Flavour Physics beyond the SM

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based on: A. Buras, JGN, C. Niehoff, D. Straub [1409.4557]
A. Buras, D. Buttazzo, JGN, R. Knegjens, JHEP 11 (2014), [1408.0728]

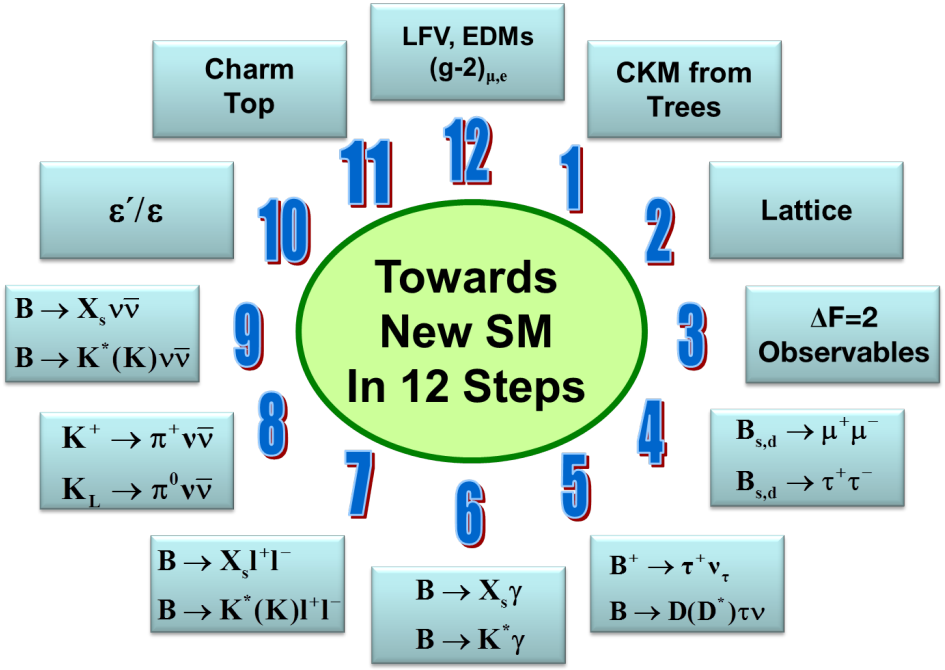
Zurich Phenomenology Workshop
The flavour of new physics

07.01–09.01.2015

How to find NP in flavour physics?

- CKM parameters should be determined by means of tree-level decays $\Rightarrow$ no NP pollution (γ, $|V_{ub}|$, $|V_{cb}|$)
- Lattice: non-perturbative parameters should have small uncertainties (F_{B_d}, F_{B_s}, $\hat{B}_{B_d}$, $\hat{B}_{B_s}$, $B \to K^{(*)}$ form factors)
- study many different observables and their correlations

[Buras, JG; Review 1306.3775]



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

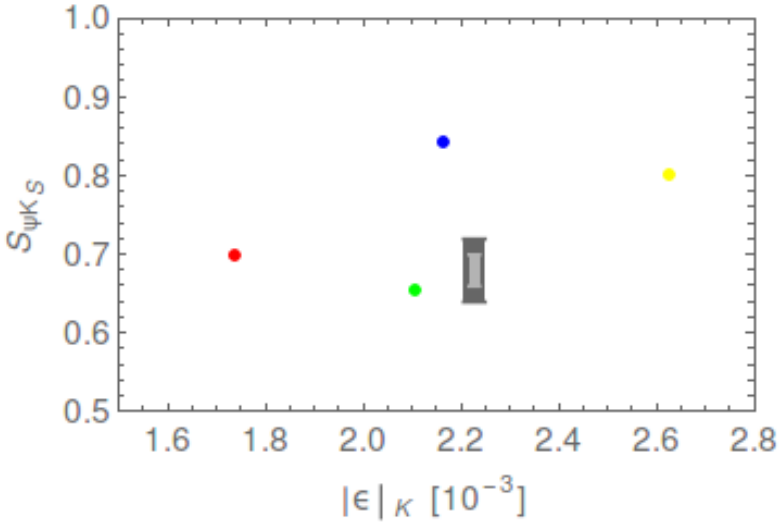
V_{ub} and V_{cb} discrepancy

Data:

$$|V_{ub}|_{\text{excl.}} = (3.42 \pm 0.31) \times 10^{-3}\,, \quad |V_{cb}|_{\text{excl.}} = (39.4 \pm 0.6) \times 10^{-3}$$
$$|V_{ub}|_{\text{incl.}} = (4.40 \pm 0.25) \times 10^{-3}\,, \quad |V_{cb}|_{\text{incl.}} = (42.4 \pm 0.9) \times 10^{-3}$$

Important for SM predictions! [Crivellin, Pokorski [1407.1320]: NP explanation for difference between excl. and incl. determinations currently ruled out]

- Example: $S_{\psi K_S}$ and ε_K:



Here only SM central values for

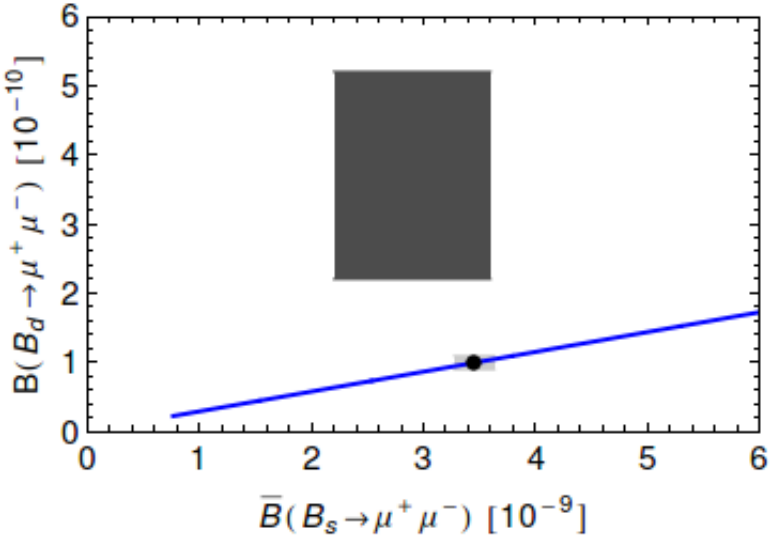
$$(|V_{ub}| \cdot 10^3, |V_{cb}| \cdot 10^3) =$$
$$(3.42,\ 39.4), \quad (4.40,\ 39.4),$$
$$(3.42,\ 42.4), \quad (4.40,\ 42.4)$$

Test of constrained MFV

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

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)^{\text{exp}} = (2.8 \pm 0.7) \times 10^{-9}$$

$$\mathcal{B}(B_d \to \mu^+\mu^-)^{\text{exp}} = \left(3.9^{+1.6}_{-1.4}\right) \times 10^{-10}$$



$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)^{\text{SM}} = (3.65 \pm 0.23) \cdot 10^{-9}$$

$$\mathcal{B}(B_d \to \mu^+\mu^-)_{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10}$$

[Bobeth,Gorbahn,Herrmann,Stamou,2014], [Buras,JG,Guadagnoli,Isidori,2012], [De Bruyn, Fleischer, Knegjens, Koppenburg, Merk, 2012], [Buras, Fleischer, JG, Knegjens, 2013]

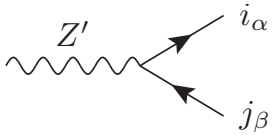
$$\left[\frac{\mathcal{B}(B_d \to \mu^+\mu^-)}{\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)}\right]_{\text{exp}} \approx (4.8 \pm 2.3) \left[\frac{\mathcal{B}(B_d \to \mu^+\mu^-)}{\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)}\right]_{\text{SM/CMFV}}$$

What happens in other NP models?

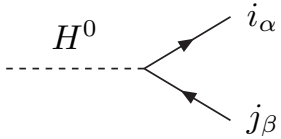
New particles?

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): $\Delta_L^{bq} = -\Delta_R^{bq} \neq 0$

Left-handed versus right-handed currents

- $\Delta F = 2$ observables: cannot distinguish between L and R

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

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

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

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

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

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

$\Delta F = 1$ can distinguish between L and R

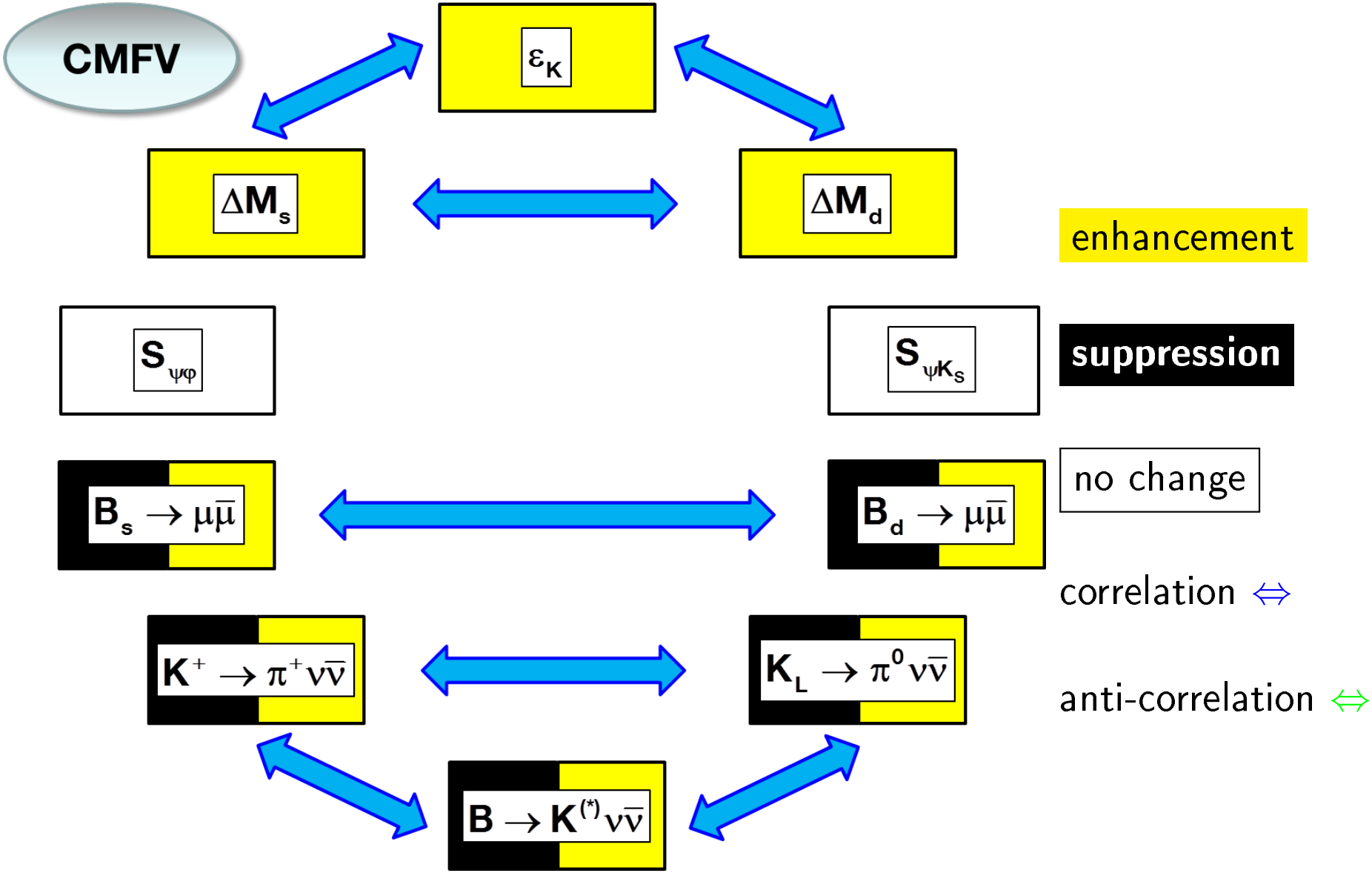
1. vector couplings γ_μ: $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, $B \to K\nu\bar{\nu}$
2. axial vector couplings $\gamma_\mu\gamma_5$: $K_L \to \mu^+\mu^-$, $B_{s,d} \to \mu^+\mu^-$, $B \to K^*\nu\bar{\nu}$

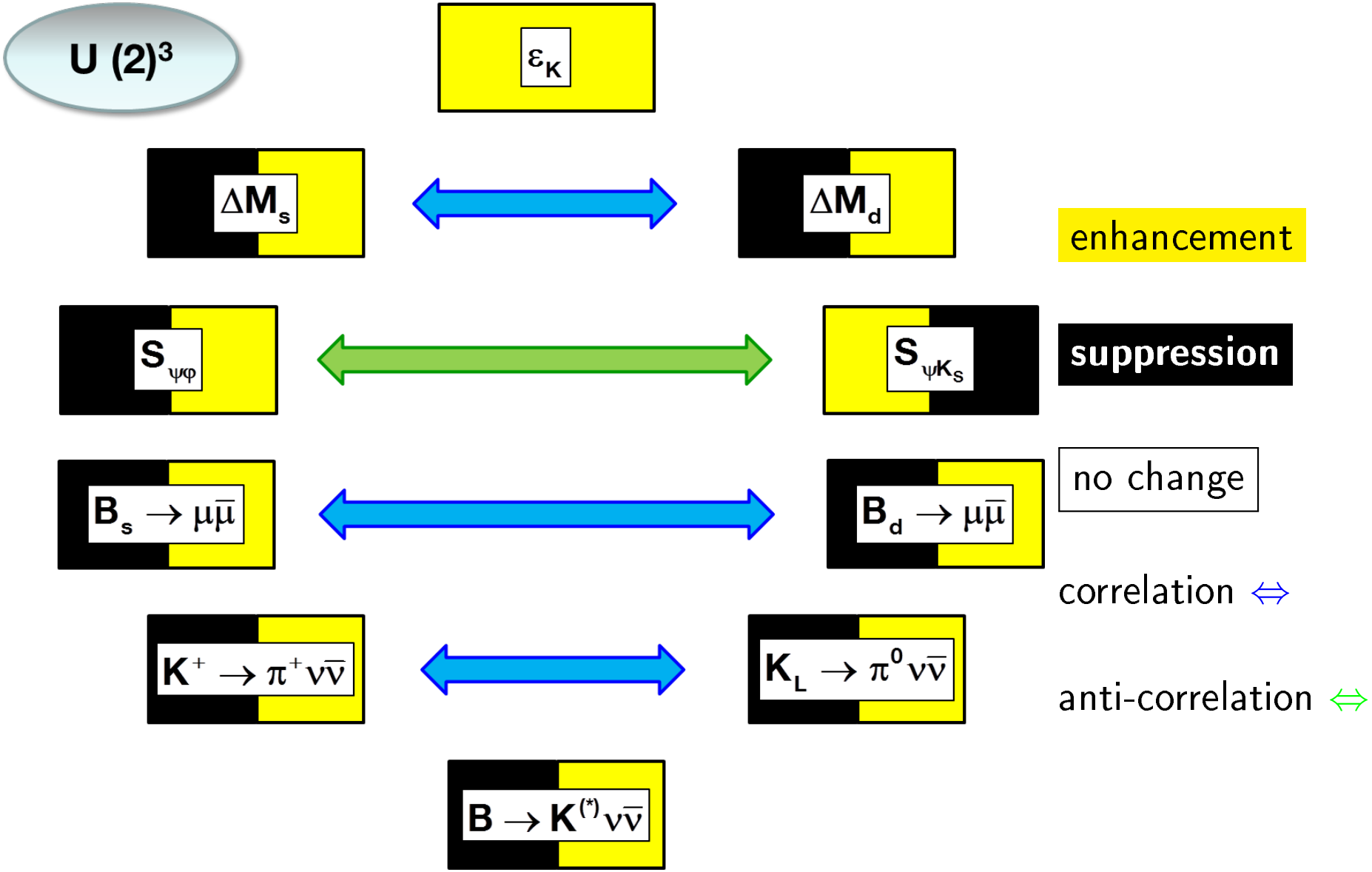
Change $L \leftrightarrow R$: sign flip in 2.) in NP contribution but not in 1.)

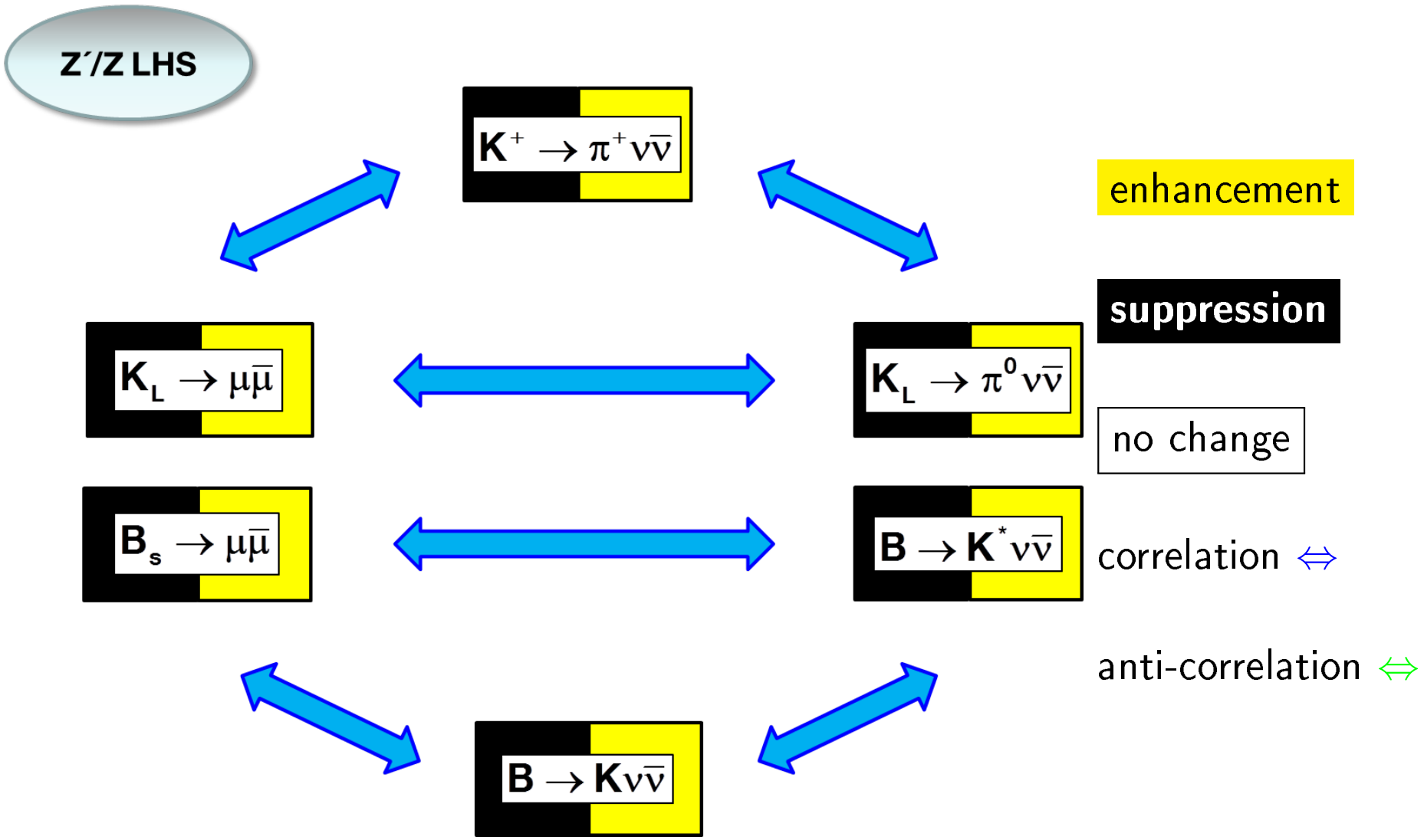
[Buras, De Fazio, JG; 1211.1896, 1311.6729, 1404.3824, 1405.3850], [Buras, De Fazio, JG, Knegjens; 1303.3723], [Buras, Fleischer, JG, Knegjens; 1303.3820]

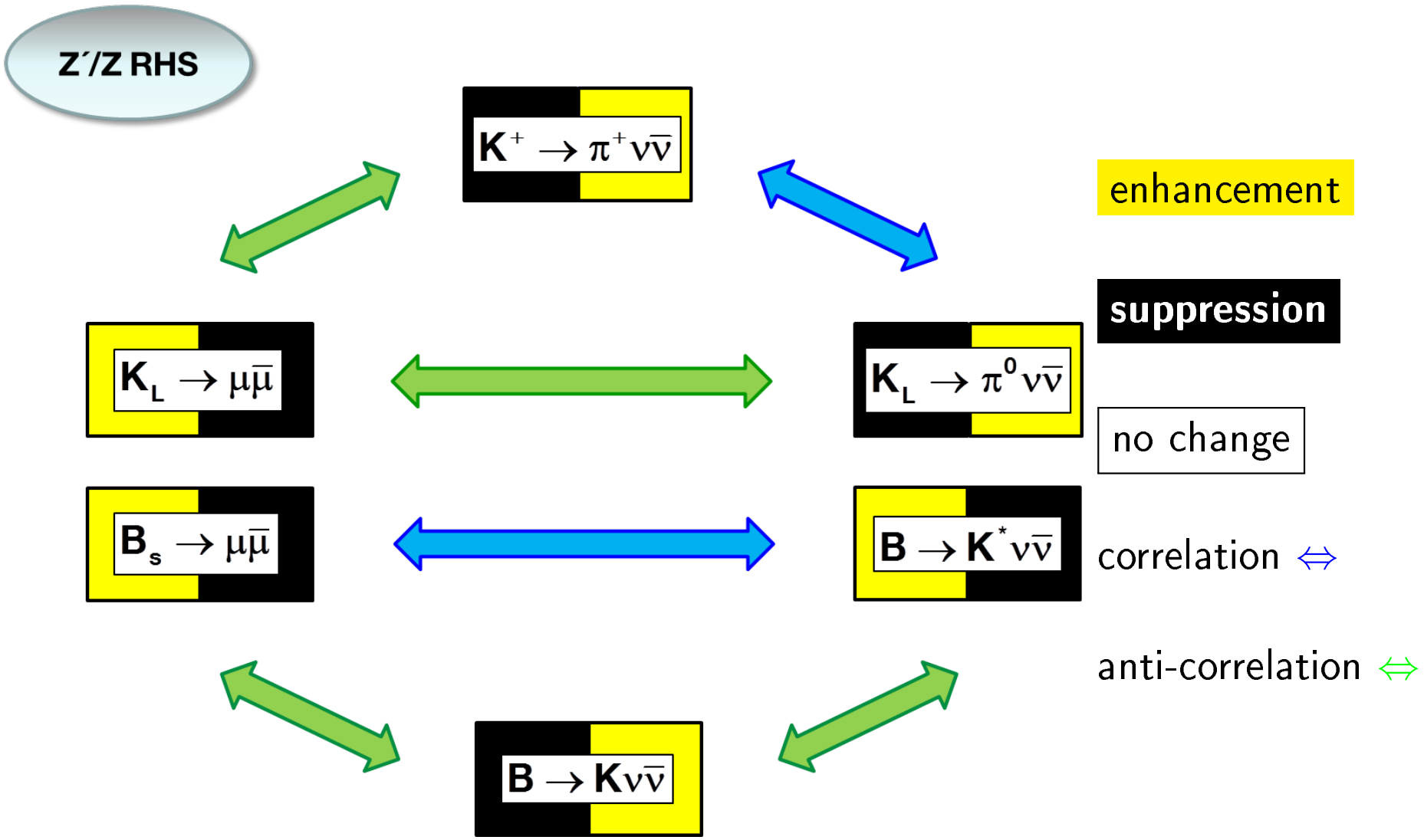
"DNA-charts"

[Buras, JG; Review 1306.3775]


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


U (2)3
εK
ΔMs
ΔMd
enhancement
Sψφ
SψKS
suppression
Bs → μμ̄
Bd → μμ̄
no change
correlation ⇔
K+ → π+νν̄
KL → π0νν̄
anti-correlation ⇔
B → K(*)νν̄


Z´/Z LHS
$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \mu\bar{\mu}$
$K_L \to \pi^0 \nu\bar{\nu}$
$B_s \to \mu\bar{\mu}$
$B \to K^* \nu\bar{\nu}$
$B \to K \nu\bar{\nu}$
enhancement
suppression
no change
correlation ⇔
anti-correlation ⇔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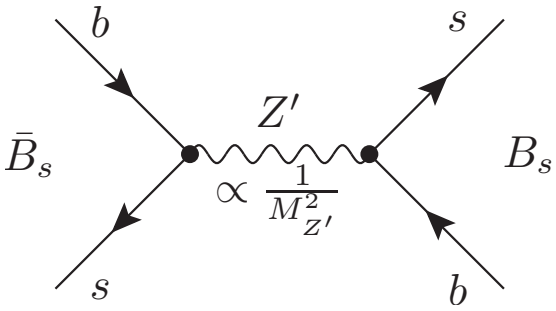
$B \to K \nu\bar{\nu}$
enhancement
suppression
no change
correlation ⇔
anti-correlation ⇔

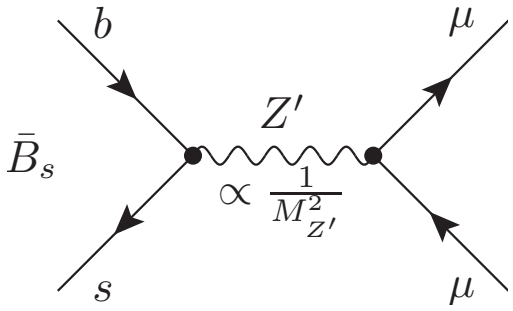
What are the shortest distance scales that we can explore with flavour physics?

[Buras, Buttazzo, JGN, Knegjens; 1407.0728]

Example: Z' models

- $\Delta F = 2$ and $\Delta F = 1$ observables correlated





For fixed lepton couplings, after $\Delta F = 2$ constraints, NP effects in rare decays decrease as $1/M_{Z'}$.

- Only LH or only RH flavour changing Z' couplings $\Rightarrow$ maximal resolution:

$$K \to \pi\nu\bar{\nu} : \Lambda_{\rm NP}^{\rm max} \simeq 200 \text{ TeV}, \quad B_{d,s} \text{ physics} : \Lambda_{\rm NP}^{\rm max} \simeq 15 \text{ TeV}$$

- For LH $= \pm$ RH couplings: scales are lower due to stronger constraints from $\Delta F = 2$

- Case LH$\ll$RH or LH$\gg$RH with LH$\neq 0 \neq$RH:

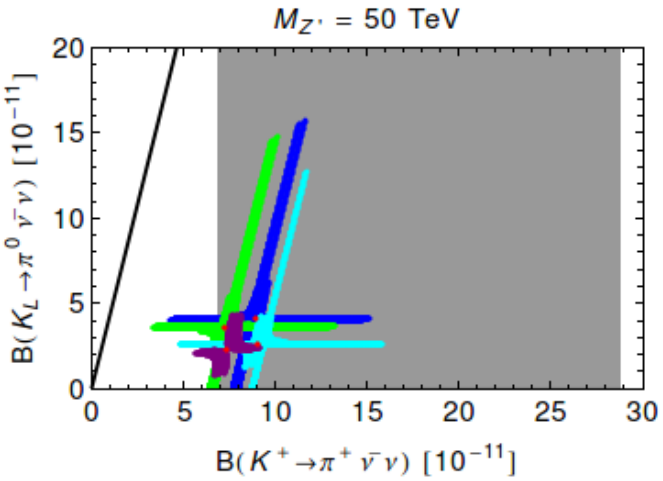
$\Rightarrow$ Much higher scales can be probed
Significant NP effects in rare decays

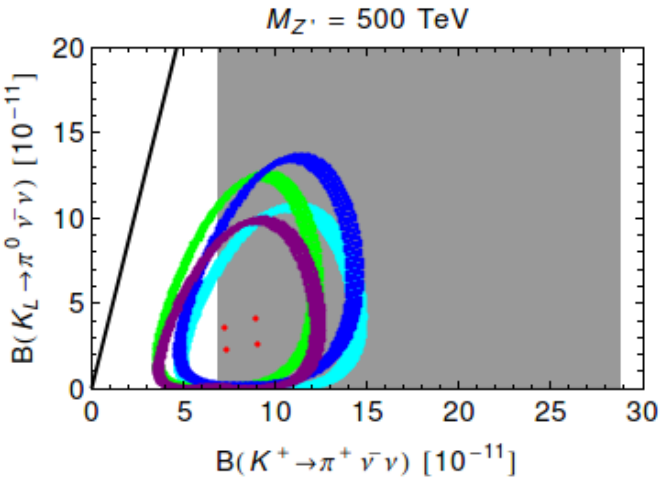
$\Delta F = 2$ constraints can be satisfied with some tuning

- $\Delta F = 2$ cannot distinguish between LH$\ll$ RH and LH$\gg$RH, but $\Delta F = 1$ can via correlations

Maximal resolution

$K \to \pi\nu\bar{\nu}$: $\Lambda_{\rm NP}^{\rm max} \simeq 2000$ TeV, $\quad B_{d,s}$ physics : $\Lambda_{\rm NP}^{\rm max} \simeq 160$ TeV





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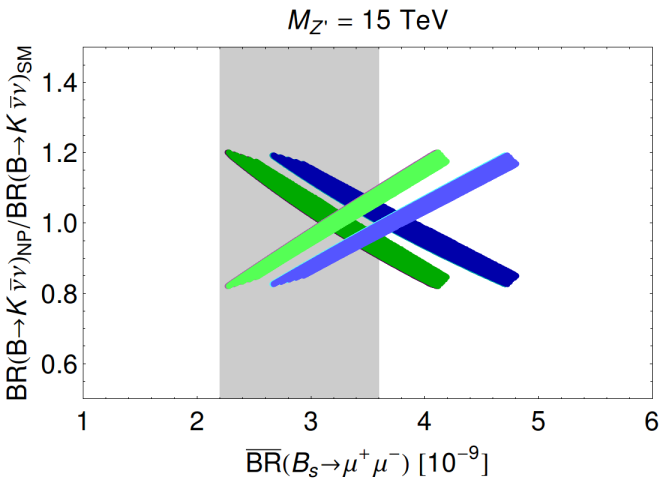

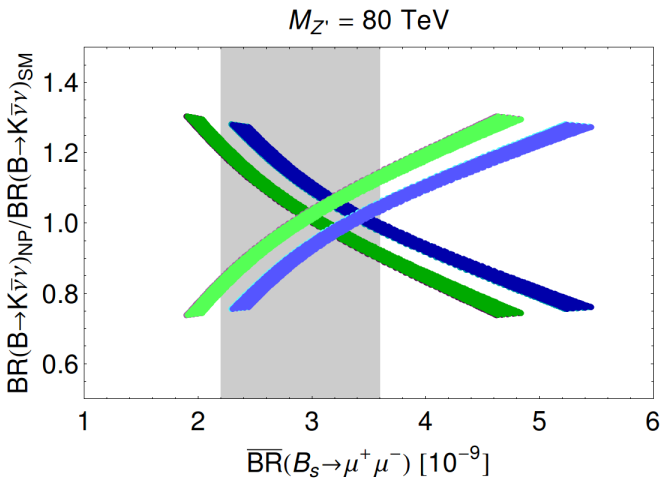

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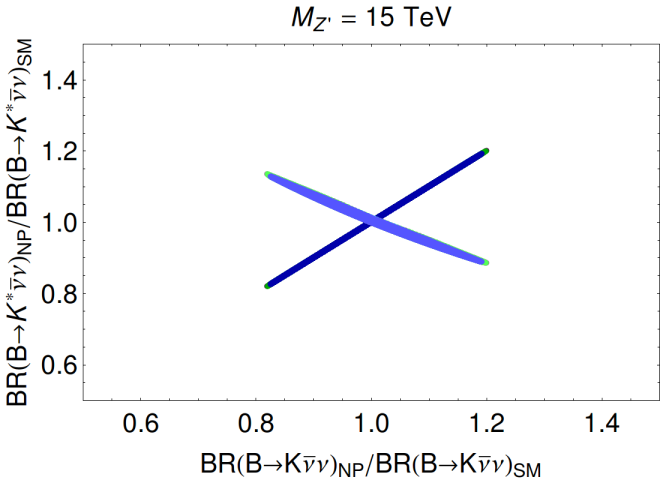
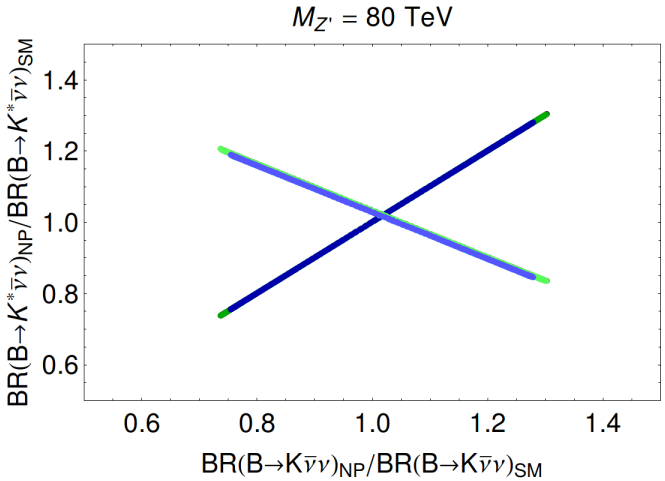


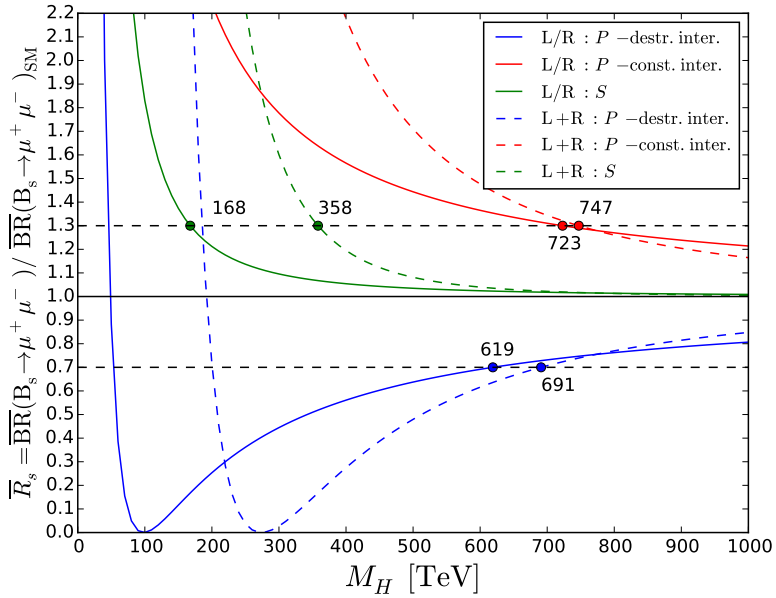


Example: (Pseudo-)scalars

- Pseudoscalars more powerful than scalars because of interference with SM contribution
- $B_{s,d} \to \mu^+\mu^-$ sensitive to (pseudo-)scalars
- no tuning needed

Maximal resolution

Scalars: $\Lambda_{\rm NP}^{\rm max} \simeq 350$ TeV, Pseudoscalars : $\Lambda_{\rm NP}^{\rm max} \simeq 700$ TeV



Dependence of $\mathcal{B}(B_s \to \mu^+\mu^-)$ on the heavy (pseudo-)scalar mass M_H, showing the pure LH (or RH) scenario and the combined L+R scenario

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

[Buras, JGN, Niehoff, Straub 1409.4557]

- $B \to K^{(*)}\nu\bar{\nu}$: theoretically very clean; sensitive to RH couplings and Z penguins $\to$ studied in detail by [Altmannshofer,Buras,Straub,Wick,'09]
- $SU(2)_L$ symmetry $\Rightarrow$ correlation between $b \to s\ell^+\ell^-$ and $b \to s\nu\bar{\nu}$ transitions
- new $B \to K^*\mu^+\mu^-$ data [Altmannshofer,Straub,'12,'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] $\Rightarrow$ impact on constraints on $b \to s\nu\bar{\nu}$
- decrease of form factor uncertainties due to lattice calculations
- Departure of lepton flavour universality (not covered in this talk)

NEW: SM update

$$\mathrm{BR}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SM}} = (3.98 \pm 0.43 \pm 0.19) \times 10^{-6}$$
$$\mathrm{BR}(B^0 \to K^{*0}\nu\bar{\nu})_{\mathrm{SM}} = (9.19 \pm 0.86 \pm 0.50) \times 10^{-6}$$
$$F_L^{\mathrm{SM}} = 0.47 \pm 0.03$$
$$\mathrm{BR}(B^+ \to K^+\nu\bar{\nu}) < 1.7 \times 10^{-5} \text{ (90\% CL, BaBar)}$$
$$\mathrm{BR}(B^0 \to K^{*0}\nu\bar{\nu}) < 5.5 \times 10^{-5} \text{ (90\% CL, Belle)},$$

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

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

$$Q_{Hq}^{(3)} = i(\bar{q}_L\gamma_\mu \tau^a q_L)H^\dagger D^\mu \tau_a H\,, \qquad Q_{q\ell}^{(3)} = (\bar{q}_L\gamma_\mu \tau^a q_L)(\bar{\ell}_L\gamma^\mu \tau_a \ell_L)\,,$$

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

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, $U(2)^3$**

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

$$C_9 = C_9^{SM} + \widetilde{c}_{qe} + \widetilde{c}_{q\ell}^{(1)} + \widetilde{c}_{q\ell}^{(3)} - \zeta\,\widetilde{c}_Z\,, \qquad C_9' = \widetilde{c}_{de} + \widetilde{c}_{d\ell} - \zeta\,\widetilde{c}_Z'\,,$$

$$C_{10} = C_{10}^{SM} + \widetilde{c}_{qe} - \widetilde{c}_{q\ell}^{(1)} - \widetilde{c}_{q\ell}^{(3)} + \widetilde{c}_Z\,, \qquad C_{10}' = \widetilde{c}_{de} - \widetilde{c}_{d\ell} + \widetilde{c}_Z'$$

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

Correlations possible

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

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After EWSB

MSSM (MFV)

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

$$C_9 = C_9^{SM} + \widetilde{c}_{qe} + \widetilde{c}_{q\ell}^{(1)} + \widetilde{c}_{q\ell}^{(3)} - \zeta\,\widetilde{c}_Z\,, \qquad C'_9 = \widetilde{c}_{de} + \widetilde{c}_{d\ell} - \zeta\,\widetilde{c}'_Z\,,$$

$$C_{10} = C_{10}^{SM} + \widetilde{c}_{qe} - \widetilde{c}_{q\ell}^{(1)} - \widetilde{c}_{q\ell}^{(3)} + \widetilde{c}_Z\,, \qquad C'_{10} = \widetilde{c}_{de} - \widetilde{c}_{d\ell} + \widetilde{c}'_Z$$

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

Correlations possible

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

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

$$Q_{Hq}^{(3)} = i(\bar{q}_L\gamma_\mu \tau^a q_L)H^\dagger D^\mu \tau_a H\,, \qquad Q_{q\ell}^{(3)} = (\bar{q}_L\gamma_\mu \tau^a q_L)(\bar{\ell}_L\gamma^\mu \tau_a \ell_L)\,,$$

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

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

MSSM (general)

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

$$C_9 = C_9^{SM} + \widetilde{c}_{qe} + \widetilde{c}_{q\ell}^{(1)} + \widetilde{c}_{q\ell}^{(3)} - \zeta\,\widetilde{c}_Z\,, \qquad C_9' = \widetilde{c}_{de} + \widetilde{c}_{d\ell} - \zeta\,\widetilde{c}_Z'\,,$$

$$C_{10} = C_{10}^{SM} + \widetilde{c}_{qe} - \widetilde{c}_{q\ell}^{(1)} - \widetilde{c}_{q\ell}^{(3)} + \widetilde{c}_Z\,, \qquad C_{10}' = \widetilde{c}_{de} - \widetilde{c}_{d\ell} + \widetilde{c}_Z'$$

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

Correlations possible

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

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

$$Q_{Hq}^{(3)} = i(\bar{q}_L\gamma_\mu \tau^a q_L)H^\dagger D^\mu \tau_a H\,, \qquad Q_{q\ell}^{(3)} = (\bar{q}_L\gamma_\mu \tau^a q_L)(\bar{\ell}_L\gamma^\mu \tau_a \ell_L)\,,$$

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

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 **331 models**

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

$$C_9 = C_9^{SM} + \widetilde{c}_{qe} + \widetilde{c}_{q\ell}^{(1)} + \widetilde{c}_{q\ell}^{(3)} - \zeta\,\widetilde{c}_Z\,, \qquad C'_9 = \widetilde{c}_{de} + \widetilde{c}_{d\ell} - \zeta\,\widetilde{c}'_Z\,,$$

$$C_{10} = C_{10}^{SM} + \widetilde{c}_{qe} - \widetilde{c}_{q\ell}^{(1)} - \widetilde{c}_{q\ell}^{(3)} + \widetilde{c}_Z\,, \qquad C'_{10} = \widetilde{c}_{de} - \widetilde{c}_{d\ell} + \widetilde{c}'_Z$$

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

Correlations possible; only LH 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 $b \to s\ell^+\ell^-$

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

$$Q_{Hq}^{(3)} = i(\bar{q}_L\gamma_\mu \tau^a q_L)H^\dagger D^\mu \tau_a H\,, \qquad Q_{q\ell}^{(3)} = (\bar{q}_L\gamma_\mu \tau^a q_L)(\bar{\ell}_L\gamma^\mu \tau_a \ell_L)\,,$$

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

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

Z' models

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

$$C_9 = C_9^{SM} + \widetilde{c}_{qe} + \widetilde{c}_{q\ell}^{(1)} + \widetilde{c}_{q\ell}^{(3)} - \zeta\,\widetilde{c}_Z\,, \qquad C'_9 = \widetilde{c}_{de} + \widetilde{c}_{d\ell} - \zeta\,\widetilde{c}'_Z\,,$$

$$C_{10} = C_{10}^{SM} + \widetilde{c}_{qe} - \widetilde{c}_{q\ell}^{(1)} - \widetilde{c}_{q\ell}^{(3)} + \widetilde{c}_Z\,, \qquad C'_{10} = \widetilde{c}_{de} - \widetilde{c}_{d\ell} + \widetilde{c}'_Z$$

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

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

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

[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 $b \to s\ell^+\ell^-$

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

$$Q_{Hq}^{(3)} = i(\bar{q}_L\gamma_\mu \tau^a q_L)H^\dagger D^\mu \tau_a H\,, \qquad Q_{q\ell}^{(3)} = (\bar{q}_L\gamma_\mu \tau^a q_L)(\bar{\ell}_L\gamma^\mu \tau_a \ell_L)\,,$$

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

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 **a Leptoquark model**

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

$$C_9 = C_9^{SM} + \widetilde{c}_{qe} + \widetilde{c}_{q\ell}^{(1)} + \widetilde{c}_{q\ell}^{(3)} - \zeta\,\widetilde{c}_Z\,, \qquad C'_9 = \widetilde{c}_{de} + \widetilde{c}_{d\ell} - \zeta\,\widetilde{c}'_Z\,,$$

$$C_{10} = C_{10}^{SM} + \widetilde{c}_{qe} - \widetilde{c}_{q\ell}^{(1)} - \widetilde{c}_{q\ell}^{(3)} + \widetilde{c}_Z\,, \qquad C'_{10} = \widetilde{c}_{de} - \widetilde{c}_{d\ell} + \widetilde{c}'_Z$$

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

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

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

[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 $b \to s\ell^+\ell^-$

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

$$Q_{Hq}^{(3)} = i(\bar{q}_L\gamma_\mu \tau^a q_L)H^\dagger D^\mu \tau_a H\,, \qquad Q_{q\ell}^{(3)} = (\bar{q}_L\gamma_\mu \tau^a q_L)(\bar{\ell}_L\gamma^\mu \tau_a \ell_L)\,,$$

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

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 **Z penguins**

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

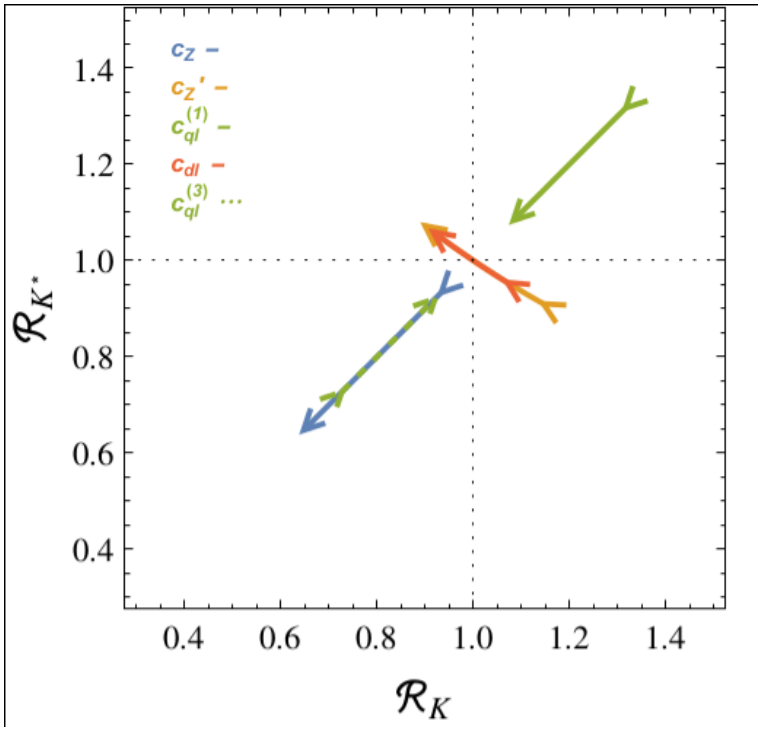
$$C_9 = C_9^{SM} + \widetilde{c}_{qe} + \widetilde{c}_{q\ell}^{(1)} + \widetilde{c}_{q\ell}^{(3)} - \zeta\,\widetilde{c}_Z\,, \qquad C_9' = \widetilde{c}_{de} + \widetilde{c}_{d\ell} - \zeta\,\widetilde{c}_Z'\,,$$

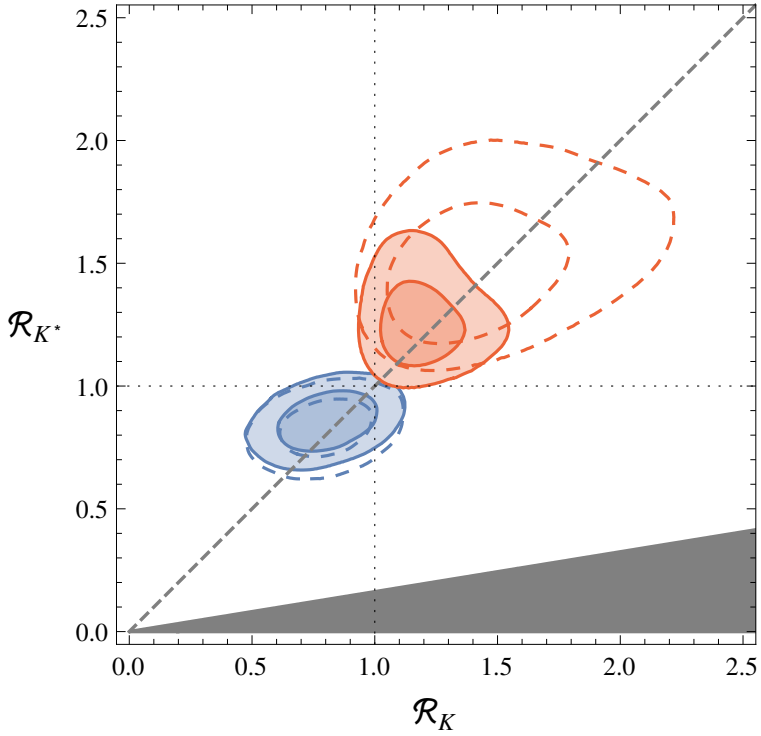
$$C_{10} = C_{10}^{SM} + \widetilde{c}_{qe} - \widetilde{c}_{q\ell}^{(1)} - \widetilde{c}_{q\ell}^{(3)} + \widetilde{c}_Z\,, \qquad C_{10}' = \widetilde{c}_{de} - \widetilde{c}_{d\ell} + \widetilde{c}_Z'$$

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

Results see next slide

Results





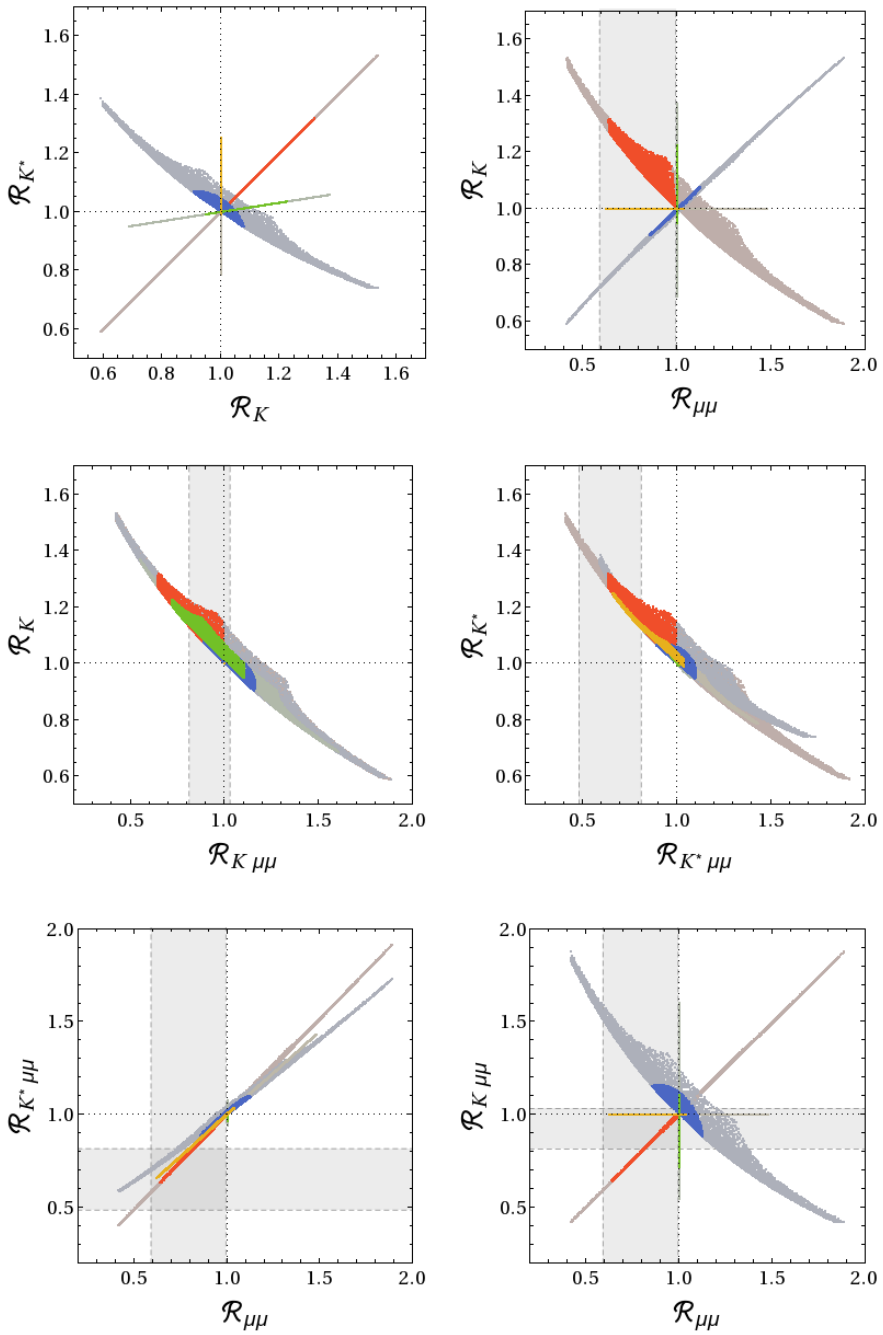
- assuming LFU
- Blue: only Z penguins, i.e. $\widetilde{c}_Z$ and $\widetilde{c}'_Z$
- Red: only 4-fermion operators, i.e. $c_{ql}^{(1)}$, c_{qe}, $c_{d\ell}$, c_{de} (Z' scenario)
- $b \to s\ell^+\ell^-$ constraints included

General Z' scenario

LHS, RHS, LRS, ALRS for $M'_Z = 3$ TeV
$0.9 \leq C_{B_s} \leq 1.1$, $-0.14 \leq S_{\psi\phi} \leq 0.14$
and 2σ range of $b \to s\ell^+\ell^-$

$\Rightarrow$ Scenarios can be distinguished through correlations

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

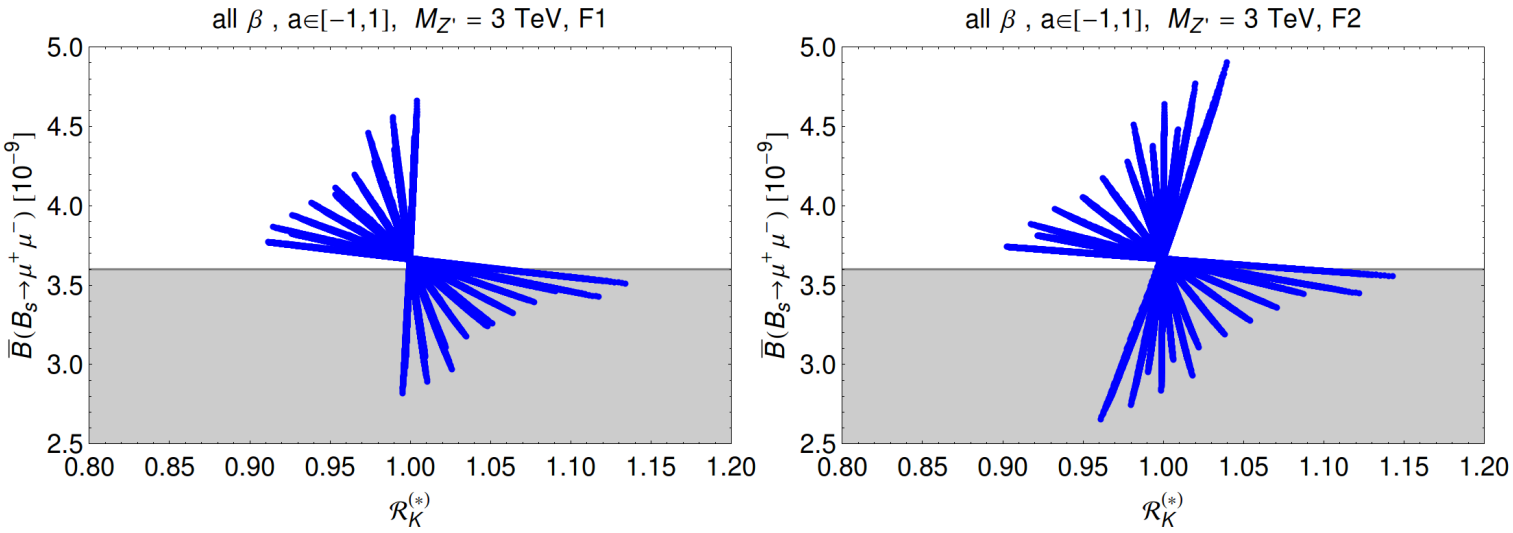
- concrete realization of LH Z' model
- breaking $SU(3)_L \to SU(2)_L \Rightarrow$ new heavy neutral gauge boson Z'
- different treatment of 3rd gen. $\Rightarrow Z'$ coupling generation non-universal $\Rightarrow$ Z' mediates FCNC at tree level
- only left-handed (LH) quark currents are flavour-violating
- $Z - Z'$ 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]

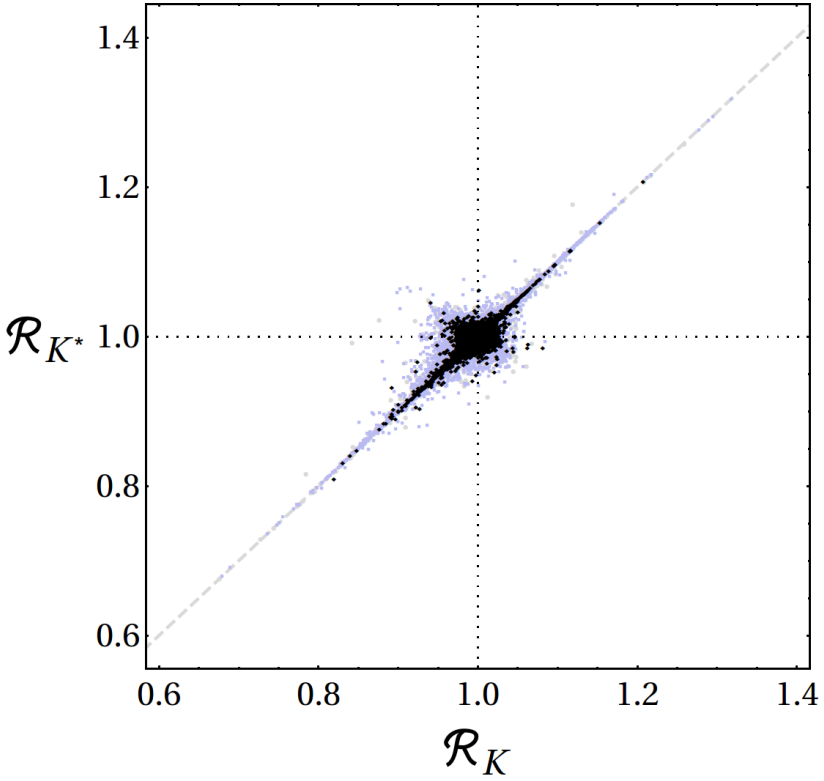
331 models

- $\widetilde{c}_{q\ell}^{(1)}$, $\widetilde{c}_Z$ 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; black points have the correct lightest Higgs mass

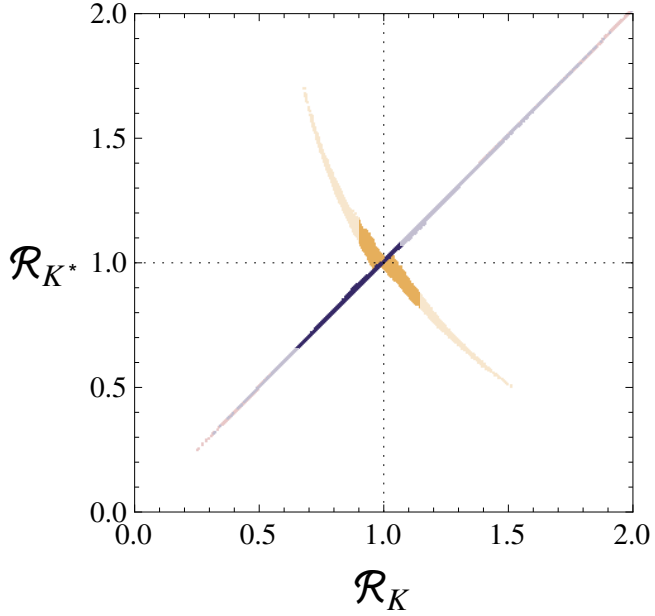
- dominant effect through $\widetilde{c}_Z$ (large only in non-MFV), $\widetilde{c}'_Z$ (small due to $B_s \to \mu^+\mu^-$)
- LSP: χ_1^0
- LHC bounds on sparticle masses: `FastLim 1.0` [Papucci,Sakurai,Weiler,Zeune,'14]
- FCNC constraints: `SUSY_FLAVOR` [Crivellin,Rosiek,Chankowski,Dedes,Jaeger]
- lightest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

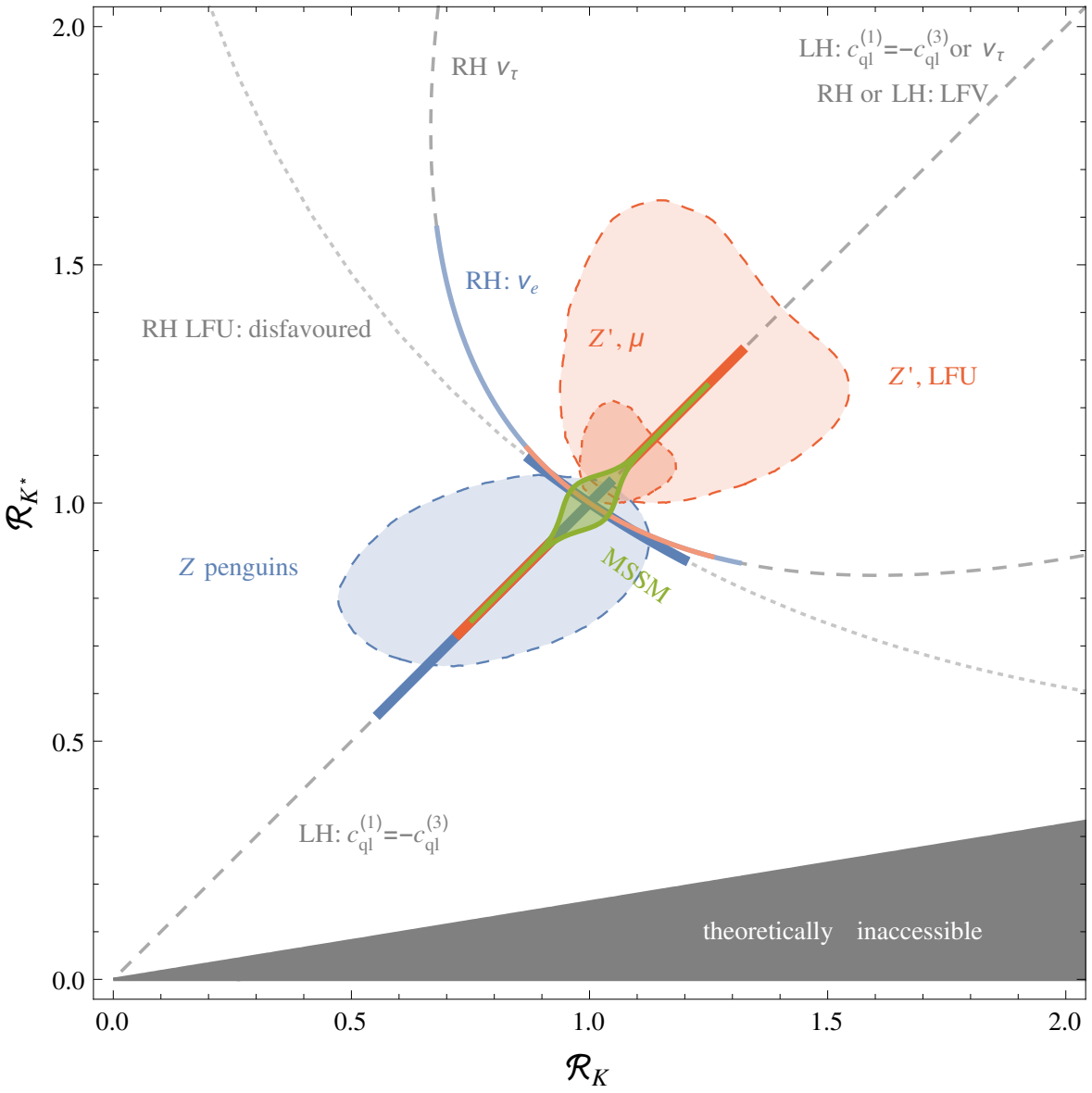
- dominant contribution to $b \to s\nu\bar{\nu}$ from tree-level flavour-changing Z couplings
  - $\widetilde{c}_Z$ (bidoublet model; blue)
  - $\widetilde{c}'_Z$ (triplet model; yellow)



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

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

Summary: $B \to K^{(*)}\nu\bar{\nu}$ for different NP models



[Buras, JGN, Niehoff, Straub 1409.4557] [plot by D. Straub]

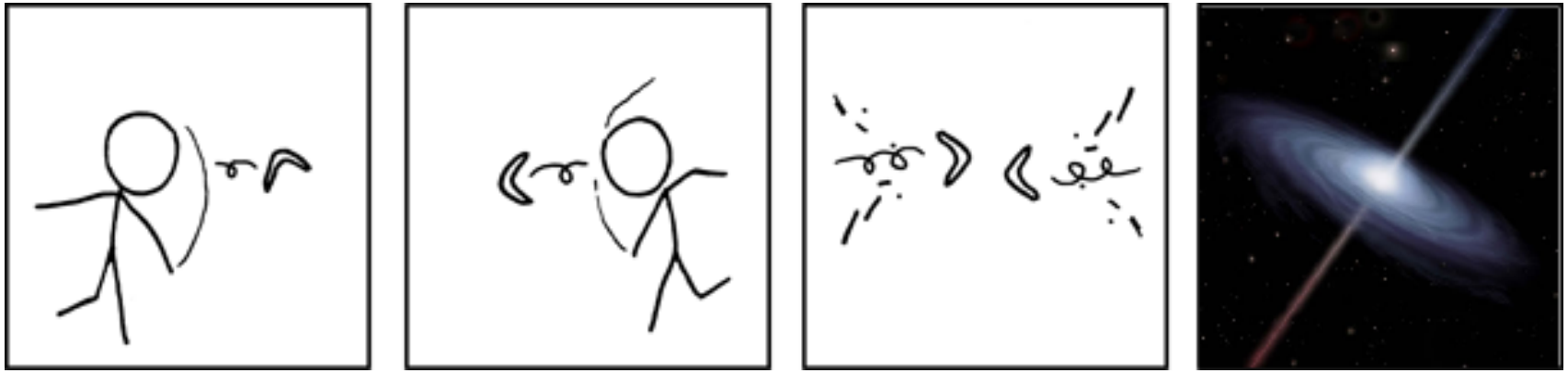
Summary

Maximal resolution from tree-level FCNCs:

- Pure LH/RH Z' scenario:
  $K \to \pi\nu\bar{\nu}$: $\Lambda_{\rm NP}^{\rm max} \simeq 200$ TeV, $B_{d,s}$ physics : $\Lambda_{\rm NP}^{\rm max} \simeq 15$ TeV
- Tuned L+R Z' scenario:
  $K \to \pi\nu\bar{\nu}$: $\Lambda_{\rm NP}^{\rm max} \simeq 2000$ TeV, $B_{d,s}$ physics : $\Lambda_{\rm NP}^{\rm max} \simeq 160$ TeV
- Scalars: $\Lambda_{\rm NP}^{\rm max} \simeq 350$ TeV, Pseudoscalars : $\Lambda_{\rm NP}^{\rm max} \simeq 700$ TeV

- $b \to s\nu\bar{\nu}$ 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 $SU(2)_L$ symmetry
- $b \to s\nu\bar{\nu}$ gives complementary information to NP in $b \to s\ell^+\ell^-$

Thanks for your attention



Backup slides

SM results

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

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

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

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

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

$$\mathrm{BR}(B^+ \to K^+\nu\bar{\nu})_{\rm SM} = (3.98 \pm 0.43 \pm 0.19) \times 10^{-6},$$
$$\mathrm{BR}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm SM} = (9.19 \pm 0.86 \pm 0.50) \times 10^{-6},$$
$$F_L^{\rm SM} = 0.47 \pm 0.03\,,$$

Present upper bounds from **BaBar**

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 1.7 \times 10^{-5} \ (90\% \ \ \mathrm{CL}),$$

and **Belle**

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

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!

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 $SU(2)_L$ 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

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 ($u \gg v, v', w$)

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

Flavour structure of 331

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

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

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

- 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 $\tilde{s}_{12}, \tilde{s}_{23}, \tilde{s}_{13}, \delta_{1,2,3} \to U_L = V_L V_{\rm CKM}^\dagger$
- 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

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

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

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

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