New Physics Correlations in Rare Decays

David M. Straub
Technische Universität München

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CKM2010, Warwick

Rare B and K decays

	$\nu\bar{\nu}$	$\ell^+\ell^-$	γ
$b \to s$ $(\propto \lambda^2)$	$B \to X_s \nu\bar{\nu}$ $B \to K^* \nu\bar{\nu}$ $B \to K \nu\bar{\nu}$	$B \to X_s \ell^+\ell^-$ $B \to K^* \ell^+\ell^-$ $B \to K \ell^+\ell^-$ $B_s \to \ell^+\ell^-$	$B \to X_s \gamma$ $B \to K^* \gamma$
$b \to d$ $(\propto \lambda^3)$	$B \to X_d \nu\bar{\nu}$	$B \to X_d \ell^+\ell^-$ $B_d \to \ell^+\ell^-$	$B \to X_d \gamma$
$s \to d$ $(\propto \lambda^5)$	$K_L \to \pi^0 \nu\bar{\nu}$ $K^+ \to \pi^+ \nu\bar{\nu}$	$K_L \to \pi \ell^+\ell^-$ $K_L \to \ell^+\ell^-$	

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$b \to d$ $(\propto \lambda^3)$	$B \to X_d \nu\bar{\nu}$	$B \to X_d \ell^+\ell^-$ $B_d \to \ell^+\ell^-$	$B \to X_d \gamma$
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significant improvement expected at:

Rare B and K decays

	$\nu\bar{\nu}$	$\ell^+\ell^-$	γ
$b \to s$ ($\propto \lambda^2$)	$B \to X_s\nu\bar{\nu}$ $B \to K^*\nu\bar{\nu}$ $B \to K\nu\bar{\nu}$	$B \to X_s\ell^+\ell^-$ $B \to K^*\ell^+\ell^-$ $B \to K\ell^+\ell^-$ $B_s \to \ell^+\ell^-$	$B \to X_s\gamma$ $B \to K^*\gamma$
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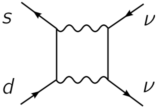
significant improvement expected at: LHCb; Belle II, SuperB; NA62, KOTO

FCNCs in the SM and beyond

In the SM, FCNCs are suppressed

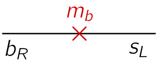
Loop factor



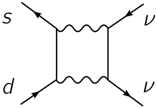
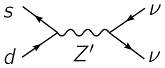
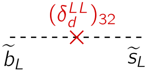
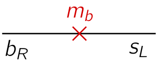
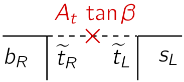
Hierarchy of CKM

GIM mechanism $O(m_c^2 - m_u^2) \ll m_W^2$

Chirality suppression



FCNCs in the SM and beyond

In the SM, FCNCs are suppressed			In the presence of NP, suppression can be lifted
Loop factor		→	
Hierarchy of CKM		→	
GIM mechanism	$O(m_c^2 - m_u^2) \ll m_W^2$	→	$O(m_{\tilde{c}}^2 - m_{\tilde{u}}^2) > m_W^2$
Chirality suppression		→	

Rare FCNC decays are highly sensitive to short-distance physics

Effective Hamiltonian for $d_i \to d_j$ transitions

$$\mathcal{H}_{\text{eff}}^{\Delta F=1} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum (C_i Q_i + C_i' Q_i')$$

$$\left.\begin{aligned}
Q_7 &\sim m_b (\bar{s}_L \sigma_{\mu\nu} b_R) F^{\mu\nu} \\
Q_8 &\sim m_b (\bar{s}_L \sigma_{\mu\nu} T^a b_R) G^{\mu\nu\, a} \\
Q_9 &\sim (\bar{s} b)_{V-A} (\bar{\ell}\ell)_V \\
Q_{10} &\sim (\bar{s} b)_{V-A} (\bar{\ell}\ell)_A \\
Q_S &\sim (\bar{s} b)_{S+P} (\bar{\ell}\ell)_S \\
Q_P &\sim (\bar{s} b)_{S+P} (\bar{\ell}\ell)_P \\
Q_L &\sim (\bar{s} b)_{V-A} (\bar{\nu}\nu)_{V-A}
\end{aligned}\right\}$$

Operators most sensitive to new physics in $\Delta F = 1$ transitions.

Analogous for $b \to d$ and $s \to d$.

Effective Hamiltonian for $d_i \to d_j$ transitions

$$\mathcal{H}_{\text{eff}}^{\Delta F=1} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum (C_i Q_i + C_i' Q_i')$$

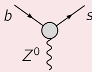
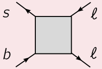
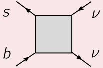
$Q_7 \sim m_b(\bar{s}_L \sigma_{\mu\nu} b_R) F^{\mu\nu}$	$C_7 \sim D'$
$Q_8 \sim m_b(\bar{s}_L \sigma_{\mu\nu} T^a b_R) G^{\mu\nu\, a}$	$C_8 \sim E'$
$Q_9 \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_V$	$C_9 \sim \frac{Y}{s_w^2} - 4Z + \ldots$
$Q_{10} \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_A$	$C_{10} \sim Y$
$Q_S \sim (\bar{s}b)_{S+P}(\bar{\ell}\ell)_S$	$C_S \approx 0$
$Q_P \sim (\bar{s}b)_{S+P}(\bar{\ell}\ell)_P$	$C_P \approx 0$
$Q_L \sim (\bar{s}b)_{V-A}(\bar{\nu}\nu)_{V-A}$	$C_L \sim X$

Inami-Lim functions:

$f\left(\frac{m_t^2}{m_W^2}\right)$ (GIM)

flavour independent!

SM: "penguin-box expansion"

e.g.  $= C$,  $= B^{\ell\bar{\ell}}$,  $= B^{\nu\bar{\nu}}$

$$X = C + B^{\nu\bar{\nu}}$$
$$Y = C + B^{\ell\bar{\ell}}$$
$$Z = C + D/4$$

Effective Hamiltonian for $d_i \to d_j$ transitions

$$\mathcal{H}_{\text{eff}}^{\Delta F=1} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum (C_i Q_i + C_i' Q_i')$$

$$Q_7 \sim m_b(\bar{s}_L \sigma_{\mu\nu} b_R) F^{\mu\nu} \qquad C_7 \sim D'$$
$$Q_8 \sim m_b(\bar{s}_L \sigma_{\mu\nu} T^a b_R) G^{\mu\nu\, a} \qquad C_8 \sim E'$$
$$Q_9 \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_V \qquad C_9 \sim \frac{Y}{s_w^2} - 4Z + \dots$$
$$Q_{10} \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_A \qquad C_{10} \sim Y$$
$$Q_S \sim (\bar{s}b)_{S+P}(\bar{\ell}\ell)_S \qquad C_S \approx 0$$
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$$Q_L \sim (\bar{s}b)_{V-A}(\bar{\nu}\nu)_{V-A} \qquad C_L \sim X$$

CMFV master functions

$f(\theta_{\text{CMFV}})$

still flavour independent!

Constrained Minimal Flavour Violation (CMFV)

- All flavour violation governed by the CKM matrix
- No new sources of CP violation
- No operators beyond the SM ones

[Buras et al. (2001)]

$$X = C + B^{\nu\bar{\nu}}$$
$$Y = C + B^{\ell\bar{\ell}}$$
$$Z = C + D/4$$

Effective Hamiltonian for $d_i \to d_j$ transitions

$$\mathcal{H}_{\text{eff}}^{\Delta F=1} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum (C_i Q_i + C_i' Q_i')$$

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$$Q_L \sim (\bar{s}b)_{V-A}(\bar{\nu}\nu)_{V-A} \qquad C_L \sim X$$

New operators!

WCs flavour independent.

Minimal Flavour Violation (MFV) [D'Ambrosio et al. (2002)]

- All flavour violation governed by the CKM matrix
- ~~No new sources of CP violation~~
- ~~No operators beyond the SM ones~~

Effective Hamiltonian for $d_i \to d_j$ transitions

$$\mathcal{H}_{\text{eff}}^{\Delta F=1} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum (C_i Q_i + C_i' Q_i')$$

$Q_7^{(\prime)} \sim m_b(\bar{s}_{L,R}\sigma_{\mu\nu} b_{R,L}) F^{\mu\nu}$	$C_7,\, C_7'$
$Q_8^{(\prime)} \sim m_b(\bar{s}_{L,R}\sigma_{\mu\nu} T^a b_{R,L}) G^{\mu\nu}$	$C_7,\, C_7'$
$Q_9^{(\prime)} \sim (\bar{s}b)_{V\mp A}(\bar{\ell}\ell)_V$	$C_7,\, C_7'$
$Q_{10}^{(\prime)} \sim (\bar{s}b)_{V\mp A}(\bar{\ell}\ell)_A$	$C_{10},\, C_{10}'$
$Q_S^{(\prime)} \sim (\bar{s}b)_{S\pm P}(\bar{\ell}\ell)_S$	$C_S,\, C_S'$
$Q_P^{(\prime)} \sim (\bar{s}b)_{S\pm P}(\bar{\ell}\ell)_P$	$C_P,\, C_P'$
$Q_{L,R} \sim (\bar{s}b)_{V\mp A}(\bar{\nu}\nu)_{V-A}$	$C_L,\, C_R$

$+$ chirality-flipped operators

All WCs independent of each other and flavour dependent:

$C_i^{b\to s} \neq C_i^{b\to d} \neq C_i^{s\to d}$!

Generic Flavour Violation

- ~~All flavour violation governed by the CKM matrix~~
- ~~No new sources of CP violation~~
- ~~No operators beyond the SM ones~~

Rare decay correlations

	$\nu\bar{\nu}$	$\ell^+\ell^-$	γ
$b \to s$ $(\propto \lambda^2)$	$B \to X_s \nu\bar{\nu}$ $B \to K^* \nu\bar{\nu}$ $B \to K \nu\bar{\nu}$	$B \to X_s \ell^+\ell^-$ $B \to K^* \ell^+\ell^-$ $B \to K \ell^+\ell^-$ $B_s \to \ell^+\ell^-$	$B \to X_s \gamma$ $B \to K^* \gamma$
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100% correlated in MFV (universality of master functions)

Rare decay correlations

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100% correlated in MFV (universality of master functions)

If Z penguin dominates

If magnetic penguin dominates

The flavour matrix

	Only SM operators	Also new operators
Flavour violation govened by CKM	**CMFV** 2HDM at low $\tan\beta$ Littlest Higgs without T-parity Universal Extra Dimensions	**MFV** MSSM with MFV 2HDM at large $\tan\beta$
Non-CKM flavour viol.	**Beyond CMFV** Littlest Higgs with T-parity SM with 4 generations	**Beyond MFV** General MSSM Warped Extra Dimensions

[A. Buras]

Outline

Correlations in concrete NP models

1. $K^+ \to \pi^+ \nu\bar{\nu}$ vs. $K_L \to \pi^0 \nu\bar{\nu}$
2. $B_s \to \mu^+\mu^-$ vs. $B_d \to \mu^+\mu^-$

SM with 4th generation
[Buras et al. 1002.2126]
RS model with custodial protection
[Blanke et al. 0812.3803]
Littlest Higgs with T-parity
[Blanke et al. 0906.5454]
MSSM flavour models
[Altmannshofer et al. 0909.1333]

→ SM4: see talk by T. Heidsieck
Thursday, 18:05

Model-independent correlations

1. Angular observables in $B \to K^* \mu^+\mu^-$
2. $B \to K^* \nu\bar{\nu}$ vs. $B \to K \nu\bar{\nu}$

$K \to \pi\nu\bar{\nu}$ decays

The "golden modes"

mode	SM	exp.	
$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$	$(8.5 \pm 0.7) \times 10^{-11}$	$17.3^{+11.5}_{-10.5} \times 10^{-11}$	[E949]
$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu})$	$(2.8 \pm 0.6) \times 10^{-11}$	$< 6.7 \times 10^{-8}$	[E391a]

Governed by $Q_{L,R}^{s\to d} \sim (\bar{s}b)_{V\mp A}(\bar{\nu}\nu)_{V-A}$

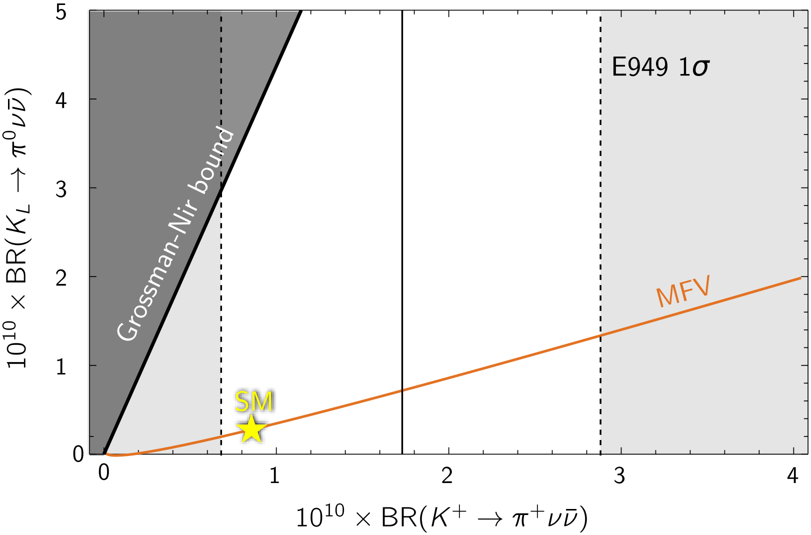
$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) \propto \left| C_L + C_R + \epsilon^{\mathrm{SM}}_{(u,c)} \right|^2$$

$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) \propto \mathrm{Im}\,(C_L + C_R)^2$$

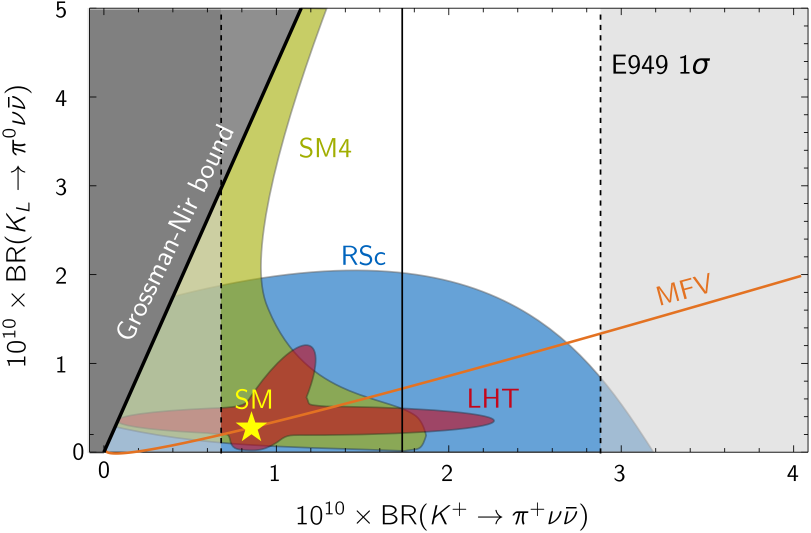
← purely CP violating

See also talk by E. Stamou Thursday, 10:00

$K^+ \to \pi^+ \nu\bar{\nu}$ vs. $K_L \to \pi^0 \nu\bar{\nu}$

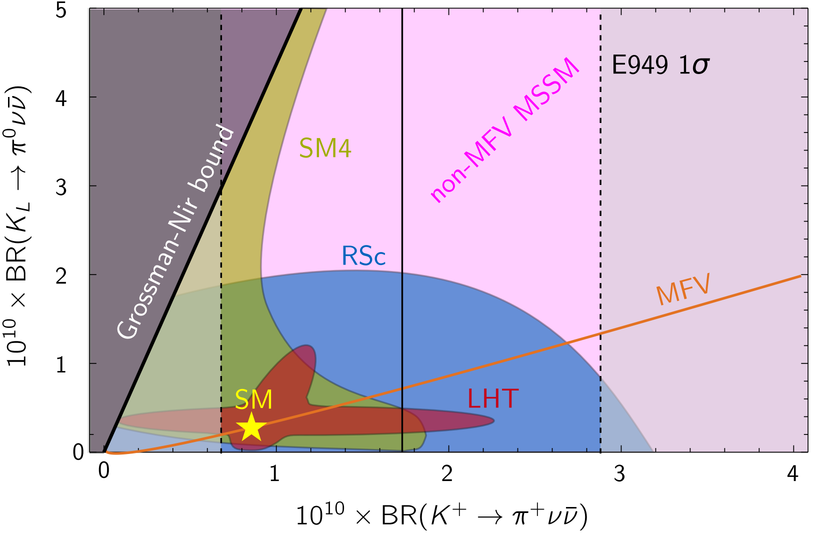


$K^+ \to \pi^+\nu\bar{\nu}$ vs. $K_L \to \pi^0\nu\bar{\nu}$



for a similar plot, see http://www.lnf.infn.it/wg/vus/content/Krare.html (Mescia & Smith)

$K^+ \to \pi^+ \nu\bar{\nu}$ vs. $K_L \to \pi^0 \nu\bar{\nu}$



for a similar plot, see http://www.lnf.infn.it/wg/vus/content/Krare.html (Mescia & Smith)

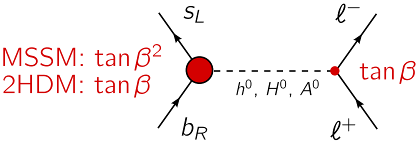
$B_q \to \mu^+\mu^-$ decays

mode	SM	exp. 95% C.L.	
$\text{BR}(B_s \to \mu^+\mu^-)$	$(3.2 \pm 0.2) \times 10^{-9}$	$< 43 \times 10^{-9}$	[CDF]
$\text{BR}(B_d \to \mu^+\mu^-)$	$(0.10 \pm 0.01) \times 10^{-9}$	$< 7.6 \times 10^{-9}$	

$$\text{BR}(B_q \to \mu^+\mu^-) \propto \left[|S|^2 \left(1 - \frac{4m_\mu^2}{m_{B_q}^2}\right) + |P|^2 \right]$$

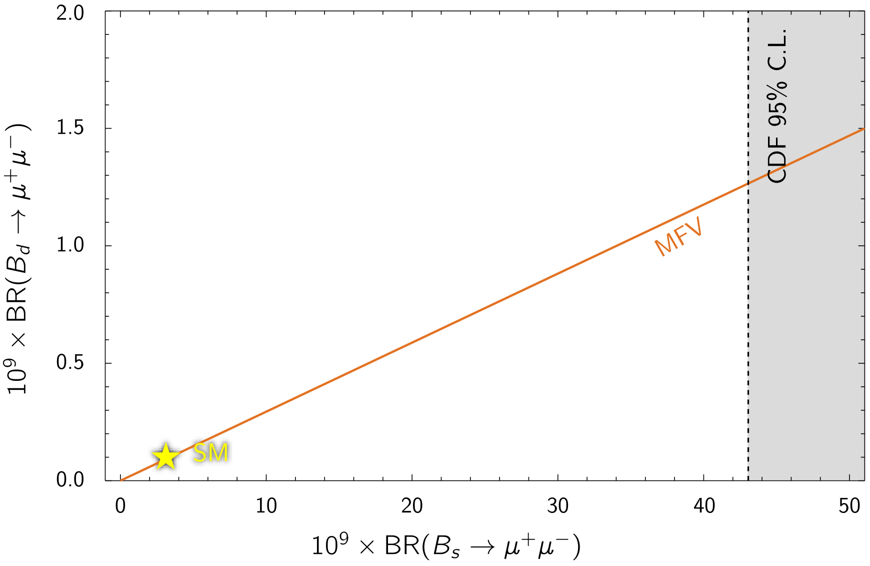
$$S = \frac{m_{B_q}^2}{2}(C_S - C_S') \qquad P = \frac{m_{B_q}^2}{2}(C_P - C_P') + m_\mu(C_{10} - C_{10}')$$

MSSM & 2HDM: large contributions to $C_{S,P}$



See also talk by S. Jäger
Thursday, 13:45

$B_s \to \mu^+\mu^-$ vs. $B_d \to \mu^+\mu^-$



SUSY flavour models

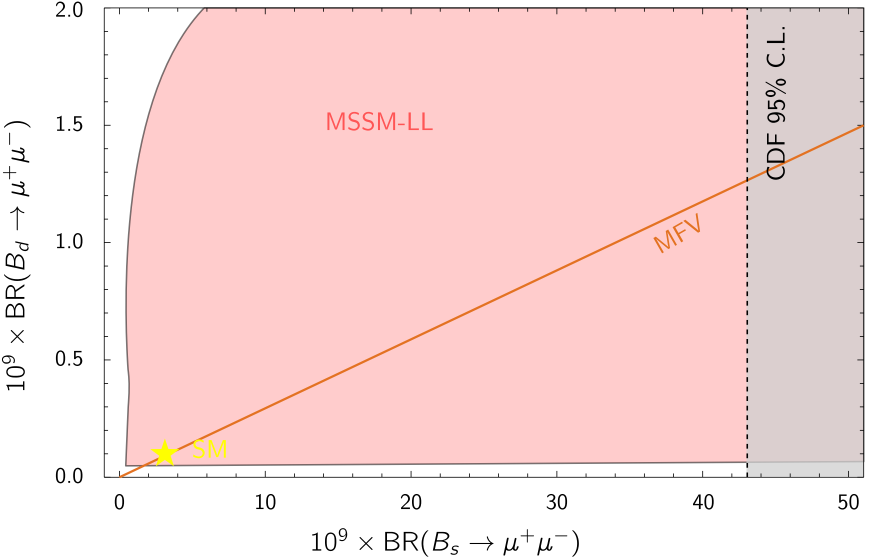
[Altmannshofer, Buras, Gori, Paradisi, Straub (2009)]

A representative set of SUSY flavour models with non-minimal FV in the down-type squark sector:

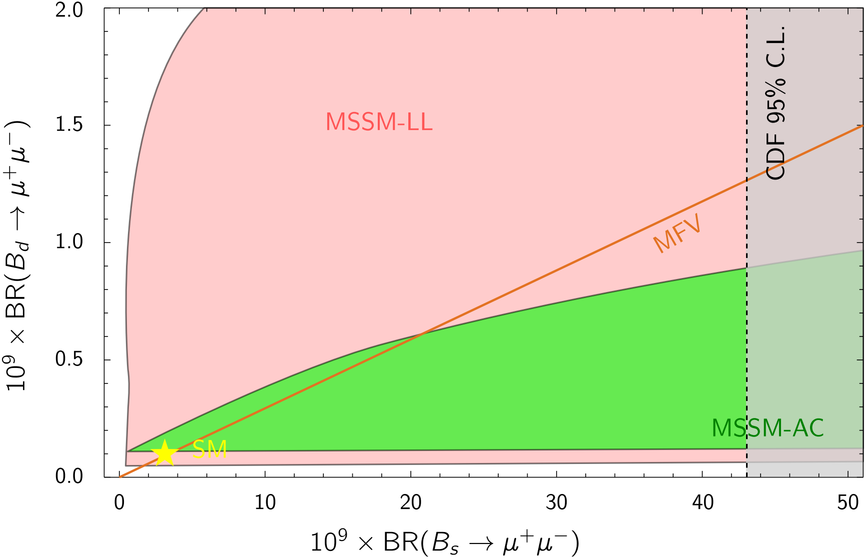
model	symm.	δ_d^{LL}	δ_d^{RR}	ref.
AC	U(1)	CKM-like	O(1)	[Agashe, Carone (2003)]
AKM	SU(3)	-	CKM-like	[Antusch et al. (2007)]
RVV	SU(3)	CKM-like	CKM-like	[Ross et al. (2004)]
LL	$(S_3)^3$	CKM-like	-	[Hall, Murayama (1995)]

See also talk by P. Paradisi

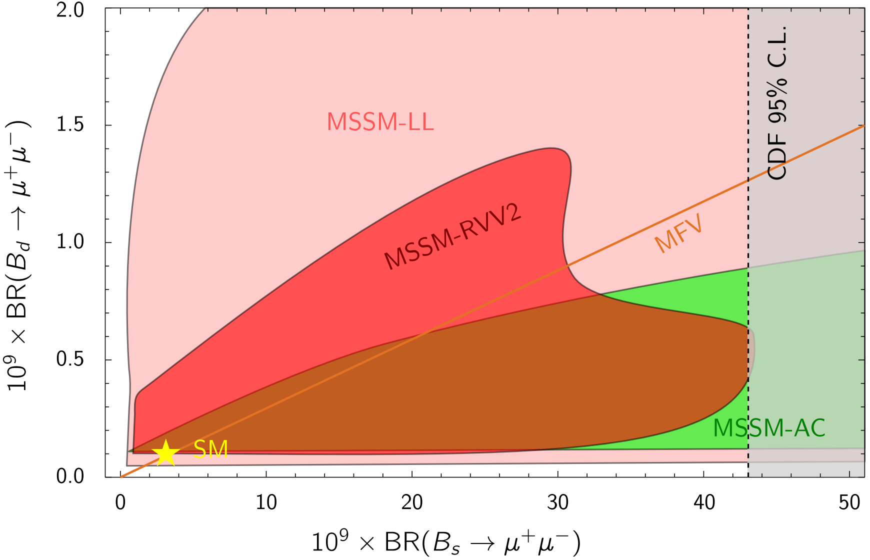
$B_s \to \mu^+\mu^-$ vs. $B_d \to \mu^+\mu^-$



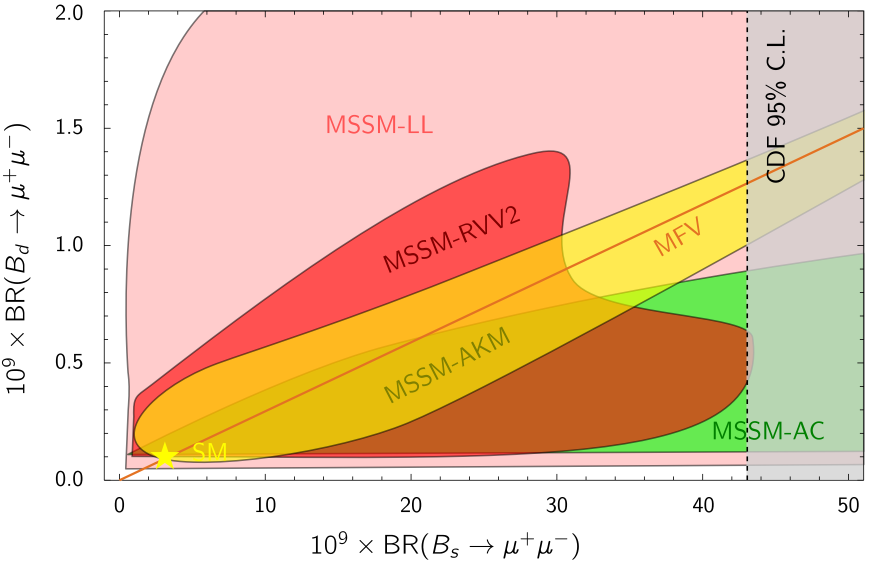
$B_s \to \mu^+\mu^-$ vs. $B_d \to \mu^+\mu^-$



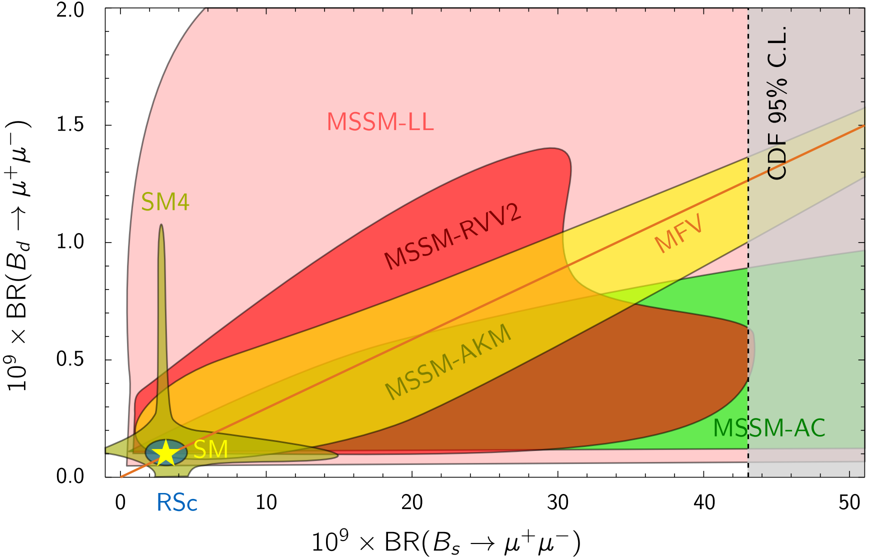
$B_s \to \mu^+\mu^-$ vs. $B_d \to \mu^+\mu^-$



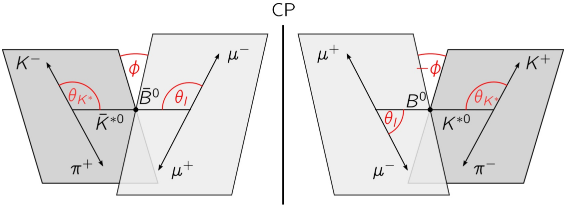
$B_s \to \mu^+\mu^-$ vs. $B_d \to \mu^+\mu^-$



$B_s \to \mu^+\mu^-$ vs. $B_d \to \mu^+\mu^-$



Angular observables in $B \to K^*\mu^+\mu^-$



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} = \sum_{i,a} I_i^{(a)}(q^2) f(\theta_l, \theta_{K^*}, \phi)$$

$$A_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) - \bar{I}_i^{(a)}(q^2)\right) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

Normalized CP asymmetries

$$S_i^{(a)}(q^2) = \left(I_i^{(a)}(q^2) + \bar{I}_i^{(a)}(q^2)\right) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}$$

Normalized CP-averaged angular coefficients

[Altmannshofer, Ball, Bharucha, Buras, Straub, DS (2008)]

See also talk by J. Matias

Magnetic penguins in $B \to K^* \ell^+ \ell^-$

$Q_7^{(\prime)} \sim m_b (\bar{s}_{L,R} \sigma_{\mu\nu} b_{R,L}) F^{\mu\nu}$

A simple scenario:

Complex NP contributions to C_7 and C_7' only

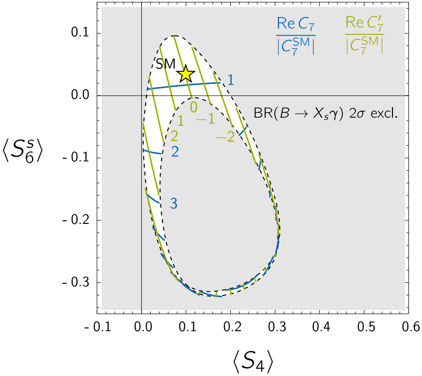
Motivation

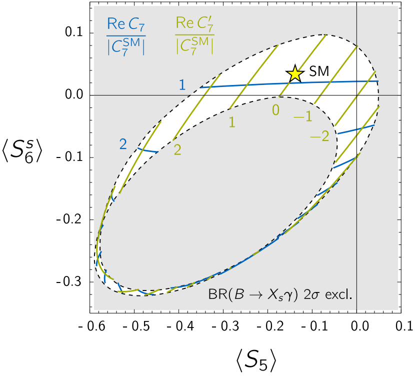
- Complex effects in C_7 arise in the MSSM with MFV but additional sources of CP violation
- Complex effects in C_7' arise in the MSSM with complex $(\delta_d)_{32}^{LR}$ mass insertion

Main constraint

$$\mathrm{BR}(B \to X_s \gamma) \propto |C_7^{\mathrm{eff}}(m_b)|^2 + |C_7'(m_b)|^2$$

CP averaged observables in $B \to K^*\mu^+\mu^-$





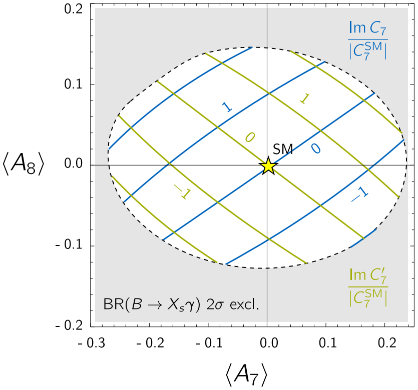
Observables integrated in the low q^2 region:

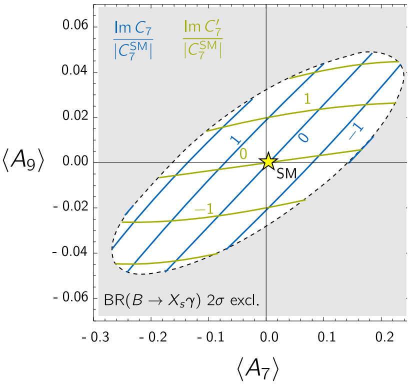
$$\langle S_i \rangle = \frac{\int_{1\ \mathrm{GeV}^2}^{6\ \mathrm{GeV}^2} (I_i(q^2) + \bar{I}_i(q^2))}{\int_{1\ \mathrm{GeV}^2}^{6\ \mathrm{GeV}^2} d(\Gamma + \bar{\Gamma})/q^2}$$

$\langle S_6^s \rangle$ is the integrated, CP-averaged FB asymmetry:

$$S_6^s = \frac{4}{3} A_{\mathrm{FB}}$$

CP asymmetries in $B \to K^* \mu^+ \mu^-$

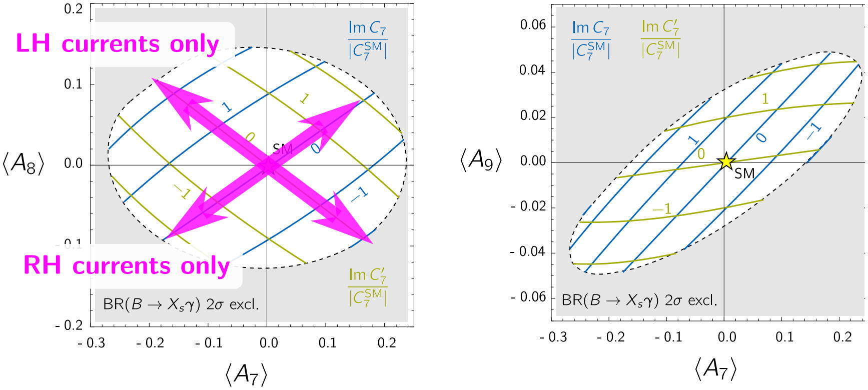




Note: A_9 can be extracted from 1-dimensional angular distribution:

$$\frac{d(\Gamma + \bar{\Gamma})}{d\phi\, dq^2} \propto 1 + S_3 \cos(2\phi) + A_9 \sin(2\phi)$$

CP asymmetries in $B \to K^* \mu^+ \mu^-$



Note: A_9 can be extracted from 1-dimensional angular distribution:

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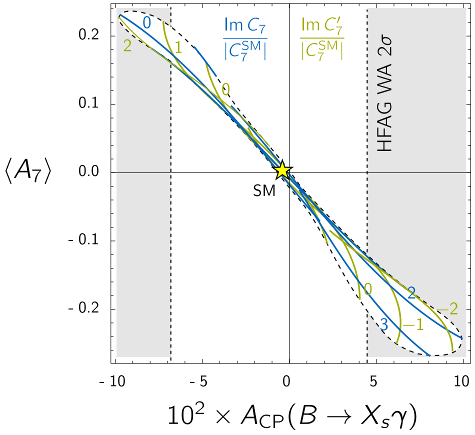
CP asymmetries in $B \to K^* \mu^+ \mu^-$ vs. $B \to X_s \gamma$



CP asymmetry in $b \to s\gamma$ is an additional constraint on complex $C_7^{(\prime)}$.

$B \to K^* \ell^+ \ell^-$ angular observables can be used to determine the magnitude, phase and chirality structure of the magnetic penguin coefficients

$b \to s\nu\bar{\nu}$ decays

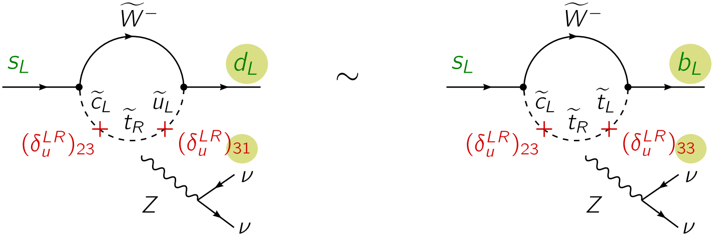
mode	SM	exp.	
$\mathrm{BR}(B \to K^*\nu\bar{\nu})$	$(6.8 \pm 1.1) \times 10^{-6}$	$< 80 \times 10^{-6}$	[BaBar]
$\mathrm{BR}(B \to K\nu\bar{\nu})$	$(3.6 \pm 0.5) \times 10^{-6}$	$< 14 \times 10^{-6}$	[Belle]
$\mathrm{BR}(B \to X_s\nu\bar{\nu})$	$(2.7 \pm 0.2) \times 10^{-5}$	$< 64 \times 10^{-5}$	[ALEPH]

Governed by $Q_{L,R}^{b\to s} \sim (\bar{s}b)_{V\mp A}(\bar{\nu}\nu)_{V-A}$

See also talk by J. Kamenik

MSSM: $s \to d\nu\bar{\nu}$ vs. $b \to s\nu\bar{\nu}$

> Why can there be no sizable effects in $b \to s\nu\bar{\nu}$, in constrast to $s \to d\nu\bar{\nu}$, in the MSSM *without* MFV?



$$\frac{A}{A^{\rm SM}} \propto \frac{(\delta_u^{LR})_{23}(\delta_u^{LR})_{31}}{V_{ts}V_{td}^*} \sim \frac{\delta^2}{\lambda^5} \gg \frac{A}{A^{\rm SM}} \propto \frac{(\delta_u^{LR})_{23}(\delta_u^{LR})_{33}}{V_{ts}V_{tb}^*} \sim \frac{\delta^2}{\lambda^2}$$

Also: Higgs-mediated contributions $\to$ Strongly constrained by $B_s \to \mu^+\mu^-$
[Isidori, Paradisi (2006)]

$b \to s\nu\bar{\nu}$ decays

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Governed by $Q_{L,R}^{b\to s} \sim (\bar{s}b)_{V\mp A}(\bar{\nu}\nu)_{V-A}$

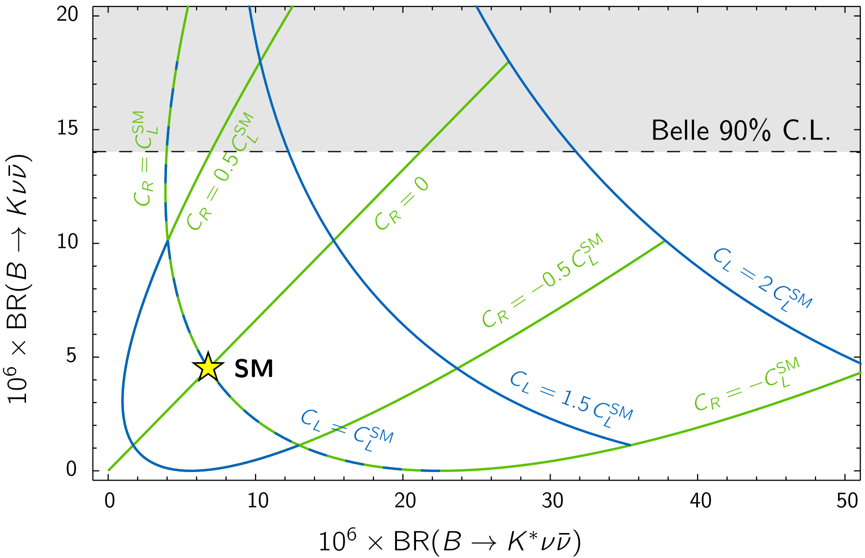
Observables depend on two real combinations of $C_{L,R}$:

$$\epsilon = \frac{\sqrt{|C_L|^2 + |C_R|^2}}{|(C_L)^{\text{SM}}|} \qquad \eta = \frac{-\text{Re}\,(C_L C_R^*)}{|C_L|^2 + |C_R|^2} \qquad (\epsilon, \eta)_{\text{SM}} = (1, 0)$$

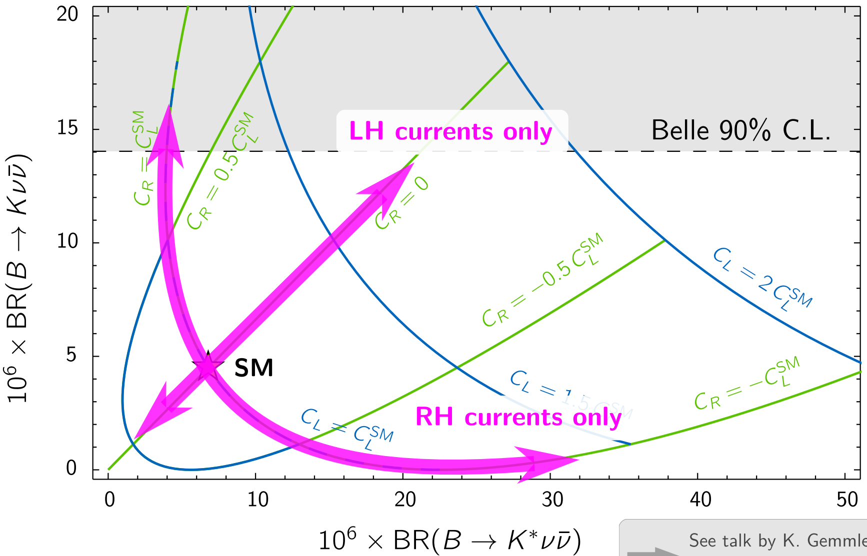
$$\text{BR}(B \to K^*\nu\bar{\nu}) = \text{BR}(B \to K^*\nu\bar{\nu})_{\text{SM}} \times (1 + 1.31\,\eta)\epsilon^2$$
$$\text{BR}(B \to K\nu\bar{\nu}) = \text{BR}(B \to K\nu\bar{\nu})_{\text{SM}} \times (1 - 2\,\eta)\epsilon^2$$

[Altmannshofer, Buras, DS, Wick (2009)]

$B \to K^* \nu\bar{\nu}$ vs. $B \to K \nu\bar{\nu}$



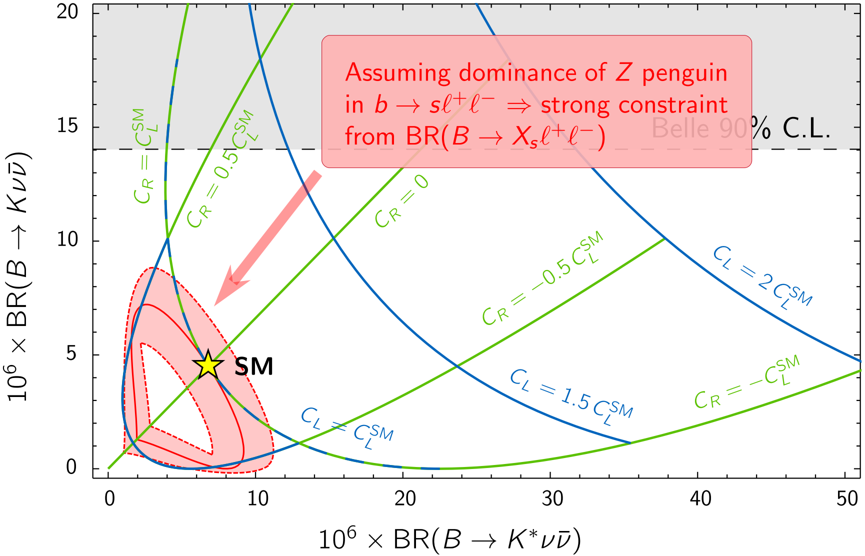
$B \to K^* \nu\bar{\nu}$ vs. $B \to K \nu\bar{\nu}$



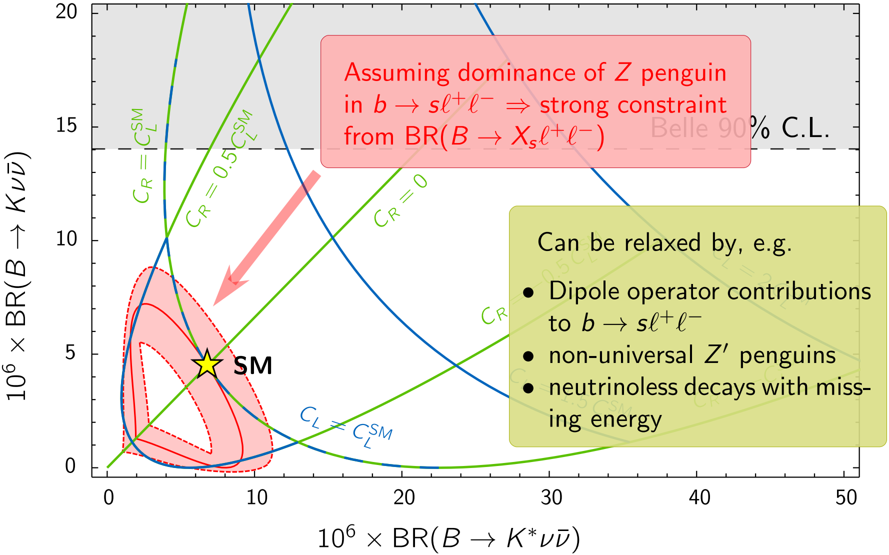
See talk by K. Gemmler

Thursday, 17:45

$B \to K^* \nu\bar{\nu}$ vs. $B \to K \nu\bar{\nu}$



$B \to K^* \nu\bar{\nu}$ vs. $B \to K \nu\bar{\nu}$



Assuming dominance of Z penguin in $b \to s\ell^+\ell^-$ $\Rightarrow$ strong constraint from $\mathrm{BR}(B \to X_s\ell^+\ell^-)$

Can be relaxed by, e.g.

- Dipole operator contributions to $b \to s\ell^+\ell^-$
- non-universal Z' penguins
- neutrinoless decays with missing energy

Conclusions

1. Correlations between rare K and B decays

- allow to **distinguish** different models of New Physics
- give us **model-independent** information about short-distance interactions (including chirality, phases)

Complementary to high p_T searches!

2. Decays that may seem less promising in MFV can be **important** in many concrete models! $(B_d \to \mu^+\mu^-,\ B \to K^*\nu\bar{\nu},\ \ldots)$

PS (At least) equally interesting correlations with $\Delta F = 2$!

Thanks for support to:
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