Recent progress and future prospects in Flavour Physics

Gino Isidori
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- Introduction: the “big” open questions
- Recent phenomenological challenges to the CKM picture
- Possible beyond-the-SM explanations of these “anomalies”
- A brief detour on the lepton sector
- Conclusions

Introduction: the "big" open questions

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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?*
  [Is there anything else beside SM Yukawa couplings & neutrino mass matrix?]

Introduction: the "big" open questions

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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.

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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:

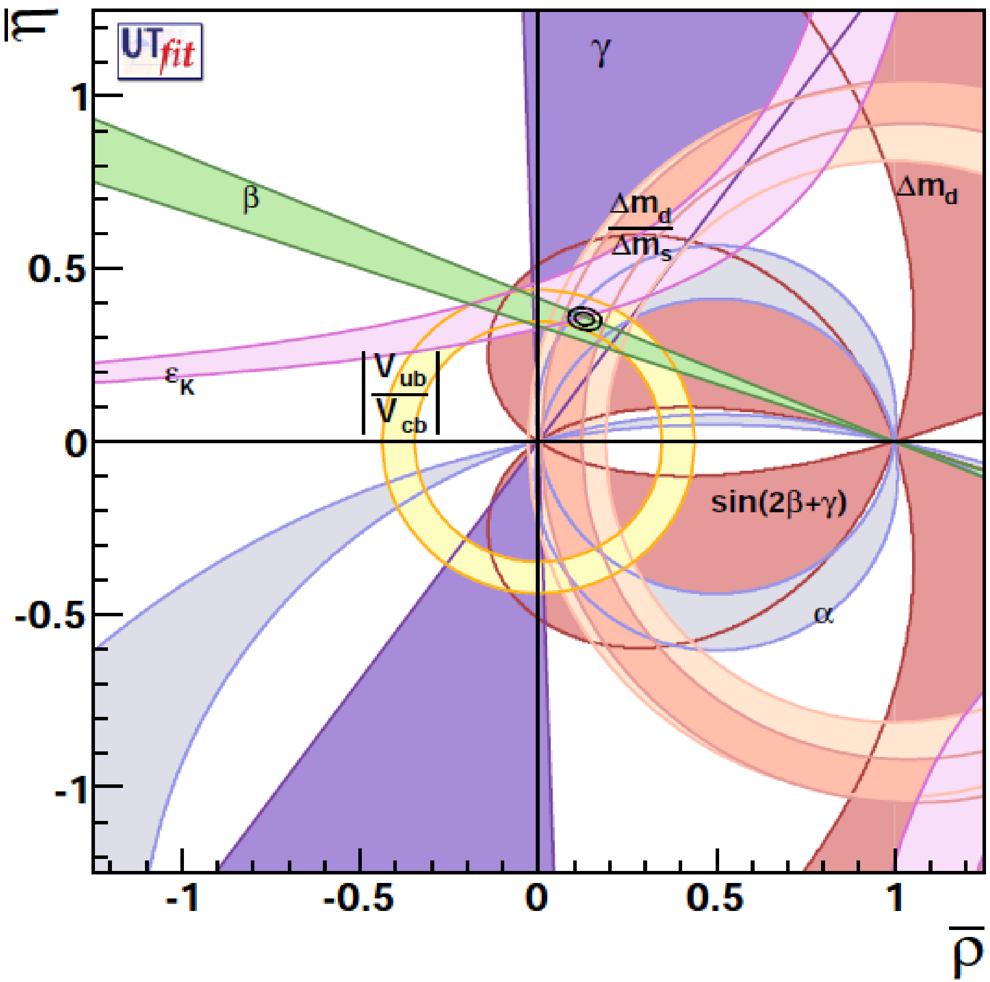
- It can be formulated independently of the UV completion of the theory.
- It is mainly a question of precision (both on the theory and on the experimental side).

⬇

Main goal of flavour-physics in the early LHC era

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

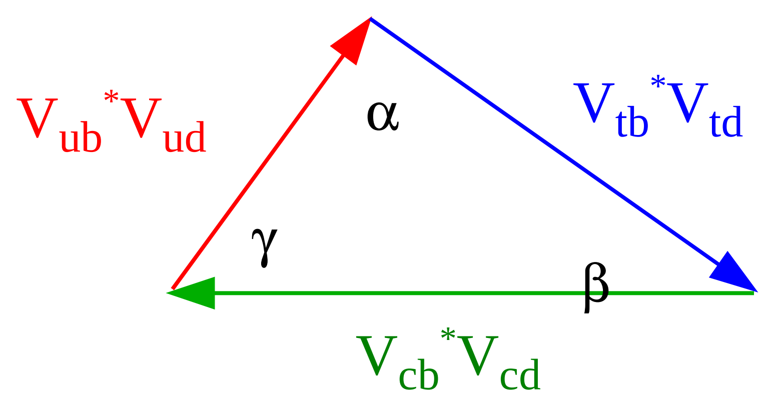
The good overall consistency of the experimental constraints appearing in the so-called CKM fits seems to indicate there is not much room for new sources of flavour symmetry breaking



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

triangular relation:

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



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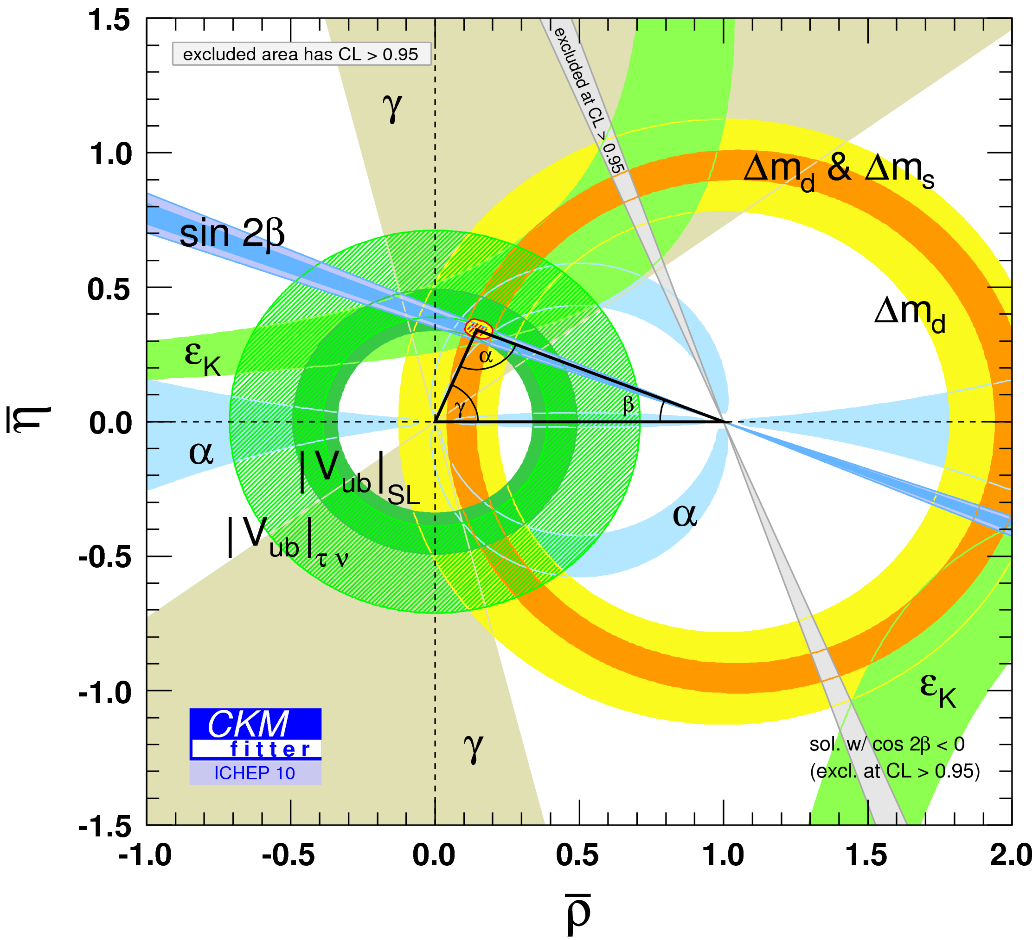


- Changing statistical treatment does not lead to significant differences: high-quality data are finally drawing the picture...!

- 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?

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

G.I, Nir, Perez '10

Operator	Bounds on Λ (TeV)		Bounds on c_{ij} (Λ = 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; $\lvert q/p\rvert$, 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; $\lvert q/p\rvert$, 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}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	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?

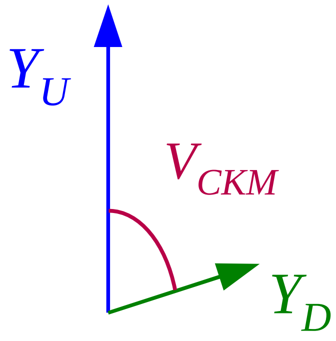
The good overall consistency of the experimental constraints appearing in the so-called CKM fits seems to indicate there is not much room for new sources of flavour symmetry breaking

↓

Minimal **F**lavour **V**iolation paradigm:

The large <u>quark-flavour symmetry</u> of the gauge SM Lagrangian is <u>broken only by the two quark Yukawa couplings</u> ⇒ 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.

  Lalak, Pokorski, Ross, '10
  Gristein, Redi, Villadoro, '10

- 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 $\tan\beta$, 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:

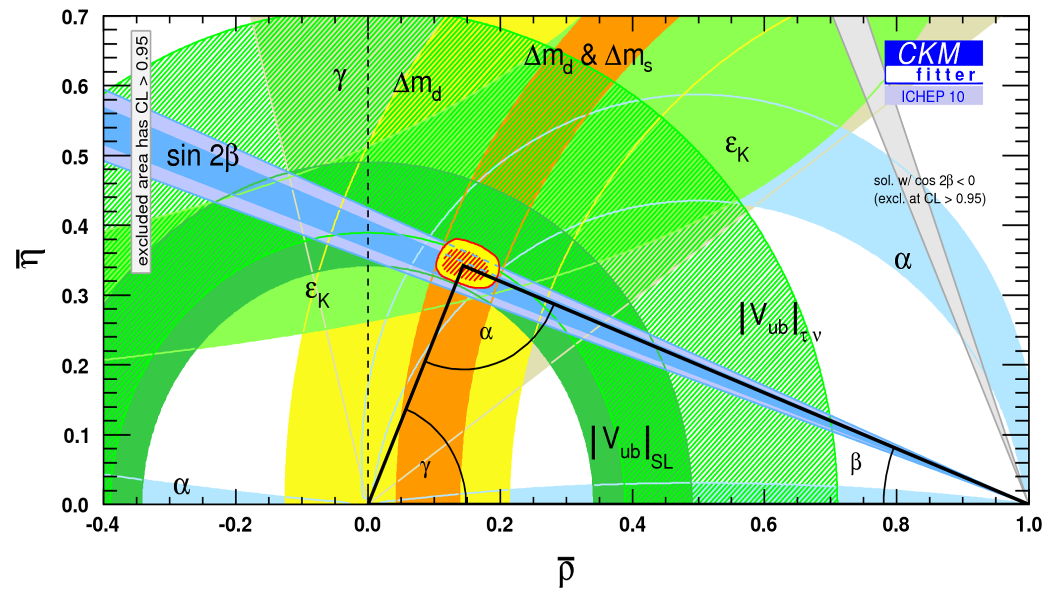
- The sin(2β) tension in the CKM fit
- CPV in Bs mixing
- $B(B \to \tau \nu)$

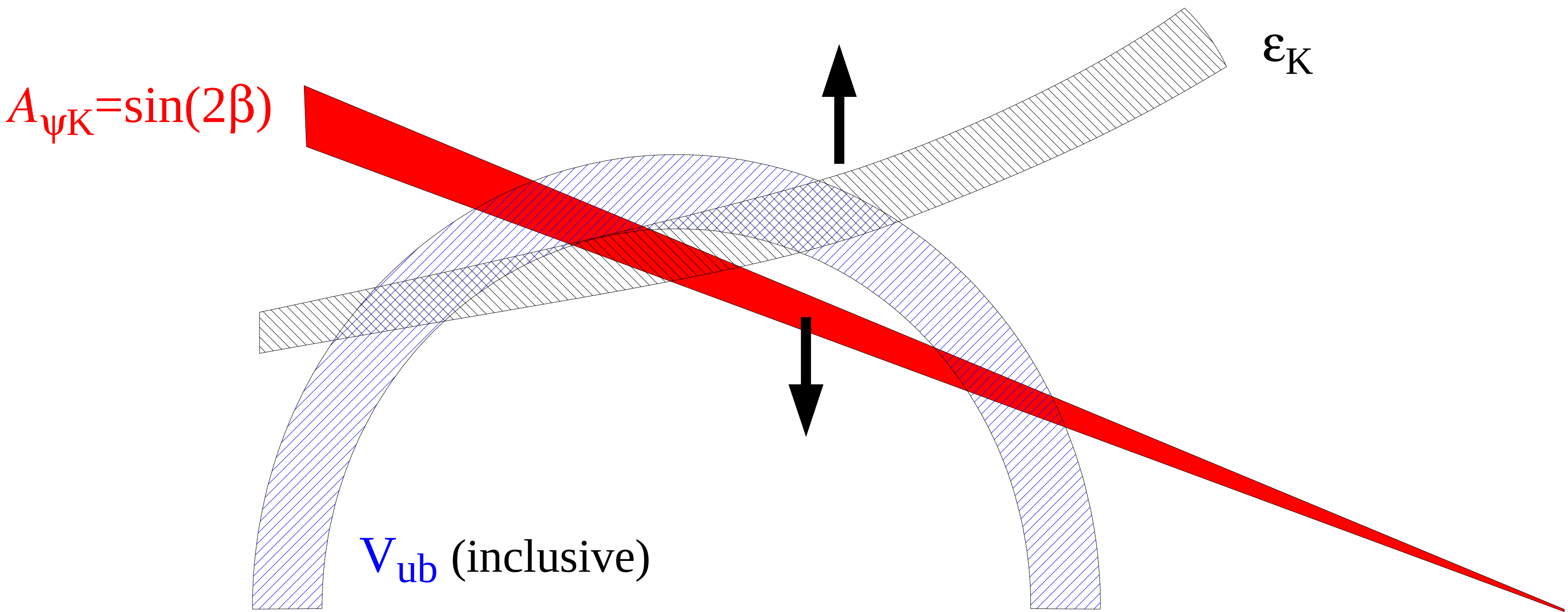
I. The sin(2β) tension in the CKM fit

At first sight the global CKM fit shows an excellent consistency.

However, a closer inspection shows a tension between $A_{\psi K}=\sin(2\beta)$ and its prediction (via ε_K and V_{ub}).

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





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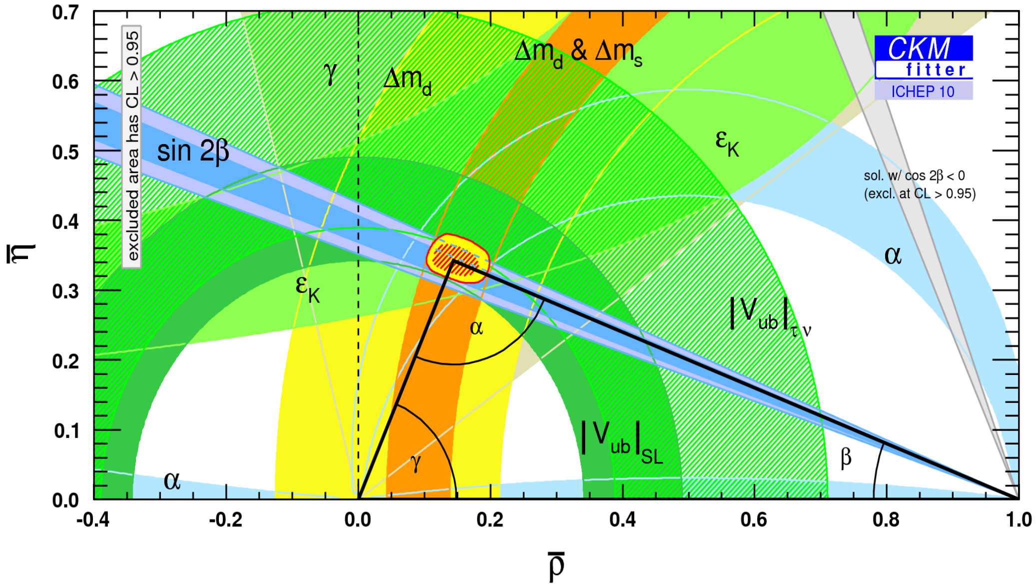
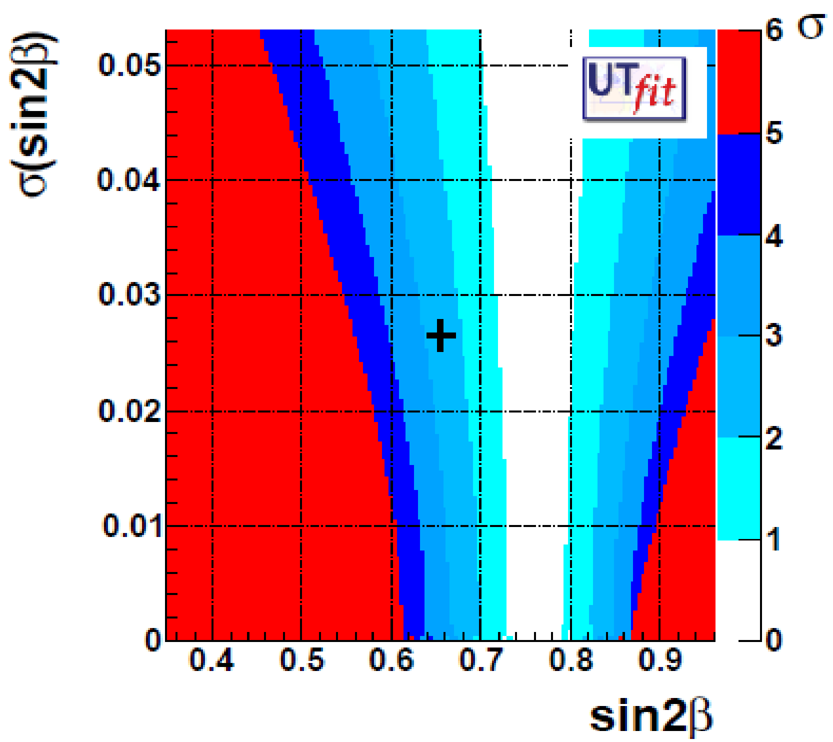


This tension has recently become more serious thanks to precise unquenched determinations of B_K

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

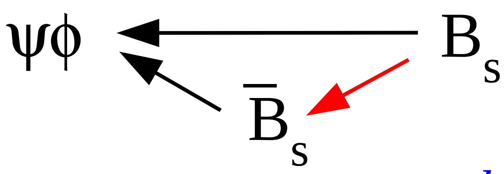
Tarantino, ICHEP '10

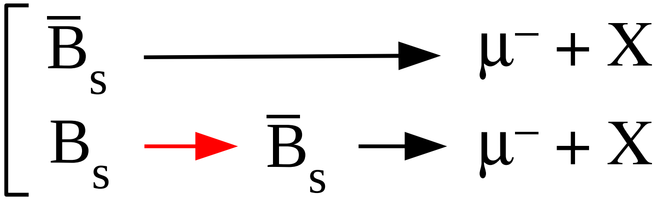


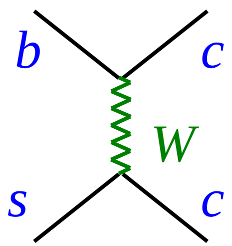
II. CP violation in B_s mixing

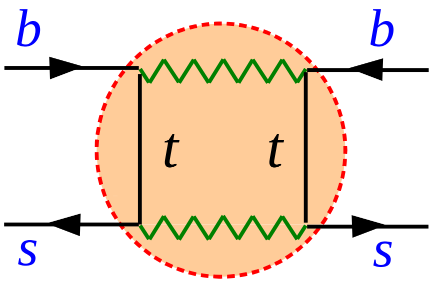
The weak phase of B_s mixing is currently under investigation at Tevatron via the time-dependent study of the $B_s \to \psi\phi$ decay [$A_{\psi\phi}$] & via the semileptonic charge asymmetry (same-sign muons) [a_{sl}]

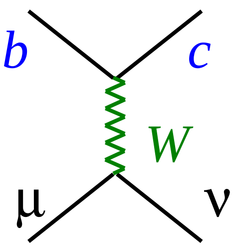
Theoretical clean extraction:











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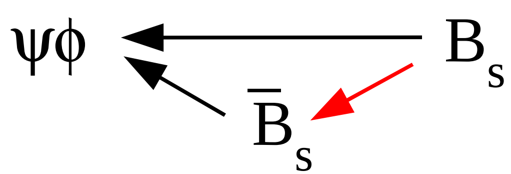
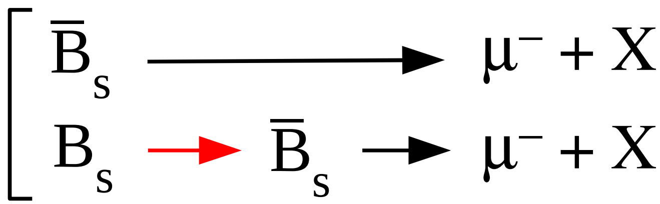
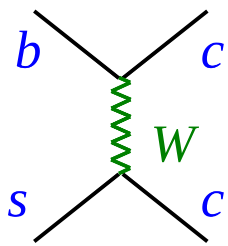
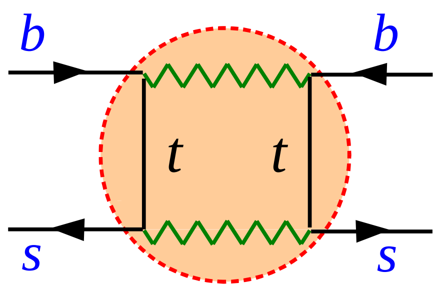
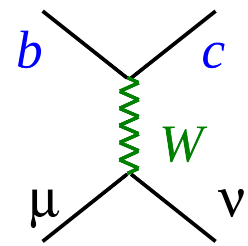






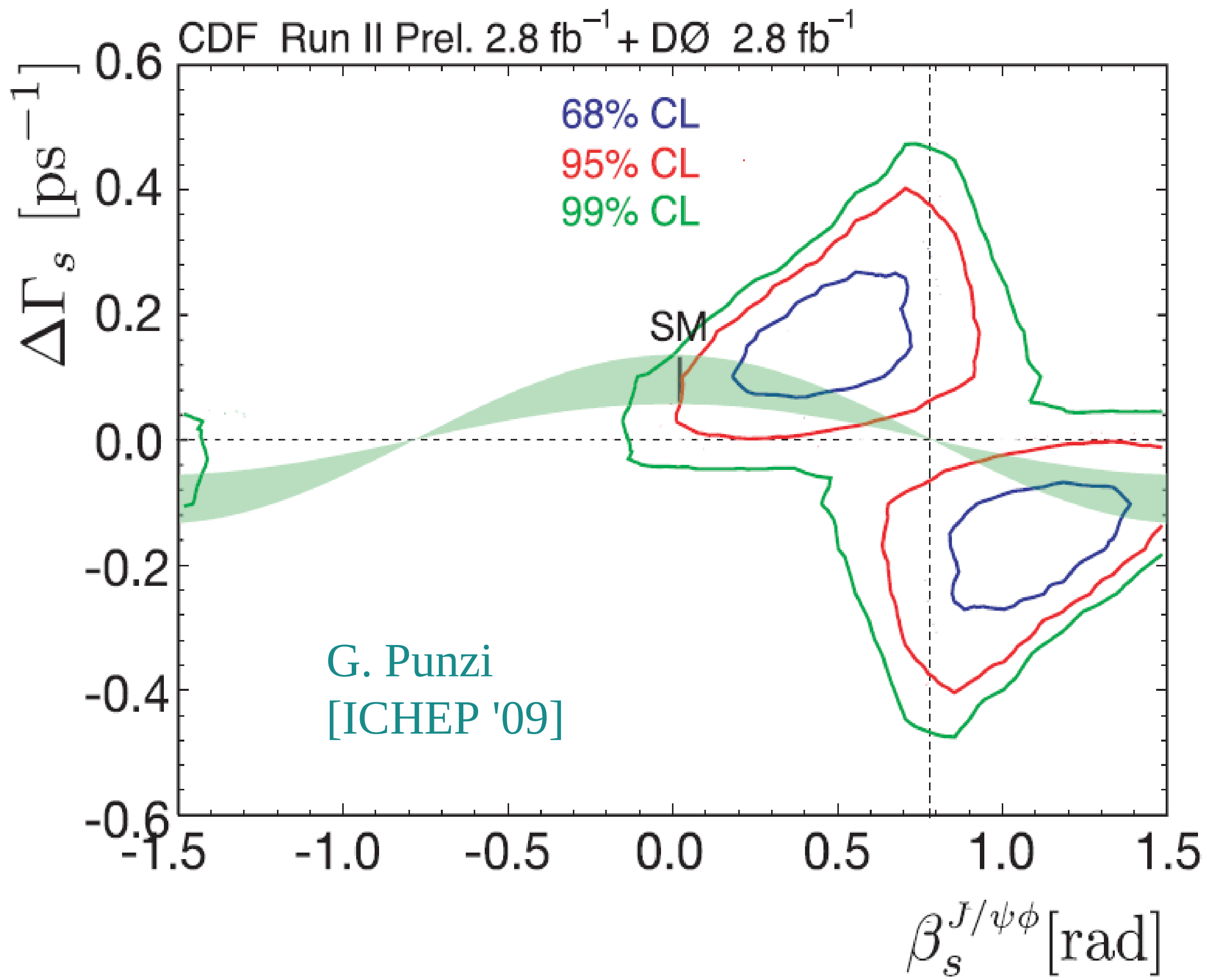




Vanishingly small result expected if the phase is determined only by the Yukawa couplings: SM and MFV with no extra CPV phases

II. CP violation in B_s mixing

The 2009 results favoured a large CPV phase...

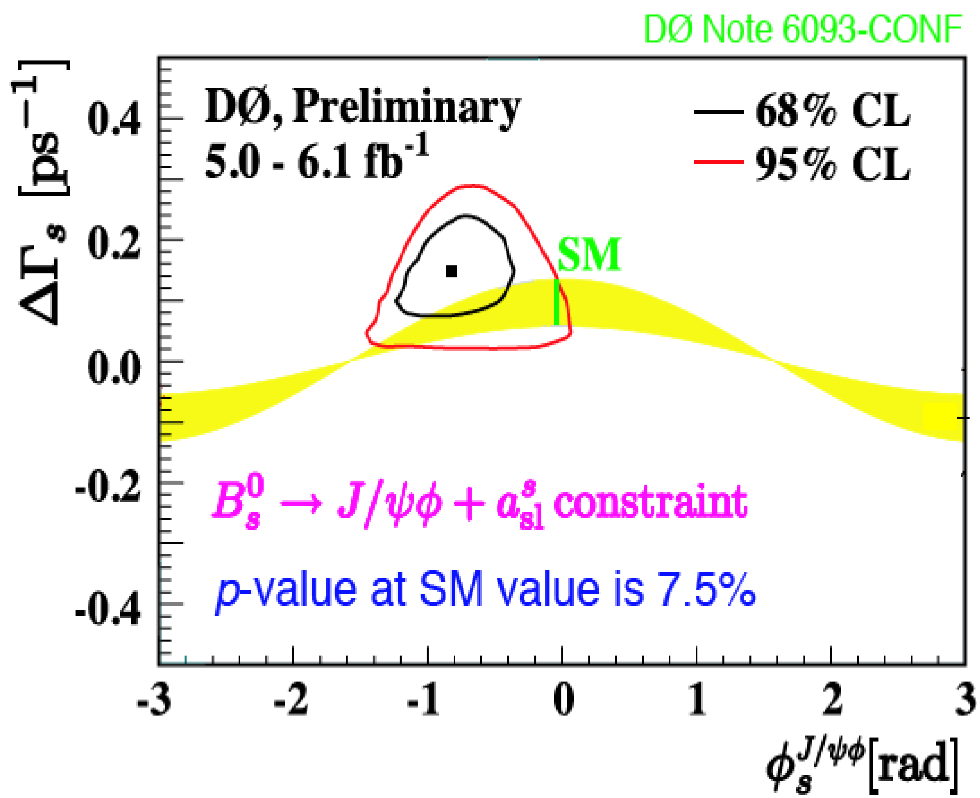


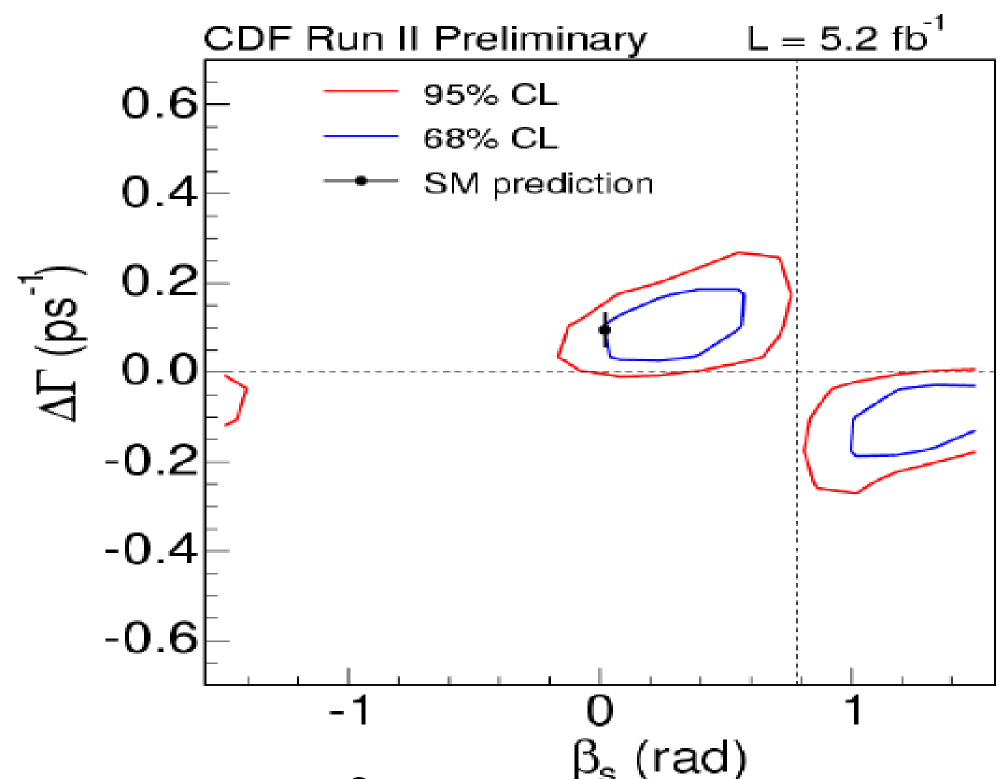
II. CP violation in B_s mixing

..several new data in 2010:

a_{sl} by D0 [*SM off by 3σ*] + updated $A_{\psi\phi}$ by CDF & D0 [*SM within ~ 1σ*]

The situation is not fully clear yet, but a large CPV pahse is still "welcome"





[$\phi_s = -2\beta_s$]

More details on the a_{sl} measurement by D0:

Raw di-muon asymmetry

$$A \equiv \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)} = (0.564 \pm 0.053)\%$$

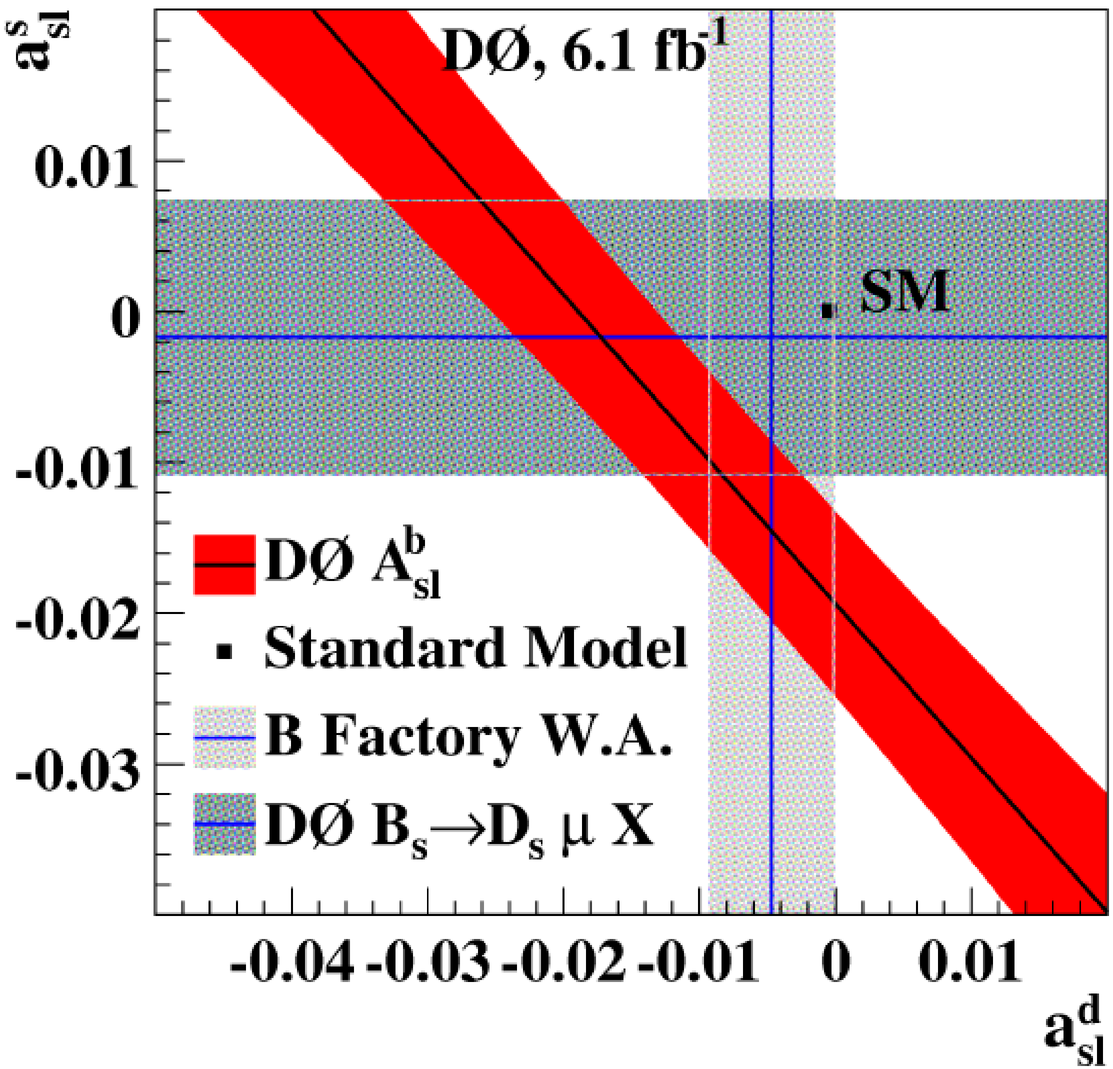
↓

$$A = A^b + \text{bkg}$$

(bkg deter. from data, controlled mainly by the single muon asym)

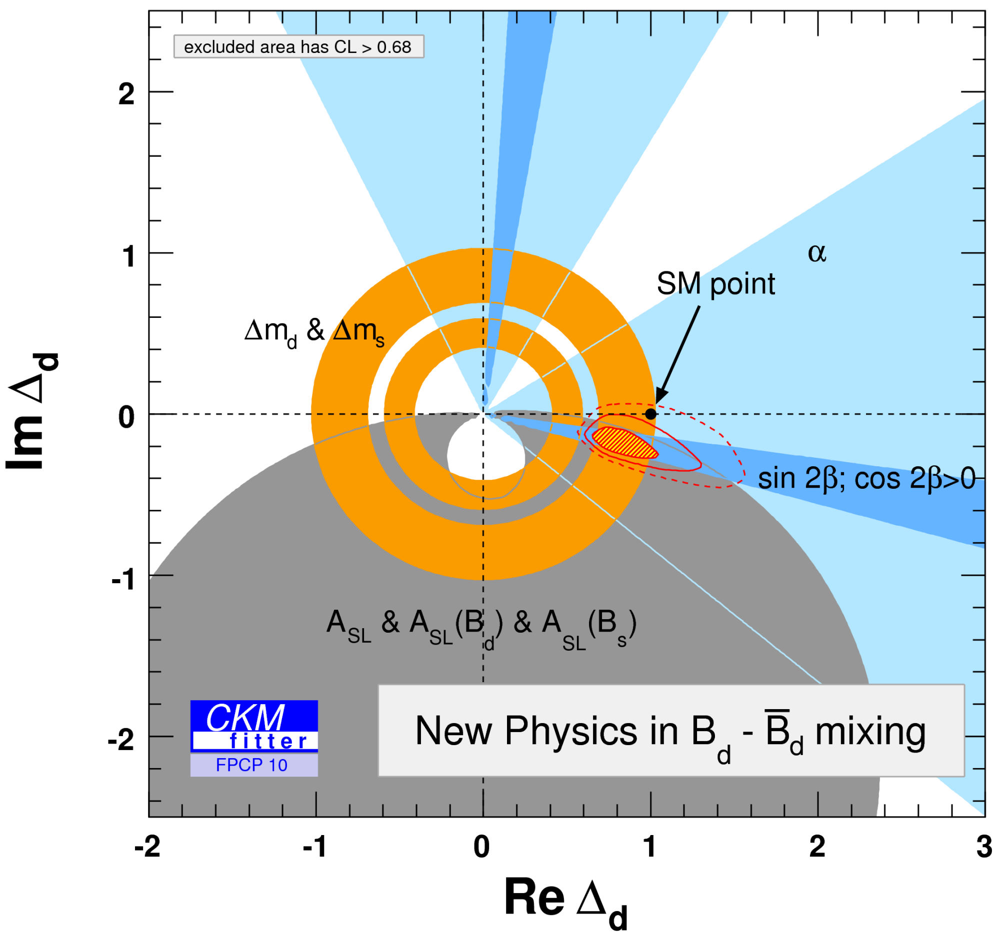
↓

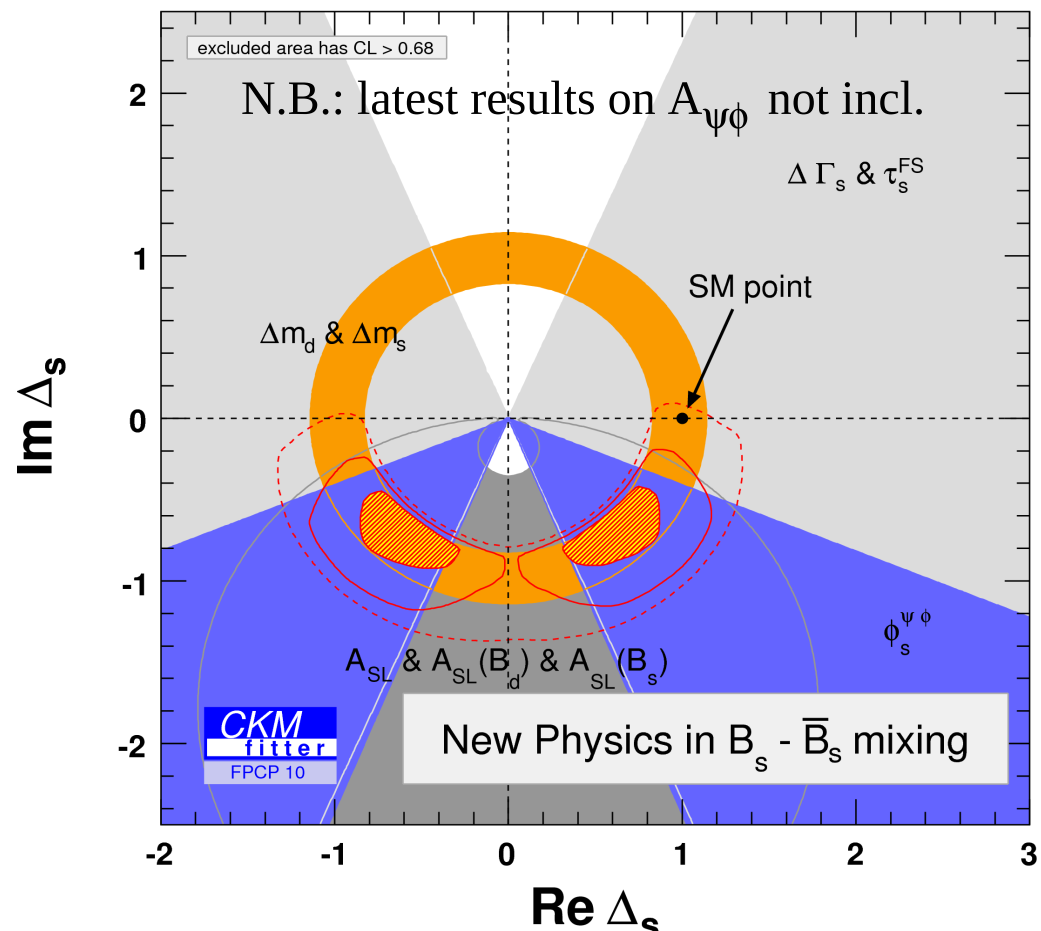
$$A^b \approx 0.51\, a_{sl}^{(d)} + 0.49\, a_{sl}^{(s)}$$



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.

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





Similar conclusions also by UTfit

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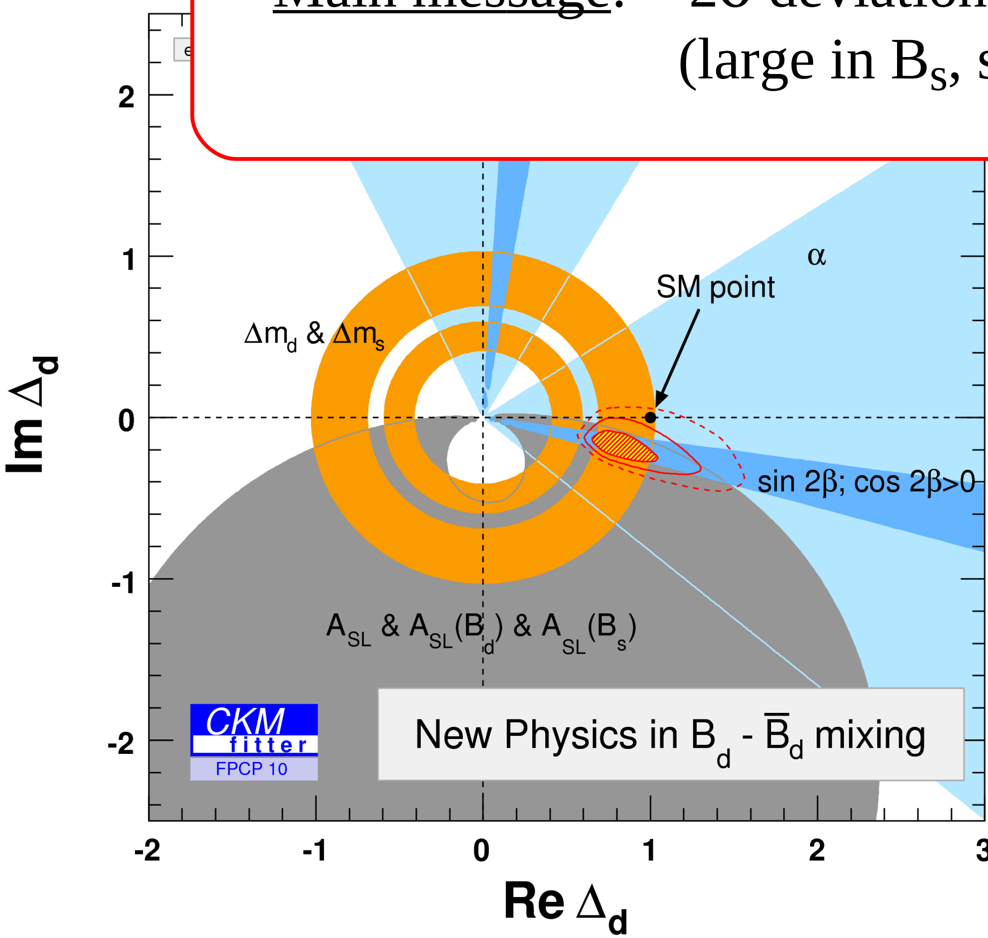
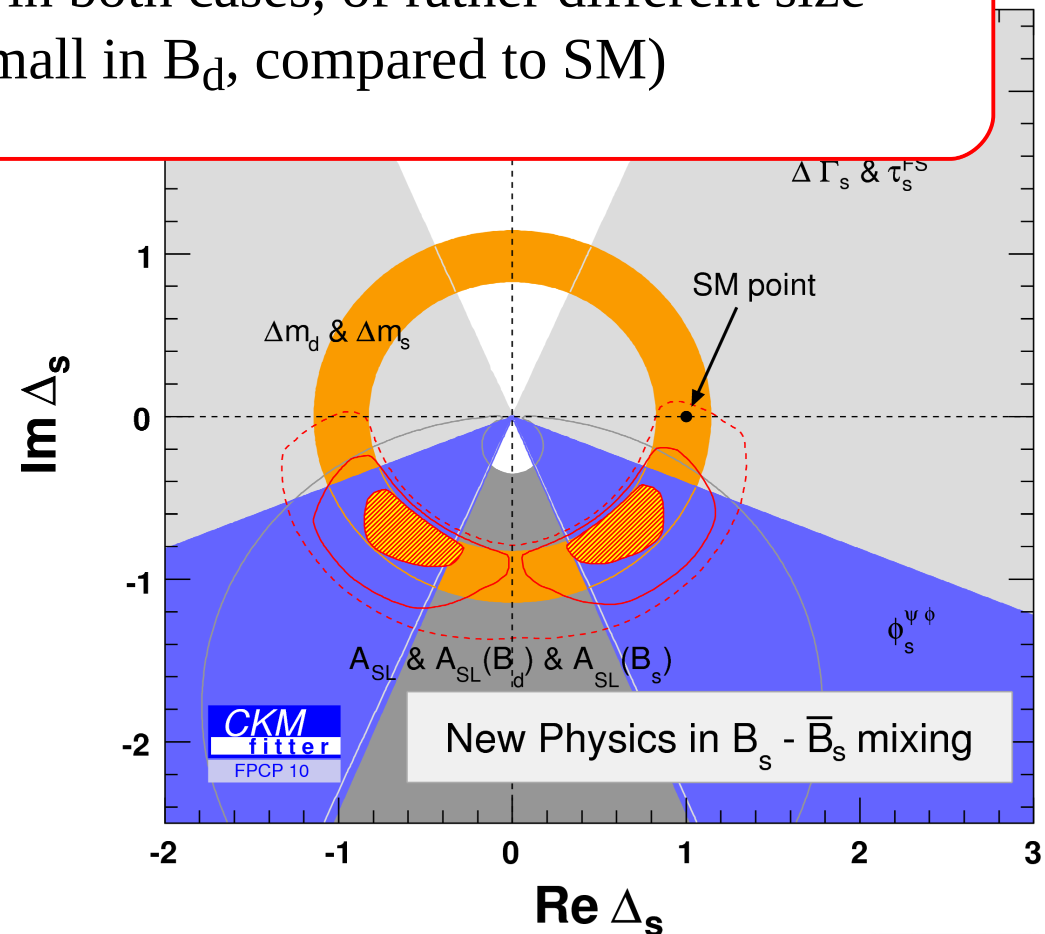
Main message: ~ 2σ deviations in both cases, of rather different size (large in B_s, small in B_d, compared to SM)





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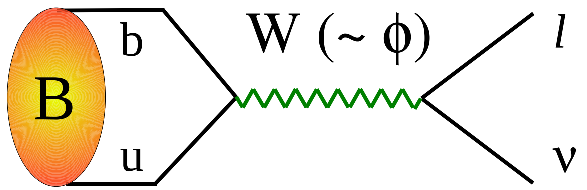
III. B(B→ τ ν)



longitudinal comp. of the W

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

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

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

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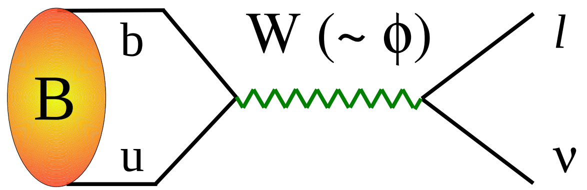

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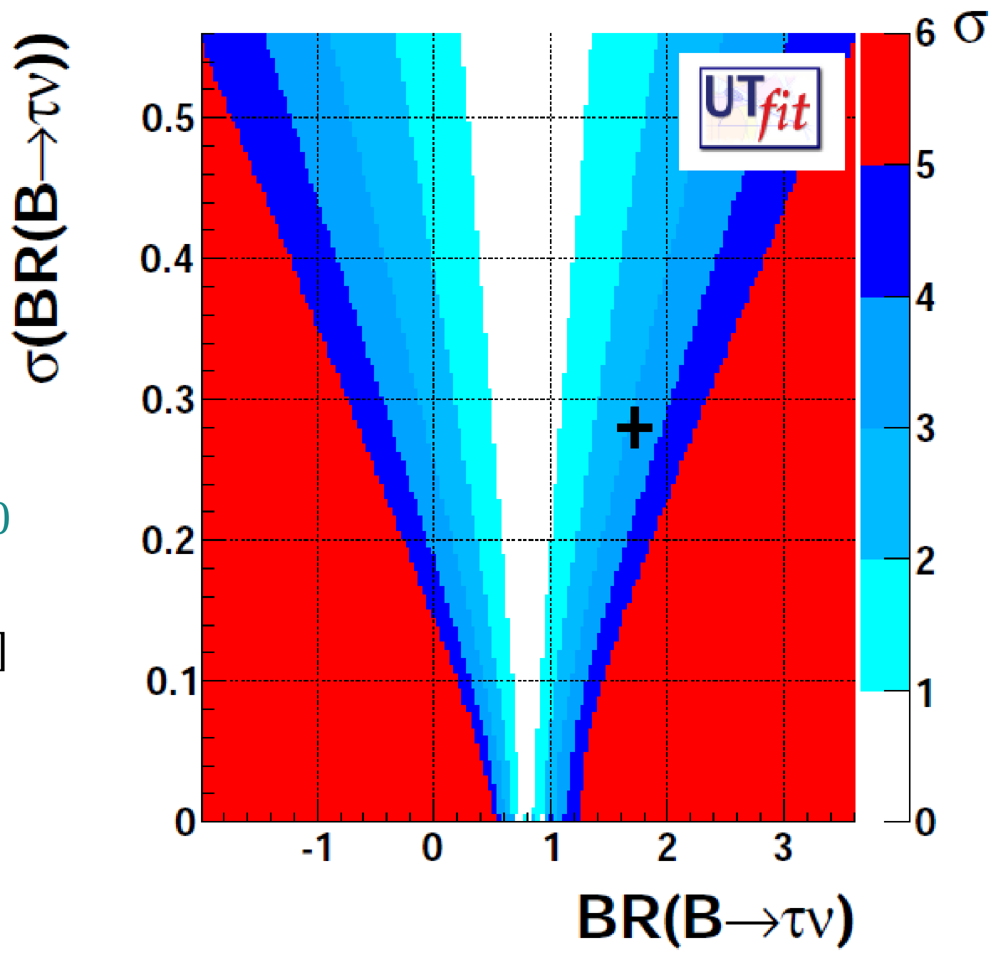
Very clean test of the SM, provided reliable independent infos on f_B & V_{ub}

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

Babar + Belle '10

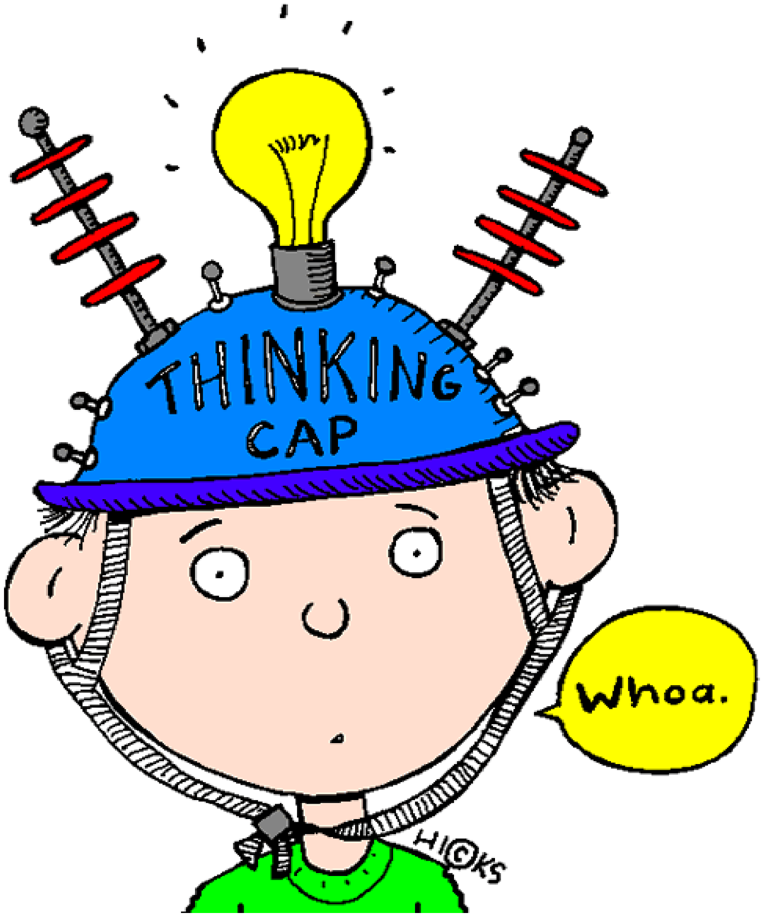
$B_{SM} = (0.79 \pm 0.07)\times 10^{-4}$ UTfit '10 [global fit]



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...*)



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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, ...)

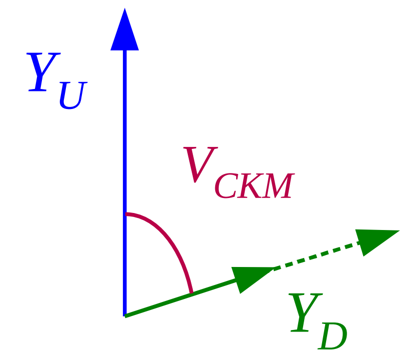
I. 2HDM with MFV, large tanβ, and flavour-blind phases

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: $Y_D \sim 3_Q \times \bar{3}_D \quad Y_U \sim 3_Q \times \bar{3}_U$

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 $\tan\beta = v_2/v_1 \gg 1$):

$$\mathscr{L}_{\rm eff} \propto \bar{d}_L^{\,i}\, V_{3i}^{*}\, [a_0 + a_1\, \delta_{3i} + a_2\, \delta_{3k}]\, V_{3k}\, y_k\, d_R^{\,k}\, H_{heavy}$$

D'Ambrosio *et al.* '02

$a_0 \uparrow$ $Y_U Y_U^{+} Y_D$

$a_1 \delta_{3i} \uparrow$ $Y_D Y_D^{+} Y_U Y_U^{+} Y_D$

$a_2 \delta_{3k} \uparrow$ $Y_U Y_U^{+} Y_D Y_D^{+} Y_D$

- double suppression: CKM (V_{3i}) + down-type Yukawa coupling ($y_k \sim m_k \tan\beta$)
- a_i = parameters of O(1) (including dependence from 3[rd] generation Yukawas), possibly complex if we include flavour-blind CPV phases

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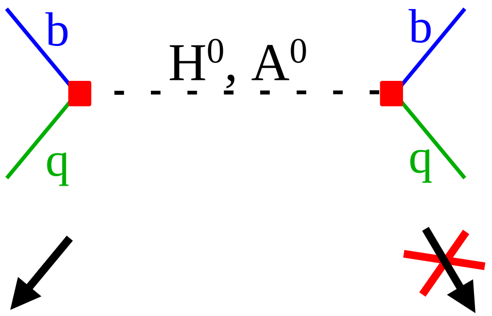
After integrating out the heavy Higgs fields:



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

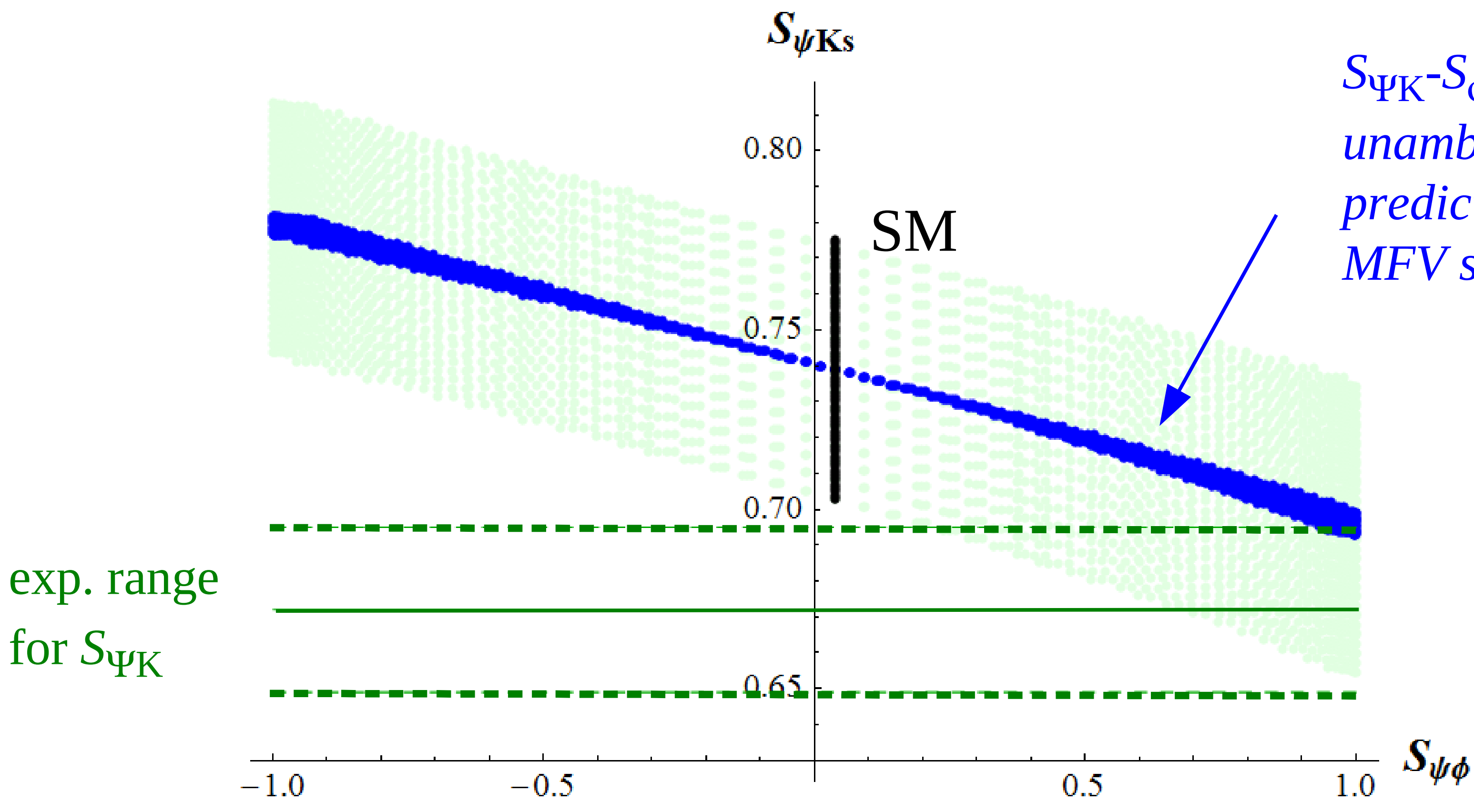
relative to the SM → *large* (B_s mixing), *small* (B_d mixing), *tiny* (K mixing)

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

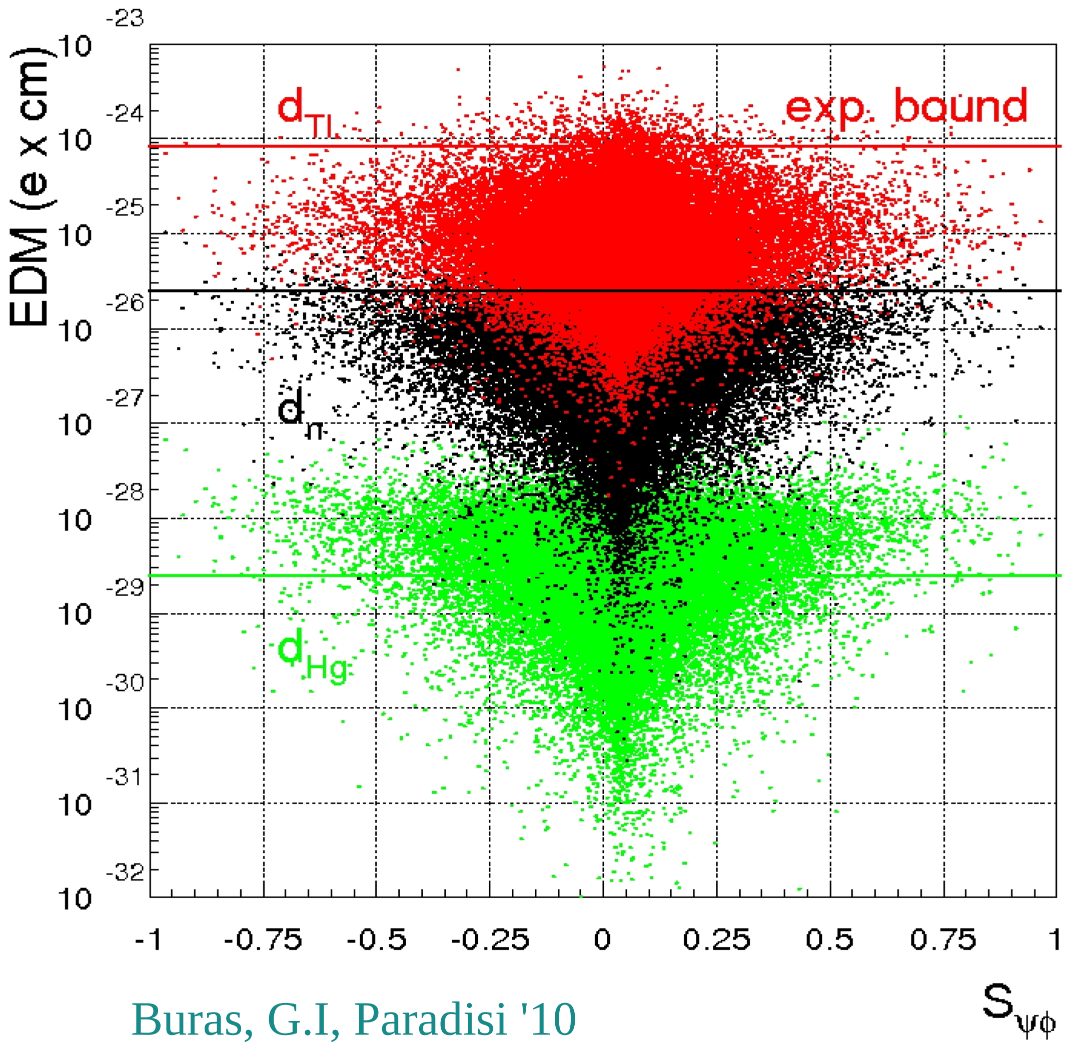
What is remarkable is that with no extra free parameters (modulo and phase of the unique $\Delta F=2$ operator fixed by ΔM_{Bs} and ϕ_{Bs}), the effect predicted for B_d mixing goes in the right direction to improve the quality of the CKM fit



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

Significant contribution to B_s mixing are obtained for reasonable values of m_H & tanβ [m_H < 1 TeV, tanβ = 10-50], 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 CPV in $B_{s,d}$ mixing, ← EDMs & $B_{s,d} \to \mu\mu$ should be "around the corner"

A sizable enhancement of $B \to \tau\nu$ over its SM predictioncould could also be accomodated, but it require some fine-tuning of the free parameters

Buras *et al.* work in prog.

II. Right-handed currents

Right-handed currents are expected in several well-motivated extensions of the SM

Main idea: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ e.w. symmetry holding at some high scale
[*two-step breaking:* $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \to SU(2)_L \times U(1)_Y \to U(1)_Q$]

- Pati-Slam type models (*explicit RH gauge sector*)

  Pati, Salam, Mohapatra, Sejanovic, ... '74 ...'10

- Higgsless/deconstructed models (*LR symmetry related to custodial symm.*)

  Csaki *et al*, Nomura, Georgi,.... '04 ...'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]

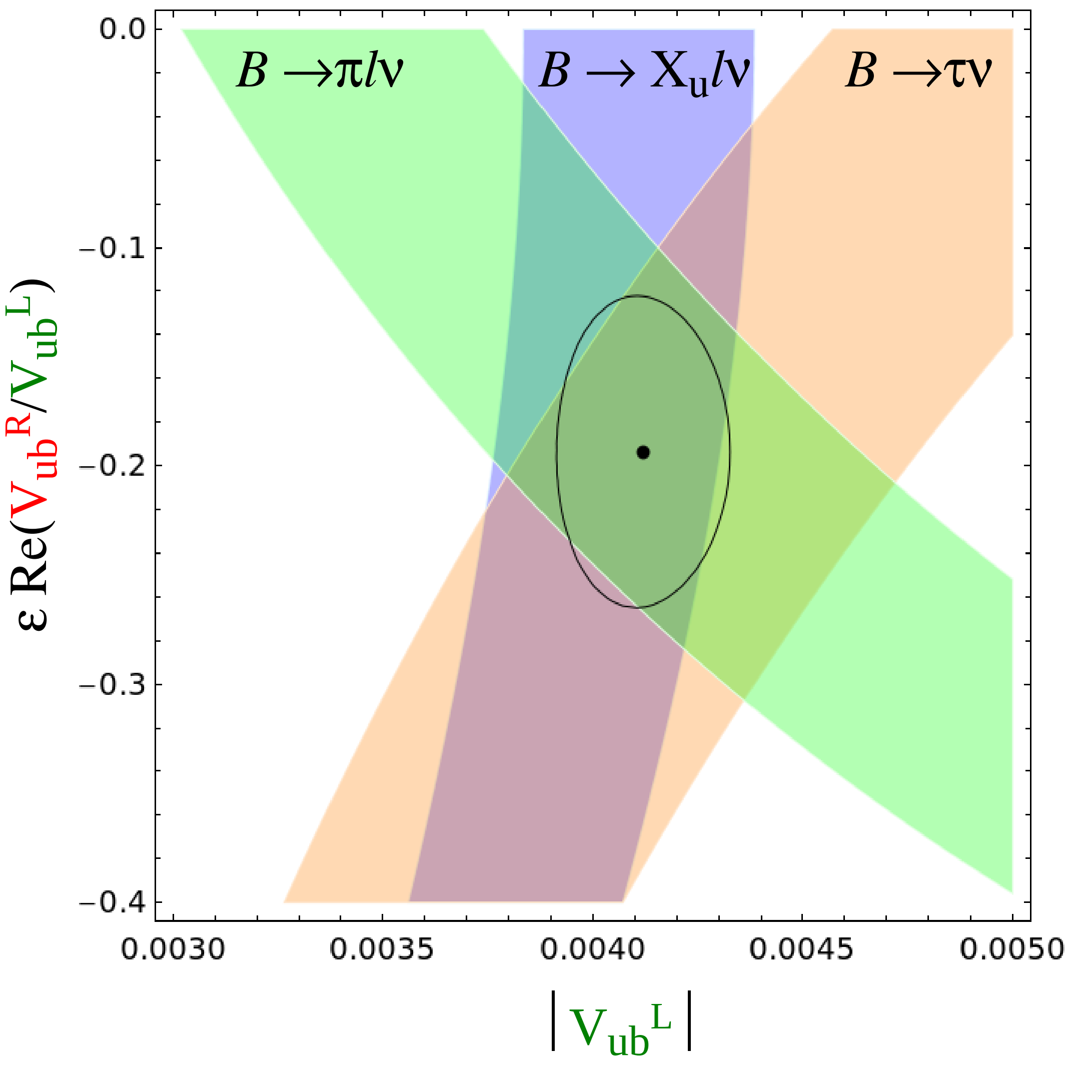
A low-energy phenomenological motivation to consider charged-current RH currents arises by a simple solution to all problems related to V_{ub} :

Crivellin '09
Chen, Nam '08

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

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

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



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)

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↓

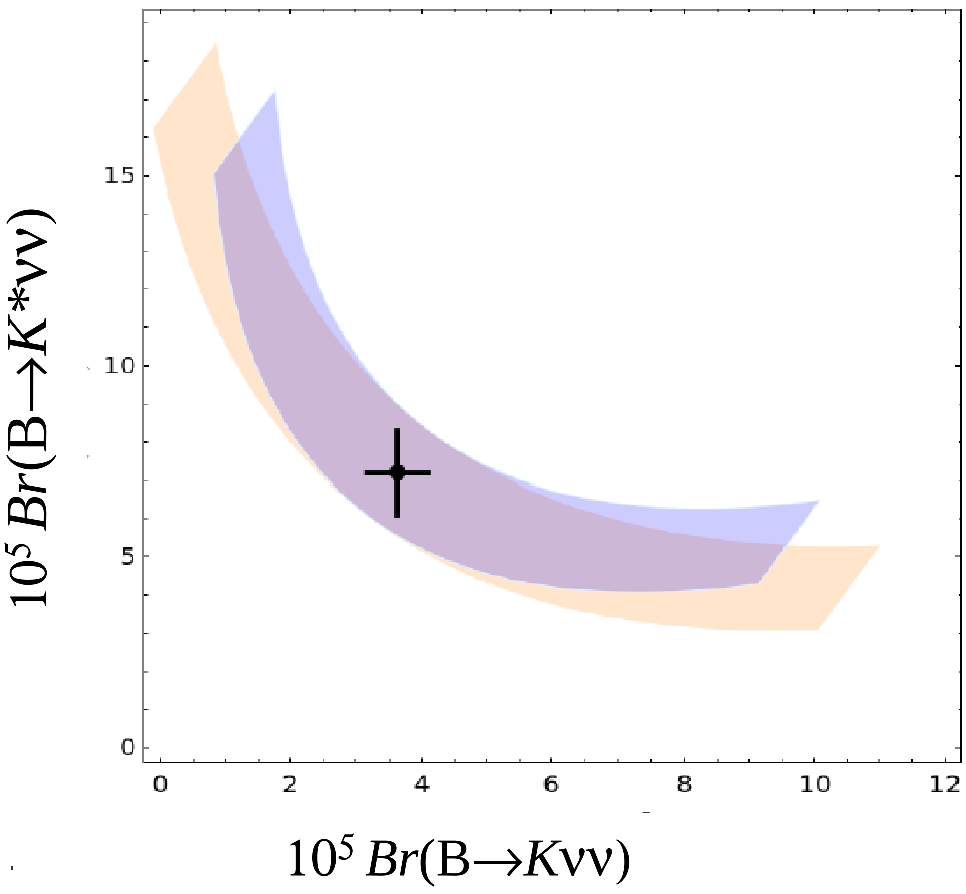
- Possible to pass all bounds with eff. RH scale ~ 3 TeV [within LHC reach]
- Easy to have large impact in Bs mixing, but no impact expected in Bd mixing
- RH currents should be visible in with more precision in b⟶s rare decays

Preferred solution:

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

II. Right-handed currents

E.g.: Correlation between $B \to K \nu\nu$ and $B \to K^* \nu\nu$ with RH currents



- the two bands correspond to the two values of $|\sin(2\phi^d_{32})|$ obtained from taking $S_{\psi\phi}$ large
- factor 2 enhancement with respect to SM value in both decays possible
- clear anti-correlation

black dot = SM value	
blue:	$|\sin(2\phi^d_{32})| = 0.95$
orange:	$|\sin(2\phi^d_{32})| = 0.30$

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)

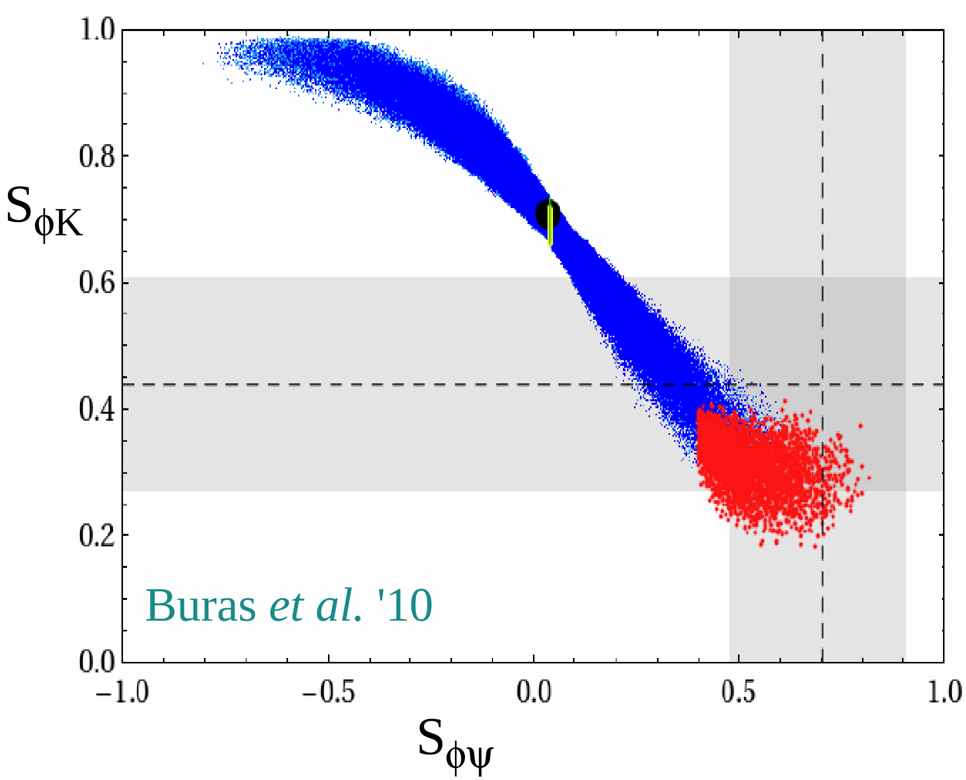
↓

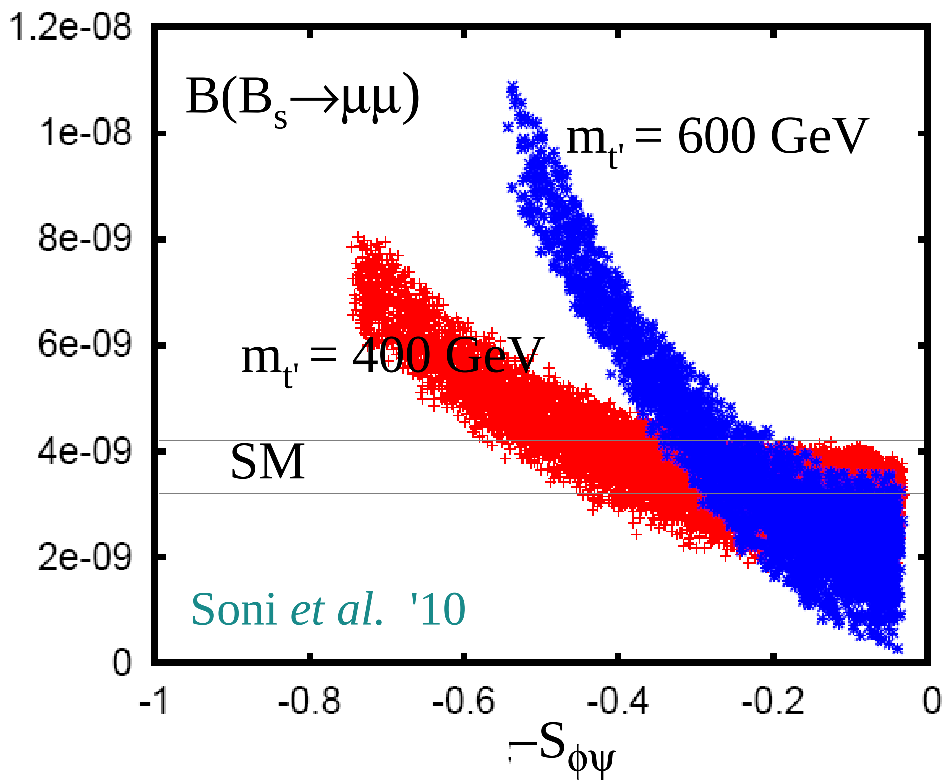
Not many new free parameters, rather constrained system

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]

A brief detour on the lepton sector

Current "anomalies" are certainly interesting and, as illustrated within specific models, they all imply spectacular effects in view of future B-physics experiments

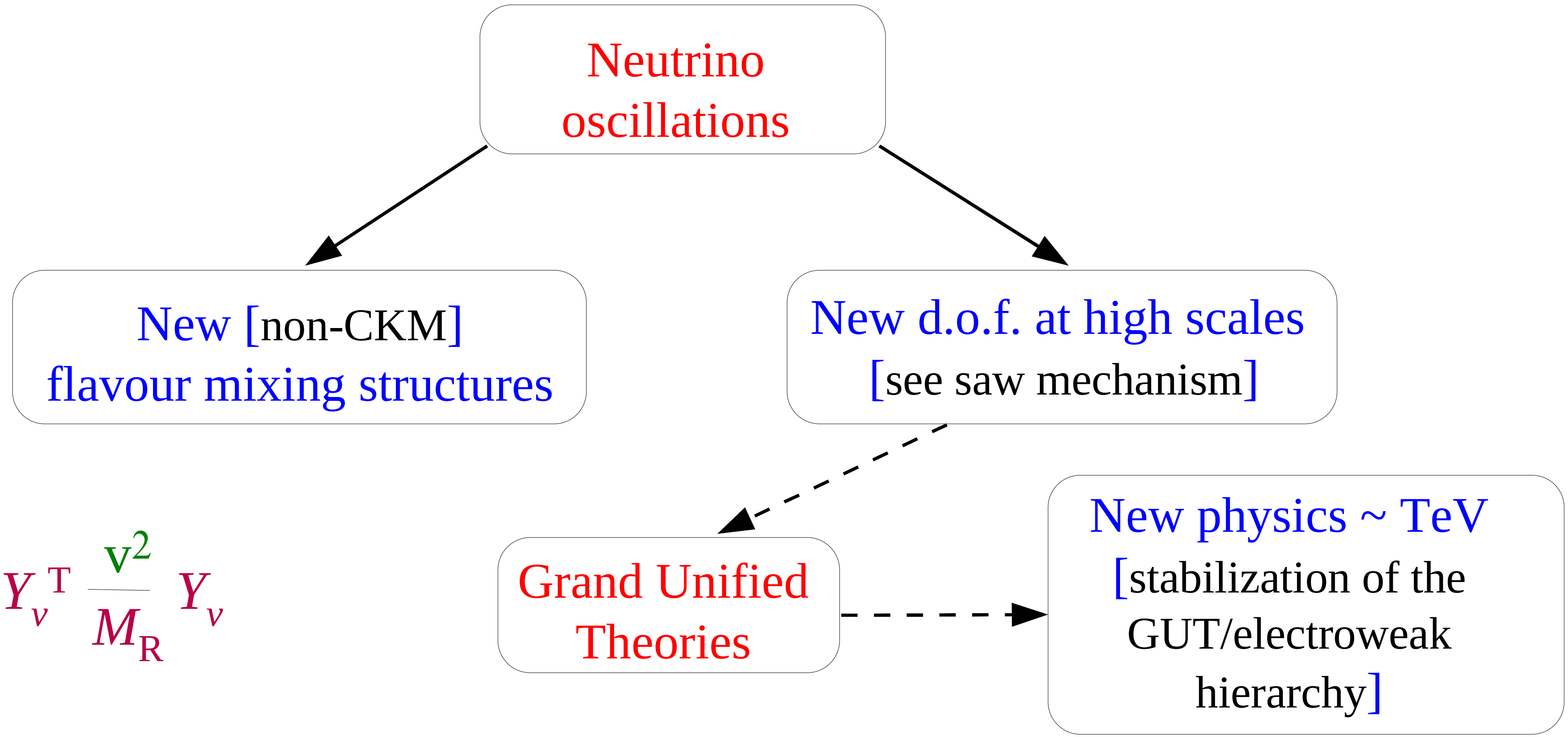
A brief detour on the lepton sector

Current "anomalies" are certainly interesting and, as illustrated within specific models, they all imply spectacular effects in view of future B-physics experiments

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

Even in this pessimistic case, there are a few other flavour-changing observables where we can expect sizable deviations from the SM (even in "conservative" beyond-SM scenarios...). The most remarkable example is LFV in charged leptons

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



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

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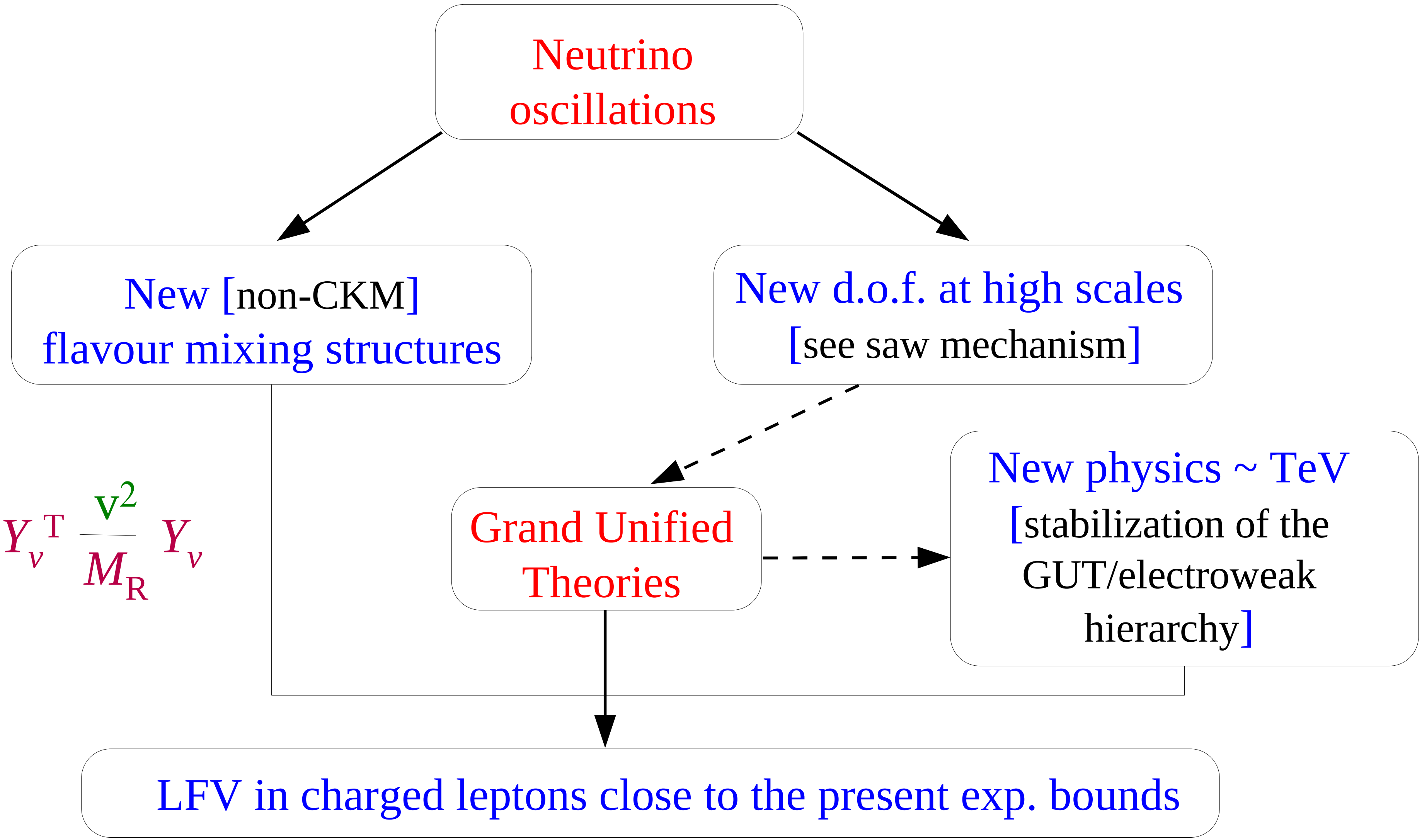
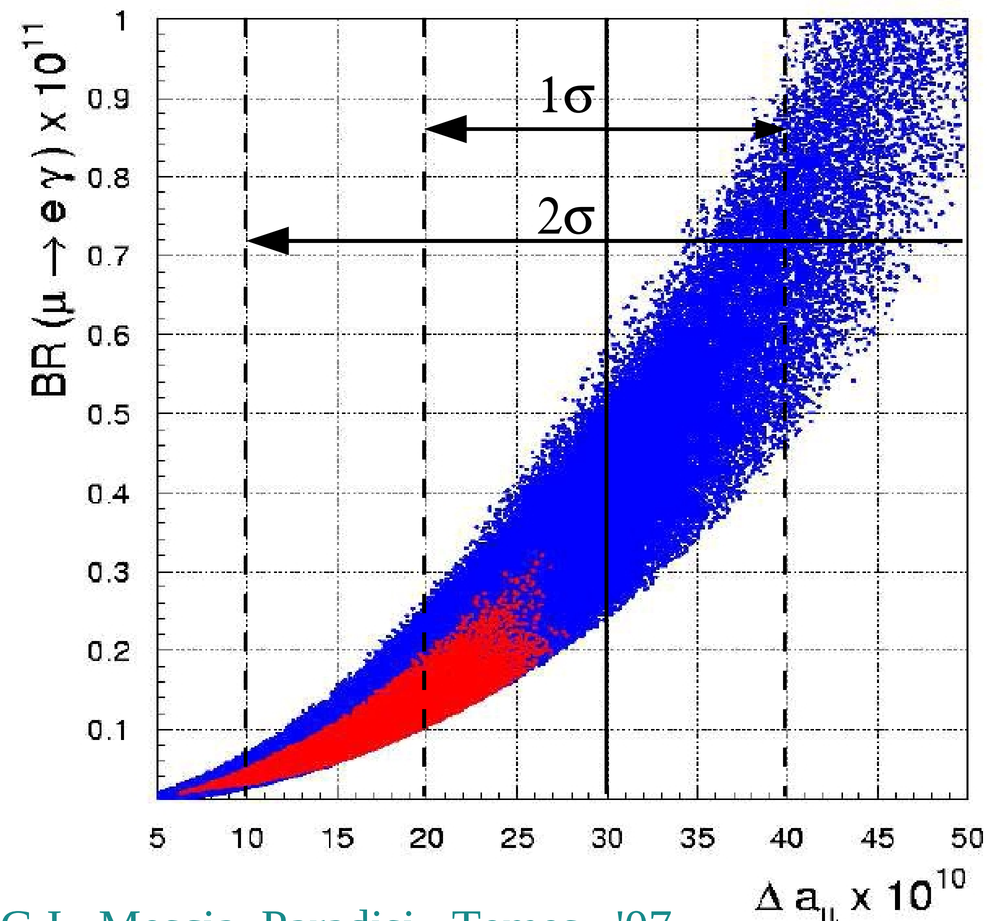
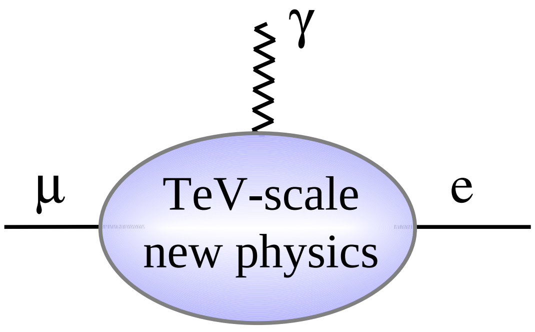


$$m_\nu \sim Y_\nu^{T} \frac{v^2}{M_R} Y_\nu$$

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 $\mu \to e\gamma$





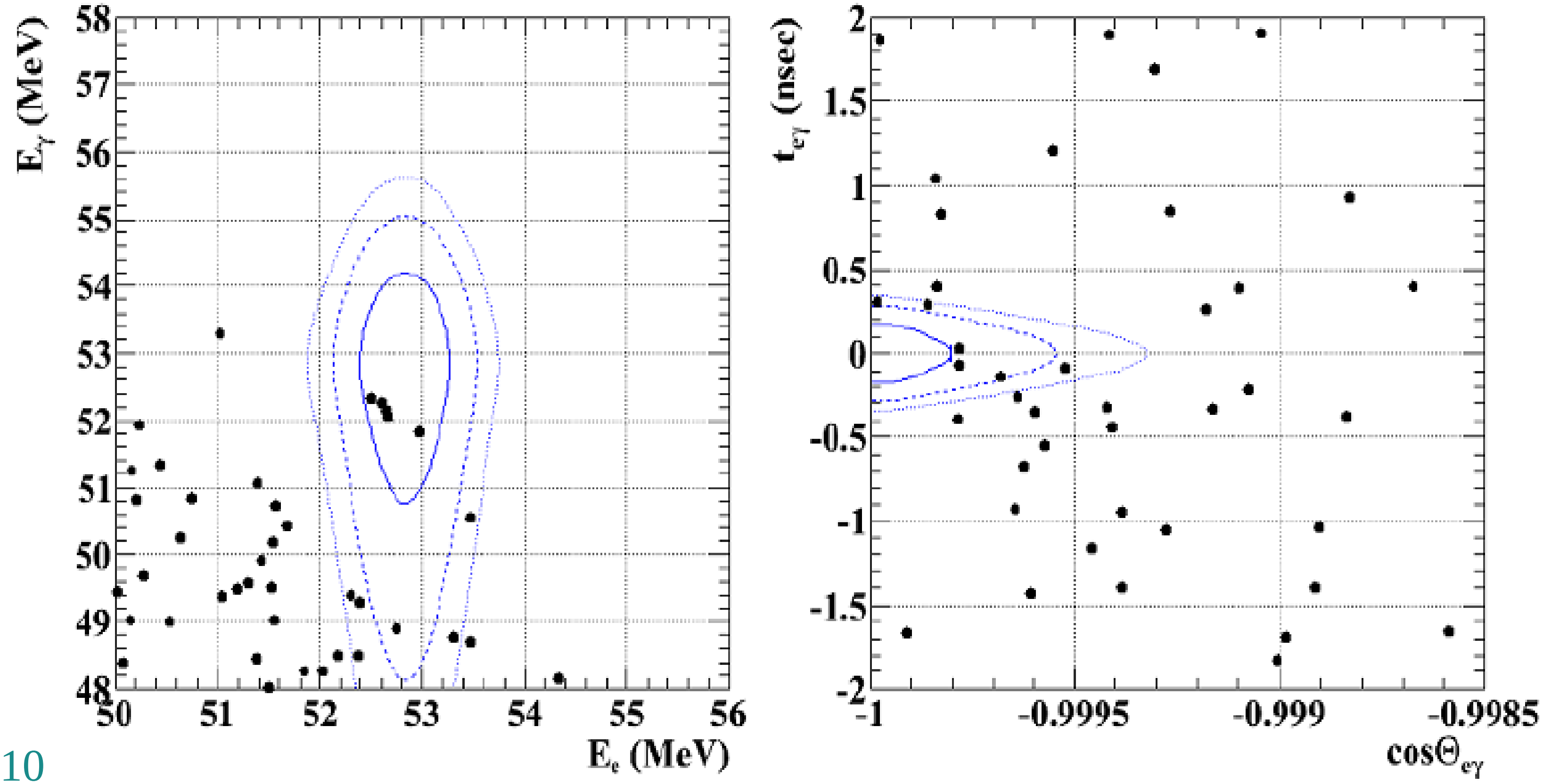
Interesting correlation with g-2 in many explicit new-physics models.

← E.g.: MSSM + heavy ν_R

G.I., Mescia, Paradisi, Temes, '07

Interestingly enough, the MEG experiment is progressing well and first results leave even some room for speculations...

Event distribution after unblinding



Baldini, ICHEP 2010

Nsig < 14.5 @ 90% C.L

Nsig=0 is in 90% confidence region

Nsig best fit = 3.0

UL = 1.2×10^{-11}

... and if MEG will see $\mu \to e\gamma$ then the search for $\tau \to \mu(e)\,\gamma$ at super-B factories becomes extremely interesting ⇒ best tool to discriminate the two most natural mechanisms of LFV in GUT theories:

$$A(l_i \to l_j \gamma) = a\,[Y_e Y_\nu^+ Y_\nu]_{ij} + b\,[Y_U^+ Y_U Y_D]_{ij}$$

LFV due to neutrino Yukawa couplings (unknown normalization depending on M_R)

LFV due to quark Yukawa couplings

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PMNS mixing structure

dominant if $M_R > 10^{12}$ GeV $\Rightarrow$ $B(\mu \to e\gamma) \sim 10^{-13}\,(M_R/10^{12}\text{GeV})\,(\Lambda/10\,\text{TeV})^4$

CKM mixing structure

dominant if $M_R < 10^{12}$ GeV $\Rightarrow$ $B(\mu \to e\gamma) \sim 10^{-13}\,(\Lambda/10\,\text{TeV})^4$

⬇

$B(\tau \to \mu\gamma):B(\tau \to e\gamma):B(\mu \to e\gamma) \sim \lambda^{-6} : \lambda^{-4} : 1 \sim 10^4 : 500 : 1$ ◀ (CKM)

$B(\tau \to \mu\gamma):B(\tau \to e\gamma):B(\mu \to e\gamma) \sim [500\text{–}10] : 1 : 1$ ◀ (PMNS)

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 ⇒ flavour pattern of the new symmetry breaking terms
- Very interesting prospects for new experiments 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*]