Rencontres de Physique de La Vallée d'Aoste, 26 February 2014

New Physics in Flavour after the first LHC phase

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Two frontiers

Direct searches at LHC

- Directly probe the scale of new physics (NP) Λ
- Limited by available energy

Flavour physics

- Probes NP indirectly through quantum effects
- Limited by size of flavour violation

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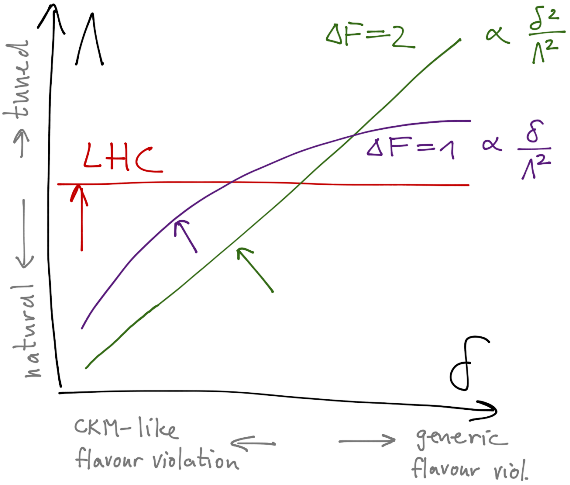
At both frontiers, strong bounds but no signs of NP

Collider vs. flavour physics



Outline

1. **News** from flavour theory & experiment
   - $B_s \to \mu^+\mu^-$
   - $B \to K^*\mu^+\mu^-$
   - B_s mixing phase

2. Collider vs. flavour: **natural SUSY** with CKM-like flavour violation
   - Model-independent bounds from meson mixing
   - Numerical analysis of meson mixing in natural SUSY

$B_s \to \mu^+\mu^-$: theory vs. experiment

Experiment

- 2013: first evidence for the decay by CMS & LHCb

$$\overline{\text{BR}}_{\text{LHCb+CMS}} = (2.9 \pm 0.7) \times 10^{-9}$$

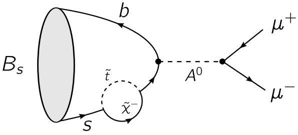
Theory

- $\Delta\Gamma_s$ taken into account [De Bruyn et al. 1204.1737]
- f_{B_s} computed on the lattice to 2% precision [HPQCD, FLAG]
- NLO electroweak corrections [Bobeth et al. 1311.1348]
- NNLO QCD corrections [Hermann et al. 1311.1347]

$$\overline{\text{BR}}_{\text{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$

$B_s \to \mu^+\mu^-$ in the MSSM

Contributions to the Wilson coefficients $C_{S,P}$ are generated by H^0 and A^0 exchange.

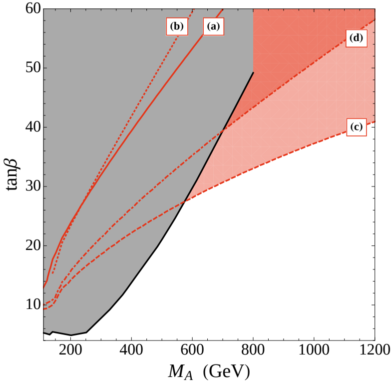


Dominant contribution: Higgsino-stop loop

$$C_S \simeq -C_P \propto \frac{\mu A_t}{m_{\tilde{t}}^2} \frac{m_{B_s} m_\mu}{m_A^2} \tan^3\beta$$

Potentially huge enhancement for large $\tan\beta$

Large tan β + light pseudoscalar Higgs disfavoured



[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)	+	+	+	-	-

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

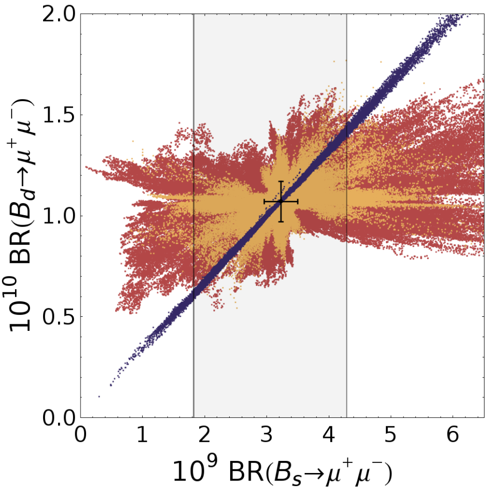
$B_{s,d} \to \mu^+\mu^-$ in other models

$B_{s,d} \to \mu^+\mu^-$ remains interesting:

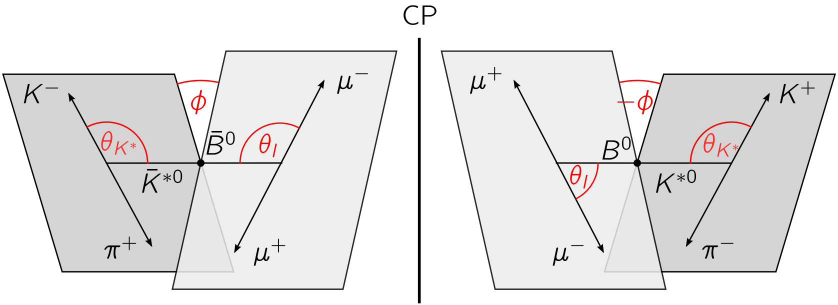
now starts to probe models without scalar operators

e.g. composite Higgs/extra-dim. models with partial compositeness

[DS 1302.4651]



$B \to K^* \mu^+ \mu^-$: SM vs. new physics



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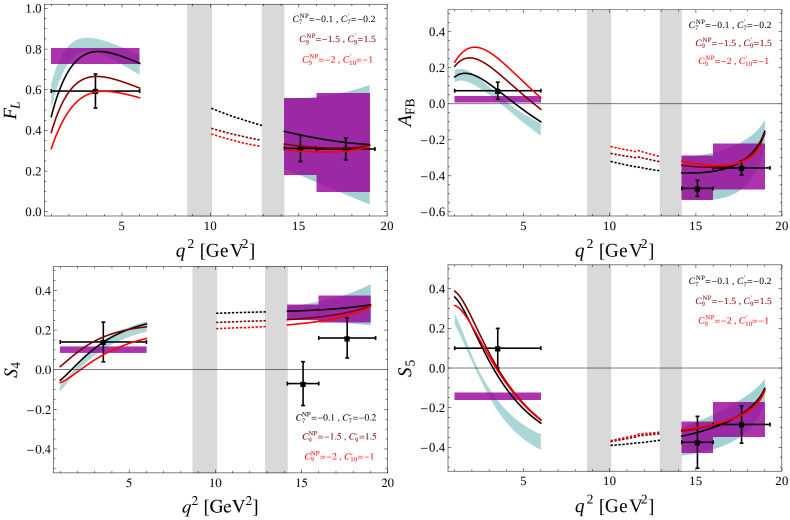


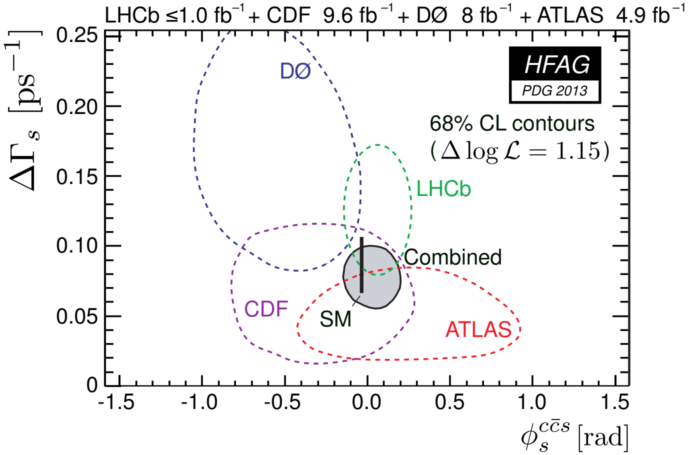
$B \to K^* \mu^+ \mu^-$: SM vs. new physics

- Several tensions at 2–3 σ level
- NP explanation is hard to realize in explicit models (impossible in SUSY, partial compositeness, ...) and leads to tensions in other observables ($B \to K\mu\mu, \ldots$)
- Subleading hadronic effects might be larger than expected
- More data on tape – stay tuned

[Descotes-Genon et al. 1307.5683, Altmannshofer and DS 1308.1501, Beaujean et al. 1310.2478]

$\rightarrow$ see talk by Matias

B_s mixing phase



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2. Collider vs. flavour: **natural SUSY** with CKM-like flavour violation
   - Model-independent bounds from meson mixing
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Based on arXiv:1402.xxxx with R. Barbieri, D. Buttazzo, and F. Sala

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

$$M_{12}^K = (M_{12}^K)_{\mathrm{SM}} \left(1 + h_K e^{2i\sigma_K}\right)$$
$$M_{12}^d = (M_{12}^d)_{\mathrm{SM}} \left(1 + h_d e^{2i\sigma_d}\right)$$
$$M_{12}^s = (M_{12}^s)_{\mathrm{SM}} \left(1 + h_s e^{2i\sigma_s}\right)$$

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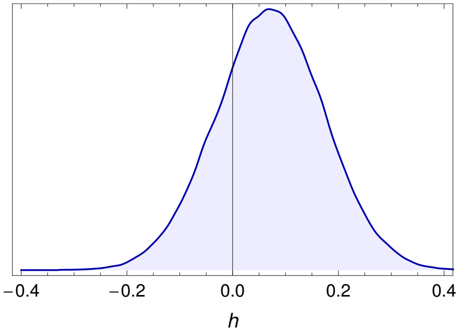
What are the allowed sizes of h or h_B, h_K, σ_B?

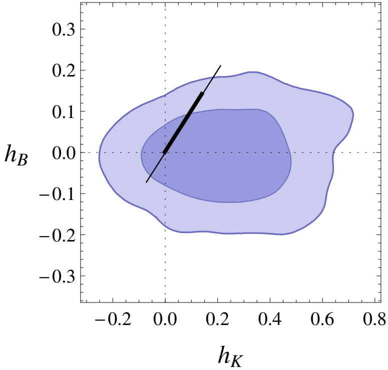
Meson-antimeson mixing in MFV

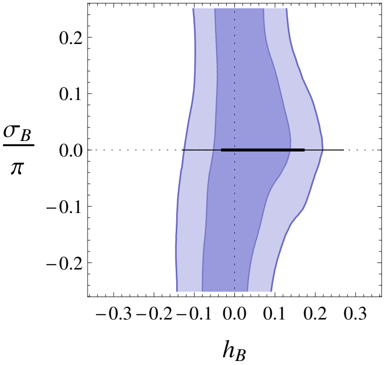
Global fit to ΔM_d, ΔM_s, ϕ_s, $S_{\psi K_S}$, ϵ_K, γ, $|V_{ud}|$, $|V_{us}|$, $|V_{cb}|$, $|V_{ub}|$:



- 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

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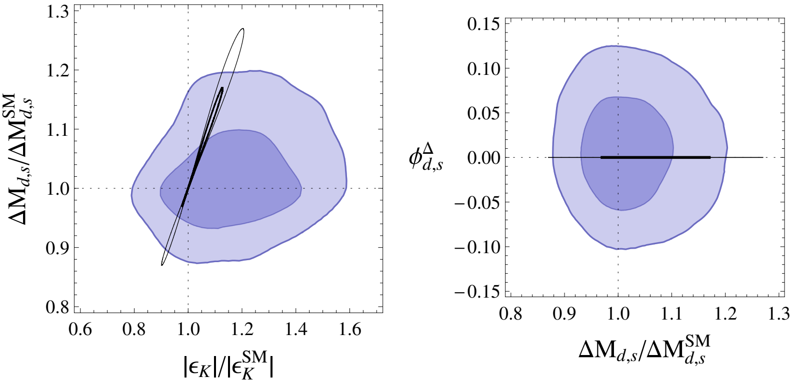

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ϵ_K vs. $S_{\psi K_S}$

- 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
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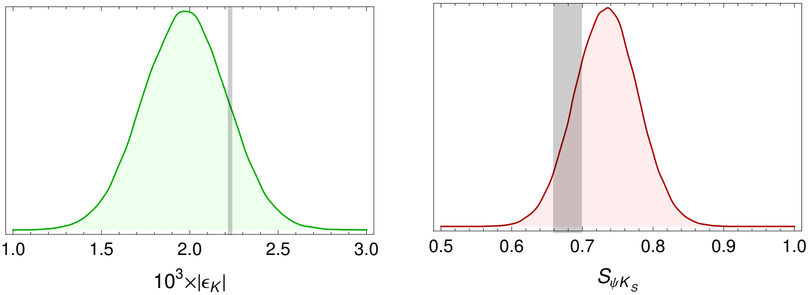
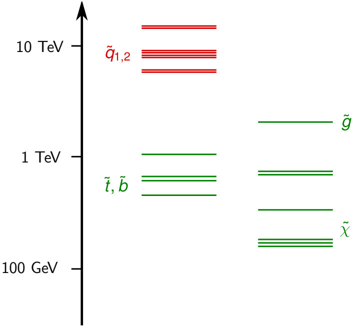


- Significance of "tension" down to 1.1σ
- Main reason: lattice bag parameter $\hat{B}_K$ moved up; theory uncertainty on η_{cc} increased

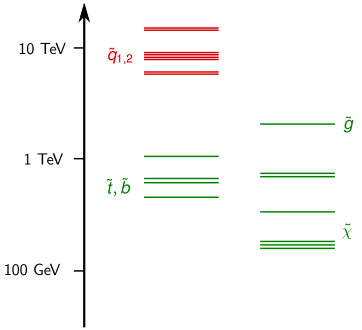
$U(2)^3$ and natural SUSY



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

Natural SUSY with split generations + CKM-like flavour violation: SUSY $U(2)^3$

$U(2)^3$ and natural SUSY



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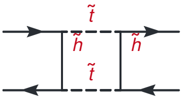
Natural SUSY with split generations + CKM-like flavour violation: SUSY $U(2)^3$

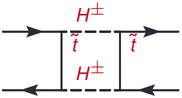
- How large can the effects in meson-antimeson mixing still be in SUSY $U(2)^3$, given the direct bounds from LHC?

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

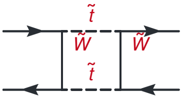
Two classes of contributions

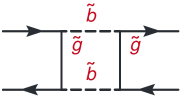
- Higgsino and ch. Higgs contributions are MFV-like ($h_K = h_B$, $\sigma_B = 0$)



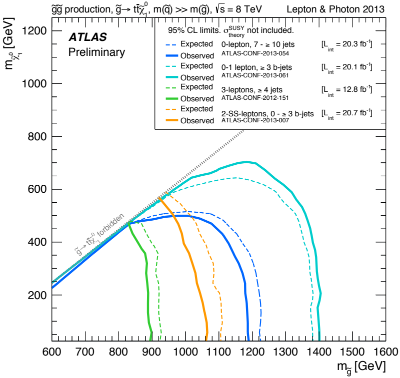


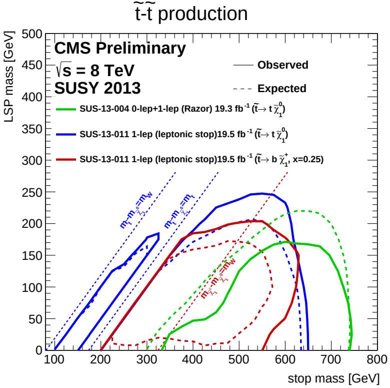
- Wino and gluino contributions can induce a new phase in B/B_s mixing





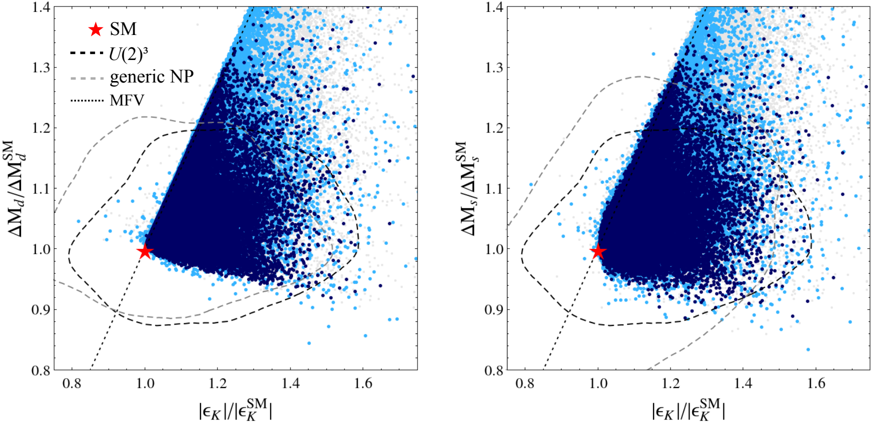
Sparticle mass bounds in natural SUSY





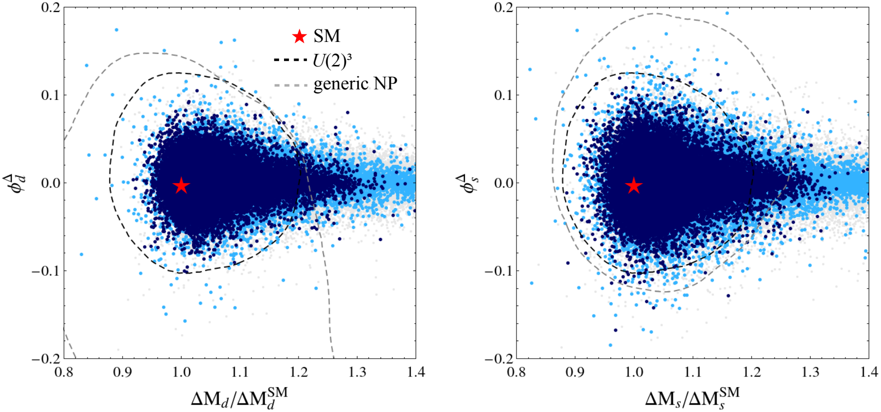
- Natural spectra
  - "heavy": $m_{\tilde g} \gtrsim 1.4\,\text{TeV}$, $m_{\tilde t,\tilde b} \gtrsim 0.7\,\text{TeV}$
  - "compressed": $m_{\tilde g} - m_{\chi_1^0} \lesssim 350\,\text{GeV}$ or $m_{\tilde t} - m_{\chi_1^0} \lesssim 150\,\text{GeV}$

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



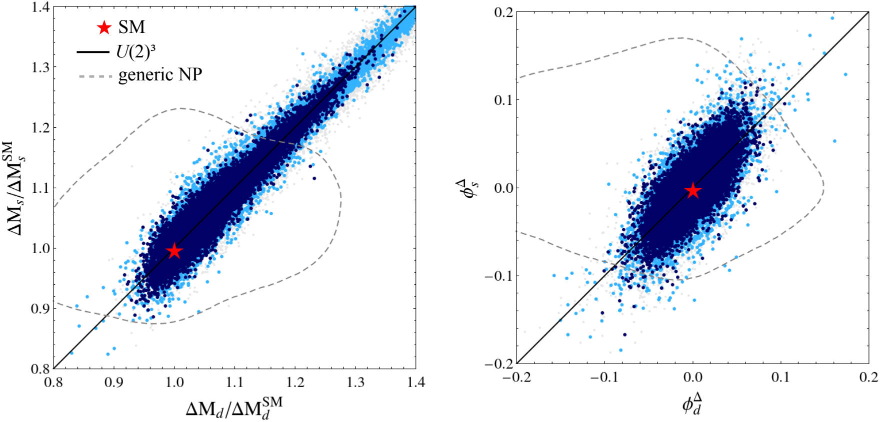
- Direct bounds almost as constraining as flavour, except for compressed spectra

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



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

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



- 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

Conclusions

Natural SUSY with split families + CKM-like flavour violation = SUSY $U(2)^3$

- New physics in meson mixing allowed at the 20–30% level
- $\Delta M_{s,d}$: for a compressed spectrum, flavour constraints stronger than collider bounds
- $\phi^{\Delta}_{d,s}$: collider bounds are as strong as flavour measurements, even for compressed spectrum.
- ϕ_s close to current experimental bound still allowed

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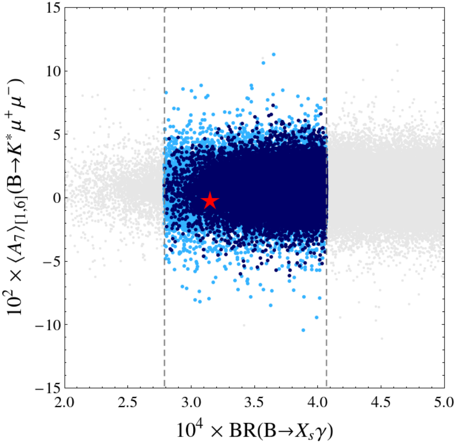
$\Rightarrow$ a close race between flavour and collider

Backup

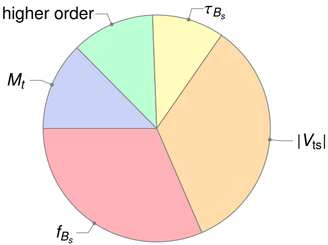
$\Delta F = 1$ in SUSY $U(2)^3$



NB: $\tan\beta \leq 5$

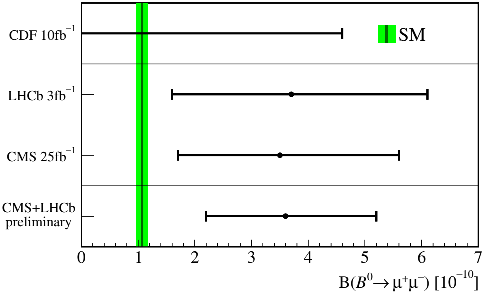
$B_s \to \mu^+\mu^-$ error budget

$$\overline{\text{BR}}(B_s \to \mu^+\mu^-)_{\text{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$



$$\text{cf.:}\ \overline{\text{BR}}(B_s \to \mu^+\mu^-)_{\text{LHCb+CMS}} = (2.9 \pm 0.7) \times 10^{-9}$$

$B_d \to \mu^+\mu^-$ experiment vs. SM



- 2.4σ above 0, 1.6σ above SM. If NP: no MFV!

Comparison of $b \to s$ global fits (C. Bobeth)

Which data is used?

q^2 Binning

	q^2-Bins [GeV^2]
lo	[1, 6]
LO	[0, 2]
	[2, 4.3]
	[4.3, 8.68]
hi	[14.18, 16]
	[16, 19]

DGMV: only LHCb data for $B \to K^* \ell\bar{\ell}$

AS, BBvD, HLMW:
use all available data from Belle, Babar, CDF, LHCb, CMS, ATLAS

decay	obs	DGMV	AS	BBvD	HLMW
$B \to X_s\gamma$	Br	✓	✓	✓	
	A_{CP}		✓		
$B \to K^*\gamma$	Br			✓	
	$S(C)$	✓	✓	✓(✓)	
	A_I	✓			
$B_s \to \mu\bar{\mu}$	Br	✓	✓	✓	
$B \to X_s\ell\bar{\ell}$	Br	lo	lo+hi	lo	
$B \to K\ell\bar{\ell}$	Br		lo+hi	lo+hi	
$B \to K^*\ell\bar{\ell}$	Br		lo+hi	lo+hi	hi
	F_L		lo+hi	lo+hi	hi
	$A_{\rm FB}$	LO+hi	lo+hi	lo+hi†	hi
	$P_{1,2}$, $P'_{4,5,6}$	LO+hi		lo+hi†	
	P'_8	LO+hi			
	$S_{3,4,5}$		lo+hi		hi
	A_9		lo+hi		
$B_s \to \phi\ell\bar{\ell}$	Br, F_L, S_3				hi

† if P_2 is available then $A_{\rm FB}$ is not used: LHCb