FCNCs in two Higgs doublet models

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Outlines

1. Introduction: the role of flavor physics in the LHC era

- The flavor problem
- Possible hints of new physics & discovery channels

2. Two Higgs doublet models (2HDMs) & the flavor problem

- The most general case
- Natural flavor conservation
- Minimal flavor violation

3. Flavor phenomenology of the model

- B_s mixing phase
- Unitary triangle analysis
- $B_s \longrightarrow \mu\mu$
- Electric dipole moments (EDMs)

4. Conclusions

Based on:

„Higgs-mediated FCNCs: natural flavor conservation vs. minimal flavor violation "

A.J.Buras, M.V.Carlucci, SG, G.Isidori

[JHEP10(2010)009]

Introduction

Open Issues in Particle Physics

Go beyond the Standard Model (SM)?

Theoretical Issues

- Gauge Hierarchy Problem
- Grand Unification

Requirement of new particles at the electroweak (EW) scale

"Observational" Issues

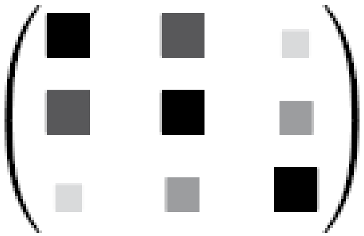
- Neutrino Masses
- Baryon-Antibaryon Asymmetry
- Dark Matter
- Inflation

No need for the new physics (NP) scale to be close to the electroweak scale

The SM flavor puzzle

$$Y_D = \mathrm{diag}(m_d, m_s, m_b)/v$$

$$Y_U = V_{CKM}^{\dagger}(m_u, m_c, m_t)/v$$

$V_{CKM} =$ 

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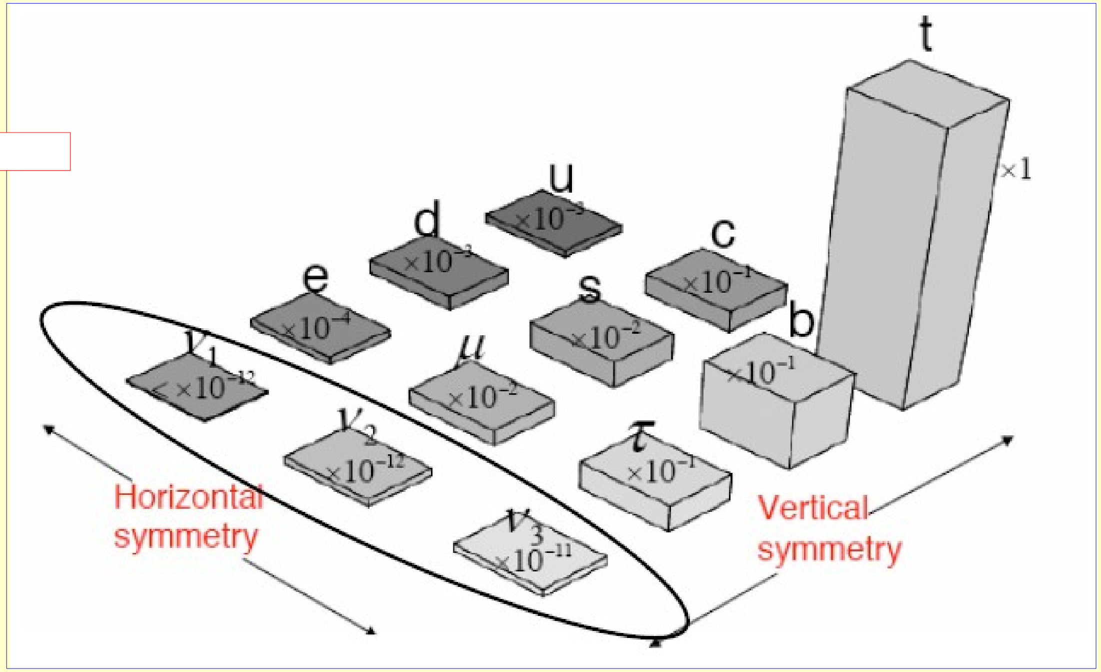

to compare with $g_s \sim 1,\ g \sim 0.6,\ g' \sim 0.3,\ \lambda_{Higgs} \sim 1$

SM Yukawa couplings have to exhibit an **extremely hierarchical structure**, **why?**

Which is the role of flavor physics? (2)

The NP flavor puzzle

Very strong constraints coming from the experiments:

- Transitions of **two units** of flavor (meson mixing observables):

Observable	Experiment	SM prediction	Exp./SM
$\lvert\varepsilon_K\rvert$	$(2.229 \pm 0.010) \times 10^{-3}$	$(1.91 \pm 0.30) \times 10^{-3}$	1.17 ± 0.18
ΔM_d	$(0.507 \pm 0.005)\ \mathrm{ps}^{-1}$	$(0.51 \pm 0.13)\ \mathrm{ps}^{-1}$	0.99 ± 0.25
$S_{\psi K_S}$	0.672 ± 0.023	0.734 ± 0.038	0.92 ± 0.06
ΔM_s	$(17.77 \pm 0.12)\ \mathrm{ps}^{-1}$	$(18.3 \pm 5.1)\ \mathrm{ps}^{-1}$	0.97 ± 0.27
$\Delta M_d/\Delta M_s$	$(2.85 \pm 0.03) \cdot 10^{-2}$	$(2.85 \pm 0.38) \cdot 10^{-2}$	1.00 ± 0.13

Big success of the SM

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- Transitions of **one unit** of flavor:

Observable	Experiment	SM prediction
$\mathrm{Br}(B_s \to \mu^+\mu^-)$	$< 3.3 \cdot 10^{-8}$	$(3.2 \pm 0.2)10^{-9}$
$\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu})$	$(1.73^{+1.15}_{-1.05})10^{-10}$	$(8.5 \pm 0.7)10^{-11}$
$\mathrm{Br}(\mu \to e\gamma)$	$< 1.2 \cdot 10^{-11}$	$\sim 10^{-54}$
$\mathrm{Br}(B \to X_s\gamma)$	$(3.52 \pm 0.25)10^{-4}$	$(3.15 \pm 0.23)10^{-4}$

- Transitions of **zero unit** of flavor:

	Experiment	SM Prediction
d_e	$< 1.6 \cdot 10^{-27} e\,cm$	$10^{-38} e\,cm$
d_n	$< 2.9 \cdot 10^{-26} e\,cm$	$10^{-32} e\,cm$

Which is the role of flavor physics? (2)

The NP flavor puzzle

One of the main problems in building (low-energy) extensions of the SM is how to get rid of too large flavor changing neutral currents...

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The NP flavor puzzle

One of the main problems in building (low-energy) extensions of the SM is how to get rid of too large flavor changing neutral currents...

Assuming there is NP at the TeV scale (Λ_{NP}), what is the impact in flavor physics?

- higher dimensional operators in the low energy effective theory

Ex. $$\frac{a_{ds}}{\Lambda_{\rm NP}{}^2}(\bar{d}_L\gamma_\mu s_L)^2 + \frac{a_{cu}}{\Lambda_{\rm NP}{}^2}(\bar{c}_L\gamma_\mu u_L)^2 + \frac{a_{db}}{\Lambda_{\rm NP}{}^2}(\bar{d}_L\gamma_\mu b_L)^2 + \frac{a_{sb}}{\Lambda_{\rm NP}{}^2}(\bar{s}_L\gamma_\mu b_L)^2$$ (meson mixing)

- Assuming coefficients order one:

$$\Lambda_{\rm NP} \geq \frac{10^{-4}}{\sqrt{\frac{\Delta m}{m}}}\,{\rm TeV}$$

Mixing	$\Lambda_{\rm NP}^{\rm CPC} \geq$	$\Lambda_{\rm NP}^{\rm CPV} \geq$
$K-\bar{K}$	1000 TeV	20000 TeV
$D-\bar{D}$	1000 TeV	3000 TeV
$B_d-\bar{B}_d$	400 TeV	800 TeV
$B_s-\bar{B}_s$	70 TeV	70 TeV

- Fixing the cutoff to 1 TeV:

$$a_{\rm ij} \lesssim 10^8 \frac{\Delta {\rm m_{ij}}}{\rm m}$$

Mixing	$\lvert a_{\rm ij}\rvert \leq$	${\rm Im}(a_{\rm ij}) \leq$
$K-\bar{K}$	8×10^{-7}	6×10^{-9}
$D-\bar{D}$	5×10^{-7}	1×10^{-7}
$B_d-\bar{B}_d$	5×10^{-6}	1×10^{-6}
$B_s-\bar{B}_s$	2×10^{-4}	2×10^{-4}

(Nir et al.)

High energy scale much bigger than the EW scale → **Little Hierarchy Problem** → A NP with **highly non trivial structure** is required

Flavor: something more than constraints?

- Processes strongly suppressed in the SM and not measured yet (or only poorly measured):

discovery channels

	Experimental value	SM Prediction	Future experiment
$d_{\rm Tl}$	$< 9.4 \cdot 10^{-25} e\,cm$	$10^{-35} e\,cm$	
d_n	$< 2.9 \cdot 10^{-26} e\,cm$	$10^{-32} e\,cm$	CryoEDM
$d_{\rm Hg}$	$< 3.1 \cdot 10^{-29} e\,cm$	$10^{-32} e\,cm$	
$B_s \to \mu^+\mu^-$	$< 5.8 \cdot 10^{-8}$	$(3.6 \pm 0.37)10^{-9}$	LHCb
$B_d \to \mu^+\mu^-$	$< 1.8 \cdot 10^{-8}$	$(1.08 \pm 0.11)10^{-10}$	LHCb
$K^+ \to \pi^+\nu\nu$	$(17.3 \pm 11)10^{-11}$	$(8.4 \pm 0.8)10^{-11}$	NA62, K0TO
$K_L \to \pi^0\nu\nu$	$< 2.1 \cdot 10^{-7}$	$\sim 2.9 \cdot 10^{-11}$	NA62, K0TO
$S_{\psi\phi}$	$0.81^{+0.12}_{-0.32}$	~ 0.036	LHCb
$A_{\rm CP}(b \to s\gamma)$	$(1.2 \pm 2.8)\%$	$(-0.44^{+0.14}_{-0.24})\%$	SuperB

(In red the observables discussed in the talk)

- Additional possible hints of new physics:

	Experimental value	SM Prediction
$B^+ \to \tau^+\nu$	$(1.73 \pm 0.35)10^{-4}$	$(0.80 \pm 0.12)10^{-4}$

&

tension in the determination of the unitary triangle (UT)

The CP asymmetry of the B_s mixing system (1)

- Schrödinger equation describing the B_s mixing

$$i\partial_t \begin{pmatrix} B_s(t) \\ \bar{B}_s(t) \end{pmatrix} = \left(M^s + \frac{i}{2}\Gamma^s \right) \begin{pmatrix} B_s(t) \\ \bar{B}_s(t) \end{pmatrix}$$

- Three physical parameters: $\left|M_{12}^s\right|, \; \left|\Gamma_{12}^s\right|, \; \phi_s = -\arg\left(\frac{\mathrm{M}_{12}^{\mathrm{s}}}{\Gamma_{12}^{\mathrm{s}}}\right)$

- Physical observables:
  - Mass and width difference: $\Delta M_s = 2\left|M_{12}^s\right|, \quad \Delta\Gamma_s = 2\left|\Gamma_{12}^s\right| \cos\phi_s$
  - CP asymmetry

$$a_{\mathrm{SL}}^s \equiv \frac{\Gamma\left(\bar{B}_s \to \ell^+ X\right) - \Gamma\left(B_s \to \ell^- X\right)}{\Gamma\left(\bar{B}_s \to \ell^+ X\right) - \Gamma\left(B_s \to \ell^- X\right)} = \left|\frac{\Gamma_{12}^s}{M_{12}^s}\right| \sin\phi_s = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s$$

(Semileptonic asymmetry)

or

$$S_{\psi\phi} = \frac{1}{\sin(\Delta M_s(t))} \cdot \frac{\Gamma\left(\bar{B}_s(t) \to \psi\phi\right) - \Gamma\left(B_s(t) \to \psi\phi\right)}{\Gamma\left(\bar{B}_s(t) \to \psi\phi\right) + \Gamma\left(B_s(t) \to \psi\phi\right)} = -\sin\phi_s$$

- Model-independent relation

(Ligeti, Papucci, Perez '06; Grossman, Nir, Perez '09)

$$a_{\mathrm{SL}}^s = -\left|\frac{\Gamma_{12}^s}{M_{12}^s}\right|^{\mathrm{SM}} S_{\psi\phi} = -\frac{\Delta\Gamma_s}{\Delta M_s} \frac{S_{\psi\phi}}{\sqrt{1 - S_{\psi\phi}{}^2}}$$

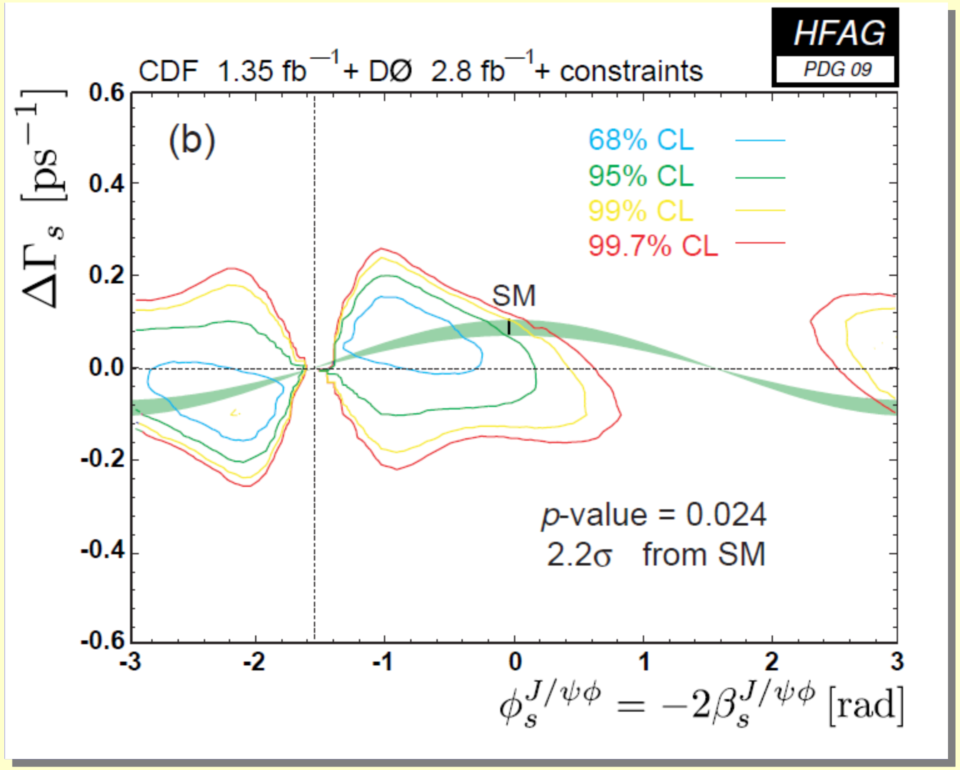
The CP asymmetry of the B_s mixing system (2)

- Small SM prediction for $S_{\psi\varphi}$

$$S_{\psi\phi}^{\rm SM} = \sin(2|\beta_s|) \simeq 0.038, \quad V_{ts} = -|V_{ts}|e^{-i\beta_s}$$

- The measurement of $S_{\psi\varphi}$ and a^s_{SL} is experimentally quite challenging!
  - 2007/8: status of the measurements:

    Data from CDF and D0 seem to hint towards a large CP asymmetry $S_{\psi\varphi}$ (2-3 σ deviation from the SM prediction)



(PDG 2009)

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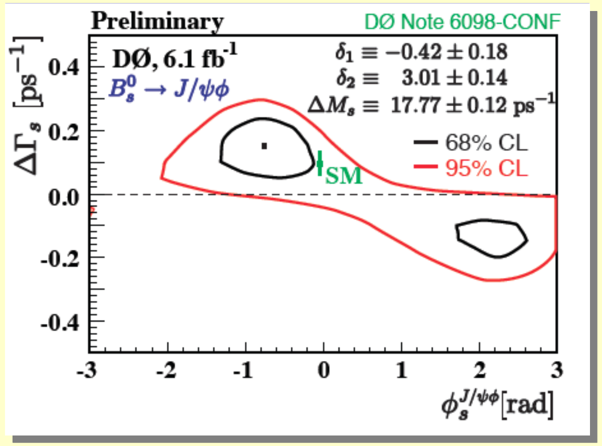
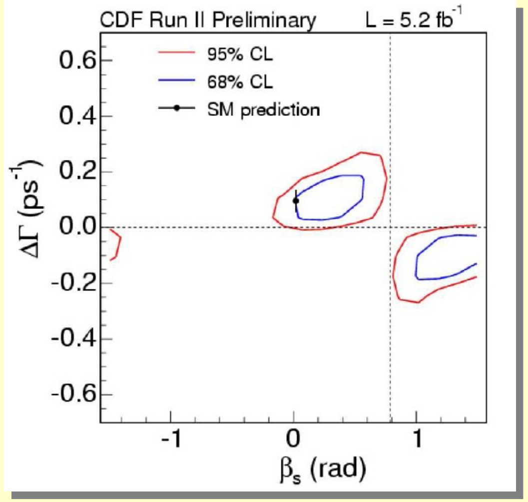


D0



CDF

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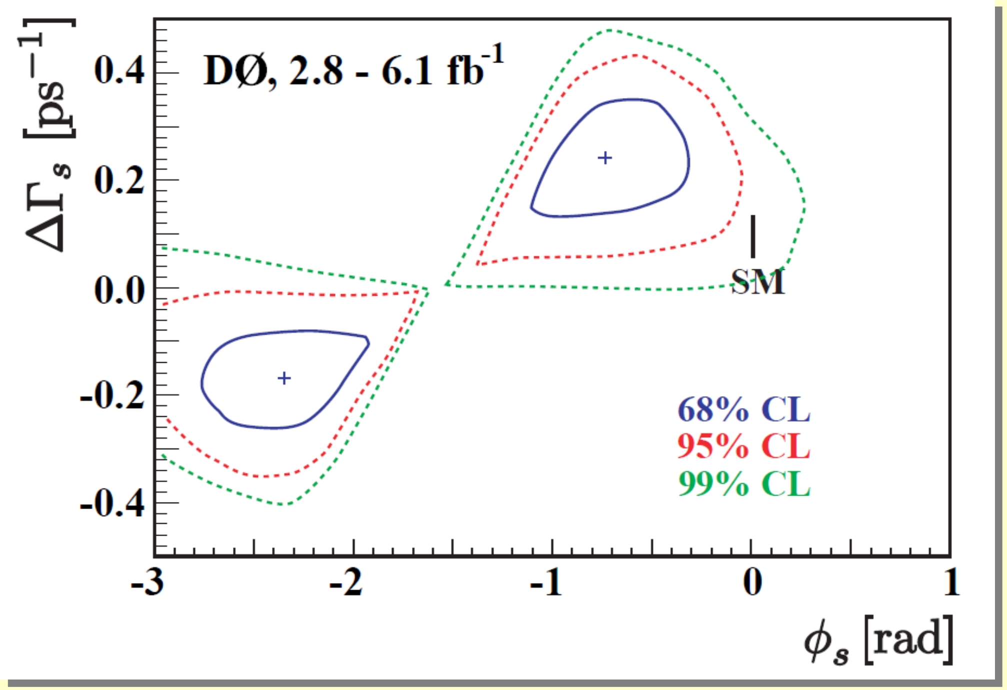

(arXiv:1005.2757 [hep-ex])

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  - global fits prefer a sizable phase in B_s mixing

    (Ligeti, Papucci, Perez, Zupan '10
    Lenz, Nierste, CKMfitter '10, ...)

$$S_{\psi\phi} \simeq 0.5$$

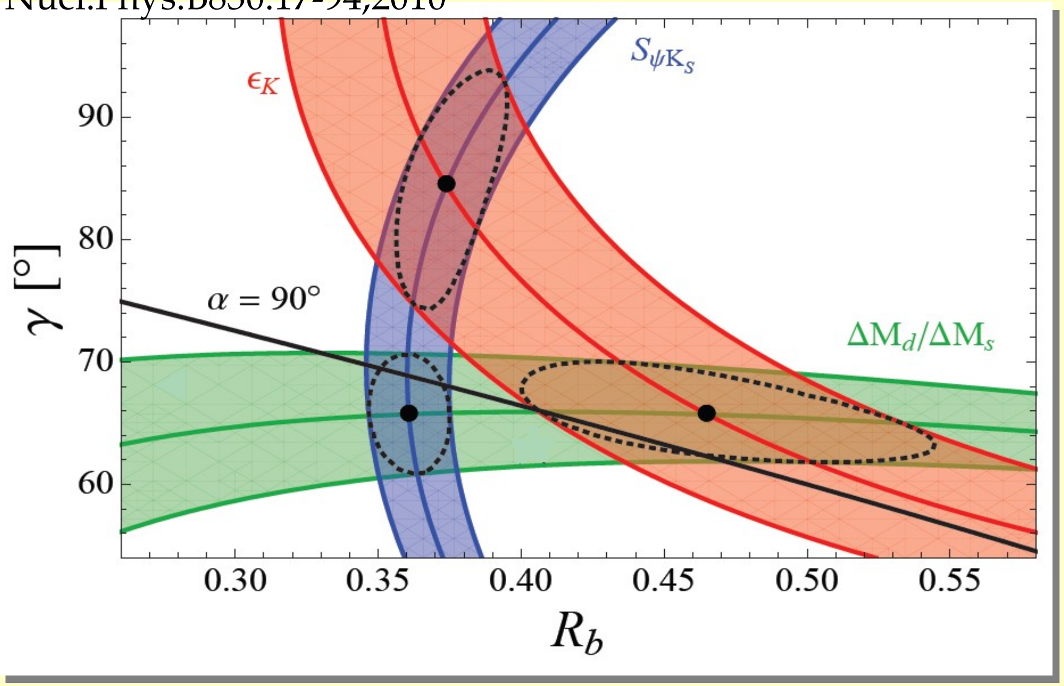
The UT tension

- The SM CKM picture is in a overall good agreement with the data

BUT

See also
- Buras, Gudagnoli
- Lunghi, Soni

Altmannshofer, Buras, SG, Paradisi, Straub, Nucl.Phys.B830:17-94,2010



Is that just a **statistical fluctuation** (since very many observables are involved in the unitary triangle fit)?

or

Is it a **hint of new physics**?

γ is the phase of V_{ub};

$$R_b \equiv \left| \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right| = \sqrt{\bar{\rho}^2 + \bar{\eta}^2}$$

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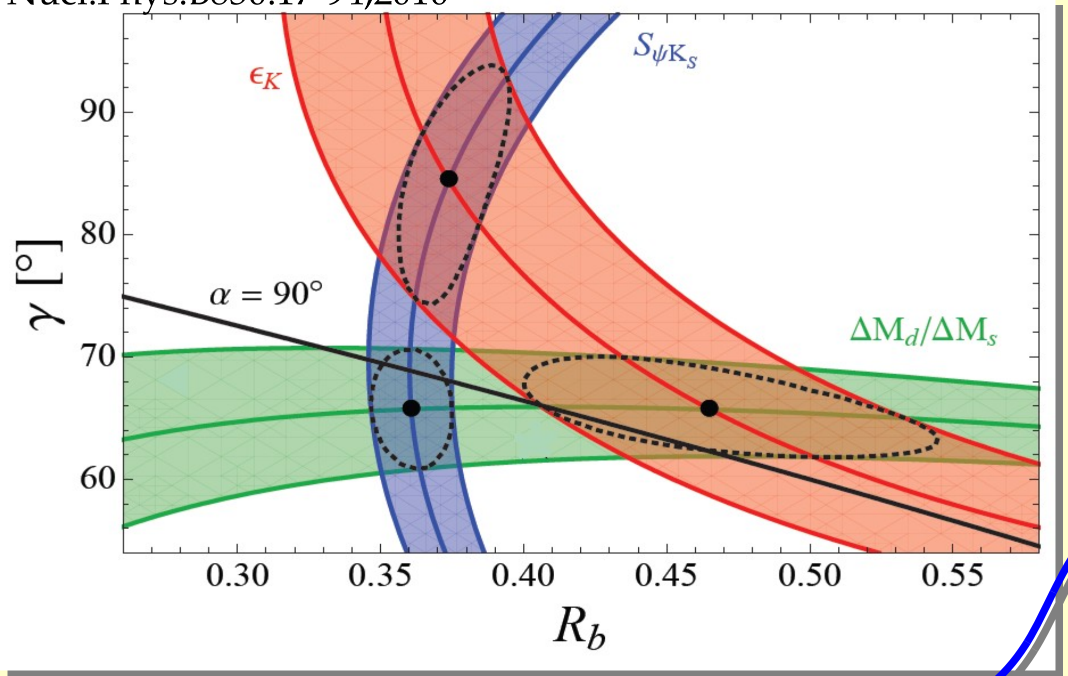

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If one takes it seriously...

assuming NP in only one sector:

1. **Solution 1:** a positive NP contribution in ε_K
2. **Solution 2:** a negative NP contribution in $S_{\psi Ks}$
3. **Solution 3:** a negative NP contribution in $\Delta M_d/\Delta M_s$

Two Higgs doublet models
and
the NP flavor problem

Brief summary:

Natural Flavor Conservation (NFC)

vs.

Minimal Flavor Violation (MFV)

Motivations

2HDMs:

- Most probably the Standard Model 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 the New Physics 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).

The model

- Field content
  - H_1, H_2 two Higgs doublets with hypercharges Y_1= 1/2 and Y_2= -1/2
  - SM gauge and matter fields

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  - SM gauge and matter fields

- Higgs autointeraction (Most general renormalizable Higgs potential)

$$V(H_1,H_2) = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + (bH_1H_2 + \text{h.c}) + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3|H_1|^2|H_2|^2$$
$$+ \lambda_4|H_1H_2|^2 + \left[\frac{\lambda_5}{2}(H_1H_2)^2 + \lambda_6|H_1|^2H_1H_2 + \lambda_7|H_2|^2H_1H_2 + \text{h.c}\right]$$

Note: $\lambda_{5,6,7}$ present only at the one loop level in the MSSM

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Note: $\lambda_{5,6,7}$ present only at the one loop level in the MSSM

- Yukawa couplings (X_i are generic 3×3 matrices in flavor space)

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

Note: in the MSSM at the tree level, because of the analiticity of the superpotential

$$X_{d2} = X_{u1} = 0$$

Too large NP contributions to flavor/CP violating observables

since

In the „Higgs basis“:

$$\begin{pmatrix} \Phi_v \\ \Phi_H \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2^c \end{pmatrix}$$

$$\langle \Phi_v^\dagger \Phi_v \rangle = v^2/2, \quad \langle \Phi_H^\dagger \Phi_H \rangle = 0$$

$$\mathcal{H}_Y^{\rm gen} = \bar{Q}_L \left[\frac{\sqrt{2}}{v} M_d \Phi_v + Z_d \Phi_H \right] D_R + \text{h.c.}$$

with

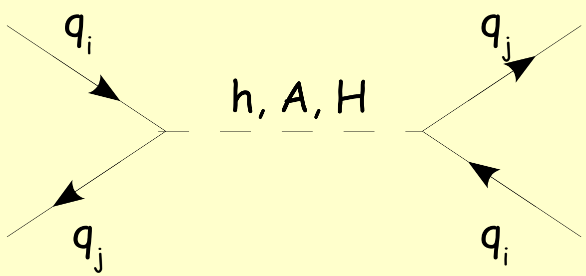
$$Z_d = \cos\beta X_{d2} - \sin\beta X_{d1}$$

$$M_d = \frac{v}{\sqrt{2}} (\cos\beta X_{d1} + \sin\beta X_{d2})$$

Not proportional!

(analogous for the up sector)

Flavor changing neutral currents at the tree level, mediated by the Higgs bosons



No loop suppression of the four fermion operators!

How to protect the model from too large flavor changing neutral currents?

Protection mechanisms: $U(1)_{PQ}$ symmetry

Largest group which commutes with the SM gauge group:

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

- Enforcing the $U(1)_{PQ}$ symmetry with H_1 and D_R with opposite charges: $X_{d2} = X_{u1} = 0$

Realization of the
Natural Flavor Conservation (NFC)
hypothesis

(as in the MSSM at the tree level)

Natural conservation laws for neutral currents*

Sheldon L. Glashow and Steven Weinberg

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 20 August 1976)

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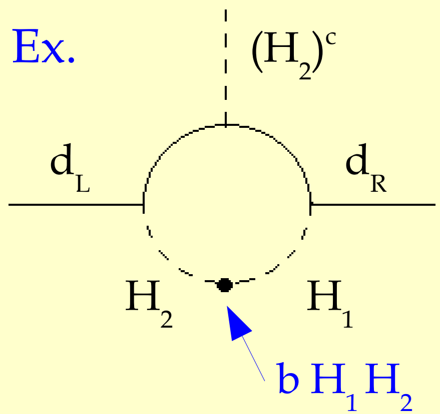
- Still if H_1 acquires a VEV, then the $U(1)_{PQ}$ symmetry must be broken (otherwise appearance of a Goldstone boson)

$$\begin{cases} X_{d2} = \epsilon_d \Delta_d \,, \\ X_{u1} = \epsilon_u \Delta_u \,, \end{cases} \quad \begin{cases} X_{d1} = Y_d \,, \\ X_{u2} = Y_u \end{cases}$$

with $\epsilon_{d,u}$ one loop suppressed

$\Delta_{d,u} = \mathcal{O}(1)$

Ex.



Is the $U(1)_{PQ}$ symmetry enough?

- In the mass eigenstate basis for fermions

$$\mathcal{H}_\epsilon^{\rm FCNC} = \frac{\epsilon_d}{c_\beta}(\Delta_d)_{ij}\ \bar{d}_L^i d_R^j\ \frac{S_2 + iS_3}{\sqrt{2}}\ +\ \text{h.c.} \qquad \left(\text{where}\quad \Phi_H = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(S_2 + iS_3)\end{pmatrix}\right)$$

- Example: the ε_K constraint

Integrating out the Higgs bosons, one obtains the effective Hamiltonian

$$\mathcal{H}_\epsilon^{|\Delta S|=2} = -\frac{\epsilon_d^2}{c_\beta^2 M_H^2}(\Delta_d)_{21}(\Delta_d)^*_{12}(\bar{s}_L d_R)(\bar{s}_R d_L)\ +\ \text{h.c.}$$

(In the hypothesis of decoupling $M_A \gg M_Z$)

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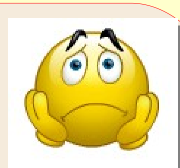
Imposing then $|\varepsilon_K^{\rm NP}| < 0.2\, |\varepsilon_K^{\rm exp}|$



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

A very high level of fine tuning is required!

A generic one loop suppression is not enough to guarantee agreement with data

$U(1)_{PQ}$ & the 5D warped structure

(wide recent literature)

- In models with 5D warped space-time geometry, Yukawa couplings have a particular structure

$$|(\Delta_d)^*_{ij}(\Delta_d)_{ji}|_{\rm RS-GIM} = \mathcal{O}(1) \times [(Y_d)_{ii}(Y_d)_{jj}] = \mathcal{O}(1) \times \frac{2m_{d_i}m_{d_j}}{c_\beta^2 v^2}$$

- Inserted in the constraint coming from ε_K:

$$|\epsilon_d|_{\rm RS-GIM} \lesssim 4 \times 10^{-3} \times \frac{c_\beta^2 M_H}{100\ \rm GeV}$$

Since ϵ_d is one loop suppressed ($\sim 10^{-2}$), $\tan(\beta)=\mathcal{O}(1)$ and a not too light Higgs boson could be **sufficient** to avoid the ε_K bound

The Randall-Sundrum (RS) model with a broken $U(1)_{PQ}$ symmetry does not generate too large contributions to FCNCs mediated by the Higgs bosons

Protection mechanisms: a $U(1)_{PQ}$ symmetry subgroup

Largest group which commutes with the SM gauge group:

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

$$Z_2 \subset \mathrm{U}(1)_{\mathrm{PQ}}$$

(H_1 and D_R with opposite charges)

- In contrast to the PQ symmetry, it can be an exact symmetry of the theory

$$X_{d2} = X_{u1} = 0$$

BUT

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

$$\Delta\mathcal{L}_Y = \frac{c_1}{\Lambda^2}\bar{Q}_L X^{(6)}_{u1} U_R H_2 |H_1|^2 + \frac{c_2}{\Lambda^2}\bar{Q}_L X^{(6)}_{u2} U_R H_2 |H_2|^2 + \frac{c_3}{\Lambda^2}\bar{Q}_L X^{(6)}_{d1} D_R H_1 |H_1|^2 + \frac{c_4}{\Lambda^2}\bar{Q}_L X^{(6)}_{d2} D_R H_1 |H_2|^2$$

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

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

- Compared to the PQ symmetry case:

$$\epsilon_d \to \sim c_4 \frac{v^2}{\Lambda^2}\sin(2\beta)$$

$$\epsilon_u \to \sim c_1 \frac{v^2}{\Lambda^2}\sin(2\beta)$$

If the additional degrees of freedom are at the TeV scale, difficult to satisfy the constraints from flavor physics ($\epsilon_d \lesssim 10^{-7}$).

Natural assumption because of the gauge hierarchy problem

Conclusion for the $U(1)_{PQ}$ symmetry

The Natural Flavor Conservation hypothesis
enforced by the $U(1)_{PQ}$ symmetry (or by a subgroup)
is **not sufficient** to protect the model from too large FCNCs,
since it is not stable under radiative corrections

we necessarily need
to „protect“ the breaking of the flavour symmetry!

Protection mechanisms: $SU(3)^3_q$ symmetry (1)

Largest group which commutes with the SM gauge group:

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

- Enforcing the $SU(3)_q^3$ symmetry: $X_{d1} = X_{d2} = X_{u1} = X_{u2} = 0$

No FCNCs but also **no fermion masses!**

- Non generic breaking of the $SU(3)_q^3$ symmetry:

Realization of the Minimal Flavor Violation (MFV) principle

Minimal Flavour Violation:
an effective field theory approach

G. D'Ambrosio, G.F. Giudice, G. Isidori, A. Strumia

(Received 2 July 2002)

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- As in the SM the symmetry is broken only by the two Yukawas Y_u and Y_d
- If Y_u and Y_d are two **spurions** with $Y_D \sim \bar{3}_Q \times 3_D$, $Y_U \sim \bar{3}_Q \times 3_U$ then the symmetry is restored

Protection mechanisms: $SU(3)^3_q$ symmetry (2)

- Most general form of the Yukawa couplings compatible with the MFV hypothesis

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

higher orders in the small Yukawa couplings

where $\varepsilon_i^{(\prime)}$ are in all generality coefficients of **O(1)**

(They are computable if the UV completion of the model is known)

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higher orders in the small Yukawa couplings

where $\varepsilon_i^{(\prime)}$ are in all generality coefficients of $\mathcal{O}(1)$

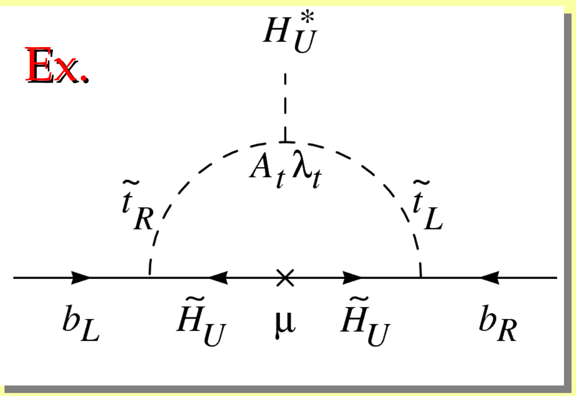
(They are computable if the UV completion of the model is known)

Instead in the MSSM with MFV...

$$\epsilon_0 \sim \epsilon'_0 \propto \frac{2\alpha_s \mu}{3\pi m_{\tilde{g}}}$$
$$\epsilon_1 \sim \epsilon_2 \propto \frac{A\lambda_t^2}{16\pi^2 \mu}$$
$$\epsilon'_1 \propto \frac{A\lambda_b^2}{16\pi^2 \mu}$$

loop induced

Ex.



Is the $SU(3)_q^3$ with MFV ansatz enough?

- In the mass eigenstate basis for fermions

$$\mathcal{H}^{\rm FCNC} = \frac{1}{s_\beta}\,\bar d_L^i\left[\left(a_0 V^\dagger\tilde\lambda_u^2 V + a_1 V^\dagger\tilde\lambda_u^2 V\Delta + a_2\Delta V^\dagger\tilde\lambda_u^2 V\right)\tilde\lambda_d\right]_{ij} d_R^j\,\frac{S_2+iS_3}{\sqrt2} + {\rm h.c.}$$

$$\left(\text{where } \Phi_H = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt2}(S_2+iS_3)\end{pmatrix},\ \tilde\lambda_d \sim [1+(\epsilon_0+\epsilon_1\Delta)t_\beta]\frac{\sqrt2\, m_d}{v\, c_\beta},\ \tilde\lambda_u \sim \frac{\sqrt2\, m_u}{v\, s_\beta},\ \Delta\sim {\rm diag}(0,0,1)\right)$$

- Example: the ε_K constraint

(In the hypothesis of decoupling $M_A \gg M_Z$)

Imposing $|\varepsilon_K^{\rm NP}| < 0.05\,|\varepsilon_K^{\rm exp}|$

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

with

$$a_0 = \frac{\epsilon_2 t_\beta (1+r_V)^2}{y_t^2\,[1+\epsilon_0 t_\beta]^2},\quad r_V \equiv \frac{(\epsilon_2+\epsilon_3)t_\beta}{1+(\epsilon_0+\epsilon_1-\epsilon_2-\epsilon_3)t_\beta}$$

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

2HDM with MFV seems promising: no additional suppression needed to cure the flavor problem

A closer look to ΔF=2 observables

- Integrating out the Higgs bosons, flavor off diagonal four fermion operators are generated:

$$Q_1^{VLL} = (\bar{q}_L^i \gamma_\mu q_L^j)(\bar{q}_L^i \gamma^\mu q_L^j) \,,$$

← already present in the SM

$$Q_1^{SLL} = (\bar{q}_R^i q_L^j)(\bar{q}_R^i q_L^j) \,,$$
$$Q_2^{SLL} = (\bar{q}_R^i \sigma_{\mu\nu} q_L^j)(\bar{q}_R^i \sigma^{\mu\nu} q_L^j) \,,$$
$$Q_1^{LR} = (\bar{q}_L^i \gamma_\mu q_L^j)(\bar{q}_R^i \gamma^\mu q_R^j) \,,$$
$$Q_2^{LR} = (\bar{q}_R^i q_L^j)(\bar{q}_L^i q_R^j)$$

additional operators,
(enhanced by renormalization group running)

- Simplifying assumption: decoupling limit of the heavy Higgs bosons:
(small $\lambda_{5,6,7}$: it resembles the MSSM)

$$m_W^2,\ \lambda_{5,6,7} v^2 \ll m_A^2$$
$$\Downarrow$$
$$m_A \sim m_H$$

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$$\Downarrow$$
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- At the first order in v^2/m_A^2, only Q_2^{LR} is generated

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

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

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

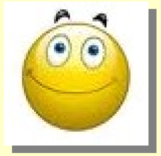
relative to the SM:

Good for the experimental constraints!

Tiny K mixing

Small B_d mixing

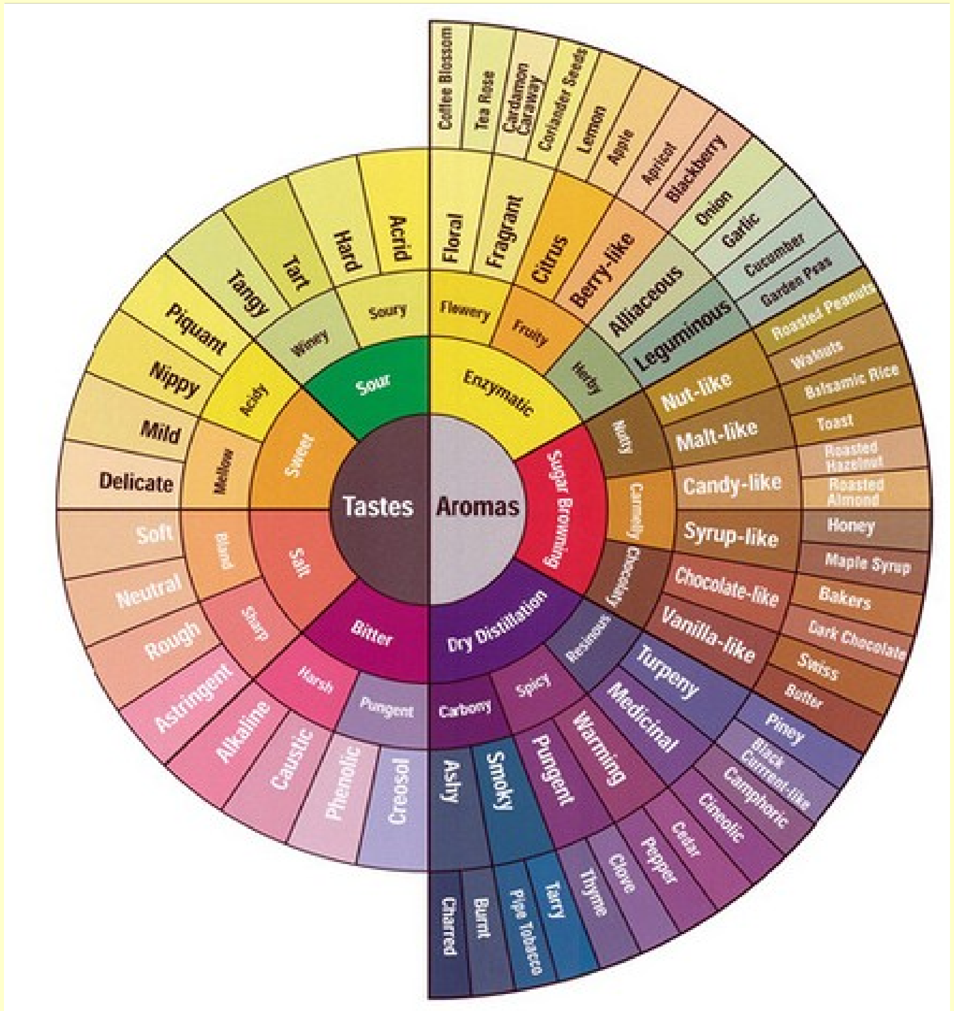
Sizable B_s mixing



Conclusion for the $SU(3)_q^3$ symmetry+MFV

MFV ansatz is enough to protect 2HDMs from too large FCNCs since

- It mimics the SM flavor structure
- It is stable under radiative corrections ⇐



Flavor Phenomenology

Brief summary:

NP in
- $S_{\psi\varphi}$
- UT tension
- $B_s \longrightarrow \mu\mu$

is very welcome :)

Paying attention to:
- EDMs

New sources of CP violation

1. In the Yukawa sector:

$$X_{d2} = \epsilon_0 Y_d + \epsilon_1 Y_d^\dagger Y_d Y_d + \epsilon_2 Y_u^\dagger Y_u Y_d$$

$$X_{u1} = \epsilon'_0 Y_u + \epsilon'_1 Y_u^\dagger Y_u Y_u + \epsilon'_2 Y_d^\dagger Y_d Y_u$$

$$\epsilon_i^{(\prime)} \in \mathbb{C} \text{ and } \mathcal{O}(1)$$

(contrary to the original approach of D´Ambrosio et. al.)

In the rest of the talk, **we decouple the breaking of the flavor group from the breaking of the CP symmetry**

Kagan, Perez, Volansky, Zupan, Phys. Rev. D 80 (2009) 076002

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Kagan, Perez, Volansky, Zupan, Phys. Rev. D 80 (2009) 076002

2. In the Higgs sector:

$$V(H_1, H_2) = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + (bH_1H_2 + \text{h.c}) + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3|H_1|^2|H_2|^2$$
$$+ \lambda_4|H_1H_2|^2 + \left[\frac{\lambda_5}{2}(H_1H_2)^2 + \lambda_6|H_1|^2H_1H_2 + \lambda_7|H_2|^2H_1H_2 + \text{h.c}\right]$$

$$\lambda_{5,6,7} \in \mathbb{C} \text{ and } \mathcal{O}(1)$$

(contrary to the MSSM in which $\lambda_{5,6,7}$ are one loop suppressed)

without loosing generality as far as the CP properties are concerned,

$$\lambda_6 = \lambda_7 = 0$$

The $B_{s,d}$ mixing systems (1)

- Considering still the decoupling limit, but at the <u>second order</u> in v^2/m_A^2, also the operator Q_1^{SLL} is generated

$$C_1^{SLL} \simeq -\frac{[V_{tb}V_{tq}^*]^2}{4}(a_0 + a_1)^2 \frac{4m_t^2 m_b^2}{v^4 s_\beta^2 c_\beta^2} \mathcal{F}_- \,,$$

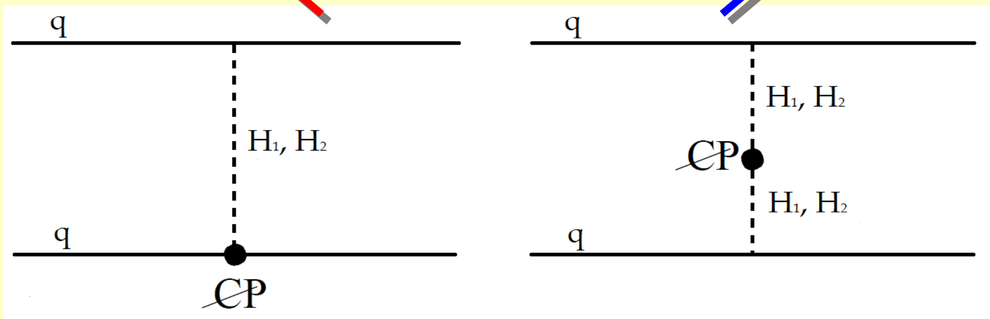
$$C_2^{LR} \simeq -\frac{[V_{tb}V_{tq}^*]^2}{2}(a_0 + a_1)(a_0^* + a_2^*) \frac{4m_t^2 m_b m_q}{v^4 s_\beta^2 c_\beta^2} \mathcal{F}_+$$

with

$$\mathcal{F}^+ \simeq \frac{2}{M_A^2}\,, \quad \mathcal{F}^- \simeq -\lambda_5 \frac{v^2}{M_A^4}$$

CP violation coming from the Yukawa couplings

CP violation coming from the Higgs potential

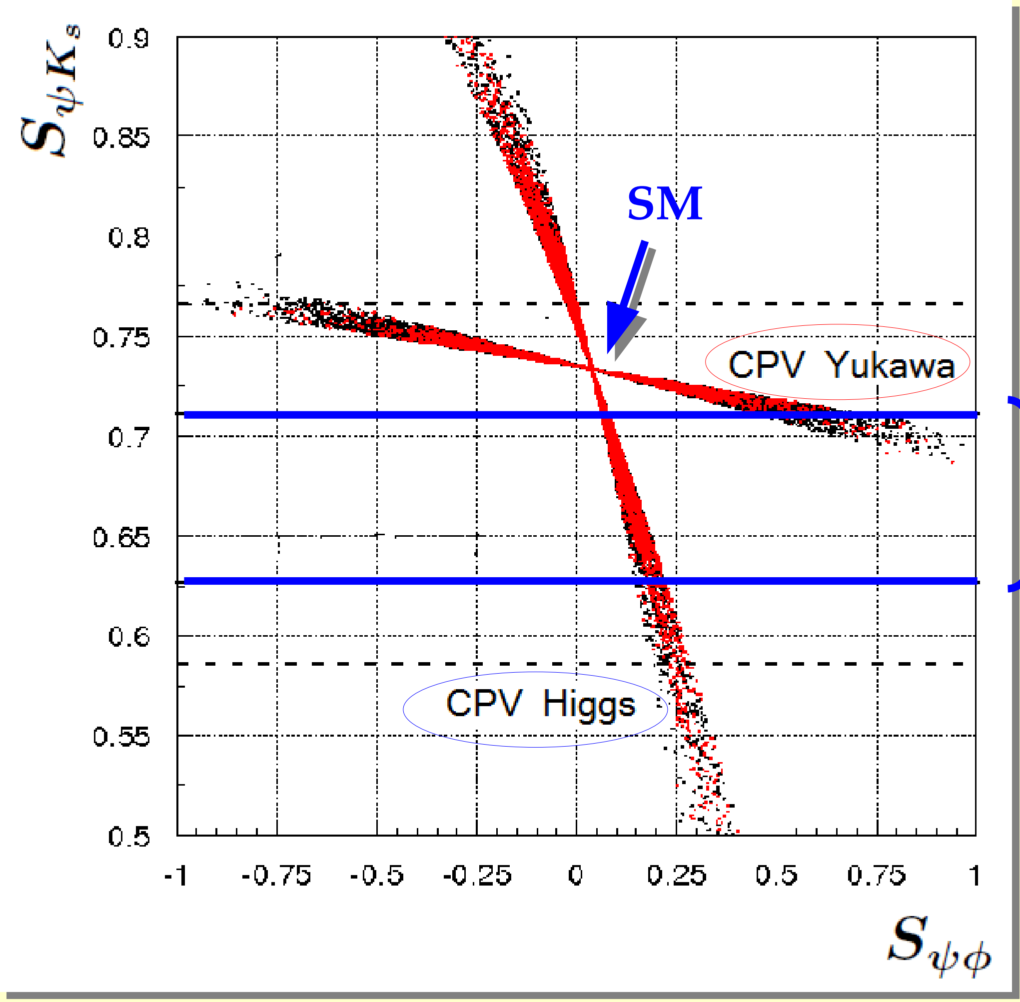


- **Observations:**

✓ The effect of Q_1^{SLL} in B_s and B_d mixings is the same, implying a **<u>common NP phase</u>** in the two sectors.

✓ C_2^{LR} contributes to CP violation only if $a_1 \neq a_2$, which requires **higher powers of the Yukawa couplings** in the MFV expansion. ⇐ It may be difficult in a concrete model

The $B_{s,d}$ mixing systems (2)



1σ experimental bound for $S_{\psi Ks}$

Buras, Isidori, Paradisi, Phys.Lett.B694:402-409,2011

- CPV Yukawa = NP CP violation coming only from yukawa couplings
- CPV Higgs = NP CP violation coming only from Higgs potential

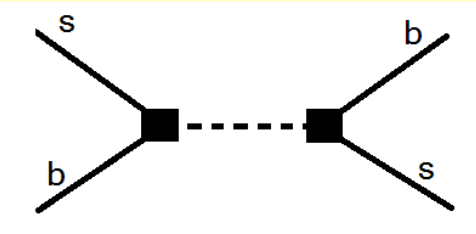
Observations:

- Huge NP effects in $S_{\psi\varphi}$ due to the CP violation in the Higgs potential are not possible ($S_{\psi Ks}$ constraint)
- In the case of CP violation only in the Yukawas, totally natural parameters are good to get a sizable value for $S_{\psi\varphi}$

Ex.

$$\tan\beta = 10, \quad m_A = 500\,\mathrm{GeV}, \quad \mathrm{Im}\left((a_0 + a_1)(a_0^* + a_2^*)\right) \sim 1 \Rightarrow S_{\psi\phi} \sim 0.2$$

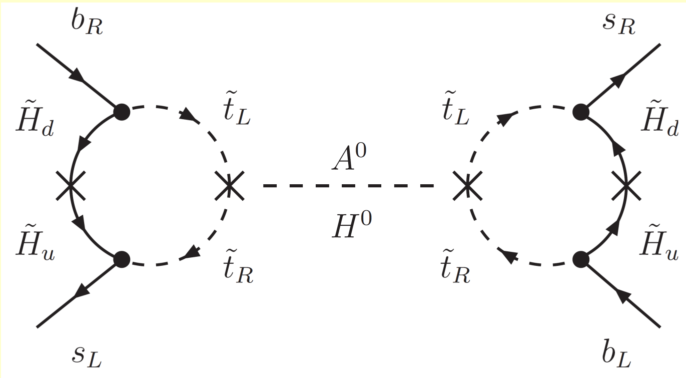
A particular 2HDM: the MSSM



Contributions of:	Operators involved:
✓ Gluino	✓ Q_1^{VLL}
✓ Chargino	✓ Q_1^{VLL}, Q_1^{SRR}, Q_2^{SRR}
✓ Double Higgs penguins	✓ Q_2^{LR}

In particular:

Double Higgs penguin contribution



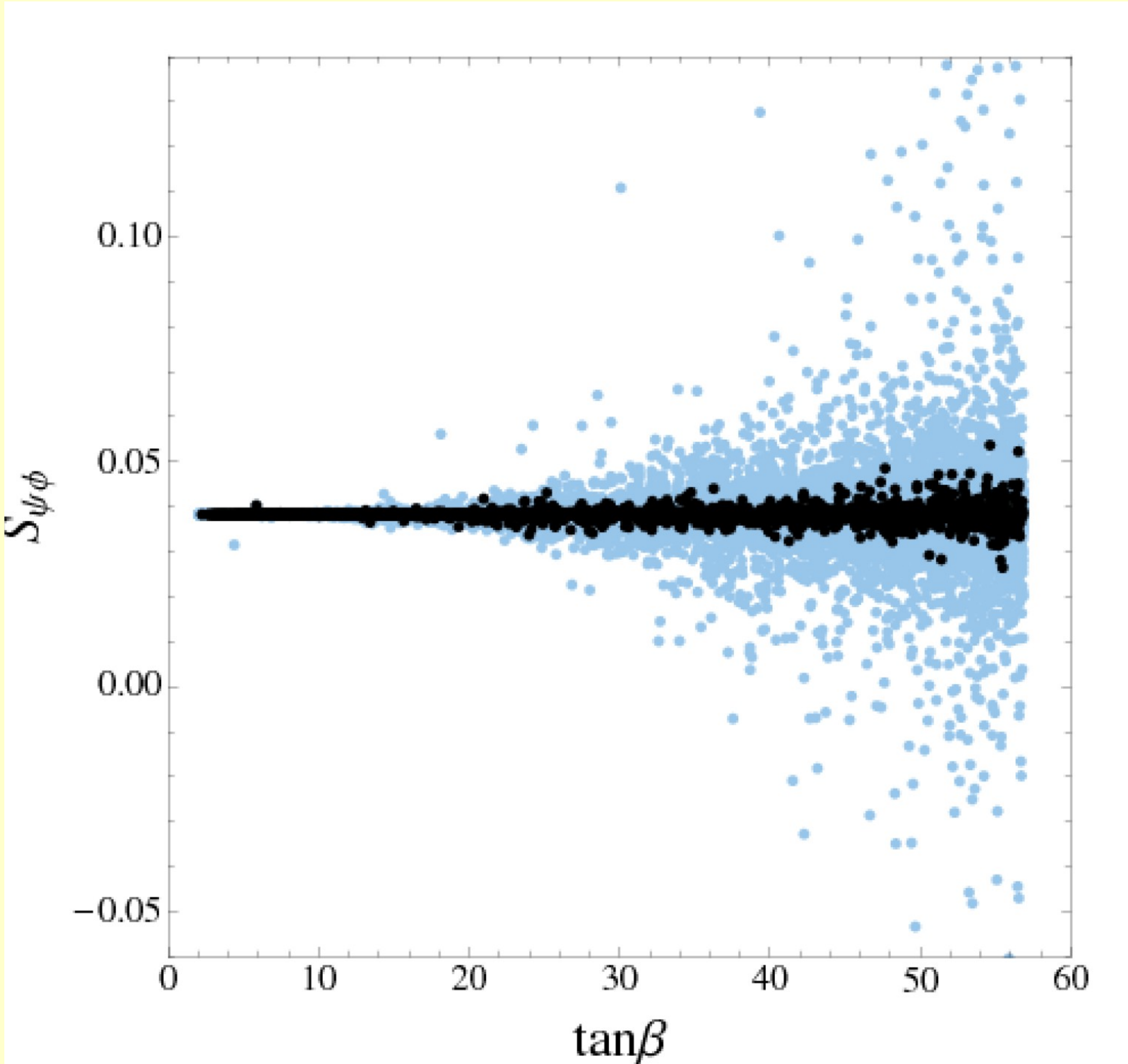
t_β enhanced

$$C_2^{LR} \propto (V_{tb}V_{ts}^*)^2 \frac{g_2^6}{(4\pi)^4} \frac{m_b m_s}{m_W^2} \frac{t_\beta^4}{m_A^2} \frac{|\mu A_t|^2}{\tilde{m}^4}$$

2 loops suppressed

Very small ⇨ **probably very difficult to generate sizable effects in $S_{\psi\phi}$**

The B_s mixing phase: the MFV MSSM limit (2)



Altmannshofer, Buras, SG, Paradisi, Straub,
Nucl.Phys.B830:17-94,2010

- Potentially sizable effects in $S_{\psi\varphi}$ require very large tanβ (blue points)

- The constraints from both $BR(B_s \to \mu\mu)$ and $BR(b \to s\gamma)$ become very powerful in this regime.

  Imposing them, the resulting $S_{\psi\varphi}$ is SM like (black points)

An interesting possibility: Uplifted Susy
Dobrescu, Fox, Martin,
Phys.Rev.Lett.105:041801,2010.

The UT tension in 2HDM with MFV

- ε_K is basically not affected by NP since:

$$C_1^{SLL} \propto (V_{td}V_{ts}^*)^2 m_s^2$$
$$C_2^{LR} \propto (V_{td}V_{ts}^*)^2 m_s m_d$$

⇒ **No solution 1** of the unitary triangle tension

- NP effects in $\Delta M_{s,d}$ can be taken small (with suitable $\varepsilon_i^{(\prime)}$ coefficients)

⇒ **No solution 3** of the unitary triangle tension

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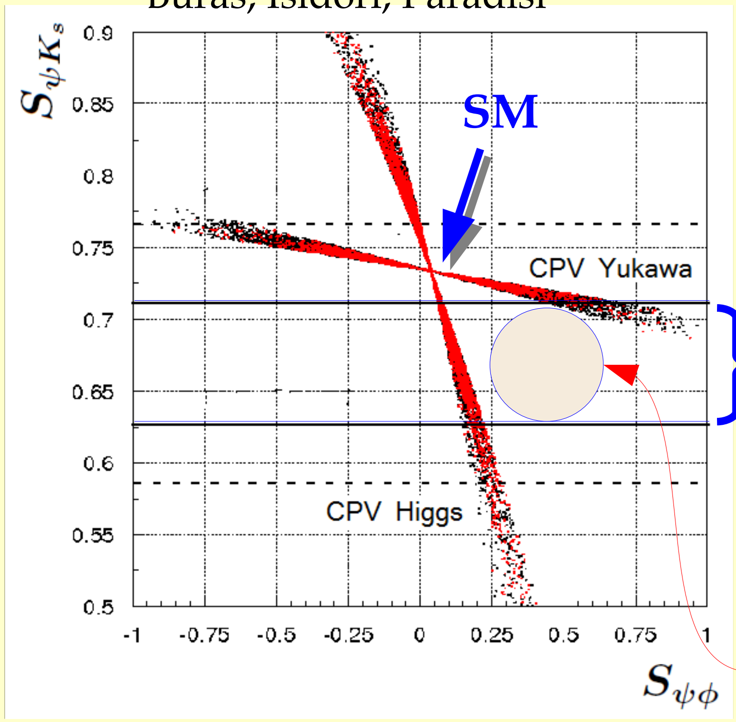
⇒ **No solution 3** of the unitary triangle tension

Solution 2 of the unitary triangle tension ?

Buras, Isidori, Paradisi



1σ experimental bound for $S_{\psi Ks}$

„hybrid scenario"
(CPV both in Yukawas and Higgs potential)

Positive sizable NP contributions in $S_{\psi\phi}$

⇕

Negative NP contributions in $S_{\psi Ks}$ of the right size (especially for the „hybrid scenario")

The rare decays $B_{s,d} \to \mu\mu$

- In the decoupling limit, the effective Hamiltonian responsible of the two processes:

$$\mathcal{H}_{\rm eff}^{|\Delta B|=1} \sim -\frac{a_0^* + a_1^*}{m_H^2} \frac{4 m_\mu m_b m_t^2}{v^4 c_\beta^2 s_\beta^2} V_{tb}^* V_{tq} \, (\bar{b}_R q_L)(\bar{\mu}_L \mu_R) \; + \; \text{h.c.}$$

- The branching ratios:

$$\begin{cases} \text{Br}(B_q \to \mu^+\mu^-) \sim \text{Br}(B_q \to \mu^+\mu^-)_{\rm SM} \times \left(|1 + R_q|^2 + |R_q|^2\right) \\ R_q \propto (a_0^* + a_1^*) \dfrac{M_{B_q}^2 t_\beta^2}{(1 + m_q/m_b) m_H^2} \end{cases}$$

⇐ almost universal

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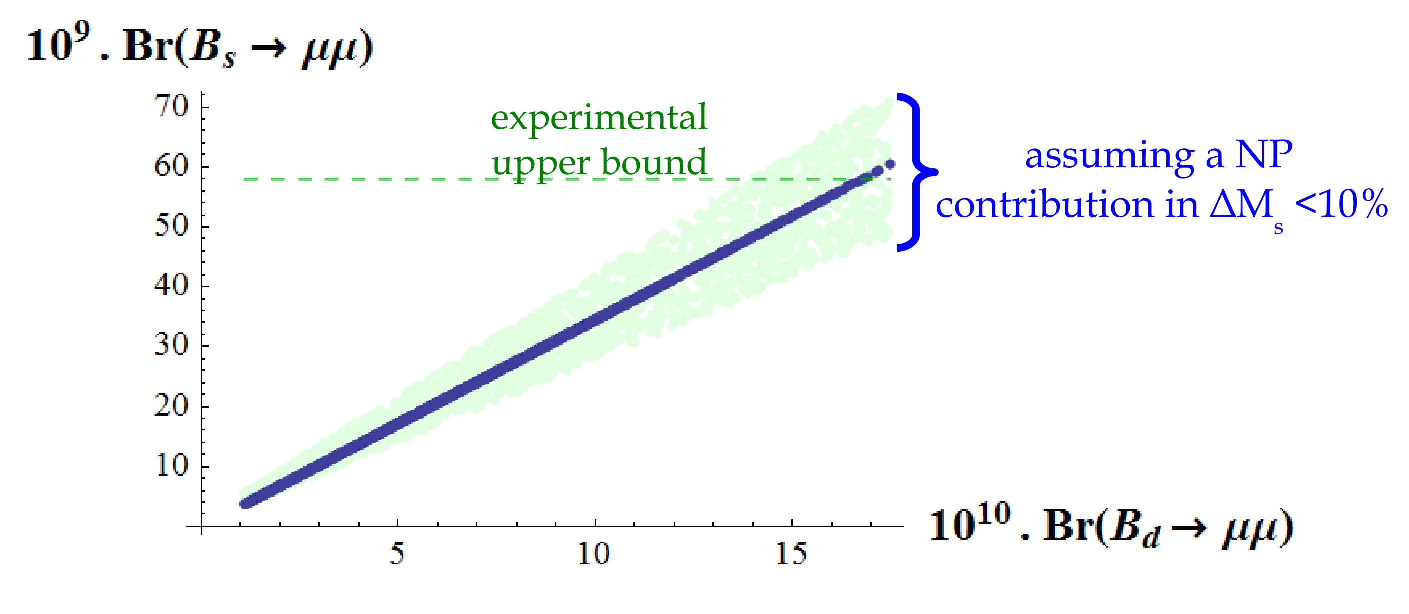
⇐ **almost universal**

To satisfy the experimental upper bound:

$$\sqrt{|a_0 + a_1|}\, t_\beta \frac{v}{M_A} < 8.5$$



$$\frac{{\rm BR}(B_s \to \mu\mu)}{{\rm BR}(B_d \to \mu\mu)} \sim \left|\frac{V_{ts}}{V_{td}}\right|^2$$

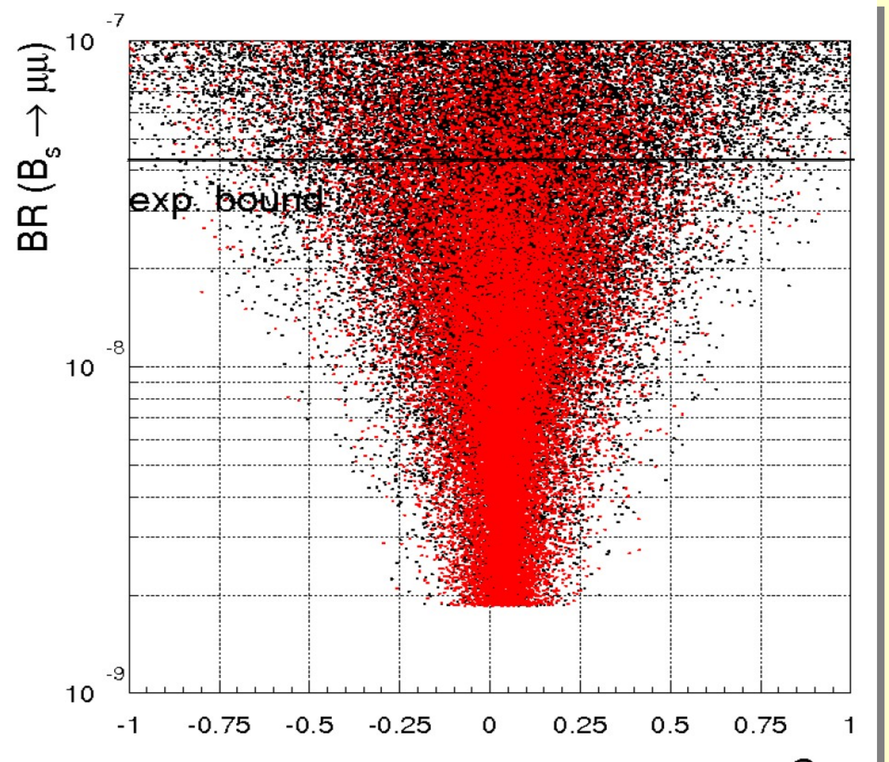
Buras, Carlucci, SG, Isidori

Conclusion: Correlation as in MFV models without NP flavor blind phases

$B_s \to \mu\mu$ vs. $S_{\psi\varphi}$

$B_s \to \mu\mu$, $S_{\psi\varphi}$:
Two golden channels of LHCb

Any correlation?



Buras, Isidori, Paradisi

Buras et. al. scanned on the three phases of a_0, a_1, a_2 and assumed $|a_0|,\ |a_1|,\ |a_2| < 2,\ \lambda_5 = 0$

The main conclusions do not change for $\lambda_5 \neq 0$

(Red dots fulfill the EDM constraints while the black ones do not)

Conclusions:

1. The **experimental bound** on BR($B_s \to \mu\mu$) is **satisfied** even with a sizable $S_{\psi\varphi}$
2. Sizable $S_{\psi\varphi}$ ⇒ **BR($B_s \to \mu\mu$) close to the experimental bound**

A possible issue: EDMs (1)

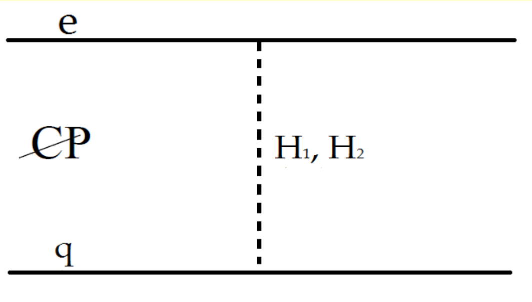
- In D´Ambrosio et. al., no additional CPV phases in the Yukawas in order to be safe with the EDMs

Buras, Isidori, Paradisi

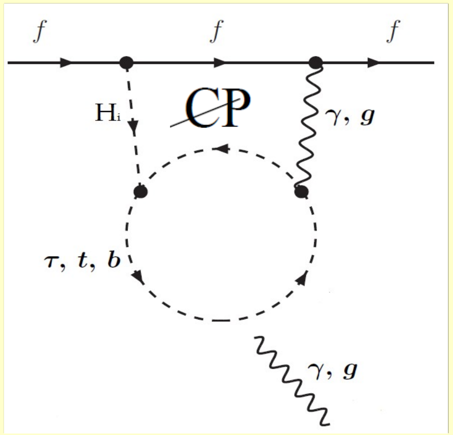
Are we in trouble?

- Tallium, neutron, mercury EDMs: most sensitive probes of CP violation
- The most important contributions:

1. Four fermion operators



2. Barr-Zee contributions

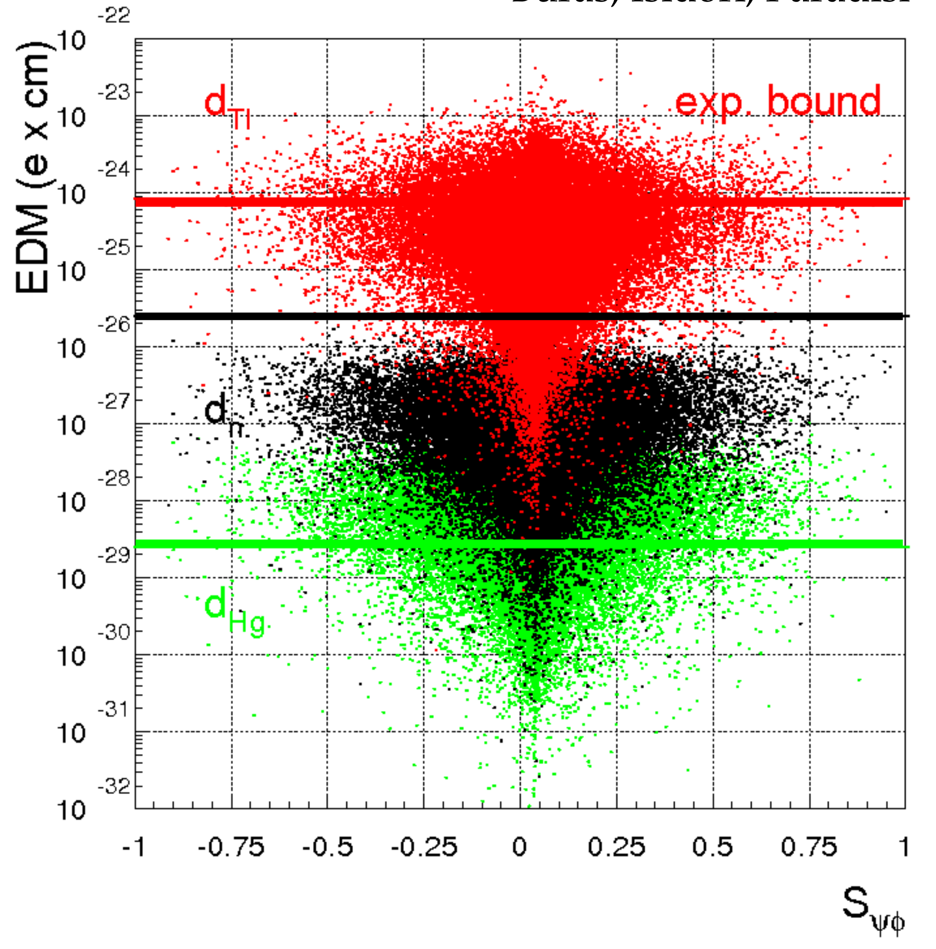


- Dependence on the CP violation arising from the combinations
  - $a_0+a_1+a_2$
  - a_0
  - λ_5

Does a sizable phase in a_i
(as required by a sizable $S_{\psi\varphi}$)
imply too large NP contributions to EDMs?

A possible issue: EDMs (2)

Buras, Isidori, Paradisi



Observable	Exp. Current	Exp. Future
$\|d_{Tl}\|$ [e cm]	$< 9.0 \times 10^{-25}$	$\approx 10^{-29}$
$\|d_{Hg}\|$ [e cm]	$< 3.1 \times 10^{-29}$	?
$\|d_n\|$ [e cm]	$< 2.9 \times 10^{-26}$	$\approx 10^{-28}$

Buras et. al. scanned on the three phases of a_0, a_1, a_2 and assumed $|a_0|, |a_1|, |a_2| < 2, \lambda_5 = 0$

The main conclusions do not change for $\lambda_5 \neq 0$

Conclusions:

1. EDM experimental bounds still **allow sizable** values of $S_{\psi\varphi}$
2. Sizable $S_{\psi\varphi}$ ⇒ generic predictions for EDMs well within **the reach of future experiments**

Conclusions and remarks

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  → Need for a protection mechanism

Conclusions and remarks

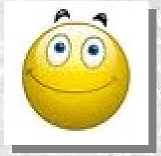
- Very many extensions of the Standard Model have an enlarged Higgs sector
- 2HDMs can be an effective field theory arising from one of these exstensions

  - The most general 2HDM we can write is highly non compatible with experiments on flavor observables

    → Need for a protection mechanism

1. The Natural Flavor Conservation hypothesis (based on the $U(1)_{PQ}$ symmetry or a subgroup) is not sufficient, since it is not stable under radiative corrections (see the MSSM)
2. The Minimal Flavor Violation hypothesis forces a particular breaking of the symmetry $SU(3)_q^3$ and protects efficiently the model

   → The New Physics flavor problem is addressed



Conclusions and remarks

- Decoupling the breaking of the flavor group from the breaking of the CP symmetry and adding CP violation in the Higgs potential enriches the phenomenology of the Minimal Flavor Violating 2HDM

- $S_{\psi\phi}$ can get sizable NP effects, still being compatible with the unitary triangle constraints, $B_s \to \mu\mu$ and EDMs

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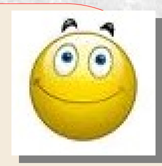

- In correspondence to sizable effects in $S_{\psi\varphi}$:

1. $S_{\psi Ks}$ gets negative NP contributions that can be of the right size to address the unitary triangle tension

(Important correlation between the two BRs)

2. The branching ratios of $B_{s,d} \to \mu\mu$ are enhanced and in particular $B_s \to \mu\mu$ is close to the experimental limits (within the reach of LHCb)

3. The EDMs of tallium, neutron and mercury are close to the experimental limits (within the reach of future experiments)