Flavour symmetries after the first LHC phase

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

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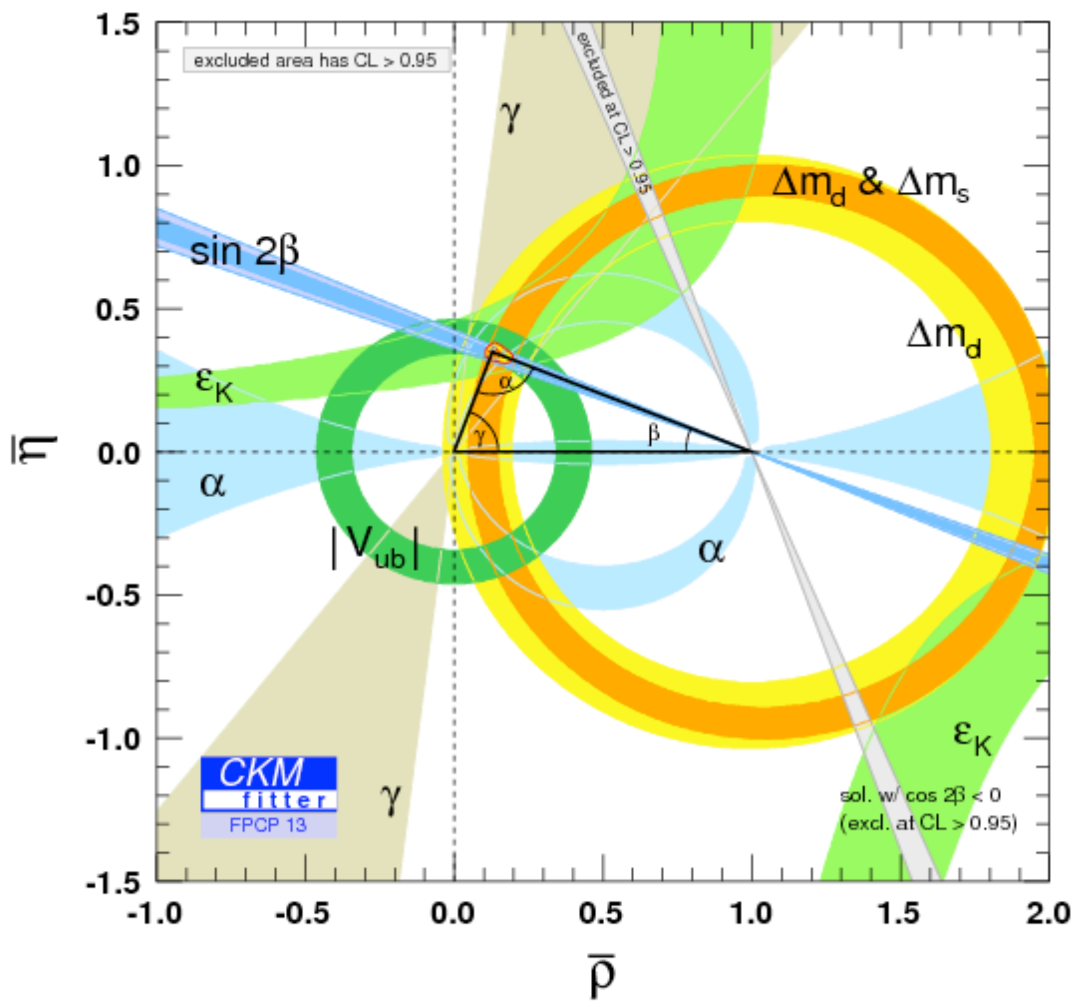
The CKM picture of flavour



Remarkable accuracy (~ 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 $10^{4\div5}$ 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 $(\xi_{ij} = V_{ti}^* V_{tj})$

$$\xi_{ij}^2 (\bar{d}_L^i \gamma_\mu d_L^j)^2 \qquad \xi_{ij} (\bar{d}_L^i \gamma_\mu d_L^j) \mathcal{O}_\alpha^\mu \qquad \xi_{ij} m_j (\bar{d}_L^i \sigma_{\mu\nu} d_R^j) \mathcal{O}_\beta^{\mu\nu}$$

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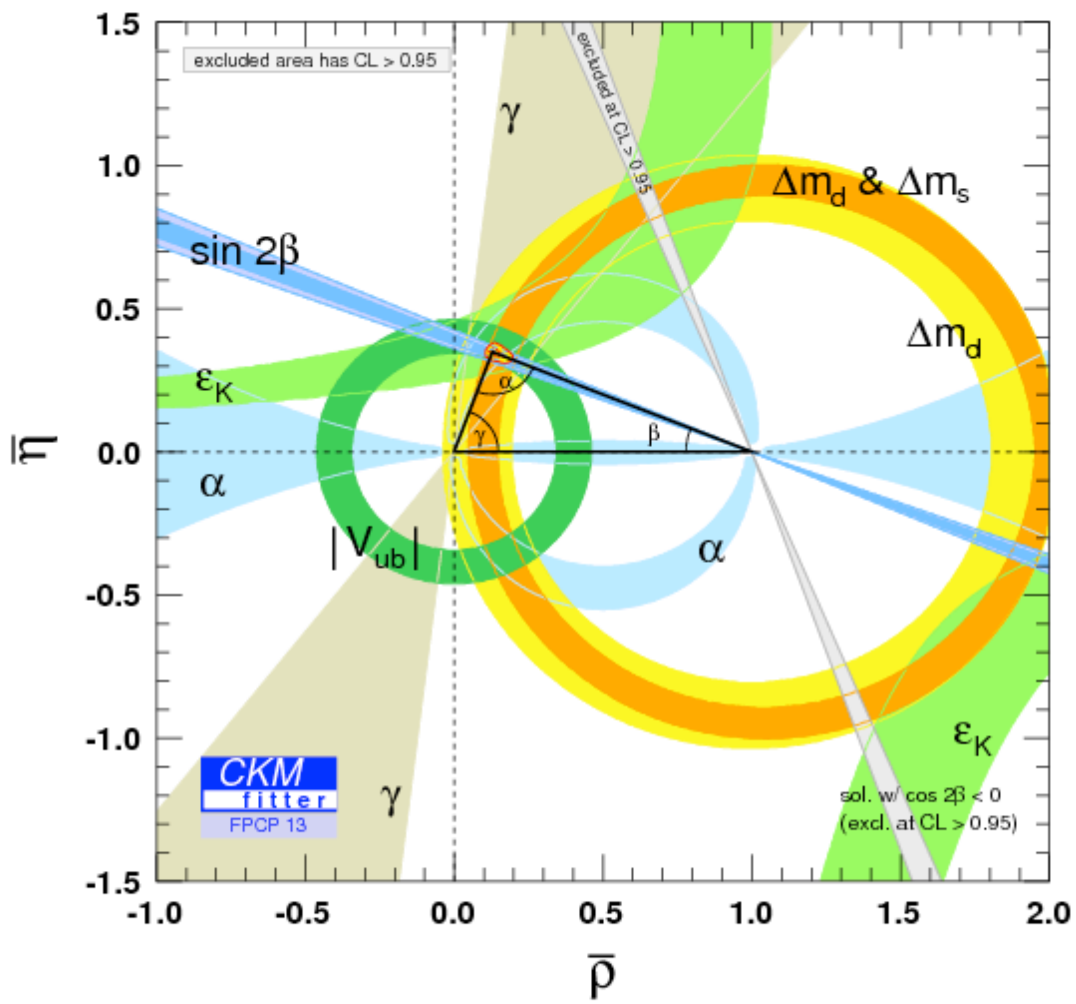

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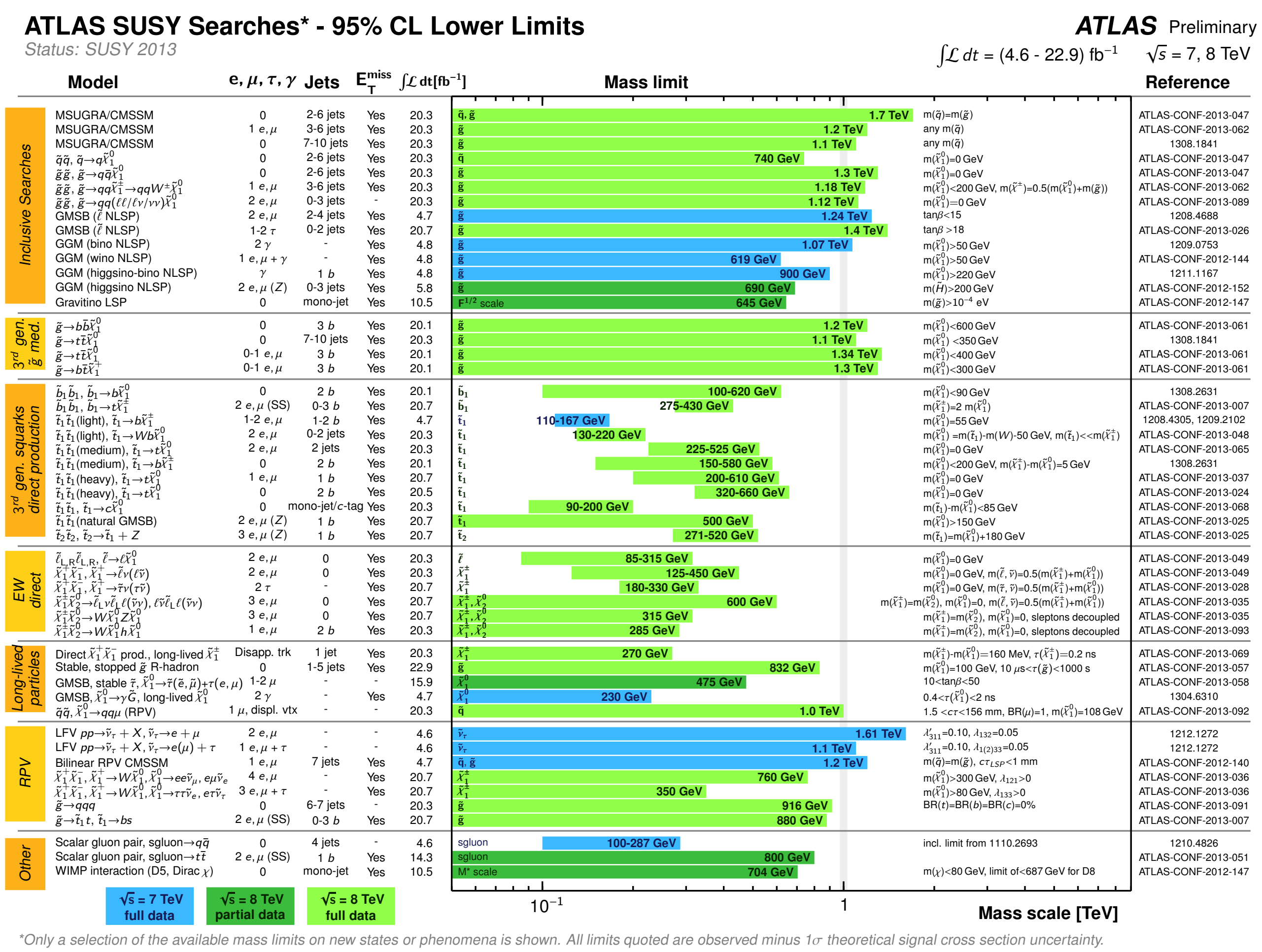
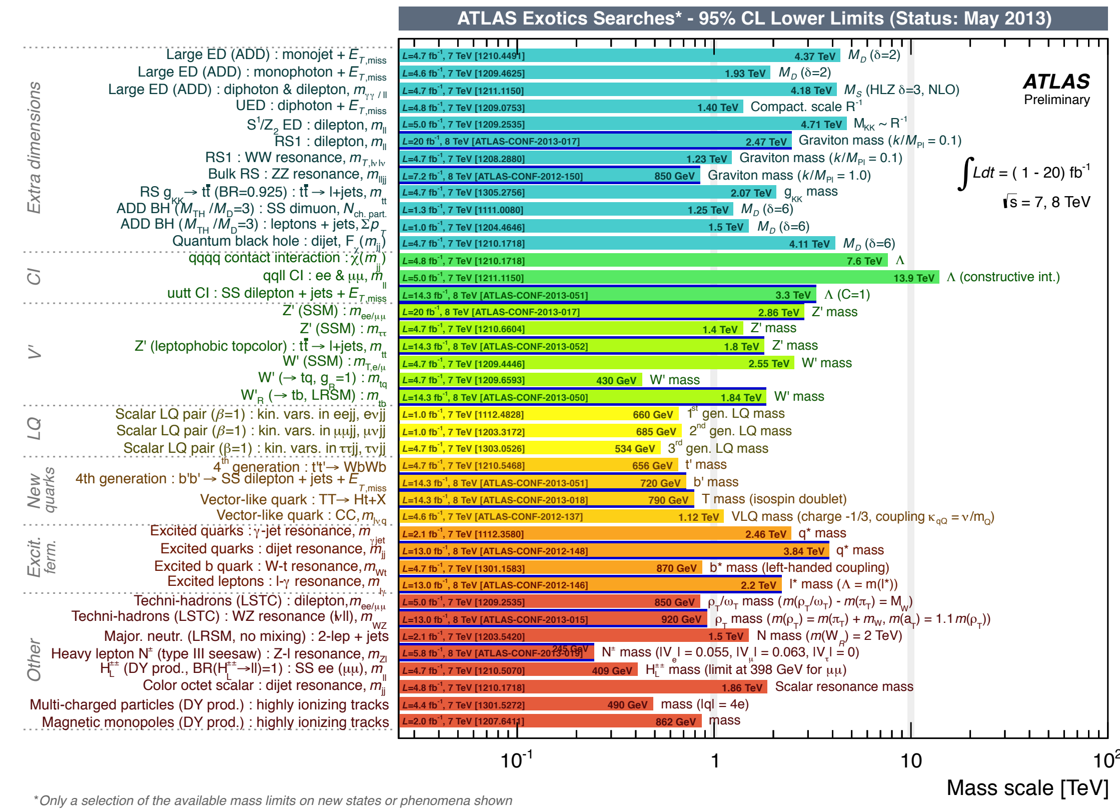
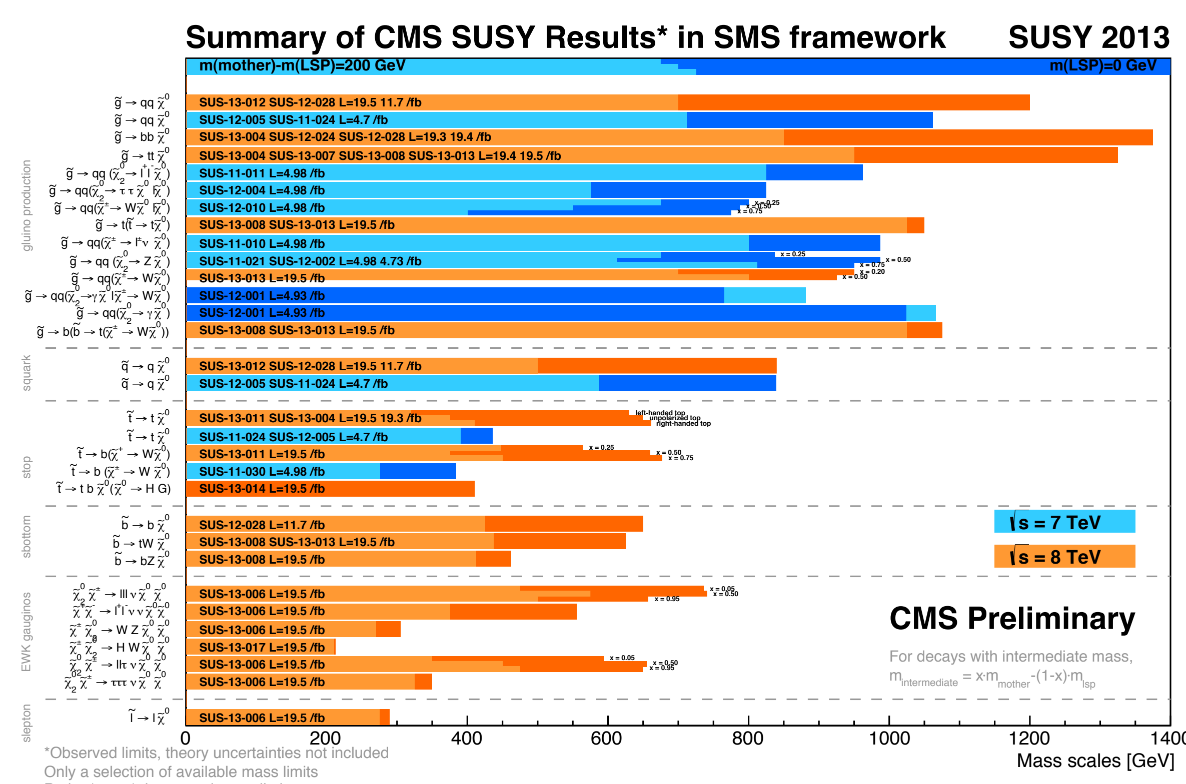
$$\xi^2_{ij} (\bar{d}^i_L \gamma_\mu d^j_L)^2 \qquad \xi_{ij} (\bar{d}^i_L \gamma_\mu d^j_L) \mathcal{O}^\mu_\alpha \qquad \xi_{ij} m_j (\bar{d}^i_L \sigma_{\mu\nu} d^j_R) \mathcal{O}^{\mu\nu}_\beta$$

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

Direct searches







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

Minimal Flavour Violation

- $U(3)^3 \equiv U(3)_q \times U(3)_u \times U(3)_d$ 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.*

- At leading order in the breaking parameters $\neq y_t$:

➡ Quark bilinears: $\bar{q}_L \, I_3 \gamma_\mu \, q_L$ $\quad$ $\bar{q}_L \, I_3 Y_d \sigma_{\mu\nu} \, d_R$

$$Y_u Y_u^\dagger \sim I_3 = \mathrm{diag}(0,0,1)$$

➡ Effective operators:

ΔF = 2: $c_{LL} \xi_{ij}^2 (\bar{d}_L^i \gamma_\mu d_L^j)^2$ $\quad$ $(\xi_{ij} \equiv V_{ti}^* V_{tj})$

ΔF = 1: $c_{\mathrm{cc}}^\alpha \xi_{ij} (\bar{d}_L^i \gamma_\mu d_L^j) \mathcal{O}_\mu^\alpha$ $\quad$ $c_{\mathrm{cb}}^\beta e^{i\phi^\beta} \xi_{ij} m_j (\bar{d}_L^i \sigma_{\mu\nu} d_R^j) \mathcal{O}_{\mu\nu}^\beta$

Minimal U(2)^3

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

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

$$q_L = (\boldsymbol{q_L}, q_L^3), \qquad d_R = (\boldsymbol{d_R}, b_R), \qquad u_R = (\boldsymbol{u_R}, t_R)$$

- At leading order in the breaking parameters:

Barbieri *et al.* '11
Barbieri, B, Sala, Straub '12

➡ Quark bilinears:

$$\bar{\boldsymbol{q}}_{\boldsymbol{L}}\boldsymbol{q_L} \qquad \bar{\boldsymbol{q}}_{\boldsymbol{L}}\,\mathcal{V}\,q_L^3 \qquad \bar{q}_L^3 q_L^3$$

$$\bar{\boldsymbol{q}}_{\boldsymbol{L}}\,\Delta_d\,\boldsymbol{d_R} \qquad \bar{\boldsymbol{q}}_{\boldsymbol{L}}\,\mathcal{V}\,b_R \qquad \bar{q}_L^3 b_R$$

➡ Effective operators:

$$c^{\beta}_{\rm cb} e^{i\phi^{\beta}} \xi_{ij} m_j (\bar{d}^i_L \sigma_{\mu\nu} d^j_R) \mathcal{O}^{\beta}_{\mu\nu}$$

$$c^K_{LL}\xi^2_{ds}(\bar{d}_L\gamma_\mu s_L)^2 \qquad c^{K,\alpha}_{\rm cc}\xi_{ds}(\bar{d}_L\gamma_\mu s_L)\mathcal{O}^{\alpha}_{\mu}$$

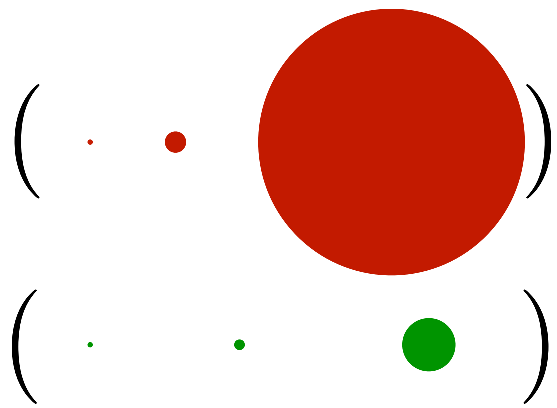
$$c^B_{LL}e^{i\phi_B}\xi^2_{ib}(\bar{d}^i_L\gamma_\mu b_L)^2 \qquad c^{B,\alpha}_{\rm cc}e^{i\phi^{\alpha}}\xi_{ib}(\bar{d}^i_L\gamma_\mu b_L)\mathcal{O}^{\alpha}_{\mu}$$

Minimal U(2)^3

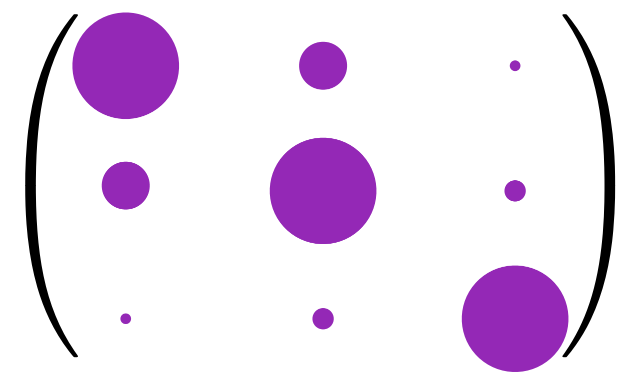
- *Weakly* broken: a good symmetry of the SM Yukawa sector

$m_u \sim$

$m_d \sim$



$V_{\mathrm{CKM}} \sim$



- 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

- The only continuous symmetry – along with U(3)^3 – which gives a near-CKM structure of flavour violation, <u>if no further assumptions on the underlying model</u>

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?

- $U(2)_q \times U(2)_u \times U(3)_d$ 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 ΔC = 1 and ΔS = 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?

- $U(2)_q \times U(2)_u \times U(3)_d$ gives rise to MFV
- Reducing the $U(2)^3$ group:
  - Distinction between left- and right-handed fermions is essential
  - 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

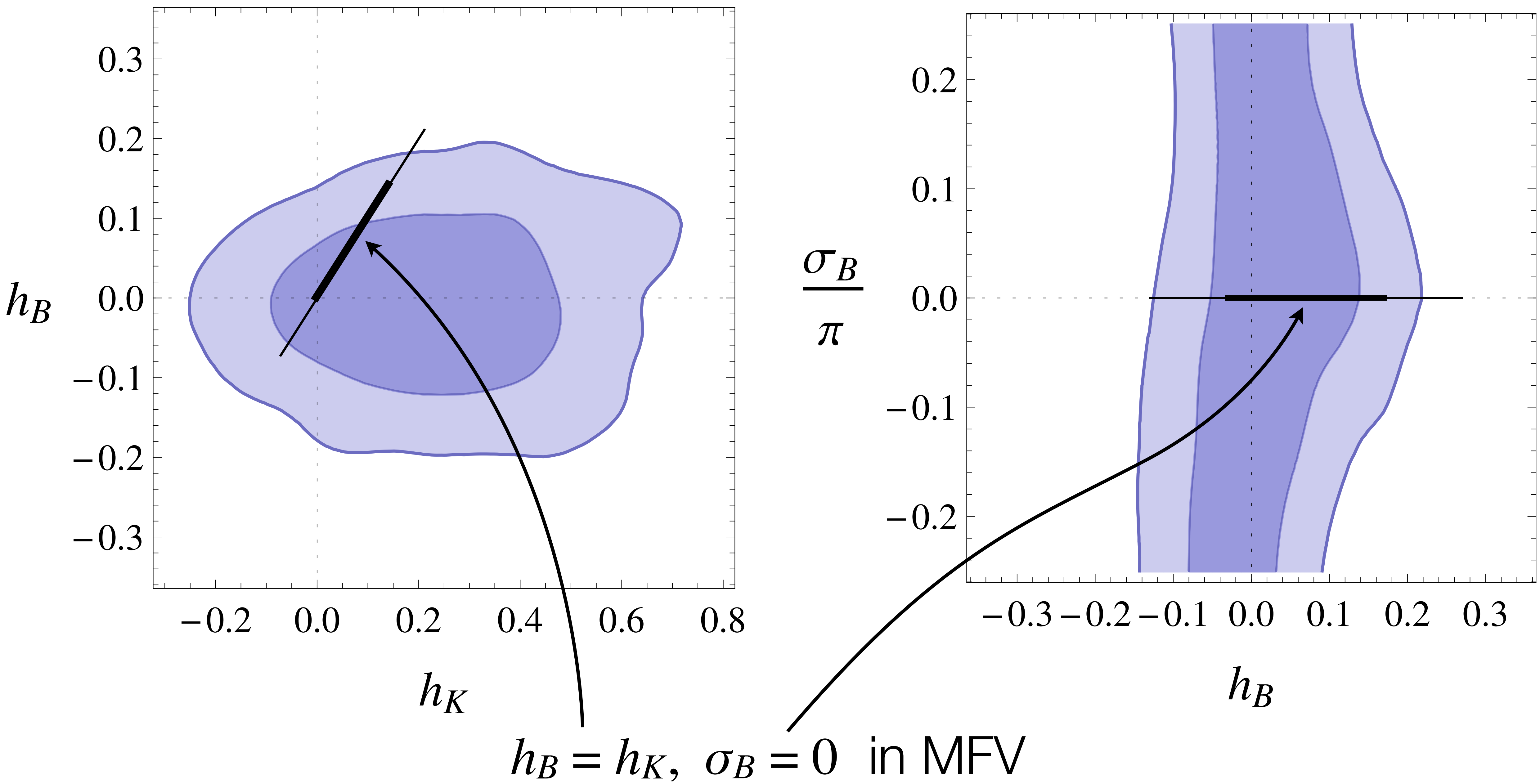
gives rise to the bilinear $\Big((c_3 - c_1)\xi_{ij} + (c_2 - c_1)V^*_{ci}V_{cj}\Big)(\bar{d}^i_L \gamma_\mu d^j_L)$

Non CKM effects unless $c_2 \sim c_1$: this can work in specific contexts.

Fit of ΔF = 2 observables

$$\Delta M_{s,d} = \Delta M_{s,d}^{\rm SM} \left|1 + h_B e^{2i\sigma_B}\right| \qquad \epsilon_K = \epsilon_K^{\rm SM} + h_K \epsilon_K^{{\rm SM},tt}$$

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



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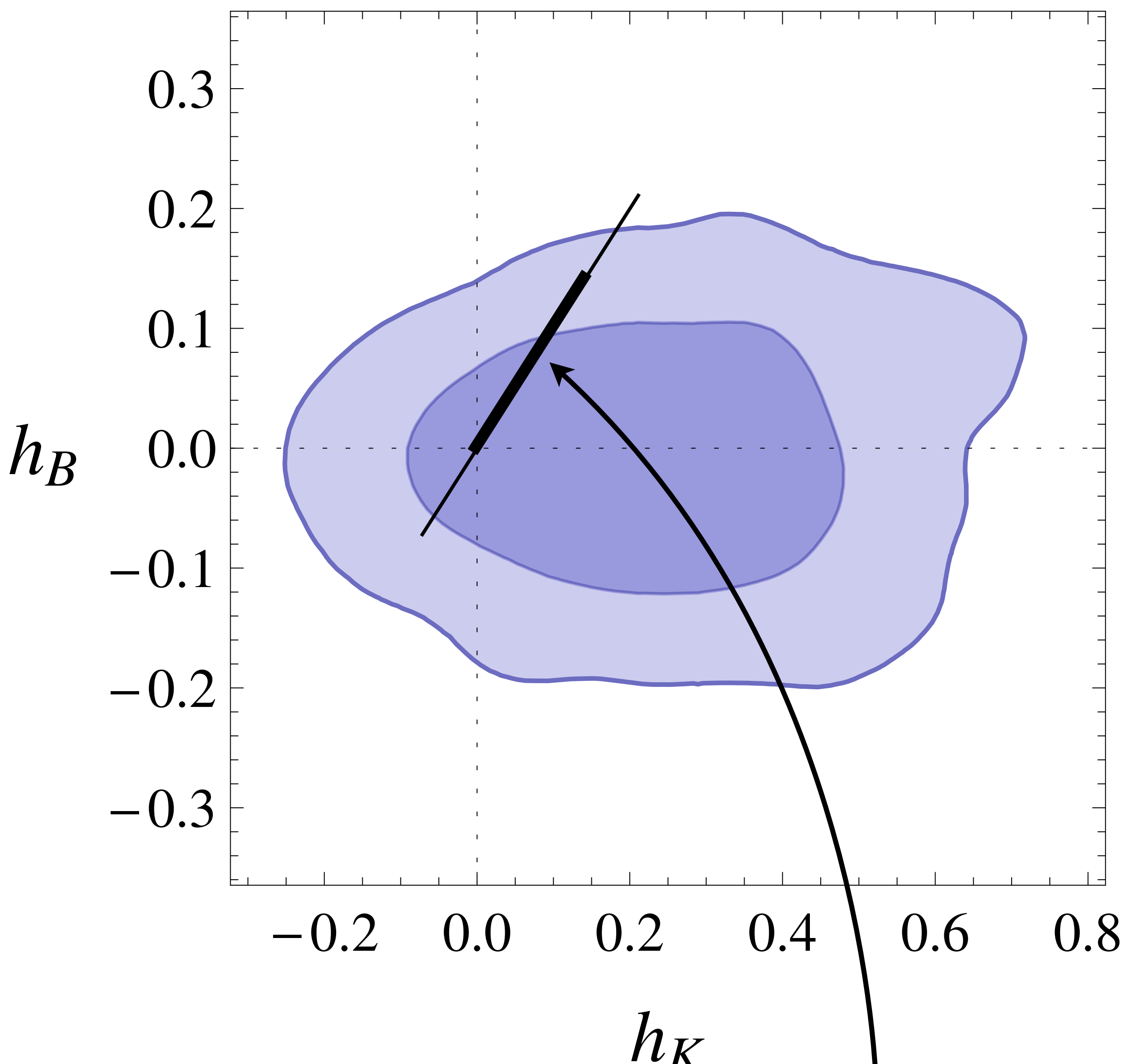
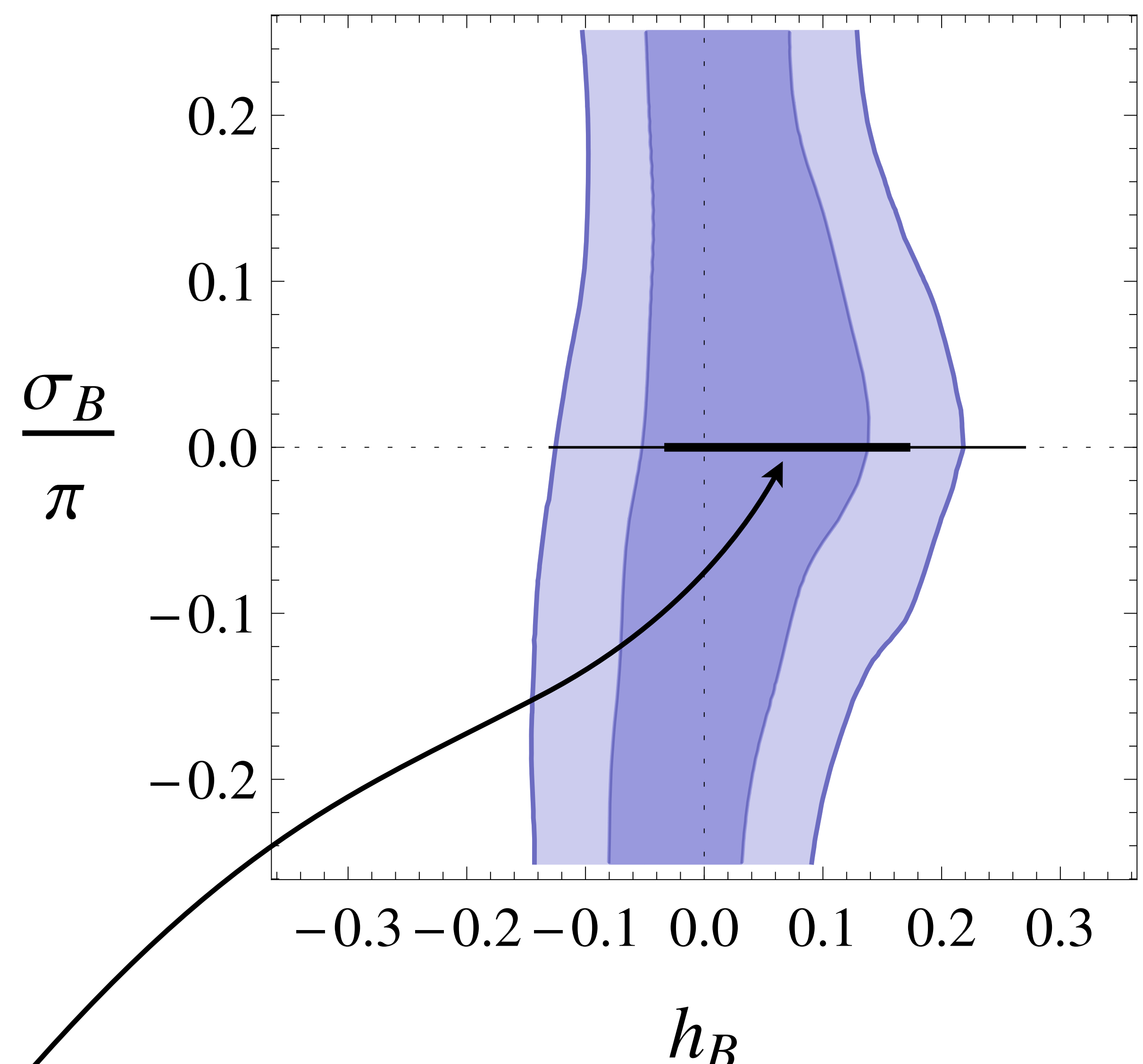
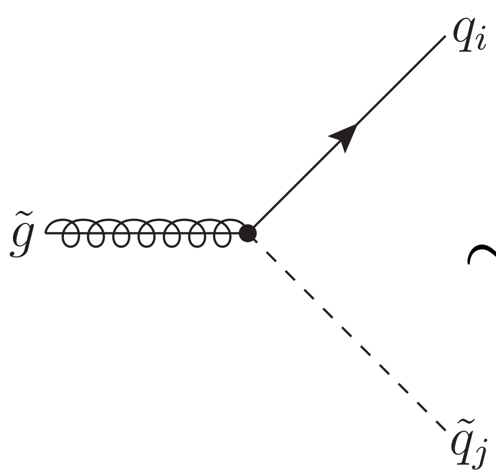




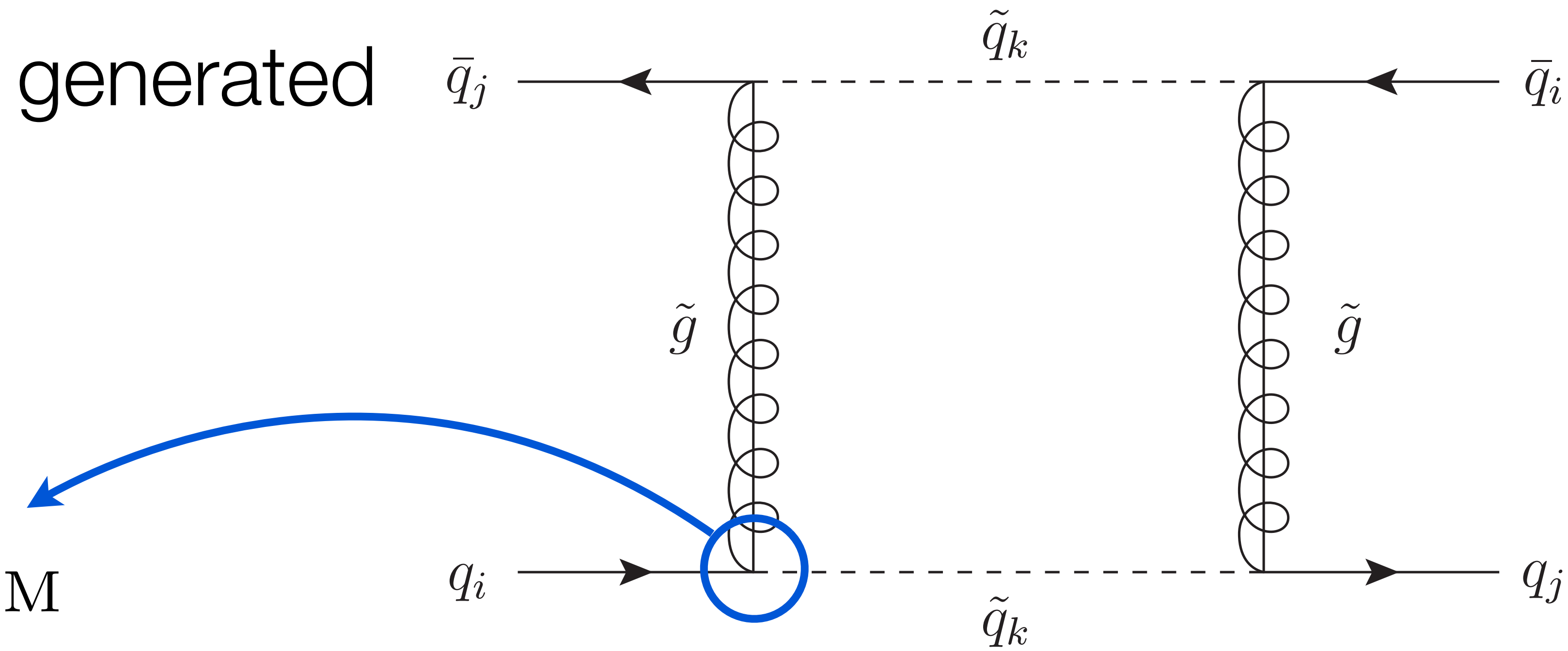
$h_B = h_K,\ \sigma_B = 0$ in MFV

Flavour and supersymmetry

- Flavour operators are generated by s-particle loops



$\sim V^{ij}_{\mathrm{CKM}}$



in a CKM-like framework

- “Natural” spectrum with light stops and gluino, and heavy squarks of 1st & 2nd generation: compatible with $U(2)^3$

- **What is the impact on flavour physics of the direct bounds on s-particle masses from the LHC?**

SUSY contributions to meson mixings

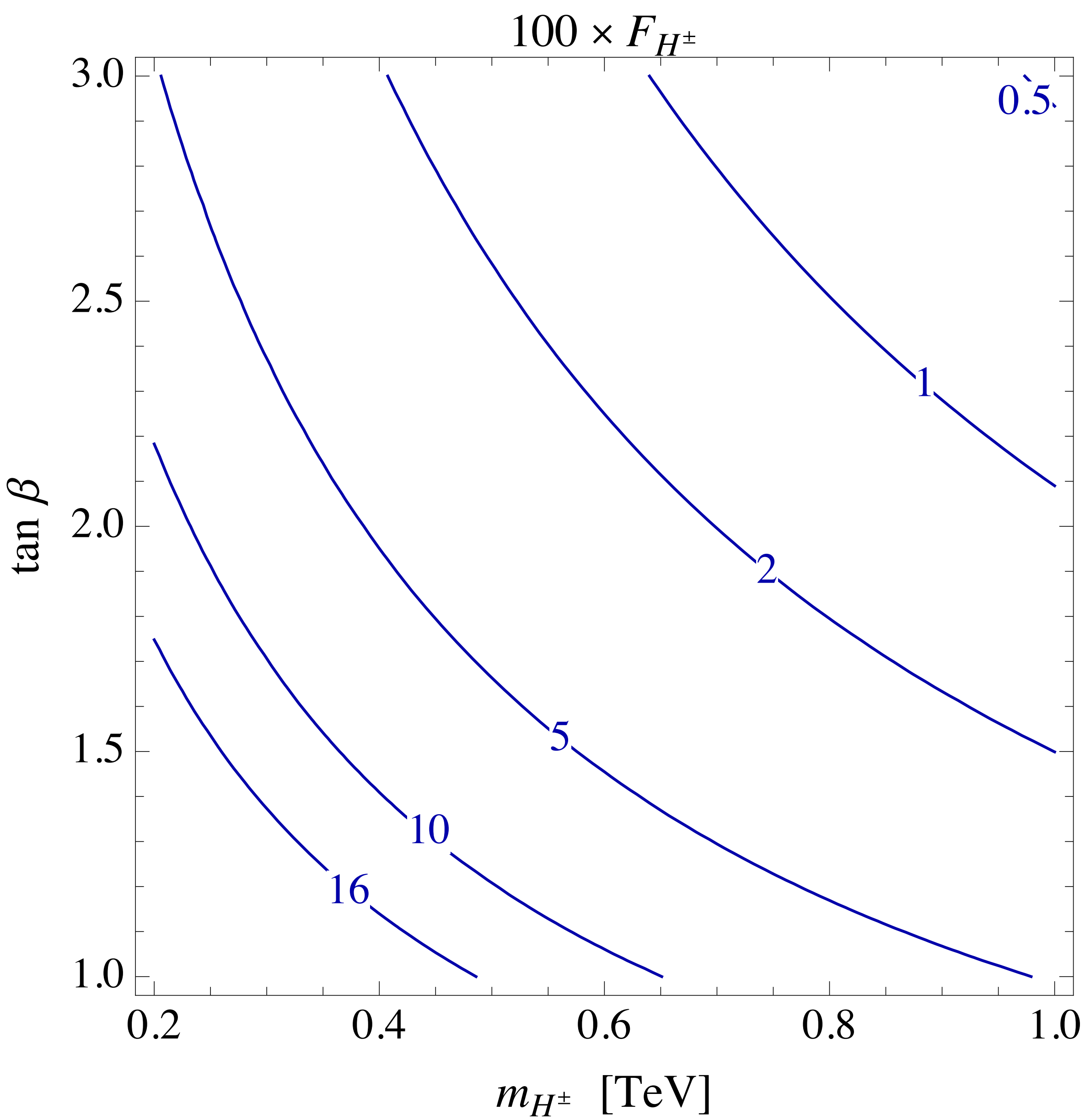
$$h_K \simeq F_{H^\pm} + |\xi_L|^4 F_{\tilde{g},1} + |\xi_L|^2 \delta\, F_{\tilde{g},2} + |\delta|^2 F_{\tilde{g},3}$$

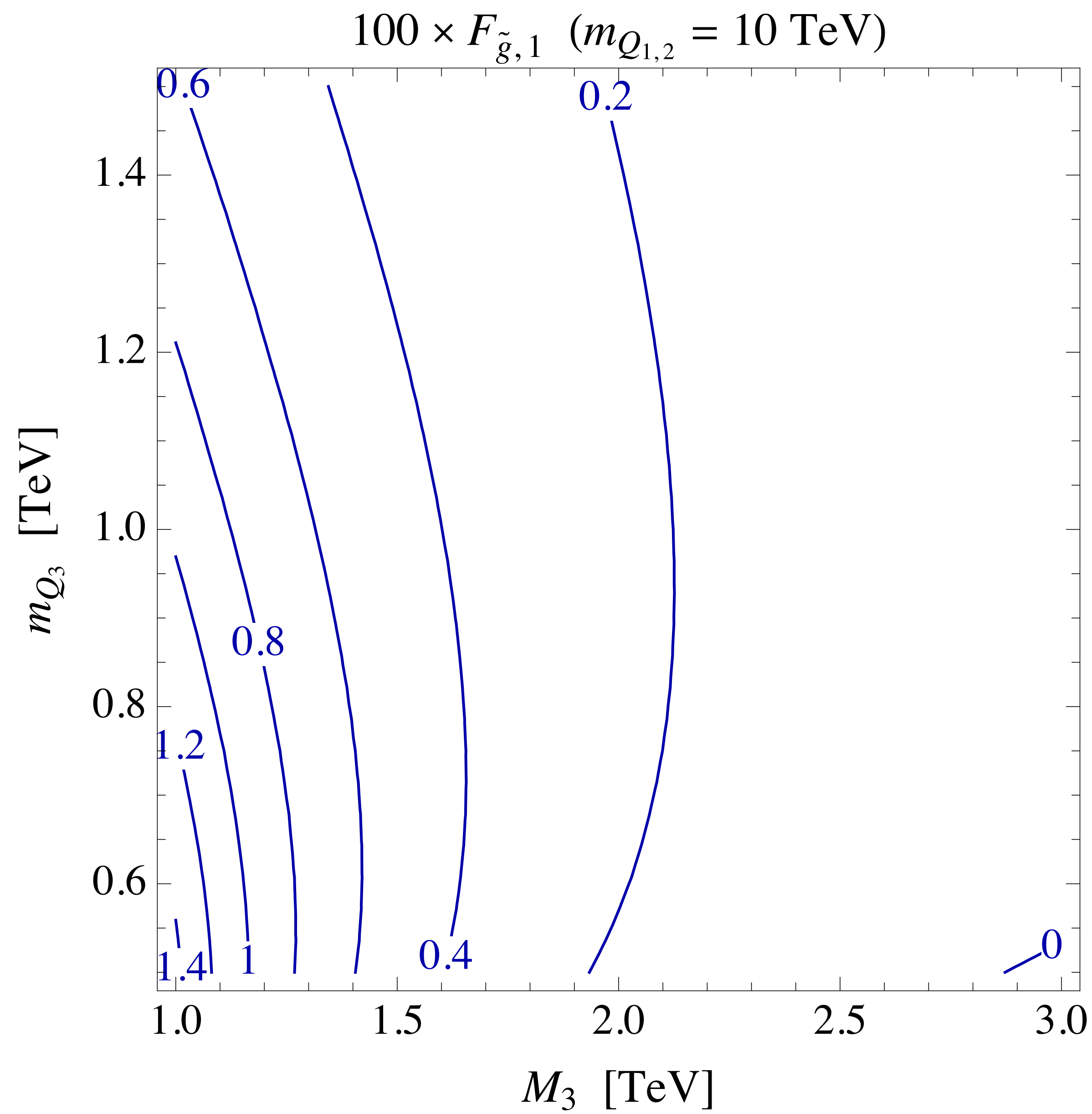
$$h_B e^{2i\sigma_B} \simeq F_{H^\pm} + |\xi_L|^2 e^{2i\gamma_L} F_{\tilde{g},1} + |\xi_L \xi_R| e^{i(\gamma_L+\gamma_R)} F_{\tilde{g},4}$$ (only for B_s)

second-order effects (gluino only)

ξ_L, ξ_R, δ are O(1) parameters

$\left(\xi_L = \left|W^{\tilde{g},L}_{ts}/V_{ts}\right|\right)$





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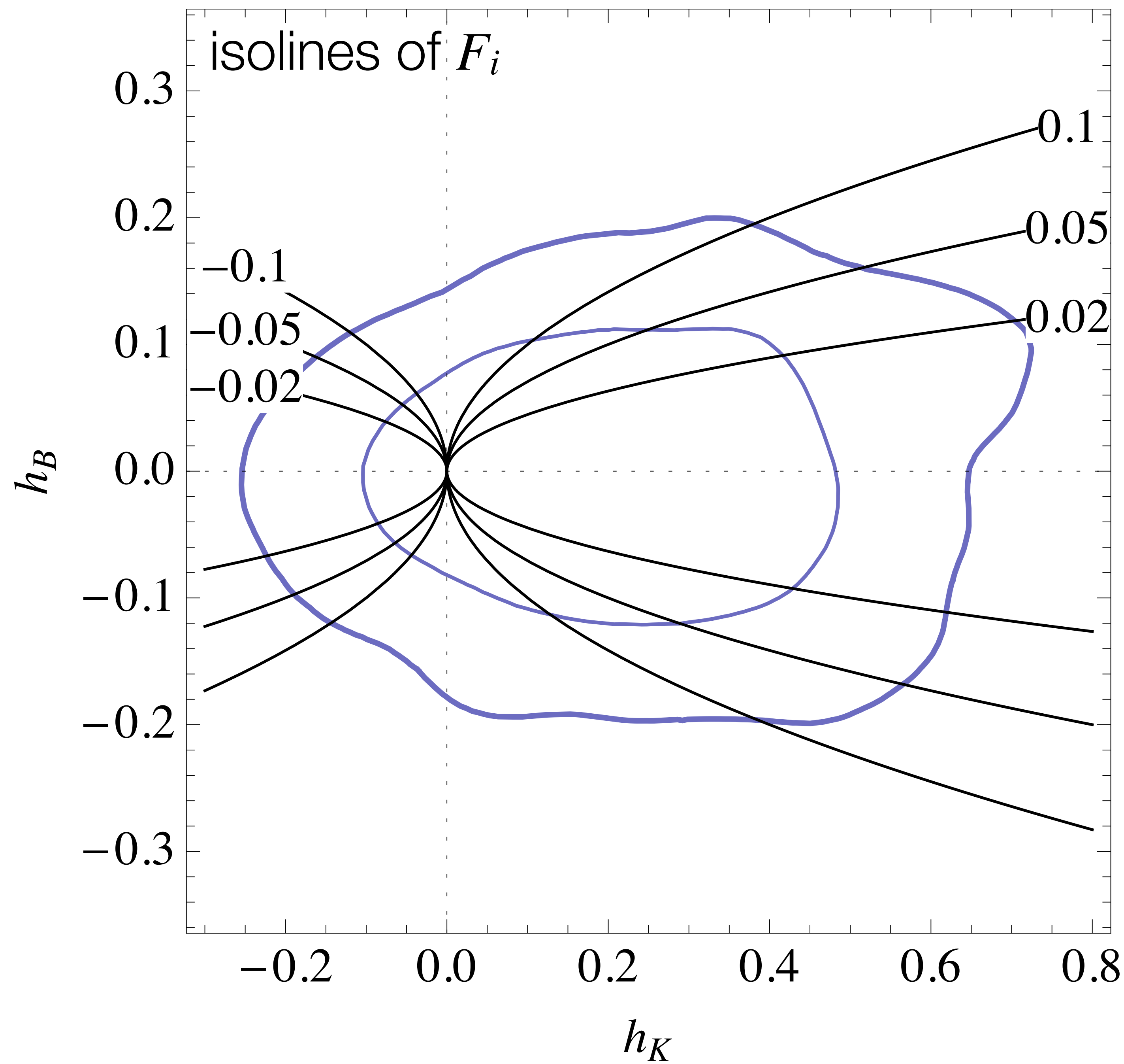

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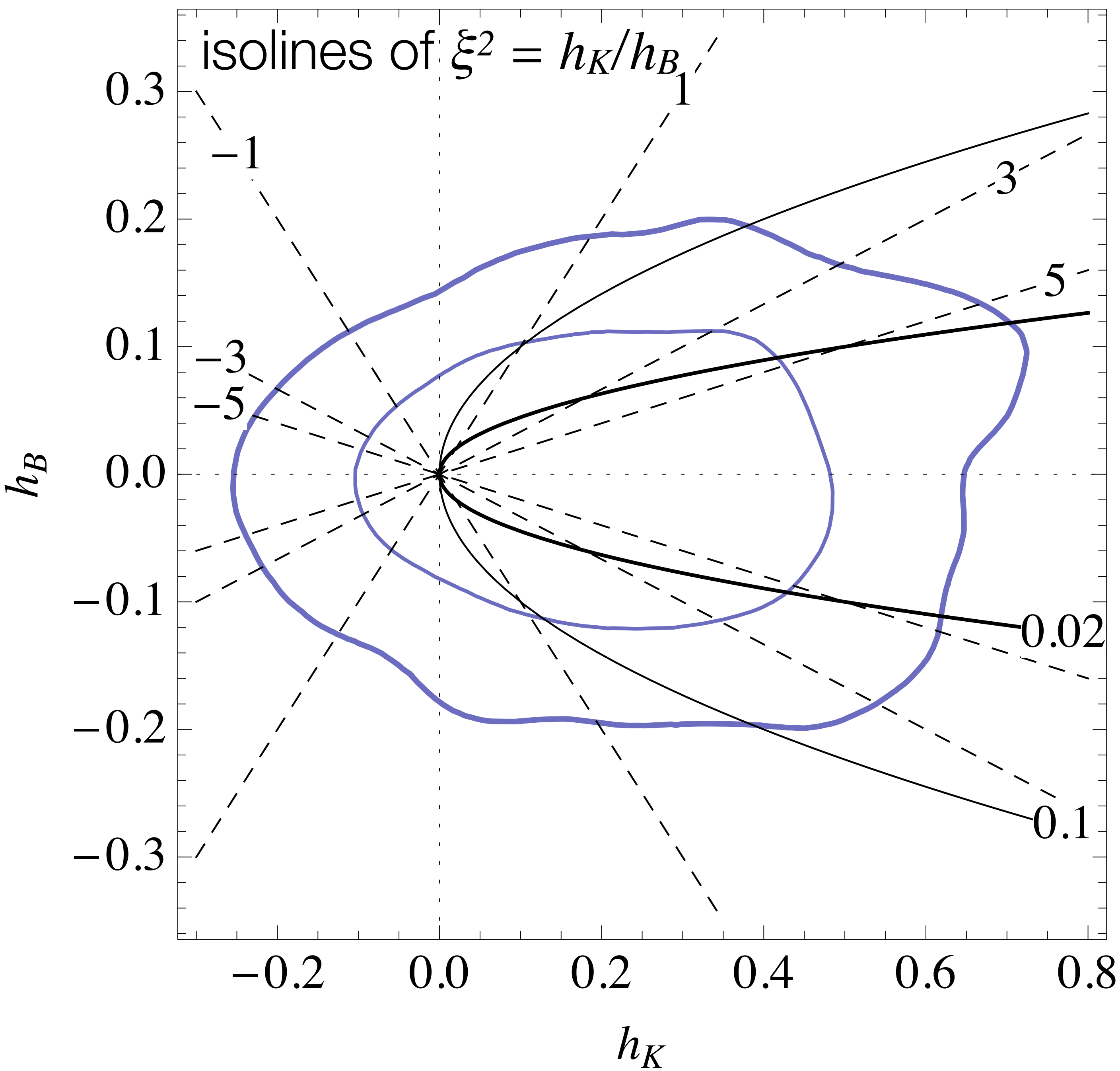

observable deviations from the SM only for large values of ξ_L

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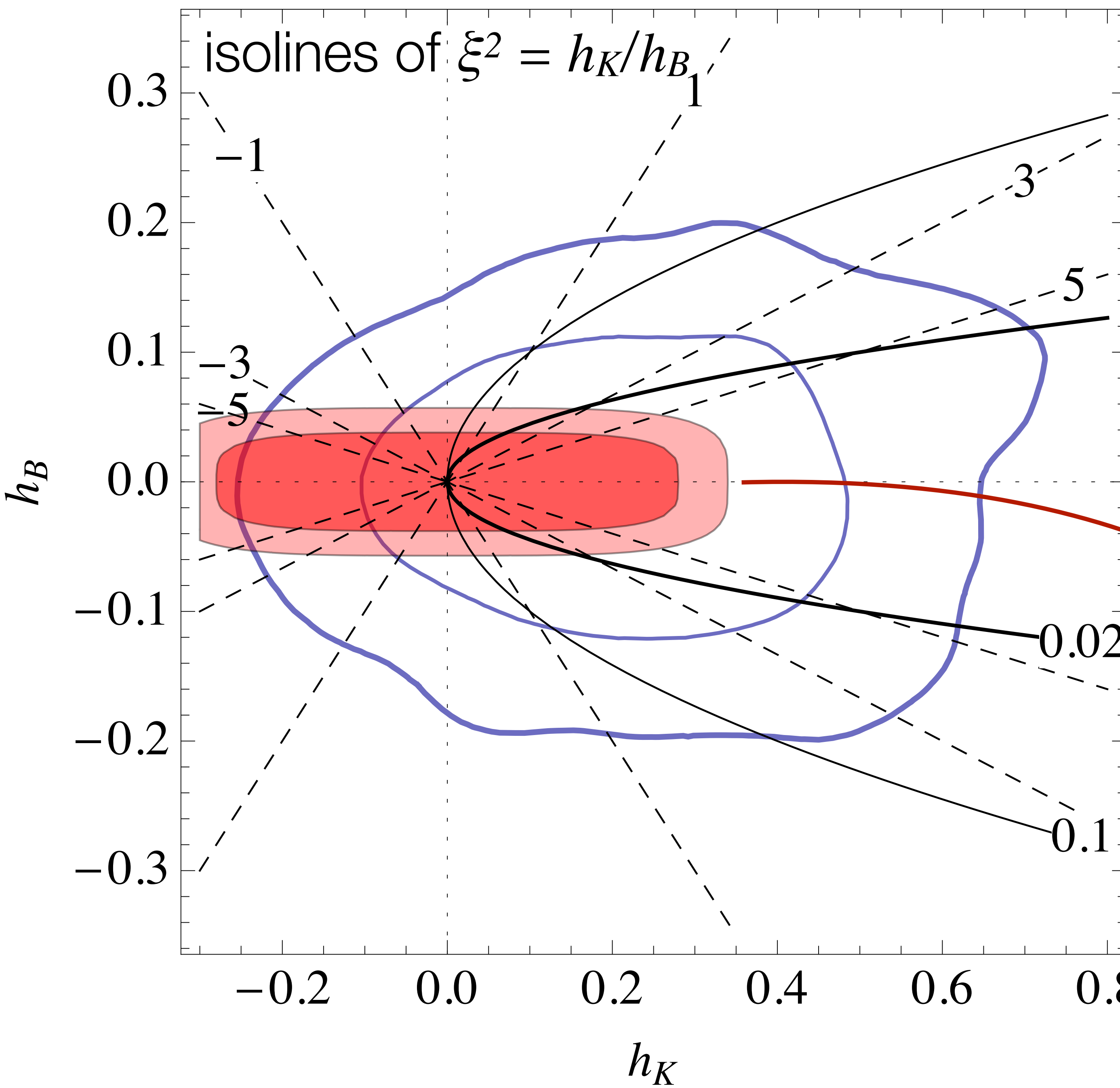
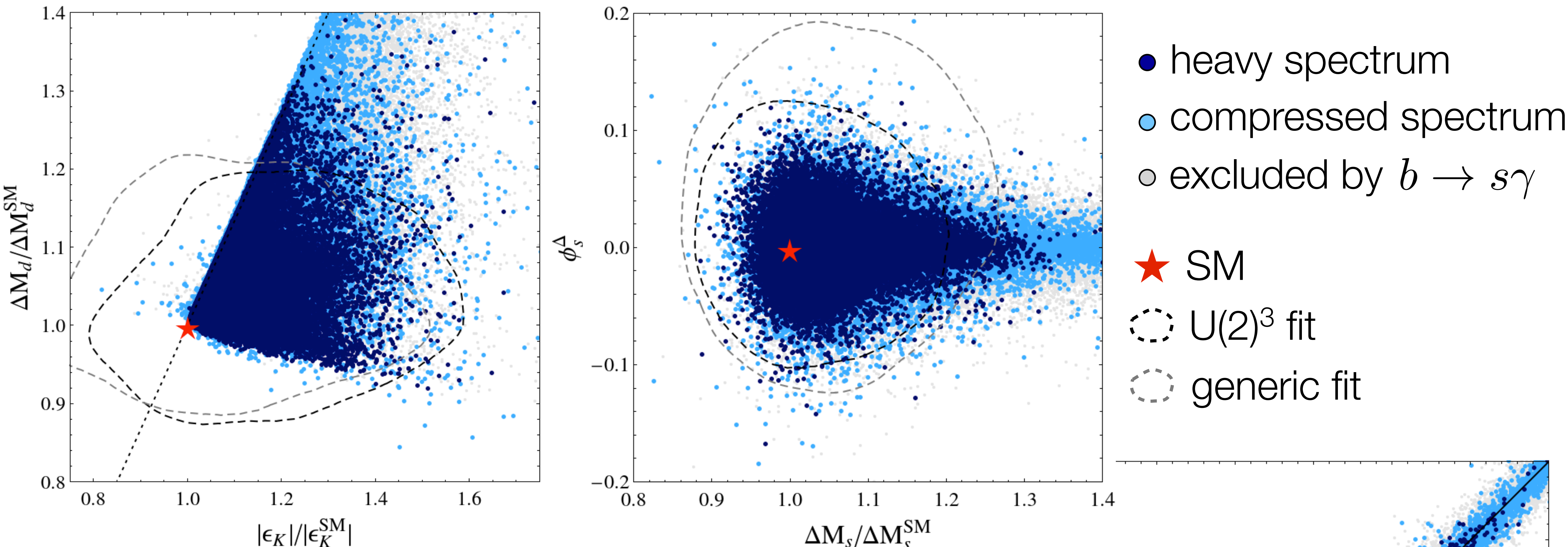
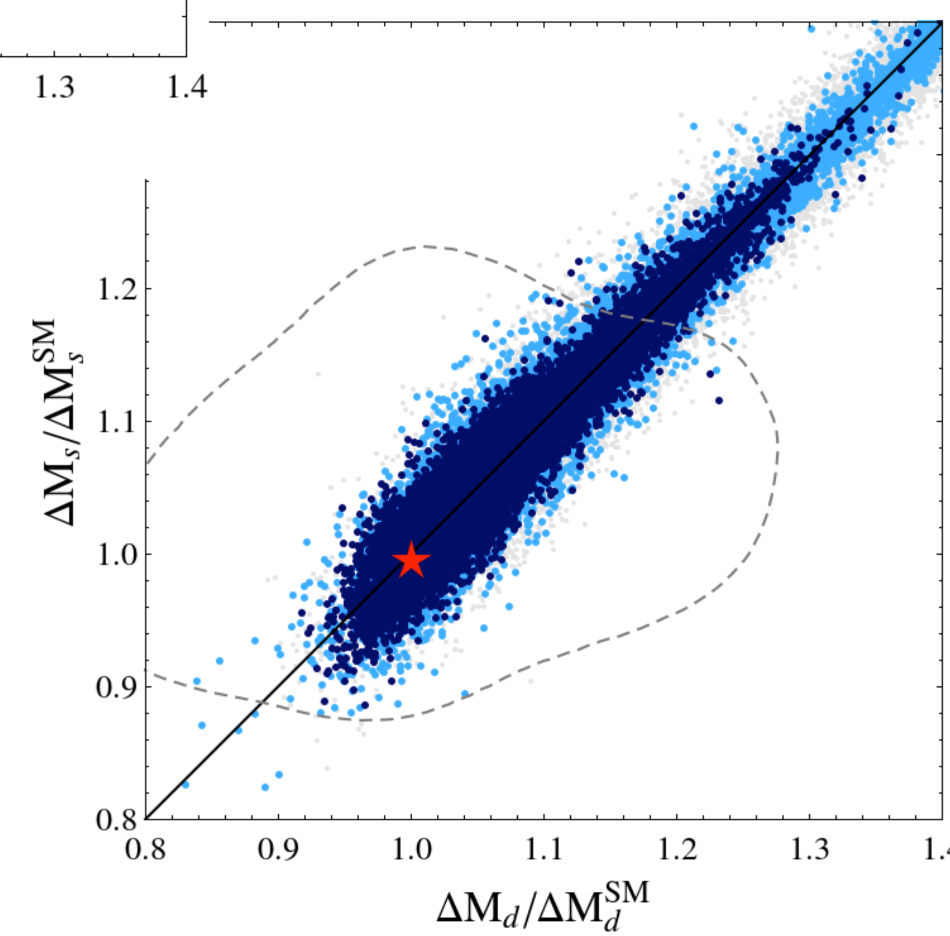


observable deviations from the SM only for large values of ξ_L

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

Numerical analysis of meson mixing





- Analysis with **SUSY_FLAVOR** Crivellin, Rosiek
- ATLAS and CMS mass bounds:

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

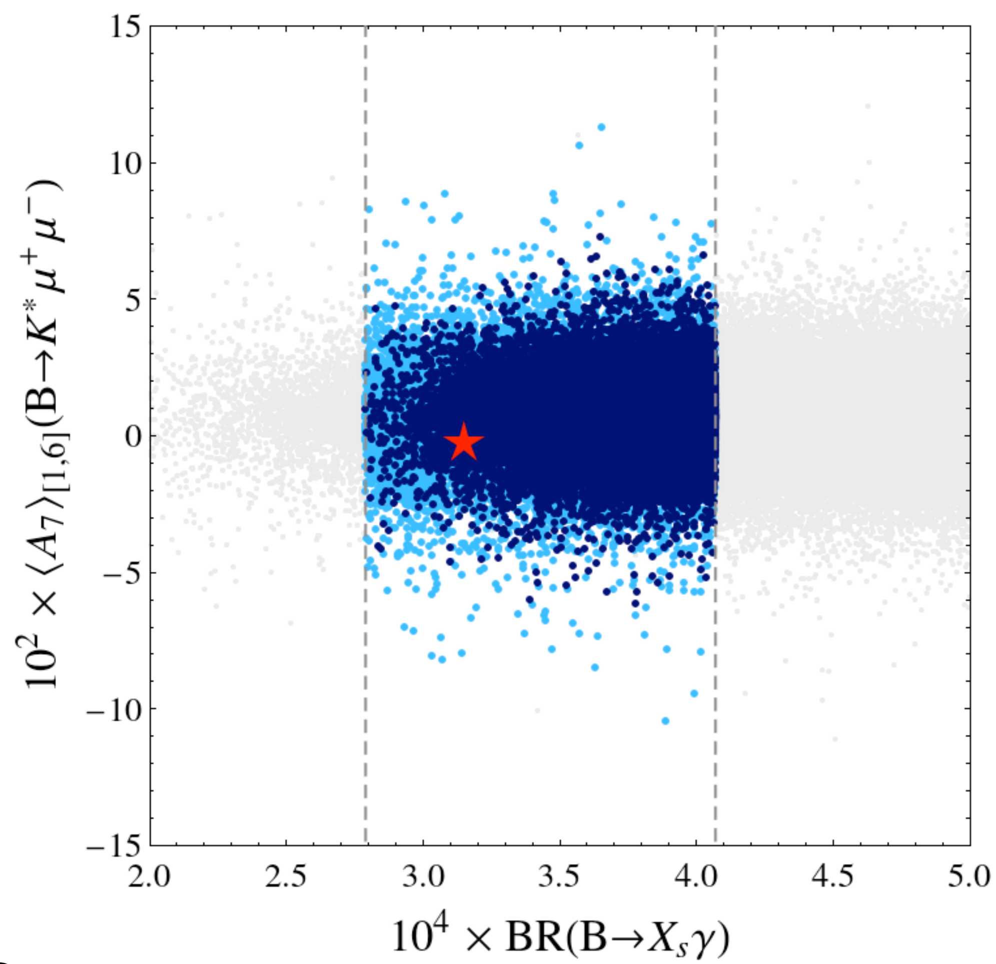
- Scan ranges: $\xi_\alpha \in [1/3, 3]$

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

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

Rare B decays

- Main ΔB = 1 effects in $U(2)^3$ arise from (chromo-)magnetic dipole operators



- Higgsino and charged Higgs contributions MFV-like, constrained by $B \to X_s \gamma$

- Gluino (and Wino) contributions, contribute to the CP asymmetries: angular asymmetry A_7 in $B \to K^* \mu^+ \mu^-$ at low $\mu\mu$ invariant mass

- $B_{d,s} \to \mu^+ \mu^-$ not relevant for moderate tan β (get tan β enhanced contributions from scalar operators)

Conclusions

- 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

- New bound: $|d_e| < 8.7 \times 10^{-29}\, e\,\mathrm{cm}$
- One loop chargino-sneutrino contribution:

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

- Two loop Barr-Zee type contributions