DISCRETE 2010

SYMPOSIUM ON PROSPECTS IN THE PHYSICS OF DISCRETE SYMMETRIES

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TWO-HIGGS-DOUBLET MODELS WITH MINIMAL FLAVOUR VIOLATION

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in collaboration with A. J. BURAS, S. GORI and G. ISIDORI

Outline

- Introduction
  - Why and what is Minimal Flavour Violation (MFV)
  - Why and how work Two-Higgs-Doublet Models

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- Conclusions and Outlook

Introduction:

Minimal Flavour Violation & Two-Higgs-Doublet Models

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?

THE FLAVOUR PROBLEM

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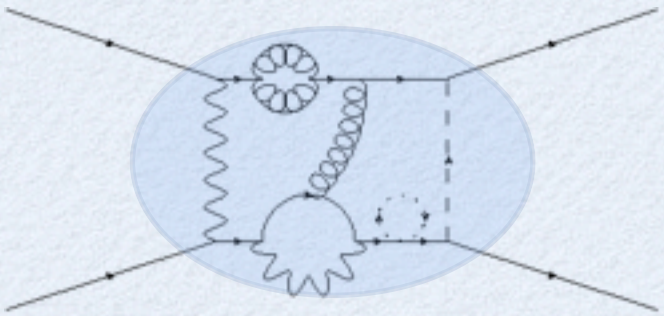

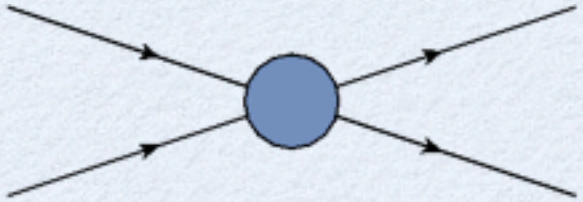

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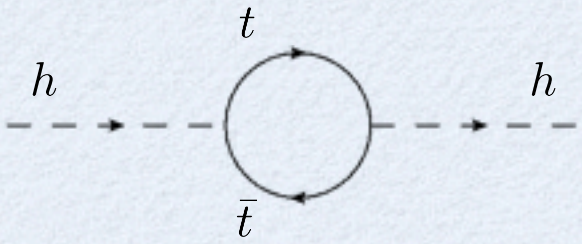
From the Higgs sector

Quantum corrections to the Higgs mass



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

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

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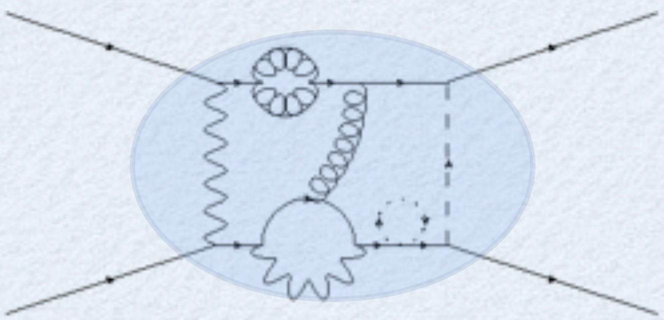

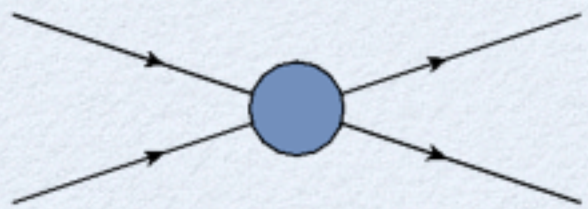

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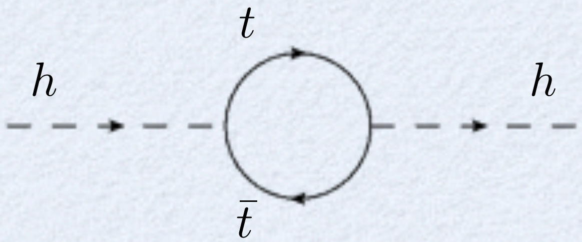

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From the Flavour sector

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

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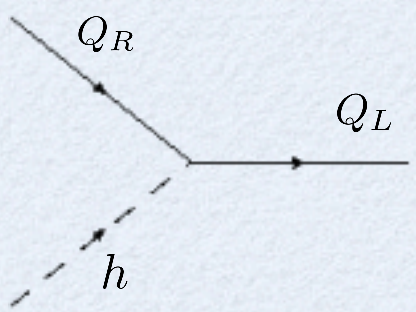

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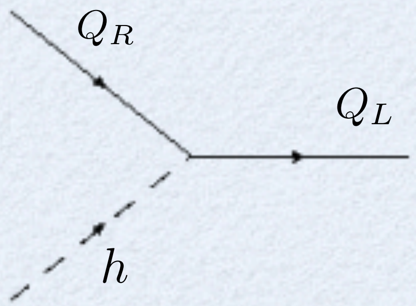

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This specific **symmetry** + **symmetry-breaking** pattern is responsible for all the successful SM predictions in the quark flavour sector.

Minimal Flavour Violation

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

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

Buras, Gambino, Gorbahn, Jager and Silvestrini, 2001
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A theory satisfies the MFV criterion if it is formally invariant under $\mathcal{G}_q$.

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

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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.

Buras, Gambino, Gorbahn, Jager and Silvestrini, 2001
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Motivations

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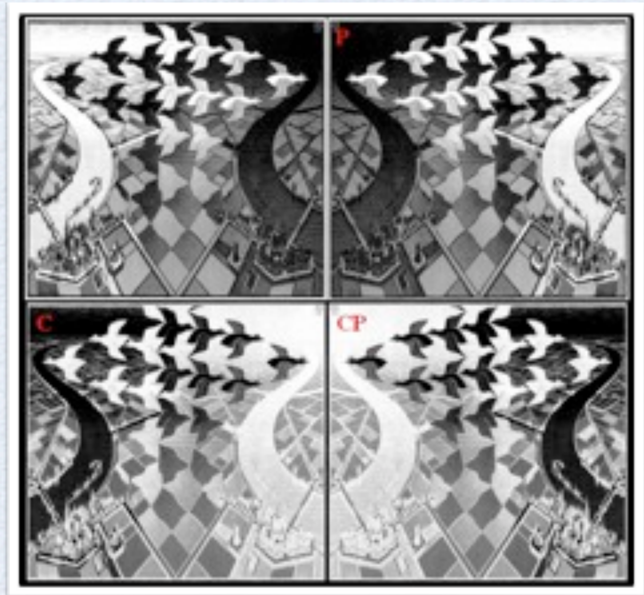
Possible but not necessary: ruled out by Occam's Razor?

- 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

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

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$$\Phi_v = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + S_1 + iG^0) \end{pmatrix}$$

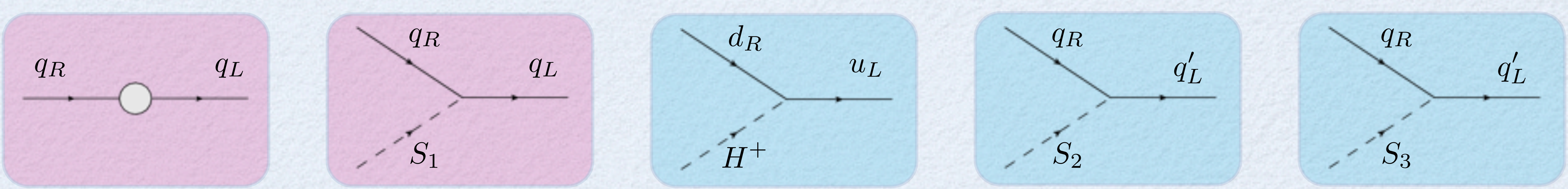
$$\Phi_H = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(S_2 + iS_3) \end{pmatrix}$$

$$M_{u,d} = \frac{v}{\sqrt{2}}(\cos\beta\, X_{u,d\,1} + \sin\beta\, X_{u,d\,2})$$

$$Z_{u,d} = \cos\beta\, X_{u,d\,2} - \sin\beta\, X_{u,d\,1}$$

(cannot be diagonalized simultaneously!)

$$-\mathcal{L}_Y = \bar{Q}_L \left(\frac{\sqrt{2}}{v} M_d \Phi_v + Z_d \Phi_H\right) D_R + \bar{Q}_L \left(\frac{\sqrt{2}}{v} M_u \Phi_v^c + Z_u \Phi_H^c\right) U_R + \text{h.c.}$$



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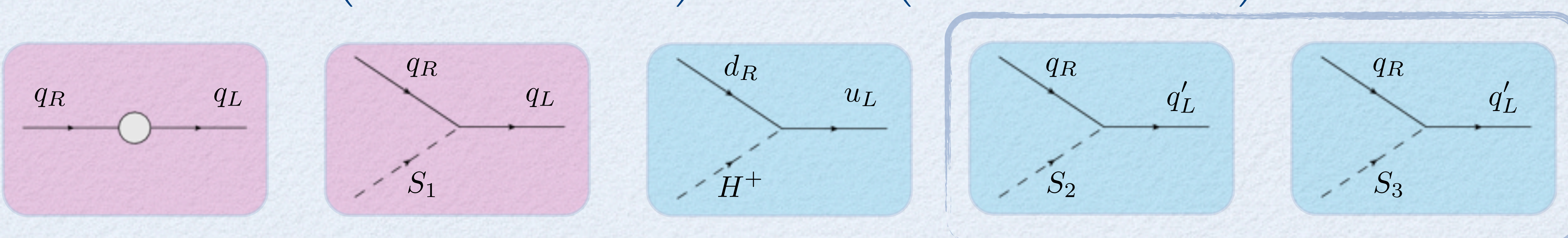

Flavour Changing Neutral Currents

Protection Mechanisms for FCNCs

Flavour Symmetries vs. Flavour-Blind Symmetries

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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.

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

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

must be broken beyond the tree level:

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

the consistency with experimental data requires

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

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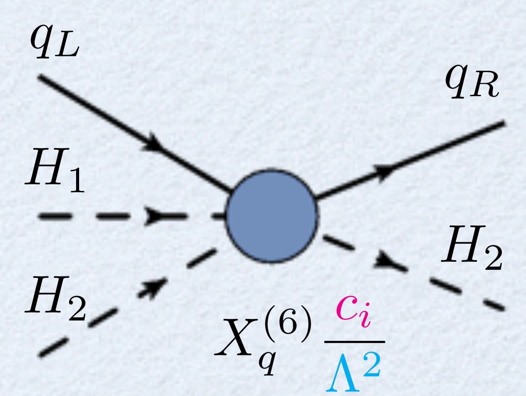
Discrete Z_2 symmetry

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



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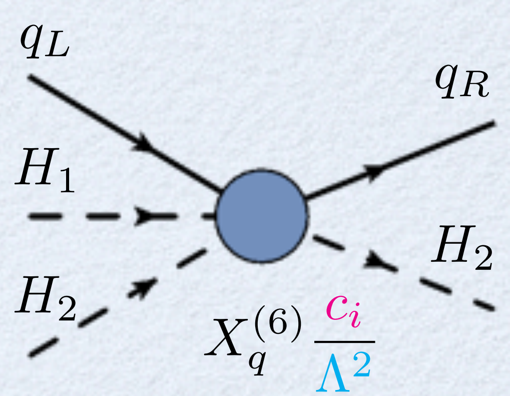

Large amount of fine tuning needed to suppress FCNCs!

Buras, MVC, Gori and Isidori, 2010

MFV STRUCTURE

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

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

$$\Downarrow$$

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

Renormalization group invariant.

D'Ambrosio, Giudice, Isidori and Strumia, 2002

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$$X_{u2} = Y_u$$

Renormalization group invariant.

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

double CKM suppression + down-type Yukawa suppression

D'Ambrosio, Giudice, Isidori and Strumia, 2002

FCNCs in MFV

Parameter constraints from experiments:

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

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

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

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$\sqrt{\lvert a_0 + a_1 \rvert} \tan\beta \dfrac{v}{M_H} < 8.5$	from $\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)$

Perfectly natural values.

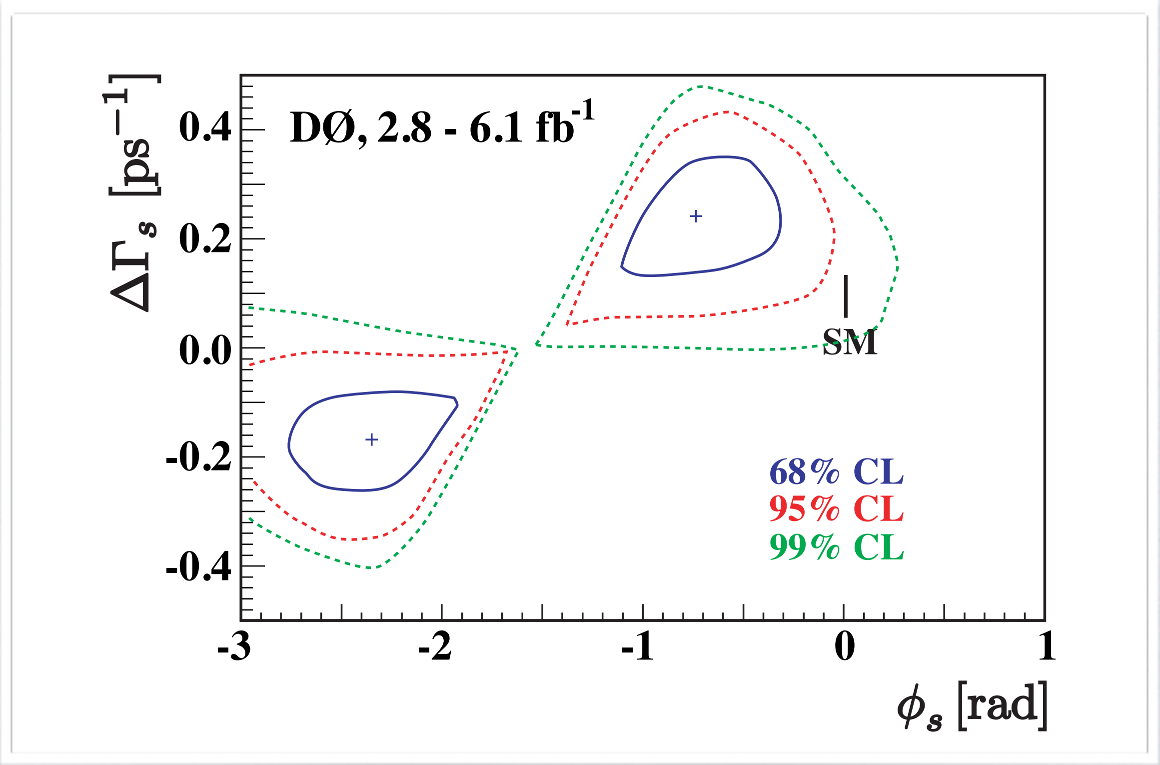
Buras, MVC, Gori and Isidori, 2010

Phenomenology of MFV with Flavour-Blind Phases

Tensions in the ΔF=2 Observables

The large mixing phase in the B_s mixing

CDF Collaboration, 2008
D0 Collaboration, 2008



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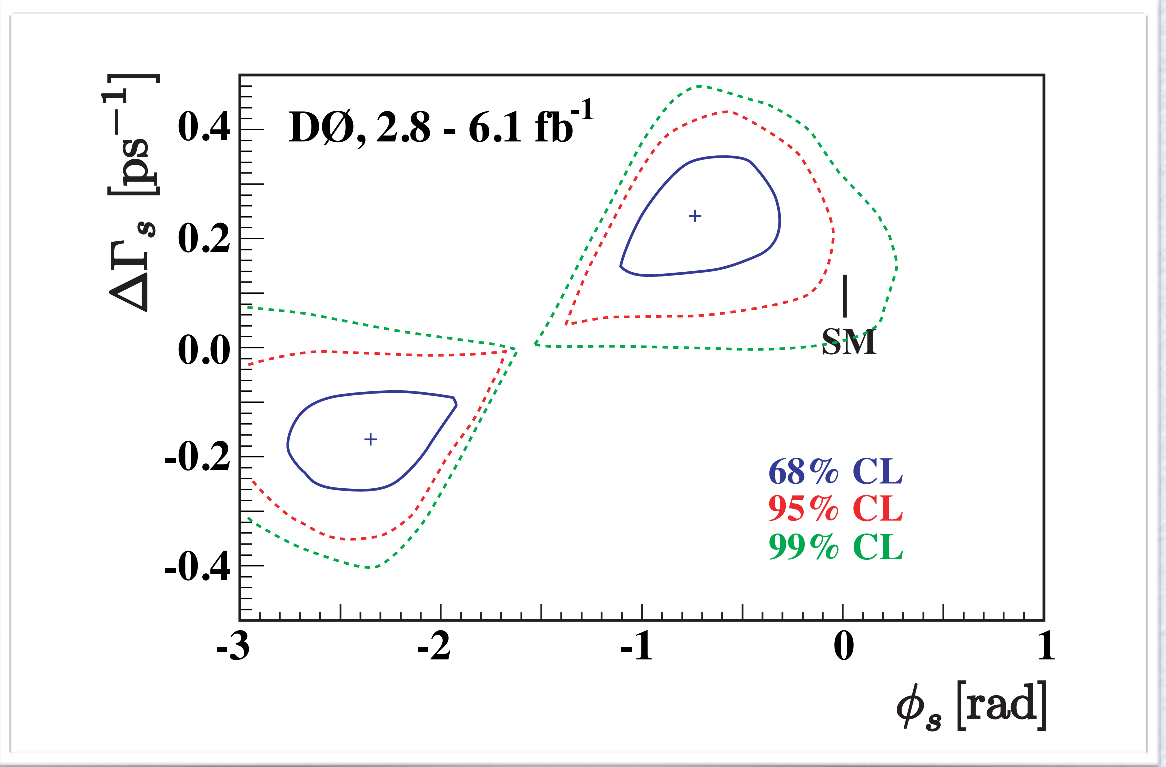
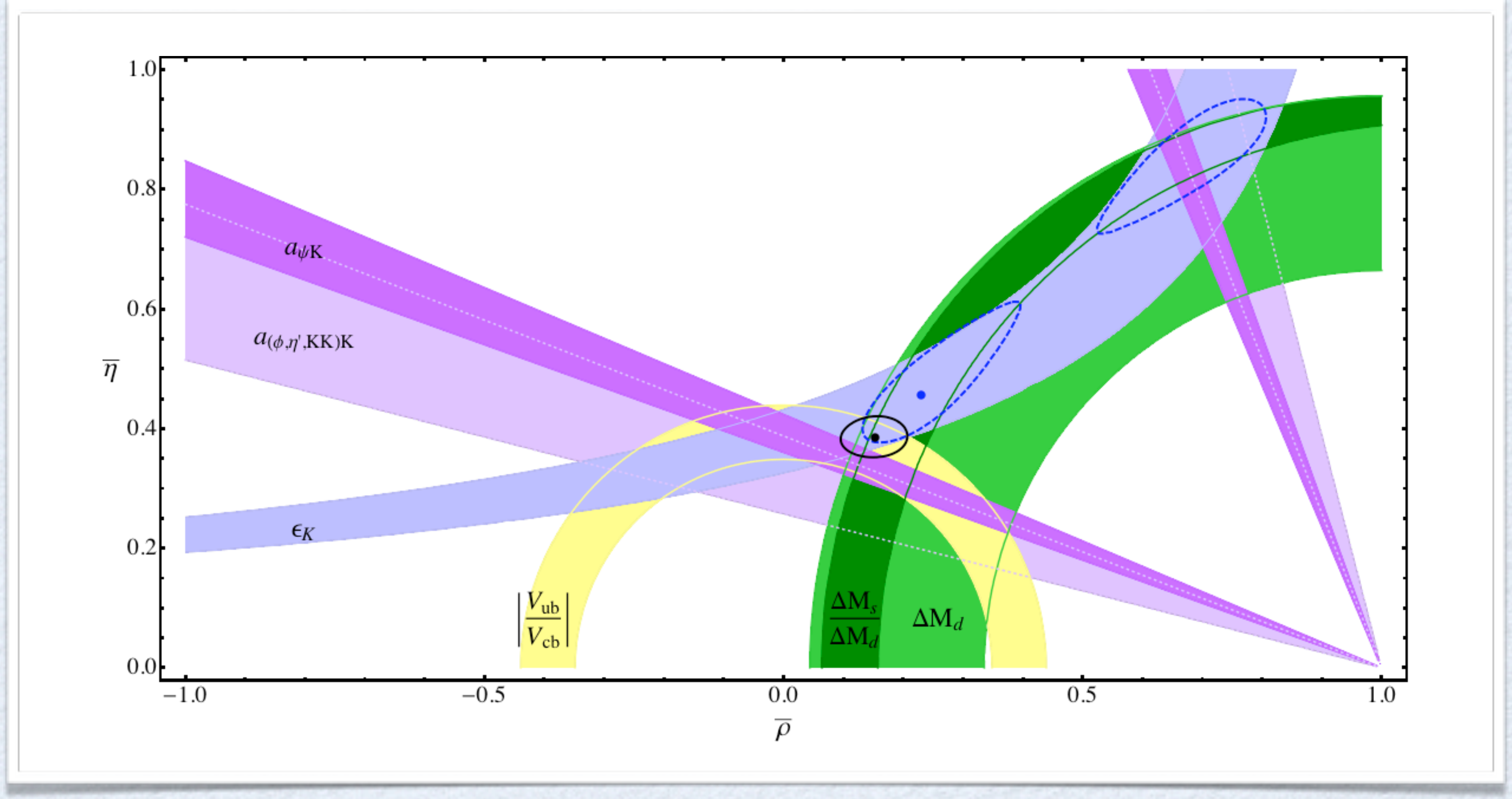


The ε_K - $S_{\psi K_S}$ anomaly

Buras and Guadagnoli, 2008
Lunghi and Soni, 2008

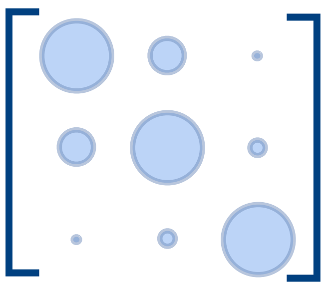


Decoupling Flavour and CP Violation

In the SM the Yukawa couplings are the only sources of

flavour breaking

$V_{\mathrm{CKM}} =$



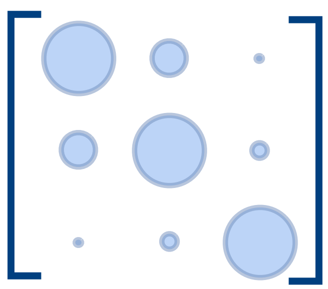
CP breaking

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

Decoupling Flavour and CP Violation

In the SM the Yukawa couplings are the only sources of

flavour breaking

$V_{\mathrm{CKM}} =$ 

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

Kagan, Perez, Volansky and Zupan, 2009

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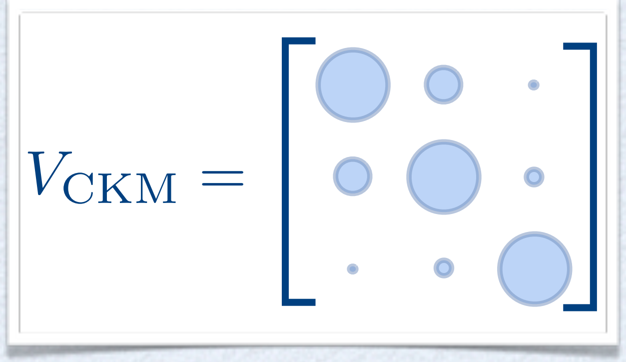

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In the two-Higgs-doublet models with MFV:

$$\mathcal{L}^{\rm FCNC}_{\rm MFV} = \frac{1}{\sin\beta}\bar{d}^i_L\left[\left(a_0 V^\dagger {\lambda_u}^2 V + a_1 V^\dagger {\lambda_u}^2 V\Delta + a_2 \Delta V^\dagger {\lambda_u}^2 V\right)\lambda_d\right]_{ij} d^j_R \,\frac{S_2 + iS_3}{\sqrt{2}} \;+\; \text{h.c.}$$

a_i complex ⟶ MFV with flavour-blind CP-violating phases

Buras, MVC, Gori and Isidori, 2010

$\Delta F = 2$ Effective Hamiltonians

$$\mathcal{H}^{|\Delta S|=2} \propto -\frac{|a_0|^2}{M_H^2} \frac{m_s}{v} \frac{m_d}{v} \left[\left(\frac{m_t}{v} \right)^2 V_{ts}^* V_{td} \right]^2 (\bar{s}_R d_L)(\bar{s}_L d_R) \ + \ \text{h.c.}$$

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Key properties:

- $K - \bar{K} \sim m_s\, m_d$
  $B_d - \bar{B}_d \sim m_d\, m_b$
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- New phases affects equally B_d and B_s systems
  → correlation between the B_s and B_d the mixing phases

Buras, MVC, Gori and Isidori, 2010

Correlation of the Mixing Phases

$S_{\psi K_S} = \sin(2\beta - \theta_d)$ $\qquad$ $S_{\psi\phi} = \sin(2\beta_s + |\theta_s|)$

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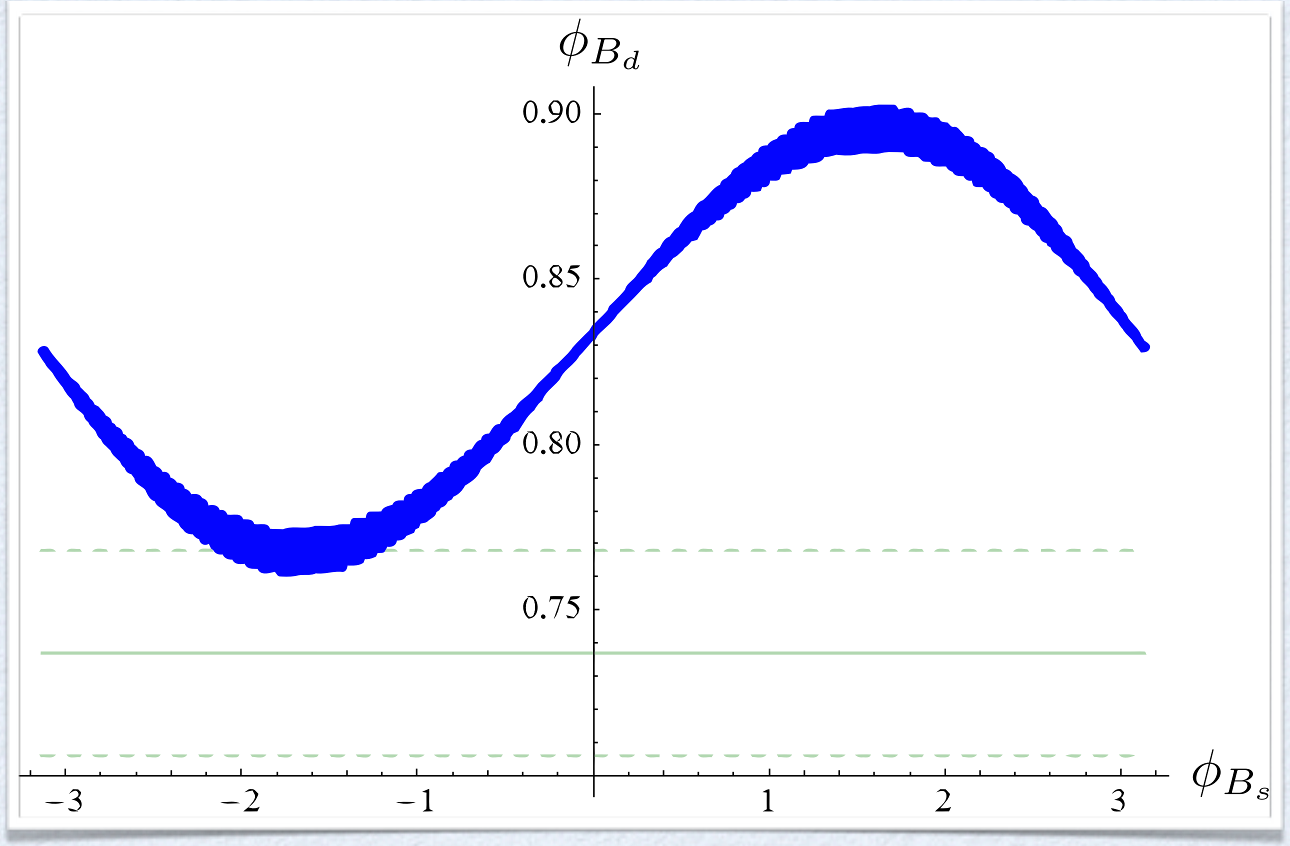

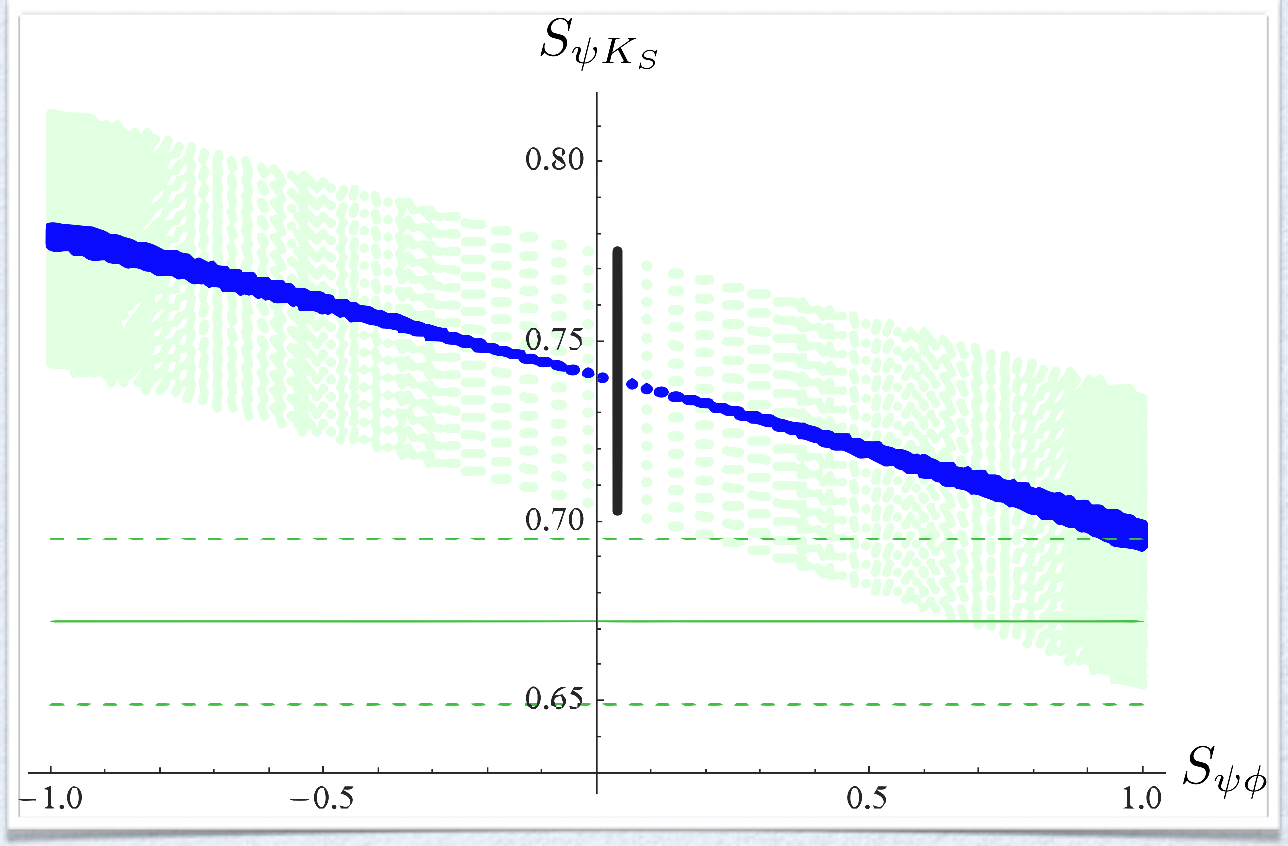

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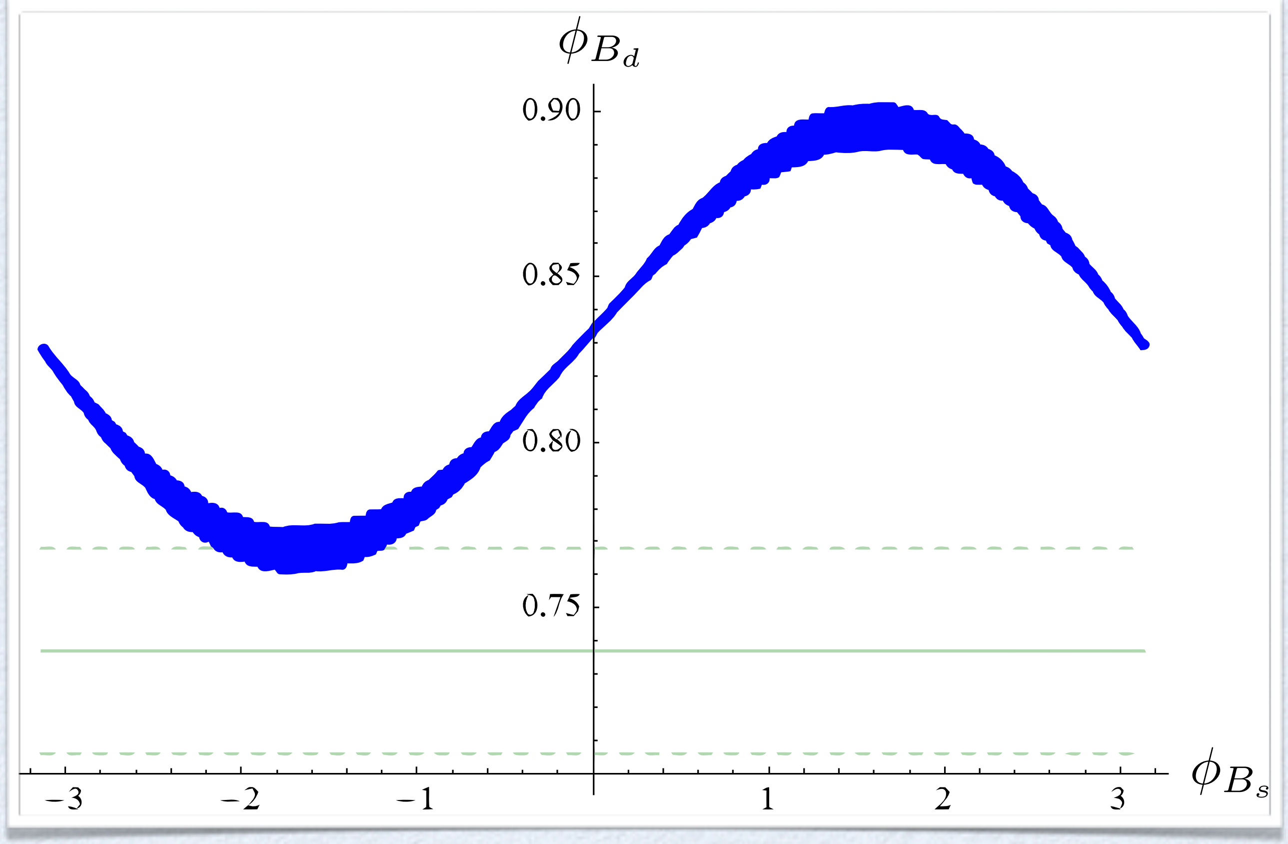

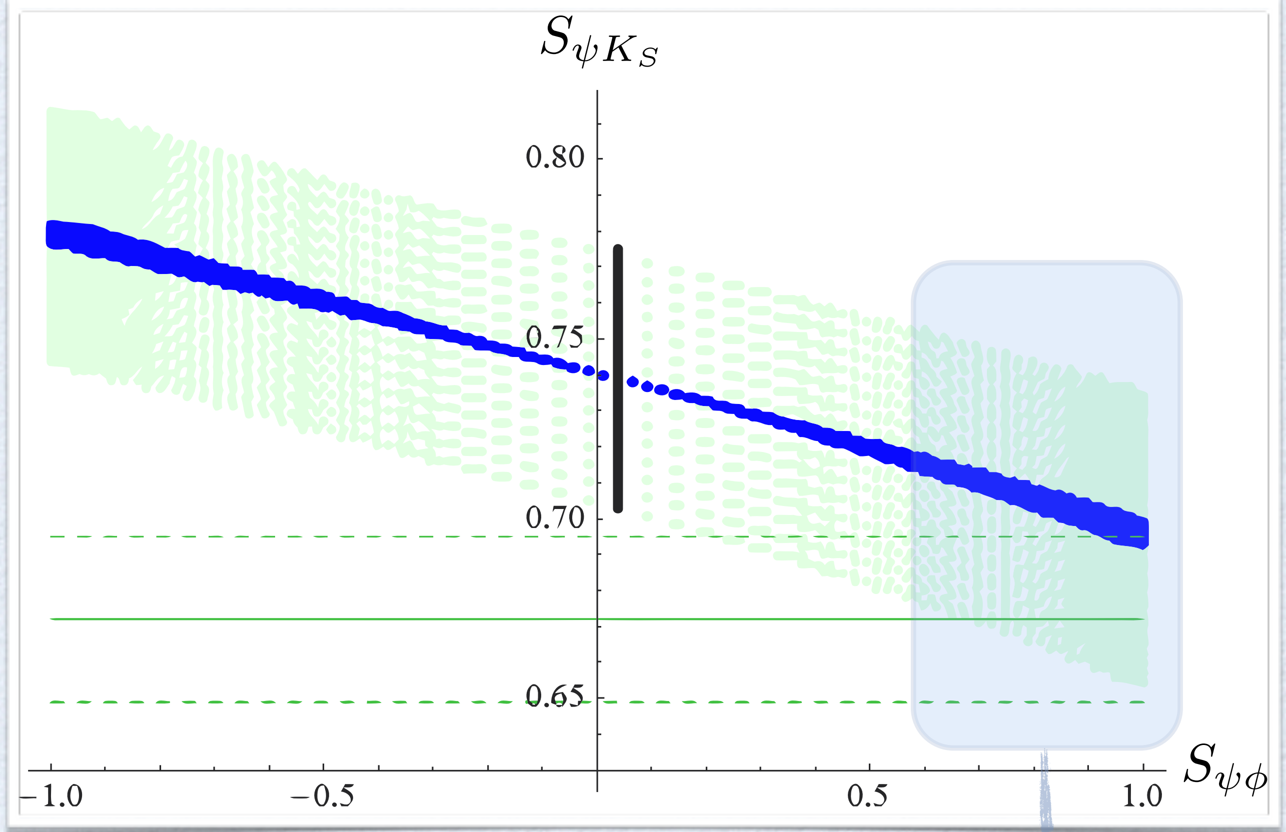

better agreement with experimental data

Buras, MVC, Gori and Isidori, 2010

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

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

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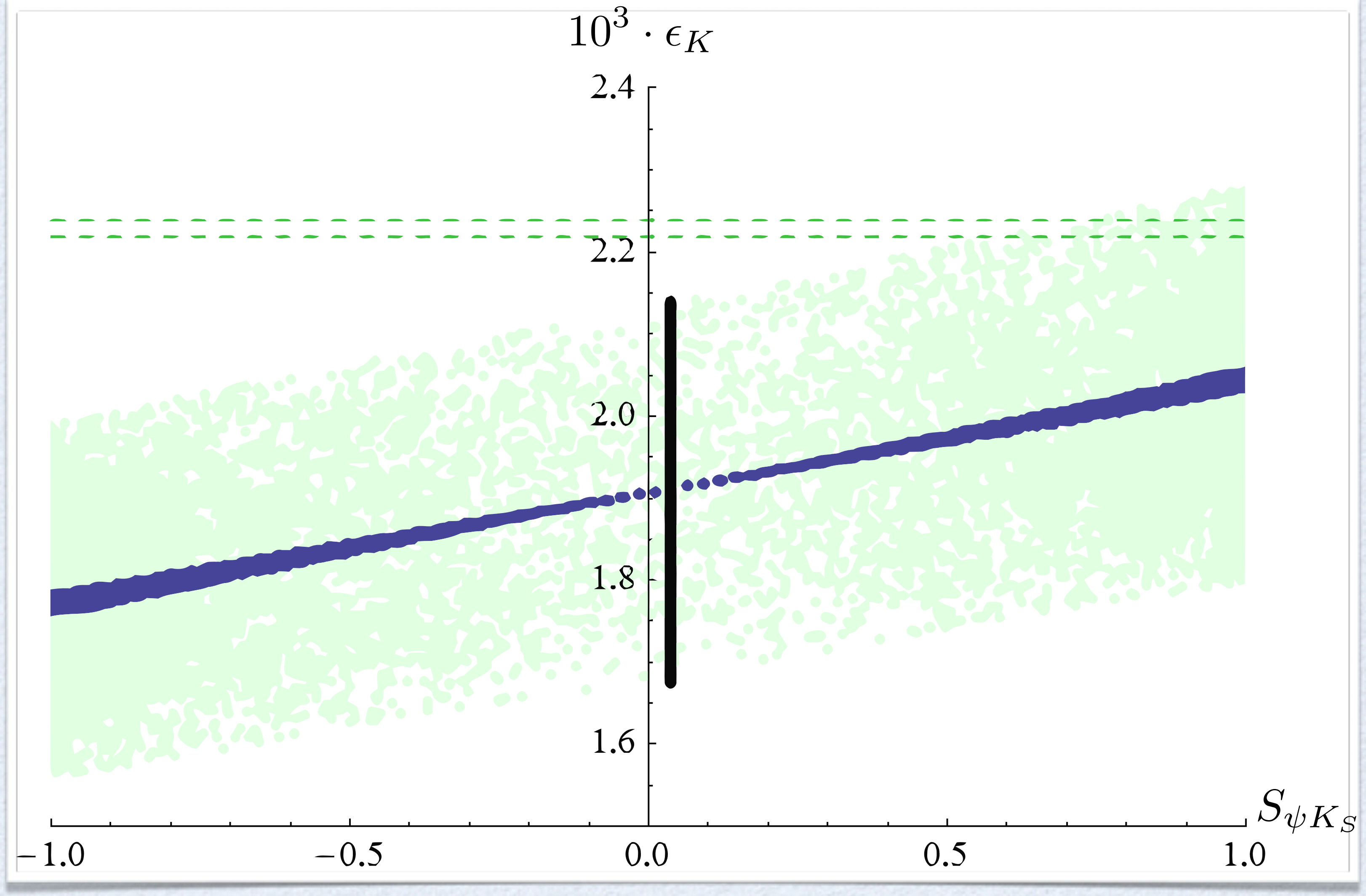

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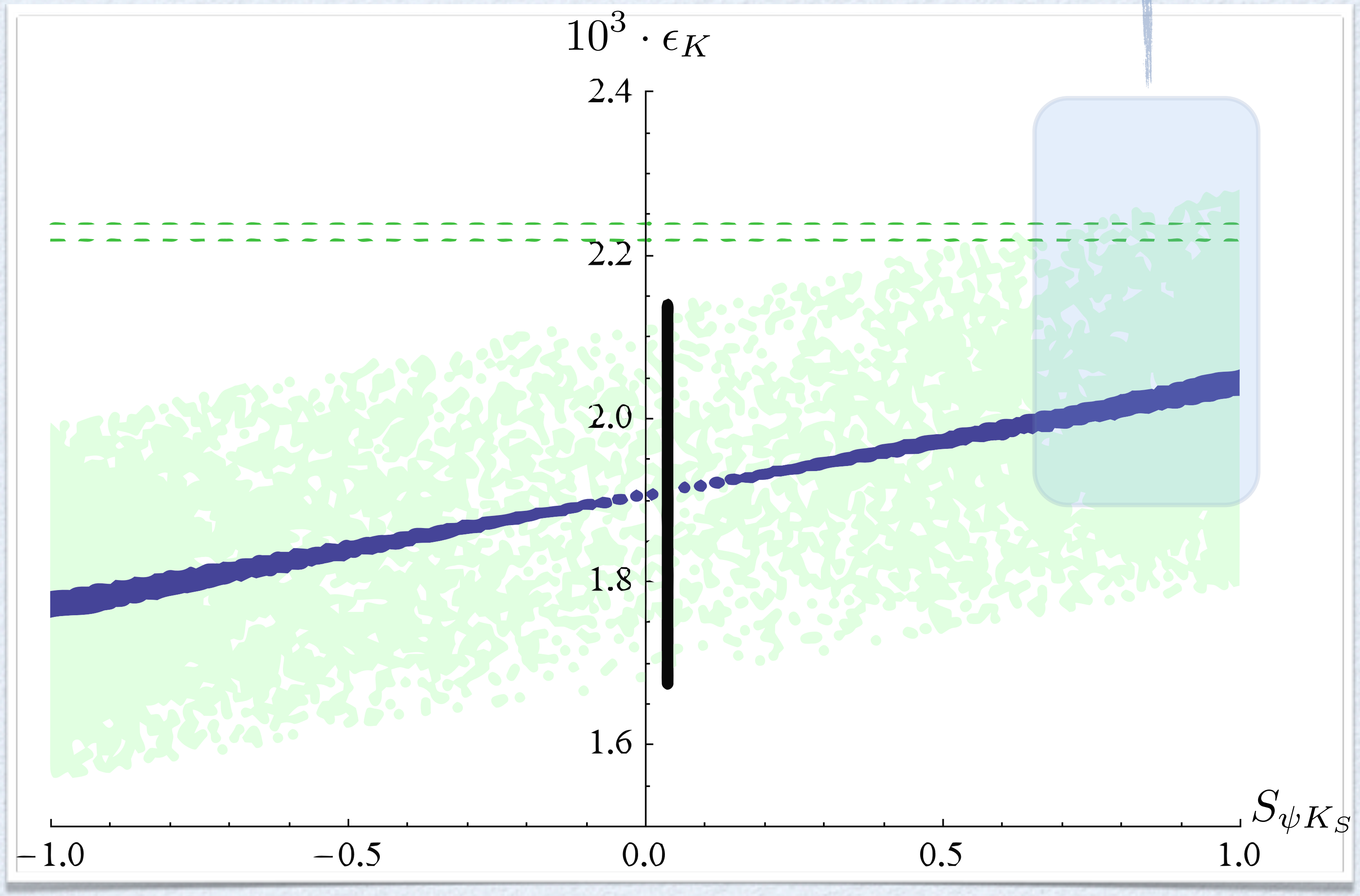
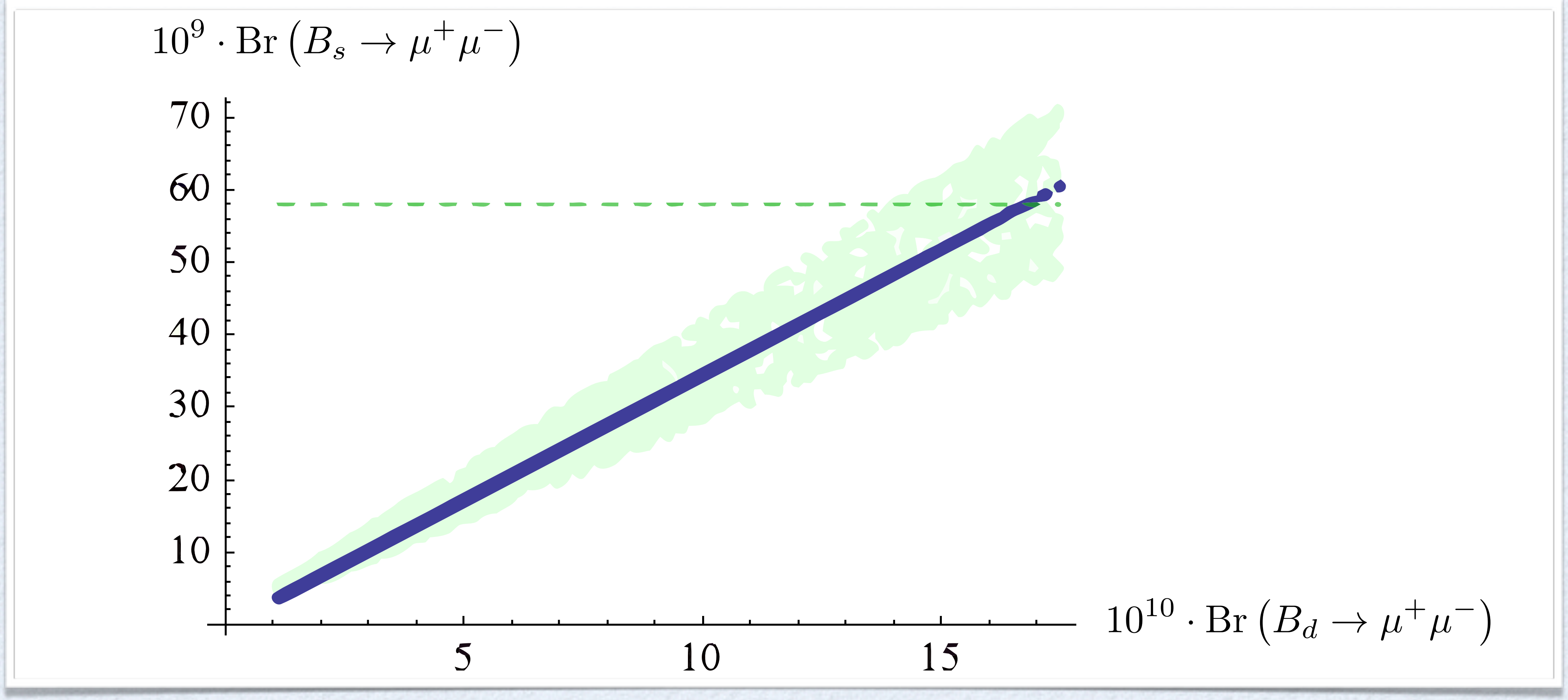


Buras, MVC, Gori and Isidori, 2010

$B_{d,s} \rightarrow \mu\,\mu$: A "SMOKING GUN" FOR MFV

$$\frac{\mathrm{Br}(B_s \to \mu^+\mu^-)}{\mathrm{Br}(B_d \to \mu^+\mu^-)} = \frac{\hat{B}_{B_d}}{\hat{B}_{B_s}} \frac{\tau(B_s)}{\tau(B_d)} \frac{\Delta M_s}{\Delta M_d}\, r$$



Buras, MVC, Gori and Isidori, 2010

Conclusions

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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.

Thanks

Backup

GENERAL FEATURES - I

$$H_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}\left(v_1 + \rho_1 + i\eta_1\right) \end{pmatrix} \qquad H_2 = \begin{pmatrix} \frac{1}{\sqrt{2}}\left(v_2 + \rho_2 + i\eta_2\right) \\ \phi_2^- \end{pmatrix}$$

$$v \equiv \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}$$

$$\tan\beta = \frac{v_2}{v_1}$$

$$\mathcal{L} = \sum_{i=1,2} D_\mu H_i D^\mu H_i^\dagger + \mathcal{L}_Y - V\left(H_1, H_2\right)$$

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

A rotation to a more convenient basis:

$$\begin{pmatrix} \Phi_v \\ \Phi_H \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2^c \end{pmatrix} \longrightarrow$$

$$\Phi_v = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + S_1 + iG^0) \end{pmatrix}$$

$$\Phi_H = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(S_2 + iS_3) \end{pmatrix}$$

Masses eigenstates: $\quad A^0 \equiv S_3 \qquad h^0, H^0 = R(S_1, S_2)$

GENERAL FEATURES - II

$$-\mathcal{L}_Y = \bar{Q}_L \left(\frac{\sqrt{2}}{v} M_d \Phi_v + Z_d \Phi_H \right) D_R + \bar{Q}_L \left(\frac{\sqrt{2}}{v} M_u \Phi_v^c + Z_u \Phi_H^c \right) U_R + \text{h.c.}$$

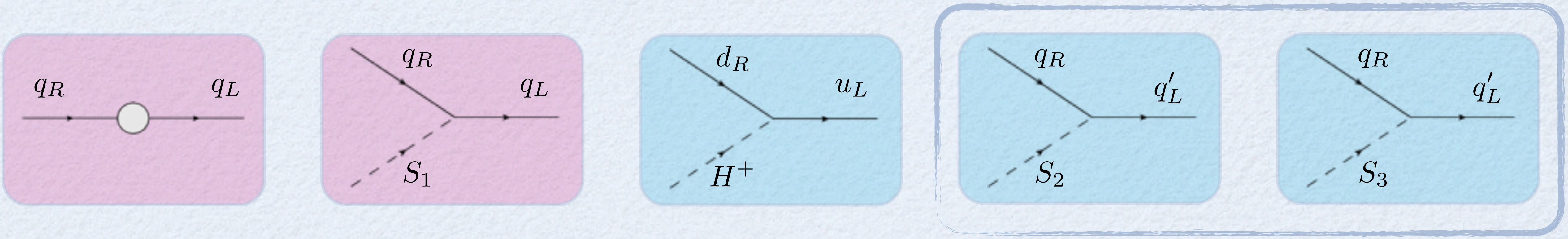
$$M_{u,d} = \frac{v}{\sqrt{2}} \left(\cos\beta \; X_{u,d\;1} + \sin\beta \; X_{u,d\;2} \right) \qquad Z_{u,d} = \cos\beta \; X_{u,d\;2} - \sin\beta \; X_{u,d\;1}$$

$M_{u,d}$ and $Z_{u,d}$ cannot be diagonalized simultaneously!

$$U^\dagger_{u,d\;L} M_{u,d} U_{u,d\;R} = D_{u,d} \equiv \text{diag}\left(m_{u,d}, m_{c,s}, m_{t,b} \right)$$

$$U^\dagger_{u,d\;L} Z_{u,d} U_{u,d\;R} = N_{u,d} \qquad \text{(non diagonal)}$$

$$-\mathcal{L}_Y = \bar{Q}_L V \left(\frac{\sqrt{2}}{v} D_d \Phi_v + N_d \Phi_H \right) D_R + \bar{Q}_L \left(\frac{\sqrt{2}}{v} D_u \Phi_v^c + N_u \Phi_H^c \right) U_R + \text{h.c.}$$



Flavour Changing Neutral Currents

NFC by a Continuous Symmetry

U(1)$_{PQ}$: the symmetry under which D_R and H_1 have opposite charge, while all the other fields are neutral.

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

U(1)$_{PQ}$ must be broken beyond the tree level to avoid a massless Higgs:

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

ϵ_d: ***O***(10^{-2}), typical loop suppression

Δ_d: 3 × 3 flavour-breaking matrix with ***O***(1) entries

But the consistency with experimental data requires

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

Large amount of fine tuning needed to suppress FCNCs!

NFC by a Discrete Symmetry

Z_2 under which $H_1 \to -H_1$, $D_R \to -D_R$ and all other fields are unchanged.

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

Z_2 could be exact in principle

but

it allows higher-dimensional operators such as

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

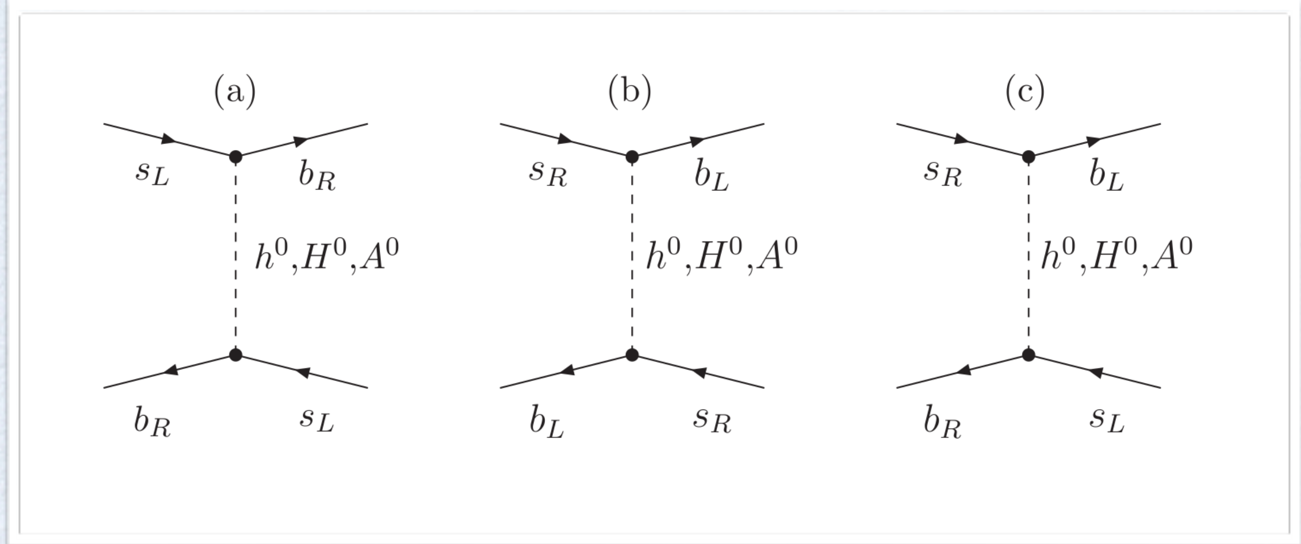
$c_i = \mathcal{O}(1)$ $\Lambda = \mathcal{O}(1\ \text{TeV})$

$\downarrow$

Too large FCNCs even at loop level!

FCNCS IN MFV - I

FCNCs at "tree" level



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

$a_i = \mathcal{O}(1)$

(real? complex?)

$$\Delta = \begin{pmatrix} 0 & & \\ & 0 & \\ & & 1 \end{pmatrix} \quad \lambda_u = \frac{1}{\sin\beta} \begin{pmatrix} \frac{m_u}{v} & & \\ & \frac{m_c}{v} & \\ & & \frac{m_t}{v} \end{pmatrix} \quad \lambda_d = \frac{1}{\cos\beta} \begin{pmatrix} \frac{m_d}{v} & & \\ & \frac{m_s}{v} & \\ & & \frac{m_b}{v} \end{pmatrix}$$

double CKM suppression + down-type Yukawa suppression

D'Ambrosio, Giudice, Isidori and Strumia, 2002

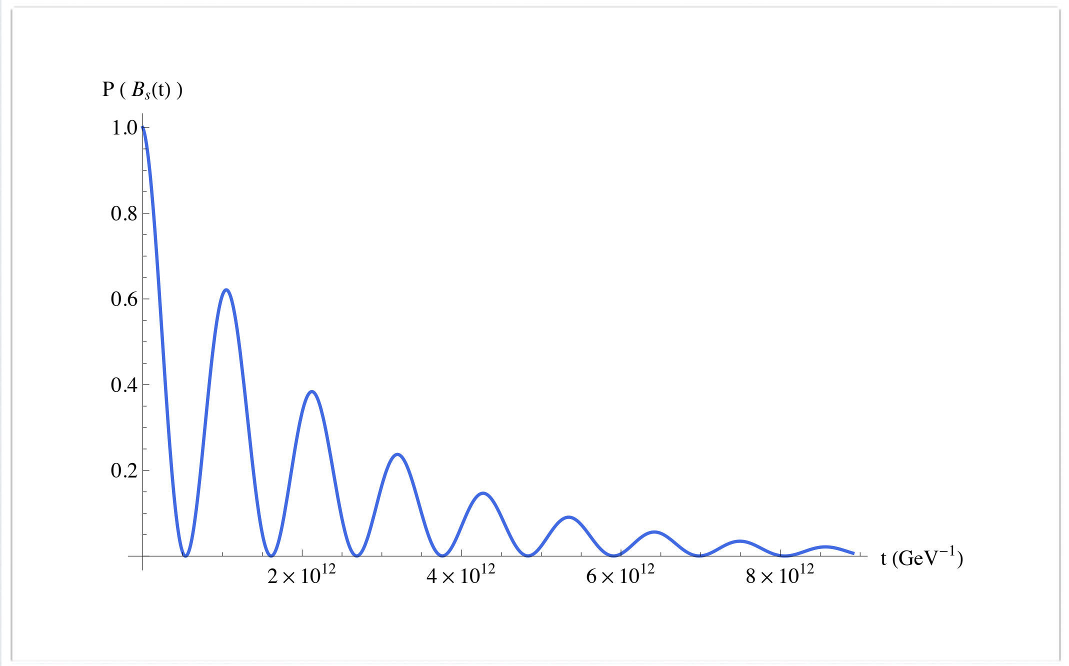
BASIC OBSERVABLES IN ΔF=2 TRANSITIONS

Neutral mesons systems:

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

Mass Eigenstates $K_L - K_S$

CP Eigenstates $K_1 - K_2$



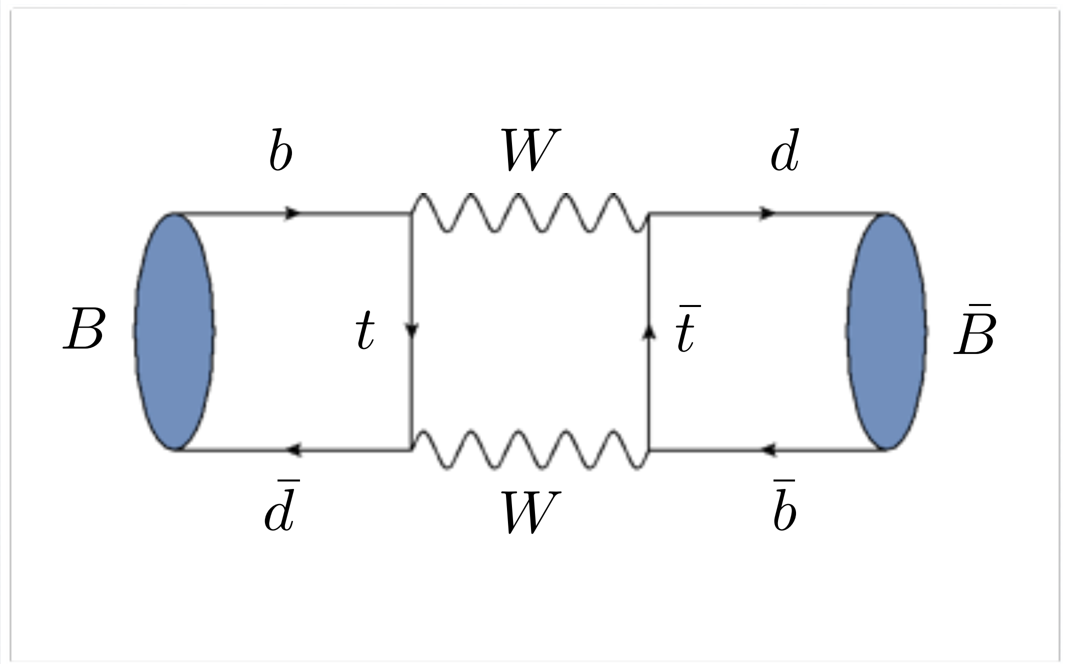
Main observables:

Mass differences

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

CP asymmetries

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



More on Asymmetries

$$\epsilon_K = \frac{\Gamma\left(K_L \to (\pi\pi)_{I=0}\right)}{\Gamma\left(K_S \to (\pi\pi)_{I=0}\right)}$$

$$a_f(t) = -\frac{A_f^{\rm dir}\cos\left(\Delta m\, t\right) + \boxed{A_f^{\rm mix}}\sin\left(\Delta m\, t\right)}{\cosh\left(\frac{\Delta\Gamma\, t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma\, t}{2}\right)}$$

$$B_d \to \psi K_S \longrightarrow S_{\psi K_S}$$

$$B_s \to \psi\phi \longrightarrow S_{\psi\phi}$$

THE ROLE OF M_{12}

$$2m_M M_{12}^M = \langle M | \mathcal{H}_{\text{eff}} | \bar{M} \rangle$$

$$\Delta m_M = 2 \left| M_{12}^M \right| \qquad \text{asymmetries} \propto \text{Arg}\left(M_{12}^M \right)$$

Parametrization of New Physics:

$$(M_{12}^d)_{SM} = |(M_{12}^d)_{SM}| \, e^{2i\beta} \longrightarrow M_{12}^d = (M_{12}^d)_{SM} \, C_{B_d} e^{i\theta_d}$$

$$(M_{12}^s)_{SM} = |(M_{12}^s)_{SM}| \, e^{2i\beta_s} \longrightarrow M_{12}^s = (M_{12}^s)_{SM} \, C_{B_s} e^{i\theta_s}$$