Flavour physics after the first run of the LHC: status and perspectives

based on 1402.6677 with R. Barbieri, F. Sala and D. Straub,
1408.0728, and 1503.02693 with A. J. Buras, J. Girrbach and R. Knegjens

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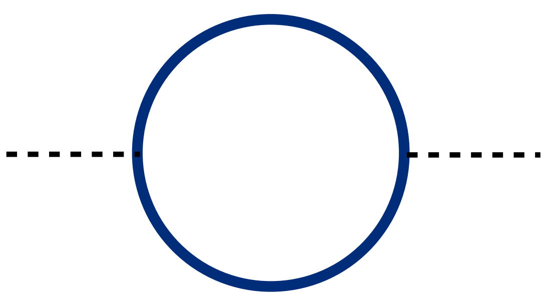
Naturalness (in one slide)

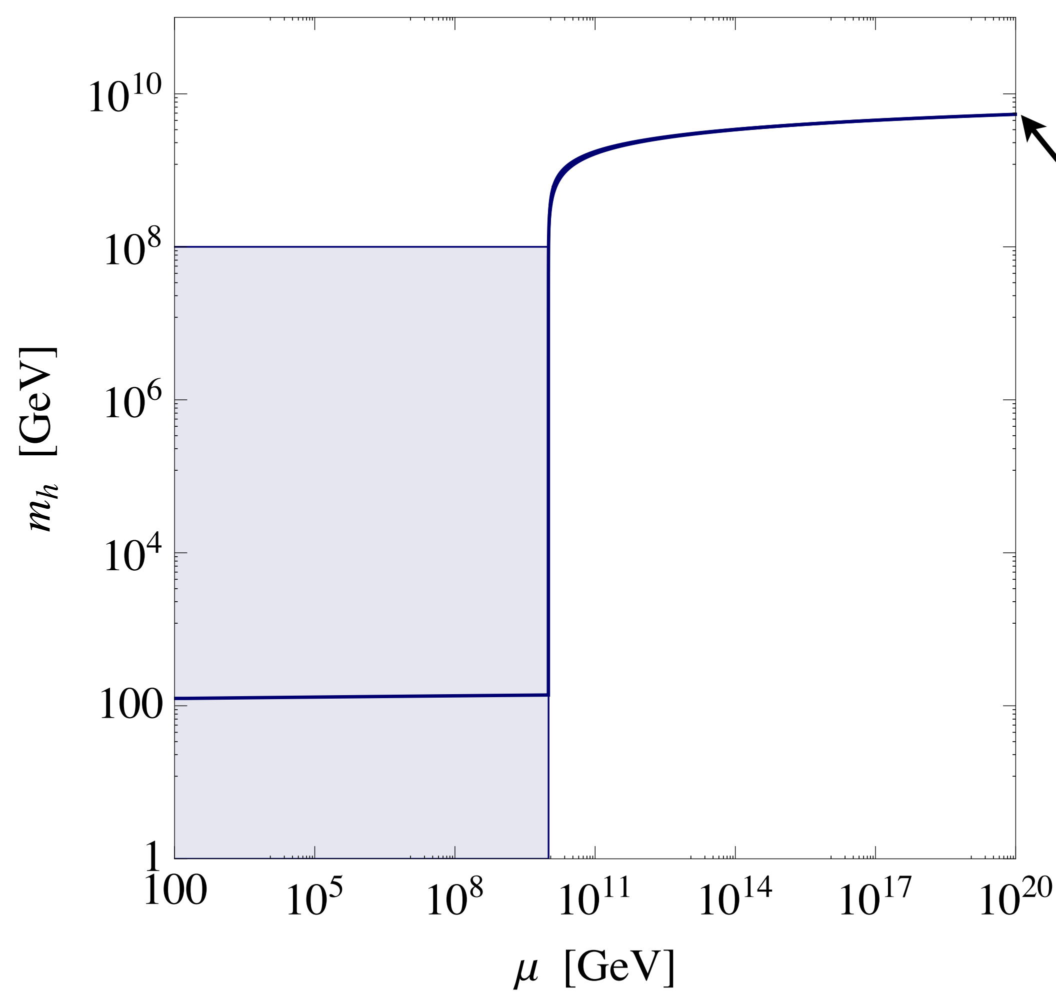
- The Standard Model alone has **no hierarchy problem**

$$\frac{d\, m_h^2(\mu)}{d \log \mu} = \frac{3 m_h^2}{8\pi^2}\left(2\lambda + y_t^2 - \frac{3 g_2^2}{4} - \frac{g_Y^2}{4}\right)$$ running Higgs mass

- Generic new particles at a scale M higher than the EW scale, coupled to the Higgs boson, generate large corrections to the Higgs mass



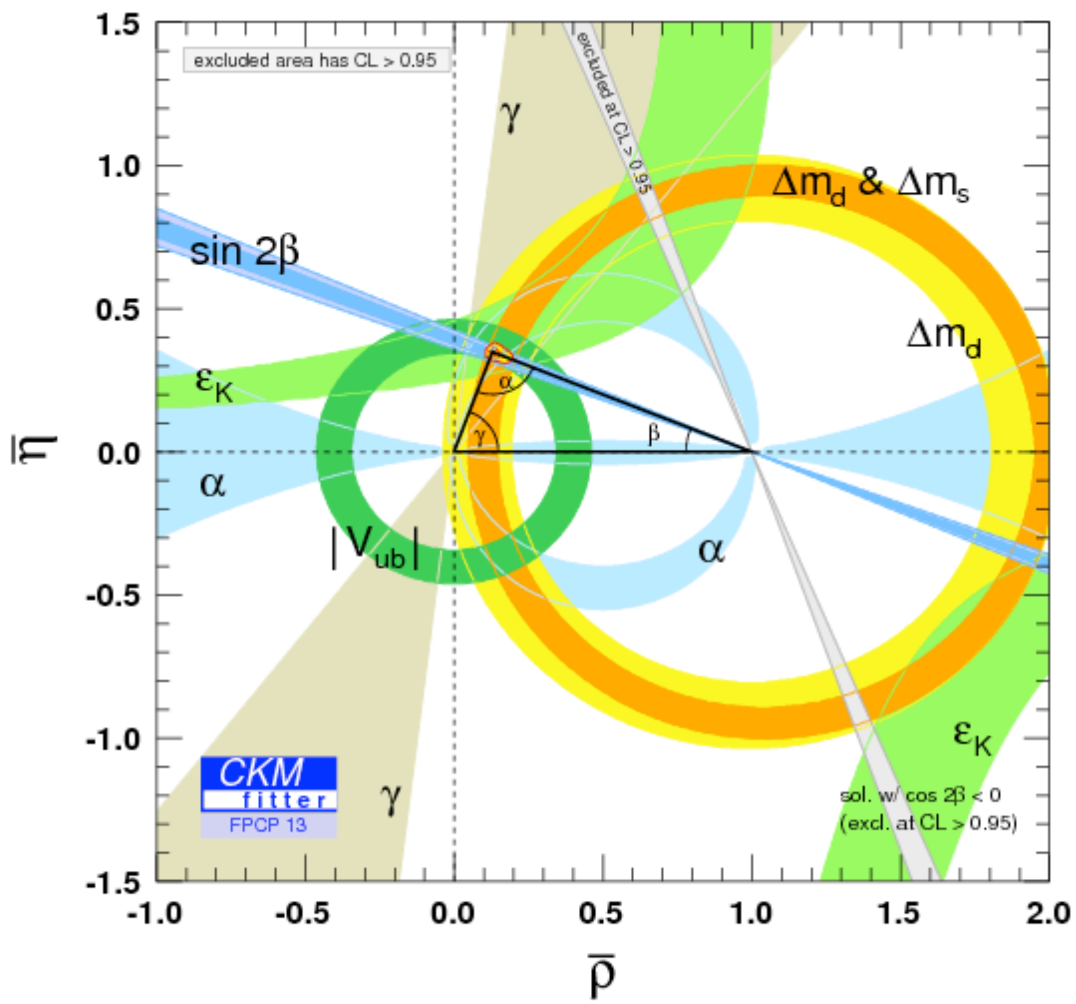
$$\left.\frac{d\, m_h^2(\mu)}{d\, \log \mu}\right|_{\rm NP} \propto \frac{g_{\rm NP}^2}{16\pi^2} M_{\rm NP}^2$$



1% variation in $m_h(\mu \gg M)$

- Ignore gravity? Maybe, but...

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

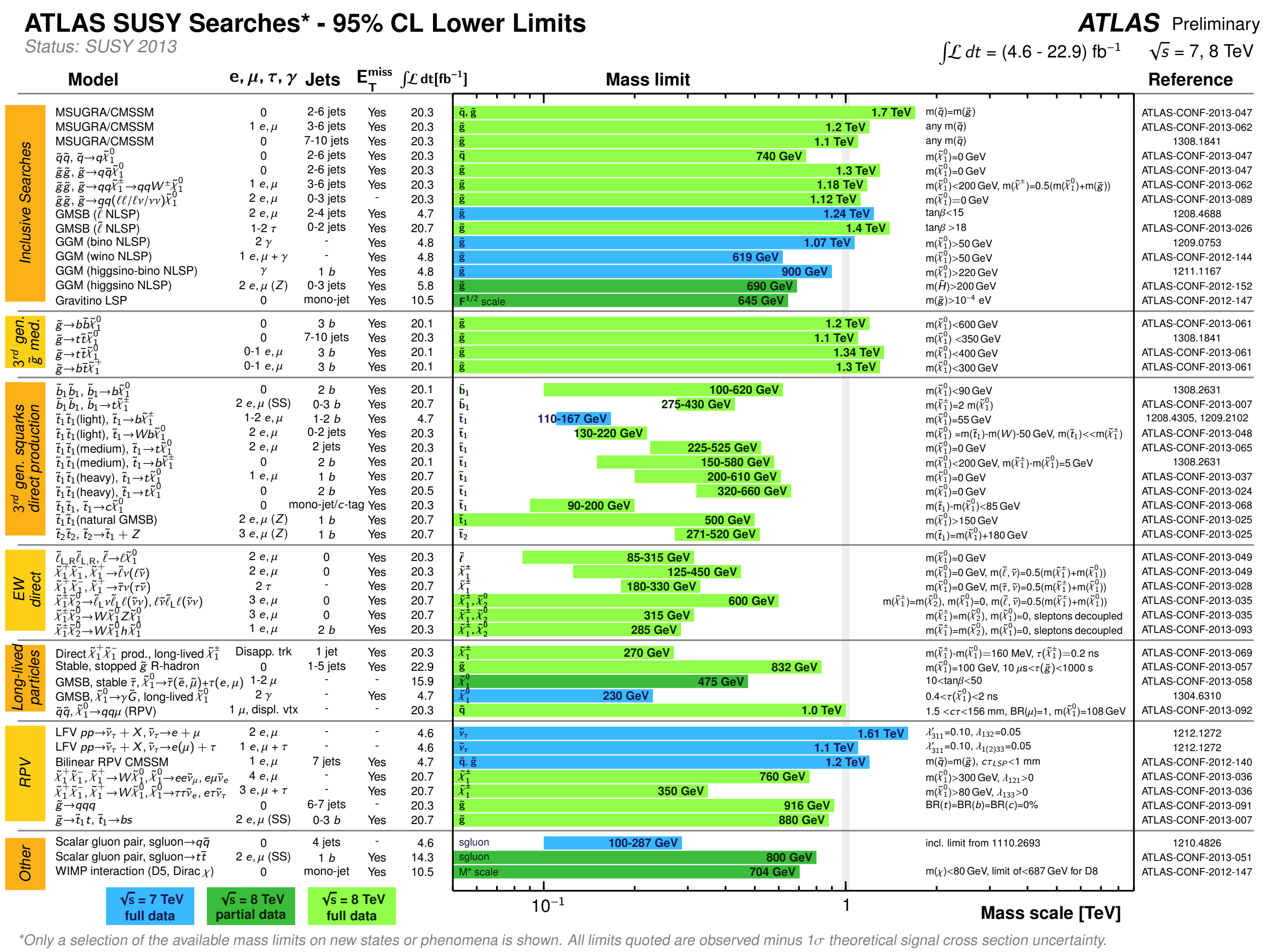
2. Physics at the TeV scale must have a very peculiar structure: symmetries

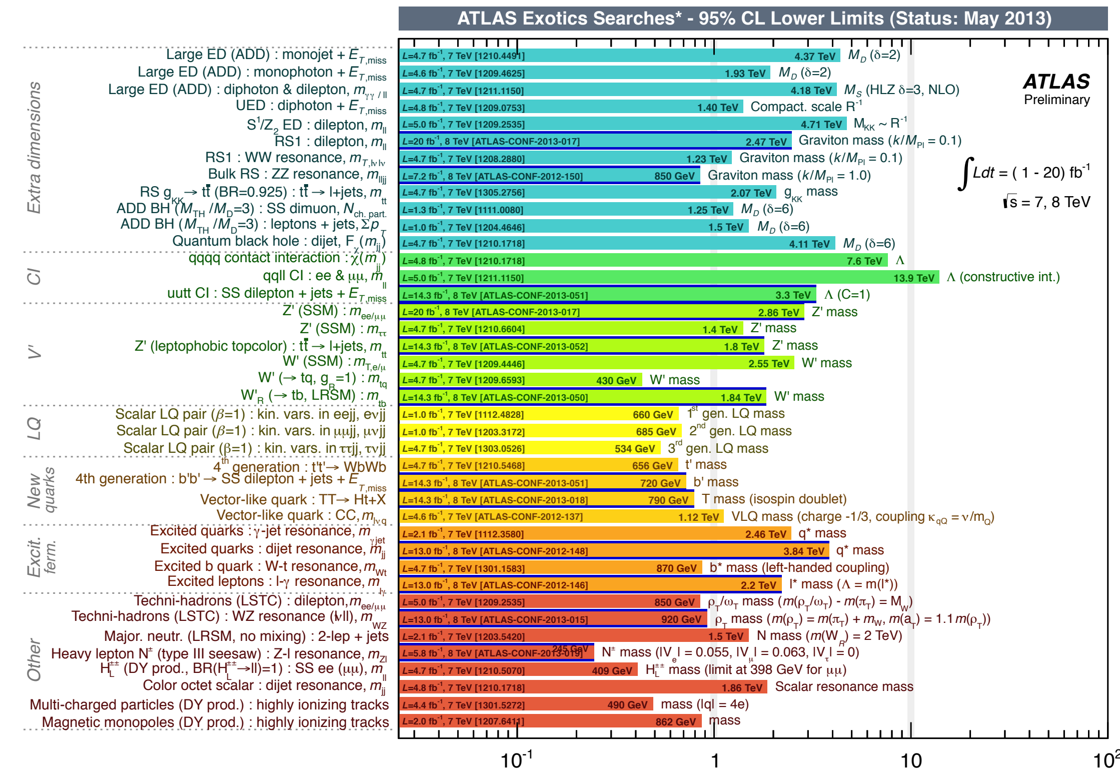
EFT approach: only a limited set of effective operators is present, size controlled by the CKM matrix V $\quad (\xi_{ij} = V_{ti}^* V_{tj})$

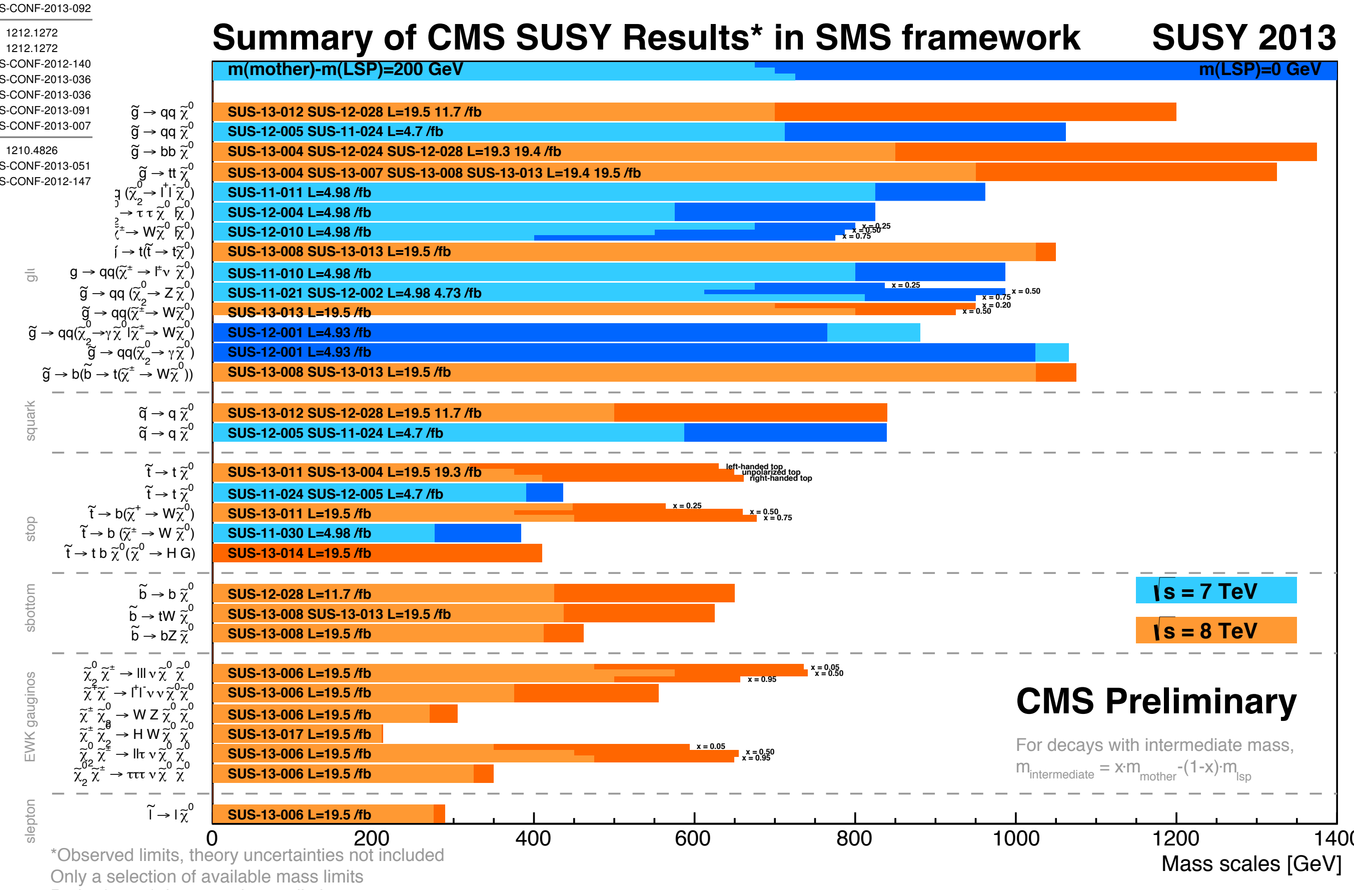
$$\xi_{ij}^2 (\bar{d}_L^i \gamma_\mu d_L^j)^2 \qquad \xi_{ij} (\bar{d}_L^i \gamma_\mu d_L^j) \mathcal{O}_\alpha^\mu \qquad \xi_{ij} m_j (\bar{d}_L^i \sigma_{\mu\nu} d_R^j) \mathcal{O}_\beta^{\mu\nu}$$

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)?

1. The way of flavour symmetries

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

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:

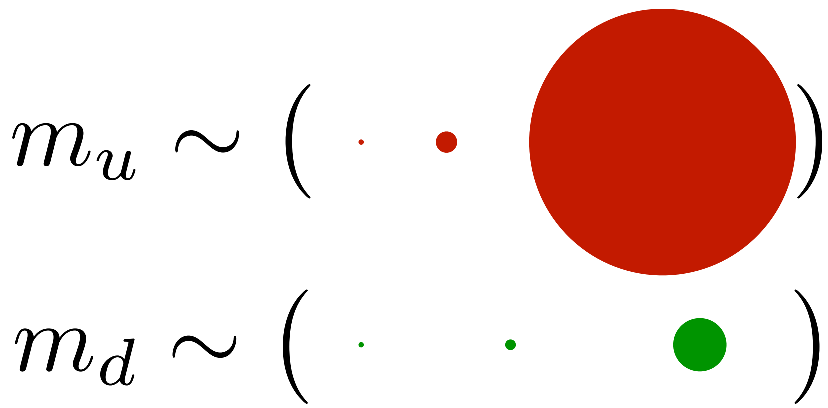
$$c_{\rm cb}^{\beta} e^{i\phi^\beta} \xi_{ij} m_j (\bar{d}_L^i \sigma_{\mu\nu} d_R^j) \mathcal{O}_{\mu\nu}^{\beta}$$

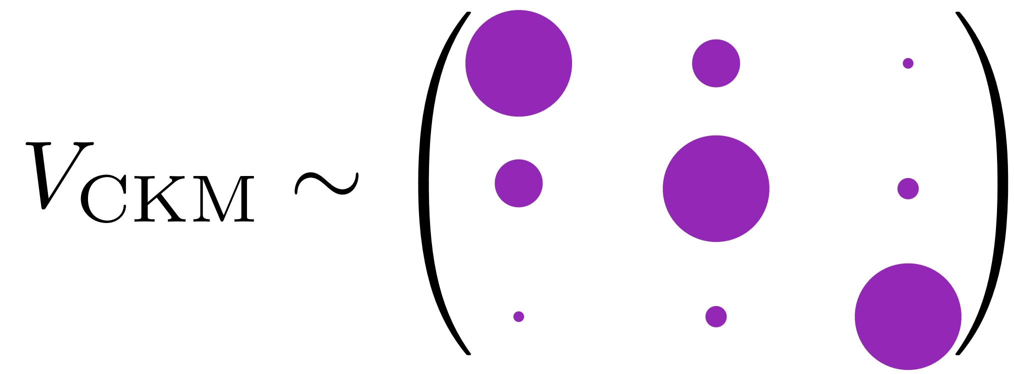
$$c_{LL}^K \xi_{ds}^2 (\bar{d}_L \gamma_\mu s_L)^2 \qquad c_{\rm cc}^{K,\alpha} \xi_{ds} (\bar{d}_L \gamma_\mu s_L) \mathcal{O}_\mu^\alpha$$

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

Minimal $U(2)^3$

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





- 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>

Barbieri, B, Sala, Straub '14

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

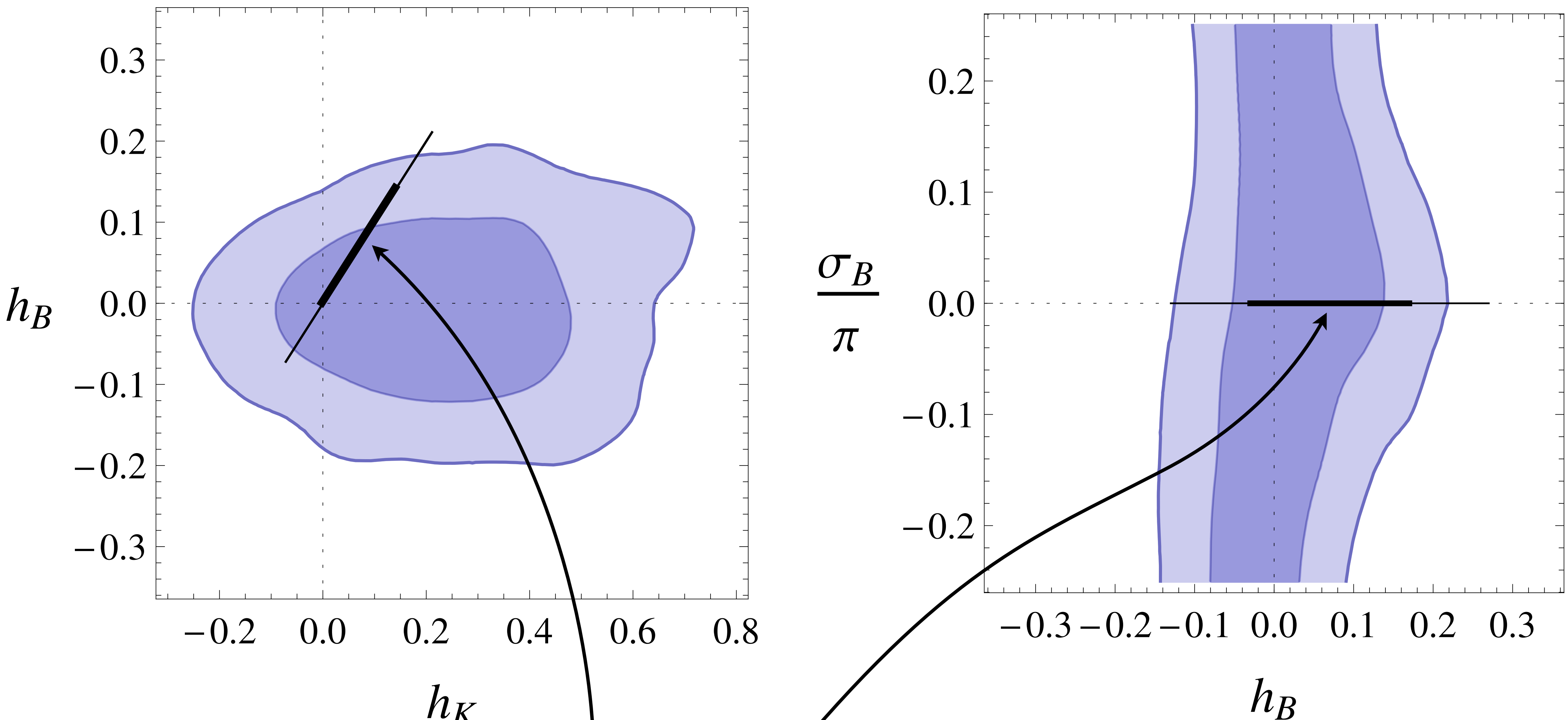
  gives rise to the bilinear $\Big((c_3 - c_1)\xi_{ij} + (c_2 - c_1)V_{ci}^* V_{cj}\Big)(\bar{d}_L^i \gamma_\mu d_L^j)$

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

Fit of ΔF = 2 observables

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

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



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

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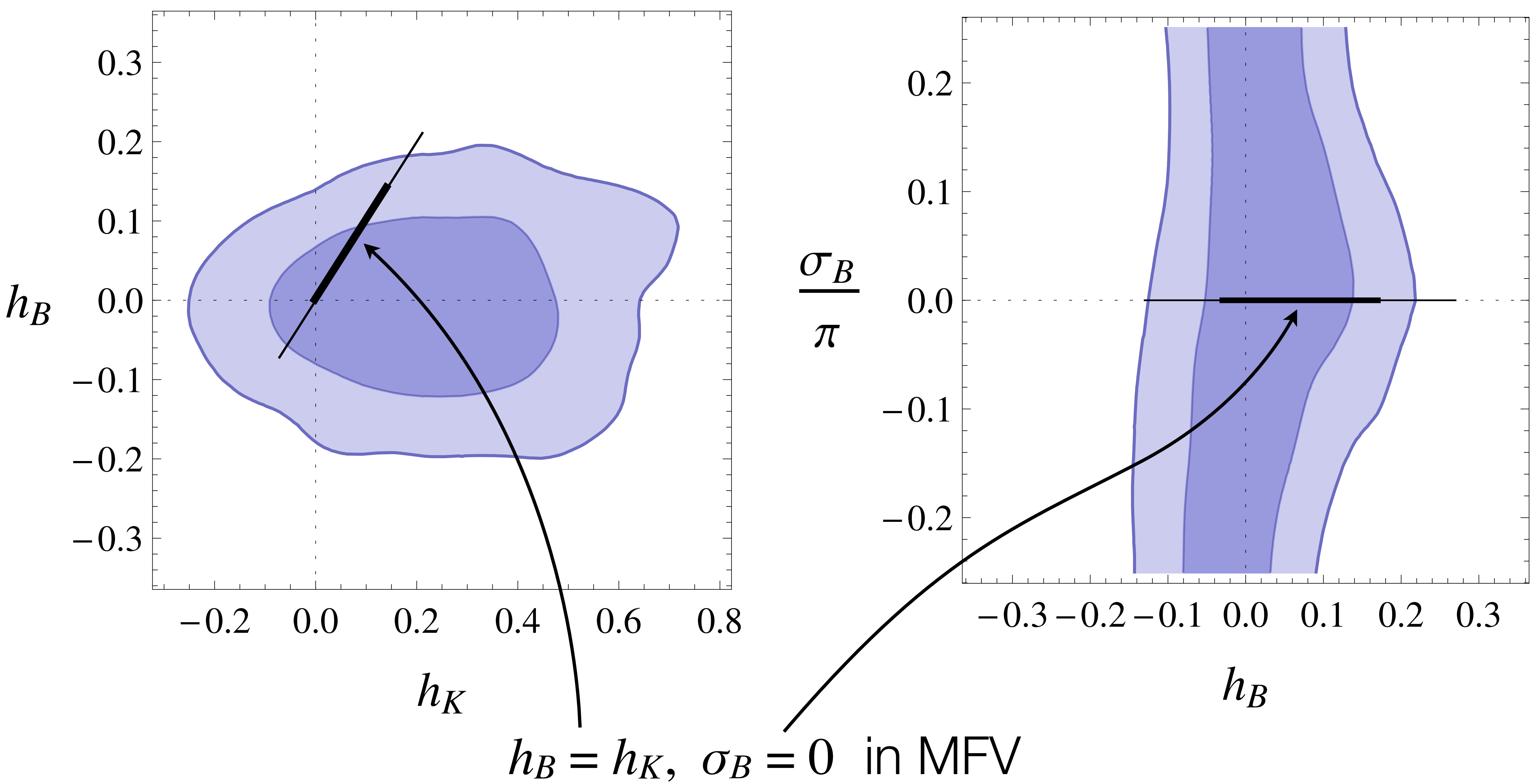
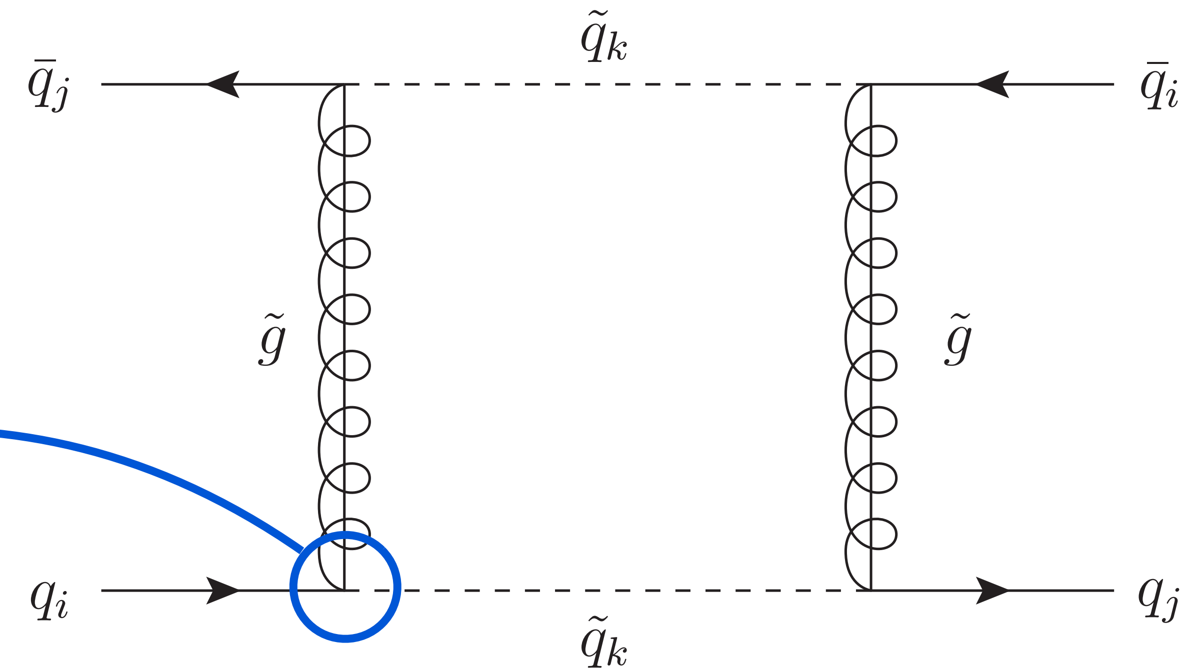
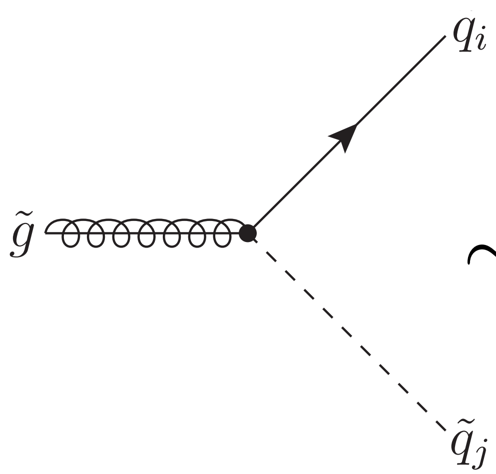


Flavour and supersymmetry

- Flavour operators are generated by s-particle loops





$$\sim V_{\rm CKM}^{ij}$$

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?**

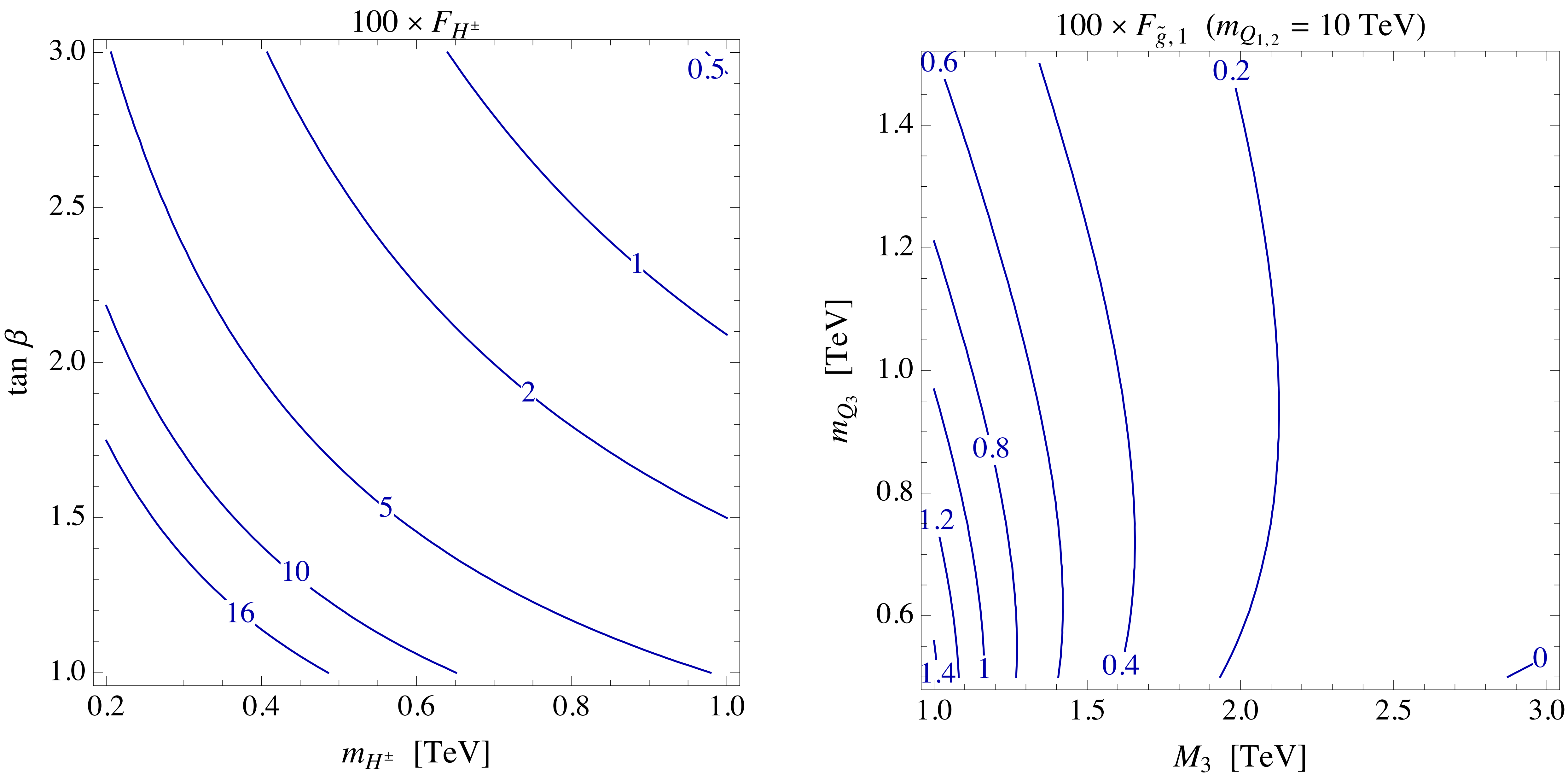
SUSY contributions to meson mixings

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

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

second-order effects (gluino only)

ξ_L, ξ_R, δ are O(1) parameters $\quad\quad$ $\left(\xi_L = \left|W^{\tilde{g},L}_{ts}/V_{ts}\right|\right)$



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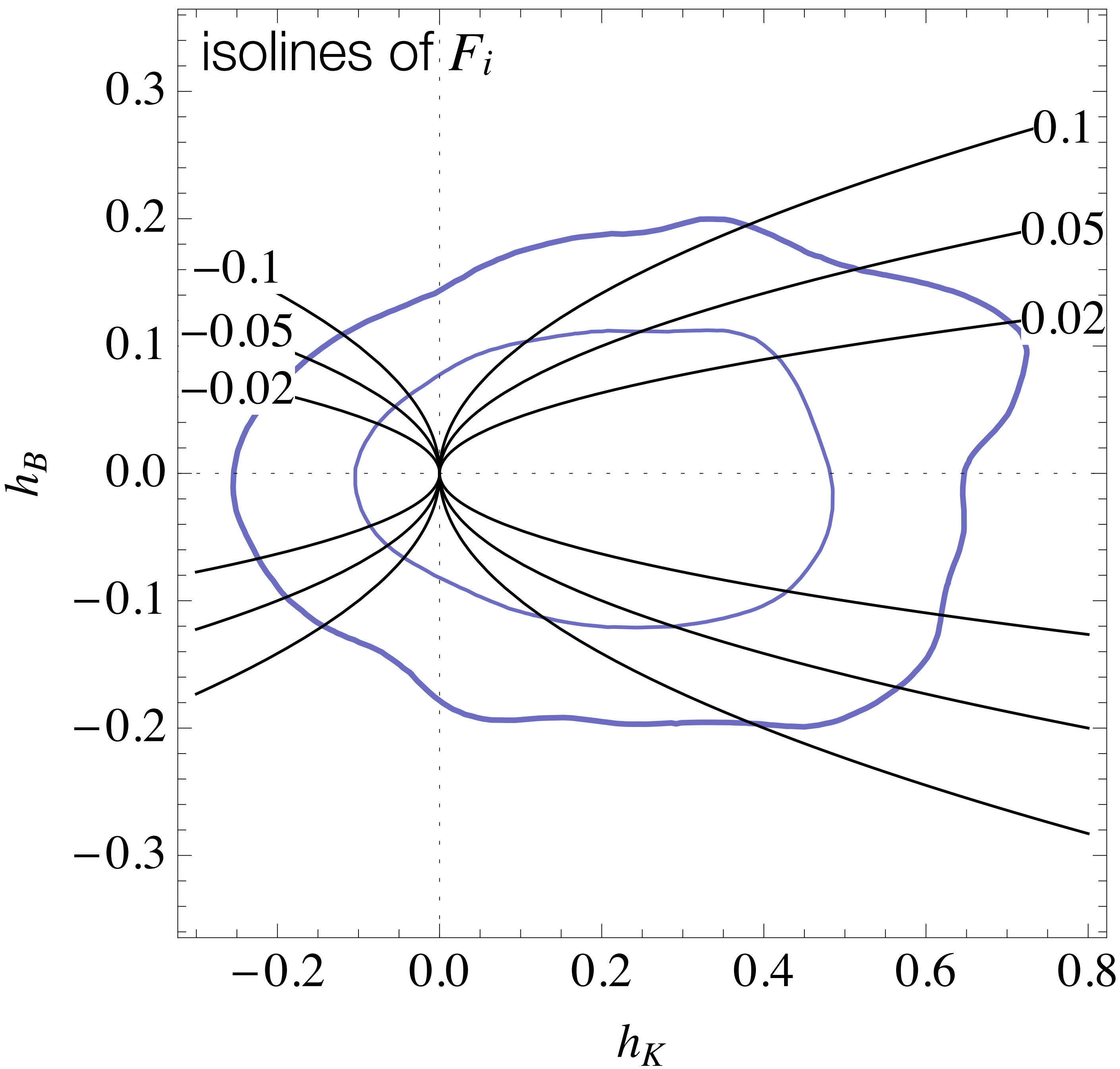

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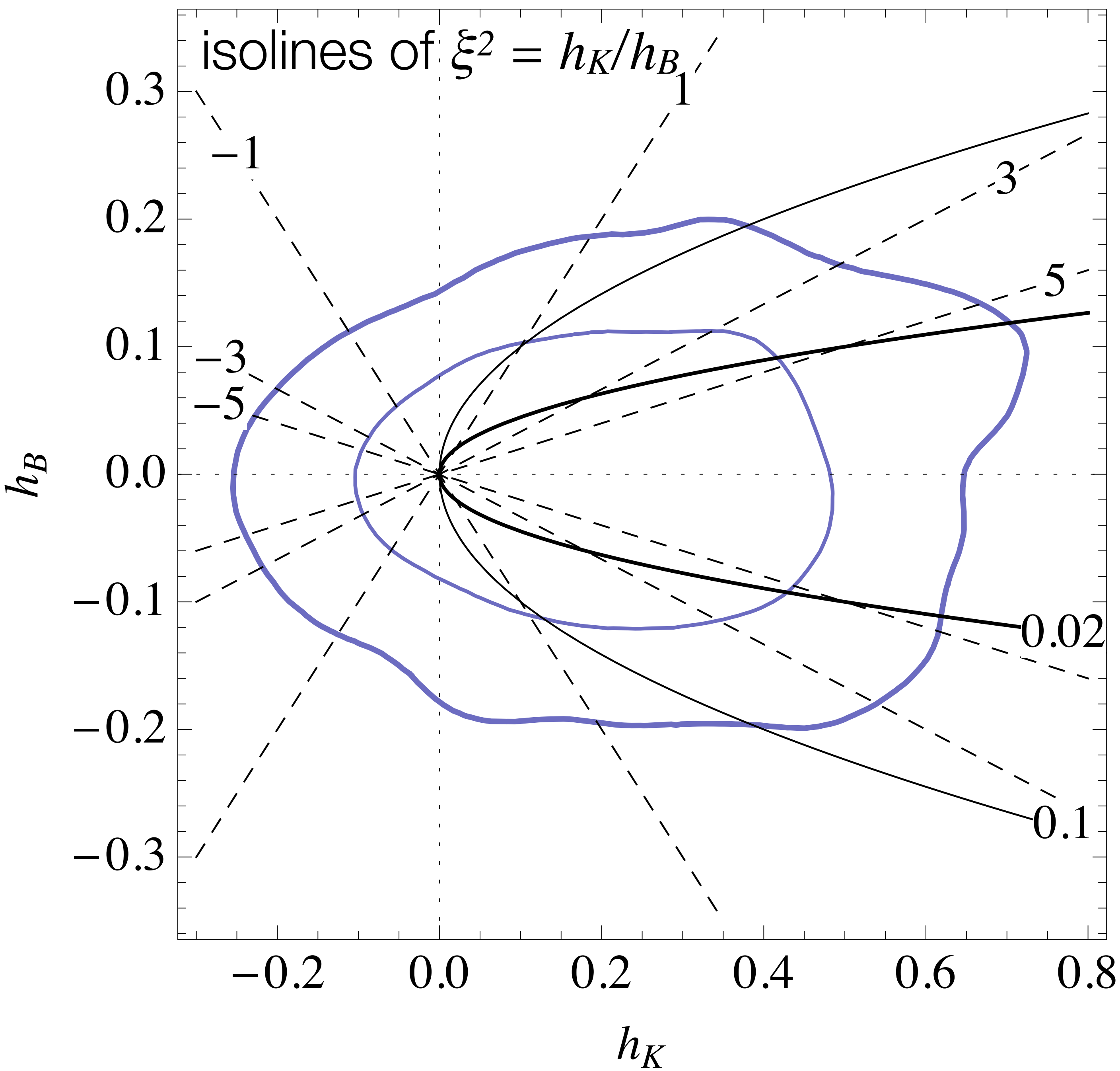

observable deviations from the SM only for large values of ξ_L

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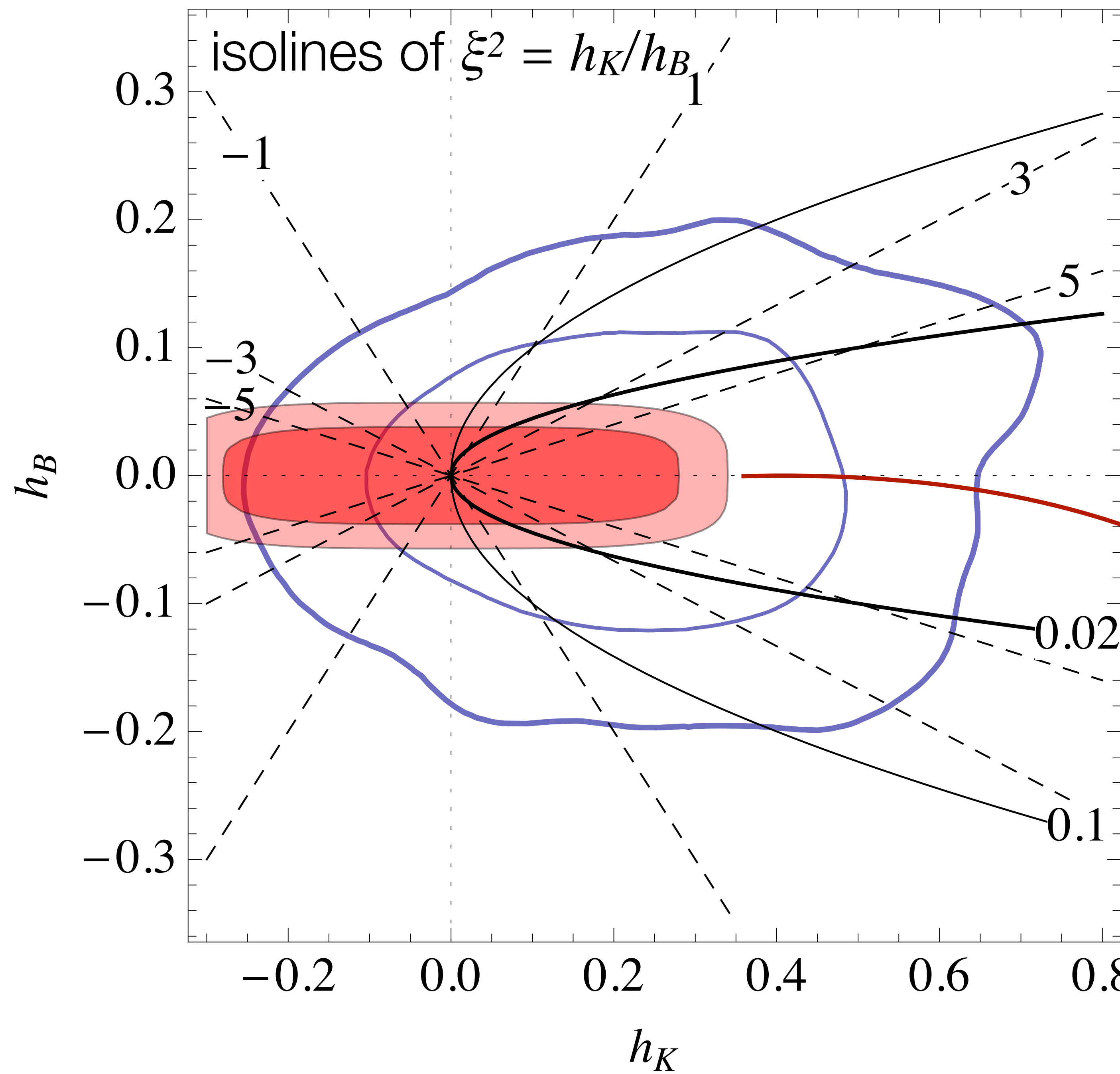


observable deviations from the SM only for large values of ξ_L

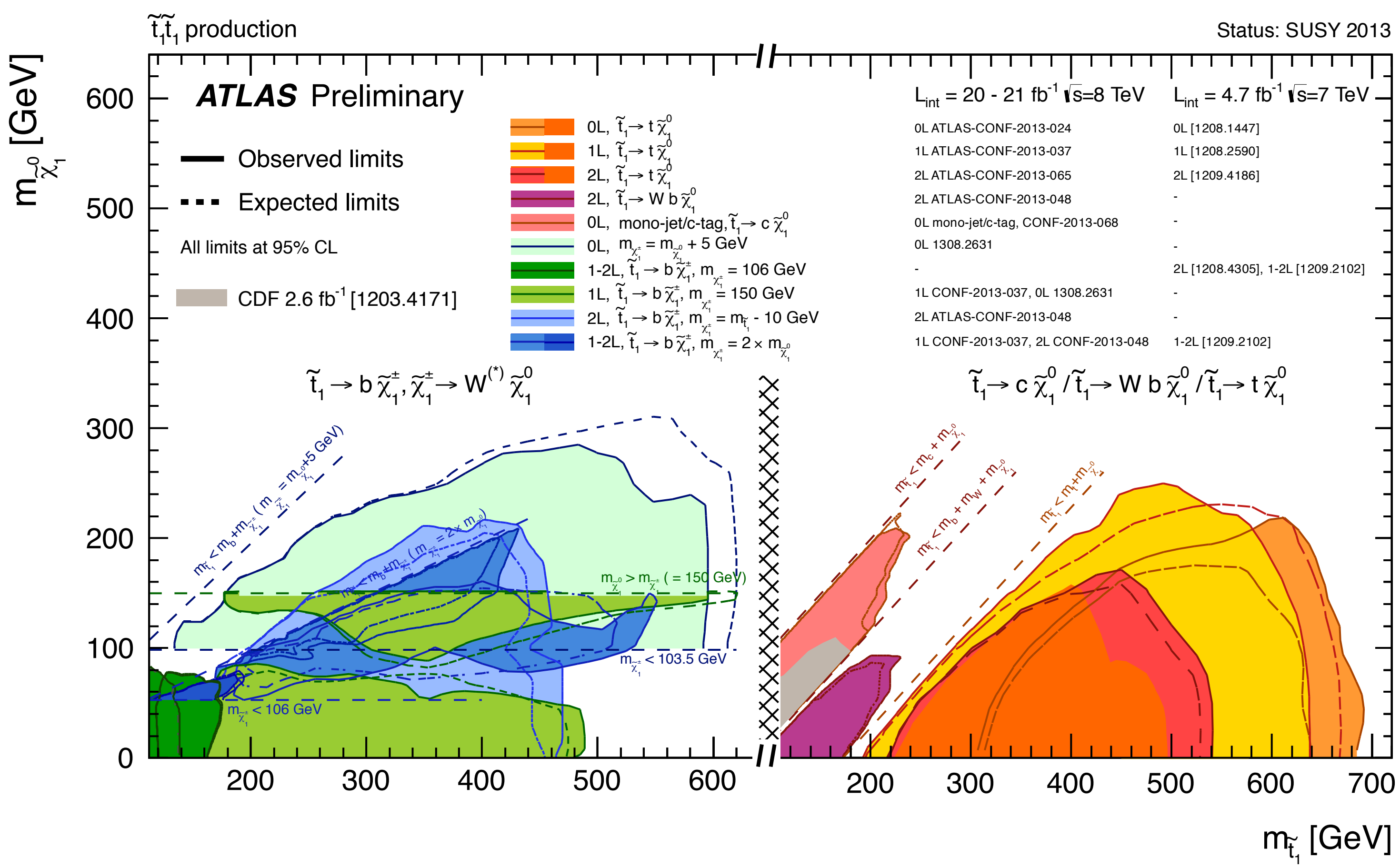
50 fb^{-1} LHCb
50 ab^{-1} Belle II
(Charles *et al.* 2013)

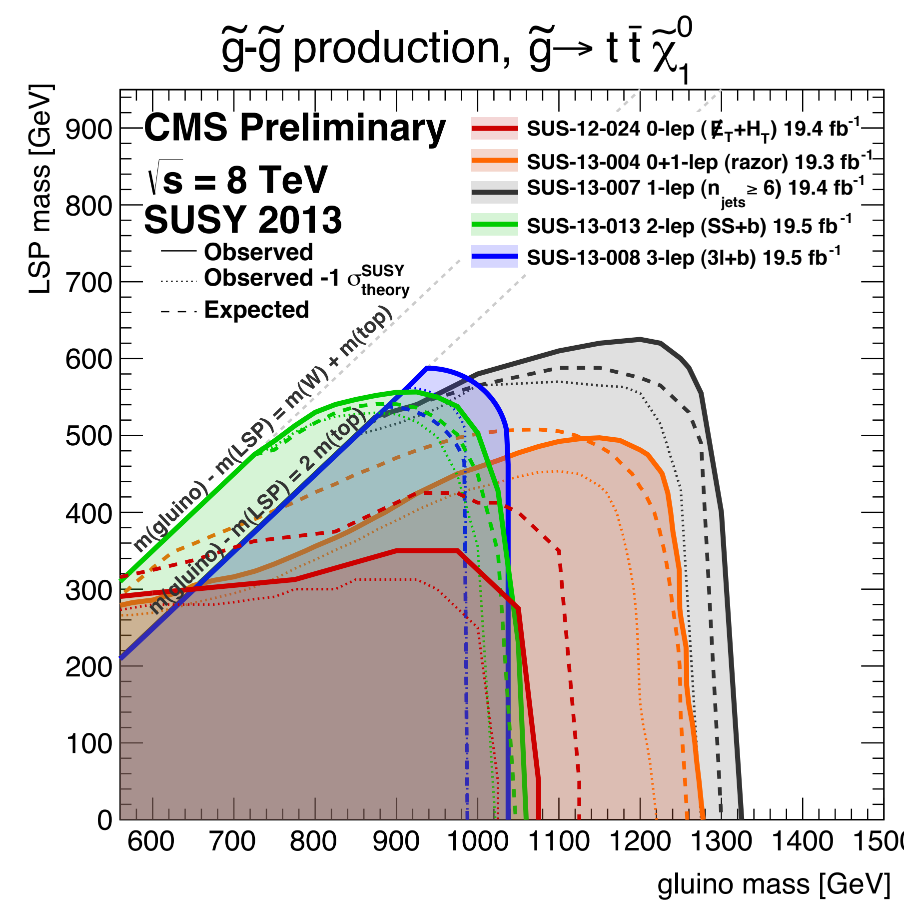
Numerical analysis of meson mixing

- Consider all the contributions. Many free parameters: scan over the parameter space (analysis with **`SUSY_FLAVOR`**)

Crivellin
Rosiek

- ATLAS and CMS mass bounds: $m_{\tilde{g}} \gtrsim 1.4\,\mathrm{TeV}$ $\quad m_{\tilde{t}} \gtrsim 700\,\mathrm{GeV}$

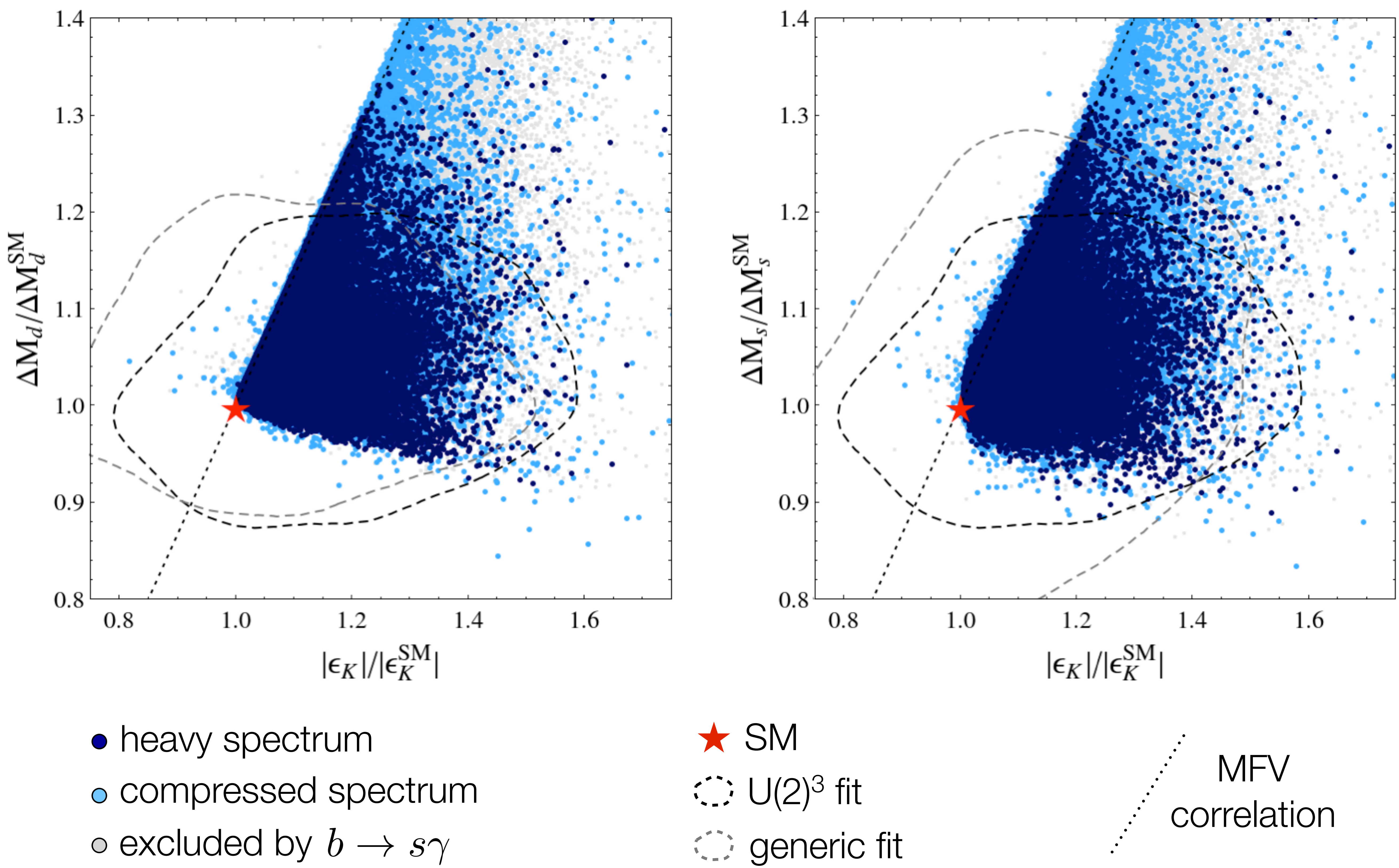




- Scan ranges: $\xi_\alpha \in [1/3, 3]$ $\quad \tilde{m}_3 \in [0.1, 1.5]\,\mathrm{TeV},$ $\quad m_{\tilde{g}} \in [0.1, 3]\,\mathrm{TeV},$

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

Numerical analysis of meson mixing



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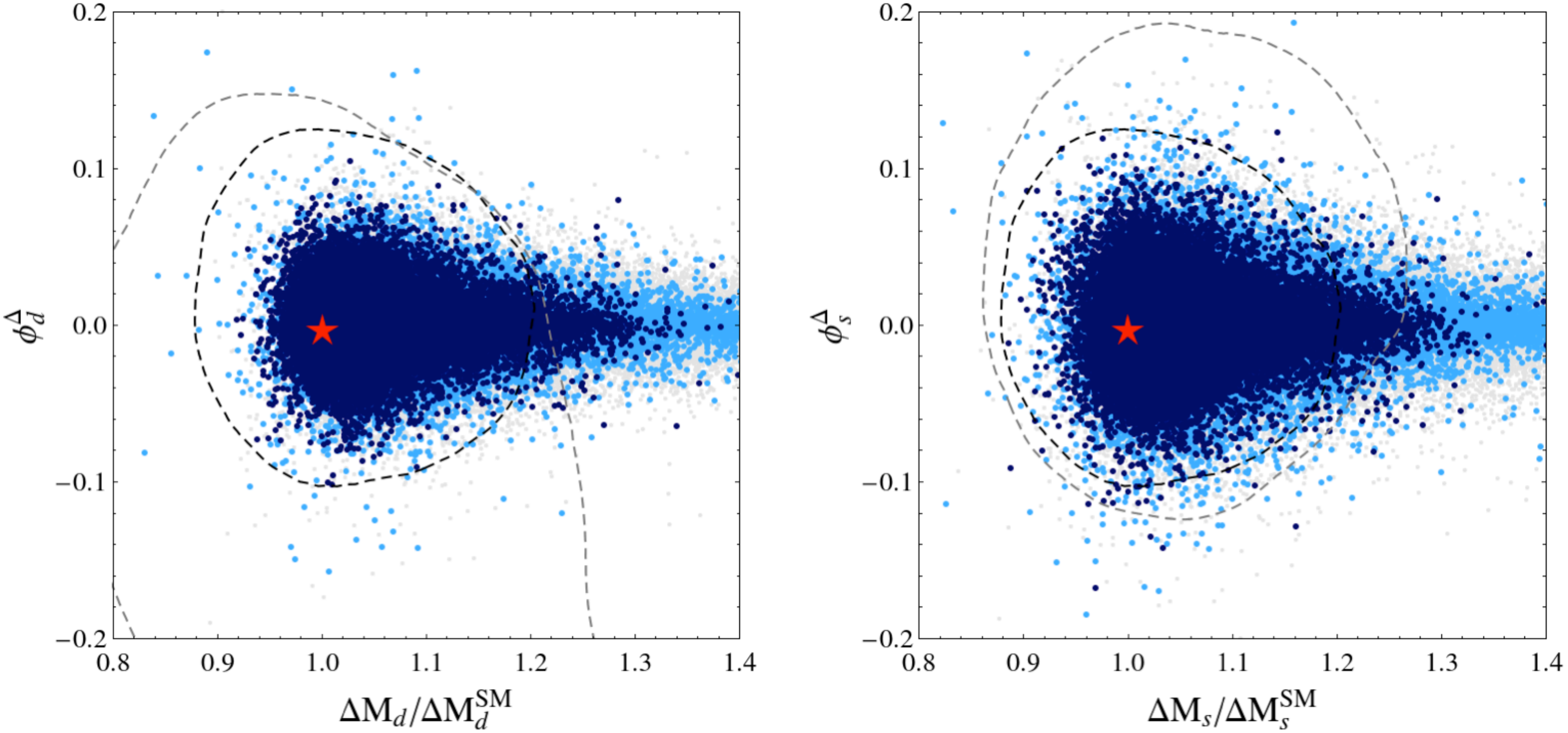
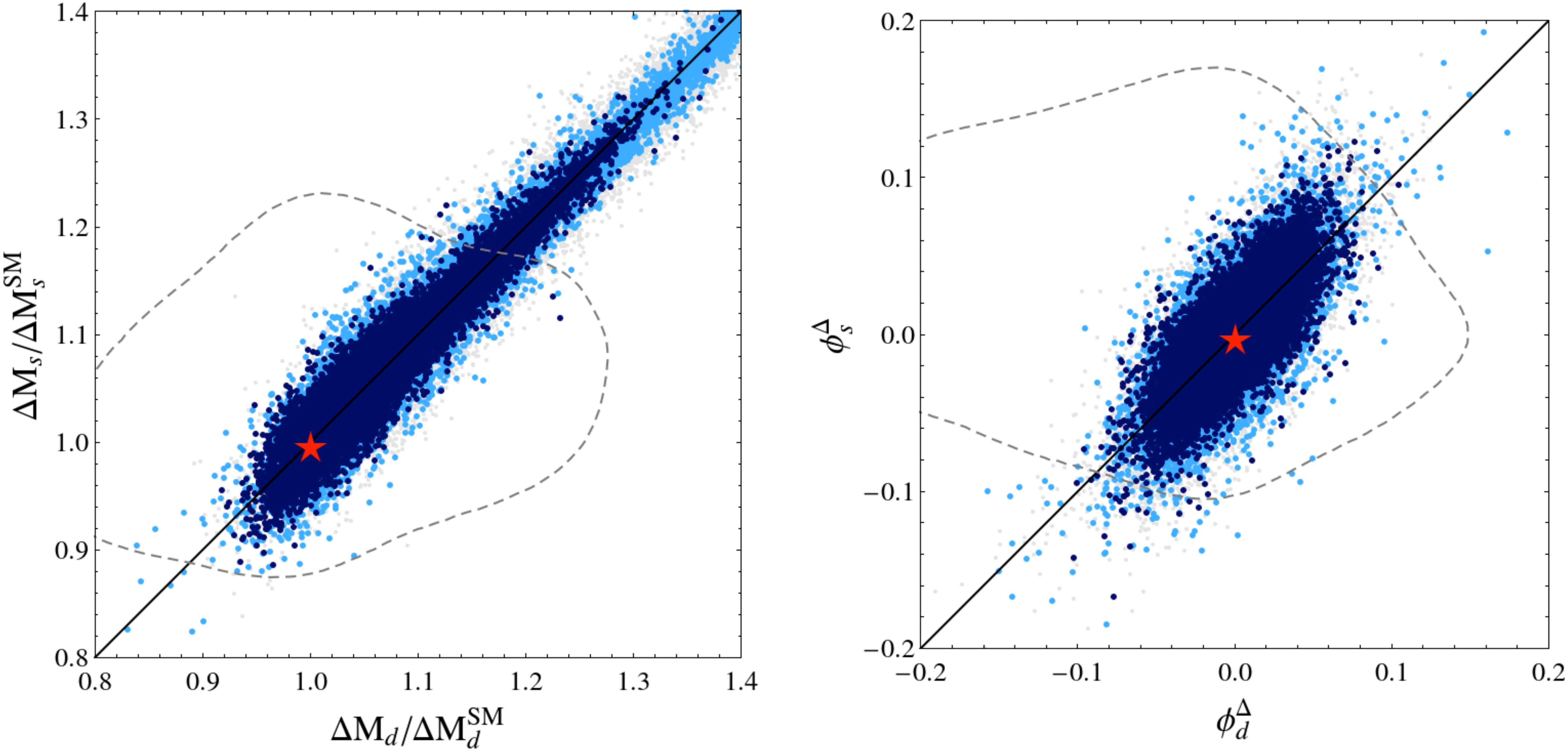


- heavy spectrum
- compressed spectrum
- excluded by $b \to s\gamma$
- SM
- $U(2)^3$ fit
- generic fit

Numerical analysis of meson mixing



- heavy spectrum
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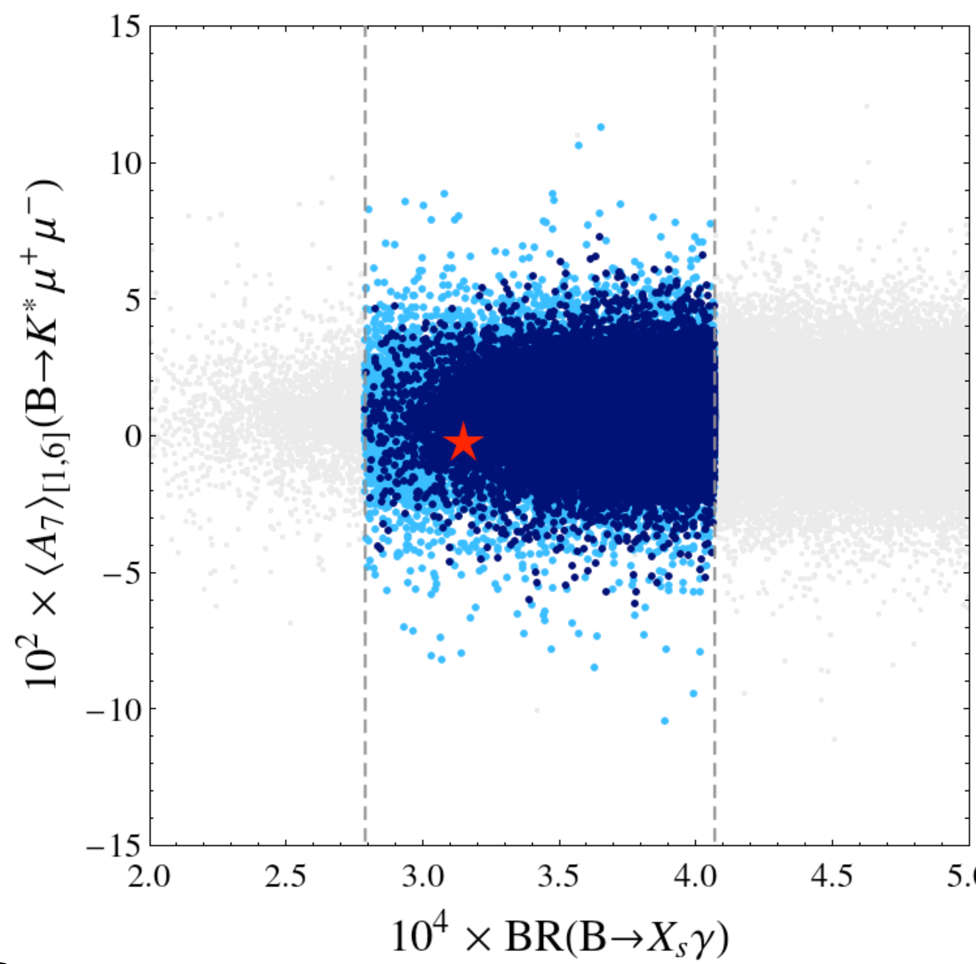
- ★ SM
- generic fit
- $U(2)^3$ correlation

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)

A different example: composite Higgs models

- In composite Higgs models large flavour effects are generated by the strongly interacting dynamics.
- In general, the bounds from flavour are stronger than the direct constraints on composite resonances.

Direct bounds: $m_\psi \gtrsim 700, \mathrm{GeV}$

Minimal fermion resonance mass [TeV]

	doublet	triplet	bidoublet
Ⓐ	$4.9^\dagger$	$1.7^\dagger$	$1.2^{*\dagger}$
$U(3)^3_{\mathrm{LC}}$	6.5	6.5	5.3
$U(3)^3_{\mathrm{RC}}$	-	-	3.3
$U(2)^3_{\mathrm{LC}}$	$4.9^\ddagger$	$0.6^\ddagger$	$0.6^\ddagger$
$U(2)^3_{\mathrm{RC}}$	-	-	1.1^*

Barbieri, B, Sala, Straub 2013

* $f > 500$ **GeV** and $g_\psi \approx 2.5$

† excluding ε_K, up to $\mathcal{O}(1)$ factors

‡ $r_b = 0.2$

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Barbieri, B, Sala, Straub 2013

- Only a few models can accommodate a 125 GeV composite Higgs with light top partners.

* $f > 500$ **GeV** and $g_\psi \approx 2.5$

† excluding ε_K, up to $\mathcal{O}(1)$ factors

‡ $r_b = 0.2$

Conclusions (part 1)

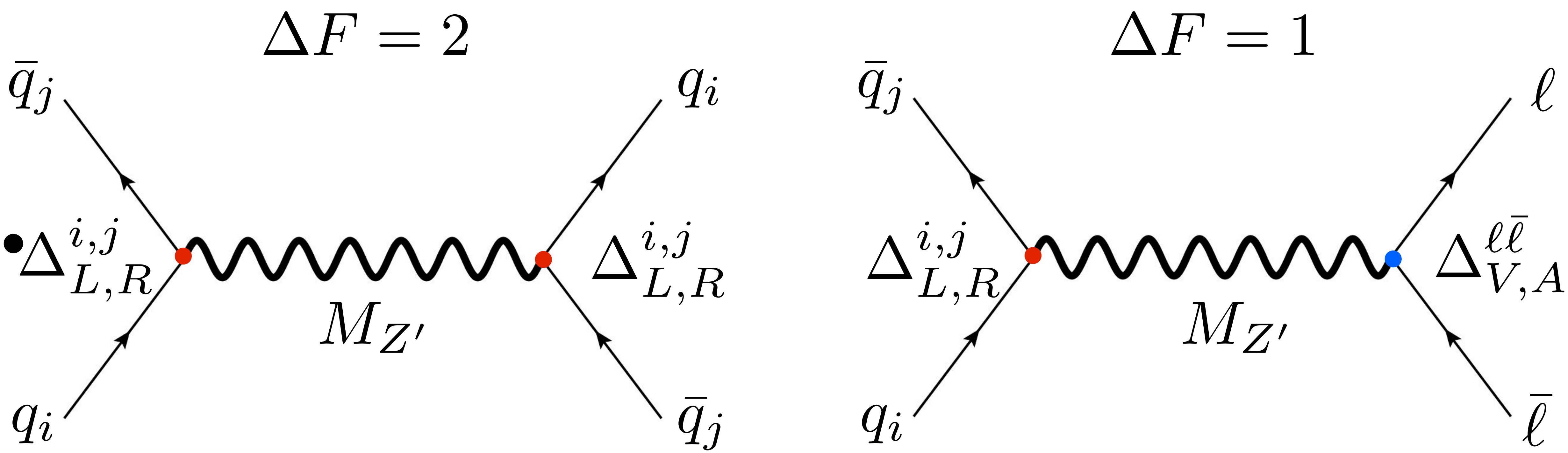
- Precision measurements in the flavour sector require a near-CKM picture of flavour-changing interactions.
- Two possible scenarios, based on symmetries only: $U(3)^3$, $U(2)^3$
- Updated fit of meson mixings in $U(2)^3$ (improved measurement of CP asymmetries in B decays and new lattice results)
- 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

2. High-scale flavour physics

A simple Z’ model

What are the highest scales testable through rare decays?

- Heavy vector resonance with flavour-changing quark couplings: a toy model to mimic FCNC



- All the 4-fermion amplitudes depend only on the ratios

$$\frac{\Delta^{ij}_{L,R}}{M_{Z'}}$$ → constrained by flavour

$$\frac{\Delta^{\ell\bar{\ell}}_{V,A}}{M_{Z'}}$$ → can be of O(1)

Projections for the coming years

Observable	2014		2019	2024	2030
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$\left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$	[32]	10% [33]	5% [34]	
$\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu})$	$< 2.6 \times 10^{-8}$ (90% CL)	[35]		5% [34]	
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$	$< 1.3 \times 10^{-5}$ (90% CL)	[36]		30%[37]	
$\mathcal{B}(B_d^0 \to K^{*0}\nu\bar{\nu})$	$< 5.5 \times 10^{-5}$ (90% CL)	[38]		35%[37]	
$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)$	$(2.9 \pm 0.7) \times 10^{-9}$	[39–41]	15%[42, 43]	12%[42]	10–12%[42, 43]
$\mathcal{B}(B_d \to \mu^+\mu^-)$	$\left(3.6^{+1.6}_{-1.4}\right) \times 10^{-10}$ †	[39–41]	66% [42]	45%[42]	18% [42]
$\mathcal{B}(B_d \to \mu^+\mu^-)/\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)$			71% [42]	47%[42]	21–35%[42, 43]

	2014		2019	2024	2030
F_{B_s}	(227.7 ± 4.5) MeV	[44]	$< 1\%$ [45]		
F_{B_d}	(190.5 ± 4.2) MeV	[44]	$< 1\%$ [45]		
$F_{B_s}\sqrt{\hat{B}_{B_s}}$	(266 ± 18) MeV	[44]	2.5% [45]	$< 1\%$ [46]	
$F_{B_d}\sqrt{\hat{B}_{B_d}}$	(216 ± 15) MeV	[44]	2.5% [45]	$< 1\%$ [46]	
$\hat{B}_K$	0.766 ± 0.010	[44]	$< 1\%$ [45]		
$\lvert V_{ub}\rvert_{\rm incl}$	$(4.40 \pm 0.25) \times 10^{-3}$	[44]	5% [37]	3% [37]	
$\lvert V_{ub}\rvert_{\rm excl}$	$(3.42 \pm 0.31) \times 10^{-3}$	[44]	12% †† [37]	5% †† [37]	
$\lvert V_{cb}\rvert_{\rm incl}$	$(42.4 \pm 0.9) \times 10^{-3}$	[47]	1% [48]	$< 1\%$ [48]	
$\lvert V_{cb}\rvert_{\rm excl}$	$(39.4 \pm 0.6) \times 10^{-3}$	[44]	1% [48]	$< 1\%$ [48]	
γ	$(70.1 \pm 7.1)^\circ$ †	[49]	6% [37]	1.5% [37]	1.3%[43]
$\phi_d^{\rm SM} = 2\beta$	$(43.0^{+1.6}_{-1.4})^\circ$	[50]	$\sim 1^\circ$ ‡[51, 52]		
$\phi_s^{\rm SM} = -2\beta_s$	$(0 \pm 4)^\circ$	[50]	1.4° [43]	$\sim 1^\circ$ ‡[53]	

Projections for the coming years

Observable	2014		2019	2024	2030
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$	$(17.3^{+11.5}_{-10.5}) \times 10^{-11}$	[32]	10% [33]	5% [34]	
$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$	$< 2.6 \times 10^{-8}$ (90% CL)	[35]		5% [34]	
$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$	$< 1.3 \times 10^{-5}$ (90% CL)	[36]		30% [37]	
$\mathcal{B}(B_d^0 \to K^{*0} \nu\bar{\nu})$	$< 5.5 \times 10^{-5}$ (90% CL)	[38]		35% [37]	
$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)$	$(2.9 \pm 0.7) \times 10^{-9}$	[39–41]	15% [42, 43]	12% [42]	10–12% [42, 43]
$\mathcal{B}(B_d \to \mu^+\mu^-)$	$(3.6^{+1.6}_{-1.4}) \times 10^{-10}$ †	[39–41]	66% [42]	45% [42]	18% [42]
$\mathcal{B}(B_d \to \mu^+\mu^-)/\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)$			71% [42]	47% [42]	21–35% [42, 43]

	2014		2019		2024		2030	
F_{B_s}	(227.7 ± 4.5) MeV	[44]	$< 1\%$	[45]				
F_{B_d}	(190.5 ± 4.2) MeV	[44]	$< 1\%$	[45]				
$F_{B_s}\sqrt{\hat{B}_{B_s}}$	(266 ± 18) MeV	[44]	2.5%	[45]	$< 1\%$	[46]		
$F_{B_d}\sqrt{\hat{B}_{B_d}}$	(216 ± 15) MeV	[44]	2.5%	[45]	$< 1\%$	[46]		
$\hat{B}_K$	0.766 ± 0.010	[44]	$< 1\%$	[45]				
$\lvert V_{ub}\rvert_{\text{incl}}$	$(4.40 \pm 0.25) \times 10^{-3}$	[44]	5%	[37]	3%	[37]		
$\lvert V_{ub}\rvert_{\text{excl}}$	$(3.42 \pm 0.31) \times 10^{-3}$	[44]	12% ††	[37]	5% ††	[37]		
$\lvert V_{cb}\rvert_{\text{incl}}$	$(42.4 \pm 0.9) \times 10^{-3}$	[47]	1%	[48]	$< 1\%$	[48]		
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Observable	2014	2019	2024	2030
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$\mathcal{B}(K_{\rm L} \to \pi^0\nu\bar{\nu})$	$< 2.6 \times 10^{-8}$ (90% CL)[35]		5% [34]	
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$	$< 1.3 \times 10^{-5}$ (90% CL)[36]		30%[37]	
$\mathcal{B}(B_d^0 \to K^{*0}\nu\bar{\nu})$	$< 5.5 \times 10^{-5}$ (90% CL)[38]		35%[37]	
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How far can we go with ΔF = 1 measurements?

- <u>Assume</u> for now only LH (or only RH) couplings to quarks
- ΔF = 2 alone would constrain only the ratio $\Delta_{ij}/M_{Z'}$...
- ΔF = 1 has a different mass/coupling dependence: we can constrain mass and couplings separately

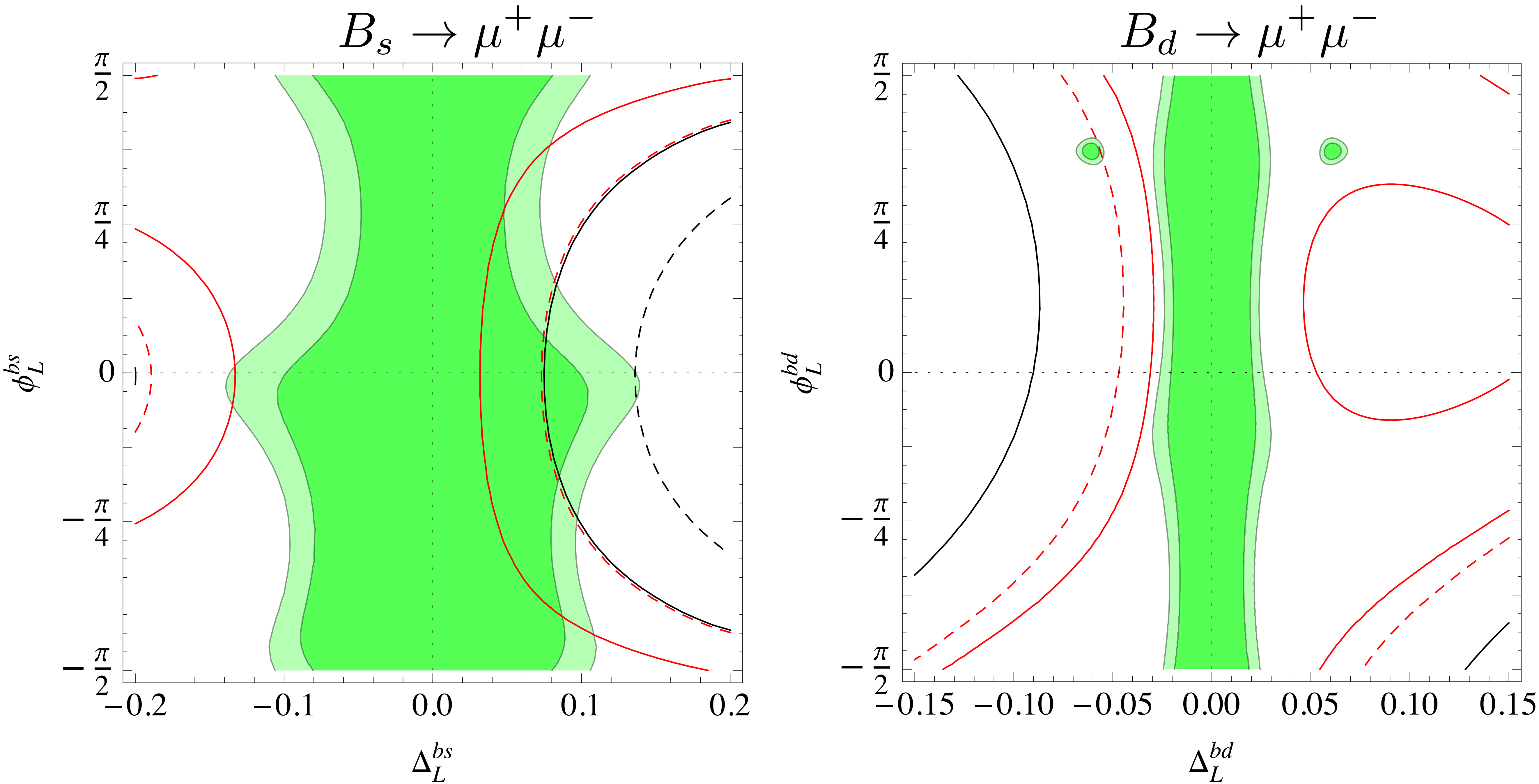
$$C_{\Delta F=2} \propto \frac{\Delta_{ij}^2}{M_{Z'}^2} \qquad C_{\Delta F=1} \propto \frac{\Delta_{ij}\Delta_{\ell\bar{\ell}}}{M_{Z'}^2}$$

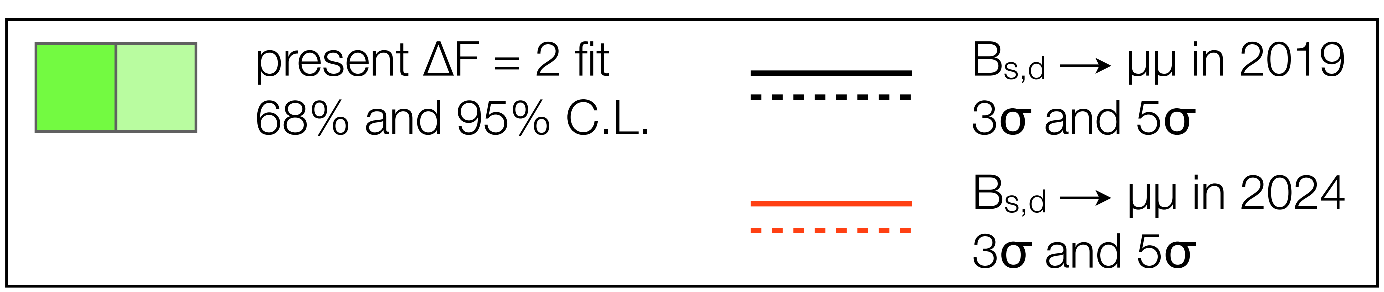
$$\Longrightarrow \quad C_{\Delta F=1} \propto \sqrt{C_{\Delta F=2}}\,\frac{\Delta_{\ell\bar{\ell}}}{M_{Z'}}$$

does not depend on the FC coupling

- **If** nothing is seen in ΔF = 2, rare decays are more effective at low mass and small couplings...

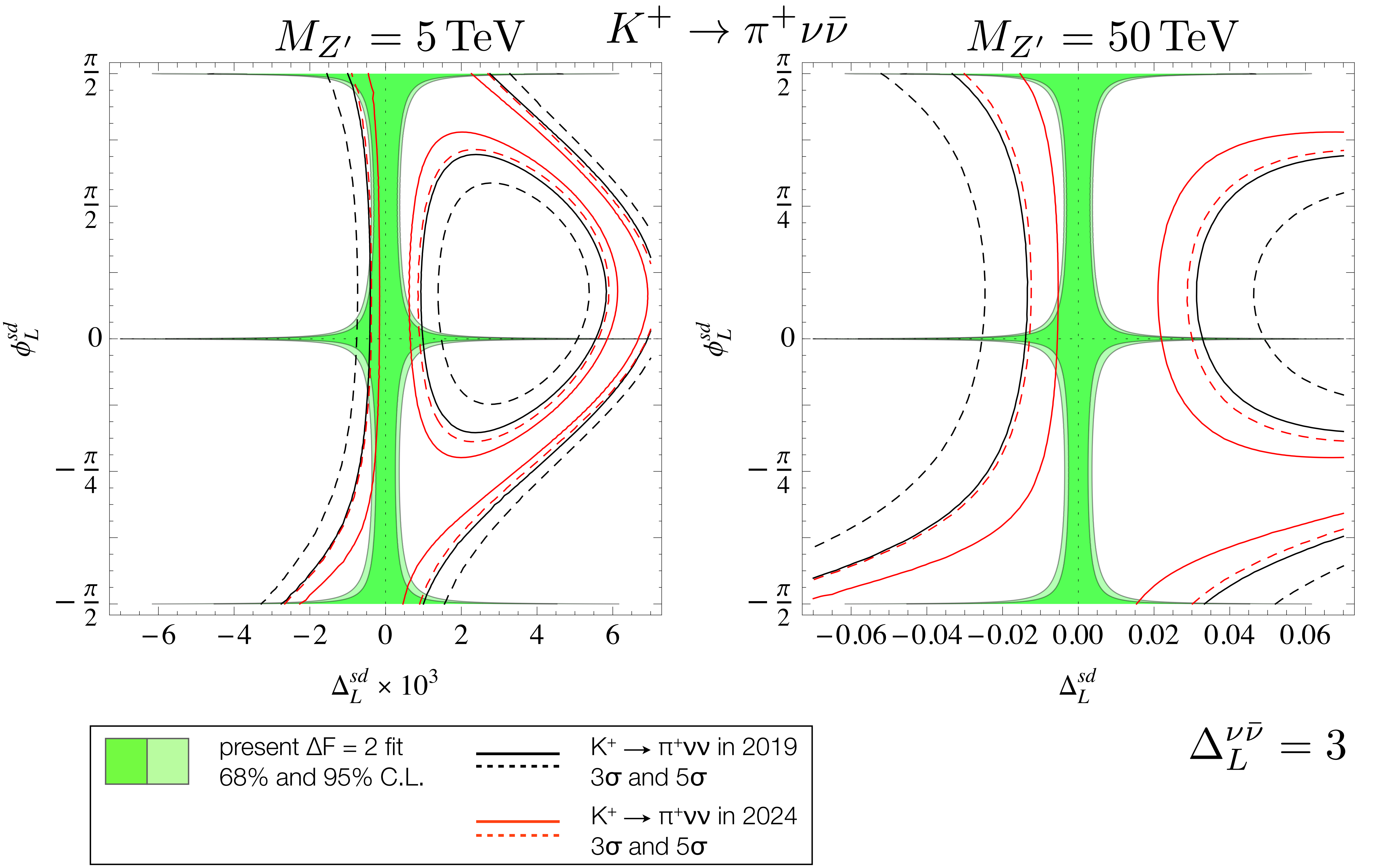
How far can we go with rare B decays?





$$M_{Z'} = 15\,\text{TeV}$$
$$\Delta_A^{\mu^+\mu^-} = -3$$

How far can we go with rare K decays?

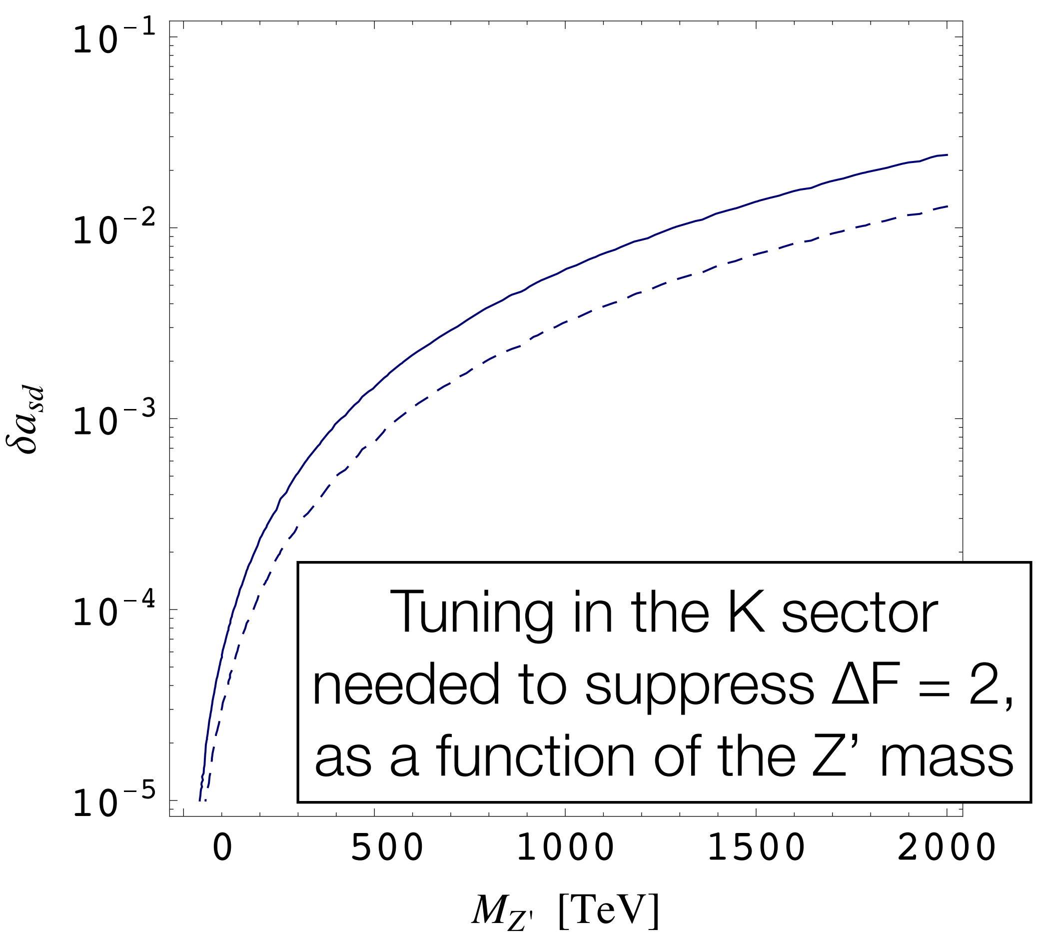


Removing the ΔF = 2 constraint by tuning

- Of course, you can complicate the model at will, and get rid of the ΔF = 2 bounds by tuning the parameters...

- If e.g. both LH and RH flavour-changing couplings are present:

$$(M_{12}^*)^{ij} = \frac{1}{2M_{Z'}^2}\left[\left((\Delta_L^{ij})^2 + (\Delta_L^{ij})^2\right)\langle \hat{Q}_1^{VLL}\rangle^{ij} + 2\Delta_L^{ij}\Delta_R^{ij}\langle \hat{Q}_1^{LR}\rangle^{ij}\right]$$



- For the largest possible flavour violation, compatibly with perturbativity (all couplings = 3):

$$M_{Z'}^{\max}(K) \approx 2000\,\mathrm{TeV}$$

$$M_{Z'}^{\max}(B_{s,d}) \approx 160\,\mathrm{TeV}$$

Buras, B, Girrbach, Knegjens '14

3. $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ in the SM

$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ in the SM

- Two *golden modes* that will be precisely measured in this decade

- Theoretically very clean prediction of the BR's in the SM

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ (1 + \Delta_{\rm EM}) \cdot \left[\left(\frac{{\rm Im}\lambda_t}{\lambda^5} X_t \right)^2 + \left(\frac{{\rm Re}\lambda_c}{\lambda} P_c + \frac{{\rm Re}\lambda_t}{\lambda^5} X_t \right)^2 \right]$$

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \cdot \left(\frac{{\rm Im}\lambda_t}{\lambda^5} X_t \right)^2,$$

- Present bounds:

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm exp} = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11}$$

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\rm exp} \leq 2.6 \cdot 10^{-8}$$

- Precision of ~ 5% by 2025 (10% by 2020)

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Hadronic parameters

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Top-quark contribution
known at NLO in the full SM

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Hadronic parameters

Top-quark contribution
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CKM matrix elements

$\lambda_t = V_{ts} V_{td}^*, \quad \lambda_c = V_{cs} V_{cd}^*,$
$\lambda = V_{us}$

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$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm exp} = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11}$$

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CKM matrix elements from tree-level decays

- Tree-level measurements can safely be assumed to be free of BSM physics effects. They determine the CKM matrix elements V_{ub}, V_{cb}, V_{us}, and γ:

$$V_{us} = 0.2252(9) \qquad\qquad \gamma = (73.2^{+6.3}_{-7.0})^\circ$$

- Discrepancy between inclusive and exclusive determinations

$$|V_{ub}|_{\rm incl} = (4.40 \pm 0.25) \times 10^{-3}, \qquad |V_{cb}|_{\rm incl} = (42.21 \pm 0.78) \times 10^{-3}.$$

$$|V_{ub}|_{\rm excl} = (3.72 \pm 0.14) \times 10^{-3}, \qquad |V_{cb}|_{\rm excl} = (39.36 \pm 0.75) \times 10^{-3}.$$

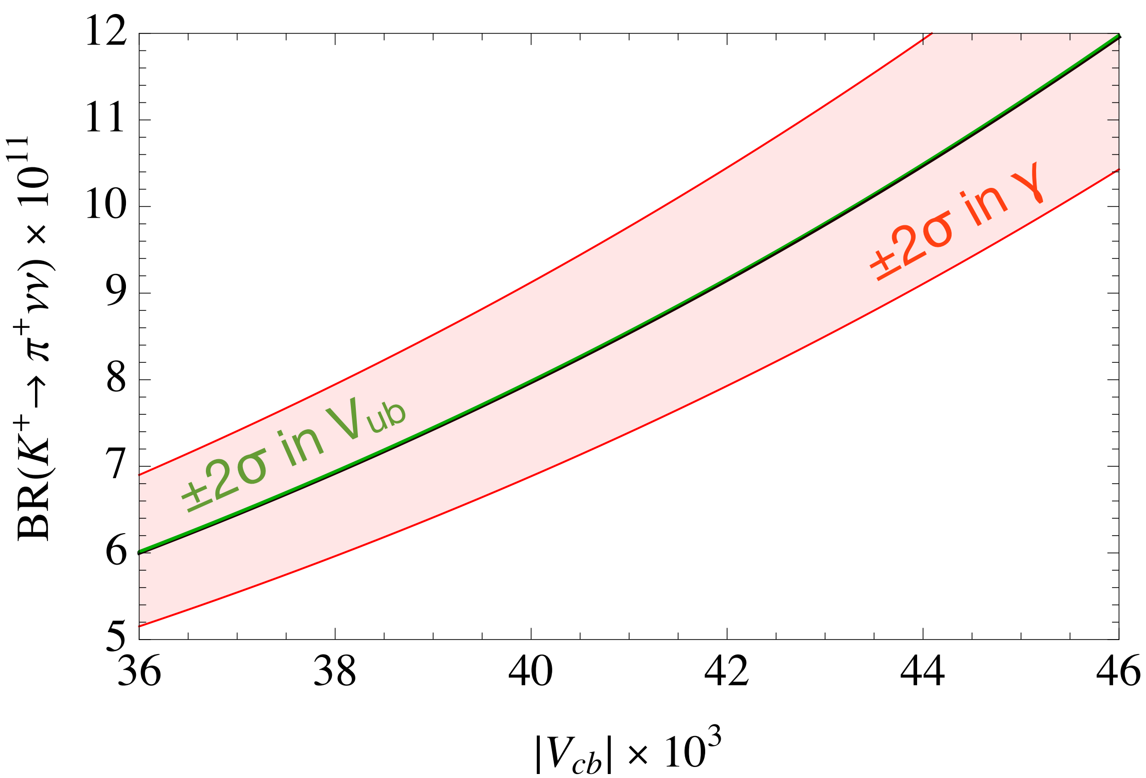
- The full CKM matrix is fixed once these parameters are known

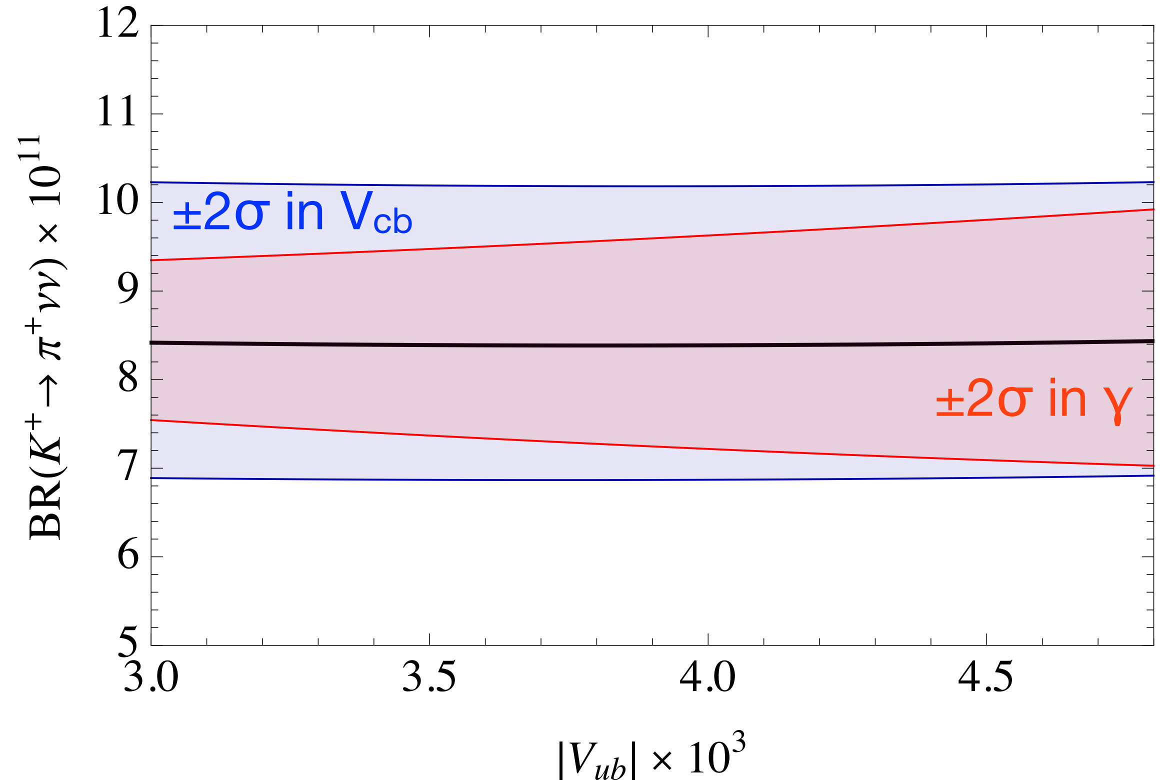
$$\mathrm{Re}\,\lambda_t = |V_{ub}||V_{cb}|\cos\gamma(1-2\lambda^2) + (|V_{ub}|^2 - |V_{cb}|^2)\lambda\left(1-\frac{\lambda^2}{2}\right) + \cdots$$

$$\mathrm{Im}\,\lambda_t = |V_{ub}||V_{cb}|\sin\gamma + \cdots \qquad \mathrm{Re}\,\lambda_c = -\lambda\left(1-\frac{\lambda^2}{2}\right) + \cdots$$

CKM matrix elements from tree-level decays

- $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2^\circ}\right]^{0.708}$

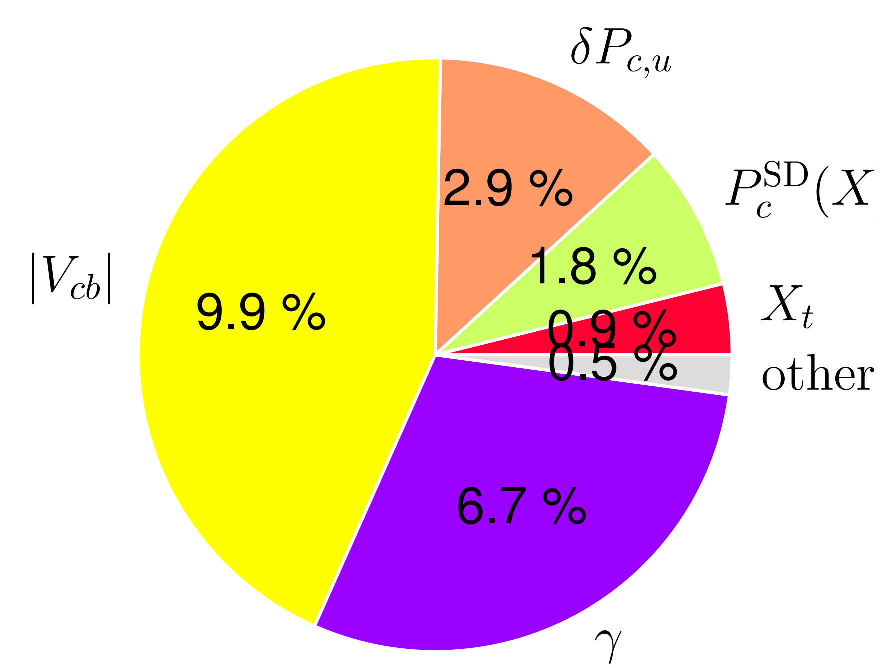




- Using an average of the previous values one gets:

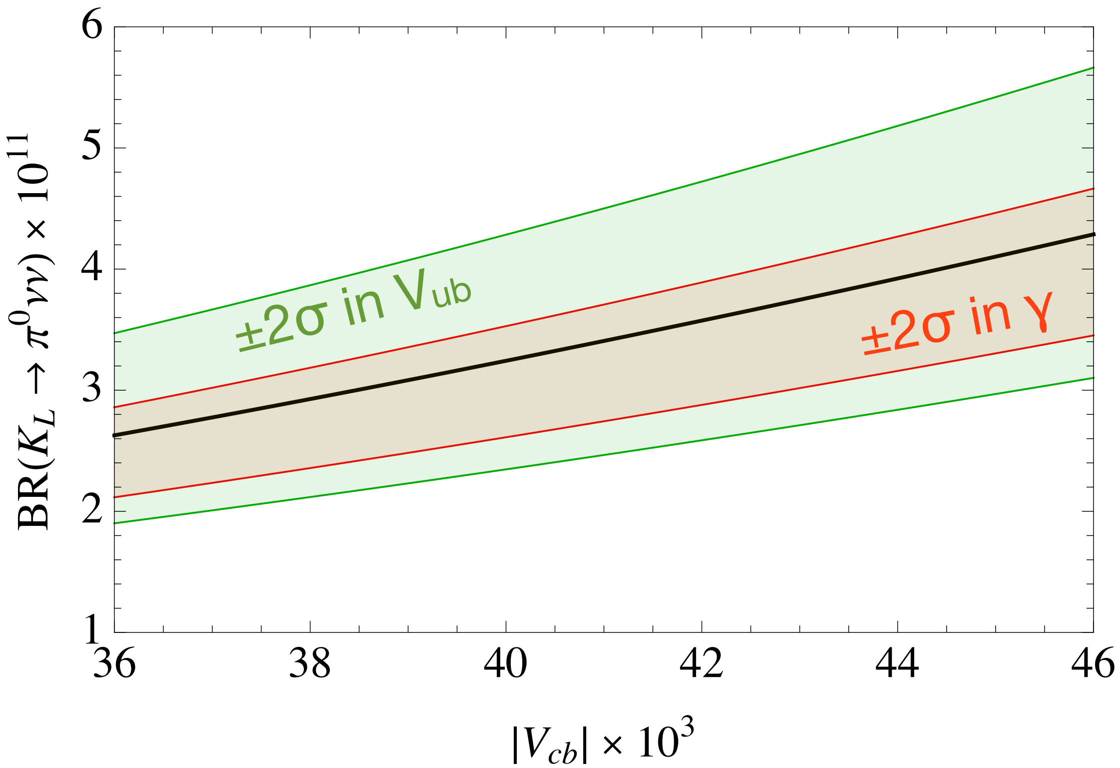
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

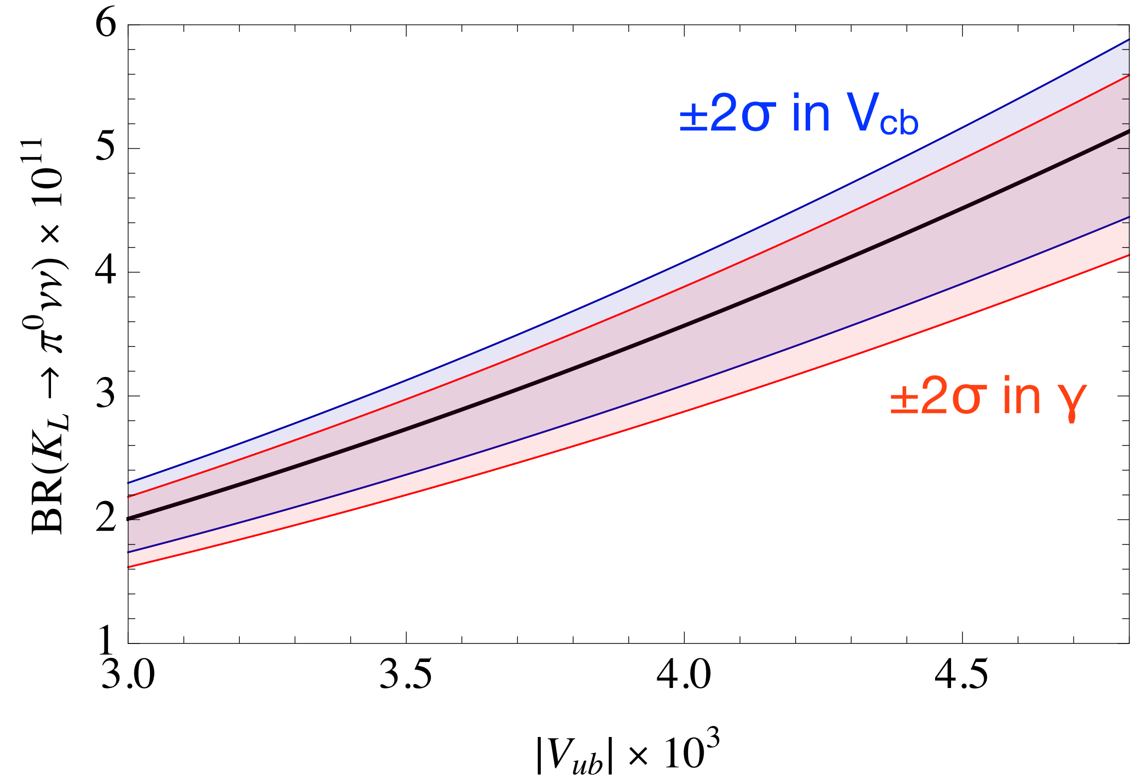
- The main uncertainty at present comes from the CKM matrix



CKM matrix elements from tree-level decays

- $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^2 \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^2 \left[\frac{\sin(\gamma)}{\sin(73.2^\circ)}\right]^2$





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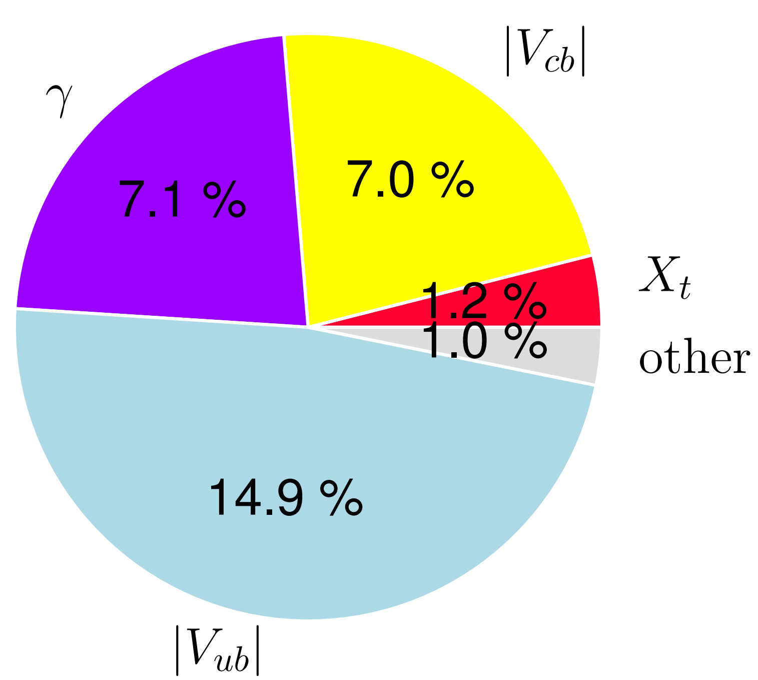
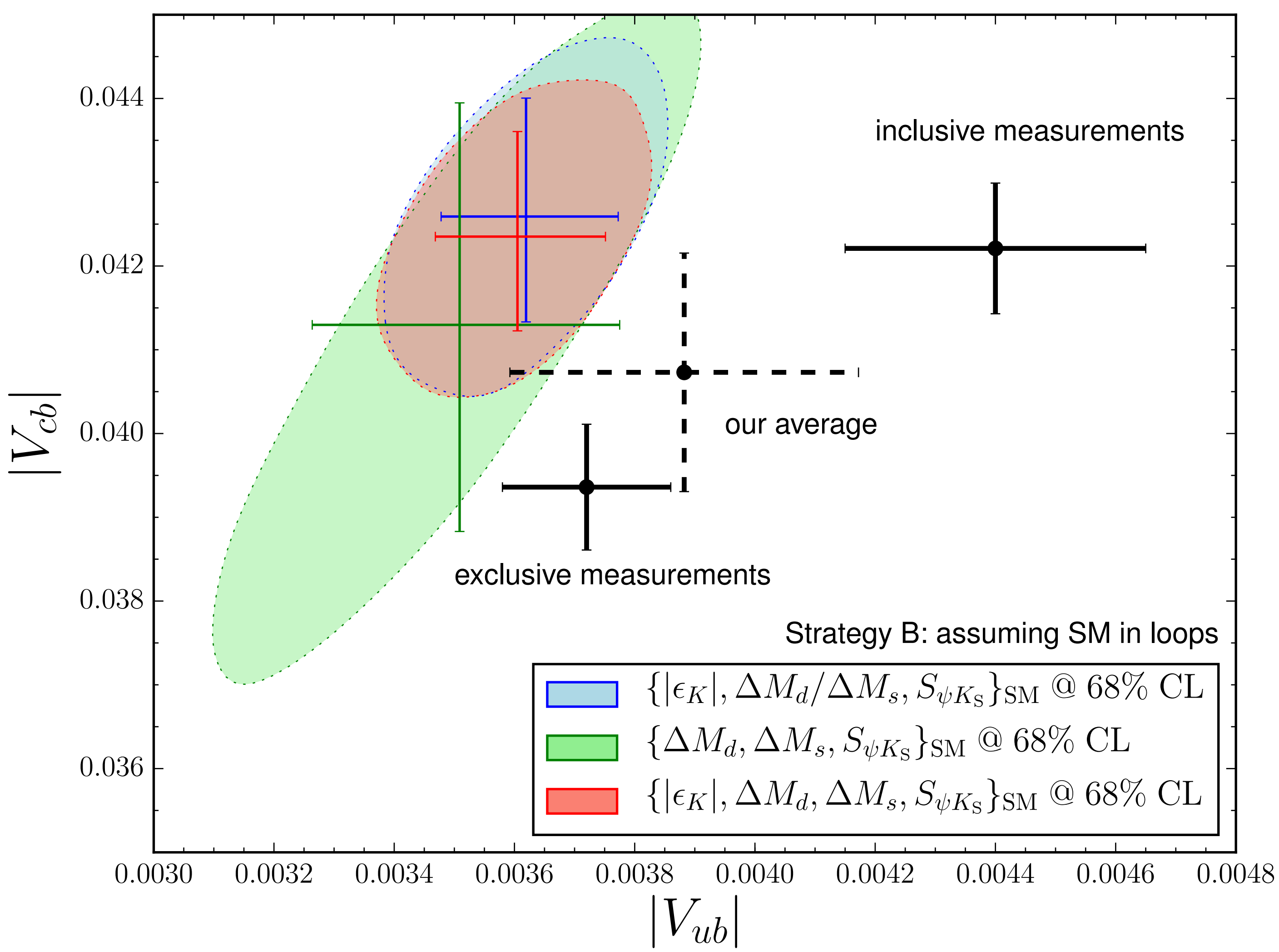


CKM matrix from loop processes

- Performing a fit to the loop-level observables $\varepsilon_K, \Delta M_s, \Delta M_d, S_{\psi K_S}$ a more precise determination of the CKM matrix is obtained (assuming that all those observables are SM-like)



$$|V_{ub}| = (3.61 \pm 0.14) \times 10^{-3},$$
$$|V_{cb}| = (42.4 \pm 1.2) \times 10^{-3},$$
$$\gamma = (69.5 \pm 5.0)^\circ.$$

using the projected lattice errors from 1412.5097:

$$|V_{cb}| = (42.0 \pm 0.9) \times 10^{-3},$$
$$\gamma = (70.8 \pm 2.3)^\circ.$$

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$$\mathcal{B}(K^+ \to \pi^+ \nu\bar\nu) = (9.11 \pm 0.72) \times 10^{-11}, \quad \mathcal{B}(K_L \to \pi^0 \nu\bar\nu) = (3.00 \pm 0.31) \times 10^{-11}$$

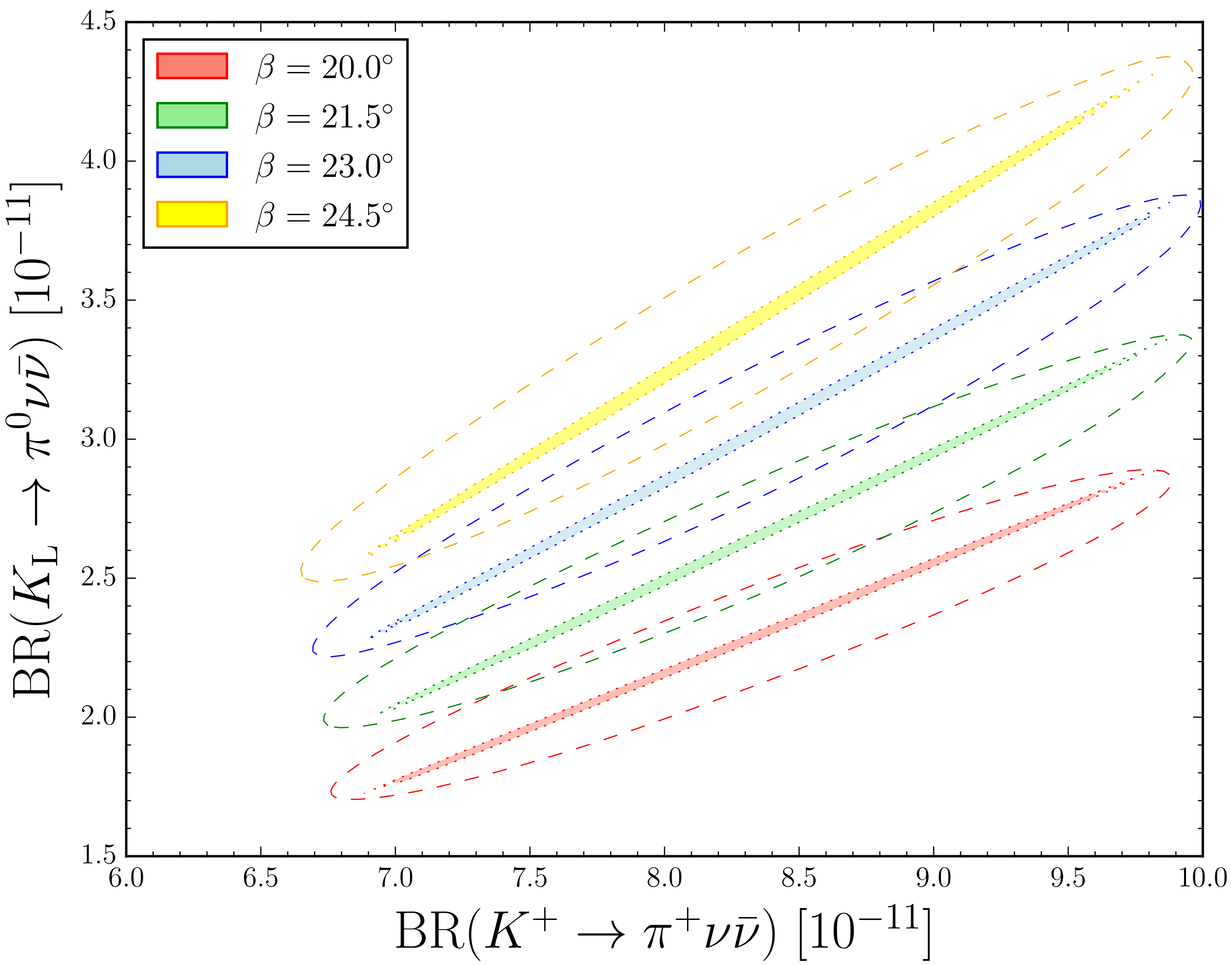
Correlation between $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$

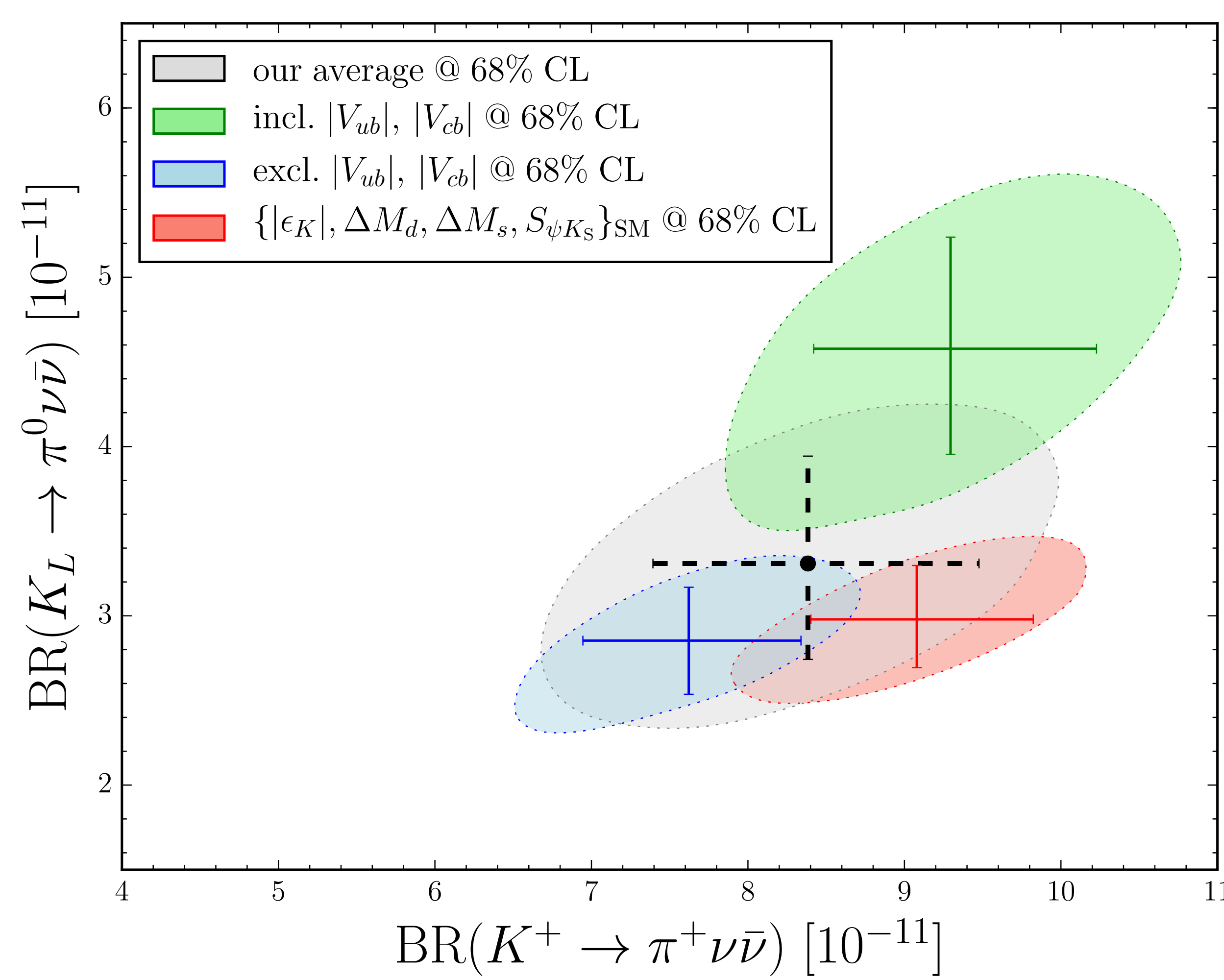
- In all models that do not change the phase of X_t (e.g. in MFV)

$$B_+ = B_L + \left[\frac{\mathrm{Re}\,\lambda_t}{\mathrm{Im}\,\lambda_t} \sqrt{B_L} - \left(1 - \frac{\lambda^2}{2}\right) P_c \,\mathrm{sgn}(X_t) \right]$$

$$B_+ = \frac{\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}}{\kappa_+ (1 + \Delta_{\mathrm{EM}})} \qquad B_L = \frac{\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}}{\kappa_L}$$

Standard Model





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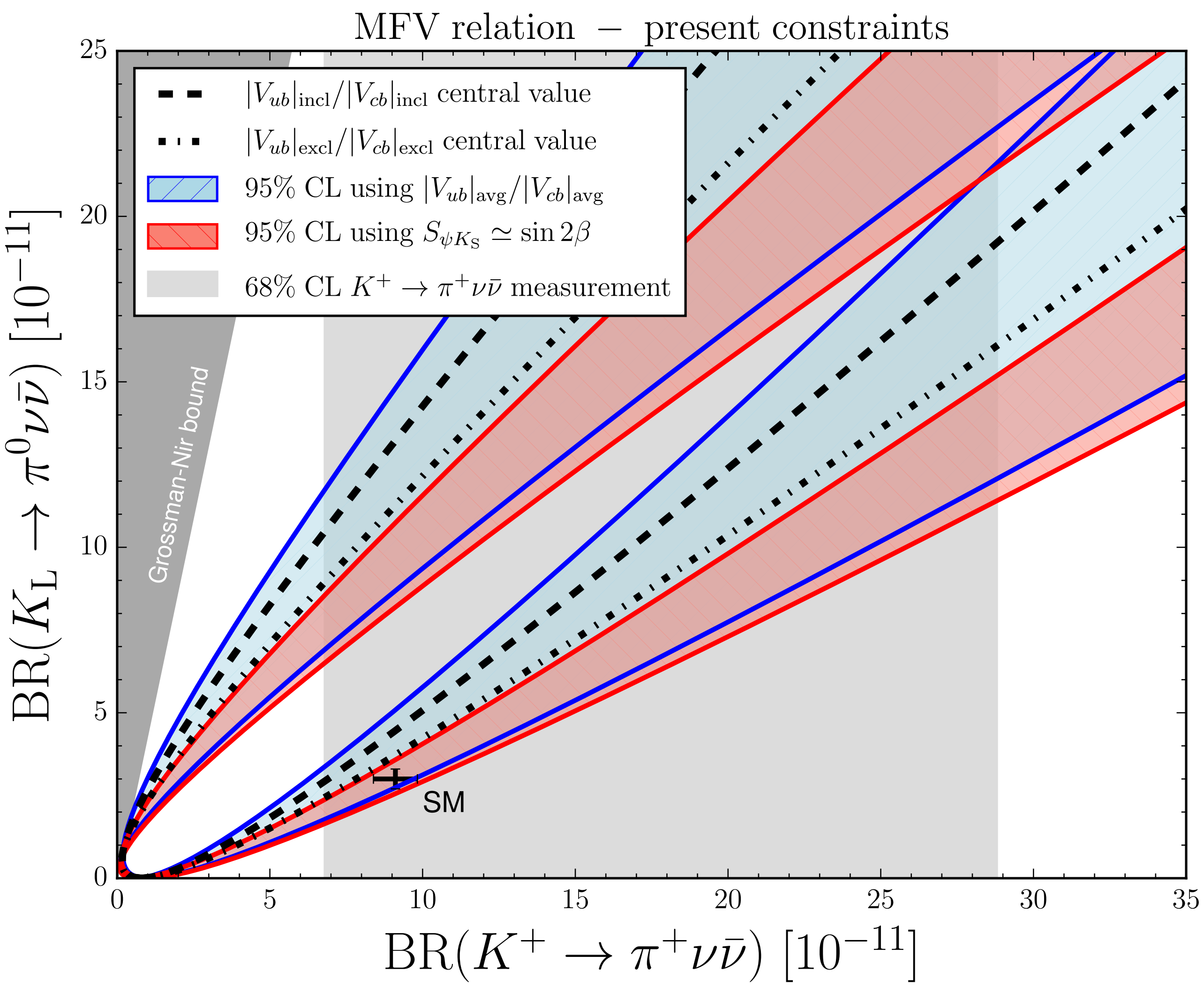
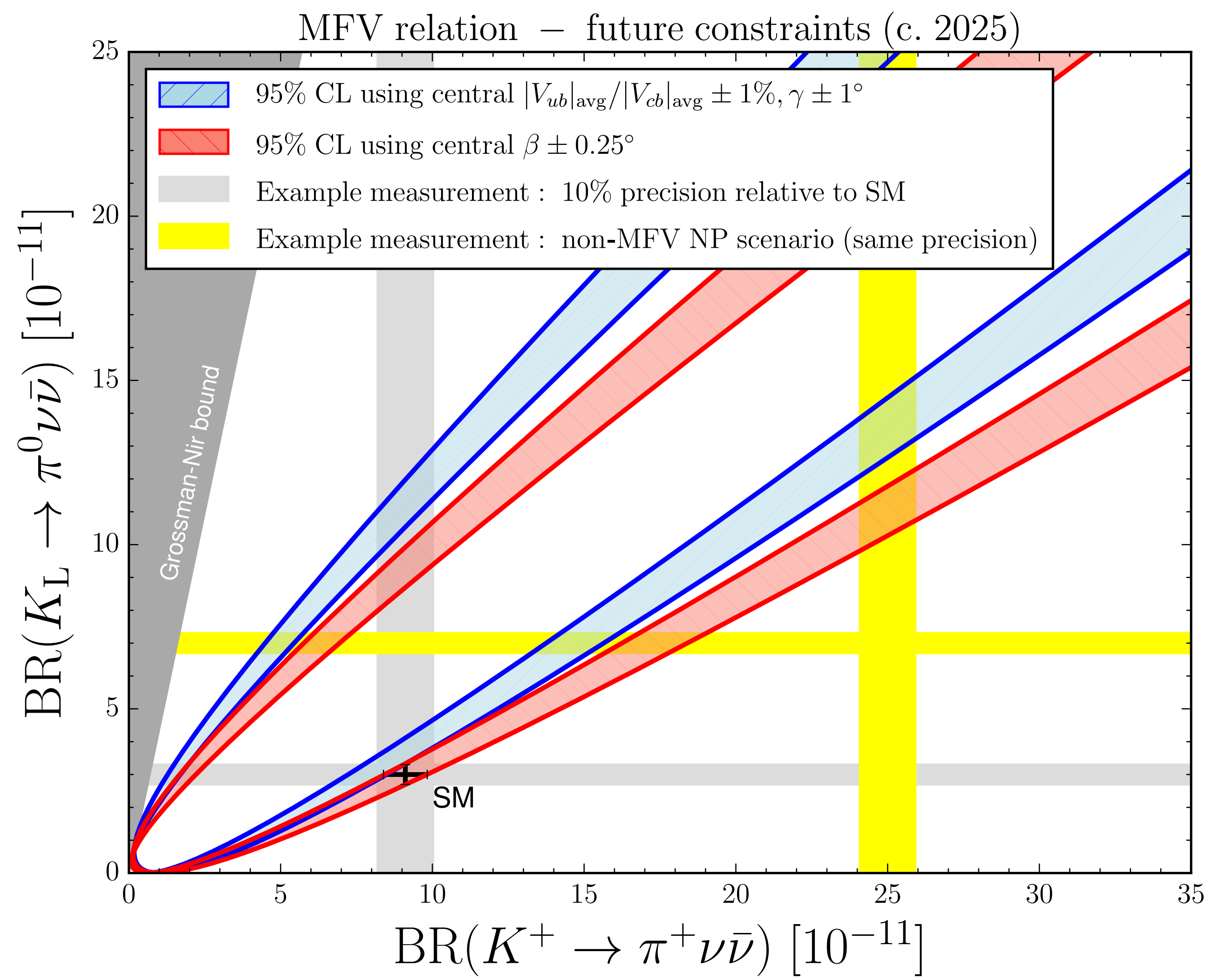
MFV





Conclusions (part 2)

- Precision measurements of rare meson decays can be used to probe high energy scales, otherwise directly unaccessible.

- In a simple Z' toy model, K decays can probe scales as high as 100 TeV, while B decays can reach only 15 – 20 TeV.
  (scales of 2000 and 200 TeV are reached tuning the parameters)

- Lattice calculations of hadronic parameters are improving quickly. Many errors are already dominated by CKM uncertainties.

- $K \to \pi \nu \bar{\nu}$ decays will be measured very precisely: stay tuned!

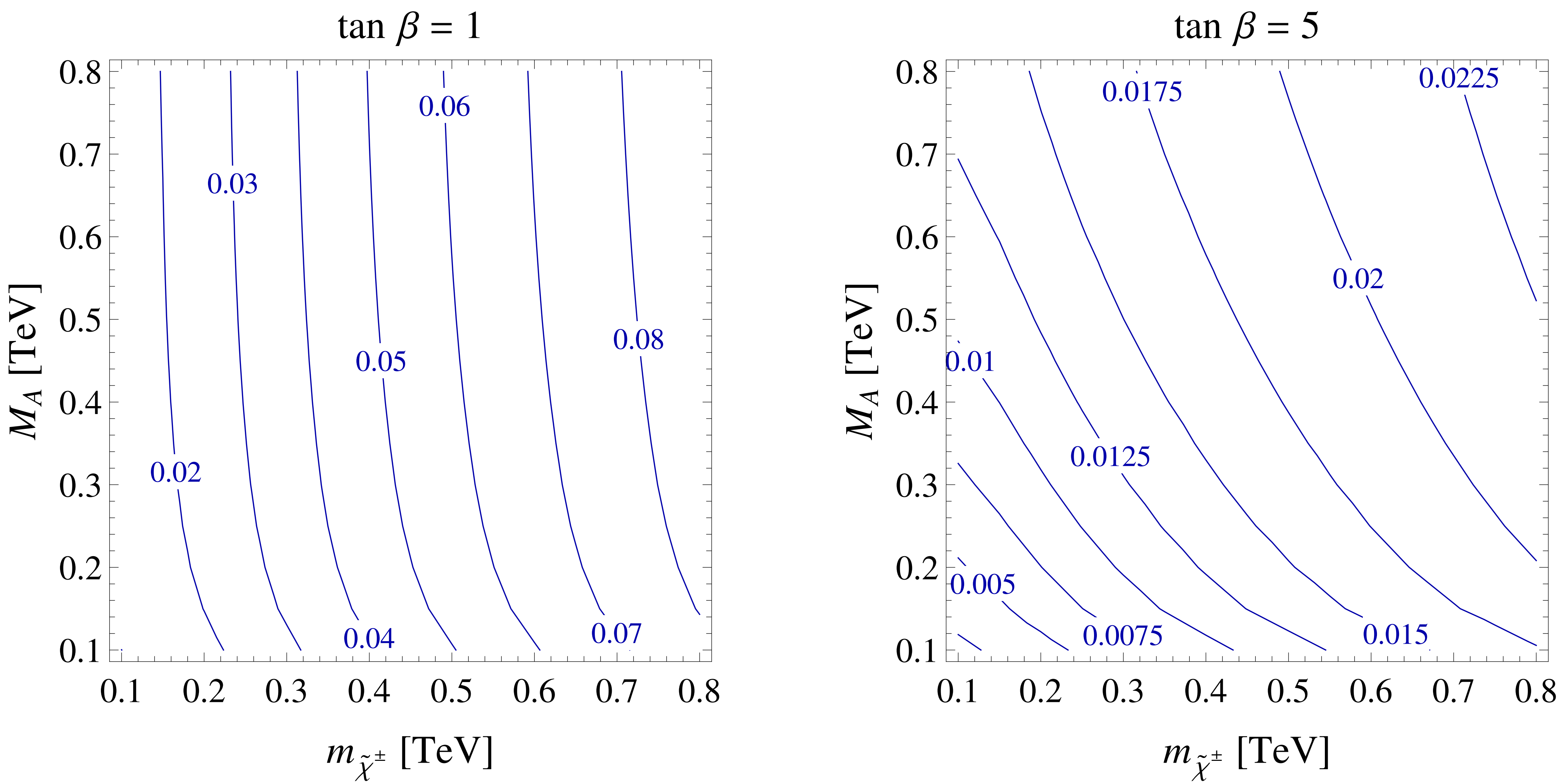
- Precise SM predictions and several correlations among observables can be used to constrain BSM physics.

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



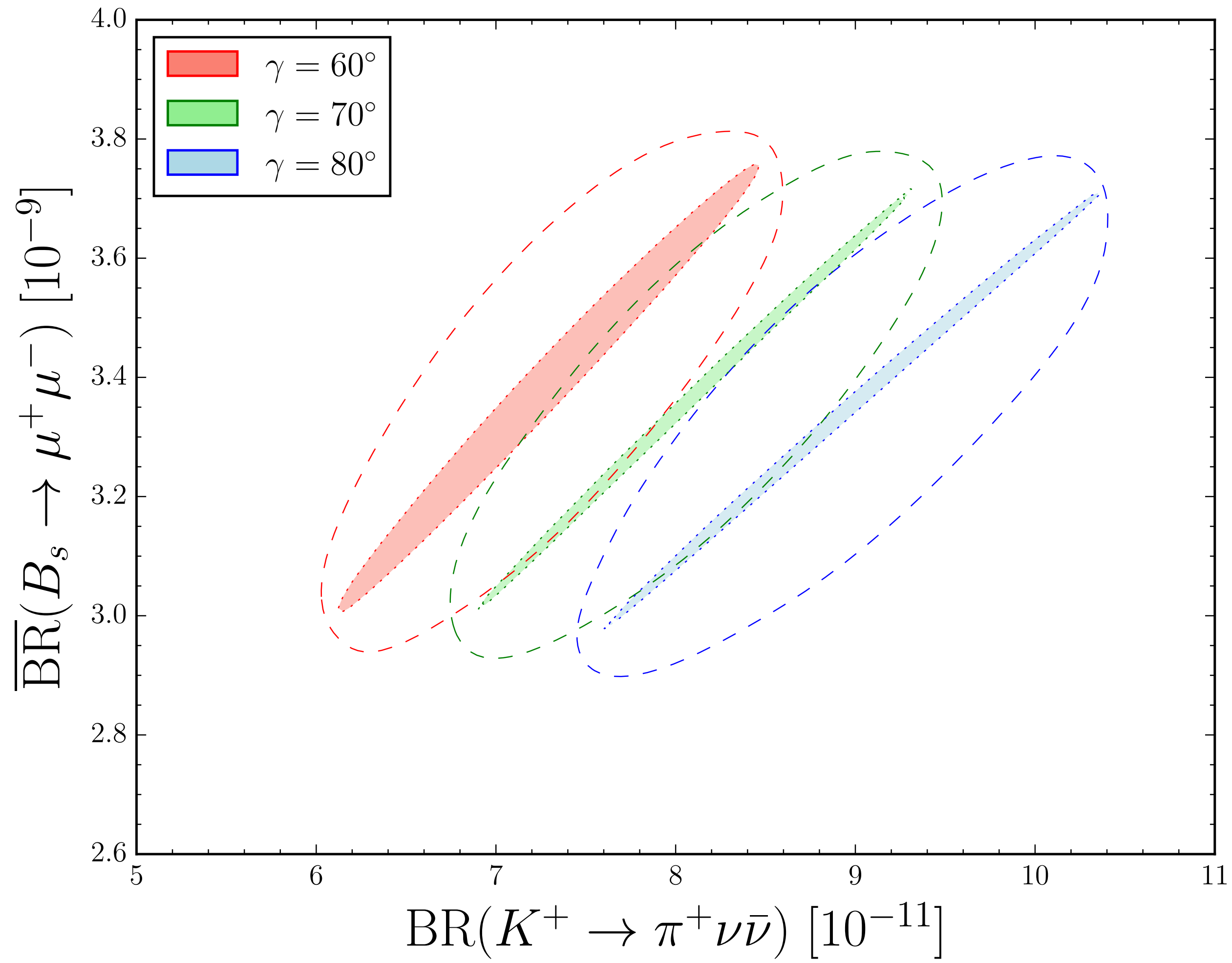
Flavour effects in composite Higgs models

	Ⓐ	$U(3)^3_{\mathrm{LC}}$	$U(3)^3_{\mathrm{RC}}$	$U(2)^3_{\mathrm{LC}}$	$U(2)^3_{\mathrm{RC}}$
$\epsilon_K,\ \Delta M_{d,s}$	★	○	★	★	★
$\Delta M_s/\Delta M_d$	★	○	○	○	○
$\phi_{d,s}$	★	○	○	★	○
$\phi_s - \phi_d$	★	○	○	○	○
C_{10}	★	○	○	★	○
C'_{10}	★	○	○	○	○
$pp \to jj$	○	★	★	○	○
$pp \to q'q'$	★	○	○	★	★

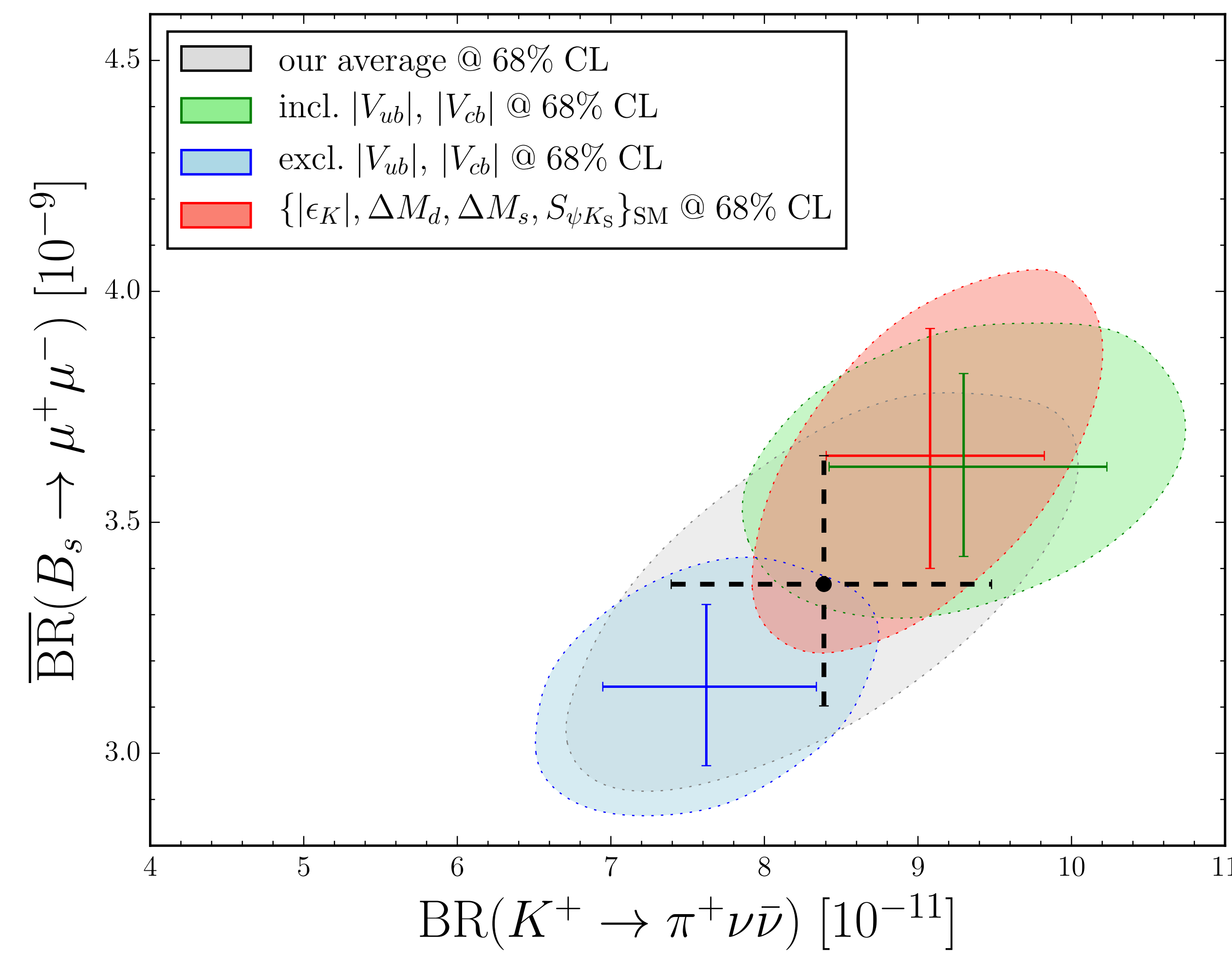
★ effect could show up in future measurements

Correlation with B -> μμ

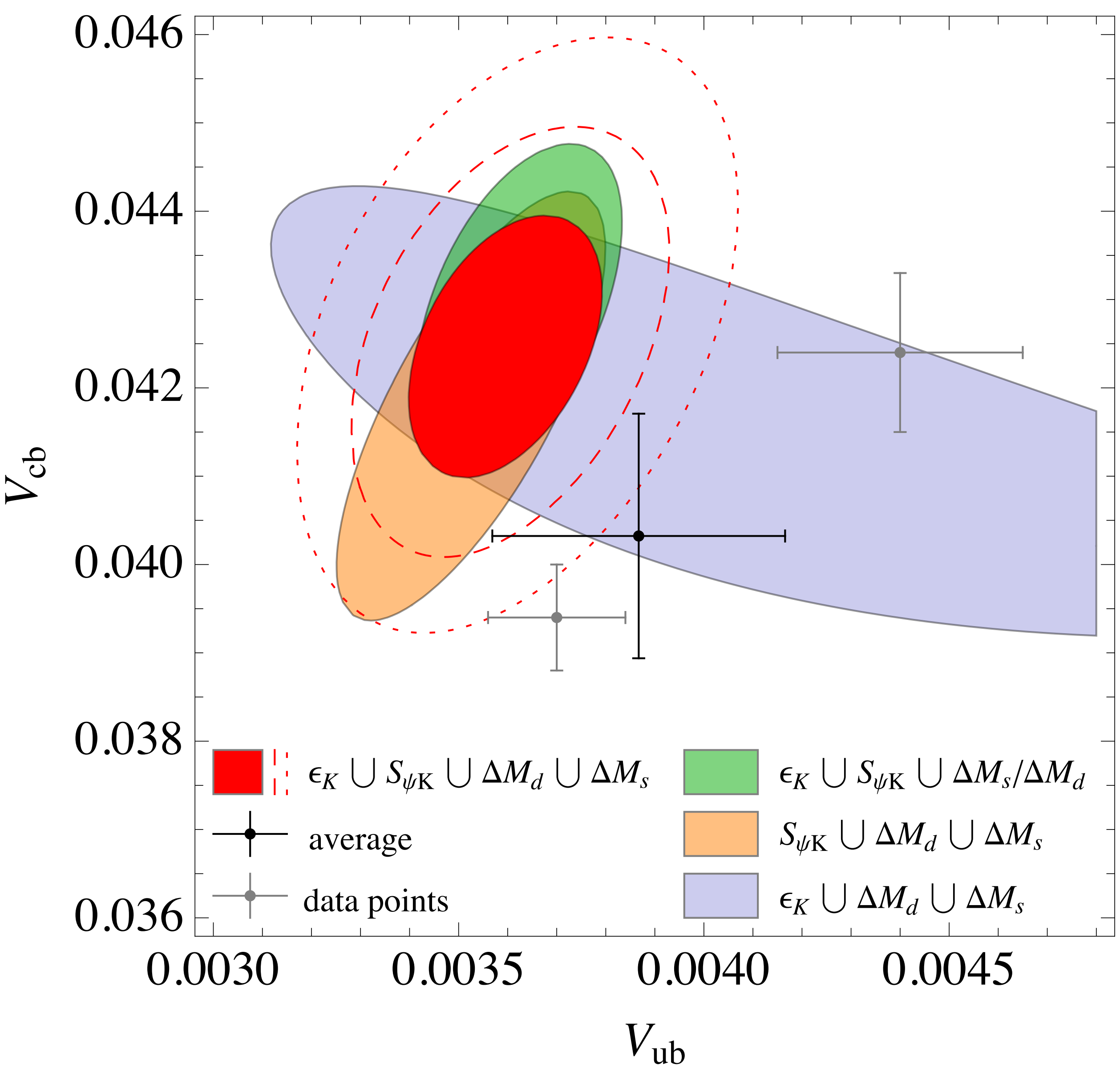
fixed γ



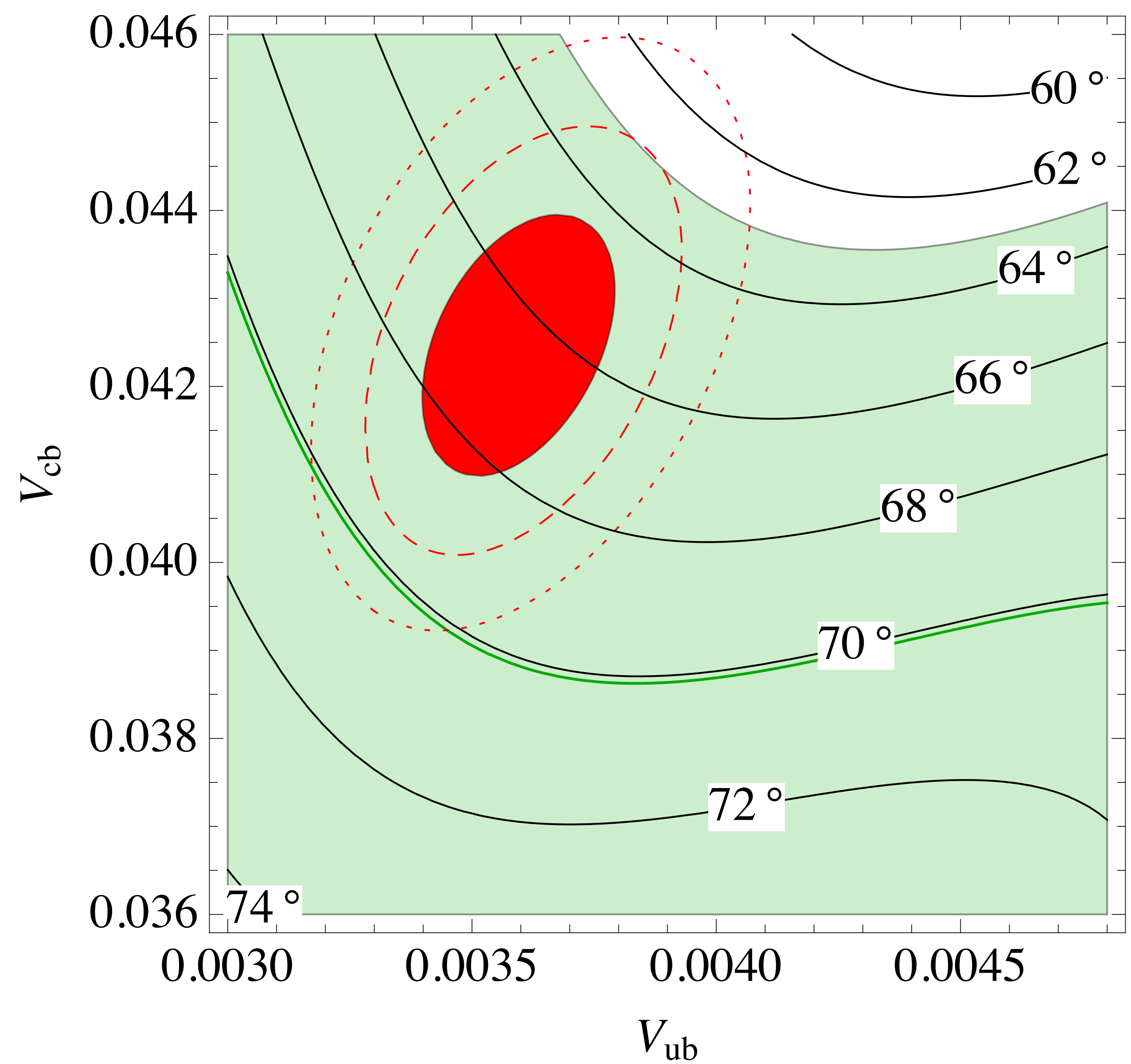
global fits



CKM fit: more plots



different fits



isolines of γ