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Constraining new physics with B mesons

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Outline

1. The Standard Model and beyond
2. Status of B physics
3. $\mathrm{B}-\overline{\mathrm{B}}$ mixing basics
3. Improved prediction of Γ_{12}^{s}
4. GUTs: linking quarks to neutrinos
5. Supersymmetry with large $\tan\beta$
6. A theorist's wishlist for LHCb

1. The Standard Model and beyond

Symmetry group: $SU(3) \times SU(2)_L \times U(1)_Y$

Particle content:

$$\begin{pmatrix} u_L, u_L, u_L \\ d_L, d_L, d_L \end{pmatrix} \quad \begin{pmatrix} c_L, c_L, c_L \\ s_L, s_L, s_L \end{pmatrix} \quad \begin{pmatrix} t_L, t_L, t_L \\ b_L, b_L, b_L \end{pmatrix}$$

$$u_R, u_R, u_R \qquad c_R, c_R, c_R \qquad t_R, t_R, t_R$$

$$d_R, d_R, d_R \qquad s_R, s_R, s_R \qquad b_R, b_R, b_R$$

$$\begin{pmatrix} \nu_{e,L} \\ e_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\mu,L} \\ \mu_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\tau,L} \\ \tau_L \end{pmatrix}$$

$$e_R \qquad \mu_R \qquad \tau_R$$

$$g \quad \gamma \quad W^+ \quad Z$$

$$H$$

Parameters of the Standard Model:

gauge sector:

3 coupling constants: $G = SU(3) \times SU(2) \times U(1)_Y$

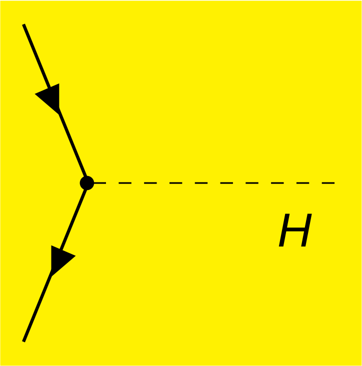
Higgs sector: 2 parameters: VEV $<H>=v$, self coupling λ

breaks $G \to SU(3) \times U(1)_{em}$ spontanously

dynamics determined from the gauge principle

Yukawa sector: Yukawa coupling of the Higgs field:

$$y_{ij}\overline{f}_i f_j (v+H)$$



$\Rightarrow$ quark mass matrix: $\quad m_{ij} = y_{ij} v$

diagonalisation $\Rightarrow$ fermion masses and CKM matrix V_{CKM}.

$V_{CKM} \neq 1$

$\Rightarrow$ couplings of the W-Bosons to quarks of different generations, flavour physics

y_{ij}, V_{CKM} complex $\Rightarrow$ CP violation

10 parameters in the quark sektor,
originally 3, but now 10 or 12 parameters in the lepton sector.

Physics beyond the Standard Model: phenomena

- Gravity. It is associated with the Planck scale $M_P = G_N^{-1/2} \approx 10^{19}$ GeV.

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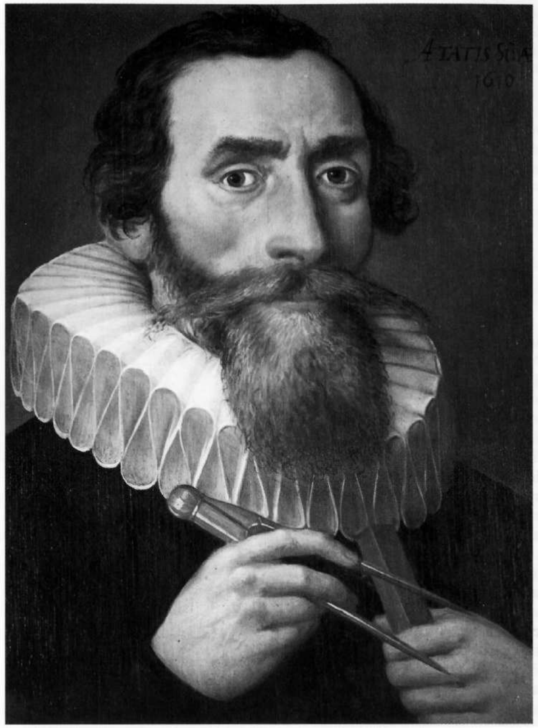
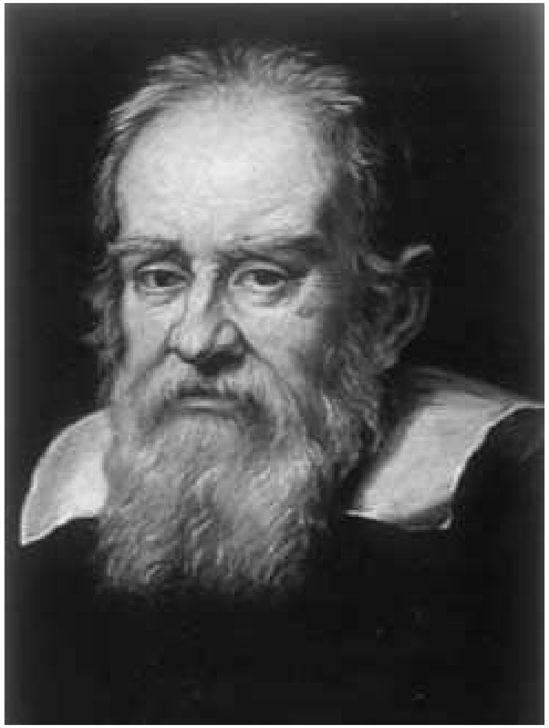
Pioneers of physics beyond the Standard Model:





Physics beyond the Standard Model: phenomena

- Gravity. It is associated with the Planck scale $M_P = G_N^{-1/2} \approx 10^{19}$ GeV.
- Dark Matter. . . not to speak of Dark Energy.
- Matter-antimatter asymmetry of the universe (too little CP violation, too heavy Higgs).
- Flavour oscillations of neutrinos unless . . .

Physics beyond the Standard Model: phenomena

- Gravity. It is associated with the Planck scale $M_P = G_N^{-1/2} \approx 10^{19}$ GeV.
- Dark Matter... not to speak of Dark Energy.
- Matter-antimatter asymmetry of the universe (too little CP violation, too heavy Higgs).
- Flavour oscillations of neutrinos unless one adds a dimension-5 term, which brings in (the inverse of) a new mass scale $M \sim 10^{15}$ GeV.

Open questions of the Standard Model

- What is the origin of the symmetry group $SU(3) \times SU(2) \times U(1)_Y$?
- Why is the hypercharge (and thereby the electric charged) quantized?
- What determines the particle content? Why are there three generations?
- What determines the quantum numbers of the particles (representation of the symmetry groups)?
- What fixes the 27 free parameters? Are (broken) symmetries governing the flavour patterns of quarks and leptons?
- Adding the dimension-5 term to accomodate lepton flavour physics yields neutrino Majorana masses of order v^2/M. What is the origin of the hierarchy $M \sim 10^{15}\,\text{GeV} \gg v = 174\,\text{GeV}$? Which fundamental dynamics is associated with M?

The Standard Model has a severe fine-tuning problem...

The Standard Model has a severe fine-tuning problem. . . the hypercharge

$$Q = T_3 + Y$$

electric charge (Q) — three-component of the weak isospin (T_3) — hypercharge (Y)

right-handed fermions: $T_3 = 0$

left-handed up-type fermions: $T_3 = 1/2$

left-handed down-type fermions: $T_3 = -1/2$

$U(1)_Y$ transformations of fermion fields: $\psi_Y \to e^{i g_1 Y \phi} \psi_Y$.

The normalisation of the coupling g_1 and the charges is arbitrary.

Y and therefore Q of any fermion could be any real number: π, $\sqrt{2}$, 1.602, $\ldots$

But: E.g. $Q(\nu) = 0$ and $Q(e) = 3Q(d)$ to all digits behind the decimal point, because neutrinos and atoms are electrically neutral.

Why is Y quantised?

Grand unified theories (GUTs) and supersymmetry

In the Standard Model the hypercharge Y is tuned from the experimentally observed electric charges.

fermions:	$\begin{pmatrix} u_L, u_L, u_L \\ d_L, d_L, d_L \end{pmatrix}$	u_R, u_R, u_R	d_R, d_R, d_R	$\begin{pmatrix} \nu_{e,L} \\ e_L \end{pmatrix}$	e_R
hypercharge Y:	$1/6$	$2/3$	$-1/3$	$-1/2$	-1

Is there a symmetry argument for Y?

Global symmetry of the Standard Model (without dim-5 term): $U(1)_{B-L}$

$B-L$: baryon number minus lepton number

fermion:	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	u_R	d_R	$\begin{pmatrix} \nu_{e,L} \\ e_L \end{pmatrix}$	e_R	$\nu_{e,R}$
$Y-(B-L)/2$:	0	$1/2$	$-1/2$	0	$-1/2$	$1/2$

$\Rightarrow$ Is $Y-(B-L)/2$ the z-component of a right-handed isospin?

The magic relation $Y = T_3^R + (B-L)/2$ with a right-handed weak isospin T_3^R allows us to embed

$$U(1)_Y \subset SU(2)_R \times U(1)_{B-L}$$

Nice: The spontaneous symmetry breaking

$$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \to SU(3) \times SU(2)_L \times U(1)_Y$$

also breaks U_{B-L} and induces Majorana masses for neutrinos.

The magic relation $Y = T_3^R + (B - L)/2$ with a right-handed weak isospin T_3^R allows us to embed

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Nice: The spontaneous symmetry breaking

$$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \rightarrow SU(3) \times SU(2)_L \times U(1)_Y$$

also breaks U_{B-L} and induces Majorana masses for neutrinos.

. . . but why is $B - L$ quantised?

The fermions also nicely fit into $SU(5)$ multiplets:

$$\underline{5} \equiv \begin{pmatrix} d^c \\ d^c \\ d^c \\ \nu_{e,L} \\ e_L \end{pmatrix} \qquad \underline{10} \equiv \begin{pmatrix} 0 & u^c & -u^c & u_L & d_L \\ -u^c & 0 & u^c & u_L & d_L \\ u^c & -u^c & 0 & u_L & d_L \\ -u_L & -u_L & -u_L & 0 & e^c \\ -d_L & -d_L & -d_L & -e^c & 0 \end{pmatrix}$$

Here the fields with superscript c denote the charge–conjugated fields of the right–handed fermions.

That this works is highly non–trivial: it requires that

- there are 15 chiral fields per generation,
- the hypercharges sum to zero separately for the $\underline{5}$ and the $\underline{10}$,
- two of the four $SU(3)$ triplets are $SU(2)$ singlets and the other two combine to $SU(2)$ doublets,
- the remaining three colourless fields form a singlet and a doublet with respect to $SU(2)$.

This embedding of the Standard Model into $SU(5)$ cannot be explained with the *anthropic principle*, since the hypercharge quantum numbers are fine–tuned to all digits behind the decimal point.

So at high energies, where $SU(5)$ is unbroken, the 15 fermions of each generation unify to just two particles, a $\underline{5}$ and a $\underline{10}$.

Can we get them into a single symmetry multiplet?

Can we reconcile $SU(5)$ and $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$?

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Can we reconcile $SU(5)$ and $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$?

Yes: The 15 fermion fields of one Standard Model generation and an extra right-handed neutrino field fit into a $\underline{16}$ of

$$SO(10)$$

and $SO(10) \supset SU(5)$
and $SO(10) \supset SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.

Ende GUT - alles GUT?

$$SU(3) \times SU(2)_L \times U(1)_Y$$

$$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \qquad SU(5)$$

$$SO(10)$$

$SO(10)$

$SO(10)$ sheds light on some of the open questions of the Standard Model:

- symmetry group: $SU(3) \times SU(2)_L \times U(1)_Y \in SO(10)$
- particle content and quantum numbers: Each fermion generation combines into a 16-dimensional spinor.
- free parameters: Only one gauge coupling. But no progress with the Higgs sector and only little insight into Yukawa couplings.
- neutrino masses: The Majorana mass of the ν_R is roughly equal to the $SO(10)$ breaking scale. Its low energy effect is the desired dimension-5 Majorana mass term.
- $\mathrm{U}(1)_{B-L}$ is gauged and broken at the $SO(10)$ breaking scale.
  $\Rightarrow$ attractive mechanism for leptogenesis and baryogenesis.

Supersymmetry

Hierarchy problem: GUTs contain particles, which are heavier than those of the Standard Model by 14 orders of magnitude. Their quantum effects destabilize the Higgs mass.

Superpartners (fermions $\leftrightarrow$ bosons) with masses below 1 TeV tame the quantum corrections to the Higgs mass.

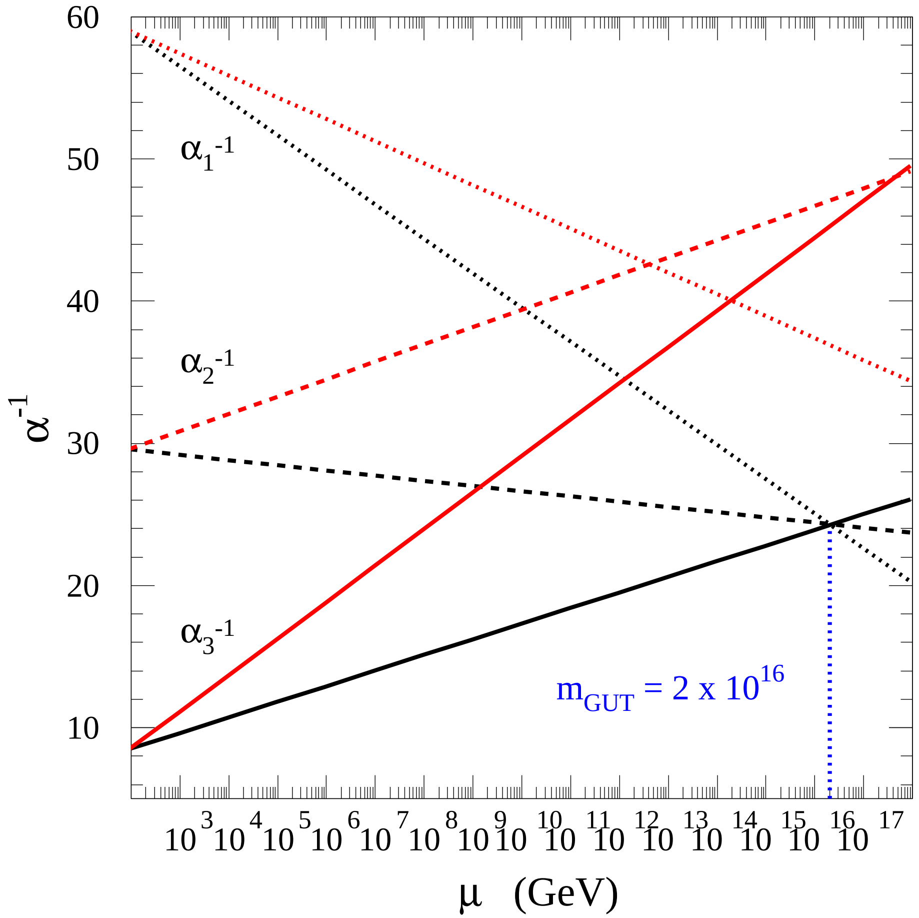
Supersymmetric theories can explain dark matter through the lightest supersymmetric particle (LSP) and provide attractive mechanisms for baryogenesis.

The unification of gauge couplings required by GUTs is improved.

The proton lifetime predicted from GUTs is reconciled with experimental bounds.

Supersymmetric theories can embed gravity.

Inverse gauge couplings with and without supersymmetry:



The GUT scale determined from the intersection of the couplings agrees sufficiently well with the right-handed neutrino mass.

B physics

Strategies to explore the TeV scale:

↙ ↘

High energy:
direct production of new particles
Tevatron, LHC

High precision:
quantum effects from new particles
high statistics

With precision measurements one studies the couplings and mixing patterns of the new particles which the LHC will discover.

But: The Standard Model was constructed from precision measurements performed well below the energy scale set by $M_W, M_Z \ldots$ and falsified as well from low-energy data on neutrino oscillations (establishing neutrino masses) and cosmology and astrophysics (establishing dark matter). There are still 2 more years to find new TeV scale physics from precision data in B physics.

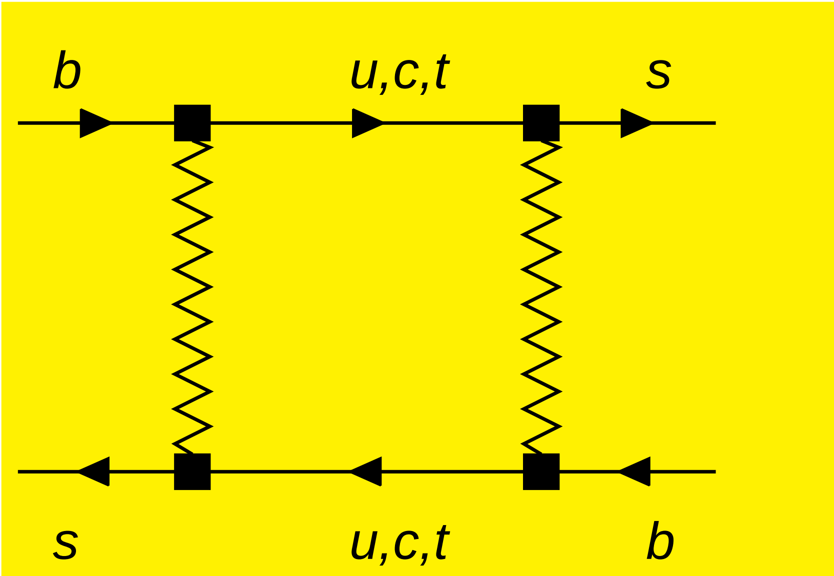
If new physics is associated with the scale Λ, effects on weak processes (such as weak B decays) are generically suppressed by a factor of order M_W^2/Λ^2 compared to the Standard Model.

$\Rightarrow$ study processes which are suppressed in the Standard Model.

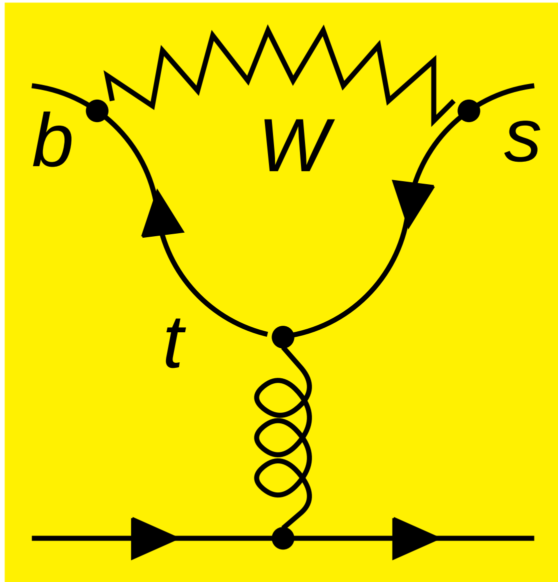
Especially sensitive to new physics are processes, in which (only) the Standard Model contribution is suppressed.

$\Rightarrow$ flavour-changing neutral current (FCNCs) processes

Examples for FCNC processes:



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



penguin diagrams

B mesons:

$B_d \sim \bar{b}d$ $\qquad B^+ \sim \bar{b}u$ $\qquad B_s \sim \bar{b}s$

In the flavour-changing neutral current (FCNC) processes of the Standard Model several suppression factors pile up:

- FCNCs proceed through electroweak loops, no FCNC tree graphs,
- small CKM elements, e.g. $|V_{ts}| = 0.04$, $|V_{td}| = 0.01$,
- GIM suppression in loops with charm or down-type quarks, $\propto m_c^2/M_W^2$, m_s^2/M_W^2.
- helicity suppression in radiative and leptonic decays, because FCNCs involve only left-handed fields, so helicity flips bring a factor of m_b/M_W or m_s/M_W.

The suppression of FCNC processes in the Standard Model is not a consequence of the $SU(3) \times SU(2)_L \times U(1)_Y$ symmetry. It results from the particle content of the Standard Model and the accidental smallness of most Yukawa couplings. It is absent in generic extensions of the Standard Model.

Examples:

extra Higgses $\Rightarrow$ Higgs-mediated FCNC's at tree-level ,
helicity suppression possibly absent,

squarks/gluinos $\Rightarrow$ FCNC quark-squark-gluino coupling,
no CKM/GIM suppression,

vector-like quarks $\Rightarrow$ FCNC couplings of an extra Z',

$\mathrm{SU(2)_R}$ gauge bosons $\Rightarrow$ helicity suppression absent

$\mathrm{B_d}-\overline{\mathrm{B}}_\mathrm{d}$ mixing and $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing are sensitive to scales up to $\Lambda \sim 100\,\mathrm{TeV}$.

Minimal supersymmetric Standard Model (MSSM)

Supersymmetry requires at least two Higgs multiplets. The Higgs sector of the MSSM is a 2-Higgs doublet model:

2 VEVs: v_d, v_u, $\tan\beta \equiv v_u/v_d$.

5 Higgs particles:

$H^\pm$	A^0	H^0	h^0
charged	CP-odd	CP-even	CP-even

The Higgs doublet H_d with $\langle H_d^0 \rangle = v_d$ only couples to down-type quarks, while H_u with $\langle H_u^0 \rangle = v_u$ only couples to up-type quarks (type-II 2-Higgs-doublet model).

MSSM = type-II 2HDM

+ scalar (fermionic) superpartner for each fermion (boson)

Supersymmetry is softly broken (i.e. via dimensionful parameters).

Effects on flavour physics:

1. FCNC gluino-squark-quark coupling
   from SUSY-breaking terms
   $\Rightarrow$ too large FCNC's,
   "supersymmetric flavour problem"

   } Non-CKM FCNCs!

2. Electroweak loops with superpartners
   Loops with charginos, squarks

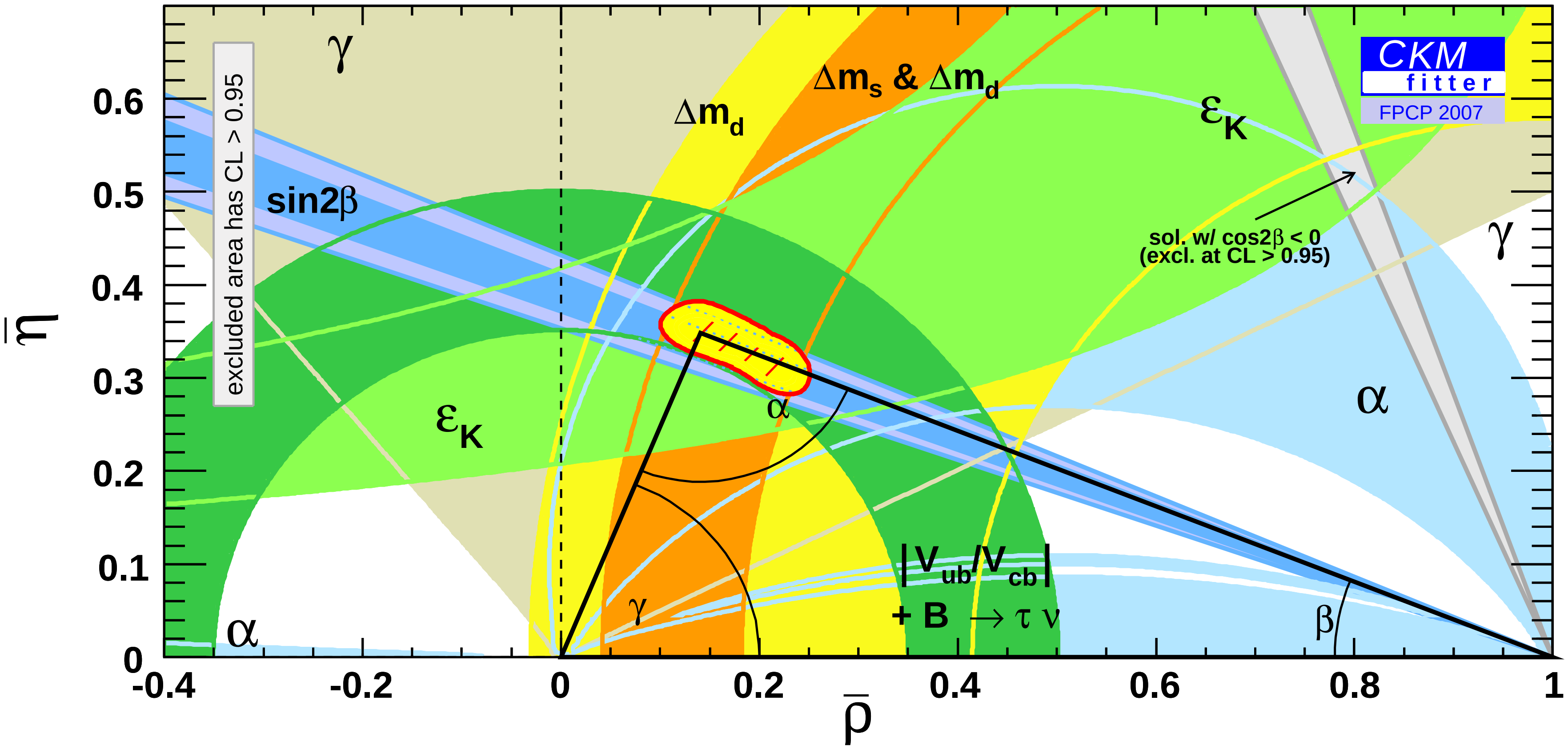
   } Minimal Flavour violation: all flavour changes from CKM elements!

3. Loop-induced Yukawa couplings
   new loop-induced FCNC Higgs couplings,
   growing with $\mu \tan \beta$

   } contributions from both 1. and 2.

2. Status of B physics

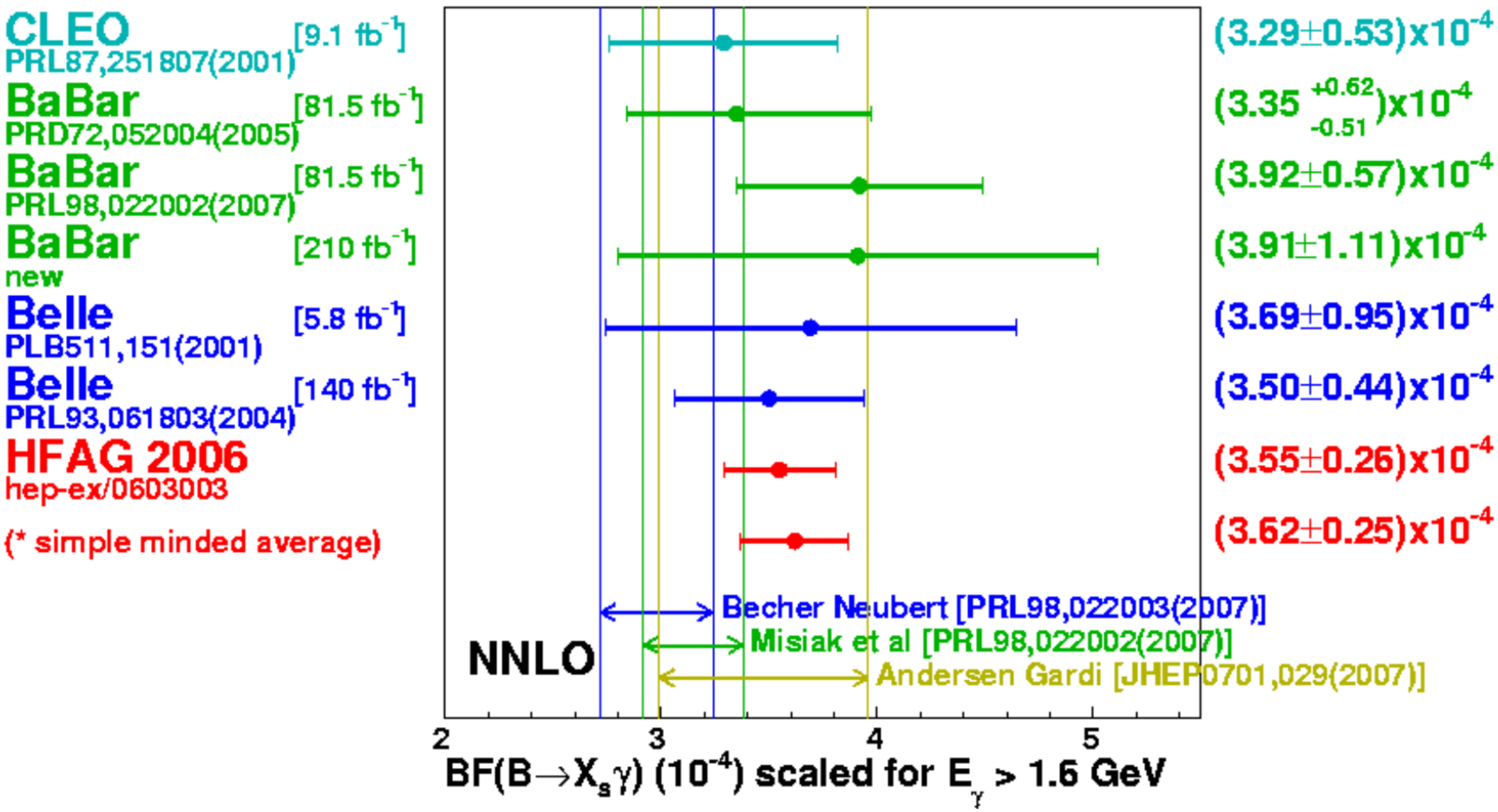
Experimental status of the unitarity triangle



consistent with the Standard Model

CKM mechanism excellently confirmed.

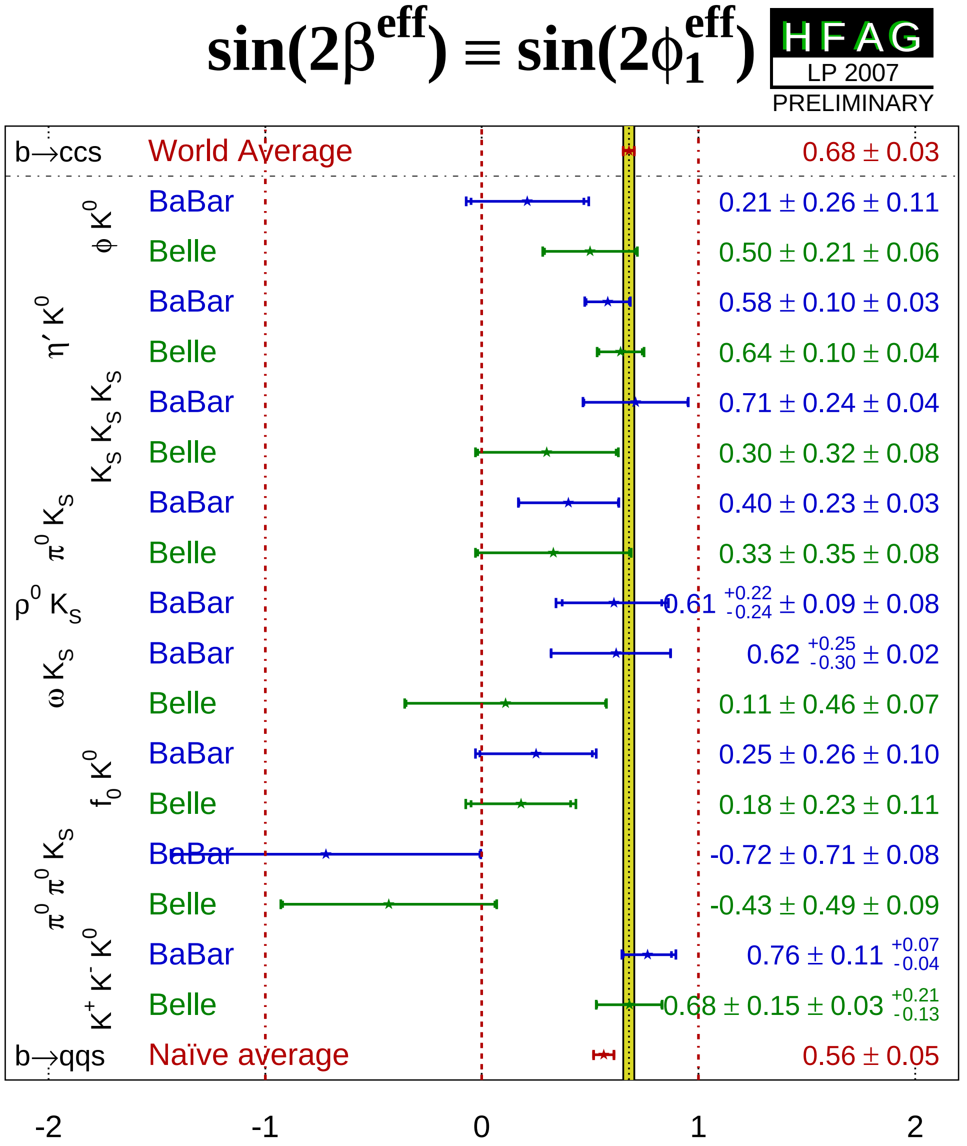
Experimental status of $b \to s\gamma$



consistent with the Standard Model prediction within $\sim 1.5\sigma$:

$$\mathcal{B}(B \to X_s\gamma) \;=\; (2.98 \pm 0.26) \cdot 10^{-4}$$ Becher,Neubert 2006

Experimental status of CP asymmetries in $b \to s$ transitions



Naive average disagrees from the Standard Model expectation by 2.2σ.

Better figure of merit: absolute deviation from the Standard Model.

Physics probed:

Unitarity Triangle: $b \to d$, $s \to d$, $b \to u$

$B \to X_s\gamma$: $b_R \to s_L$

C$\not{P}$ in $b \to s$ transitions: $b \to s$

$\Rightarrow$ Yukawa sector is the dominant source of flavor violation.

The Standard Model works too well:

Flavor problem of TeV scale physics

Physics probed:

Unitarity Triangle:	$b \to d$, $s \to d$, $b \to u$
$B \to X_s\gamma$:	$b_R \to s_L$
CP̸ in $b \to s$ transitions:	$b \to s$

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The Standard Model works too well:

Flavor problem of TeV scale physics

In the Minimal Supersymmetric Standard Model (MSSM) all potential new sources of flavor violation come from the SUSY breaking sector. The success of the flavor physics programs at the B factories and the Tevatron severely constrains the associated parameters in the squark mass matrices.

Minimal Flavor Violation (MFV)

If whatever breaks supersymmetry is flavor–blind, the only source of flavor violation is the Yukawa sector.

$\Rightarrow$ a) The FCNC suppression of the Standard Model essentially stays intact and new physics is suppressed by a factor of $M_W^2/\Lambda_{\rm NP}^2$.
b) Parametric enhancements are still possible, e.g. in scenarios with large $\tan\beta$.
c) MFV still allows for new CP phases, e.g. $\arg A_t$.
d) If MFV is realized above the GUT scale, deviations from CKM–driven FCNCs occur at low energies.

It is difficult to distinguish the Standard Model from MFV new physics scenarios using global fits of the unitarity triangle.
Better: Rare decays, preferably $b \to s$.

New physics in B decays

To sum up:

MFV new physics without parametric enhancement factors is suppressed by a factor of $M_W^2/\Lambda_{\rm NP}^2$.

$\Rightarrow$ Current B factory data are not sensitive yet!
Either not enough statistics, or too large hadronic uncertainties!

At present: Constrain non-MFV scenarios and scenarios with a large value of $\tan\beta \sim 50$, because the Yukawa coupling to b quarks is enhanced:

$$y_b \sin\beta \; = \; \frac{g\, m_b}{\sqrt{2} M_W} \, \tan\beta.$$

Why B_s physics?

i) CKM elements in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing are well-known.

ii) Most CP asymmetries are small in the Standard Model.

iii) The mixing–induced CP asymmetries in $b \to s$ penguin modes can be studied in B_s decays into any final state, while the B_d penguin decays require a neutral K meson. Study $B_s \to \phi\phi$ and $B_s \to K^+K^-$!

iv) $Br(B_s \to \ell^+\ell^-) \gg Br(B_d \to \ell^+\ell^-)$ in all MFV scenarios.

v) GUT models can naturally put large new effects into $b \to s$ transitions.

Illustration of iii)

To measure a mixing-induced CP asymmetry (S_f term) in a $b \to s\overline{q}q$ 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.

Moreover: The CP asymmetries are essentially zero in the Standard Model.

$\Rightarrow$ B_s physics could be the El Dorado of $b \to s\overline{q}q$ penguin physics!

3. $\mathrm{B}-\overline{\mathrm{B}}$ mixing basics

Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix} |\,B(t)\,\rangle \\ |\,\overline{B}(t)\,\rangle \end{pmatrix} = \left(M - i\,\frac{\Gamma}{2}\right)\begin{pmatrix} |\,B(t)\,\rangle \\ |\,\overline{B}(t)\,\rangle \end{pmatrix}$$

3 physical quantities in $\mathrm{B}-\overline{\mathrm{B}}$ mixing:

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

Two mass eigenstates:

Lighter eigenstate: $|\,B_L\,\rangle = p|\,B^0\,\rangle + q|\,\overline{B}^0\,\rangle.$

Heavier eigenstate: $|\,B_H\,\rangle = p|\,B^0\,\rangle - q|\,\overline{B}^0\,\rangle$ with $|p|^2 + |q|^2 = 1.$

with masses $M_{L,H}$ and widths $\Gamma_{L,H}$.

Here B represents either B_d or B_s.

To determine $|M_{12}|$, $|\Gamma_{12}|$ and ϕ measure

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

and

$$a_{\mathrm{fs}} = \mathrm{Im}\,\frac{\Gamma_{12}}{M_{12}} = \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi.$$

a_{fs} is the CP asymmetry in flavour-specific B decays (semileptonic CP asymmetry). a_{fs} measures CP violation in mixing.

Define the average rate $\Gamma \equiv (\Gamma_L + \Gamma_H)/2$.

Standard Model expectations:

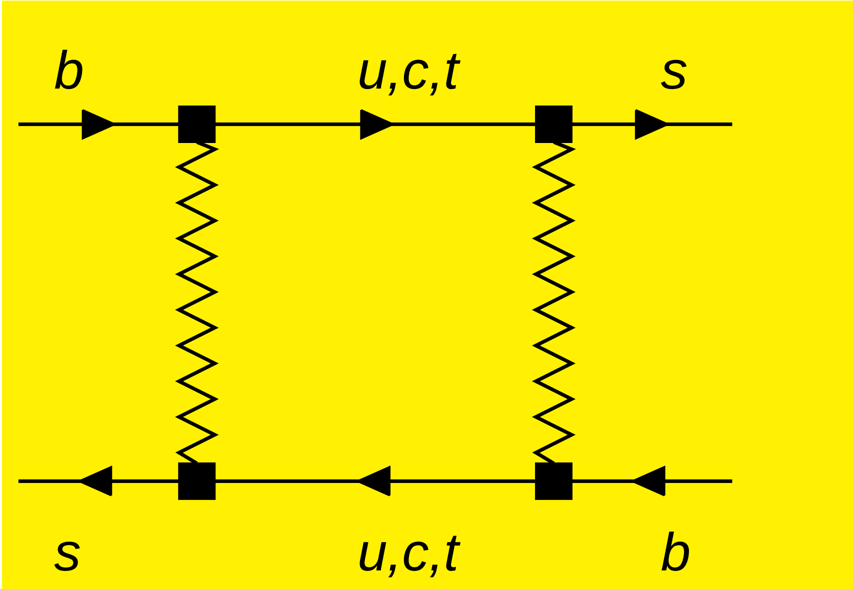
	B_d system	B_s system
$\Delta m =$	$0.5\,\text{ps}^{-1}$	$20\,\text{ps}^{-1}$
$\Delta \Gamma =$	$3 \cdot 10^{-3}\,\text{ps}^{-1}$	$0.10\,\text{ps}^{-1}$
$\dfrac{\Delta\Gamma}{\Gamma} =$	$4 \cdot 10^{-3}$	0.15
$\dfrac{\Delta\Gamma}{\Delta m} = \left\| \dfrac{\Gamma_{12}}{M_{12}} \right\| \cos\phi =$	$5 \cdot 10^{-3} = \mathcal{O}\left(\dfrac{m_b^2}{M_W^2}\right)$	
$a_{\text{fs}} = \left\| \dfrac{\Gamma_{12}}{M_{12}} \right\| \sin\phi =$	$-5 \cdot 10^{-4}$	$2 \cdot 10^{-5}$
$\phi =$	$-0.9 = -5^\circ = \mathcal{O}\left(\dfrac{m_c^2}{m_b^2}\right)$	$4 \cdot 10^{-3} = 0.2^\circ = \mathcal{O}\left(\|V_{us}\|^2 \dfrac{m_c^2}{m_b^2}\right)$

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

Standard Model:

M_{12}^s from dispersive part of box,
only internal t relevant;

Γ_{12}^s from absorptive part of box,
only internal u, c contribute.



New physics can barely affect Γ_{12}^s, which stems from tree-level decays.

M_{12}^s is very sensitive to virtual effects of new heavy particles.

$\Rightarrow$ $\Delta m \simeq 2|M_{12}^s|$ can change.

and in $\phi_s \simeq \arg(-M_{12}^s/\Gamma_{12}^s)$ the GIM suppression of ϕ_s can be lifted.

$\Rightarrow$ $|\Delta\Gamma_s| = \Delta\Gamma_{s,\mathrm{SM}}\,|\cos\phi_s|$ is depleted

and $|a_{\mathrm{fs}}^s|$ is enhanced, by up to a factor of 200 in the B_s system.

To identify or constrain new physics one wants to measure both the magnitude and phase of M_{12}^s.

$$\rightarrow \qquad \Delta m_s = 2|M_{12}^s|$$

Information on $\arg M_{12}^s$ can be gained from mixing-induced CP asymmetries, in particular $a_{\rm mix}^{\rm CP}(B_s \to J/\psi\phi)$. This requires tagging, which is difficult at hadron colliders.

Three untagged measurements are sensitive to $\arg M_{12}^s$:

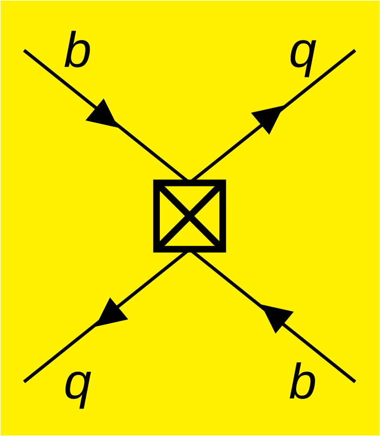
1. $|\Delta\Gamma_s| = \Delta\Gamma_{s,{\rm SM}}\,|\cos\phi_s| = \left|{\rm Re}\,\dfrac{\Gamma_{12}^s}{M_{12}^s}\right| \Delta m_s$
2. $a_{\rm fs}^s = \left|\dfrac{\Gamma_{12}^s}{M_{12}^s}\right| \sin\phi = {\rm Im}\,\dfrac{\Gamma_{12}^s}{M_{12}^s}$
3. the angular distribution of $\overset{(-)}{B}_s \to VV'$, where V, V' are vector bosons.

$$\Rightarrow \text{Want good theoretical control of } \frac{\Gamma_{12}^s}{M_{12}^s}.$$

Improved prediction of Γ_{12}^s

A. Lenz, U.N., hep-ph/0612167

Γ_{12} in $\mathrm{B_q}-\overline{\mathrm{B}}_\mathrm{q}$ mixing with $q = d$ or $q = s$ involves two local four-quark operators:



$$Q = \overline{q}_L^i \gamma_\nu b_L^i \, \overline{q}_L^j \gamma^\nu b_L^j$$

$$\widetilde{Q}_S = \overline{q}_L^i b_R^j \, \overline{q}_L^j b_R^i, \qquad i,j\text{: color indices}$$

Theoretical uncertainty dominated by matrix element:

$$\langle \, \mathrm{B_q} \, | Q | \, \overline{\mathrm{B}}_q \, \rangle = \frac{2}{3} m_B^2 \, f_{B_q}^2 \, B$$

$$\langle B_s | \widetilde{Q}_S | \overline{B}_s \rangle = \frac{1}{12} M_{B_s}^2 \, f_{B_s}^2 \, \widetilde{B}_S'$$

The hadronic parameters $f_{B_q}^2 \, B$ and $f_{B_q}^2 \, \widetilde{B}_S'$ must be computed with lattice QCD or QCD sum rules. $f_{B_q}^2$ is the decay constant of the B_q meson.

The mass difference Δm_q only involves the operator Q, so that

$$\Delta m_q \propto \langle \mathrm{B_q} | Q | \overline{\mathrm{B}}_q \rangle = \frac{2}{3} m_B^2 f_{B_q}^2 B$$

Width difference:

$$\frac{\Delta\Gamma_s}{\Gamma} = \left(\frac{f_{B_s}}{240\,\mathrm{MeV}} \right)^2 \left[0.160\, B + 0.058\, \widetilde{B}_S - 0.041 \right]$$
$$= 0.15 \pm 0.05 \qquad \text{for } f_{B_s} = 240 \pm 40\,\mathrm{MeV}.$$

Last term: contributions from $1/m_b$-suppressed operators.

f_{B_s} drops out from $\Delta\Gamma_s/\Delta m_s$. Including the uncertainties of the coefficients:

$$\frac{\Delta\Gamma_s}{\Delta m_s} = \left[34 \pm 6 + (17 \pm 1) \frac{\widetilde{B}_S}{B} \right] \cdot 10^{-4} = (50 \pm 9) \cdot 10^{-4}$$

Standard Model prediction:

$$\Delta\Gamma_s = \frac{\Delta\Gamma_s}{\Delta m_s} \Delta m_s^{\mathrm{exp}} = (0.088 \pm 0.017)\,\mathrm{ps}^{-1}$$

Don't use this formula, if you are hunting new physics!

Generic new physics

The phase $\phi_s = \arg(-M_{12}/\Gamma_{12})$ is negligibly small in the Standard Model: $\phi_s^{\rm SM} = 0.2^\circ$.

Define the complex parameter Δ_s through

$$M_{12}^s \equiv M_{12}^{\rm SM,s} \cdot \Delta_s\,, \qquad \Delta_s \equiv |\Delta_s| e^{i\phi_s^\Delta}.$$

In the Standard Model $\Delta_s = 1$.

The CDF measurement

$$\Delta m_s = (17.77 \pm 0.10 \pm 0.07)\ \mathsf{ps}^{-1}$$

and

$$f_{B_s}\sqrt{B} = 221 \pm 46\ \mathsf{MeV}$$

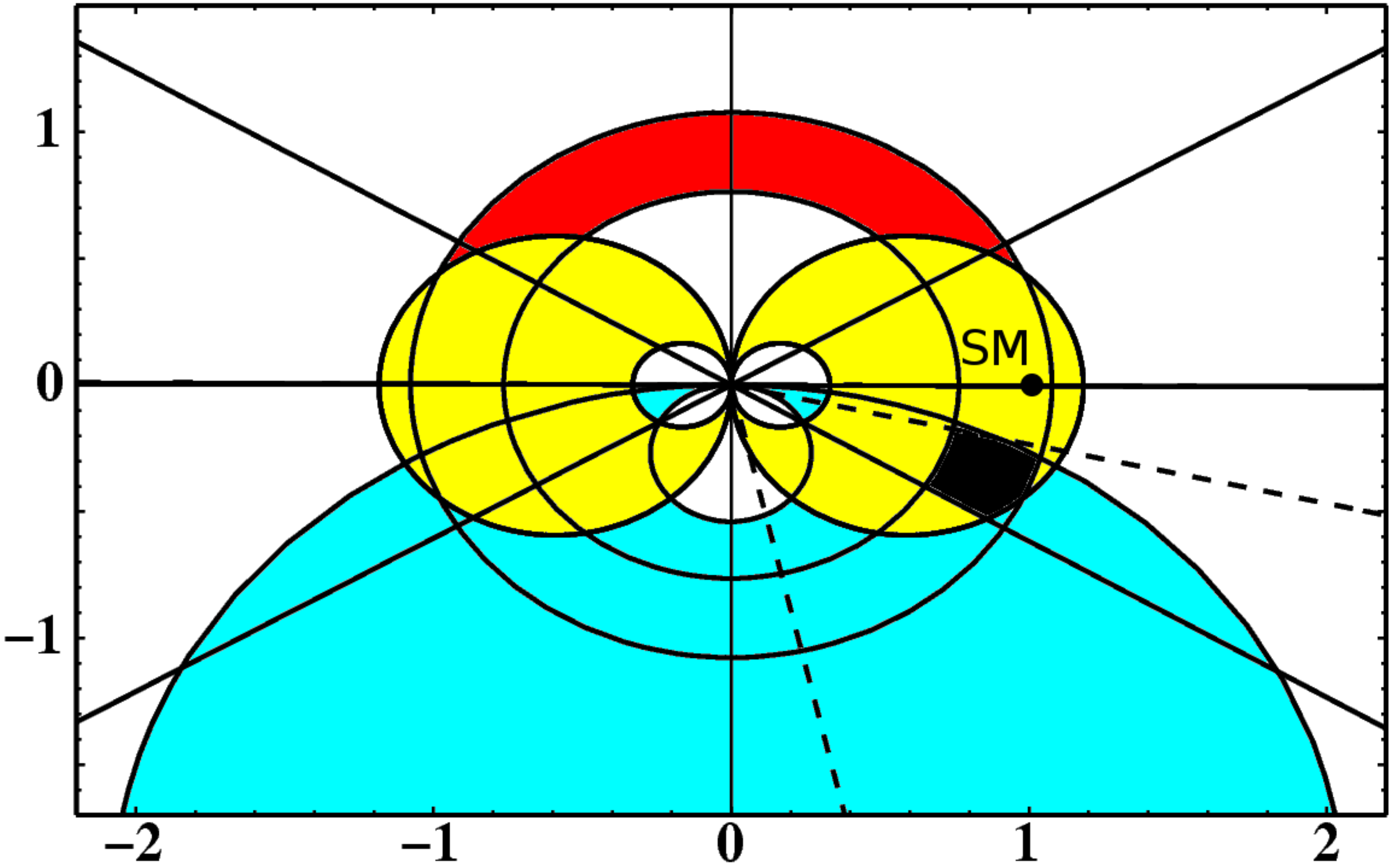
imply

$$|\Delta_s| = 0.92 \pm 0.32_{\sf (th)} \pm 0.01_{\sf (exp)}$$

To further constrain Δ_s we have analysed the CDF data on Δm_s and the DØ data on

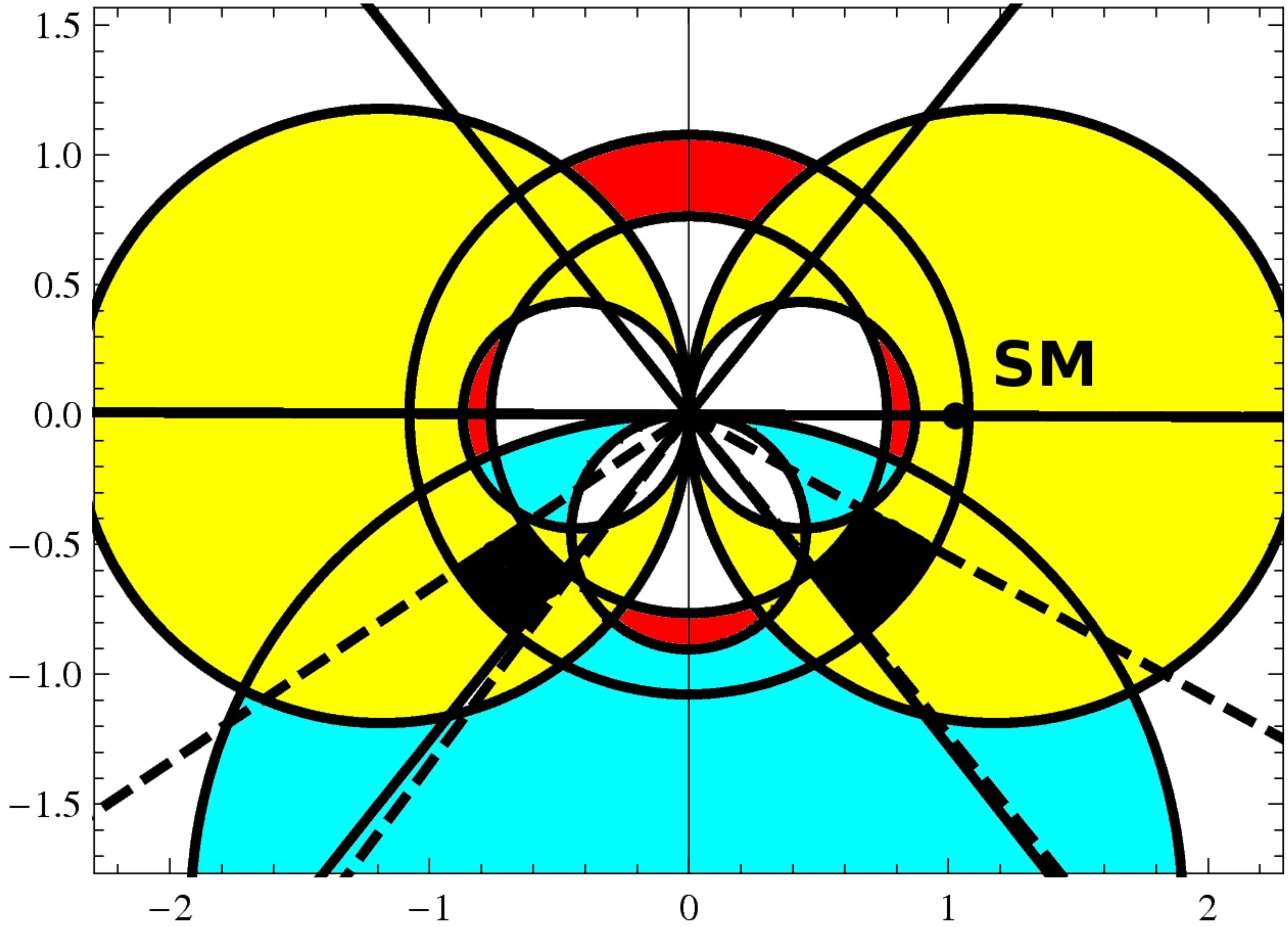
- the semileptonic CP asymmetry a_{fs}^s,
- the angular distribution in $\overset{(-)}{B}_s \to J/\psi\phi$ and
- $\Delta\Gamma_s$.

Constraints on the complex Δ_s plane (from 2006 data):



We found a deviation from the Standard Model by 2σ.

Adding the results from the tagged CDF and DØ analyses (and updating $a_{\rm fs}^s$):



4. GUTs: linking quarks to neutrinos

Flavour mixing:

quarks: Cabibbo-Kobayashi-Maskawa (CKM) matrix

leptons: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

Consider SU(5) multiplets:

$$\overline{\mathbf{5}}_{\mathbf{1}} = \begin{pmatrix} d_R^c \\ d_R^c \\ d_R^c \\ e_L \\ \nu_e \end{pmatrix}, \qquad \overline{\mathbf{5}}_{\mathbf{2}} = \begin{pmatrix} s_R^c \\ s_R^c \\ s_R^c \\ \mu_L \\ \nu_\mu \end{pmatrix}, \qquad \overline{\mathbf{5}}_{\mathbf{3}} = \begin{pmatrix} b_R^c \\ b_R^c \\ b_R^c \\ \tau_L \\ \nu_\tau \end{pmatrix}.$$

If the observed large atmospheric neutrino mixing angle stems from a rotation of $\overline{\mathbf{5}}_{\mathbf{2}}$ and $\overline{\mathbf{5}}_{\mathbf{3}}$, it will induce a large $\tilde{b}_R - \tilde{s}_R$-mixing (Moroi).

$\Rightarrow$ new $b_R - s_R$ transitions from gluino–squark loops

The CMM model is based on the symmetry breaking chain

SO(10)$\rightarrow$ SU(5) $\rightarrow$ SU(3)$\times$SU(2)$_L\times$U(1)$_Y$. Chang, Masiero and Murayama

1. The SUSY-breaking terms are universal at the Planck scale.
2. Renormalization effects from the top-Yukawa coupling destroy the universality at $M_{\rm GUT}$.
3. Rotating $\overline{\mathbf{5}}_{\mathbf{2}}$ and $\overline{\mathbf{5}}_{\mathbf{3}}$ into mass eigenstates generates a $\tilde{b}_R - \tilde{s}_R$ element in the mass matrix of right-handed squarks.

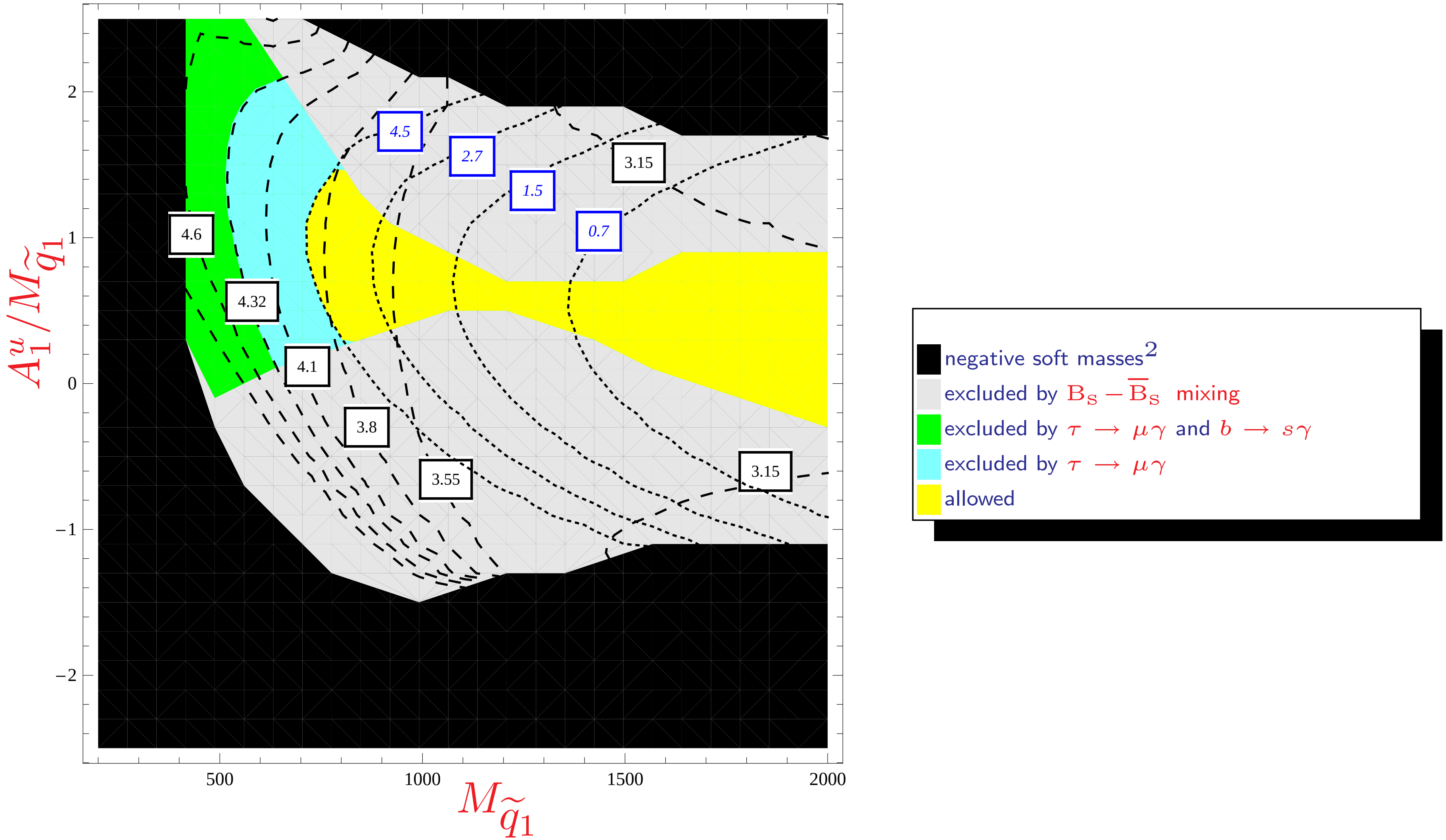
Phenomenological effect: leads to MSSM with

1. new loop-induced $b_R \rightarrow s_R$ and $b_L \rightarrow s_R$ transitions, while all other FCNC transitions are CKM-like,
2. all MSSM masses and couplings fixed in terms of a few GUT parameters.

$\Rightarrow$ well-motivated falsifiable version of the MSSM without minimal flavour violation (MFV),
puts largest effects into $b_R \rightarrow s_R$, where Standard Model is tested least.

Constraints from $B_s - \overline{B}_s$ mixing, $\tau \to \mu\gamma$ and $b \to s\gamma$ on $M_{\tilde{q}_1}$ and $A_1^u / M_{\tilde{q}_1}$

Contour plot



dashed lines: $10^4 \cdot Br(b \to s\gamma)$; dotted lines: $10^8 \cdot Br(\tau \to \mu\gamma)$.

5. Supersymmetry with large $\tan\beta$

Tree-level Higgs sector of the MSSM:

type-II Two-Higgs-doublet model (2HDM):

2 VEV's: v_d, v_d, $\tan\beta \equiv v_u/v_d$.

5 Higgs fields:

$H^\pm$	A^0	H^0	h^0
charged	CP-odd	CP-even	CP-even

Right–handed down-type quarks d_R^I $(I = 1, 2, 3)$ only couple to H_d with $\langle H_d^0 \rangle = v_d$, while the right–handed up-type quarks u_R^I only couple to H_u with $\langle H_u^0 \rangle = v_u$.

The tree-level relations between the Yukawa couplings y_b, y_t and the bottom and top masses are:

$$m_b = y_b v_d = y_b v \cos\beta, \qquad m_t = y_t v_u = y_t v \sin\beta$$

with $v = \sqrt{v_d^2 + v_u^2} = 174$ GeV.

$\Rightarrow y_b = \mathcal{O}(1)$ possible for $\tan\beta \sim 50$.

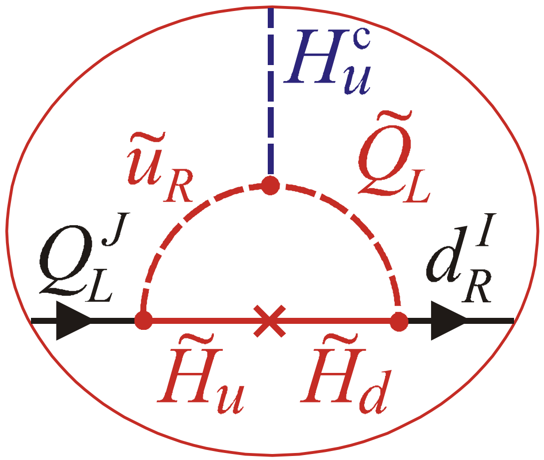
Motivation:

- $\tan\beta \sim 60 \Leftrightarrow y_b$–$y_t$ unification (probes minimal SO(10))
- $g-2$ invites large $\tan\beta$.

Large $\tan\beta$ scenarios are usually studied in an effective field theory framework, which is exact for $M_{\rm SUSY} \gg M_{A^0}, M_{H^0}, M_{H^+}, M_{h^0}, v$.

The SUSY–breaking terms lead to loop–induced couplings of H_u to the d_R^I's:
For $v_u \gg v_d$ their contribution to m_b competes with the tree–level term.

Hall, Rattazzi, Sarid



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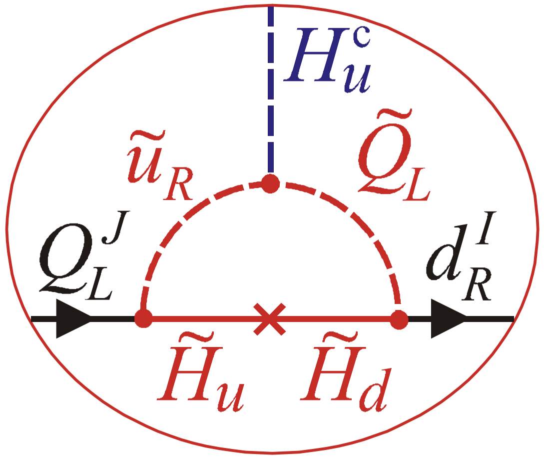


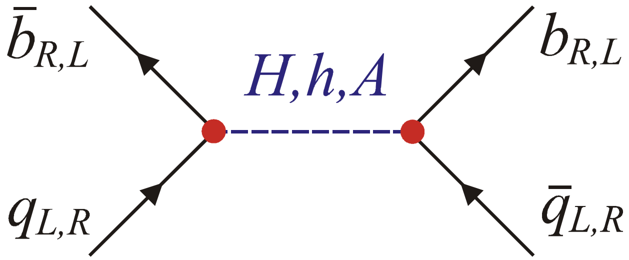
The resulting Higgs sector is a general 2HDM with sizable FCNC couplings of A^0 and H^0, even for MFV. Hamzaoui, Pospelov, Toharia; Babu, Kolda

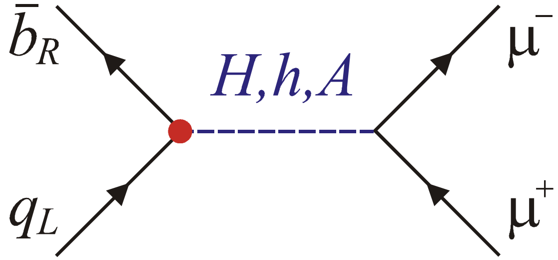
Yukawa interaction of neutral Higgs fields:

$$\mathcal{L}_Y = \kappa^{IJ} \overline{d}_R^I d_L^J \left(\cos\beta h_u^{0*} - \sin\beta h_d^{0*}\right) + \kappa^{JI} \overline{d}_L^I d_R^J \left(\cos\beta h_u^0 - \sin\beta h_d^0\right)$$

↖ FCNC couplings

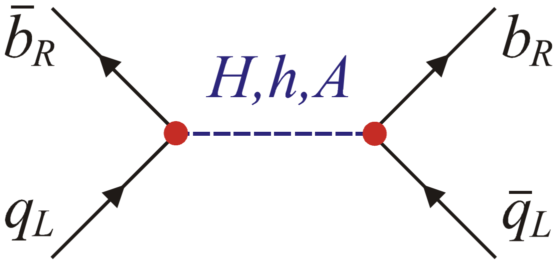
In the effective theory the diagrams for $\mathrm{B_q - \overline{B}_q}$ mixing and $B_s \to \mu^+\mu^-$ are tree–level:





$\mathcal{B}(B_s \to \mu^+\mu^-)$ could be enhanced dramatically, the experimental upper bound $\mathcal{B}^{\mathrm{exp}}(B_s \to \mu^+\mu^-) \leq 15 \cdot \mathcal{B}^{\mathrm{SM}}(B_s \to \mu^+\mu^-)$ already severely constrains the MSSM parameter space.

However: In $\mathrm{B_q - \overline{B}_q}$ mixing the leading contribution,



$$\propto \mathcal{F}^- = \frac{\sin^2(\alpha-\beta)}{M_H^2} + \frac{\cos^2(\alpha-\beta)}{M_h^2} - \frac{1}{M_A^2},$$

vanishes, if the tree–level relationship between the masses and the mixing angles α, β is used.

Hamzaoui, Pospelov, Toharia; Babu, Kolda

Trading one $\bar{b}_R q_L$ for $\bar{b}_L q_R$ brings a suppression factor of m_q/m_b, but the Higgs propagators give something non–zero. Only relevant for $q = s$.

Correlation: Δm_s decreases with increasing $\mathcal{B}(B_s \to \mu^+\mu^-)$.

Buras, Chankowski, Rosiek, Sławianowska

Recent updates: Carena, Menon, Noriega-Papaqui, Szynkman, Wagner

Carena, Menon, Wagner

Altmannshofer, Buras, Guadagnoli,

The current upper bound on $\mathcal{B}(B_s \to \mu^+\mu^-)$ from the Tevatron does not permit changes in Δm_s exceeding ~ 3 ps^{-1} in MFV scenarios.

$\mathcal{B}(B_s \to \mu^+\mu^-)$ is very sensitive to MSSM parameters, if $\tan\beta$ is large.

$Br(B_s \to \mu^+\mu^-)$

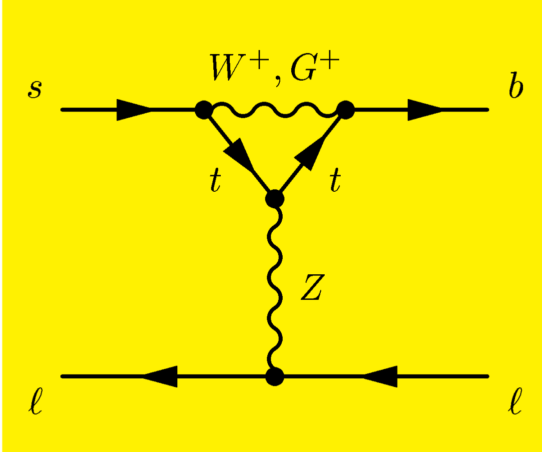
$B_s \to \mu^+\mu^-$:

Standard Model:

amplitude $\propto V_{ts}\dfrac{m_\mu}{M_W}$

$$Br(B_s \to \mu^+\mu^-)_{\rm SM} \;=\; (3.8 \pm 1.0) \times 10^{-9}$$

Buchalla,Buras; Misiak,Urban



Experiment:

$Br(B_s \to \mu^+\mu^-) < 5.8 \cdot 10^{-8}$ (CDF 2007)

MSSM:

$$Br(B_s \to \mu^+\mu^-)_{\rm MSSM} \;\propto\; |V_{ts}|^2 \tan^6\beta \, \frac{m_\mu^2 M_{B_s}^2}{M_{A^0}^4} f(\mu A_t, M_{\tilde{t}_i}, M_{\tilde{\chi}_i^+})$$

where $f \to$ const. $\neq 0$ for $M_{\rm SUSY} \to \infty$.

$\Rightarrow$ In the MFV-MSSM the branching ratio can be larger by three orders of magnitude than in the Standard Model.

$Br(B \to \ell^+\ell^-) \propto m_b^2 m_\ell^2 \tan^6\beta$ is the observable with the largest sensitivity to SUSY with large $\tan\beta$. A factor of $m_b^2 m_\mu^2 \tan^6\beta$ can only appear in flavor-changing transitions.

6. A theorist's wishlist for LHCb

1. $a_{\rm mix}^{\rm CP}(B_s \to J/\psi\phi)$
2. $Br(B_s \to \mu^+\mu^-)$
3. $a_{\rm fs}^s$ and $a_{\rm fs}^d$
4. angular analysis of tagged $B_s \to \phi\phi$
5. tagged $B_s \to K_S K_S$, $B_s \to K_S K^{*0}$, $B_s \to \overline{K}^{*0} K_S$ and (with angular analysis) $B_s \to K^{*0}\overline{K}^{*0}$
6. Can you do $B \to D\tau\overline{\nu}$? ($\longrightarrow$ charged Higgs effects)
7. branching fraction and $a_{\rm mix}^{\rm CP}$ in $B_s \to \phi\rho^0$ ($\longrightarrow$ electroweak penguin physics)
8. $Br(B_s \to X\ell^+\ell^-)$ and $Br(B_d \to X\ell^+\ell^-)$

Penguins in $b \to s\bar{s}s$ and $b \to s\bar{d}d$:

Wake-up call for New Physics?