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SFB Flavour Workshop

The potential of B_s physics and supersymmetry in flavour physics

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Outline

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1. The potential of B_s physics

I first discuss measurements which provide novel information unaccessible with B^+ and B_d physics. Then I turn to phenomena where measurements with B_s mesons could complement studies with B^+ and B_d mesons.

$\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing

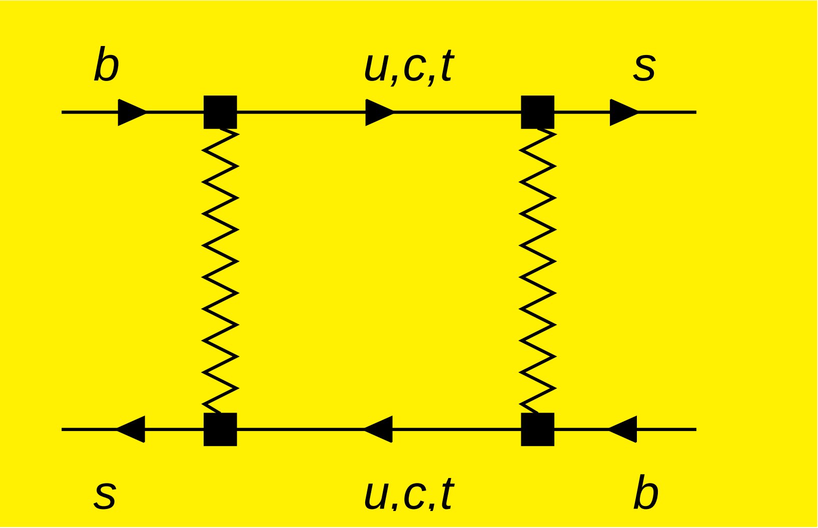
$\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing is a $\Delta B = 2$, $\Delta S = 2$ process and has no counterpart in B_d or B^+ physics. It is more sensitive to generic new physics in $b \longrightarrow s$ transitions than $\Delta B = 1$ decays. Once the $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ oscillation frequency is measured, it will e.g. strengthen bounds on the off-diagonal 2-3 elements of the squark mass matrices in supersymmetry.

3 physical quantities in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing, involving the off-diagonal elements of mass and decay matrices:

$$|M_{12}|, \quad |\Gamma_{12}|, \quad \phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

Relation of Δm and $\Delta\Gamma$ to $|M_{12}|$, $|\Gamma_{12}|$ and ϕ:

$$\Delta m = M_H - M_L \simeq 2|M_{12}|, \qquad \Delta\Gamma = \Gamma_L - \Gamma_H \simeq 2|\Gamma_{12}|\cos\phi$$



Standard Model:

M_{12} stems from the dispersive (real) part of the box diagram, internal $(\bar{t}, t)$.

Γ_{12} stems from the absorpive (imaginary) part of the box diagram, internal $(\bar{c}, c)$.

(u's are negligible).

New physics can change $|M_{12}|$ and $\arg M_{12}$.

M_{12} is computed in the most popular versions of the MSSM. There are even computations of hadronic matrix elements, which may appear in addition to $\langle\, \overline{B}_s \,|\overline{b}s_{V-A}\, \overline{b}s_{V-A}|\, B_s \,\rangle$.

In the near future (Tevatron Run-II data) the only way to access the phase of M_{12} is through $\Delta\Gamma$. At the Tevatron $\Delta\Gamma$ is inferred from lifetime measurement in the CP-even mode $\overset{(-)}{B}_s \to (J/\psi\phi)_{L=0}$ and the CP-odd mode $\overset{(-)}{B}_s \to (J/\psi\phi)_{L=1}$.

In the presence of new physics this measurement really determines

$$\Delta\Gamma'_{\rm CP} \equiv \Delta\Gamma \,\cos\phi \;=\; \Delta\Gamma_{\rm SM}\, \cos^2\phi$$

$\Rightarrow$ theory progress on $\Delta\Gamma_{\rm SM}$ desirable.

NLO QCD corrections are known. Unlike in Δm there are corrections of order Λ_{QCD}/m_b in $\Delta\Gamma$ and they are large, of order 30%.

July 2004: CDF reported the measurement

$$\frac{\Delta\Gamma}{\Gamma_s} = 0.71^{+0.24}_{-0.28} \pm 0.01 \qquad \text{constrained with } \Gamma_d = \Gamma_s,$$

$$\frac{\Delta\Gamma}{\Gamma_s} = 0.65^{+0.25}_{-0.33} \pm 0.01 \qquad \text{unconstrained,}$$

which is 2.0 σ or 1.5 σ above the central value of the theory prediction.

July 2005: DØ reported the measurement

$$\frac{\Delta\Gamma}{\Gamma_s} = 0.24^{+0.28}_{-0.38} \qquad \text{unconstrained,}$$

$$\frac{\Delta\Gamma}{\Gamma_s} = 0.25^{+0.14}_{-0.15} \qquad \text{constrained with exp. world average for } \overline{\tau}(B_s).$$

Prediction:

$$\left(\frac{\Delta\Gamma}{\Gamma}\right)_{B_s} = \left(\frac{f_{B_s}}{210\,\mathrm{MeV}}\right)^2 \left[0.006\,B \;+\; 0.172\,B_S \;-\; 0.063\right]$$
$$= 0.12^{+0.04}_{-0.03}$$

using lattice results for hadronic parameters (Lattice 2004 average):

$$f_{B_s} \;=\; 246 \pm 16\,\mathrm{MeV}, \qquad n_f = 2 \text{ and } n_f = 2+1$$
$$B_S \;=\; 0.86 \pm 0.07\,\mathrm{MeV}, \qquad n_f = 0$$

With the MILC result (hep-ph/0311130):

$$f_{B_s} \;=\; 260 \pm 29\,\mathrm{MeV}, \qquad n_f = 2+1$$
$$\Rightarrow \left(\frac{\Delta\Gamma}{\Gamma}\right)_{B_s} = 0.14 \pm 0.05$$

$\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing is theoretically widely studied, there is demand for progress in $\Delta\Gamma$, namely lattice QCD results for the operators which occur at order Λ_{QCD}/m_b (and then possibly also perturbative $\alpha_s\,\Lambda_{QCD}/m_b$ terms).

Isospin-violating $b \longrightarrow s$ decays

There is currently a controversial debate on whether the Standard Model can explain the isospin-breaking amplitudes in $B \longrightarrow K\pi$ decays ("enhanced electroweak penguins"). The extraction requires non-trivial QCD input using e.g. SU(3)$_F$ or QCDF.

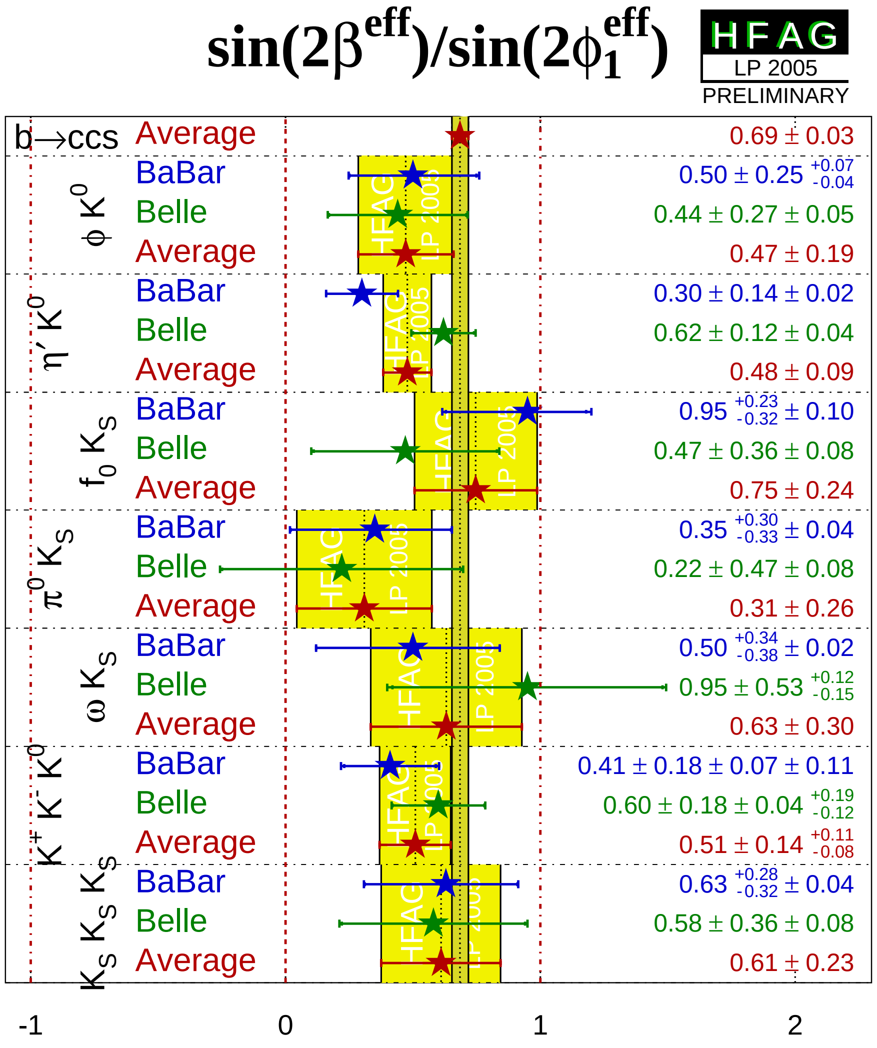
Unlike in B^+ and B_d decays there are pure $\Delta I = 1$ (I is the isospin) $b \longrightarrow s$ decays of the B_s:

$$B_s \longrightarrow \phi\pi^0, \qquad\qquad B_s \longrightarrow \phi\rho^0.$$

The branching fraction of the second decay can be measured at CDF. QCD penguins drop out, tree diagrams are CKM-suppressed.

$\Rightarrow$ calculation of branching fraction with QCDF desirable

CP violation in $b \longrightarrow s$ penguin decays



Naive averages:

Winter 2005:

$\sin(\beta)^{\rm eff} = 0.43 \pm 0.07$,

see right plot:

LP 2005:

$\sin(\beta)^{\rm eff} = 0.51 \pm 0.06$,

well below

$\sin(2\beta)^{b\to c\bar{c}s} = 0.69 \pm 0.03$.

QCD Factorization finds small corrections to $\sin(2\beta_{\rm eff}) - \sin(2\beta)$, which are positive.

Note: To measure a mixing-induced CP asymmetry (S_f term) in a $b \to s\bar{q}q$ decay of a B_d meson one needs a neutral Kaon in the final state, so that the

$$b(\overline{d}) \to \overline{q}qs(\overline{d}) \qquad \text{and} \qquad \overline{b}(d) \to \overline{q}q\overline{s}(d)$$

decays of B_d and $\overline{B}_d$ can interfere.

In a $\overset{(-)}{B}_s$ decay, however, one has a flavorless final state:

$$b(\overline{s}) \to \overline{q}qs(\overline{s}), \qquad \overline{b}(s) \to \overline{q}q\overline{s}(s)$$

and the needed interference occurs in any final state.

⇒ B_s physics could be the El Dorado of $b \to s\bar{q}q$ penguin physics!
More effort on B_s tagging is needed!

Meanwhile... a way out?

Consider a new CP phase σ in the $b \to s\bar{s}s$ decay. Let now $\overset{(-)}{B}_s \to f_{CP+}$ denote a $b \to s\bar{s}s$ decay into a CP-even final state, e.g. $f_{CP+} = (\phi\phi)_{L=0}$. With

$$\langle\, f_{CP+}\, | B_s \rangle \;\propto\; e^{i\sigma} \qquad \text{and} \qquad \langle\, f_{CP+}\, | \overline{B}_s \rangle \;\propto\; -e^{-i\sigma}$$

the coefficients in

$$\Gamma[f,t] \;\propto\; |\langle\, f\, | B_L \rangle|^2 e^{-\Gamma_L t} + |\langle\, f\, | B_H \rangle|^2 e^{-\Gamma_H t}$$

read:

$$|\langle\, f_{CP+}\, | B_L \rangle|^2 \;\propto\; \frac{1+\cos(\phi+2\sigma)}{2}, \qquad |\langle\, f_{CP+}\, | B_H \rangle|^2 \;\propto\; \frac{1-\cos(\phi+2\sigma)}{2}$$

$$\Gamma[f_{CP+},t] \propto \frac{1+\cos(\phi+2\sigma)}{2} e^{-\Gamma_L t} + \frac{1-\cos(\phi+2\sigma)}{2} e^{-\Gamma_H t}$$

For the Standard Model case $\phi = \sigma = 0$ only B_L can decay into f_{CP+} and the lifetime measured in e.g. $\overset{(-)}{B}_s \to (\phi\phi)_{L=0}$ determines Γ_L.

If the lifetime measured in $\overset{(-)}{B}_s \to (\phi\phi)_{L=0}$ is longer than the one measured in $\overset{(-)}{B}_s \to (J/\psi\phi)_{L=0}$, new physics in the $b \to s\bar{s}s$ decay amplitude is established through $\sigma \neq 0$, with the possibility of $\phi = 0$ or $\phi \neq 0$.

If the lifetime measured in $\overset{(-)}{B}_s \to (\phi\phi)_{L=0}$ is shorter than the one measured in $\overset{(-)}{B}_s \to (J/\psi\phi)_{L=0}$, new physics in both the $b \to s\bar{s}s$ decay amplitude and $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing is established through $\sigma \neq 0$ and $\phi \neq 0$.

SU(3)$_F$

Finally B_s decays can be combined with B_d decays to probe the SU(3)$_F$ symmetry.

2. Supersymmetry

Superpotential of the MSSM: only source of flavour-changing transitions are the Yukawa interactions as in the SM.

SUSY-breaking terms have additional sources of FCNC's: If one rotates the (s)quark superfields to a basis in which the quark mass matrices are diagonal (super-CKM basis), the squark mass matrices are nondiagonal in general.

⇒ flavour physics probes SUSY-breaking

Two widely studied versions of the MSSM:

1. Assume flavour-blind SUSY-breaking terms, Minimal Flavour Violation (MFV).
2. Allow for arbitrary, but small, off-diagonal elements of the squark mass matrices, generic MSSM.

Scenario 2 has too many parameters to study correlations in a meaningful way.

B physics and SUSY Higgses: large $\tan\beta$

MSSM: two Higgs doublets, coupling to either up- or down-type fermions, vacuum expectation values v_u and v_d with $\sqrt{v_u^2 + v_d^2} = v = 174\,\text{GeV}$.

If $\tan\beta \equiv v_u/v_d \sim 50$, then the Yukawa coupling y_b of the non-standard Higgses H^+, H^0 and A^0 and their superpartners Higgsinos, which are components of charginos and neutralinos, to b_R quarks are large: $m_b \tan\beta/v \sim 1$.

$\Rightarrow$ Large effects in b physics FCNC diagrams with $(\chi^+, \tilde{t})$ loops and tree and loop diagrams with H^+.

Motivations to study large $\tan\beta$:

1. probes bottom-top unification, i.e. upper bounds on $\tan\beta$ quantify the violation of $y_b = y_t$, implying lower bounds on couplings of Higgses in SUSY GUT's like SO(10).
2. b physics probes the portion of the $(\tan\beta, M_A)$ parameter space most relevant to Higgs searches at the Tevatron.
3. well-motivated scenario of b physics with operators with new Dirac structures, but the same flavour structure as in the SM.

Vast literature on large $\tan\beta$, but practically all assume MFV at the electroweak scale. Also extra CP-phases, which appear in the flavour-conserving piece of the MSSM, are usually neglected, although many of them are poorly constrained from EDM's. Further when certain all-order effects are resummed, the limit $M_{\text{SUSY}} \gg v$ is employed.

$\longrightarrow$ see tomorrow's talk on project C2.

MSSM with new $b \to s$ transitions

The data on $b_L \to d_L$, $s_L \to d_L$ and $b_R \to s_L$ transitions confirm the Standard Model and don't allow for $O(1)$ effects of non-MFV new physics. However, the data leave room for new contributions to $b_L \to s_L$ and in particular to $b_{L,R} \to s_R$ transitions, since $\sin(2\beta_{\text{eff}})(b \to s\bar{q}q)$ is below $\sin(2\beta) = 0.69 \pm 0.03$ by 3σ.

A natural mechanism for new effects in $b_R \to s_R$ occurs in SUSY GUT models:

SUSY-GUT's unify quarks and leptons. E.g.

$$\overline{\mathbf{5}} = \begin{pmatrix} d_R^c \\ d_R^c \\ d_R^c \\ \ell_L \\ \nu_\ell \end{pmatrix} \qquad \text{in SU(5)}$$

Experiment: ν_μ–ν_τ mixing is large. If the large mixing angle comes from the rotation of a $\overline{\mathbf{5}}$ in flavour space, a large $\tilde{s}_R$–$\tilde{b}_R$ mixing is possible.

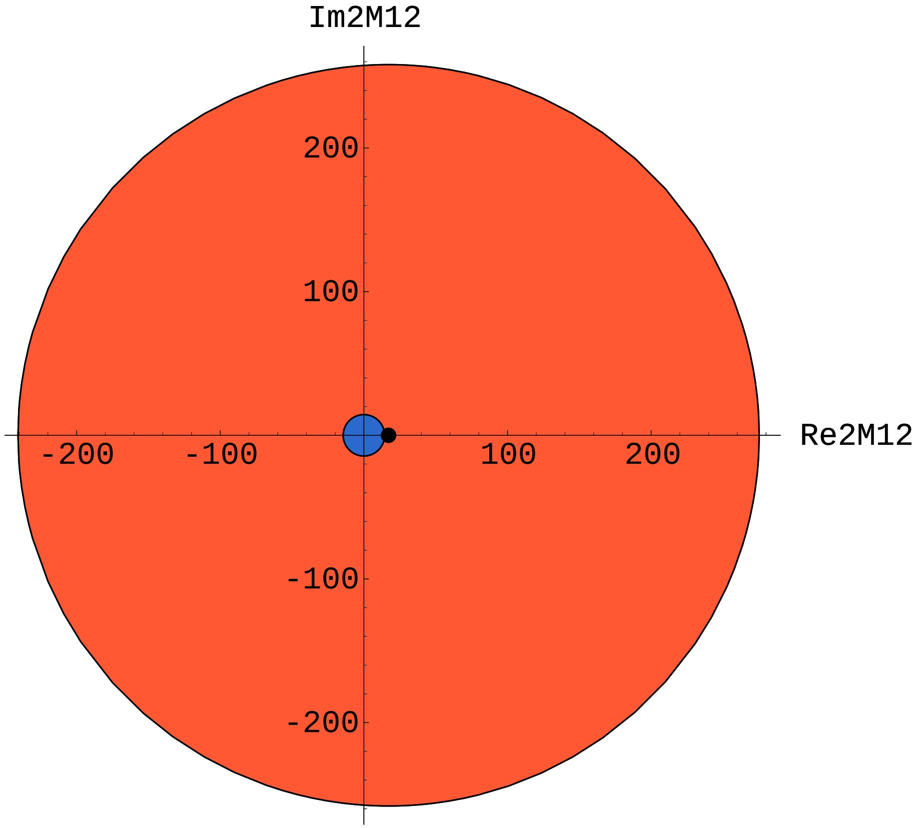
Chang, Masiero, Murayama (CMM): Model based on the breaking chain

$$\mathrm{SO}(10) \to \mathrm{SU}(5) \to \mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)$$

with SUSY-breaking terms universal near the Planck scale.

Renormalisation group effects from the top Yukawa coupling destroy the universality. Large $\tilde{s}_R$–$\tilde{b}_R$ mixing is generated when the $\overline{\mathbf{5}}$ is rotated to the mass eigenstate basis.

Effect: New operators with s_R and b_R fields, i.e. $\overline{b}_R\gamma_\mu s_R\overline{s}_R\gamma^\mu s_R$ or $\overline{b}_R s_L\overline{s}_L s_R$. Here $2|M_{12}|$ is the $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ oscillation frequency and $\phi = \arg M_{12}$ is the new CP phase in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing.



Black: Standard Model prediction, Blue: experimentally excluded,
Red: allowed in the CMM model

3. Summary

- Novel features of B_s physics compared to B^+ and B_d physics:
  1. $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing with Δm and $\Delta\Gamma$ constraining magnitude and phase of M_{12},
  2. pure $\Delta I = 1$ $b \to s$ decays like $B_s \to \phi\rho^0$.
- B_s physics has the potential to complement B_d physics by studying the mixing-induced CP asymmetry in $b \to s\overline{q}q$ decays in any hadronic final state. It may further shed light on the quality of SU(3)$_F$ breaking.
- Flavour physics is sensitive to scales well above the electroweak scale. In supersymmetry it probes the SUSY-breaking sector.
- In the region of large $\tan\beta$ it probes the SUSY Higgs sector with relations to Higgs collider physics.
- In GUT models one can link the large atmosperic neutrino mixing angle to new $b_R \to s_R$ transitions, which are least tested and may even now show hints of deviations from the SM.