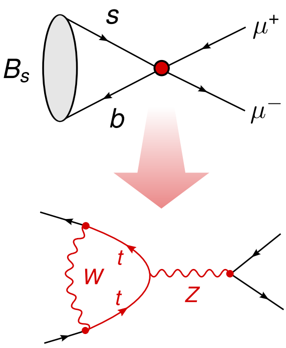
Model-dependent Flavour Constraints on New Physics

Presented by David M. Straub

Junior Research Group “New Physics”
Excellence Cluster Universe, Munich

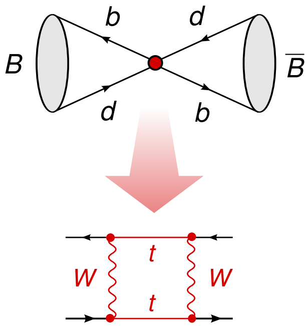
Flavour-changing neutral currents

$\Delta F = 1$: rare decays



$$\mathcal{H}_{\text{eff}} \supset \frac{\delta}{\Lambda^2}\,\mathcal{O}$$

$\Delta F = 2$: meson-antimeson mixing



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Typical new physics model: scale Λ, flavour changing parameter δ

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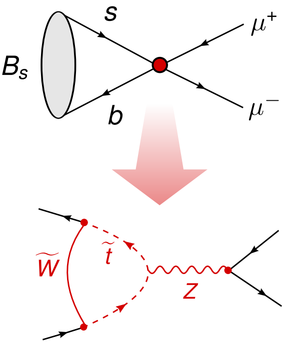

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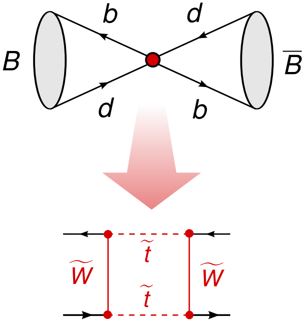

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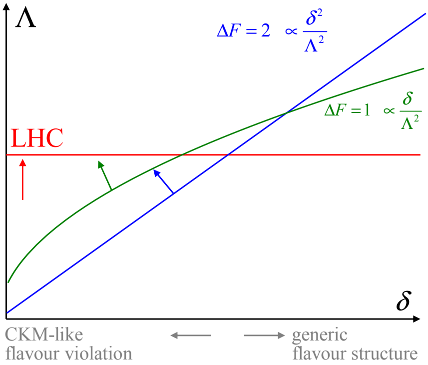
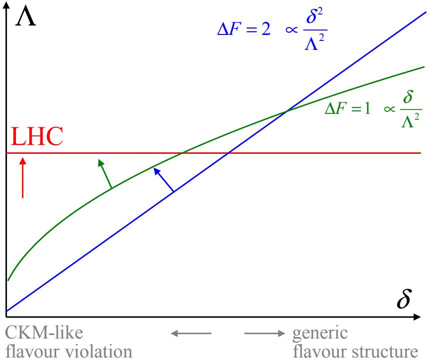
Typical new physics model: scale Λ, flavour changing parameter δ

Flavour vs. collider bounds on the new physics scale Λ



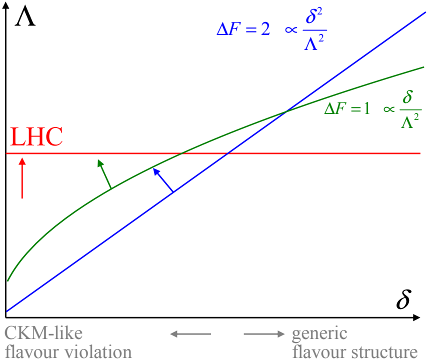
- Collider physics: directly probes Λ – limited by $\sqrt{s}$

Flavour vs. collider bounds on the new physics scale Λ



- Meson-antimeson mixing: can probe the highest scales
  But only small number of observables sensitive to NP (ΔM, ϕ)

Flavour vs. collider bounds on the new physics scale Λ



- Rare decays: much more observables, more sensitive to “small” flavour violation at “natural” scales

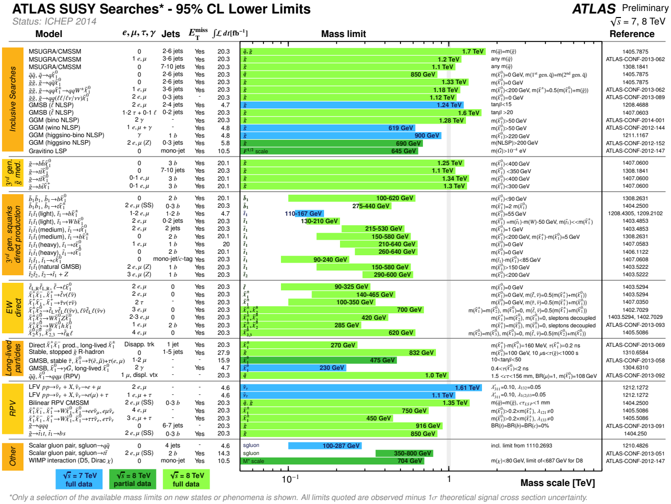
Outline

1. Introduction

2. Flavour vs. collider bounds on Supersymmetry
   - Meson mixing in natural SUSY
   - $B_s \to \mu^+ \mu^-$

3. Rare decays in Composite Higgs models

Direct searches: no sign of SUSY!



NB: bounds on 3rd gen' quarks and EWinos generally weakest

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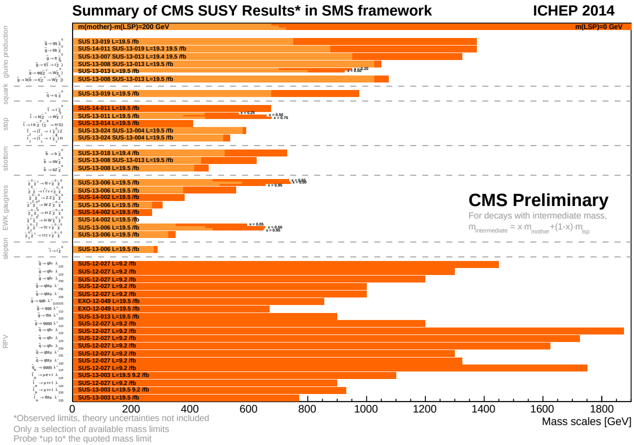

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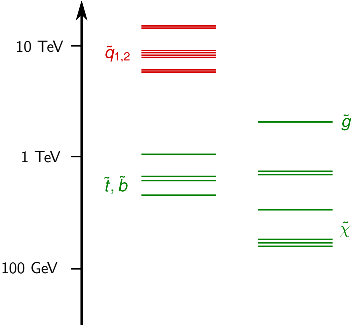
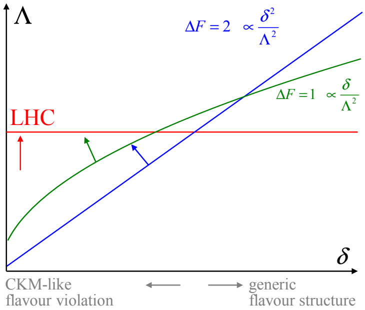
A natural SUSY spectrum, summer 2014



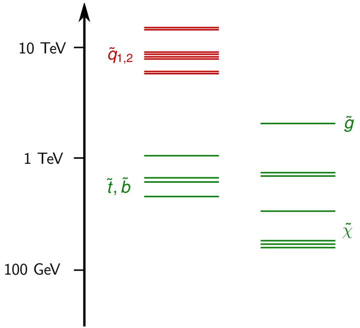
- Strong LHC bounds on 1st/2nd generation squarks
- Light 3rd generation squarks to solve hierarchy problem

Are flavour bounds competitive with collider bounds?



Considering the case where flavour bounds are weakest: CKM-like flavour violation

Natural SUSY & $U(2)^3$



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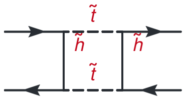
Natural SUSY with split generations + CKM-like flavour violation: approximate, minimally broken $U(2)^3$ flavour symmetry ("split MFV")

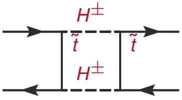
[Barbieri et al. 1105.2296]

Meson mixing in SUSY $U(2)^3$

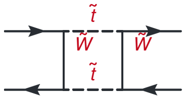
Two classes of contributions

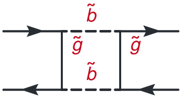
- Higgsino and ch. Higgs contributions are MFV-like





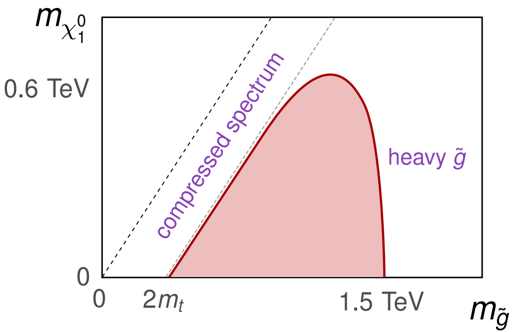
- Wino and gluino contributions can induce a new phase in B/B_s mixing





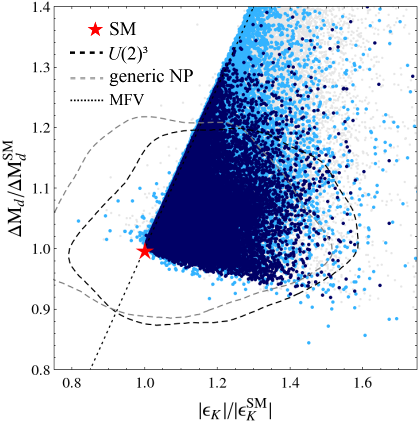
Sparticle mass bounds in natural SUSY

Typically, two ways for sparticles to evade LHC bounds. E.g., $\tilde{g} \to t\bar{t}\chi_1^0$:



- heavy spectrum: contribution to flavour observables will be suppressed
- compressed spectrum: potentially large contribution to flavour obs.
- similarly for $\tilde{t}$, $\tilde{b}$

Numerical results for $\Delta F = 2$ observables



- All blue points fullfil collider bounds
- Dashed lines: $\Delta F = 2$ constraints (black: $U(2)^3$, gray: generic)
- Direct bounds almost as constraining as flavour, except for compressed spectra

[Barbieri et al. 1402.6677]

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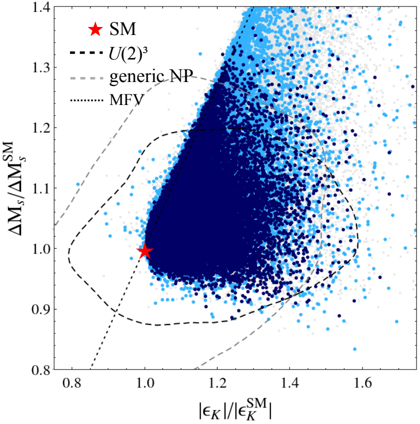

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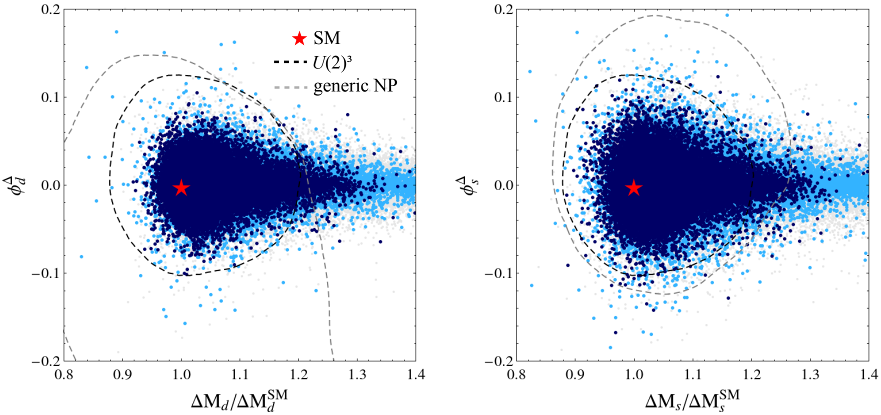

- $B_{s,d}$ mixing phase at most 0.1, whether compressed or not

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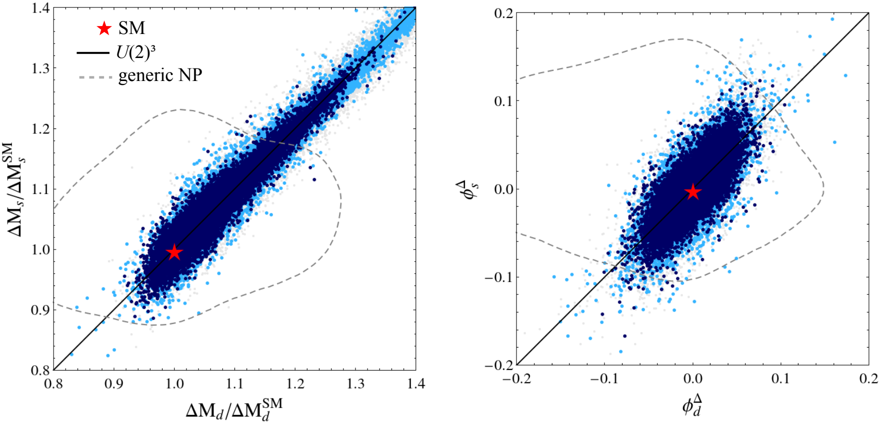

- $U(2)^3$ symmetry relates B_s and B_d mixing

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$B_s \to \mu^+\mu^-$ beyond the SM

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2} V_{tb}V_{ts}^* \sum_i C_i O_i + C_i' O_i' + \text{h.c.}$$

$$O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

$$O_S^{(\prime)} = (\bar{s}P_{R(L)} b)(\bar{\ell}P_{L(R)}\ell)$$

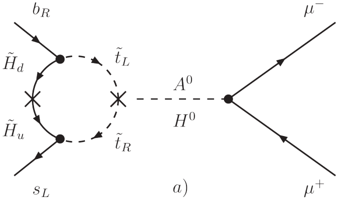
$$\text{BR}(B_s \to \mu^+\mu^-) \propto |S|^2 + |P|^2$$

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

Scalar contributions lift the helicity suppression!

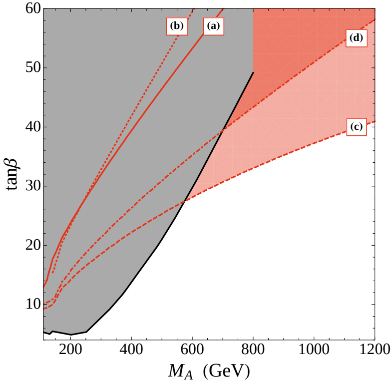
Scalar operators in the MSSM

Even with Minimal Flavour Violation, $(\tan\beta)^3$ enhanced contribution to C_S



$$C_S^{\tilde{H}} \propto \frac{\tan\beta^3}{M_A^2} \frac{A_t \mu}{m_{\tilde{t}}^2} f_{\tilde{H}}\left(\frac{|\mu|^2}{m_{\tilde{t}}^2}\right)$$

Complementarity with Higgs searches



[Altmannshofer et al. 1211.1976]

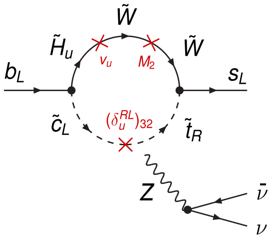
$m_{\tilde{q}} = 2$ TeV, $6M_1 = 3M_2 = M_3 = 1.5$ TeV

Scenario	(a)	(b)	(c)	(d)	(e)
μ [TeV]	1	4	-1.5	1	-1.5
sign(A_t)	+	+	+	-	-

- Large tan β + light Higgs spectrum disfavoured
- Direct Higgs searches more constraining for tan $\beta \lesssim 25$
- Milder bounds for $\mu A_t > 0$ (destructive interference with SM)

New physics in Z penguins: C_{10} in SUSY

- If there are no sizable scalar operators, $B_s \to \mu^+\mu^-$ allows a clean measurement of Z penguin!
- Complementary to $B \to K^{(*)}\mu^+\mu^-$ and $B \to K^{(*)}\nu\bar{\nu}$
- Only way to get sizable C_{10} in SUSY: Z penguin with chargino loop



- Up to 25% effect in BR

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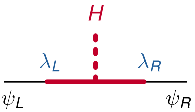
Composite Higgs & partial compositeness

- Solving the hierarchy problem without SUSY: the Higgs is composite
- Successful theory of flavour requires quarks to be partially composite

$$\mathcal{L} \supset \lambda_L \bar{\psi}_L \mathcal{O}_R + \lambda_R \bar{\psi}_R \mathcal{O}_L$$



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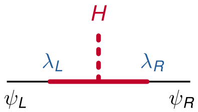
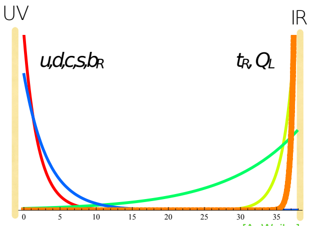


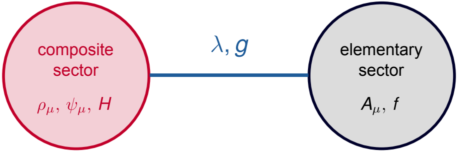
Related by AdS/CFT to models with a warped extra dimension



The two-site picture

[Contino et al. hep-ph/0612180]

A simple 4D theory realizing the partial compositeness paradigm



$$\mathcal{L}_s = -\bar{Q}_L\, m_Q\, Q_R - \bar{U}_L\, m_U\, U_R - \bar{D}_L\, m_D\, D_R$$
$$+\bar{Q}_L \mathcal{H}\, Y_U\, U_R + \bar{Q}_L \mathcal{H}\, Y_D\, D_R + \text{h.c}$$
$$\mathcal{L}_{\text{mix}} = \lambda_L\, \bar{q}_L Q_R + \lambda_{Ru}\, \bar{U}_L u_R + \lambda_{Rd}\, \bar{D}_L d_R$$

$$q^{\text{phys}} = c_L\, q + s_L\, Q \qquad \frac{s_L}{c_L} = \frac{\lambda_L}{m_Q} \qquad m_{q^{\text{phys}}} = \frac{v}{\sqrt{2}} Y\, s_L\, s_R \qquad \text{etc.}$$

Flavour anarchy

- Structureless (“anarchic”) composite Yukawas
- Hierarchies in quark masses and mixing generated by hierarchical composite-elementary mixing

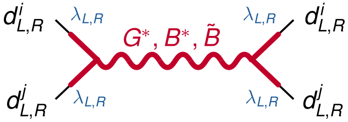
$$y_u^i = s_{Li} Y_{U*} s_{Rui}$$

$$s_{L3} \gg s_{L2} \gg s_{L1}$$

$$s_{Ru3} \gg s_{Ru2} \gg s_{Ru1}$$

$$V_{\text{CKM}}^{ij} \sim \frac{s_{Li}}{s_{Lj}}$$

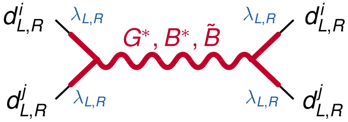
Anarchic FCNCs



Relation between c.-el. mixings and quark masses & CKM leads to a suppression of FCNCs (“RS-GIM”):

$$s_{Li}^2 s_{Lj}^2 \sim \left(V_{3i}^* V_{3j}\right)^2 s_{Lt}^2$$

Anarchic FCNCs



Relation between c.-el. mixings and quark masses & CKM leads to a suppression of FCNCs ("RS-GIM"):

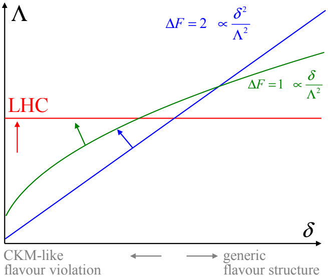
$$s^2_{Li} s^2_{Lj} \sim \left(V^*_{3i} V_{3j}\right)^2 s^2_{Lt}$$

but also RR and LR FCNCs

$$s^2_{Li} s^2_{Rj} \sim y_{di} y_{dj}$$

Operator $(\bar{s}_R d_L)(\bar{s}_L d_R)$ leads to a bound of order 14 TeV from ϵ_K!

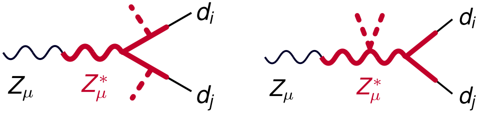
Flavour symmetries for partial compositeness



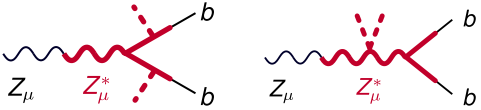
- flavour anarchy ⇒ high compositeness scale required by $\Delta F = 2$
- Introducing a flavour symmetry, comp. scale can be sub-TeV: $U(2)^3$ symmetry minimally broken by composite-elementary mixings [Barbieri et al. 1203.4218, Barbieri et al. 1211.5085]
- Potentially interesting effects in $\Delta F = 1$

Z penguins from partial compositeness

After EWSB, composite-elementary mixing leads to correlated tree-level contributions to flavour-changing Z couplings . . .



. . . and $Z \to b\bar{b}$

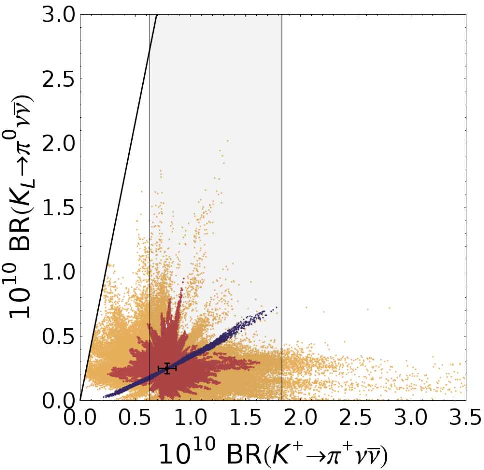


Numerical analysis of Z penguins in 3 models

- Two choices for the fermion content (represenations of $SU(2)_L \times SU(2)_R \times U(1)_X$) to protect T parameter and $Z \to b\bar{b}$
  - $(2,2)_{2/3} + (2,2)_{-1/3} + (1,1)_{2/3} + (1,1)_{-1/3}$ ("**bidoublet** model")
  - $(2,2)_{2/3} + (1,3)_{2/3} + (3,1)_{2/3}$ ("**triplet** model")
- Two choices for the flavour structure
  - flavour **anarchy**
  - $\boldsymbol{U(2)^3}$ flavour symmetry

see [Barbieri et al. 1203.4218, Barbieri et al. 1211.5085, Straub 1302.4651] and ref. therein

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



triplet + anarchy

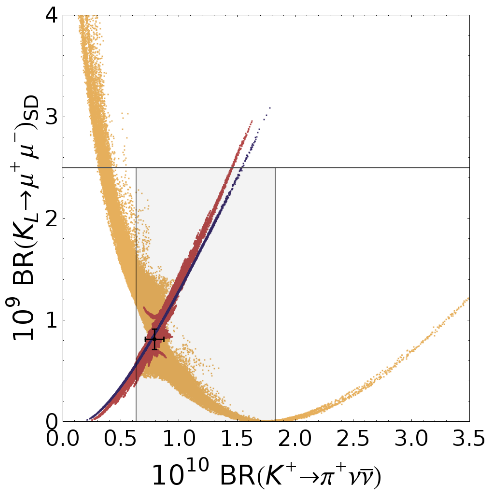
bidoublet + anarchy

bidoublet + $U(2)^3$

- Visible effects in both modes
- $U(2)^3$: aligned in phase with the SM

[Straub 1302.4651]

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

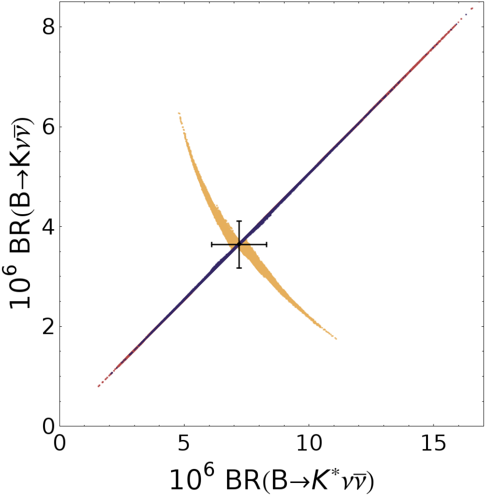


triplet + anarchy
bidoublet + anarchy
bidoublet + $U(2)^3$

- triplet: RH coupling
- bidoublet: LH coupling

[Straub 1302.4651]

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



triplet + anarchy

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bidoublet + $U(2)^3$

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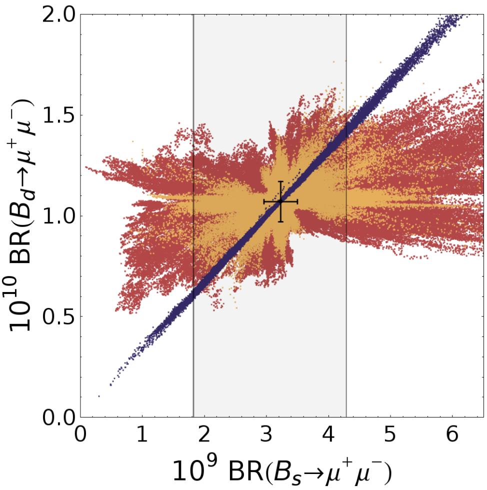
[Straub 1302.4651]

$B_s \to \mu\mu$ vs. $B_d \to \mu\mu$

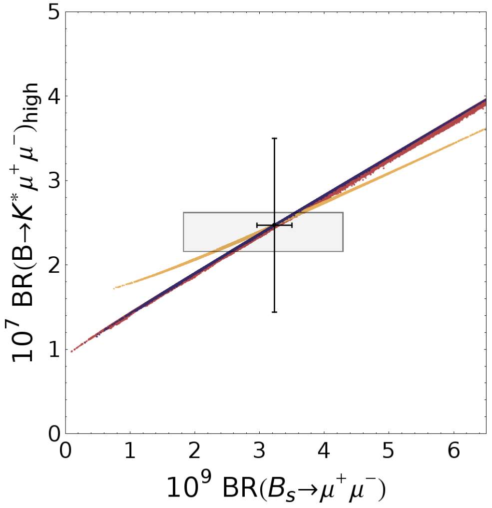


triplet + anarchy
bidoublet + anarchy
bidoublet + $U(2)^3$

- LHCb **starts** to probe the models
- MFV-like $B_d \leftrightarrow B_s$ correlation in $U(2)^3$

[Straub 1302.4651]

$B_s \to \mu\mu$ vs. $B \to K^*\mu\mu$



triplet + anarchy

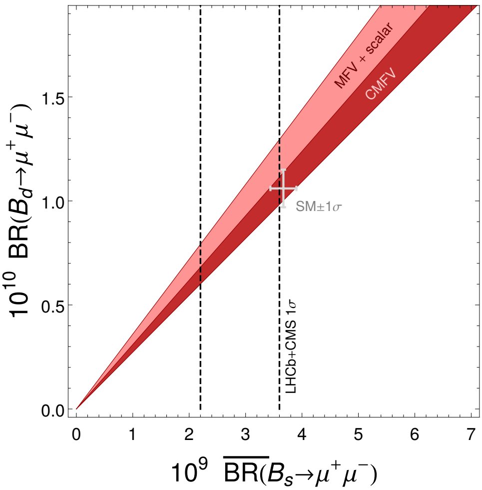
bidoublet + anarchy

bidoublet + $U(2)^3$

- Correlation due to protection of LH *or* RH *bsZ* coupling

[Straub 1302.4651]

Model-independently: $B_s \to \mu\mu$ vs. $B_d \to \mu\mu$



- $B_s \to \mu\mu$ vs. $B_d \to \mu\mu$: powerful test of Minimal Flavour Violation

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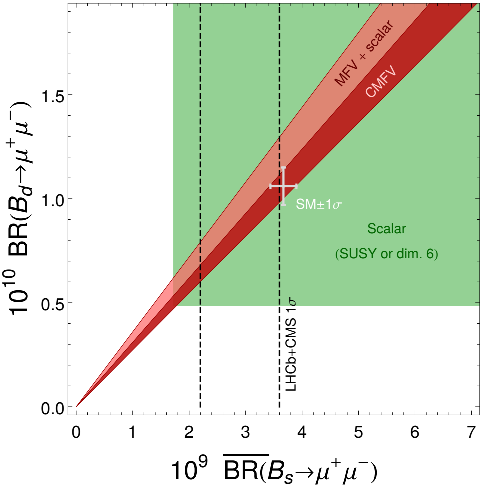

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- Beyond MFV: scalar operators (e.g. SUSY) unconstrained by other processes

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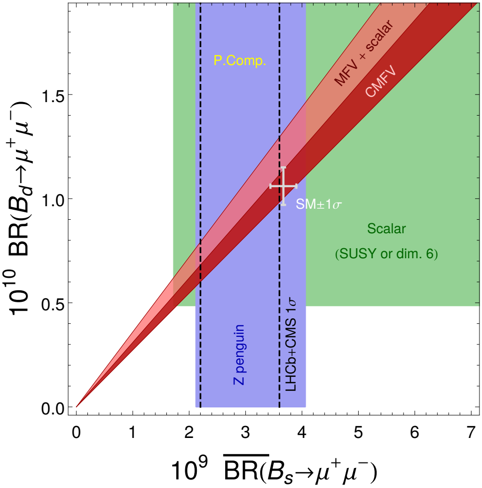

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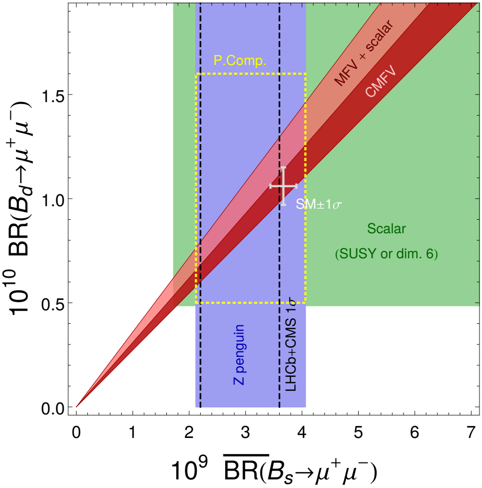
- Beyond MFV: scalar operators (e.g. SUSY) unconstrained by other processes
- Z penguins beyond MFV: size constrained by $b \to s\ell^+\ell^-$ processes (notably $B \to K^*\mu^+\mu^-$)

Model-independently: $B_s \to \mu\mu$ vs. $B_d \to \mu\mu$



- $B_s \to \mu\mu$ vs. $B_d \to \mu\mu$: powerful test of Minimal Flavour Violation
- Beyond MFV: scalar operators (e.g. SUSY) unconstrained by other processes
- Z penguins beyond MFV: size constrained by $b \to s\ell^+\ell^-$ processes (notably $B \to K^*\mu^+\mu^-$)

Conclusions

Natural SUSY with minimally broken $U(2)^3$ flavour symmetry:

- flavour & collider bounds complementary
- flavour bounds stronger for compressed spectrum
- ϕ_s small, but potentially around the corner

Rare decays in composite Higgs models:

- Flavour symmetry desirable to suppress CPV in kaon mixing
- Pattern of effects in rare decays could allow to distinguish models

Backup

Two ways to CKM-like flavour violation

Minimal Flavour Violation (MFV) [D'Ambrosio et al. hep-ph/0207036]

- $U(3)_{Q_L} \times U(3)_{U_R} \times U(3)_{D_R}$ flavour symmetry
- broken minimally by Yukawa couplings Y_u, Y_d
- all FCNC amplitudes suppressed by same CKM factors as in SM
- perfect correlation between $s \leftrightarrow d$, $b \leftrightarrow s$, $b \leftrightarrow d$

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"Minimal $U(2)^3$" [Barbieri et al. 1105.2296]

- $U(2)_{Q_L} \times U(2)_{U_R} \times U(2)_{D_R}$ flavour symmetry
- broken minimally by three spurions
- all FCNC amplitudes suppressed by same CKM factors as in SM
- perfect correlation only between $b \leftrightarrow s$ and $b \leftrightarrow d$, new phases

Meson-antimeson mixing

Mixing amplitudes M_{12} in the K, B_d, B_s systems can be written as

$$M_{12}^K = (M_{12}^K)_{SM} \left(1 + h_K e^{2i\sigma_K}\right)$$
$$M_{12}^d = (M_{12}^d)_{SM} \left(1 + h_d e^{2i\sigma_d}\right)$$
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- **MFV**: $\sigma_{K,d,s} = 0$ and $h_{K,d,s} \equiv h$
- $\boldsymbol{U(2)^3}$: $\sigma_K = 0$, h_K, $h_{d,s} \equiv h_B$ $\sigma_{d,s} \equiv \sigma_B$

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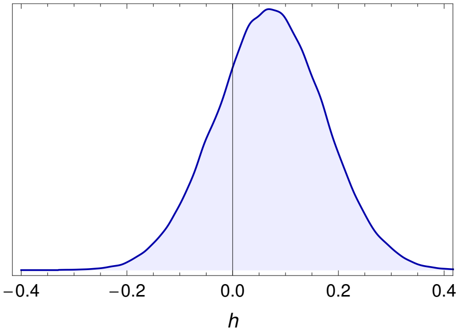
What are the allowed sizes of h or h_B, h_K, σ_B?

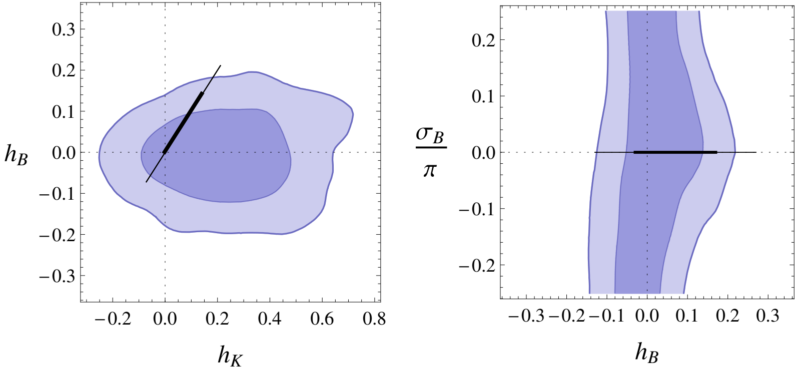
Meson-antimeson mixing in MFV

Global fit to ΔM_d, ΔM_s, ϕ_s, $S_{\psi K_S}$, ϵ_K, γ, $|V_{ud}|$, $|V_{us}|$, $|V_{cb}|$, $|V_{ub}|$:



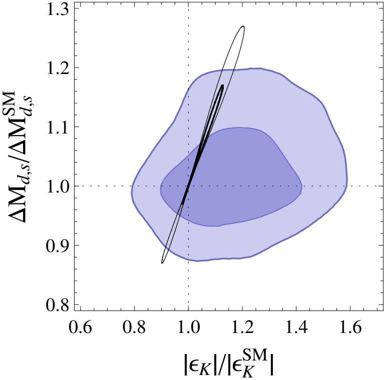
- MFV-like modification of mixing amplitudes constrained to $\pm 20\%$

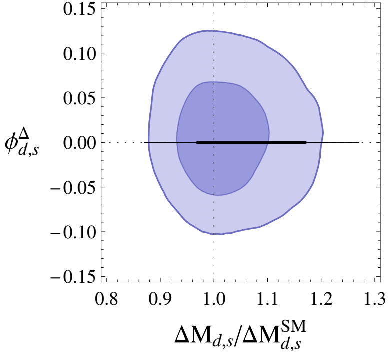
Meson-antimeson mixing in $U(2)^3$



- Slight preference for a positive contribution to h_K (ϵ_K)
- Modification in B/B_s mixing phase small due to ϕ_s constraint

Meson-antimeson mixing in $U(2)^3$





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ϵ_K vs. $S_{\psi K_S}$

- There is a long-standing tension in the SM CKM fit between ϵ_K, $S_{\psi K_S} = \sin 2\beta$ and $\Delta M_d / \Delta M_s$ that can be solved in $U(2)^3$, not in MFV
- What is the status of this tension?

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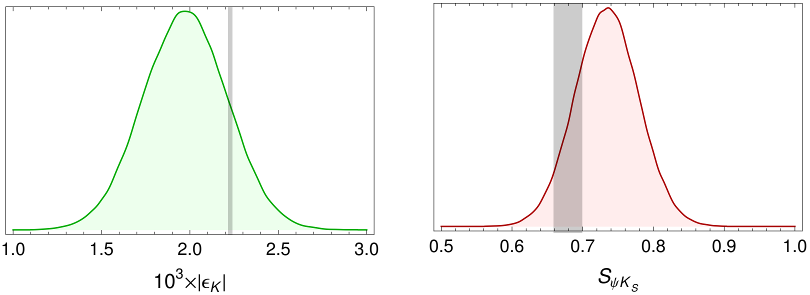
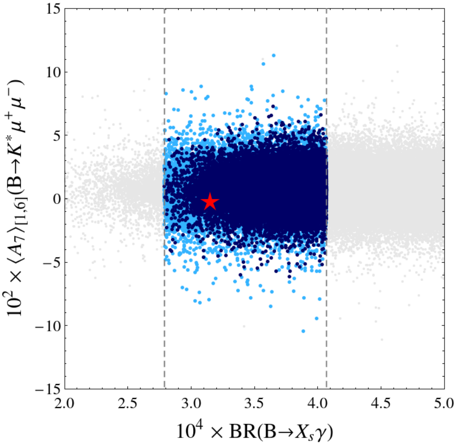


- Significance of “tension” down to 1.1σ
- Main reason: lattice bag parameter $\hat{B}_K$ moved up; theory uncertainty on η_{cc} increased

$\Delta F = 1$ in SUSY $U(2)^3$



NB: $\tan\beta \leq 5$

(Pseudo-)scalar operators in the MSSM *without* MFV

$$C_S^{\tilde{W}} \propto (\delta_d^{LL})_{32} \frac{\tan\beta^3}{M_A^2} \frac{M_2 \mu}{m_{\tilde{t}}^2} f_{\tilde{W}}\left(\frac{|\mu|^2}{m_{\tilde{t}}^2}, \frac{|M_2|^2}{m_{\tilde{t}}^2}\right)$$

$$C_S^{\tilde{g}} \propto -(\delta_d^{LL})_{32} \frac{\tan\beta^3}{M_A^2} \frac{M_3 \mu}{m_{\tilde{b}}^2} f_{\tilde{g}}\left(\frac{|M_3|^2}{m_{\tilde{b}}^2}\right)$$

$$C_S'^{\tilde{g}} \propto -(\delta_d^{RR})_{32} \frac{\tan\beta^3}{M_A^2} \frac{M_3 \mu}{m_{\tilde{b}}^2} f_{\tilde{g}}\left(\frac{|M_3|^2}{m_{\tilde{b}}^2}\right)$$

- $(\delta_d^{LL})_{32}$ strongly constrained by $b \to s\gamma$
- $(\delta_d^{RR})_{32}$ constrained by $b \to s\gamma$ and ΔM_s

CHM: pattern of flavour-changing Z couplings

- triplet model: P_{LR} forbids g_L^{ij}
- bidoublet model: P_C forbids g_R^{ij}
- $U(2)^3$ forbids g_R^{ij}

		K		$B_{d,s}$		D	
		L	R	L	R	L	R
Ⓐ	triplet		$\mathbb{C}$		$\mathbb{C}$	$\mathbb{C}$	
	bidoublet	$\mathbb{C}$		$\mathbb{C}$		$\mathbb{C}$	
$U(2)^3_{\text{LC}}$	triplet					$\mathbb{R}$	
	bidoublet	$\mathbb{R}$		$\mathbb{C}$		$\mathbb{R}$	