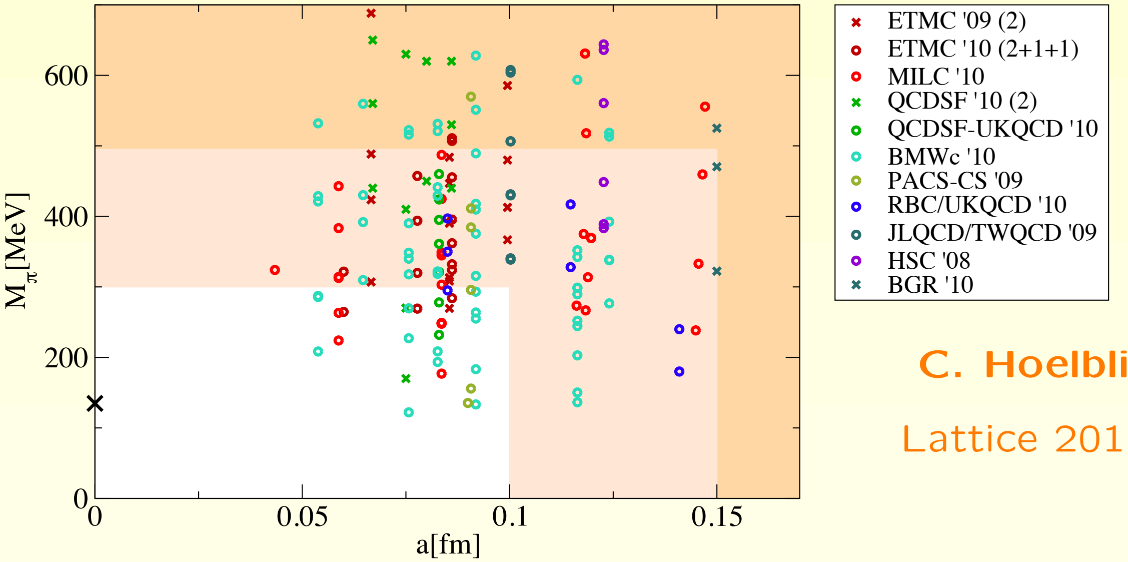
1. Introduction

Unquenched calculations

- * Quenching the strange quark could have an error as large as 5% and need a $N_f = 2+1$ to have an estimate → want $N_f = 2+1$
- * Neglecting sea charm has effects $\mathcal{O}(1\%)$ (can be estimated with HQET). **Starting to need sea charm effects.**

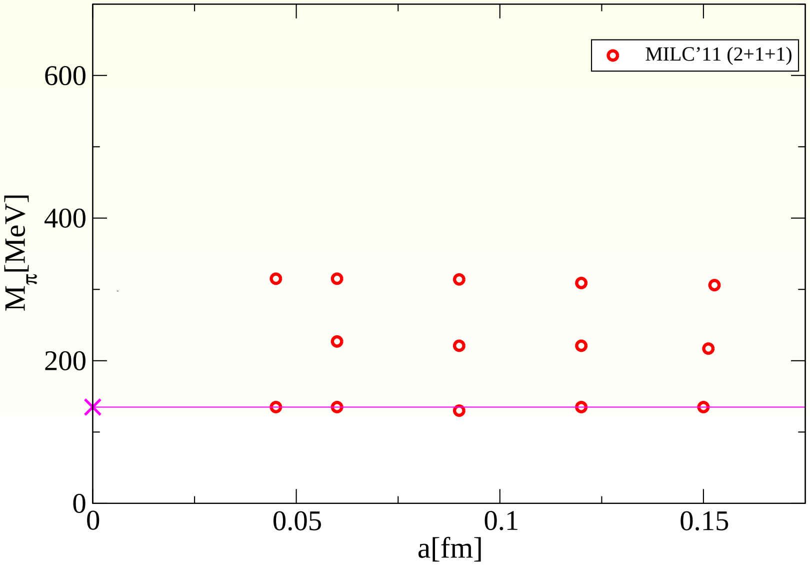
1. Introduction

Overview of simulations parameters today



C. Hoelbling,

Lattice 2010, 1102.0410



MILC $N_f = 2 + 1 + 1$

Some ensembles still in production

1.1. Introduction: Averaging lattice QCD results

J. Laiho, E. Lunghi, and R. Van de Water (LLV)

Phys.Rev.D81:034503,2010, most updated results in **www.latticeaverages.org**

* Hadronic weak matrix element relevant for phenomenological analyses.

* Include only $N_f = 2 + 1$.

* Only published results (including proceedings).

Flavianet Lattice Average group:

arXiv:1011.4408, most updated results in **http://itpwiki.unibe.ch/flag**

* K and π physics, including `LEC's`.

* Include separate averages for $N_f = 2$ and $N_f = 2 + 1$.

* Only published results with the exception of update proceedings.

Averages agree in between them when they use the same inputs.

2. Light quarks matrix elements

2.1. f_K/f_π: Determination of $|V_{us}|$ and test of unitarity

Decay constants come from simple matrix element
$\langle 0|\bar{q}_1\gamma_\mu\gamma_5 q_2|P(p)\rangle = i f_P p_\mu$ → precise calculations

- Even higher precision for ratios due to cancellation of statistics and systematics uncertainties

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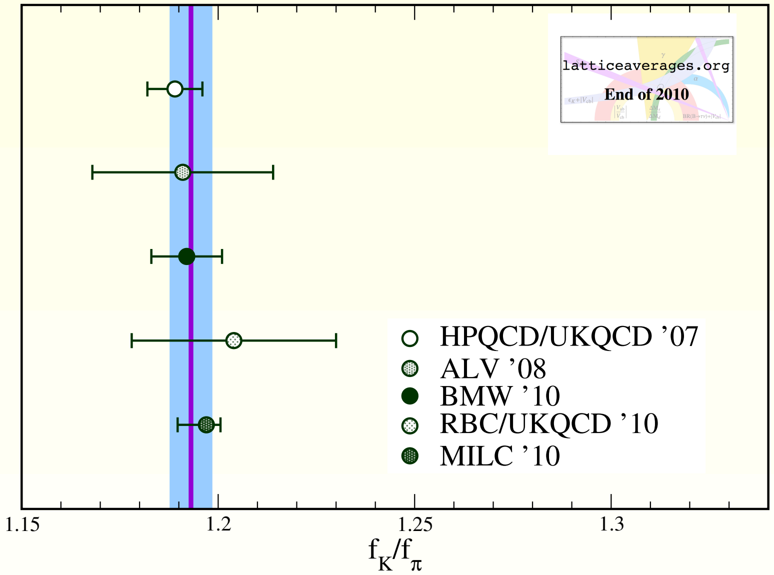

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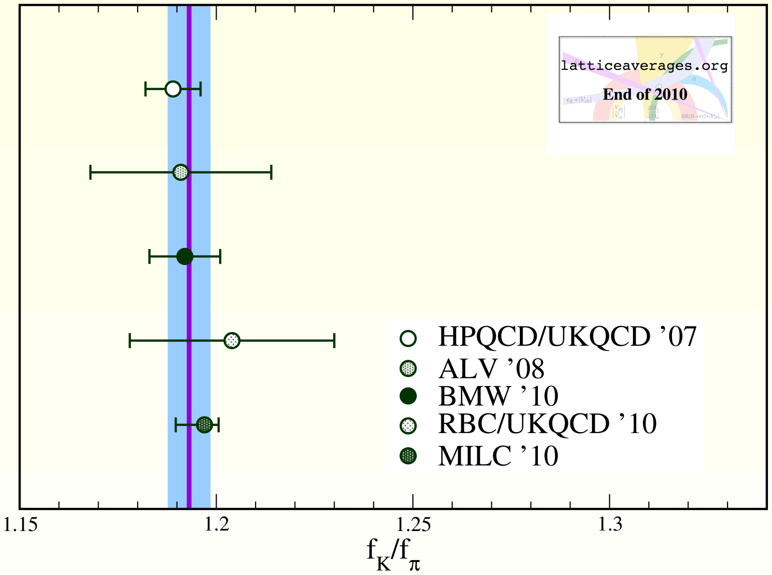

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Marciano 2004 $\frac{|V_{us}|^2}{|V_{ud}|^2} \times \frac{f_K^2}{f_\pi^2} \propto \frac{\Gamma(K\to\mu\bar{\nu}_\mu(\gamma))}{\Gamma(\pi\to\mu\bar{\nu}_\mu(\gamma))}$

$$\Longrightarrow \quad |V_{us}| = 0.2252(11)^*$$

$$(|V_{us}|^{unitarity} = 0.22545(22))$$

M. Antonelli et al., 1005.2323

* Using $|V_{us}|/|V_{ud}| \times f_K/f_\pi = 0.2758(5)$ **M. Antonelli et al.**, 1005.2323 and $|V_{ud}| = 0.97425(22)$ **Hardy and Towner**, PRC79(2009)

2.2. $K \to \pi l \nu$: Determination of $|V_{us}|$ and test of unitarity

\# $|V_{us}|$ can also be extracted from K_{l3} decay rates via

$$\Gamma[K \to \pi l \nu_l(\gamma)] = \frac{G_F^2}{192\pi^3} C^2 I_K^l S_{EW} (1 + \delta_K^l)\, |V_{us}|^2 f_+^2(0)$$

using $f_+(0)$ as calculated with lattice QCD from the 3-point function

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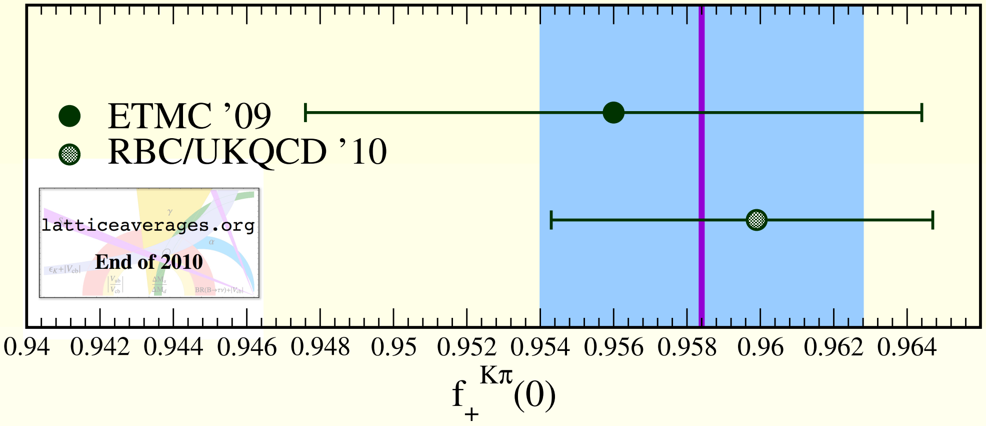

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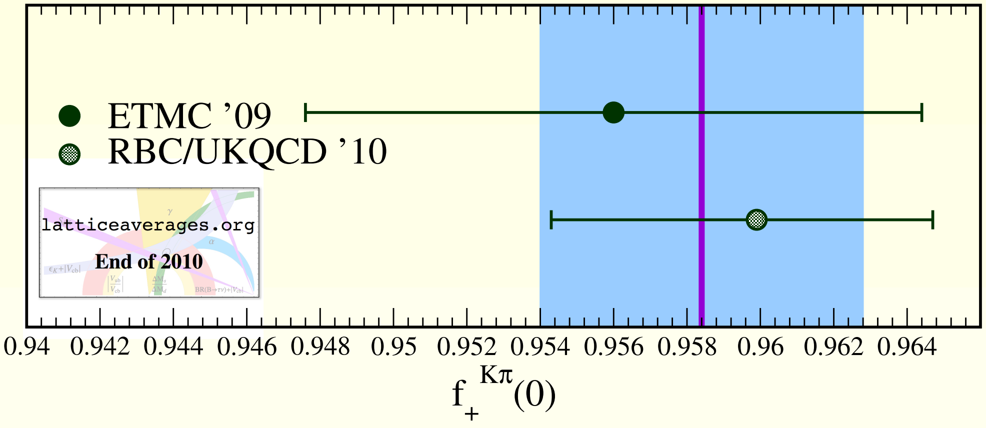

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$$|V_{us}| = 0.2257(12)$$

* LLV average $N_f = 2$ ETMC result because they include the known quenching effects at NLO in ChPT and an estimate of NNLO effects

** Extrapolation to $q^2 = 0$ using pole dominance and quadratic polynomial

** Extrapolation to physical masses using NLO `SU(2)` and `SU(3) ChPT`.

** Two lattice spacings analyzed → extrapolation to the continuum

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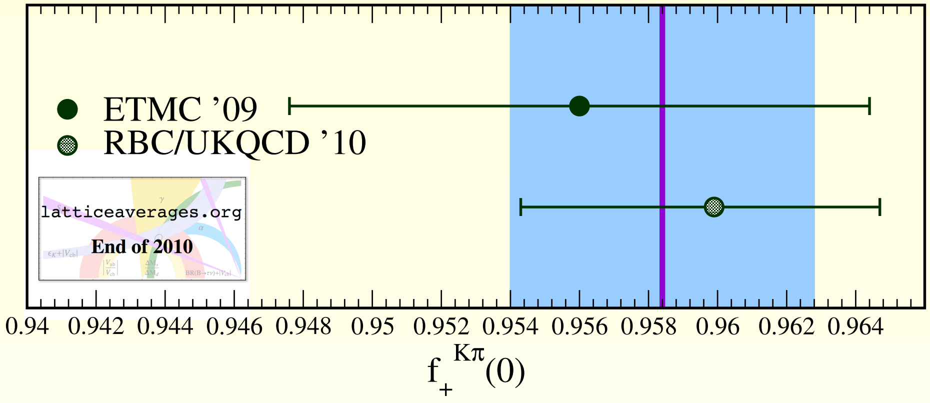

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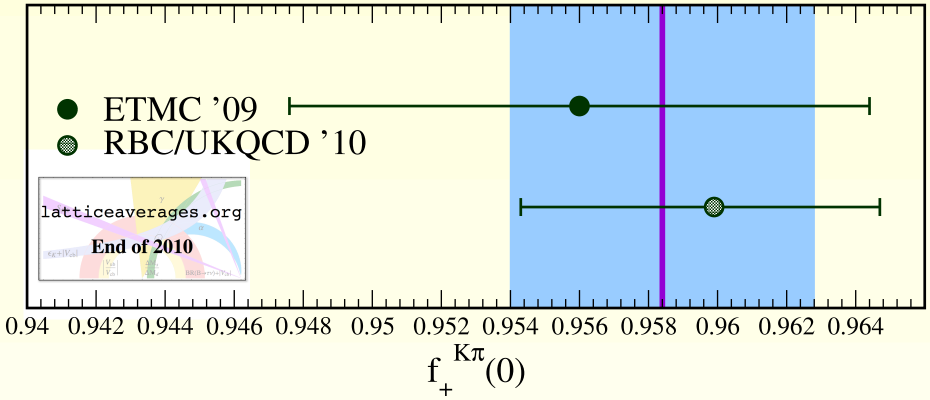

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- ** Extrapolation to physical masses using NLO `ChPT`.
- ** Two lattice spacings → extrapolation to the continuum

In progress: * $N_f = 2+1$ staggered calculation on **MILC** lattices with t.b. conditions at several lattice spacings **FNAL/MILC** POS(Lattice 2010)306

* $N_f = 2+1$ overlap calculation: **JLQCD** POS(Lattice 2010)146

2.3. $K^0 - \bar{K}^0$ mixing

One of the most stringent constraints in UT analyses.

$$|\epsilon_K| = \left|\frac{A(K_L \to (\pi\pi)_{I=0})}{A(K_S \to (\pi\pi)_{I=0})}\right| = e^{i\phi_\epsilon}\ \sin\phi_\epsilon \left(\frac{\text{Im } M^K_{12,SD}}{\Delta M_K} + \frac{\text{Im } M^K_{12,LD}}{\Delta M_K} + \underbrace{\frac{\text{Im } A_0}{\text{Re } A_0}}_{\Gamma^K_{12}}\right)$$

$$= e^{i\phi_\epsilon}\kappa_\epsilon C_\epsilon \hat{B}_K |V_{cb}|^2\lambda^2\eta\left(|V_{cb}|^2(1-\bar{\rho}) + \eta_{tt}S_0(x_t) + \eta_{ct}S_0(x_c, x_t) - \eta_{cc}x_c\right)$$

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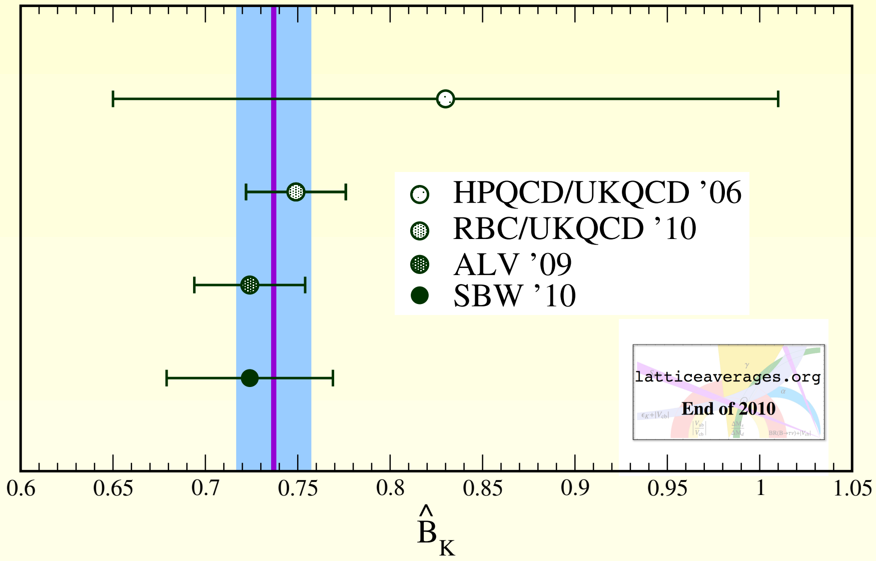

$$\boxed{\hat{B}_K^{\mathbf{LLV}} = 0.737 \pm 0.020}$$

* Good agreement with $\hat{B}_K^{N_f=2} = 0.729(30)$ **ETMC**, 1009.5606
(not included in average because of unknown quenching errors)

* Different fermion formulations (staggered, domain wall, twisted mass), set of configurations **(MILC,RBC/UKQCD, ETMC)** and renormalization procedures.

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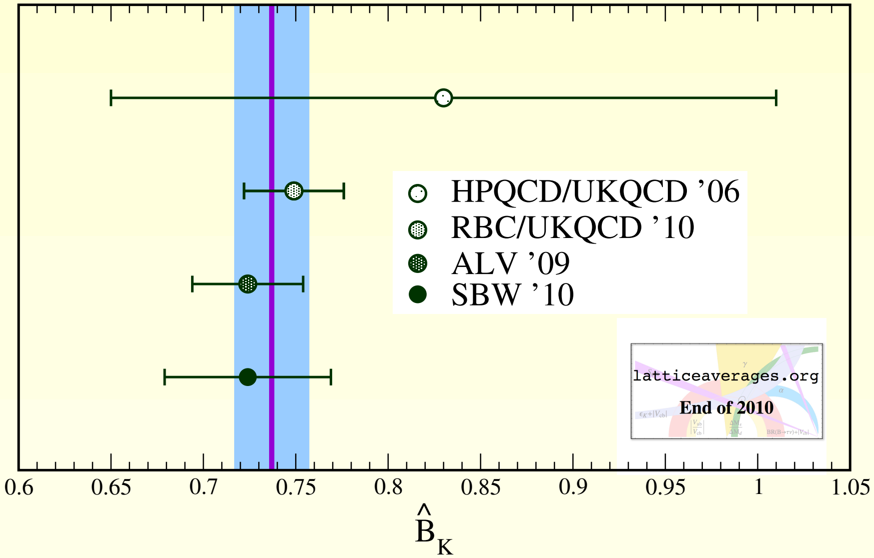

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* $\hat{B}_K$ is no longer the dominant source of uncertainty in neutral K mixing.

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- Need to include subleading effects.

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Where κ_ϵ parametrizes $\phi_\epsilon \neq \pi/4$ and long-distance contributions

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* ρ can be estimated using ChPT **Buras, Guadagnoli, and Isidori**, 1002.3612.

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$$\boxed{\kappa_\varepsilon = 0.94 \pm 0.02}$$ **Laiho, Lunghi, and Van de Water**

3. Heavy quark phenomenology

Problem is discretization errors ($\simeq m_Q a, (m_Q a)^2, \cdots$) if $m_Q a$ is large.

* **Effective theories:** Need to include multiple operators matched to full QCD (NRQCD,HQET,static). `B-physics` $\surd$

* **Relativistic (improved) formulations:**

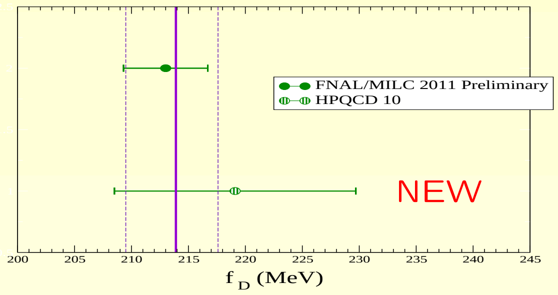
** Allow accurate results for `charm` (especially twisted mass, Hisq (Highly improved staggered quarks)).

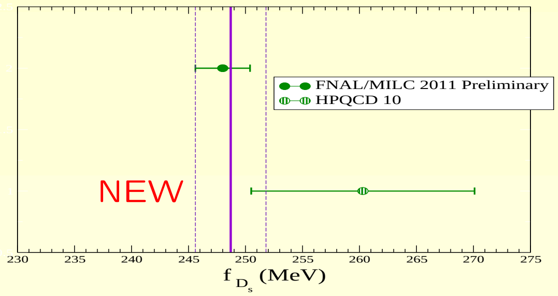
** Advantages of having the same f ormulation for light and charm: ratios light/charm, PCAC for heavy-light, ...

One could get the same precision for D as for K

** Starting to be extended to the `bottom` region.

3.1. D and D_s meson decay constants





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* From **HFAG** 2010:

$$f_D^{exp} = (206.7 \pm 8.9) MeV$$
$$f_{D_s}^{exp} = (257.3 \pm 5.3) MeV$$

\# Not in average **ETMC** 0904.0954 ($N_f = 2$)

$f_D = 197(9) MeV$; $f_{D_s} = 244(8) MeV$

PACS-CS, 1104.4600($N_f = 2 + 1$) Promising but needs complete error budget

\# Current error at 2-4% level

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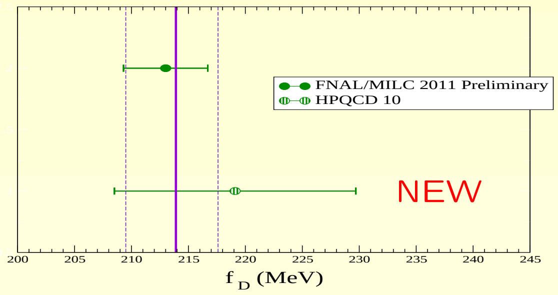
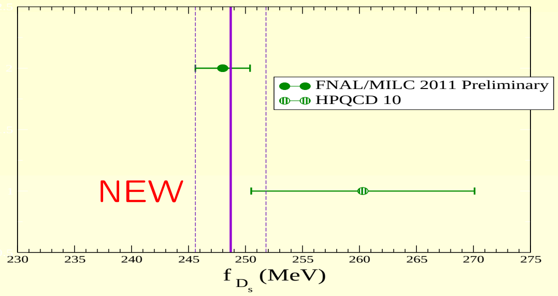
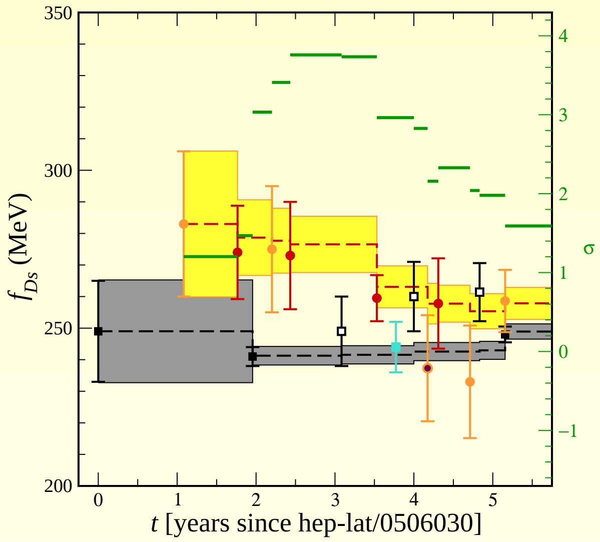
f_{D_s} **puzzle** **A. Kronfeld**







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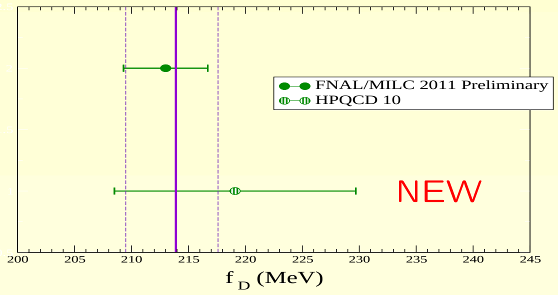

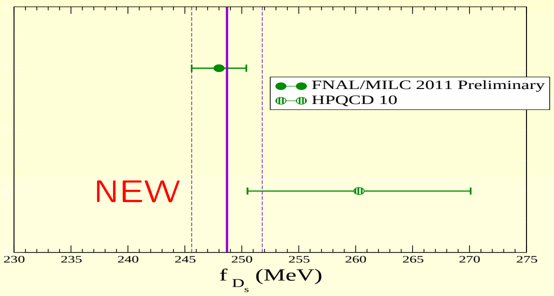

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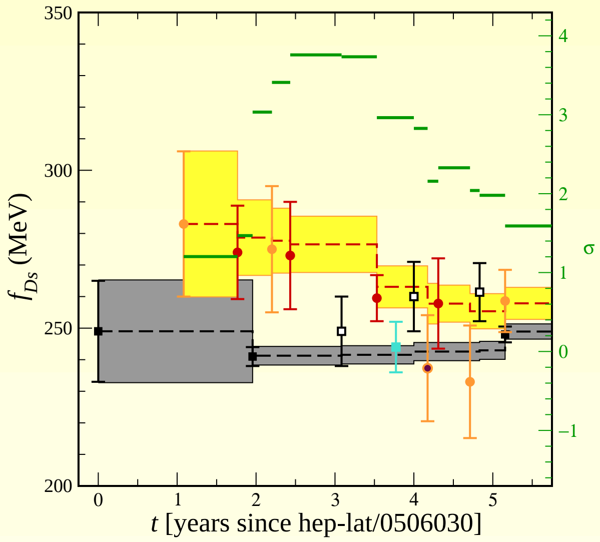

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\# Current error at 2-4% level → $\sim 1\%$ **error reachable in 3-5 years**

3.2. B and B_s `meson` decay constants

\# Needed for processes potentially sensitive to NP: for ex. $B_s \to \mu^+\mu^-$

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

- * Tension in output from UT fits and $f_B^{lattice}$ (driven by $\sin(2\beta)$ from $B_d \to \psi K_s$) **Lunghi and Soni**, 1104.2117

- * Agreement of $Br(B \to \tau\nu)$ with $f_B^{lattice}$ and experiment when using $|V_{ub}^{inc.}|$ but not when using $|V_{ub}^{exc.}|$ $\sim 2.8\sigma$ **Lunghi and Soni**, 1104.2117

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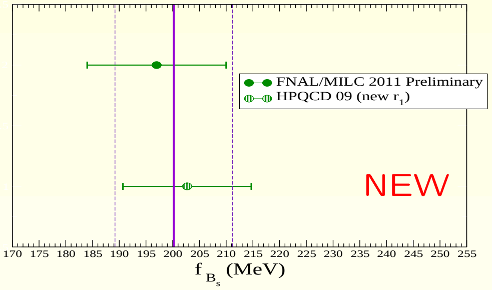
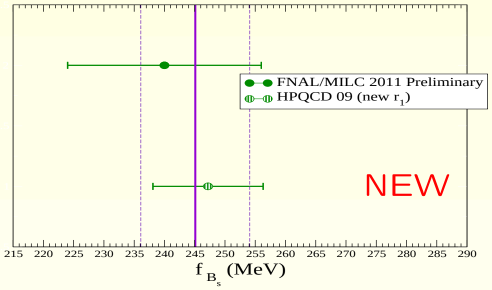


$$\boxed{f_B^{\mathbf{lat}} = (200 \pm 11)\ MeV}$$



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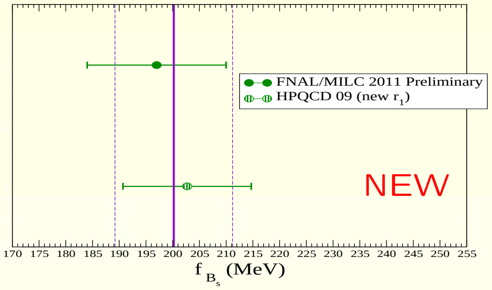

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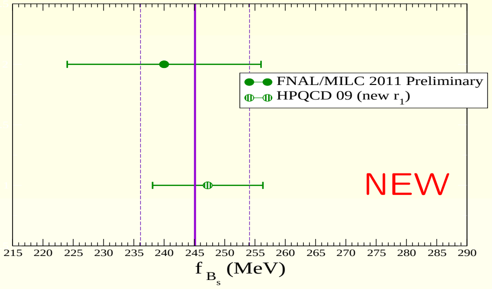

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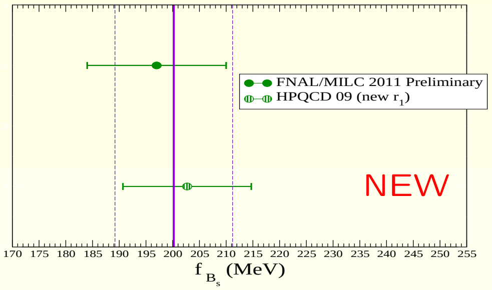

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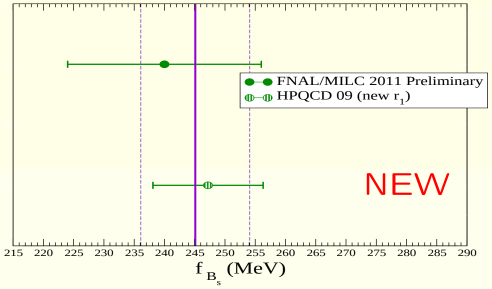

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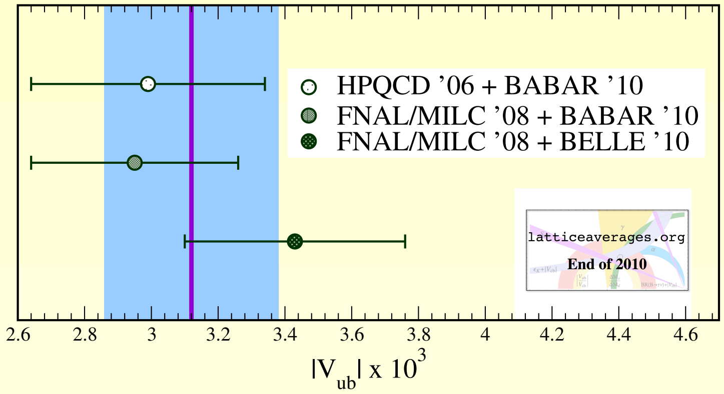
In progress: **HPQCD** calculation using relativistic b quarks (extrapol. to m_b using HQET)

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



* `z-expansion` used with **FNAL/MILC** data to parametrize $f_{+(0)}(q^2)$ shape

based on analyticity, unitarity, and HQ symmetry

* `BK` parametrization used with **HPQCD** data for $f_{+(0)}(q^2)$ shape

3-parameters description given by the M_{B^*} pole

$$\boxed{|V_{ub}^{exc.}|^{\textbf{LLV}} = (3.12 \pm 0.26) \times 10^{-3}}$$

* Reminder: A 100% correlation is taken for the theory/experimental errors in calculations using the same lattice/exper. data.

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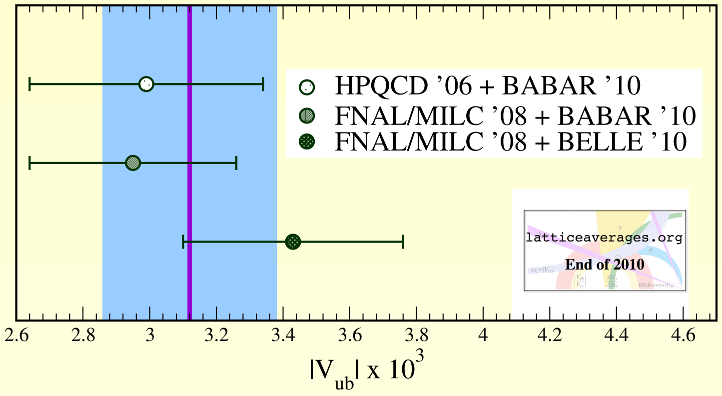

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\# There is a 3.3σ discrepancy with inclusive calculations

$|V_{ub}^{incl}| = (4.34^{+0.22}_{-0.27}) \times 10^{-3}$ **HFAG**, 1010.1589

* Discrepancy could be due to right handed currents → need calculation of $B \to \rho l\nu$ **M. Neubert**

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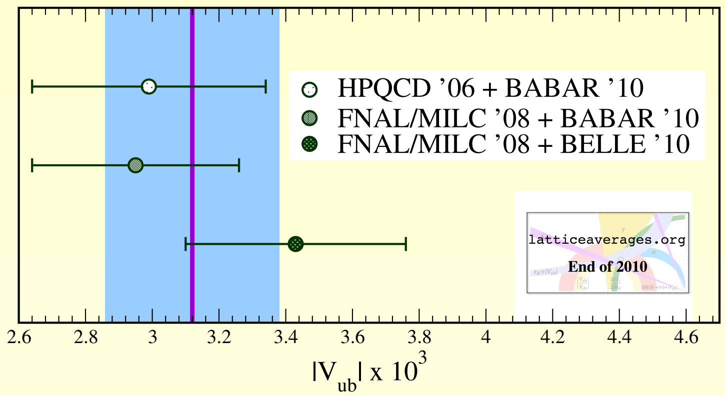

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\# **In progress** **FNAL/MILC** is addressing the main sources of error: $4\times$ more configurations, add smaller lattice spacing, more sophisticated analysis techniques, improvements on parametrization of shape ...

3.3. Exclusive determination of $|V_{cb}|$

\# $|V_{cb}|$ normalizes the whole unitarity triangle.

\# $|V_{cb}|$ needed as an input in ϵ_K (dominant error after improvements in B_K) and rare kaon decays $Br(K \to \pi\nu\bar{\nu})$.

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\# Updated **FNAL/MILC** determination of $B \to D^* l\nu$ form factor at zero recoil (blind anlysis)

* Double ratio method: $|h_A(1)|^2 = \frac{\langle D^*|\bar{c}\gamma_j\gamma_5 b|\bar{B}\rangle\langle\bar{B}|\bar{b}\gamma_j\gamma_5 c|D^*\rangle}{\langle D^*|\bar{c}\gamma_4 c|D^*\rangle\langle\bar{B}|\bar{b}\gamma_4 b|\bar{B}\rangle}$

$$|V_{cb}| \times 10^3 = (39.7 \pm 0.7_{exp} \pm 0.7_{LQCD})$$ **J. Laiho**, CKM2010

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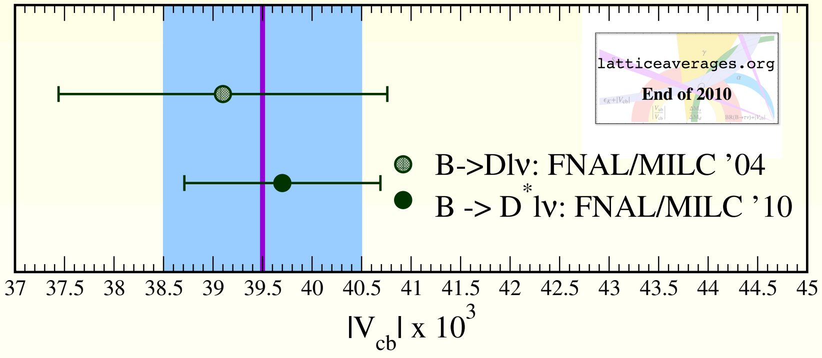

$$|V_{cb}^{inc.}| \times 10^3 = 41.68 \pm 0.73$$

HFAG, 1010.1589

→ 2.2σ discrepancy.

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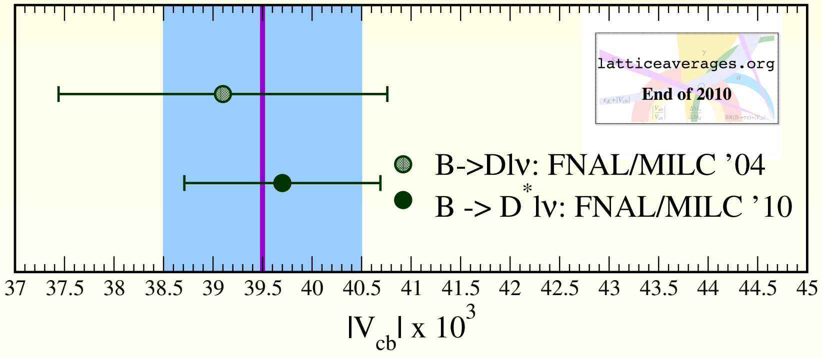

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In progress: New calculation of $|V_{cb}|$ from $B \to Dl\nu$, and form factors shape for both $B \to D(D^*)l\nu$ **FNAL/MILC**

3.4. D semileptonic decays

Errors in the extraction of $|V_{cd(cs)}|$ from semileptonic decays dominated by lattice uncertainties.

Testing lattice QCD: shape of the form factors

→ use same methodology for other processes like $B \to \pi l \nu$ or $B \to K l \bar{l}$

Correlated signals of NP to those in leptonic decays.

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Determination of $|V_{cs}|$ from $D \to K l \nu$ by **HPQCD**, Phys.Rev.D82:114506(2010) with $N_f = 2+1$, two $a's$ (**MILC** configurations) and **Hisq** valence quarks.

* Use PCVC to relate $f_0(q^2)$ to three-point functions with a scalar (versus vector) insertion $\boxed{f_+(0) = f_0(0) = \frac{m_c - m_q}{m_D^2 - m_\pi^2} \langle D|S|K\rangle}$

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$\boxed{f_+^{D\to K}(0) = 0.747(19)}$ error: 11% → 2.5%.

3.4. D semileptonic decays

Several lattice groups working on $D \to K(\pi)l\nu$:

- * **HPQCD** $N_f = 2+1$ on **MILC** configurations with **Hisq** action for valence quarks and **Asqtad** for sea quarks ($D \to \pi$).
- * **FNAL/MILC** $N_f = 2+1$ on **MILC** configurations with **Fermilab** action for c and **Asqtad** for u, d, s.
- * **ETMC** $N_f = 2$ with **twisted mass** sea and valence quarks.

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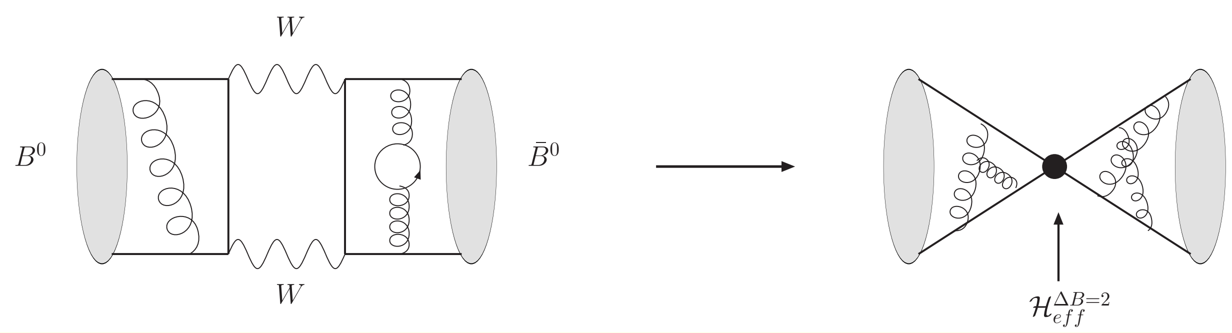
Current state-of-the-art results from the lattice

$$f_+^{D\to K}(0) = 0.747(19)$$ **HPQCD**, Phys.Rev.D82(2010)

$$f_+^{D\to \pi}(0) = 0.64(3)(6)$$ **Aubin et al.** PRL94(2005)

3.5. Neutral B-meson mixing

In the Standard Model



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

** Non-perturbative input

$$\frac{8}{3} f_{B_q}^2 B_{B_q}(\mu) M_{B_q}^2 = \langle \bar{B}_q^0 | O_1 | B_q^0 \rangle(\mu) \quad \text{with} \quad O_1 \equiv [\overline{b^i}\, q^i]_{V-A} [\overline{b^j}\, q^j]_{V-A}$$

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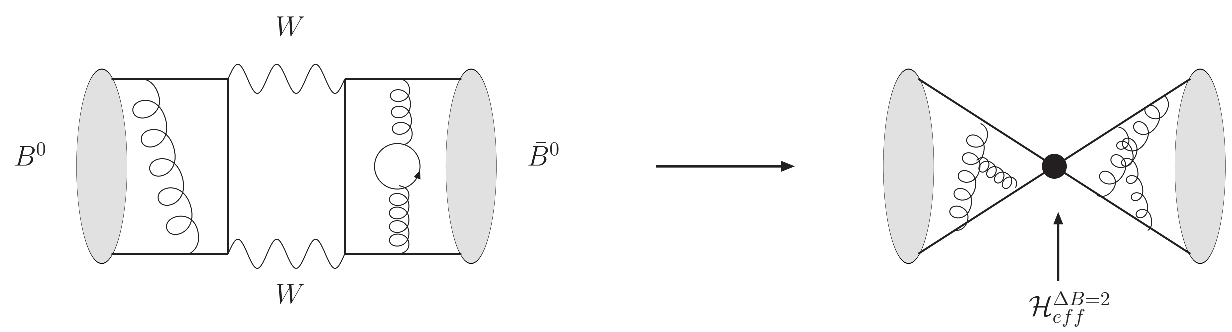

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Specially interesting for phenomenology (UT analyses):

$$f_{B_q}\sqrt{\hat{B}_{B_q}} \qquad \xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$$

3.5. Neutral B-meson mixing

Only published result with $N_f = 2+1$ available so far for $\sqrt{f_B \hat{B}_B}$:

HPQCD, PRD80 (2009) 014503

$$\boxed{f_{B_s}\sqrt{\hat{B}_{B_s}} = 276(6)(18)\mathrm{MeV}} \qquad \boxed{f_{B_d}\sqrt{\hat{B}_{B_d}} = 224(9)(12)\mathrm{MeV}}$$

* Using new value for the lattice scale $r_1 = 0.3133(23)(3)$**Davies et al.**,PRD81(2010)

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* **NEW: Preliminary** results from **FNAL/MILC**:

$$f_{B_s}\sqrt{\hat{B}_{B_s}} = 268(8)(14)\mathrm{MeV} \qquad f_{B_d}\sqrt{\hat{B}_{B_d}} = 221(9)(11)\mathrm{MeV}$$

** Final results expected for **Lattice 2011** (July)

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** Final results expected for **Lattice 2011** (July)

\# Bag parameters B_{B_s} and B_{B_d} can be used for theoretical predictions of, for example, $\mathcal{B}r(B \to \mu^+\mu^-)$.

$$\frac{\mathcal{B}r(B_q \to \mu^+\mu^-)}{\Delta M_q} = \tau(B_q)\,6\pi\frac{\eta_Y}{\eta_B}\left(\frac{\alpha}{4\pi M_W sin^2\theta_W}\right)^2 m_\mu^2\,\frac{Y^2(x_t)}{S(x_t)}\,\frac{1}{\hat{B}_q}$$

3.5. **Neutral** B-meson **mixing**

* Using **HPQCD** determinations of $\hat{B}_q$ PRD80 (2009) 014503

$\rightarrow \mathcal{B}r(B_s \to \mu^+\mu^-) = (3.19 \pm 0.19) \times 10^{-9}$ and

$\mathcal{B}r(B_d \to \mu^+\mu^-) = (1.02 \pm 0.09) \times 10^{-10}$

* **CDF (DØ)[LHCb]** bounds $\mathcal{B}r(B_s \to \mu^+\mu^-) \leq 4.3(5.1)[5.6] \times 10^{-8}$,

$\mathcal{B}r(B_d \to \mu^+\mu^-) \leq 0.76[1.5] \times 10^{-8}$

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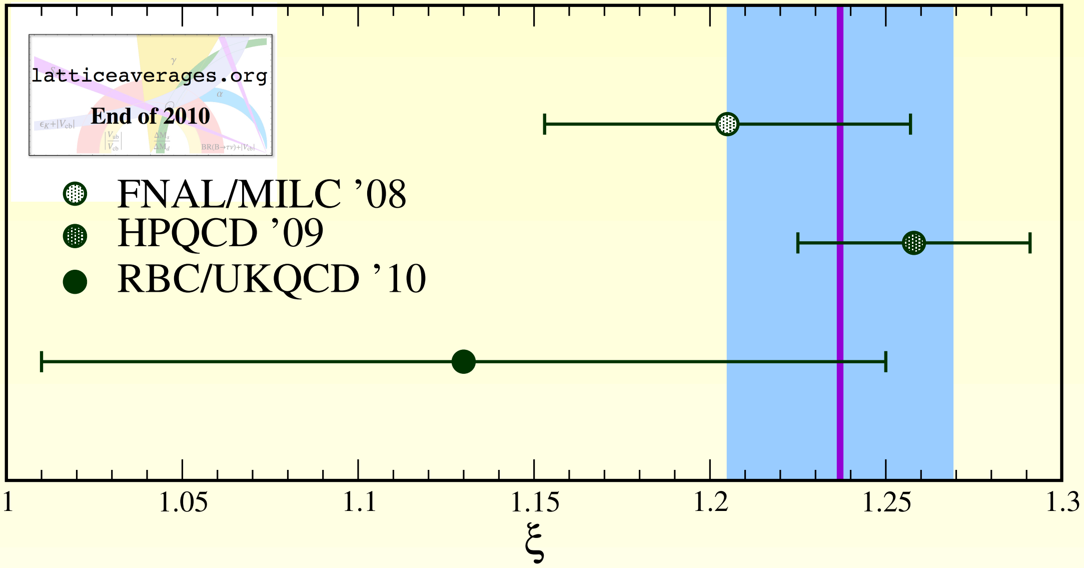
* Real test in LHC.

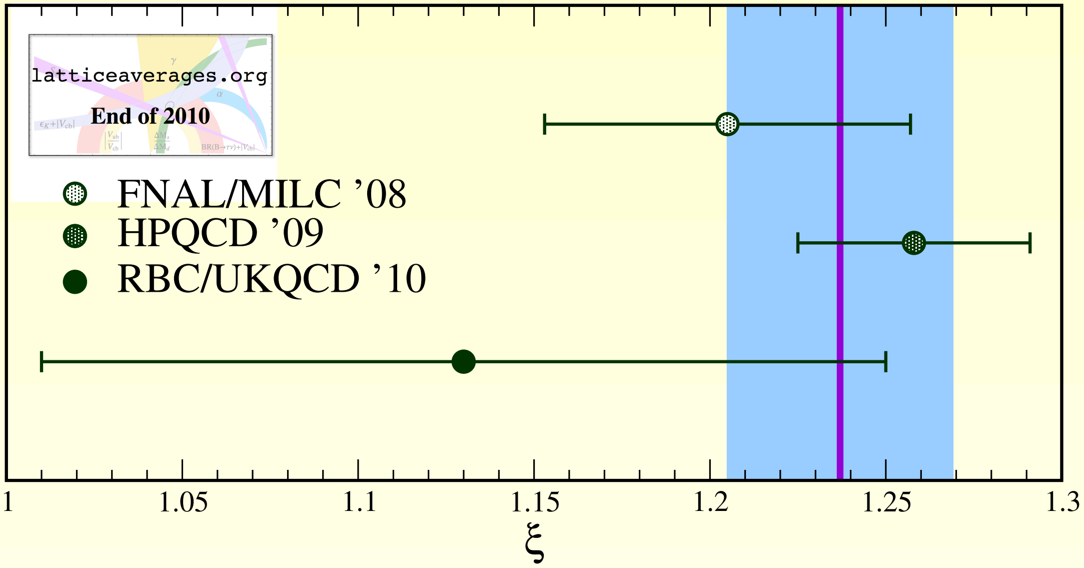
3.5. Neutral B-meson mixing



Results for $\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$

$$\boxed{\xi^{\mathbf{LLV}} = 1.237 \pm 0.032}$$

3.5. Neutral B-meson mixing



Results for $\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$

$$\boxed{\xi^{\mathbf{LLV}} = 1.237 \pm 0.032}$$

* **RBC/UQCD** result using domain wall fermions is an exploratory study
A project aimed to the precision calculations of both ξ and $f_B\sqrt{B_B}$ is **in progress** **Witzel and Van de Water** POS(Lattice 2010)318

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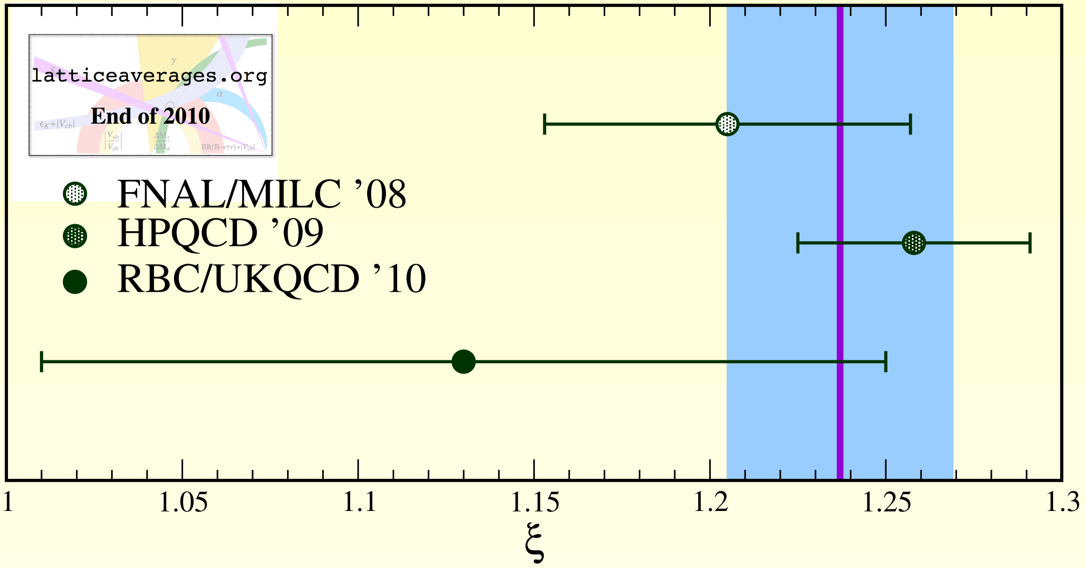

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We expect results with errors around $4-5\%$ for $f_B\sqrt{B_B}$ and $1.5-2\%$ for ξ in ~ 2 years, and using at least two different sets of configurations and fermion formulations for light and heavy quarks.

3.6. Neutral meson mixing BSM

Effects of heavy new particles seen in the form of effective operators built with **SM** degrees of freedom

$$\mathcal{H}_{eff}^{\Delta F=2} = \sum_{i=1}^{5} C_i Q_i + \sum_{i=1}^{3} \widetilde{C}_i \widetilde{Q}_i$$

$$Q_1^q = \left(\bar{\psi}_f^i \gamma^\nu (\mathrm{I} - \gamma_5) \psi_q^i\right) \left(\bar{\psi}_f^j \gamma^\nu (\mathrm{I} - \gamma_5) \psi_q^j\right)$$

SM

$$Q_2^q = \left(\bar{\psi}_f^i (\mathrm{I} - \gamma_5) \psi_q^i\right) \left(\bar{\psi}_f^j (\mathrm{I} - \gamma_5) \psi_q^j\right) \qquad Q_3^q = \left(\bar{\psi}_f^i (\mathrm{I} - \gamma_5) \psi_q^j\right) \left(\bar{\psi}_f^j (\mathrm{I} - \gamma_5) \psi_q^i\right)$$

$$Q_4^q = \left(\bar{\psi}_f^i (\mathrm{I} - \gamma_5) \psi_q^i\right) \left(\bar{\psi}_f^j (\mathrm{I} + \gamma_5) \psi_q^j\right) \qquad Q_5^q = \left(\bar{\psi}_f^i (\mathrm{I} - \gamma_5) \psi_q^j\right) \left(\bar{\psi}_f^j (\mathrm{I} + \gamma_5) \psi_q^i\right)$$

$$\tilde{Q}_{1,2,3}^q = Q_{1,2,3}^q \text{ with the replacement } (\mathrm{I} \pm \gamma_5) \rightarrow (\mathrm{I} \mp \gamma_5)$$

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$\tilde{Q}^q_{1,2,3} = Q^q_{1,2,3}$ with the replacement $(\mathrm{I}\pm\gamma_5)\rightarrow(\mathrm{I}\mp\gamma_5)$

* $C_i, \widetilde{C}_i$ Wilson coeff. calculated for a particular BSM theory
* $\langle \bar{F}^0|Q_i|F^0\rangle$ calculated on the lattice

SM predictions + BSM contributions = experiment

→ $\boxed{\text{constraints on BSM building}}$

3.6. Neutral meson mixing BSM

\# Same programme can be applied for extra operators on the lattice. Only quenched calculations for BSM operators available.

→ Need unquenched calculations of matrix elements for the complete basis.

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* Imposing `short-distance` $\leq$ `experiment` can exclude large regions of parameters in many models, constraining BSM building.

E. Golowich, J. Hewett, S. Pakvasa and A. Petrov, PRD76 (2007);PRD79 (2009)

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\# Work in progress:

- * **FNAL/MILC** $B^0 - \bar{B}^0$: Fermilab HQ + staggered **C. Bouchard et al.** POS(Lat2010)299
- * **RBC/UKQCD** $B^0 - \bar{B}^0$: Relativistic HQ + domain wall
- * **HPQCD** $B^0 - \bar{B}^0$: NRQCD + staggered

3.6. Neutral meson mixing BSM

- **FNAL/MILC** $D^0 - \bar{D}^0$: Fermilab HQ + staggered
- **ETMC** $(N_f = 2)$ $K^0 - \bar{K}^0$ mixing: twisted mass **O. Dimopoulos et al.**

POS(Lattice 2010)302

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\# Calculation of the decay width differences $\Delta\Gamma_{s,d}$ also possible

* Need the matrix elements for $\mathcal{Q}_1, \mathcal{Q}_2$ or $\mathcal{Q}_1, \mathcal{Q}_3$

* Theoretical prediction for like-sign dimuon charge asymmetry A^b_{sl}

$$A^b_{sl} \simeq a^s_{sl}/2 \text{ with } \boxed{a^s_{sl} = \frac{\Delta\Gamma}{\Delta M_s} tan(\phi_s)}, \text{ and } \phi_s \equiv \left(-M^2_{12}/\Gamma^s_{12}\right)$$

4. Conclusions and outlook

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

- * Precise new results (few percent errors) in `Kaon` and `D` sectors.
  - ** Relativistic improved description of c.
- * Results from several collaborations (especially light-light) quantities → excellent checks.
- * Approaching the physical light quark masses.

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- New precise results in b physics: decay constants and mixing parameters **FNAL/MILC, RBC/UQCD,HPQCD**
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\# **Expected for next few years**

- * New precise results in b physics: decay constants and mixing parameters **FNAL/MILC, RBC/UQCD,HPQCD**
  - ** Including BSM operators and $\Delta\Gamma$.
- * First results with $N_f = 2+1+1$ configurations **(MILC, ETMC)**

  (some preliminary results already presented at Lattice 2010)

4. Conclusions and outlook

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* Improved determinations of B semileptonic decays.

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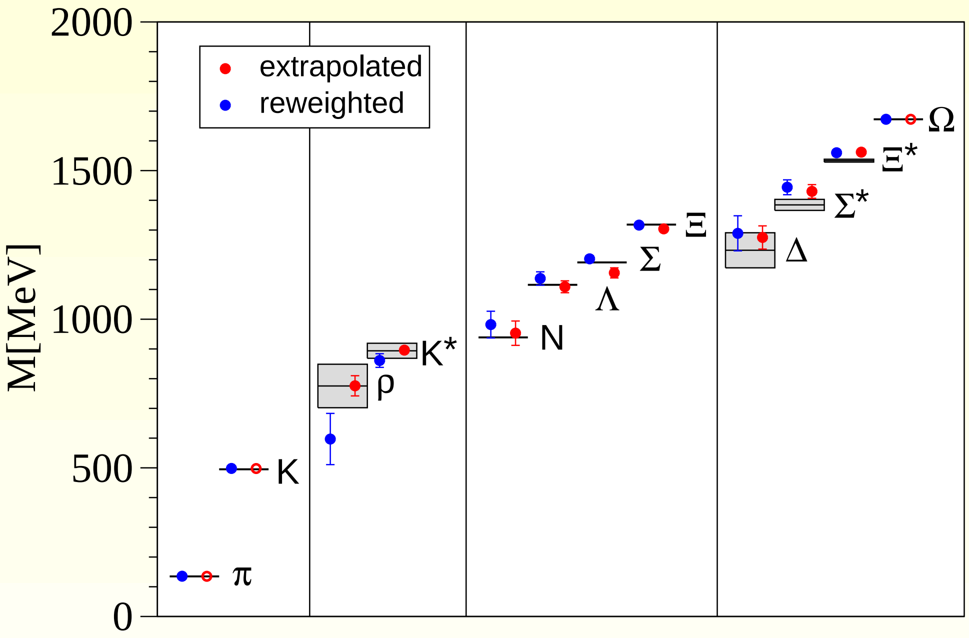
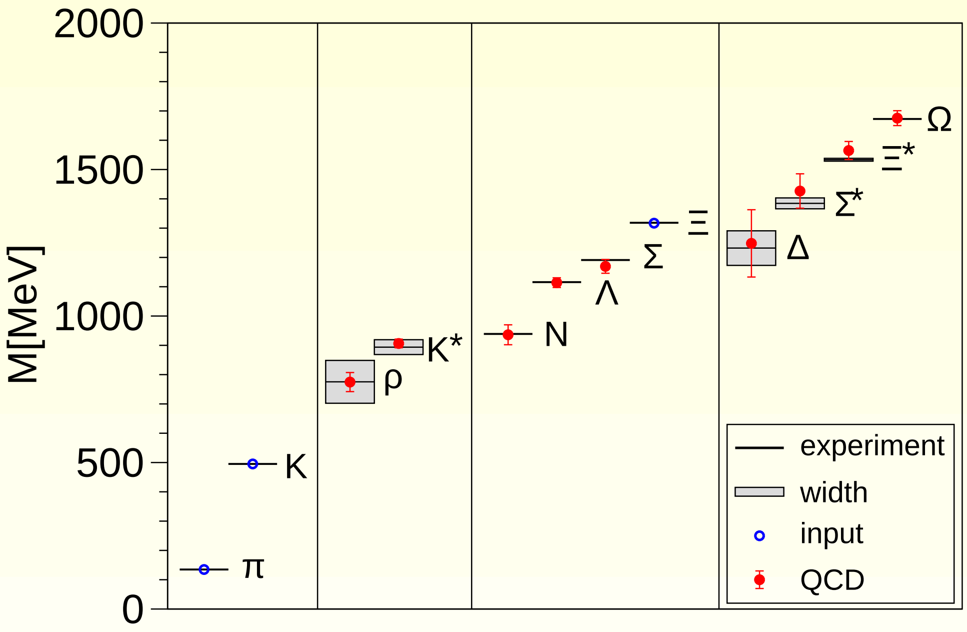
- * D semileptonic decays analized by several collaborations.
- * Improved determinations of B semileptonic decays.
- * Reduction in uncertainties of quantities relevant for CKM to the 1-2% level
- * Studies of $K \to \pi\pi$ **(RBC/UQCD, Coumbe-Laiho-Lightman-Van de Water)**, rare decays ($B \to K(K^*)$...), spectrum of excited hadrons ...

A.1. Spectrum of light hadrons: test of lattice QCD

Good agreement between $N_f = 2+1$ lattice calculations and the experimentally measured light spectrum.



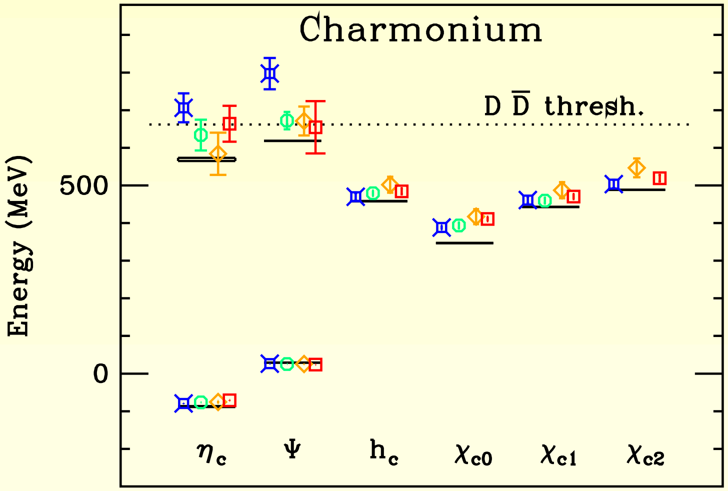
PACS-CS 0807.1661,0911.2561



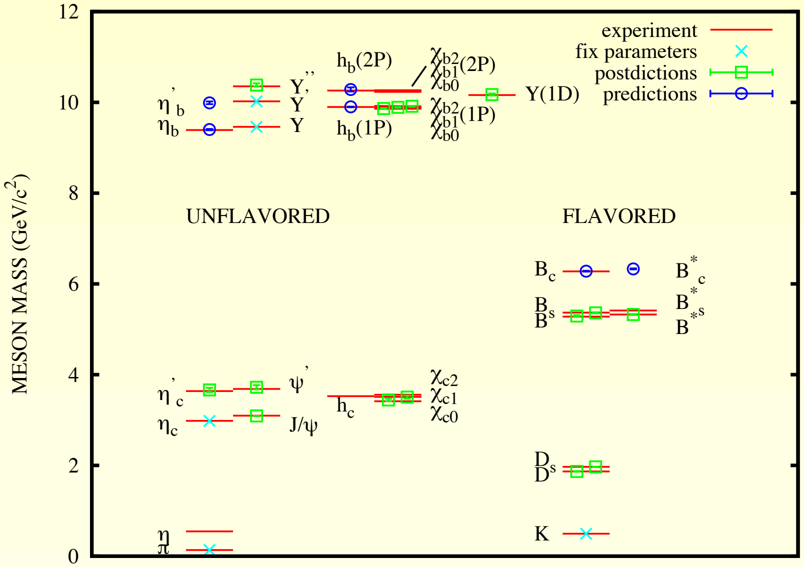
BMW 0906.3599

A.2. Spectrum of heavy hadrons

FNAL/MILC



HPQCD



\# Some post/predictions with NRQCD b (**S. Meinel**, 1007.3966, 1010.0889)

$$(m_\Upsilon - m_{\eta_b})(1S) = (60.3 \pm 7.7)\ \text{MeV}\ \left((m_\Upsilon - m_{\eta_b})(1S)^{exp} = 69.3 \pm 2.9\right)$$

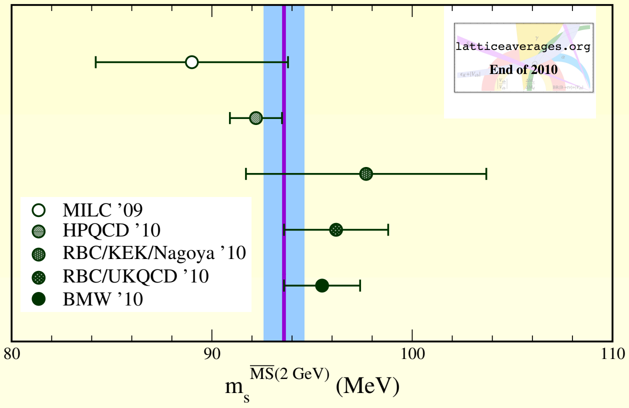
$$(m_\Upsilon - m_{\eta_b})(2S) = (23.5 \pm 4.7)\ \text{MeV}$$

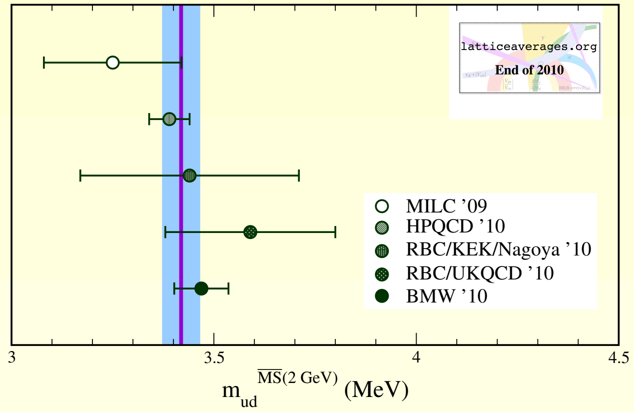
$$m_{\Omega_{bbb}} = (14.371 \pm 0.012)\ \text{GeV}$$

\# Prediction for $\boxed{m_{B_c^*} = 6.3330(6)(2)(6)\ \text{GeV}}$

B.1. Light quark masses

\# Determination of m_s with around $1-5\%$ errors from several $N_f = 2+1$ collaborations.





$$m_s^{\mathbf{LLV},\overline{MS}}(2\text{GeV}) = (93.6 \pm 1.1)\ \text{MeV}; \qquad m_{ud}^{\mathbf{LLV},\overline{MS}}(2\text{GeV}) = (3.419 \pm 0.047)\ \text{MeV}$$

B.2. Heavy quark masses

Heavy masses from current-current correlators **HPQCD**, PRD82(2010) $(N_f = 2+1)$

$$m_c(3 \text{ GeV}, n_f = 4) = 0.986(6) \text{ GeV}$$

$$m_b(10 \text{ GeV}, n_f = 5) = 3.617(25) \text{ GeV}$$

$N_f = 2+1$ NRQCD b quarks **A. Hart et al.**, Pos(Lat2010)223

$$m_b(m_v) = 4.25(12) \text{ GeV}$$

$N_f = 2$ twisted mass calculation from **ETMC**, Pos(Lat2010)239

$$\bar{m}_c(\bar{m}_c) = 1.28(4) \text{ GeV}$$

$$\bar{m}_b \bar{m}_b = 4.3(2) \text{ GeV}$$