Flavor changing neutral currents in two Higgs doublet models

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Outline

- Motivations
- Protection mechanisms for Higgs mediated FCNCs
  - Natural flavor conservation (NFC)
  - Minimal flavor violation (MFV)

  vs.
- 2HDM with MFV and flavor blind phases

  $2HDM_{\overline{MFV}}$
  - ΔF=2 anomalies
  - $B_{s,d} \to \mu^+\mu^-$
- Conclusions

Based on a recent work with
A. J. Buras, M. V. Carlucci and G. Isidori
[arXiv: 1005:5310]

Motivations

2HDMs:

- Most probably the Standard Model (SM) Higgs mechanism is only an effective description of a more complicated sector responsible for the breaking of the electroweak symmetry.

- Several extensions of the SM involve an extended Higgs sector, with more than one Higgs doublet.

  (See for example Supersymmetry, Extra dimensional models)

- Possible sizable Flavor Changing Neutral Currents (FCNCs) due to the exchange of (one or more) Higgs bosons.

Some recent works:

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

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

- Worth to investigate in a general Two Higgs Doublet Model (2HDM) the New Physics (NP) contributions to flavor observables.

It can represent the low energy effective theory which arises as the limit of more complete models (like Supersymmetry, Warped Extra Dimensions).

See Dobrescu, Fox, Martin, '10 (uplifted Susy)

Problems of the most general 2HDM

- H_1, H_2 two Higgs doublets with hypercharges Y_1= 1/2 and Y_2= -1/2
- Most general Yukawa interaction Hamiltonian

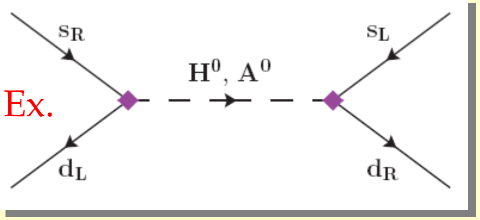
$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}$$

where X_i are generic 3×3 matrices in flavor space

In general too large NP contributions to flavor changing neutral processes, since quark mass matrices and Yukawa couplings are not alligned

→ FCNCs at the tree level

Ex.



How to protect the model from too large FCNCs?

Protection mechanisms

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

Largest group which commutes with the SM gauge group:

$$\mathcal{G}_q = {\rm SU}(3)_q^3 \otimes {\rm U}(1)_B \otimes {\rm U}(1)_Y \otimes {\rm U}(1)_{\rm PQ}$$

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D'Ambrosio et al., '02

- Minimal Flavor Violation hypothesis:
  $SU(3)^3$ symmetry broken only by two spurions

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

- Tree level implication

$$X_{d1} \propto X_{d2}\,, \quad X_{u1} \propto X_{u2}$$

See also Yukawa alignment, Pich, Tuzon, '09

- Including radiative corrections, one gets

$$\begin{cases} X_{d1} = Y_d & \text{(definition)} \\ X_{d2} = \epsilon_0 Y_d + \epsilon_1 Y_d^\dagger Y_d Y_d + \epsilon_2 Y_u^\dagger Y_u Y_d + \dots \\ X_{u1} = \epsilon_0' Y_u + \epsilon_1' Y_u^\dagger Y_u Y_u + \epsilon_2' Y_d^\dagger Y_d Y_u + \dots \\ X_{u2} = Y_u & \text{(definition)} \end{cases}$$

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Glashow, Weinberg, '77
Paschos, '77

- Natural Flavor Conservation hypothesis:
  only a Higgs field can couple to a given quark species
- The hypothesis is enforced by the $U(1)_{PQ}$ symmetry
- Tree level implication
  $X_{d2} = X_{u1} = 0$

  (D_R and H_1 with opposite PQ charges)
- The symmetry $U(1)_{PQ}$ must be broken
  (otherwise appearance of a Goldstone boson)

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Largest group which commutes with the SM gauge group:

$$\mathcal{G}_q = SU(3)_q^3 \otimes U(1)_B \otimes U(1)_Y \otimes U(1)_{PQ}$$

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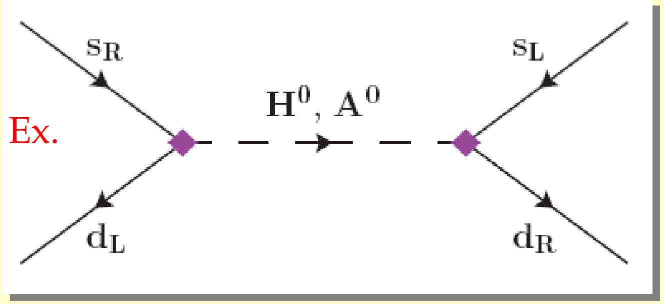
FCNCs

Constraints on the two hypothesis

Constraint from the K meson mixing system: ε_K



Buras, Carlucci, S.G., Isidori, '10

Natural flavor conservation

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

A very high level of fine tuning is required!

found imposing $|\varepsilon_K^{\mathrm{NP}}| < 0.2\,|\varepsilon_K^{\mathrm{exp}}|$

A loop suppression $\epsilon_d \sim 10^{-2}$ is not sufficient

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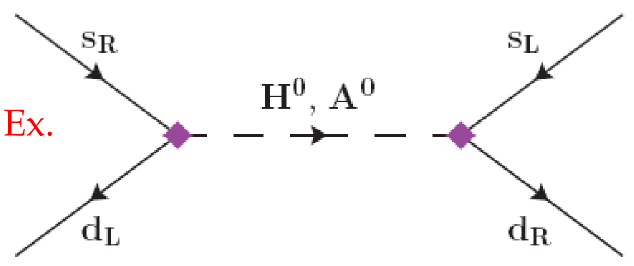

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Minimal flavor violation

$$|a_0| \lesssim 8 \times \frac{M_H}{100\ \mathrm{GeV}} \frac{1}{t_\beta}$$

found imposing $|\varepsilon_K^{\mathrm{NP}}| < 0.05\, |\varepsilon_K^{\mathrm{exp}}|$

The constraint is satisfied very naturally, even for relatively light Higgs bosons!

where

$$a_0 = \frac{\epsilon_2 t_\beta (1 + r_V)^2}{y_t^2\, [1 + \epsilon_0 t_\beta]^2}$$

$$r_V \equiv \frac{(\epsilon_2 + \epsilon_3) t_\beta}{1 + (\epsilon_0 + \epsilon_1 - \epsilon_2 - \epsilon_3) t_\beta}$$

ΔF=2 transitions in MFV 2HDMs

- Tree level Higgs exchange generates NP contributions to the operators (after integrating out the Higgs fields)

$$Q_1^{SLL} = (\bar{s}_R d_L)(\bar{s}_R d_L)$$
$$Q_1^{SRR} = (\bar{s}_L d_R)(\bar{s}_L d_R)$$
$$Q_2^{LR} = (\bar{s}_R d_L)(\bar{s}_L d_R)$$

- However, in the limit of decoupling of the heavy Higgs doublet, the heavy H^0 and A^0 are almost degenerate in mass and the contributions to Q_1^{SLL} and Q_1^{SRR} cancel approximately each other

⇒ Q_2^{LR} is the only relevant operator

(*)

K mixing: $C_2^{LR,K} \propto -\frac{|a_0|^2}{M_H^2} m_s m_d \, [V_{ts}^* V_{td}]^2$

B_d mixing: $C_2^{LR,B_d} \propto -\frac{(a_0^* + a_1^*)(a_0 + a_2)}{M_H^2} m_b m_d \, [V_{tb}^* V_{td}]^2$

B_s mixing: $C_2^{LR,B_s} \propto -\frac{(a_0^* + a_1^*)(a_0 + a_2)}{M_H^2} m_b m_s \, [V_{tb}^* V_{ts}]^2$

relative to the SM:

Good for the experimental constraints!

Tiny K mixing

Small B_d mixing

Sizable B_s mixing

Possibility of solving some ΔF=2 "anomalies" introducing flavor blind phases (decoupling between the breaking of CP and flavor symmetries)

(*) a_1, a_2 linear combinations of the ϵ_i, ϵ_i' parameters

The ΔF=2 "anomalies"

1. Tension between $S_{\psi K_s}$ and ε_K in the UT fit at the level of 2σ

(CP violating observables of the B_d and K system, respectively)

More specifically, determining the value of sin(2β) from the measurement of ε_K and of V_{ub}, one predicts in the SM:

$$S^{SM}_{\psi K_S} > S^{exp}_{\psi K_S}$$

⇨ Needs of a negative NP contribution in $S_{\psi K_s}$

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

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2. Discrepancy between the SM prediction and the experimental value of $S_{\psi\varphi}$ at the level of $\sim 2\sigma$

(CP violating observable of the B_s system)

- HFAG world average:

D0 ⊕ CDF — Barberio et. al., '08

$$S^{\rm exp}_{\psi\phi} = 0.81^{+0.12}_{-0.32}$$

- Very recent data of D0

Abazov et. al., '10

vs.

$$S^{\rm SM}_{\psi\phi} \sim 0.04$$

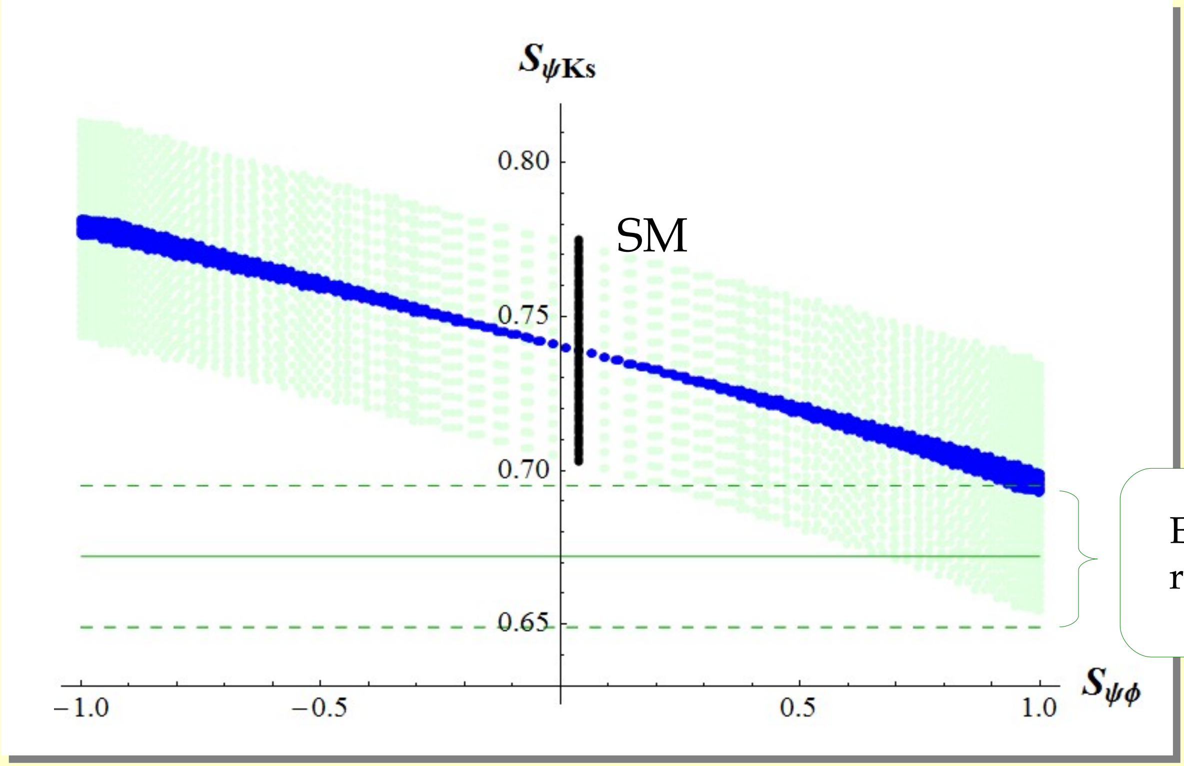
⇨ Needs of a sizable positive NP contribution in $S_{\psi\varphi}$

Are they solved/addressed in a 2HDM with MFV and additional flavor blind phases?

The anomalies in the MFV 2HDM

Buras, Carlucci, S.G., Isidori, '10

The constraint
$(\Delta M_s)^{\rm NP} < 0.1\,(\Delta M_s)^{\rm SM}$
is imposed



Experimental range for $S_{\psi Ks}$

Note:
in the same scenario the EDMs are predicted to be consistent with the data
Buras, Isidori, Paradisi, '10

Reason for the correlation:
because of flavor blind phases, we have

$$\left(M_{12}^{(s,d)}\right)_{\rm 2HDM} \propto \left(V_{tb}V^*_{t(s,d)}\right)^2 F^2_{B_{s,d}} M_{B_{s,d}} \hat{B}_{B_{s,d}} S_{(s,d)} \qquad \text{where} \qquad S_{(s,d)} = S_0(x_t) - T_{(s,d)}$$

real function (SM) → $S_0(x_t)$

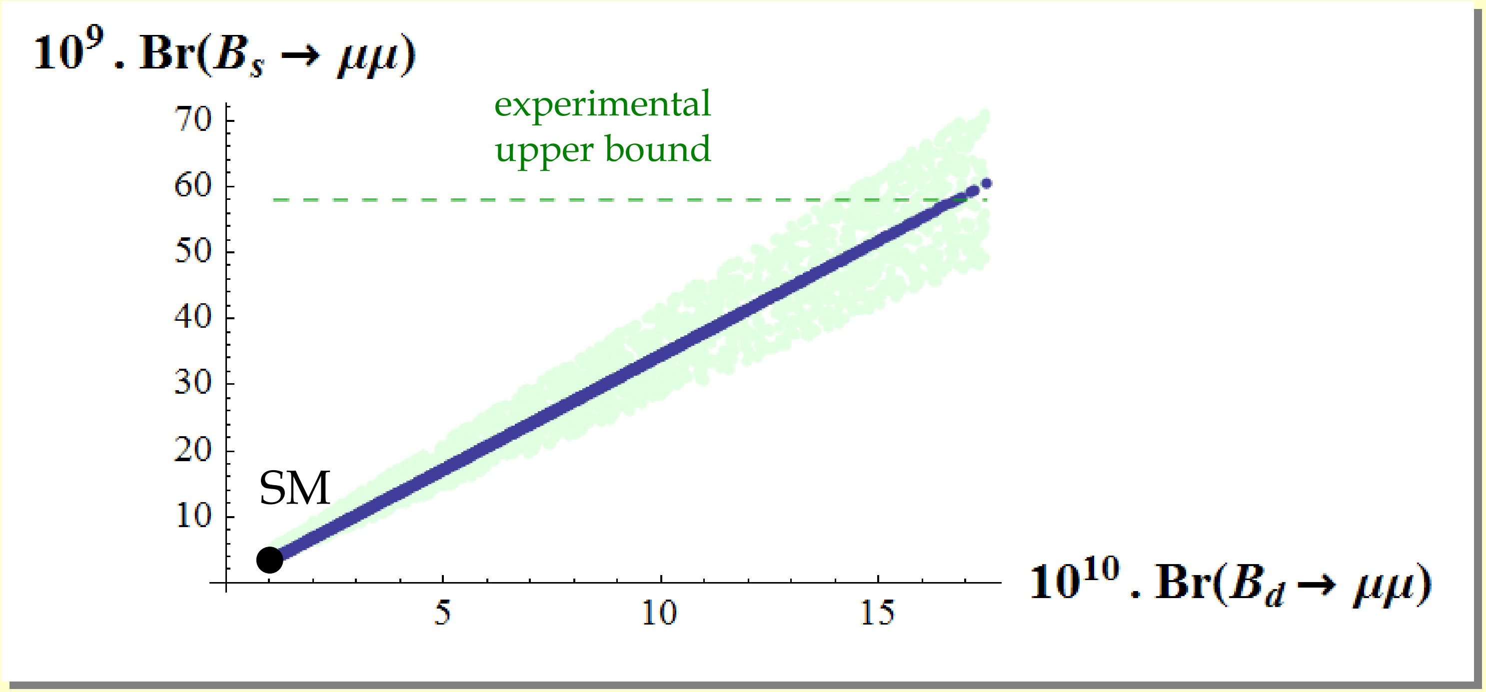
complex function (NP) → $T_{(s,d)}$

with $T_d \approx \dfrac{m_d}{m_s} T_s$ ⇐ They depend on the same NP phase

A unique flavor blind phase is entering in the expression of the two observables

A "smoking gun" of the framework

Buras, Carlucci, S.G., Isidori, '10



Reason for the correlation:

$$\mathrm{Br}(B_q \to \mu^+\mu^-) = \mathrm{Br}(B_q \to \mu^+\mu^-)_{\mathrm{SM}} \times \left(|1 + R_q|^2 + |R_q|^2\right)$$

with $$R_q \propto (a_0^* + a_1^*)\,\frac{M_{B_q}^2 t_\beta^2}{(1 + m_q/m_b) M_H^2}$$

Almost universal function, because of the light quark masses

"Smoking gun" of the MFV hypothesis

Conclusions

In 2HDMs:

- Natural flavor conservation hypothesis is based on the imposition of flavor blind symmetries and does not hold beyond the tree level.

VS.

- Minimal flavor violation hypothesis is based on a symmetry and symmetry-breaking pattern in the flavor sector that is renormalization group invariant.

⇒ MFV hypothesis is superior in protecting 2HDMs from too large FCNCs.

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⇨ MFV hypothesis is superior in protecting 2HDMs from too large FCNCs.

- Higgs-mediated FCNCs with MFV and flavor 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.
  - Possible sizable positive NP contributions in $S_{\psi\phi}$
  - In correspondence, negative NP contributions in $S_{\psi K_S}$

$\mathrm{2HDM}_{\overline{\mathrm{MFV}}}$

- Independently on the flavor blind phases, the decay $B_{s,d} \to \mu^+\mu^-$ provides a decisive test of the flavor breaking structure implied by MFV.

NFC hypothesis and Z_2 symmetry

Discrete subgroup of $U(1)_{PQ}$: $\mathbf{Z_2}$

- Differently than the PQ symmetry, it can be an exact symmetry of the theory

- If the theory has additional degrees of freedom at the TeV scale:

$$\Delta_Y = \frac{c_1}{\Lambda^2}\bar{Q}_L X_{u1}^{(6)} U_R H_2 |H_1|^2 + \frac{c_2}{\Lambda^2}\bar{Q}_L X_{u2}^{(6)} U_R H_2 |H_2|^2 + \frac{c_3}{\Lambda^2}\bar{Q}_L X_{d1}^{(6)} D_R H_1 |H_1|^2 + \frac{c_4}{\Lambda^2}\bar{Q}_L X_{d2}^{(6)} D_R H_1 |H_2|^2$$

- After the Higgs fields get a VEV, flavor changing neutral currents are introduced

- Compared to the PQ symmetry case:

$$\epsilon_d \to c\frac{v^2}{\Lambda^2}$$

Same kind of problem of the PQ symmetry case, if NP at the TeV scale