B-meson mixing on the lattice

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· Fermilab, April 26 (2010) ·

1. Impact of B^0 mixing on the flavour physics program

Determination of fundamental parameters of the SM

* CKM matrix elements: $|V_{td}|$, $|V_{ts}|$

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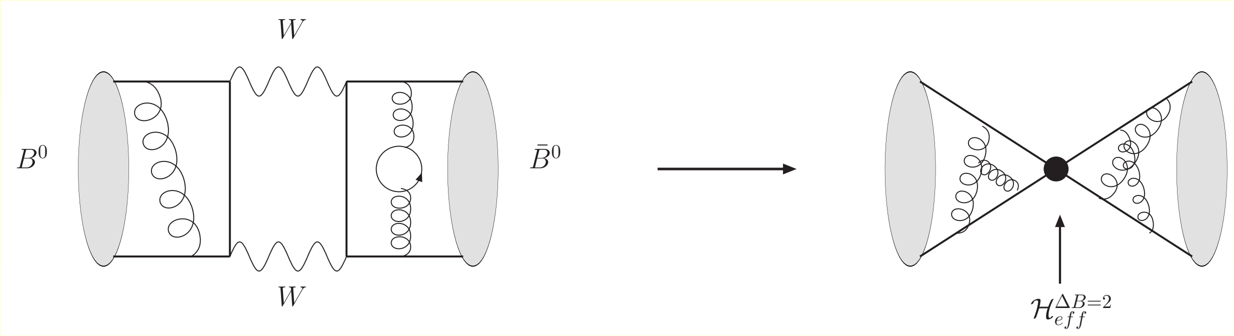
In the Standard Model



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

** 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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* CKM matrix elements: $|V_{td}|$, $|V_{ts}|$

Unveiling New Physics effects.

* **Hints of discrepancies** between SM expectations and some flavour observables

A. Buras, talk at EPS-HEP 2009 or **R. Van de Water**, plenary talk at Lat09

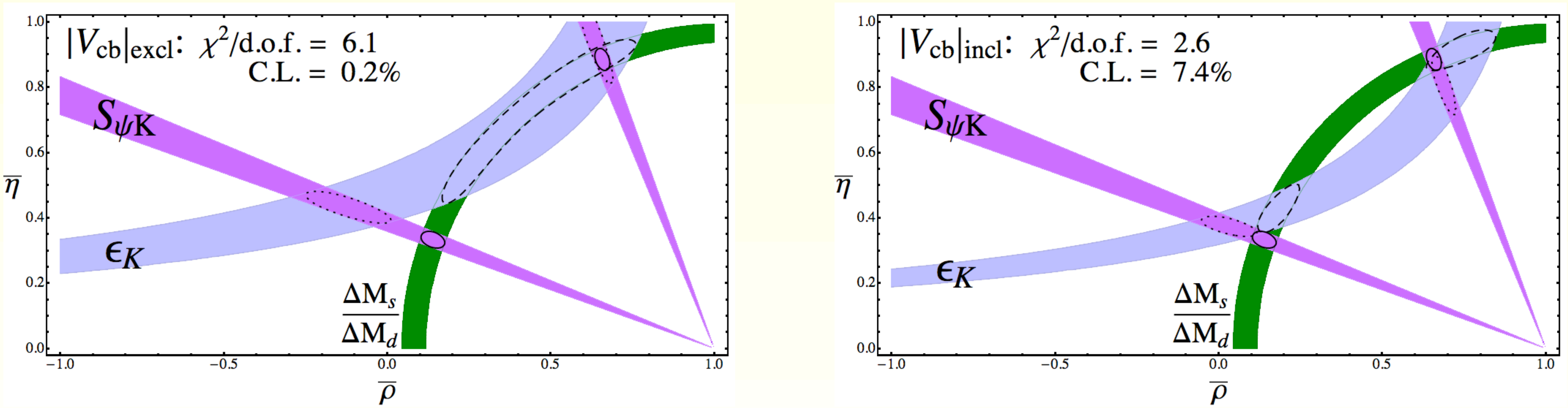
** B_s mixing phase β_s as extracted from experiment $(S_{J/\psi\phi})$ and in the SM.

1. Impact of B^0 mixing on the flavour physics program

UT fit: Global fit to the CKM unitarity triangle using experimental and theoretical constraints. talk by **E. Lunghi**

$2-3\sigma$ tension in the CKM description

* Tension is between the three most precise constraints: the $K^0-\bar{K}^0$ mixing parameter ϵ_K, the ratio of mass differences $\Delta M_{B_s}/\Delta M_{B_d}$ describing $B^0-\bar{B}^0$ mixing and $\sin(2\beta)$.



Laiho, Van de Water and Lunghi, Phys.Rev.D81:034503(2010)

* Constraints from $\Delta M_d/\Delta M_s$ limited by lattice errors for $\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$.

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Constraining NP models.

* Comparison of ΔM and $\Delta\Gamma$ with experiment also provides bounds for **NP** effects

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

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

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

$\to \mathcal{B}r(B_s \to \mu^+\mu^-) = (3.19 \pm 0.19) \times 10^{-9}$ and
$\mathcal{B}r(B_d \to \mu^+\mu^-) = (1.02 \pm 0.09) \times 10^{-10}$

* **CDF (DØ)** bounds $\mathcal{B}r(B_s \to \mu^+\mu^-) \leq 3.3(5.3) \times 10^{-8}$,
$\mathcal{B}r(B_d \to \mu^+\mu^-) \leq 1 \times 10^{-8}$

1. Impact of B^0 mixing on the flavour physics program

In conjunction with experimental measurements . . .

HFAG 10 | **CDF** (Run II)

$$\Delta M_d|_{exp.} = (0.507 \pm 0.005) ps^{-1} \qquad \Delta M_s|_{exp.} = (17.77 \pm 0.12) ps^{-1}$$

HFAG 10

$$\left(\frac{\Delta\Gamma}{\Gamma}\right)_d = 0.010 \pm 0.037 \qquad \left(\frac{\Delta\Gamma}{\Gamma}\right)_s = 0.09 \pm 0.05$$

2. $N_f = 2+1$ unquenched lattice calculation of B^0 mixing parameters

Quenched approximation: neglect vacuum polarization effects

→ uncontrolled and irreducible errors   talk by **A. Kronfeld**

- HPQCD: **E. Gámiz** *et al.*, Phys.Rev.D80:014503,2009
  - * Configurations: **MILC** staggered.
  - * Light quarks: Improved staggered (Asqtad)
  - * Heavy quarks: NRQCD
- Fermilab lattice/MILC: **R.T. Evans** *et al.* ,PoS(LAT2009)245; **R.T. Evans** *et al.*, PoS(LAT2008)052 **preliminary**
  - * Configurations: **MILC** staggered.
  - * Light quarks: Improved staggered (Asqtad)
  - * Heavy quarks: Fermilab → it can also be used for c quarks.
- RBC/UKQCD: **C. Albertus** *et al.*, **arXiv:1001.2023** **exploratory**
  - * Configurations: **RBC/UKQCD** domain wall.
  - * Light quarks: Domain wall.
  - * Heavy quarks: Static.

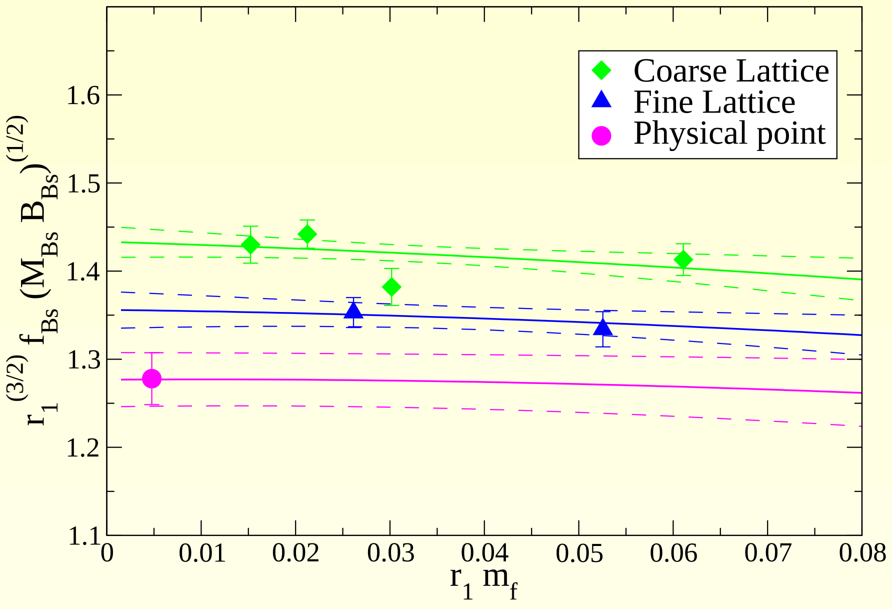
2.1. Some details of the simulations

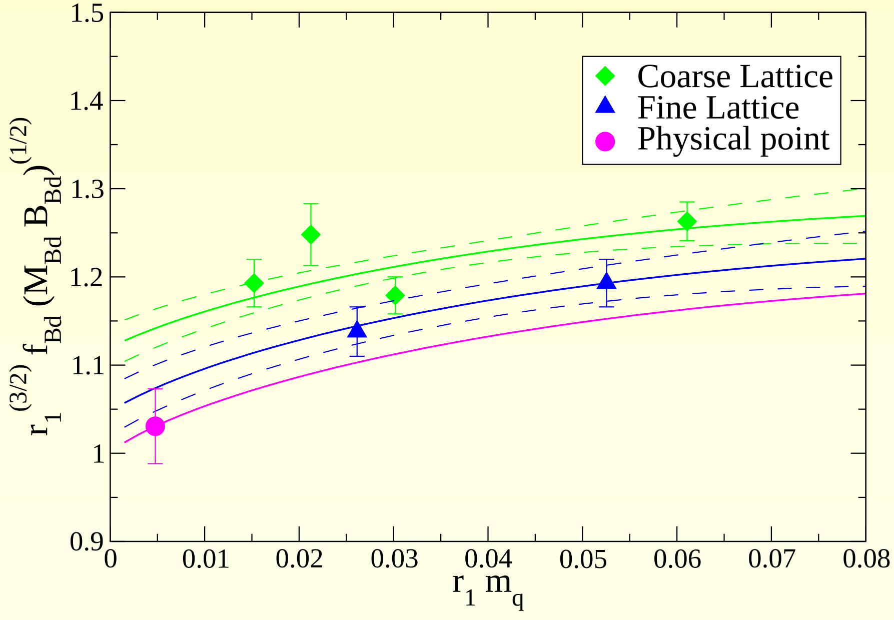
	HPQCD	FNAL/MILC	RBC/UKQCD
a	0.12 fm 0.09 fm	0.12 fm 0.09 fm	0.11 fm
$\#m_{light}^{sea}/m_s^{sea}$	4 2	4 2	3
$\#m^{valence}$	full QCD	6 (include full QCD)	full QCD
$renormalization$	one-loop	one-loop	one-loop
lightest π (MeV)	$\sim$ 230	$\sim$ 230	$\sim$ 430

See talk by **C. Bernard**

2.2. Results: $f_{B_q}\sqrt{B_{B_q}}$

HPQCD, PRD80 (2009) 014503





$$f_{B_s}\sqrt{\hat{B}_{B_s}} = 266(6)(17)\text{MeV}$$

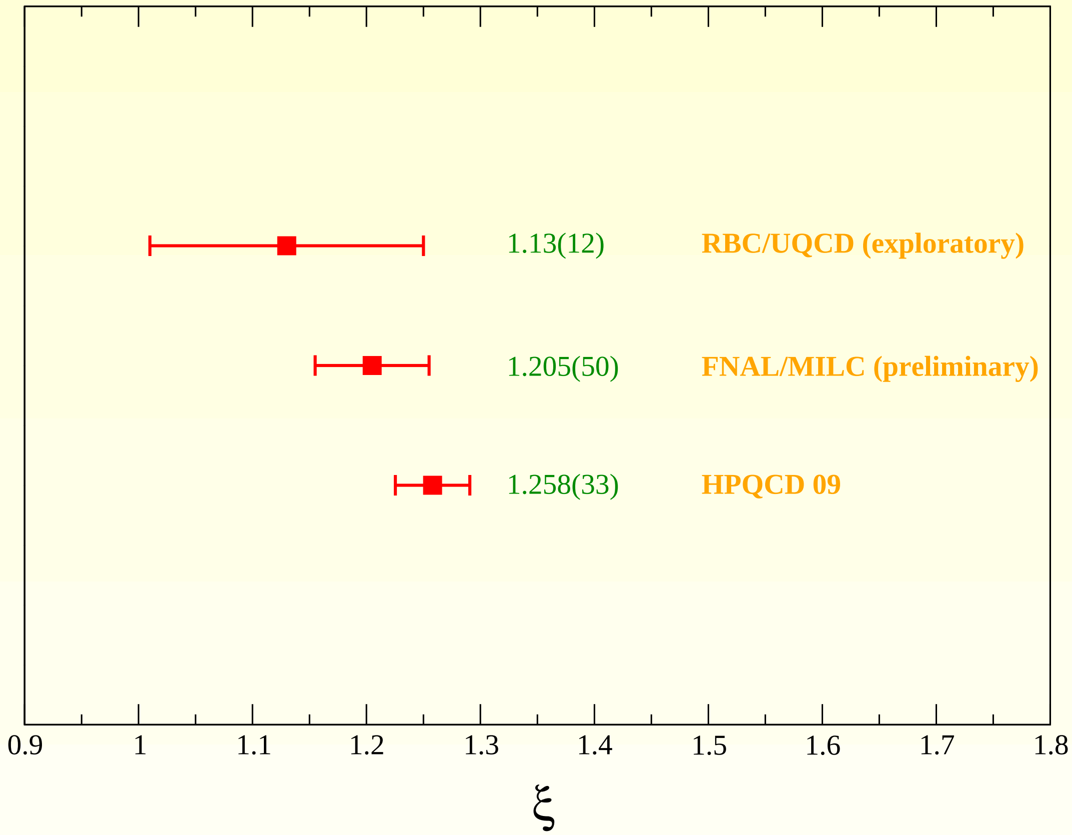
$$f_{B_d}\sqrt{\hat{B}_{B_d}} = 216(9)(12)\text{MeV}$$

Chiral+continuum extrapolations: NLO Staggered CHPT.

* accounts for NLO quark mass dependence.

* accounts for light quark discretization effects through $\mathcal{O}\left(\alpha_s^2 a^2 \Lambda_{QCD}^2\right)$
  $\rightarrow$ remove the dominant light discretization errors

2.2. Results: $\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$



RBC/UKQCD: No extrapolation to the continuum

FNAL/MILC: No renormalization included, but we expect a large cancellation between B_s^0 and B_d^0 renor. corrections.

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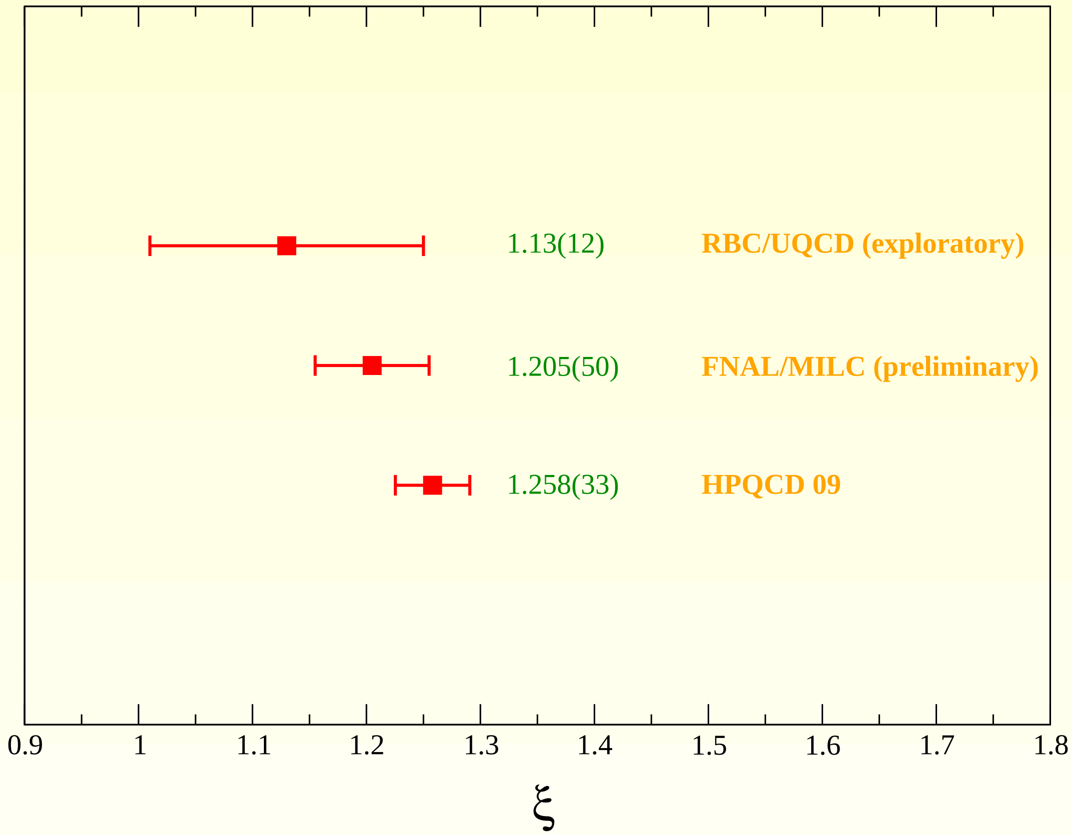

RBC/UKQCD: No extrapolation to the continuum

FNAL/MILC: No renormalization included, but we expect a large cancellation between B_s^0 and B_d^0 renor. corrections.

$$\text{HPQCD} \quad \text{result} \quad \Longrightarrow \quad \left|\frac{V_{td}}{V_{ts}}\right| = \boxed{0.214(1)(5)}$$

2.3. Error budget for $f_B\sqrt{\hat{B}_B}$

Source (%)	HPQCD (final)	FNAL/MILC (preliminary)
stat. + chiral extrap.	2.3-4.1	2.7-4.0
χPT + light quark disc.	-	0.4-2.5
residual a^2 extrap. (heavy quark disc.)	3.0-2.0	2.0
$r_1^{3/2}$ uncertainty	2.3	3.0-3.1
$g_{B^*B\pi}$ uncertainty	1.0	0.3-0.6
quark masses tuning	1.5-1.0	0.6-0.5
operator matching	4.0	4.0
relativistic corr.	2.5	-
Finite volume	$\leq$ 0.5	$\leq$ 0.5
Total	**6.7-7.1**	**6.1-7.3**

* Ranges indicate $B_s^0 - B_d^0$ values.

2.3. Error budget for ξ

Source (%)	HPQCD (final)	FNAL/MILC (preliminary)	RBC/UKQCD (exploratory)
stat. + chiral extrap.	2.0	3.1	6-5
χPT + light quark disc.	-	2.8	7
residual a^2 extrap. (heavy quark disc.)	0.3	0.2	4
$r_1^{3/2}$ uncertainty	0.	0.2	*
$g_{B^*B\pi}$ uncertainty	1.0	0.3	2
quark masses tuning	1.0	0.7	1*
operator matching	0.7	$\leq$ 0.5	2
relativistic corr.	0.4	-	2
Finite volume	$\leq$ 0.1	$\leq$ 0.1	1
Total	**2.6**	$\sim$ **4.3**	**9**

2.4. Improvements of lattice calculations of ξ in 2 years

Source (%)	HPQCD	FNAL/MILC	improvement (factor of)
stat. + chiral extrap.	2.0	3.1	
χPT + light quark disc.	-	2.8	
residual a^2 extrap. (heavy quark disc.)	0.3	0.2	
$r_1^{3/2}$ uncertainty	0.	0.2	
$g_{B^* B\pi}$ uncertainty	1.0	0.3	
quark masses tuning	1.0	0.7	
operator matching	0.7	$\leq$ 0.5	
relativistic corr.	0.4	-	
Finite volume	$\leq$ 0.1	$\leq$ 0.1	

2.4. Improvements of lattice calculations of ξ in 2 years

Source (%)	HPQCD	FNAL/MILC	improvement
stat. + chiral extrap.	1.0	1.5	2 $\surd$
χPT + light quark disc.	-	2.8	
residual a^2 extrap. (heavy quark disc.)	0.3	0.2	
$r_1^{3/2}$ uncertainty	0.	0.2	
$g_{B^* B\pi}$ uncertainty	1.0	0.3	
quark masses tuning	1.0	0.7	
operator matching	0.7	$\lesssim$ 0.5	
relativistic corr.	0.4	-	
Finite volume	$\lesssim$ 0.1	$\lesssim$ 0.1	

* Better statistics: More configurations (**MILC** multiplied by 4 $N_{configurations}$), improved techniques for correlation fits (`smearing, random wall sources, ...`)

$\surd$ checked for one coarse ensemble (**C. Bouchard for FNAL/MILC**)

2.4. Improvements of lattice calculations of ξ in 2 years

Source	HPQCD	FNAL/MILC	improvement
stat. + chiral extrap.	1.0	1.5	**2**
χPT + light quark disc.	-	1.6	**1.5-2**
residual a^2 extrap. (heavy quark disc.)	0.2	0.1	**1.5**
$r_1^{3/2}$ uncertainty	0.	0.2	
$g_{B^* B\pi}$ uncertainty	1.0	0.3	
quark masses tuning	1.0	0.7	
operator matching	$\leq$0.5	$\leq$ 0.5	**
relativistic corr.	0.4	-	
Finite volume	$\leq$ 0.1	$\leq$ 0.1	

* Smaller values of lattice spacing (FNAL/MILC and HPQCD)

$a = 0.09\ fm$ (fine) $\rightarrow$ $a = 0.06\ fm$ (superfine) (eventually $a = 0.045\ fm$)

** Matching ($f_B\sqrt{B_B}$): $4\% \rightarrow 2.5\%$

2.4. Improvements of lattice calculations of ξ in 2 years

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stat. + chiral extrap.	1.0	1.5	**2**
χPT + light quark disc.	-	1.6	**1.5-2**
residual a^2 extrap. (heavy quark disc.)	0.2	0.1	**1.5**
$r_1^{3/2}$ uncertainty	0.	0.2	
$g_{B^*B\pi}$ uncertainty	0.5	0.2	**2**
quark masses tuning	0.5	0.3	**1.5**
operator matching	$\leq$0.5	$\leq$ 0.5	$\sim$
relativistic corr.	0.4	-	
Finite volume	$\leq$ 0.1	$\leq$ 0.1	

* Better determination of inputs

* Improving the actions: **HISQ**, heavy formulations (improved Fermilab action, improved NRQCD)

2.4. Improvements of lattice calculations of ξ in 2 years

Source	HPQCD	FNAL/MILC	improvement
stat. + chiral extrap.	1.0	1.5	**2**
χPT + light quark disc.	-	1.6	**1.5-2**
residual a^2 extrap. (heavy quark disc.)	0.2	0.1	**1.5**
$r_1^{3/2}$ uncertainty	0.	0.2	
$g_{B^*B\pi}$ uncertainty	0.5	0.2	**2**
quark masses tuning	0.5	0.3	**1.5**
operator matching	$\leq$0.5	$\leq$ 0.5	$\sim$
relativistic corr.	0.4	-	
Finite volume	$\leq$ 0.1	$\leq$ 0.1	
Total (2 years)	**1.4**	$\sim$ **2.3**	**1.5-2**

2.4. Improvements of lattice calculations of ξ in 2 years

Source	RBC/UKQCD (now)	RBC/UKQCD (in two years)
stat. + chiral extrap.	5-6	≤ 3
χPT + light quark disc.	7	~ 2
residual a^2 extrap. (heavy quark disc.)	3	≤ 1
$scale$ and quark masses uncertainty	1	≤ 1
$g_{B^* B \pi}$ uncertainty	3	≤ 1
operator matching	0-2	≤ 2
Finite volume	≤ 1	≤ 0.5
$1/m_b$ corrections	2	-
Total	9	$\leq$ **4**

O. Witzel at All Hands' Meeting 2010: USQCD Collaboration Meeting

2.5. Summary of expected lattice errors

	$f_B\sqrt{B_B}$	ξ
current	6-7%	3-4%
2 years	$\sim$ 4-5%	$\sim$ 1.5-2%
5 years*	$\sim$ 2%	$\sim$ 1%

Several high precision determinations of B_s^0 and B_d^0 mixing parameters with different heavy and light formulations.

* From **FNAL/MILC** estimates (talk by **C. Bernard**)

3. B_0 mixing beyond the SM

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

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The most general `Effective Hamiltonian` describing $\Delta B = 2$ processes is

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

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

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

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

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

where ψ_b is a heavy b-fermion field and ψ_q a light ($q = d, s$) fermion field.

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where ψ_b is a heavy b-fermion field and ψ_q a light $(q = d, s)$ fermion field.

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

3. B_0 mixing beyond the SM

Some examples:

F. Gabbiani et al, Nucl.Phys.B477 (1996), **D. Bećirević et al**, Nucl.Phys.B634 (2002); `general SUSY models`

M. Ciuchini and L. Silvestrini, PRL 97 (2006) 021803; `SUSY`

Constraints on the mass insertions ($|Re(\delta^d_{23})_{RR}| < 0.4$, $|(\delta^d_{23})_{LL}| < 0.1$,...)

M. Blanke et al, JHEP 12(2006) 003; `Little Higgs model with T-parity`

ΔM_q can be used to test viability of the model. To constrain and test the model in detail $\Delta M_s/\Delta M_d$ and $\Delta\Gamma_q$.

Lunghi and Soni, JHEP0709(2007)053; `Top Two Higgs Doublet Model`

Constraints on β_H (ratio of vev's of the two Higgs) and m_{H^+}

M. Blanke et al, JHEP0903(2009)001; `Warped Extra Dimensional Models`

Constraints on the KK mass scale: anarchic approach seems implausible, generally $M_{KK} > 20TeV$ but can be as low as $M_{KK} \simeq 3TeV$ (moderate fine tunning).

3. B_0 mixing beyond the SM

Some examples:

W. Altmannshofer et al, 0909.1333; `SUSY flavor models`

Identify useful flavour observables ($S_{\psi\phi}$, $B_s \to \mu^+\mu^-$, ...) to exclude some SUSY models and/or distinguish them from LHT and RS models. Updated analysis of bound on flavor violating terms in the SUSY soft sector.

A. Soni et al, 1002.0595; `SM with four generations`

$m_{t'} \sim 400 - 600$ GeV, $|V^*_{t'b} V_{t's}| = (0.05 - 1.4) \times 10^{-2}$, ...

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* Only quenched calculation available **Becirevic et al**, JHEP **04** (2002) 025

* Straightforward extension of previous calculations
  $\to$ **FNAL/MILC**: work in progress

4. D_0 mixing beyond the SM

SM short-distance description alone can not successfully describe D^0 mixing.

Neither short-distance nor long-distance SM predictions can be calculated accurately.

SM contribution of the order of experiment and dominated by long-distance effects.

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\# SM short-distance description alone can not successfully describe D^0 mixing.

\# Neither short-distance nor long-distance SM predictions can be calculated accurately.

\# SM contribution of the order of experiment and dominated by long-distance effects.

What can we calculate on the lattice?

× * Long distance: Current lattice techniques are inefficient for calculating non-local operators

√ * Short distance: High precision calculation on the lattice

** Same effective hamiltonian as for $\Delta B = 2$ processes.

** Comparison with experiment can exclude large regions of parameters in many models, constraining BSM building.

E. Golowich, J. Hewett, S. Pakvasa and A. Petrov, PRD 76 (2007)

4. D_0 mixing beyond the SM

** A consistent unquenched determination of all matrix elements involved, free of the uncontrolled uncertainties associated to quenching is needed

Latest SM calculations (**quenched**): **L. Lellouch, C.-J. D Lin** Phys.Rev.D64 (2001); **Huey-Wen Lin et al**, Phys.Rev.D74 (2006)

Latest BSM calculation (**quenched**): **R. Gupta et al.**, Phys.Rev.D55 (1997)

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** Work in progress: (goal: 10% errors) **FNAL/MILC**

5. Future prospects and goals

Reduction of errors for $f_{B_q}\sqrt{B_{B_q}}$ and ξ

$\longrightarrow$ high precision tests of the SM.

	$f_B\sqrt{B_B}$	ξ
current	6-7%	3-4%
2 years	$\sim$ 4-5%	$\sim$ 1.5-2%
5 years*	$\sim$ 2%	$\sim$ 1%

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Calculation of matrix elements needed for $\Delta\Gamma_q$ **Lenz and Nierste**, JHEP0706 (2007) 072

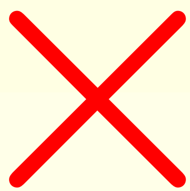
$$\left(\frac{\Delta\Gamma}{\Gamma}\right) = \left(\frac{1}{245\mathrm{MeV}}\right)^2 \left[0.170\left(f_{B_q}^2 B_{B_q}\right) + 0.059R^2\left(f_{B_q}^2 \tilde{B}_S R^2\right) - 0.044\, f_{B_q}^2\right]$$

* Useful to impose constraints on BSM building, **M. Blanke et al**, LHT

5. Future prospects and goals

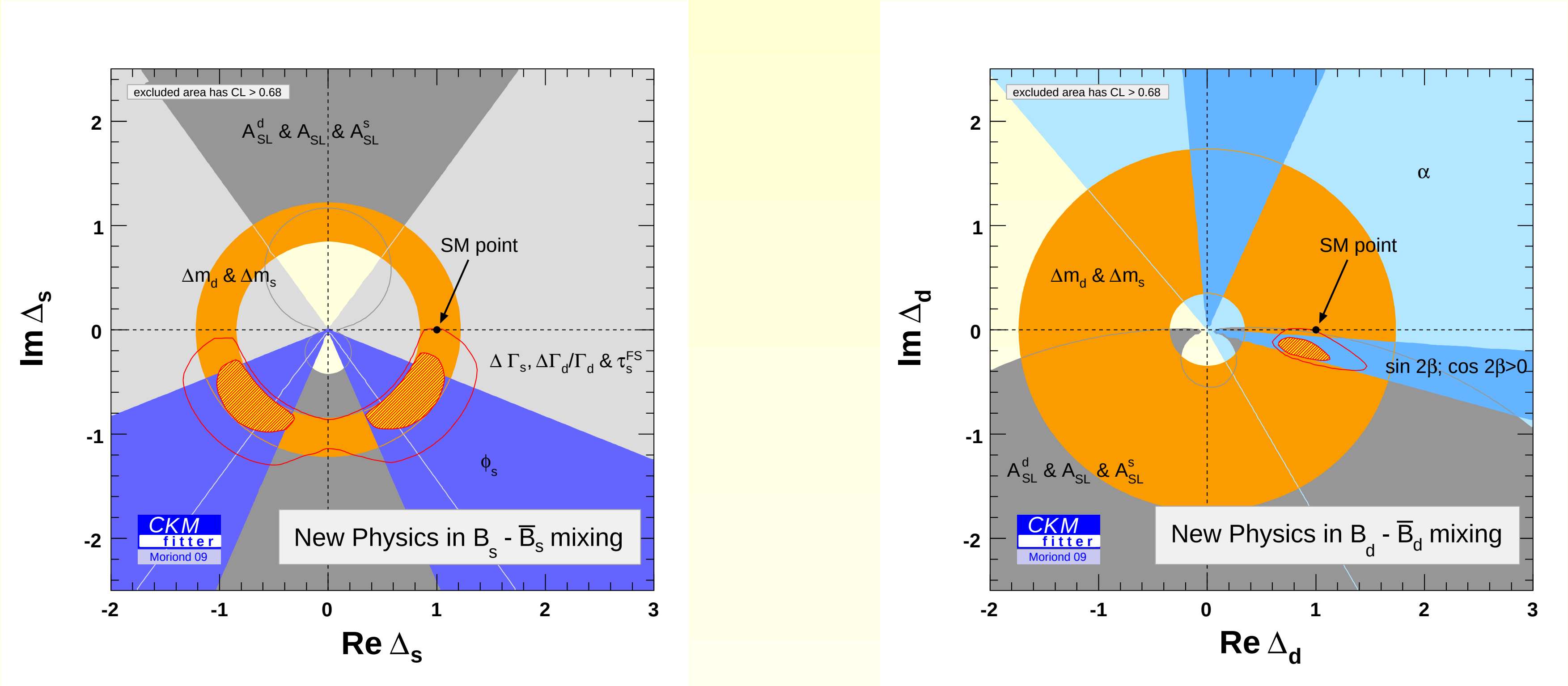
Unquenched calculation of matrix elements corresponding to operators that only appear in BSM theories for $B^0 - \bar{B}^0$ and $D^0 - \bar{D}^0$ mixing (10%).

* Work in progress by FNAL/MILC



3.1. Tension in the CKM unitarity triangle

CKMfitter: $\langle B_q^0 | M_{12}^{SM+NP} | \bar{B}_q^0 \rangle = \Delta_q^{NP} \langle B_q^0 | M_{12}^{SM} | \bar{B}_q^0 \rangle$ V. Tisserand, 0905.1572



$\boxed{1.9\sigma}$: Tension driven by the exp. measurement $(2\beta_s, \Delta\Gamma_s)$.

$\boxed{2.1\sigma}$: Tension between $sin(2\beta)$ and $|V_{ub}|_{\tau\nu}$

* Tree-level mediated decays through a Four Flavor Change ($b \longrightarrow q_i \bar{q}_j q_k$) are SM

* NP effects in oscillation parameters, weak phases, semi-leptonic asymmetries and B lifetime differences parametrized through Δ

3.2. Measurement of $Br(B_{s,d} \to \mu^+\mu^-)$

* Scalar operators in the effective hamiltonian can enhance branching ratios to current experimental bounds (example: Higgs penguin).

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* In some models there is a strong correlation between $\mathcal{B}r(B_q \to \mu^+\mu^-)$ and $\Delta M_{B_q^0}$ (example: some MSSM models.)

  ** Testing the correlation predicted by those kind of models needs a reduction of errors in the theoretical prediction for ΔM_s^{SM}
  $\rightarrow$ need smaller lattice errors for the non-perturbative inputs.

3.2. Measurement of $Br(B_{s,d} \to \mu^+\mu^-)$

Tests of MFV: In the SM model and CMFV models, the following **model independent relation** hold with $r = 1$ **Buras**, PLB566 (2003) 115

$$\frac{\mathcal{B}r(B_s \to \mu^+\mu^-)}{\mathcal{B}r(B_d \to \mu^+\mu^-)} = \frac{\hat{B}_d}{\hat{B}_s} \frac{\tau(B_s)}{\tau(B_d)} \frac{\Delta M_s}{\Delta M_d} r$$

Any deviation from this relation ($r \neq 1$) would indicate NP effects.

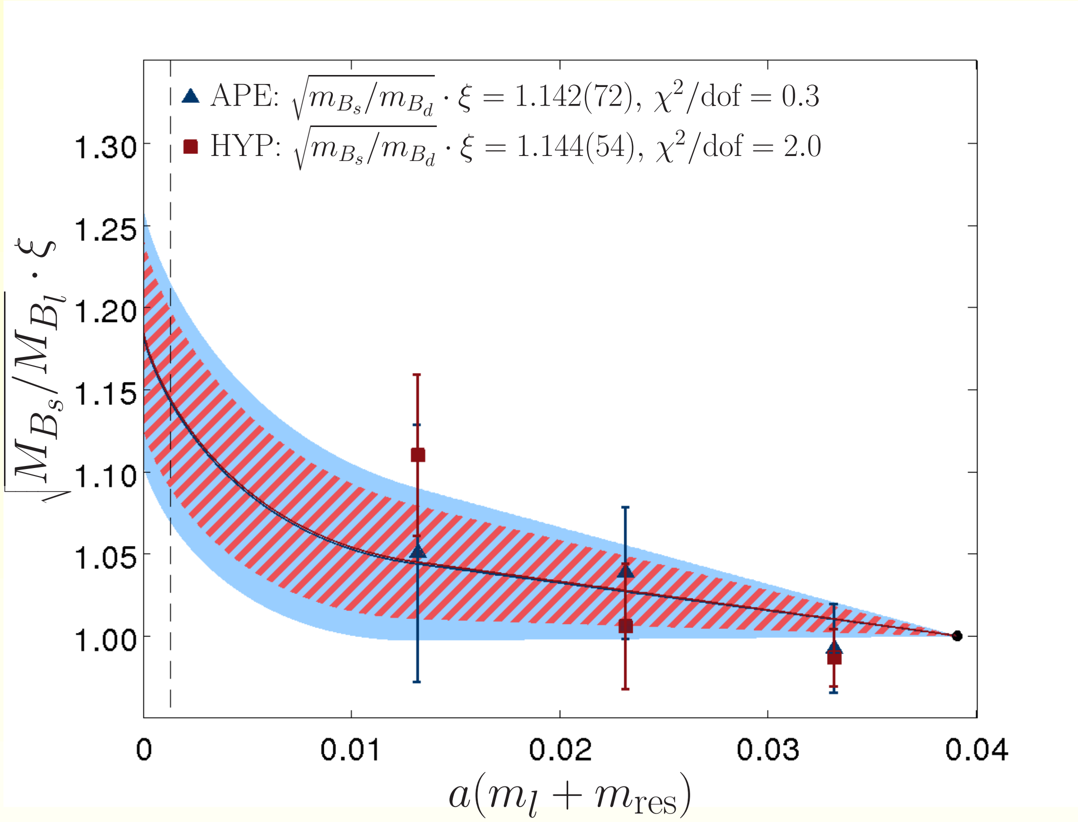
Supersymmetry, little Higgs models, extra space dimensions ...
discussed in **Buras, arXiv:0910.1032**

LHT: $0.3 \leq r \leq 1.6$, RSc: $0.6 \leq r \leq 1.3$

* **LHCb** can reach the SM level for this branching ratio.

4.2. Results: $\xi\sqrt{\frac{M_{B_s}}{M_{B_d}}}$ (exploratory)

RBC/UKQCD, arXiv:1001.2023

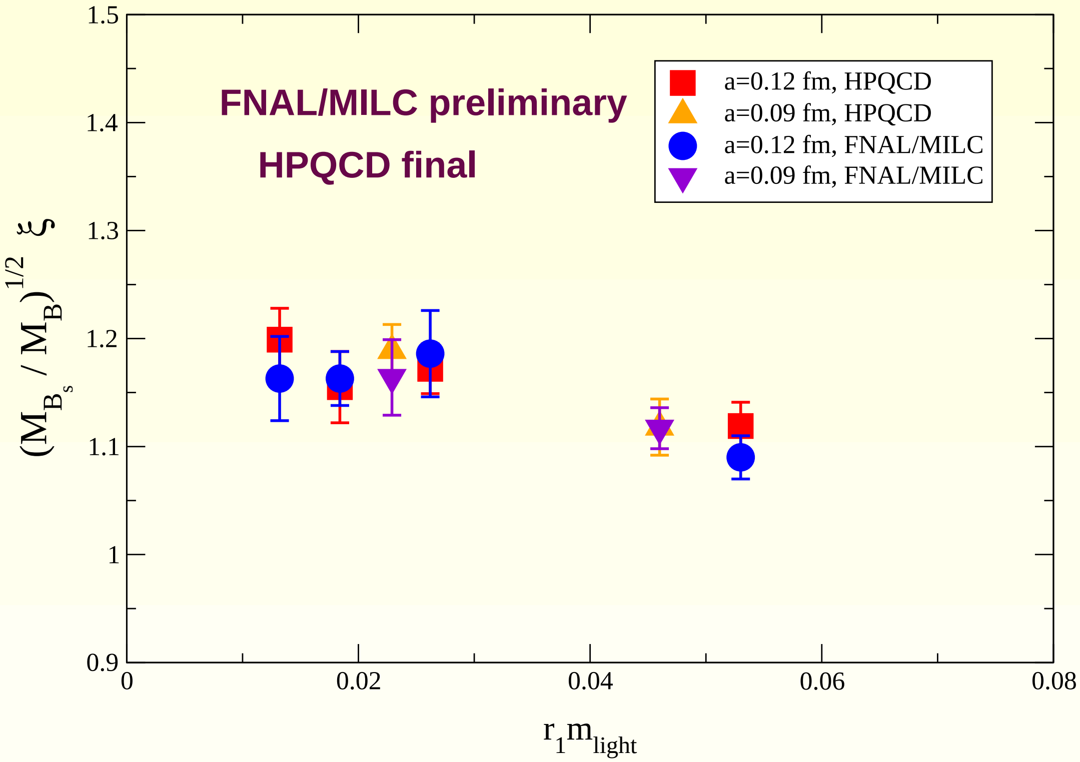


* No extrapolation to the continuum

$$\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}} = 1.13(12)$$

4.2. Results: $\xi\sqrt{\frac{M_{B_s}}{M_{B_d}}}$

\# Comparison of final **HPQCD**, PRD80 (2009) 014503 and preliminary **FNAL/MILC**, PoS LATTICE 2009, 245 (2009)



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

HPQCD	**1.258(25)(21)**
FNAL/MILC	1.205(37)(34)

$$\Longrightarrow \quad \left|\frac{V_{td}}{V_{ts}}\right| = 0.214(1)(5)$$