

# Flavour symmetries after the first LHC phase

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based on 1402.6677 with R. Barbieri, F. Sala and D. Straub

Dario Buttazzo

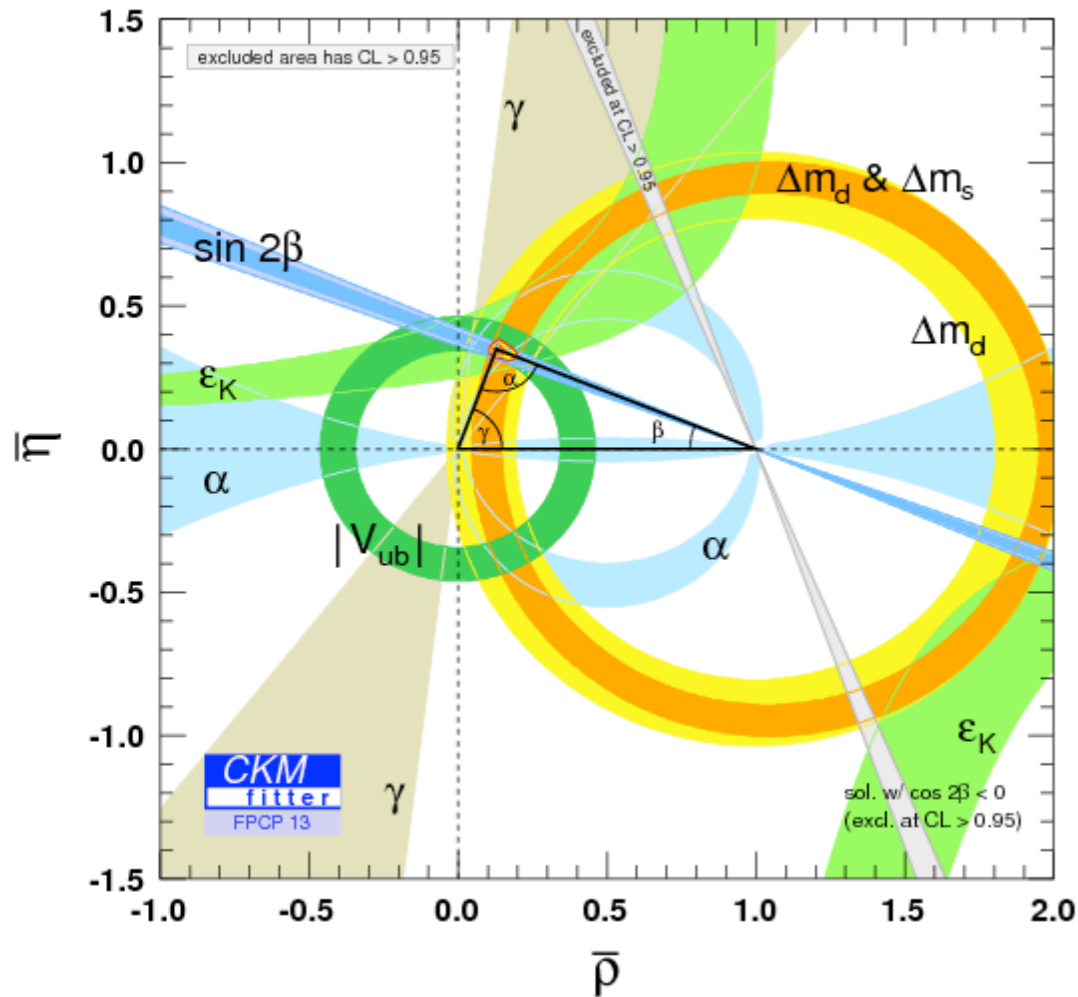
Institute for Advanced Study – TU Munich



Planck 2014 – “From the Planck scale to the electroweak scale”

Paris, 29.5.2014

# The CKM picture of flavour



Remarkable accuracy ( $\sim 20\%$ ) of the CKM picture of flavour changing interactions

1. Explore the highest energies indirectly testable, assuming generic flavour effects: in several cases up to  $10^{4\div 5}$  TeV
2. Physics at the TeV scale must have a very peculiar structure: symmetries

EFT approach: only a limited set of effective operators is present, size controlled by the CKM matrix  $V$

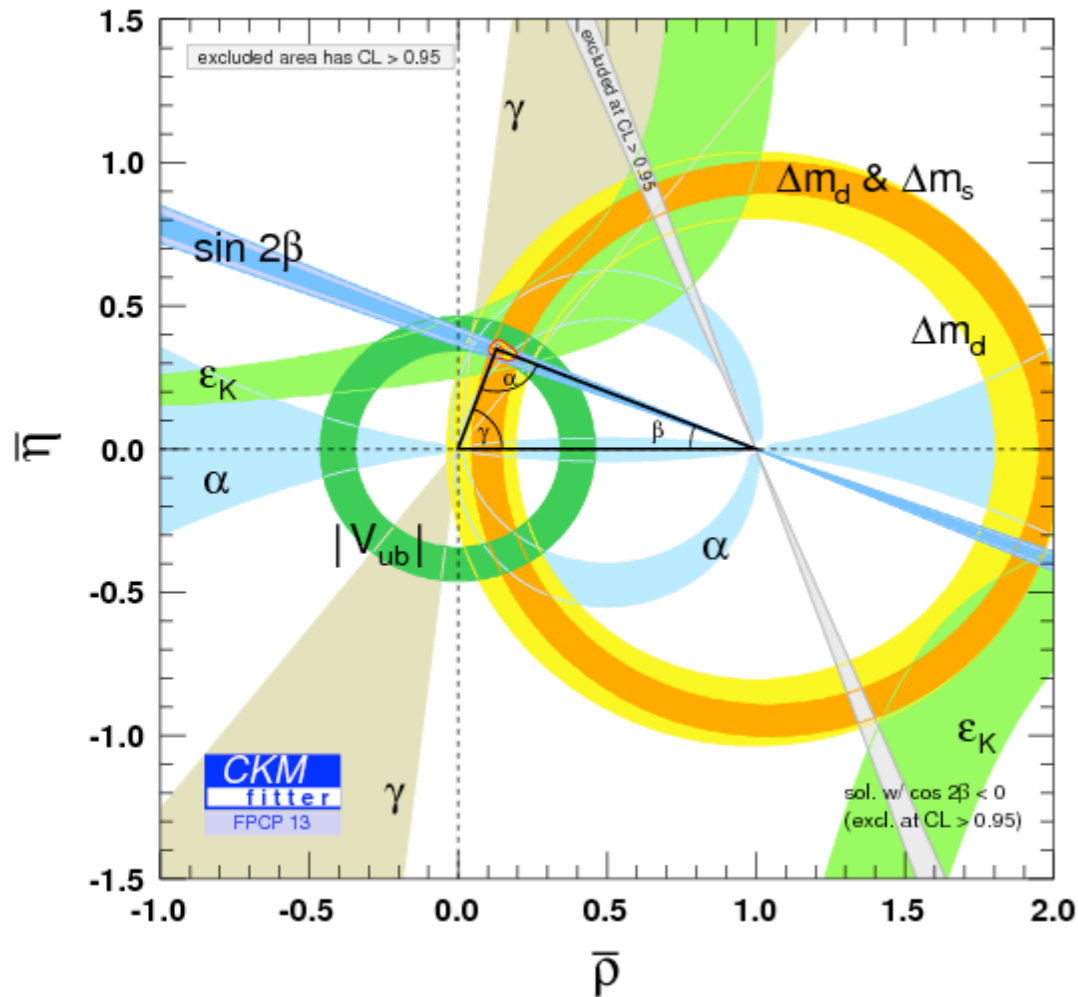
$$\xi_{ij}^2 (\bar{d}_L^i \gamma_\mu d_L^j)^2$$

$$\xi_{ij} (\bar{d}_L^i \gamma_\mu d_L^j) \mathcal{O}_\alpha^\mu$$

$$\xi_{ij} m_j (\bar{d}_L^i \sigma_{\mu\nu} d_R^j) \mathcal{O}_\beta^{\mu\nu}$$

$$(\xi_{ij} = V_{ti}^* V_{tj})$$

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$$(\xi_{ij} = V_{ti}^* V_{tj})$$

**How to get a flavour scenario close to CKM, beyond the SM?**

# Direct searches

## ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: SUSY 2013

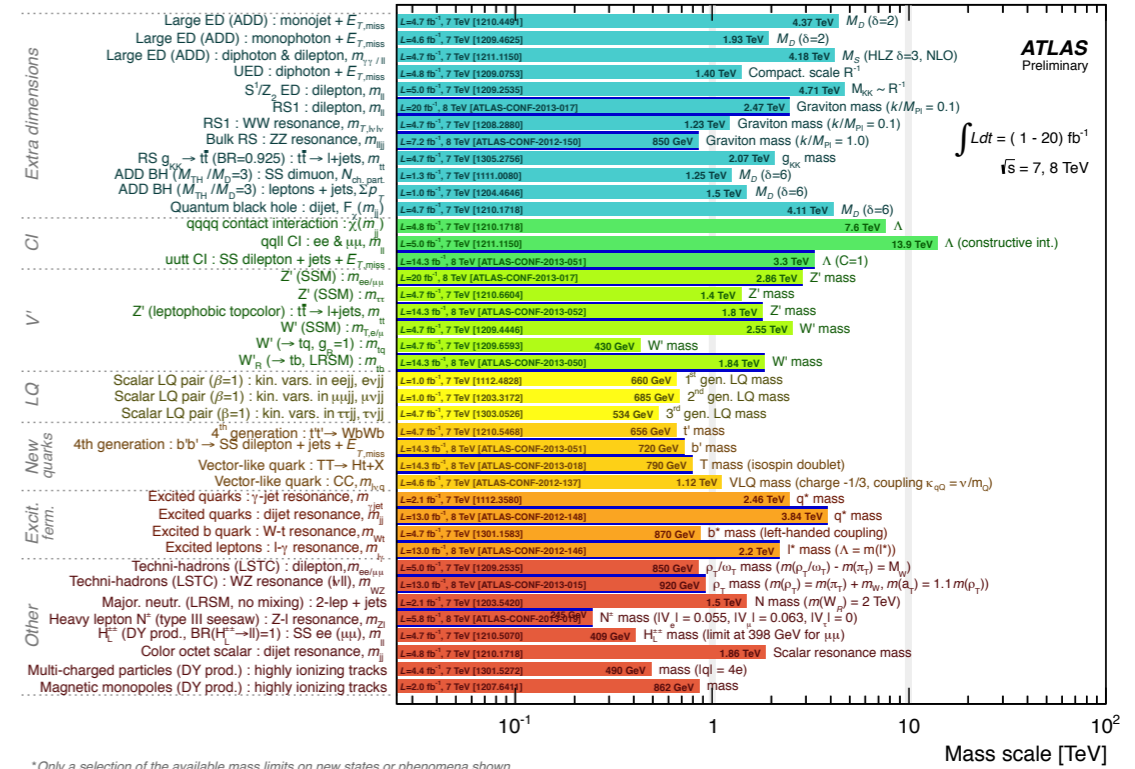
ATLAS Preliminary

$\int \mathcal{L} dt = (4.6 - 22.9) \text{ fb}^{-1}$   $\sqrt{s} = 7, 8 \text{ TeV}$

Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference	
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{g}, \tilde{g} \rightarrow q\bar{q}$ 1.7 TeV	
	MSUGRA/CMSSM	1 $e, \mu$	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\bar{q}$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}$	1 $e, \mu$	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}$	2 $e, \mu$	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	
	GMSB ( $\tilde{L}$ NLSP)	2 $e, \mu$	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	
	GMSB ( $\tilde{L}$ NLSP)	1-2 $\tau$	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	
	GGM (bino NLSP)	2 $\gamma$	-	Yes	4.8	$\tilde{g}$ 1.07 TeV	
3rd gen. squarks & med.	$\tilde{g} \rightarrow b\bar{b}$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	
	$\tilde{g} \rightarrow t\bar{t}$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	
	$\tilde{g} \rightarrow t\bar{t}$	0-1 $e, \mu$	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	
	$\tilde{g} \rightarrow b\bar{b}$	0-1 $e, \mu$	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	
	3rd gen. squarks direct production	$\tilde{t}_1 \tilde{t}_1$	0	2 b	Yes	20.1	$\tilde{t}_1$ 100-620 GeV
		$\tilde{t}_1 \tilde{t}_1$ (light)	2 $e, \mu$ (SS)	0-3 b	Yes	20.7	$\tilde{t}_1$ 275-430 GeV
		$\tilde{t}_1 \tilde{t}_1$ (medium)	1-2 $e, \mu$	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV
		$\tilde{t}_1 \tilde{t}_1$ (heavy)	2 $e, \mu$	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-220 GeV
		$\tilde{t}_1 \tilde{t}_1$ (heavy)	2 $e, \mu$	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV
		$\tilde{t}_1 \tilde{t}_1$ (heavy)	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV
$\tilde{t}_1 \tilde{t}_1$ (heavy)		1 $e, \mu$	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	
$\tilde{t}_1 \tilde{t}_1$ (heavy)		0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	
$\tilde{t}_1 \tilde{t}_1$ (natural GMSB)		2 $e, \mu$ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 90-200 GeV	
$\tilde{t}_1 \tilde{t}_1$ (natural GMSB)		3 $e, \mu$ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	
EW direct	$\tilde{Z} \tilde{Z}$	2 $e, \mu$	0	Yes	20.3	$\tilde{Z}$ 85-315 GeV	
	$\tilde{Z} \tilde{Z}$	2 $e, \mu$	0	Yes	20.7	$\tilde{Z}$ 125-450 GeV	
	$\tilde{Z} \tilde{Z}$	2 $\tau$	0	Yes	20.3	$\tilde{Z}$ 180-330 GeV	
	$\tilde{Z} \tilde{Z}$	3 $e, \mu$	0	Yes	20.7	$\tilde{Z}$ 315 GeV	
	$\tilde{Z} \tilde{Z}$	3 $e, \mu$	0	Yes	20.7	$\tilde{Z}$ 600 GeV	
	$\tilde{Z} \tilde{Z}$	1 $e, \mu$	2 b	Yes	20.3	$\tilde{Z}$ 285 GeV	
	Long-lived particles	Direct $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^0$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^0$ 270 GeV
		Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 832 GeV
		GMSB, stable $\tilde{\tau}$ , $\tilde{\tau} \rightarrow \tau(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$	1-2 $\mu$	-	-	15.9	$\tilde{\tau}$ 230 GeV
		GMSB, $\tilde{\chi}_1^0 \rightarrow G$ , long-lived $\tilde{\chi}_1^0$	2 $\gamma$	-	Yes	4.7	$\tilde{\chi}_1^0$ 475 GeV
$\tilde{q}\tilde{q}, \tilde{\chi}_1^0 \rightarrow q\bar{q}$ (RPV)		1 $\mu$ , displ. vtx	-	-	20.3	$\tilde{q}$ 230 GeV	
RPV		LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$	2 $e, \mu$	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV
		LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV
		Bilinear RPV CMSSM	1 $e, \mu$	7 jets	Yes	4.7	$\tilde{g}, \tilde{g}$ 1.2 TeV
		$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow W \tilde{Z}$	4 $e, \mu$	-	Yes	20.7	$\tilde{\chi}_1^0$ 760 GeV
		$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow W \tilde{Z}$	3 $e, \mu + \tau$	-	Yes	20.7	$\tilde{\chi}_1^0$ 350 GeV
	$\tilde{g} \rightarrow q\bar{q}$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	
	$\tilde{g} \rightarrow t\bar{t}, \tilde{t}_1 \rightarrow b\bar{s}$	2 $e, \mu$ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV	
	Other	Scalar gluon pair, sgluon $\rightarrow q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV
		Scalar gluon pair, sgluon $\rightarrow t\bar{t}$	2 $e, \mu$ (SS)	1 b	Yes	14.3	sgluon 800 GeV
		WIMP interaction (D5, Dirac $\chi$ )	0	mono-jet	Yes	10.5	$\tilde{M}^{\text{scale}}$ 704 GeV

\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus  $1\sigma$  theoretical signal cross section uncertainty.

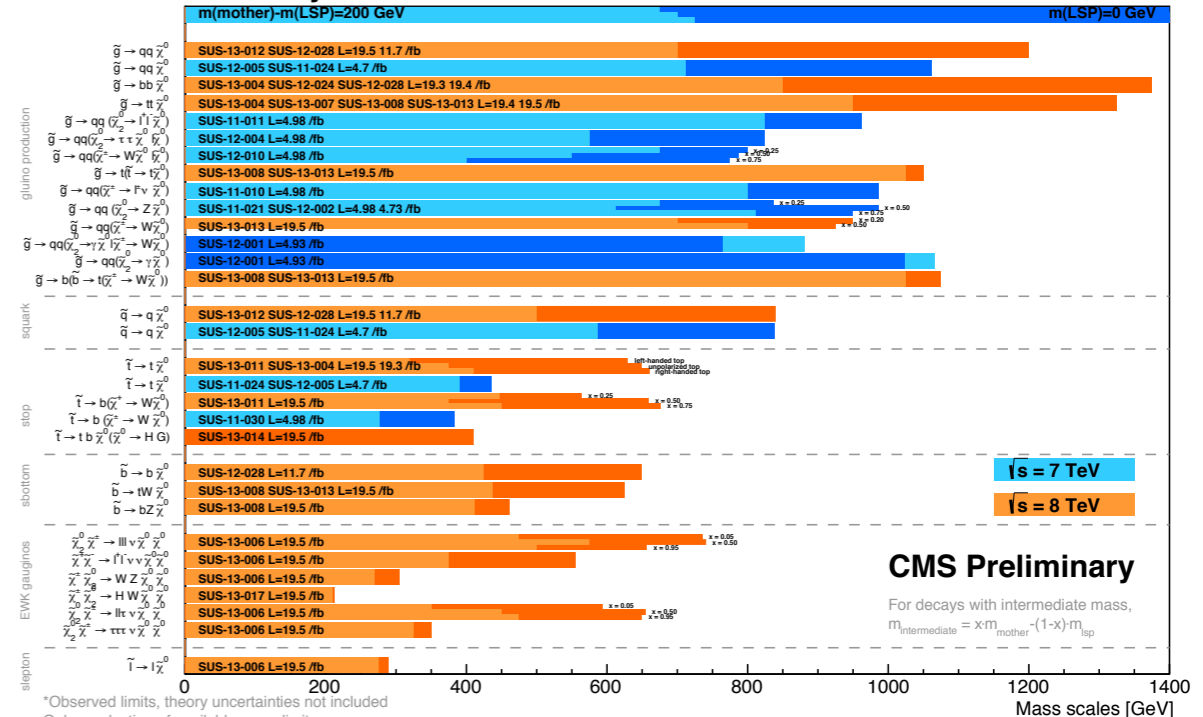
## ATLAS Exotics Searches\* - 95% CL Lower Limits (Status: May 2013)



\*Only a selection of the available mass limits on new states or phenomena is shown

# How do flavour measurements compare with direct searches at the LHC (e.g. in SUSY)?

## Summary of CMS SUSY Results\* in SMS framework SUSY 2013



\*Observed limits, theory uncertainties not included. Only a selection of available mass limits. Probe \*up to\* the quoted mass limit.

# Minimal Flavour Violation

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- $U(3)^3 \equiv U(3)_q \times U(3)_u \times U(3)_d$  broken by the SM Yukawa's

$$Y_u \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}), \quad Y_d \sim (\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}})$$

Chivukula, Georgi  
Hall, Randall  
D'Ambrosio *et al.*

- Leading order in the breaking param.s  $\neq y_t$ :  $Y_u Y_u^\dagger \sim I_3 = \text{diag}(0, 0, 1)$

➔ Quark bilinears:

$$\bar{q}_L I_3 \gamma_\mu q_L$$

$$\bar{q}_L I_3 Y_d \sigma_{\mu\nu} d_R$$

➔ Effective operators:

$\Delta F = 2$ :

$$c_{LL} \xi_{ij}^2 (\bar{d}_L^i \gamma_\mu d_L^j)^2$$

$$(\xi_{ij} \equiv V_{ti}^* V_{tj})$$

$\Delta F = 1$ :

$$c_{cc}^\alpha \xi_{ij} (\bar{d}_L^i \gamma_\mu d_L^j) \mathcal{O}_\mu^\alpha$$

$$c_{cb}^\beta e^{i\phi^\beta} \xi_{ij} m_j (\bar{d}_L^i \sigma_{\mu\nu} d_R^j) \mathcal{O}_{\mu\nu}^\beta$$

# Minimal $U(2)^3$

- $U(2)^3 \equiv U(2)_q \times U(2)_u \times U(2)_d$  broken by the spurions

$$\mathcal{V} \sim (\mathbf{2}, \mathbf{1}, \mathbf{1}), \quad \Delta_u \sim (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{1}), \quad \Delta_d \sim (\mathbf{2}, \mathbf{1}, \bar{\mathbf{2}})$$

$$q_L = (\mathbf{q}_L, q_L^3), \quad d_R = (\mathbf{d}_R, b_R), \quad u_R = (\mathbf{u}_R, t_R)$$

- At leading order in the breaking parameters: Barbieri *et al.* '11  
Barbieri, B, Sala, Straub '12

➔ Quark bilinears:

$$\bar{q}_L q_L$$

$$\bar{q}_L \mathcal{V} q_L^3$$

$$\bar{q}_L^3 q_L^3$$

$$\bar{q}_L \Delta_d d_R$$

$$\bar{q}_L \mathcal{V} b_R$$

$$\bar{q}_L^3 b_R$$

➔ Effective operators:

$$c_{cb}^\beta e^{i\phi^\beta} \xi_{ij} m_j (\bar{d}_L^i \sigma_{\mu\nu} d_R^j) \mathcal{O}_{\mu\nu}^\beta$$

$$c_{LL}^K \xi_{ds}^2 (\bar{d}_L \gamma_\mu s_L)^2$$

$$c_{cc}^{K,\alpha} \xi_{ds} (\bar{d}_L \gamma_\mu s_L) \mathcal{O}_\mu^\alpha$$

$$c_{LL}^B e^{i\phi^B} \xi_{ib}^2 (\bar{d}_L^i \gamma_\mu b_L)^2$$

$$c_{cc}^{B,\alpha} e^{i\phi^\alpha} \xi_{ib} (\bar{d}_L^i \gamma_\mu b_L) \mathcal{O}_\mu^\alpha$$

# Minimal $U(2)^3$

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- *Weakly* broken: a good symmetry of the SM Yukawa sector

$$m_u \sim \begin{pmatrix} \cdot & \cdot & \text{Large Red Circle} \end{pmatrix}$$
$$m_d \sim \begin{pmatrix} \cdot & \cdot & \text{Small Green Circle} \end{pmatrix}$$
$$V_{\text{CKM}} \sim \begin{pmatrix} \text{Large Purple Circle} & \text{Small Purple Circle} & \text{Very Small Purple Circle} \\ \text{Small Purple Circle} & \text{Large Purple Circle} & \text{Very Small Purple Circle} \\ \text{Very Small Purple Circle} & \text{Very Small Purple Circle} & \text{Large Purple Circle} \end{pmatrix}$$

- Potentially more observable effects w.r.t. MFV
- Naturally arises from a minimum principle in the dynamical breaking of  $U(3)^3$ 

*Alonso et al. '13*  
(see talk by B. Gavela)
- The only continuous symmetry – along with  $U(3)^3$  – which gives a near-CKM structure of flavour violation, without further assumptions on the underlying model

# Are there other pictures naturally close to CKM?

---

- $U(2)_q \times U(2)_u \times U(3)_d$  , broken by  $\Delta_u \sim (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{1})$ ,  $\Delta_d \sim (\mathbf{2}, \mathbf{1}, \bar{\mathbf{3}})$ , and  $\tilde{\Delta}_d \sim (\mathbf{1}, \mathbf{1}, \bar{\mathbf{3}})$  , gives rise to MFV (*i.e.* has the same effective operators)



# Are there other pictures naturally close to CKM?

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- $U(2)_q \times U(2)_u \times U(3)_d$  gives rise to MFV
- Reducing the  $U(2)^3$  group:
  - ▶ Distinction between left- and right-handed fermions is essential (*e.g.*  $U(2)_{q+u+d}$  has large non-CKM LR currents);
  - ▶  $U(2)_L \times U(2)_R$  broken by  $\Delta_u \sim (\mathbf{2}, \mathbf{2})$ ,  $\Delta_d \sim (\mathbf{2}, \mathbf{2})$ ,  $\mathcal{V} \sim (\mathbf{2}, \mathbf{1})$ , generates non-CKM chirality breaking op.s in  $\Delta C = 1$  and  $\Delta S = 1$ : distinction between  $u$  and  $d$  quarks is needed;
  - ▶  $U(2)_L \times SU(2)_R \times U(1)_u \times U(1)_d$ , broken by  $\mathcal{V} \sim (\mathbf{2}, \mathbf{1})_{(0,0)}$ ,  $\Delta_u \sim (\mathbf{2}, \mathbf{2})_{(-1,0)}$ ,  $\Delta_d \sim (\mathbf{2}, \mathbf{2})_{(0,-1)}$ , is equivalent to  $U(2)^3$  at leading order in the breaking parameters

# Are there other pictures naturally close to CKM?

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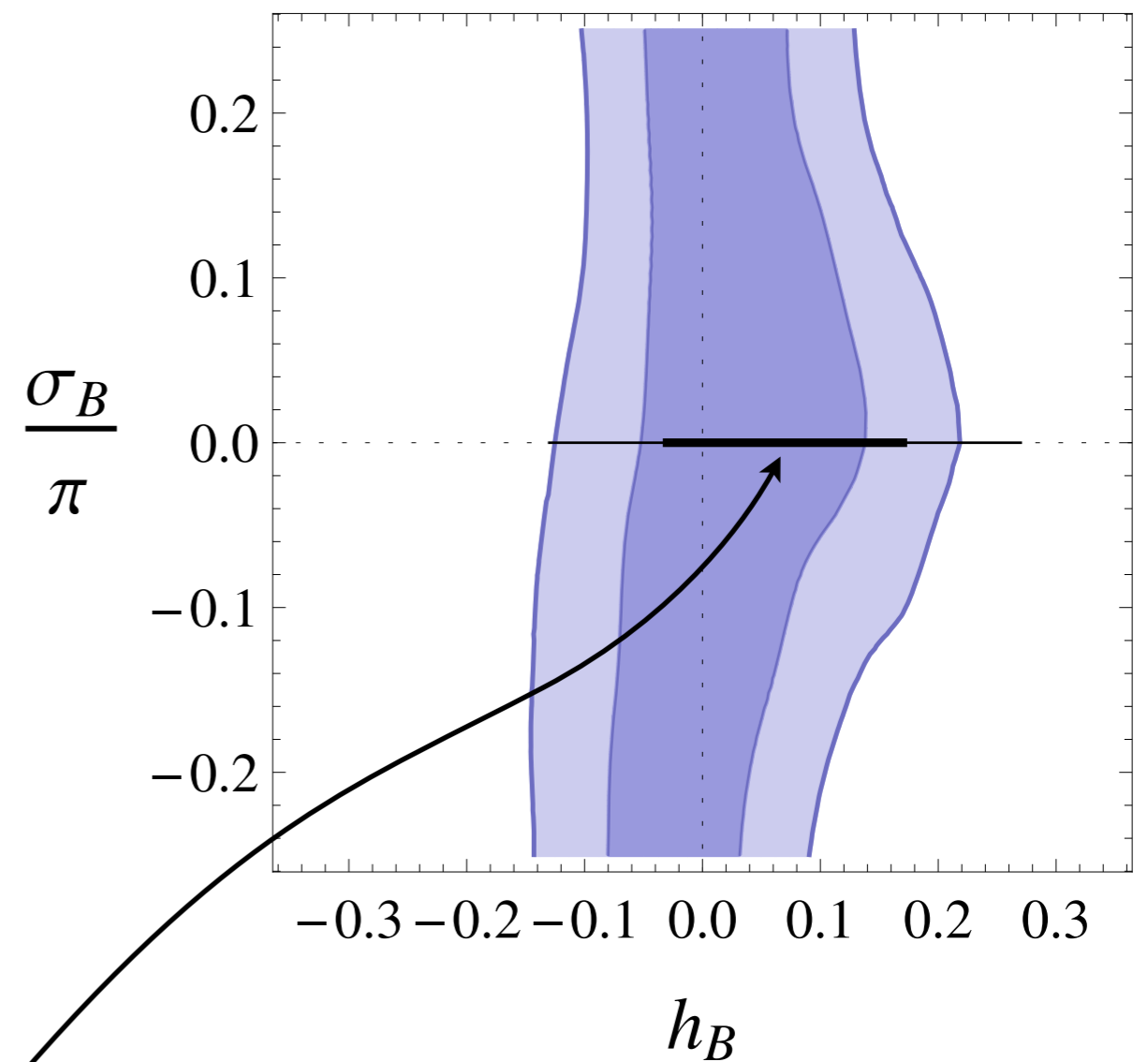
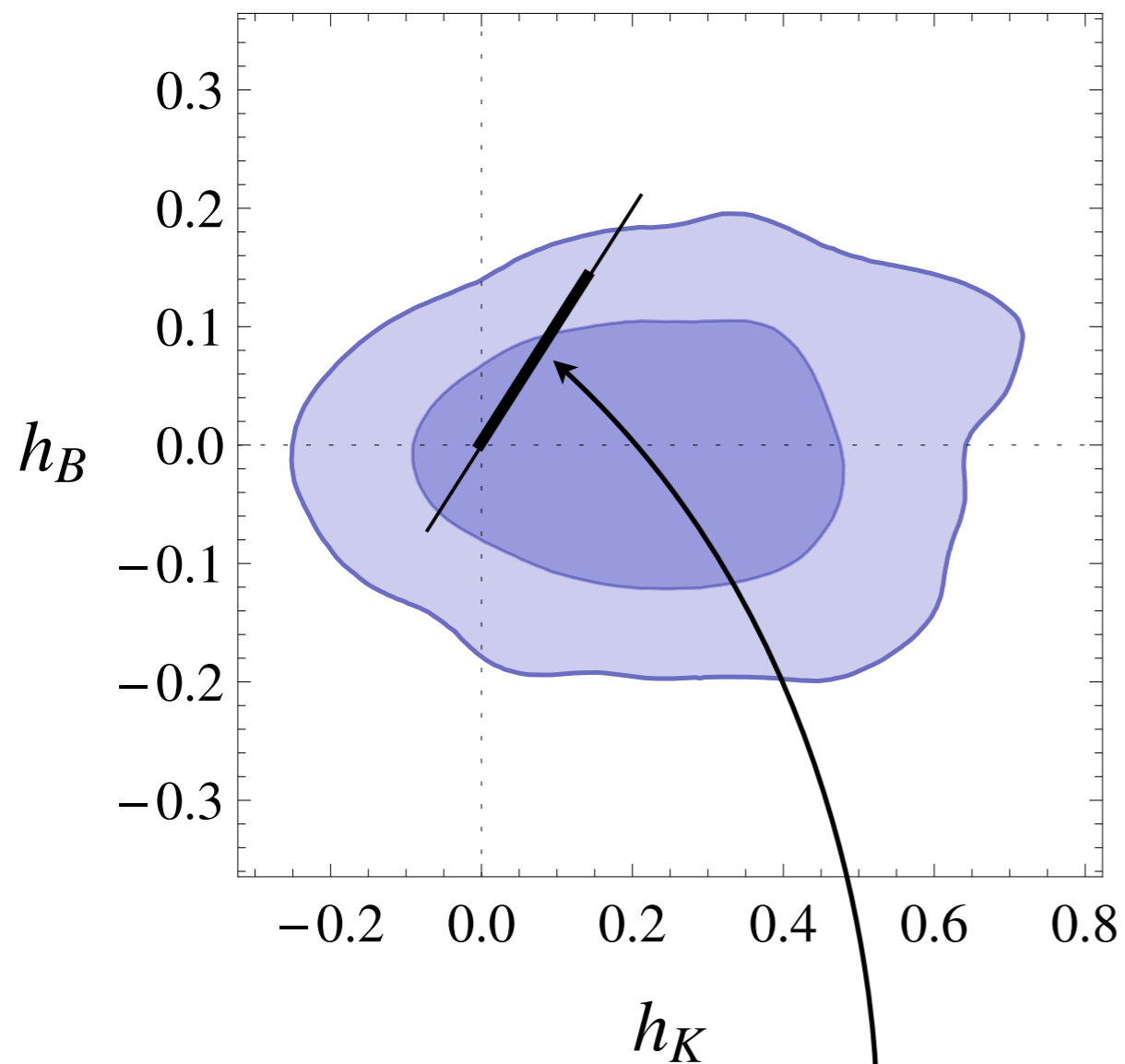
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  - ▶ Distinction between  $u$  and  $d$  quarks is needed;
  - ▶  $U(2)_L \times SU(2)_R \times U(1)_u \times U(1)_d$  is equivalent to  $U(2)^3$
- Alignment: e.g.  $U(3)_d \times U(1)_{(q+u)_1} \times U(1)_{(q+u)_2} \times U(1)_{(q+u)_3}$   
broken by  $\Delta_1 \sim \mathbf{3}_{(1,0,0)}$ ,  $\Delta_2 \sim \mathbf{3}_{(0,1,0)}$ ,  $\Delta_3 \sim \mathbf{3}_{(0,0,1)}$  Barbieri *et al.* '10  
gives rise, in the physical mass basis, to the bilinear
$$\left( (c_3 - c_1)\xi_{ij} + (c_2 - c_1)V_{ci}^*V_{cj} \right) (\bar{d}_L^i \gamma_\mu d_L^j)$$
  
Non CKM effects unless  $c_2 \sim c_1$ : this can work in specific contexts.

# Fit of $\Delta F = 2$ observables

$$\Delta M_{s,d} = \Delta M_{s,d}^{\text{SM}} |1 + h_B e^{2i\sigma_B}|$$

$$S_{\psi K_S} = \sin(2\beta + \arg(1 + h_B e^{2i\sigma_B}))$$

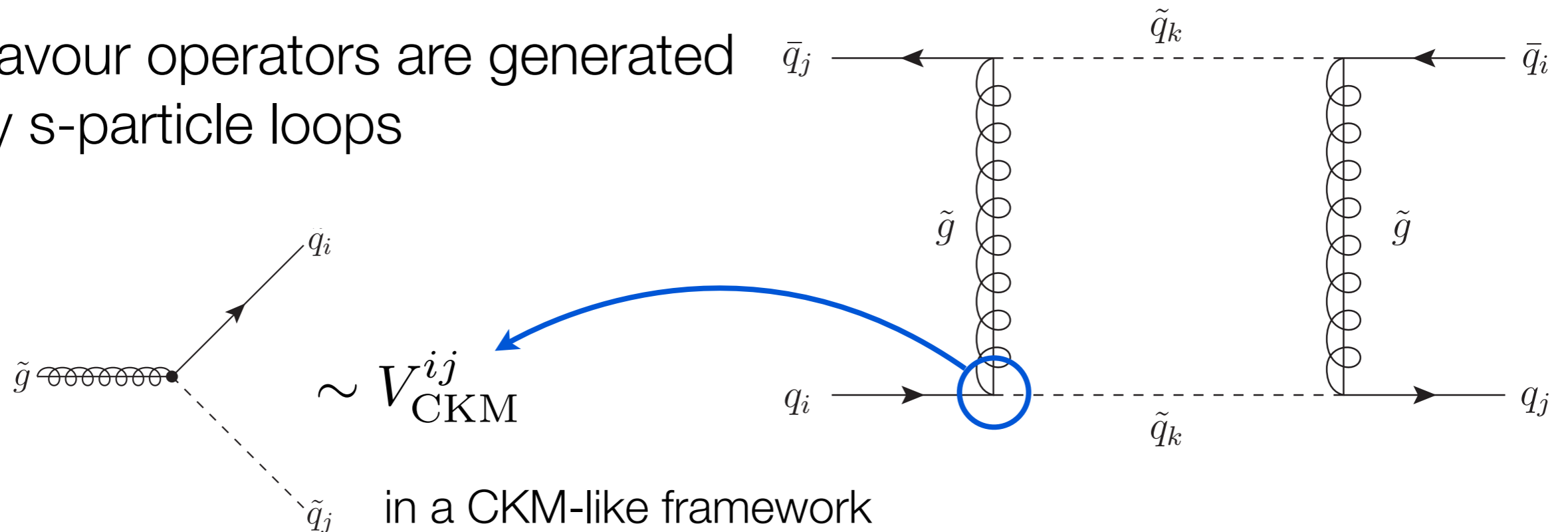
$$\epsilon_K = \epsilon_K^{\text{SM}} + h_K \epsilon_K^{\text{SM},tt}$$



$h_B = h_K, \sigma_B = 0$  in MFV

# Flavour and supersymmetry

- Flavour operators are generated by s-particle loops



- “Natural” spectrum with light stops and gluino, and heavy squarks of 1st & 2nd generation: compatible with  $U(2)^3$
- **What is the impact of direct bounds on s-particle masses from the LHC?**

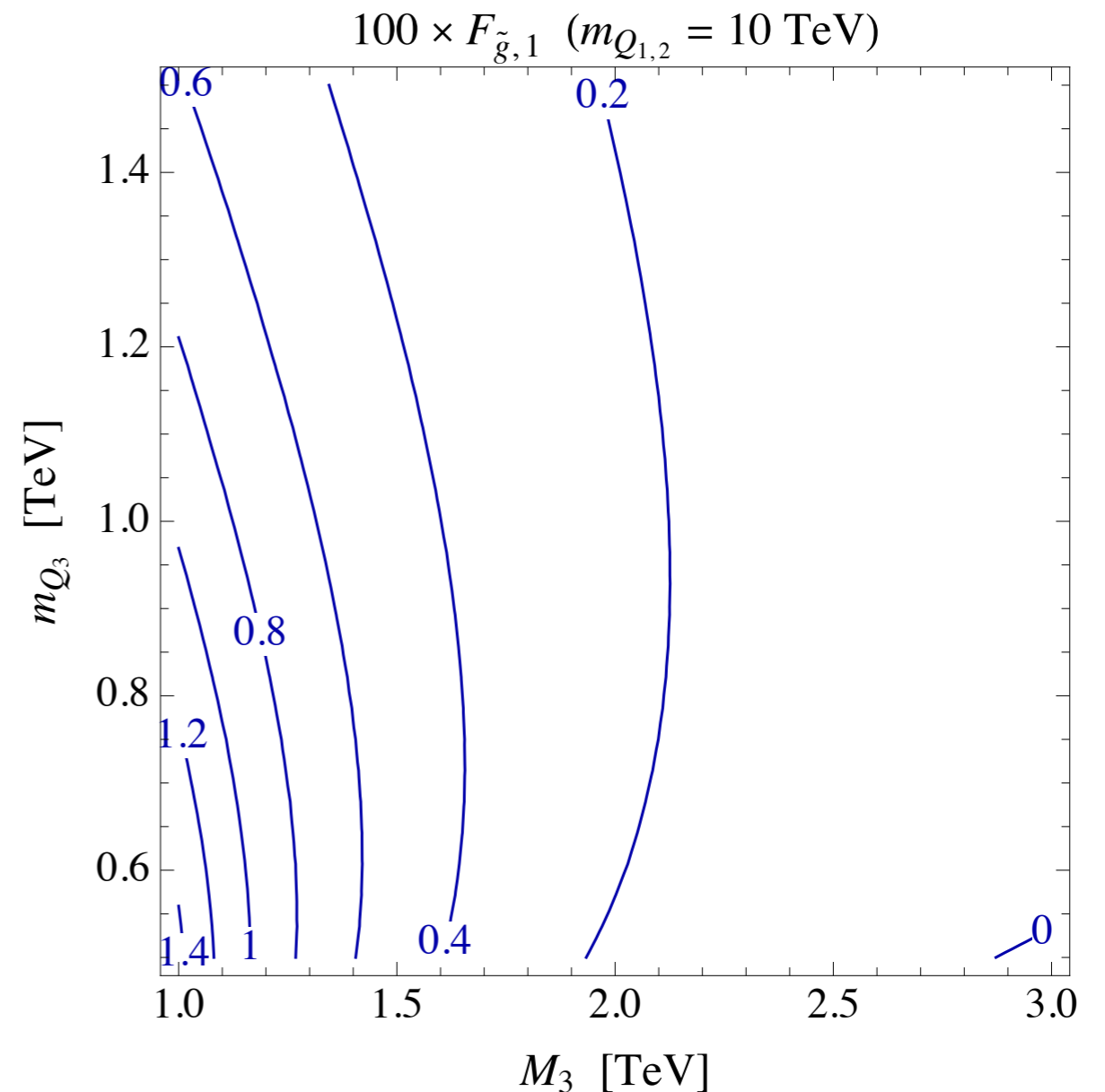
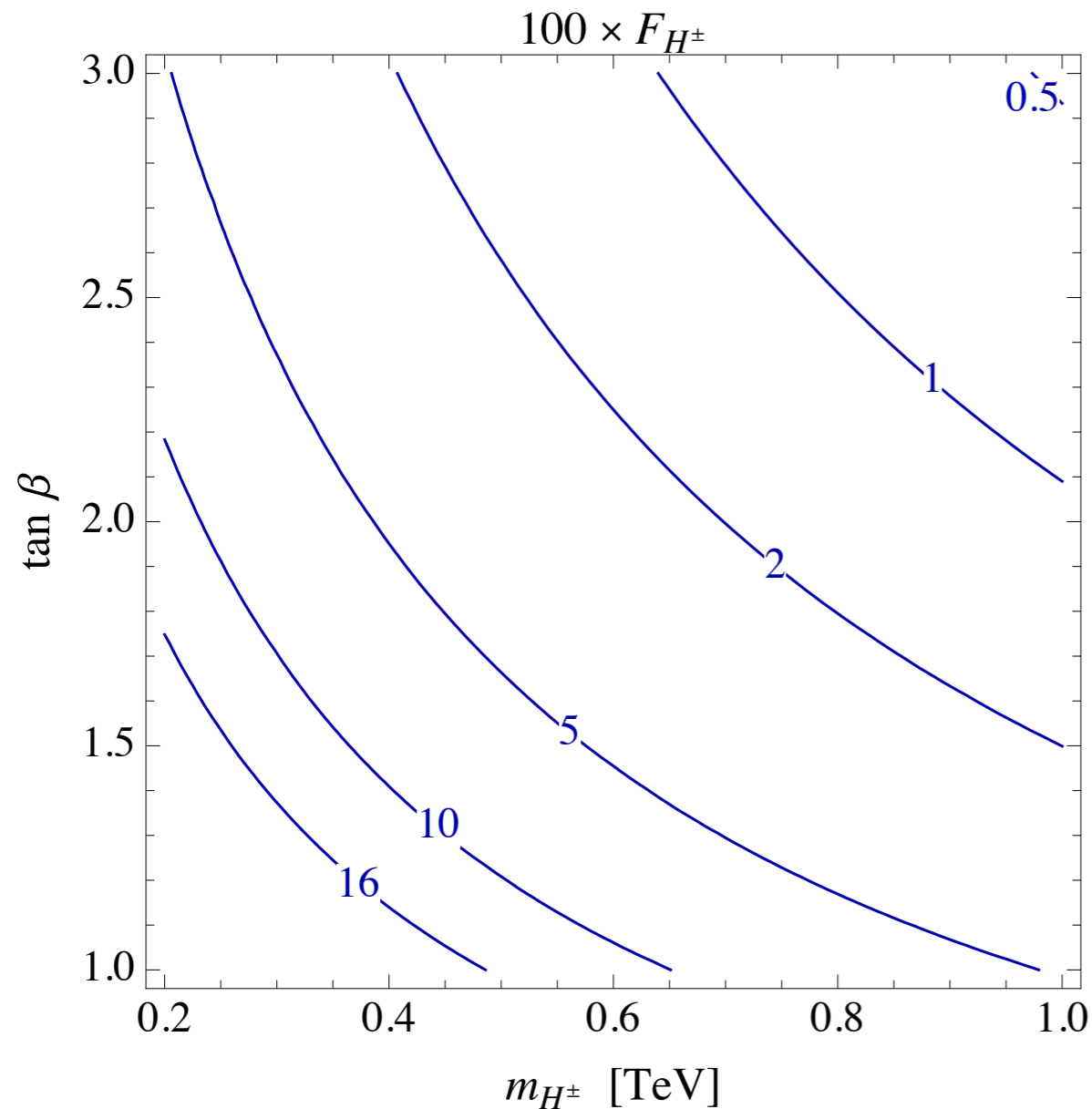
# SUSY contributions to meson mixings

$$h_K \simeq F_{H^\pm} + |\xi_L|^4 F_{\tilde{g},1} + |\xi_L|^2 \delta F_{\tilde{g},2} + |\delta|^2 F_{\tilde{g},3}$$

$$h_B \simeq F_{H^\pm} + |\xi_L|^2 e^{2i\gamma_L} F_{\tilde{g},1} + |\xi_L \xi_R| e^{i(\gamma_L + \gamma_R)} F_{\tilde{g},4} \quad (\text{only for } B_s)$$

second-order effects  
(gluino only)

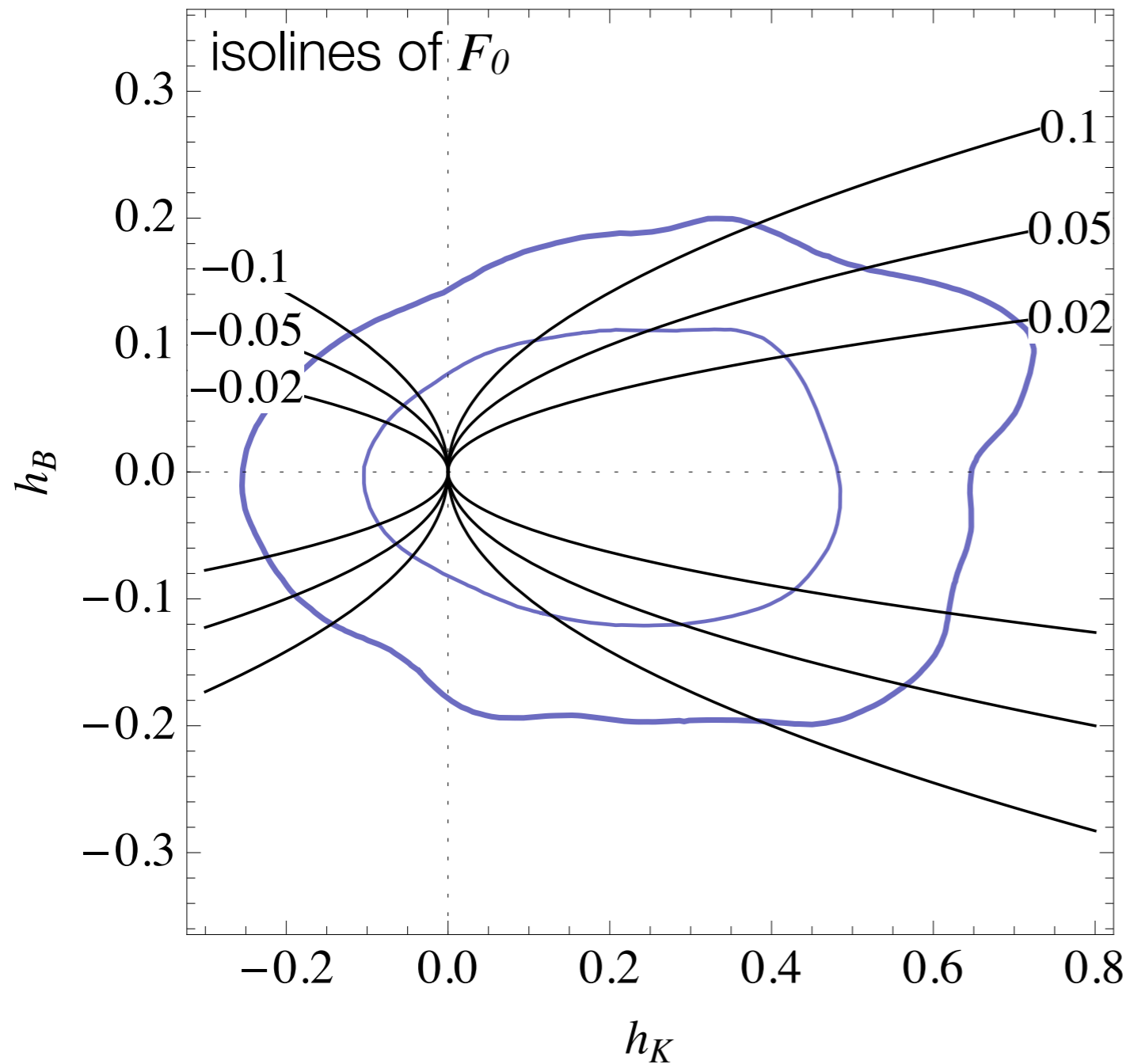
$\xi_L, \xi_R, \delta$  are O(1) parameters



# SUSY and $U(2)^3 / U(3)^3$

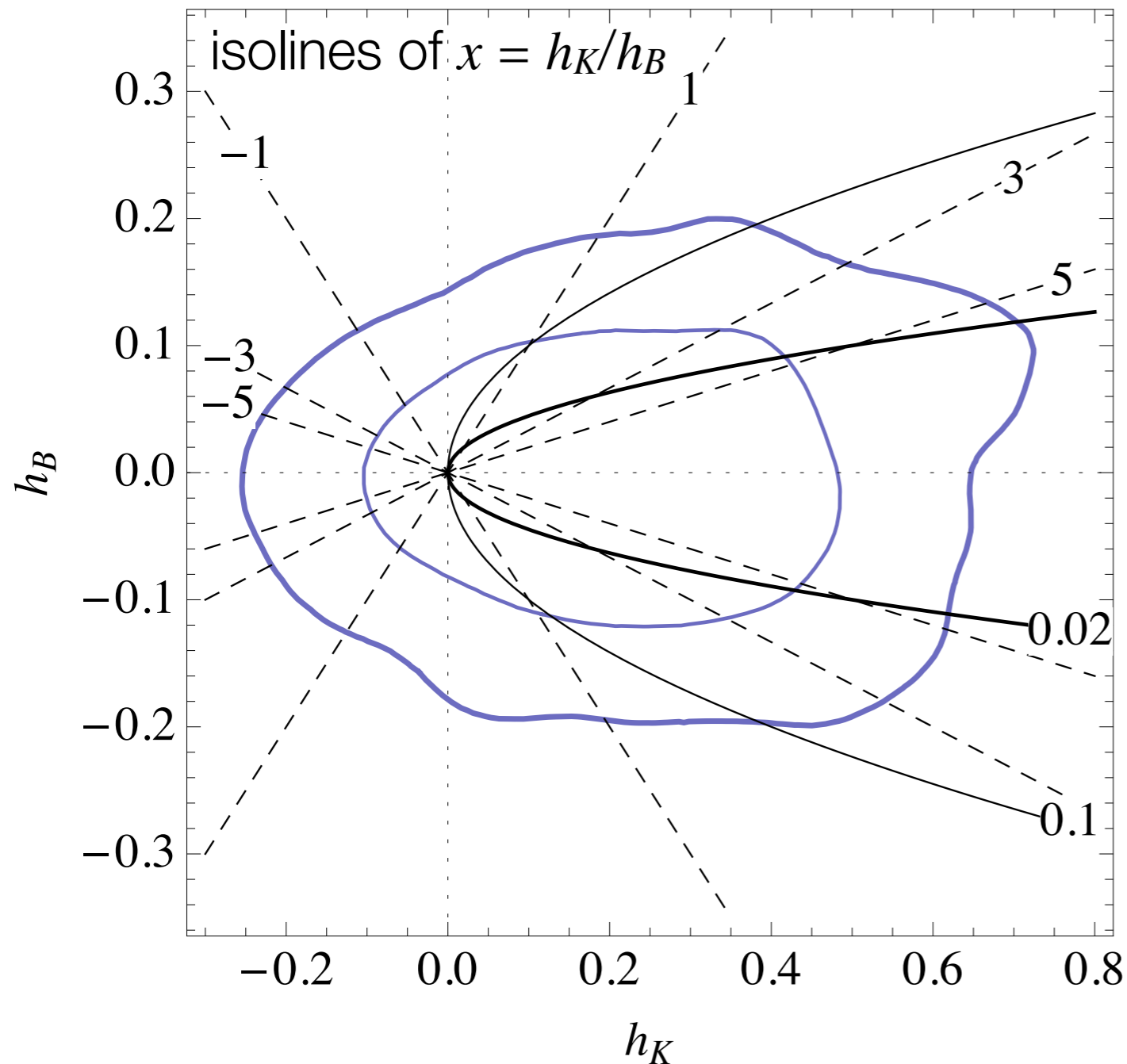
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$$[h_K]_i \approx x^2 F_{0,i}, \quad [h_B]_i \approx x F_{0,i} \quad x = 1 \text{ in MFV}$$



# SUSY and $U(2)^3 / U(3)^3$

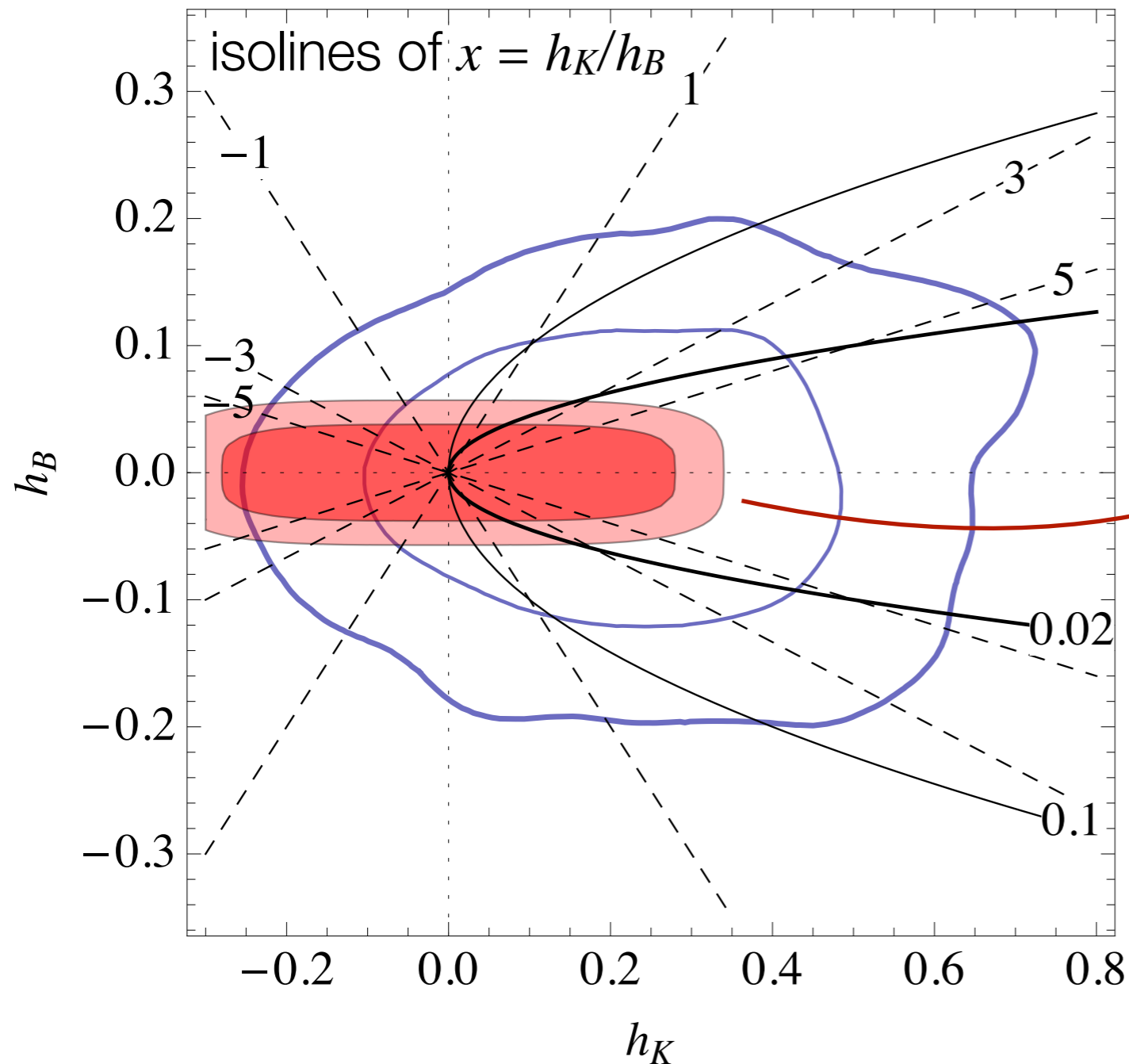
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observable deviations  
from the SM  
for large values of  $x$

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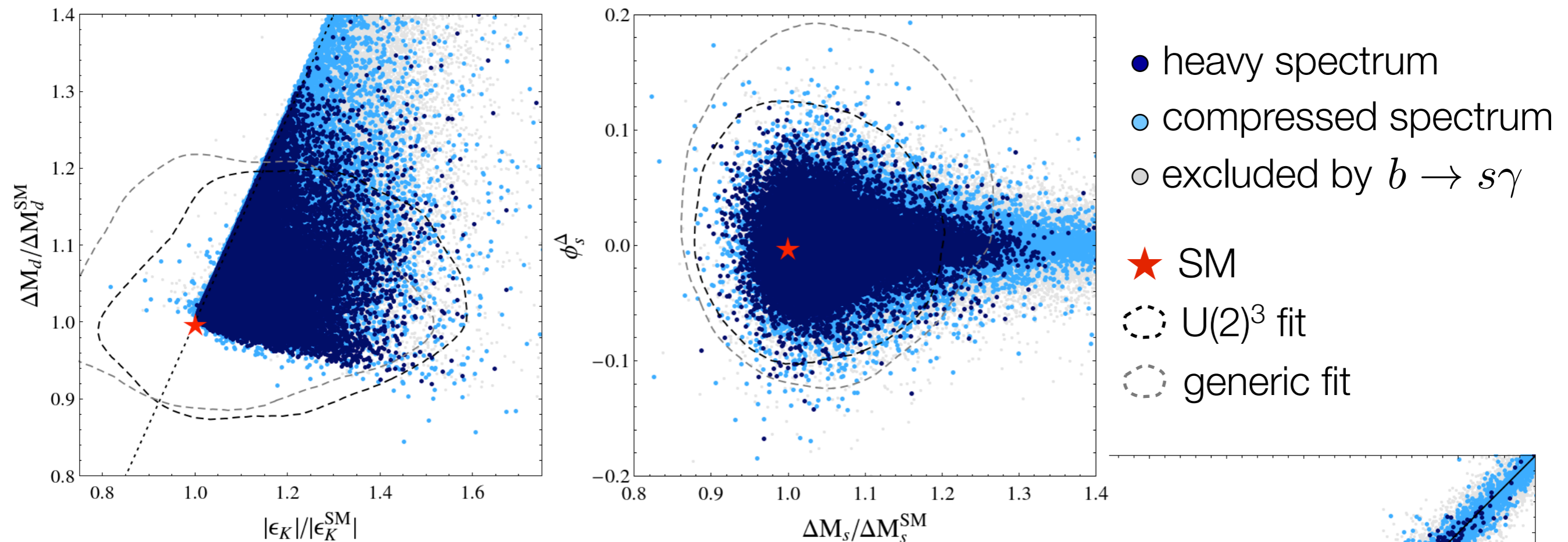


50  $\text{fb}^{-1}$  LHCb  
50  $\text{ab}^{-1}$  Belle II  
(Charles *et al.* 2013)

observable deviations  
from the SM  
for large values of  $x$



# Numerical analysis of meson mixing



- Analysis with **SUSY\_FLAVOR** Crivellin, Rosiek

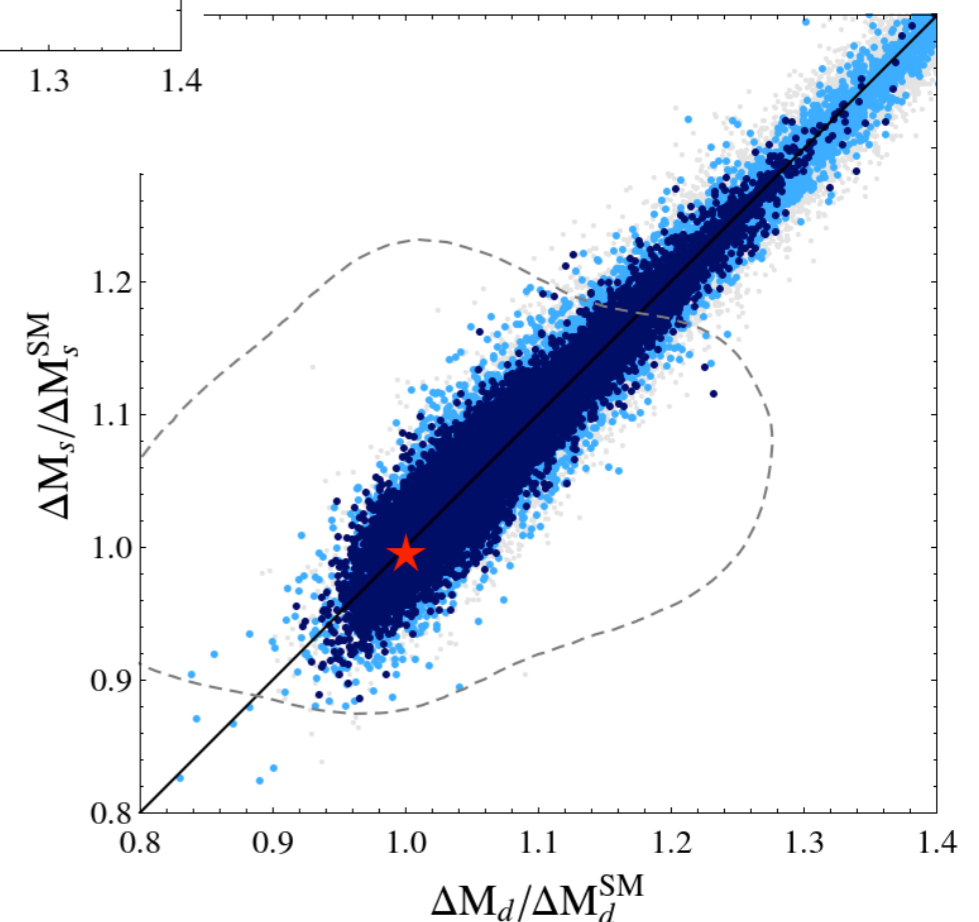
- ATLAS and CMS mass bounds:

$$m_{\tilde{g}} \gtrsim 1.4 \text{ TeV} \quad m_{\tilde{t}} \gtrsim 700 \text{ GeV}$$

- Scan ranges:

$$\tilde{m}_3 \in [0.1, 1.5] \text{ TeV}, \quad m_{\tilde{g}} \in [0.1, 3] \text{ TeV},$$

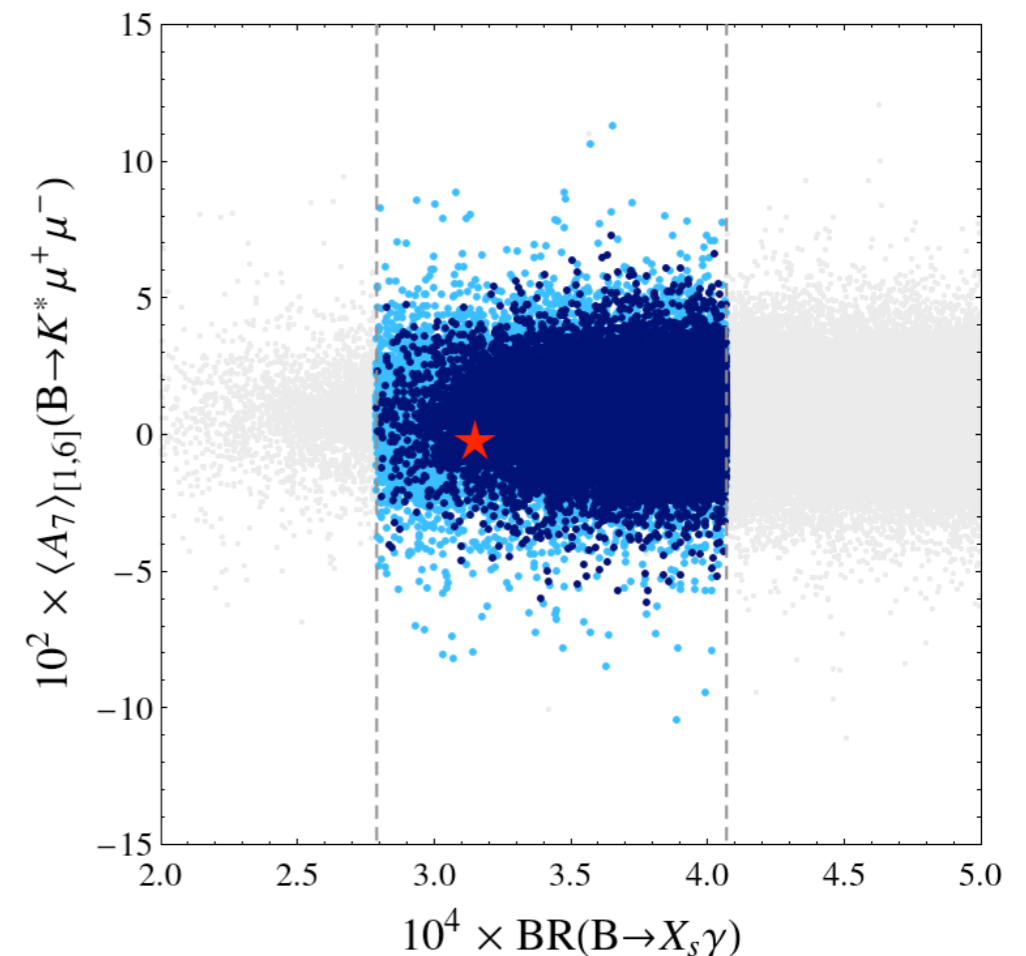
$$m_{\tilde{\chi}} \in [0.1, 0.8] \text{ TeV}, \quad \tan \beta \in [1, 5]$$



# Rare B decays

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- Main  $\Delta B = 1$  effects in  $U(2)^3$  arise from (chromo-)magnetic dipole operators
- MFV-like Higgsino and charged Higgs contributions, constrained by  $B \rightarrow X_s \gamma$
- Gluino (and Wino) contributions, contribute to the CP asymmetries: angular asymmetry  $A_7$  in  $B \rightarrow K^* \mu^+ \mu^-$  at low  $\mu\mu$  invariant mass  $q^2$
- $B_{d,s} \rightarrow \mu^+ \mu^-$  get  $\tan \beta$  enhanced contributions from scalar operators (not relevant for moderate  $\tan \beta$ )



# Conclusions

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- Precision measurements in the flavour sector require a near-CKM picture of flavour-changing interactions.
- Two possible scenarios, based on symmetries only:  $U(3)^3$ ,  $U(2)^3$
- Updated fit of meson mixings in  $U(2)^3$  (improved measurement of CP asymmetries in B decays and new lattice results)
- SUSY: direct bounds on s-particle masses are becoming competitive with flavour constraints
- Still room for observable deviations from SM in meson mixings, if s-particles in the reach of LHC14



# Electric dipole moment of the electron

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- New bound:  $|d_e| < 8.7 \times 10^{-29} e \text{ cm}$

- One loop chargino-sneutrino contribution:

$$m_{\tilde{\nu}_1} > 17 \text{ TeV} \times (\sin \phi_\mu \tan \beta)^{\frac{1}{2}}$$

- Two loop Barr-Zee type contributions

