Theoretical Insights to Heavy Flavour Physics

Gino Isidori
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- The two main open questions in flavour physics
- Recent decline of a few "hopes" (*a tribute to LHCb*)
- Persisting "anomalies" and possible BSM explanations
- Future prospects (*a personal view*)
- Conclusions

The two main open questions in flavour physics

To a large extent, the origin of "flavour" is still a mystery...

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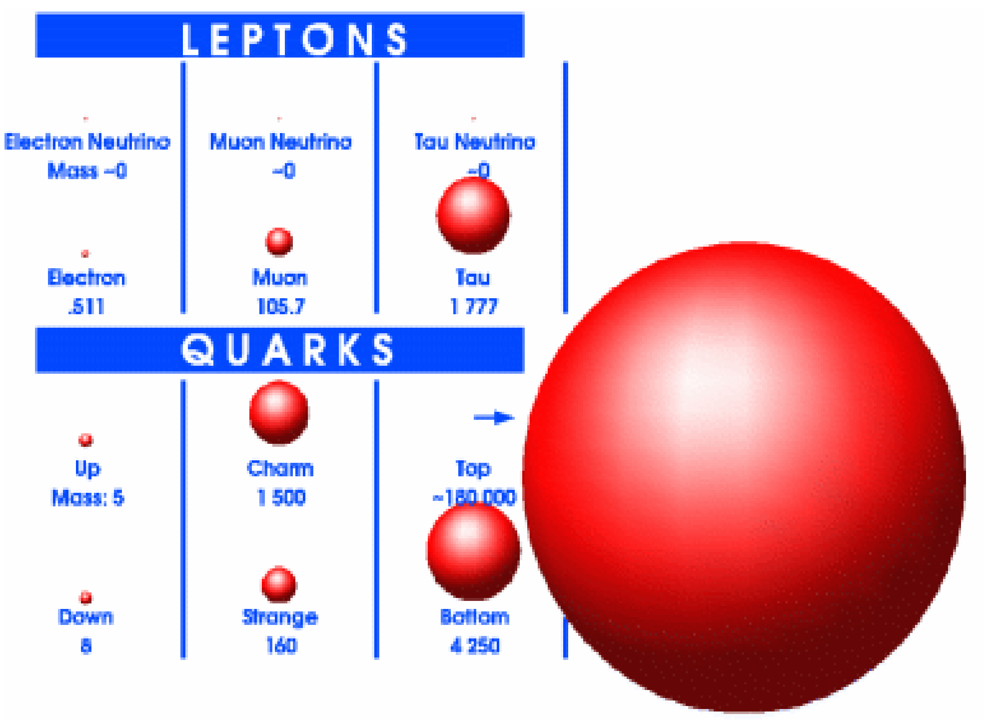
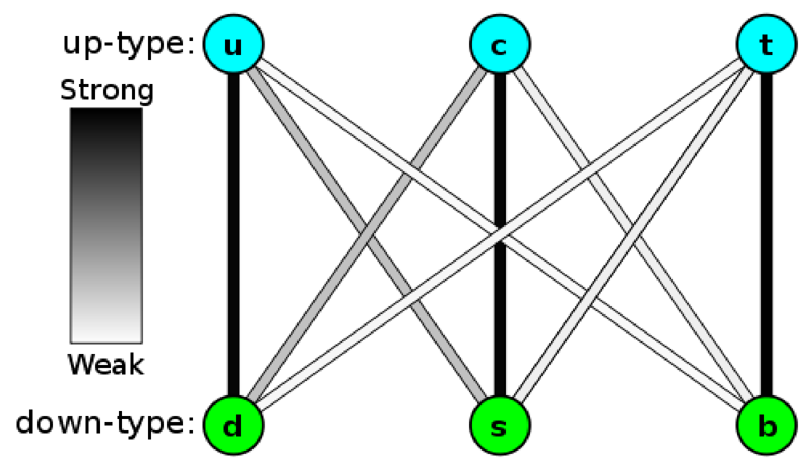
Our "ignorance" can be summarized by the following two open questions:

- *What determines the observed pattern of masses and mixing angles of quarks and leptons?*

- *Which are the sources of flavour symmetry breaking accessible at low energies?*





The two main open questions in flavour physics

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Answers to this question are usually obtained by means of

- New (flavour) symmetries
- New dynamics (e.g. fermion profiles in extra dimensions)

Several plausible options on the market, with no outstanding case.

It is quite easy to reproduce the observed mass matrices in terms of a reduced number of free parameters, while it is difficult to avoid problems with FCNCs (without some amount of fine-tuning).

Hard to make progress without knowing the ultraviolet completion of the SM.

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- *Which are the sources of flavour symmetry breaking accessible at low energies?*
  [Is there anything else beside SM Yukawa couplings & neutrino mass matrix?]

Answering this question is more easy:

- It can be formulated independently of the UV completion of the theory.
- It is mainly a question of precision (both on the theory and on the experimental side).

⬇

Main goal of flavour-physics in the early LHC era

The two main open questions in flavour physics

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- *Which are the sources of flavour symmetry breaking accessible at low energies?* [Is there anything else beside SM Yukawa couplings & neutrino mass matrix?]

High-Intensity Frontier

↕

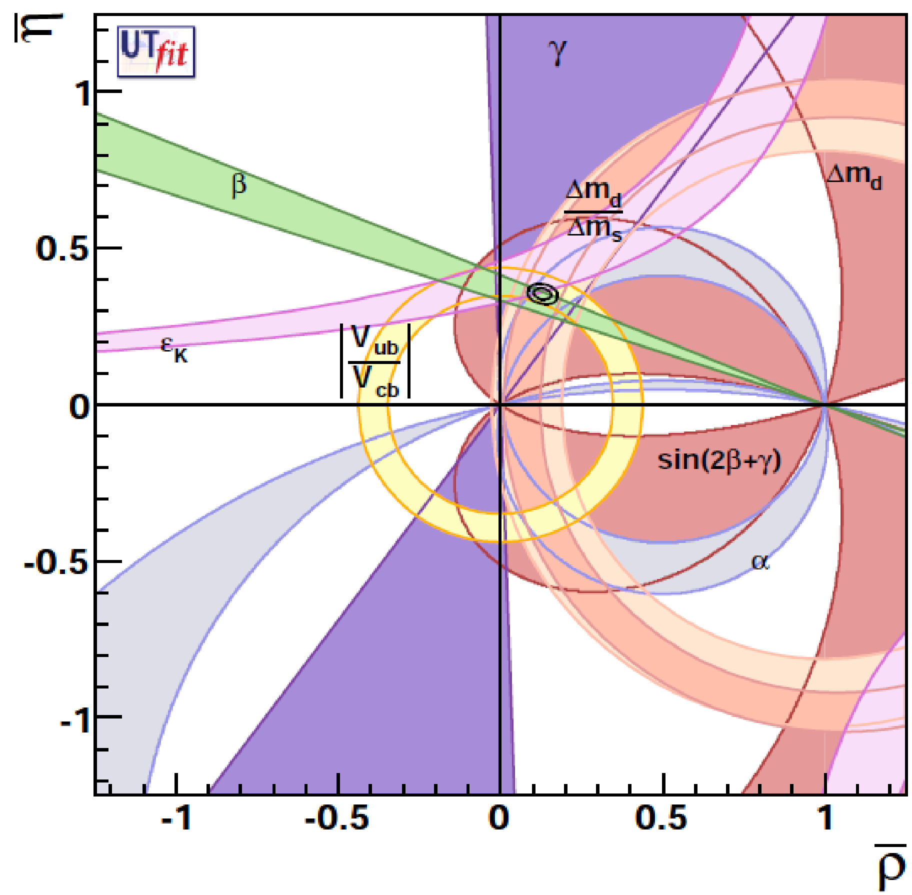
- *What determines the Fermi scale?*
- *Is there anything else beyond the SM Higgs at the TeV scale?*

High-Energy Frontier

Which are the sources of flavour symmetry breaking accessible at low energies?

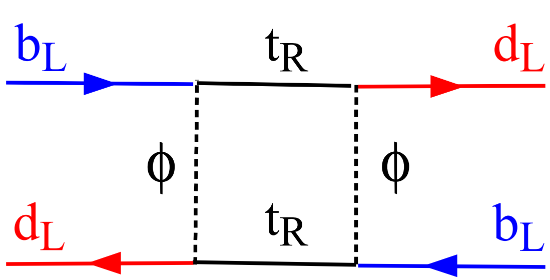
The measurements of quark flavor-violating observables show a remarkable overall success of the CKM picture

This success is quite "embarrassing" if we assume there is some New Physics around the TeV scale...



$$M(B_d\text{-}\bar{B}_d) \sim \frac{y_t^4 (V_{tb}^* V_{td})^2}{16\pi^2 m_t^2} + \frac{c_{NP}}{\Lambda_{NP}^2}$$

tiny SM contribution (Yukawa interaction)



possible large contribution (if $\Lambda_{NP} \sim$ TeV and $c_{NP} \sim 1$), excluded by present data

Which are the sources of flavour symmetry breaking accessible at low energies?

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_{ij}}{\Lambda^2} O_{ij}^{(6)}$$

G.I, Nir, Perez '10

Operator	Bounds on Λ (TeV)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ε_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ε_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\|q/p\|$, ϕ_D
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\|q/p\|$, ϕ_D
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2	1.1×10^2	7.6×10^{-5}	7.6×10^{-5}	Δm_{B_s}
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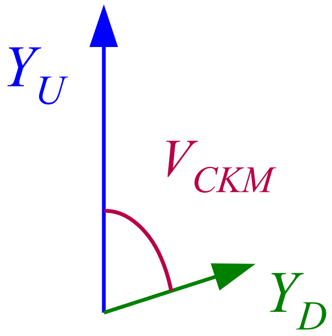
New flavor-breaking sources at the TeV scale (if any) are highly tuned

Which are the sources of flavour symmetry breaking accessible at low energies?

The good overall consistency of the experimental constraints appearing in the so-called CKM fits seems to indicate there is not much room for new sources of flavour symmetry breaking

Minimal Flavour Violation paradigm:

The large quark-flavour symmetry of the gauge SM Lagrangian is broken only by the two quark Yukawa couplings => The CKM matrix controls all flavour-changing phenomena in the quark sector also beyond SM



Naturally small effects in most of the flavour-changing observables measured so far even for new-physics within the LHC reach

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N.B: The MFV hypothesis is very unlikely to be exact.
Most likely, it is only an approximate low-energy property => important to search for possible deviations (even if tiny) from MFV predictions.

Even if MFV holds , it does not imply negligible effects in flavour physics

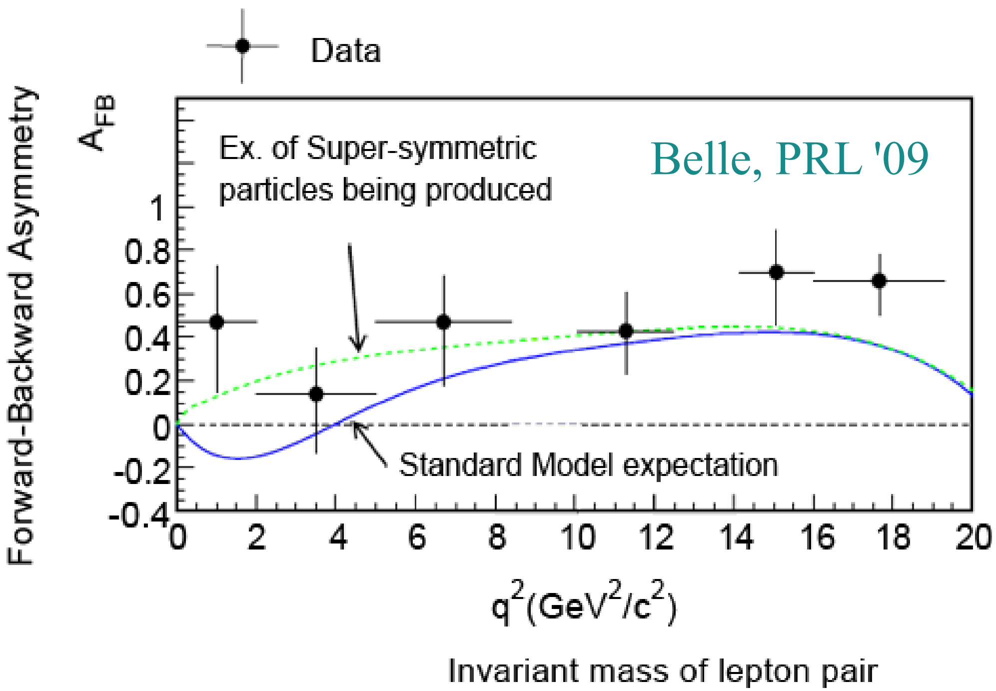
...but it is clear we have little hopes of observing large deviations from the SM
=> need for high precision and th.-clean observables...

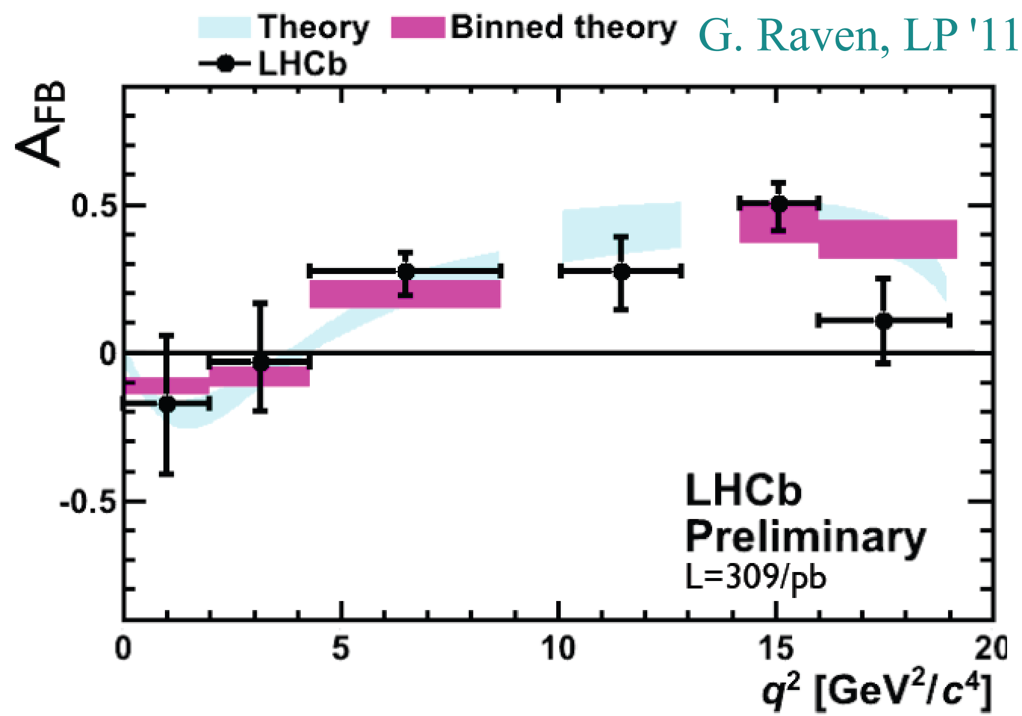
This conclusion -which was already quite clear after LEP + B/K-facotries results- has been substantially reinforced by the first LHC results.

Recent decline of a few "hopes" (a tribute to LHCb)

Before the summer we still had a few exp. hints + well-motivated th. hopes pointing to large deviations from the SM is a few selected NP observables:

- Hints of non-standard FB asymmetry in B→K*ll





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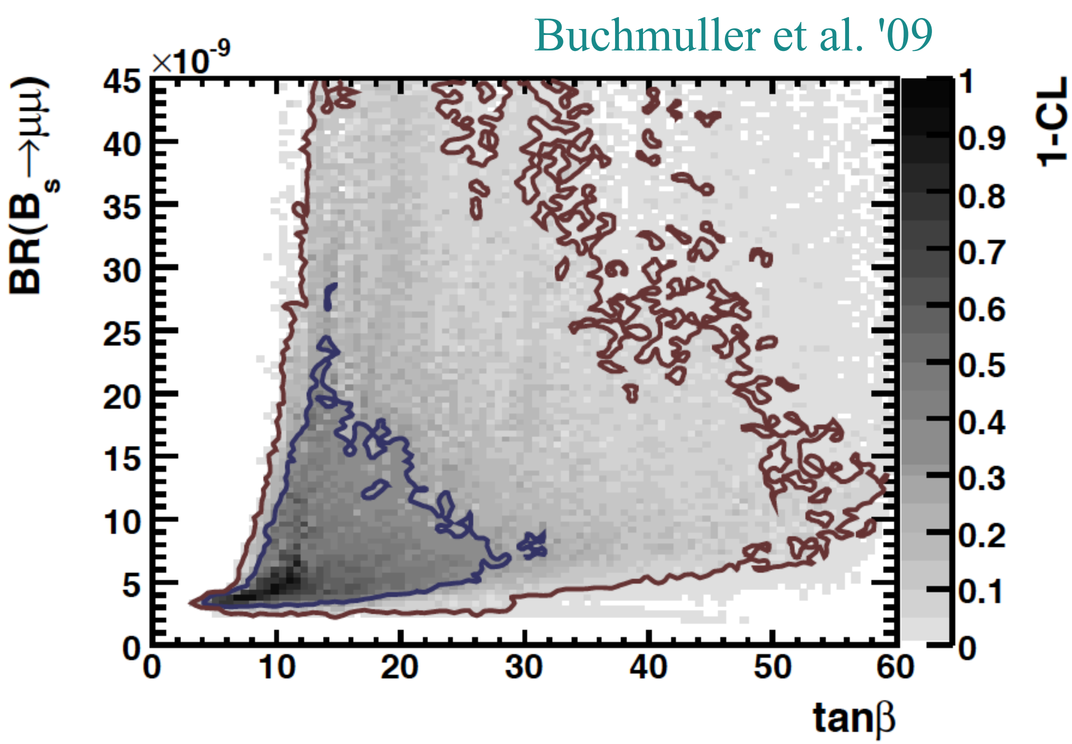

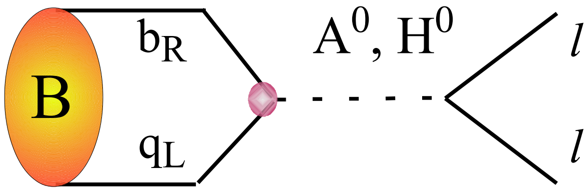

$$A(B \to ll)_H \sim \frac{m_b\, m_l}{M_A^{\,2}} \frac{\mu\, A_U}{\tilde{M}_q^{\,2}} \tan^3\beta$$

Possible large enhancement even in MFV, even in constrained MSSM, provided large μ and large $\tan\beta$

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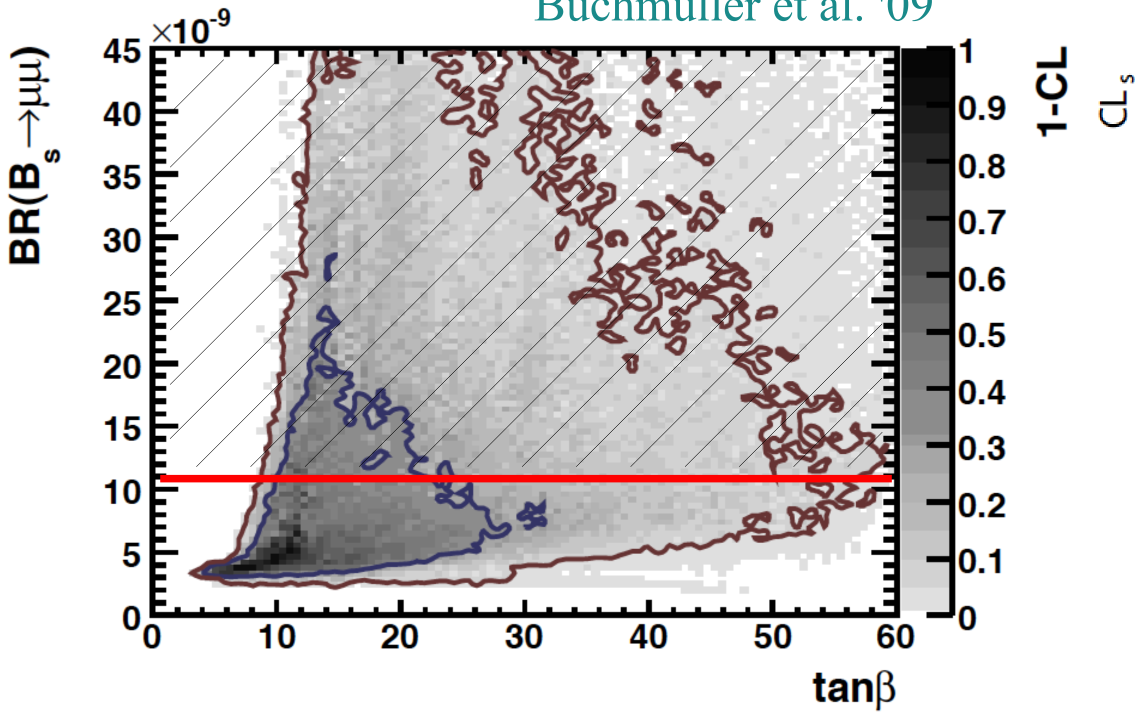
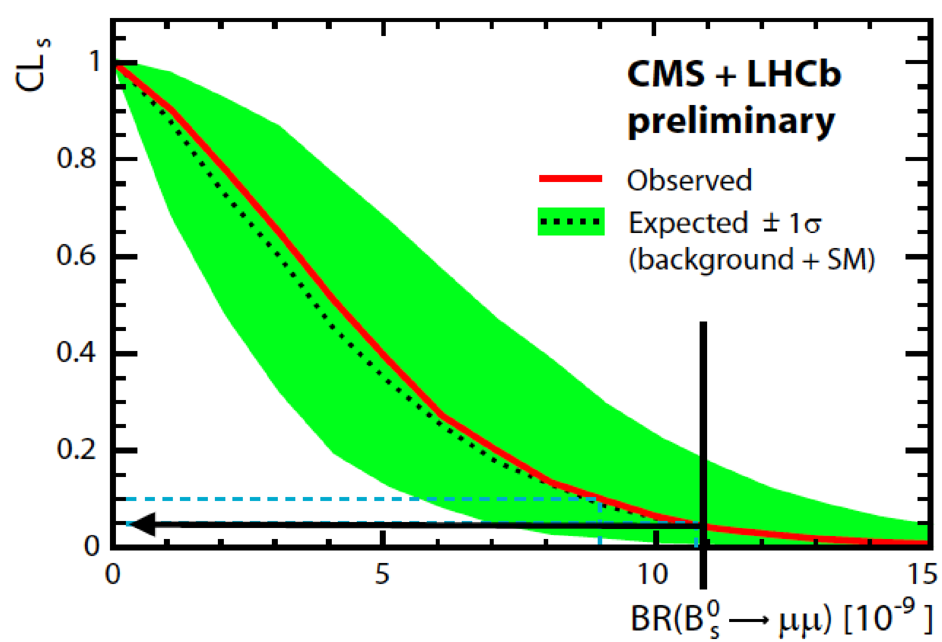
N.B: still a long way to go before saturating the th. error...

Buchmuller et al. '09



G. Raven, LP '11



$< 11 \times 10^{-9}$ @ 95% CL

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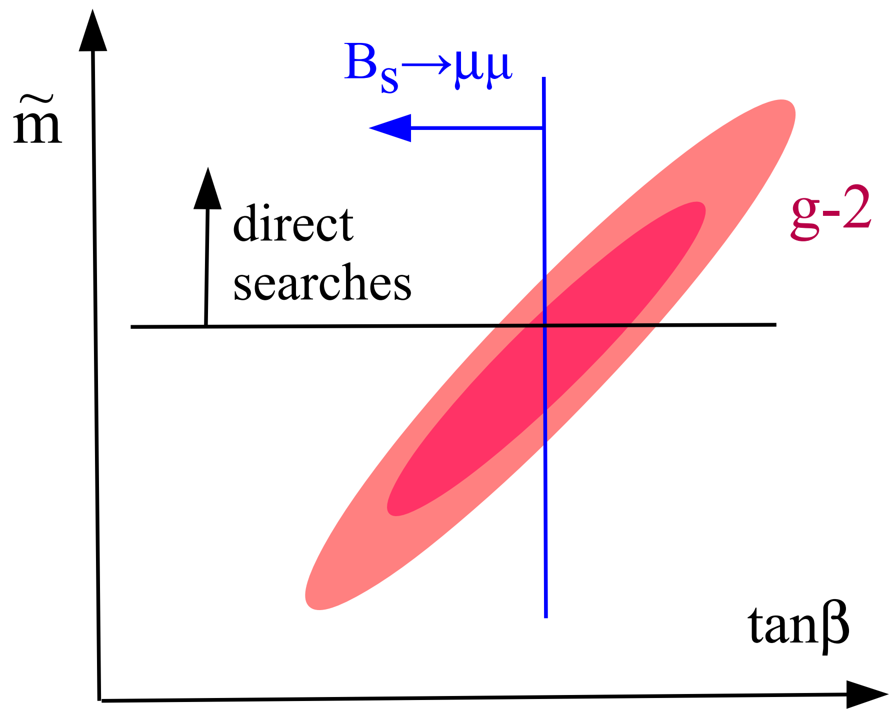
N.B: One of the main players against the C-MSSM ...



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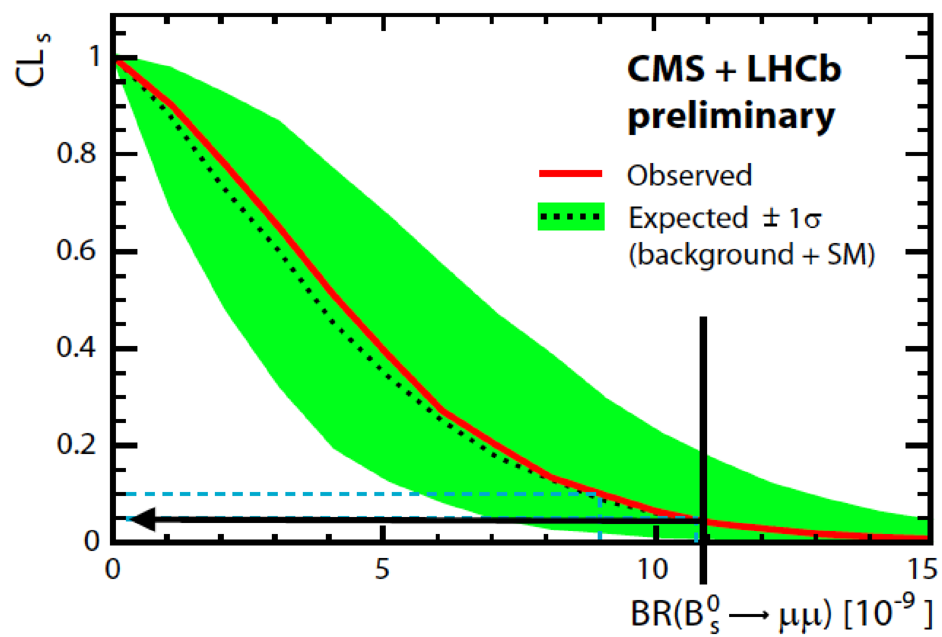

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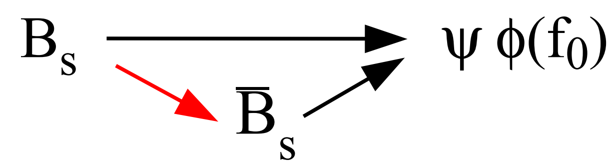
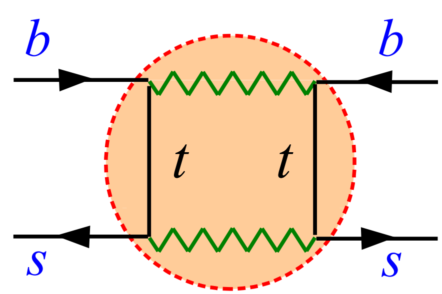
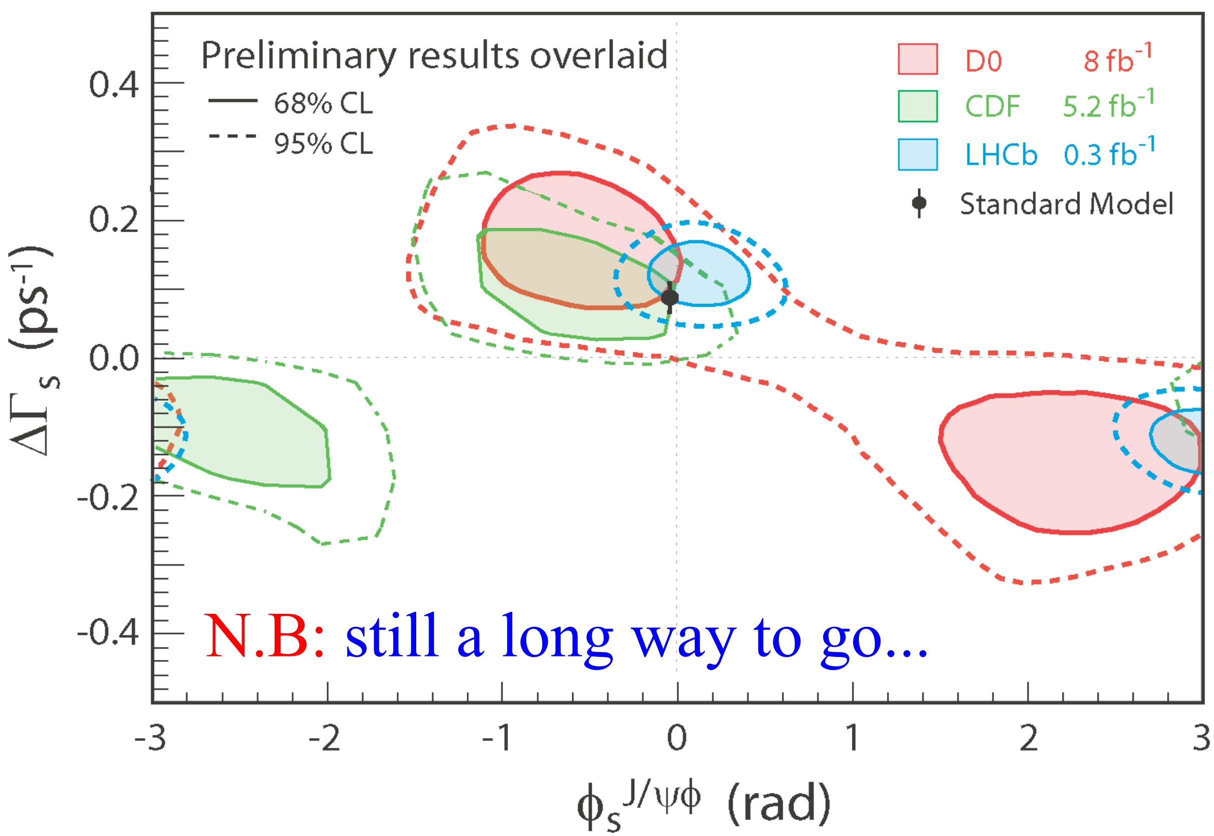
- Hope and hints of large B_s mixing phase







Tiny asymmetry if the phase is determined only by the Yukawa couplings

Persisting "anomalies" and possible BSM explanations

Despite the overall success of the standard picture,
and this recent negative results...

...there are still a few "*anomalies*" that is worth to *investigate* in more detail.

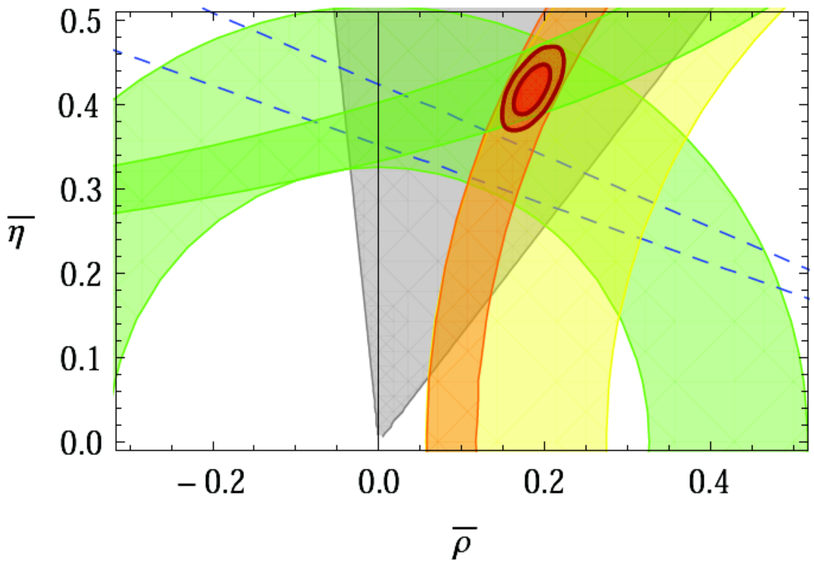
Most interesting case (in my opinion):

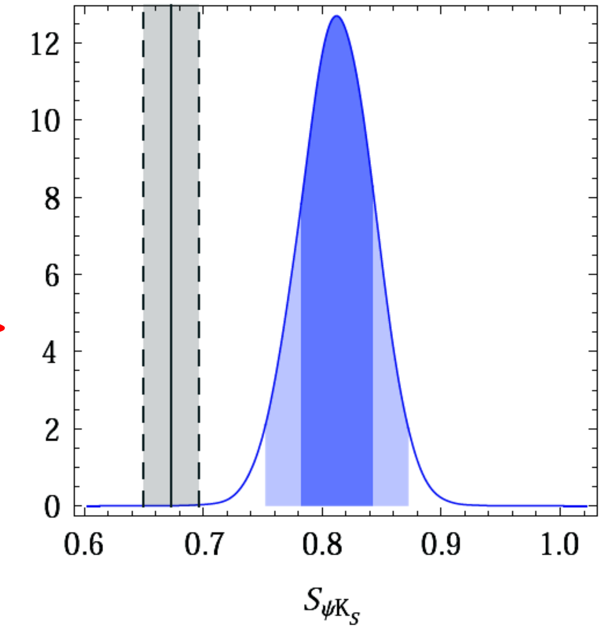
the ε_K - $\sin(2\beta)$ tension in the CKM fit

The ε_K - sin(2β) tension in the CKM fit:

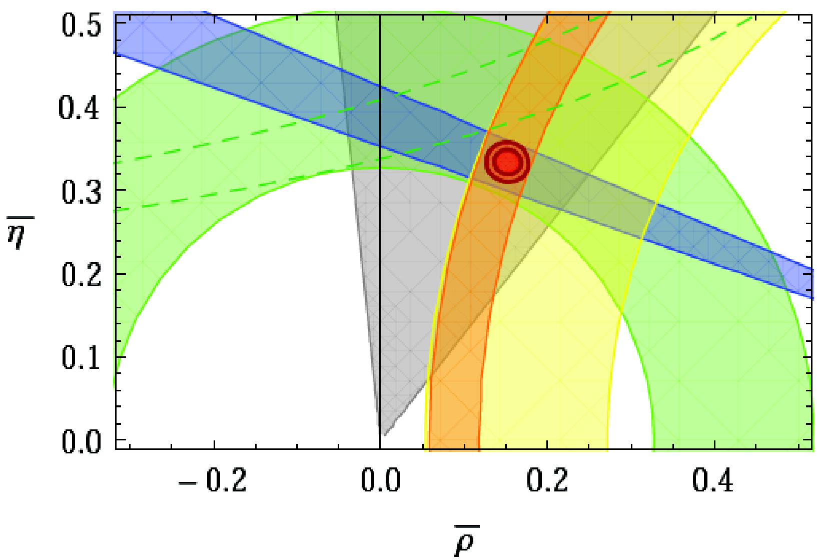
Barbieri *et al.* '11

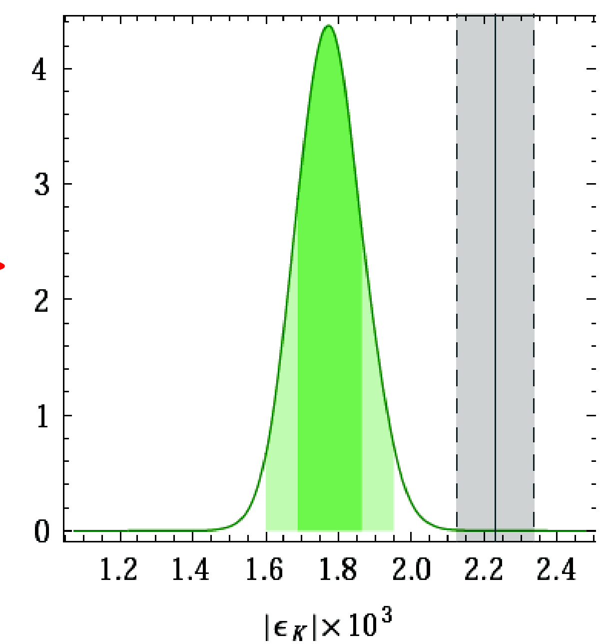
I. SM fit, no $S_{\Psi K}$





II. SM, no ε_K





Similar results by CKMfitter & UTfit

This "anomaly" fits well with a well-motivated attempt to go beyond MFV:

MFV virtue

Naturally small effects in FCNC observables

MFV main open problems

No explanation for small CPV flavor-conserving observables (edms)

No explanation for Y hierarchies (masses and mixing angles)

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A solutions of both these problems is obtained in the so-called "effective susy" framework:

Susy + horizontal U(2) flavor symmetry acting on the first two generations only, such that $\tilde{m}_1 = \tilde{m}_2 \gg \tilde{m}_3$

Dimopulos, Giudice, '95
Cohen, Kaplan, Nelson '96

Pomarol, Tommasini, '96
Barbieri, Dvali, Hall, '96
Barbieri, Hall, Romanino, 97

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↓

Naturally small effects in FCNC observables

Effective susy with a U(2) flavour symmetry

↙ ↘

Naturally small CPV flavor-conserving observables (edms)

Partial explanation for *Y* hierarchies ($|V_{td}/V_{ts}| = \vartheta_d = (m_d/m_s)^{1/2}$, ...)

Well motivated beyond flavor physics...
(hierarchy problem + non-observation of SUSY so far)

...not efficient as MFV in FCNC observables
(too large flavor-violating effects in the RH sector)

- Fine-tuning in the kaon system (ε_K & ε')
- Sizable non-standard CPV phases in $\Delta B=1$ obs.

This "anomaly" fits well with a well-motivated attempt to go beyond MFV:

MFV virtue

Effective susy with a U(2) flavour symmetry

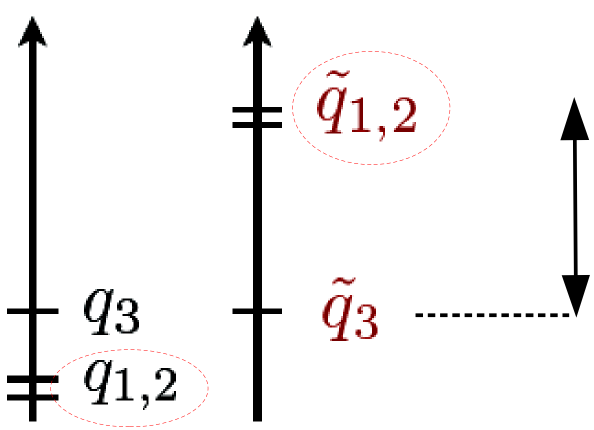
Naturally small effects in FCNC observables

Naturally small CPV flavor-conserving observables (edms)

Partial explanation for Y hierarchies

Effective susy with a $U(2)^3 = U(2)_{Q_L} \times U(2)_{U_R} \times U(2)_{D_R}$ flavor symmetry

Barbieri, G.I., Jones-Perez, Lodone, Straub, '11



Large mass gap (several TeV) not controlled by flavor symmetries (as opposite to MFV) and fine-tuning considerations

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Naturally small CPV flavor-conserving observables (edms)

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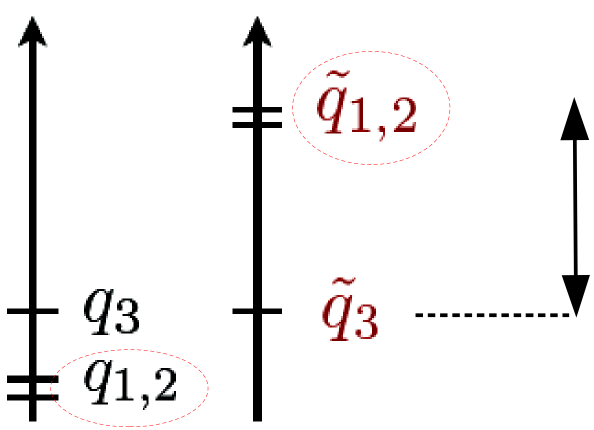
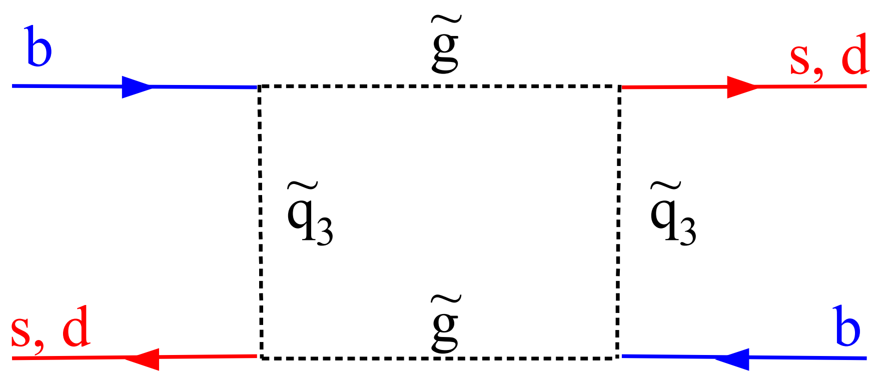


Exact symmetry is a good approximation to the SM quark spectrum (m_u=m_d= m_s=m_c=0, V_{CKM}=1)

=> we only need small breaking terms

Effective susy with $U(2)^3$

The leading and most clean deviations from the SM are expected in meson-anti-meson mixing, from gluino-box diagrams:



- Correction to K^0 mixing aligned in phase with the SM amplitude, with definite sign (constructive interference)
- New CPV appearing in $B_{s,d}$ mixing (in a universal way)

Equivalent to non-linear MFV
(Feldmann, Mannel, '08; Kagan *et al*. '09)

⬇

Solution of the "ε_K - sin(2β) tension" + clean predictions for the LHC

Effective susy with U(2)^3

Two clean predictions for the LHC:

I. Small non standard CPV in B_s mixing

$$S_{\psi K}^{U(2)} = 0.12 \pm 0.05$$

$$\left[\ S_{\psi K}^{SM} = 0.041 \pm 0.01\ \right]$$

Compatible with present
LHCb data,
possibly within their near-future reach

II. Relatively "light" gluinos and 3rd generation squarks

$$m_{\tilde{g}},\ m_{\tilde{q}_3} < 1.0,\ \ 1.5\ \text{TeV}$$

Compatible with present
ATLAS & CMS data,
within their near-future reach

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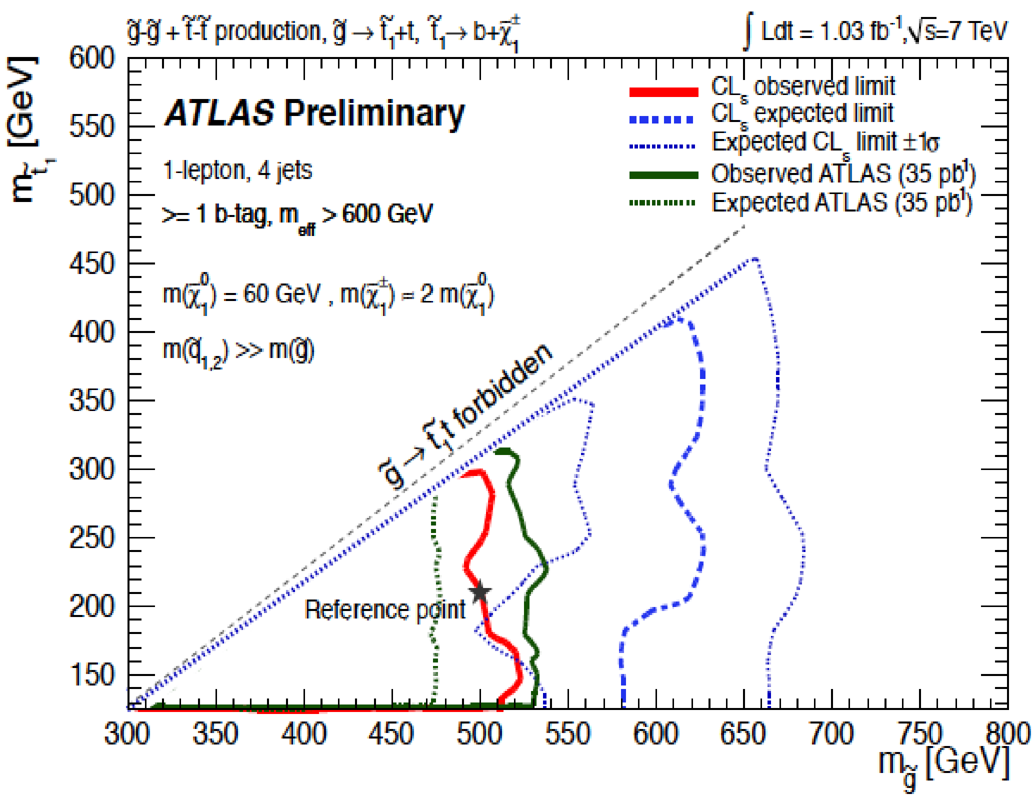

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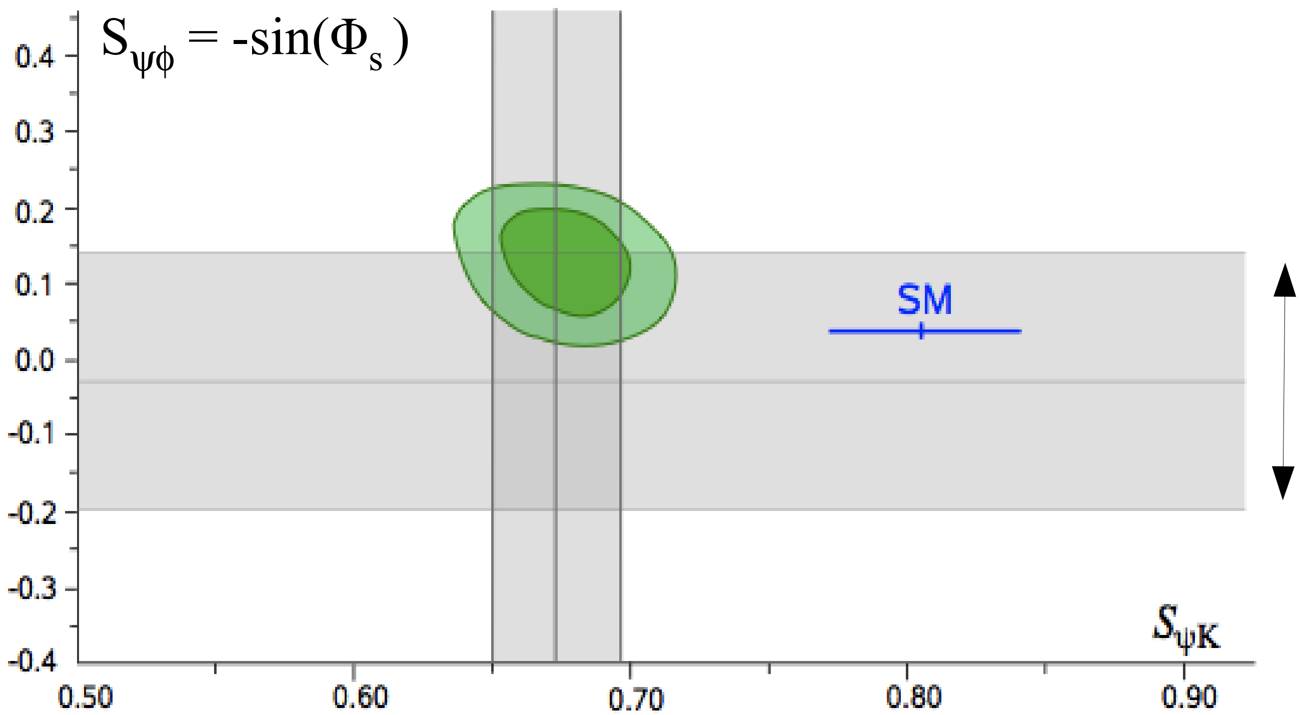

1σ, prelim. LHCb result (LP2011)

$-\Phi_s^{exp} = -0.03 \pm 0.16 \pm 0.07$

Not easy to distinguish form the SM, but not impossible...

Representative example of the type of non-standard effects we should search for.

Future prospects (a personal view)

General decomposition of flavour-violating observables:

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

trivial kinematical factors

(adimensional) effective couplings

This decomposition is very general.
It holds for both for forbidden processes ($\tau \to \mu\gamma$) and precision measurements

It is based only on the assumption that the new degrees of freedom respect the $SU(2)_L \times U(1)$ gauge symmetry

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General decomposition of flavour-violating observables:

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

↓

- The sensitivity to the energy scale grows slowly with the statistics or the luminosity of the experiment ($\sigma \sim 1/N^{1/4}$)
- The interest of a given flavour obs. depends on the magnitude of c_{SM} vs. c_{NP} and on the theoretical error of c_{SM} => concentrate on clean & rare processes
- No way to disentangle Λ & c_{NP}, but the combined information which can be extracted is fully complementary to direct searches at high-p_T: flavour symmetry structure of NP

Future prospects (a personal view)

"Minimalistic" list of key (quark-) flavour-physics observables:

- γ from tree ($B \to DK$, ...)
- $|V_{ub}|$ from exclusive semilept. B decays
- $B_{s,d} \to \mu\mu$
- CPV in B_s mixing
- $B \to K^*\mu\mu$ (angular analysis)
- $B \to \tau\nu$, $\mu\nu$
- $K \to \pi\nu\nu$
- CPV in D mixing

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- γ from tree ($B \to DK$, ...)
- $|V_{ub}|$ from exclusive semilept. B decays

→ Tree-level CKM → $\sin(2\beta)^{\text{th.-SM}}$
[th. error on $B \to \pi$ likely to reach 5% from lattice]

- $B_{s,d} \to \mu\mu$ — Higgs-mediated FCNCs [$\sigma(f_B) < 5\%$ from lattice]
- CPV in B_s mixing — New CPV (SUSY,...) [$\sigma(S_{\psi\varphi}) \sim 0.01$ + control channels]
- $B \to K^*\mu\mu$ (angular analysis) — Non-standard FCNCs [$\sigma(A_{FB}) \sim 5\%$]
- $B \to \tau\nu, \mu\nu$ — Scalar charged curr. (H^+) [$\sigma(f_B) \to 5\%$ from lattice]
- $K \to \pi\nu\nu$ — Best probe of non-MFV [$\sigma(BR) \lesssim 5\%$]
- CPV in D mixing — Null test for SM and MFV [$\sigma(CPV) < 1\%$]

Conclusions

To a large extent, the origin of "flavour" is still a mystery...

...but we are making some progress:

- We have understood that large new sources of flavour symmetry breaking at the TeV scale are excluded
- The lack of large deviations from SM, even in suppressed observables, points toward almost exact flavour symmetry + weakly interacting NP at the TeV (coherent picture with e.w. precision tests + lack of large deviations at high-pT) => (non-minimal) SUSY remains a very good candidate
- Key tool to make progress in this field is to push forward the precision in the most clean observables => *full complementarity both between low-energy and high-pT physics and also between different low-energy facilities*

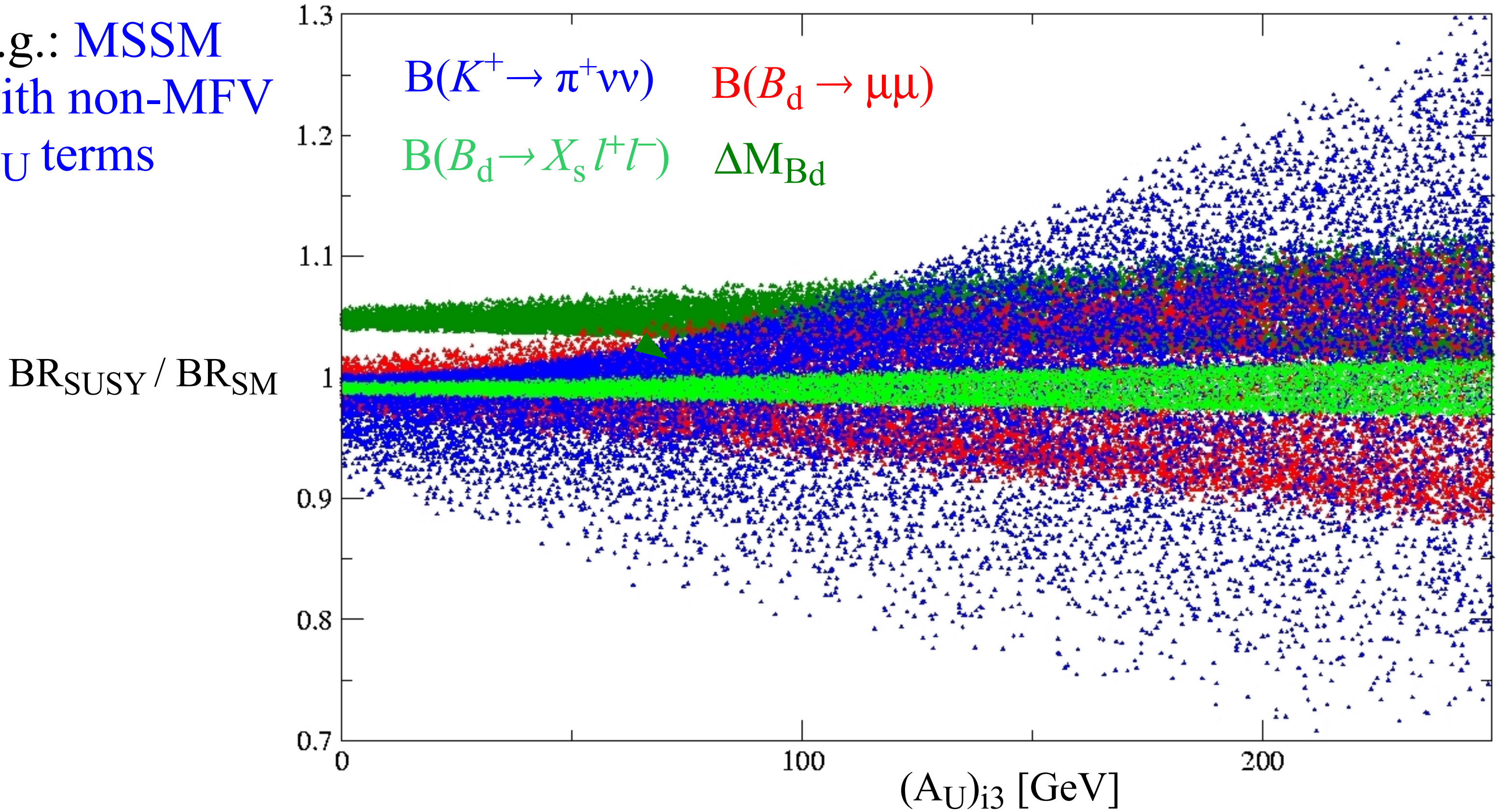
▶ *Additional material*

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): $\sigma(K_L)\sim 2\%$, $\sigma(K^+)\sim 5\%$

Unique probes of possible deviations from MFV

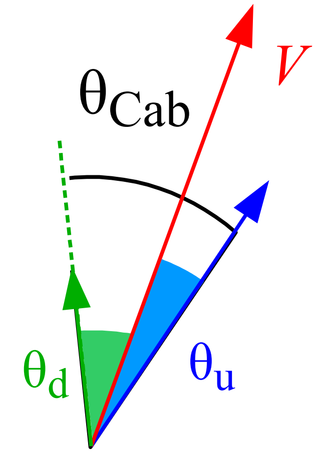
E.g.: MSSM with non-MFV A_U terms



Effective susy with $U(2)^3$

Exact symmetry is a good approximation to the SM quark spectrum ($m_u = m_d = m_s = m_c = 0$, $V_{CKM} = 1$)

=> we only need small breaking terms



$V \sim (2,1,1)$	V_{cb} & V_{ts}	$O(\lambda^2 \sim 0.04)$
$\Delta Y_u \sim (2,2,1)$	m_c, m_u, θ_u	$O(y_c \sim 0.006)$
$\Delta Y_d \sim (2,1,2)$	m_s, m_d, θ_d	$O(y_s < 0.001)$

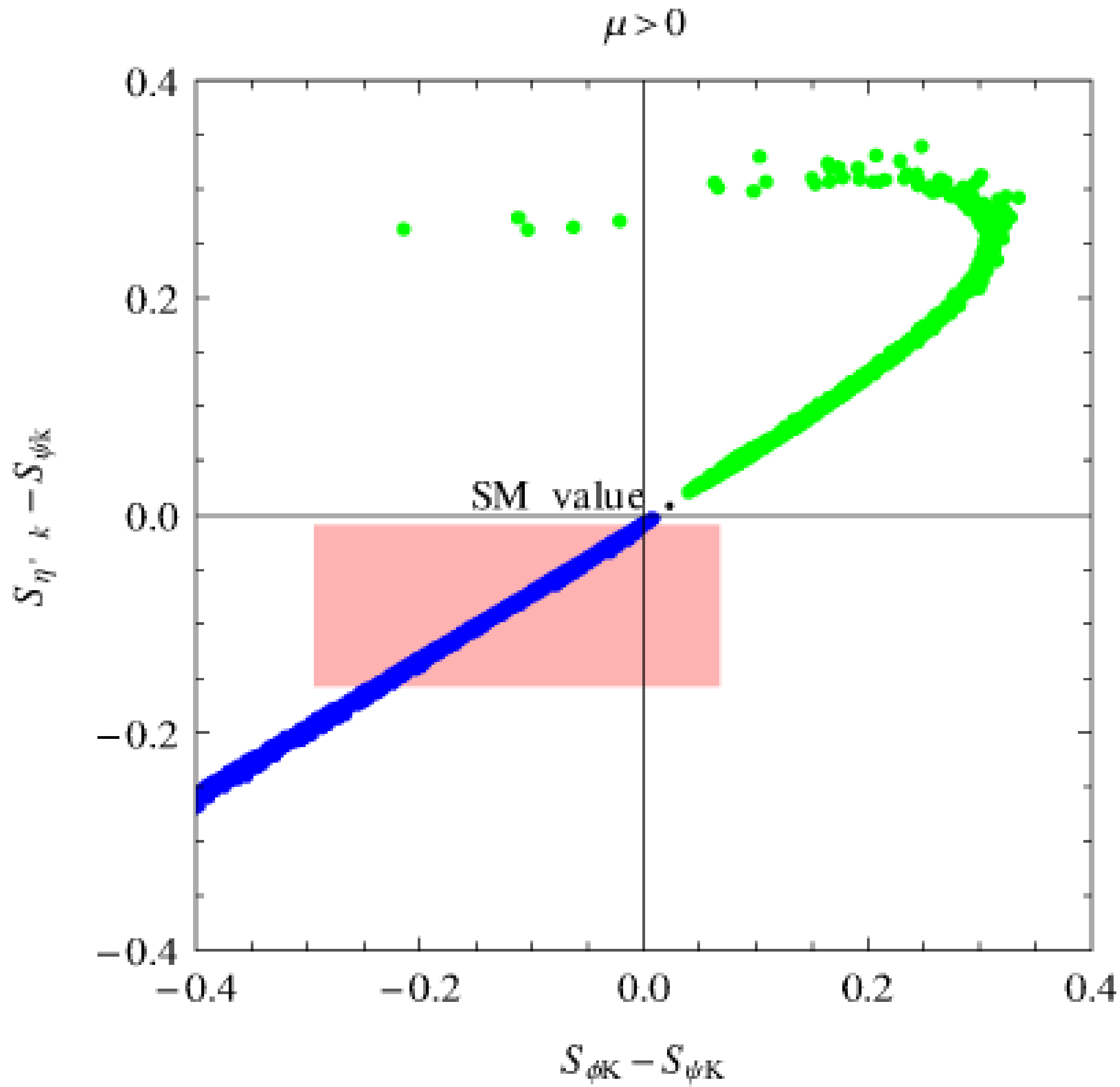
$$U(2)^3 = U(2)_Q \times U(2)_U \times U(2)_D$$

$$Y_u = y_t \begin{bmatrix} \Delta Y_u & V \\ 0 & 1 \end{bmatrix} \qquad Y_d = y_b \begin{bmatrix} \Delta Y_d & \sim V \\ 0 & 1 \end{bmatrix}$$

→

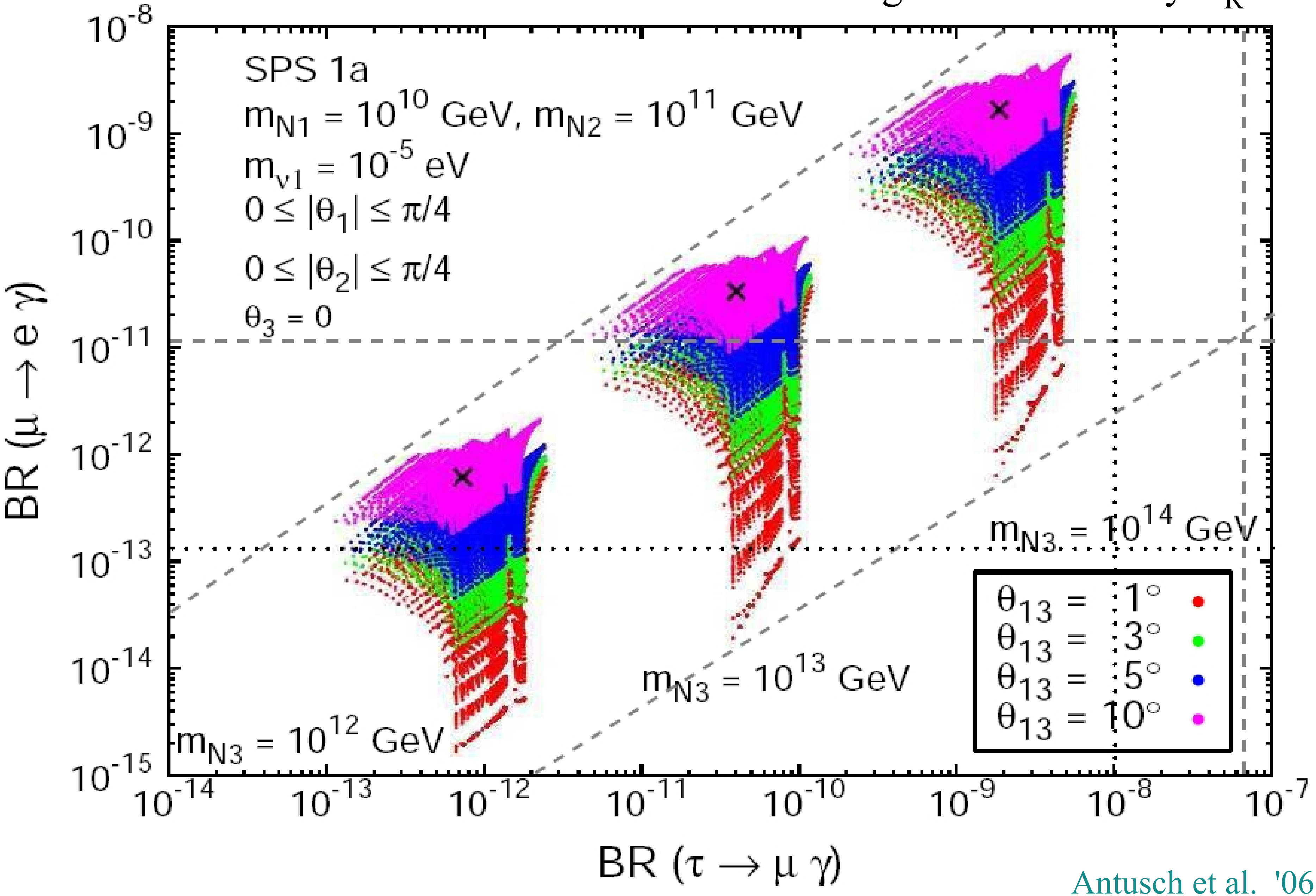
$$|V_{us}| \sim \theta_u - \theta_d$$
$$|V_{td}/V_{ts}| = \theta_d$$
$$|V_{ub}/V_{cb}| = \theta_u$$

Effective susy with U(2)^3



LFV in Charged Leptons

E.g. MSSM + heavy N_R



Antusch et al. '06

Charm Physics

In most realistic models rare D decays are not too interesting for NP searches [*large LD contrib. which is difficult to suppress* - most interesting oservable in the D system is *CPV in D mixing*]

But we should be open also to more exotic possibilities. In this respect rare D decays offer some interesting SM null-tests:

- $D \to \mu\mu$ $BR_{SM} \sim few\ 10^{-13}$
- $D \to \mu e$ $BR_{SM} \sim 0$
- ...

Model	$\mathcal{B}_{D^0\to\mu^+\mu^-}$
Experiment	$\lesssim 1.3 \times 10^{-6}$
Standard Model (SD)	$\sim 10^{-18}$
Standard Model (LD)	$\sim$ several $\times 10^{-13}$
$Q = +2/3$ Vectorlike Singlet	4.3×10^{-11}
$Q = -1/3$ Vectorlike Singlet	$1 \times 10^{-11}\ (m_S/500\ \text{GeV})^2$
$Q = -1/3$ Fourth Family	$1 \times 10^{-11}\ (m_S/500\ \text{GeV})^2$
Z' Standard Model (LD)	$2.4 \times 10^{-12}/(M_{Z'}(\text{TeV}))^2$
Family Symmetry	0.7×10^{-18} (Case A)
RPV-SUSY	$4.8 \times 10^{-9}\ (300\ \text{GeV}/m_{\tilde{d}_k})^2$

Golowich et al. '09