The Challenges of Flavour Physics

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

- Introduction: the “big” challenges of flavour physics
- Recent phenomenological challenges to the CKM picture
- Possible beyond-the-SM explanations of these “anomalies”
- Experimental challenges for the near future
- Conclusions

Introduction: the "big" challenges of flavour physics

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

Introduction: the "big" challenges of flavour physics

To a large extent, the origin of "flavour" is still a mystery...
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?* [Is there anything else beside SM Yukawa couplings & neutrino mass matrix?]

Introduction: the "big" challenges of flavour physics

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

Some "popular" answers to this question are obtained by means of

- Abelian or non-Abelian continuos flavour symmetries
- Discrete flavour symmetries
- Fermion profiles in extra dimensions

But other options are also possible.

In all cases 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.

Introduction: the "big" challenges of flavour physics

To a large extent, the origin of "flavour" is still a mystery...
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?*
  [Is there anything else beside SM Yukawa couplings & neutrino mass matrix?]

Answering this question is more easy:

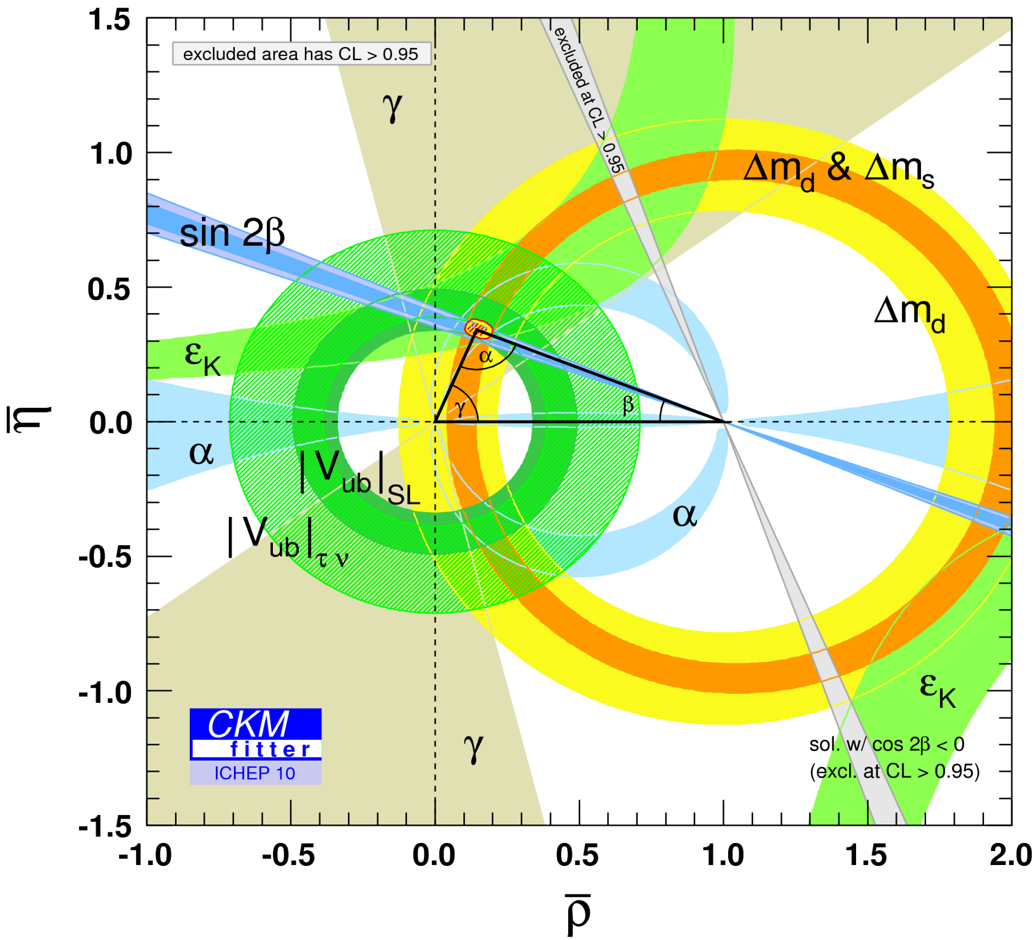
- It can be formulated independently of the UV completion of the theory.
- It is mainly a question of precision (both on the theory and on the experimental side).

⬇

Main goal of flavour-physics in the early LHC era

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

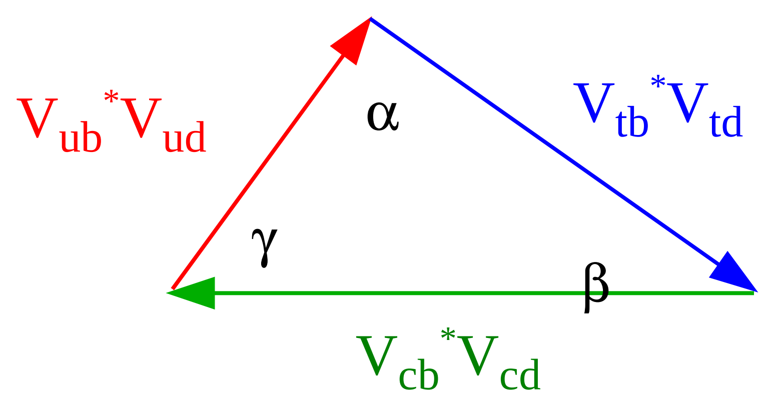
The good overall consistency of the experimental constraints appearing in the so-called CKM fits seems to indicate there is not much room for new sources of flavour symmetry breaking



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

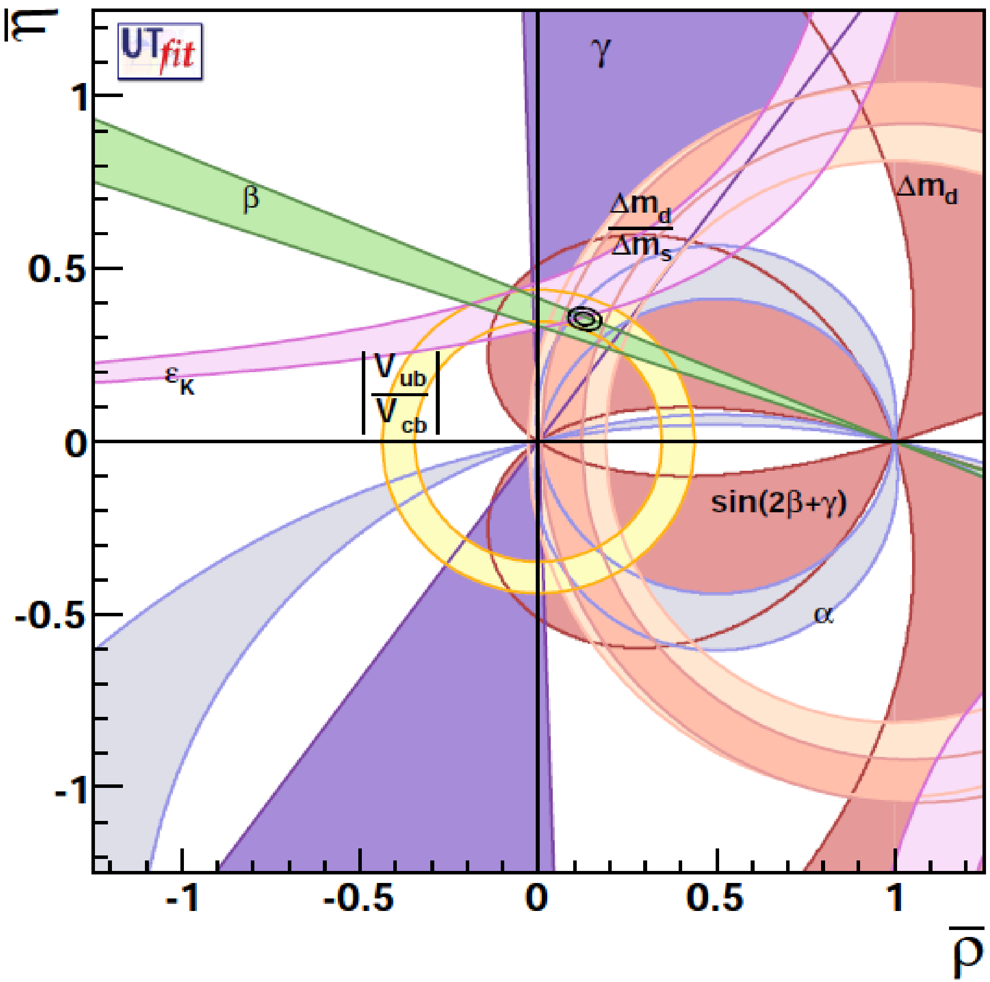
triangular relation:

$$V_{ub}^{*}V_{ud} + V_{cb}^{*}V_{cd} + V_{tb}^{*}V_{td} = 0$$



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



- Changing statistical treatment does not lead to significant differences: high-quality data are finally drawing the picture...!

- There is much more, not shown in such fits, that confirms the good success of the SM in describing flavour mixing ($B \to X_s \gamma$, 1st raw CKM unitarity, ...)

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

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

G.I, Nir, Perez '10

Operator	Bounds on Λ (TeV) Re	Bounds on Λ (TeV) Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Bounds on c_{ij} ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	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; $\lvert q/p \rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	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}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2	3.7×10^2	1.3×10^{-5}	1.3×10^{-5}	Δm_{B_s}

New flavor-breaking sources of O(1) at the TeV scale are definitely excluded

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

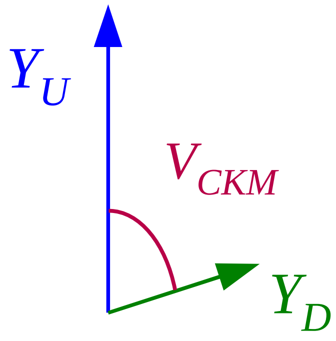
The good overall consistency of the experimental constraints appearing in the so-called CKM fits seems to indicate there is not much room for new sources of flavour symmetry breaking

↓

Minimal Flavour Violation paradigm:

The large <u>quark-flavour symmetry</u> of the gauge SM Lagrangian is <u>broken only by the two quark Yukawa couplings</u> $\Rightarrow$ 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
(with a few interesting exceptions),
even for new-physics within the LHC reach

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

- 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 the MFV predictions.

- Even if MFV holds , it does not necessarily imply small effects in all flavour-changing phenomena: MFV can be implemented in different ways (small or large tanβ, w/ or w/o flavour-blind CPV phases, w/ or w/o SUSY) which imply deviations from the SM just below current bounds, with testable correlations in different observables.

Kagan, Perez, Volasky, Zupan, '09
Altmannshofer *et al*. '09
Buras, Calrucci, Gori, G.I., '10
Ligeti *et al*., '10
Blum, Hochberg, Nir '10

⬇

The investigation of the structure of flavour symmetry breaking beyond the SM has just started...

Recent phenomenological challenges to the CKM picture

Despite the overall success of the "standard picture"...

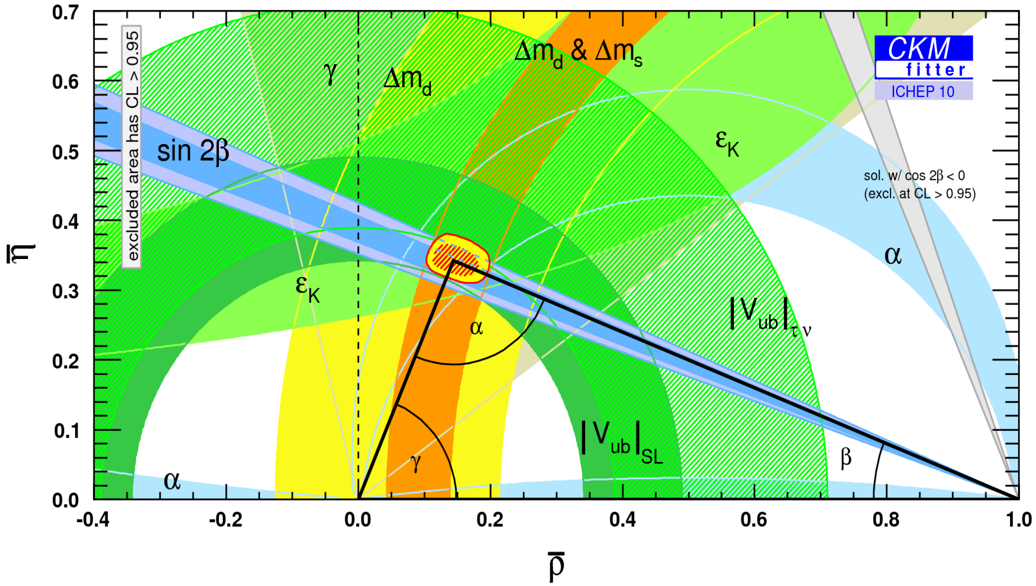
..looking more closely there a few "*anomalies*" that is worth to investigate in more detail

Three particularly interesting cases:

- The sin(2β) tension in the CKM fit
- CPV in Bs mixing
- $B(B \rightarrow \tau \nu)$

I. The sin(2β) tension in the CKM fit

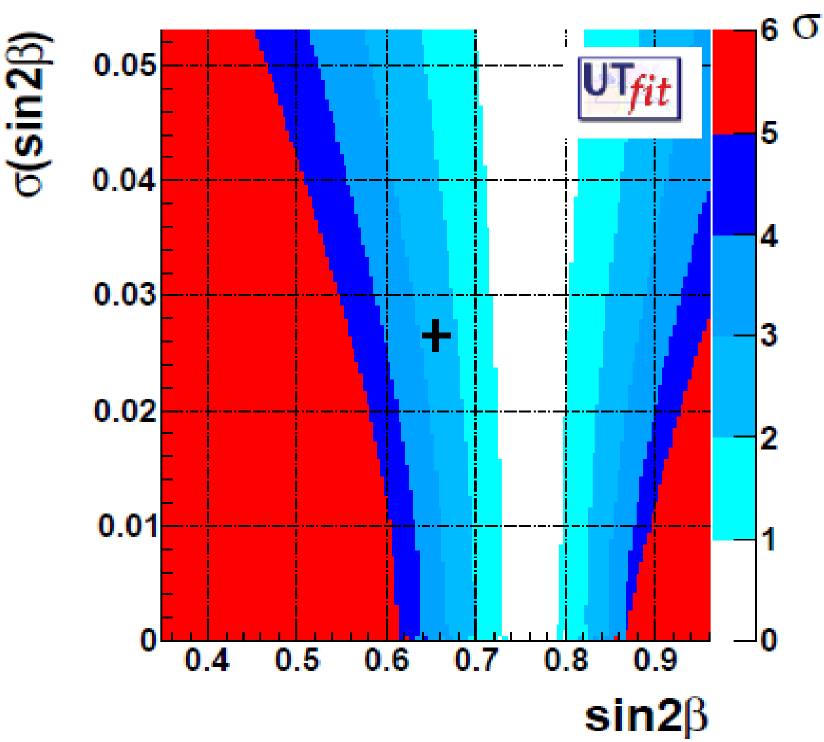
At first sight the global CKM fit shows an excellent consistency. However, a closer inspection shows a tension between $A_{\psi K}$=sin(2β) and its prediction (via ε_K and V_{ub}).



Buras & Guadagnoli, '08
Soni & Lunghi, '08-'09

This tension becomes quite clear if we take into account only the recent unquenched determinations of B_K

Antonio *et al.* '08
Aubin *et al.* '10



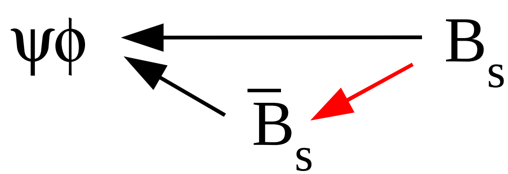
The indirect determination of sin(2β) turns out to be at ~2.6 σ from the experimental measurement

Talk by C. Tarantino

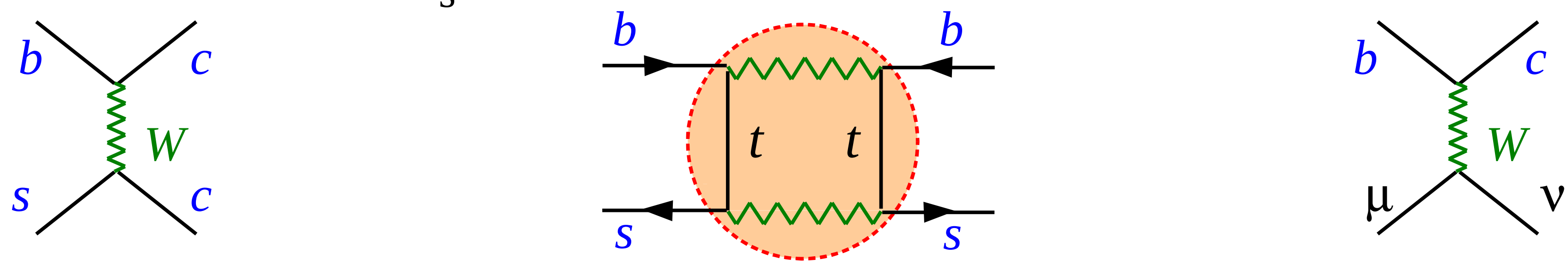
II. CP violation in B_s mixing

The weak phase of B_s mixing is currently under investigation at Tevatron via the time-dependent study of the $B_s \to \psi\phi$ decay [$A_{\psi\phi}$] & via the semileptonic charge asymmetry (same-sign muons) [a_{sl}]

Theoretical clean extraction:



$$\left[\begin{array}{l} \bar{B}_s \longrightarrow \mu^- + X \\ B_s \to \bar{B}_s \to \mu^- + X \end{array}\right.$$



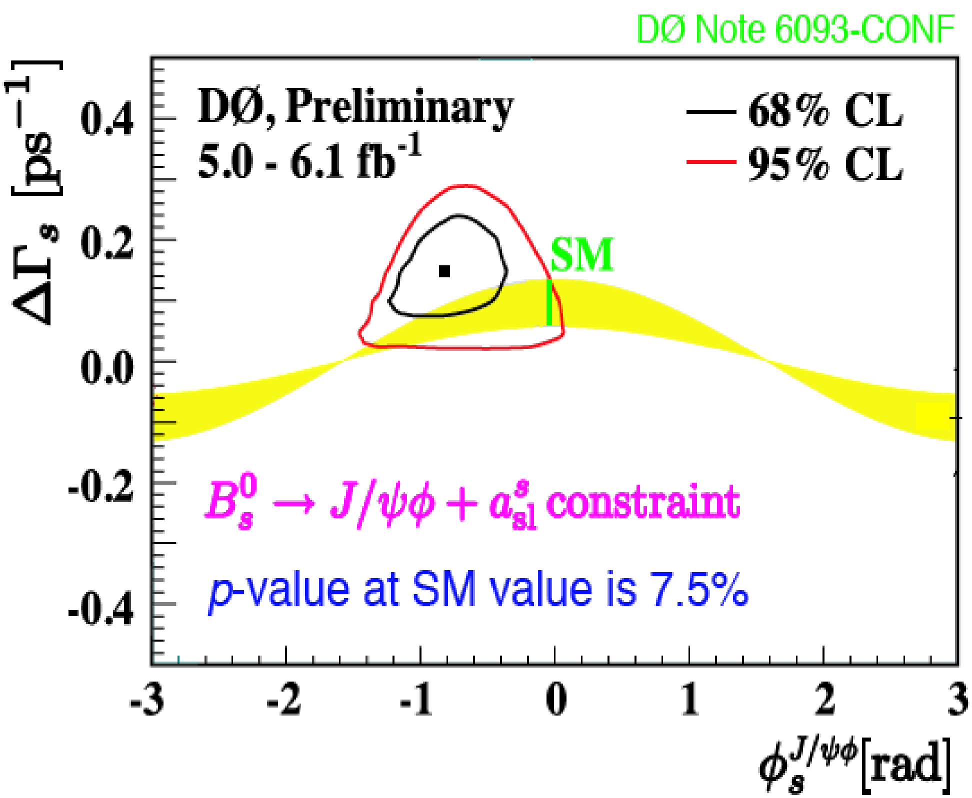
More details in the next talk

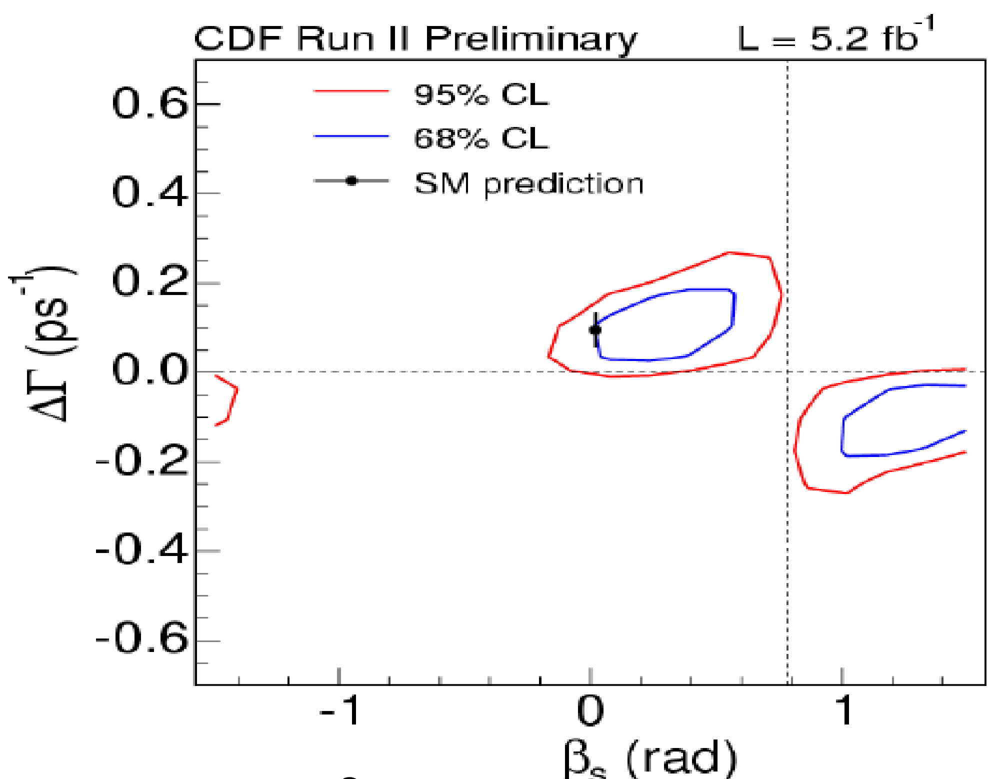
Vanishingly small result expected if the phase is determined only by the Yukawa couplings: SM and MFV with no extra CPV phases

II. CP violation in B_s mixing

The weak phase of B_s mixing is currently under investigation at Tevatron via the time-dependent study of the $B_s \to \psi\phi$ decay [$A_{\psi\phi}$] & via the semileptonic charge asymmetry (same-sign muons) [a_{sl}]

Several new results in 2010: a_{sl} by D0 [*with ~ 3σ deviation from SM*] + updated $A_{\psi\phi}$ by both CDF & D0 [*with agreement with SM at ~ 1σ*]



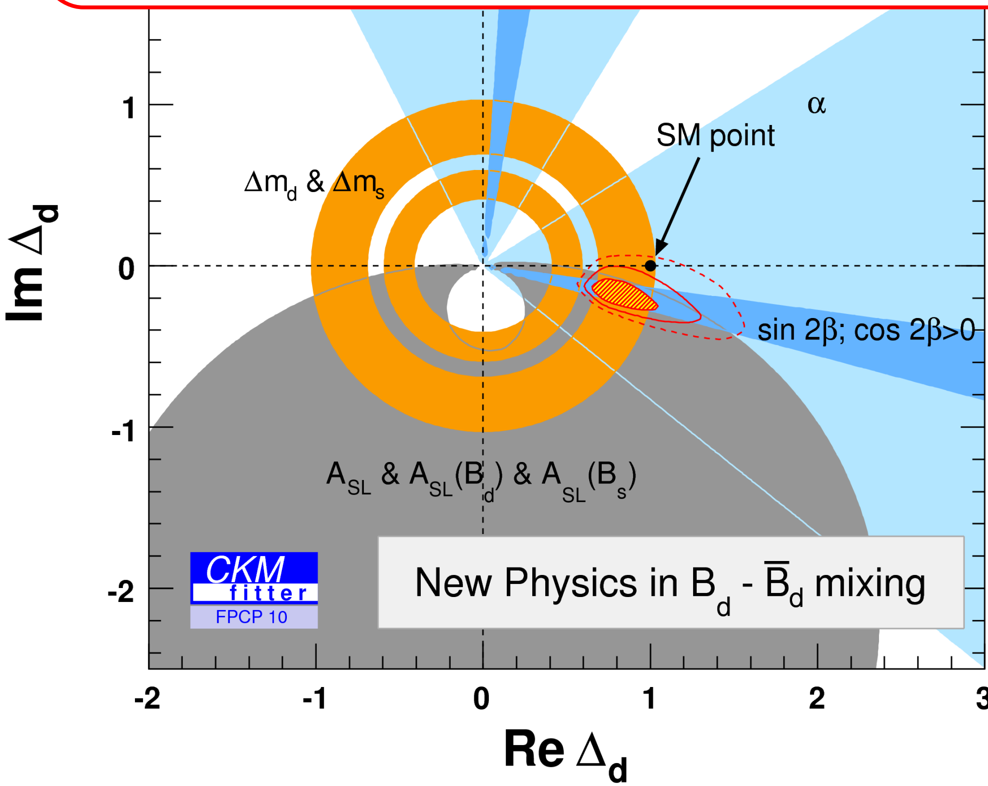


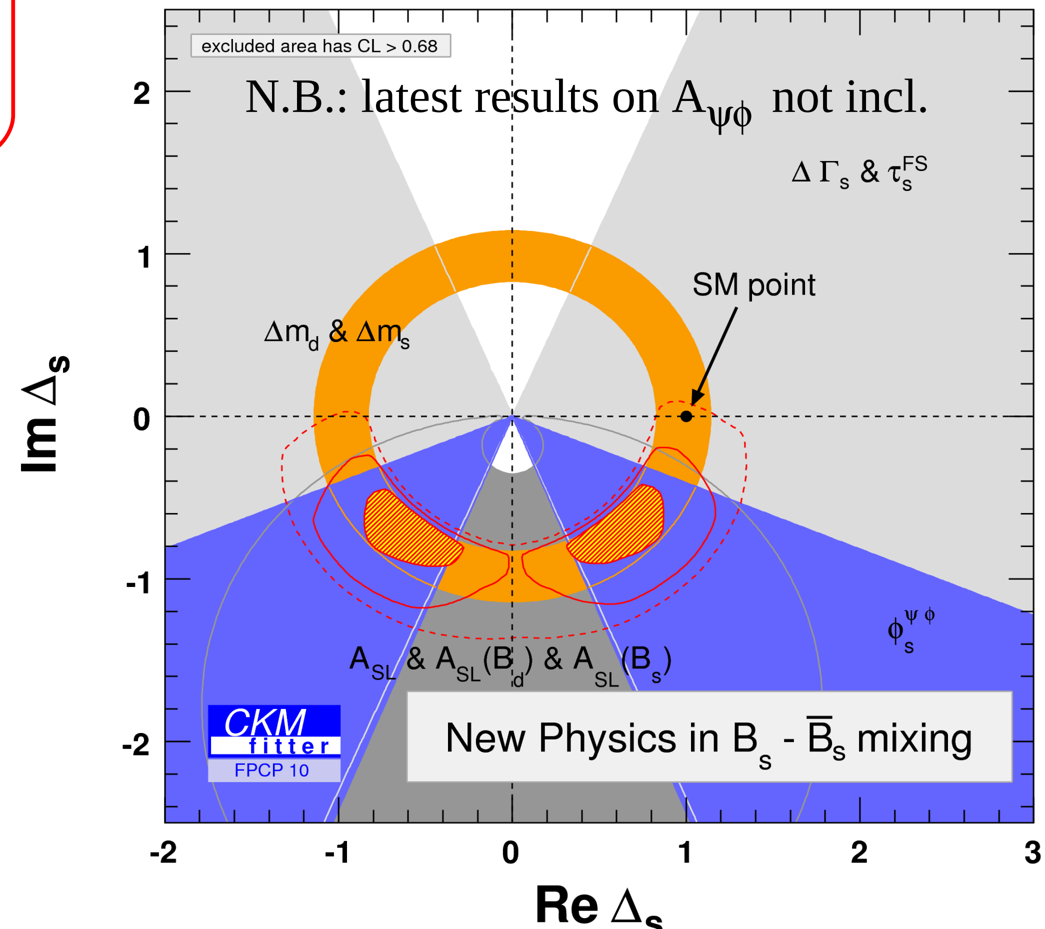
[$\phi_s = -2\beta_s$]

Present data allows us to fix the CKM matrix using tree-level observables only, extracting in a model-independent way the amount of "new physics" in all $\Delta F=2$ observables.

$$\langle B_q|M_{12}^{\mathrm{SM+NP}}|\bar{B}_q\rangle = \Delta_q^{\mathrm{NP}} \langle B_q|M_{12}^{\mathrm{SM}}|\bar{B}_q\rangle$$

Main mess: ~ 2σ deviations in both cases, of rather different size (large in B_s, small in B_d, compared to SM)



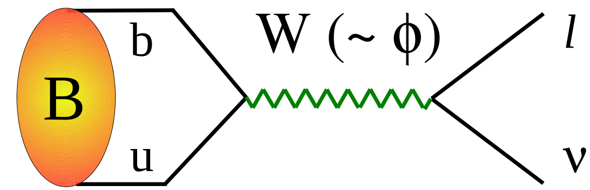


Talk by S. T'Jampens

Similar conclusions also by UTfit

III. B(B→ τ ν)

The helicity suppression of the SM amplitude makes B→τν an excellent probe of models with an extended scalar sector.



longitudinal comp. of the W

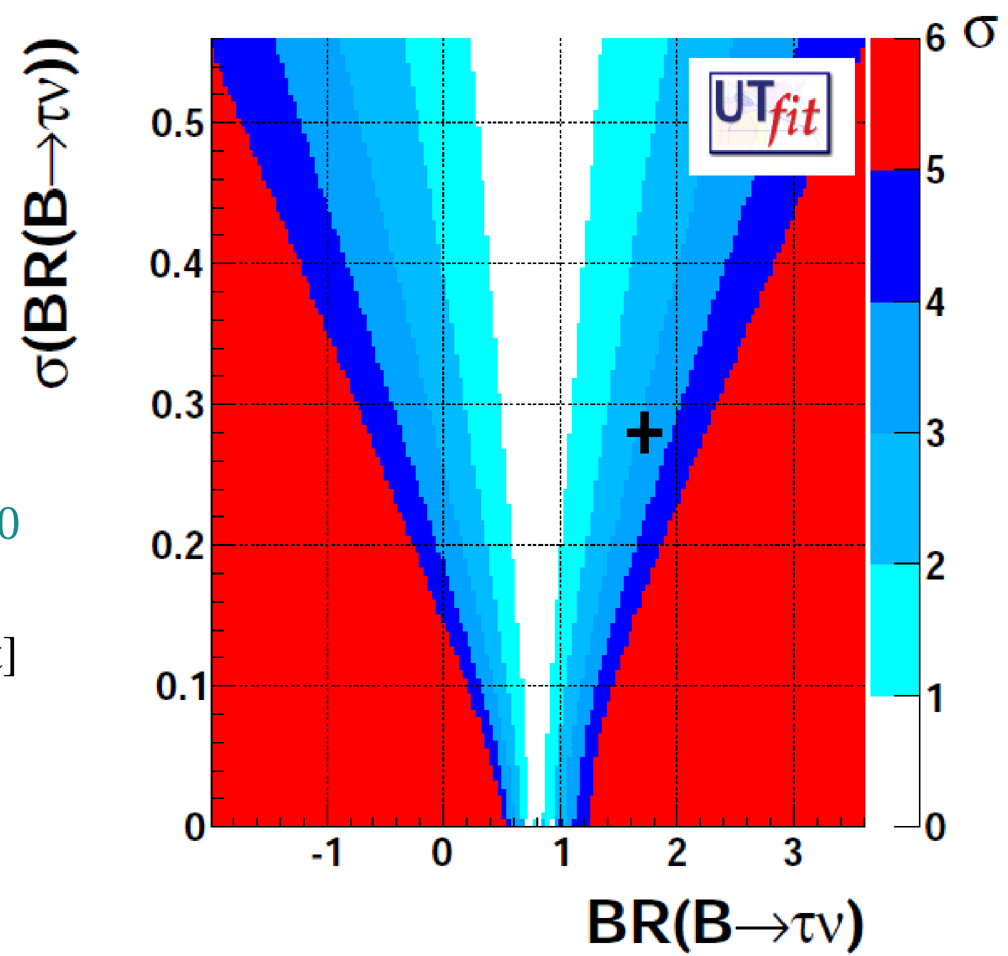
$$B(B\to l\nu)_{SM} = C_0\, f_B^{\,2}\, |V_{ub}|^2$$

Very clean test of the SM, provided reliable independent infos on f_B & V_{ub}

$$B(B\to\tau\,\nu)_{exp} = (1.68 \pm 0.31)\times 10^{-4}$$

Babar + Belle '10

$B_{SM} = (0.79 \pm 0.07)\times 10^{-4}$ UTfit '10 [global fit]



Similar conclusions also by CKMfitter

▶ Possible beyond-SM-explanation of these "anomalies"

Several attempts to explain these effects have appeared in the recent literature (*we are desperately waiting for signals of physics beyond the SM*...)

Possible beyond-SM-explanation of these "anomalies"

Several attempts to explain these effects have appeared in the recent literature (*we are desperately waiting for signals of physics beyond the SM...*)

In the following I will focus on three classes of models where there has been considerable activity in the last few months, and which are quite interesting because of clear correlations among various observables:

- Two Higgs Doublet Model (2HDM) with MFV, large tanβ, and flavour-blind phases
- Right-handed currents
- Fourth generation

N.B.: All the three models can be viewed as "simple" effective theories which could arise as the low-enery limit of more ambitiuos (and more complete) models (Supersymmetry, Warped extra-dimensions, ...)

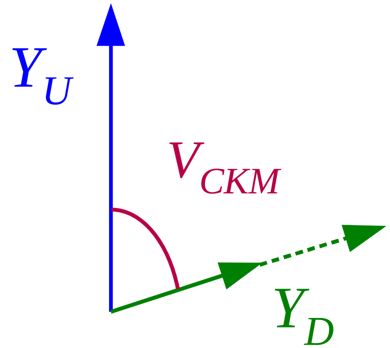
I. 2HDM with MFV, large tanβ, and flavour-blind phases

MFV= assumption of a well-defined symmetry + symmetry-breaking structure (in all sectors of the theory):

- Quark-Flavour symmetry: $SU(3)_Q \times SU(3)_U \times SU(3)_D$
- Symmetry-breaking: $Y_D \sim 3_Q \times \bar{3}_D$ $Y_U \sim 3_Q \times \bar{3}_U$

D'Ambrosio *et al.*, '02

- With two Higgs doublets (coupled at the tree-level only to up or down) we can change the relative normalization of Y_D & Y_U playing with the ratio of the two Higgs vevs



- The breaking of CP (*flavour-blind*) does not need to be related to the breaking of the flavour symmetry

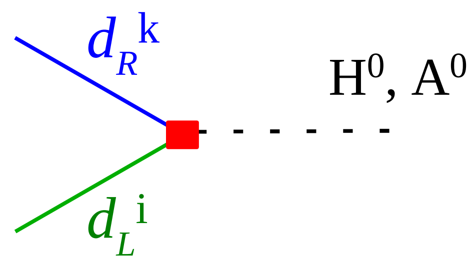
Ellis, Lee, Pilaftsis, '07
Kagan, Perez, Volansky, Zupan '09
Mercolli, Smith '09; Paradisi, Straub, '09

↓

Phenomenology of Higgs-mediated FCNCs with MFV particularly interesting with large $\tan\beta = v_2/v_1$ + large flavour-blind CPV phases

I. 2HDM with MFV, large tanβ, and flavour-blind phases

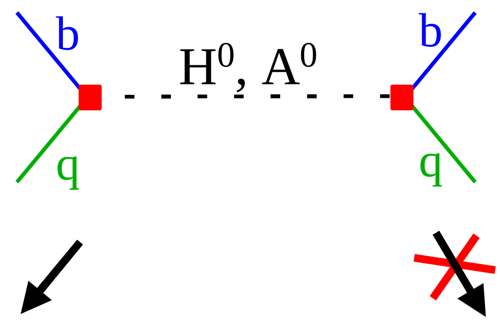
Structure of the FCNC couplings to the Higgs (in the limit $\tan\beta \gg 1$):



$A \sim V_{3i}^* V_{3k}\, m_{d_k}$

Double suppression: CKM + down-type mass

After integrating out the heavy Higgs fields:



$\bar{b}_R q_L \bar{b}_L q_R$

$\bar{b}_R q_L \bar{b}_R q_L$ forbidden in the exact $SU(2)_L$ limit

Effects scale (almost) as

- $m_b m_s$ (B_s mixing)
- $m_b m_d$ (B_d mixing)
- $m_s m_d$ (K mixing)

relative to the SM →

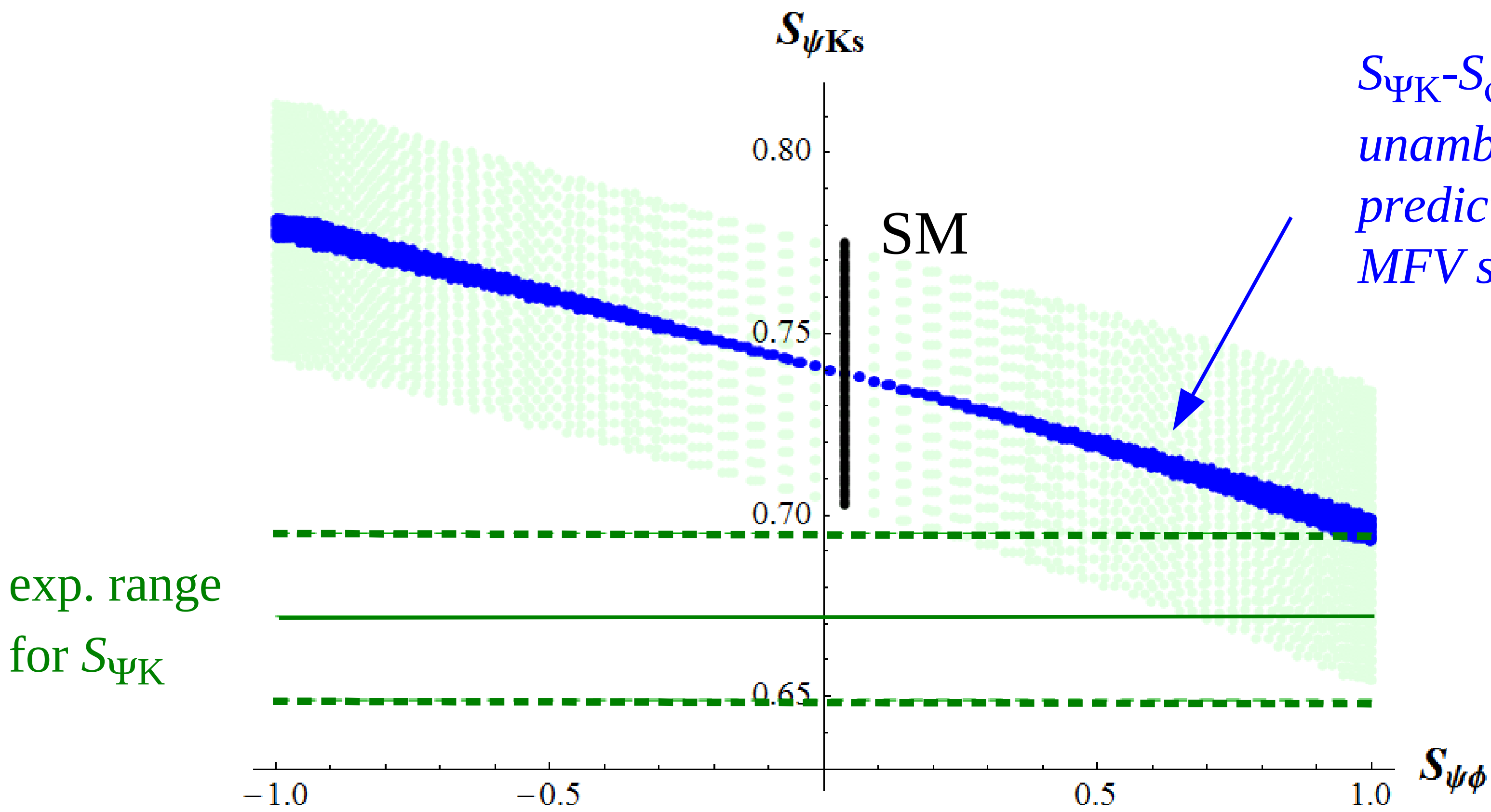
- *large* (B_s mixing)
- *small* (B_d mixing)
- *tiny* (K mixing)

Very interesting pattern given the present ΔF=2 "*anomalies*"

With Higgs-mediated FCNCs with flavour-blind phases it is relatively easy to fit a large Bs mixing phase

Kagan *et al*. '09

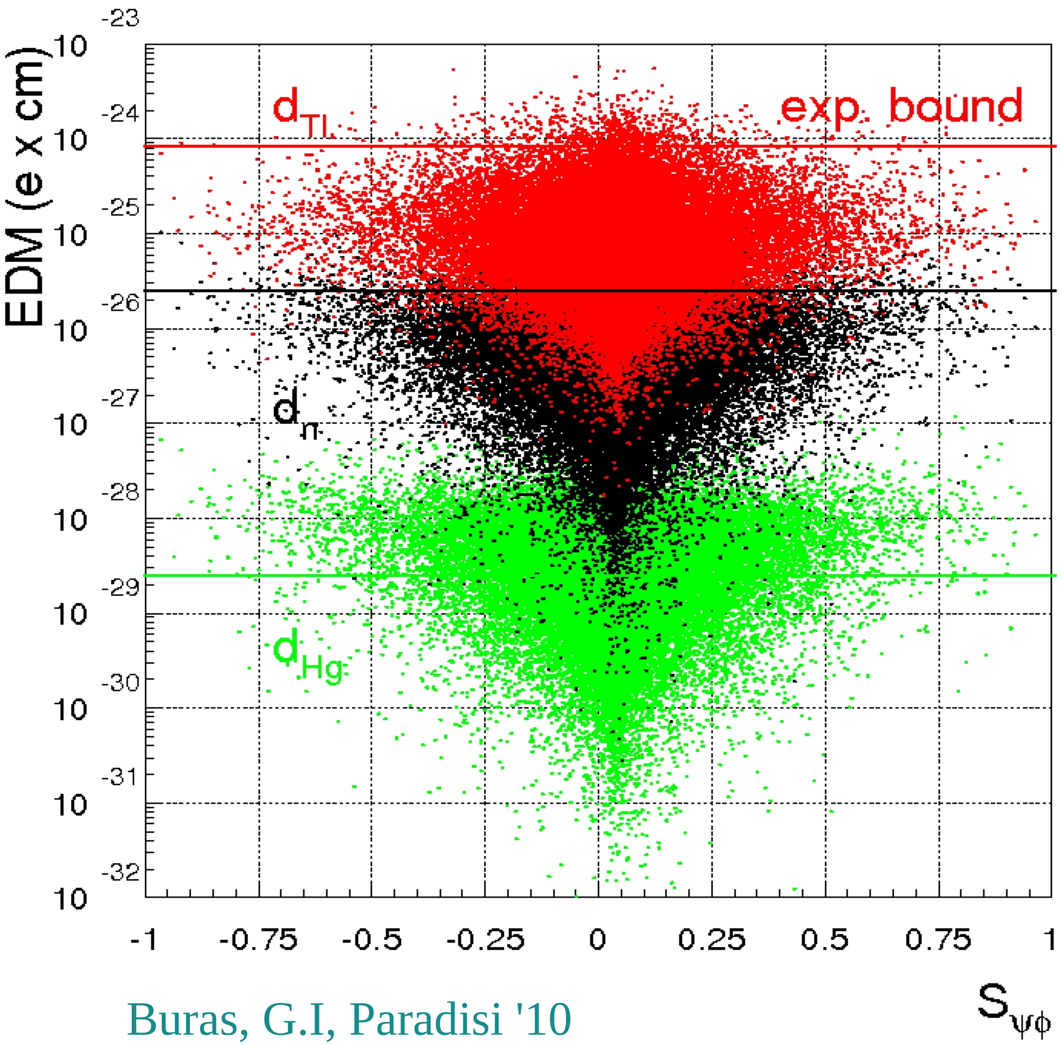
What is remarkable is that <u>with no extra free parameters</u> (modulo and phase of the unique $\Delta F=2$ operator fixed by ΔM_{Bs} and ϕ_{Bs}), the effect predicted for B_d mixing goes in the right direction to <u>improve the quality of the CKM fit</u>



Buras, Carlucci, Gori, G.I, '10

Significant contribution to B_s mixing are obtained for reasonable values of m_H & $\tan\beta$ [$m_H < 1$ TeV, $\tan\beta = 10\text{-}50$], but they require conspiracy of ops. with several Yukawa insertions on the UV side: not possible in the usual MSSM, maybe in more exotic versions (e.g. uplifted SUSY) or beyond SUSY

Dobrescu, Fox, Martin '10



Buras, G.I, Paradisi '10

One of the virtues of this scenario is that is very predictive: beside the correlation of $B_{s,d}$ mix., $B_{s,d} \to \mu\mu$ & ← EDMs should be "around the corner"

N.B.: if $\tan\beta$ is small, the correlation of B_s & B_d mixing phases change: equal effect (relative to SM)

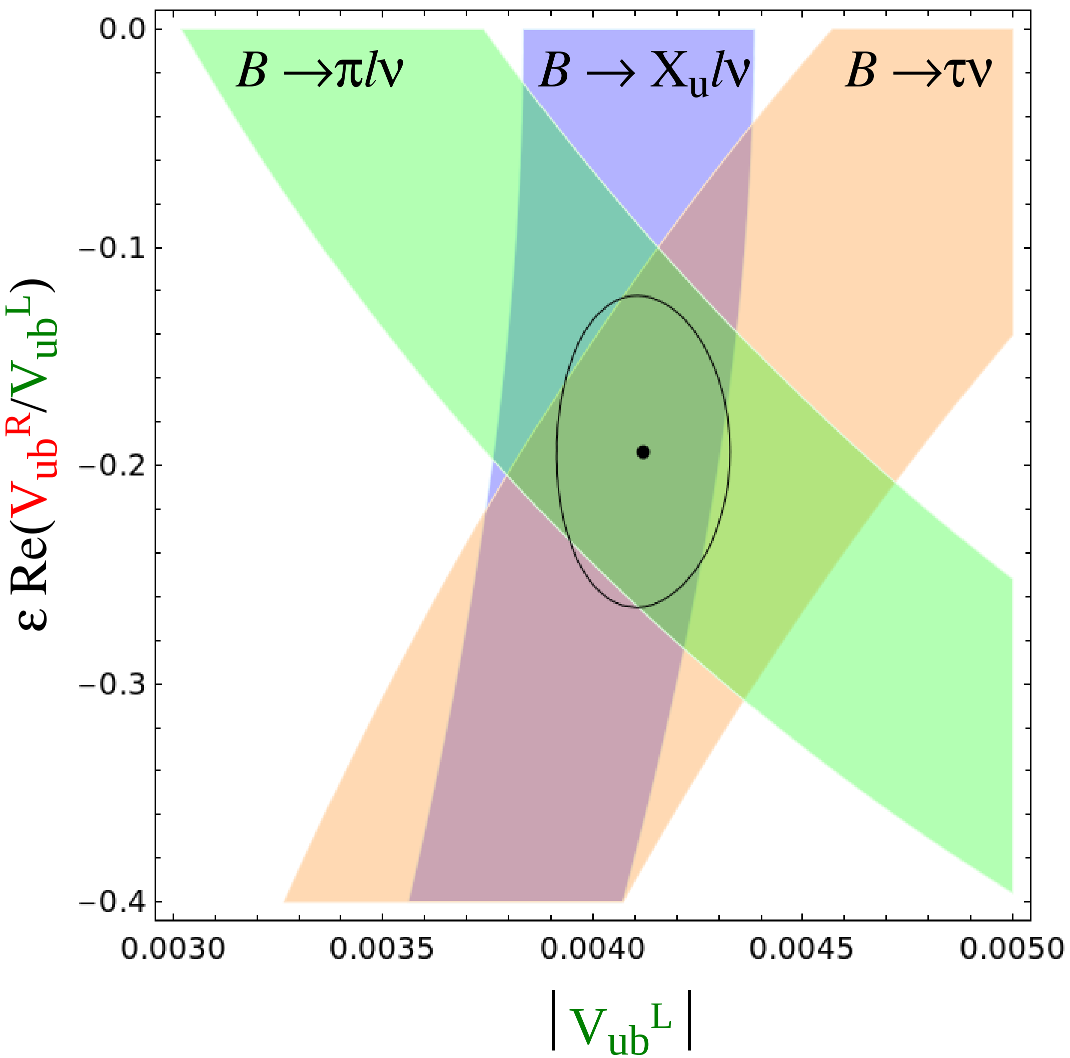
Ligeti *et al.* '10
Pich *et al.* '10
Blum, Hochberg, Nir '10

II. Right-handed currents

Right-handed currents are expected in several well-motivated extensions of the SM [e.g. $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ e.w. symmetry]

A low-energy phenomenological motivation to consider charged-current RH currents arises by a simple solution to all problems related to V_{ub} :

Crivellin '09
Chen, Nam '08



$$B(B \to \pi\, l\nu) \propto \left| V_{ub}^L + V_{ub}^R \right|^2$$

$$B(B \to \tau\nu) \propto \left| V_{ub}^L - V_{ub}^R \right|^2$$

$$B(B \to X_u l\nu) \propto \left| V_{ub}^L \right|^2 + \left| V_{ub}^R \right|^2$$

II. Right-handed currents

Is this effect compatible with other flavour constraints? Where else can we see the effects of RH? ⇒ The problem can be analysed by means of a general effective theory approach

Buras, Gemmler, G.I. '10

- Assuming the two Yukawas as the only symmetry-breaking terms, we have only one new unitary mixing matrix (V_R) controlling $u_R - d_R$ misalignment
- Significant constraints from V_{ub} (*signal*) + all other c.c. (*bounds*) + unitarity + FCNCs (*strong bounds from* ε_K)

↓

- Possible to pass all bounds with eff. RH scale ~ 3 TeV [within LHC reach]
- Easy to have large impact in Bs mixing, but no impact expected in Bd
- RH currents should be visible in semileptonic K decays with more precision

Preferred solution:

$$|V_R| \sim \begin{bmatrix} - & 0.7 & 0.7 \\ 1 & - & - \\ - & 0.7 & 0.7 \end{bmatrix}$$

Bernard, Ortel, Passemar, Stern, '08-'09

III. Fourth generation

Adding a 4th generation to the SM may appear quite "ugly" at first sight...
But why not... It is not so unnatural if the new heavy states are interpreted as the lower end of a more complicated spectrum, with several new states (*composite models*,...)

⇒ Renewed recent interest in flavour physics

Hou *et al.* '06-'10; Soni *et al.* '09-'10
Burdman *et al.* '09; Holdom, '09
Eilam *et al.* '09; Bobrowski *et al.* '09
Godbole *et al.* '09; Buras *et al.* '10;
Lenz *et al.* '10 ....

V_{CKM} (3x3) ⟶ V_{4GSM} (4x4)

3 new mixing angles + 2 new CPV phases
(+ 2 masses)

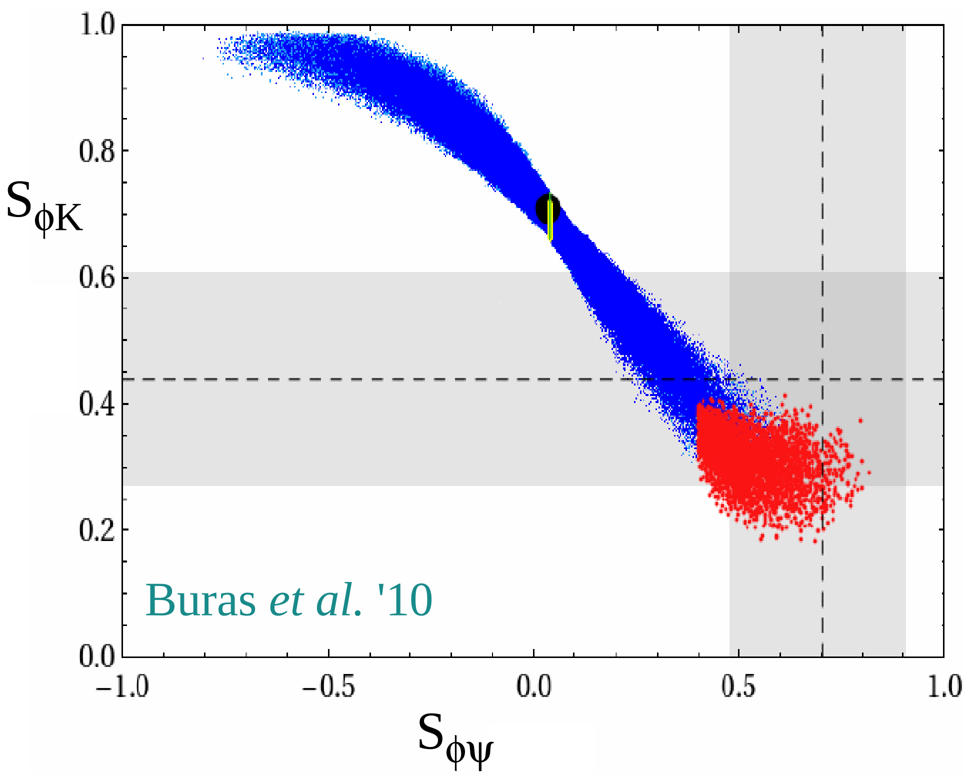
↓

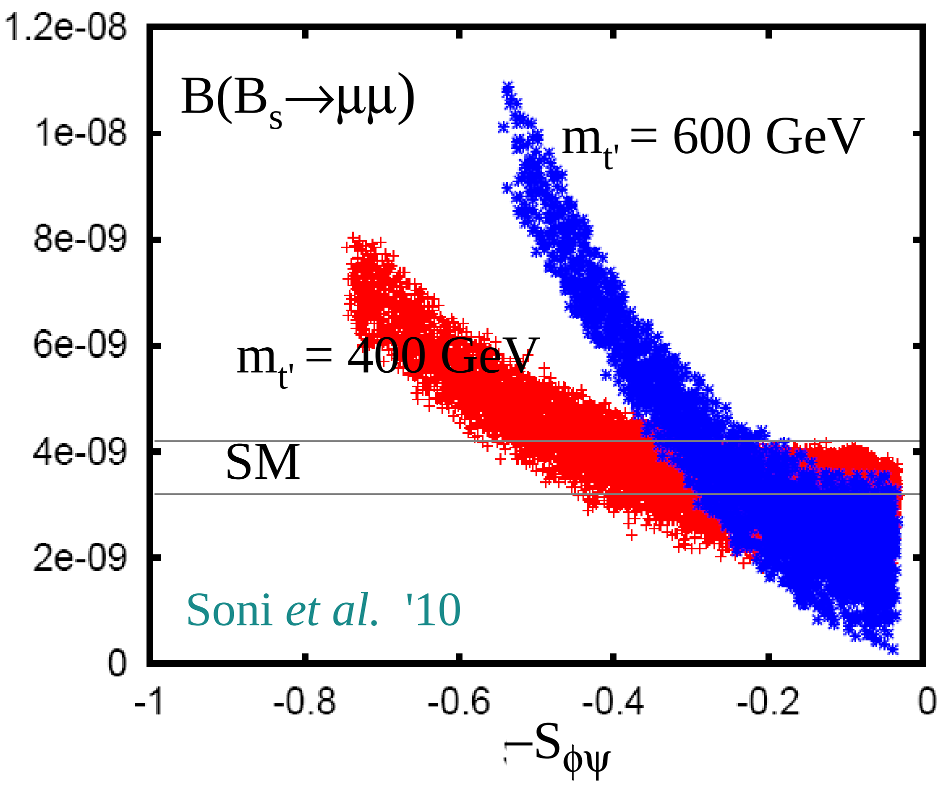
Not many new free parameters rather constrained system

III. Fourth generation

Highlights:

- Enhancement of B_s mixing phase possible, but it implies a suppression of $S_{\phi K}=A_{CP}(B_d\to\phi K)$ [good news] and an enhancement of $B(B_s\to\mu\mu)$ [testable]





- Large effects in rare K decays quite likely [testable], some tension with ε'/ε [potential problem, still ok given present th. errors]

Experimental challenges for the near future

Experimental challenges for the near future

Current "anomalies" are certainly interesting, but we cannot exclude they will all disappear with higher statistics [*they are not the most natural expectations in the most "conservative" beyond-SM scenarios, such as MFV with no extra phases*].

Even in this pessimistic case, there are a few other channels where we can expect sizable deviations from the SM (even in "conservative" beyond-SM scenarios...), and for which we expect results in the near future.

Personal choice of "golden modes":

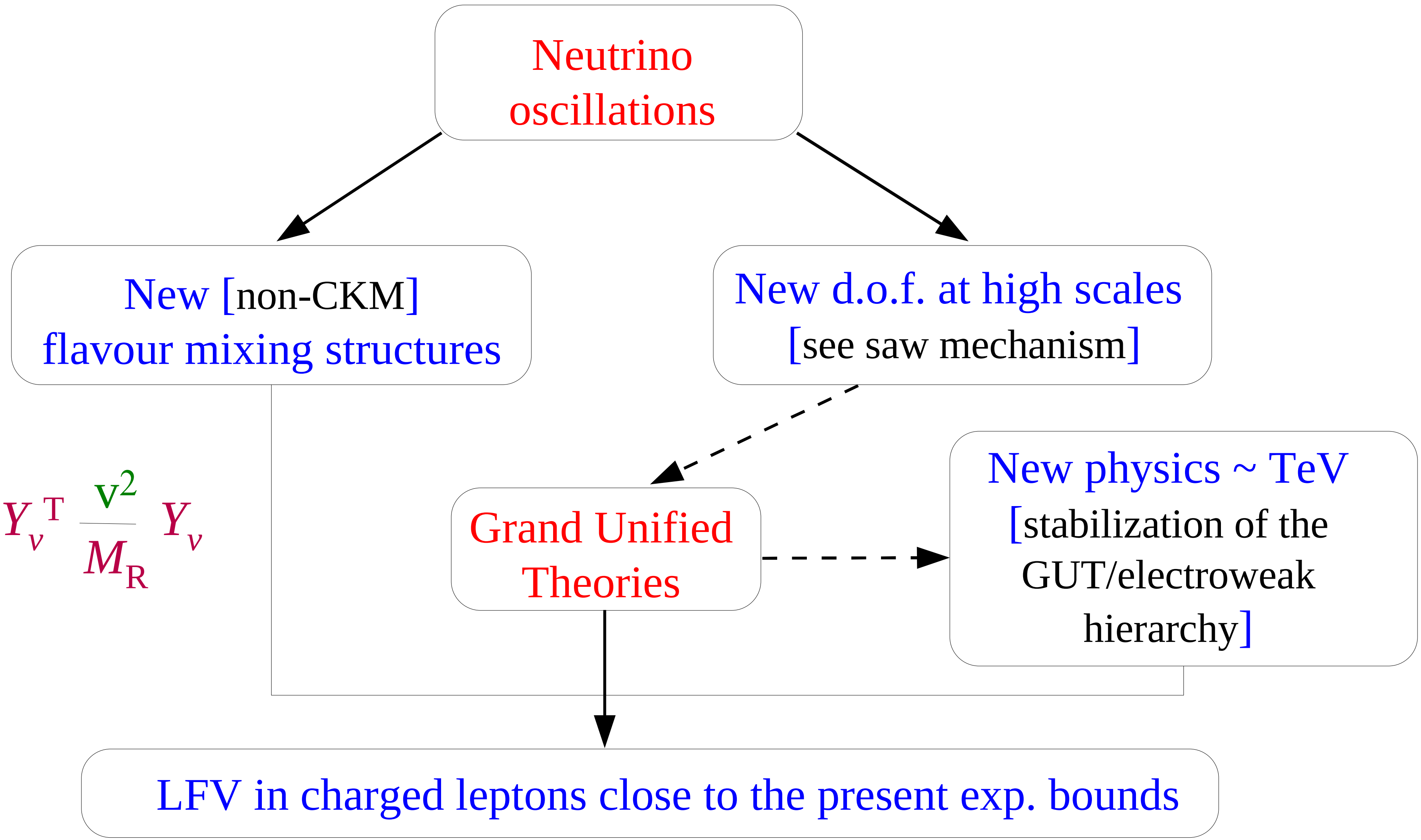
LFV in charged leptons

Very rare K decays

Helicity- suppressed rare B decays

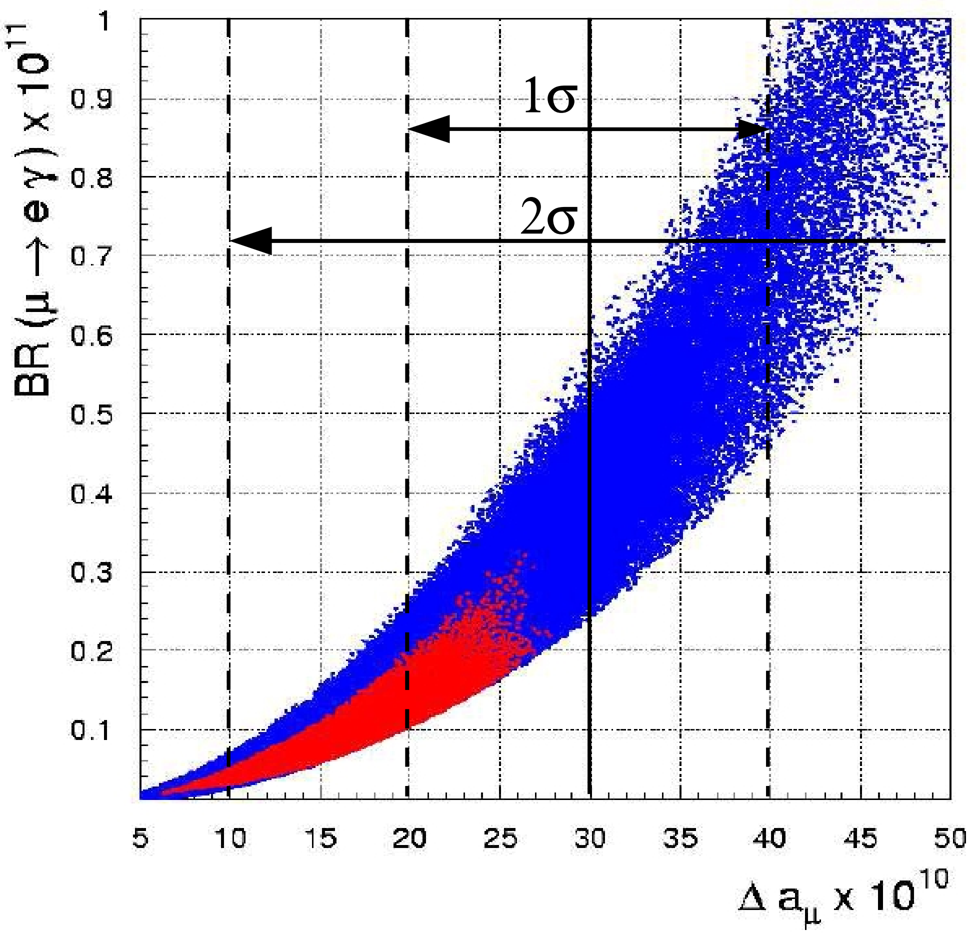
I. *Lepton Flavour Violation in charged leptons*

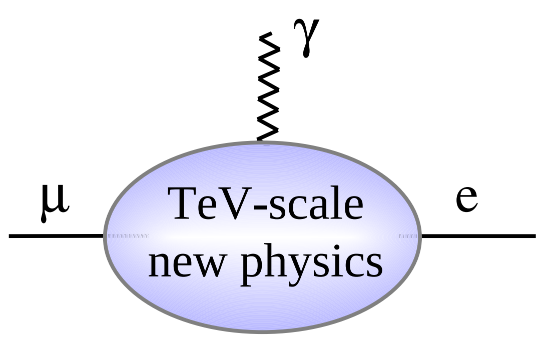
After what we learned from neutrino physics, LFV in charged leptons is probably the most interesting search in the flavour sector:



$$m_\nu \sim Y_\nu^T \frac{v^2}{M_R} Y_\nu$$

In the most conservative scenarios the LFV observable where the theory predictions are closer to the present experimental sensitivity is $\mu \to e\gamma$: in GUT theories with new particles carrying lepton-flavor at the TeV scale (*e.g. sleptons in the MSSM*), the MEG experiment at PSI has good chances to see $\mu \to e\gamma$





Interesting correlation with g-2 in many explicit new-physics models.

← E.g.: MSSM + heavy ν_R

II. *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 ($V_{ts}^* V_{td} \sim \lambda^5$)

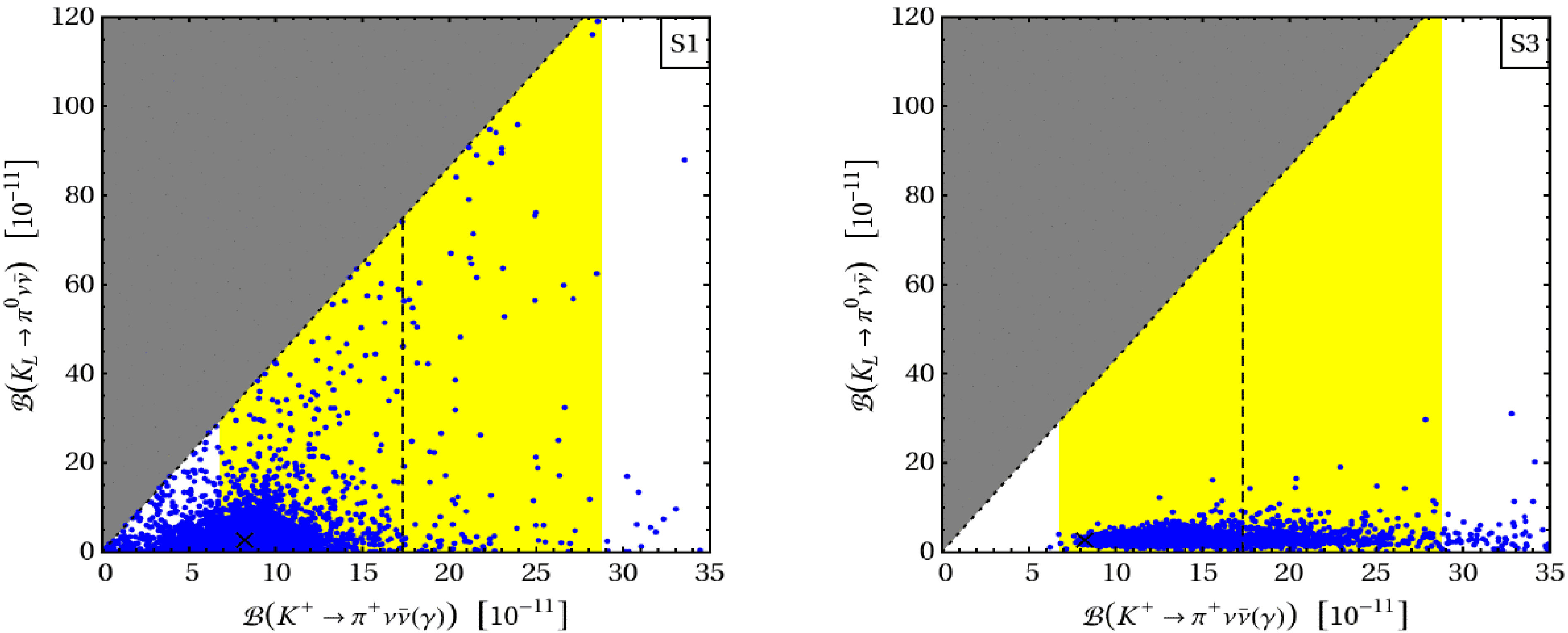
II. Very rare K decays

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 -

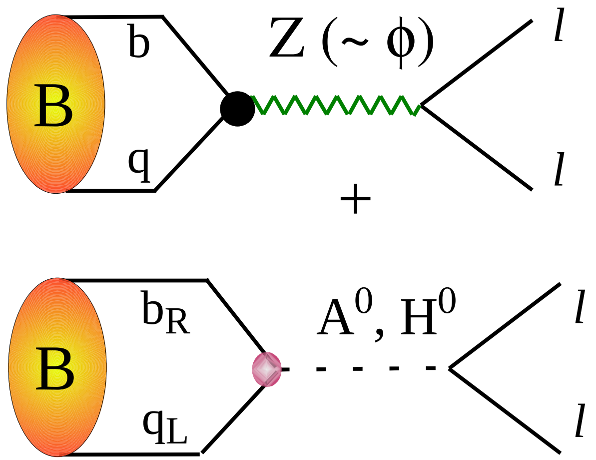
E.g.: $K \to \pi \nu\nu$ in models with warped extra space-time dimensions [RS models]



Blanke *et al.* '08, Buer *et al.* '09

III. Helicity-suppressed rare B decays

$B \to l^+ l^-$ decays are both helicity suppressed and GIM suppressed (FCNC)



Excellent probes of models with 2 Higgs doublets (such as the MSSM) at large/moderate tanβ

Within the MSSM, with MFV:

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

- The $B(B_d \to \mu\mu)/B(B_s \to \mu\mu)$ ratio is a key observable to proof or falsify MFV

- Possible large enhancement over the SM for "natural values" of the free parameters (contrary to CPV in Bs mixing, no new CPV phases needed). But the magnitude of the effect can vary a lot in different SUSY-breaking scenarios

III. Helicity-suppressed rare B decays

Present exp. status:

$B(B_s \to \mu\mu) < 4.3 \times 10^{-8}$ (95%CL)

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

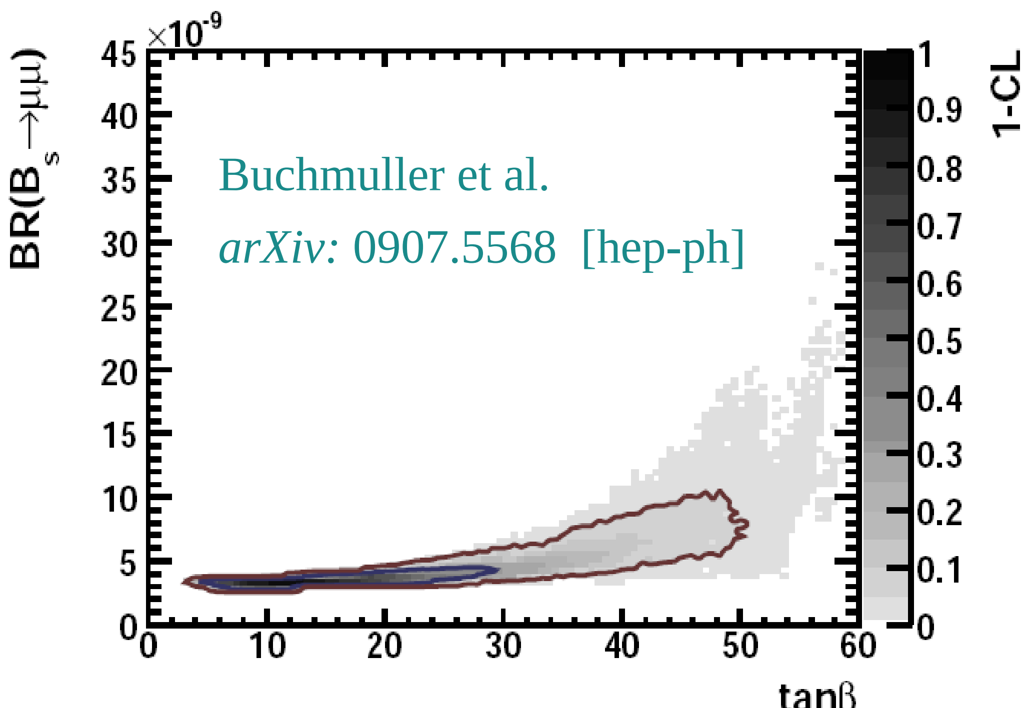
CDF '09, very similar by D0 @ this conf.

SM expectations:

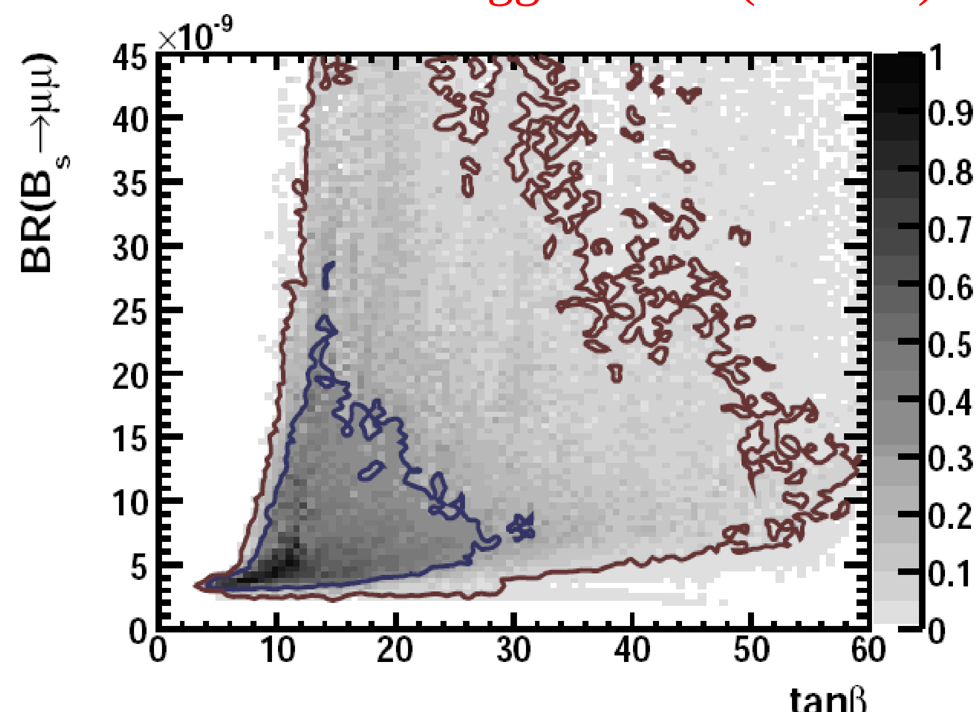
$B(B_s \to \mu\mu)_{SM} = 3.2(2) \times 10^{-9}$

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

Constrained - MSSM



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



Conclusions

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

But we are making progress:

- We have understood that large new sources of flavour symmetry breaking at the TeV scale are excluded
- But several anomalies in the CKM picture are starting to show up: some of them will go away, some others (with some optimism...) may well be the *first signals of new physics at the TeV scale*.
- Key tool to make progress in this field is to identify correlations among different non-standard effects $\Rightarrow$ flavour pattern of the new symmetry breaking terms
- Bright future thanks to a series of new experiments/analyses focused on clean observables in B, τ, K, μ decays [*full complementarity both between low-energy and high-Pt physics and also between different low-energy facilities*]

Backup

IV. 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:

Gedalia *et al.* '09
Buras *et al.* '10
Fajfer *et al.* '10
+ ...

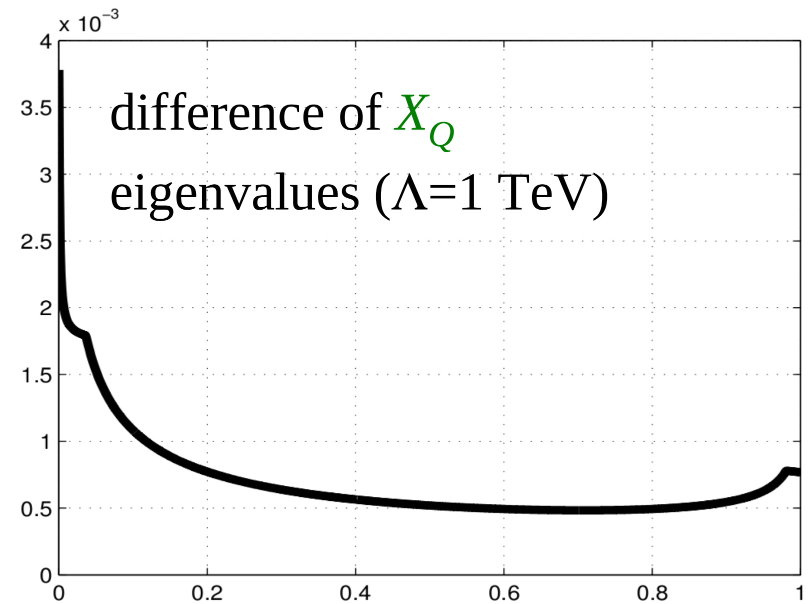
- Clear SM null test
- Highly sensitive to NP [unique window on up-type mixing of light generations], no sizable effects in MFV with no new phases, but up to 10% effects quite natural in other frameworks SUSY, RS, 4th gen...
- Interesting correlation with K mixing

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



relevant comb. of CPV phases