MFV vs. NMFV: Theory Overview

Gino Isidori
[*INFN, Frascati & IAS-TUM, Munich*]

- About the interplay of high-p_T and low-energy flavour physics
- What we learned so far from: the global picture
- Looking more closely: some *hints* of deviations from the SM
- MFV vs NMFV: what we could still hope to learn al low-energies
- Conclusions

About the interplay of high-p_T and low-energy flavour physics

Two main roads to explore physics beyond the SM:

- High-energy experiments [*the high-energy frontier*]
  - Which is the energy scale of New Physics, and which are its "gross features"
- High-precision low-energy exp. [*the high-intensity frontier*]
  - Which is the symmetry structure of the new degrees of freedom

Natural interplay of these two appraoches in constraining NP.

In general this interplay can be fully explored only if we select a specific NP model (explicit evaluation of the correlations between high-p & low-energy effects)
$\Rightarrow$ hard to play this game without clear non-SM clues on both sides...

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But there are also interesting questions we can adress considering only one the two roads, such as: *"which are the sources of flavour-symmetry breaking in the quark sector?"* The answer to this question is likely to come only (or mainly) from the low-energy side (the situation of the lepton sector may be quite different....)

About the interplay of high-p_T and low-energy flavour physics

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In order to pose (and try to answer) this question in general terms, we can analyse the extesnions fo the SM using a generic effective theory approach (*a bit boring... but is definitely quite general*)

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In order to pose (and try to answer) this question in general terms, we can analyse the extesnions fo the SM using a generic effective theory approach (*a bit boring... but is definitely quite general*):

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm gauge}(A_a, \psi_i) + \mathcal{L}_{\rm Higgs}(\phi, A_a, \psi_i) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

$\mathcal{L}_{\rm SM}$ = renormalizable part of $\mathcal{L}_{\rm eff}$
[= all possible operators with $d \leq 4$ compatible with the gauge symmetry]

Λ = effective scale of new physics (cut-off of the eff. theory)

operators of $d\geq 5$ containing SM fields only and compatible with the SM gauge symmetry

[=most general parameterization of the new (heavy) degrees of freedom, as long as we perform low-energy experiments]

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→ 3 identical replica of the basic fermion family [$\psi_i = Q_L, u_R, d_R, L_L, e_R$]

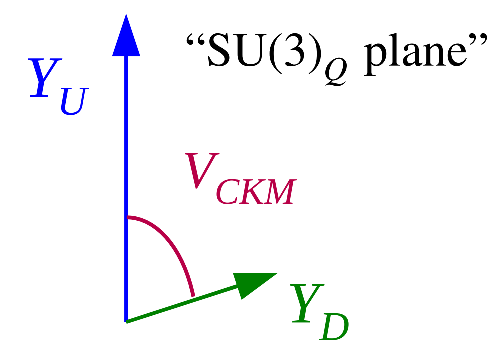
Large global <u>flavour symmetry</u>: $U(1)_L \times U(2)_B \times SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$

→ Flavour-degeneracy broken the Yukawa interaction:

in the quark sector:

$$\bar{Q}_L^{\,i}\, Y_D^{\,ik}\, d_R^{\,k}\, \phi \;\rightarrow\; \bar{Q}_L^{\,i}\, M_D^{\,ik}\, d_R^{\,k}$$

$$\bar{Q}_L^{\,i}\, Y_U^{\,ik}\, u_R^{\,k}\, \phi_c \;\rightarrow\; \bar{Q}_L^{\,i}\, M_U^{\,ik}\, u_R^{\,k}$$



$$M_D = {\rm diag}(m_d, m_s, m_b) \qquad M_U = V^{+} \times {\rm diag}(m_u, m_c, m_t)$$

(*The flavour structure of the SM*)

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vs.

natural... *...artificial*

(*The flavour structure of the SM*) (*The flavour structure BSM*)

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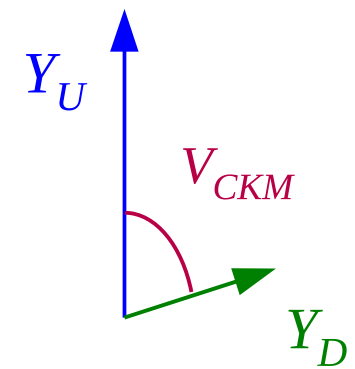
This is why MFV is quite popular...

MFV = *assumption that the SM Yukawa couplings are the only non-trivial flavour-breaking terms also beyond the SM*



Symmetry + Symmetry-breaking

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

$Y_D \sim (3,1,\bar{3})$ $Y_U \sim (3,\bar{3},1)$

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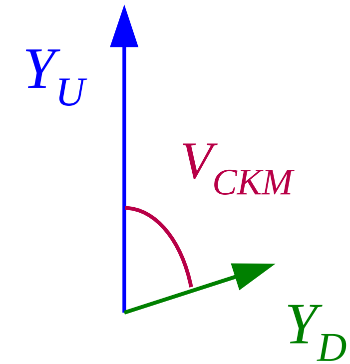


MFV = *assumption that the SM Yukawa couplings are the only non-trivial flavour-breaking terms also beyond the SM*

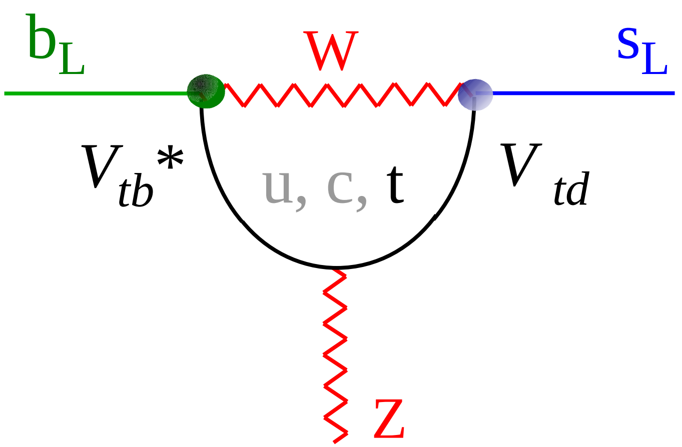
However, at this stage these is still a theoretical speculation (mainly driven by $\Delta F=2$ data) far from being clearly established

One of the main goal of flavour physics is trying to understand if there are additional non-trivial flavour breaking terms beside the SM Yukawas

The fact that -within the SM- flavour dynamics is controlled by the Yukawas is particularly clear in flavour-changing-neutral currents (FCNCs):

- No tree-level contribution
- One-loop contribution dominated by top-quark loops because $A \sim m_{up}^2$ ("hard" GIM mechanism or apparent non-decoupling behaviour)

E.g.: $b \to s + Z (\to l^+l^-, \nu\nu)$



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- No tree-level contribution
- One-loop contribution dominated by top-quark loops because $A \sim m_{up}^2$ ("hard" GIM mechanism or apparent non-decoupling behaviour)
- The origin of this behaviour is clear if we keep separated gauge and Yukawa interactions (the leading term surives even in the *gauge-less* limit of the SM)

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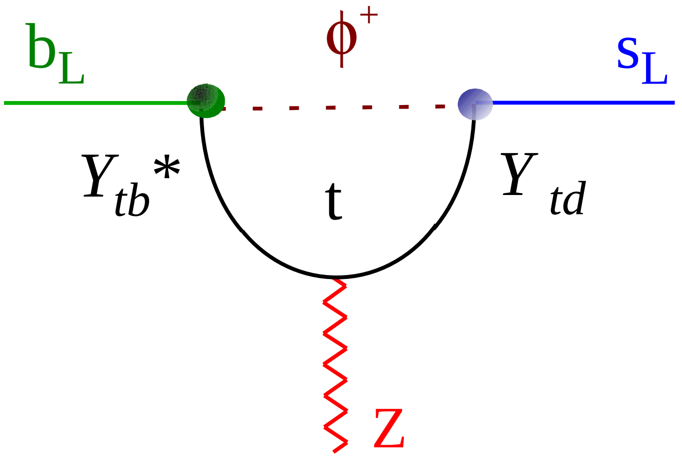
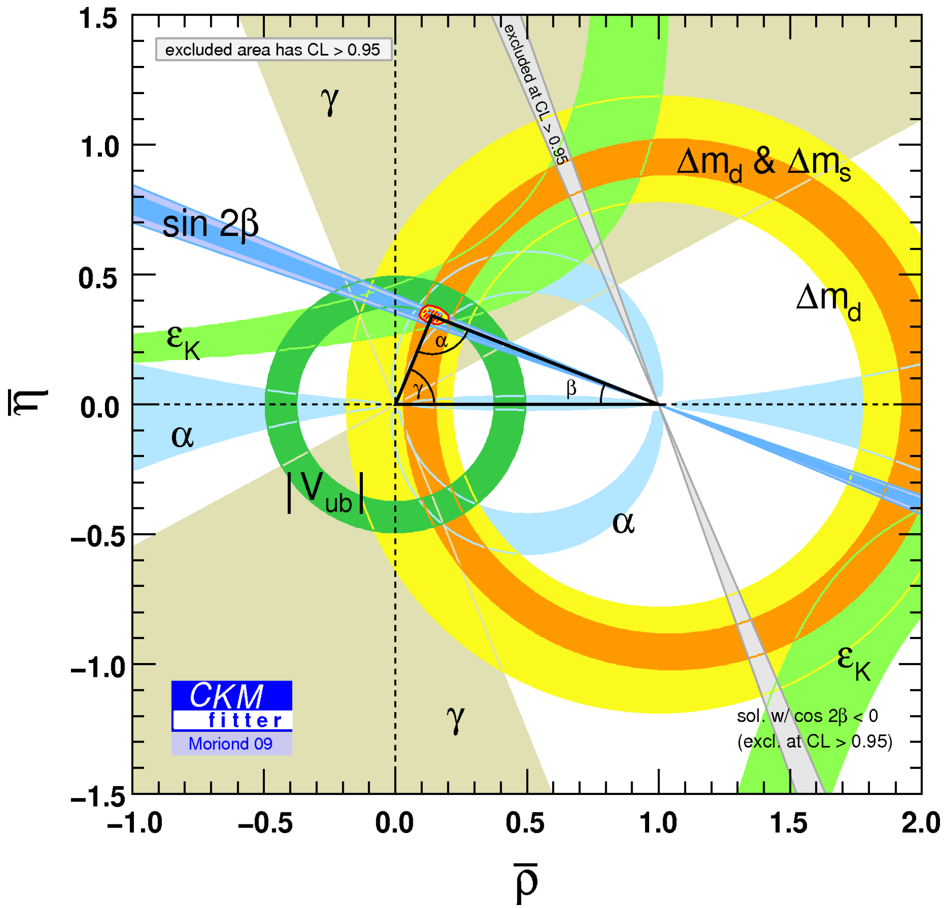


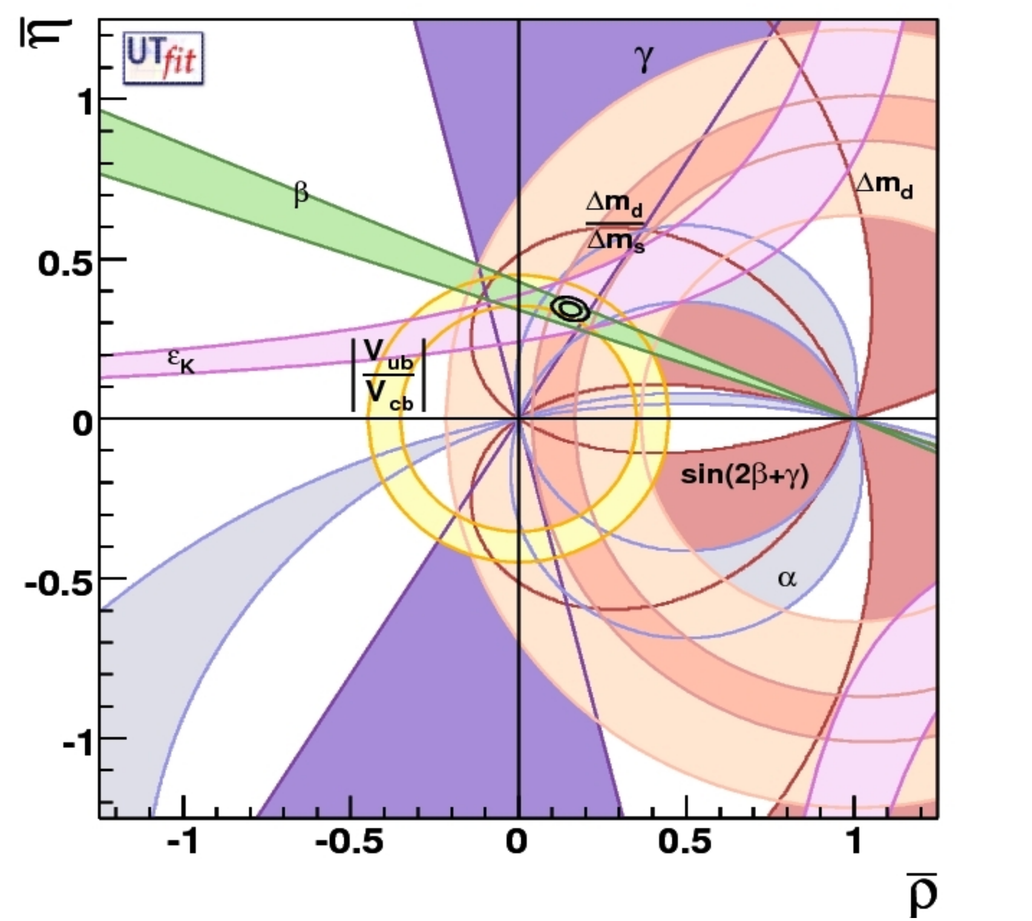
In such processes we are testing in depth the interplay of the gauge-symmetry and flavour-symmetry breaking mechanisms of the SM

What we learned so far: the global picture

The SM is very successful in describing quark-flavour mixing !

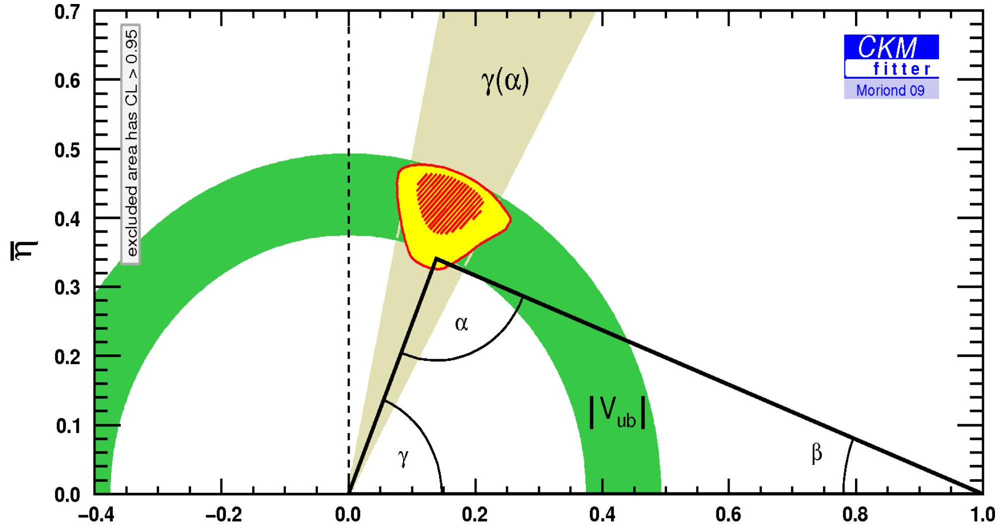
This is quite clear by looking at the consistency of the experimental constraints appearing in the so called CKM fits, but there are several more observables not shown in such fits that point in the same direction.





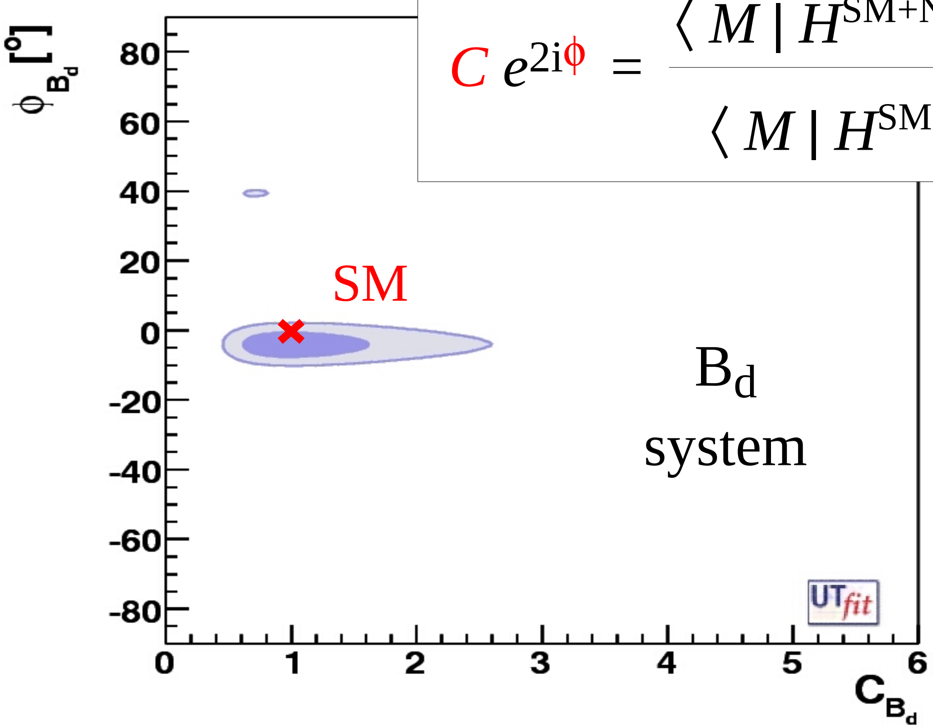
I. The CKM fits [constraints in the ρ–η plane]

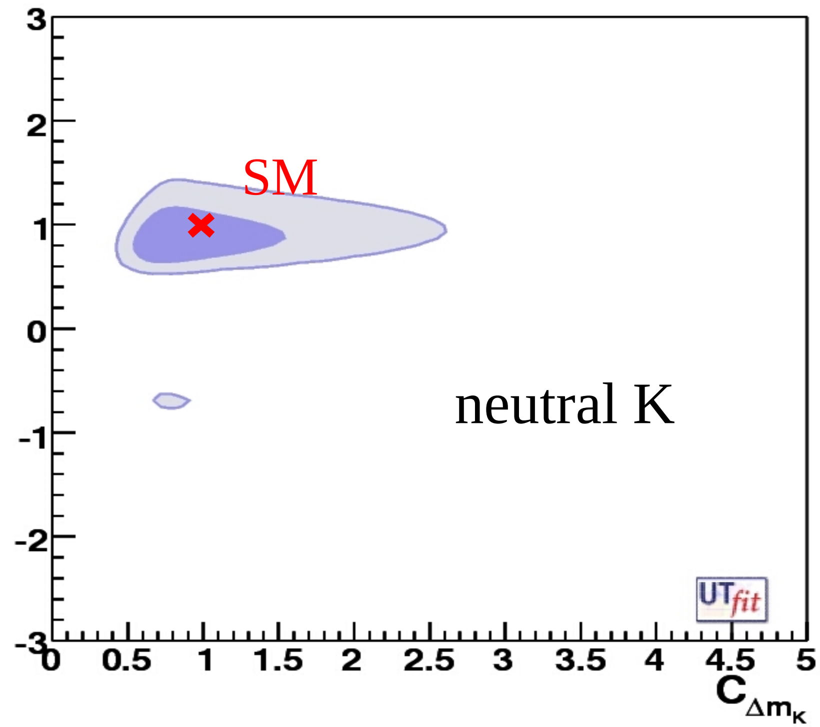
CKM unitarity triangle using only tree-level dominated amplitudes →



General fit of NP in ΔF=2 amplitudes

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





I. The CKM fits [constraints in the ρ–η plane]

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

$$M(B_d\text{-}\bar{B}_d) \sim \frac{(V_{tb}{}^* V_{td})^2}{16\,\pi^2 M_W{}^2} + c_{NP}\frac{1}{\Lambda^2}$$

← contrbution of the new heavy degrees of freedom

c_{NP}:

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

This is why MFV (or something very similar at least for $s\to d$ & $b\to d$ $\Delta F=2$), is mandatory if we want to keep Λ in the TeV range

II. Rare decays

Good agreement with SM expectations is found also in rare FCNC ΔF=1 decays.
Most remarkable example: $B \to X_s \gamma$

Most accurate SM th. estimate:

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

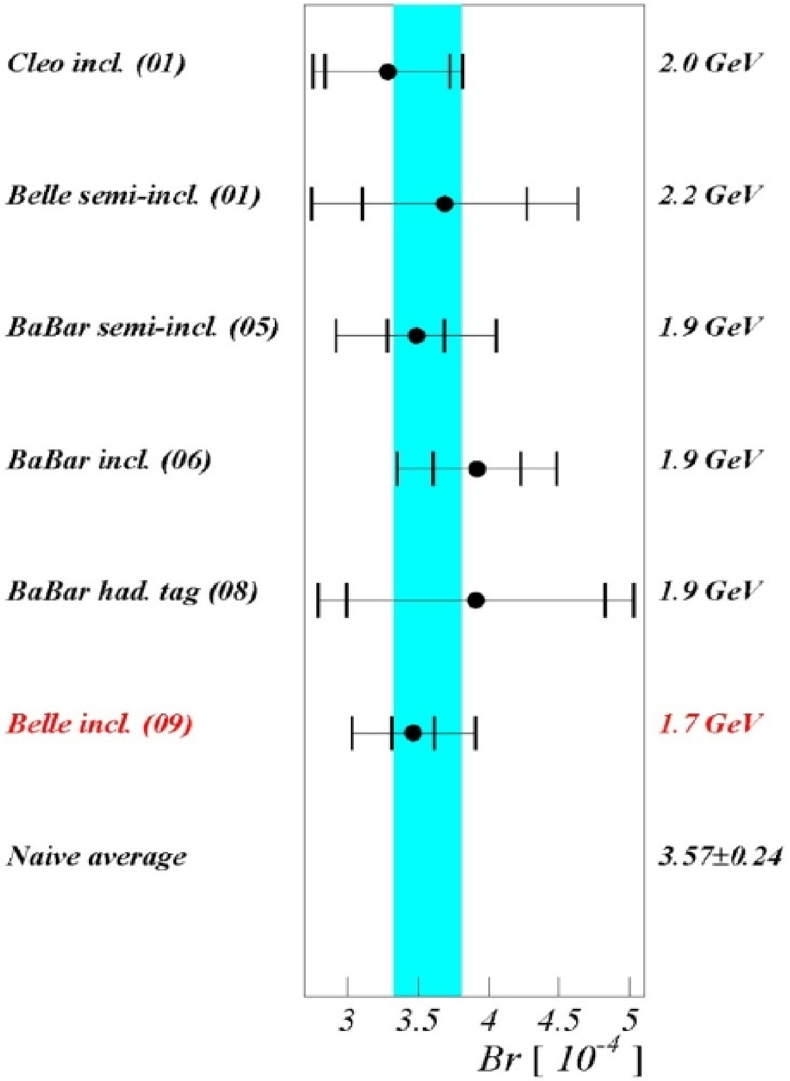
[Misiak *et al.* '07]

- NNLO perturbative calculation
- Inclusive non-pert. effects using HQET
- E_γ cut controlled by shape-function analysis
- Hard (impossible ?) to improve further in the near future...

To be compared with:

$$\mathcal{B}(B \to X_s\gamma) = (3.57 \pm 0.24) \times 10^{-4}$$

[2009 exp. WA]



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One of the most significant constraint in many SM extensions (*with MFV as stringent as EW precision observables*)

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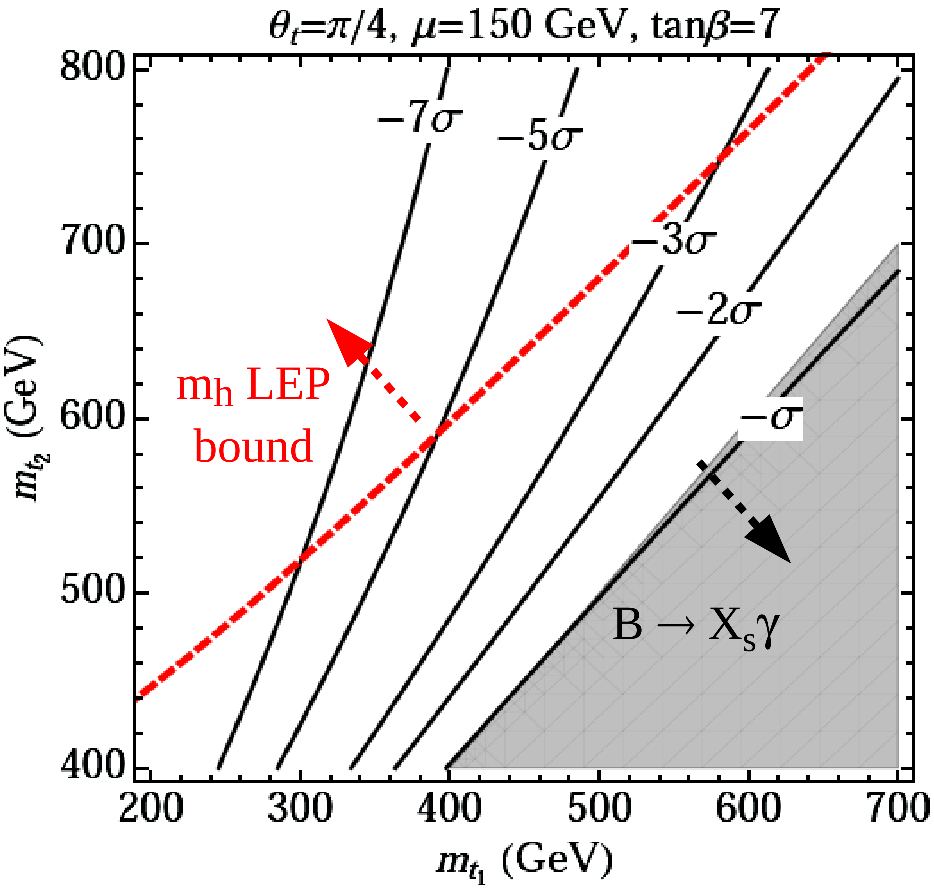
E.g.: *contraints on the stop sector of the MSSM*
[with MFV & heavy gauginos]



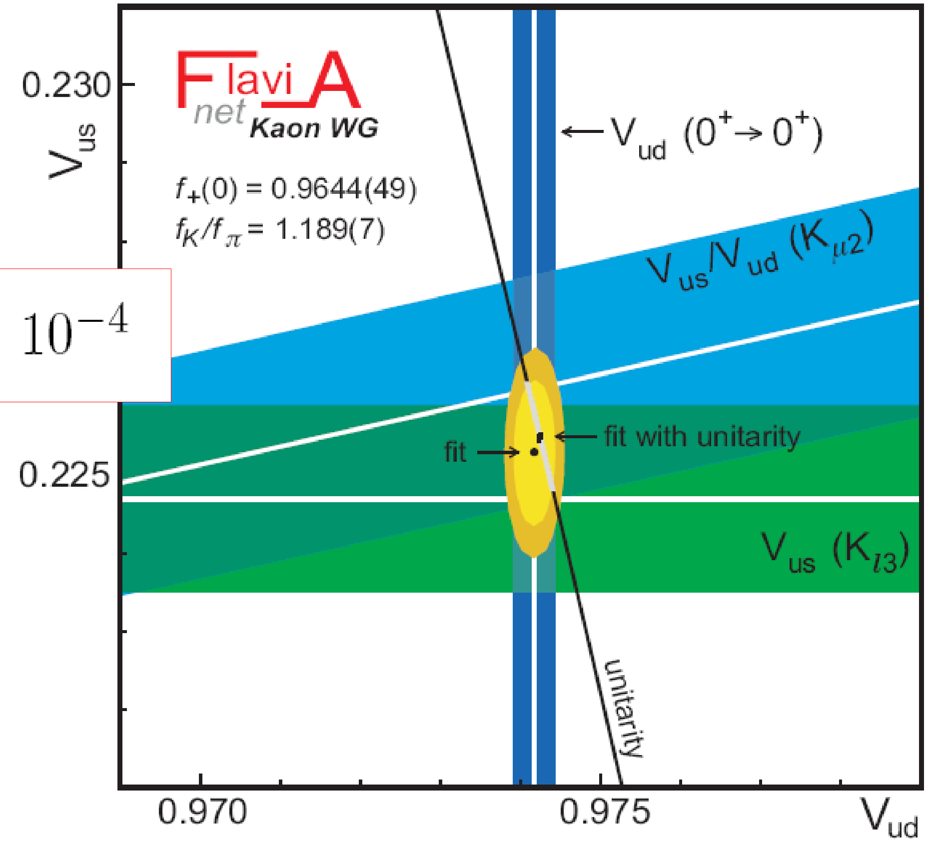
Barbieri & Pappadopulo '09

III. Vus & CKM Unitarity

An impressive progress has been obtained also in testsing charged-current interactions:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = (-1 \pm 6) \times 10^{-4}$$

few 0.1% error !



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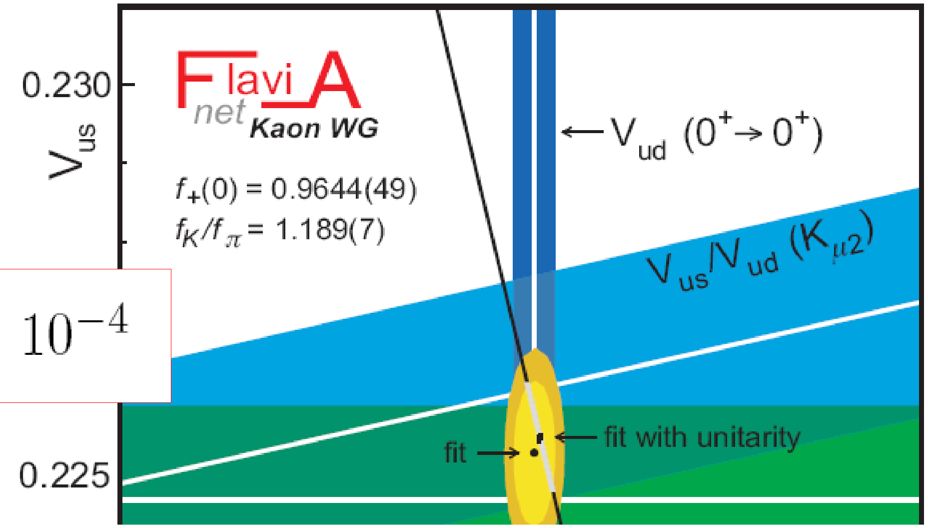


$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = (-1 \pm 6) \times 10^{-4}$$

Very challenging for all extensions of the SM predicting some breaking of universality between quarks & leptons (*strong e.w. symm. breaking*, *extra dim*....)

$$\mathscr{L}_{\text{c.c.-eff.}} = G_F^{CKM} (U_L \gamma_\mu D_L)(l_L \gamma_\mu \nu_L) + G_F^{(\mu)} (\nu_L \gamma_\mu l_L)(l_L \gamma_\mu \nu_L) + \ldots$$

$$G_F^{CKM} = G_F^{(\mu)} [\, |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \,]^{(1/2)}$$

$$G_F^{CKM} - G_F^{(\mu)} = \frac{c^{(i)}}{\Lambda^2}$$

bounds on Λ of several TeV

Cirigliano *et al.* '09

Looking more closely: some hints of deviations from the SM

Looking more closely, there are also a few observables where the agreement with the SM is not so good, such as

- $A_{FB}(B\to K^* l^+ l^-)$, CPV in B_s mixing, $B\to\tau\nu$
- Non-leptonic direct CPV in $B\to K\pi$
- Time-dependent CPV in $b\to s$ penguin modes

But we are still far from claiming serious discrepancies either because of limited statistics, or because of uncontrolled/underestimated theory errors, or because of both...

I. $A_{FB}(B \to K^* l^+ l^-)$

$$A_{FB} = \int \frac{d^2 B(B \to K^* \mu^+ \mu^-)}{ds\, d\cos\theta} sgn(\cos\theta) \quad \propto \quad \Re\left\{ C_{10}^* \left[s C_9 + r(s) C_7 \right] \right\}$$

θ = angle between μ^+ & B momenta in the dilepton rest frame

q^2 = dilepton inv. mass
$s = q^2/M_B^2$

- Direct access to the *relative phases* of the Wilson coeff.
- Proportional to C_{10} (interf. of axial & vector currents)
- Uncertainties of hadronic form factors under control in the low-q^2 region (pQCD, sum-rules)

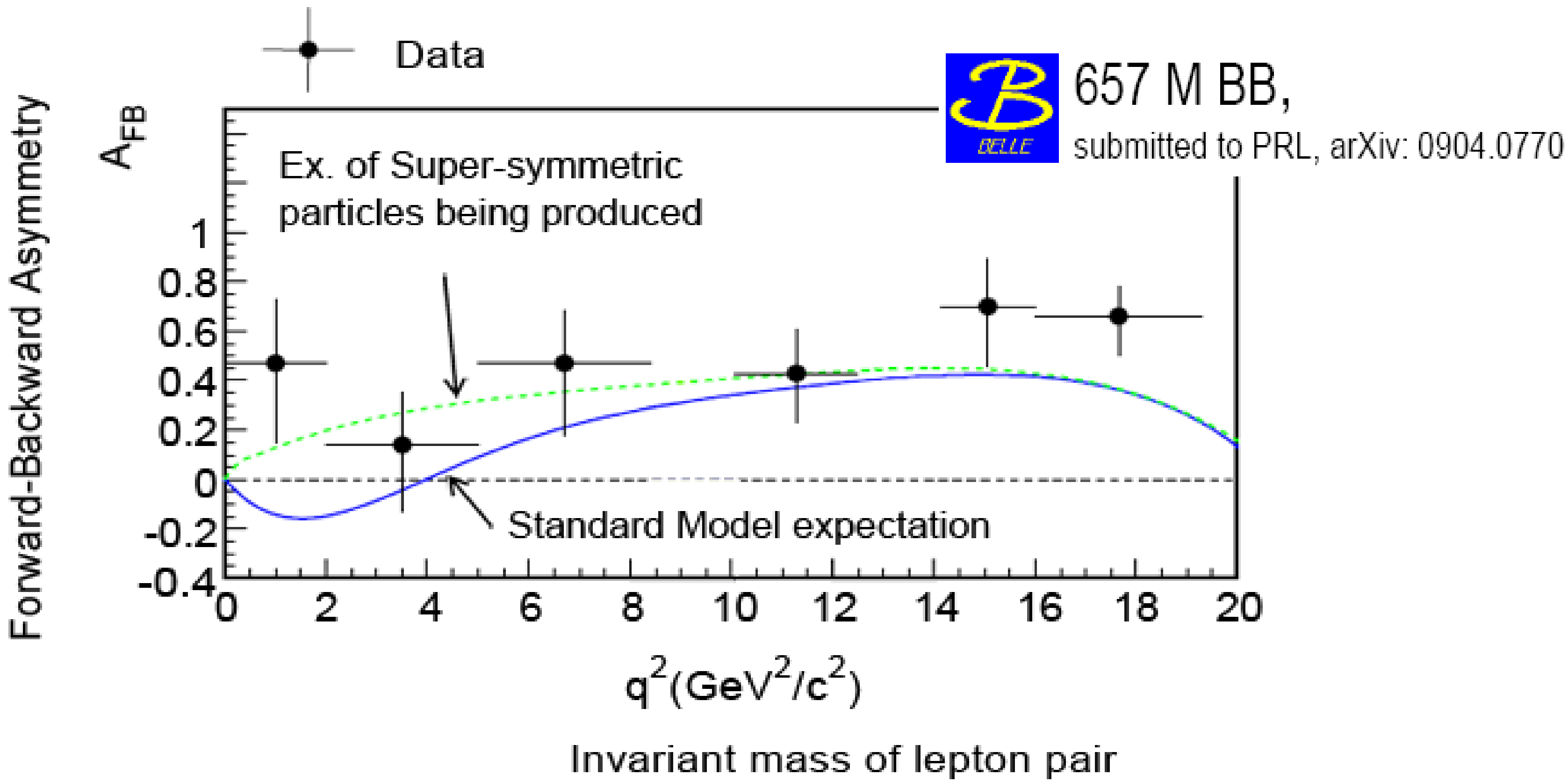
⬇

Sensitive test of various realistic extensions of the SM
(e.g. non-standard Zbs effective coupling)

wide literature, recent update by Altmannshofer *et al.* '09

I. $A_{FB}(B \to K^* l^+ l^-)$

Belle has just reached an interesting sensitivity on this observable:



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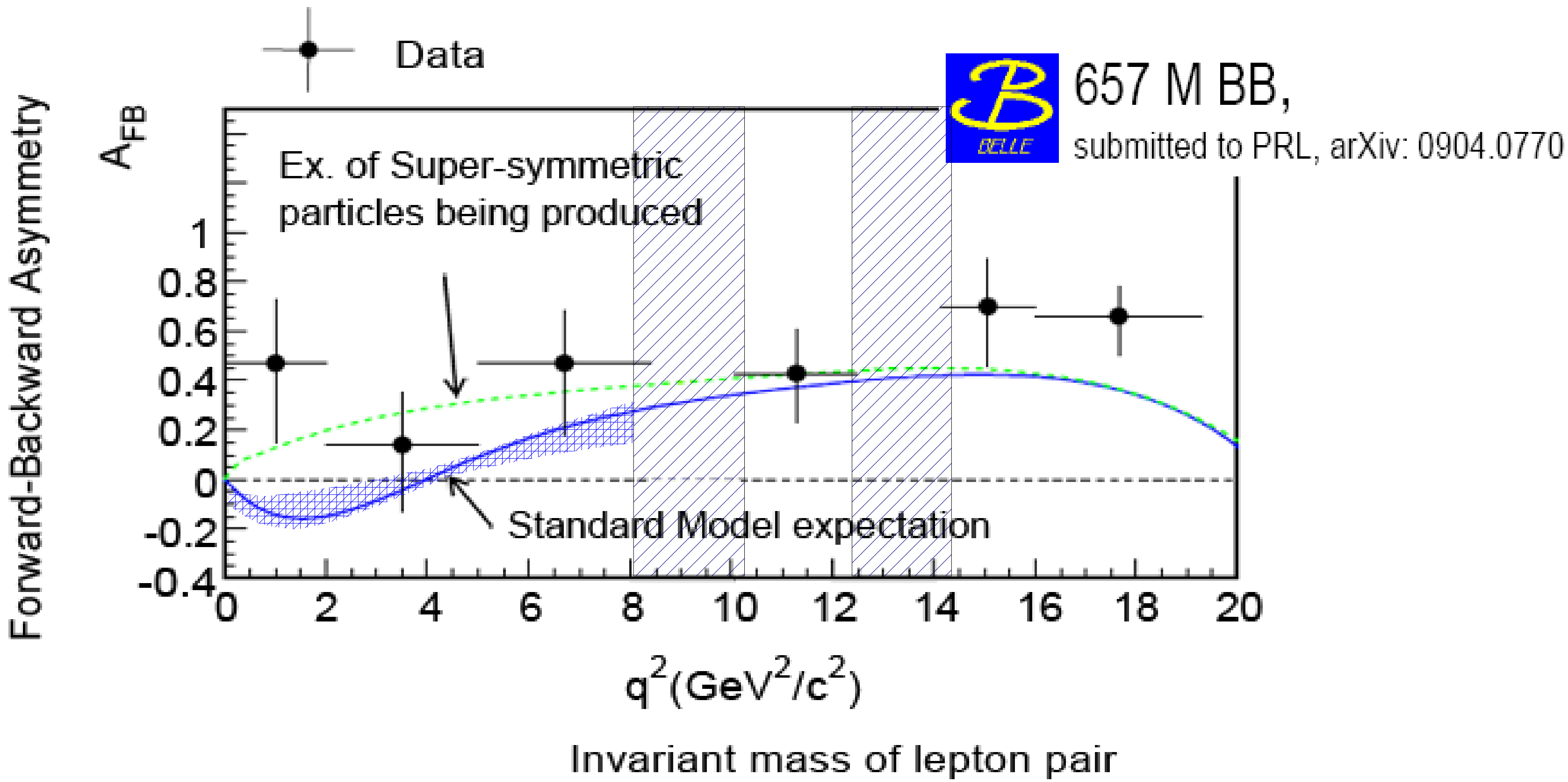

The agreement with SM expectations is not perfect, but claiming a significant deviation is definitely premature !

LHCb will find out if the discrepancy is serious...

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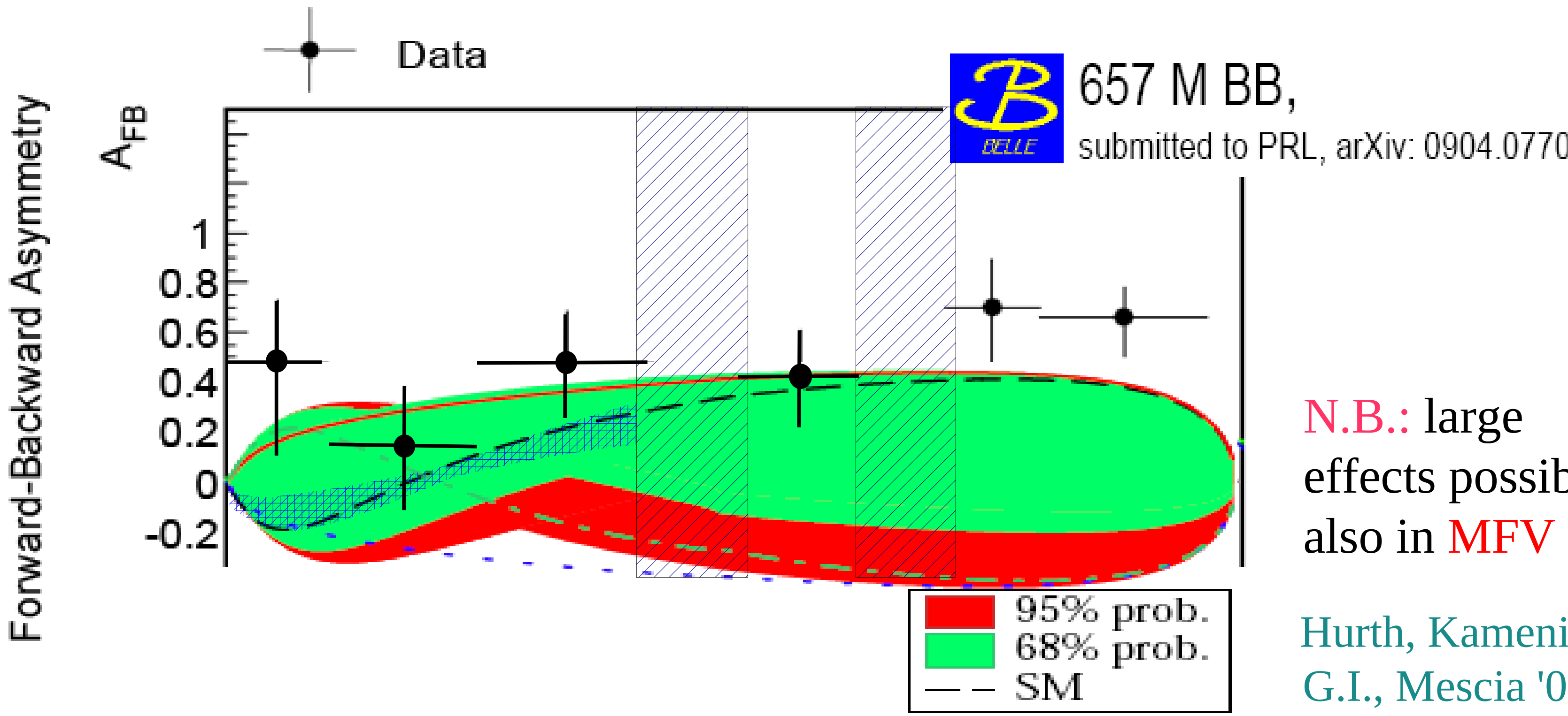

N.B.: large effects possible also in MFV

Hurth, Kamenik
G.I., Mescia '08

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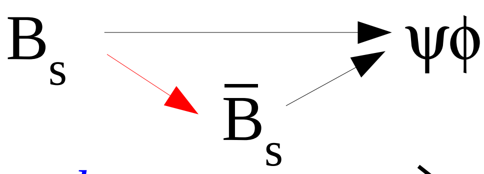
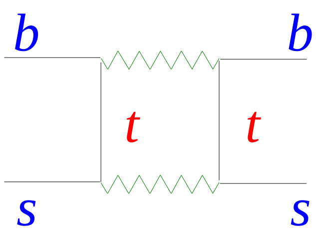
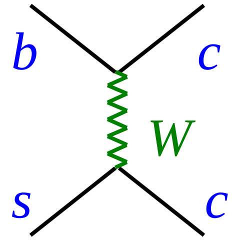
II. CPV in B_s mixing

The weak phase of B_s mixing is the last missing ingredients about down-type $\Delta F=2$ transitions [K, B_d, B_s]: a key element to understand if there is room for new sources of flavour symmetry breaking.

Theoretical clean extraction via $B_s \to \psi\phi$ [$b+s \to ccs+s$]







Experimentally quite challenging:

- Fast oscillations
- Non-trivial angular analysis
- Simultaneous fit of $\Delta\Gamma_s$ and the mixing phase

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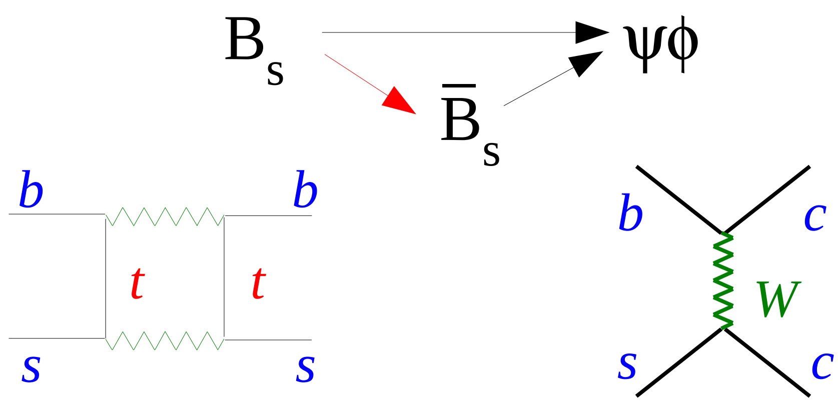
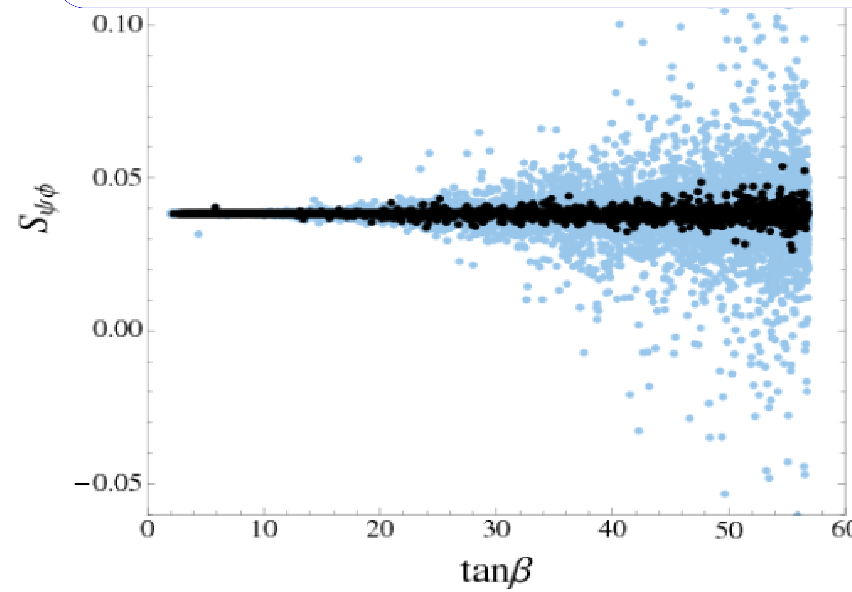


A non-zero CP asym. in $B_s \to \psi\phi$ rules out both SM and MFV



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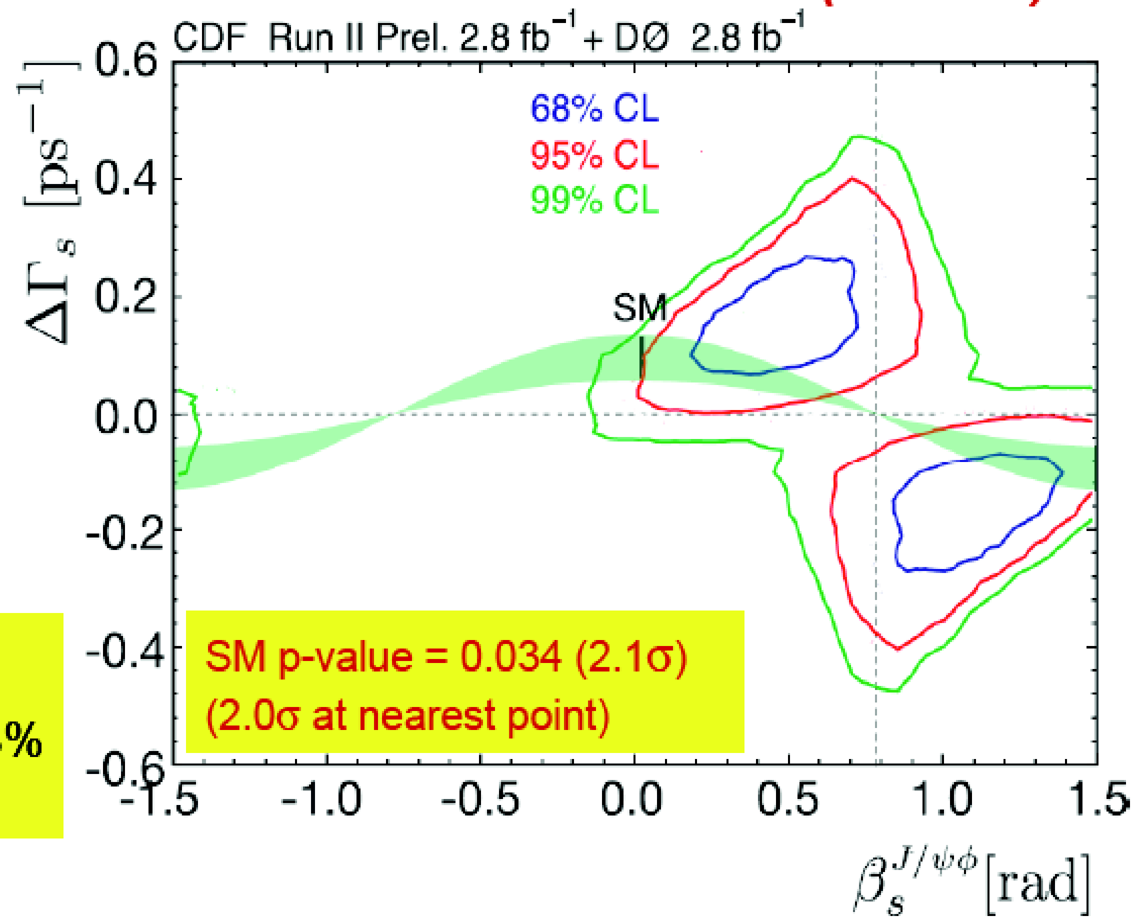
Altmannshofer *et al.* '09

Combined Tevatron result *(NEW)*

- Full inclusion of systematics and non-Gaussian effects
- No constraints. Make available to combination groups.



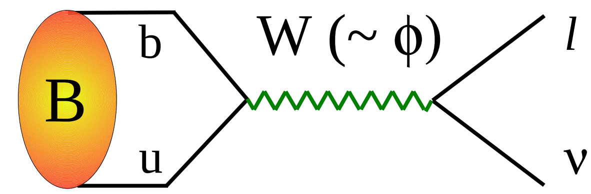
$\beta_s^{J/\psi\phi}$ **range:**
[0.27,0.59] U [0.97,1.30] @68%
[0.10,1.42] @95%

- Compared to HFAG 2008:
  Larger CDF sample + Better accounting for tails ⇒ same level of SM agreement.
- Both CDF and D0 currently working on **2x** samples.
- Expect improved precision by ***simultaneous fit*** of CDF and D0 samples.

G. Punzi, EPS 2009

III. $B(B\to\tau\nu)$

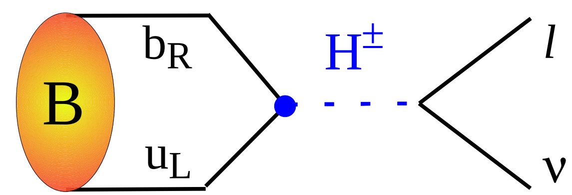
The helicity suppression of the SM amplitude makes $B\to\tau\nu$ an excellent probe of models with 2 Higgs doublets (such as the MSSM):



longitudinal comp. of the W

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

B_{SM} ↑ $C_0\, f_B^2\, |V_{ub}|^2$



extra tree-level contribution
simple M_H & $\tan\beta$ dependence

Clean test of the SM, provided we have reliable independet infos on f_B & V_{ub}

up to ~ 30% (negative) correction in the MSSM at large $\tan\beta$

Clean MFV test otained by comparison with similar effect in $K\to l\nu$ $[m_B \to m_K]$

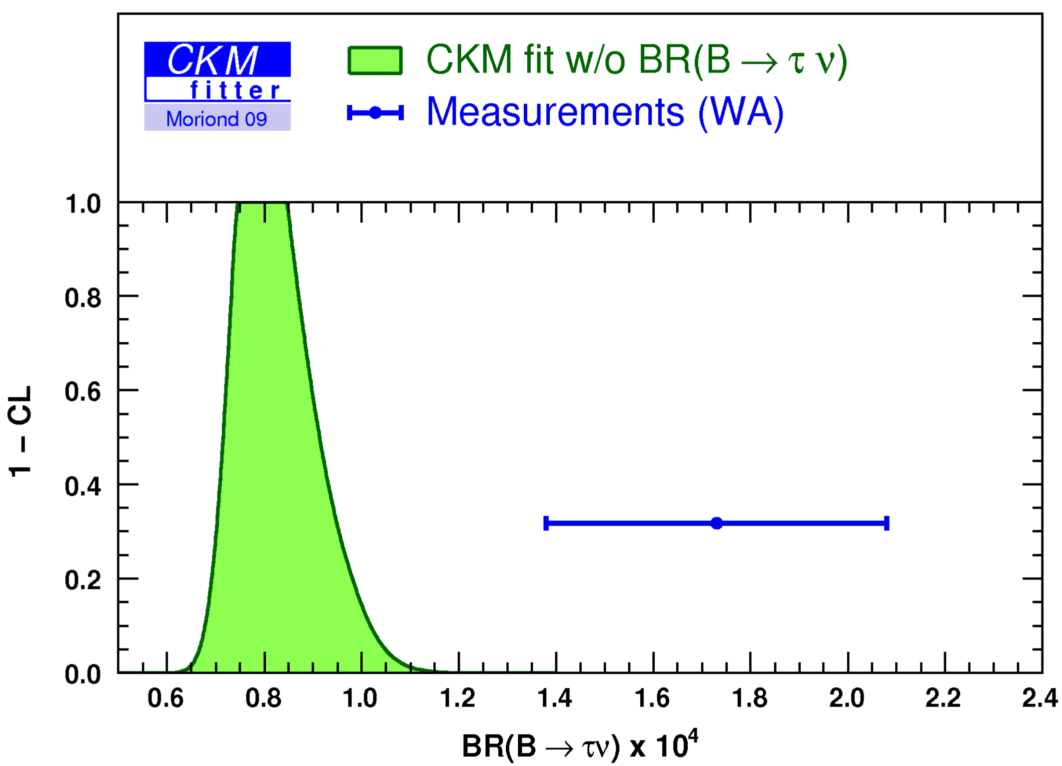
III. $B(B\to\tau\nu)$

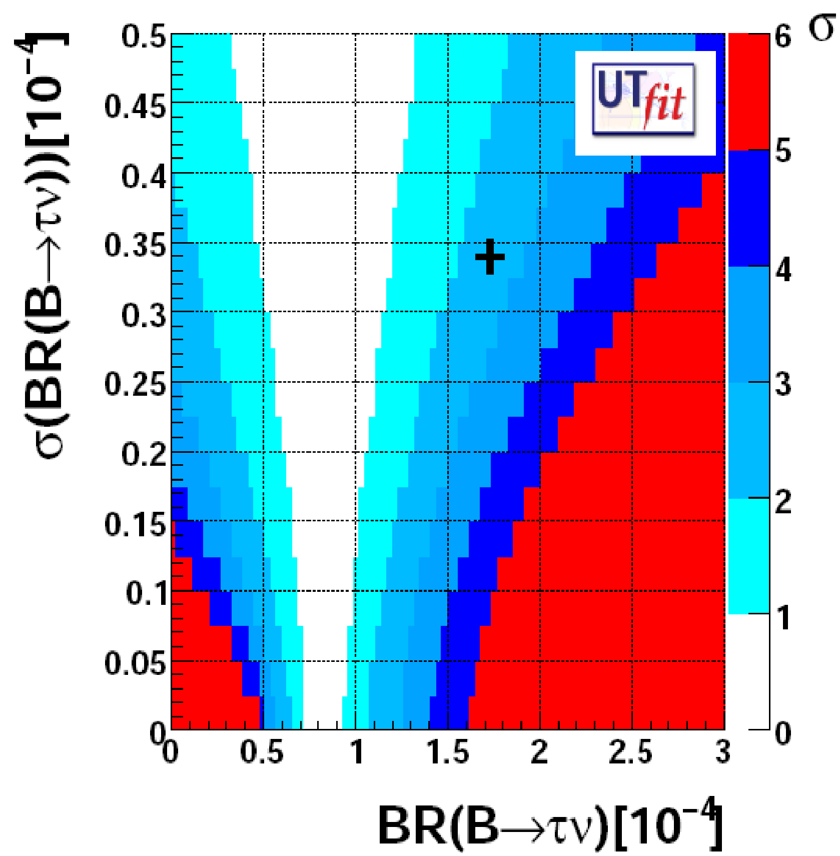
$B(B\to\tau\nu)_{exp} = (1.73 \pm 0.34)\times 10^{-4}$ Babar + Belle '09

$(0.88 \pm 0.11)\times 10^{-4}$ UTfit '09 – global SM fit [5% error on f_b ! - very dangerous]

$B_{SM} =$ $(0.98 \pm 0.24)\times 10^{-4}$ UTfit '09 – no global fit [$f_b = 200 \pm 20$]

$(1.14 \pm 0.28)\times 10^{-4}$ [V_{ub} from UTfit '09 + $f_b = 216 \pm 21$ HPQCD '05]





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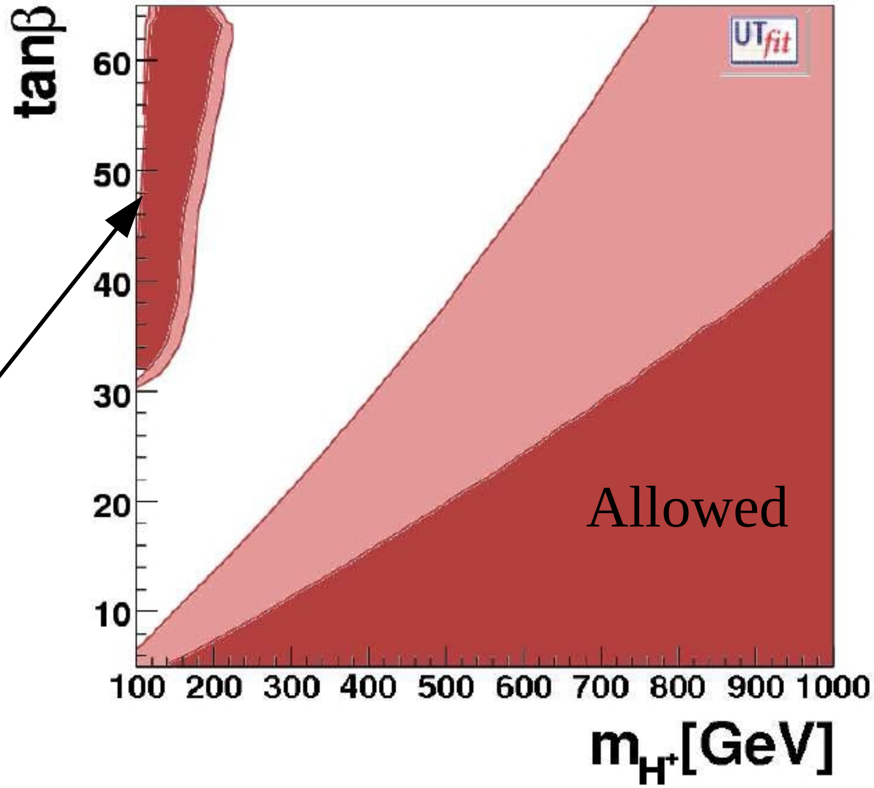
Once more, it is too early to claim new physics...

...but it is certainly a stringent constraint on 2HDM & MSSM at large tanβ, with great potential of improvement in the future



Fine-tuned area with large $B(B\to\tau\nu)$
[excluded by $K\to\mu\nu$, assuming MFV]

What we could still hope to learn from the low-energy side

A closer look to three sets of particularly promising low-energy observables, for which we can expect soon significant exp. improvements:

- $K \to \pi\nu\nu$ → NA62
- CPV in neutral D mixing → LHCb
- Rare B decays → LHCb

I. *Very rare K decays*

The MFV hypothesis is unlikely to be exact:

- not compatible (in its more constrained form) with GUTs ⇒ at some level we should expect some *contamination from the lepton Yukawa couplings* in the quark sector
- it could well be only an approximate infrared property of the underlying theory ⇒ some *deviations* could appear *in the most suppressed processes*

⬇

Potentially large non-SM effects in $K \to \pi\nu\nu$ decays which receive the strongest CKM suppression within the SM ($V_{ts}^* V_{td} \sim \lambda^5$)

I. *Very rare K decays*

The unique features of $K \to \pi \nu\nu$

- Smallness of the CKM suppression factor ($V_{ts}^{*} V_{td} \sim \lambda^5$)
- High th. cleanness (unique for loop-induced meson decays):
  ~2% for $BR(K_L)$ & ~ 5% for $BR(K^+)$

⬇

Unique probes of possible deviations from MFV

⇒ *a must to improve their measurements in the LHC era*

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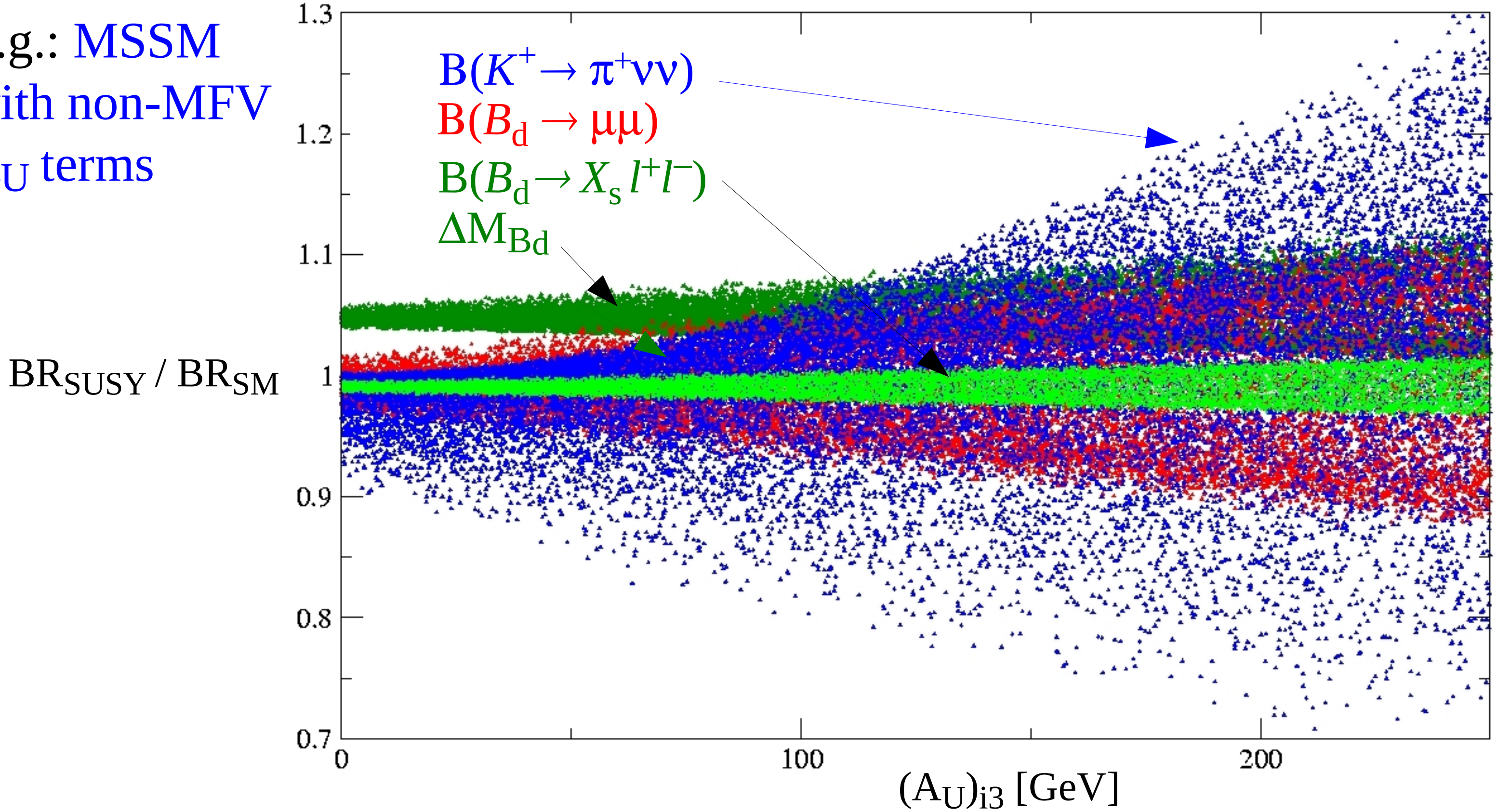
Unique probes of possible deviations from MFV

E.g.: MSSM with non-MFV A_U terms



G.I., Mescia, Paradisi, Smith, Trine, '06

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Deviations from the SM possible also under MFV,

but expected to be much smaller and with a clear correlation between charged & neutral modes.

II. CPV in neutral D mixing

Charm physics is usually considered not too interesting for precise SM tests, and searches of NP, because of large long-distance effects.

CPV in neutral D mixing is a remarkable exception:

- Clear SM null test
- Highly sensitive to NP [unique window on up-type mixing of light generations], no sizable effects in MFV(*), but up to 10% effects quite natural beyond MFV (SUSY, RS,...)

Gedalia, Grossman, Nir, Perez '09

(*) visible effects possible in MFV, beyond the linear regime, for very large values of tanβ [*too fine tuned scenario for my taste...*]

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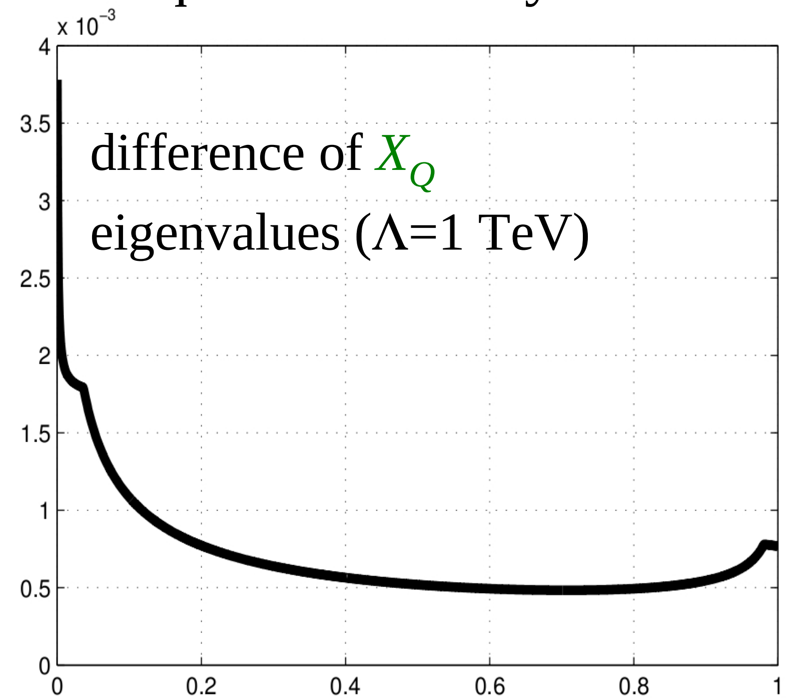
- Highly sensitive to NP [unique window on up-type mixing of light generations], no sizable effects in MFV$^{(*)}$, but up to 10% effects quite natural beyond MFV (SUSY, RS,...)
- Interesting correlation with K mixing

E.g.: $$\frac{1}{\Lambda^2}\,[\bar{Q}^i_L\, X_Q{}^{ik} Q_L{}^k]^2$$

New source of flavour symmetry breaking

If $X_Q \neq 1$ or $Y_U Y_U{}^+$ we cannot easily satisfy both K and D mixing constraints

Blum *et al.* '09



III. Rare B decays

Beside the improvements in $A_{CP}(B_s \to \psi\phi)$, $B\to\tau\nu$, $A_{FB}(B\to K^* l^+ l^-)$, $A_{CP}(B \to X_s\gamma)$

B-physics observables of great interest in the LHC era the helicity-suppressed $B\to l^+ l^-$ decays

⬇

Present status:

$$\mathcal{B}(B_s \to \mu\mu) < 4.8 \times 10^{-8} \text{ (95\%CL)}$$

$$\mathcal{B}(B_s \to \mu\mu) < 7.6 \times 10^{-9} \text{ (95\%CL)}$$

[CDF '09]

$$\mathcal{B}(B_s \to \mu\mu)_{SM} = 3.2(2) \times 10^{-9}$$

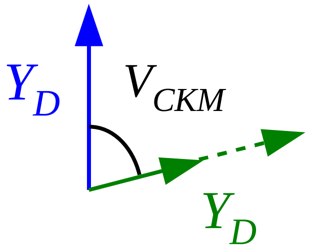
$$\mathcal{B}(B_d \to \mu\mu)_{SM} = 1.0(1) \times 10^{-10}$$

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

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

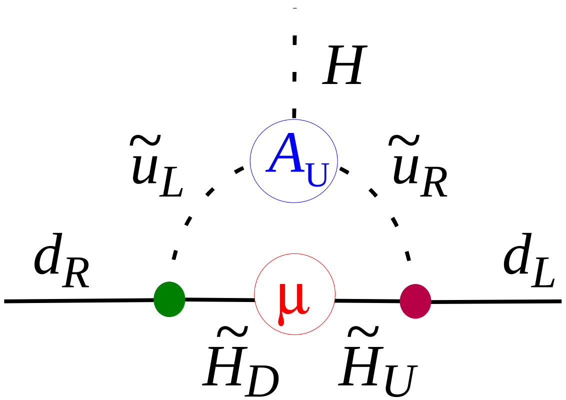
Unique probes of the MSSM at moderate/large $\tan\beta$

III. Rare B decays

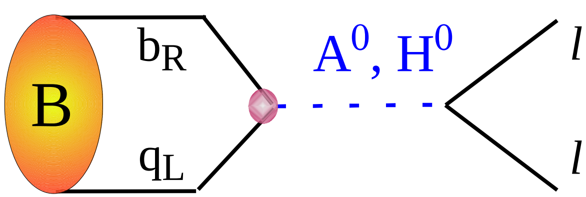


$$\mathrm{diag}(Y_U) = \mathrm{diag}(m_u) / \langle H_U \rangle$$
$$\mathrm{diag}(Y_D) = \mathrm{diag}(m_d) / \langle H_D \rangle = \tan\beta \, m_d / \langle H_U \rangle$$

The different normalization of the Yukawa couplings induces an effective <u>Higgs-mediated FCNC coupling</u>:



no impact in helicity-conserving processes,
but possible large effect in $B \to l^+ l^-$



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

<u>Possible large enhancement over the SM</u>
(but the magnitude of the effect can vary a lot in different SUSY-breaking scenarios)

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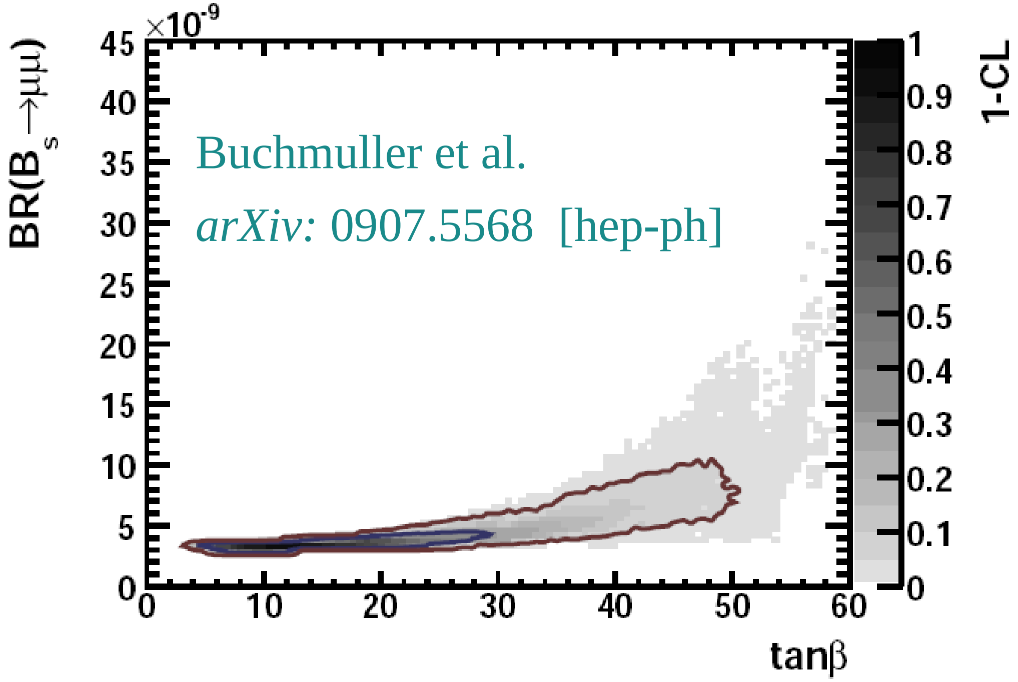
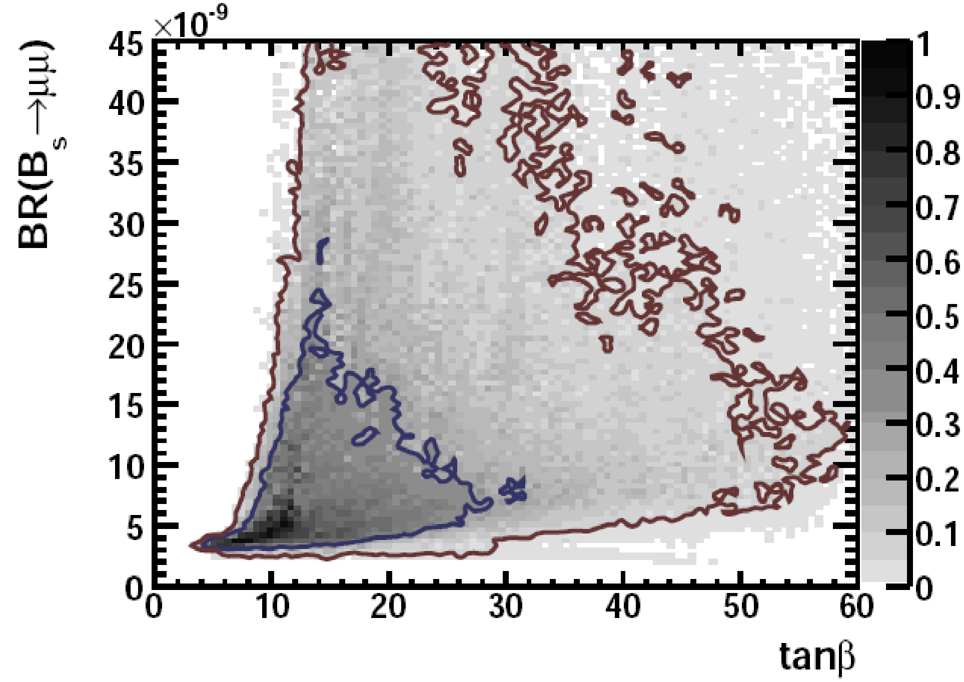
Constrained - MSSM



Constrained – MSSM with non-universal Higgs masses (NUHM)



Reaching the SM level would lead to a very significant constraint in the (C)MSSM

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- Th. error controlled by f_B ($\Rightarrow$lattice). Not a big issue if deviations from SM are large, but important to improve in view of future precise measurements
- The $B(B_d \to \mu\mu)/B(B_s \to \mu\mu)$ ratio is a key observable to proof or falsify MFV

Conclusions

Present low-energy data tell us that TeV-scale NP models must have a rather sophisticated flavour structure (not to be already excluded), but we have not clearly identified this structure yet. The MFV hypothesis is a plausible explanation, but it is far from being the only allowed possibility.

To establish 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]

which is quite hard, except maybe in $B_{s,d} \to \mu\mu$

But MFV could easily be falsified ($B_s \to \psi\phi$, large $K \to \pi\nu\nu$,...)

Any of these two information would be extremely valuable in the identification of physics beyond the SM, which hopefully will be discovered directly by the high-pT expts...