On the Higgs mediated FCNCs

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

- Motivations
- Protection mechanisms for Higgs-mediated FCNCs
  - Problems of flavour-blind symmetries
  - Minimal Flavour Violation
  - Partial compositness (hierarchical wave functions)
- MFV with flavour-blind phases and $\Delta F=2$ "anomalies"
  - Survey of the "anomalies" in the $\Delta F=2$ sector
  - Possible "solutions" with Higgs-mediated FCNCs
- Conclusions

Based on recent work with
A.J. Buras, M.V. Carlucci, and S. Gori
[*arXiv:1005.5310*]

Motivations

I. General motivation:

The SM Higgs mechanism is likely to be only an effective description of a more complicated sector responsible for the breaking of the electroweak symmetry.

Several extensions of the Higgs sector proposed in the recent literature (elementary/composite, SUSY/non-SUSY, ...).

In most of them there is more than one Higgs doublet, with possible sizable flavour-changing neutral-current couplings.

Recent papers:

Botella, Branco, Rebelo '09; Pich, Tuzon '09
Gupta, Wells, '10, ...

Giudice, Lebedev '08; Agashe, Contino '09
Azatov, Toharia, Zhu '09, ...

Motivations

II. FCNC scalar amplitudes (mediated by one or more Higgs field) are a particularly useful tool to distinguish different patterns of flavour symmetry breaking:

- Easy to mimic the SM (or MFV) in LL operators.
- More difficult to reproduce the SM (or MFV) suppression for LR operators (double suppression down-type Yukawa + CKM).

III. FCNC scalar amplitudes are less explored (because of their double suppression) on the phenomenological side:

- Interesting window to "cure" some of the recent "anomalies" in the $\Delta F=2$ observables, without spoiling the overall success of the CKM picture.

Protection mechanisms for Higgs-mediated FCNCs

One of the main problems in building (low-energy) extensions of the SM is how to get rid of too large FCNCs

Generic Yukawa interaction of a model with two Higgs doublets:

$$\mathcal{L}_{Y}^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}$$

X_a = 3 × 3 matrices in flavour space

Protection mechanisms for Higgs-mediated FCNCs

One of the main problems in building (low-energy) extensions of the SM is how to get rid of too large FCNCs

Generic Yukawa interaction of a model with two Higgs doublets:

$$\mathcal{L}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \cancel{\bar{Q}_L X_{u1} U_R H_1^c} + \cancel{\bar{Q}_L X_{d2} D_R H_2^c} + \bar{Q}_L X_{u2} U_R H_2 + {\rm h.c.}$$

Two main strategies to “protect” FCNCs:

I. Flavour-blind symmetries (“Natural Flavour Conservation”)

E.g.: U(1) or Z_2 such that $X_{u1} = X_{d2} = 0$

Glashow, Weinberg '77
Paschos '77

Protection mechanisms for Higgs-mediated FCNCs

One of the main problems in building (low-energy) extensions of the SM is how to get rid of too large FCNCs

Generic Yukawa interaction of a model with two Higgs doublets:

$$\mathcal{L}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}$$

Two main strategies to “protect” FCNCs:

I. Flavour-blind symmetries

E.g.: U(1) or Z_2 such that $X_{u1} = X_{d2} = 0$

II. Flavour symmetries (& symm. breaking pattern)

E.g.: MFV $X_{d1} \propto X_{d2}$ & $X_{u1} \propto X_{u2}$

Protection mechanisms for Higgs-mediated FCNCs

One of the main problems in building (low-energy) extensions of the SM is how to get rid of too large FCNCs

Generic Yukawa interaction of a model with two Higgs doublets:

$$\mathcal{L}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \mathrm{h.c.}$$

Two main strategies to "protect" FCNCs:

I. Flavour-blind symmetries

E.g.: U(1) or Z_2 such that $X_{u1} = X_{d2} = 0$

II. Flavour symmetries (& symm. breaking pattern)

E.g.: MFV $X_{d1} \propto X_{d2}$ & $X_{u1} \propto X_{u2}$

None of the two ansatz is stable beyond the tree level.

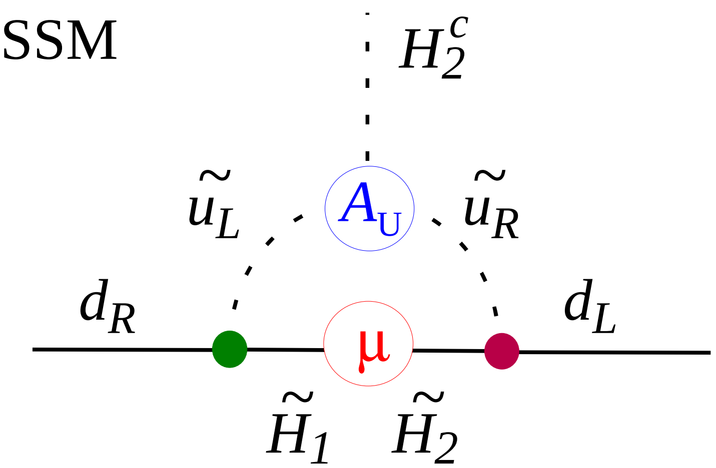
The problem is particularly severe if the theory contains additional degrees of freedoms at the TeV scale: in this case only the strategy II. can be sufficiently stable

Problems of flavour blind symmetries:

I. These symmetries are typically broken in other sectors of the theory.

This is necessarily the case if we introduce a U(1) symmetry to ensure “Natural Flavour Conservation”: the symmetry must be broken in the Higgs potential in order to avoid a massless pseudoscalar field

E.g.: MSSM



Tree level:

$X_{d2} = 0$ $\qquad$ $X_{d1} = Y_d$

One loop:

$X_{d2} = \varepsilon\, \Delta_d$ $\qquad$ $X_{d1} = Y_d$ +...

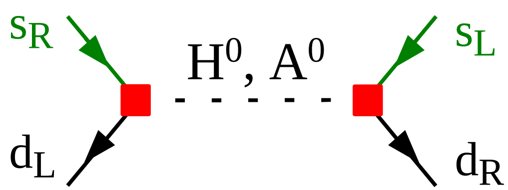
Even if $\varepsilon \sim 10^{-2}$ (typical loop suppression) too large FCNCs if Δ_d is not very small or closely aligned in flavour space to Y_d

Problems of flavour blind symmetries:

I. These symmetries are typically broken in other sectors of the theory.

This is necessarily the case if we introduce a U(1) symmetry to ensure “Natural Flavour Conservation”: the symmetry must be broken in the Higgs potential in order to avoid a massless pseudoscalar field

The most severe bound comes from CP violation in neutral K mixing (ε_K)



Tree level:

$$X_{d2} = 0 \qquad X_{d1} = Y_d$$

One loop:

$$X_{d2} = \varepsilon\, \Delta_d \qquad X_{d1} = Y_d + \ldots$$

Chiral enhancement + large RGE effects $\Rightarrow \sim 10^2$ enhancement with respect to LL operators:

$$|\,\varepsilon\,| \times \left| \mathrm{Im}[(\widetilde{\Delta}_d)^*_{21} (\widetilde{\Delta}_d)_{12}] \right|^{1/2} \lesssim 3 \times 10^{-7} \times \frac{c_\beta M_H}{100\ \mathrm{GeV}}$$

Problems of flavour blind symmetries:

I. These symmetries are typically broken in other sectors of the theory.

II. Even if exact (discrete case) these symmetries do not protect FCNCs when higher-dimensional operators are taken into account:

$$\Delta\mathcal{L}_Y = \frac{c_{\rm eff}}{\Lambda^2}\,\bar{Q}_L\,\Delta_{u2}\,U_R H_2 |H_1|^2 + \ldots$$

Exact Z_2 symmetry, but FCNC generated after the Higgs get vevs unless $\Delta_{u2} \propto$ tree-level coupling (d=4 ops) $\Rightarrow$ role of the U(1) breaking term (ε) replaced by $c_{\rm eff}\, v^2 / \Lambda^2$ $\Rightarrow$ tight constraint if Λ = few TeV

N.B.: This type of problem is present even with a single Higgs field.

Giudice, Lebedev '08
Agashe, Contino, '09
Azatov, Toharia, Zhu, '09

Problems of flavour blind symmetries:

I. These symmetries are typically broken in other sectors of the theory.

II. Even if exact (discrete case) these symmetries do not protect FCNCs when higher-dimensional operators are taken into account.

↓

To reach a sufficient "protection" of FCNC we necessarily need to protect the breaking of the flavour symmetry

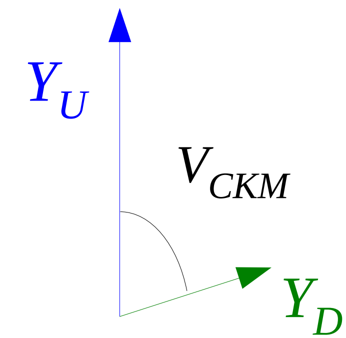
Minimal Flavour Violation:

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

- Flavour symmetry:

  $U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$

  [global symmetry of the SM gauge sector]



$SU(3)_Q$ component of the Flavor Group

- Symmetry-breaking terms:

  $Y_D \sim \bar{3}_Q \times 3_D \quad Y_U \sim \bar{3}_Q \times 3_U \quad (Y_L \sim \bar{3}_L \times 3_E)$

  [quark (& lepton) Yukawa couplings]

- Most efficient protection given we need to accommodate quark masses and CKM

- General effective theory with two Higgs doublets, with masses O(100 GeV), and higher-order operators suppressed by TeV scale, perfectly compatible with present data (even for $\tan\beta = v_2/v_1 \gg 1$)

Minimal Flavour Violation:

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

- Flavour symmetry:

$$U(3)^5 = \underbrace{SU(3)_Q \times SU(3)_U \times SU(3)_D}_{SU(3)_q^3} \times \ldots$$

- Symmetry-breaking:

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

D'Ambrosio *et al.*, '02

N.B.:

- $U(3)^5$ contains also the *flavour-blind* $U(1)_{PQ}$ relevant to 2HDMs, however, once we protect $SU(3)_q^3$ we already have a sufficient protection of FCNCs

- The breaking of CP (*flavour-blind*) does not need to be related to the $SU(3)_q^3$ breaking (although small flavour-blind phases suggested by edm's)

Kagan, Perez, Volansky, Zupan '09; Mercolli, Smith '09; Paradisi, Straub, '09

$\Downarrow$

Phenomenology of Higgs-mediated FCNCs with MFV particularly interesting with large $U(1)_{PQ}$ breaking + large flavour-blind CPV phases

$$\mathcal{L}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}$$

Structure of the effective Yukawa couplings with MFV:

$$\begin{aligned}
X_{d1} &= Y_d \quad \text{(def)} \\
X_{d2} &= \epsilon_0 Y_d + \epsilon_1 Y_d^\dagger Y_d Y_d + \boxed{\epsilon_2 Y_u^\dagger Y_u Y_d} + \ldots \\
X_{u1} &= \epsilon'_0 Y_u + \epsilon'_1 Y_u^\dagger Y_u Y_u + \boxed{\epsilon'_2 Y_d^\dagger Y_d Y_u} + \ldots \\
X_{u2} &= Y_u \quad \text{(def)}
\end{aligned}$$

leading terms relevant to FCNCs

- The values of the ϵ_i are connected by RGE (computable if the UV completion of the model is know): not consistent to set them to zero (fine-tuning)
- Even with $\epsilon_i = O(1)$ the parametric expansion in powers of V_{i3} (off-diagonal CKM elements) and m_i/m_3 (small quark masses) is stable and rapidly convergent

Structure of the FCNC couplings to the Higgs (in the limit $\tan\beta = v_2/v_1 \gg 1$):

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

$$\underbrace{[a_0}_{Y_U Y_U^+ Y_D} \quad \underbrace{a_1\,\delta_{3i}}_{Y_D Y_D^+ Y_U Y_U^+ Y_D} \quad \underbrace{a_2\,\delta_{3k}]}_{Y_U Y_U^+ Y_D Y_D^+ Y_D}$$

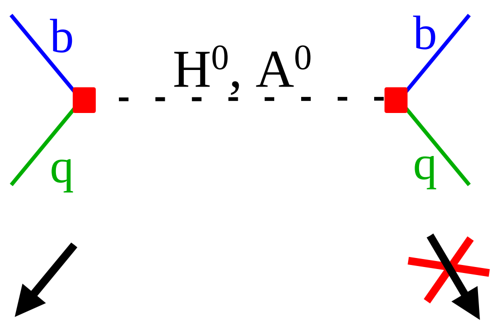
D'Ambrosio *et al.* '02

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

Structure of the FCNC couplings to the Higgs (in the limit $\tan\beta = v_2/v_1 \gg 1$):

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

$\Delta F=2$ effective interaction 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 $\longrightarrow$

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

Very interesting pattern given the present $\Delta F=2$ "anomalies"

Partial Compositness (hierarchical fermion profiles)

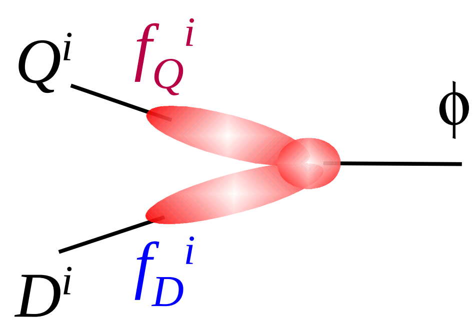
MFV is certainly not the only flavour-symmetry breaking pattern allowed by data. An interesting (and rather general) alternative is the mechanism at work in models with partial compositness (or 5D warped models) [wide recent lit.]

SM fermions couples to the new-physics sector via some hierarchical wave functions f_Q, f_D, f_U (in the quark sector), such that

$$Y_D^{ij} = f_Q^{\,i}\,(\boldsymbol{Y}_{\boldsymbol{D}}^{\boldsymbol{5D}})\,f_D^{\,j} \approx f_Q^{\,i} f_D^{\,j} \qquad Y_U^{ij} = f_Q^{\,i}\,(\boldsymbol{Y}_{\boldsymbol{U}}^{\boldsymbol{5D}})\,f_U^{\,j} \approx f_Q^{\,i} f_U^{\,j}$$

anarchic

hierarchical



$$f_Q^{\,3} \gg f_Q^{\,2} \gg f_Q^{\,1}$$
$$f_D^{\,3} \gg f_D^{\,2} \gg f_D^{\,1}$$
$$f_U^{\,3} \gg f_U^{\,2} \gg f_U^{\,1}$$

Partial Compositness (hierarchical fermion profiles)

MFV is certainly not the only flavour-symmetry breaking pattern allowed by data. An interesting (and rather general) alternative is the mechanism at work in models with partial compositness (or 5D warped models) [wide recent lit.]

SM fermions couples to the new-physics sector via some hierarchical wave functions f_Q, f_D, f_U (in the quark sector), such that

$$Y_D^{ij} = f_Q^{\,i}\,(\boldsymbol{Y}_{\boldsymbol{D}}^{\boldsymbol{5D}})\,f_D^{\,j} \approx f_Q^{\,i} f_D^{\,j} \qquad\qquad Y_U^{ij} = f_Q^{\,i}\,(\boldsymbol{Y}_{\boldsymbol{U}}^{\boldsymbol{5D}})\,f_U^{\,j} \approx f_Q^{\,i} f_U^{\,j}$$

- The condition on the (4D)Yukawa $\Rightarrow$ $f_Q^{\,i} / f_Q^{\,3} \sim |V_{3i}|$
- All the left-handed FCNC operators (the leading ones in the SM) have the same suppression as in MFV:

$$f_Q^{\,i} f_Q^{\,j}\, \bar{Q}_L^{\,i}\, Q_L^{\,j} \sim V_{3i} V_{3j}\, \bar{Q}_L^{\,i}\, Q_L^{\,j}$$

This property is shared by several explicit flavour models

Lalack, Pokorski, Ross [*to appear*]

Partial Compositness (hierarchical fermion profiles)

Substantial differences with MFV arises only when considering LR operators (this is why Higgs-mediated FCNCs are particularly interesting):

- MFV: double suppression: CKM + down-type Yukawa couplings

ΔF=2 amplitudes scaling	$m_b\, m_s$ (B_s mixing)	relative to the SM	→	*large* (B_s mixing)
	$m_b\, m_d$ (B_d mixing)			*small* (B_d mixing)
	$m_s\, m_d$ (K mixing)			*tiny* (K mixing)

- Partial compositness: Yukawa suppression only ($f_Q^{\,j} f_D^{\,i} \times f_Q^{\,i} f_D^{\,j} \sim y_d^{\,i} y_d^{\,j}$)

ΔF=2 amplitudes scaling	$m_b\, m_s$ (B_s mixing)	<u>in absolute terms</u>	→	*small* (B_s mixing)
	$m_b\, m_d$ (B_d mixing)			*small* (B_d mixing)
	$m_s\, m_d$ (K mixing)			<u>*large*</u> (K mixing)

MFV with flavour-blind phases and $\Delta F=2$ "anomalies"

The overall agreement of flavour-changing data with SM prediction is remarkable.

However, two interesting problems have recently emerged in the (highly-suppressed) $\Delta F=2$ down-type transitions:

I. The ε_K - $S_{\Psi K}$ tension in the CKM fit (B_d vs. K mixing)

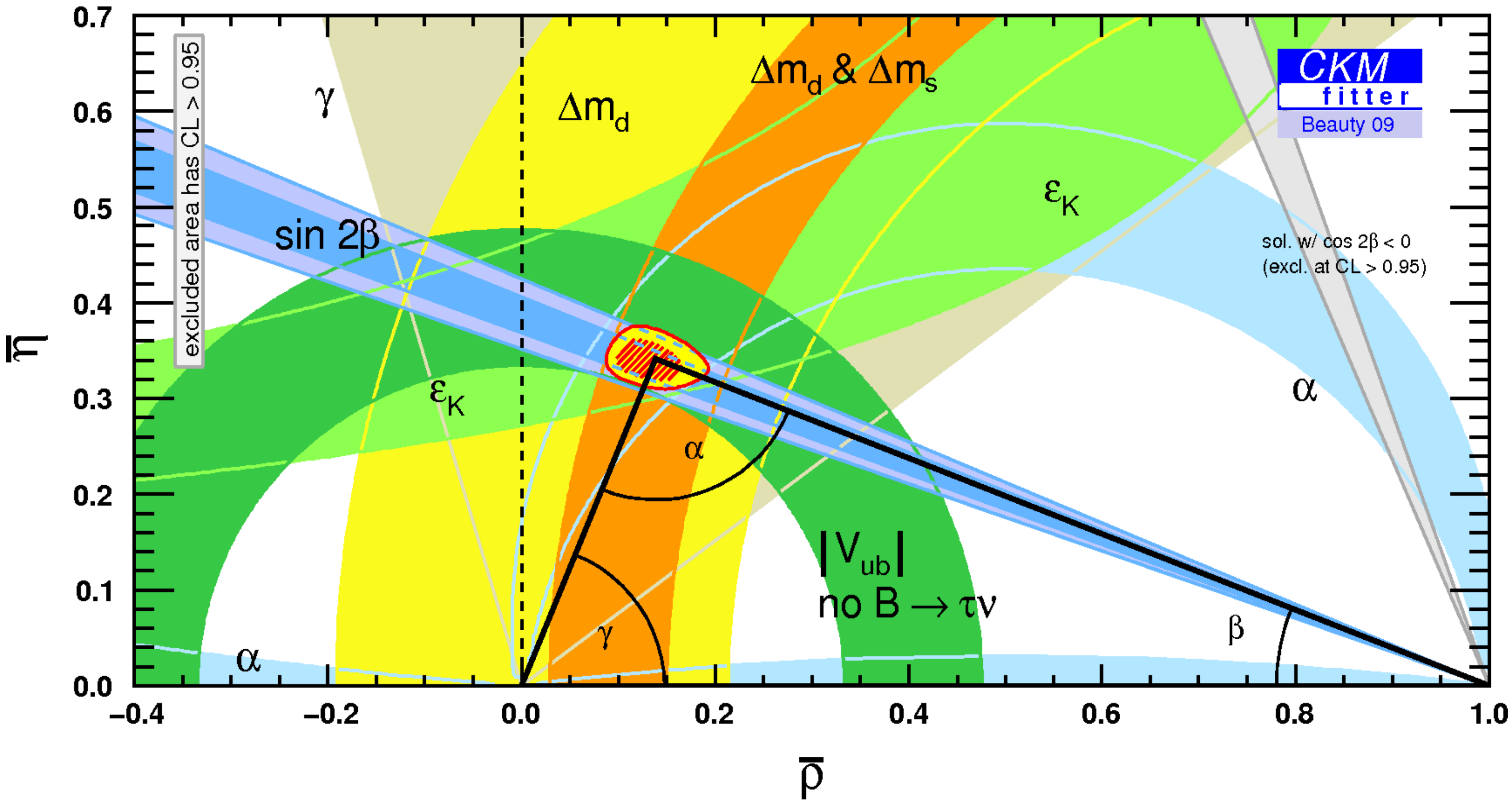
II. The large mixing phase in B_s mixing

The size of these two effects is very different, but is rather suggestive in view of Higgs-mediated FCNCs with MFV and flavour-blind phases

I. The ε_K - $S_{\Psi K}$ tension in the CKM fit

The global fit by the CKMfitter collaboration shows an excellent consistency of the various observables. However, an underlying tension is hidden by the rather conservative choice of the theory (Lattice) errors.

Definitely too conservative is the error assigned to B_K: $B_K = 0.79\,^{+0.20}_{-0.12}$



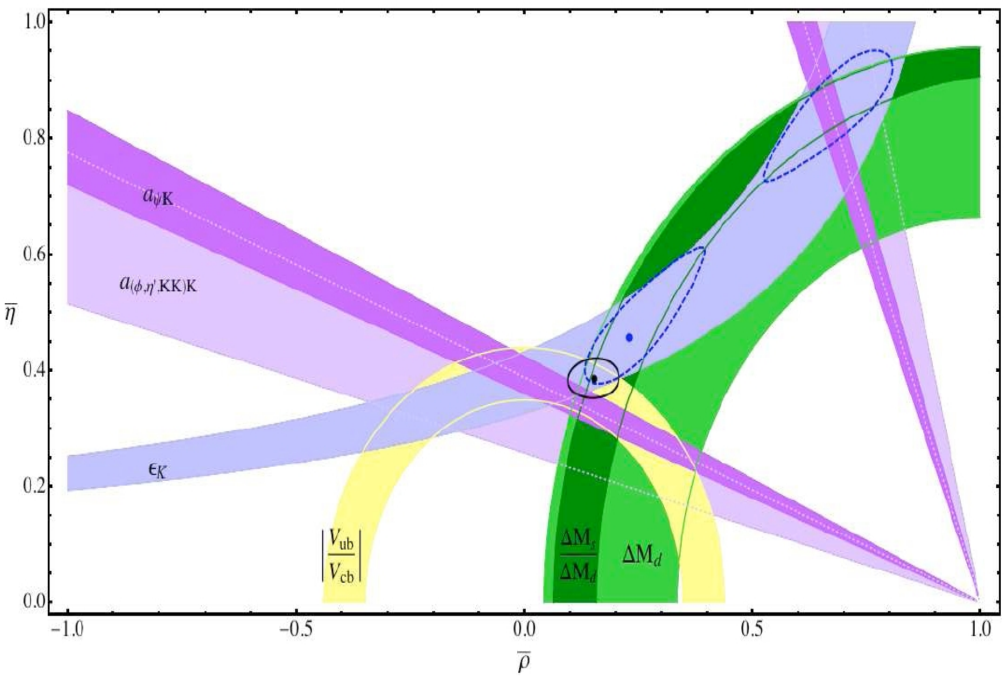
I. The ε_K - $S_{\Psi K}$ tension in the CKM fit

This tension is more evident if we take into account only the recent unquenched determinations of B_K

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

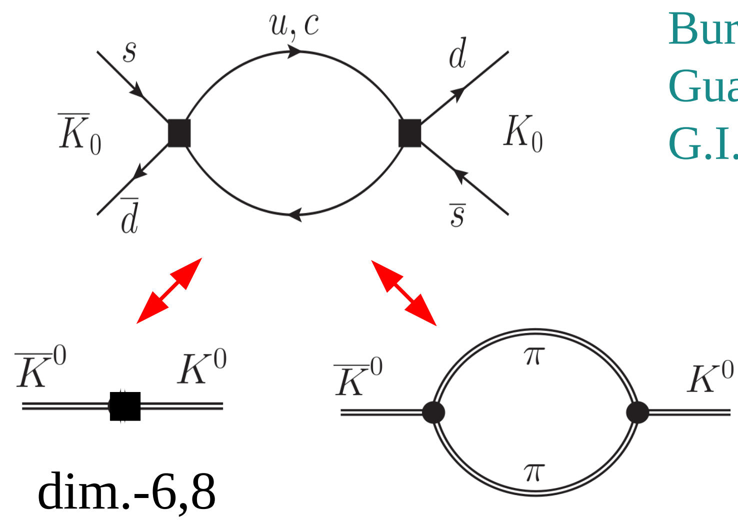
$B_K = 0.720 \pm 0.013 \pm 0.037$ D.J. Anotnio *et al.* [RBC Collab.] PRL '08

$B_K = 0.724 \pm 0.008 \pm 0.029$ Aubin, Laiho, Van de Water, PRD '10



Soni & Lunghi, '08-'09

The tension survive even after subleading terms in the OPE are taken into account



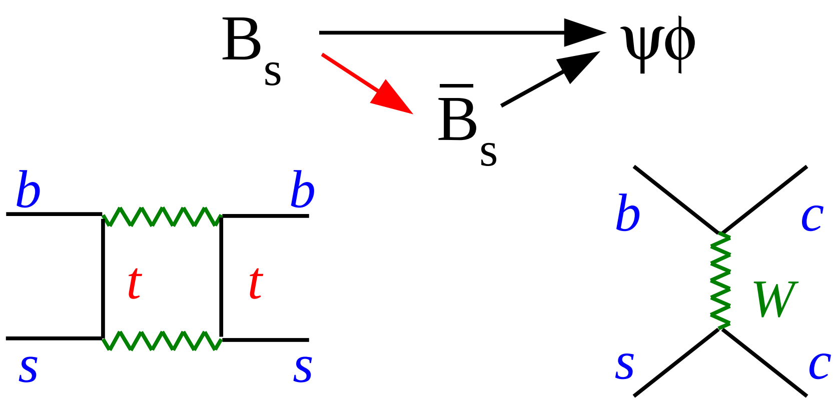
Buras, Guadagnoli, G.I. '10

$-(4\pm2)\%$ corr. to ε_K

II. The large mixing phase in B_s mixing

The weak phase of B_s mixing (the last missing piece of down-type $\Delta F=2$) is currently under investigation at Tevatron via the time-dependent study of the $B_s \to \psi\phi$ decay & via the semileptonic charge asymmetry (same-sign muons)

Theoretical clean extraction:



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

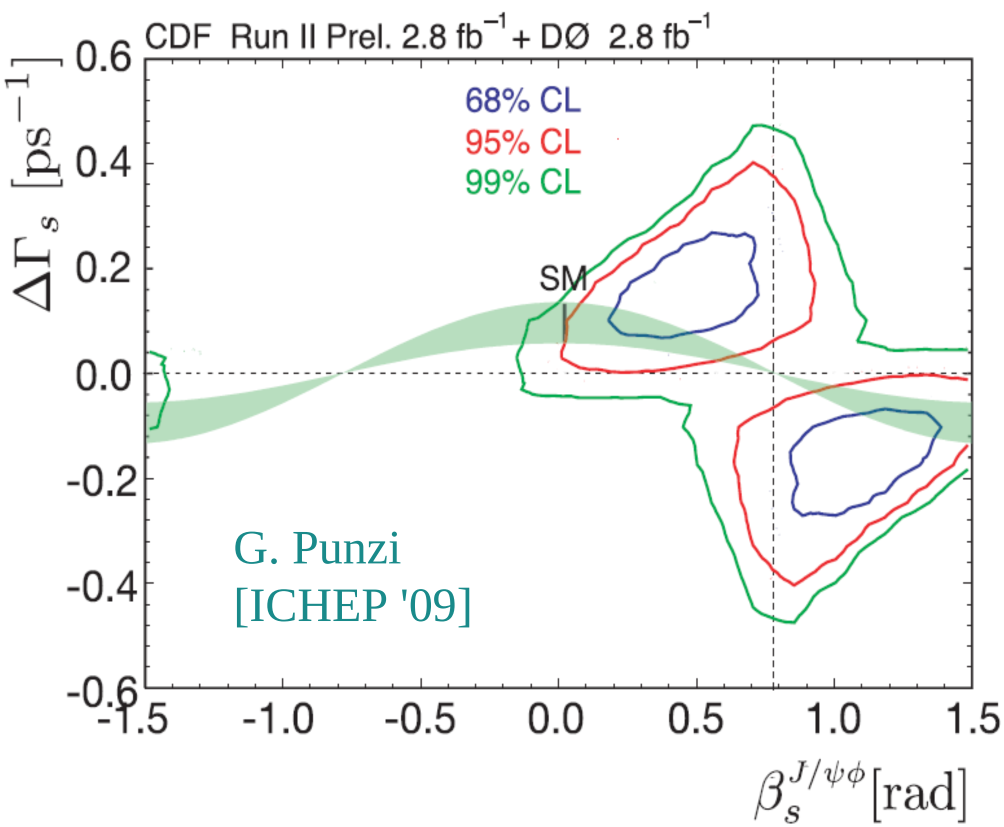
Experimentally quite challenging:

- Fast oscillations
- Non-trivial angular analysis (in $B_s \to \psi\phi$)
- Simultaneous fit of $\Delta\Gamma_s$ and the mixing phase

II. The large mixing phase in B_s mixing

The weak phase of B_s mixing (the last missing piece of down-type $\Delta F=2$) is currently under investigation at Tevatron via the time-dependent study of the $B_s \to \psi\phi$ decay & via the semileptonic charge asymmetry (same-sign muons)

First results seem to indicate a large CPV phase



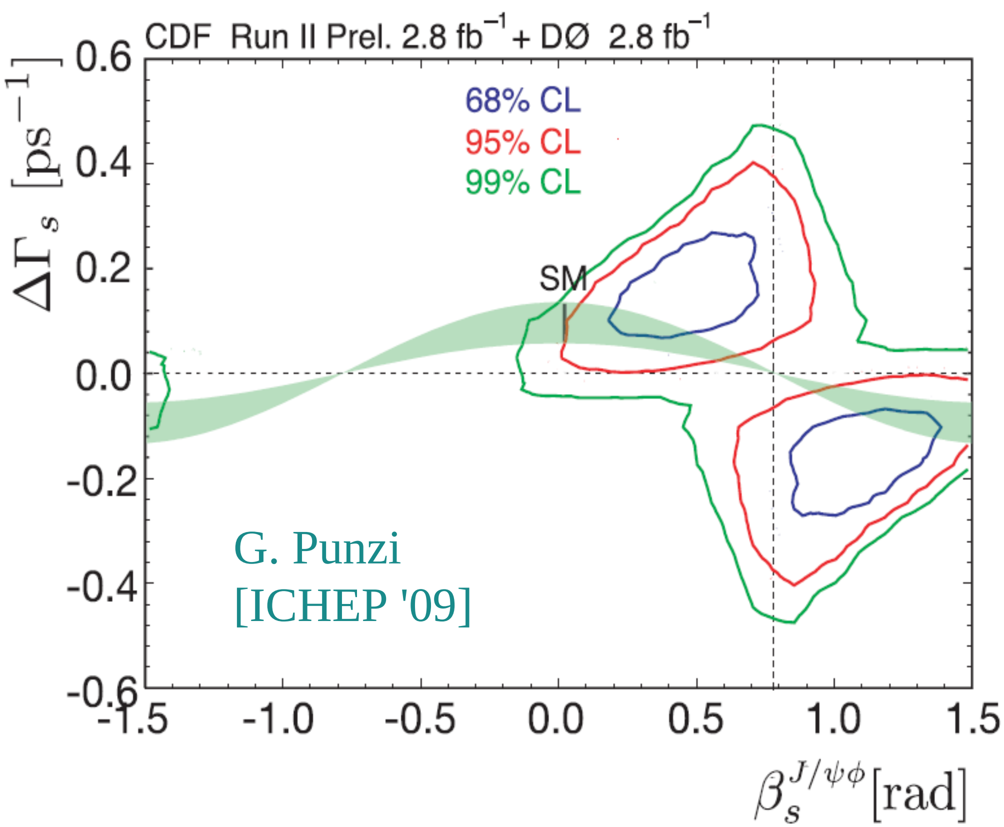
G. Punzi
[ICHEP '09]

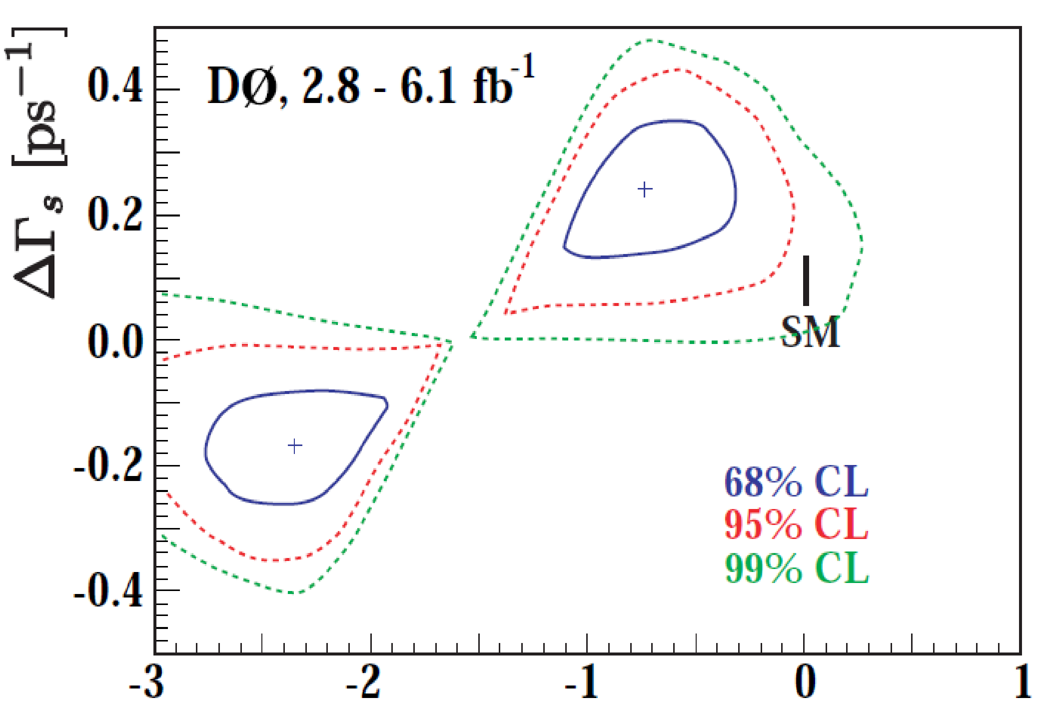
II. The large mixing phase in B_s mixing

The weak phase of B_s mixing (the last missing piece of down-type $\Delta F=2$) is currently under investigation at Tevatron via the time-dependent study of the $B_s \to \psi\phi$ decay & via the semileptonic charge asymmetry (same-sign muons)

First results seem to indicate a large CPV phase

Significance since summer '09 increased at D0, decreased at CDF

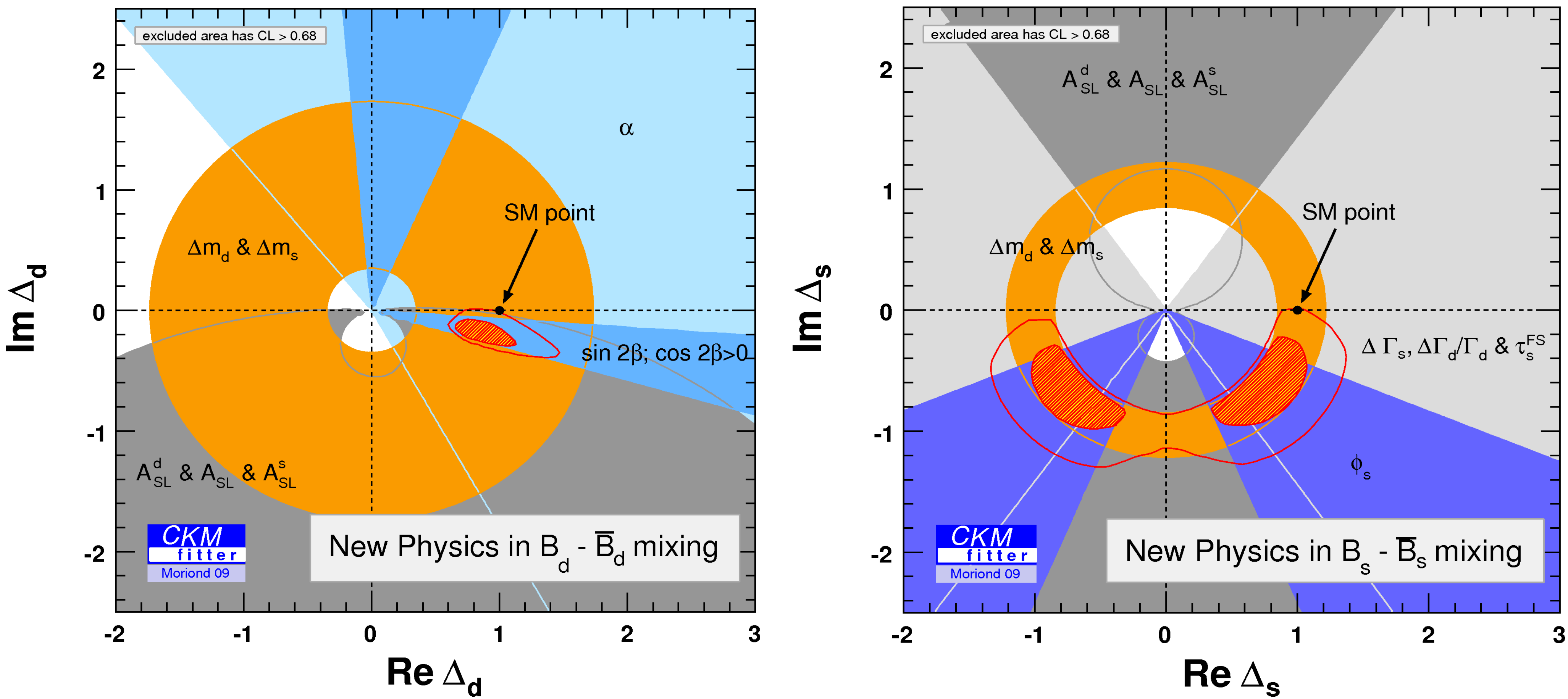




$[\ \phi_s = -2\ \beta_s\ ]$

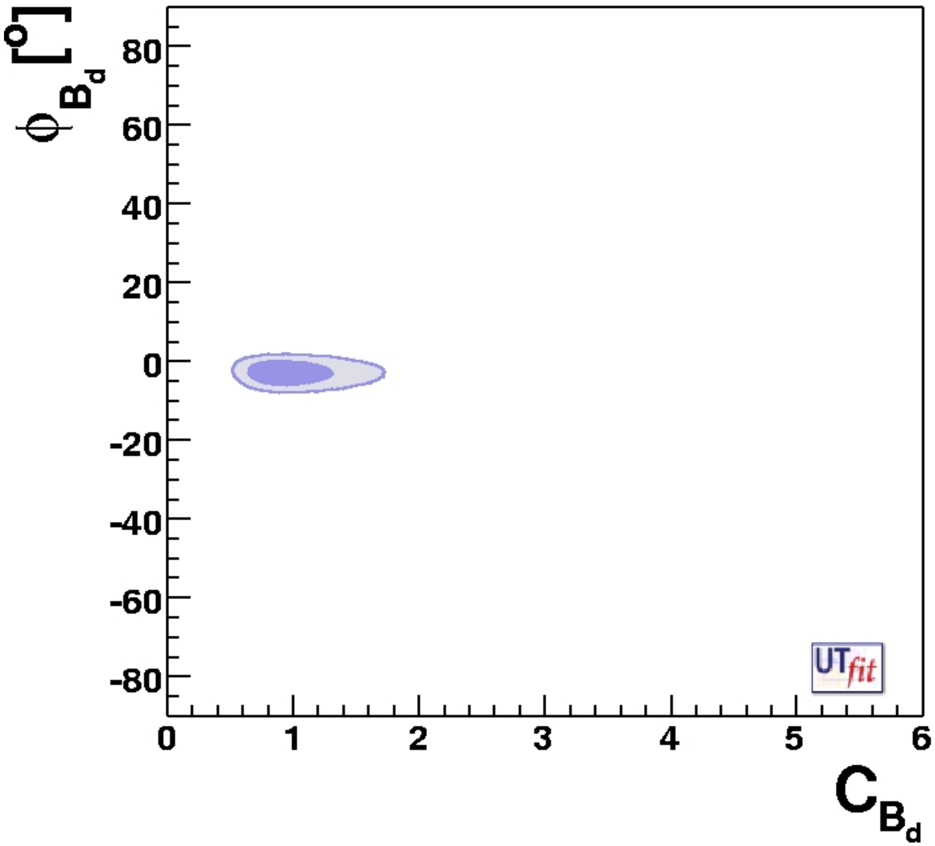
Taking as reference values the 2009 results, the two “anomalies” are both at the ~2σ level

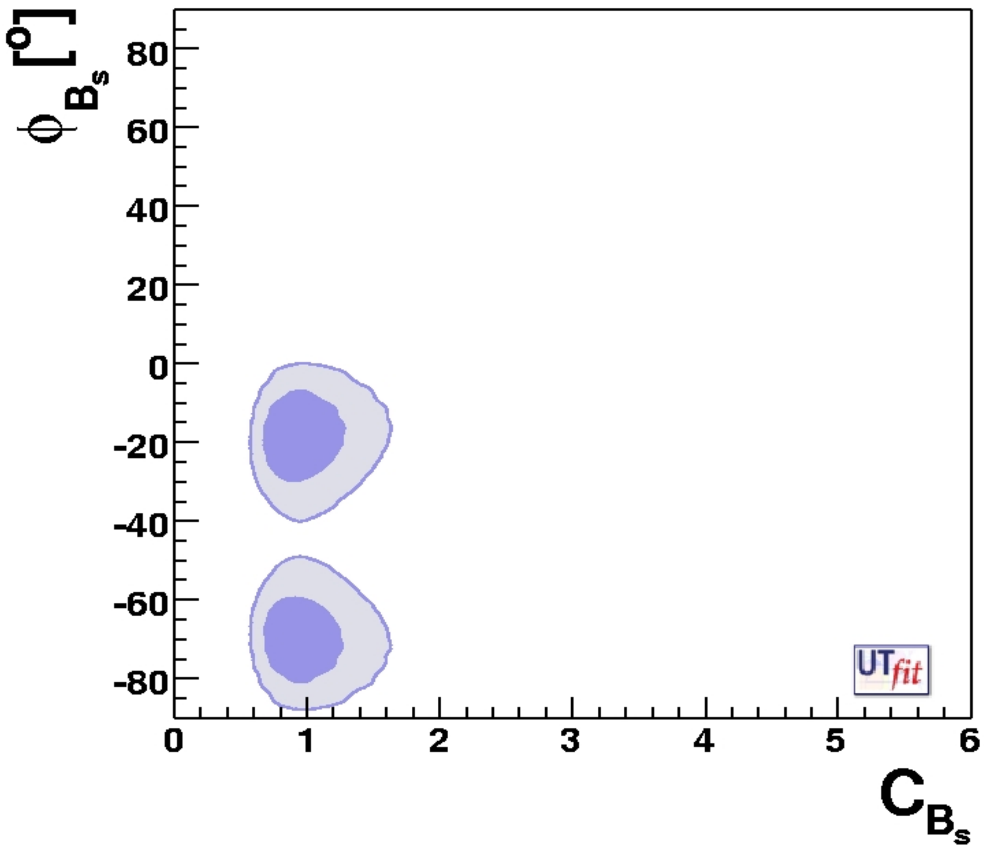
$$\langle B_q | M_{12}^{\rm SM+NP} | \bar{B}_q \rangle = \Delta_q^{\rm NP} \langle B_q | M_{12}^{\rm SM} | \bar{B}_q \rangle$$



Taking as reference values the 2009 results, the two "anomalies" are both at the ~2σ level

$$\langle B_q | M_{12}^{\rm SM+NP} | \bar{B}_q \rangle = C_{Bq} e^{2i\phi_{Bq}} \langle B_q | M_{12}^{\rm SM} | \bar{B}_q \rangle$$

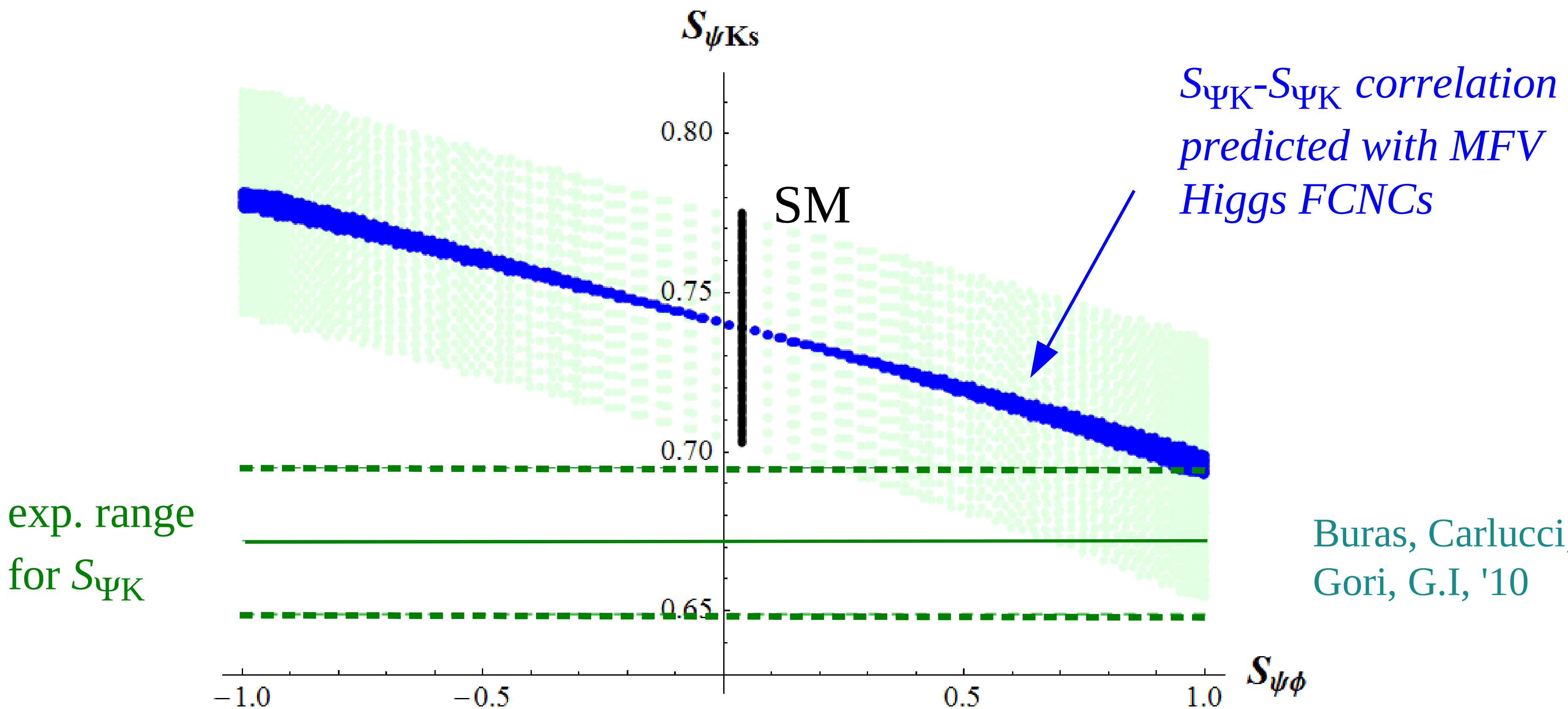




With Higgs mediated FCNCs with flavour-blind phases it is relatively easy to fit a large Bs mixing phase

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 solve the first anomaly



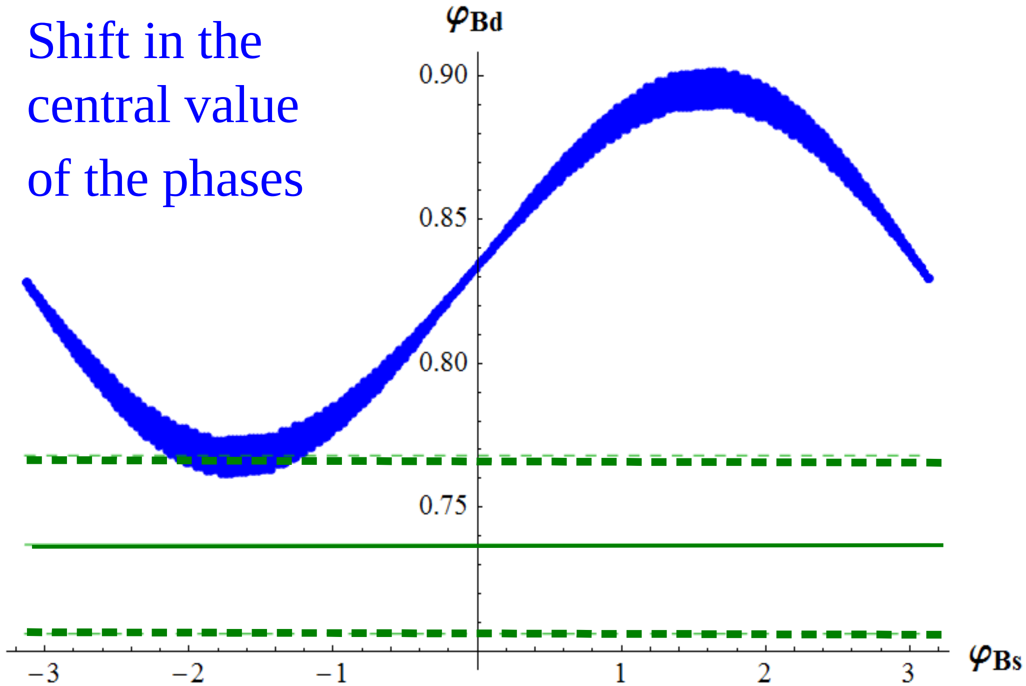
Buras, Carlucci, Gori, G.I, '10

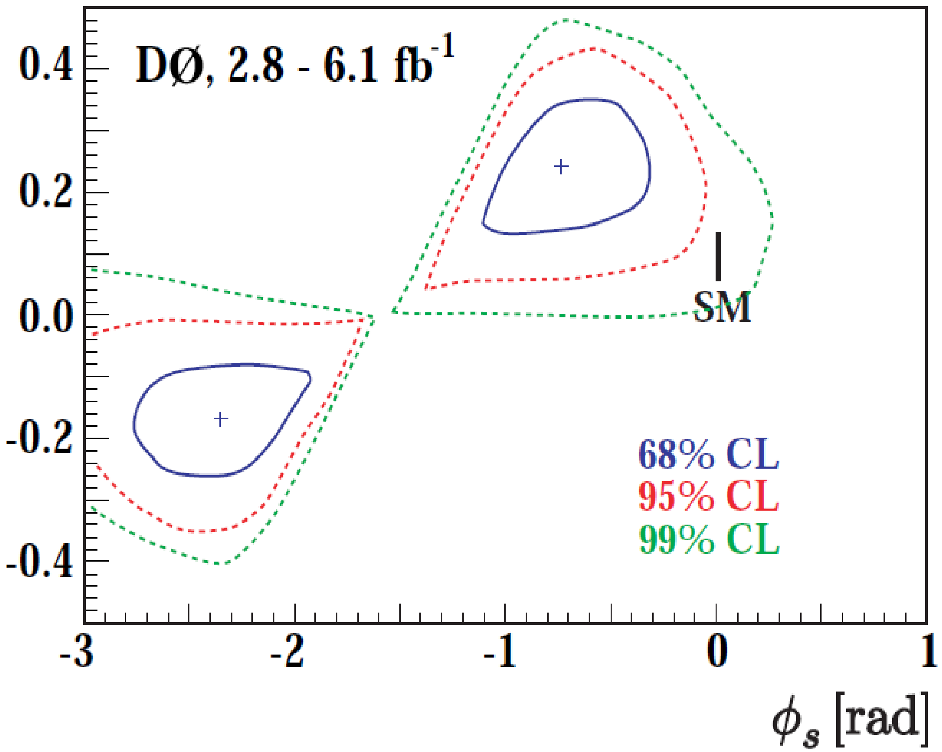
$$\mathcal{H}_{\rm MFV}^{|\Delta B|=2} = -\frac{(a_0^* + a_1^*)(a_0 + a_2)}{M_H^2}\, y_b y_q [y_t^2 V_{tb}^* V_{tq}]^2\ (\bar b_R q_L)(\bar b_L q_R)\ +\ \text{h.c.} \quad (q = d, s)$$

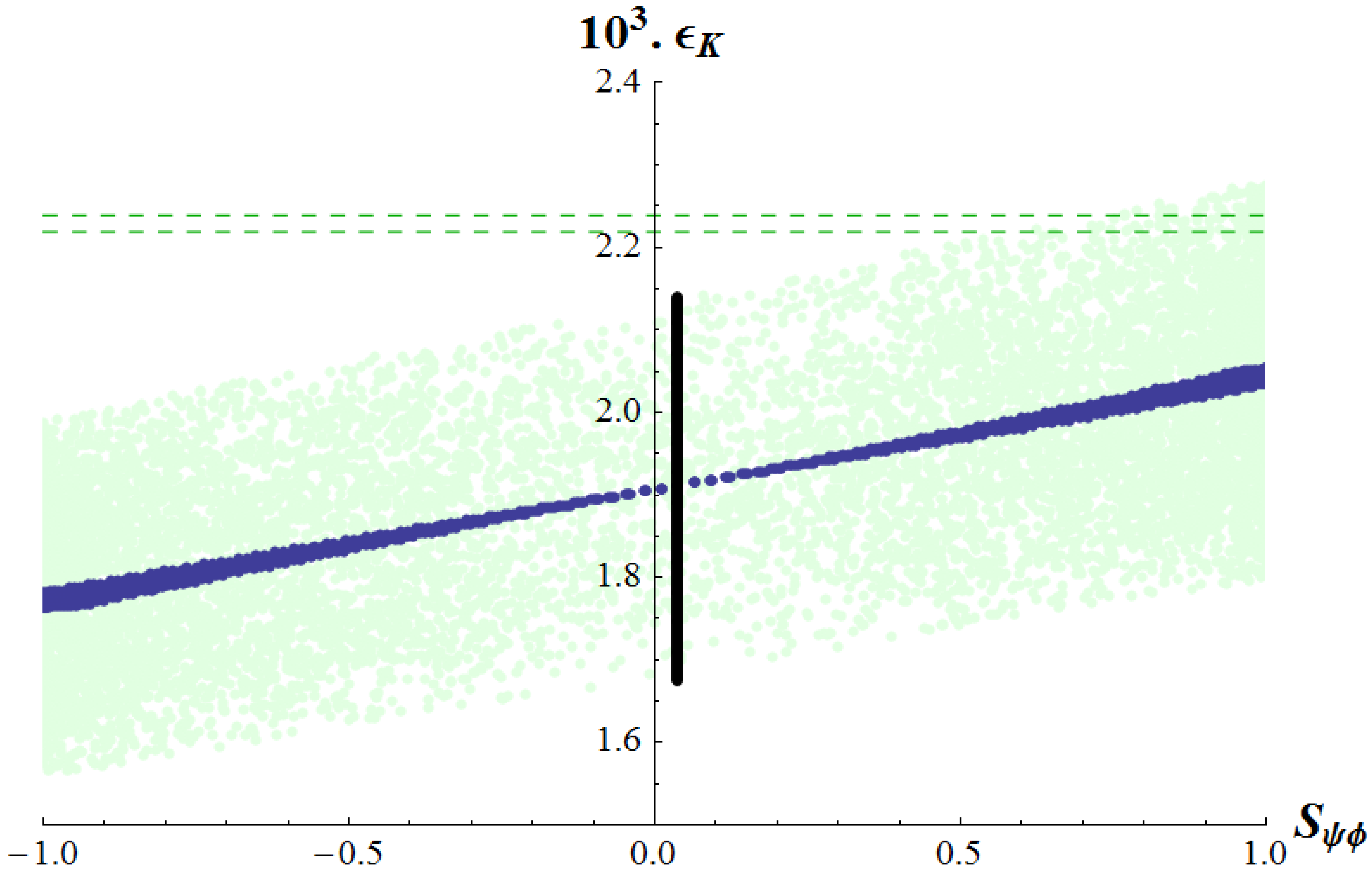
Modulo and phase of the operator fixed by ΔM_{Bs} and ϕ_{Bs}

$\Rightarrow$ effect in B_d mixing scale as m_d/m_s

Shift in the central value of the phases



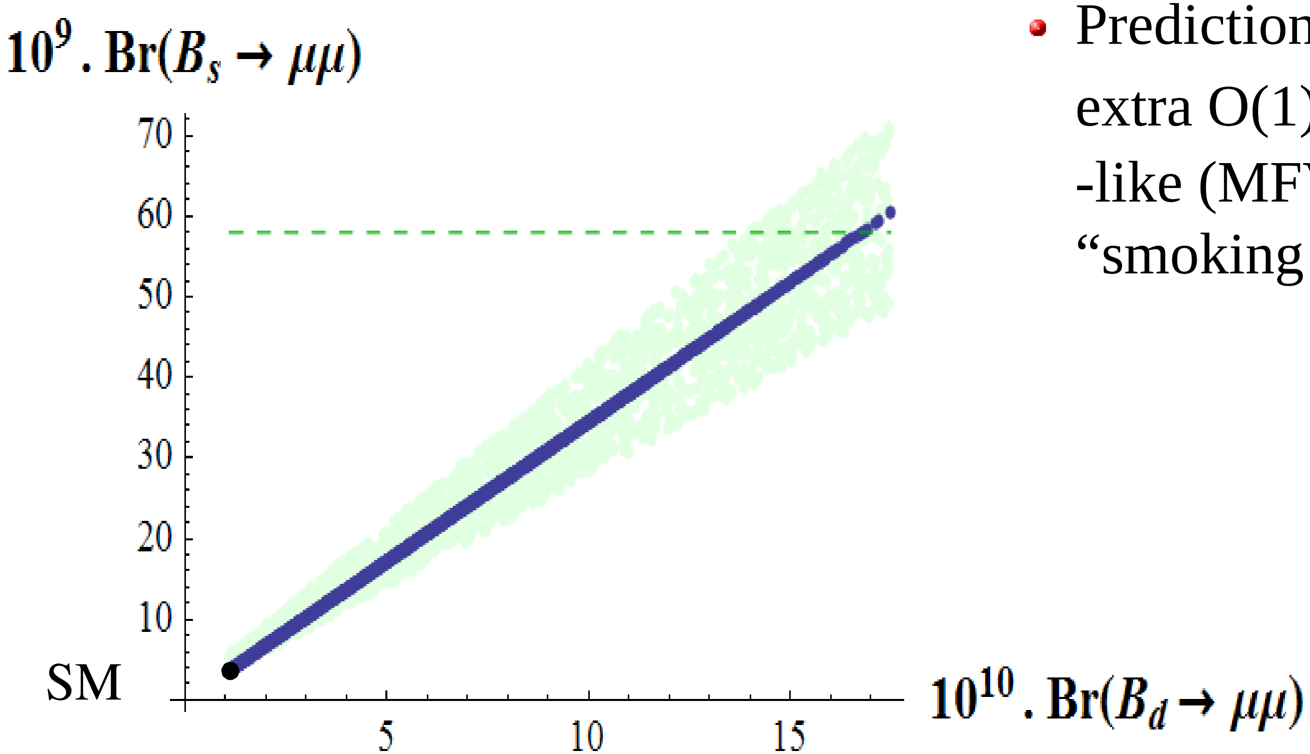




...the prediction of is also improved, even with no direct NP contribution, simply because of the higher "true value" of sin(2β) and V_{ub} extracted from $S_{\Psi K}$

Significant contribution to B_s mixing are obtained for

- $a_i \tan\beta\,(250\ \mathrm{GeV}/m_H) = O(10)$ [natural]
- $a_{1\text{-}3}$ comparable in size [not possible in the MSSM] and with large CPV phases [*constraints from edm's to be investigated*]
- constraints from $B_{s,d} \to \mu\mu$ ok, but B_s likely to be around present bound



- Prediction for $B_{s,d} \to \mu\mu$ affected by extra O(1) parameters, but with CKM -like (MFV) correlation ⇒ possible “smoking gun” of this framework

Conclusions

Higgs-mediated FCNCs would provide (if observed) a very interesting window both on the Higgs sector and on the structure of flavour symmetry breaking

- When considering two-Higgs doublet models, the protection of FCNCs based on flavour-blind symmetries is not stable beyond the tree level $\Rightarrow$ sufficient protection can be achieved only protecting the breaking of the flavour symmetry.
- The most efficient protection is obtained with MFV.
- Higgs-mediated FCNCs with MFV and flavour blind CPV phases could provide a clean explanation of recent anomalies in the $\Delta F=2$ sector, which could easily be confirmed or ruled out.