Searching for New Physics through correlations of Flavour Observables

Jennifer Girrbach

Institute for Advanced Study, Technical University Munich (TUM)

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 [arXiv:1303.3723]
A. Buras, R. Fleischer, JG, R. Knegjens [arXiv:1303.3820]
A. Buras, JG, R. Ziegler [arXiv:1301.5498], A. Buras, JG: JHEP **1301** [arXiv:1206.3878]

Beauty 2013, Bologna

08.04–12.04.2013

Outline for the next 25 minutes

1. Current status
2. Phenomenology of Z' and scalar H^0/A^0
   - concrete model with Z' FCNC: 331
   - general Z' and H^0/A^0 scenarios
3. Minimal Theory of fermion masses: new vectorlike fermions F
4. Summary

LHCb results

There were hopes to find clear signals of NP in

$$\boxed{S_{\psi\phi} \text{ and } \mathcal{B}(B_s \to \mu^+\mu^-)}$$

LHCb measurement:

$$\boxed{S_{\psi\phi}^{\text{exp}} = 0.001 \pm 0.087\,, \qquad \overline{\mathcal{B}}(B_s \to \mu^+\mu^-)^{\text{exp}} = (3.2^{+1.5}_{-1.2}) \times 10^{-9}}$$

SM prediction:

$$S_{\psi\phi}^{\text{SM}} = 0.038 \pm 0.005$$
$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\text{SM}} = (3.25 \pm 0.17) \cdot 10^{-9}$$
$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)^{\text{SM}} = (3.56 \pm 0.18) \cdot 10^{-9}$$

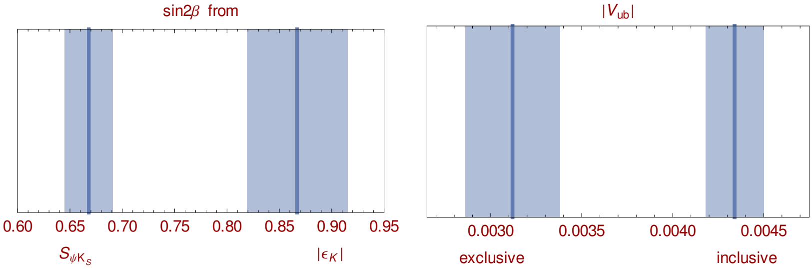
[Buras,JG,Guadagnoli,Isidori,2012], [De Bruyn,Fleischer,Knegjens, Koppenburg,Merk,2012], [Buras,Fleischer,JG,Knegjens,2013]

But so far everything is consistent with SM prediction

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?

- 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: $SU(3)_C \times SU(3)_L \times U(1)_X$
  - GUT models, e.g. $SO(10) \to SU(5) \times U(1)'$
  - Left-Right symmetric models: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
  - Little Higgs models, extra dimensions,...

- Breaking $U(1)'$ symmetry $\Rightarrow$ extended Higgs sector

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$\propto (b-a)$

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

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

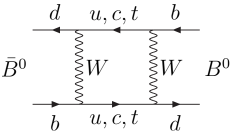
- only left-handed (LH) quark currents are flavour-violating
- V_L parametrized by $\tilde{s}_{12}, \tilde{s}_{23}, \tilde{s}_{13}, \delta_{1,2,3} \rightarrow U_L = V_L V_{\text{CKM}}^\dagger$
- B_d sector depends on $\tilde{s}_{13}, \delta_1$
  B_s sector depends on $\tilde{s}_{23}, \delta_2$
  K sector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

Flavour observables: Meson-Antimeson mixing

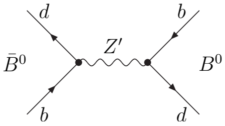
- $\Delta F = 2$ observables

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

SM loop contribution



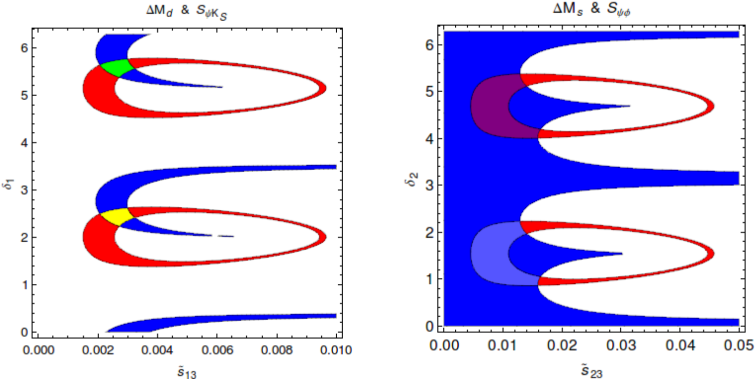
tree-level NP contribution



Constraints on free parameters $\tilde{s}_{ij}, \delta_i$
Correlation between observables

Finding oases in parameter space in $\overline{331}$

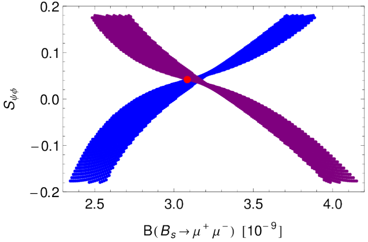
$B_i = (\tilde{s}_{13}, \delta_1)$ and $A_i = (\tilde{s}_{23}, \delta_2)$ oases $(i = 1-4)$ for $M_{Z'} = 1$ TeV and $|V_{ub}| = 0.004 \Rightarrow S_{\psi K_S}$ must be suppressed below SM value

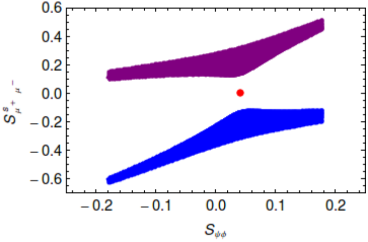


Inclusion of $\Delta F = 1$ observables helps to select the optimal oases

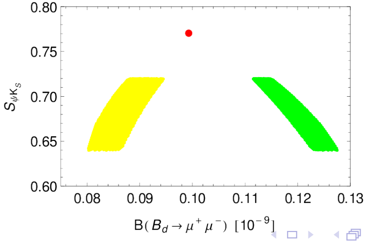
Finding the optimal oases

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



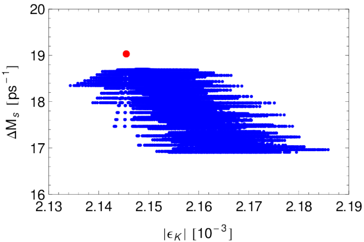


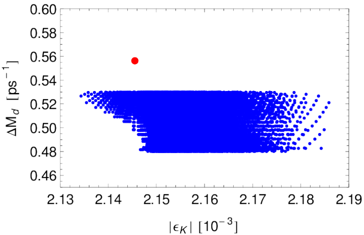
- $B_d \to \mu^+\mu^-$ differ betw. δ_2 and $\delta_2 + 180°$



$\overline{331}$: K sector

- 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 $|V_{ub}| = 0.004$

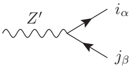




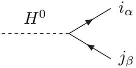
Generalizations

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

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



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



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

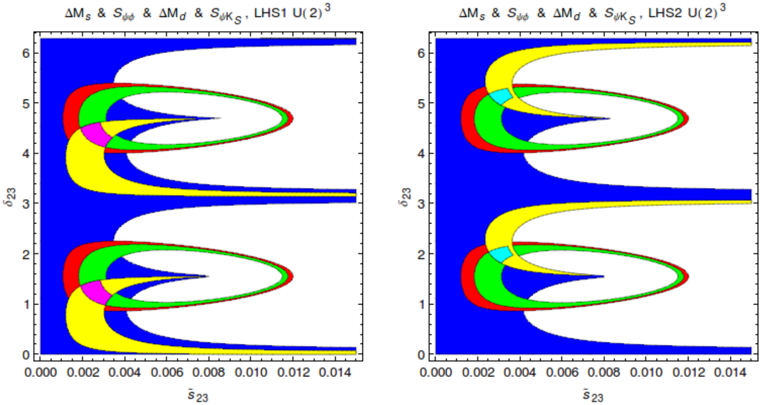
- different scenarios: LHS, RHS, LRS, ALRS
- both $|V_{ub}|$ scenarios (S1: excl.; S2: incl.)
- at first: no correlation between K, B_d and B_s systems
- Difference to 331: assumptions about lepton couplings

$U(2)^3$ 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:

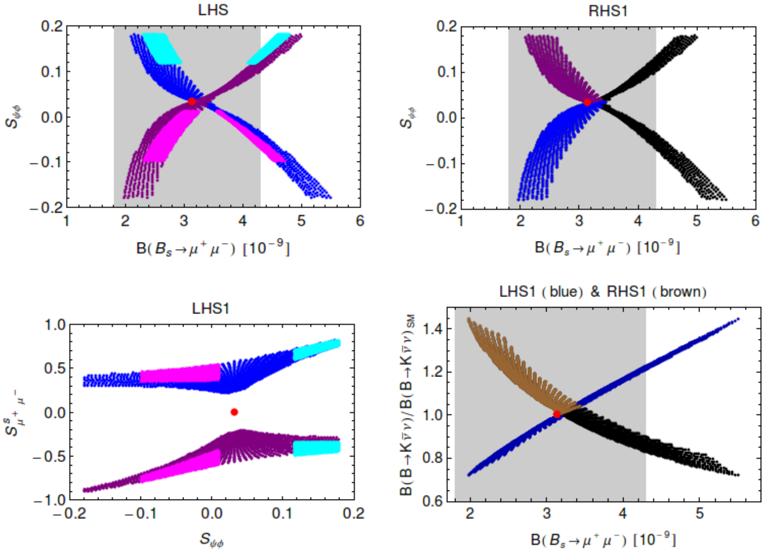
$$\frac{\tilde{s}_{13}}{|V_{td}|} = \frac{\tilde{s}_{23}}{|V_{ts}|}, \quad \delta_{13} - \delta_{23} = \beta - \beta_s. \qquad \text{triple correlation: } V_{ub} - S_{\psi K_S} - S_{\psi\phi}$$

Example: Scalar LHS case [Buras,JG, 1206.3878]



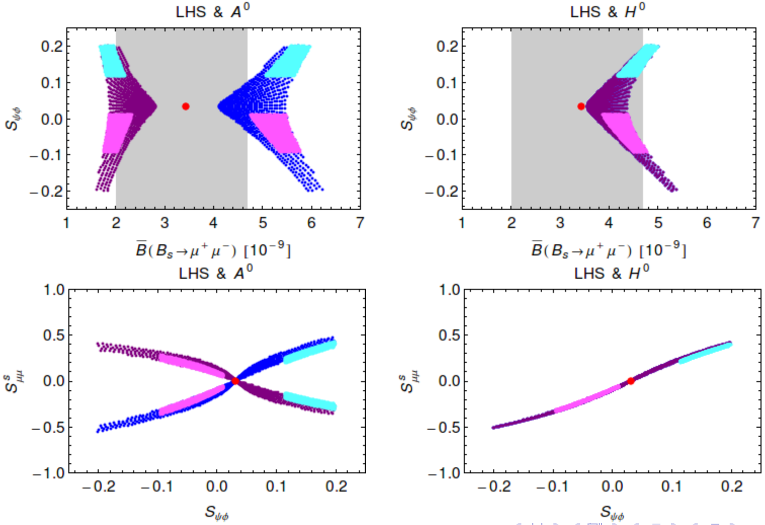
general Z' scenarios: B_s sector

LH vs. RH currents: black: excluded due to $b \to s\ell^+\ell^-$ ($B \to X_s\ell^+\ell^-$, $B \to K^{(\star)}\ell^+\ell^-$); $b \to s\bar{\nu}\nu$ transitions distinguish LHS and RHS.

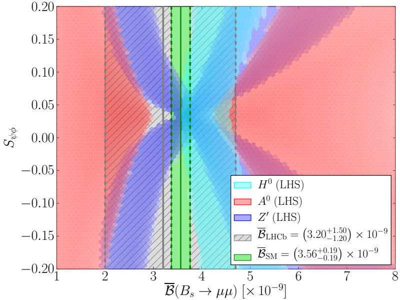


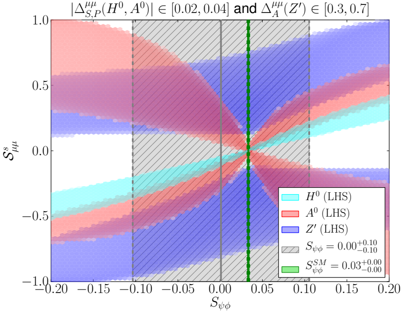
general H^0/A^0 scenarios: B_s sector

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



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

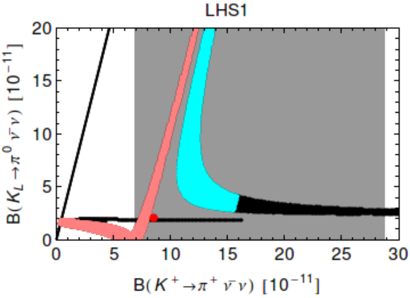


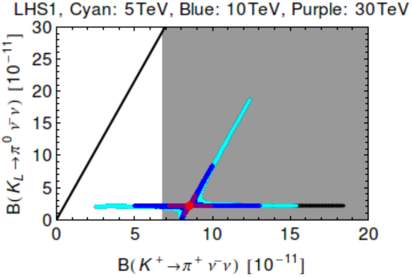


[see also talk on Friday 9am by Rob Knegjens]

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)

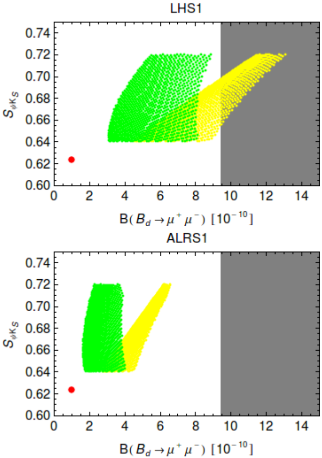




no difference between LHS and RHS (vector currents)
Black region: excluded by $\mathcal{B}(K_L \to \mu^+\mu^-) \leq 2.5 \cdot 10^{-9}$, black line: GN bound

Z^0 FCNCs

- $B_d \to \mu^+\mu^-$: effects small in MFV, CMFV and Z', but large in Z^0 FCNCs
- $S_{\psi K_S}$ versus $\mathcal{B}(B_d \to \mu^+\mu^-) \Rightarrow$ Enhancement up to current bound possible



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]

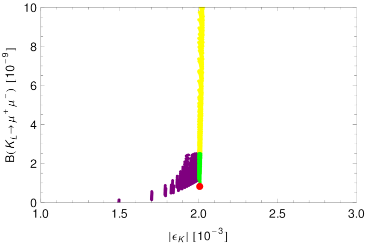
- reduce number of parameters such that it is still possible to reproduce SM Yukawas and suppress flavour violation $\Rightarrow$ identify minimal FCNC effects.
- TUM (Trivially Unitary Model):
  - Universality of heavy masses $M_i^Q = M_i^U = M_i^D = M$
  - Unitarity of the Yukawa matrices $\lambda^{U,D}$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

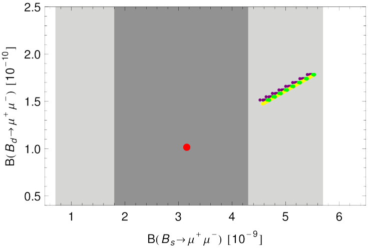
4 new real parameters and 0 new phases
$M, \quad \varepsilon_3^Q, \quad s_{13}^d, \quad s_{23}^d$

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

Phenomenology

- Flavour changing Z^0 couplings
- large effects in ε_K and $K_L \to \mu^+\mu^-$ possible, but NP effects in ε_K bounded by $K_L \to \mu^+\mu^-$
- NP effects in $B_{s,d}$ mixings negligible
- B decays: CMFV-like but $B_{s,d} \to \mu^+\mu^-$ enhanced by $\approx 35\%$ relative to SM





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

Summary

TUM

- TUM favours $|V_{ub}| \approx 0.0037$ and $M \geq 3$ TeV
- NP effects in ε_K bounded by $K_L \to \mu^+\mu^-$
- Pattern in B decays: CMFV-like but, $B_{s,d} \to \mu^+\mu^-$ enhanced by $\approx 35\%$ relative to SM values
- 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

$\overline{331}$ model

- FCNC from Z' in quark sector (purely left-handed)
- 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
- 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 $5-10\%$

Summary general Z' and Scalar scenarios

Z' scenarios:

- Distinction between LHS and RHS possible in $b \to s\bar{\nu}\nu$ transitions
- 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

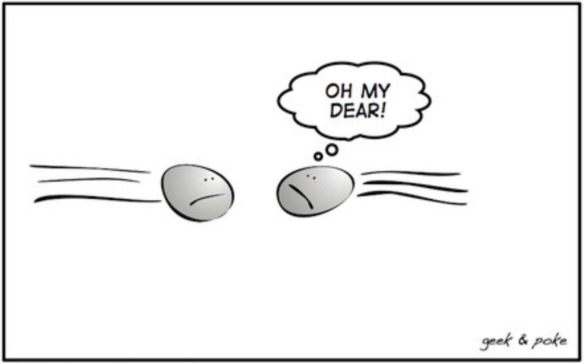
H^0/A^0 scenarios:

- 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
- expect negligible effects in channels with neutrinos

Both:

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

Thanks for your attention



LATELY INSIDE THE LHC:
2 PROTONS 0.000000000000000000001 SEC BEFORE THE COLLISION

Backup slides

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

$B_s \to \mu^+\mu^-$: 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: $\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm LHCb} = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$
- 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]

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

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

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

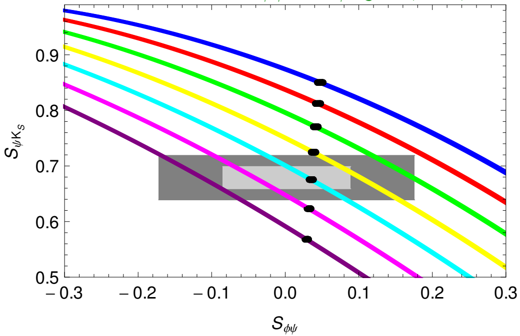
or in experimental value: $\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm LHCb} = (2.9^{+1.4}_{-1.1}) \times 10^{-9}$

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

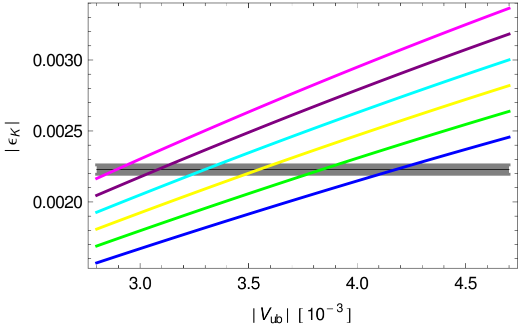
Determine $|V_{ub}|$ in $MU(2)^3$ with $S_{\psi\phi}$ and $S_{\psi K_S}$

Phenomenology in $MU(2)^3$

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

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

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



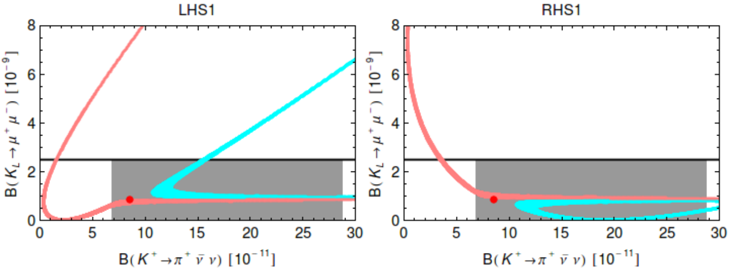
Connection between ε_K and $S_{\psi\phi}$ due to $|V_{ub}|$

$|V_{ub}| \in [0.0028, 0.0046]$
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

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

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

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

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

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

$$e^c, \mu^c, \tau^c \quad \sim \quad -1$$

$$\nu_e^c, \nu_\mu^c, \nu_\tau^c \quad \sim \quad 0$$

$$d^c, s^c, b^c \quad \sim \quad \tfrac{1}{3}$$

$$u^c, c^c, t^c \quad \sim \quad -\tfrac{2}{3}$$

$$C^c, S^c \quad \sim \quad \tfrac{1}{3}$$

$$T^c \quad \sim \quad -\tfrac{2}{3}$$

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 $\to$ identify four allowed oases $\to$ inclusion of $\Delta F = 1$ observables can select the opimal oases (correlation $B_s \to \mu^+\mu^- - S_{\psi\phi} - S^s_{\mu^+\mu^-}$) 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) $\to V, Y$ have letpon number $L = \mp 2$ but no lepten generation number ($\to$ 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

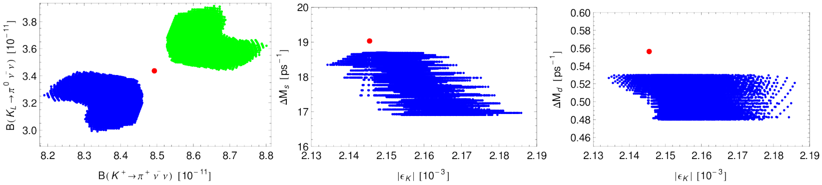
- reproduce data for $\Delta M_{d,s}$ within $\pm 5\%$ and 2σ for $S_{\psi\phi}, S_{\psi K_S}$

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

- 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)

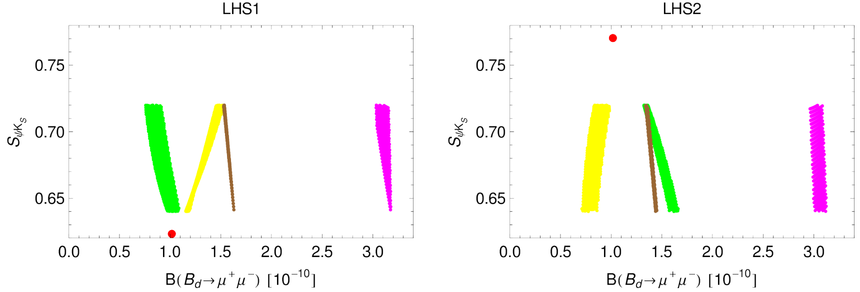


What happens for $M_{Z'} = 10$ TeV?

- 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

general Z' scenarios: B_d sector

V_{ub} dependence important in B_d sector $\rightarrow$ sign of correlations can change!
$S_{\psi K_S}$ vs. $B_d \rightarrow \mu^+\mu^-$: depends on oases!

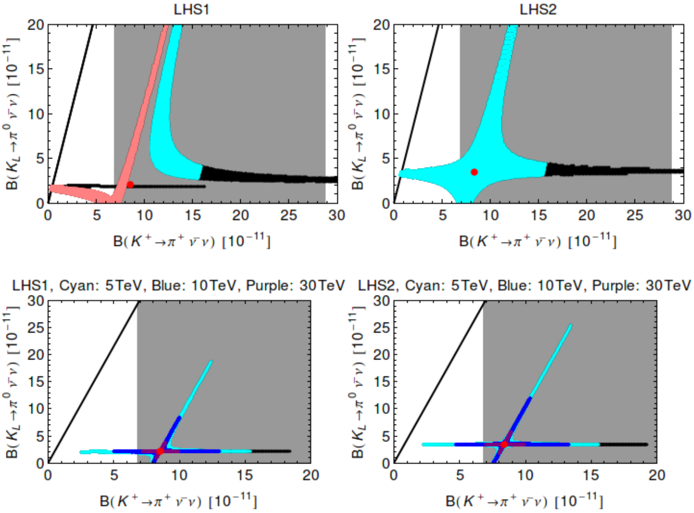


- colour code: (A_1,B_1): blue, (A_1,B_3): green, (A_3,B_1): yellow, (A_3,B_3): purple, (A_1,B_2): red, (A_1,B_4): gray, (A_3,B_2): magenta, (A_3,B_4): brown.
- A_1: blue, A_3: purple
- B_1: yellow, B_3: green, B_2: magenta, B_4: brown.

Summary $\overline{331}$ model

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

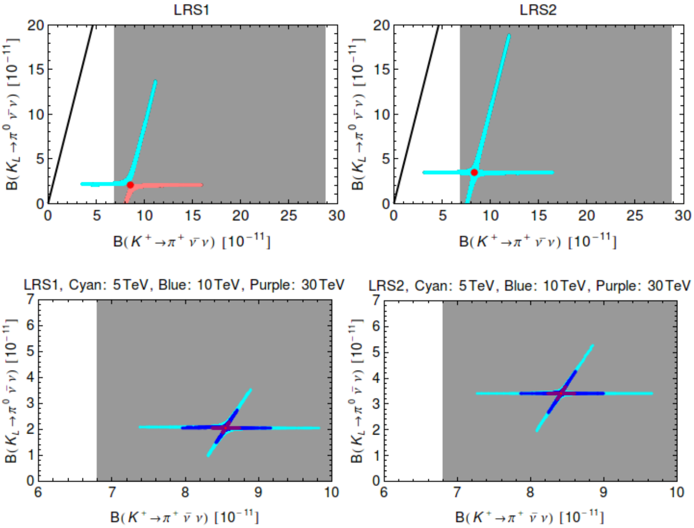
general Z' scenarios: K sector



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

general Z' scenarios: K sector



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

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

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

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

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

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

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

MTFM: The model II

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

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

In Unitary Model (still in flavour eigenstates):

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

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

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

MTFM: The model III: Rotating to mass eigenstates

$$m_{ij}^X = v\lambda_{ij}^X \varepsilon_i^Q \varepsilon_j^X , \quad V_L^{X\dagger} m^X V_R^X = m_{\text{diag}}^X , \quad X = U, D , \quad V_{\text{CKM}} = (V_L^U)^\dagger V_L^D .$$

Unitary Model:

$$\tilde{A}_L^X = \frac{v^2}{M_X^2} V_L^{X\dagger} \,\text{diag}\left(\varepsilon_1^{Q2}, \varepsilon_2^{Q2}, \varepsilon_3^{Q2}\right) V_L^X ,$$

$$\tilde{A}_R^X = \frac{v^2}{M_Q^2} V_R^{X\dagger} \,\text{diag}\left(\varepsilon_1^{X2}, \varepsilon_2^{X2}, \varepsilon_3^{X2}\right) V_R^X ,$$

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

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

$$\Delta_R^{ij}(Z) = \frac{g}{2c_W} (\tilde{A}_R^D)_{ij} .$$

$$\Delta_L^{ij}(W) = \frac{g}{2\sqrt{2}} \left[\left(\tilde{A}_L^U V_{\text{CKM}} \right)_{ij} + \left(V_{\text{CKM}} \tilde{A}_L^D \right)_{ij} \right] ,$$

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

MTFM: Couplings in TUM

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

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

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

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

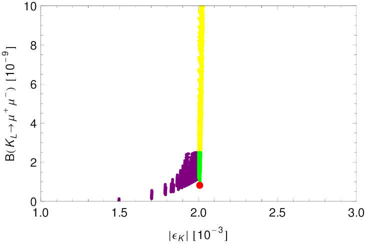
$$\tilde{A}_R^{UD} = \frac{1}{M_Q^2} m_{\mathrm{diag}}^U \mathrm{diag}\left(\frac{1}{\varepsilon_1^{Q2}}, \frac{1}{\varepsilon_2^{Q2}}, \frac{1}{\varepsilon_3^{Q2}}\right) V_{\mathrm{CKM}} m_{\mathrm{diag}}^D .$$

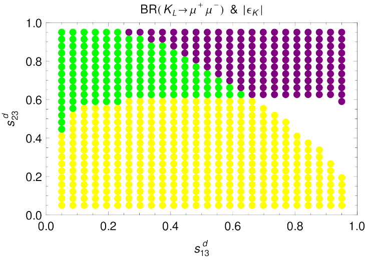
$$\frac{\varepsilon_1^Q}{\varepsilon_2^Q} = |V_{us}|X_{12}, \quad \frac{\varepsilon_1^Q}{\varepsilon_3^Q} = |V_{ub}|X_{13}, \quad \frac{\varepsilon_2^Q}{\varepsilon_3^Q} = |V_{cb}|X_{23},$$

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

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 $K_L \to \mu^+\mu^-$

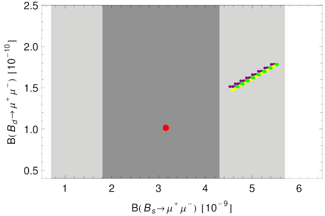




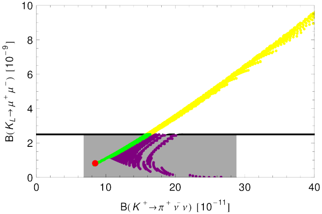
- TUM favours $|V_{ub}| \approx 0.0037$ and $M \geq 3$ TeV $\to S_{\psi K_S} \approx 0.72$ a bit to high

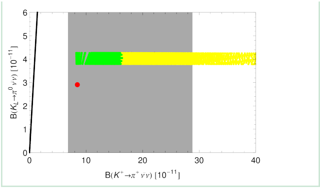
Phenomenology

- 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





Summary of MTFM: TUM

- TUM only 4 new parameters after fitting SM quark masses and $V_{\rm CKM}$
- 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