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Flavour physics in the LHC era

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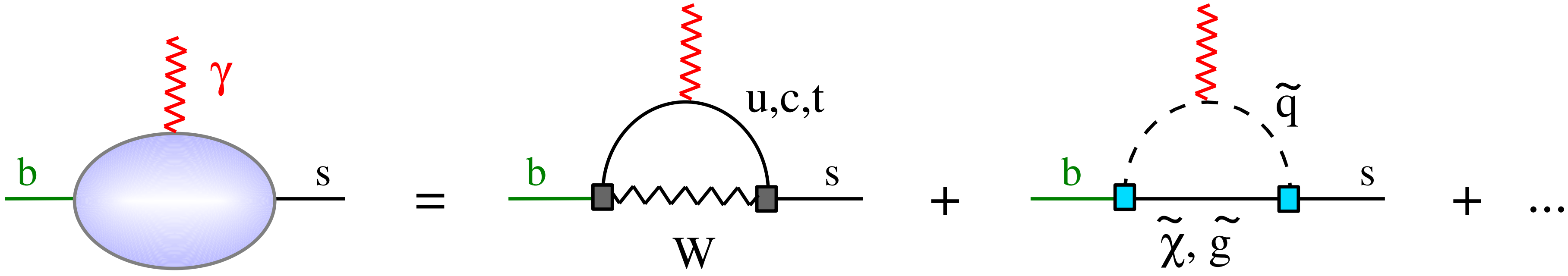
- Introduction
- What we learned so far
  - Model-independent fits
  - The MFV hypothesis
- What we could still hope to learn
  - The most interesting observables in the MSSM with MFV
  - Other observables
- Conclusions

Introduction

I. In most realistic BSM scenarios, the new degrees of freedom of the model are heavier than B or K mesons (usually heavier also than W & Z bosons) and contribute to meson decays only via virtual effects → *indirect sensitivity to NP*

E.g.:



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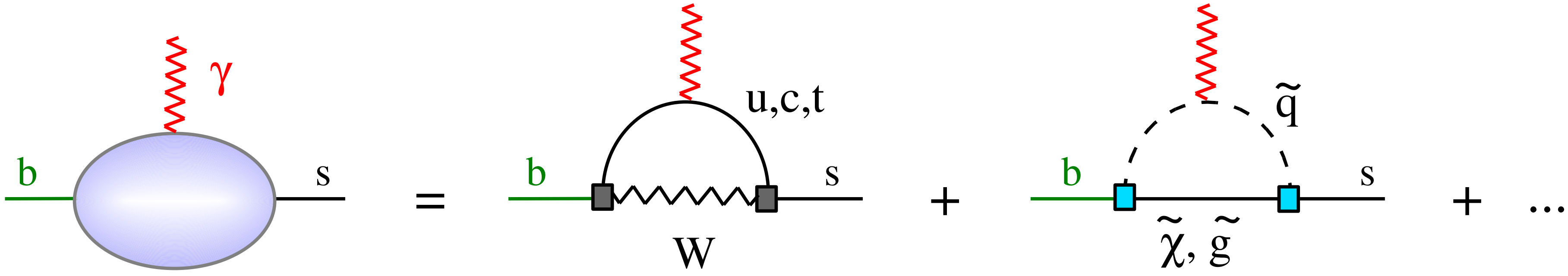

II. If the new degrees of freedom respect the $SU(2)_L \times U(1)$ gauge symmetry (very reasonable/general assumption) → *NP effects at low energies decouple as* $1/\Lambda^2$ (Λ = energy scale of the new degrees of freedom)

trivial kinematical factors

$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

(adimensional) effective couplings

Introduction

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Λ = energy scale of the new particles

$c_{SM(NP)}$ = eff. couplings

- The sensitivity to the energy scale grows very slowly with the statistics or the luminosity of the experiment ($\sigma \sim 1/N^{1/4}$)
- The interest of a given observable depends on the magnitude of c_{SM} vs. c_{NP} (*loop-induced observables usually more interesting because of small c_{SM}, but other type of suppressions, such as the helicity suppression, can make specific tree-level processes particularly interesting*)

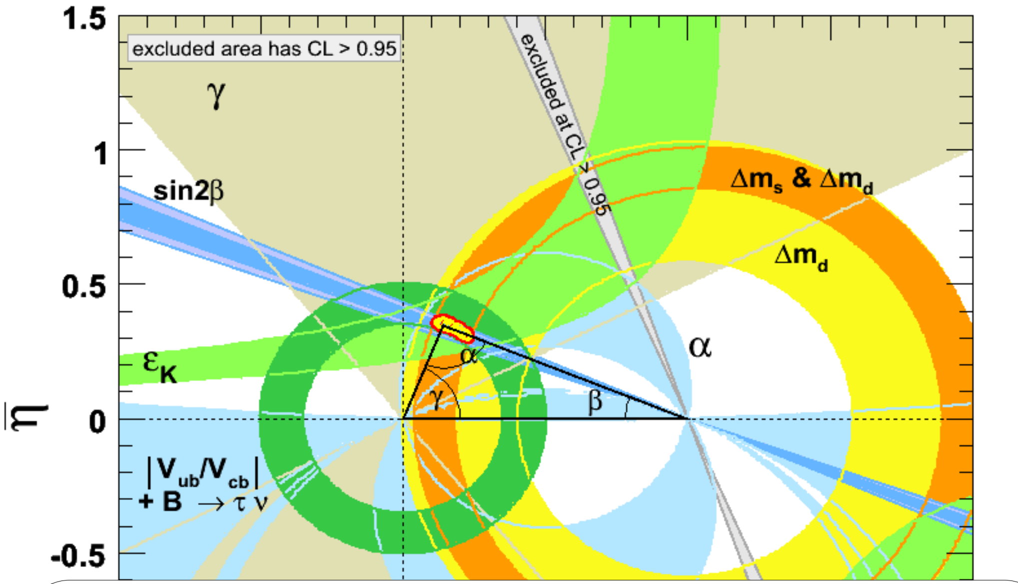
  and on the theoretical error of c_{SM}

  (*CKM + hadronic uncertainties → important role of auxiliary observables*)
- There is no way of disentangling the information on Λ and c_{NP}, but the combined information which can be extracted is fully complementary to the direct searches performed at high-p_T: key role of (low-energy) flavour physics in determining the flavour symmetry structure of NP

What we learned so far

The SM is very successful in describing quark-flavour mixing

This is quite clear by looking at the consistency of the exp. constraints appearing in the so called CKM fits, and is confirmed by the absence of significant deviations from the SM in clean rare decays such as $B \to X_s \gamma$

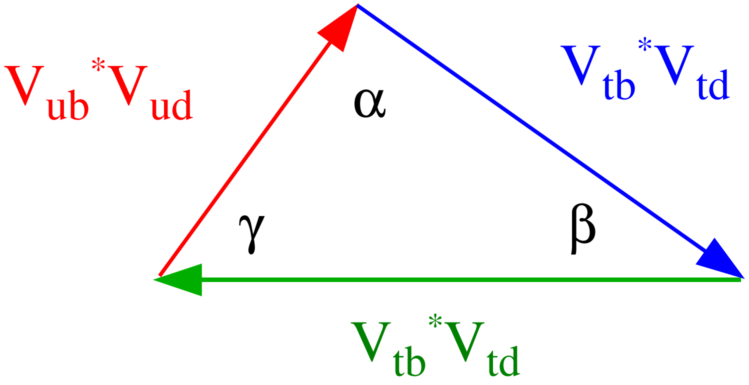


New physics effects in quark-flavour mixing can only appear as small corrections to the leading CKM mechanism

$$V_{CKM} V_{CKM}^{+} = I$$

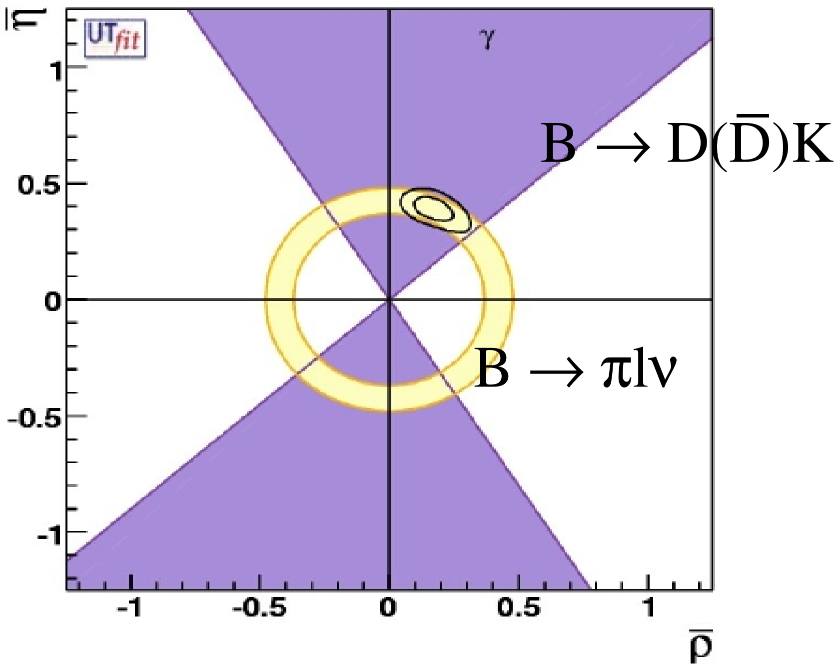
triangular relations:

$$V_{i1} (V^+)_{1j} + V_{i2} (V^+)_{2j} + V_{i3} (V^+)_{3j} = 0$$



Model-independent fits of ΔF=2 amplitudes

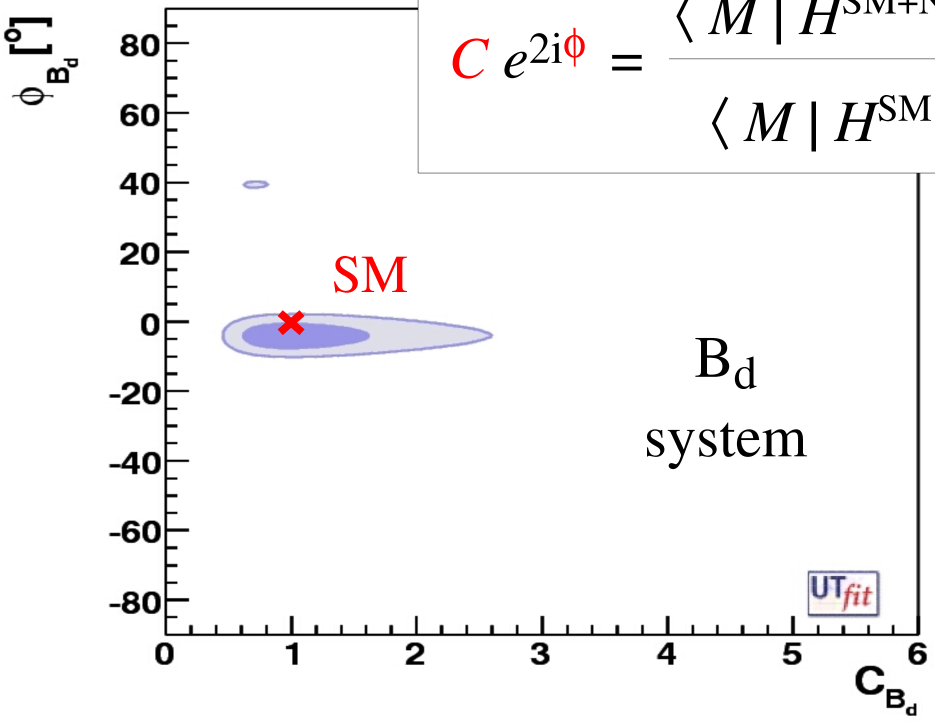
Present data allow us to determine the CKM unitarity triangle using only tree-level dominated amplitudes

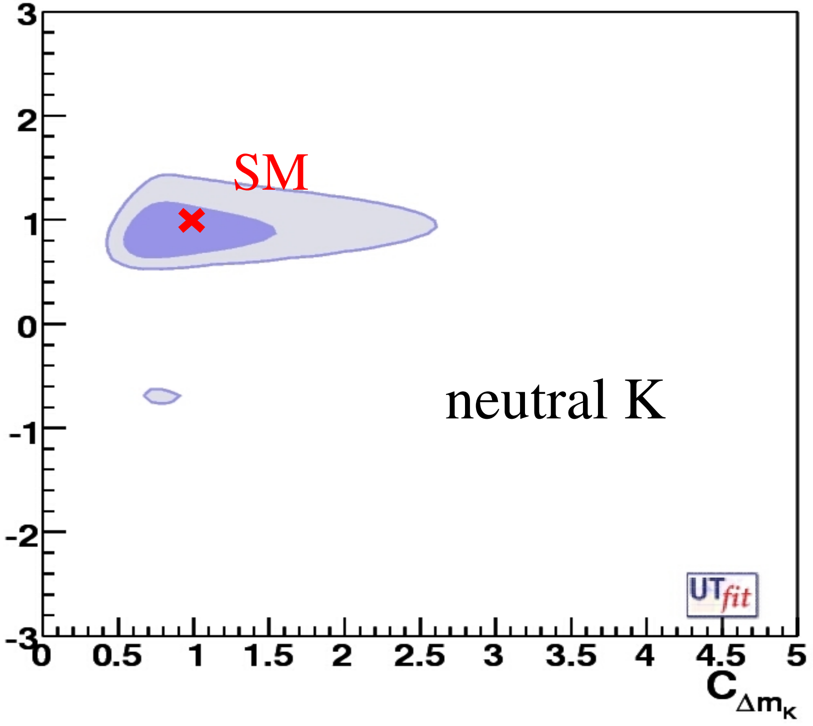


⬇

General fit of NP in ΔF=2 amplitudes

$$C\, e^{2i\phi} = \frac{\langle\, M \,|\, H^{\mathrm{SM+NP}} \,|\, \bar{M} \,\rangle}{\langle\, M \,|\, H^{\mathrm{SM}} \,|\, \bar{M} \,\rangle}$$





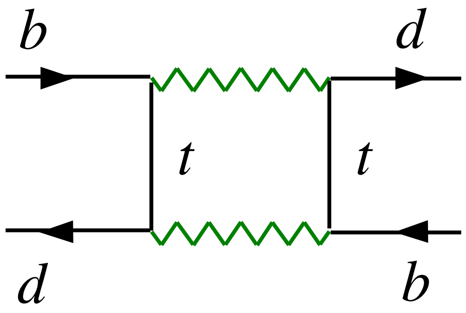
Model-independent fits of ΔF=2 amplitudes

These general results are quite instructive if interpreted as bounds on the scale of new physics:

contrbution of the new heavy degrees of freedom

$$M(\mathrm{B}_d\text{-}\overline{\mathrm{B}}_d) \sim \frac{(V_{tb}{}^{*}V_{td})^2}{16\,\pi^2\,M_\mathrm{w}{}^2} + c_{\mathrm{NP}}\,\frac{1}{\Lambda^2}$$

$$\mathscr{L}_{\mathrm{eff}} = \mathscr{L}_{\mathrm{SM}} + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}}\,\mathrm{O}_n{}^d$$



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contrbution of the new
heavy degrees of freedom

c_{NP}

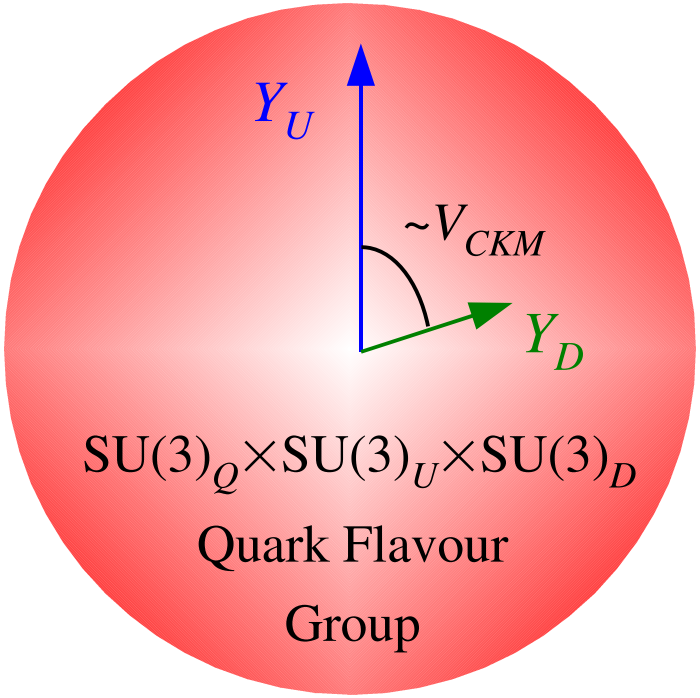
- $\sim 1 \xrightarrow{\text{tree/strong + generic flavour}} \Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\,\pi^2) \xrightarrow{\text{loop + generic flavour}} \Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (V_{ti}{}^{*}V_{tj})^2 \xrightarrow{\text{tree/strong + MFV}} \Lambda \gtrsim 5$ TeV [K & B]
- $\sim (V_{ti}{}^{*}V_{tj})^2/(16\,\pi^2) \xrightarrow{\text{loop + MFV}} \Lambda \gtrsim 0.5$ TeV [K & B]

If you don't think this is an accident of ΔF=2... ⇒ MFV (Minimal Flavour Violation)

A rigorous definition of the Minimal Flavour Violation hypothesis:

The flavour structure of the SM is quite constrained:

- a large global symmetry in the gauge sector
  $U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$
- broken only by the Yukawa couplings
  $Y_D \sim \bar{3}_Q \times 3_D \quad Y_U \sim \bar{3}_Q \times 3_U \quad (Y_E \sim \bar{3}_L \times 3_E)$



$SU(3)_Q \times SU(3)_U \times SU(3)_D$

Quark Flavour

Group

$$\mathscr{L}_{\text{SM}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}}$$

$$\longrightarrow \bar{Q}_L^{\,i}\, Y_U^{ij}\, U_R^{\,j}\, \phi + \bar{Q}_L^{\,i}\, Y_D^{ij}\, D_R^{\,j}\, \phi_c$$

This specific symmetry + symmetry-breaking
pattern is responsible for the GIM suppression of FCNCs,
the suppression of CPV,... *the successful SM predictions in the quark flavour sector*

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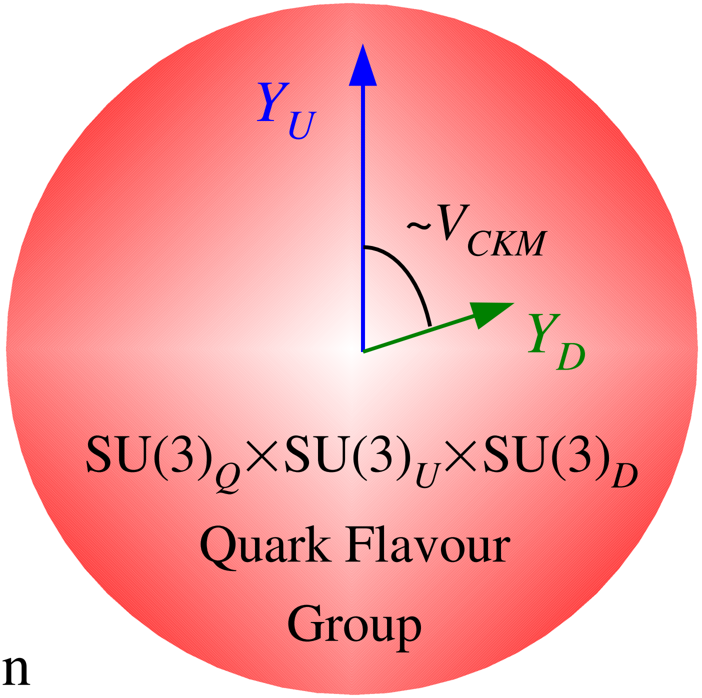
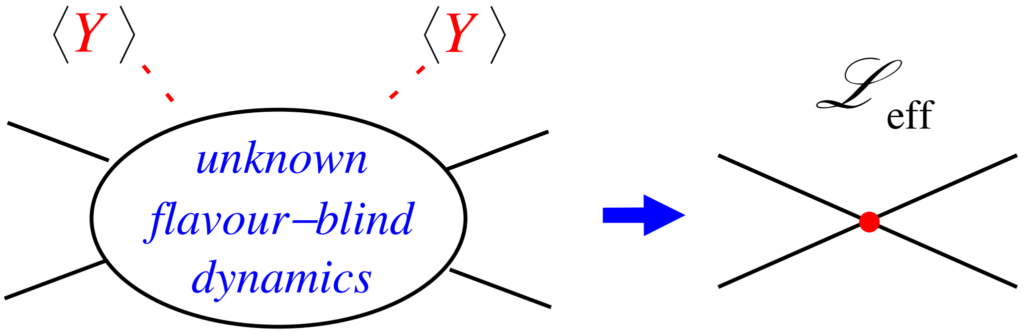


A natural mechanism to reproduce the SM successes in flavour physics -without fine tuning- is the MFV hypothesis:

Yukawa couplings = unique sources of flavour symmetry breaking also beyond SM

General principle which can be applied to any TeV-scale NP model

D'Ambrosio, Giudice, G.I., Strumia '02



A rigorous definition of the Minimal Flavour Violation hypothesis:

basic MFV:

- global symmetry
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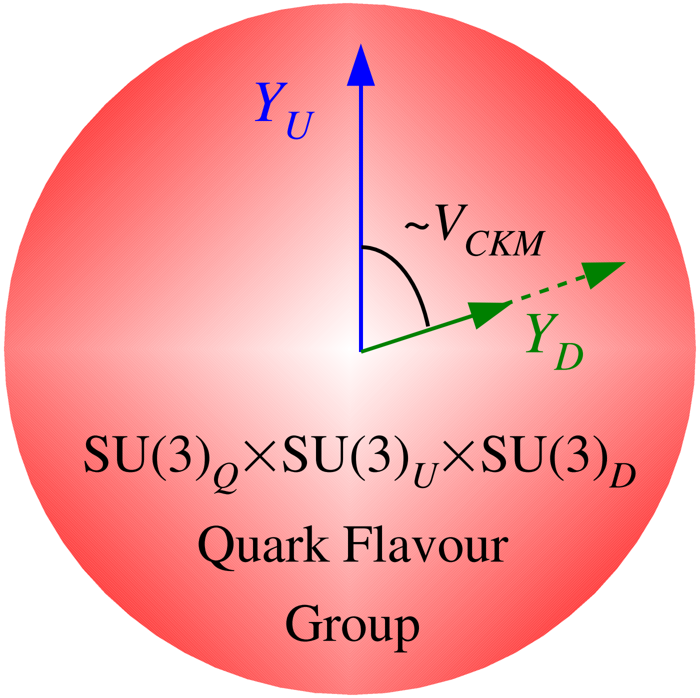

Interesting extension/variation in case of more than one Higgs doublet:

- With two Higgs doublets we can change the relative normalization of Y_U & Y_D (controlled by $\tan\beta = \langle H_U \rangle / \langle H_D \rangle$)

$$\mathcal{L}_{\text{q-Yukawa}} = \bar{Q}_L Y_D D_R H_D + \bar{Q}_L Y_U U_R H_U + \text{h.c.}$$

$$y_u = m_u / \langle H_U \rangle$$

$$y_d = m_d / \langle H_D \rangle = \tan\beta \; m_d / \langle H_U \rangle$$

A few important comments:

I) There is still room for non-MFV effects

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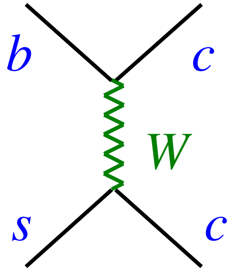
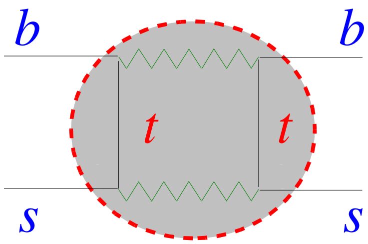
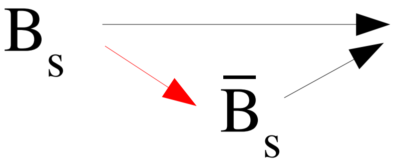
According to a recent analysis by the UTfit collaboration [based on recent CDF & D0 results on $B_s \to \psi\phi$], there is even a hit of a deviation from the SM in the CPV phase of B_s mixing that -*if confirmed*- would rule out both SM and MFV

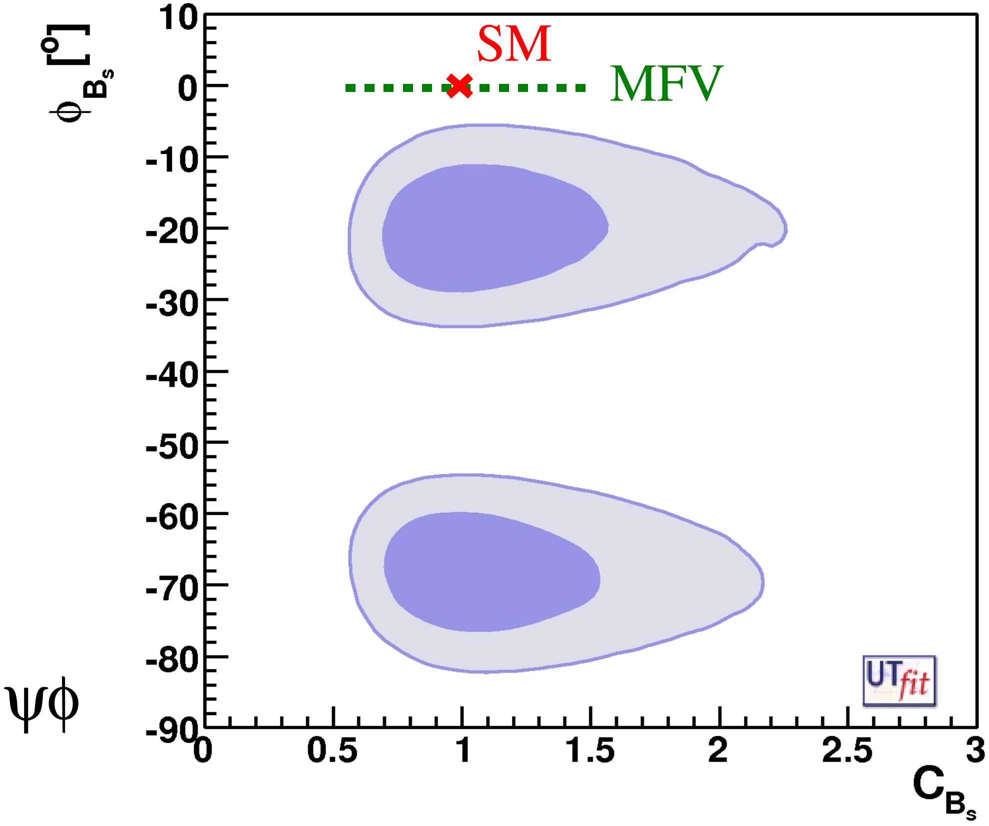
$$C\, e^{2i\phi} = \frac{\langle\, M \mid H^{\mathrm{SM+NP}} \mid \bar{M}\,\rangle}{\langle\, M \mid H^{\mathrm{SM}} \mid \bar{M}\,\rangle}$$






B_s → ψφ
B_s → $\bar{B}_s$ → ψφ

Bona *et al.* arXiv:0803.0659



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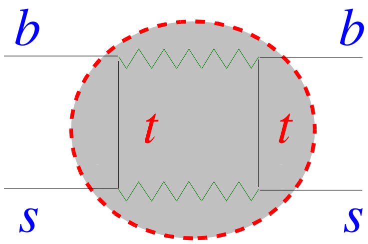
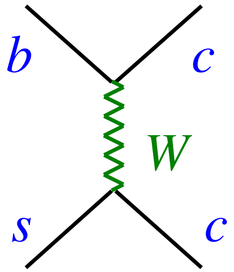
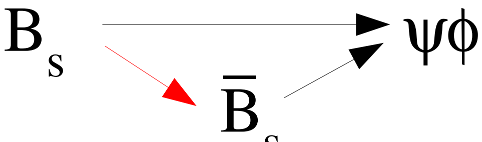
Caution needed given non-Gaussian errors (remember lesson from $B_d \to \phi K$)







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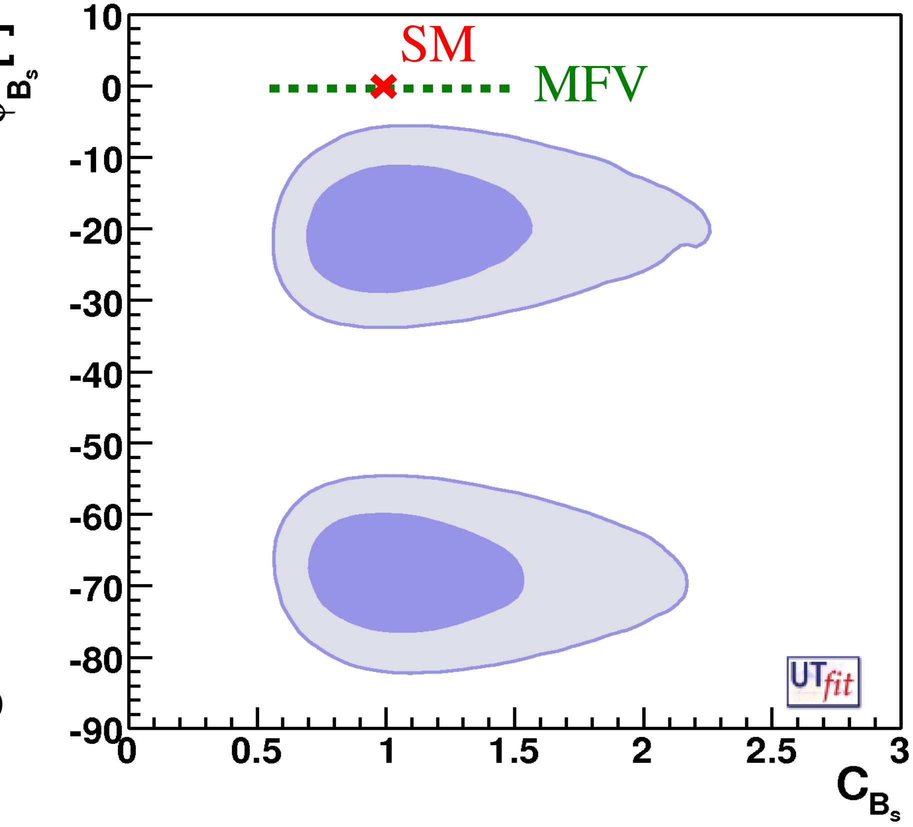

A few important comments:

I) There is still room for non-MFV effects

II) Even if we forget about B_s mixing, MFV is far from being "verified"

To prove MFV from data we would need to

- observe some deviation form the SM in FCNCs
- observe the CKM pattern predicted by MFV [within same type of FCNCs]

$$A_{\mathrm{FCNC}}\,[b \to d(s)] \;\sim\; V_{td(s)} \left[c_{\mathrm{SM}}^{(0)} \frac{1}{M_W^{\;2}} \;+\; c_{\mathrm{NP}}^{(0)} \frac{1}{\Lambda^2} \right]$$

ΔF =2 processes are in principle good candidates to prove MFV,
but so far we are limited by theoretical (Lattice) uncertainties

Some ΔF=1 rare decays could provide more useful infos to proof (or disproof) the MFV hypothesis from data (very interesting candidates: $B_{d,s} \to l^+l^-$)

A few important comments:

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II) Even if we forget about B_s mixing, MFV is far from being “verified”

III) Even within the “pessimisic” MFV hypothesis we can still expect sizable deviations from the SM in various B physics observables

Typical examples:

$B_{d,s} \to l^+ l^-$	up to order of magnitude enhancements if tanβ is large
$A_{FB}(B \to K^* l^+ l^-)$	up to O(1) deviations from the SM

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IV) The fact we have not observed yet a significant deviation from the SM in a few rare B decays (in particular $B \to X_s \gamma$) puts significant constraints on the parameter space of NP models, even if they respect the MFV hypothesis

What we could still hope to learn

Two main roads

MFV

non -MFV

What we could still hope to learn

Two main roads

MFV

non -MFV

- Long list of useful observables (B and K physics: leptonic, radiative & non-leptonic channels)
- The absence of significant deviations from the SM in any of these, makes generic non-MFV scenarios rather contrived / fine-tuned. No clear reference scenarios
- In several realistic cases (MFV-GUT scenarios, new couplings only for the 3rd family, etc...) the most significant constraints are derived from Kaon physics (λ^5 suppression in the SM, because of $1\leftrightarrow3\leftrightarrow2$).

What we could still hope to learn

Two main roads

MFV

Small tanβ
[and small μ]

- Most of the (present) flavour constraints naturally satisfied after imposing EWPO
- Only notable exception provided by $B \to X_s \gamma$

Large tanβ
[or moderate tanβ + large μ]

- A few more helicity suppressed observ. play a key role: $B \to ll$, $B(K) \to l\nu$
- ΔF=2 ops. in B(K) mixing might also be relevant in specific corners of the param. space)

non -MFV

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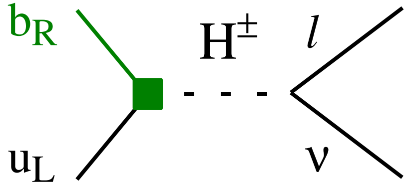
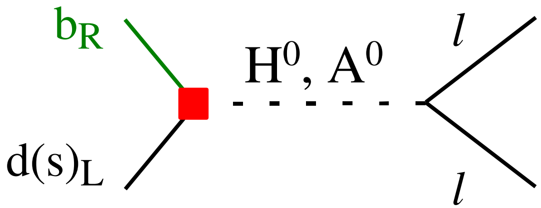
The most interesting observables in the MSSM with MFV:

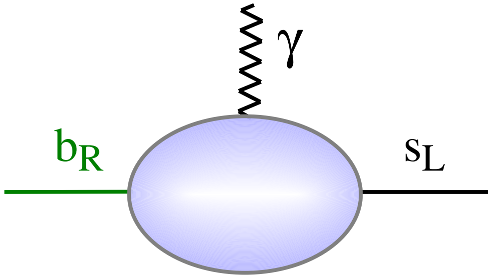


$B^{\pm} \to l^{\pm} \nu$

$(B \to D \tau \nu)$



$B_{s,d} \to l^+ l^-$



$B \to X_s \gamma$

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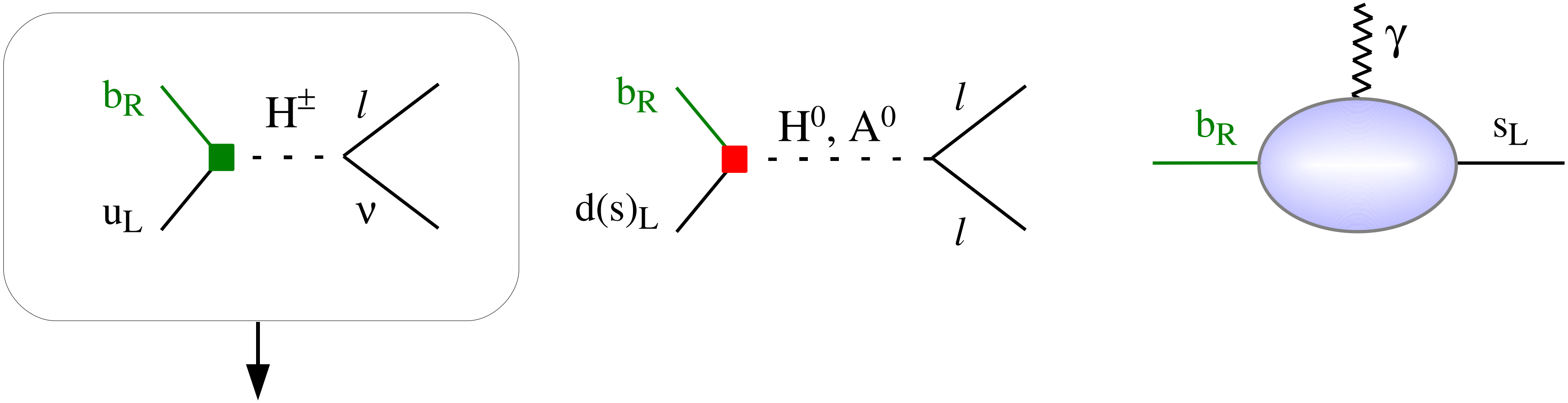


In models with 2 Higgs doublets (such as the MSSM) the $H^\pm$ exchange appear at the tree-level in charged-current amplitudes. The effect is usually negligible (suppression of Yukawa couplings), except for helicity suppressed observables ($B \to l\nu$) or τ final states ($B \to D\tau\nu$)

Simple M_H & tanβ dependence

[mild dependence on other parameters]:

$$B(B \to l\nu) = B_{SM} \left(1 - \frac{m_B^2 \tan\beta^2}{M_H^2 (1 + \epsilon_0 \tan\beta)} \right)^2$$

- O[(10-30)%] effect in $B \to l\nu$
- O[(3-10)%] in $B \to D\tau\nu$
- O[(0.1-0.3)%] in $K \to l\nu$

The most interesting observables in the MSSM with MFV:

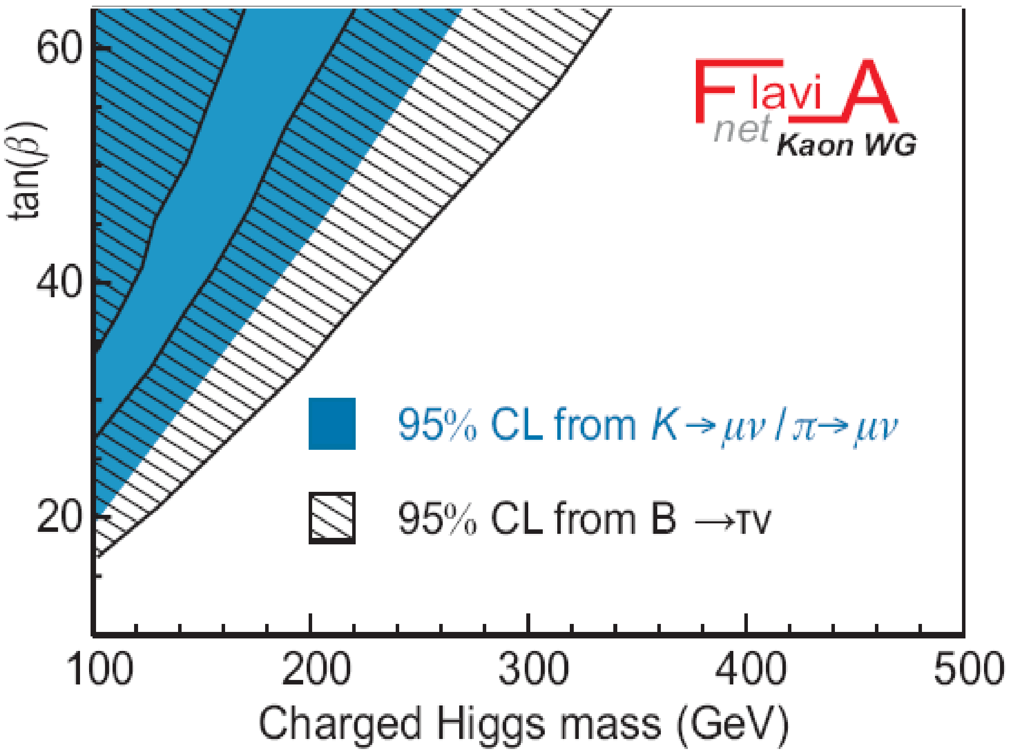
Present status:

$B(B \to \tau\nu) = (1.43 \pm 0.43)\times 10^{-4}$

Babar+Belle '07

$B(B \to \tau\nu)_{SM} = B_0\, F_B^2\, V_{ub}^2 \approx 1.2\times 10^{-4}$

sizable theoretical
(parametric) error

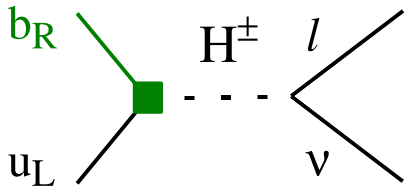


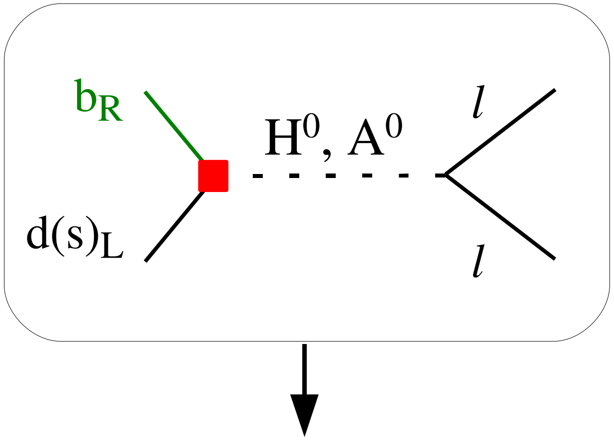
$B(K \to \mu\nu) = (63.66 \pm 0.17)\%$ KLOE '06

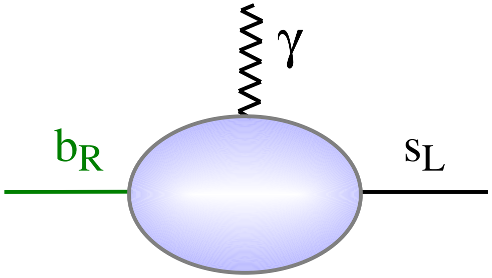
$+\ f_K/f_\pi$ @ 0.7% MILC, UKQCD '07-'08
$+\ V_{us}$ @ 0.5% KLOE, NA48, KTeV '06-'08

Improving th. and exps.
on these channels can
lead to very valuable
infos on M_H & tanβ !

The most interesting observables in the MSSM with MFV:

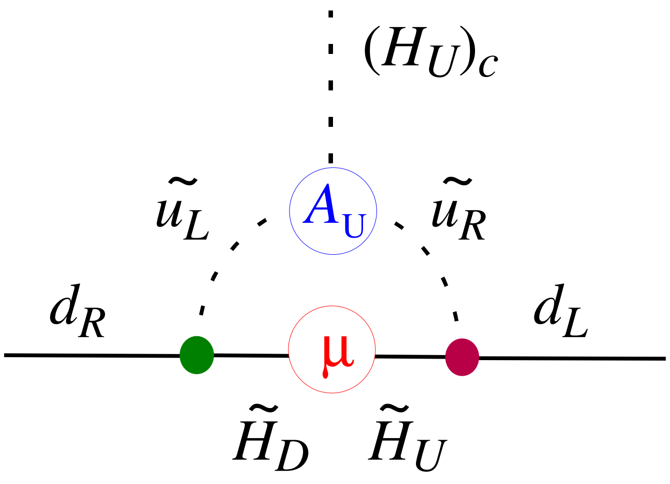






$B \to X_s \gamma$

There are no tree-level FCNC couplings of the neutral Higgses in MFV models; however, effective couplings can appear at the one loop level and they are potentially quite large in the MSSM



Crucial dependence on μ and A_U [+ M_H & $\tan\beta$]

$$A(B\to ll)_H \sim \frac{m_b\, m_l}{M_A^{\;2}}\, \frac{\mu\, A_U}{\tilde{M}_q^{\;2}}\, \tan^3\beta$$

Possible large enhancement over the SM, but the magnitude of the effect can vary a lot in different SUSY-breaking scenarios

The most interesting observables in the MSSM with MFV:

$B(B_s \to \mu\mu)_{SM} \approx 3.5 \times 10^{-9}$

$B(B_d \to \mu\mu)_{SM} \approx 1.3 \times 10^{-10}$

e channels suppressed by $(m_e/m_\mu)^2$

τ channles enhanced by $(m_\tau/m_\mu)^2$

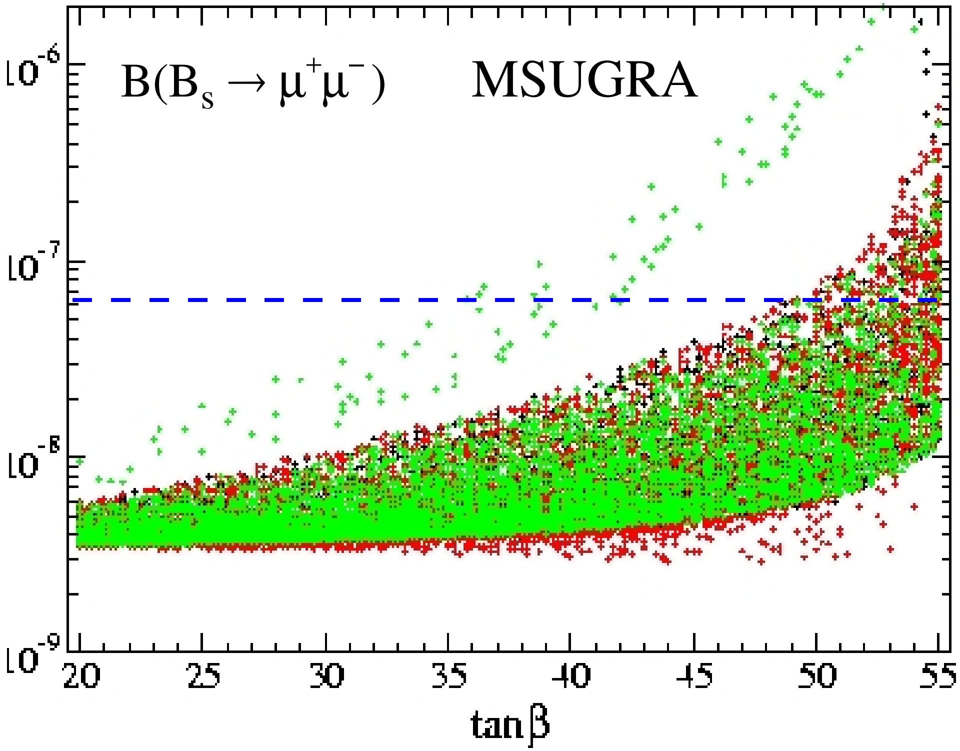
Most interesting bound set by:

$B(B_s \to \mu\mu) < 5.8 \times 10^{-8}$ (95%CL)

CDF+D0 '07

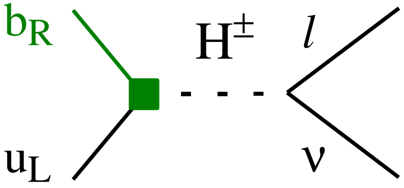
Significant constraint, but a good fraction of the parameter space is still allowed

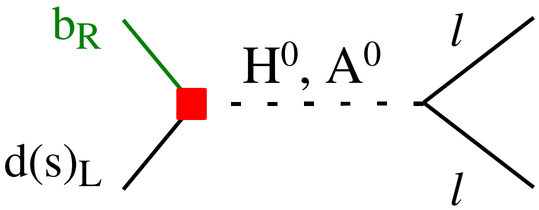
N.B.: the $B(B_d \to \mu\mu)/B(B_s \to \mu\mu)$ ratio is a key observable to proof or falsify MFV

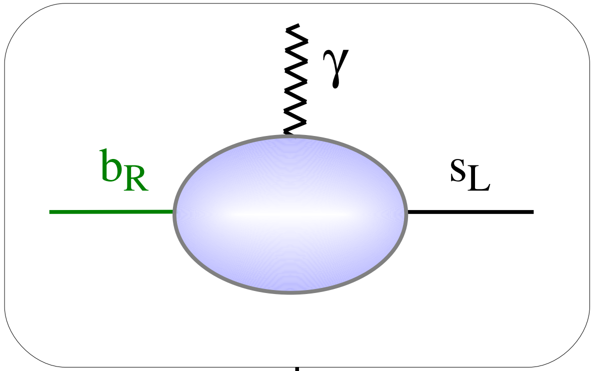


Kane *et al.* '03

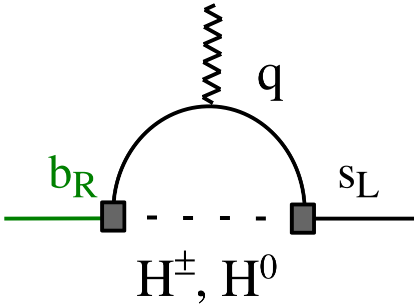
The most interesting observables in the MSSM with MFV:



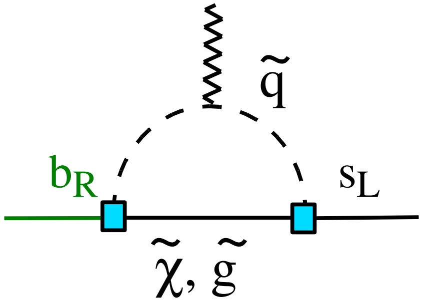




Most complicated observable with several, naturally competitive, contributions:

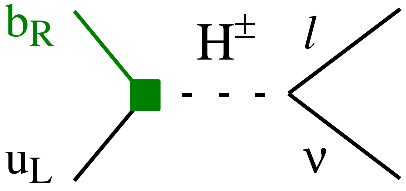


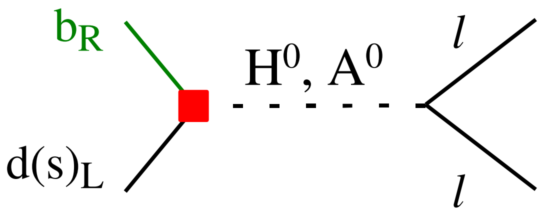
- positive
- decreasing with tanβ

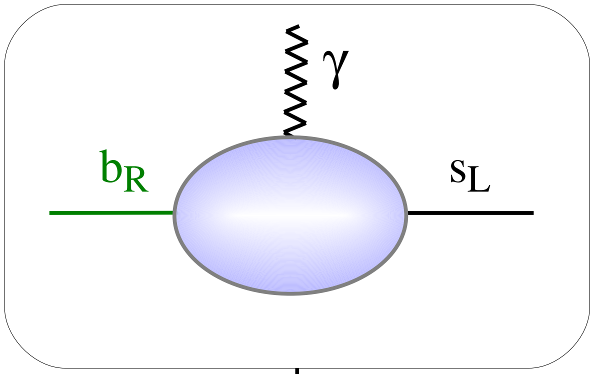


- sign ~ sgn(μ,A)
- increasing with tanβ

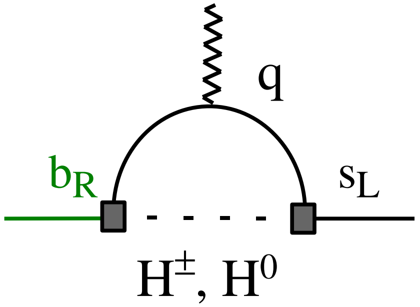
The most interesting observables in the MSSM with MFV:

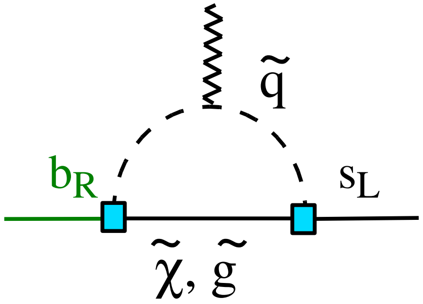






Most complicated observable with several, naturally competitive, contributions:





- positive
- decreasing with tanβ

- sign ~ sgn(μ,A)
- increasing with tanβ

One of the most significant constraint of the MSSM (even at small tanβ)

$$B(B \to X_s\gamma)^{\mathrm{exp}} = (3.55 \pm 0.26)\times 10^{-4}$$

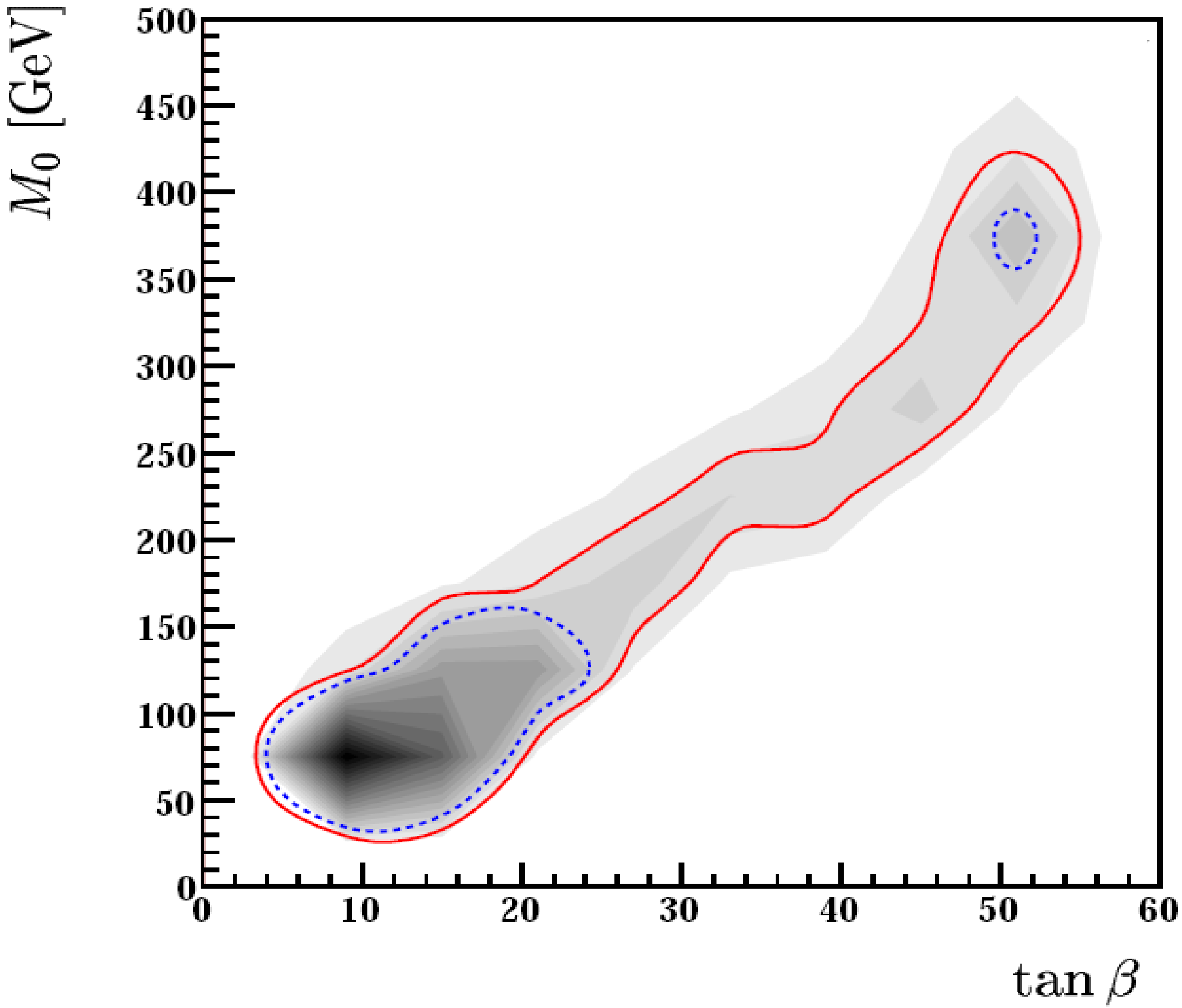
HFAG '06

$$B(B \to X_s\gamma)^{\mathrm{SM}} = (3.15 \pm 0.23)\times 10^{-4}$$

Misiak et al. '06

E.g.: The role of indirect constraints in a global fit of the CMSSM:

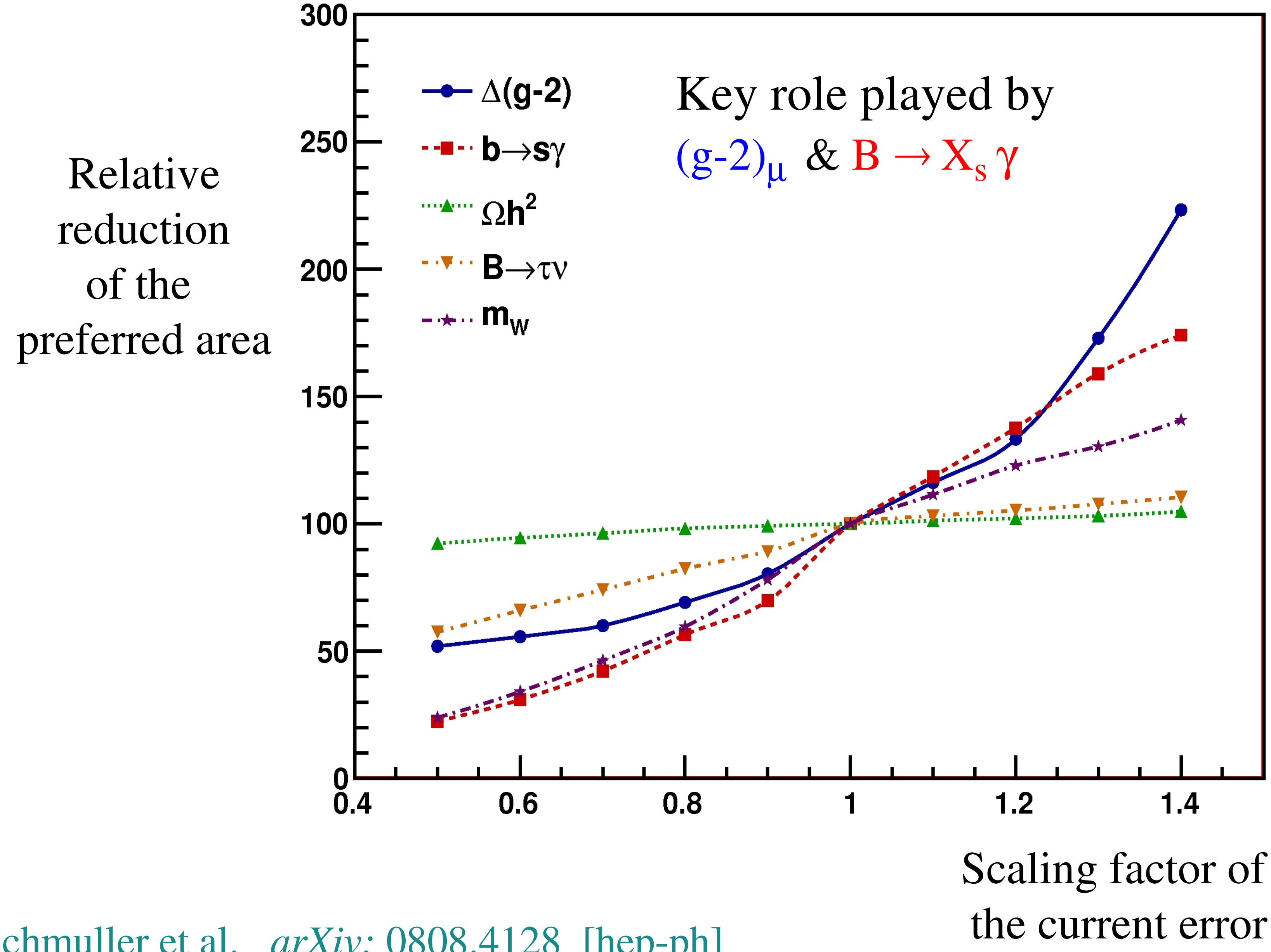
- Multi-parameter χ^2 fit
- fitting for all CMSSM parameters: M_0, $M_{1/2}$, A_0, $\tan\beta$;
- including relevant SM uncertainties (*e.g.* $m_{\rm top}$);



- overall preferred minimum at low $\tan\beta$, low squark mass;
- less preferred region at high $\tan\beta$, higher squark mass;
- consistent with previous studies.

Buchmuller et al.
arXiv: 0707.3447 [hep-ph]

E.g.: The role of indirect constraints in a global fit of the CMSSM:

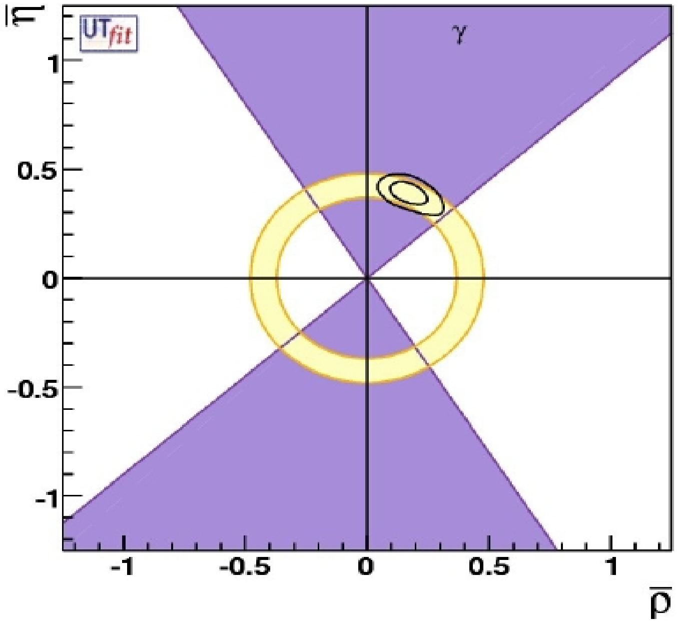


Key role played by $(g\text{-}2)_\mu$ & $B \to X_s\,\gamma$

Buchmuller et al. *arXiv:* 0808.4128 [hep-ph]

Other observables (a very incomplete list):

I. *Improved CKM fits*

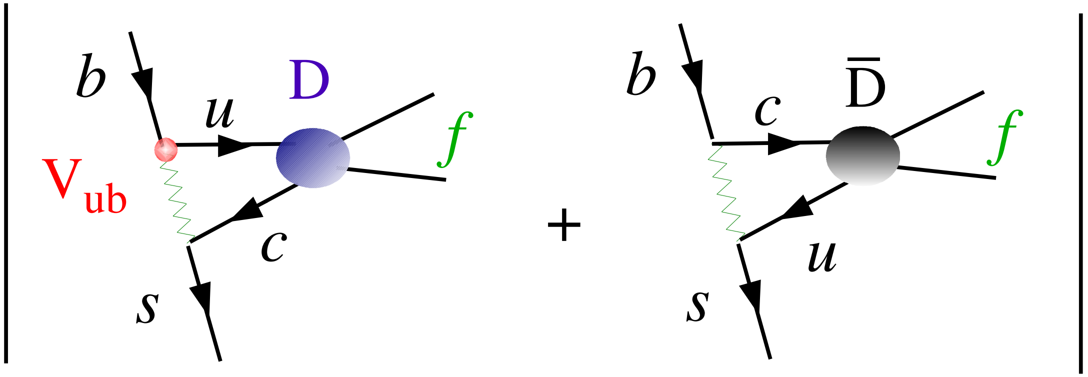


Improving the determination of the CKM matrix from tree-level processes offer a valuable tool to improve constraints on NP (including MFV models).

Key measurements:

- γ from various $B_{(s)} \to D(\bar{D})$ modes

good prospects of improvements from LHCb



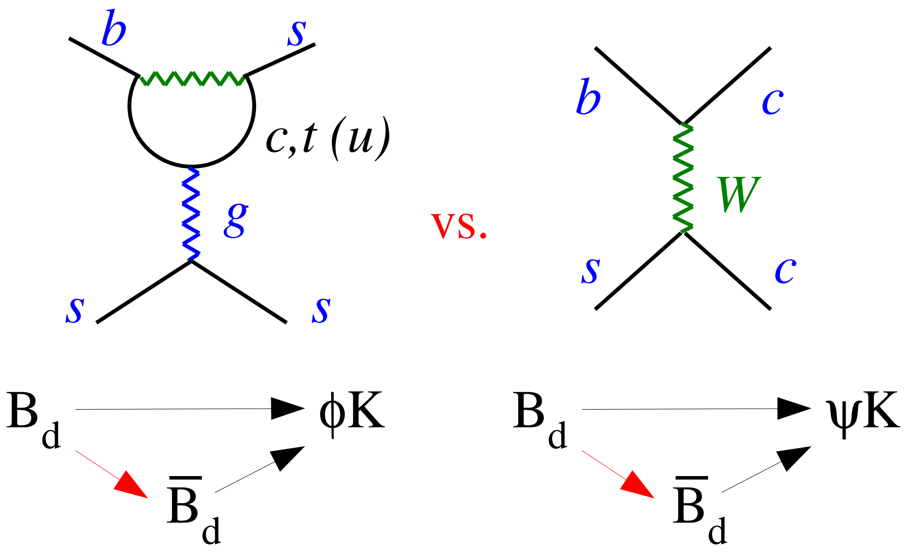
All relevant hadronic parameters extracted from data with no theoretical assumptions

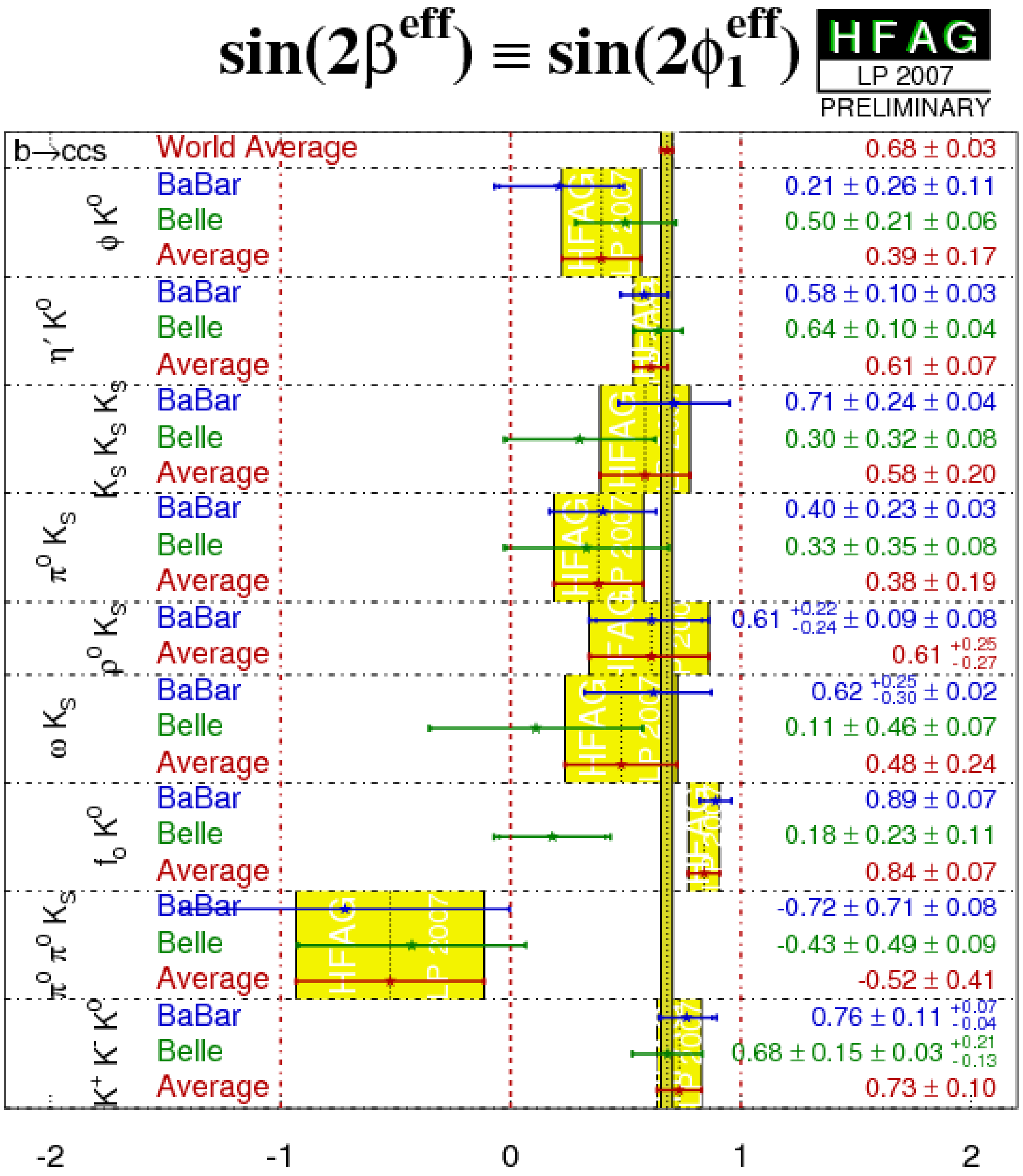
Other observables (a very incomplete list):

II. *Time-dependent CPV*

Is there still some hope to observe *significant* NP effects in time-dep. CPV asymmetries in $b \to s$ hadronic-penguin modes ?

E.g.:





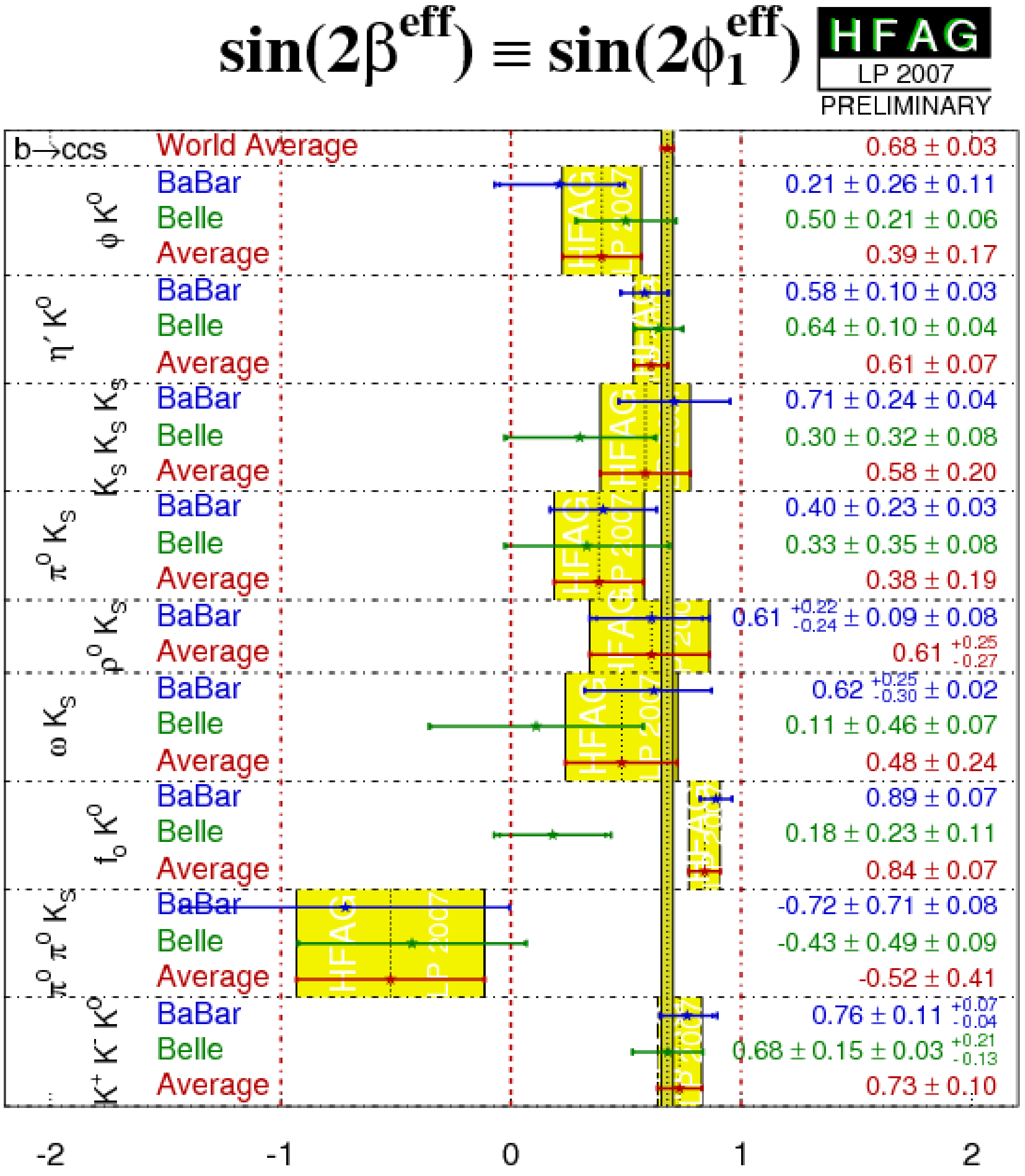
Other observables (a very incomplete list):

II. *Time-dependent CPV*

Is there still some hope to observe *significant* NP effects in time-dep. CPV asymmetries in b→s hadronic-penguin modes ?

Personally I'm quite skeptical...

- Best observables [high stat. + full Dalitz Plot analysis] show no significant effect
- We are already close to the level of irredcible th. errors [remember the ε'/ε lesson...]

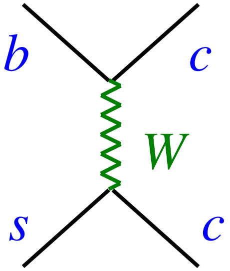


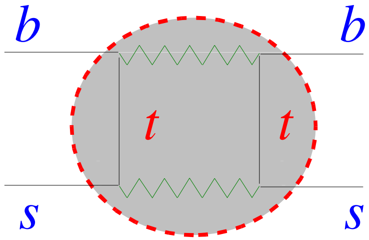
Other observables (a very incomplete list):

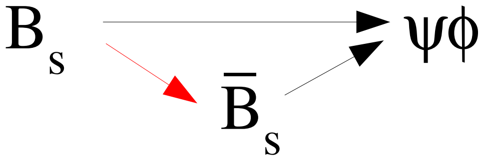
II. *Time-dependent CPV*

The time-dependent CPV asymmetry which is definitely worth to improve in the LHC era is the phase of B_s mixing from $B_s \to \psi\phi$ ⇒ Tevatron/LHCb

New theoretically clean observable which could allow to falsify MFV [or to constraint viable non-MFV models] in the $\Delta F = 2$ sector







Other observables (a very incomplete list):

III. *Lepton Flavour Violation*

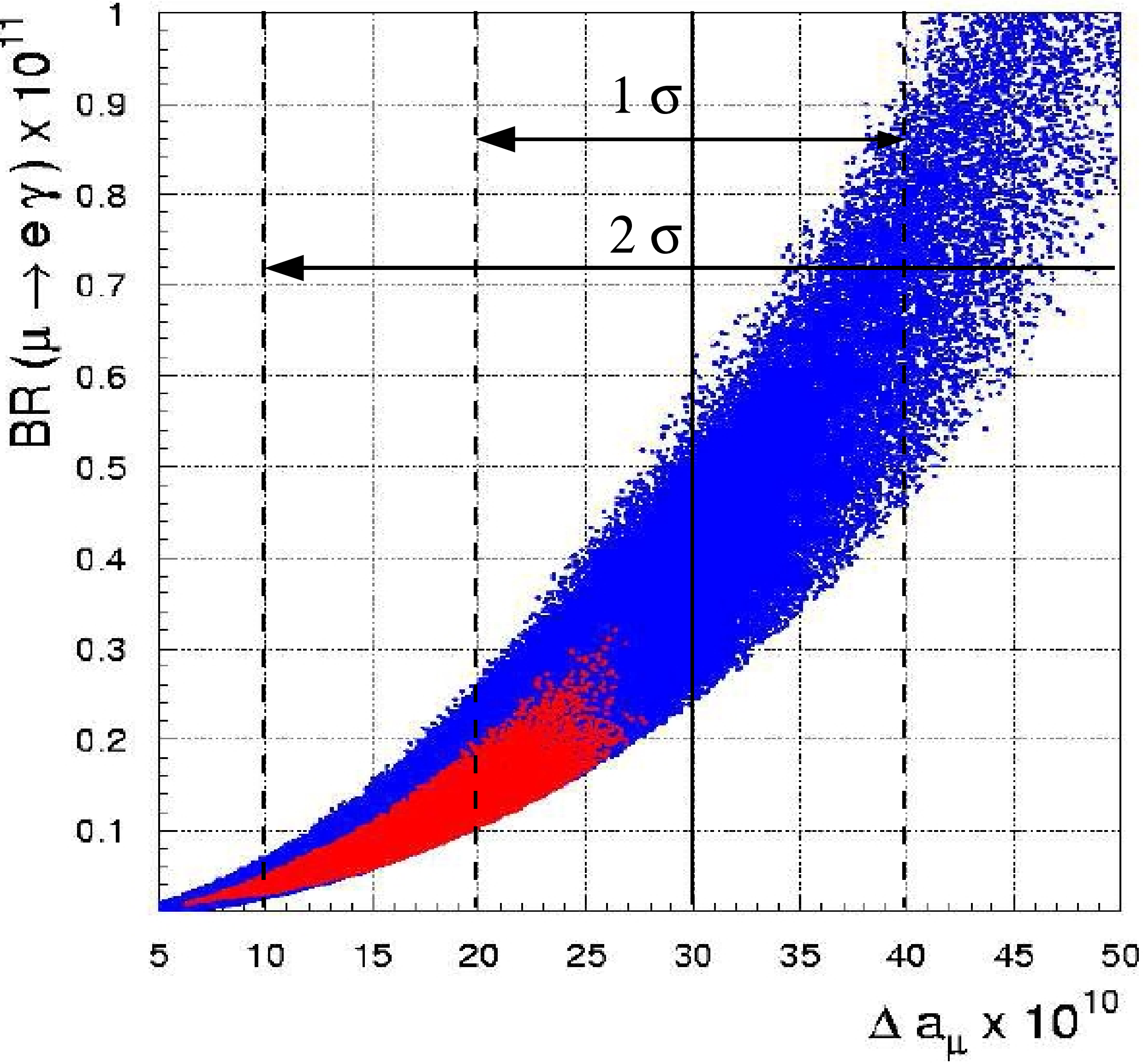
After what we learned from neutrino physics, LFV in charged leptons is probably the most interesting search in the flavour sector.

Good prospects in several SUSY-GUT models

E.g. MSSM + heavy ν_R →

$M_R \sim 10^{12}$ GeV $\Rightarrow$ $(\delta_{LL})_{12} \sim 10^{-4}$

- 🟦 No constraints from B physics
- 🟥 With B physics constraints



▶ Conclusions

We learned a lot about flavour physics in the recent past...
..but what is still to be discovered is more !

TeV-scale NP models must have a rather sophisticated flavour structure (not to be excluded by present data) but we have not clearly identified this structure yet

⬇

Very important to continue high-precision flavour physics in the LHC era

- There is not a unique (or a unique class) of outstanding observable(s), we need to improve in several directions: B, τ, K, μ rare decays and/or theoretically-clean observables [*leptonic/semileptonic final states*]

- Full complementarity both between low-energy and high-Pt physics, and also between different low-energy facilities