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TWO-HIGGS-DOUBLET MODELS WITH MINIMAL FLAVOUR VIOLATION

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MAX-PLANCK-GESELLSCHAFT

Outline

- Introduction
  - Why and what is Minimal Flavour Violation (MFV)
  - Why and how work Two-Higgs-Doublet Models
- Protection mechanisms for Higgs-mediated Flavour Changing Neutral Currents (FCNCs): Minimal Flavour Violation vs. Natural Flavour Conservation (NFC)
- Minimal Flavour Violation with flavour-blind phases and the $\Delta F = 2$ anomalies
- Conclusions and Outlook

Introduction:

Minimal Flavour Violation & Two-Higgs-Doublet Models

Symmetries and Symmetry Breakings in the SM

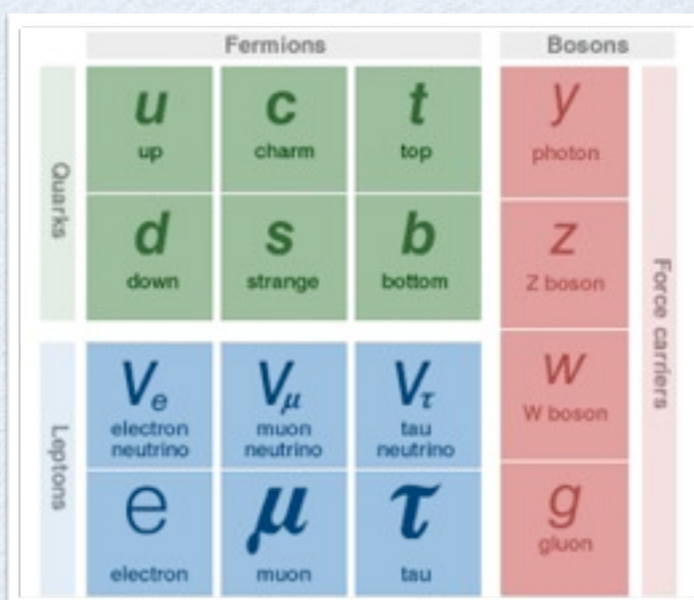
$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{gauge}} + \mathcal{L}_{\mathrm{Higgs}}$$

- Natural: 3 parameters of order 1
- Highly experimentally tested
- Stable under quantum corrections
- Highly symmetric:

Local gauge symmetry

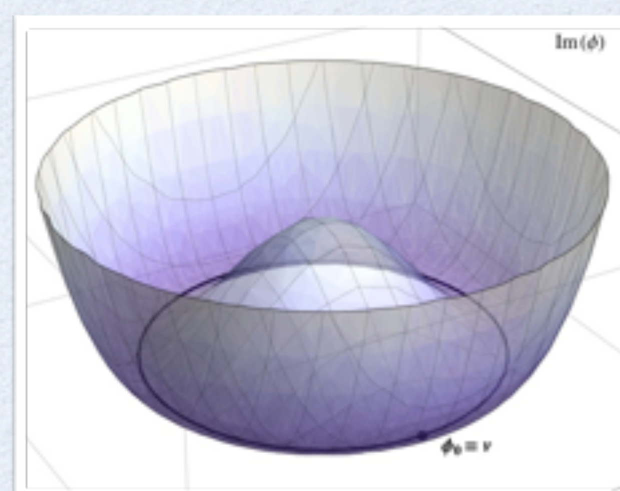
$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

Global flavour symmetry

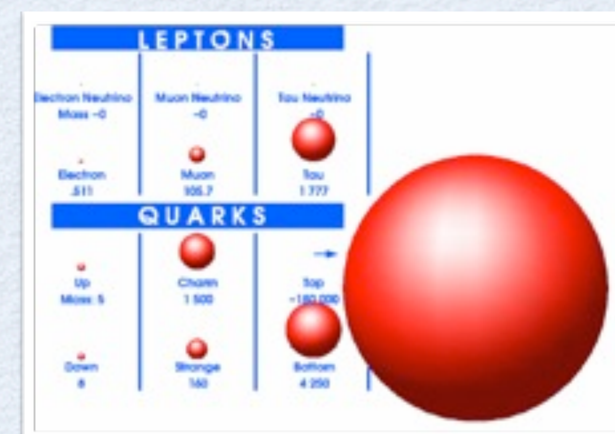


- Ad hoc: 19 parameters, 5 orders
- Poorly tested in its dynamical form
- Not stable under quantum corrections
- Symmetry breakings:

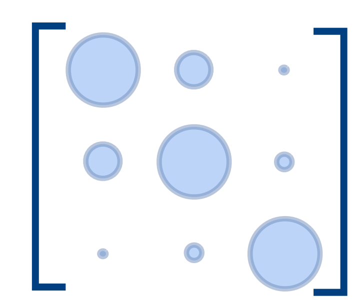
Gauge breaking



Flavour breaking



$V_{\mathrm{CKM}} =$



Main Problems of the SM

Theoretical

$$V(H) = -\mu^2 \left(H^\dagger H\right) + \lambda \left(H^\dagger H\right)^2 + \bar{\psi}_L H\, Y \psi_R$$

- Quadratic divergence of the Higgs mass
- Landau pole / vacuum instability: possible internal inconsistency
- Structure of the Yukawa coupling

Flavour problem

Experimental

- Where is the Higgs boson?
- Not enough CP violation
- Dark matter
- Gravity

The SM is likely to be only an **effective theory**,
i. e. the low-energy limit of a more fundamental theory.

THE FLAVOUR PROBLEM

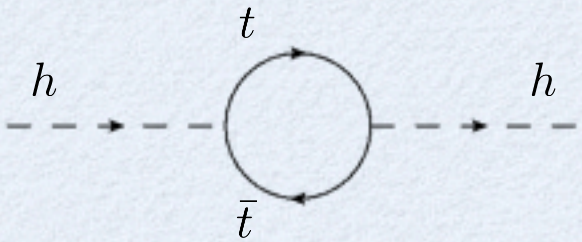
The SM as an effective theory:

$$\mathcal{L}_{\rm NP} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm Higgs} + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}$$

How large is the New Physics scale Λ?

From the Higgs sector

Quantum corrections to the Higgs mass



$$\Delta m_H^2 = -\frac{|\lambda_t|^2}{8\pi^2}\Lambda^2$$

$$\Lambda \lesssim \mathcal{O}(1\text{TeV})$$

From the Flavour sector

Precision flavour physics

$$\Delta M^{\rm theor}\left(B_d - \bar{B}_d\right) \approx \frac{\left(y_t V_{tb}^* V_{td}\right)^2}{16\pi^2 M_W^2} + \frac{c_{\rm NP}}{\Lambda^2}$$

$$\Delta M^{\rm exp}\left(B_d - \bar{B}_d\right) = 3.337 \text{ MeV } \pm 1\ \%$$

$$\Lambda \gtrsim \mathcal{O}(10 \text{ TeV})$$

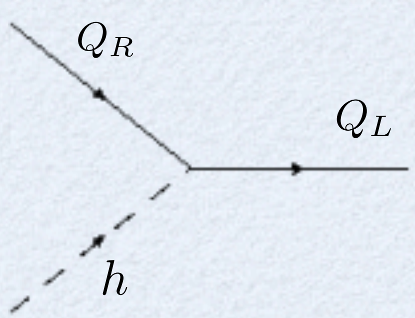
The Flavour Structure of the SM

Large global symmetry in the gauge sector

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

$$SU(3)^3 = SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R} \qquad U(1)^3 = U(1)_B \otimes U(1)_Y \otimes U(1)_{PQ}$$

broken only by the Yukawa couplings

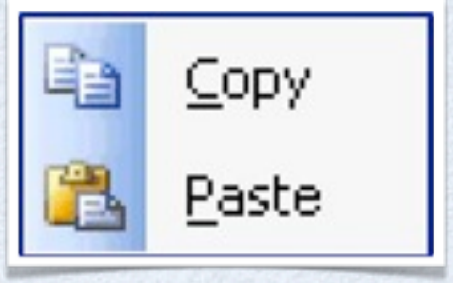


$$\mathcal{L}_Y = -\bar{Q}_L Y_d D_R H - \bar{Q}_L Y_u U_R H^c$$

This specific **symmetry** + **symmetry-breaking** pattern is responsible for all the successful SM predictions in the quark flavour sector.

MINIMAL FLAVOUR VIOLATION

Idea: using the same flavour structure of the SM in the NP models.



Flavour symmetry is formally recovered by promoting the Yukawa couplings to **spurions**

$$Y_u \sim (3, \bar{3}, 1)_{SU(3)^3} \qquad\qquad Y_d \sim (3, 1, \bar{3})_{SU(3)^3}$$

Minimal Flavour Violation hypotesis:

A theory satisfies the MFV criterion if it is formally invariant under $\mathcal{G}_q$.

↓

MFV requires that the dynamics of flavour violation is completely determined by the structure of the SM Yukawa couplings.

Buras, Gambino, Gorbahn, Jager and Silvestrini, 2001
D'Ambrosio, Giudice, Isidori and Strumia, 2002

MFV: Short Overview of Characteristics

MFV does:

- provide additional suppression factors for NP flavour transitions;
- imply correlations between different flavour observables;
- reduce the free parameters in NP flavour sector;
- allow to formulate flavour violation within effective theory approach.

MFV does not:

- represent a theory of flavour violation;
- explain the size of fermion masses and mixing angles.

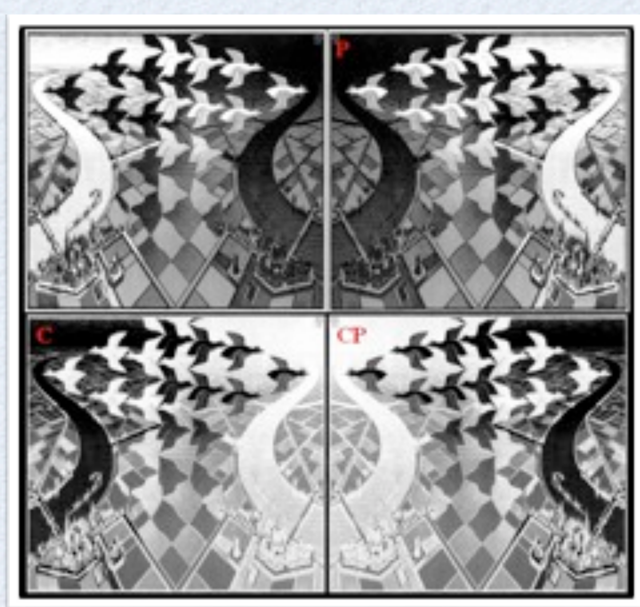
MOTIVATIONS

In the SM the chioce of only one Higgs doublet is not the only possible, but just the most economical.

Possible but not necessary: ruled out by Occam's Razor?

- Several New Physics models contain more Higgs doublets.
- Adding more Higgs doublet brings many interesting phenomenological features:

New sources of CP violation



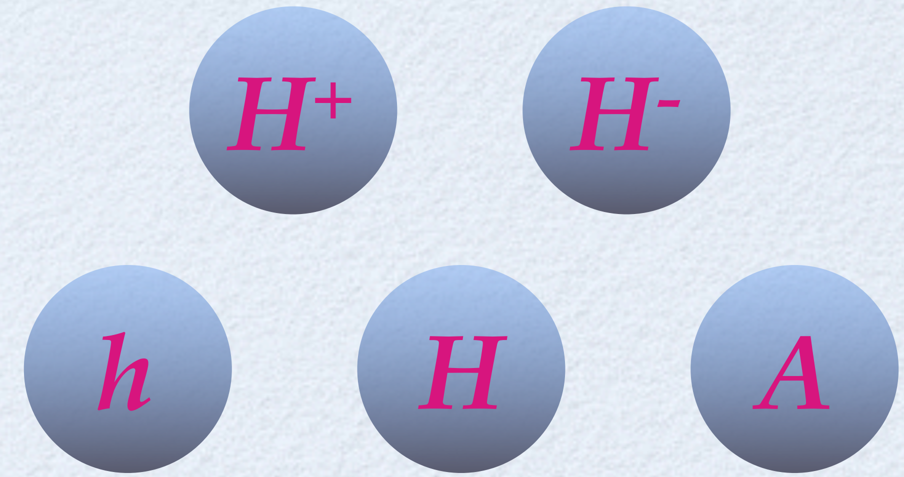
Dark matter candidates

Axion phenomenology

GENERAL FEATURES

$$H_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}\left(v_1 + \rho_1 + i\eta_1\right) \end{pmatrix}$$

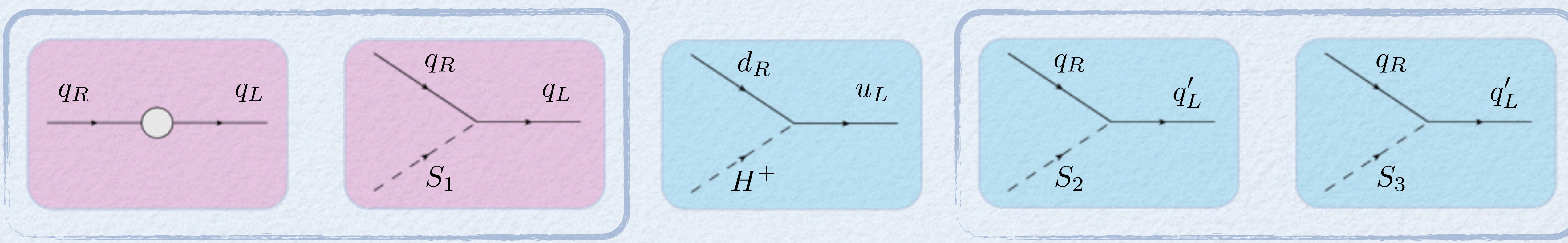
$$H_2 = \begin{pmatrix} \frac{1}{\sqrt{2}}\left(v_2 + \rho_2 + i\eta_2\right) \\ \phi_2^- \end{pmatrix}$$



The most general renormalizable and gauge-invariant Yukawa interaction is

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

X_i : 3 × 3 matrices with a generic flavour structure



Standard Model-like

Flavour Changing Neutral Currents

Protection Mechanisms for FCNCs

FLAVOUR SYMMETRIES VS. FLAVOUR-BLIND SYMMETRIES

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

flavour symmetries

flavour-blind symmetries

Suppression of FCNCs obtained by protecting the breaking of one of these types of symmetry:

flavour symmetries $\longrightarrow$ Minimal Flavour Violation

flavour-blind symmetries $\longrightarrow$ Natural Flavour Conservation

NATURAL FLAVOUR CONSERVATION

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)

Condition III. We demand that the coupling of each neutral Higgs meson be such as naturally to conserve all quark flavors: strangeness, charm, etc.

For a two-Higgs doublet model:

assumption that only one Higgs field can couple to a given quark species.

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

Continuous symmetry $U(1)_{PQ}$

must be broken beyond the tree level:

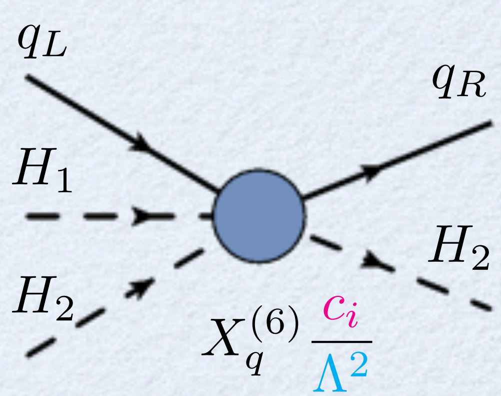
$$X_{d2} = \epsilon_d \, \Delta_d$$

the consistency with experimental data requires

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

Discrete Z_2 symmetry

Z_2 could be exact in principle
but it allows higher-dimensional operators:



Large amount of fine tuning needed to suppress FCNCs!

Buras, MVC, Gori and Isidori - arXiv:1005.5310

MFV STRUCTURE

Beyond the lowest order in the Yukawas the only relevant non-diagonal structures are

$$Y_u Y_u^\dagger,\ Y_d Y_d^\dagger \sim (8,1,1)_{SU(3)_q^3} \oplus (1,1,1)_{SU(3)_q^3}$$

$$\begin{aligned}
X_{d1} &= Y_d \\
X_{d2} &= P_{d2}(Y_u Y_u^\dagger, Y_d Y_d^\dagger) \times Y_d = \epsilon_0 Y_d + \epsilon_1 Y_d Y_d^\dagger Y_d + \epsilon_2 Y_u Y_u^\dagger Y_d + \dots \\
X_{u1} &= P_{u1}(Y_u Y_u^\dagger, Y_d Y_d^\dagger) \times Y_u = \epsilon_0' Y_u + \epsilon_1' Y_u Y_u^\dagger Y_u + \epsilon_2' Y_d Y_d^\dagger Y_u + \dots \\
X_{u2} &= Y_u
\end{aligned}$$

Renormalization group invariant.

$$\mathcal{L}_{\mathrm{MFV}}^{\mathrm{FCNC}} = \frac{1}{\sin\beta} \bar{d}_L^i \left[\left(a_0 V^\dagger {\lambda_u}^2 V + a_1 V^\dagger {\lambda_u}^2 V \Delta + a_2 \Delta V^\dagger {\lambda_u}^2 V \right) \lambda_d \right]_{ij} d_R^j \, \frac{S_2 + i S_3}{\sqrt{2}} \ + \ \mathrm{h.c.}$$

double CKM suppression + down-type Yukawa suppression

D'Ambrosio, Giudice, Isidori and Strumia, 2002

FCNCs in MFV

Parameter constraints from experiments:

$$|a_0| \tan\beta \frac{v}{M_H} < 18 \qquad \text{from } \epsilon_K$$

$$\sqrt{|(a_0^* + a_1^*)(a_0 + a_2)|} \tan\beta \frac{v}{M_H} = 10 \qquad \text{from } \Delta M_s$$

$$\sqrt{|a_0 + a_1|} \tan\beta \frac{v}{M_H} < 8.5 \qquad \text{from Br}\left(B_s \to \mu^+\mu^-\right)$$

Perfectly natural values.

Buras, MVC, Gori and Isidori - arXiv:1005.5310

Phenomenology of MFV with Flavour-Blind Phases

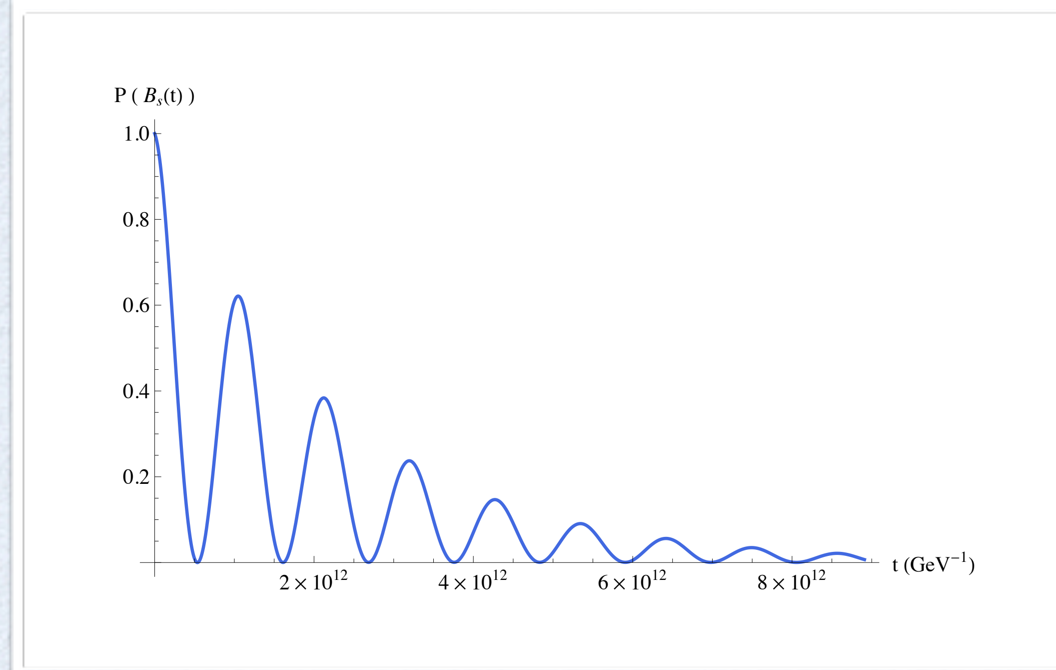
Basic Observables in ΔF=2 Transitions

Neutral mesons systems:

Flavour Eigenstates $K^0 - \bar{K}^0$

Mass Eigenstates $K_L - K_S$

CP Eigenstates $K_1 - K_2$



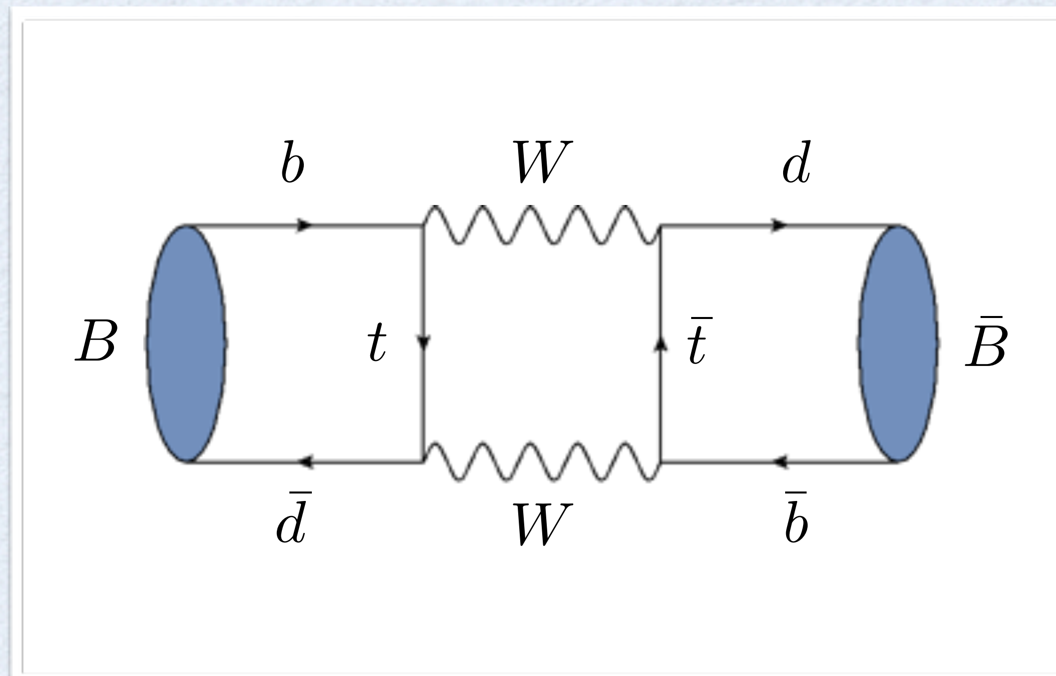
Main observables:

Mass differences

$$\Delta m = m_{M_H} - m_{M_L}$$

CP asymmetries

$$a_f(t) = \frac{\Gamma\left(\bar{M}(t)\to f\right) - \Gamma\left(M(t)\to f\right)}{\Gamma\left(\bar{M}(t)\to f\right) + \Gamma\left(M(t)\to f\right)}$$

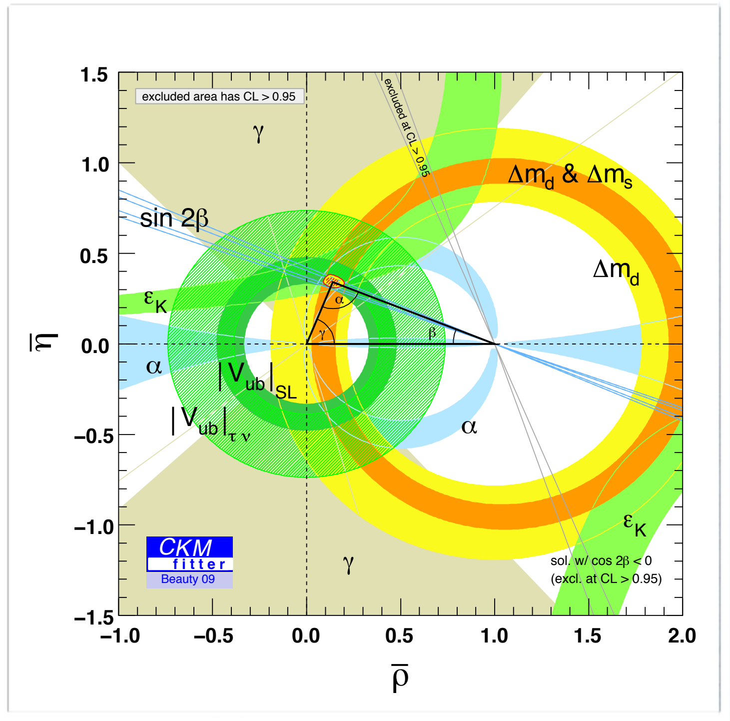


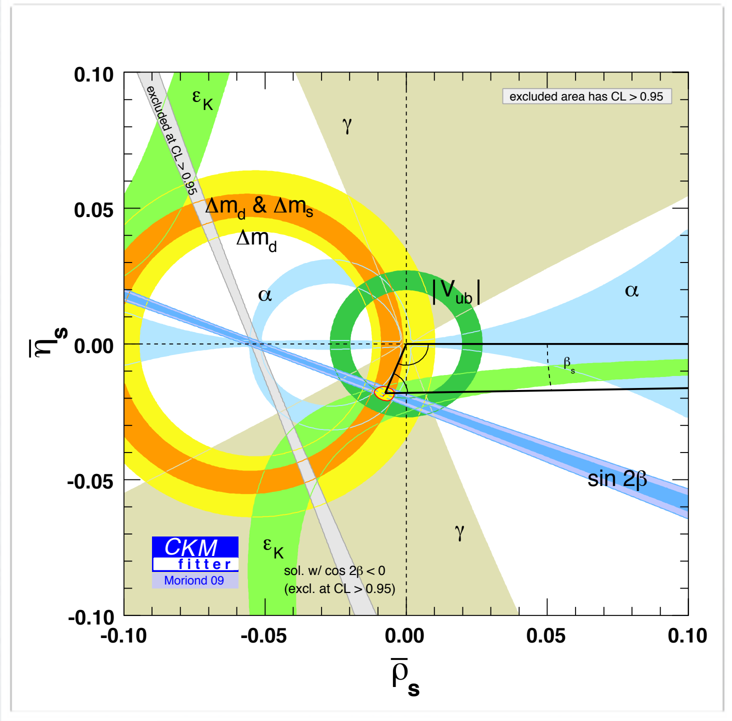
Tensions in the ΔF=2 Observables

The Unitarity Triangles

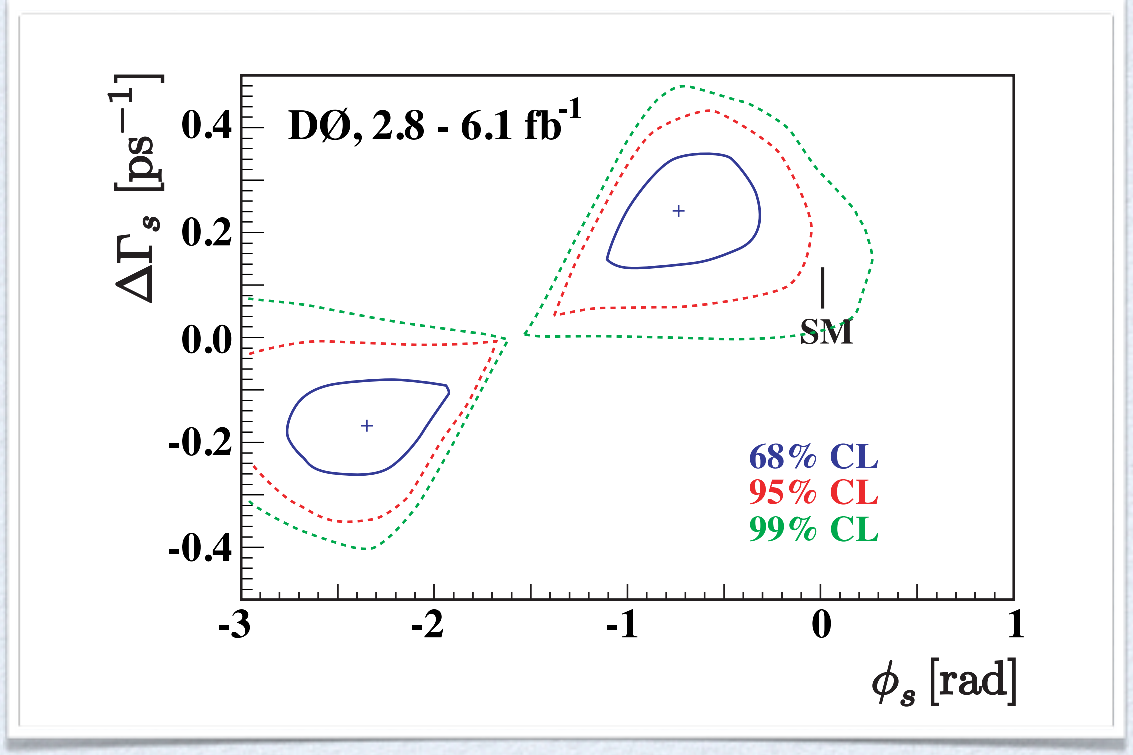
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

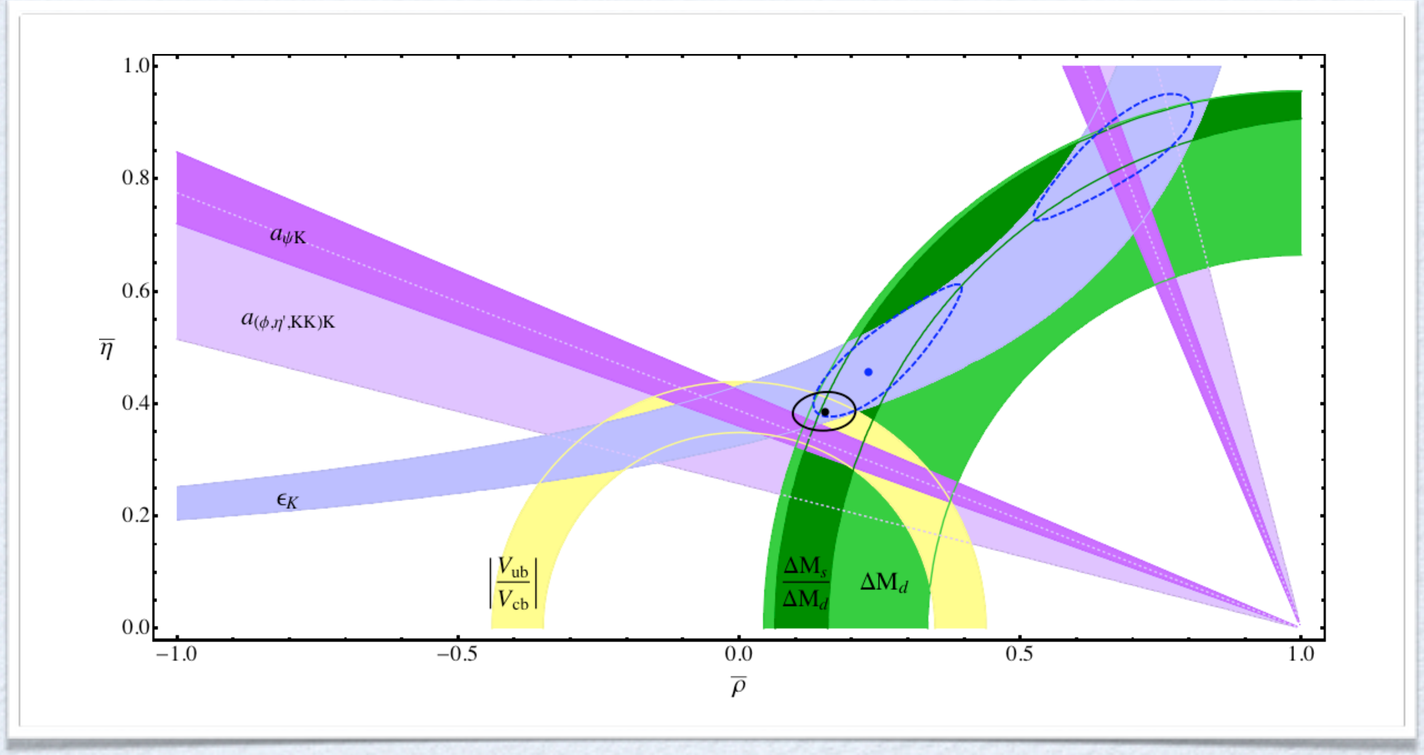




The large mixing phase in the B_s mixing



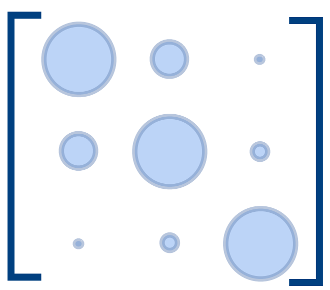
The ε_K - $S_{\psi K_S}$ anomaly



DECOUPLING FLAVOUR AND CP VIOLATION

In the SM the Yukawa couplings are the only sources of

flavour breaking

$V_{\mathrm{CKM}} =$ 

CP breaking

$$V_{CKM} = \begin{pmatrix} c_1 c_3 & s_1 c_3 & s_3 e^{-i\delta} \\ -s_1 c_2 - c_1 s_2 s_3 e^{-i\delta} & c_1 c_2 - s_1 s_2 s_3 e^{i\delta} & s_2 c_3 \\ s_1 s_2 - c_1 c_2 s_3 e^{i\delta} & -c_1 s_2 - s_1 c_2 s_3 e^{i\delta} & c_2 c_3 \end{pmatrix}$$

However, the mechanisms of flavour and CP violation do not necessary need to be related.

In the two-Higgs-doublet models with MFV:

$$\mathcal{L}_{\mathrm{MFV}}^{\mathrm{FCNC}} = \frac{1}{\sin\beta} \bar{d}_L^i \left[\left(a_0 V^\dagger {\lambda_u}^2 V + a_1 V^\dagger {\lambda_u}^2 V \Delta + a_2 \Delta V^\dagger {\lambda_u}^2 V \right) \lambda_d \right]_{ij} d_R^j \, \frac{S_2 + i S_3}{\sqrt{2}} \; + \; \mathrm{h.c.}$$

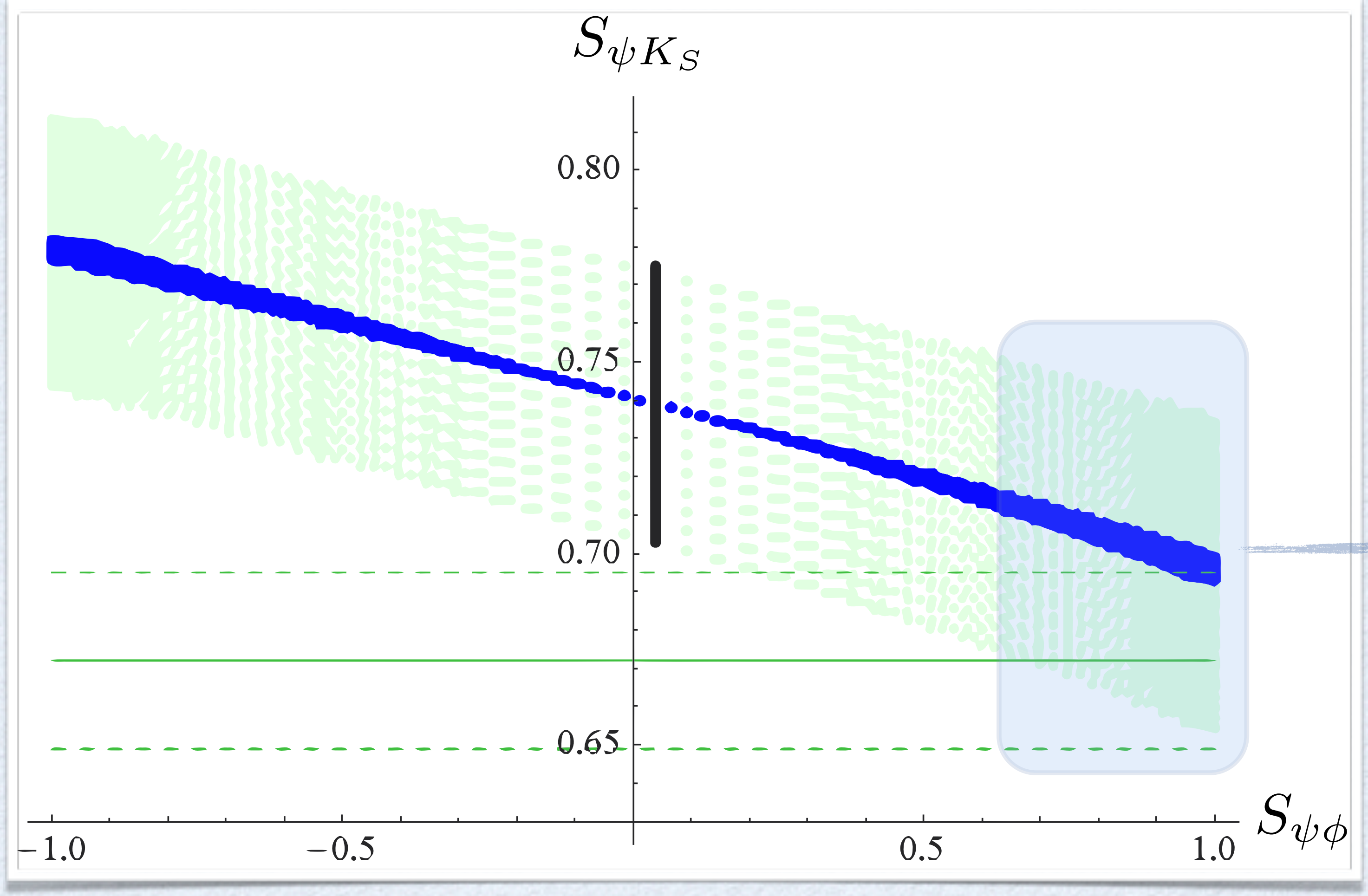
a_i complex $\longrightarrow$ MFV with flavour-blind CP-violating phases

Buras, MVC, Gori and Isidori - arXiv:1005.5310

Correlation of the Mixing Phases

New complex phases → $S_{\psi\phi} = \sin(2\beta_s + |\theta_s|)$ → possibility to accommodate a large mixing phase

Moreover, MFV implies a definite relation between $S_{\psi\varphi}$ and $S_{\psi K_S}$.



→ better agreement with experimental data

Buras, MVC, Gori and Isidori - arXiv:1005.5310

Relaxing the ε_K-$S_{\psi K_S}$ Tension

Corrections to $\varepsilon_K \sim m_d\, m_s$: to small to hope in an improvement.

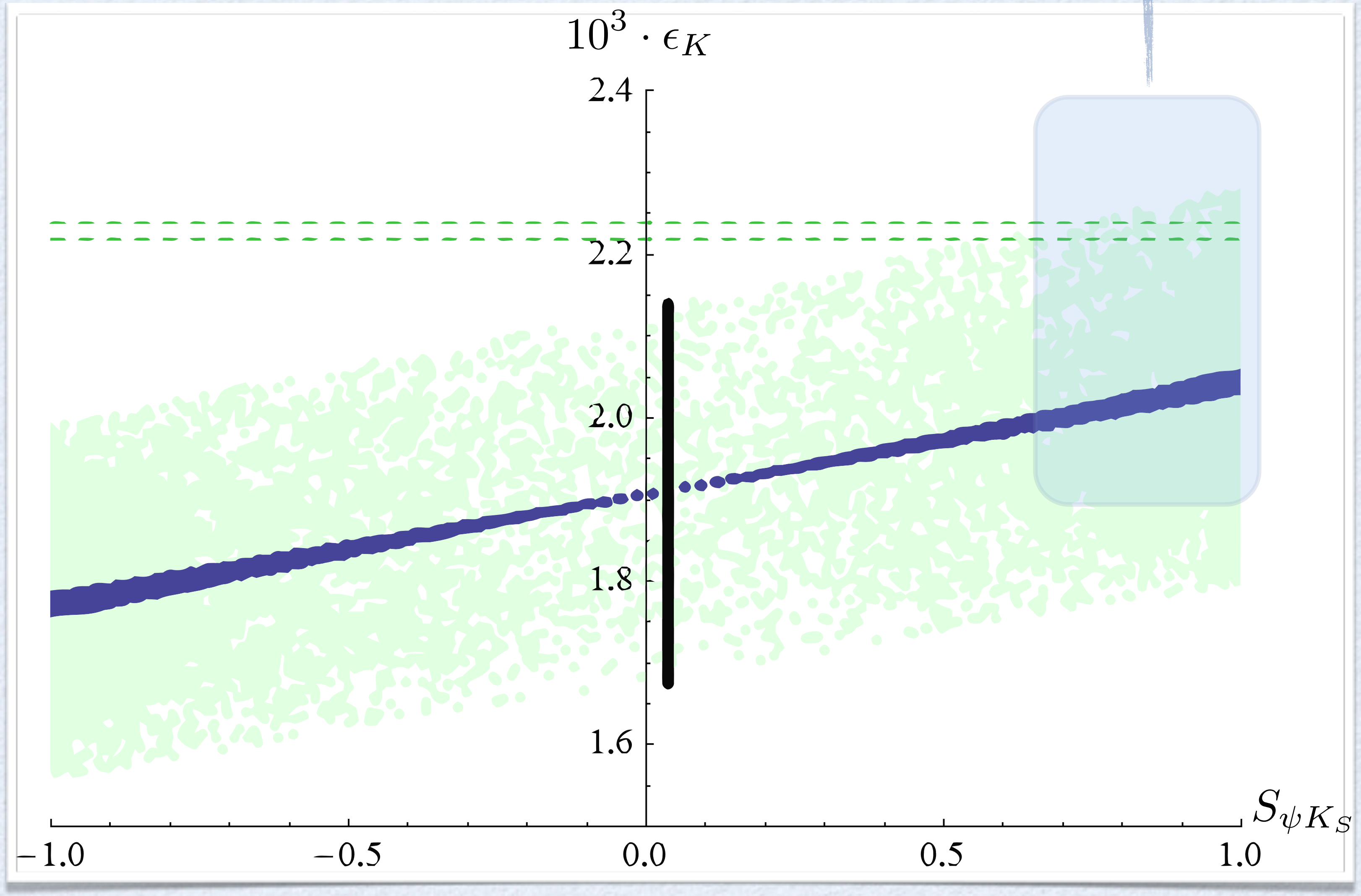
but

$$S_{\psi K_S} = \sin(2\beta - \theta_d)$$

extraction of the “real” β

$$\epsilon_K \propto \sin\beta$$

better agreement



Buras, MVC, Gori and Isidori - arXiv:1005.5310

Conclusions

Conclusions

- Two-Higgs-doublet models: interesting features but dangerous FCNCs.

- Two mechanisms to protect from FCNCs:
  - ⁎ Natural Flavour Conservation $\longrightarrow$ not stable under quantum corrections
  - ⁎ Minimal Flavour Violation $\longrightarrow$ natural and renormalization group invariant

- With MFV and flavour-blind CP-violating phases we can describe the recent $\Delta F = 2$ anomalies.

- Next step: extimation of the contributions of the charged Higgses.

Thanks