$B \to K^{(*)}\nu\bar{\nu}$ decays in the SM and beyond

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based on: A. Buras, JGN, C. Niehoff, D. Straub (in preparation)

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Outline

1. Introduction
2. SM results
3. Going beyond the SM
   - Effective field theory approach
   - Concrete NP models
4. Summary

Introduction

Why study and measure $B \to K^{(*)}\nu\bar{\nu}$?

- $\nu\bar{\nu}$ final state $\to$ theoretically clean
- especially sensitive to Z penguins ($b \to s\ell^+\ell^-$ also sensitive to dipole and scalar operators)
- sensitive to right-handed couplings $\Rightarrow$ powerful test of MFV
- $\to$ studied in detail by [Altmannshofer,Buras,Straub,Wick,'09]

What is new?

- decrease of form factor uncertainties due to lattice calculations
- further reduction of form factors uncertainties [Bharucha,Straub,Zwicky,'14]
- new $B \to K^*\mu^+\mu^-$ data $\Rightarrow$ impact on constraints on $b \to s\nu\bar{\nu}$ [Altmannshofer,Straub,'12,'13,'14]
- include SU(2)$_L$ symmetry $\Rightarrow$ correlation between $b \to s\ell^+\ell^-$ and $b \to s\nu\bar{\nu}$ transitions
- Correlations in concrete NP models
- Departure of lepton flavour universality (not covered in this talk)

SM results

$$\mathcal{H}_{\text{eff}}^{\text{SM}} \sim C_L^{\text{SM}} \mathcal{O}_L\,, \qquad \mathcal{O}_L = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

$$C_L^{\text{SM}} = -X_t/s_w^2 \approx -6.35$$

[Brod,Gorbahn,Stamou,'11]

Three observables: differential branching ratios and K^* longitudinal polarization fraction (ρ_i : rescaled form factors)

$$\frac{d\text{BR}(B^+ \to K^+\nu\bar{\nu})_{\text{SM}}}{dq^2} \equiv \mathcal{B}_K^{\text{SM}}(q^2) = \tau_{B^+} 3|N|^2 \frac{X_t^2}{s_w^4} \rho_K(q^2),$$

$$\frac{d\text{BR}(B^0 \to K^{*0}\nu\bar{\nu})_{\text{SM}}}{dq^2} \equiv \mathcal{B}_{K^*}^{\text{SM}}(q^2) = \tau_{B^0} 3|N|^2 \frac{X_t^2}{s_w^4} \left[\rho_{A_1}(q^2) + \rho_{A_{12}}(q^2) + \rho_V(q^2)\right],$$

$$F_L(B \to K^*\nu\bar{\nu})_{\text{SM}} \equiv F_L^{\text{SM}}(q^2) = \frac{\rho_{A_{12}}(q^2)}{\rho_{A_1}(q^2) + \rho_{A_{12}}(q^2) + \rho_V(q^2)}.$$

- exclusive decays $B \to K^{(*)}\nu\bar{\nu}$: form factors with non-perturbative methods

SM results and experimental upper bounds

q^2-binned observables $\langle \mathcal{B}^{\text{SM}}_{K^{(*)}} \rangle_{[a,b]} \equiv \int_a^b dq^2 \mathcal{B}^{\text{SM}}_K(q^2)$

$$\text{BR}(B \to K^{(*)}\nu\bar{\nu})_{\text{SM}} \equiv \langle \mathcal{B}^{\text{SM}}_{K^{(*)}} \rangle_{[0,q^2_{\text{max}}]} \,.$$

NEW: [Buras,JGN,Niehoff,Straub,'14]

$$\text{BR}(B^+ \to K^+\nu\bar{\nu})_{\text{SM}} = (4.20 \pm 0.33 \pm 0.15) \times 10^{-6},$$
$$\text{BR}(B^0 \to K^{*0}\nu\bar{\nu})_{\text{SM}} = (9.93 \pm 0.74 \pm 0.35) \times 10^{-6},$$
$$F_L^{\text{SM}} = 0.53 \pm 0.05\,,$$

Present upper bounds from **BaBar**

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 1.3 \times 10^{-5}\ (90\%\ \text{CL}),$$

and **Belle**

$$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu}) < 5.5 \times 10^{-5}\ (90\%\ \text{CL}),$$

Going beyond the SM

Low energy effective theory: additionally $\mathcal{O}_R^\ell = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\nu}_\ell \gamma^\mu (1-\gamma_5)\nu_\ell)$
Define:

$$\epsilon_\ell = \frac{\sqrt{|C_L^\ell|^2 + |C_R^\ell|^2}}{|C_L^{\mathrm{SM}}|} \qquad \eta_\ell = \frac{-\mathrm{Re}\left(C_L^\ell C_R^{\ell *}\right)}{|C_L^\ell|^2 + |C_R^\ell|^2}$$

$$\mathcal{R}_K \equiv \frac{\mathcal{B}_K}{\mathcal{B}_K^{\mathrm{SM}}} = \frac{1}{3}\sum_\ell (1 - 2\,\eta_\ell)\epsilon_\ell^2 \quad \longrightarrow \quad (1-2\,\eta)\epsilon^2\,,$$

$$\mathcal{R}_{K^*} \equiv \frac{\mathcal{B}_{K^*}}{\mathcal{B}_{K^*}^{\mathrm{SM}}} = \frac{1}{3}\sum_\ell (1 + \kappa_\eta \eta_\ell)\epsilon_\ell^2 \quad \longrightarrow \quad (1+\kappa_\eta \eta)\epsilon^2\,,$$

$$\mathcal{R}_{F_L} \equiv \frac{F_L}{F_L^{\mathrm{SM}}} = \frac{\sum_\ell \epsilon_\ell^2 (1 + 2\,\eta_\ell)}{\sum_\ell \epsilon_\ell^2 (1 + \kappa_\eta \eta_\ell)} \quad \longrightarrow \quad \frac{1+2\eta}{1+\kappa_\eta \eta}\,.$$

Sensitive to RH currents!

Exploiting SU(2)$_L$ symmetry in $b \to s\nu\bar{\nu}$ and $b \to s\ell^+\ell^-$

[Grzadkowski,Iskrzynski,Misiak,Rosiek,'10], [Hiller,Schmaltz,'14], [Camalich,Grinstein,'14]

Dim. 6 operators invariant under G_{SM}: contribute to $b \to s\nu\bar{\nu}$ and $b \to s\ell^+\ell^-$

$$Q_{Hq}^{(1)} = i(\bar{q}_L\gamma_\mu q_L)H^\dagger D^\mu H\,, \qquad Q_{q\ell}^{(1)} = (\bar{q}_L\gamma_\mu q_L)(\bar{\ell}_L\gamma^\mu\ell_L)\,,$$
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$$Q_{Hd} = i(\bar{d}_R\gamma_\mu d_R)H^\dagger D^\mu H\,, \qquad Q_{d\ell} = (\bar{d}_R\gamma_\mu d_R)(\bar{\ell}_L\gamma^\mu\ell_L)$$

Contribute to $b \to s\ell^+\ell^-$: $Q_{de} = (\bar{d}_R\gamma_\mu d_R)(\bar{e}_R\gamma^\mu e_R)$, $Q_{qe} = (\bar{q}_L\gamma_\mu q_L)(\bar{e}_R\gamma^\mu e_R)$

After EWSB

$$B \to K^{(*)}\nu\bar{\nu}: \quad C_L = C_L^{SM} + \widetilde{c}_{q\ell}^{(1)} - \widetilde{c}_{q\ell}^{(3)} + \widetilde{c}_Z\,, \qquad C_R = \widetilde{c}_{d\ell} + \widetilde{c}'_Z\,,$$
$$B \to K^{(*)}\ell^+\ell^-: \quad C_9 = C_9^{SM} + \widetilde{c}_{qe} + \widetilde{c}_{q\ell}^{(1)} + \widetilde{c}_{q\ell}^{(3)} - \zeta\,\widetilde{c}_Z\,, \qquad C'_9 = \widetilde{c}_{de} + \widetilde{c}_{d\ell} - \zeta\,\widetilde{c}'_Z\,,$$
$$B_s \to \mu^+\mu^-: \quad C_{10} = C_{10}^{SM} + \widetilde{c}_{qe} - \widetilde{c}_{q\ell}^{(1)} - \widetilde{c}_{q\ell}^{(3)} + \widetilde{c}_Z\,, \qquad C'_{10} = \widetilde{c}_{de} - \widetilde{c}_{d\ell} + \widetilde{c}'_Z$$

$$\widetilde{c}_Z = \tfrac{1}{2}(\widetilde{c}_{Hq}^{(1)} + \widetilde{c}_{Hq}^{(3)})\,, \qquad \widetilde{c}'_Z = \tfrac{1}{2}\widetilde{c}_{Hd}\,,$$

In complete generality: NP effects in $b \to s\nu\bar{\nu}$ not constrained by $b \to s\ell^+\ell^-$

Exploiting $SU(2)_L$ symmetry in $b \to s\nu\bar{\nu}$ and $b \to s\ell^+\ell^-$

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After EWSB **MFV, $U(2)^3$**

$$C_L = C_L^{SM} + \widetilde{c}_{q\ell}^{(1)} - \widetilde{c}_{q\ell}^{(3)} + \widetilde{c}_Z\,, \qquad C_R = \widetilde{c}_{d\ell} + \widetilde{c}_Z'\,,$$

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$$\widetilde{c}_Z = \tfrac{1}{2}(\widetilde{c}_{Hq}^{(1)} + \widetilde{c}_{Hq}^{(3)})\,, \qquad \widetilde{c}_Z' = \tfrac{1}{2}\widetilde{c}_{Hd}\,,$$

Correlations possible

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After EWSB

MSSM (MFV)

$$C_L = C_L^{SM} + \widetilde{c}_{q\ell}^{(1)} - \widetilde{c}_{q\ell}^{(3)} + \widetilde{c}_Z\,, \qquad C_R = \widetilde{c}_{d\ell} + \widetilde{c}_Z'\,,$$

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Correlations possible

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After EWSB **MSSM (general)**

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Correlations possible

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After EWSB

331 models

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Correlations possible; only LH currents!

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After EWSB

Z' models

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Different correlations depending on structure of couplings (LH, RH, LR, ALR)

Exploiting SU(2)$_L$ symmetry in $b \to s\nu\bar{\nu}$ and $b \to s\ell^+\ell^-$

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After EWSB **a Leptoquark model**

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$b \to s\nu\bar{\nu}$ unconstrained by $b \to s\ell^+\ell^-$

Exploiting $SU(2)_L$ symmetry in $b \to s\nu\bar{\nu}$ and $b \to s\ell^+\ell^-$

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After EWSB **Z penguins**

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Results see later

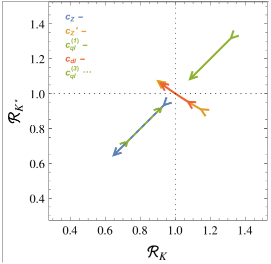
Bounds from $b \to s\ell^+\ell^-$

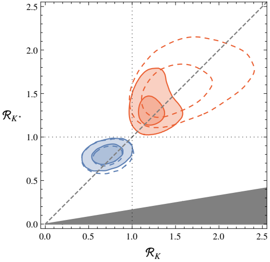
- a lot of studies have been done: [Altmannshofer, Straub, '13,'14],[Bobeth, Hiller, van Dyk, '12], [Descotes-Genon, Hurth, Matias, Virto, '13], [Descotes-Genon, Matias, Virto, '13], [Gault, Goertz, Haisch, '13], [Buras, Girrbach, '13], [Hiller, Schmaltz, '14] . . .
- here: bounds based on [Altmannshofer, Straub, '14]
- constraints on individual Wilson coefficients

$$\begin{aligned} \mathrm{Re}(\tilde{c}_{q\ell}^{(1)} + \tilde{c}_{q\ell}^{(3)}) &\in [-0.94, -0.26]\,, & \mathrm{Im}(\tilde{c}_{q\ell}^{(1)} + \tilde{c}_{q\ell}^{(3)}) &\in [-0.77, +0.77]\,, \\ \mathrm{Re}\,\tilde{c}_{dl} &\in [-0.22, +0.27]\,, & \mathrm{Im}\,\tilde{c}_{dl} &\in [-0.90, +0.91]\,, \\ \mathrm{Re}\,\tilde{c}_{Z} &\in [-0.21, +1.2]\,, & \mathrm{Im}\,\tilde{c}_{Z} &\in [-1.1, +1.1]\,, \\ \mathrm{Re}\,\tilde{c}'_{Z} &\in [-0.45, +0.32]\,, & \mathrm{Im}\,\tilde{c}'_{Z} &\in [-1.1, +1.1]\,. \end{aligned}$$

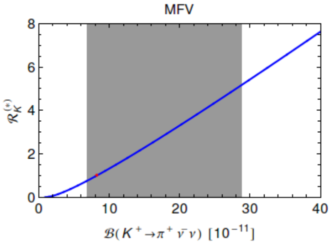
- $\Rightarrow$ Impact on $\mathcal{R}_K$, $\mathcal{R}_{K^*}$, $B_s \to \mu^+\mu^-$, $B \to K\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$

Results



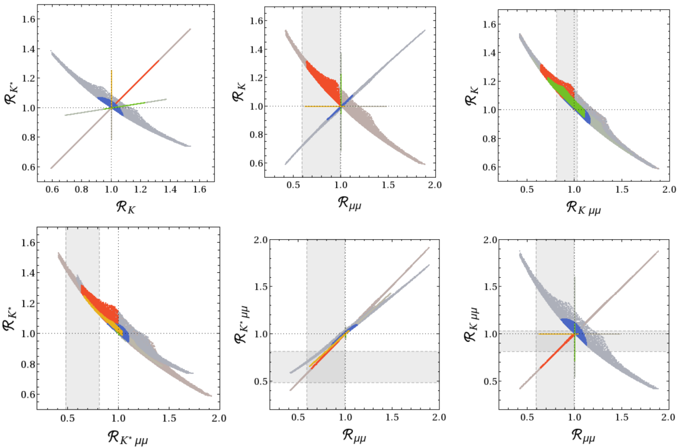


- assuming LFU
- Blue: only Z penguins, i.e. $\tilde{c}_Z$ and $\tilde{c}'_Z$
- Red: only 4-fermion operators, i.e. $c_{ql}^{(1)}$, c_{qe}, $c_{d\ell}$, c_{de}
- $b \to s\ell^+\ell^-$ constraints included



- no RH currents in MFV $\Rightarrow \mathcal{R}_K = \mathcal{R}_K^*$
- strict correlation between $\mathcal{R}_K^{(*)}$ and $K \to \pi\nu\bar{\nu}$: both decribed by $X(v) = -s_w^2 C_L$
- here for fixed CKM

general Z' models



- LHS (red), RHS (blue), LRS (green), ALRS (yellow)
- $0.9 \leq C_{B_s} \leq 1.1$, $-0.14 \leq S_{\psi\phi} \leq 0.14$ and 2σ range of $b \to s\mu^+\mu^-$

$\Rightarrow$ Scenarios can be distinguished through correlations

Consequences

- The present suppressions in the data in $B_s \to \mu^+\mu^-$, $B \to K^{(*)}\mu^+\mu^-$ favour left-handed currents $\to$ can be explained by Z (tree or penguins) and Z'
- $B \to K^{(*)}\nu\bar{\nu}$ can distinguish these two mechanism: both enhanced for Z' and both suppressed for Z

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

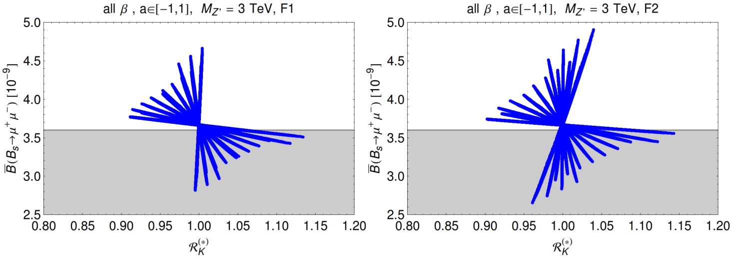
- breaking $SU(3)_L \to SU(2)_L \Rightarrow$ new heavy neutral gauge boson Z'
- different treatment of 3rd gen. $\Rightarrow Z'$ coupling generation non-universal $\Rightarrow$ Z' mediates FCNC at tree level
- only left-handed (LH) quark currents are flavour-violating
- $Z - Z'$ mixing (depends on a parameter $\tan\bar{\beta}$)
- requirement of anomaly cancellation and asymptotic freedom of QCD $\Rightarrow$ number of **generations fixed to $N = 3$!**

Different versions of the model: characterized by parameter β

- discussed here: $\beta = \pm\frac{2}{\sqrt{3}}, \pm\frac{1}{\sqrt{3}}$ (all gauge particles have integer charges) [Buras,De Fazio,JG,'14]

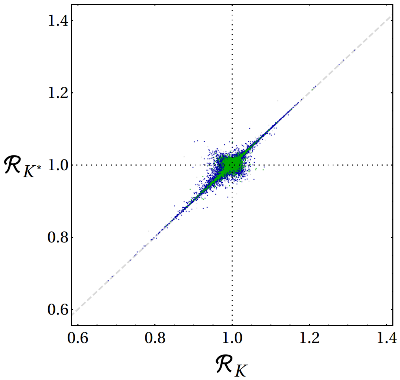
331 models

- $\widetilde{c}_{q\ell}^{(1)}$, $\widetilde{c}_Z$ and $\widetilde{c}_{qe}$ enters with $\widetilde{c}_{q\ell}^{(1)} \propto \widetilde{c}_Z$



- Included: Constraints from $\Delta F = 2$ obs., $b \to s\ell^+\ell^-$ and EWPO
- $\widetilde{c}_{qe} + \widetilde{c}_{q\ell}^{(1)}$ enters C_9, $\widetilde{c}_{qe} - \widetilde{c}_{q\ell}^{(1)}$ enters C_{10} $\Rightarrow$ difficult to get large effects in $B_d \to K^*\mu^+\mu^-$ and $B_s \to \mu^+\mu^-$ simultaneously

MSSM



All dark points pass flavour and collider constraints; green points have the correct lightest Higgs mass

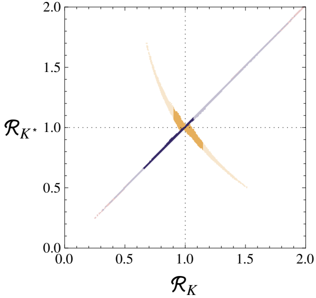
- dominant effect through $\tilde{c}_Z$ (large only in non-MFV), $\tilde{c}'_Z$ (small due to $B_s \to \mu^+\mu^-$)
- LSP: χ_1^0
- LHC bounds on sparticle masses: `FastLim 1.0` [Papucci,Sakurai,Weiler,Zeune,'14]
- FCNC constraints: `SUSY_FLAVOR` [Crivellin,Rosiek,Chankowski,Dedes,Jaeger]
- lightest Higgs mass: `SPheno 3.3.2` [Porod,Staub,'11]

$\Rightarrow$ RH currents small in MSSM, so that $\mathcal{R}_K \approx \mathcal{R}_{K^*}$; $B \to K^{(*)}\nu\bar{\nu}$ at most 30% enhanced/suppressed

Partial Compositness and Leptoquarks

Partial Compositness [Straub,'13]

- dominant contribution to $b \to s\nu\bar{\nu}$ from tree-level flavour-changing Z couplings
  - $\widetilde{c}_Z$ (bidoublet model; blue)
  - $\widetilde{c}'_Z$ (triplet model; yellow)



A Leptoquark model [Angel,Cai,Rodd,Schmidt,Volkas,'13]

- $\widetilde{c}_{q\ell}^{(1)} \approx -\widetilde{c}_{q\ell}^{(3)}$
- large effects in $B \to K^{(*)}\nu\bar{\nu}$ possible and all constraints from $B \to K^{(*)}\ell^+\ell^-$ still fulfilled

Summary

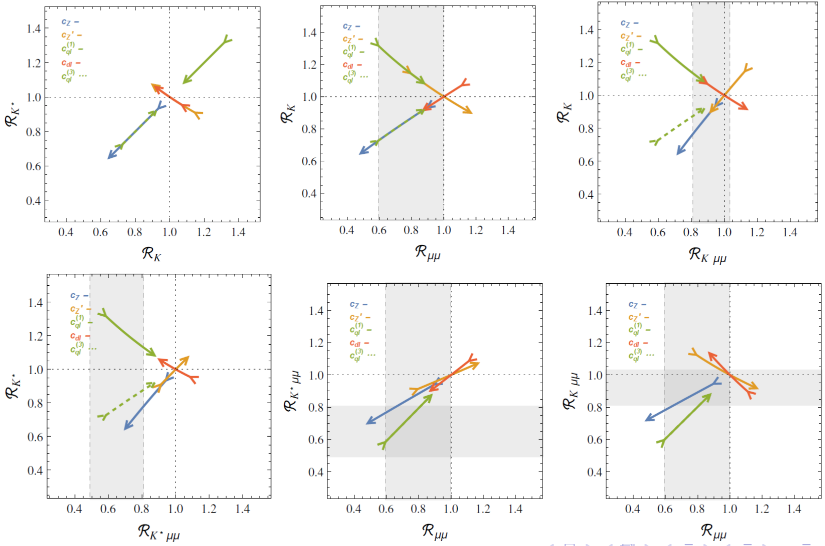
- $b \to s\nu\bar{\nu}$ observables theoretically cleaner than $b \to s\ell^+\ell^-$; sensitive to RH couplings
- updated SM results: reduced to 10% uncertainties
- correlations with $b \to s\ell^+\ell^-$ due to $\mathrm{SU}(2)_L$ symmetry
- effective field theory approach $\to$ factor 2 enhancement/suppression still possible
- small effects in $b \to s\ell^+\ell^-$ does not imply small effects in $b \to s\nu\bar{\nu}$
- NP models: MFV, Z' models, 331 models, MSSM, Partial Compositness

- $b \to s\nu\bar{\nu}$ gives complementary information to NP in $b \to s\ell^+\ell^-$
- but large effects in $b \to s\nu\bar{\nu}$ from more exotic NP only if $b \to s\ell^+\ell^-$ is SM like

Thanks for your attention

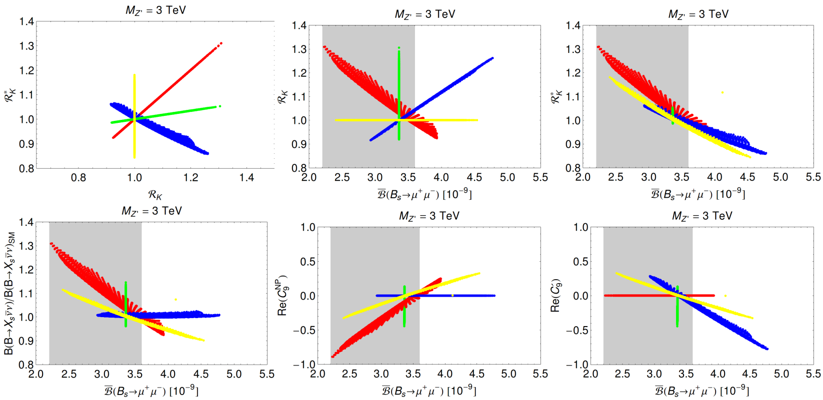
Backup slides

Results



c_Z
c_Z'
$c_{ql}^{(1)}$
c_{dl}
$c_{ql}^{(3)}$
$\mathcal{R}_K$
$\mathcal{R}_{K^*}$
$\mathcal{R}_{\mu\mu}$
$\mathcal{R}_{K\,\mu\mu}$
$\mathcal{R}_{K^*\,\mu\mu}$
0.4
0.6
0.8
1.0
1.2
1.4

general Z' models



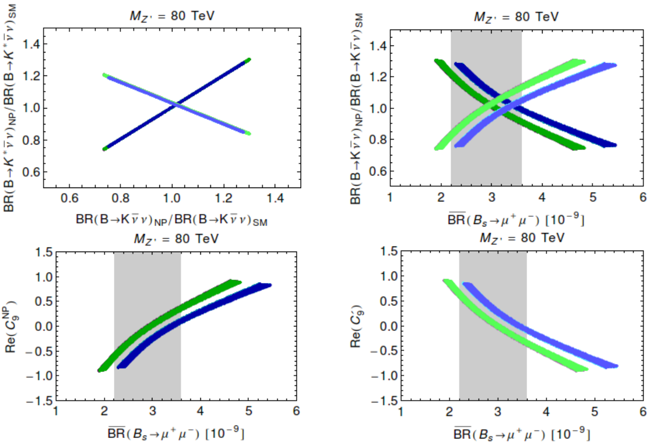
- LHS (red), RHS (blue), LRS (green), ALRS (yellow) for $M'_Z = 3$ TeV
- $\Delta_A^{\mu\mu} = -1$, $\Delta_L^{\nu\nu} = 1$, $\Delta_V^{\mu\mu} = 1$, $|V_{ub}| = 0.0036$, $|V_{cb}| = 0.0040$
- $0.9 \leq C_{B_s} \leq 1.1$, $-0.14 \leq S_{\psi\phi} \leq 0.14$ and 2σ range of $b \to s\ell^+\ell^-$

$\Rightarrow$ Scenarios can be distinguished through correlations

general Z' models

[Buras,Buttazzo,JG,Knegjens,'14]

In principle also sensitive to very high scales in certain models



Here "L+R" model with $M_Z' = 80$ TeV for two different CKM scenarios (lighter/darker colours RH/LH couplings dominate)

SM results

q^2-binned observables $\langle \mathcal{B}^{\text{SM}}_{K^{(*)}} \rangle_{[a,b]} \equiv \int_a^b dq^2 \mathcal{B}^{\text{SM}}_K(q^2)$

$$\text{BR}(B \to K^{(*)}\nu\bar{\nu})_{\text{SM}} \equiv \langle \mathcal{B}^{\text{SM}}_{K^{(*)}} \rangle_{[0,q^2_{\text{max}}]} \,.$$

$$\text{BR}(B^+ \to K^+\nu\bar{\nu})_{\text{SM}} = (4.20 \pm 0.33 \pm 0.15) \times 10^{-6},$$
$$\text{BR}(B^0 \to K^{*0}\nu\bar{\nu})_{\text{SM}} = (9.93 \pm 0.74 \pm 0.35) \times 10^{-6},$$
$$F_L^{\text{SM}} = 0.53 \pm 0.05 \,,$$

q^2 [GeV]^2	$10^6 \langle \mathcal{B}^{\text{SM}}_{K^*} \rangle$	κ_η	$\langle F_L^{\text{SM}} \rangle$	$10^6 \langle \mathcal{B}^{\text{SM}}_K \rangle$
$0-4$	$1.58 \pm 0.18 \pm 0.06$	1.70 ± 0.04	0.83 ± 0.02	$0.99 \pm 0.14 \pm 0.04$
$4-8$	$2.05 \pm 0.19 \pm 0.07$	1.35 ± 0.06	0.61 ± 0.02	$0.98 \pm 0.09 \pm 0.04$
$8-12$	$2.42 \pm 0.19 \pm 0.09$	1.20 ± 0.06	0.47 ± 0.02	$0.91 \pm 0.06 \pm 0.03$
$12-16$	$2.51 \pm 0.17 \pm 0.09$	1.25 ± 0.06	0.38 ± 0.02	$0.75 \pm 0.04 \pm 0.03$
$16-q^2_{\text{max}}$	$1.37 \pm 0.10 \pm 0.05$	1.57 ± 0.05	0.33 ± 0.03	$0.58 \pm 0.02 \pm 0.02$
$0-q^2_{\text{max}}$	$9.93 \pm 0.74 \pm 0.35$	1.37 ± 0.05	0.52 ± 0.02	$4.20 \pm 0.33 \pm 0.15$

Particle content of $\overline{331}$ model

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

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

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

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

- 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$\propto (b-a)$

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

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

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

Particle content of $\overline{331}$ model

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

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

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

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

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

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

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

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

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