Sometimes I drive recklessly, just to kill off close copies of me in the multiverse.

Effects of Sfermion Mixing induced by RGE Running in the MFV CMSSM

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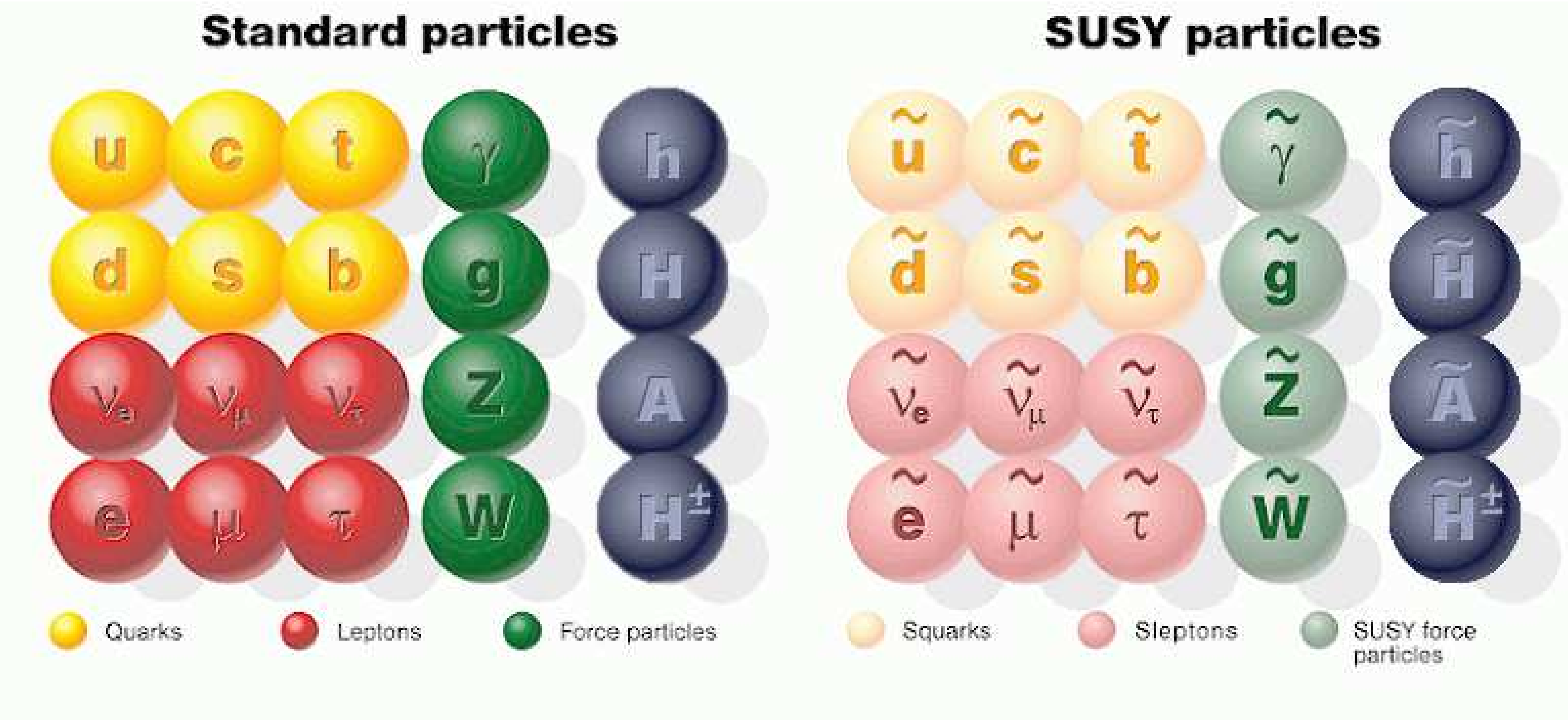
Lake Tahoe, 08/2015

based on collaboration with *M. Gomez, M. Rehman*

1. Motivation
2. Calculation Set-Up
3. Numerical Results
4. Conclusions

1. Motivation

MSSM: Superpartners for Standard Model particles



Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature
has so many free parameters!

GUT based models: CMSSM (sometimes wrongly called mSUGRA):

⇒ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu$$

m_0 : universal scalar mass parameter

$m_{1/2}$: universal gaugino mass parameter

A_0 : universal trilinear coupling

} at the GUT scale

$\tan\beta$: ratio of Higgs vacuum expectation values

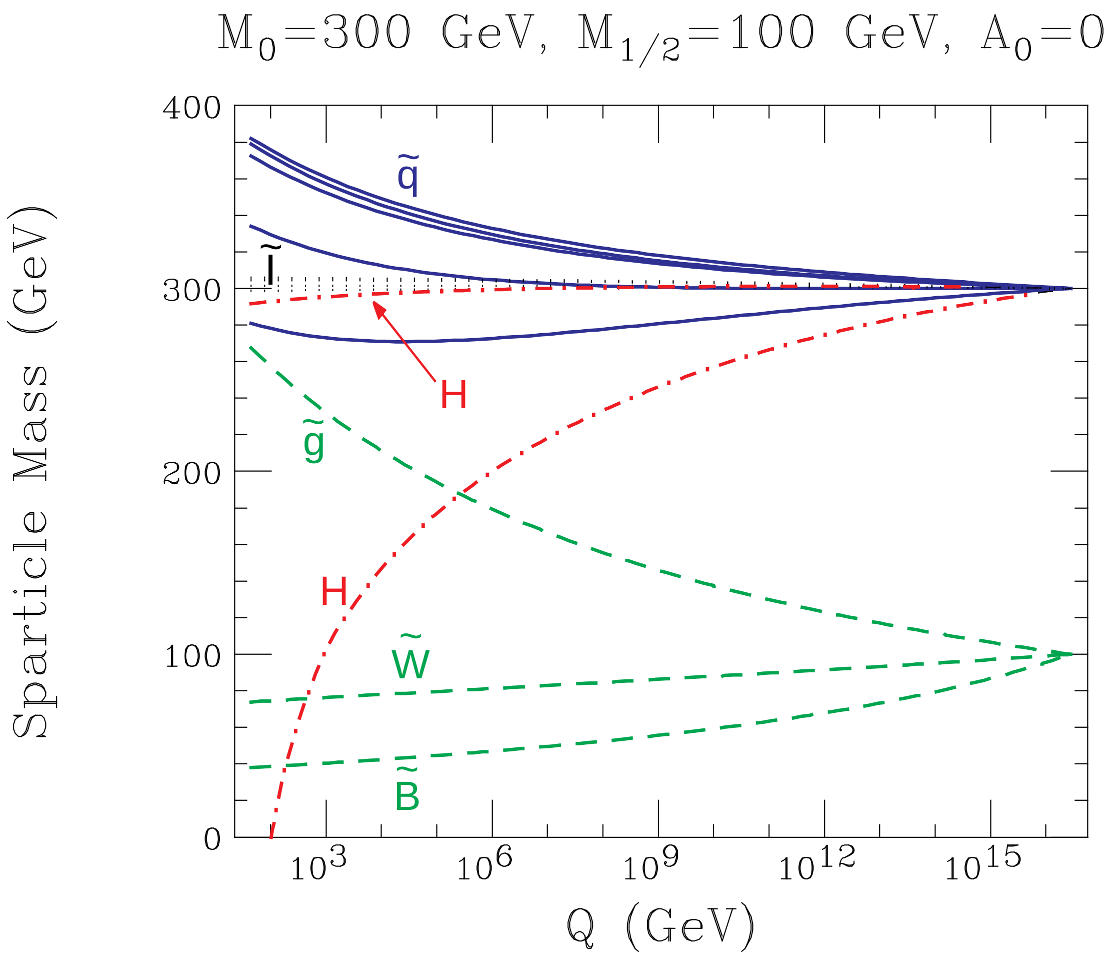
sign(μ) : sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale

⇒ Lightest SUSY particle (LSP) is the lightest neutralino ⇒ DM!

GUT based models: CMSSM (sometimes wrongly called mSUGRA):

⇒ particle spectra from renormalization group running to weak scale



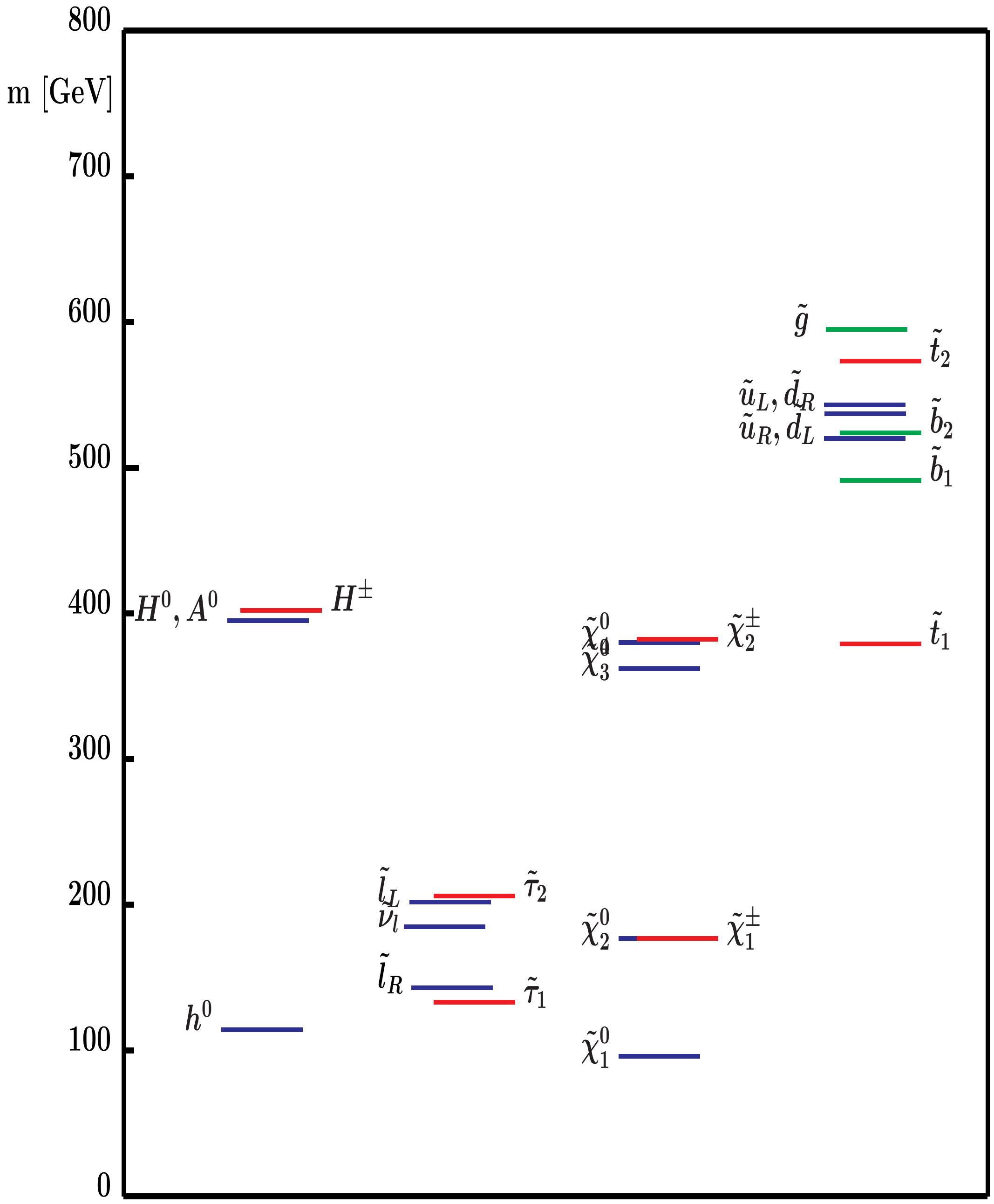
⇒ one parameter turns negative ⇒ Higgs mechanism for free

“Typical” CMSSM scenario

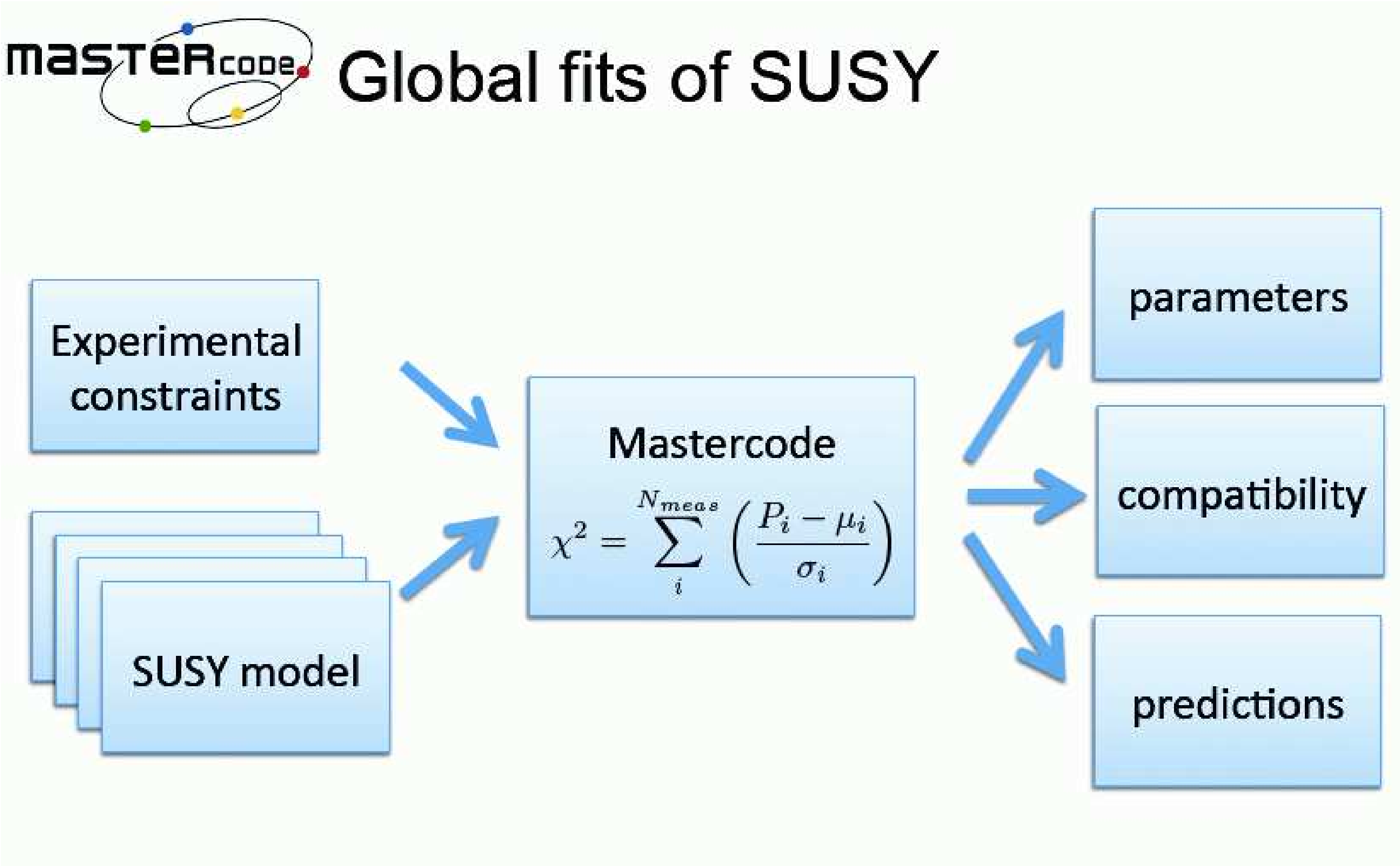
(SPS 1a benchmark scenario):

Strong connection between

all the sectors



SUSY fits (in the CMSSM), e.g. with MasterCode:



⇒ assumes no flavor violation at the EW scale!

⇒ justified? Overlooked effects?

2. Calculation Set-Up

Squarks at the low-energy scale:

$$m^2_{\tilde{U}_L} = \begin{pmatrix} m^2_{\tilde{Q}_1} & \delta^{QLL}_{12} m_{\tilde{Q}_1} m_{\tilde{Q}_2} & \delta^{QLL}_{13} m_{\tilde{Q}_1} m_{\tilde{Q}_3} \\ \delta^{QLL}_{21} m_{\tilde{Q}_2} m_{\tilde{Q}_1} & m^2_{\tilde{Q}_2} & \delta^{QLL}_{23} m_{\tilde{Q}_2} m_{\tilde{Q}_3} \\ \delta^{QLL}_{31} m_{\tilde{Q}_3} m_{\tilde{Q}_1} & \delta^{QLL}_{32} m_{\tilde{Q}_3} m_{\tilde{Q}_2} & m^2_{\tilde{Q}_3} \end{pmatrix}$$

$$m^2_{\tilde{D}_L} = V^\dagger_{\rm CKM}\, m^2_{\tilde{U}_L}\, V_{\rm CKM} \ ,$$

$$m^2_{\tilde{U}_R} = \begin{pmatrix} m^2_{\tilde{U}_1} & \delta^{URR}_{12} m_{\tilde{U}_1} m_{\tilde{U}_2} & \delta^{URR}_{13} m_{\tilde{U}_1} m_{\tilde{U}_3} \\ \delta^{URR}_{21} m_{\tilde{U}_2} m_{\tilde{U}_1} & m^2_{\tilde{U}_2} & \delta^{URR}_{23} m_{\tilde{U}_2} m_{\tilde{U}_3} \\ \delta^{URR}_{31} m_{\tilde{U}_3} m_{\tilde{U}_1} & \delta^{URR}_{32} m_{\tilde{U}_3} m_{\tilde{U}_2} & m^2_{\tilde{U}_3} \end{pmatrix}$$

$$m^2_{\tilde{D}_R} = \begin{pmatrix} m^2_{\tilde{D}_1} & \delta^{DRR}_{12} m_{\tilde{D}_1} m_{\tilde{D}_2} & \delta^{DRR}_{13} m_{\tilde{D}_1} m_{\tilde{D}_3} \\ \delta^{DRR}_{21} m_{\tilde{D}_2} m_{\tilde{D}_1} & m^2_{\tilde{D}_2} & \delta^{DRR}_{23} m_{\tilde{D}_2} m_{\tilde{D}_3} \\ \delta^{DRR}_{31} m_{\tilde{D}_3} m_{\tilde{D}_1} & \delta^{DRR}_{32} m_{\tilde{D}_3} m_{\tilde{D}_2} & m^2_{\tilde{D}_3} \end{pmatrix}$$

$$v_2 \mathcal{A}^u = \begin{pmatrix} m_u A_u & \delta^{ULR}_{12} m_{\tilde{Q}_1} m_{\tilde{U}_2} & \delta^{ULR}_{13} m_{\tilde{Q}_1} m_{\tilde{U}_3} \\ \delta^{ULR}_{21} m_{\tilde{Q}_2} m_{\tilde{U}_1} & m_c A_c & \delta^{ULR}_{23} m_{\tilde{Q}_2} m_{\tilde{U}_3} \\ \delta^{ULR}_{31} m_{\tilde{Q}_3} m_{\tilde{U}_1} & \delta^{ULR}_{32} m_{\tilde{Q}_3} m_{\tilde{U}_2} & m_t A_t \end{pmatrix}$$

$\Rightarrow$ only source for $\delta^{\rm FAB}_{ij} \neq 0$: CKM matrix

Calculation set-up:

1. CMSSM input: scan $m_{1/2}$, m_0, fix A_0, $\tan\beta$
   $\to$ no flavor violation!

2. Use Spheno 3.2.4 to generate low-energy spectra

3. $\Rightarrow$ generation of $\delta_{ij}^{\mathrm{FAB}} \neq 0$ at the low-energy scale

4. Use FeynHiggs to evaluate $M_h, \ldots, M_W, \sin^2\theta_{\mathrm{eff}}$:

$$\Delta M_W \approx \frac{M_W}{2} \frac{c_\mathrm{W}^2}{c_\mathrm{W}^2 - s_\mathrm{W}^2} \Delta\rho, \quad \Delta \sin^2\theta_{\mathrm{eff}} \approx -\frac{c_\mathrm{W}^2 s_\mathrm{W}^2}{c_\mathrm{W}^2 - s_\mathrm{W}^2} \Delta\rho$$

$$\Delta\rho = \frac{\Sigma_Z^\mathrm{T}(0)}{M_Z^2} - \frac{\Sigma_W^\mathrm{T}(0)}{M_W^2}$$

   $\to$ including 6×6 generation mixing

5. Use SuFla (as implemented into FeynHiggs) to calculate
   $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$, ΔM_{B_s}

Experimental/theoretical uncertainties (MSSM!): $\Rightarrow$ to set the scale!

$$\delta M_h^{\text{exp,today}} \sim 200 \text{ MeV}, \quad \delta M_h^{\text{exp,future}} \lesssim 50 \text{ MeV},$$
$$\delta M_h^{\text{theo,today}} \sim 3 \text{ GeV}, \quad \delta M_h^{\text{theo,future}} \lesssim 0.5 \text{ GeV}$$

$$\delta M_W^{\text{exp,today}} \sim 15 \text{ MeV}, \quad \delta M_W^{\text{exp,future}} \sim 4 \text{ MeV},$$
$$\delta M_W^{\text{theo,today}} \lesssim 5-10 \text{ MeV}, \quad \delta M_W^{\text{theo,future}} \lesssim 2-4 \text{ MeV}$$

$$\delta \sin^2\theta_{\text{eff}}^{\text{exp,today}} \sim 15 \times 10^{-5}, \quad \delta \sin^2\theta_{\text{eff}}^{\text{exp,future}} \sim 1.3 \times 10^{-5},$$
$$\delta \sin^2\theta_{\text{eff}}^{\text{theo,today}} \lesssim 5-7 \times 10^{-5}, \quad \delta \sin^2\theta_{\text{eff}}^{\text{theo,future}} \lesssim 2-4 \times 10^{-5}$$

Observable	Experimental Value	SM Prediction
$\text{BR}(b \to s\gamma)$	$3.43 \pm 0.22 \times 10^{-4}$	$3.15 \pm 0.23 \times 10^{-4}$
$\text{BR}(B_s \to \mu^+\mu^-)$	$(3.0)^{+1.0}_{-0.9} \times 10^{-9}$	$3.23 \pm 0.27 \times 10^{-9}$
ΔM_{B_s}	$116.4 \pm 0.5 \times 10^{-10}$ MeV	$(117.1)^{+17.2}_{-16.4} \times 10^{-10}$ MeV

3. Numerical results

Details can be found in [*arXiv:1501.02258*]

Shown are:

$$\Delta X^{\mathrm{MFV}} = X - X^{\mathrm{MSSM}}$$

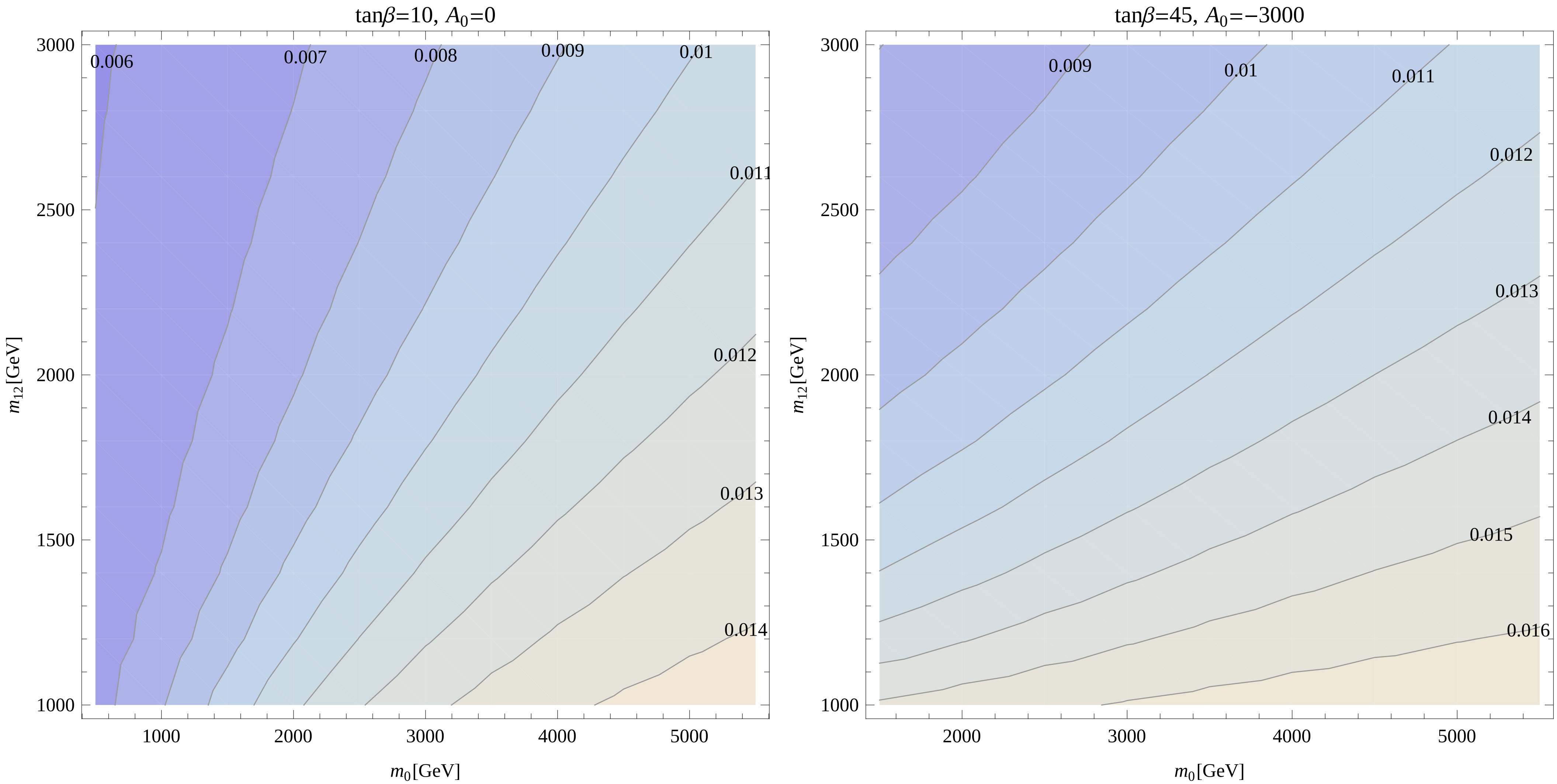
X^{MSSM}: prediction setting all $\delta_{ij}^{\mathrm{FAB}} = 0$ at the EW scale

X: prediction taking all the $\delta_{ij}^{\mathrm{FAB}} \neq 0$ into account
(as evaluated with Spheno)

$\Rightarrow$ shows what is neglected by setting all $\delta_{ij}^{\mathrm{FAB}} = 0$

small effects: ok, good approximation
large effects: bad approximation!

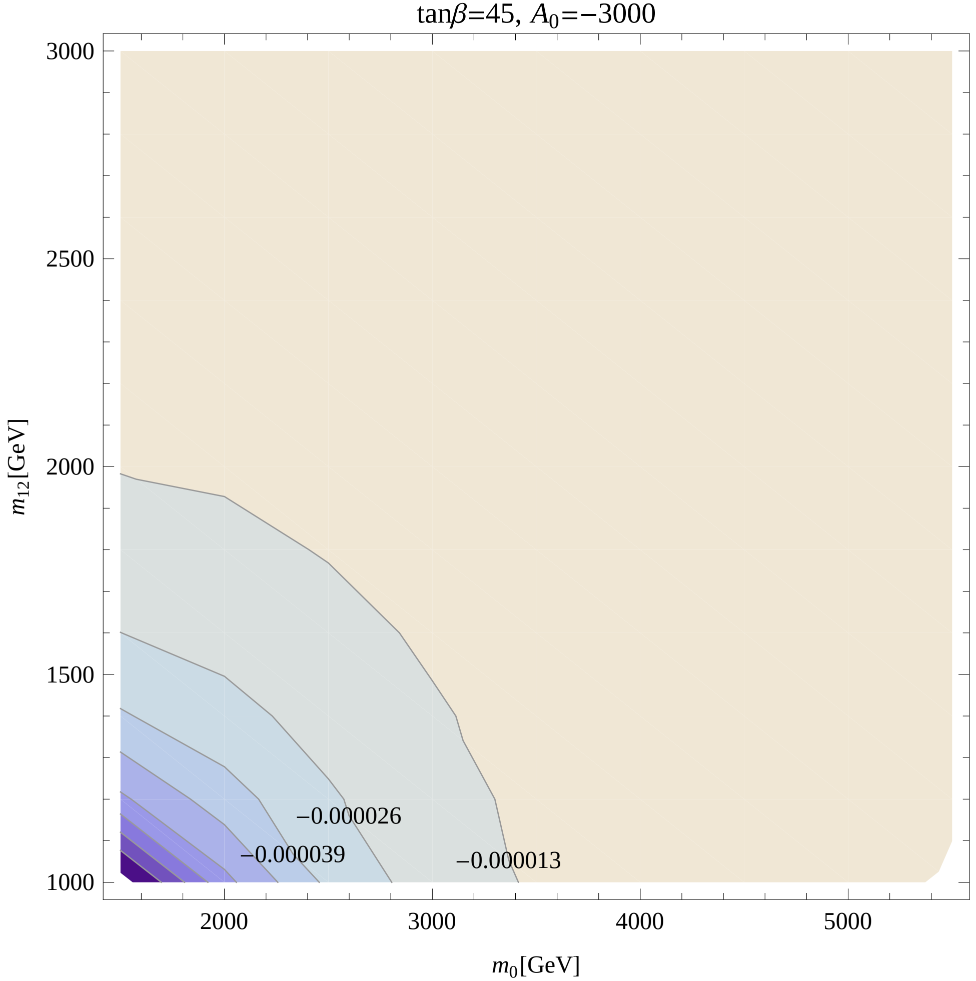
Induced $\delta_{ij}^{\mathrm{FAB}}$ via CKM effects in the RGE running: $\delta_{23}^{\mathrm{QLL}}$:



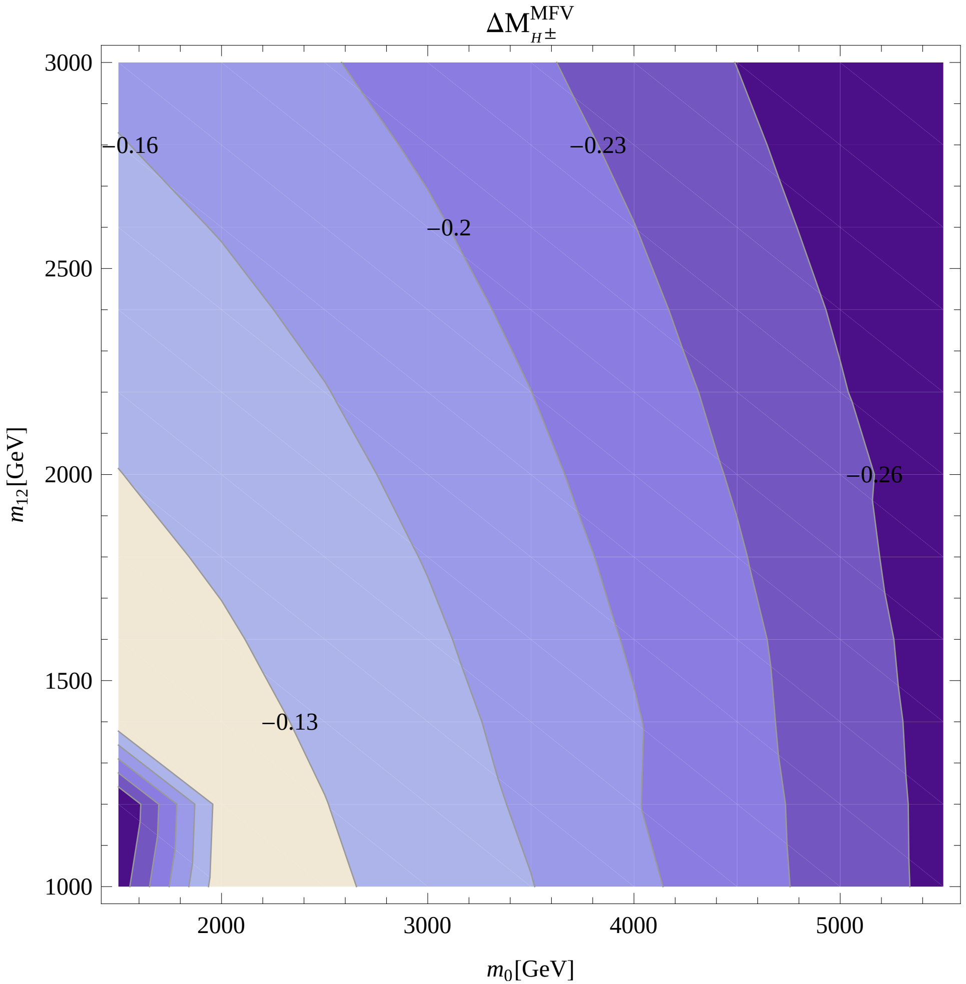
$\Rightarrow$ large $\delta_{23}^{\mathrm{QLL}}$ induced, no decoupling for large m_0

Induced Higgs mass effects via CKM effects in the RGE running:

$\Delta M_h^{\mathrm{MFV}}$



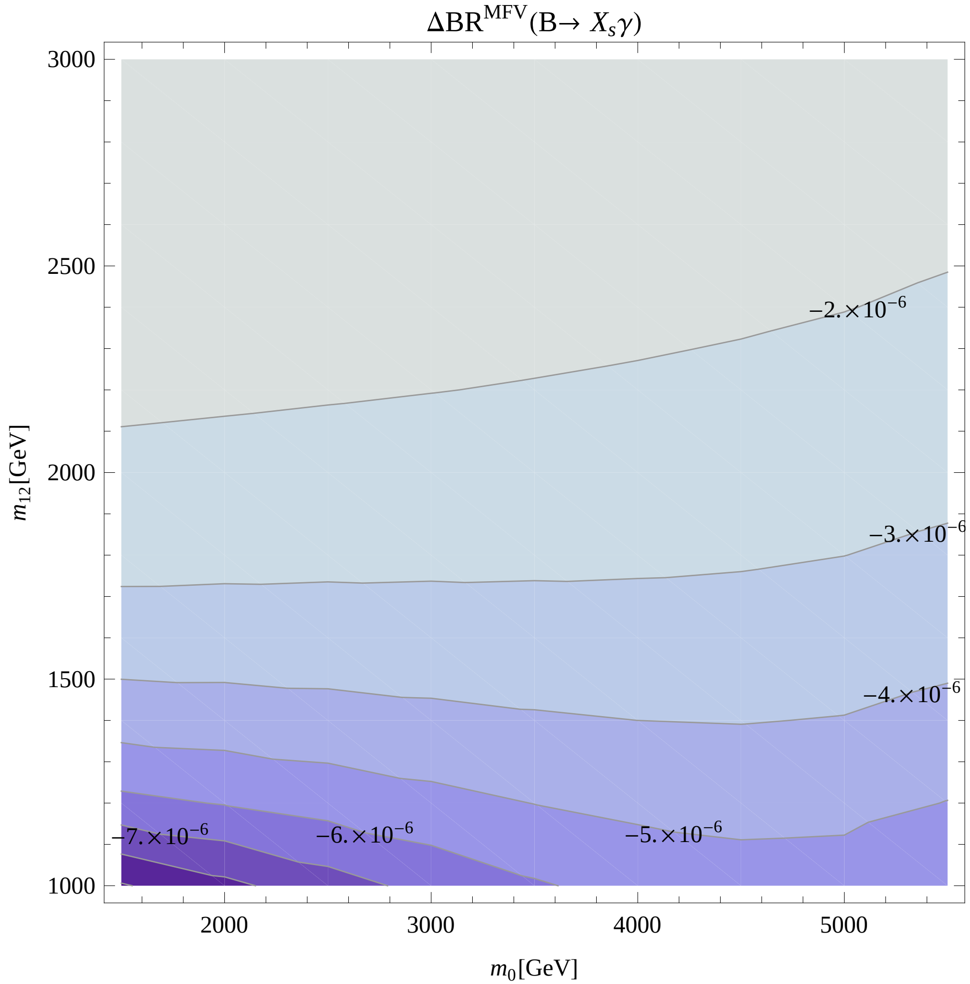
$\Delta M_{H^\pm}^{\mathrm{MFV}}$

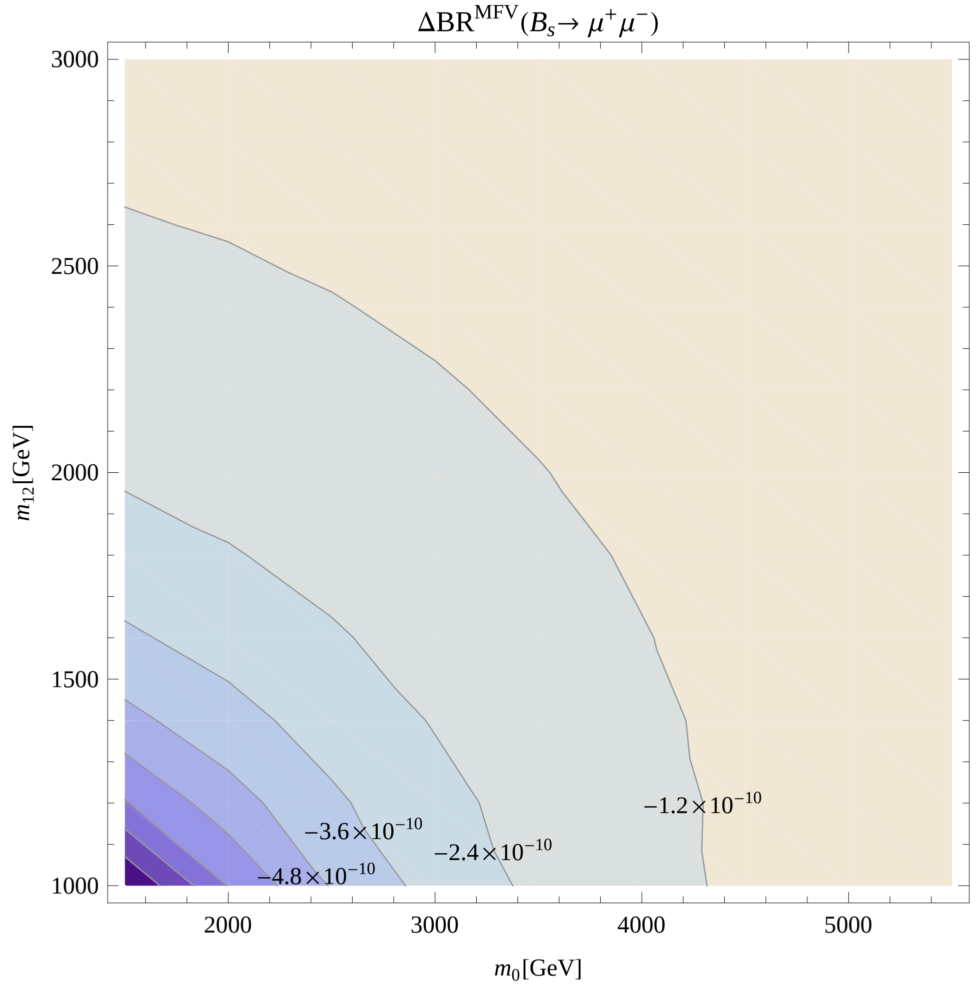


⇒ small effects

Induced BPO mass effects via CKM effects in the RGE running:

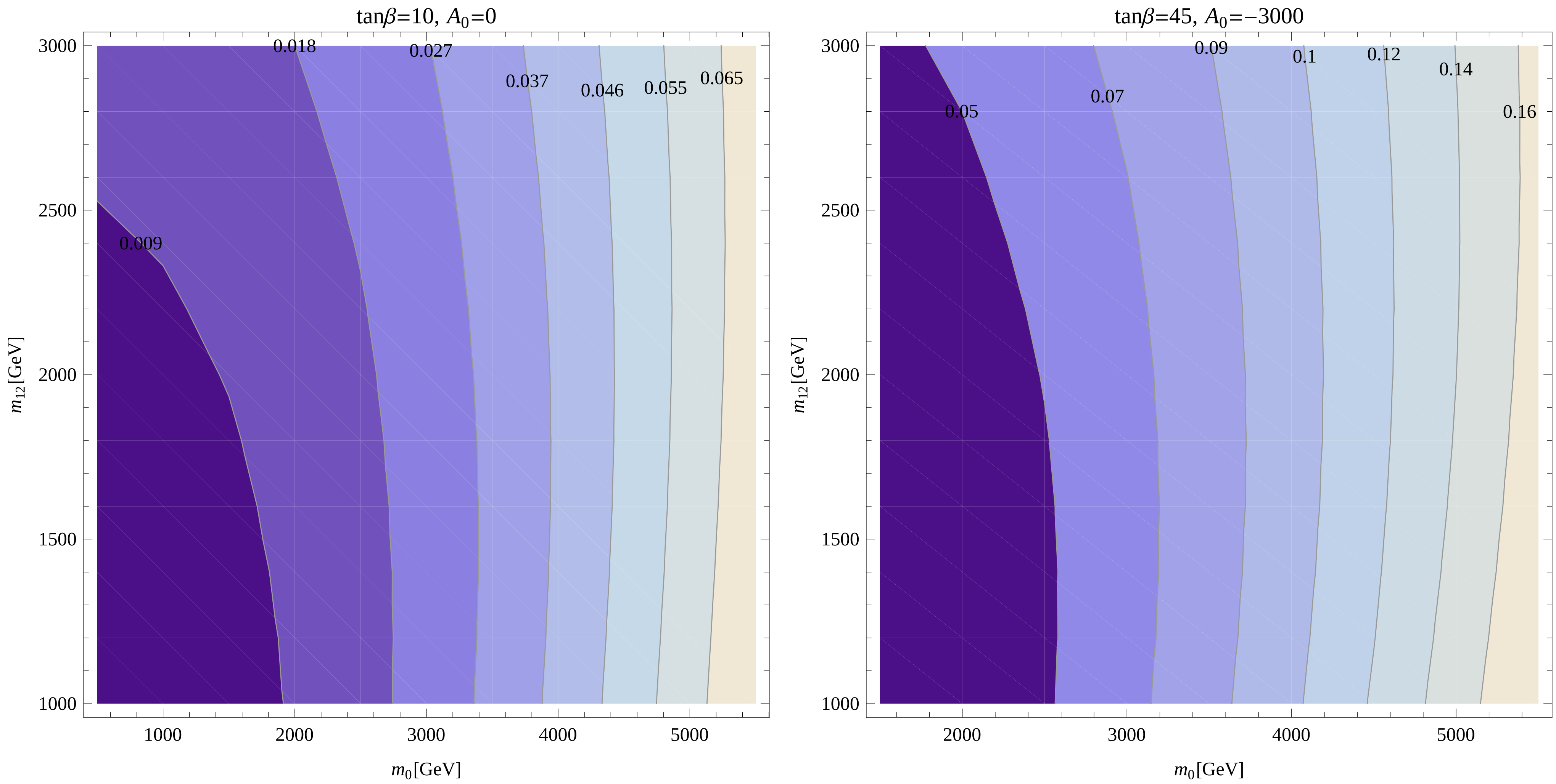
$A_0 = -3000$ GeV, $\tan\beta = 45$ (largest effects)





⇒ small effects

Induced $\Delta M_W^{\rm MFV}$ via CKM effects in the RGE running:



$\Rightarrow$ large $\Delta M_W^{\rm MFV}$ induced, no decoupling for large m_0

$\Rightarrow$ Effects can be several times the current exp. uncertainty!

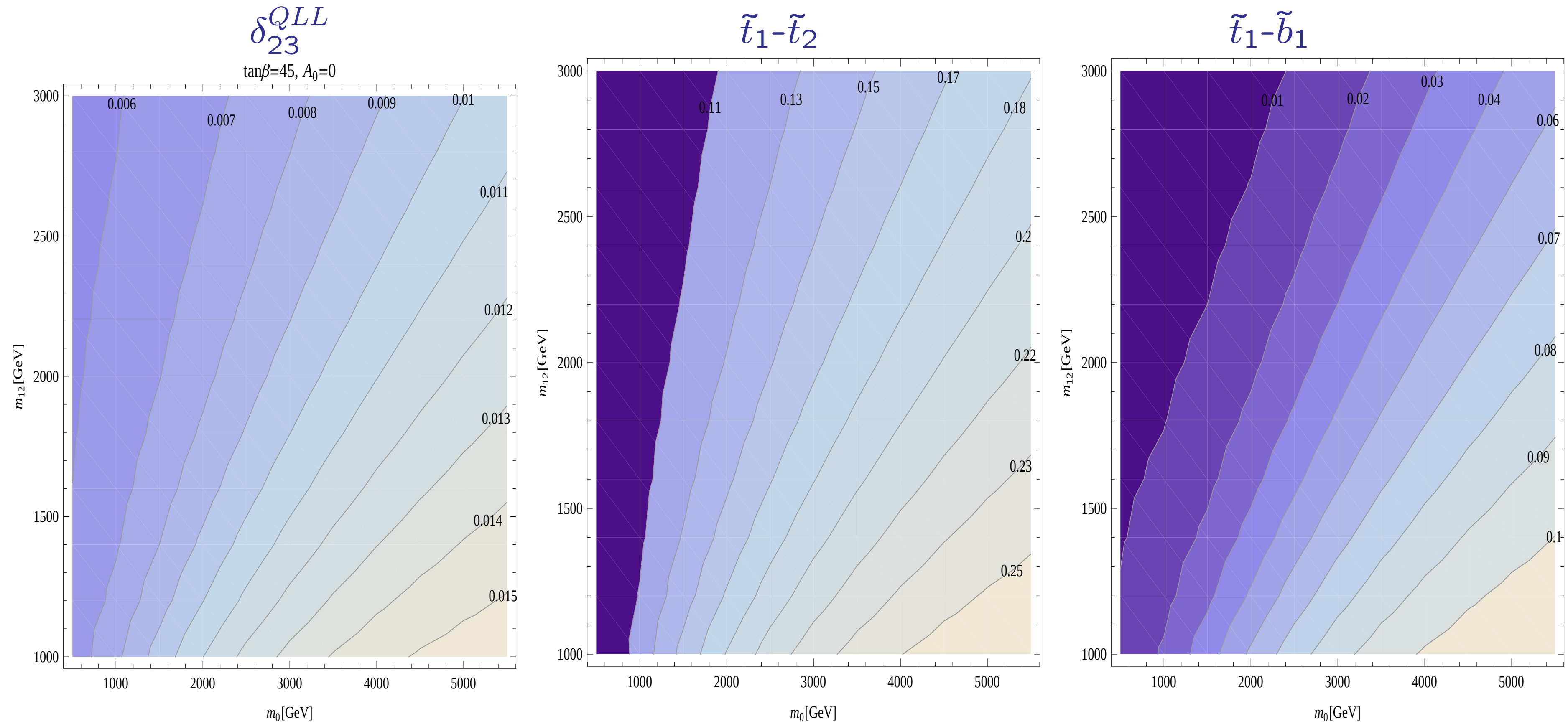
$\Rightarrow$ new bounds on the CMSSM?

How can these large effects be understood?

– RGE running induces non-decoupling $\delta_{ij}^{\mathrm{FAB}} \neq 0$

– this induces $SU(2)$ doublet mass splittings,
e.g. "$\tilde{t}_1$-$\tilde{b}_1$" $((m^2_{\tilde{t}_1} - m^2_{\tilde{b}_1})/(m^2_{\tilde{t}_1} + m^2_{\tilde{b}_1}))$, . . .

– $\Delta\rho$ is sensitive to exactly these $SU(2)$ doublet mass splittings



4. Conclusinos

- GUT based analyses often assume no generation mix. at the EW scale
  $\Rightarrow$ justified? Overlooked effects?

- Some generation mixing always induced by CKM matrix

- Calculation set-up: Spheno for RGE running
  $\Rightarrow$ generation of $\delta_{ij}^{\mathrm{FAB}} \neq 0$ at the low-energy scale
  FeynHiggs/SuFla for the evaluaion of M_h, M_W, $\sin^2\theta_{\mathrm{eff}}$, BPO

- RGE running induces non-decoupling $\delta_{ij}^{\mathrm{FAB}} \neq 0$

- Negligible effects on M_h, . . . , BPO

- $\Rightarrow$ large $\Delta M_W^{\mathrm{MFV}}$ induced, no decoupling for large m_0
  $\Rightarrow$ Effects can be several times the current exp. uncertainty!
  $\Rightarrow$ new bounds on the CMSSM?

Back-up

The W boson mass

Experimental accuracy:

Today: LEP2, Tevatron: $M_W^{\text{exp}} = 80.385 \pm 0.015$ GeV

ILC/TLEP: – polarized threshold scan
– kinematic reconstruction of W^+W^- [*G. Wilson '13*]
– hadronic mass (single W)

$$\delta M_W^{\text{exp,ILC(TLEP)}} \lesssim 3\,(1) \text{ MeV (from thr. scan)} \quad \Leftarrow \text{TU neglected}$$

Theoretical accuracies:

intrinsic today: $\delta M_W^{\text{SM,theo}} = 4$ MeV, $\delta M_W^{\text{MSSM,today}} = 5 - 10$ MeV

intrinsic future: $\delta M_W^{\text{SM,theo,fut}} = 1$ MeV, $\delta M_W^{\text{MSSM,fut}} = 2 - 4$ MeV

parametric today: $\delta m_t = 0.9$ GeV, $\delta(\Delta\alpha_{\text{had}}) = 10^{-4}$, $\delta M_Z = 2.1$ MeV

$$\delta M_W^{\text{para},m_t} = 5.5 \text{ MeV}, \quad \delta M_W^{\text{para},\Delta\alpha_{\text{had}}} = 2 \text{ MeV}, \quad \delta M_W^{\text{para},M_Z} = 2.5 \text{ MeV}$$

parametric future: $\delta m_t^{\text{ILC/TLEP}} = 0.1$ GeV, $\delta(\Delta\alpha_{\text{had}})^{\text{fut}} = 5 \times 10^{-5}$

$$\Delta M_W^{\text{para,fut},m_t} = 1 \text{ MeV}, \quad \Delta M_W^{\text{para,fut},\Delta\alpha_{\text{had}}} = 1 \text{ MeV}$$

The effective weak leptonic mixing angle: $\sin^2\theta_{\rm eff}$

Experimental accuracy:

Today: LEP, SLD: $\sin^2\theta_{\rm eff}^{\rm exp} = 0.23153 \pm 0.00016$

GigaZ/TeraZ: both beams polarized, Blondel scheme

$$\delta\sin^2\theta_{\rm eff}^{\rm exp,ILC(TLEP)} = 13\,(3) \times 10^{-6} \qquad \Leftarrow \text{TU neglected}$$

Theoretical accuracies: $[10^{-6}]$

intrinsic today: $\delta\sin^2\theta_{\rm eff}^{\rm SM,theo} = 47 \quad \delta\sin^2\theta_{\rm eff}^{\rm MSSM,today} = 50 - 70$

intrinsic future: $\delta\sin^2\theta_{\rm eff}^{\rm SM,theo,fut} = 15 \quad \delta\sin^2\theta_{\rm eff}^{\rm MSSM,fut} = 25 - 35$

parametric today: $\delta m_t = 0.9$ GeV, $\delta(\Delta\alpha_{\rm had}) = 10^{-4}$, $\delta M_Z = 2.1$ MeV

$$\delta\sin^2\theta_{\rm eff}^{{\rm para},m_t} = 70, \quad \delta\sin^2\theta_{\rm eff}^{{\rm para},\Delta\alpha_{\rm had}} = 36, \quad \delta\sin^2\theta_{\rm eff}^{{\rm para},M_Z} = 14$$

parametric future: $\delta m_t^{\rm ILC/TLEP} = 0.1$ GeV, $\delta(\Delta\alpha_{\rm had})^{\rm fut} = 5 \times 10^{-5}$

$$\Delta\sin^2\theta_{\rm eff}^{{\rm para,fut},m_t} = 4, \quad \Delta\sin^2\theta_{\rm eff}^{{\rm para,fut},\Delta\alpha_{\rm had}} = 18$$