Correlations between Flavour Observables in NP Models

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A. Buras, JG: [arXiv:1306.3775], A. Buras, JG: [arXiv:1309.2466]
A. Buras, F. De Fazio, JG, M. V. Carlucci: JHEP **1301** [arXiv:1211.1237]
A. Buras, F. De Fazio, JG: JHEP **1302** [arXiv:1211.1896]
A. Buras, F. De Fazio, JG, R. Knegjens, M. Nagai, JHEP **1306** [arXiv:1303.3723]
A. Buras, R. Fleischer, JG, R. Knegjens, JHEP **1306** [arXiv:1303.3820]

A. Buras, JG: JHEP **1301** [arXiv:1206.3878]

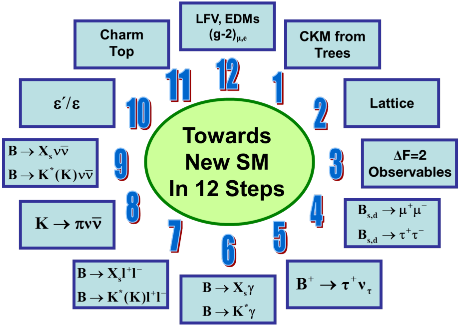
3rd workshop on implications of LHCb measurements and future prospects

14-16th October 2013

Greetings from Andrzej!

How to find NP in flavour physics?

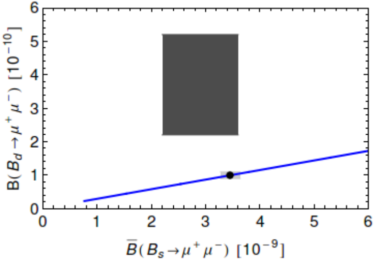
- CKM parameters should be determined by means of tree-level decays ⇒ no NP pollution
- Lattice: non-perturbative parameters should have small uncertainties
- study many different observables and their correlations



Predictions on correlations among flavour observables provide the path to identify which NP model, if any at all, is realized in nature

Test of constrained MFV

$$\frac{\mathcal{B}(B_s \to \mu^+\mu^-)}{\mathcal{B}(B_d \to \mu^+\mu^-)} = \frac{\hat{B}_d}{\hat{B}_s}\frac{\tau(B_s)}{\tau(B_d)}\frac{\Delta M_s}{\Delta M_d}$$



$$S_{\psi\phi}^{\rm exp} = -(0.04^{+0.10}_{-0.13})$$
$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)^{\rm exp} = (2.9 \pm 0.7) \times 10^{-9}$$
$$\mathcal{B}(B_d \to \mu^+\mu^-)^{\rm exp} = \left(3.6^{+1.6}_{-1.4}\right) \times 10^{-10}$$

$$S_{\psi\phi}^{\rm SM} = 0.038 \pm 0.005$$
$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)^{\rm SM} = (3.56 \pm 0.18) \cdot 10^{-9}$$
$$\mathcal{B}(B_d \to \mu^+\mu^-)_{\rm SM} = (1.05 \pm 0.07) \times 10^{-10}$$

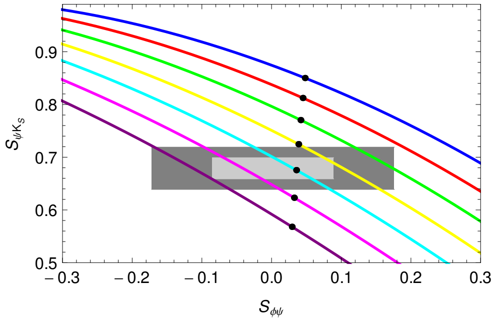
[Buras,JG,Guadagnoli,Isidori,2012], [De Bruyn, Fleischer, Knegjens, Koppenburg, Merk, 2012], [Buras, Fleischer, JG, Knegjens, 2013]

$$\left[\frac{\mathcal{B}(B_d \to \mu^+\mu^-)}{\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)}\right]_{\rm exp} \approx (4.3 \pm 1.8)\left[\frac{\mathcal{B}(B_d \to \mu^+\mu^-)}{\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)}\right]_{\rm SM/CMFV}$$

What happens in other NP models?

Models with a $U(2)^3$ symmetry

- Global flavour symmetry $G_F = U(2)_Q \times U(2)_u \times U(2)_d$ (MFV: $U(3)^3$)
  [Pomarol, Tommasini: hep-ph/9507462; Barbieri, Dvali, Hall: hep-ph/9512388; Barbieri, Buttazzo, Isidori, Jones-Perez, Lodone, Sala, Straub: 1105.2296, 1108.5125, 1203.4218, 1203.4218
- third generation is treated separately
- K system governed by MFV structure; B_d and B_s system correlated:

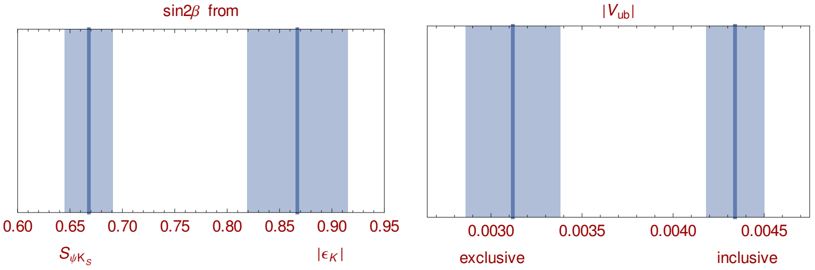


triple correlation $S_{\psi\phi} - S_{\psi K_S} - |V_{ub}|$
For different values of $|V_{ub}|$: 0.0046 (blue)– 0.0028 (purple)
[Buras, JG: 1206.3878]

Tensions in the Flavour data

$S_{\psi K_S} - |\varepsilon_K|$ tension $\longleftrightarrow$ $|V_{ub}|$ problem

- SM: $S_{\psi K_S} = \sin 2\beta$, $|\varepsilon_K| \propto \sin 2\beta |V_{cb}|^4$: 3.2$\sigma$ discrepancy
  [Buras, Guandagnoli, Phys. Rev. D 78 (2008), Lunghi, Soni, Phys. Lett. B 708 (2012)]
- $\beta_{\text{true}} = \beta_{\text{true}}(|V_{ub}|, \gamma)$

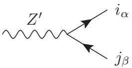


1. exclusive (small) $|V_{ub}|$: $S_{\psi K_S}$ in agreement with data, $|\varepsilon_K|$ below the data
2. inclusive (large) $|V_{ub}|$: $S_{\psi K_S}$ above data, $|\varepsilon_K|$ in agreement with data

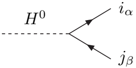
New particles?

heavy gauge boson, heavy (pseudo) scalar, heavy (vectorial) fermion

- Assumptions: tree-level flavour changing couplings
  - 331 models: $SU(3)_C \times SU(3)_L \times U(1)_X$: left-handed Z' FCNCs
    A. Buras, F. De Fazio, JG, M. V. Carlucci, [1211.1237]
  - A Minimal Theory of Fermion Masses: model with new vectorlike fermions and tree-level Z^0 FCNCs A. Buras, JG, R. Ziegler, [1301.5498]
- Flavour-changing couplings: $\Delta_L^{bs} = -\tilde{s}_{23} e^{-i\delta_{23}}$, etc.



$i\gamma_\mu \delta_{\alpha\beta} \left[\Delta_L^{ij}(Z')P_L + \Delta_R^{ij}(Z')P_R\right]$



$i\delta_{\alpha\beta} \left[\Delta_L^{ij}(H^0)P_L + \Delta_R^{ij}(H^0)P_R\right]$

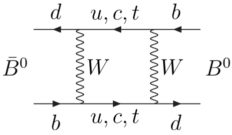
1. Left-handed Scenario (LHS): $\Delta_L^{bq} \neq 0$ and $\Delta_R^{bq} = 0$
2. Right-handed Scenario (RHS): $\Delta_L^{bq} = 0$ and $\Delta_R^{bq} \neq 0$
3. Left-Right Scenario (LRS): $\Delta_L^{bq} = \Delta_R^{bq} \neq 0$
4. Asymmetric Left-Right Scenario (ALRS): $\Delta_L^{bq} = -\Delta_R^{bq} \neq 0$

Strategy

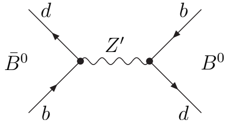
- $\Delta F = 2$ observables [A. Buras, F. De Fazio, JG: JHEP **1302** [1211.1896]]

$$\boxed{B_d : \Delta M_d \,,\, S_{\psi K_S} \,, \qquad B_s : \Delta M_s \,,\, S_{\psi\phi} \,, \qquad K : \Delta M_K \,,\, \varepsilon_K}$$

SM loop contribution



tree-level NP contribution



$$\boxed{\text{Constraints on free parameters } \tilde{s}_{ij}, \delta_{ij} \Rightarrow \text{“oases”}}$$

- Include $\Delta F = 1$ observables and find correlations

$B_{s,d} \to \mu^+\mu^-$ $\quad S_{\mu\mu}^{s,d}$ $\quad B \to K^{(*)}\ell^+\ell^-$ $\quad B \to K^{(*)}\nu\bar{\nu}$ $\quad B \to X_s\nu\bar{\nu}$

$K^+ \to \pi^+\nu\bar{\nu}$ $\quad K_L \to \pi^0\nu\bar{\nu}$ $\quad K_L \to \mu^+\mu^-$

$\Delta F = 2$ constraints: Oases in parameter space

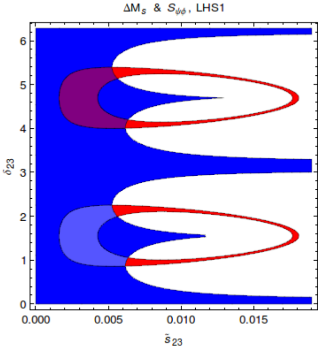
A. Buras, F. De Fazio, JG: JHEP **1302** [1211.1896]

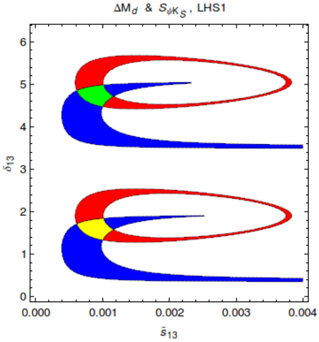
A. Buras, F. De Fazio, JG, M. V. Carlucci: JHEP **1301** [1211.1237]

Finding oases in parameter space in LHS for Z'

$M_{Z'} = 1$ TeV, $C_{B_s} = 0.93 \pm 0.05$, $C_{B_d} = 0.92 \pm 0.05$, $|V_{ub}| = 0.0034$

$$16.9\text{ps}^{-1} \leq \Delta M_s \leq 18.7\text{ps}^{-1}, \quad -0.20 \leq S_{\psi\phi} \leq 0.20,$$
$$0.48\text{ps}^{-1} \leq \Delta M_d \leq 0.53\text{ps}^{-1}, \quad 0.64 \leq S_{\psi K_S} \leq 0.72$$



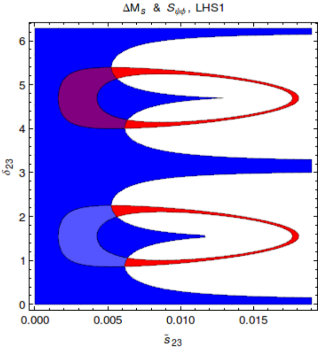


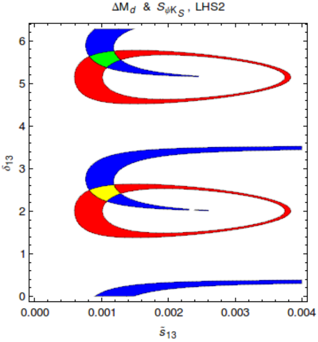
Same approach for RHS, LRS, ALRS and also for H^0/A^0 case
Inclusion of $\Delta F = 1$ observables helps to select the optimal oases

Finding oases in parameter space in LHS for Z'

$M_{Z'} = 1$ TeV, $C_{B_s} = 0.93 \pm 0.05$, $C_{B_d} = 0.92 \pm 0.05$, $|V_{ub}| = 0.0040$

$$16.9\mathrm{ps}^{-1} \leq \Delta M_s \leq 18.7\mathrm{ps}^{-1}, \quad -0.20 \leq S_{\psi\phi} \leq 0.20,$$
$$0.48\mathrm{ps}^{-1} \leq \Delta M_d \leq 0.53\mathrm{ps}^{-1}, \quad 0.64 \leq S_{\psi K_S} \leq 0.72$$





Same approach for RHS, LRS, ALRS and also for H^0/A^0 case
Inclusion of $\Delta F = 1$ observables helps to select the optimal oases

$U(2)^3$ limit

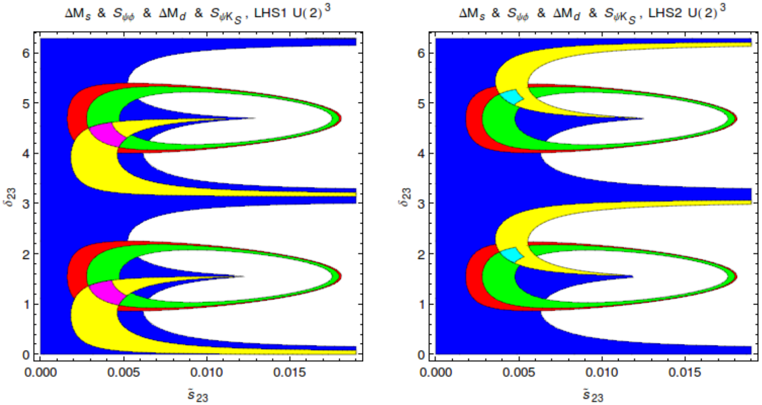
- Global flavour symmetry $U(2)_Q \times U(2)_u \times U(2)_d$ broken *minimally* by three spurions
- K system governed by MFV structure; B_d and B_s system correlated:

$$\frac{\tilde{s}_{13}}{|V_{td}|} = \frac{\tilde{s}_{23}}{|V_{ts}|}, \quad \delta_{13} - \delta_{23} = \beta - \beta_s.$$

triple correlation: $V_{ub} - S_{\psi K_S} - S_{\psi\phi}$

Example: Z' LHS case

[Buras,JG, 1206.3878]



B_s sector for Z', H^0 and A^0 scenario

Some definitions before:

$$\mathcal{B}(B_s \to \mu^+\mu^-) = \left[\frac{1-y_s^2}{1+\mathcal{A}_{\Delta\Gamma}^{\mu\mu} y_s}\right] \overline{\mathcal{B}}(B_s \to \mu^+\mu^-),$$

Time-dependent tagged rate asymmetry:

$$\frac{\Gamma(B_s^0(t) \to \mu^+\mu^-) - \Gamma(\bar{B}_s^0(t) \to \mu^+\mu^-)}{\Gamma(B_s^0(t) \to \mu^+\mu^-) + \Gamma(\bar{B}_s^0(t) \to \mu^+\mu^-)} = \frac{S_{\mu\mu} \sin(\Delta M_s t)}{\cosh(y_s t/\tau_{B_s}) + \mathcal{A}_{\Delta\Gamma}^{\mu\mu} \sinh(y_s t/\tau_{B_s})}.$$

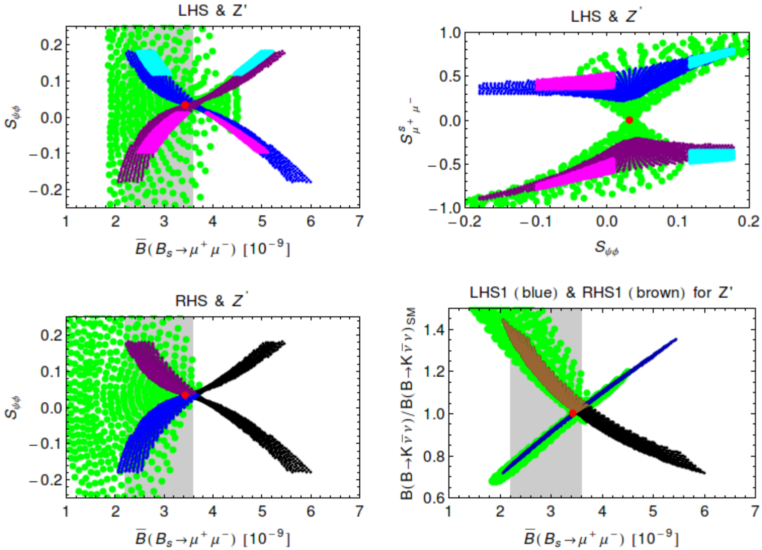
$$(\mathcal{A}_{\Delta\Gamma}^{\mu\mu})^{\text{SM}} = 1\,, \qquad S_{\mu\mu}^{\text{SM}} = 0$$

$\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ can also be determined through measurement of effective lifetime

[A. Buras, R. Fleischer, JG, R. Knegjens, JHEP **1306** [1303.3820]]

general Z' scenarios: B_s sector

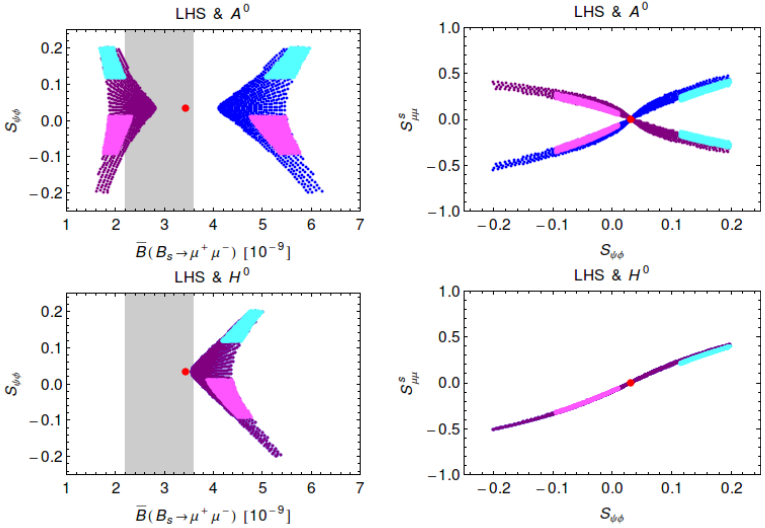
triple correlation: $S_{\psi\phi} - B_s \to \mu^+\mu^- - S^s_{\mu\mu}$ [Buras, De Fazio, JG, 1211.1896]
green: compatible with $b \to s\ell^+\ell^-$ [Altmannshofer,Straub, 1206.0273, 1308.1501]



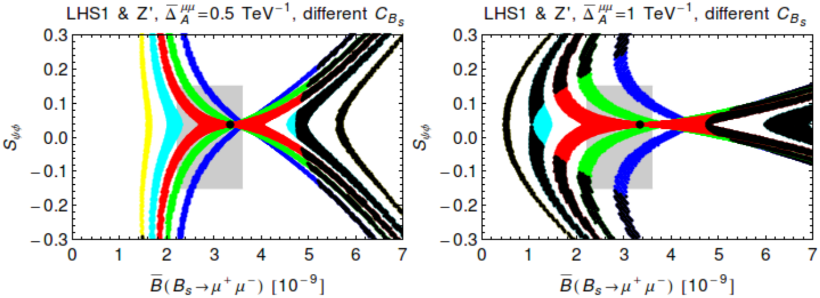
general H^0/A^0 scenarios: B_s sector

Buras,De Fazio,JG,Knegjens,Nagai,[1303.3723]; Buras,Fleischer,JG,Knegjens,[1303.3820]

LHS: Pseudoscalar vs scalar; magenta/cyan: $U(2)^3$ limit with excl/incl. $|V_{ub}|$



[A. Buras, JG, 1309.2466]



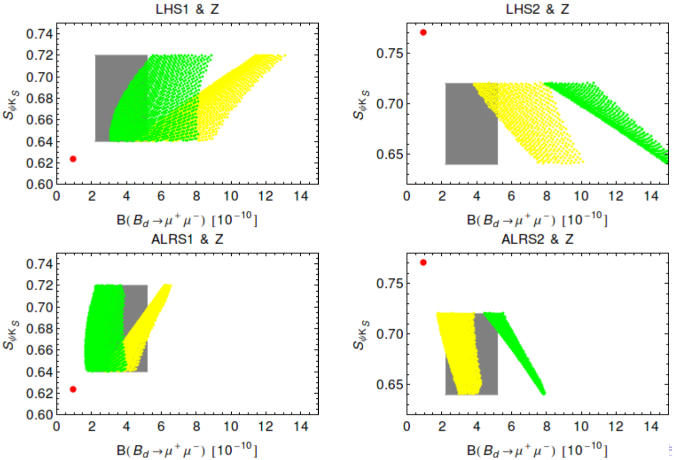
For different $C_{B_s} = 0.90 \pm 0.01$ (blue), 0.96 ± 0.01 (green), $1.00 \pm\ 0.01$ (red), 1.04 ± 0.01 (cyan), 1.10 ± 0.01 (yellow)
Lepton coupling $\bar{\Delta}_A^{\mu\bar{\mu}} = 0.5\ \text{TeV}^{-1}$ (left) and $1.0\ \text{TeV}^{-1}$ (right)
black: excluded due to (simplified) $b \to s\ell^+\ell^-$ constraints by Altmannshofer and Straub

Tree-level Z^0 FCNCs

Lepton couplings fixed and mass scale fixed

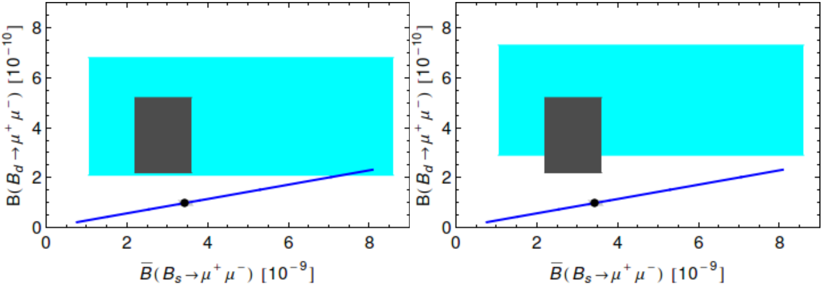
Z^0 FCNCs: B_d sector

- $B_d \to \mu^+\mu^-$: effects small in MFV, CMFV and Z', but large in Z^0 FCNCs
- $S_{\psi K_S}$ vs $B_d \to \mu^+\mu^-$ $\Rightarrow$ Enhancement possible [Buras,De Fazio,JG,1211.1896]



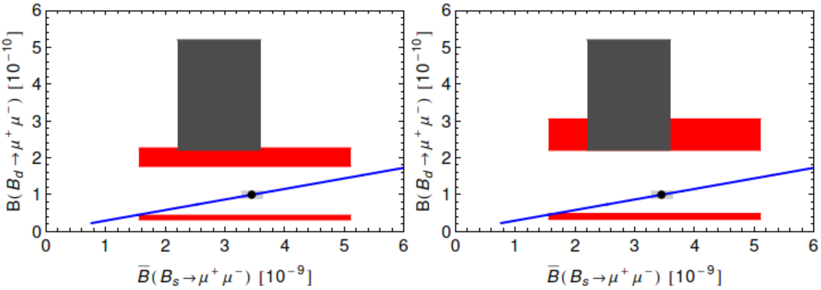
$B_d \to \mu^+\mu^-$ versus $B_s \to \mu^+\mu^-$

For LHS Z scenario [A. Buras, JG, 1309.2466]



$C_{B_d} = 0.96 \pm 0.01$, $C_{B_s} = 1.00 \pm 0.01$, $0.639 \leq S_{\psi K_s} \leq 0.719$ and $-0.15 \leq S_{\psi\phi} \leq 0.15$. Left $|V_{ub}| = 0.0034$, right $|V_{ub}| = 0.0040$.

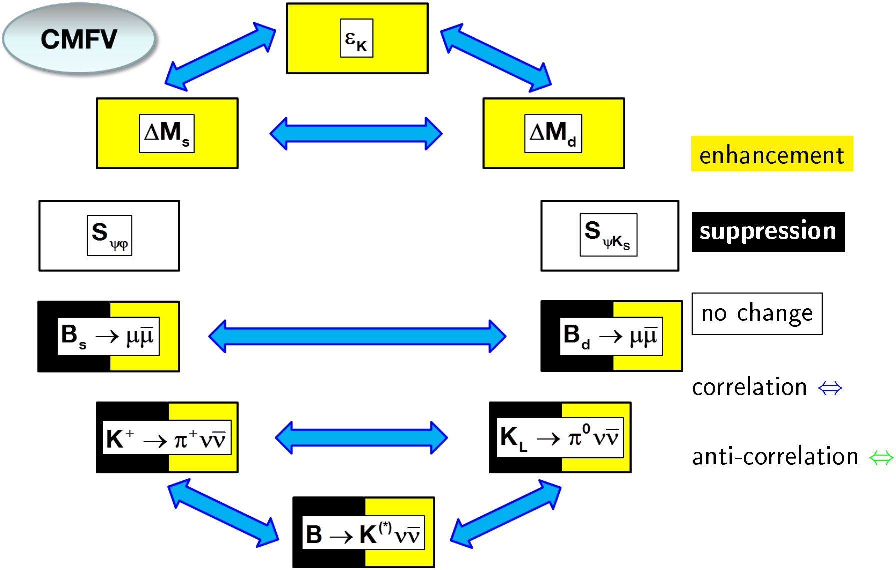
For LHS Z' scenario [A. Buras, JG, 1309.2466]

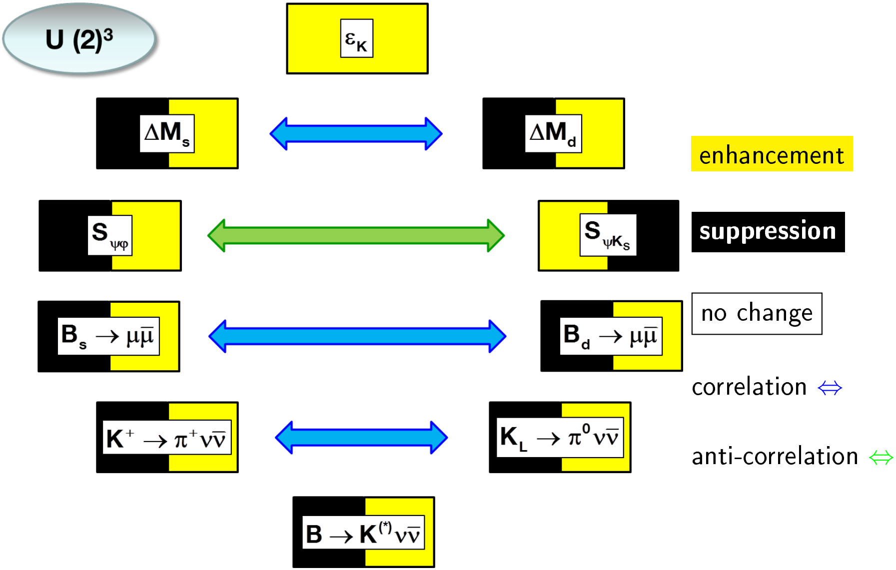


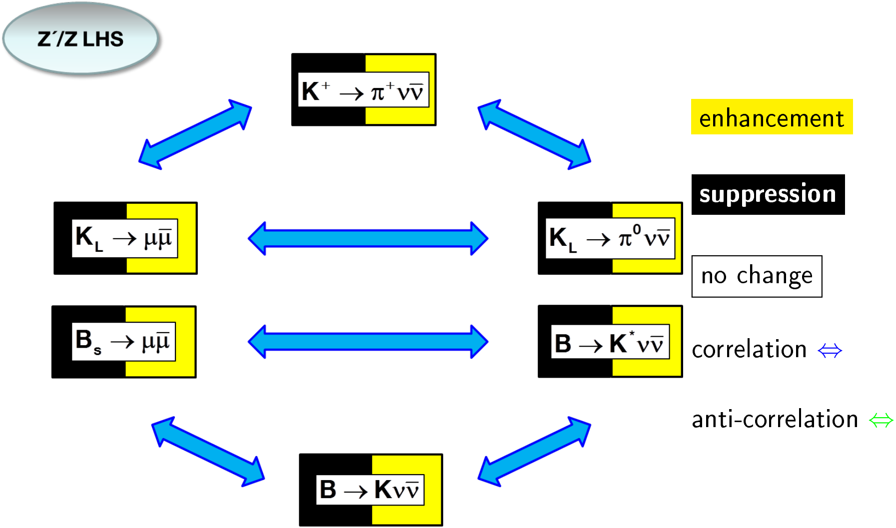
$C_{B_d} = 1.04 \pm 0.01$, $C_{B_s} = 1.00 \pm 0.01$, $\bar{\Delta}_A^{\mu\bar{\mu}} = 1\ \text{TeV}^{-1}$, $0.639 \leq S_{\psi K_s} \leq 0.719$, $-0.15 \leq S_{\psi\phi} \leq 0.15$. Left $|V_{ub}| = 0.0034$, right $|V_{ub}| = 0.0040$.

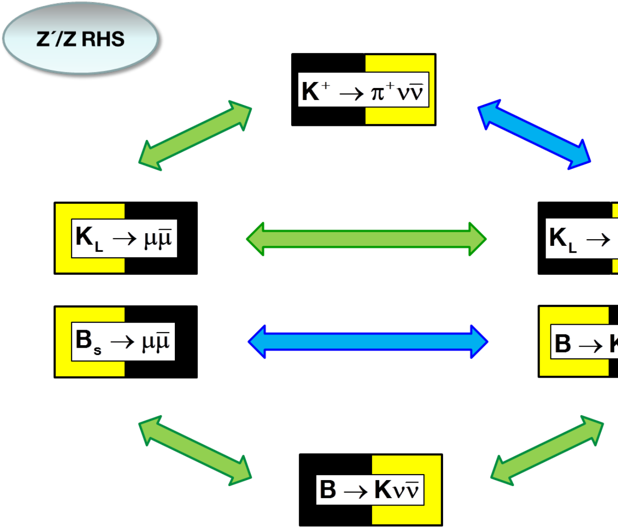
"DNA-charts"

[Buras, JG; Review 1306.3775]


CMFV
εK
ΔMs
ΔMd
Sψφ
SψKS
Bs → μμ̄
Bd → μμ̄
K+ → π+νν̄
KL → π0νν̄
B → K(*)νν̄
enhancement
suppression
no change
correlation ⇔
anti-correlation ⇔


U (2)^3
ε_K
ΔM_s
ΔM_d
$S_{\psi\phi}$
$S_{\psi K_S}$
$B_s \to \mu\bar{\mu}$
$B_d \to \mu\bar{\mu}$
$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$B \to K^{(*)} \nu\bar{\nu}$
enhancement
suppression
no change
correlation ⇔
anti-correlation ⇔


Z′/Z LHS
K+ → π+νν̄
KL → μμ̄
KL → π0νν̄
Bs → μμ̄
B → K*νν̄
B → Kνν̄
enhancement
suppression
no change
correlation ⇔
anti-correlation ⇔



enhancement

suppression

no change

correlation ⇔

anti-correlation ⇔

Summary

Summary

Z' scenarios:

- Small tensions in $\Delta F = 2$ observables can be removed
- RHS: strong constraints from $b \to s\ell^+\ell^-$, LRS: no effects in $B_{s,d} \to \mu^+\mu^-$
- $K \to \pi\bar{\nu}\nu$ important role to flavour-violating Z' masses outside the reach of the LHC

H^0/A^0 scenarios:

- rich pattern of NP effects in $B_{d,s}$ system but only small effects in K sector
- correlations between $S_{\psi\phi}$, $\mathcal{B}(B_s \to \mu^+\mu^-)$ and $S^s_{\mu^+\mu^-}$: differences between A^0, H^0 and Z' case due to spin and CP-parity

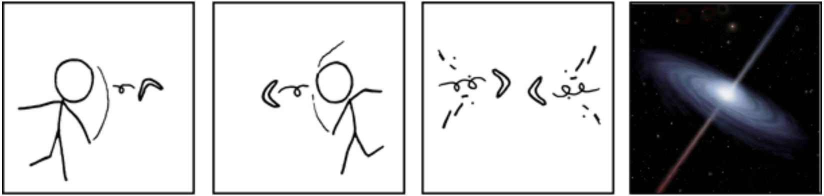
Both scalar and Z' scenarios

- $U(2)^3$ symmetry $\to$ prediction for correlation of $S_{\psi\phi}$ vs $B_s \to \mu^+\mu^-$ ($|V_{ub}|$ dependence!)

Z scenarios:

- Data for $B_{s,d} \to \mu^+\mu^-$ can be understood but not $B \to K^\star\mu^+\mu^-$ (vector couplings to muons too small)
- very large effects in $K \to \pi\bar{\nu}\nu$ possible (bounded by $K_L \to \mu^+\mu^-$)

Thanks for your attention



Backup slides

Recent highlights of flavour physics

There were hopes to find clear signals of NP in

$$\boxed{S_{\psi\phi} \text{ and } \mathcal{B}(B_{s,d} \to \mu^+\mu^-)}$$

LHCb/CMS measurement and SM predictions:

$$S_{\psi\phi}^{\text{exp}} = 0.001 \pm 0.087\,, \qquad \overline{\mathcal{B}}(B_s \to \mu^+\mu^-)^{\text{exp}} = (2.9 \pm 0.7) \times 10^{-9}$$

$$\mathcal{B}(B_d \to \mu^+\mu^-)^{\text{exp}} = \left(3.6^{+1.6}_{-1.4}\right) \times 10^{-10}$$

$$S_{\psi\phi}^{\text{SM}} = 0.038 \pm 0.005\,, \qquad \overline{\mathcal{B}}(B_s \to \mu^+\mu^-)^{\text{SM}} = (3.56 \pm 0.18) \cdot 10^{-9}$$

$$\mathcal{B}(B_d \to \mu^+\mu^-)_{\text{SM}} = (1.05 \pm 0.07) \times 10^{-10}$$

[Buras,JG,Guadagnoli,Isidori,2012], [De Bruyn,Fleischer,Knegjens, Koppenburg,Merk,2012], [Buras,Fleischer,JG,Knegjens,2013]

But so far everything is consistent with SM prediction

$B_s \to \mu^+\mu^-$: How to compare theory and experiment

- $\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM} = (3.25 \pm 0.17) \cdot 10^{-9}$ [Buras,JG,Guadagnoli,Isidori,2012]
- LHCb: $\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm LHCb/CMS} = (2.9 \pm 0.7) \times 10^{-9}$
- Comparing th. branching ratio with exp. data $\Rightarrow$ correction factor needed which takes care of $\Delta\Gamma_s$ effects (th. BR is for flavour eigenstates)

$$\mathcal{B}(B_s \to \mu^+\mu^-) = r(y_s)\, \overline{\mathcal{B}}(B_s \to \mu^+\mu^-)$$ [De Bruyn et al. 2012]

$$r(y_s) = \frac{1 - y_s^2}{1 + \mathcal{A}_{\Delta\Gamma} y_s}\,, \qquad y_s = 0.088 \pm 0.014\,, \qquad \text{SM:}\mathcal{A}_{\Delta\Gamma} = 1$$

- Include $r(y_s)$ either in th. branching ratio:

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm SM} = \frac{\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM}}{r(y_s)} = (3.53 \pm 0.18) \cdot 10^{-3}$$

or in experimental value: $\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm LHCb} = (2.6 \pm 0.6) \times 10^{-9}$

New particles?

- What is the first new particle beyond the SM Higgs to be discovered?

heavy gauge boson,	heavy (pseudo) scalar,	heavy (vectorial) fermion

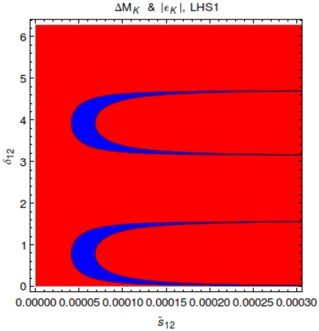
If too heavy for direct discovery $\Rightarrow$ High precision flavour experiments

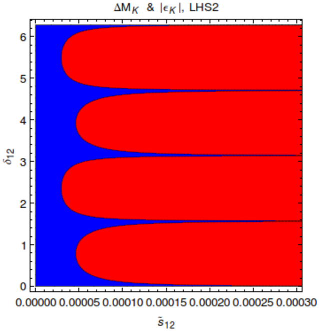
- Z' = a neutral, colourless, spin-1 gauge boson that is a carrier of a new force based on a $U(1)'$
- additional $U(1)'$ symmetry appears in many extensions of the SM:
  - 331 models: $SU(3)_C \times SU(3)_L \times U(1)_X$
    A. Buras, F. De Fazio, JG, M. V. Carlucci: JHEP **1301** [1211.1237]
  - GUT models, e.g. $SO(10) \rightarrow SU(5) \times U(1)'$
  - Left-Right symmetric models: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
  - Little Higgs models, extra dimensions,. . .

Finding oases in parameter space in LHS for Z'

Oases for $M_{Z'} = 1$ TeV and $|V_{ub}| = 0.0034$ (left) $|V_{ub}| = 0.0040$ (right)

$$0.75 \leq \frac{\Delta M_K}{(\Delta M_K)_{\rm SM}} \leq 1.25, \qquad 2.0 \times 10^{-3} \leq |\varepsilon_K| \leq 2.5 \times 10^{-3}$$





Same approach for RHS, LRS, ALRS and also for H^0/A^0 case

Inclusion of $\Delta F = 1$ observables helps to select the optimal oases

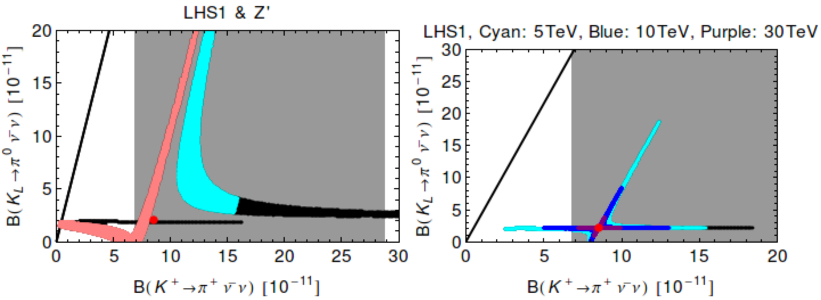
K sector for Z' scenario

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ is CP conserving and $K_L \rightarrow \pi^0 \nu\bar{\nu}$ is CP violating

both dominated by Z penguins; theoretically very clean

general Z' scenarios: K sector

$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ vs $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ (LHS/RHS)



no difference between LHS and RHS (vector currents)
Black region: excluded by $\mathcal{B}(K_L \to \mu^+\mu^-) \leq 2.5 \cdot 10^{-9}$, black line: GN bound

Concrete example with tree-level Z' FCNCs: 331 model based on $SU(3)_C \times SU(3)_L \times U(1)_X$

Main difference to general Z' scenarios:
lepton couplings are fixed and connection between $B_{d,s}$ and K sector $\Rightarrow$ only small effects in ε_K, $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$

331 model: $SU(3)_C \times SU(3)_L \times U(1)_X$

Theoretical features:

- breaking $SU(3)_L \to SU(2)_L \Rightarrow$ new heavy neutral gauge boson Z'
- different treatment of 3rd gen. $\Rightarrow Z'$ mediates FCNC at tree level
- requirement of anomaly cancellation and asymptotic freedom of QCD $\Rightarrow$ number of **generations fixed to $N = 3$!**

[Frampton; Pisano, Pleitez, 1992]

Flavour structure of 331

- Fermions: triplets, anti-triplets and singlets (w.r.t $SU(3)_L$)

$$\begin{pmatrix} e \\ -\nu_e \\ \nu_e^c \end{pmatrix}_L, \begin{pmatrix} \mu \\ -\nu_\mu \\ \nu_\mu^c \end{pmatrix}_L, \begin{pmatrix} \tau \\ -\nu_\tau \\ \nu_\tau^c \end{pmatrix}_L, \qquad \begin{pmatrix} u \\ d \\ D \end{pmatrix}_L, \begin{pmatrix} c \\ s \\ S \end{pmatrix}_L, \begin{pmatrix} b \\ -t \\ T \end{pmatrix}_L$$

$$e_R,\, \mu_R,\, \tau_R, \qquad u_R,\, d_R,\, c_R,\, s_R,\, t_R,\, b_R, \qquad D_R, S_R, T_R$$

- Z' coupling generation non-universal $(a \neq b)$! $\Rightarrow$tree-level FCNC$\propto (b-a)$

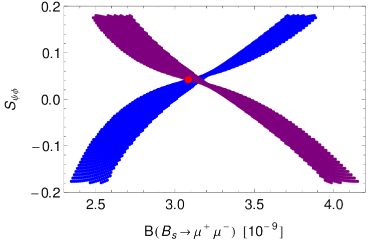
$$\mathcal{L}^{Z'} = J_\mu Z'^\mu\,, \qquad V_{\text{CKM}} = U_L^\dagger V_L,$$

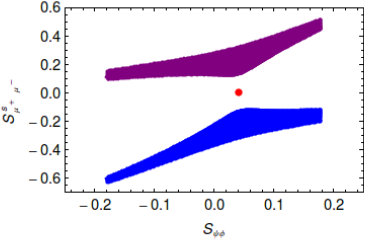
$$J_\mu = \bar{u}_L \gamma_\mu U_L^\dagger \begin{pmatrix} a & & \\ & a & \\ & & b \end{pmatrix} U_L u_L + \bar{d}_L \gamma_\mu V_L^\dagger \begin{pmatrix} a & & \\ & a & \\ & & b \end{pmatrix} V_L d_L\,,$$

- only left-handed (LH) quark currents are flavour-violating
- V_L parametrized by $\tilde{s}_{12}, \tilde{s}_{23}, \tilde{s}_{13}, \delta_{1,2,3} \rightarrow U_L = V_L V_{\text{CKM}}^\dagger$
- B_d sector depends on $\tilde{s}_{13}, \delta_1$
  B_s sector depends on $\tilde{s}_{23}, \delta_2$
  K sector depends on $\tilde{s}_{13}, \tilde{s}_{23}, \delta_2 - \delta_1$

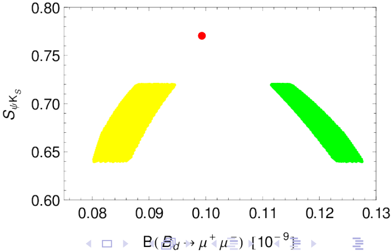
Finding the optimal oases

- $S_{\psi\phi}$ vs. $B_s \to \mu^+\mu^-$ and $S^s_{\mu^+\mu^-}$ vs. $S_{\psi\phi}$



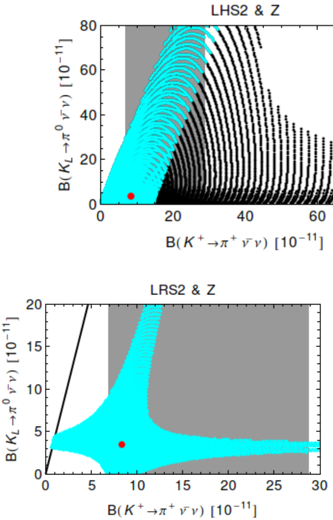


- small effects in $B_d \to \mu^+\mu^-$
- small effects in ε_K, $K_L \to \pi^0\bar{\nu}\nu$ and $K^+ \to \pi^+\bar{\nu}\nu$
- $S_{\psi K_S} - \varepsilon_K$ tension solved using inclusive $|V_{ub}| = 0.004$



Z^0 FCNCs: K sector

$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ versus $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ in LHS, RHS and LRS



black points excluded due to $K_L \to \mu^+\mu^-$
branch unaffected by $K_L \to \mu^+\mu^-$ constraint survives

Left-handed Z' and Z FCNC quark couplings facing new $b \to s\mu^+\mu^-$ data

[Buras, JG; 1309.2466]

Anomaly in $B \to K^* \mu^+ \mu^-$

- 24 angular observables
- good agreement with SM predictions but three deviations
- SM values [Altmannshofer, Straub, 1308.1501]

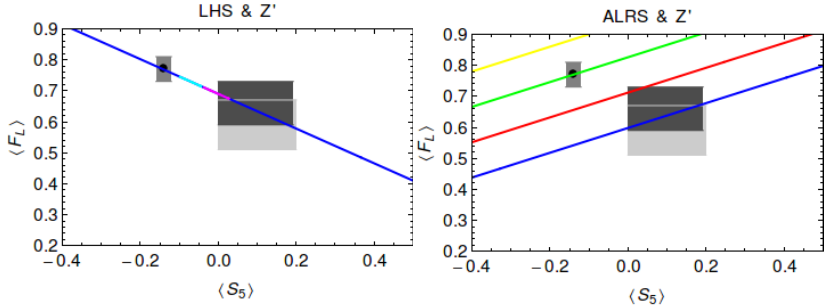
$$\langle F_L \rangle = 0.77 \pm 0.04, \quad \langle S_4 \rangle = 0.29 \pm 0.07, \quad \langle S_5 \rangle = -0.14 \pm 0.02.$$

- LHCb

$$\langle F_L \rangle_{[1,6]} = 0.59 \pm 0.08, \quad \langle S_4 \rangle_{[14.2,16]} = -0.07 \pm 0.11, \quad \langle S_5 \rangle_{[1,6]} = 0.10 \pm 0.10$$

- $\langle F_L \rangle$ and $\langle S_5 \rangle_{[1,6]}$ can be explained by negative C_9^{NP} (and $C_{7\gamma}^{\mathrm{NP}}$) [Altmannshofer, Straub, 1308.1501; Descotes-Genon, Matias, Virto, 1307.5683]

Correlations in LHS and ALRS



Magenta: $C_9^{\rm NP} = -1.6 \pm 0.3$

Cyan: $C_9^{\rm NP} = -0.8 \pm 0.3$

Blue: $C_9^{\rm NP} = -2$

Red: $C_9^{\rm NP} = -1$

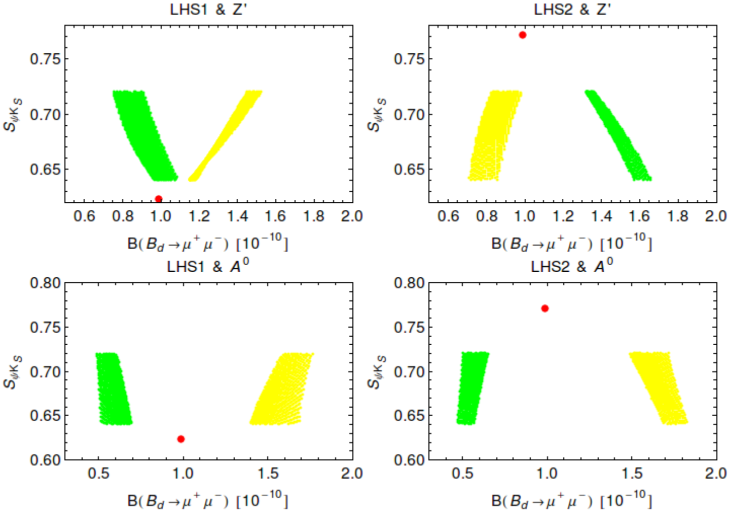
Green: $C_9^{\rm NP} = 0$

Yellow: $C_9^{\rm NP} = -1$

B_d sector for Z' and A^0 scenario

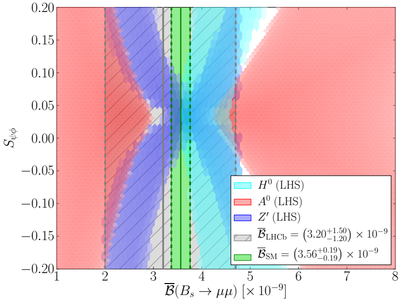
$$\mathcal{B}(B_d \to \mu^+\mu^-)_{\rm SM} = (1.05 \pm 0.07) \cdot 10^{-10}$$
$$\mathcal{B}(B_d \to \mu^+\mu^-)_{\rm exp} = \left(3.6^{+1.6}_{-1.4}\right) \times 10^{-10}$$

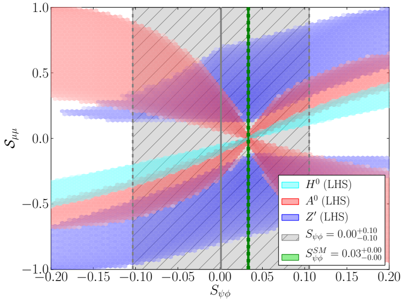
$S_{\psi K_S}$ versus $\mathcal{B}(B_d \to \mu^+\mu^-)$ for $M_{Z'} = 1 = M_{A^0}$ TeV: rather small effects



$$\mathcal{B}(B_d \to \mu^+\mu^-)_{\rm SM} = (1.05 \pm 0.07) \cdot 10^{-10}, \quad \mathcal{B}(B_d \to \mu^+\mu^-)_{\rm exp} \leq 9.4 \cdot 10^{-10}$$

Comparison Z', H^0 and A^0 case in LHS





- Lepton couplings varied in wider range
- For RHS the Z' range is much smaller due to $b \to s\ell^+\ell^-$ constraints
- In LRS: no effects in $B_s \to \mu^+\mu^-$!

A model with new vectorlike fermions and tree-level Z^0 FCNCs

Minimal Theory of Fermion Masses (MTFM)

Idea: explain SM fermion masses and mixings by their dynamical mixing with new heavy vectorlike fermions

- simplified: $\mathcal{L} \propto m\bar{f}F + M\bar{F}F + \lambda hFF$
- light SM fermions have admixture of heavy fermions with explicit mass terms
- $\Rightarrow$ corrections to Z^0, $W^\pm$ and Higgs couplings to quarks $\rightarrow$ tree-level FCNCs!
- central formulae:

$$m_{ij}^X = v\varepsilon_i^Q \varepsilon_j^X \lambda_{ij}^X\,, \qquad (X = U, D)\,, \qquad \varepsilon_i^{Q,U,D} = \frac{m_i^{Q,U,D}}{M_i^{Q,U,D}}$$

Assumptions

[Buras,Gorjean,Pokoski,Ziegler 1105.3725], [Buras,JG,Ziegler 1302.5498]

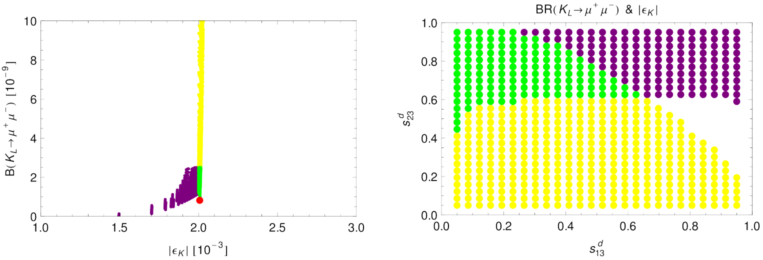
- reduce number of parameters such that it is still possible to reproduce SM Yukawas and suppress flavour violation ⇒ identify minimal FCNC effects.
- TUM (Trivially Unitary Model):
  - Universality of heavy masses $M_i^Q = M_i^U = M_i^D = M$
  - Unitarity of the Yukawa matrices $\lambda^{U,D}$ with $\lambda^U = \mathbb{1}$
  - TUM: after fitting SM quark masses and V_{CKM} ⇒

4 new real parameters and 0 new phases
$M, \quad \varepsilon_3^Q, \quad s_{13}^d, \quad s_{23}^d$

  - Fitting $m_t \Rightarrow 0.8 \leq \varepsilon_3^Q \leq 1$ and we set $M = 3$ TeV

Phenomenology

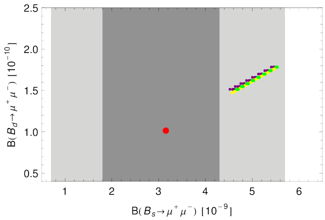
- Flavour changing Z^0 couplings
- NP effects in $B_{s,d}$ mixings negligible
- large effects in ε_K and $K_L \to \mu^+\mu^-$ possible, but NP effects in ε_K bounded by $K_L \to \mu^+\mu^-$



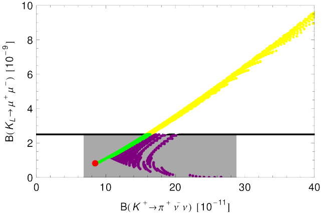
- TUM favours $|V_{ub}| \approx 0.0037$ and $M \geq 3$ TeV $\to S_{\psi K_S} \approx 0.72$ a bit to high

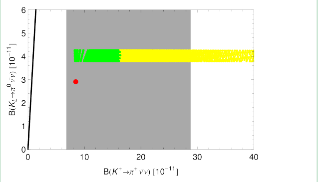
Phenomenology

- B decays: CMFV-like but $B_{s,d} \to \mu^+\mu^-$ enhanced by $\approx 35\%$ relative to SM



- Enhancement of $K \to \pi\bar{\nu}\nu$ and correlation of $K_L \to \pi^0\bar{\nu}\nu$ and $K^+ \to \pi^+\bar{\nu}\nu$ non-CMFV like





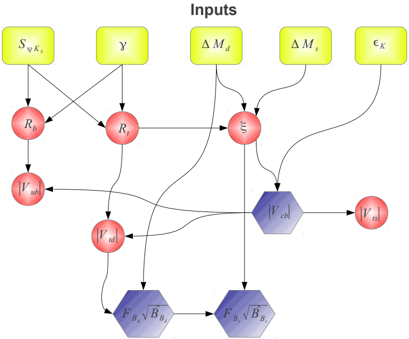
Stringent test of CMFV

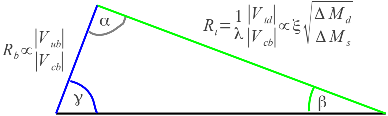
[Buras, JG; 1304.6835]

Test of CMFV using $\Delta F = 2$ data

- $\Delta F = 2$ data for $\Delta M_{s,d}$, ε_K, $S_{\psi K_S}$ very precise
- Which values $|V_{cb}|$, $F_{B_s}\sqrt{\hat{B}_s}$, $F_{B_d}\sqrt{\hat{B}_d}$ needed to fit the data (SM/CMFV)?
- CMFV: $S_0(x_t) \to S(v) \geq S_0(x_t)$
- CMFV: $\gamma = (66.6^\circ \pm 3.7^\circ)$. LHCb: $\gamma = (67.2^\circ \pm 12^\circ)$

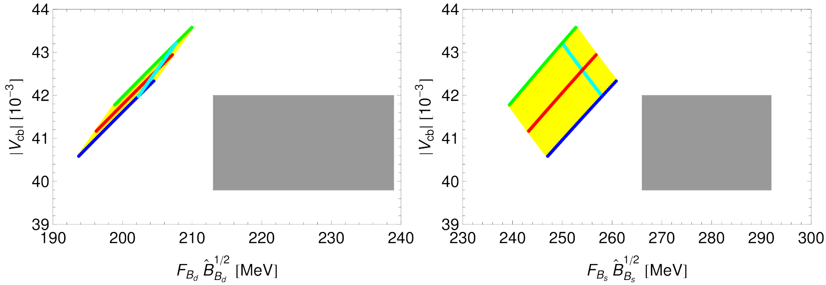
Overview of determination of various quantities [Buras, JG; 1304.6835]





$|V_{cb}|$ vs $F_{B_q}\sqrt{\hat{B}_q}$ within CMFV

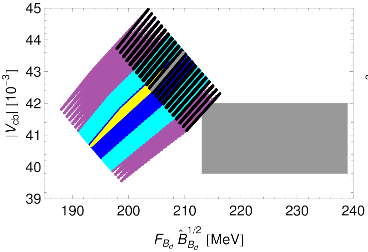
$\gamma = 63^\circ/67^\circ/71^\circ$ (green, red, blue)
$S_{\psi K_S} \in [0.659, 0.699]$
fixed $S(v) = 2.4$ (cyan), $\eta_{cc} = 1.87$, $\eta_{ct} = 0.496$



Decrease of $F^2_{B_s}\hat{B}_{B_s}$ and $F^2_{B_d}\hat{B}_{B_d}$ needed and/or increase of $|V_{cb}|$

Uncertainty due to η_{cc}

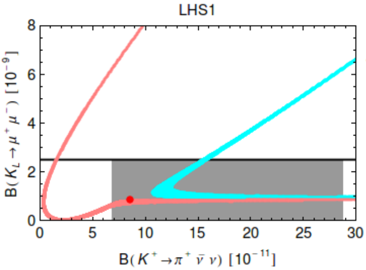
- $\eta_{cc} = 1.87 \pm 0.77$ (error of 41%) enters ε_K
- reduce uncertainty using $\Delta M_K^{\rm exp} \Rightarrow \eta_{cc} \approx 1.70 \pm 0.21$ (error of 12%)



$\gamma \in [63^\circ, 71^\circ]$
Yellow: $S(v) \in [2.31, 2.8]$, $\eta_{cc} = 1.87$, $\eta_{ct} = 0.496$
Purple: $S(v) \in [2.31, 2.8]$, $\eta_{cc} \in [1.10, 2.64]$, $\eta_{ct} \in [0.451, 0.541]$
Cyan: $S(v) \in [2.31, 2.8]$, $\eta_{cc} \in [1.49, 1.91]$, $\eta_{ct} \in [0.451, 0.541]$
Blue: $S(v) \in [2.31, 2.8]$, $\eta_{cc} \in [1.49, 1.91]$, $\eta_{ct} = 0.496$
Black: as purple but with fixed $S(v) = S_0(x_t) = 2.31$

general Z' scenarios: K sector

$\mathcal{B}(K_L \to \mu^+\mu^-)$ vs $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ and LH vs RH senario;



$K_L \to \pi^0\nu\bar{\nu}$ and $K^+ \to \pi^+\nu\bar{\nu}$ are not useful for the search of RH currents as they are sensitive only to the vector couplings but $\mathcal{B}(K_L \to \mu^+\mu^-)$ sensitive to axial-vector coupling

Further NP models by many authors

- MFV/CMFV
- THDM
- Fourth Generation (SM4)
  [Eberhardt,Herbert,Lacker,Lenz,Menzel,Nierste,Wiebusch '12]

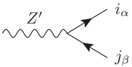
SM4 is excluded at 5.3σ

- Supersymmetry, MSSM ($\tan\beta$ important for $B_s \to \mu^+\mu^-$)
- (SUSY) GUT models
- Left-Right Symmetric Models
- Randall-Sundrum Model
- Little Higgs Model

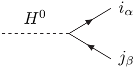
Generalizations

General Z' and Scalar (H^0/A^0) models

- both left- and right-handed Z'/Scalar FCNC couplings



$i\gamma_\mu\delta_{\alpha\beta}\left[\Delta_L^{ij}(Z')P_L + \Delta_R^{ij}(Z')P_R\right]$



$i\delta_{\alpha\beta}\left[\Delta_L^{ij}(H^0)P_L + \Delta_R^{ij}(H^0)P_R\right]$

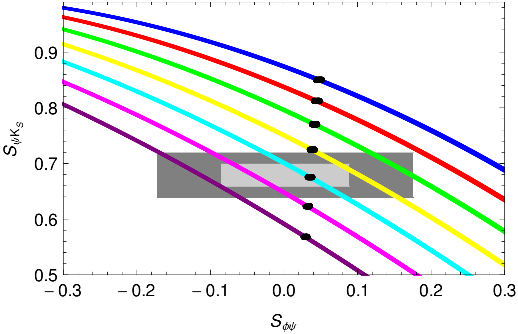
- different scenarios: LHS, RHS, LRS, ALRS
- both $|V_{ub}|$ scenarios (S1: excl.; S2: incl.)
- at first: no correlation between K, B_d and B_s systems
- Difference to 331: assumptions about lepton couplings

Phenomenology in $MU(2)^3$

- $\Delta F = 2$ observables: [Buras, JG: 1206.3878]

$$S_{\psi K_S} = \sin(2\beta + 2\varphi_{\text{new}}) , \qquad S_{\psi\phi} = \sin(2|\beta_s| - 2\varphi_{\text{new}}) ,$$
$$\Delta M_{s,d} = \Delta M_{s,d}^{\text{SM}} r_B , \qquad \varepsilon_K = r_K \varepsilon_K^{\text{SM,tt}} + \varepsilon_K^{\text{SM,cc+ct}}$$

triple correlation $S_{\psi\phi} - S_{\psi K_S} - |V_{ub}|$



For different values of $|V_{ub}|$: 0.0046 (blue)– 0.0028 (purple)

negative $S_{\psi\phi}$ only for small $|V_{ub}|$ possible

incl. $|V_{ub}|$: $S_{\psi\phi} \geq S_{\psi\phi}^{\text{SM}}$

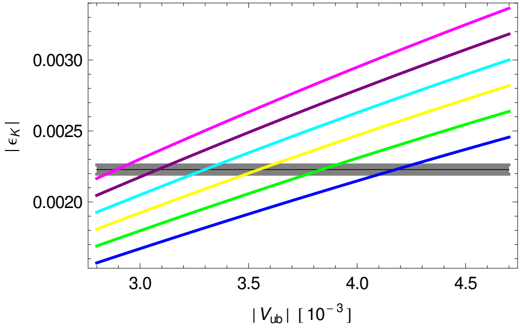
Determine $|V_{ub}|$ in $MU(2)^3$ with $S_{\psi\phi}$ and $S_{\psi K_S}$

Phenomenology in $MU(2)^3$

- $\Delta F = 2$ observables: [Buras, JG: 1206.3878]

$$S_{\psi K_S} = \sin(2\beta + 2\varphi_{\text{new}}), \qquad S_{\psi\phi} = \sin(2|\beta_s| - 2\varphi_{\text{new}}),$$

$$\Delta M_{s,d} = \Delta M_{s,d}^{\text{SM}} r_B, \qquad \varepsilon_K = r_K \varepsilon_K^{\text{SM,tt}} + \varepsilon_K^{\text{SM,cc+ct}}$$



Connection between ε_K and $S_{\psi\phi}$ due to $|V_{ub}|$

$|V_{ub}| \in [0.0028, 0.0046]$
fixed $S_{\psi K_S} = 0.679$
r_K: 1 (blue)– 1.5 (magenta)

In concrete $U(2)^3$ models r_K and r_B can be correlated

Particle content of $\overline{331}$ model

Fermions: triplets, anti-triplets and singlets (w.r.t $SU(3)_L$)

$$\begin{pmatrix} e \\ -\nu_e \\ \nu_e^c \end{pmatrix}_L, \begin{pmatrix} \mu \\ -\nu_\mu \\ \nu_\mu^c \end{pmatrix}_L, \begin{pmatrix} \tau \\ -\nu_\tau \\ \nu_\tau^c \end{pmatrix}_L, \qquad \begin{pmatrix} u \\ d \\ D \end{pmatrix}_L, \begin{pmatrix} c \\ s \\ S \end{pmatrix}, \begin{pmatrix} b \\ -t \\ T \end{pmatrix}_L$$

$$e_R,\, \mu_R,\, \tau_R, \qquad u_R,\, d_R,\, c_R,\, s_R,\, t_R,\, b_R, \qquad D_R, S_R, T_R$$

Gauge bosons:

$$W^{\pm}, Y^{\pm Q_Y}, V^{\pm Q_V}$$

$$W^3, W^8, X \xrightarrow[\theta_{331}]{\text{mix}} W^3, B, Z' \xrightarrow[\theta_W]{\text{mix}} A, Z, Z' \qquad \text{with} \cos\theta_{331} = \beta \tan\theta_W$$

Higgs sector: triplets and sextet ($u \gg v, v', w$)

$$\langle\chi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \\ u \end{pmatrix} \quad \langle\rho\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \\ 0 \end{pmatrix} \langle\eta\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v' \\ 0 \\ 0 \end{pmatrix} \quad \langle S\rangle = \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & w \\ 0 & w & 0 \end{pmatrix}$$

Flavour structure of 331

- Z' coupling generation non-universal $(a \neq b)$! $\Rightarrow$ neutral currents are affected by quark mixing $\Rightarrow$tree-level FCNC

$$\mathcal{L}^{Z'} = J_\mu Z'^\mu \,, \qquad V_{\text{CKM}} = U_L^\dagger V_L ,$$

$$J_\mu = \bar{u}_L \gamma_\mu U_L^\dagger \begin{pmatrix} a & & \\ & a & \\ & & b \end{pmatrix} U_L u_L + \bar{d}_L \gamma_\mu V_L^\dagger \begin{pmatrix} a & & \\ & a & \\ & & b \end{pmatrix} V_L d_L \,,$$

FCNC $\propto (b - a)$

- only left-handed (LH) quark currents are flavour-violating
- V_L parametrized by $\tilde{s}_{12}, \tilde{s}_{23}, \tilde{s}_{13}, \delta_{1,2,3} \rightarrow U_L = V_L V_{\text{CKM}}^\dagger$
- B_d sector depends on $\tilde{s}_{13}, \delta_1$
  B_s sector depends on $\tilde{s}_{23}, \delta_2$
  K sector depends on $\tilde{s}_{13}, \tilde{s}_{23}, \delta_2 - \delta_1$

331 model: technical stuff

- charge operator: $\hat{Q} = \hat{T}^3 + \beta \hat{T}^8 + X\mathbb{1}$ with hypercharge $\frac{\hat{Y}}{2} = \beta \hat{T}^8 + X\mathbb{1}$. The coefficient β determines particle content of particular model
- gauge bosons of $SU(3)_L$: $W^{\pm}$, $Y^{\pm Q_Y}$, $V^{\pm Q_V}$ ($\beta = 1/\sqrt{3}$: $Q_Y = 1, Q_V = 0$)
- Yukawa interaction

$$\begin{aligned} L_{Yuk} = & \quad \lambda^d_{i,a} \bar{Q}_i \rho d_{a,R} + \lambda^d_{3,a} \bar{Q}_3 \eta^\star d_{a,R} \\ + & \quad \lambda^u_{i,a} \bar{Q}_i \eta u_{a,R} + \lambda^u_{3,a} \bar{Q}_3 \rho^\star u_{a,R} \\ + & \quad \lambda^J_{i,j} \bar{Q}_i \chi J_{j,R} + \lambda^J_{3,3} \bar{Q}_3 \chi^\star T_R + h.c. \end{aligned}$$

Q_i, $i = 1, 2$: left-handed triplets; Q_3 left-handed anti-triplet; $J_{1,\,2} = D,\, S$; $a = 1, 2, 3$ with $d_{(1,2,3)R} = d_R,\, s_R,\, b_R$ and $u_{(1,2,3)R} = u_R,\, c_R,\, t_R$.

$$\begin{pmatrix} u'_L \\ c'_L \\ t'_L \end{pmatrix} = U_L^{-1} \begin{pmatrix} u_L \\ c_L \\ t_L \end{pmatrix}, \qquad \begin{pmatrix} d'_L \\ s'_L \\ b'_L \end{pmatrix} = V_L^{-1} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix},$$

Particle content of $\overline{331}$ model

$$\psi_{1,2,3} = \begin{pmatrix} e \\ -\nu_e \\ \nu_e^c \end{pmatrix}, \quad \begin{pmatrix} \mu \\ -\nu_\mu \\ \nu_\mu^c \end{pmatrix}, \quad \begin{pmatrix} \tau \\ -\nu_\tau \\ \nu_\tau^c \end{pmatrix} \quad \sim \quad (\mathbf{1}, \bar{\mathbf{3}}, -\tfrac{1}{3})$$

$$Q_{1,2} = \begin{pmatrix} u \\ d \\ D \end{pmatrix}, \quad \begin{pmatrix} c \\ s \\ S \end{pmatrix} \quad \sim \quad (\mathbf{3}, \bar{\mathbf{3}}, 0)$$

$$Q_3 = \begin{pmatrix} b \\ -t \\ T \end{pmatrix} \quad \sim \quad (\mathbf{3}, \bar{\mathbf{3}}, \tfrac{1}{3})$$

$$\begin{aligned} e^c, \mu^c, \tau^c &\sim -1 \\ \nu_e^c, \nu_\mu^c, \nu_\tau^c &\sim 0 \\ d^c, s^c, b^c &\sim \tfrac{1}{3} \\ u^c, c^c, t^c &\sim -\tfrac{2}{3} \\ C^c, S^c &\sim \tfrac{1}{3} \\ T^c &\sim -\tfrac{2}{3} \end{aligned}$$

Notes

331:

- same operator structure as SM and CMFV except that the one-loop master functions become complex and non-universal
- $\Delta F = 2$ observables $\rightarrow$ identify four allowed oases $\rightarrow$ inclusion of $\Delta F = 1$ observables can select the opimal oases (correlation $B_s \rightarrow \mu^+\mu^- - S_{\psi\phi} - S^s_{\mu^+\mu^-}$) play prominent role.
- these correlation should allow to monitor how this model will face the data in the coming years
- anomaly-free: number of triplets = number of antitriplets (take into account the three colours of quarks) $\Rightarrow \ldots$ two quark generations triplets and one antitriplet.
- $V^{\pm Q_V}$, $Y^{\pm Q_Y}$ couple to SM leptons but not to SM quarks (only to new heavy quarks) $\rightarrow V, Y$ have letpon number $L = \mp 2$ but no lepten generation number ($\rightarrow$ lepton flavour/number violation not correlated with quark flavour violation)

Notes

331:

- in some 331 models, e.g. $\beta = \sqrt{3}$ the Z' mass is bounded from above

$$\frac{g_X^2}{g^2} = \frac{6\sin^2\theta_W}{1-(1+\beta^2)\sin^2\theta_W}$$

$\beta = \sqrt{3}$: $\sin^2\theta_W(M_{Z'}) < \frac{1}{4}$; $\sin^2\theta_W(M_Z) \simeq 0.23 \Rightarrow M_{Z'}$ below a few TeV

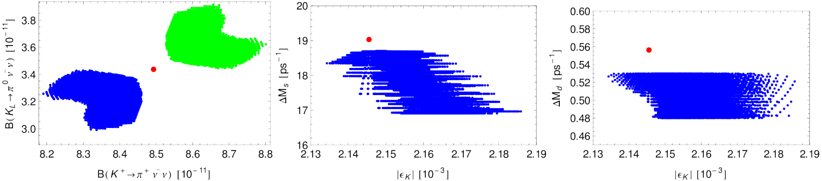
- reproduce data for $\Delta M_{d,s}$ within $\pm 5\%$ and 2σ for $S_{\psi\phi}, S_{\psi K_S}$

$$16.9/\mathrm{ps} \le \Delta M_s \le 18.7/\mathrm{ps}, \quad -0.18 \le S_{\psi\phi} \le 0.18,$$
$$0.48/\mathrm{ps} \le \Delta M_d \le 0.53/\mathrm{ps}, \quad 0.64 \le S_{\psi K_S} \le 0.72.$$

- Increase of $M_{Z'}$ allows to increases $\tilde{s}_{13}$, $\tilde{s}_{23}$ by the same factor $\rightarrow$ impact on rare $B_{s,d}$ decays (smaller for larger $M_{Z'}$). In rare K decays increase of $M_{Z'}$ is compensated by the increase of $\tilde{s}_{13}$ and $\tilde{s}_{23}$ $\Rightarrow$ decays practically do not depend on $M_{Z'}$. In ε_K the same phenomenon even increases the room for NP effects with increasing $M_{Z'}$ for values of several TeV, where all FCNC constraints can be satisfied.

$\overline{331}$: K sector

- correlation between $K_L \to \pi^0 \bar{\nu}\nu$ and $K^+ \to \pi^+ \bar{\nu}\nu$ (independent of $M_{Z'}$) but far below exp. sensitivity
- no $\Delta M_{d,s} - \varepsilon_K$ tension (that is present in CMFV)



What happens for $M_{Z'} = 10$ TeV?

- Increase $\tilde{s}_{13,23} \Rightarrow \Delta F = 2$ in $B_{d,s}$ fine
- effects in ε_K get larger (as long as $\Delta^{sd}(Z') <$ max. value) $\Rightarrow$ even exclusive V_{ub} possible
- effects in rare B/K decays suppressed and thus SM like

Summary $\overline{331}$ model

- FCNC from Z' in quark sector (purely left-handed), no FCNC in lepton sector
- favours inclusive (large) $|V_{ub}| \approx 0.0040 \to$ removes $\varepsilon_K - S_{\psi K_S}$ "tension"
- correlations between observables that differ from CMFV models
- consistent with data for $B_{s,d} \to \mu^+\mu^-$ but can still differ from SM prediction
- triple correlation $B_s \to \mu^+\mu^- - S_{\psi\phi} - S^s_{\mu^+\mu^-}$ important test of the model
- Z' contributions to $b \to s\nu\bar{\nu}$ transitions, $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ are found typically below $5-10\%$
- our analysis helps to monitor the future confrontations of the $\overline{331}$ model with the data

Notes to Z'

Difference to 331

- also RH currents
- K sector decoupled from $B_{d,s}$ sector at fundamental level
- significant effects in ε_K and rare K decays possible
- Z' couplings to neutrinos and charged leptons not fixed from the model
- analysis for both $|V_{ub}|$ values

For 1 TeV $\leq M_{Z'} \leq$ 3 TeV indirect Z' effects can be tested by rare K and B decays: effects up to 50% in BR and measurable effects in CP-asymmetries. For $M_{Z'} \geq 5$ TeV NP effects typically below 10% but larger effects allowed in rare K decays.

Notes to Z'

- In $K_L \to \pi^0 \nu\bar{\nu}$ vs $K^+ \to \pi^+ \nu\bar{\nu}$ plots: horizontal line $\to$ NP contributions is real; second branch parallel to GN bound $\to$ NP contribution is purely imaginary
- change from LHS to RHS: no change in $\Delta F = 2$; in $\Delta F = 1$ with Y function: the two big oases changes $\to$ not possible to distinguish between the two big oases from $B_s \to \mu^+\mu^-$, $S_{\psi\phi}$ and $S^s_{\mu^+\mu^-}$.
- $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ are not useful for the search of RH currents as they are sensitive only to the vector couplings
- LR scenario: NP contributions to $\Delta F = 2$ are dominated by LR operators (enhanced by RG effects) $\to$ other oases; NP contributions to $B_{s,d} \to \mu^+\mu^-$ and $K_L \to \mu^+\mu^-$ vanish; important role $b \to s/d\bar{\nu}\nu$ transitions and $B \to K^{(\star)}\mu^+\mu^-$
- Anomally cancellation $\Rightarrow$ existence of new (vector-like) fermions ("exotics", ν_R)
- For $M_{Z'} \leq 3$ TeV deviations from SM in $B_{d,s}$ and K meson systems. For $M_{Z'} \geq 5$ TeV effects below 10% in $B_{d,s}$ decays, but $K \to \pi\nu\bar{\nu}$ and

MTFM: The model I

$$u_{Ri}, d_{Ri}, q_{Li} = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix} \qquad i = 1, 2, 3$$

$$U_{Ri}, U_{Li}, D_{Ri}, D_{Li}, Q_{Ri} = \begin{pmatrix} U^Q_{Ri} \\ D^Q_{Ri} \end{pmatrix}, Q_{Li} = \begin{pmatrix} U^Q_{Li} \\ D^Q_{Li} \end{pmatrix} \qquad i = 1, 2, 3.$$

$$-\mathcal{L} = \tilde{h}\lambda^U_{ij}\bar{Q}_{Li}U_{Rj} + h\lambda^D_{ij}\bar{Q}_{Li}D_{Rj} + M^U_i\bar{U}_{Li}U_{Ri} + M^D_i\bar{D}_{Li}D_{Ri} + M^Q_i\bar{Q}_{Ri}Q_{Li}$$
$$+ m^U_i\bar{U}_{Li}u_{Ri} + m^D_i\bar{D}_{Li}d_{Ri} + m^Q_i\bar{Q}_{Ri}q_{Li} + \mathrm{h.c.}$$

$$-\mathcal{L}_{\mathrm{eff}} \supset \frac{g}{\sqrt{2}}\left(W^+_\mu j^{\mu-}_{\mathrm{charged}} + \mathrm{h.c.}\right) + \frac{g}{2c_{\mathrm{w}}}Z_\mu j^\mu_{\mathrm{neutral}}$$
$$+ \overline{u}_{Li}m^U_{ij}u_{Rj} + \overline{d}_{Li}m^D_{ij}d_{Rj} + \frac{H}{\sqrt{2}}\left(\overline{u}_{Li}y^U_{ij}u_{Rj} + \overline{d}_{Li}y^D_{ij}d_{Rj}\right) + \mathrm{h.c.}$$

$$m^X_{ij} = v\bar{\varepsilon}^Q_i\bar{\varepsilon}^X_j\lambda^X_{ij} - \frac{v}{2}\left(A^X_L\right)_{ik}\bar{\varepsilon}^Q_k\bar{\varepsilon}^X_j\lambda^X_{kj} - \frac{v}{2}\left(A^X_R\right)_{kj}\bar{\varepsilon}^Q_i\bar{\varepsilon}^X_k\lambda^X_{ik},$$

$$y^X_{ij} = \frac{m^X_{ij}}{v} - \left(A^X_L\right)_{ik}\bar{\varepsilon}^Q_k\bar{\varepsilon}^X_j\lambda^X_{kj} - \left(A^X_R\right)_{kj}\bar{\varepsilon}^Q_i\bar{\varepsilon}^X_k\lambda^X_{ik}.$$

MTFM: The model II

$$j^{\mu -}_{\text{charged}} = \bar{u}_{Li} \left[\delta_{ij} - \frac{1}{2} \left(A^U_L\right)_{ij} - \frac{1}{2} \left(A^D_L\right)_{ij} \right] \gamma^\mu d_{Lj} + \bar{u}_{Ri} \left(A^{UD}_R\right)_{ij} \gamma^\mu d_{Rj} \,,$$

$$\begin{aligned} j^{\mu}_{\text{neutral}} &= \bar{u}_{Li} \left[\delta_{ij} - \left(A^U_L\right)_{ij} \right] \gamma^\mu u_{Lj} + \bar{u}_{Ri} \left(A^U_R\right)_{ij} \gamma^\mu u_{Rj} \\ &- \bar{d}_{Li} \left[\delta_{ij} - \left(A^D_L\right)_{ij} \right] \gamma^\mu d_{Lj} - \bar{d}_{Ri} \left(A^D_R\right)_{ij} \gamma^\mu d_{Rj} - 2 s^2_{\text{w}} j^{\mu}_{\text{elmag}} \end{aligned}$$

In Unitary Model (still in flavour eigenstates):

$$\left(A^U_L\right)_{ij} = \frac{v^2}{\bar{M}^2} \bar{\varepsilon}^Q_i \bar{\varepsilon}^Q_j \delta_{ij} \qquad \left(A^D_L\right)_{ij} = \frac{v^2}{\bar{M}^2} \bar{\varepsilon}^Q_i \bar{\varepsilon}^Q_j \delta_{ij}$$

$$\left(A^{UD}_R\right)_{ij} = \frac{v^2}{\bar{M}^2} \bar{\varepsilon}^U_i \bar{\varepsilon}^D_j \lambda^D_{kj} \lambda^{*U}_{ki}$$

$$\left(A^U_R\right)_{ij} = \frac{v^2}{\bar{M}^2} \bar{\varepsilon}^U_i \bar{\varepsilon}^U_j \delta_{ij} \qquad \left(A^D_R\right)_{ij} = \frac{v^2}{\bar{M}^2} \bar{\varepsilon}^D_i \bar{\varepsilon}^D_j \delta_{ij}$$

$$m^X_{ij} = v\lambda^X_{ij}\varepsilon^Q_i\varepsilon^X_j\,, \quad V^{X\dagger}_L m^X V^X_R = m^X_{\rm diag}\,, \quad X = U, D\,, \quad V_{\rm CKM} = (V^U_L)^\dagger V^D_L.$$

Unitary Model:

$$\tilde{A}^X_L = \frac{v^2}{M^2_X} V^{X\dagger}_L \,\mathrm{diag}\left(\varepsilon^{Q2}_1, \varepsilon^{Q2}_2, \varepsilon^{Q2}_3\right) V^X_L\,,$$

$$\tilde{A}^X_R = \frac{v^2}{M^2_Q} V^{X\dagger}_R \,\mathrm{diag}\left(\varepsilon^{X2}_1, \varepsilon^{X2}_2, \varepsilon^{X2}_3\right) V^X_R\,,$$

$$\tilde{A}^{UD}_R = \frac{1}{M^2_Q} m^U_{\rm diag}\,\tilde{V}^{U\dagger}_L \,\mathrm{diag}\left(\varepsilon^{Q2}_1, \varepsilon^{Q2}_2, \varepsilon^{Q2}_3\right) V^D_L\, m^D_{\rm diag}\,.$$

$$\Delta^{ij}_L(Z) = -\frac{g}{2c_W}(\tilde{A}^D_L)_{ij}\,,$$

$$\Delta^{ij}_R(Z) = \frac{g}{2c_W}(\tilde{A}^D_R)_{ij}\,.$$

$$\Delta^{ij}_L(W) = \frac{g}{2\sqrt{2}}\left[\left(\tilde{A}^U_L V_{\rm CKM}\right)_{ij} + \left(V_{\rm CKM}\tilde{A}^D_L\right)_{ij}\right]\,,$$

$$\Delta^{ij}_R(W) = -\frac{g}{\sqrt{2}}\left(\tilde{A}^{UD}_R\right)_{ij}\,.$$

MTFM: Couplings in TUM

$$\tilde{A}_L^U = \frac{1}{M_U^2}\text{diag}\left(\frac{m_u^2}{\varepsilon_1^{U2}}, \frac{m_c^2}{\varepsilon_2^{U2}}, \frac{m_t^2}{\varepsilon_3^{U2}}\right) = \frac{v^2}{M_U^2}\text{diag}\left(\varepsilon_1^{Q2}, \varepsilon_2^{Q2}, \varepsilon_3^{Q2}\right) ,$$

$$\tilde{A}_R^U = \frac{1}{M_Q^2}\text{diag}\left(\frac{m_u^2}{\varepsilon_1^{Q2}}, \frac{m_c^2}{\varepsilon_2^{Q2}}, \frac{m_t^2}{\varepsilon_3^{Q2}}\right) = \frac{v^2}{M_Q^2}\text{diag}\left(\varepsilon_1^{U2}, \varepsilon_2^{U2}, \varepsilon_3^{U2}\right) ,$$

$$\tilde{A}_L^D = \frac{v^2}{M_D^2} V_{\text{CKM}}^\dagger \text{diag}\left(\varepsilon_1^{Q2}, \varepsilon_2^{Q2}, \varepsilon_3^{Q2}\right) V_{\text{CKM}} ,$$

$$\tilde{A}_R^D = \frac{1}{M_Q^2} m_{\text{diag}}^D V_{\text{CKM}}^\dagger \text{diag}\left(\frac{1}{\varepsilon_1^{Q2}}, \frac{1}{\varepsilon_2^{Q2}}, \frac{1}{\varepsilon_3^{Q2}}\right) V_{\text{CKM}} m_{\text{diag}}^D ,$$

$$\tilde{A}_R^{UD} = \frac{1}{M_Q^2} m_{\text{diag}}^U \text{diag}\left(\frac{1}{\varepsilon_1^{Q2}}, \frac{1}{\varepsilon_2^{Q2}}, \frac{1}{\varepsilon_3^{Q2}}\right) V_{\text{CKM}} m_{\text{diag}}^D .$$

$$\frac{\varepsilon_1^Q}{\varepsilon_2^Q} = |V_{us}|X_{12}, \quad \frac{\varepsilon_1^Q}{\varepsilon_3^Q} = |V_{ub}|X_{13}, \quad \frac{\varepsilon_2^Q}{\varepsilon_3^Q} = |V_{cb}|X_{23},$$

$$[V_{ij}^{\text{CKM}}]_{\text{eff}} = V_{ij}^{\text{CKM}}(1 - \frac{v^2}{M^2}\varepsilon_i^{Q2}).$$

Summary of MTFM: TUM

- TUM only 4 new parameters after fitting SM quark masses and V_{CKM}
- tree-level flavour violating Z couplings to quarks
- TUM favours $|V_{ub}| \approx 0.0037$ and $M \geq 3$ TeV
- negligible effects in $B_{d,s}$ sector $\rightarrow S_{\psi K_S} \approx 0.72$ a bit to high
- NP effects in ε_K bounded by $K_L \rightarrow \mu^+\mu^-$
- Pattern in B decays: CMFV-like but, $B_{s,d} \rightarrow \mu^+\mu^-$ enhanced by $\approx 35\%$ relative to SM values
- Enhancement of $K \rightarrow \pi\bar{\nu}\nu$ and correlation of $K_L \rightarrow \pi^0\bar{\nu}\nu$ and $K^+ \rightarrow \pi^+\bar{\nu}\nu$ non-CMFV like