Phenomenology of B-meson mixing and decay constants

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1. Introduction

Flavour-violating and CP-violating processes allow us to test high energy physics

* Tests limited by precision.

* Standard Model (SM) predictions for those observables depend on a few parameters $\rightarrow$ overconstrain those parameters.

Test the SM

Already several $2-3\ \sigma$ tensions between flavour data and SM predictions

Phenomenological goals:

* Determination of fundamental parameters of the SM: quark masses, Cabibbo-Kobayashi-Maskawa matrix elements.

* Unveiling New Physics (NP) effects. **Even before non-SM particles directly produced at LHC.**

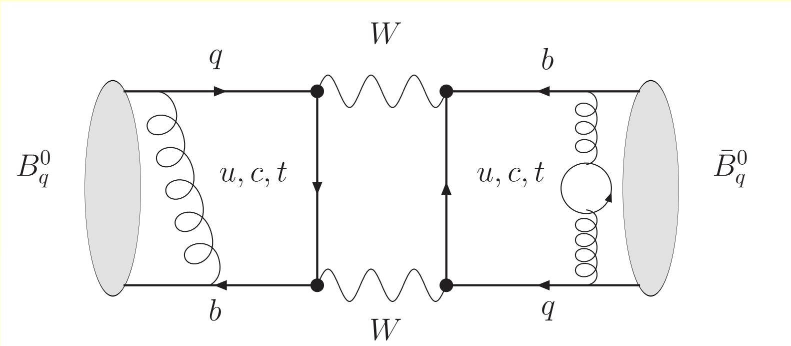
* Constraining NP models.

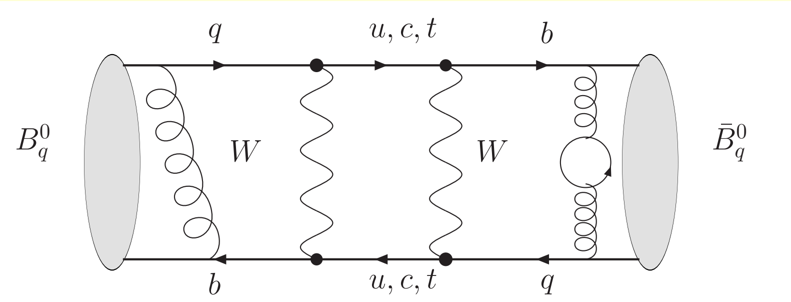
1. Introduction

Interplay flavour physics with direct searches for new physics and electroweak precision studies

$\longrightarrow$ $\boxed{\texttt{Which is the correct extension of the SM?}}$

2. Neutral B mixing





- B_0 mixing parameters determined by the off diagonal elements of the mixing matrix

$$i\frac{d}{dt}\begin{pmatrix} |B_{s/d}(t)\rangle \\ |\bar{B}_{s/d}(t)\rangle \end{pmatrix} = \left(M^{s/d} - \frac{i}{2}\Gamma^{s/d}\right)\begin{pmatrix} |B_{s/d}(t)\rangle \\ |\bar{B}_{s/d}(t)\rangle \end{pmatrix}$$

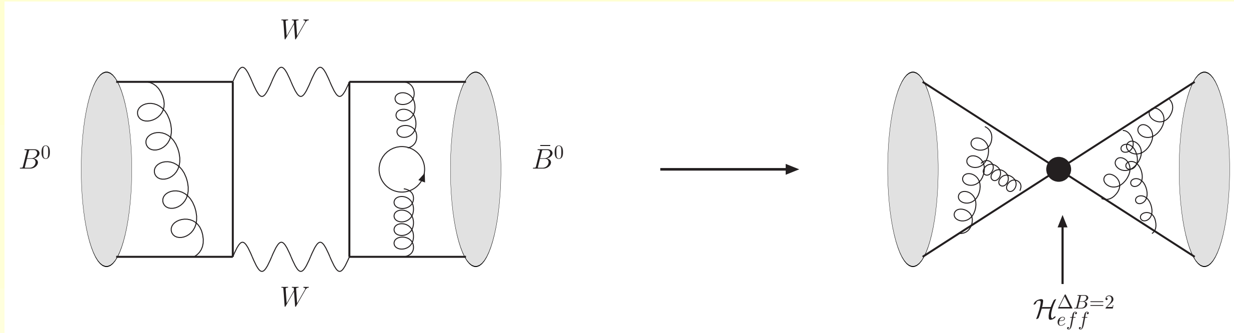
$$\Delta M_{s/d} \propto |M_{12}^{s/d}| \qquad \Delta\Gamma_{s/d} \propto |\Gamma_{12}^{s/d}|$$

New physics can significantly affect $M_{12}^{s/d} \propto \Delta M_{s/d}$

* Γ_{12} dominated by `CKM-favoured` $b \to c\bar{c}s$ tree-level decays.

2.1. Mixing parameters in the Standard Model

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

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

In terms of decay constants and bag parameters

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

* Many uncertainties in the theoretical (lattice) determination cancel totally or partially in the ratio $\Longrightarrow$ **very accurate calculation**

2.1. Mixing parameters in the Standard Model

Experimentally: Mass differences very well measured.

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

HFAG 09 **CDF**

Experimentally: Decay width differences still have large errors.

$$\left(\frac{\Delta\Gamma}{\Gamma}\right)_d = 0.010 \pm 0.037 \qquad \left(\frac{\Delta\Gamma}{\Gamma}\right)_s = 0.15 \pm 0.07$$

HFAG 09

2.2. B_0 mixing beyond the SM

Comparison of experimental measurements and theoretical predictions can constraint some BSM parameters and help to understand BSM physics.

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

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.

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

2.2. 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).

2.2. 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.

2.2. B_0 mixing beyond the SM

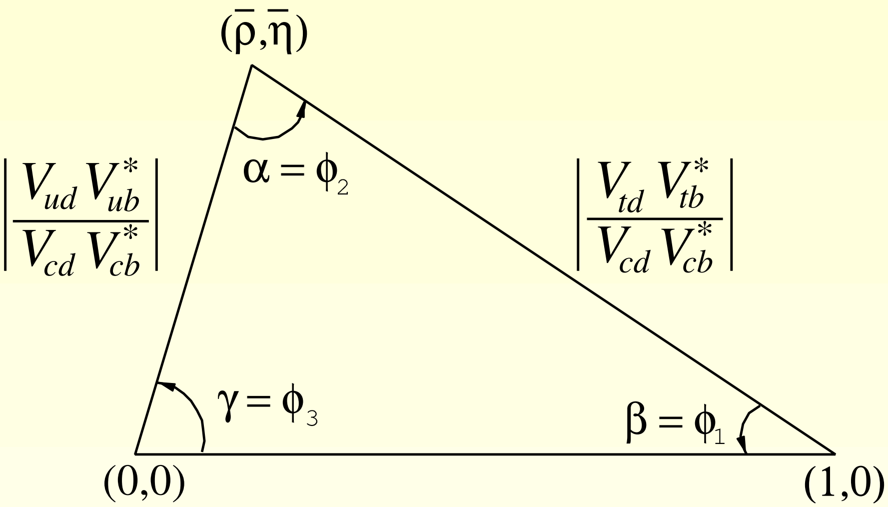
NP effects in $B^0 - \bar{B}^0$ mixing can be parametrized by

$$\langle B_q^0 | H_{eff}^q | \bar{B}_q^0 \rangle = A_q^{SM} + A_q^{NP} = C_{B_q^0} e^{2i\,\phi_{B_q^0}} A_q^{SM}$$

* The mixing phase also governs `mixing-induced CP` violation in exclusive channels like $B_s \to J/\psi\phi$.

2.3. Unitarity Triangle analyses

For $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$ → **CKM unitarity triangle**.



Can use the following set of parameters

$$\lambda \equiv |V_{us}|,\ |V_{cb}|,\ R_t \text{ and } \beta$$

where

$$R_t \equiv \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| = \sqrt{(1-\bar\rho)^2 + \bar\eta^2} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right|, \qquad V_{td} = |V_{td}|e^{-i\beta}$$

Within the SM and CMFV

$$R_t = \xi \frac{1}{\lambda}\sqrt{\frac{m_{B_s^0}}{m_{B_d^0}}}\sqrt{\frac{\Delta M_{B_d^0}}{\Delta M_{B_s^0}}} \qquad sin\, 2\beta = S_{\psi K_S}$$

2.3. Unitarity Triangle analyses

* Mixing-induced CP asymmetry

$$\mathcal{A}_{\psi K_S} = \frac{\Gamma(\bar{B}^0_d(t)\to\psi K_S)-\Gamma(B^0_d(t)\to\psi K_S)}{\Gamma(\bar{B}^0_d(t)\to\psi K_S)+\Gamma(B^0_d(t)\to\psi K_S)} \simeq S_{\psi K_S}\, sin(\Delta M\, t) - C_{\psi K_S}\, cos(\Delta M\, t)$$

In the presence of NP those relations are modified by

$$R_t = \xi \frac{1}{\lambda}\sqrt{\frac{m_{B^0_s}}{m_{B^0_d}}}\sqrt{\frac{\Delta M_{B^0_d}}{\Delta M_{B^0_s}}}\boxed{\sqrt{\frac{C_{B^0_s}}{C_{B^0_d}}}} \qquad sin\,(2\beta + 2\,\boxed{\phi_{B^0_d}}) = S_{\psi K_S}$$

with the NP parameters defined as

$$\langle B^0_q|H^q_{eff}|\bar{B}^0_q\rangle = A^{SM}_q + A^{NP}_q = \boxed{C_{B^0_q}}\, e^{2i\,\boxed{\phi_{B^0_q}}} A^{SM}_q$$

3. Hints of New Physics in the Flavour Sector

Most observations in the flavour sector are consistent with SM expectations but ...

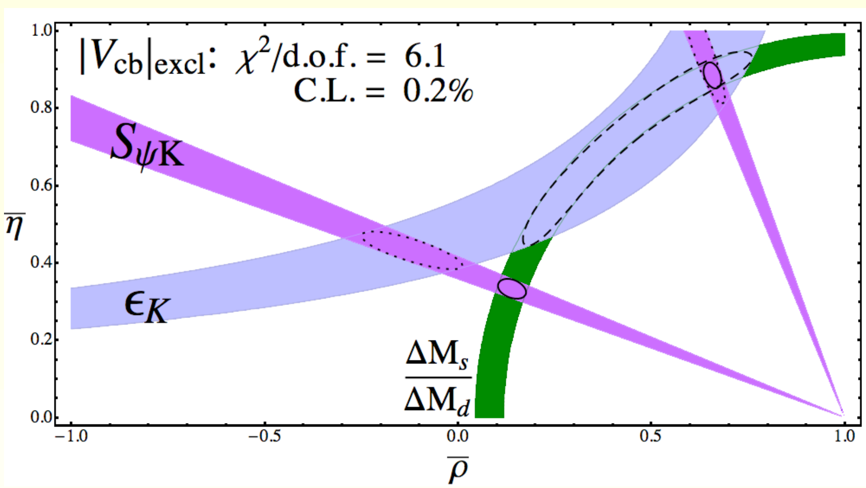
... there are currently several $2 - 3\sigma$ tensions that may indicate New Physics.

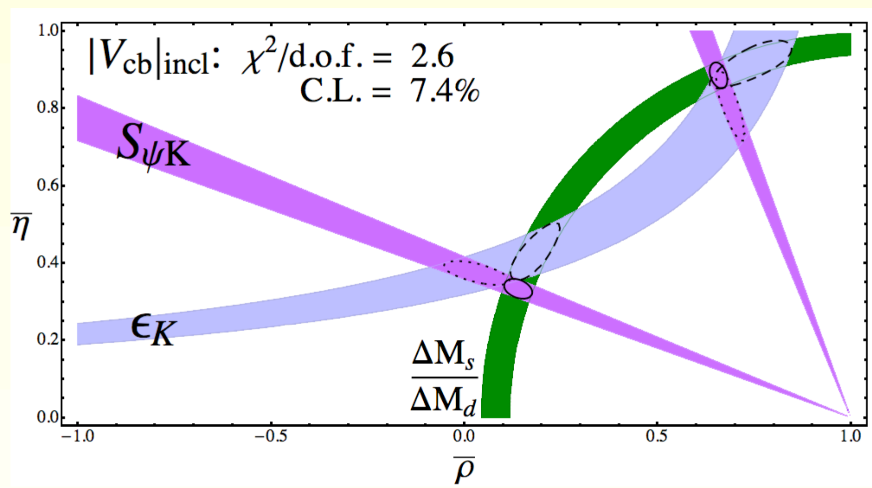
3.1. Tension in the CKM unitarity triangle

UT fit: Global fit to the CKM unitarity triangle using experimental and theoretical constraints.

$\boxed{2-3\sigma \text{ tension in the CKM description}}$

* 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, arXiv:0910.2928

** Degree of tension depend on $|V_{cb}|$

$$|V_{cb}^{exc.}(latt.\,average)| = (38.6 \pm 1.2) \times 10^{-3} \qquad |V_{cb}^{inc.}| = (41.6 \pm 0.6) \times 10^{-3}$$

3.1. Tension in the CKM unitarity triangle

$\boxed{2-3\sigma \text{ tension in the CKM description}}$

** Independent of (controversial) $|V_{ub}|$

$$|V_{ub}^{exc.}(latt.\,average)| = (3.42 \pm 0.37) \times 10^{-3} \qquad |V_{ub}^{inc.}| = (4. - 4.5) \times 10^{-3}$$

* If we assume no NP at tree-level at current precision
  $\rightarrow$ tension can be a sign of NP either in K^0 or B^0 mixing.

  ** Current data prefer NP in K^0 mixing.

* Constraints from ε_K, $\Delta M_d/\Delta M_s$, and $|V_{ub}/V_{cb}|$ limited by lattice errors for $|V_{cb}|_{excl.}$, ξ, and $|V_{ub}|_{excl.}$

3.1. Tension in the CKM unitarity triangle

E. Lunghi and A. Soni, arXiv:0912.0002: UT analysis without using semileptonic decays

* $|V_{ub}|$ and $|V_{cb}|$ inclusive and exclusive disagree by $\approx 2\sigma$
$\rightarrow$ eliminate the $|V_{cb}|$ constraint from the analysis in favor of

$$f_{B_s^0}\sqrt{\hat{B}_{B_s^0}} \text{ or } \mathcal{B}r(B \to \tau\nu) \times f_{B_d}^{-2}$$

* 1.8σ tension observed. Slight preference for NP in B_d^0 mixing.

* Improvement in $f_{B_s^0}\sqrt{\hat{B}_{B_s^0}}$ and f_B will help a lot to identify the origin of the tension.

3.2. Mixing in the B_s system: the $S_{J/\psi\phi}$ asymmetry

Lenz and Nierste, JHEP **06**, 072 (2007)

\# Study the mixing-induced CP asymmetry.

$$\mathcal{A}_{J/\psi\phi} = \frac{\Gamma(\bar{B}^0_s(t)\rightarrow J/\psi\phi) - \Gamma(B^0_s(t)\rightarrow J/\psi\phi)}{\Gamma(\bar{B}^0_s(t)\rightarrow J/\psi\phi) + \Gamma(B^0_s(t)\rightarrow J/\psi\phi)} = S_{J/\psi\phi}\, sin(\Delta M\, t) - C_{J/\psi\phi}\, cos(\Delta M\, t)$$

\# B_s mixing phase β_s responsible for this asymmetry in the SM

$$\langle B_s | H^{SM}_{eff} | \bar{B}_s \rangle = A^{SM}_s e^{-2i\beta_s}$$

$$(S_{J/\psi\phi})_{SM} = sin(2|\beta_s|) = sin\left(2\left|\arg\left(\frac{-V_{ts}V^*_{tb}}{V_{cs}V_{cb}}\right)\right|\right) \approx 0.04$$

\# World average based on flavour-tagged analyses of $B_s \rightarrow J/\psi\phi$ decays in **CDF** and **DØ** is 2.2σ different from SM predictions

$$(S_{J/\psi\phi})_{exper.} \approx 0.81^{+0.12}_{-0.32}$$

* Expect improvements of experimental measurements of $S_{J/\psi\phi}$ asymmetry in **CDF, DØ, LHCb, ATLAS** and **CMS**.

3.2. Mixing in the B_s system: the $S_{J/\psi\phi}$ asymmetry

* Possible new phases in B_s decays would lead to correlated effects between $\Delta B = 2$ processes and $b \to s$ decays

$$(S_{J/\psi\phi}) = sin(2|\beta_s| - 2\phi_{B_s^0})$$

$\longrightarrow$ need to improve measurements of CP-violation in $b \to s$ penguin decays.

Enhancement of the asymmetry can be found in RSc and GMSSM. Also supersymmetric flavour models with significant right-handed curr.

Buras, arXiv:0910.1032

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

One of the main targets of flavour physics is measuring the highly suppressed decay $Br(B_s \to \mu^+\mu^-)$.

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

* The SM prediction for these branching ratios is given by

$$\mathcal{B}r(B_q \to \mu^+\mu^-)_{SM} = \tau_{B_q} \frac{G_F^2}{\pi} \eta_Y^2 \left(\frac{\alpha}{4\pi \sin^2\theta_W} \right)^2 f_{B_q}^2 m_\mu^2 m_{B_q} |V_{tb}^* V_{tq}|^2 Y^2(x_t)$$

** Uncertainty dominated by error in f_{B_q}: 9-11%

* The most precise way of extracting these branching ratios is from (in the SM)

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

** Uncertainty dominated by error in $\hat{B}_q$: 5-9%

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

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

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

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

** An error of 0.14 in $\mathcal{B}r(B_s \to \mu^+\mu^-)$ is coming from $\hat{B}$ uncertainty.

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

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

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

3.3. 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

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

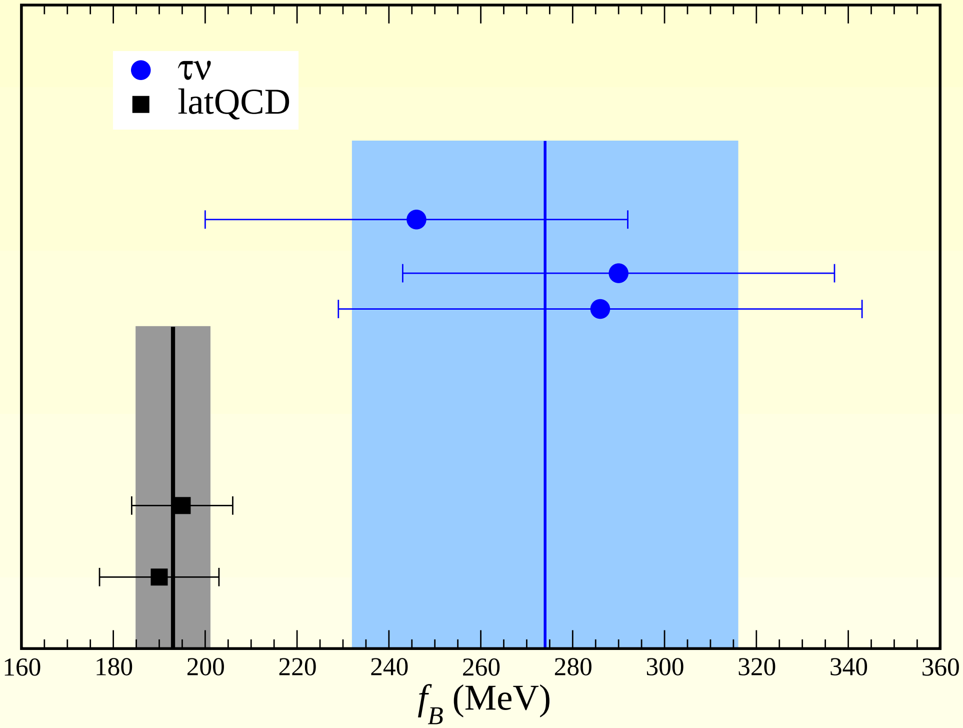
Any deviation from this relation ($r \neq 1$) would indicate NP effects.

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

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

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

3.4. $B \to \tau\nu$ leptonic decay



1.9σ discrepancy between f_B values from lattice (HPQCD and FNAL/MILC) and experiment (using V_{ub} from lattice QCD)

A. Kronfeld, PHENO '09

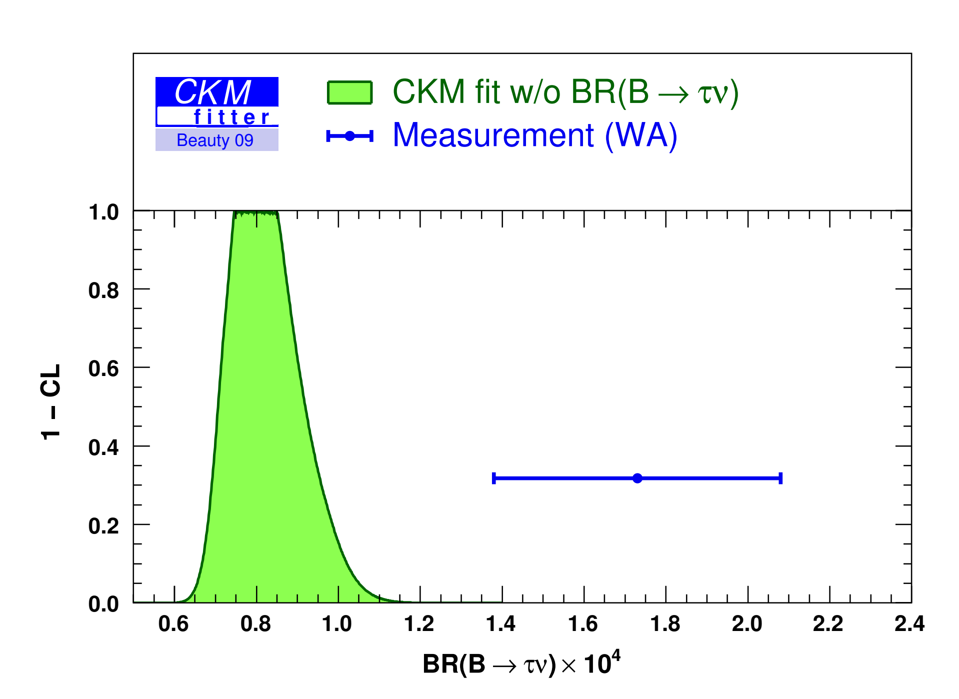
$$\mathcal{B}r(B^+ \to \tau^+\nu)_{SM} = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_{B^+}^2}\right)^2 f_{B^+}^2 |V_{ub}|^2 \tau_B^+$$

* **Differences:** Fermion discretization describing b quarks.

HPQCD 09, PRD80(2009)014503: NRQCD.

FNAL/MILC 09, PoS LATTICE2008 278 (2008): Fermilab formulation.

3.4. $B \to \tau\nu$ leptonic decay



2.4σ discrepancy between SM prediction for $Br(B \to \tau\nu)$ from UT fit (**relies on several lattice inputs** $f_{B^0_{d,s}}$, $\hat{B}_{B^0_{d,s}}$, $f_{B^0_{d,s}}\sqrt{\hat{B}_{B^0_{d,s}}}$) and experimental average **BaBar, Belle**

CKM fitter, Moriond 09, Beauty 09

$$\mathcal{B}r(B^+ \to \tau^+\nu)_{exp} = (1.73 \pm 0.35) \times 10^{-4}$$

$$\mathcal{B}r(B^+ \to \tau^+\nu)_{CKM\,fit} = (0.80^{+0.16}_{-0.11}) \times 10^{-4}$$

Alternative extraction of SM prediction

$$\frac{\mathcal{B}r(B^+ \to \tau^+\nu)_{SM}}{\Delta M_{B^0_d}} = \frac{3\pi}{4\eta_B S_0(x_t)\hat{B}^0_d}\frac{m_\tau^2}{m_W^2}\left(1 - \frac{m_\tau^2}{m_{B^+}^2}\right)^2 \left|\frac{V_{ub}}{V_{td}}\right|^2 \tau_B^+$$

with $\left|\frac{V_{ub}}{V_{td}}\right| = \left(\frac{1}{1-\lambda^2}\right)^2 \frac{1+R_t^2-2R_t cos\beta}{R_t^2}$

$$\mathcal{B}r(B^+ \to \tau^+\nu)_{SM} = (0.80 \pm 0.12) \times 10^{-4}$$

3.4. $B \to \tau\nu$ leptonic decay

Discrepancy can be due to charged Higgs, but not a natural explanation. Could increase or decrease SM $\mathcal{B}r$.

* Most MSSM scenarios would lead to a suppression of the branching fraction.

* Example: Limits in the 2HDM $\tan\beta - m_{H+}$ plane

$$(m_{H+}/\tan\beta > 3.3\ \mathrm{GeV})$$

Reducing experimental errors will be difficult at LHCb. Good prospects for a super-B factory

4. Lattice calculation of B^0 mixing parameters and decay constants

\# **Hints of discrepancies** between SM expectations and some flavour observables (see, for example, **A. Buras**, talk at EPS-HEP 2009 or **R. Van de Water**, plenary talk at Lattice 2009)

These analyses depend on several theoretical inputs including:

$f_{B_q^0}\sqrt{\hat{B}_{B_q^0}}$, $f_{B_q^0}$, and the SU(3) breaking mixing parameter ξ:

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

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

4.1. Some details of the lattice formulations and simulations

HPQCD, PRD80 (2009) 014503

Unquenched: Fully incorporate vacuum polarization effects

MILC $N_f^{sea} = 2 + 1$

u,d,s **Asqtad** action: improved staggered quarks $\Longrightarrow$ errors $\mathcal{O}(a^2\alpha_s)$, $\mathcal{O}(a^4)$

- * good chiral properties
- * accessible dynamical simulations

b **NRQCD**: `Non-relativistic QCD` improved through $\mathcal{O}(1/M^2)$, $\mathcal{O}(a^2)$ and leading relativistic $\mathcal{O}(1/M^3)$

- * Simpler and `faster algorithms` to calculate b `propagator`

Improved gluon action

- * For further reduction of discretization errors

4.1. Some details of the lattice formulations and simulations: Parameters of the simulation

\# Lattice spacing: Two different values $a \simeq 0.12\ fm, 0.09\ fm$.
Extracted from Υ 2S-1S splitting.

\# Bottom mass: Fixed to its physical value from Υ mass.

\# Light masses: We work with full QCD points ($m_{valence} = m_{sea}$).

* Strange mass: Very close to its physical value (from Kaon masses).
* up, down masses: six different values ($m_\pi^{min.} \simeq 230\mathrm{MeV}$)

$\rightarrow$ $\boxed{\text{chiral regime}}$

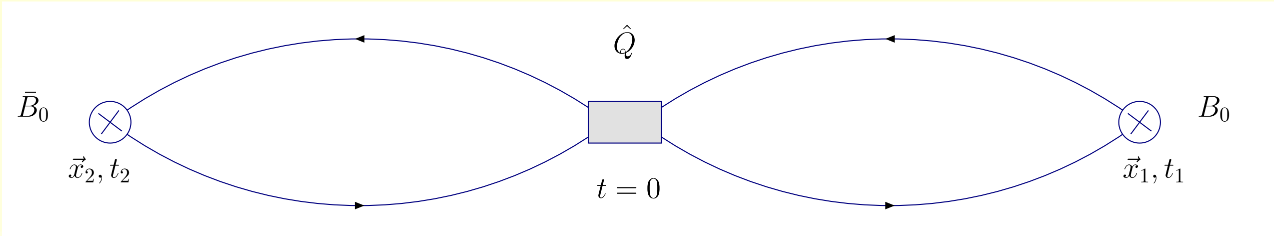
\# Renormalization and matching to the continuum: One-loop.

$$< O_1 >^{\overline{MS}} \propto (1 + \rho_{LL}\alpha_s) < O_1 >^{latt.} + \rho_{LS}\alpha_s < O_2 >^{latt}$$

with $O_1 = \left[\bar{b}\gamma_\mu(1-\gamma_5)q\right]\left[\bar{b}\gamma_\mu(1-\gamma_5)q\right]$ and $O_2 = \left[\bar{b}(1-\gamma_5)q\right]\left[\bar{b}(1-\gamma_5)q\right]$.

4.1. Some details of the lattice formulations and simulations

Need 3-point (for any $\hat{Q} = Q_X, Q_X^{1j}$) and 2-point correlators



$$C^{(4f)}(t_1, t_2) = \sum_{\vec{x}_1, \vec{x}_2} \langle 0 | \Phi_{\bar{B}_q}(\vec{x}_1, t_1) \left[\hat{Q} \right] (0) \Phi^{\dagger}_{\bar{B}_q}(\vec{x}_2, -t_2) | 0 \rangle$$

$$C^{(B)}(t) = \sum_{\vec{x}} \langle 0 | \Phi_{\bar{B}_q}(\vec{x}, t) \Phi^{\dagger}_{\bar{B}_q}(\vec{0}, 0) | 0 \rangle$$

- $\Phi_{\bar{B}_q}(\vec{x}, t) = \bar{b}(\vec{x}, t)\gamma_5 q(\vec{x}, t)$ is an interpolating operator for the B_q^0 meson.

  * Use smearing functions ϕ to increase overlap with the ground state

$$\Phi_{\bar{B}_q}(t) = \bar{b}(\vec{x}_2, t)\gamma_5 \phi(|\vec{x}_2 - \vec{x}_1|) q(\vec{x}_1, t)$$

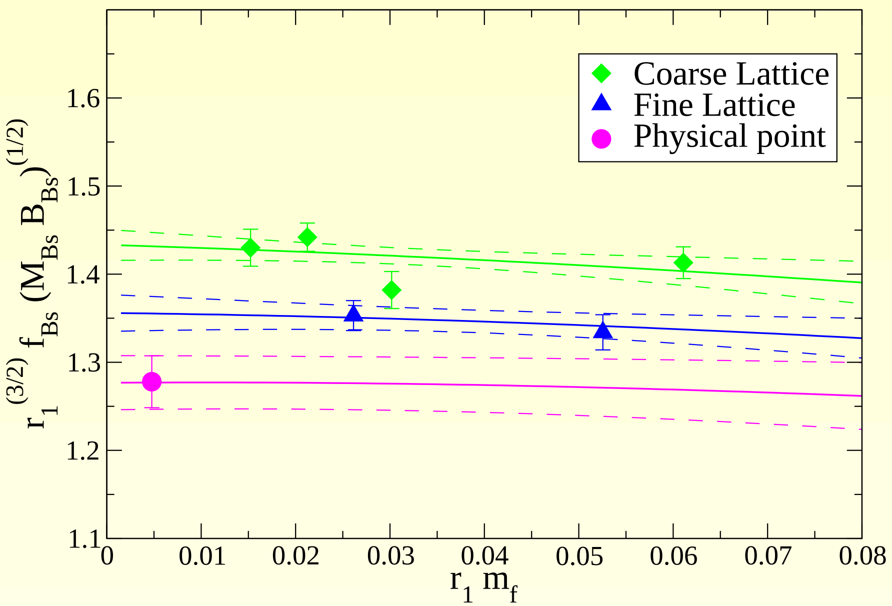
4.1. Some details of the lattice formulations and simulations

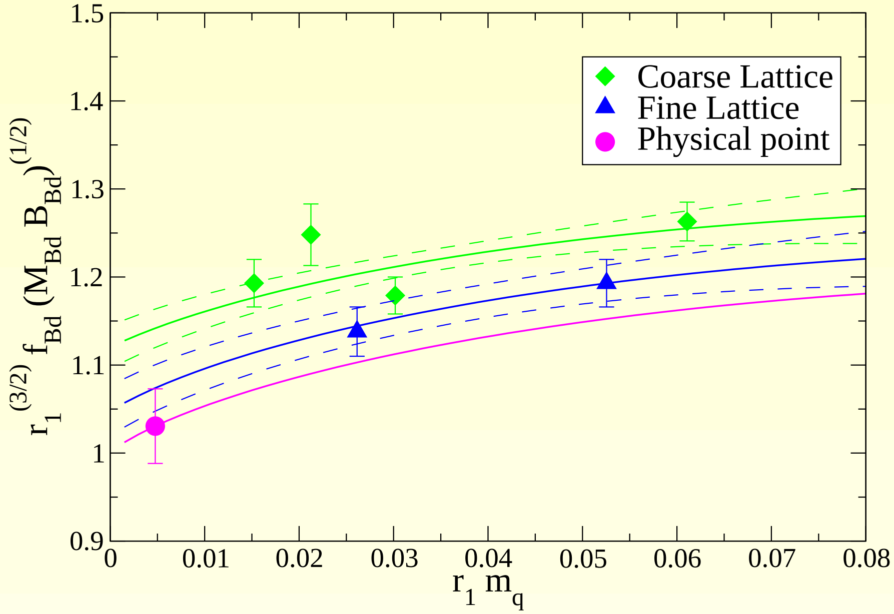
We carried out **simultaneous** fits of the 3-point and 2-point correlators using Bayesian statistics to the forms $\rightarrow$ extract $< O_X >$ and $f_{B_{s(d)}}$.

$$C^{(4f)}(t_1, t_2) \quad = \quad \sum_{j,k=0}^{N_{exp}-1} A_{jk}\, \zeta_i\, \zeta_j\, (-1)^{j \cdot t_1}\, (-1)^{k \cdot t_2}\, e^{-E_B^{(j)}(t_1-1)}\, e^{-E_B^{(k)}(t_2-1)}$$

$$C^B(t) \quad = \quad \sum_{j=0}^{N_{exp}-1} \zeta_j\, (-1)^{j \cdot t}\, e^{-E_B^{(j)}(t-1)}$$

4.2. Results: $f_{B_q}\sqrt{M_{B_q}B_{B_q}}$





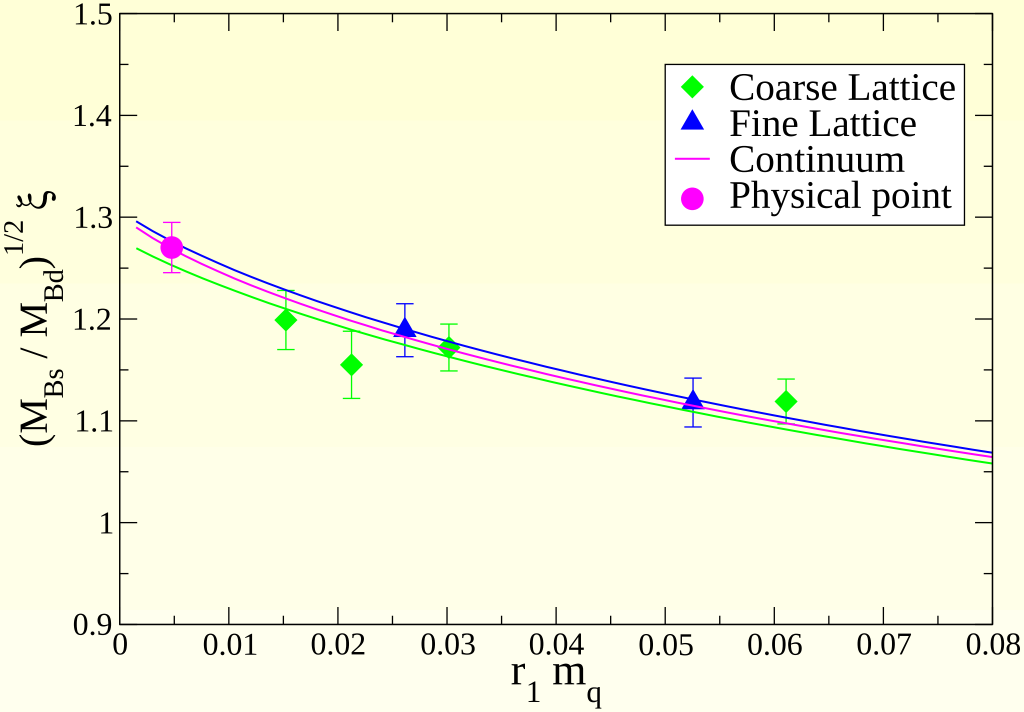
$$\boxed{f_{B_s}\sqrt{\hat{B}_{B_s}} = 266(6)(17)\mathrm{MeV}}$$

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

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

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



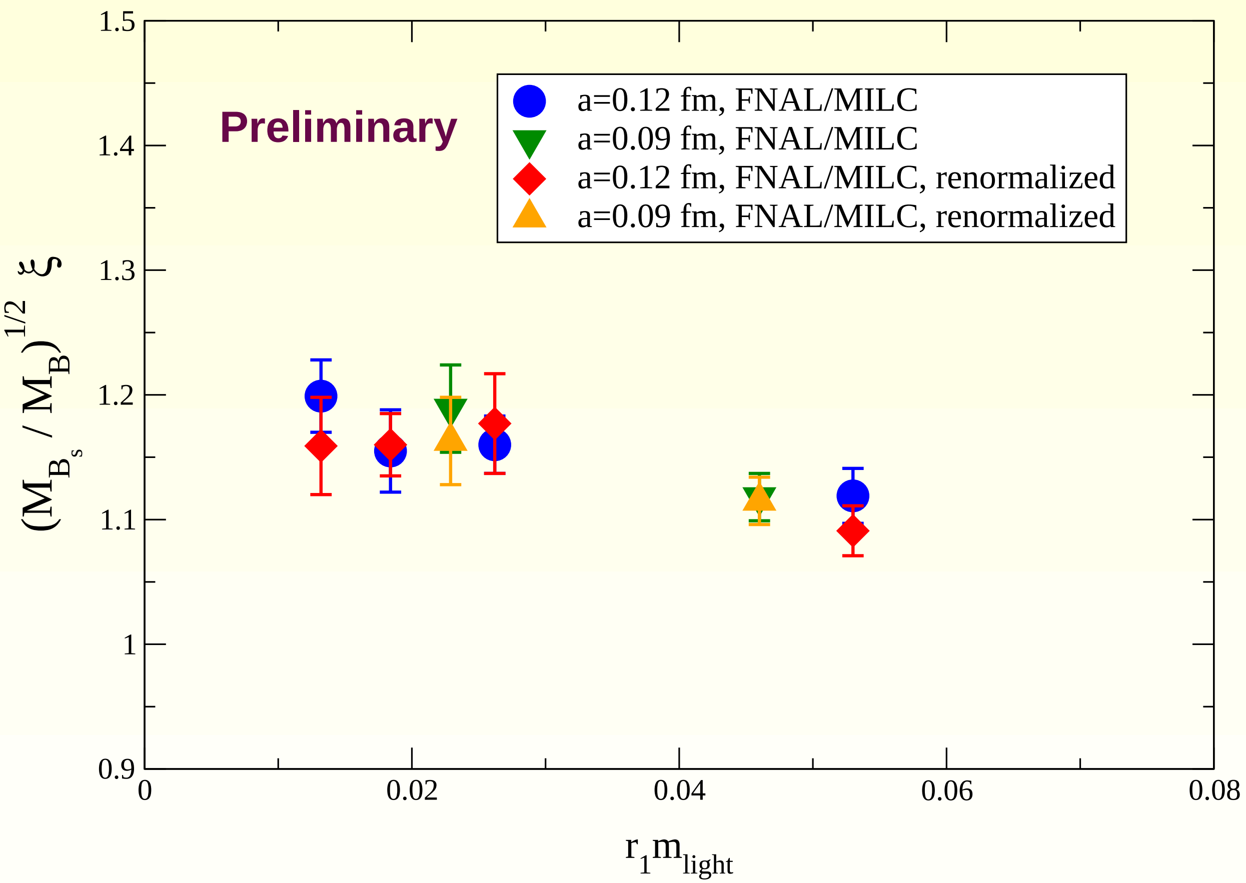
$$\xi = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}} = 1.258(25)(21) \quad \Longrightarrow \quad \boxed{\left|\frac{V_{td}}{V_{ts}}\right| = 0.214(1)(5)}$$

* Previous value used in UT fits and another analyses (HPQCD/JLQCD):

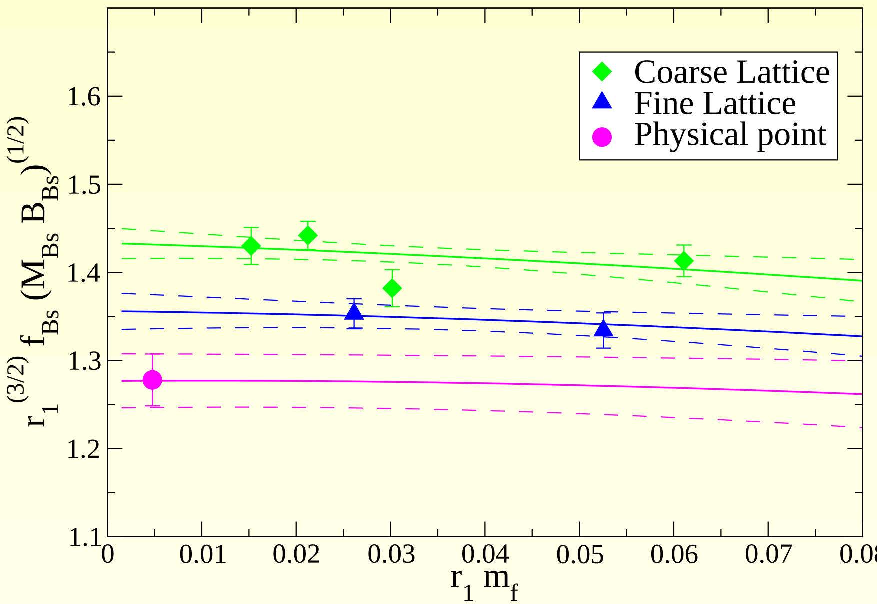
$$\xi = 1.20 \pm 0.06$$

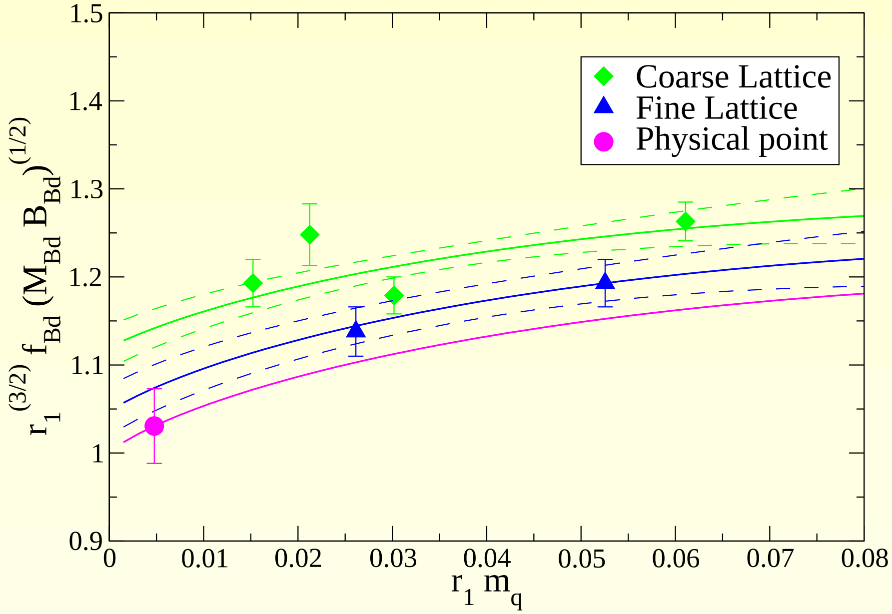
4.2. Results: $\xi\sqrt{\frac{M_{B_s}}{M_{B_d}}}$

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



4.2. Results: $f_{B_q}\sqrt{M_{B_q}}$





$$\boxed{f_{B_s} = 231(15)MeV} \qquad \boxed{f_{B_d} = 190(13)MeV}$$

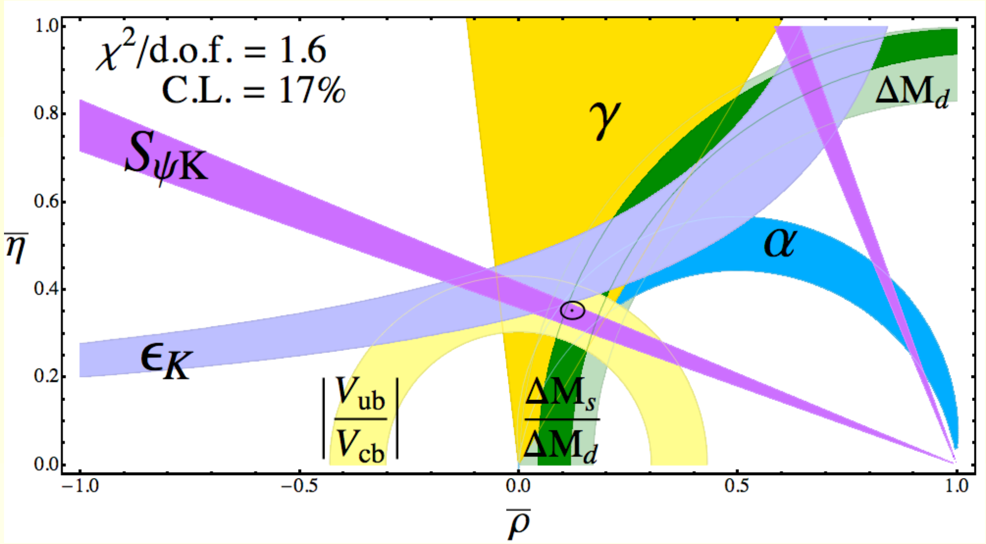
$$\frac{f_{B_s}}{f_{B_d}} = 1.226(26)$$

* To be compared with preliminary **FNAL/MILC**, PoS LATTICE 2008, 278 (2008)

$$\boxed{f_{B_s} = 243(11)MeV} \qquad \boxed{f_{B_d} = 195(11)MeV}$$

5. Impact of up-to-date lattice averages on UT.

Laiho, Lunghi & Van de Water, arXiv:0910.2928



* $\boxed{2-3\sigma \text{ tension}}$

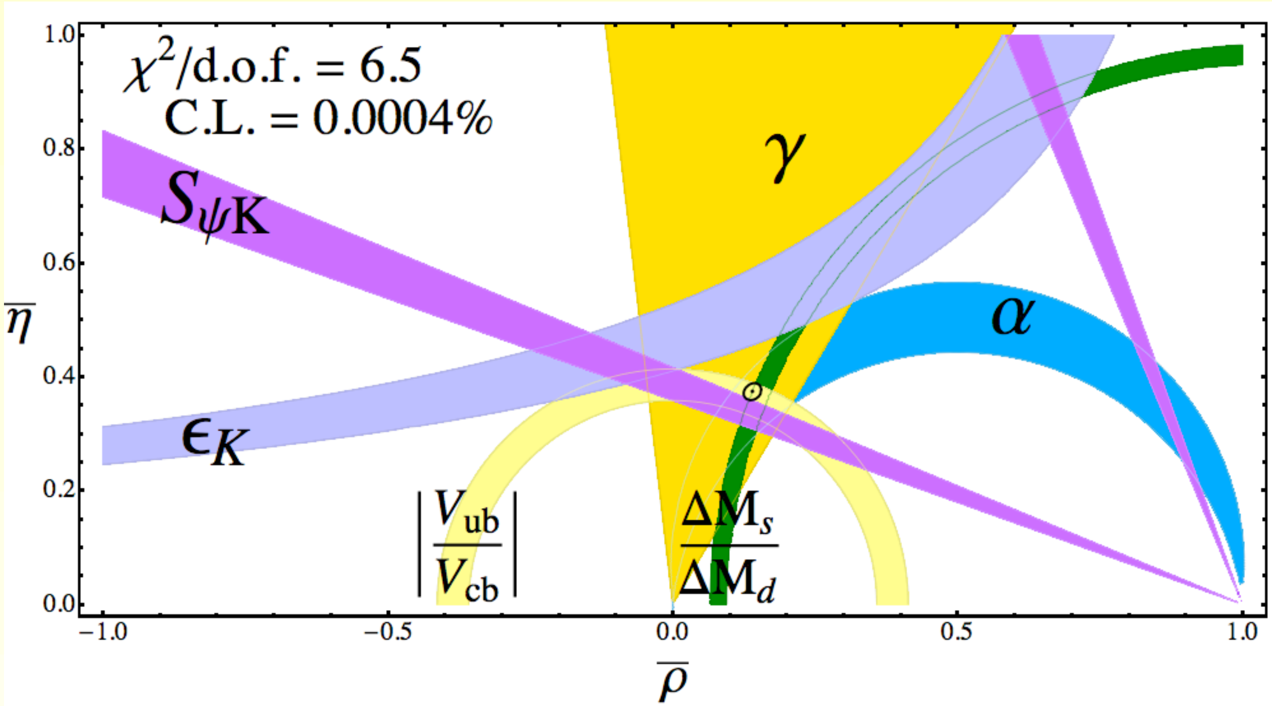
* If we assume no NP at tree-level at current precision
→ tension can be a sign of NP either in K^0 or B^0 mixing.

** Current data prefer NP in K^0 mixing.

* Constraints from ε_K, $\Delta M_d/\Delta M_s$, and $|V_{ub}/V_{cb}|$ limited by lattice errors for $|V_{cb}|_{excl.}$, ξ, and $|V_{ub}|_{excl.}$

5. Impact of up-to-date lattice averages on UT

When lattice QCD uncertainties become smaller



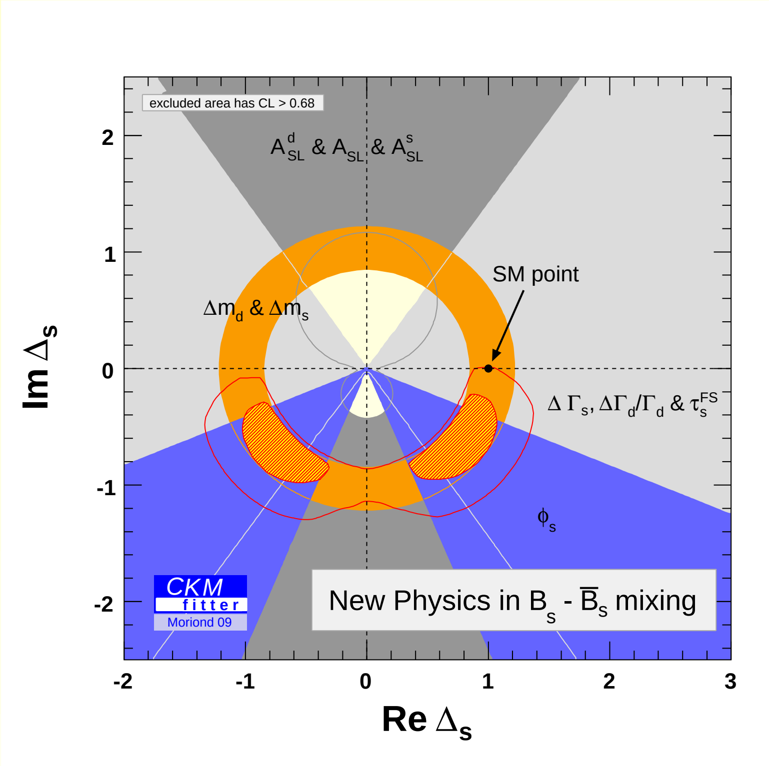
* Lattice QCD errors are reduced to 1% keeping central values.

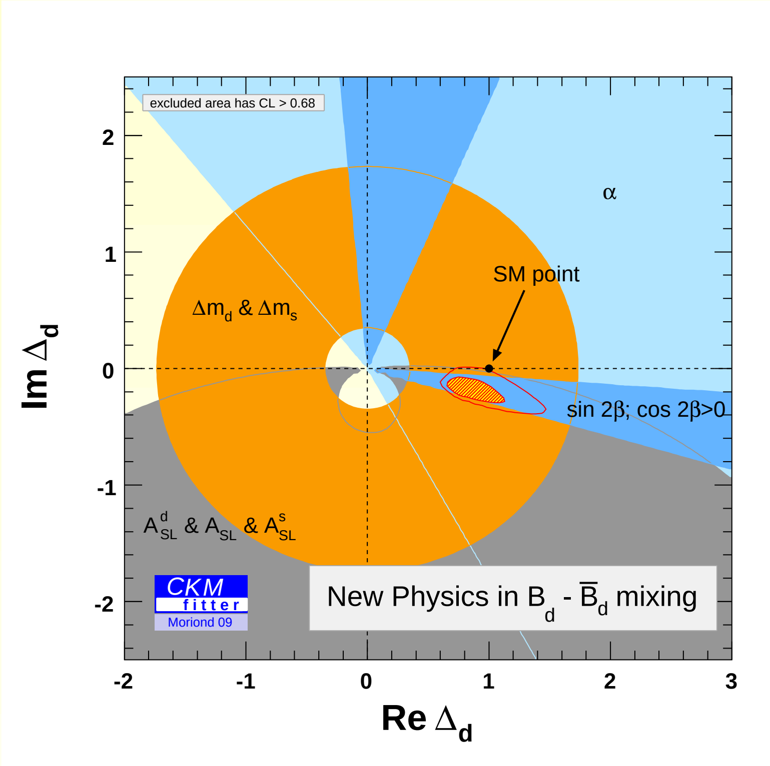
* Use only exclusive $|V_{cb}|$.

Could see NP with a high significance!

5.1. Hints of New Physics in neutral B mixing

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

6. Future plans for lattice analyses of B^0 mixing and decay constants

Reduction of errors for f_{B_q}, $f_{B_q}\sqrt{B_{B_q}}$, ξ: smaller lattice spacing ($a = 0.06,\ 0.045$), more statistics, improved renormalization methods, improved actions, better fitting and smearing methods ...

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

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

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

* Allows a theoretical prediction for

$$(A^s_{SL})_{SM} \equiv \frac{\Gamma(\bar{B}^0_s \to l^+X) - \Gamma(B^0_s \to l^-X)}{\Gamma(\bar{B}^0_s \to l^+X) + \Gamma(B^0_s \to l^-X)} = \mathrm{Im}\left(\frac{\Gamma^s_{12}}{M^s_{12}}\right)$$

$(A^s_{SL})_{SM} \sim 10^{-5}$ **Lenz and Nierste**, JHEP **06** (2007) 072

6. Future plans for lattice analyses of B^0 mixing and decay constants

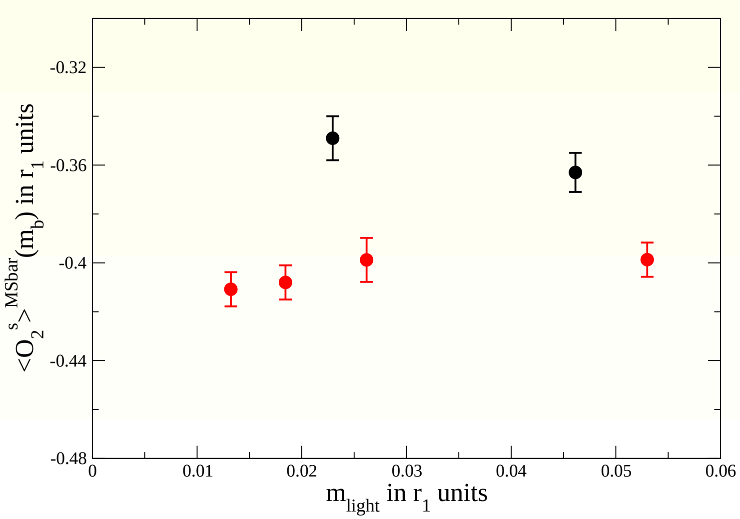
to compare with the value of the asymmetry in the presence of NP

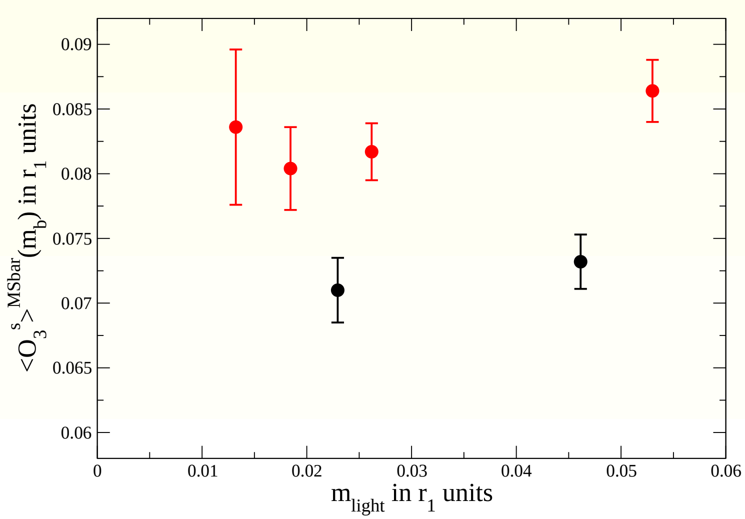
Z. Ligeti, M. Papucci and G. Perez, PRL **97** (2006) 101801

$$A^s_{SL} = -\frac{\Delta\Gamma_s}{\Delta M_s}\frac{S_{\psi\phi}}{C_{B^0_s}} \simeq -(2.6 \pm 1.0) \times 10^{-3}\frac{S_{\psi\phi}}{C_{B^0_s}}$$

** Even $S_{\psi\phi} \simeq 0.1$ would lead to an order of magnitude enhancement relative to SM.

* Some preliminary results **HPQCD**





6. Future plans for lattice analyses of B^0 mixing and decay constants

Calculation of matrix elements corresponding to operators that only appear in BSM theories.

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

* Straightforward extension of previous calculation
  $\rightarrow$ **FNAL/MILC**: work in progress

Analysis of short-distance contributions to $D^0 - \bar{D}^0$ mixing

* Also provides strong constraints on BSM physics **E. Golowich, J. Hewett, S. Pakvasa and A. Petrov**, PRD 76 (2007)

* **FNAL/MILC** already working on extending their calculation to $D^0 - \bar{D}^0$ mixing

7. More conclusions

High precision measurements/calculations of low energy observables allow to indirectly probe very short-distances.

* Test SM and BSM theories

* Learning about the flavour structure of the new physics.

Error budget for B^0 mixing parameters

source of error	$f_{B_s}\sqrt{\hat{B}_{B_s}}$	$f_{B_d}\sqrt{\hat{B}_{B_d}}$	ξ
stat. + chiral extrap.	2.3	4.1	2.0
residual a^2 extrap. uncertainty	3.0	2.0	0.3
$r_1^{3/2}$ uncertainty	2.3	2.3	—
$g_{B^* B\pi}$ uncertainty	1.0	1.0	1.0
m_s and m_b tuning	1.5	1.0	1.0
operator matching	4.0	4.0	0.7
relativistic corr.	2.5	2.5	0.4
Total	6.7	7.1	2.6

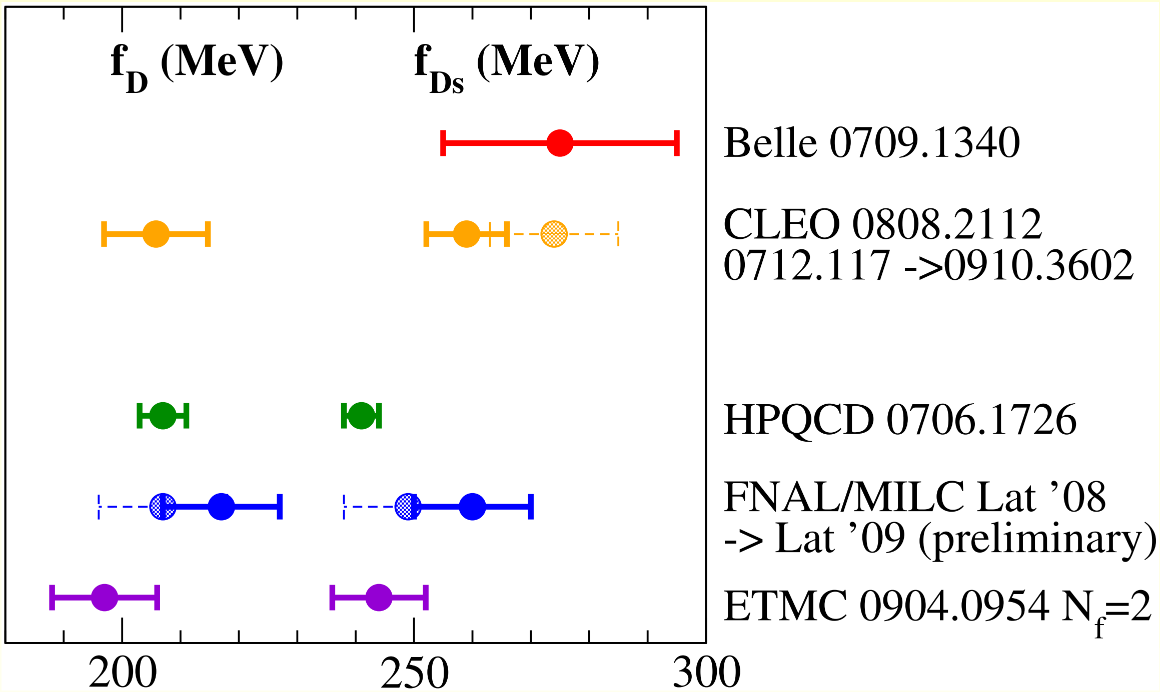
5.2.2 Value of the UT angle $\sin(2\beta)$

The value of the UT angle $\sin(2\beta)$ obtained from $b \to q\bar{q}s$ penguin decays is lower than from tree-level $b \to c\bar{c}s$ (expected to be less sensitive to NP).

* For example, $\sin(2\beta)_{B\to\phi K^0}$ is 1.3σ from tree-level average (including, for example, $\sin(2\beta)_{\Psi K_S}$).
* This tension can not be resolved at LHCb (only some clues from $B_S \to \phi\phi$). Need Super Belle at KEK and Super-B machine at Frascati.
* Need better measurements of $b \to q\bar{q}s$ penguin decays.

5.2.4 The f_{D_s} puzzle

R. van de Water (Lattice09)



2008 3.6σ discrepancy in f_{D_s} between HPQCD and experiment. Agreement in f_K, f_π, f_D, m_D, m_{D_s}, $\frac{2m_{D_s}-m_{\eta_c}}{2m_D-m_{\eta_c}}$.

2009 $\boxed{2.3\sigma \text{ discrepancy}}$

lattice(average)-exper.(average)

New CLEO, BaBar and FNAL/MILC results.

* Leptonic decays occurs at tree level $\rightarrow$ disagreement difficult to accommodate in BSM.

* Models with charged Higgs or leptoquarks can work Kronfeld and Dobrescu $\rightarrow$ signal in $D \rightarrow K(\pi)l\nu$.

5.2.4 The f_{D_s} puzzle

* Lattice calculations.

  ** HPQCD has redetermined the scale that converts lattice quantities to physical units r_1. New value will make their value lower by $1 - 1.5\sigma \rightarrow$ disagreement under 2σ. Update soon.

  ** Include effects of sea charm since errors are around 1%

  ** Need lattice results with different fermion formulations.

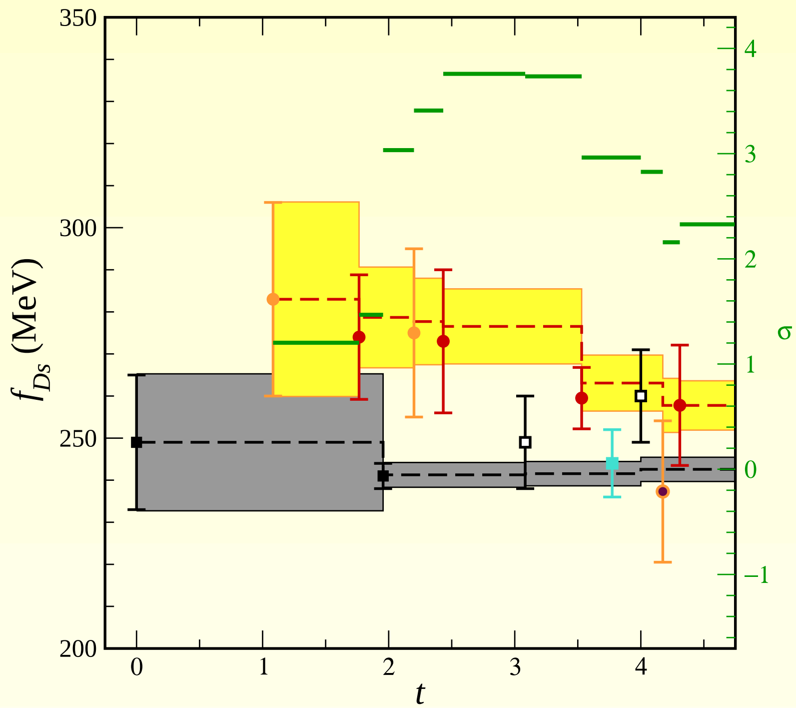
* Some experimental issues.

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

  ** Better understanding of radiative corrections.

* BES-III should measure f_D and f_{D_s} with $\sim 1\%$ precision.

5.2.4 The f_{D_s} puzzle



Andreas Kronfeld

5.2.6 Clarification of μ anomalous magnetic moment, $(g-2)_\mu$ anomaly

The measured $(g-2)_e$ is in excellent agreement with SM but measured $(g-2)_\mu$ is significantly larger (3.1σ) than predicted.

* Hadronic (non-perturbative) contributions to $(g-2)_\mu$ make the comparison of data and theory a bit problematic.

* New experiments are being designed to reduce the experimental error by a factor of 5.

* Need theoretical improvements too. Goal in light-by-light contribution: a 20-40% reduction of the error.

* Example: Confirmation of exper. measurements $\rightarrow$ favour the MSSM over LHT.

2.2. B_0 mixing beyond the SM

Some examples:

Isidori, Nir and Perez, Ann. Rev. Nucl. Part. Sci 2010:

Bounds on representative dimension-six $\Delta F = 2$ operators.

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}$$

Operator	Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	
$(\bar{c}_L \gamma^\mu u_L)^2$	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	8.8×10^{-7}	2.6×10^{-7}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_L \gamma^\mu s_L)^2$	6.0×10^{-5}	6.0×10^{-5}	Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	1.6×10^{-5}	1.6×10^{-5}	Δm_{B_s}

Effects of NP in some flavour observables involving neutral meson mixing parameters

(**Altmannshofer** et al., arXiv:0909.1333 and **Buras**, EPS-HEP 2009)

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★

AC = SUSY flavour model with right-handed currents

RVV2 = SUSY flavour model with right-handed currents

AKM = SUSY flavour model with right-handed currents

δLL = SUSY flavour model with only left-handed currents

FBMSSM = flavour blind MSSM

LHT = Little Higgs models with T-parity.

RS = Randall Sundrum models