Testing the NMFV MSSM
with Precision Observables

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2. Results for M_W and $\sin^2\theta_{\rm eff}$
3. Results for m_h
4. News from *FeynArts/FormCalc*
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1. Introduction

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^0_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales, many parameter relations

NMFV in the MSSM

NMFV: Non Minimal Flavor Violation

$\to$ Mixing of scalar quark families (beyond CKM)

Mixing of stop/scharme and of sbottom/sstrange:

$$(\tilde{t}_L, \tilde{t}_R, \tilde{c}_L, \tilde{c}_R) \begin{pmatrix} \widetilde{T} & 0 \\ 0 & \widetilde{C} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \\ \tilde{c}_L \\ \tilde{c}_R \end{pmatrix} \qquad (\tilde{b}_L, \tilde{b}_R, \tilde{s}_L, \tilde{s}_R) \begin{pmatrix} \widetilde{B} & 0 \\ 0 & \widetilde{S} \end{pmatrix} \begin{pmatrix} \tilde{b}_L \\ \tilde{b}_R \\ \tilde{s}_L \\ \tilde{s}_R \end{pmatrix}$$

$\downarrow$ add NMFV $\downarrow$

$$(\tilde{t}_L, \tilde{t}_R, \tilde{c}_L, \tilde{c}_R) \begin{pmatrix} \widetilde{T} & \neq 0 \\ \neq 0 & \widetilde{C} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \\ \tilde{c}_L \\ \tilde{c}_R \end{pmatrix} \qquad (\tilde{b}_L, \tilde{b}_R, \tilde{s}_L, \tilde{s}_R) \begin{pmatrix} \widetilde{B} & \neq 0 \\ \neq 0 & \widetilde{S} \end{pmatrix} \begin{pmatrix} \tilde{b}_L \\ \tilde{b}_R \\ \tilde{s}_L \\ \tilde{s}_R \end{pmatrix}$$

$\neq 0$:

– experimentally only partially restricted

– can e.g. be induced by RGE running in mSUGRA

– changes Higgs-squark couplings

– changes Gauge boson-squark couplings

Results exist for:

– b-physics observables

– Higgs decays

– . . .

Connection to other sectors?

Connection to (other) LHC measurements?

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Results exist for:

– b-physics observables

– Higgs decays

– ...

Connection to other sectors?

Connection to (other) LHC measurements?

$\Rightarrow$ Investigate effects on electroweak precision observables

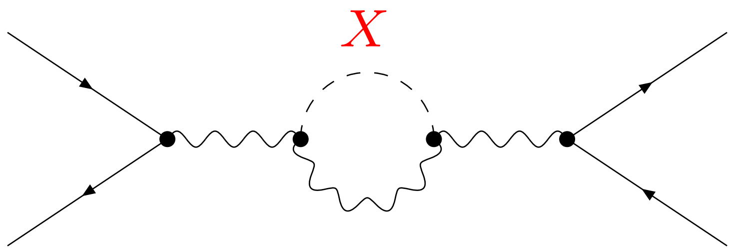
Precision Observables (POs):

Comparison of electro-weak precision observables with theory:

EW Precision data:		Theory:
$M_W, \sin^2\theta_{\rm eff}, m_h$	$\leftrightarrow$	SM, MSSM, extensions

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections

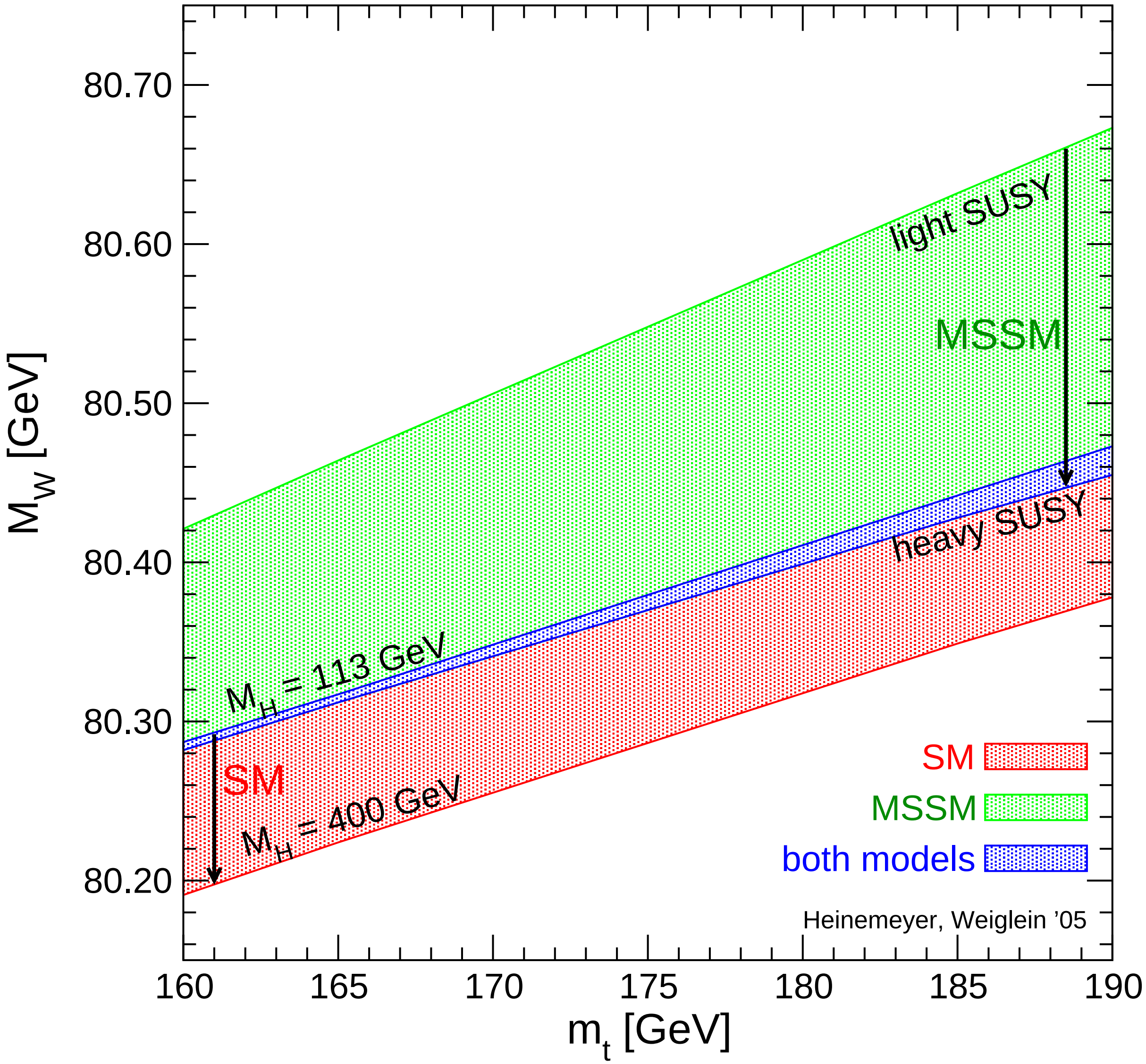


$\Downarrow$

Very high accuracy of measurements and theoretical predictions needed

- Which model fits better?
- Does the prediction of a model contradict the experimental data?

MSSM Example: Prediction for M_W in the SM and the MSSM :



MSSM uncertainty:

unknown masses

of SUSY particles

SM uncertainty:

unknown Higgs mass

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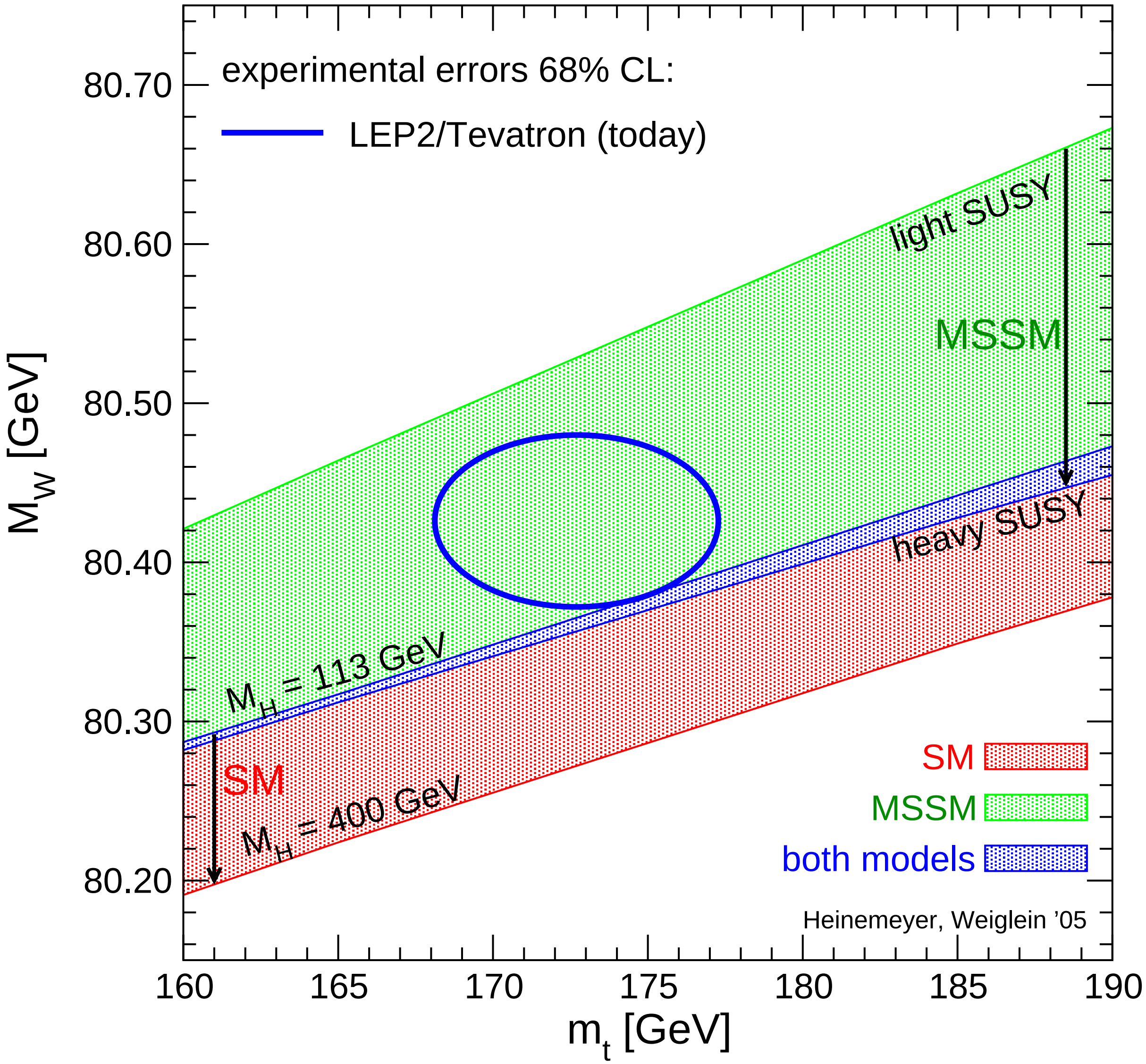

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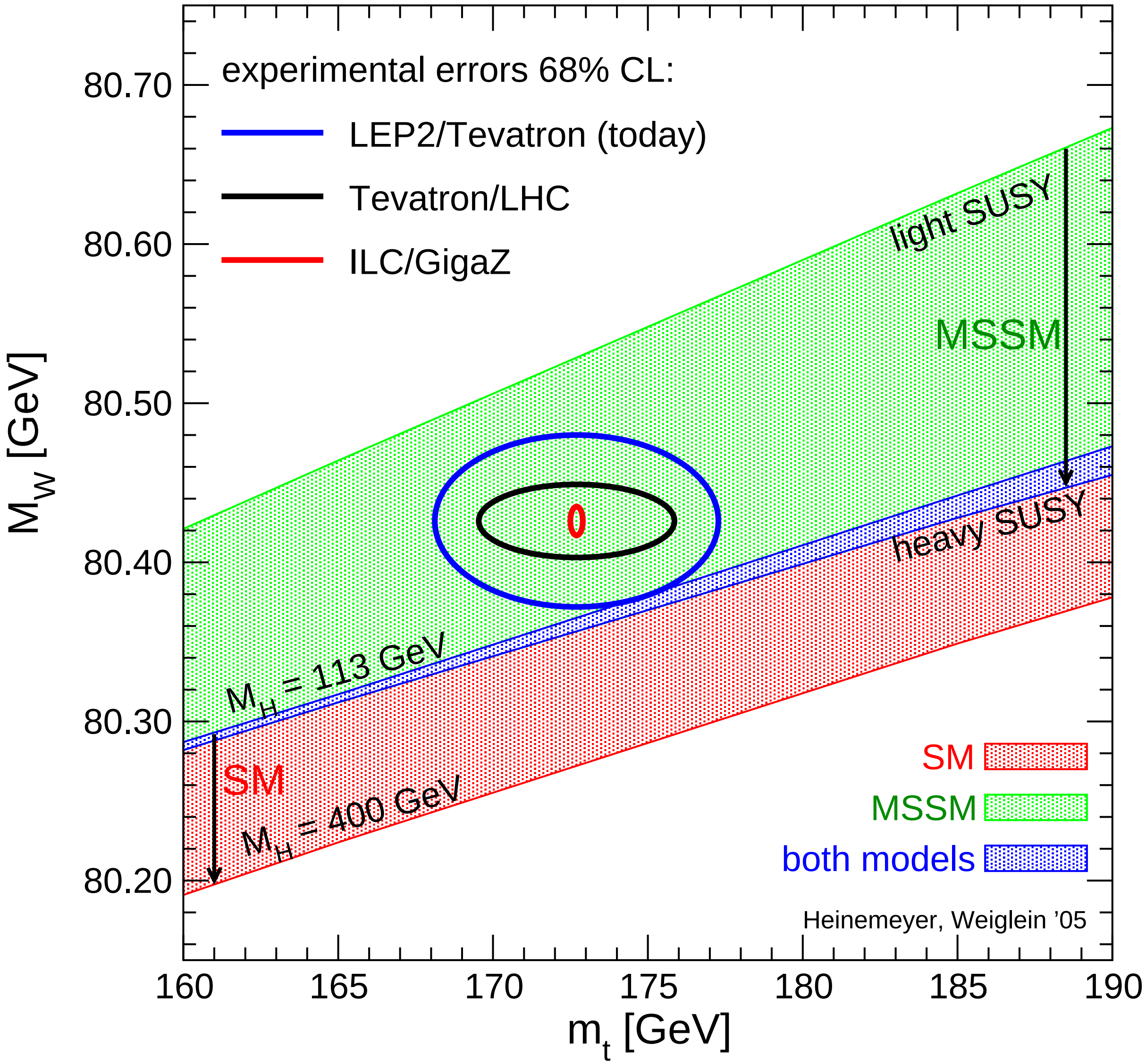

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Powerful precision observables for SUSY:

M_W, $\sin^2\theta_{\text{eff}}$, m_h, $(g-2)_\mu$, ...

Comparison of current experimental errors with anticipated precision at

Run II of the Tevatron, LHC, and
ILC with and without low-energy running mode (GigaZ)

	now	Tev. Run II	LHC	ILC	GigaZ
$\delta\sin^2\theta_{\text{eff}}(\times 10^5)$	16	78	14–20	—	1.3
δM_W [MeV]	34	27	15	10	7
δm_h [MeV]	—	$\mathcal{O}(2000)$	200	50	50
δm_t [GeV]	2.9	2	1.0	0.1	0.1

⇒ Also in this field: great expectations for the LHC

(smaller δm_t reduces parametric uncertainties)

$\Rightarrow$ Evaluate electroweak precision observables including NMFV effects:

Mixing of stop/scharme and of sbottom/sstrange:

$$(\tilde{t}_L, \tilde{t}_R, \tilde{c}_L, \tilde{c}_R) \begin{pmatrix} \widetilde{T} & \neq 0 \\ \neq 0 & \widetilde{C} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \\ \tilde{c}_L \\ \tilde{c}_R \end{pmatrix} \qquad (\tilde{b}_L, \tilde{b}_R, \tilde{s}_L, \tilde{s}_R) \begin{pmatrix} \widetilde{B} & \neq 0 \\ \neq 0 & \widetilde{S} \end{pmatrix} \begin{pmatrix} \tilde{b}_L \\ \tilde{b}_R \\ \tilde{s}_L \\ \tilde{s}_R \end{pmatrix}$$

Analytical result:

evaluation with arbitrary NMFV couplings

Numerical result: LL mixing most relevant for EWPO:

$$\tilde{t}/\tilde{c}: \begin{pmatrix} \lambda\sqrt{\widetilde{T}_{LL}\widetilde{C}_{LL}} & 0 \\ 0 & 0 \end{pmatrix} \qquad \tilde{b}/\tilde{s}: \begin{pmatrix} \lambda\sqrt{\widetilde{B}_{LL}\widetilde{S}_{LL}} & 0 \\ 0 & 0 \end{pmatrix}$$

$SU(2)$: $\widetilde{T}_{LL} \approx \widetilde{B}_{LL}$, $\widetilde{C}_{LL} \approx \widetilde{S}_{LL}$

$\rightarrow$ suggested by RGE analysis: $LL > LR, RL > RR$

$\rightarrow$ no relevant experimental bounds on λ

2. Results for M_W and $\sin^2\theta_{\mathrm{eff}}$

1.) Theoretical prediction for M_W in terms of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\,\alpha}{\sqrt{2}\,G_\mu} \left(\frac{1}{1 - \Delta r}\right)$$

$\Updownarrow$

loop corrections

2.) Effective mixing angle:

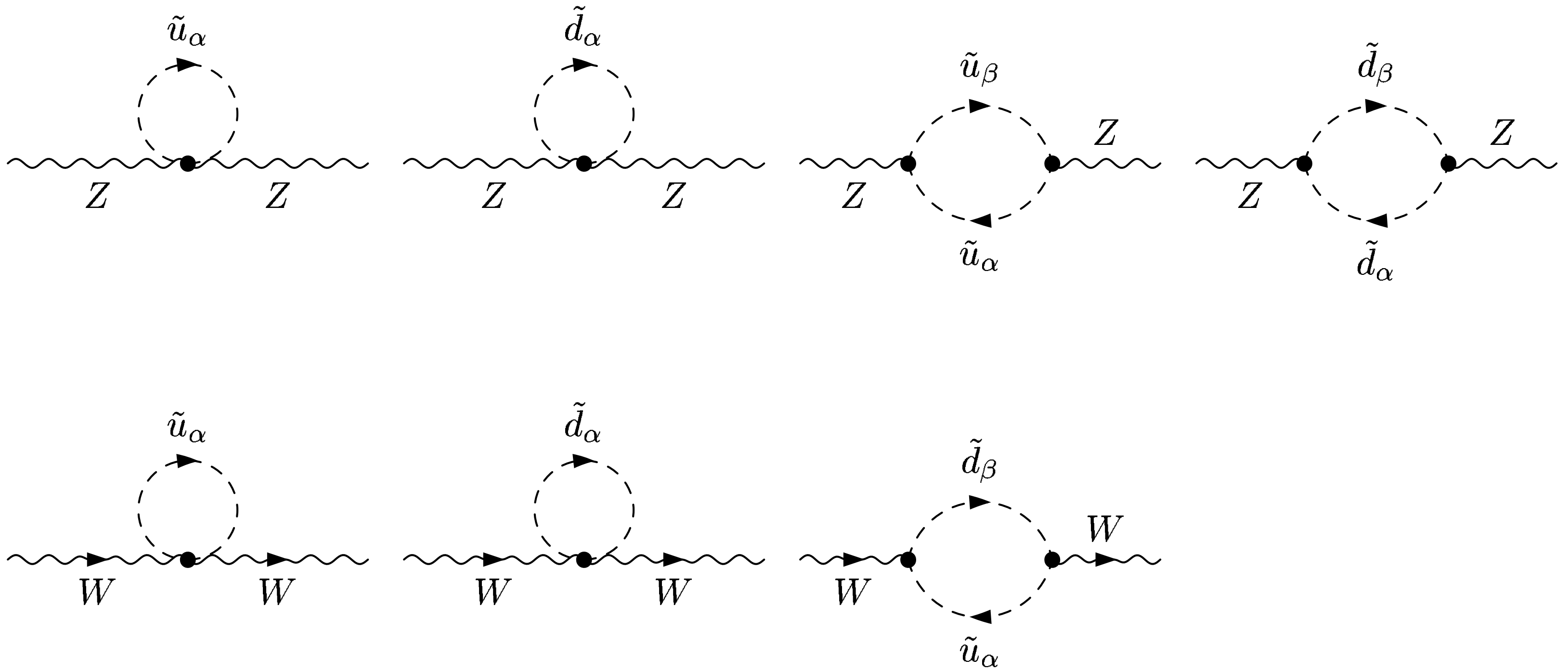
$$\sin^2\theta_{\mathrm{eff}} = \frac{1}{4\,|Q_f|}\left(1 - \frac{\mathrm{Re}\,g_V^f}{\mathrm{Re}\,g_A^f}\right)$$

Higher order contributions:

$$g_V^f \to g_V^f + \Delta g_V^f, \quad g_A^f \to g_A^f + \Delta g_A^f$$

Typical Feynman diagrams for squark contributions to M_W and $\sin^2\theta_{\rm eff}$:

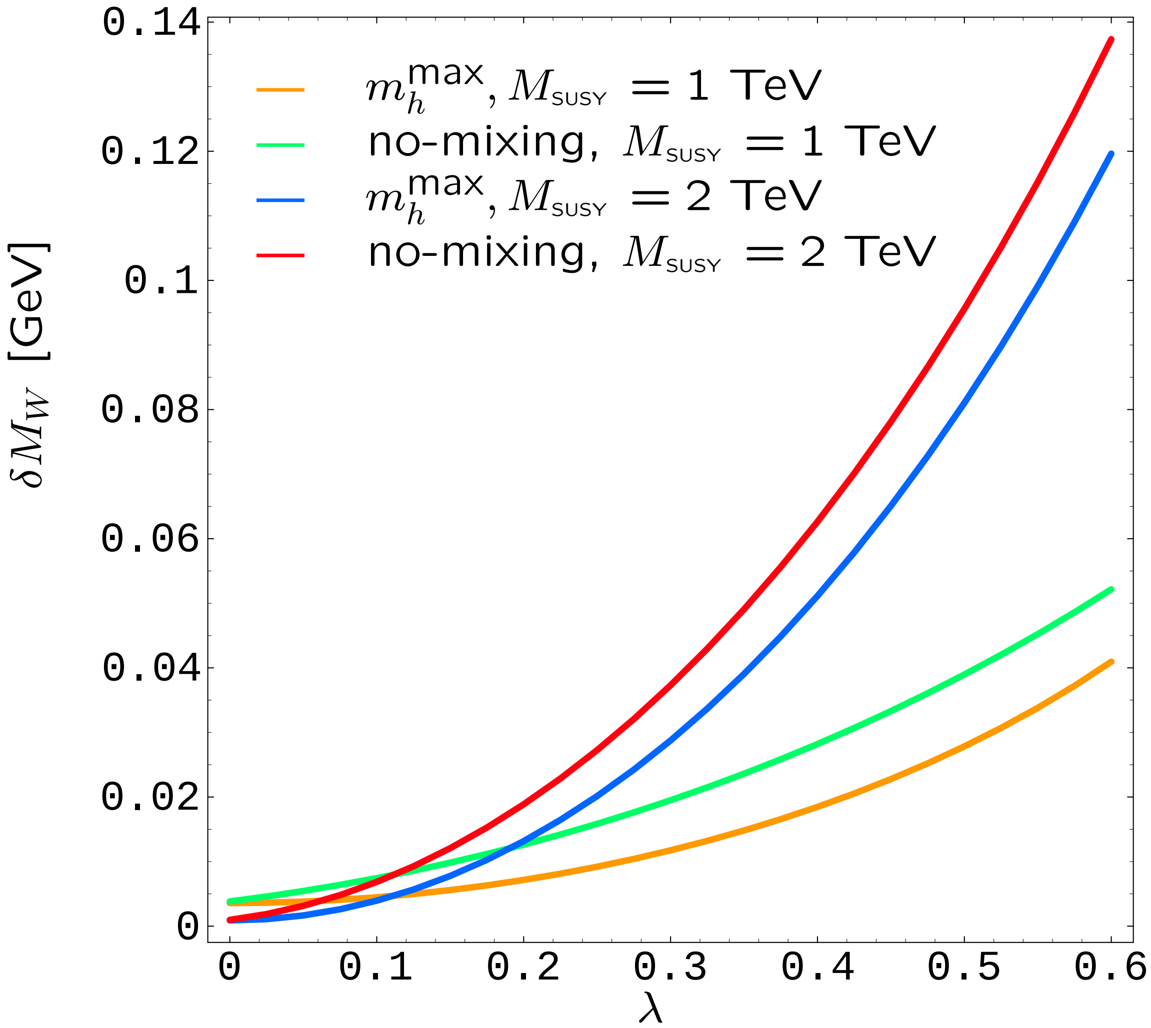
only self-energy diagrams enter:



$\rightarrow$ evaluated with the help of *FeynArts* and *FormCalc*

δM_W as a function of λ:

[S.H., W. Hollik, F. Merz, S. Peñaranda '04]



increasing λ
$\Rightarrow$ increasing mixing
$\Rightarrow$ increasing M_W

increasing M_{SUSY}
$\Rightarrow$ increasing mixing
$\Rightarrow$ increasing M_W

$\delta M_W^{\text{exp,today}} = 34$ MeV

$\delta M_W^{\text{exp,LHC}} = 15$ MeV

$\Rightarrow$ extreme parameter regions already ruled out

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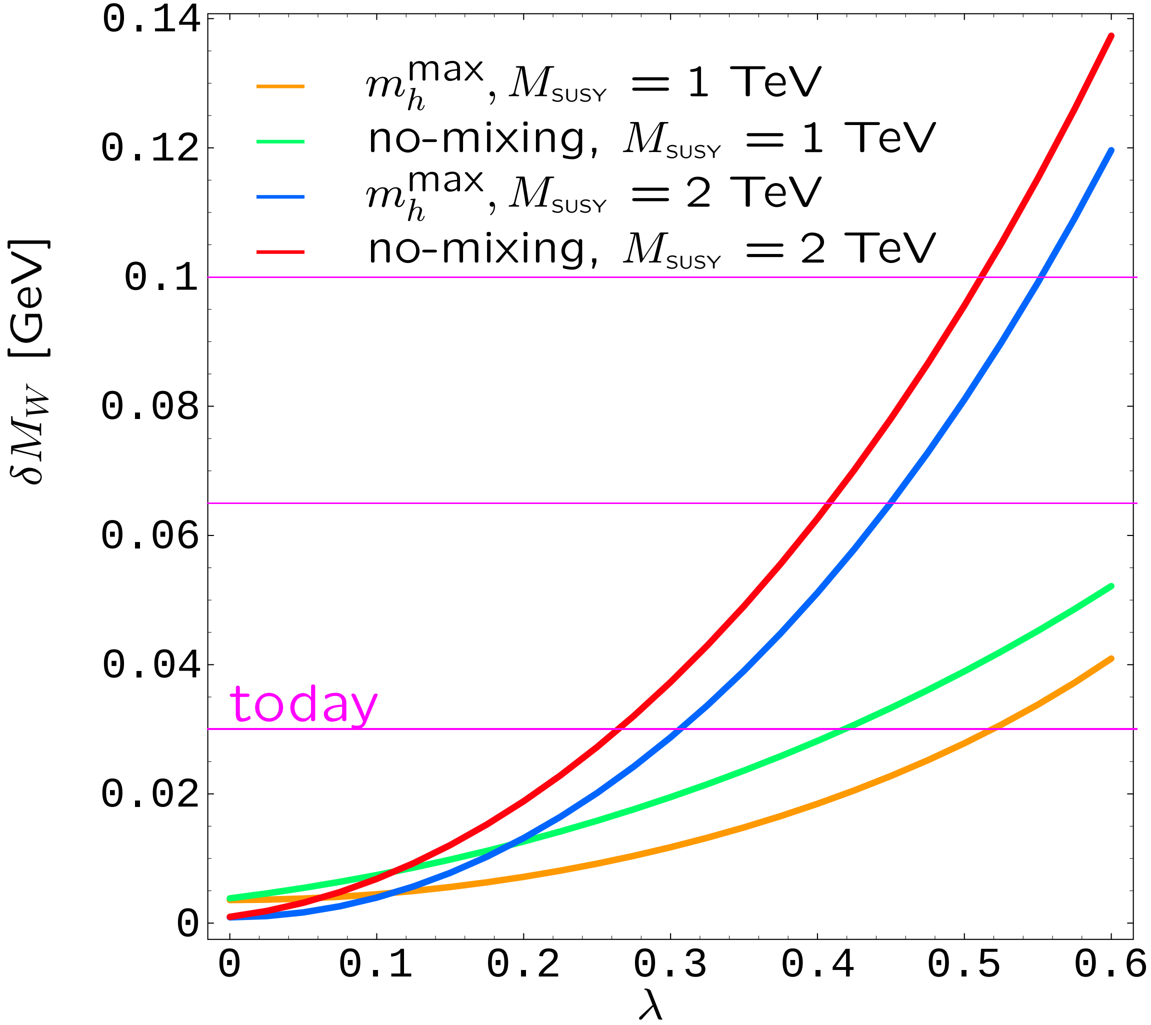

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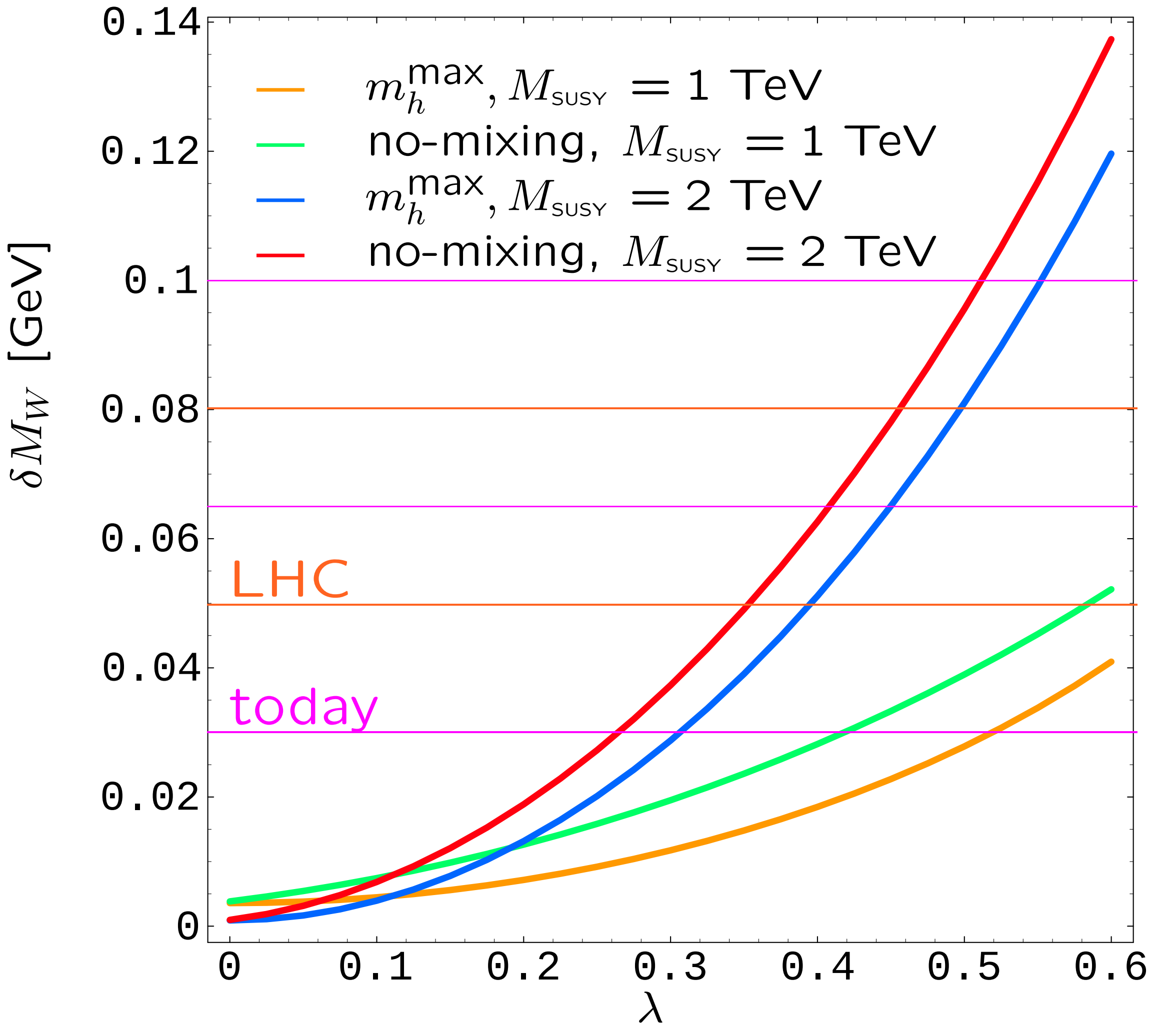

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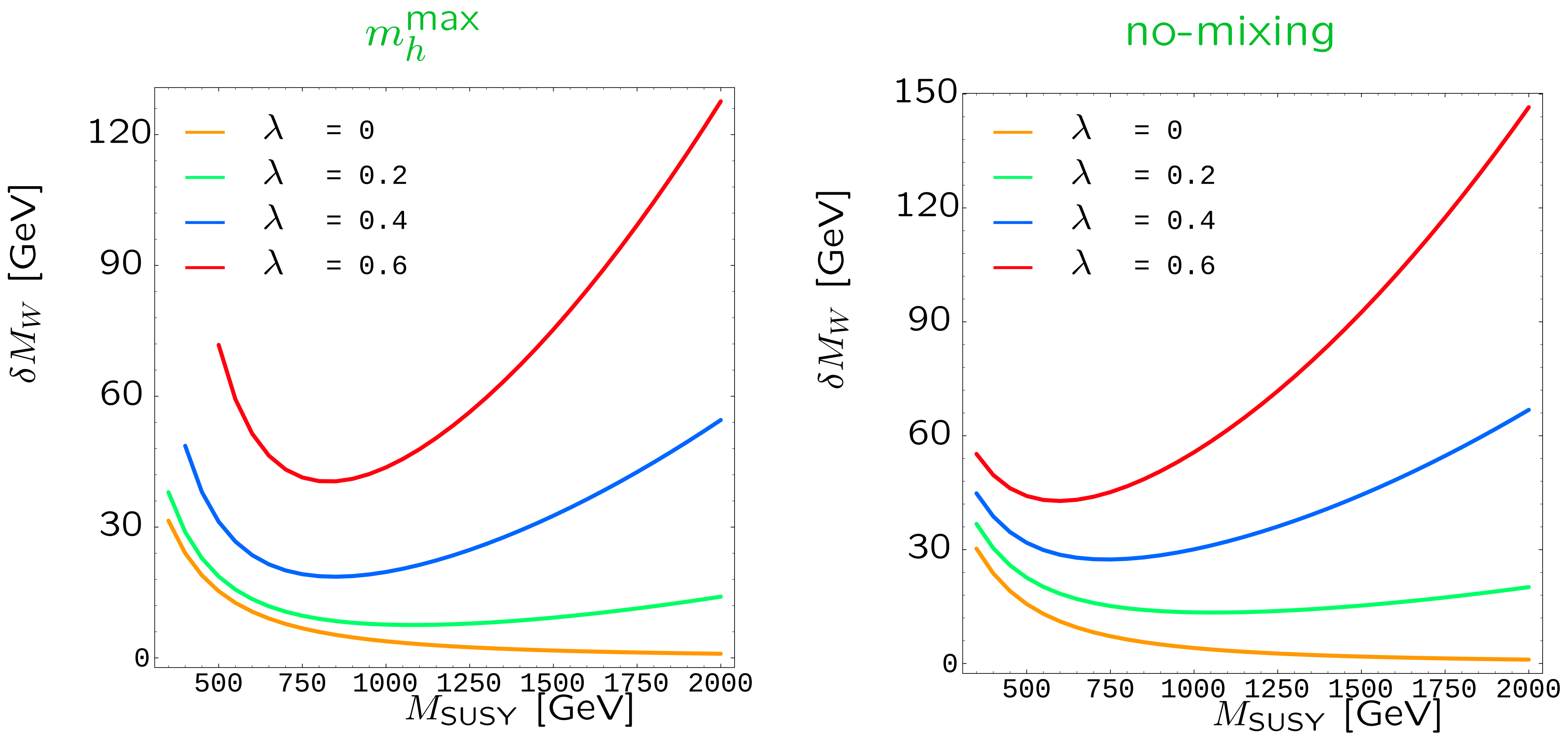
δM_W as a function of M_{SUSY}:

[S.H., W. Hollik, F. Merz, S. Peñaranda '04]

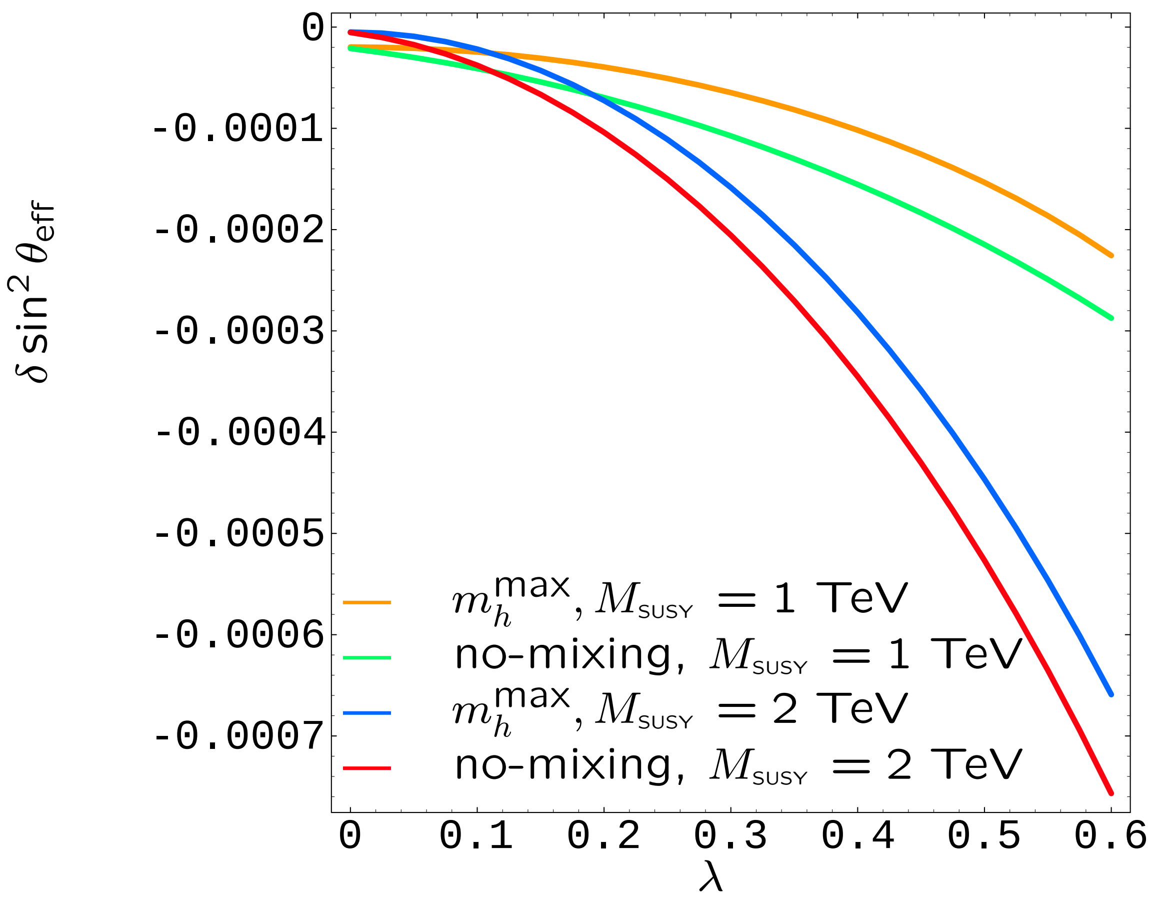


→ decoupling for $\lambda = 0$ as expected

→ $\lambda \neq 0$: minimum at moderate M_{SUSY}
increase for large M_{SUSY} (due to enlarged mixing)

$\delta \sin^2\theta_{\text{eff}}$ as a function of λ:

[*S.H., W. Hollik, F. Merz, S. Peñaranda '04*]



increasing λ
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$\Rightarrow$ decreasing $\sin^2\theta_{\text{eff}}$

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$\Rightarrow$ decreasing $\sin^2\theta_{\text{eff}}$

$\delta \sin^2\theta_{\text{eff}}^{\text{exp,today}} = 16 \times 10^{-5}$

$\delta \sin^2\theta_{\text{eff}}^{\text{exp,LHC}} = 14 \times 10^{-5}$

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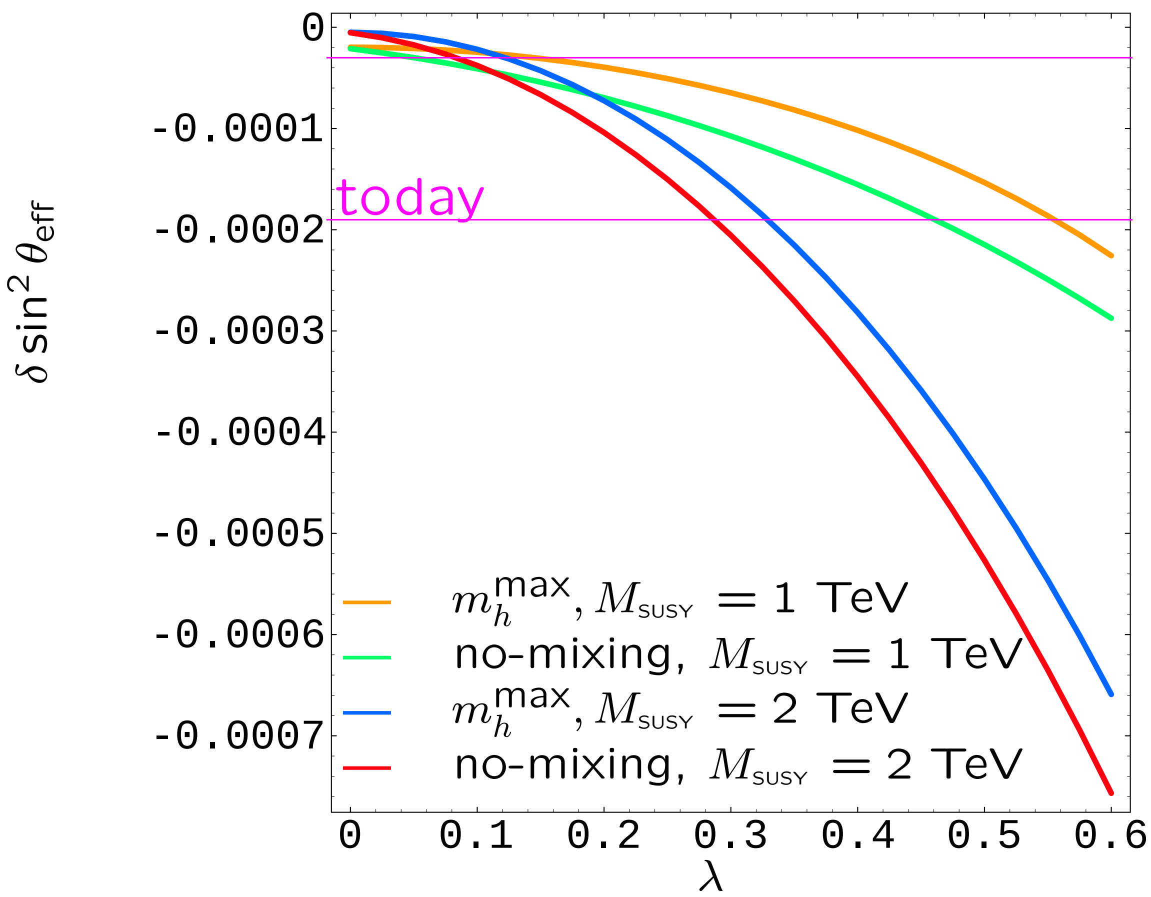

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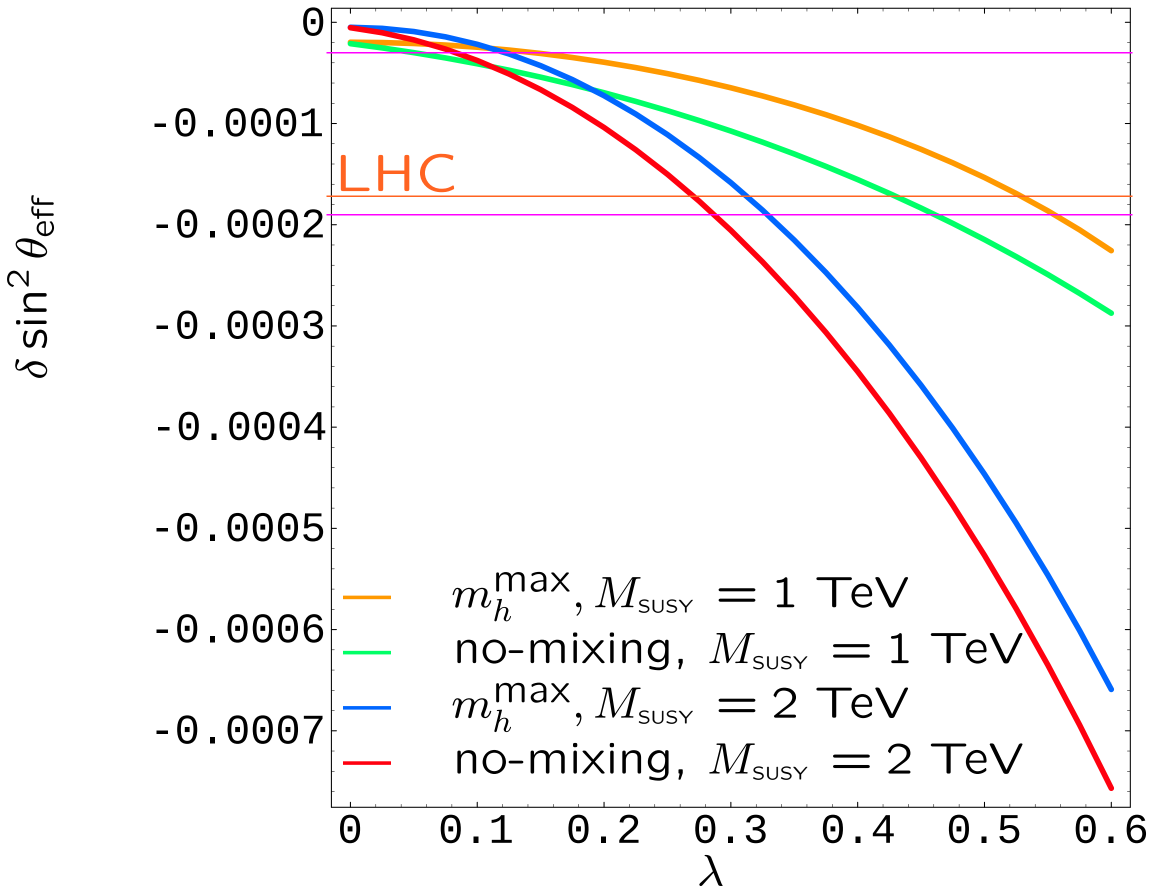

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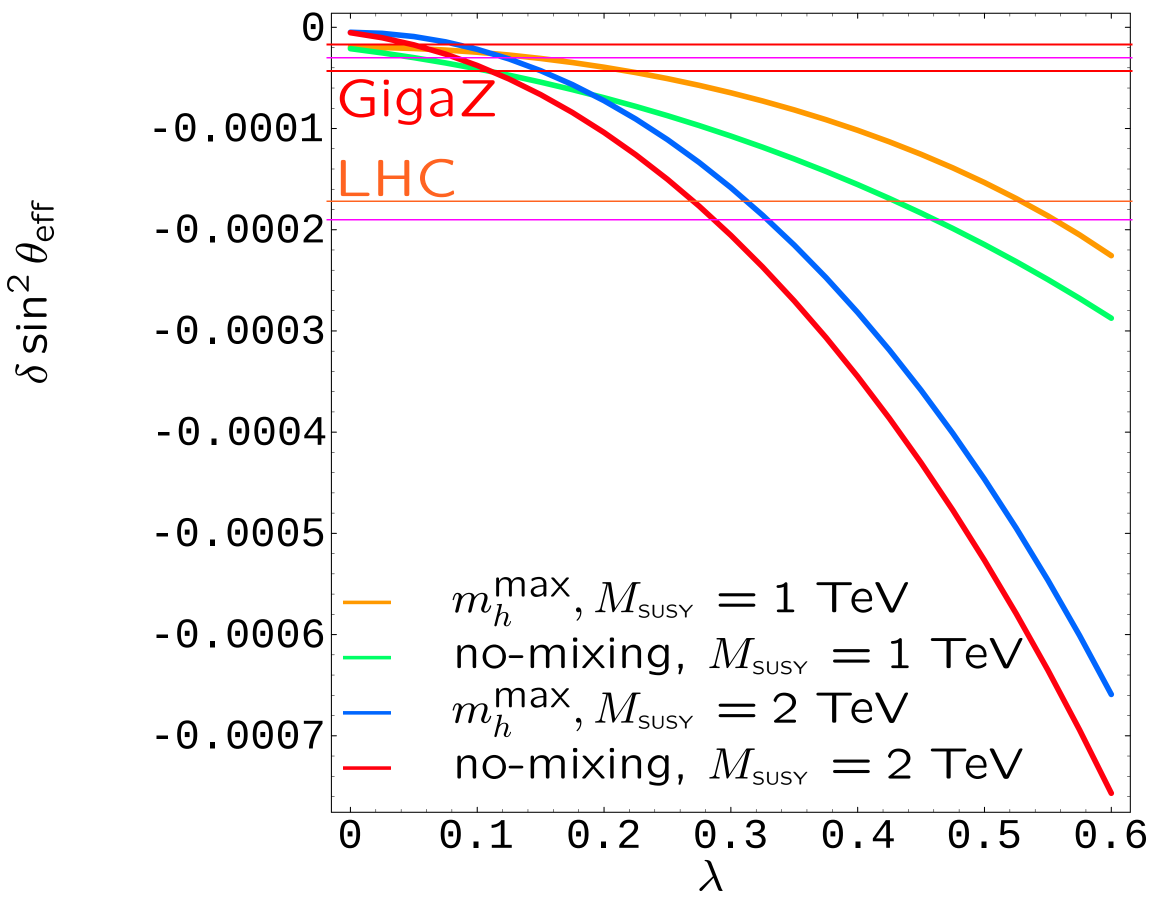

increasing λ
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increasing $M_{\rm SUSY}$
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$\delta \sin^2\theta_{\rm eff}^{\rm exp,LHC} = 14 \times 10^{-5}$

$\delta \sin^2\theta_{\rm eff}^{\rm exp,GigaZ} = 1.3 \times 10^{-5}$

$\Rightarrow$ extreme parameter regions already ruled out

3. Results for m_h

MSSM: enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}(H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$ Goldstone bosons: $G^0, G^\pm$

Input parameters:

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

Contrary to the SM: m_h is not a free parameter

MSSM tree-level bound: $m_h < M_Z$, excluded by LEP Higgs searches

Large radiative corrections:

Dominant one-loop corrections: $\sim G_\mu m_t^4 \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

Measurement of m_h, Higgs couplings $\Rightarrow$ test of the theory

LHC: $\Delta m_h \approx 0.2$ GeV

ILC: $\Delta m_h \approx 0.05$ GeV

$\Rightarrow m_h$ will be (the best?) electroweak precision observable

For not too large $\tan\beta$: only $\tilde{t}/\tilde{c}$ sector relevant

$\Rightarrow$ Evaluation of Σ_h, Σ_H, Σ_{hH}, Σ_A, T_h, T_H

(contributions from $t/\tilde{t}$ and $c/\tilde{c}$ only) $\longrightarrow$ T

Higgs boson sector analysis performed in 5 benchmark scenarios

[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

– m_h^{max} (to maximize the lightest Higgs boson mass)

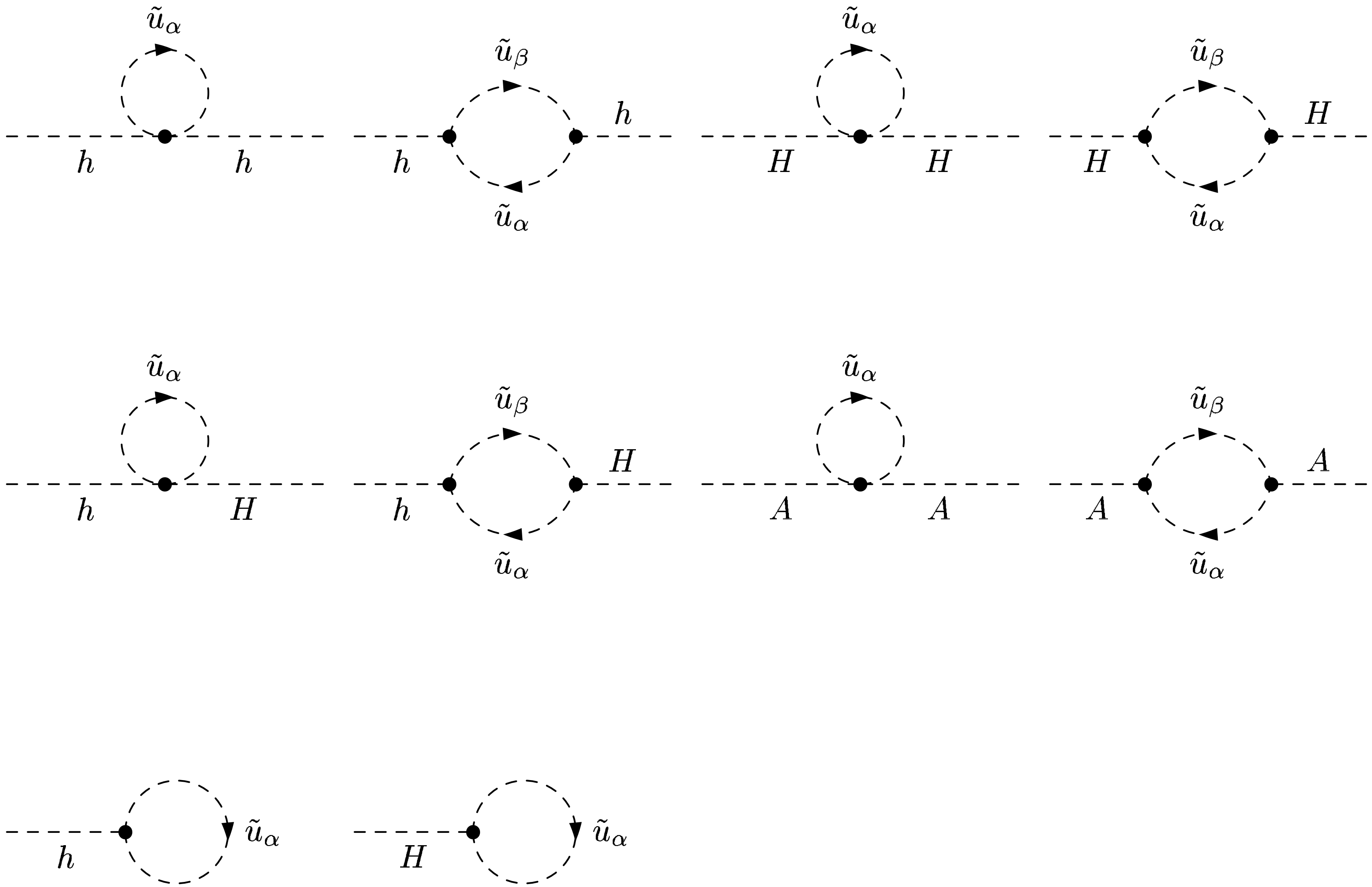
– constrained m_h^{max} (with $X_t/M_{\text{SUSY}} = -2$ for $b \to s\gamma$)

– no-mixing (with no mixing in the MFV $\tilde{t}$ sector)

– gluophobic Higgs (with reduced ggh coupling)

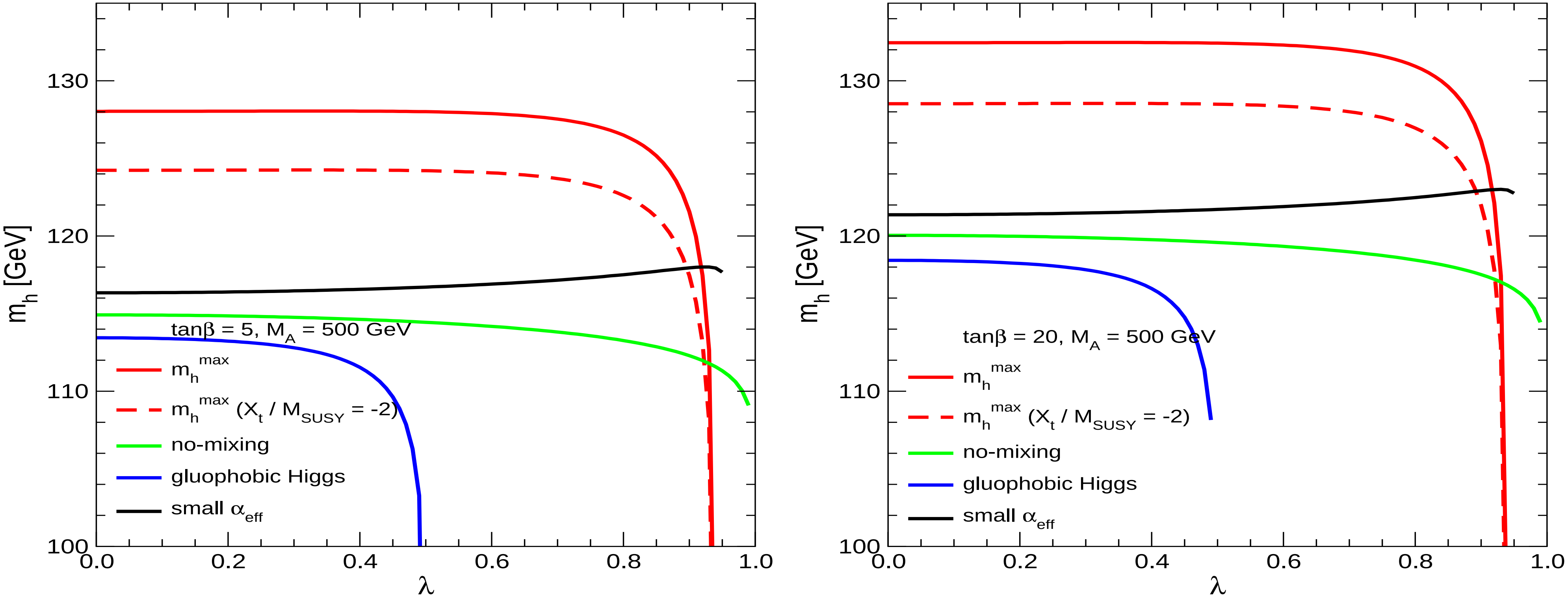
– small α_{eff} (with reduced $h\bar{b}b$ and $h\tau^+\tau^-$ coupling)

Feynman diagrams for m_h: evaluation of Σ_h, Σ_H, Σ_{hH}, Σ_A, T_h, T_H



Effects in benchmark scenarios:

[S.H., W. Hollik, F. Merz, S. Peñaranda '04]



⇒ small effects for small/moderate λ

⇒ $\delta m_h = \mathcal{O}(5 \text{ GeV})$ only for very large λ

→ mostly decreasing m_h, but also increase possible (e.g. in small α_{eff} scenario)

Computer codes:

Results in the NMFV MSSM for

electroweak precision observables

and

Higgs sector (masses and mixing angles)

are implemented into

FeynHiggs

[*S.H., W. Hollik, G. Weiglein '98, '00, '02*]

[*T. Hahn, S.H., W. Hollik, G. Weiglein '03, '04*]

`www.feynhiggs.de`

$\rightarrow$ all Higgs masses, couplings, BRs (easy to link, easy to use :-)

Planned:

– Allow all terms (LL, LR, RL, RR) $\neq 0$

– Include 3 generation mixing

4. News from FeynArts/FormCalc

Already implemented, to be released soon: [*T. Hahn '05*]

– Full 3-generation mixing for squark masses and mixing

– Off-diagonal A terms (3-generation mixing)

– Implemented in model file (`FVMSSM.mod` already available)
  [*T. Hahn, J. Illana, S. Peñaranda '05*]

– Parameter determination (including 6×6 diagonalization) of squark mass matrices implemented in *FormCalc*

This allows:

– fully automated (one-loop) calculations

– going beyond mass insertion method

– easy numerical evaluation

5. Conclusinos

- Precision observables can
  - give valuable information about the "true" Lagrangian
  - constrain MSSM parameter space already today
- MSSM with NMFV:

  considered: mixing in the $\tilde{t}/\tilde{c}$ and in the $\tilde{b}/\tilde{s}$ sector
- $\Rightarrow$ Evaluation of M_W, $\sin^2\theta_{\rm eff}$, m_h in NMFV MSSM
- Analytical results: for arbitrary mixing

  Numerical results: only for LL mixing, parametrized with λ

  corresponds to $(\delta_{LL})_{23}$
- large effects possible for M_W, $\sin^2\theta_{\rm eff}$: $\lambda \lesssim 0.2 \Rightarrow \delta M_W \lesssim 20$ MeV

  $\lambda \lesssim 0.2 \Rightarrow \delta \sin^2\theta_{\rm eff} \lesssim 10^{-4}$

  larger effects possible for smaller $M_{\rm SUSY}$
- moderate effects possible for m_h only for large λ
- Full 3 generation mixing implemented in *FeynArts, FormCalc*