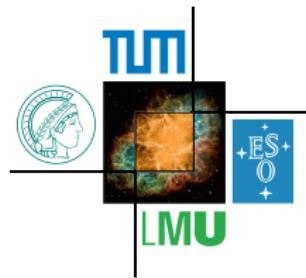


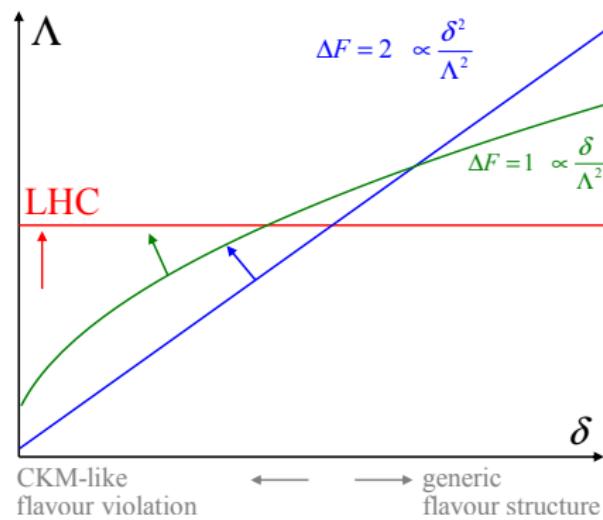
Flavour physics in SUSY

Presented by David M. Straub

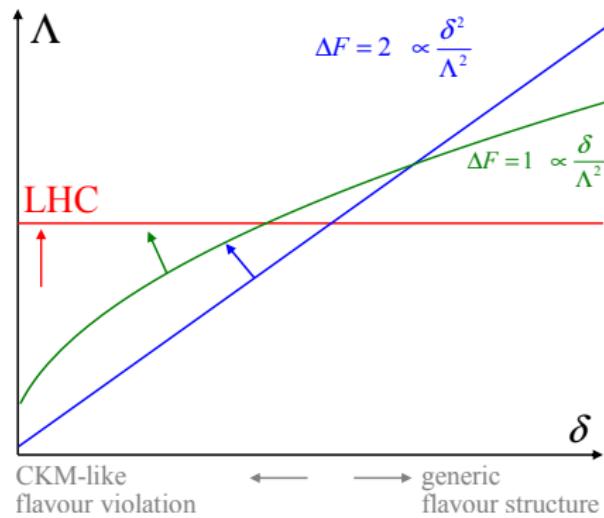
Junior Research Group “New Physics”
Excellence Cluster Universe, Munich



Flavour vs. direct bounds on the SUSY scale



Flavour vs. direct bounds on the SUSY scale



- ▶ PeV or split SUSY & generic flavour violation: $\Delta F = 2$ dominates
- ▶ Natural SUSY & CKM-like flavour violation: $\Delta F = 2$ vs. $\Delta F = 1$ vs. LHC

Outline

1 $\Delta F = 2$

- Status of CKM & new physics in meson mixing
- Numerical analysis of meson mixing in $U(2)^3$ SUSY

2 $\Delta F = 1$

- Anomalies in $b \rightarrow s$ transitions
- Z penguins & flavour-changing trilinears
- Lepton flavour non-universality & R_K

Based on:

[Barbieri, Buttazzo, Sala, DS (2014)]

[Altmannshofer & DS (2014)]

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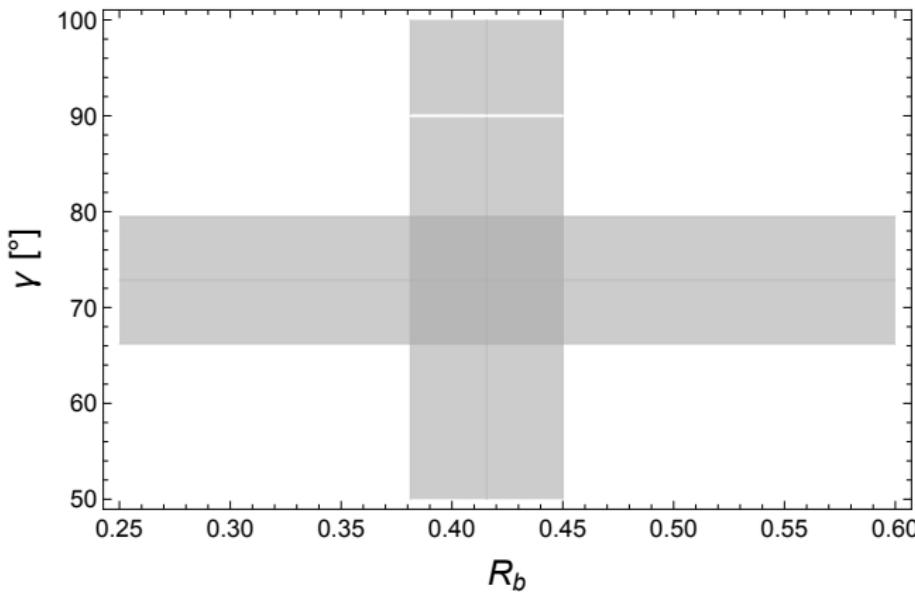
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“Minimal $U(2)^3$ ” [Barbieri et al. 1105.2296]

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- ▶ 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

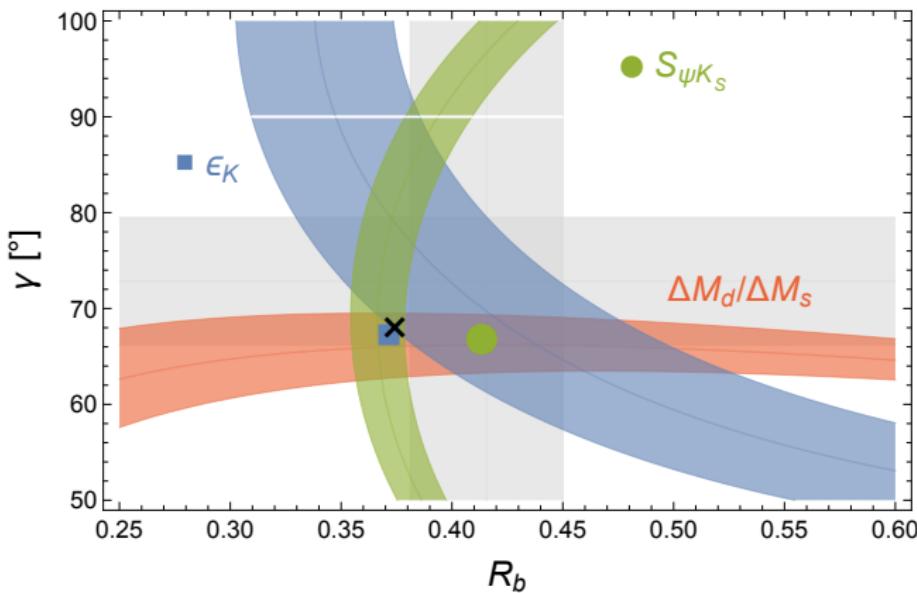
Consistency of CKM: tree vs. loop



$$R_b = \frac{|V_{ud} V_{ub}^*|}{|V_{cd} V_{cb}^*|}$$

cf. [Altmannshofer et al. 0909.1333]

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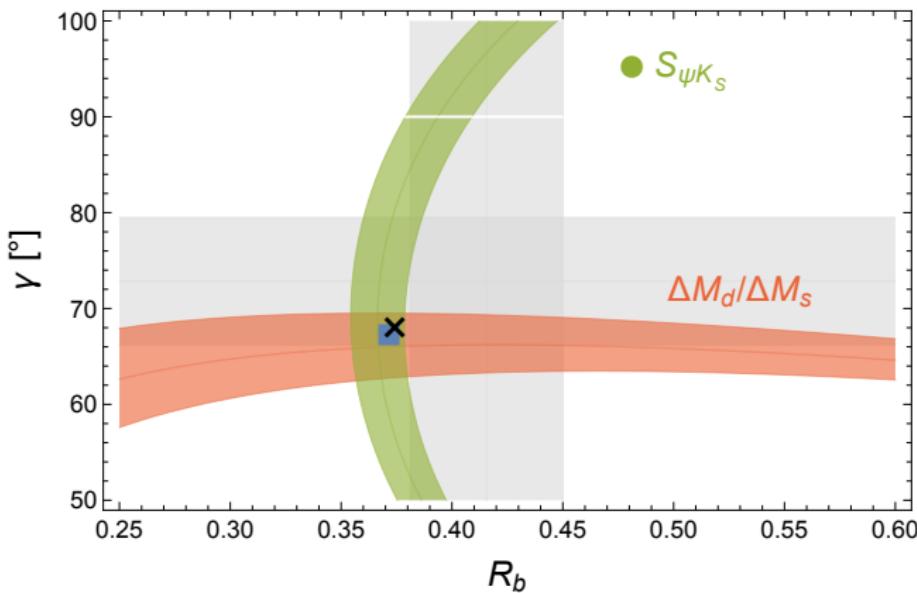


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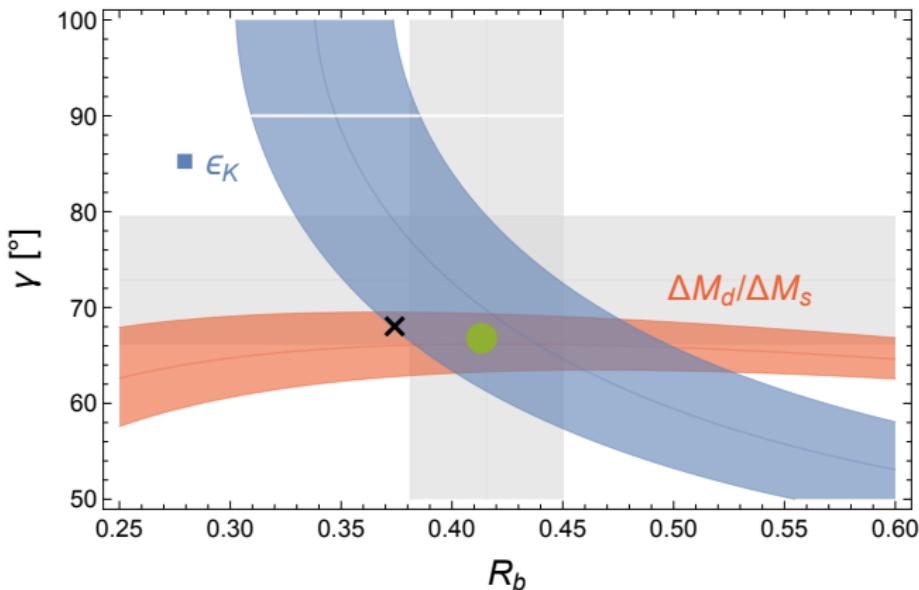
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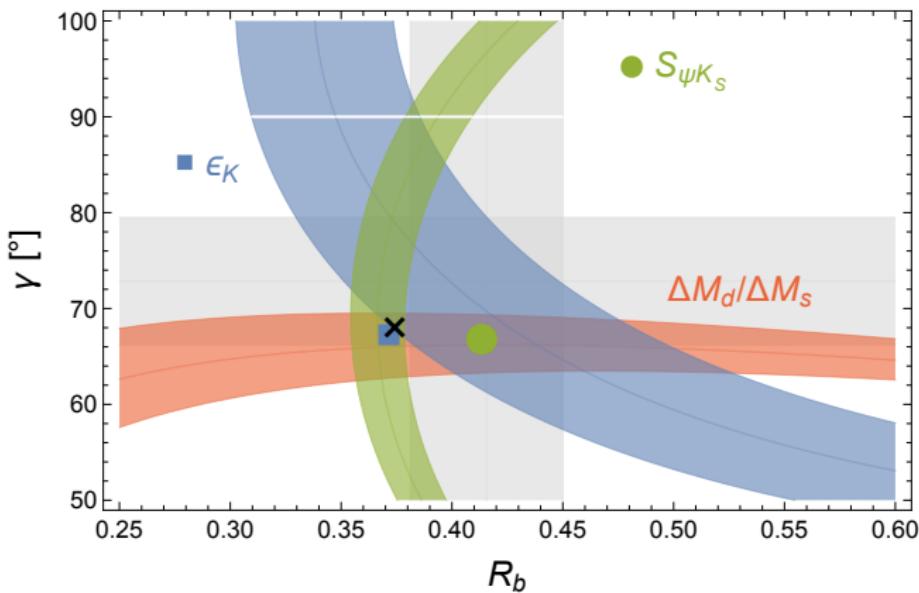
● b.f. without ϵ_K

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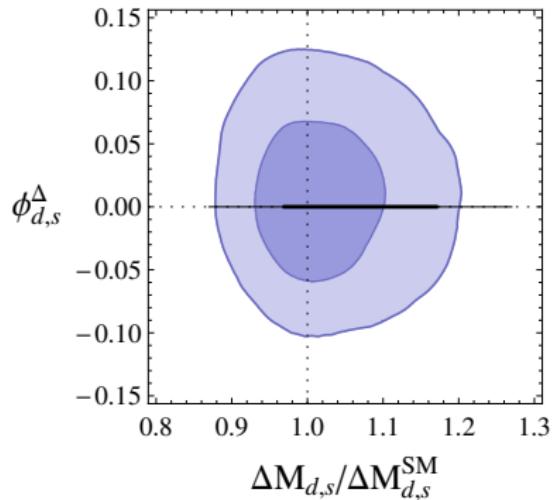
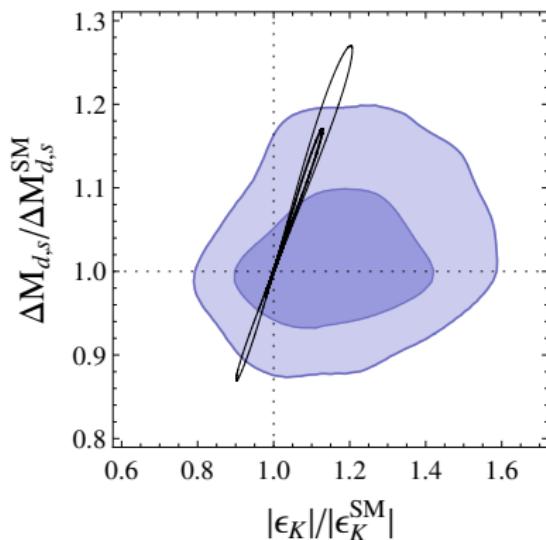
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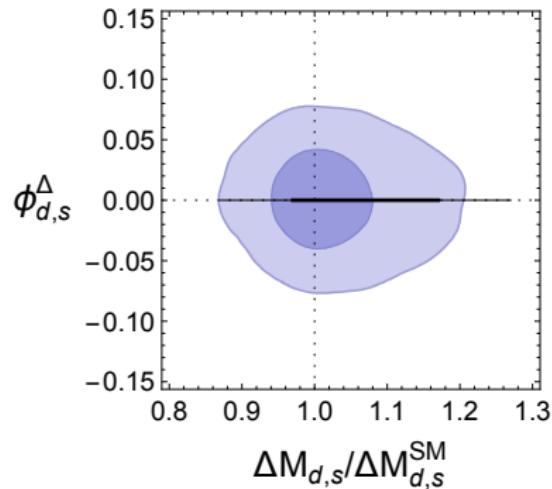
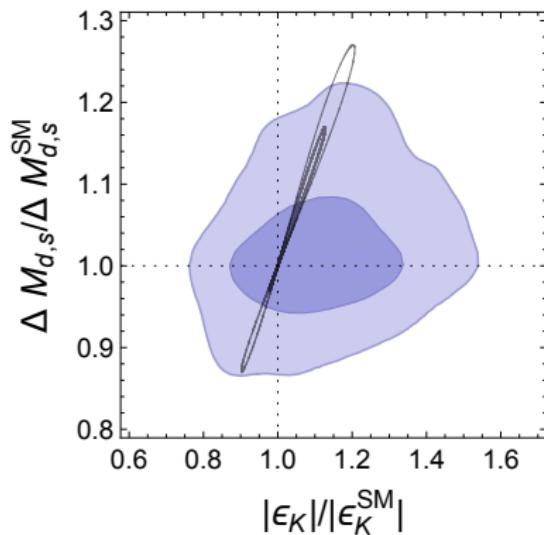
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Meson-antimeson mixing in $U(2)^3$



- ▶ Slight preference for a positive contribution to 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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Outline

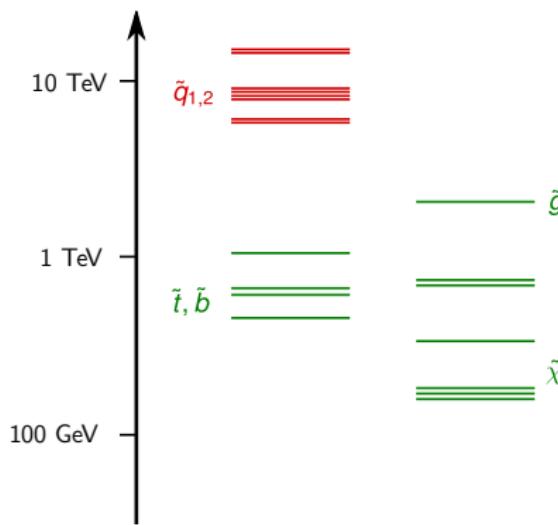
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$U(2)^3$ and natural SUSY

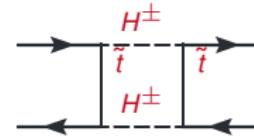
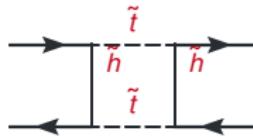


- ▶ How large can the effects in meson-antimeson mixing still be in SUSY $U(2)^3$, given the direct bounds from LHC?

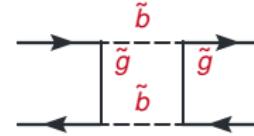
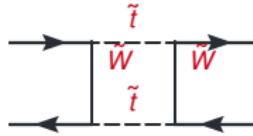
Meson mixing in SUSY $U(2)^3$

Two classes of contributions

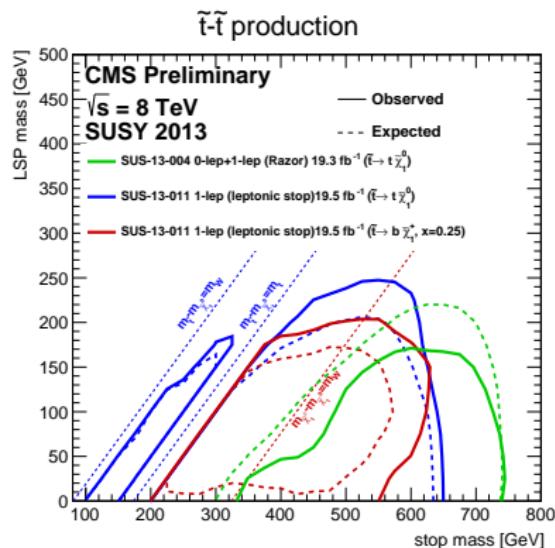
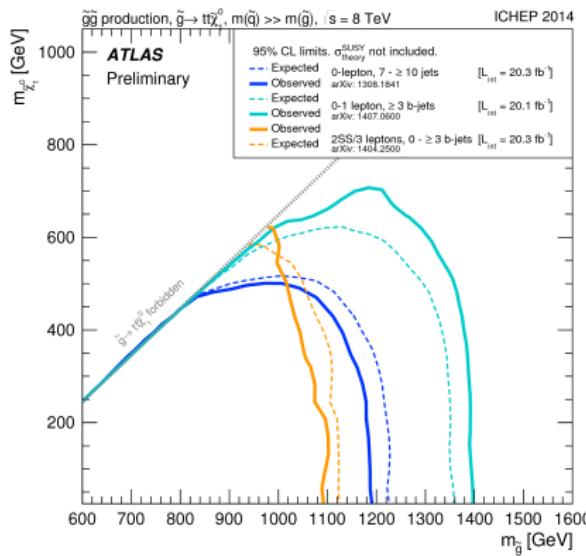
- ▶ Higgsino and ch. Higgs contributions are **MFV-like** ($h_K = h_B$, $\sigma_B = 0$)



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



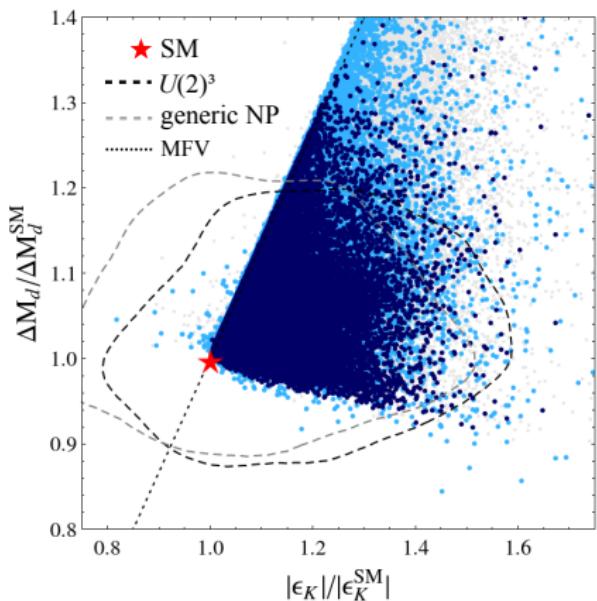
Sparticle mass bounds in natural SUSY



► Natural spectra

- “heavy”: $m_{\tilde{g}} \gtrsim 1.4$ TeV, $m_{\tilde{t}, \tilde{b}} \gtrsim 0.7$ TeV
- “compressed”: $m_{\tilde{g}} - m_{\tilde{\chi}_1^0} \lesssim 350$ GeV or $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \lesssim 150$ GeV

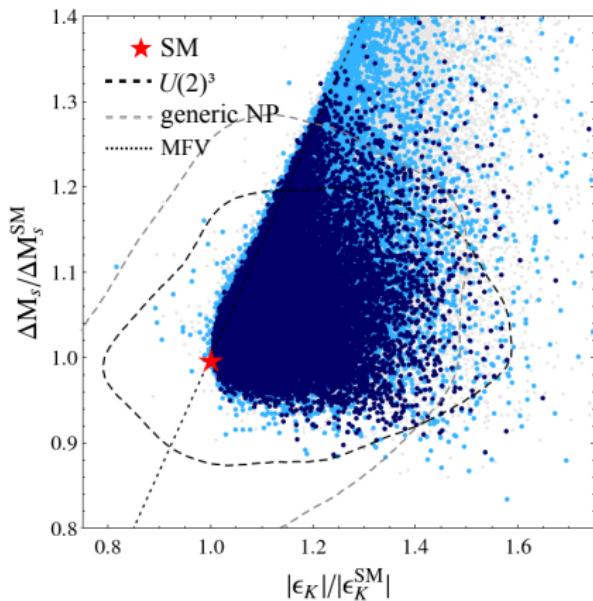
Numerical results for $\Delta F = 2$ observables



- ▶ All blue points compatible with direct searches
- ▶ 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]

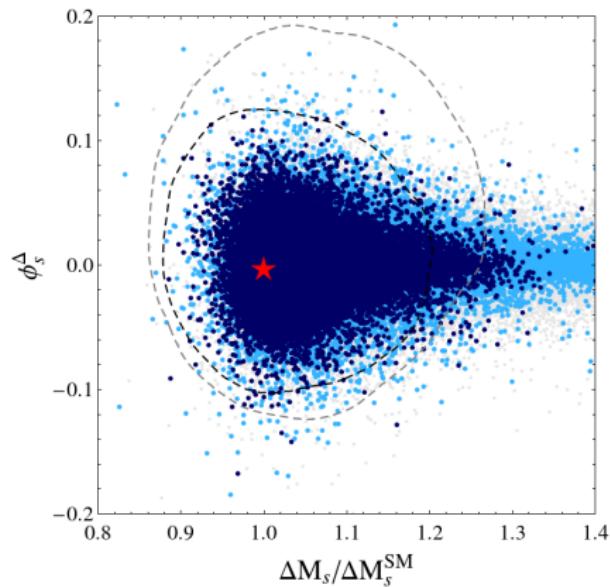
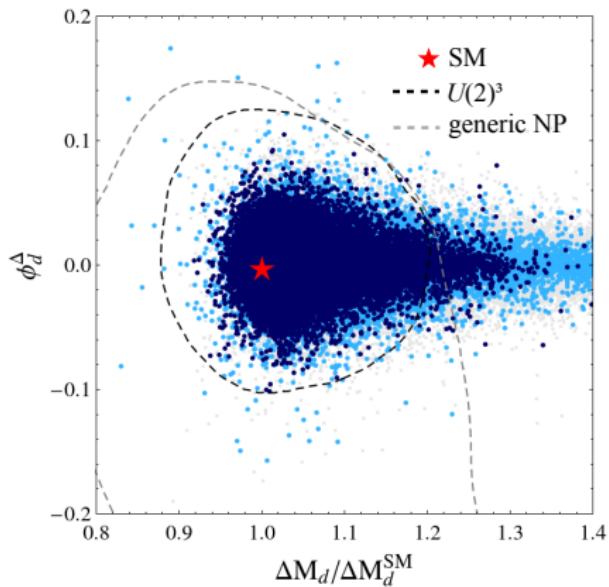
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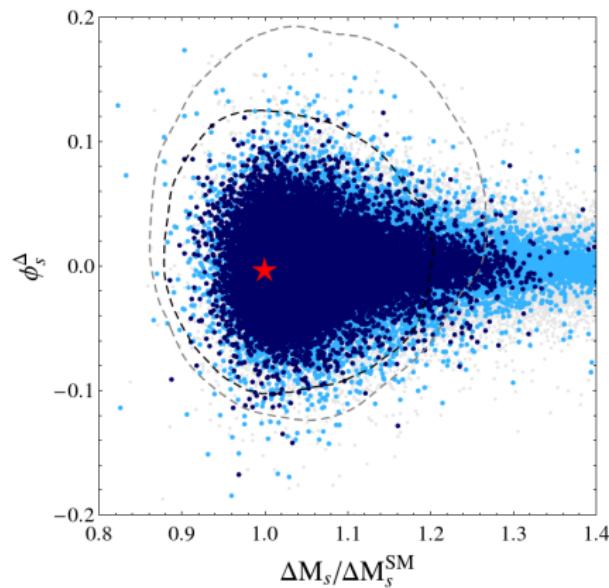
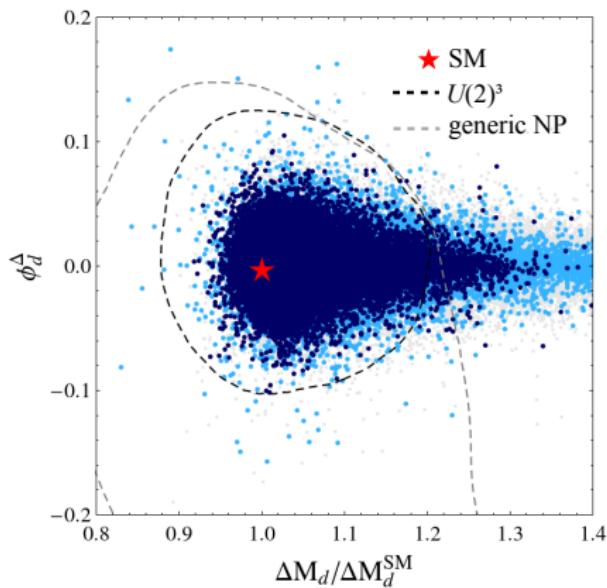
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Meson mixing in SUSY $U(2)^3$



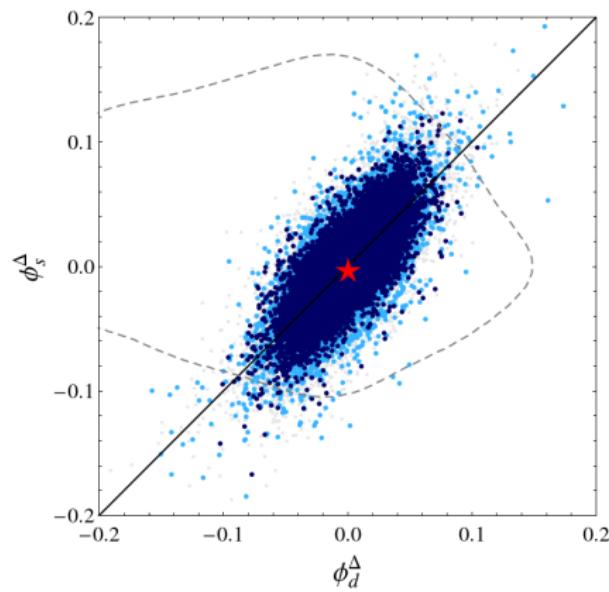
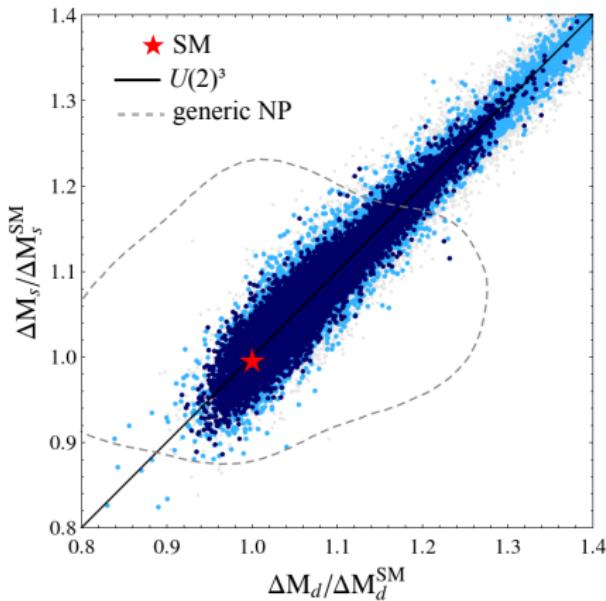
- NP contribution to $B_{s,d}$ mixing phase at most 0.1

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



- ▶ NP contribution to $B_{s,d}$ mixing phase at most 0.1
- ▶ New LHCb meas. cuts into parameter space left open by direct searches

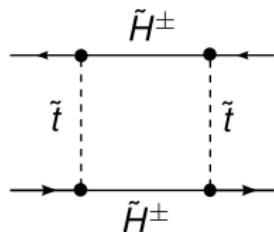
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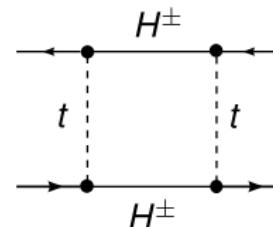
- The $U(2)^3$ relation $\phi_s^\Delta = \phi_d^\Delta$ is broken by an accidental enhancement of the LR operator in B_s mixing, at subleading order in the spurion expansion

Where do the large MFV-like effects come from?

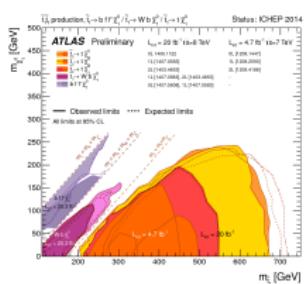
1. compressed stop



2. light charged Higgs



- stop gap still open



- $\tan \beta \sim$ and $m_{H^\pm} \sim 300$ GeV: not necess. excluded by LEP (heavy sfermions, NMSSM)
- could be probed through $A^0 \rightarrow Zh$

[Djouadi and Quevillon 1304.1787]

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Effective Hamiltonian for $b \rightarrow s$ transitions

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

$$\mathcal{O}_7 = \frac{m_b}{e} (\bar{s} \sigma_{\mu\nu} P_R b) F^{\mu\nu}$$

$$\mathcal{O}_8 = \frac{m_b}{e} (\bar{s} \sigma_{\mu\nu} P_R T^a b) G^{a\mu\nu}$$

$$\mathcal{O}_9 = (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu \ell)$$

$$\mathcal{O}_{10} = (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu \gamma_5 \ell)$$

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Anomalies in $b \rightarrow s\mu^+\mu^-$ processes

There are a number of $2\text{--}3\sigma$ anomalies in exclusive $b \rightarrow s\mu^+\mu^-$ decays:

1. Angular observables in $B \rightarrow K^*\mu^+\mu^-$
($P'_5, P_1; S_5, F_L, A_{\text{FB}}$)
2. Low branching ratios in $B \rightarrow K\mu^+\mu^-$, $B \rightarrow K^*\mu^+\mu^-$, $B_s \rightarrow \phi\mu^+\mu^-$
3. Ratio R_K of $B \rightarrow K\mu^+\mu^-$ and $B \rightarrow Ke^+e^-$ branching ratios below 1

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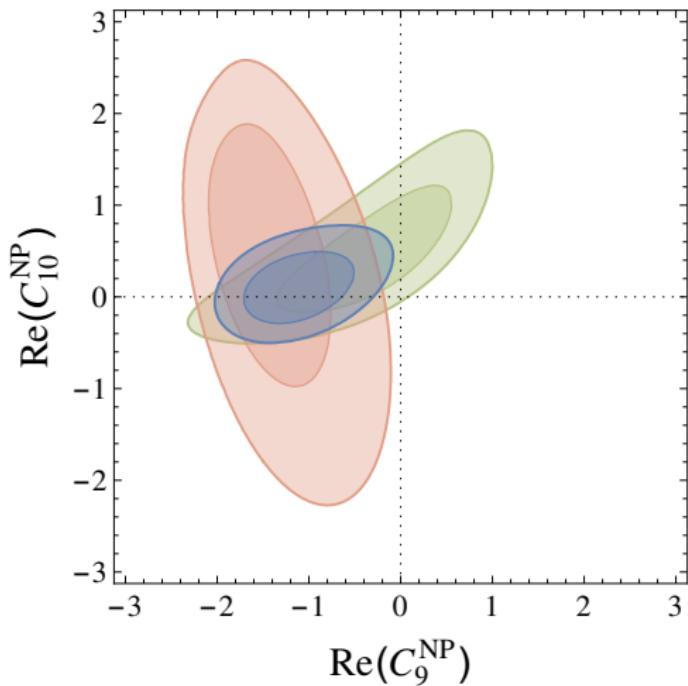
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cf. [Descotes-Genon et al. 1307.5683, Altmannshofer and Straub 1308.1501, Beaujean et al. 1310.2478, Lyon and Zwicky 1406.0566, Descotes-Genon et al. 1407.8526, Altmannshofer and Straub 1411.3161, Hiller and Schmaltz 1408.1627, Ghosh et al. 1408.4097, Glashow et al. 1411.0565, Jäger and Camalich 1412.3183, ...]

Global fit to $b \rightarrow s\mu^+\mu^-$ data [Altmannshofer and Straub 1411.3161]



- ▶ Green: all branching ratios
- ▶ Red: $B \rightarrow K^*\mu^+\mu^-$ angular observables only
- ▶ Blue: global fit

Outline

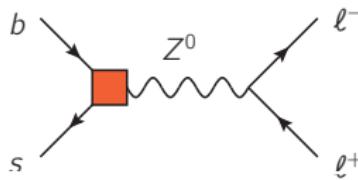
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Flavour-changing Z penguins

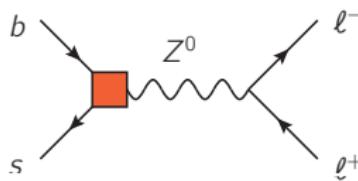


- ▶ Can be thought of as coming from dim.-6 operators

$$i(\bar{q}_L \gamma_\mu q_L) H^\dagger D^\mu H \quad i(\bar{d}_R \gamma_\mu d_R) H^\dagger D^\mu H$$

- ▶ Contribution to $C_9^{(\prime)\text{NP}} = -(1 - 4s_w^2) C_{10}^{(\prime)\text{NP}} \approx 0.08 C_{10}^{(\prime)\text{NP}}$
- ▶ Are lepton flavour universal

Flavour-changing Z penguins



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- ▶ Are lepton flavour universal
- ▶ Can Z penguins in the MSSM explain some of the anomalies in B decays?
- ▶ Which parameters are constrained by recent measurements of B decays?

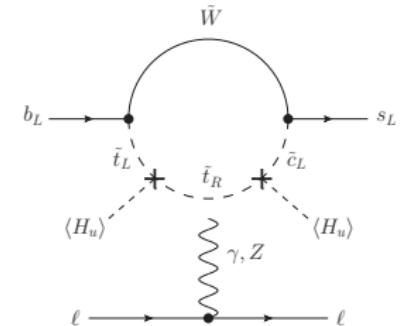
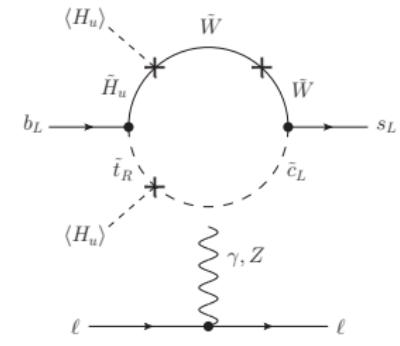
Z penguins in the general MSSM

[Altmannshofer and Straub 1411.3161]

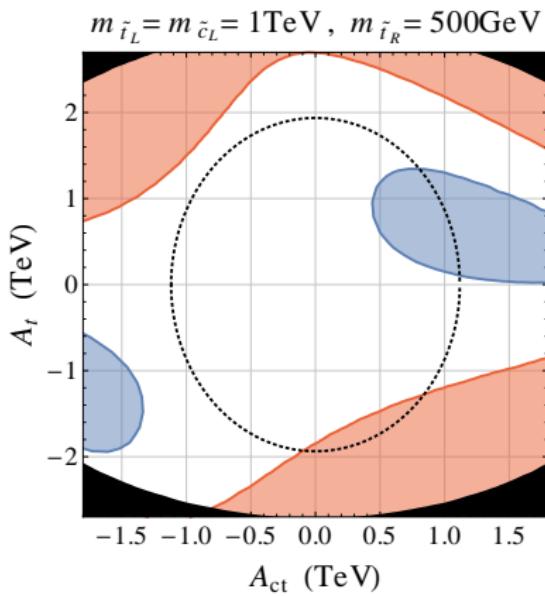
Taking into account other constraints, sizable effects can (only) be generated with flavour-changing trilinears:

$$\mathcal{L} \supset A_{ct} Y_t \tilde{c}_L^* \tilde{t}_R H_u + \text{h.c.}$$

- ▶ small contribution to $C_{7,8}$
- ▶ negligible contribution to C'_Z
- ▶ potentially sizable contribution to C_Z



Bounds on A_{ct}



- ▶ Blue: preferred by $b \rightarrow s\mu\mu$
- ▶ Red: disfavoured by $b \rightarrow s\mu\mu$
- ▶ Dotted: vacuum stability
- ▶ Black: \tilde{u} LSP

Implications:

1. MSSM could lead to visible effects in Z -mediated $b \rightarrow sll$
2. $b \rightarrow sll$ data lead to strongest limit on A_{ct} so far

[Altmannshofer and Straub 1411.3161]

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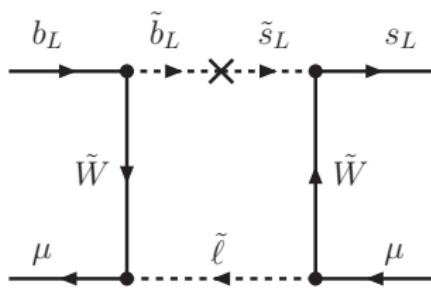
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Trying to explain $R_K < 1$ in the MSSM

Only hope to generate an appreciable effect: Wino box

[Altmannshofer and Straub 1308.1501, Altmannshofer and Straub 1411.3161]

Need:

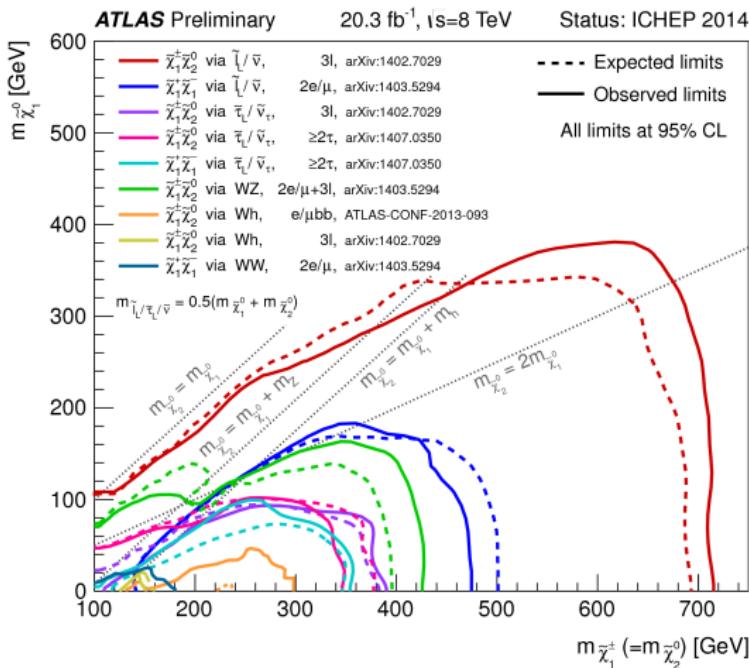


- ▶ Extremely light \tilde{W}
- ▶ Extremely light $\tilde{\mu}_L$
- ▶ Heavy \tilde{e}_L
- ▶ Large \tilde{b}_L - \tilde{s}_L mixing
- ▶ Not too heavy \tilde{b}_L , \tilde{s}_L (\tilde{t}_L , \tilde{c}_L)

(e)

- ▶ Implies $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$
- ▶ Best-fit value $C_9^{\text{NP}} \approx -0.7$

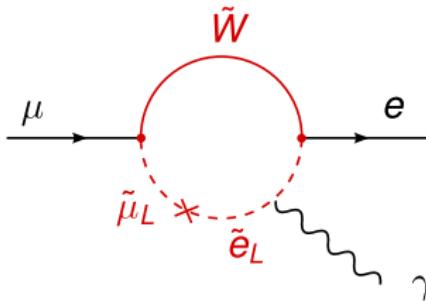
Extremely light \tilde{W} ?



- If \tilde{W}^0 is not LSP, $\tilde{W}^\pm\tilde{W}^0 \rightarrow 3\mu + E_T$ via off-shell $\tilde{\mu}$ leads to very strong constraint!
- For \tilde{W}^0 LSP, $m_{\tilde{W}} \sim 100 \text{ GeV}$ might be allowed

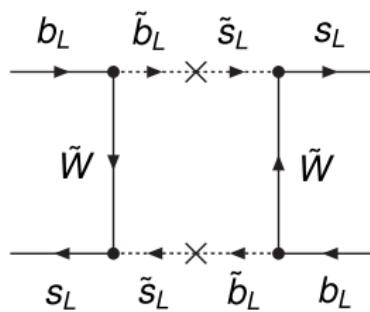
Large $\tilde{\mu}_L$ - \tilde{e}_L mass splitting?

- ▶ statement “slepton mass matrix is non-universal but diagonal” is weak basis dependent
- ▶ even 10^{-3} level misalignment between diagonality basis and charged lepton mass basis would be in conflict with $\mu \rightarrow e\gamma$



Large \tilde{b}_L - \tilde{s}_L mixing?

- ▶ Potentially large contribution to B_s - \bar{B}_s mixing



Conclusions

$\Delta F = 2$

- ▶ In $U(2)^3$ SUSY, collider bounds force effects to be smallish, in particular $\phi_s^\Delta \lesssim 0.1$
- ▶ Large MFV-like effects from charged Higgs/Higgsinos due to gaps in collider searches

$\Delta F = 1$

- ▶ Z penguins constrain A_{ct} – could lead to visible effects (and improve BR tensions)
- ▶ $|R_K - 1|$ from box contribution \lesssim few %