FeynHiggs
The Swiss Army Knife for MSSM Higgs Physics*

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Brussels, 11/2007

based on collaboration with
T. Hahn, W. Hollik, H. Rzehak, G. Weiglein

1. Introduction
2. Recent theory developments
3. Parameter planes
4. Implementation into FeynHiggs 2.6
5. Conclusions

* thanks to Pietro Slavich

1. Introduction

Higgs potential of the cMSSM contains two Higgs doublets:

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

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

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) + \underbrace{\frac{g'^2 + g^2}{8}}(H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

Five physical states: $h^0, H^0, A^0, H^\pm$ (no $\mathcal{CP}$V at tree-level)

2 $\mathcal{CP}$-violating phases: ξ, $\arg(m_{12})$ $\Rightarrow$ can be set/rotated to zero

Input parameters: $\tan\beta = \frac{v_2}{v_1}$ and $M_{H^\pm}$

Effects of complex parameters in the Higgs sector:

Complex parameters enter via loop corrections:

– μ : Higgsino mass parameter

– $A_{t,b,\tau}$: trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b} - \mu^* \{\cot\beta, \tan\beta\}$ complex

– $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)

– $m_{\tilde{g}}$: gluino mass

$\Rightarrow$ can induce $\mathcal{CP}$-violating effects

Result:

$$(A, H, h) \to (h_3, h_2, h_1)$$

with

$$M_{h_3} > M_{h_2} > M_{h_1}$$

Propagator/Mass matrix at tree-level:

$$\begin{pmatrix} q^2 - m_A^2 & 0 & 0 \\ 0 & q^2 - m_H^2 & 0 \\ 0 & 0 & q^2 - m_h^2 \end{pmatrix}$$

Propagator / mass matrix with higher-order corrections
($\longrightarrow$ Feynman-diagrammatic approach):

$$M_{hHA}^2(q^2) = \begin{pmatrix} q^2 - m_A^2 + \hat{\Sigma}_{AA}(q^2) & \hat{\Sigma}_{AH}(q^2) & \hat{\Sigma}_{Ah}(q^2) \\ \hat{\Sigma}_{HA}(q^2) & q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hA}(q^2) & \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ $(i,j = h, H, A)$: renormalized Higgs self-energies

$\hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH} \neq 0 \Rightarrow \mathcal{CP}$V, $\mathcal{CP}$-even and $\mathcal{CP}$-odd fields can mix

$\Rightarrow$ complex roots of det$(M_{hHA}^2(q^2))$: $\mathcal{M}_{h_i}^2 (i = 1,2,3)$: $\mathcal{M}^2 = M^2 - iM\Gamma$

2. Recent theory developments

2A) New two-loop corrections in the cMSSM

Propagator / mass matrix with higher-order corrections:

$$M^2_{hHA}(q^2) = \begin{pmatrix} q^2 - m_A^2 + \hat{\Sigma}_{AA}(q^2) & \hat{\Sigma}_{AH}(q^2) & \hat{\Sigma}_{Ah}(q^2) \\ \hat{\Sigma}_{HA}(q^2) & q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hA}(q^2) & \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ $(i,j = h,H,A)$: renormalized Higgs self-energies

$\hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH} \neq 0 \Rightarrow \mathcal{CP}$V

Our result for $\hat{\Sigma}_{ij}$:

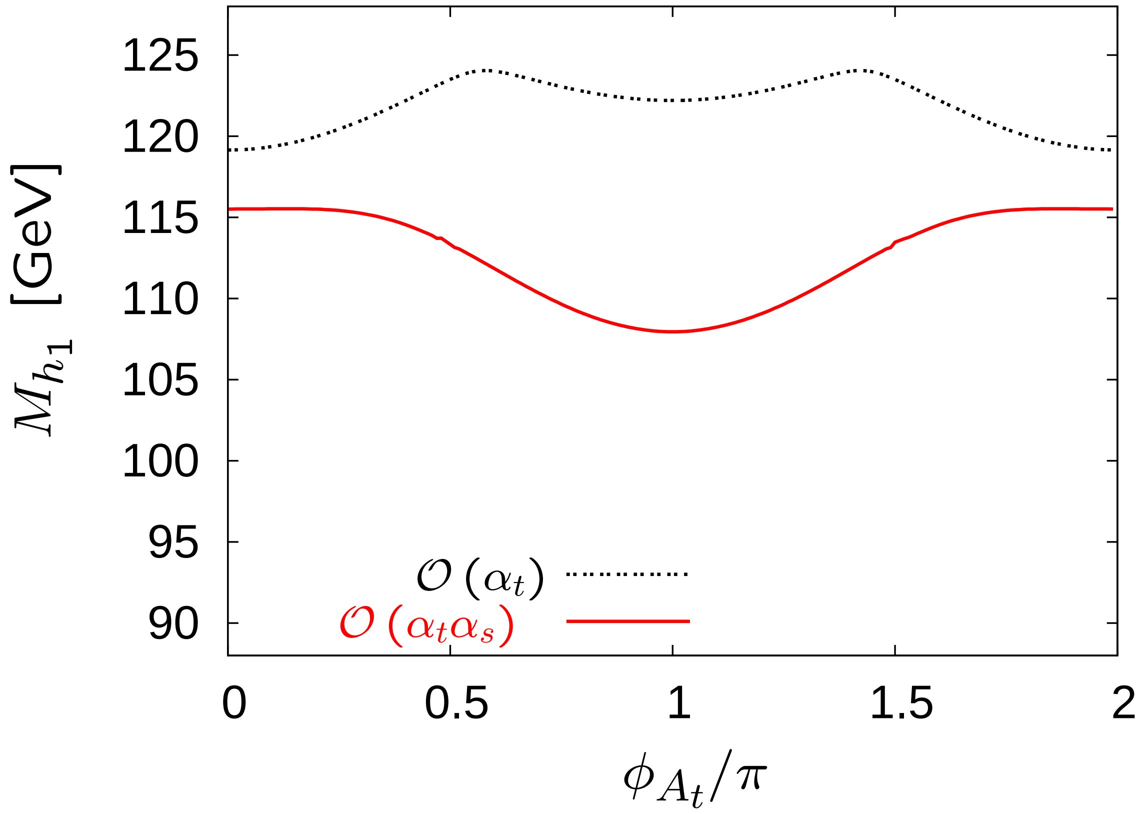
– full 1-loop: complex phases, q^2-dep., imaginary parts

– newly implemented: cMSSM $\mathcal{O}(\alpha_t \alpha_s)$ corrections in the FD approach
  rMSSM: difference between FD and RGiEP approach $\mathcal{O}$(few GeV)

$\Rightarrow$ numerical search for the complex roots of $\det(M^2_{hHA}(q^2)) \Rightarrow \mathcal{M}^2_{h_i}$

M_{h_1} as a function of ϕ_{A_t}:

[S.H., W. Hollik, H. Rzehak, G. Weiglein '07]



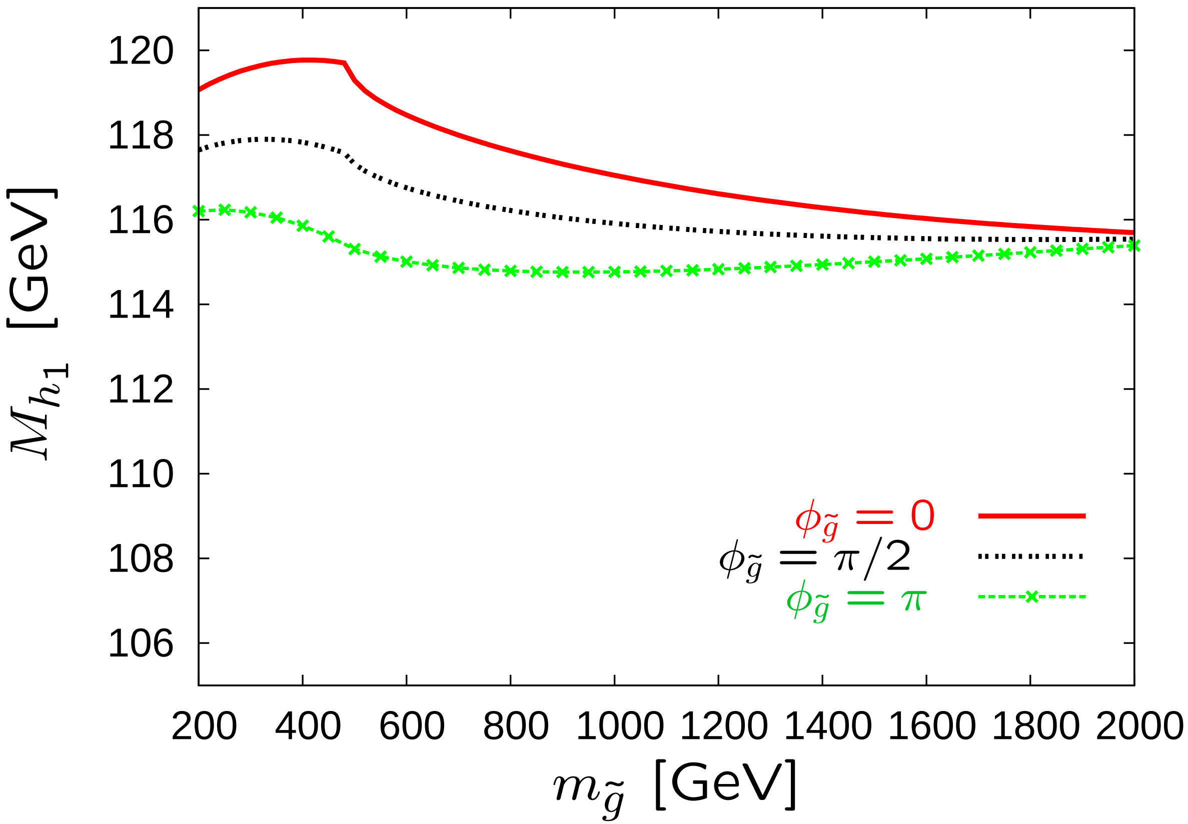
$M_{\text{SUSY}} = 1000$ GeV
$|A_t| = 2000$ GeV
$\tan\beta = 10$
$M_{H^\pm} = 150$ GeV

OS renormalization

$\Rightarrow$ modified dependence on ϕ_{A_t} at the 2-loop level

M_{h_1} as a function of $\phi_{\tilde{g}}$:

[S.H., W. Hollik, H. Rzehak, G. Weiglein '07]



$M_{\mathrm{SUSY}} = 500$ GeV
$A_t = 1000$ GeV
$\tan\beta = 10$
$M_{H^\pm} = 500$ GeV

OS renormalization

$\Rightarrow$ threshold at $m_{\tilde{g}} = m_{\tilde{t}} + m_t$

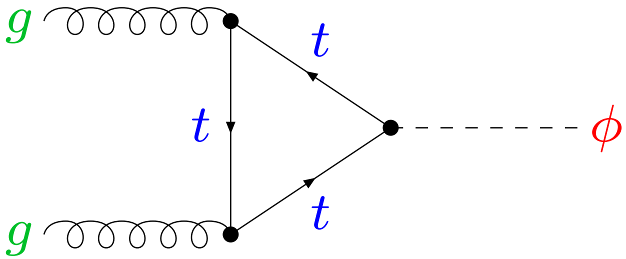
$\Rightarrow$ large effects around threshold

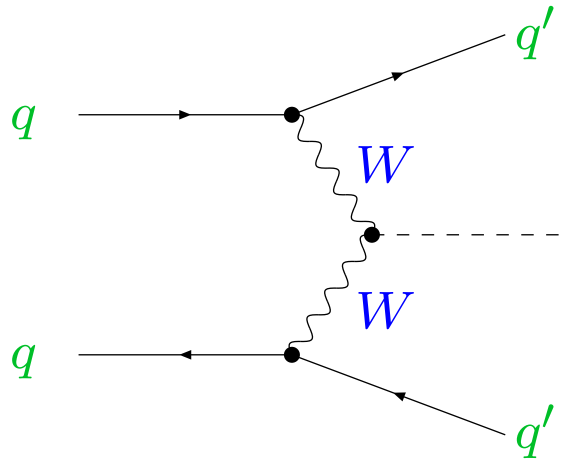
$\Rightarrow$ phase dependence has to be taken into account

2B) External (on-shell) Higgs bosons

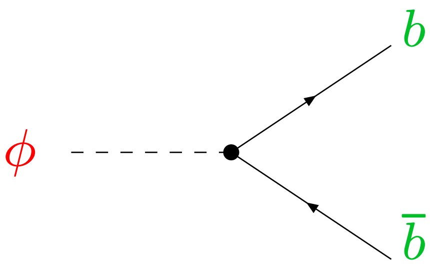
Examples for external (on-shell) Higgs bosons ($\phi = h_1, h_2, h_3$):

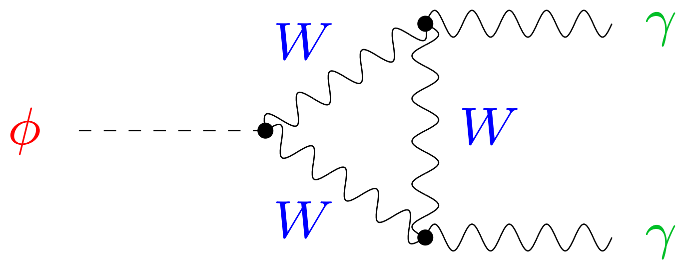
Higgs production:





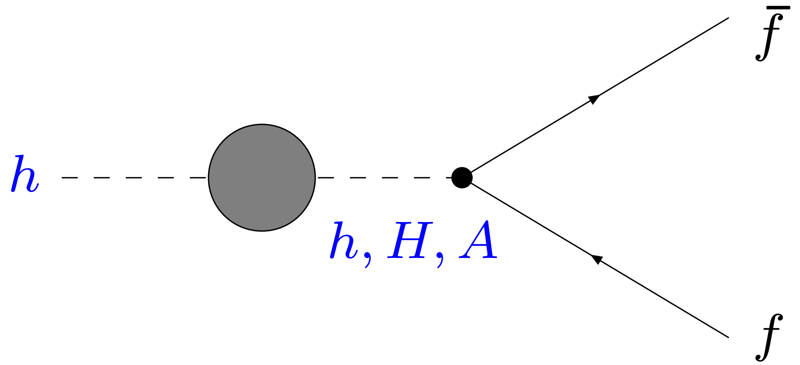
Higgs decays:





$\Rightarrow$ important to ensure on-shell properties of external Higgs boson

Evaluation of amplitudes:



h, H, A : loop-corrected (neutral) Higgs bosons

Amplitude:

$$A(h \to f\bar{f}) = \sqrt{Z_h}\,(\Gamma_h + Z_{hH}\Gamma_H + Z_{hA}\Gamma_A)$$

$\Gamma_{h,H,A}$: coupling of h, H, A to $f\bar{f}$

$\sqrt{Z_h}$: ensures that the residuum of the external Higgs boson is set to 1

Z_{hH}, Z_{hA} : describes the transition from $h \to H/A$

Written more compact with the $\mathbf{Z}$ matrix:

$$\mathbf{Z}_{ij} = \sqrt{Z_i}\,Z_{ij}$$

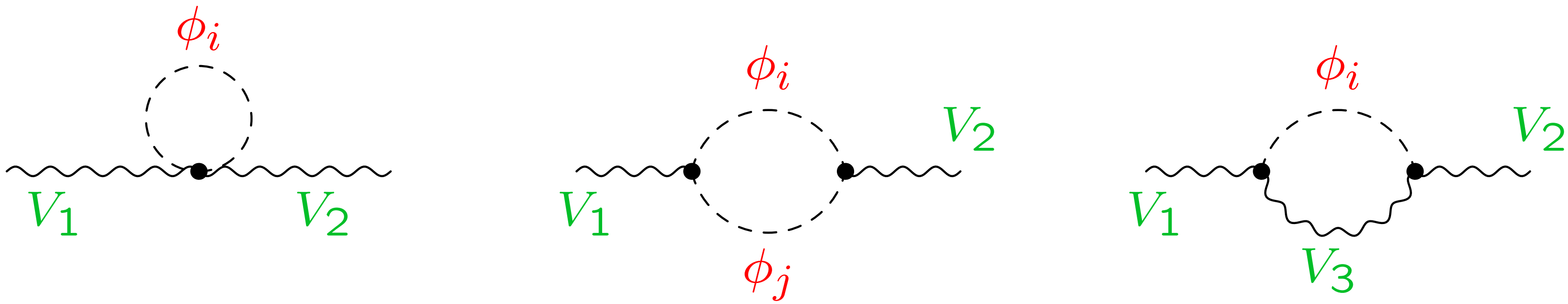
2C) Internal Higgs bosons

Examples for Higgs bosons entering loop corrections:

Vector boson self-energies:

e.g. in μ decay, precision observables, ...

$(V_{1,2,3} = Z, W^{\pm})$



$\phi_{i,j} = h, H, A$ (tree-level states): $\Rightarrow$ ok

But what if $\phi_{i,j} = h_1, h_2, h_3$?

$\Rightarrow$ How to include higher-order corrections to the Higgs bosons properly?

$\Rightarrow$ How to define "effective couplings"?

Two possibilities:

1.) "p^2 on-shell" : $\mathbf{U}$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}_{p^2\ \text{on-shell}} = \mathbf{U} \cdot \begin{pmatrix} h \\ H \\ A \end{pmatrix}, \quad p^2\,\text{on-shell}: \begin{array}{lcl} \hat{\Sigma}_{ii}(p^2) & \to & \hat{\Sigma}_{ii}(m_i^2) \\ \hat{\Sigma}_{ij}(p^2) & \to & \hat{\Sigma}_{ij}((m_i^2 + m_j^2)/2) \end{array}$$

$$\mathbf{U}\,\text{Re}\left(\mathbf{M}_{hHA}(p^2\,\text{on-shell})\right)\mathbf{U}^\dagger = \begin{pmatrix} M^2_{h_1,p^2\text{os}} & 0 & 0 \\ 0 & M^2_{h_2,p^2\text{os}} & 0 \\ 0 & 0 & M^2_{h_3,p^2\text{os}} \end{pmatrix}$$

2.) "$p^2 = 0$" : $\mathbf{R}$ ($\mathcal{CP}$C case, 2×2 mixing $\Rightarrow \alpha_{\text{eff}}$)

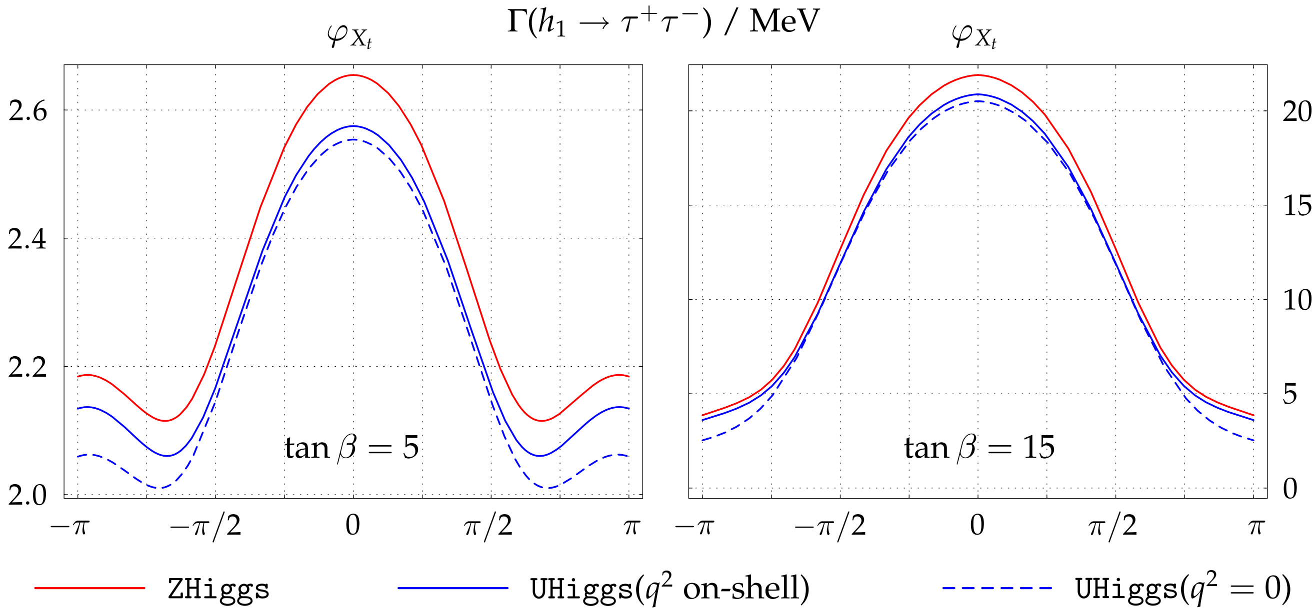
$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}_{p^2=0} = \mathbf{R} \cdot \begin{pmatrix} h \\ H \\ A \end{pmatrix}, \quad \mathbf{R}\,\mathbf{M}_{hHA}(0)\,\mathbf{R}^\dagger = \begin{pmatrix} M^2_{h_1,p^2=0} & 0 & 0 \\ 0 & M^2_{h_2,p^2=0} & 0 \\ 0 & 0 & M^2_{h_3,p^2=0} \end{pmatrix}$$

Numerical example for external Higgs bosons:

[*T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '07*]

$M_{\text{SUSY}} = m_{\tilde{g}} = M_2 = 500$ GeV, $A_t = 1000$ GeV, $\mu = 1000$ GeV, $M_{H^\pm} = 150$ GeV

$\Gamma(h_1 \to \tau^+\tau^-)$ as a function of ϕ_{X_t}



red solid: **Z** , blue solid: **U** , blue dashed: **R**

⇒ **U** gives results closer to full result than **R**

⇒ deviations at the 5-10% level

Numerical example for external Higgs bosons:

[*T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '07*]

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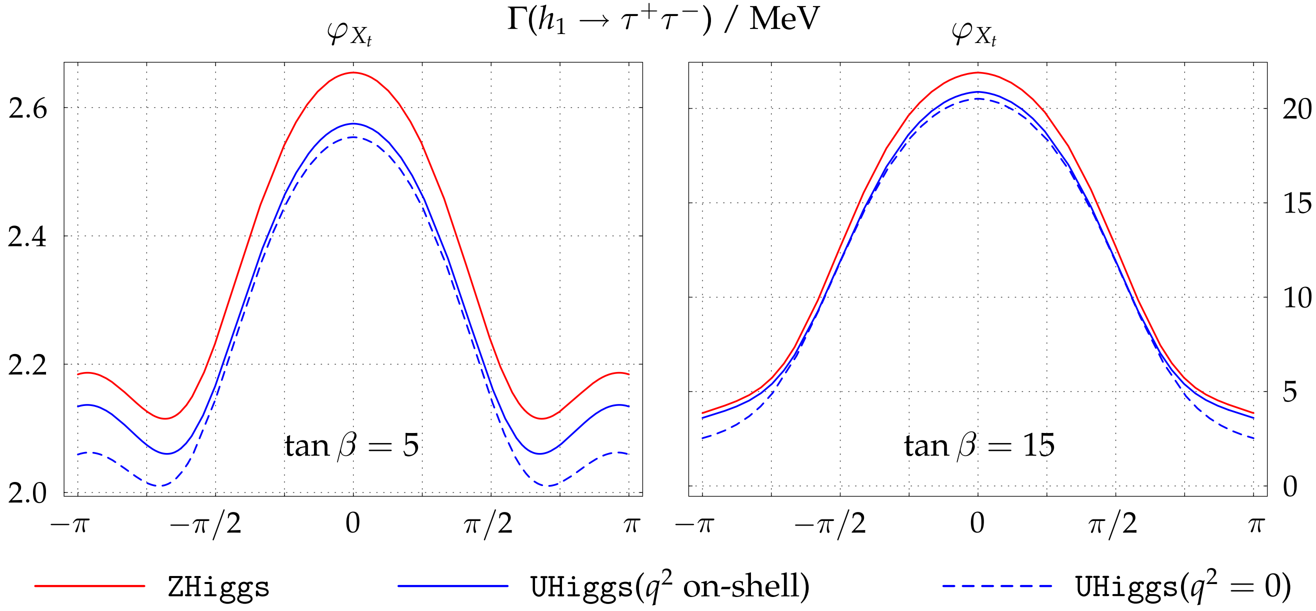
$\Gamma(h_1 \to \tau^+\tau^-)$ as a function of ϕ_{X_t}



red solid: **Z** , blue solid: **U** , blue dashed: **R**

Included in FeynHiggs: **Z**, **U**, **R**

Comparison with other codes/calculations:

FeynHiggs is the only code that has

– evaluation of $\Gamma(h_i \to \ldots)$ with external Higgs, bosons on-shell i.e. evaluated with $\mathbf{Z}$

– evaluation of $\mathrm{BR}(h_i \to \ldots)$ with external Higgs, bosons on-shell i.e. evaluated with $\mathbf{Z}$

– evaluation of $\sigma_{\mathrm{Tev,LHC}}(\ldots \to h_i + X)$ with external Higgs bosons on-shell, i.e. evaluated with $\mathbf{Z}$

– evaluation of effective couplings with $\mathbf{U}$ or $\mathbf{R}$

– $\mathrm{Im}\,\hat{\Sigma}$ included consistently in mass and coupling evaluation

Other codes/calculations:

– rely on evaluation of Γ, BR with $\mathbf{R}$ (possibly with $\mathbf{U}$)

– effective potential approach corresponds to $\mathbf{R}$

$\Rightarrow$ see numerical examples (in the back-up slides) for size of effects

3. Parameter planes

Search for the MSSM Higgs bosons:

$\rightarrow$ investigate benchmark scenarios:

> $\rightarrow$ Vary only M_A and $\tan\beta$
> $\rightarrow$ Keep all other SUSY parameters fixed

1. $m_h^{\rm max}$ scenario:
   $\rightarrow$ obtain conservative $\tan\beta$ exclusion bounds ($X_t = 2\,M_{\rm SUSY}$)
2. no-mixing scenario
   $\rightarrow$ no mixing in the scalar top sector ($X_t = 0$)
3. small $\alpha_{\rm eff}$ scenario
   $\rightarrow$ $hb\bar{b}$ coupling $\sim \sin\alpha_{\rm eff}/\cos\beta$ can be zero: $\alpha_{\rm eff} \rightarrow 0$:
   main decay mode vanishes, important search channel vanishes
4. gluophobic Higgs scenario
   $\rightarrow$ hgg coupling is small: main LHC production mode vanishes

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

$\rightarrow$ included in FeynHiggs for a long time

Possible external constraints:

- cold dark matter (CDM)
- BR($b \to s\gamma$)
- anomalous magnetic moment of the μ
  (reason for change from $\mu = -200$ GeV $\to$ $\mu = +200$ GeV)

$\Rightarrow$ so far ignored (for (good) reasons)

Wanted: M_A–$\tan\beta$ planes in agreement with CDM

Possible external constraints:

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$\Rightarrow$ so far ignored (for (good) reasons)

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Possible models:

1.) CMSSM (or mSUGRA):

$\Rightarrow$ Scenario characterized by

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

$\Rightarrow$ too restricted

Possible external constraints:

– cold dark matter (CDM)
– BR($b \to s\gamma$)
– anomalous magnetic moment of the μ
  (reason for change from $\mu = -200$ GeV $\to$ $\mu = +200$ GeV)

$\Rightarrow$ so far ignored (for (good) reasons)

Wanted: M_A–$\tan\beta$ planes in agreement with CDM

2.) NUHM: (Non-universal Higgs mass model)

Assumption: no unification of scalar fermion and scalar Higgs parameters at the GUT scale

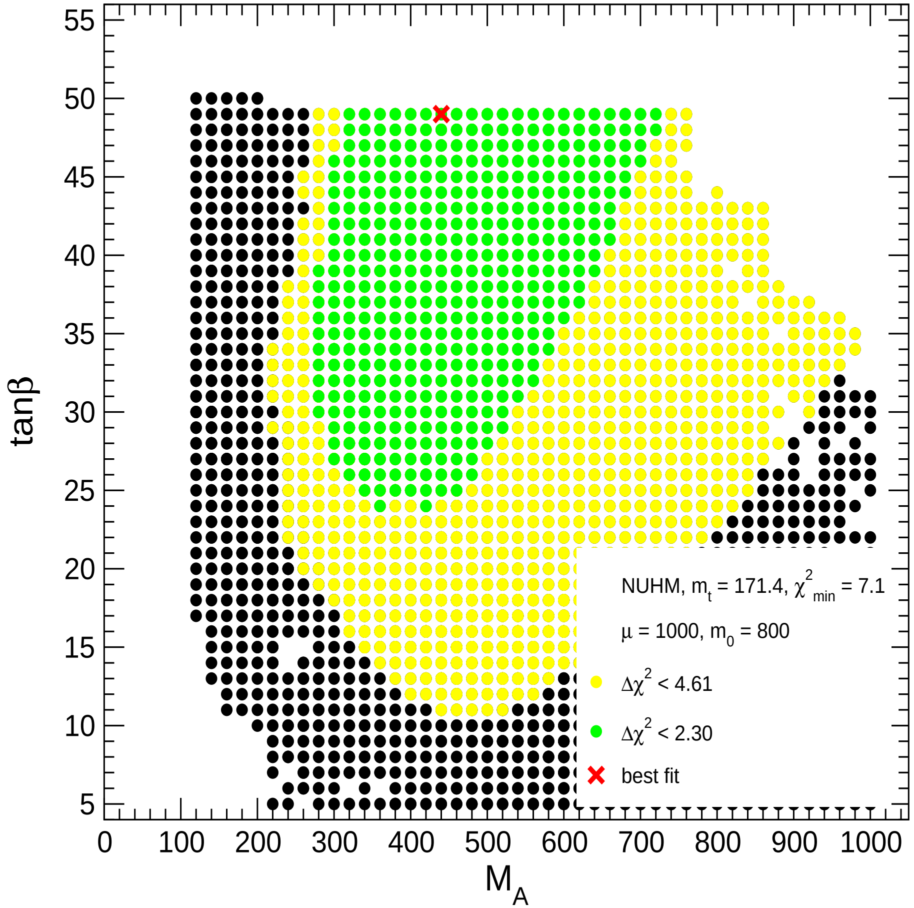
$\Rightarrow$ effectively M_A and μ free parameters at the EW scale

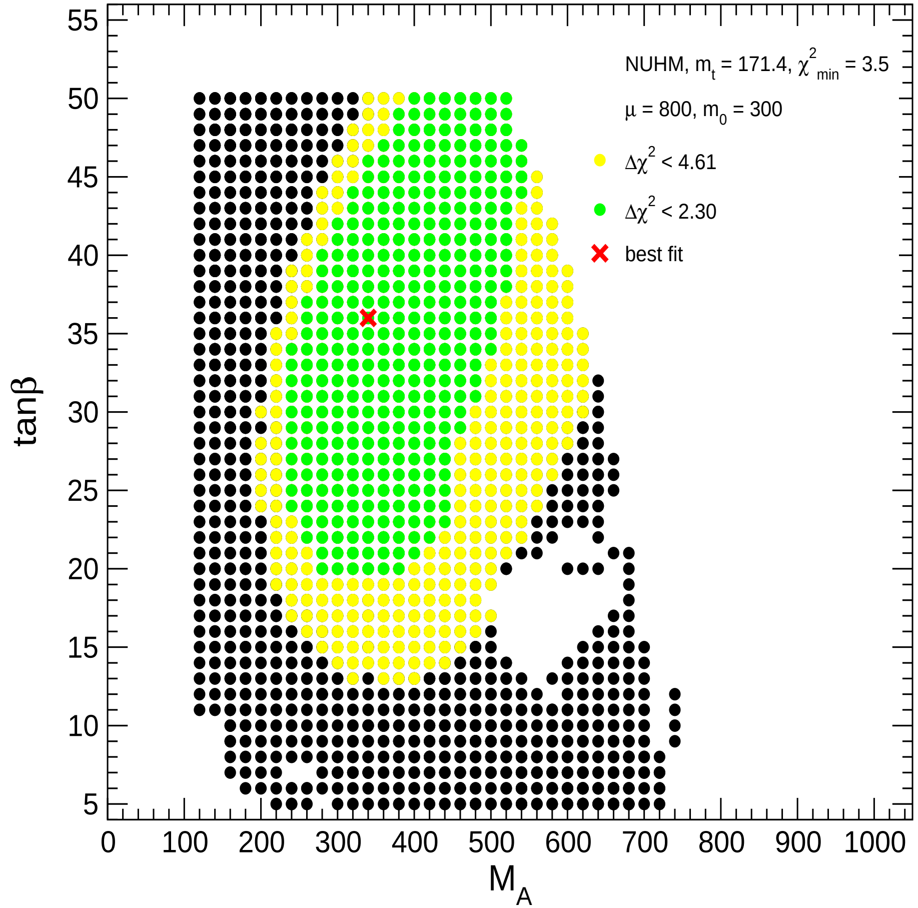
$\Rightarrow$ besides the CMSSM parameters

$$M_A \text{ and } \mu$$

Results: NUHM: planes 1,2

[*J. Ellis, T. Hahn, S.H., K. Olive, G. Weiglein '07*]



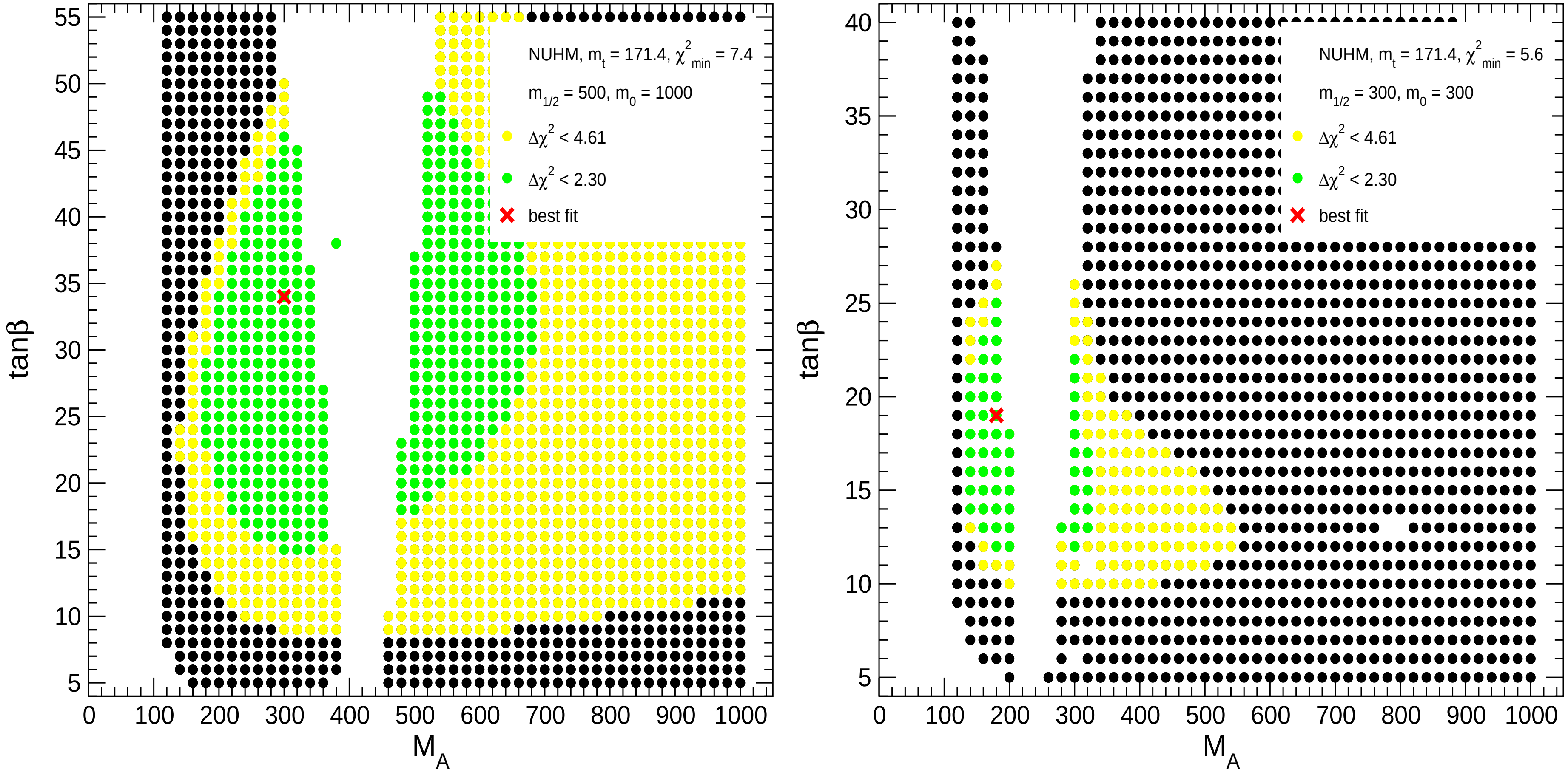


$\Rightarrow$ good χ^2 (M_W, $\sin^2\theta_{\rm eff}$, Γ_Z, M_h, $(g-2)_\mu$, BR($b \to s\gamma$) and other BPO)

$\Rightarrow$ larger regions o.k.

Results: NUHM: planes 3,4

[*J. Ellis, T. Hahn, S.H., K. Olive, G. Weiglein '07*]



$\Rightarrow$ good χ^2 (M_W, $\sin^2\theta_{\rm eff}$, Γ_Z, M_h, $(g-2)_\mu$, BR($b \to s\gamma$) and other BPO)

$\Rightarrow$ larger regions o.k.

4. Implementation into FeynHiggs 2.6

Latest version: FeynHiggs 2.6.2 (11/07) (gestern!)

version FeynHiggs 2.6.3 to be released this year . . .

FeynHiggs2.2 → FeynHiggs 2.6: main new features

- $\mathcal{O}(\alpha_t \alpha_s)$ corrections in the cMSSM
- Complex contributions to Higgs mass matrix taken into account (from Im $B_0(\ldots) \neq 0$)
- Higgs masses are now the real part of the complex pole
- $\Rightarrow$ complex 3×3 mixing matrix Z $\Rightarrow$ external (on-shell) Higgs bosons

  unitary 3×3 mixing matrix U or R $\Rightarrow$ Higgs bosons in loops

  $\Rightarrow$ included in all Higgs production and decay
- inclusion of full one-loop NMFV effects
- Implementation of new M_A–$\tan\beta$ planes in agreement with CDM
- EDMs of electron, neutron, Hg, . . .

Included in FeynHiggs 2.6 (I):

Evaluation of all Higgs boson masses and mixing angles

- $M_{h_1}, M_{h_2}, M_{h_3}, M_{H^\pm}$, $\alpha_{\rm eff}$, $\mathbf{Z}_{ij}$, $\mathbf{U}_{ij}$, $\mathbf{R}_{ij}$, ...

Evaluation of all neutral Higgs boson decay channels $\Leftarrow$ with $\mathbf{Z}$

- total decay width $\Gamma_{\rm tot}$
- $\mathrm{BR}(h_i \to f\bar{f})$: decay to SM fermions
- $\mathrm{BR}(h_i \to \gamma\gamma, ZZ^{(*)}, WW^{(*)}, gg)$: decay to SM gauge bosons
- $\mathrm{BR}(h_i \to h_j Z^{(*)}, h_j h_k)$: decay to gauge and Higgs bosons
- $\mathrm{BR}(h_i \to \tilde{f}_i \tilde{f}_j)$: decay to sfermions
- $\mathrm{BR}(h_i \to \tilde{\chi}^\pm_i \tilde{\chi}^\pm_j, \tilde{\chi}^0_i \tilde{\chi}^0_j)$: decay to charginos, neutralinos

Evaluation for the SM Higgs (same masses as the three MSSM Higgses)

- total decay width $\Gamma^{\rm SM}_{\rm tot}$
- $\mathrm{BR}(h_i^{\rm SM} \to f\bar{f})$: decay to SM fermions
- $\mathrm{BR}(h_i^{\rm SM} \to \gamma\gamma, ZZ^{(*)}, WW^{(*)}, gg)$: decay to SM gauge bosons

Included in FeynHiggs 2.6 (II):

Evaluation of all neutral Higgs boson production cross sections at Tevatron/LHC ⇐ with **Z**

SM: (more or less) up-to-date, MSSM: additional effective couplings

- $gg \to h_i$: gluon fusion (→ updated in FeynHiggs 2.6.3)
- $WW \to h_i$, $ZZ \to h_i$: gauge boson fusion
- $W \to Wh_i$, $Z \to Zh_i$: Higgs strahlung
- $b\bar{b} \to b\bar{b}h_i$: bottom Yukawa process
- $b\bar{b} \to b\bar{b}h_i$, $h_i \to b\bar{b}$, one b tagged
- $t\bar{t} \to t\bar{t}h_i$: top Yukawa process
- $\tilde{t}\bar{\tilde{t}} \to \tilde{t}\bar{\tilde{t}}h_i$: stop Yukawa process

Evaluation for the SM Higgs (same masses as the three MSSM Higgses)

- all SM channels as above

Included in FeynHiggs 2.6 (III):

Evaluations for the charged Higgs boson (rMSSM/cMSSM)

- total decay width Γ_{tot}
- $\text{BR}(H^+ \to f^{(*)}\bar{f}')$: decay to SM fermions
- $\text{BR}(H^+ \to h_i W^{+(*)})$: decay to gauge and Higgs bosons
- $\text{BR}(H^+ \to \tilde{f}_i \tilde{f}'_j)$: decay to sfermions
- $\text{BR}(H^+ \to \tilde{\chi}_i^0 \tilde{\chi}_j^+)$: decay to charginos and neutralinos
- H^+ production cross sections at Tevatron and LHC
- $\text{BR}(t \to H^+\bar{b})$ for $M_{H^\pm} \le m_t$ ($H^\pm$ production)

Evaluation of additional couplings: $\Leftarrow$ with $\mathbf{U}$ or $\mathbf{R}$

- $g(V \to V h_i, h_i h_j)$: coupling of gauge and Higgs bosons
- $g(h_i h_j h_k)$: all Higgs self couplings (including charged Higgs)

Included in FeynHiggs 2.6 (IV):

Evaluation of theory error on masses and mixing

$\rightarrow$ estimate of uncertainty in $M_{h_i}, \mathbf{U}_{ij}, \mathbf{Z}_{ij}$ from unknown higher-order corr.

Evaluation of masses, mixing and decay in the NMFV MSSM

NMFV: Non Minimal Flavor Violation *[Hahn, S.H., Hollik, Merz, Peñaranda '04-'06]*
$\Rightarrow$ Connection to Flavor physics

Evaluation of additional constraints (rMSSM/cMSSM)

- ρ-parameter: $\Delta\rho^{\text{SUSY}}$ at $\mathcal{O}(\alpha)$, $\mathcal{O}(\alpha\alpha_s)$, ..., including NMFV effects
  $\Rightarrow M_W$, $\sin^2\theta_{\text{eff}}$ via SM formula + $\Delta\rho^{\text{SUSY}}$, including NMFV effects
- anomalous magnetic moment of the μ: $(g-2)_\mu$
- BR$(b \rightarrow s\gamma)$, including NMFV effects *[T. Hahn, W. Hollik, J. Illana, S. Peñaranda '06]*
- LEP Higgs constraints (preliminary) *[LEP Higgs WG '06]*
- EDMs of electron, neutron, Hg, ...

Included in FeynHiggs 2.6 (V):

Planned:

- ILC production cross sections
- γC production cross sections
- full one-loop corrections to all (remaining) Higgs decays
- flavor violating Higgs decays
- . . .

If you need something, just let us know!

New M_A–$\tan\beta$ planes:

Data accessed within FeynHiggs in terms of tables with a grid for M_A and $\tan\beta$

MT	MSUSY	MA0	TB	AT	MUE	...
171.4	500	200	5	1000	761	...
171.4	500	210	5	1000	753	...
⋮	⋮	⋮	⋮	⋮	⋮	⋮
171.4	500	200	6	1000	742	...
171.4	500	210	6	1000	735	...
⋮	⋮	⋮	⋮	⋮	⋮	⋮

FeynHiggs interpolates between the four NWSE points in M_A and $\tan\beta$
FeynHiggs gives an error if $\{M_A, \tan\beta\}$ combination is not allowed

4 M_A–$\tan\beta$ planes can be downloaded from www.feynhiggs.de
Definition of new planes by the user is possible (respect table format)

How to install FeynHiggs 2.6

1. Go to www.feynhiggs.de
2. Download the latest version
3. type `./configure`, `make`, `make install`
   ⇒ library `libFH.a` is created
4. 4 possible ways to use *FeynHiggs*:

   A) Command-line mode (allows also running on the GRID)

   B) called from a Fortran/C++ code

   C) called within Mathematica

   D) WWW mode

   processing of Les Houches Accord data possible
5. Detailed instructions and help are provided in the man pages

How to run FeynHiggs 2.6

A) Command-line mode

Input File

```
MT          172.7
MB          4.7
MW          80.4
MZ          91.1
MSusy       975
MA0         200
Abs(M_2)    332
Abs(MUE)    980
TB          50
Abs(At)     -300
Abs(Ab)     1500
Abs(M_3)    975
```

Command

FeynHiggs *file* [*flags*] →

Screen Output

```
------------------- HIGGS MASSES -------------------
| Mh0     =   116.022817
| MHH     =   199.943497
| MA0     =   200.000000
| MHp     =   216.973920
| SAeff   =  -0.02685112
| UHiggs  =   0.99999346  -0.00361740   0.00000000 \
|             0.00361740   0.99999346   0.00000000 \
|             0.00000000   0.00000000   1.00000000

-------------- ESTIMATED UNCERTAINTIES -------------
| DeltaMh0  =  1.591957
| DeltaMHH  =  0.004428
| DeltaMA0  =  0.000000
| DeltaMHp  =  0.152519
  ...
```

- Loops over parameter values possible (parameter scans).
- Mask off details with `FeynHiggs` *file [flags]* `| grep -v %`
- `table` utility converts to machine-readable format, e.g.
  `FeynHiggs` *file [flags]* `| table TB Mh0 > outfile`

Example for new M_A–$\tan\beta$ planes:

Input File ("normal")

```
MT          172.7
MB          4.7
MW          80.4
MZ          91.1
MSusy       975
MA0         200
Abs(M_2)    332
Abs(MUE)    980
TB          50
Abs(At)     -300
Abs(Ab)     1500
Abs(M_3)    975
```

Input File ("new")

```
MA0         227
TB          23
table ehoww.A2.dat MA0 TB
```

- Loops over parameter values possible (parameter scans).

```
MA0         200 500 10
TB          5 50 *2
```

- Mask off details with `FeynHiggs` *file [flags]* `| grep -v %`

- `table` utility converts to machine-readable format, e.g.
  `FeynHiggs` *file [flags]* `| table TB Mh0 > outfile`

SUSY Les Houches Accord(2) Format

Input File

```
BLOCK MODSEL
    1    1
BLOCK MINPAR
    1   0.10000E+03   # m0
    2   0.25000E+03   # m12
    3   0.10000E+02   # tanb
    4   0.10000E+01   # sgn mu
    5  -0.10000E+03   # A
BLOCK SMINPUTS
    4   0.91187E+02   # MZ
    5   0.42500E+01   # mb(mb)
    6   0.17500E+03   # t
  ...
```

Command

`FeynHiggs` *file* [*flags*] →

file.fh

```
BLOCK MASS
   25   1.12697840E+02   # Mh0
   35   4.00145460E+02   # MHH
   36   3.99769788E+02   # MA0
   37   4.08050556E+02   # MHp
  ...
BLOCK ALPHA
       -1.10658125E-01   # Alpha
  ...
```

- { Uses / was developed into } the SLHA(2) I/O Library. [*T. Hahn '04, '06*]
- SLHA(2) can also be used in Library Mode with `FHSetSLHA`.
- *FeynHiggs* tries to read each file in SLHA(2) format first.
  If that fails, fallback to native format.

B) Called from a Fortran/C++ code

Link *FeynHiggs* as a subroutine ⇒ link `libFH.a`

`call FHSetFlags(...)` :
→ specification of accuracy etc.

`call FHSetPara(...)` :
→ specify input parameters

`call FHGetPara(...)` :
→ obtain derived parameters

`call FHHiggsCorr(...)` :
→ obtain Higgs boson masses and mixings

`call FHUncertainties(...)` :
→ obtain theory error on Higgs boson masses and mixings from unknown higher-order corrections

`call FHCouplings(...), FHHiggsProds(...), ...` :
→ obtain decay widths, BRs, XSs, etc.

C) Called within Mathematica

- install the math link to *MFeynHiggs* , e.g.:

  `Install[''MFeynHiggs'']`

- `FHSetFlags[...]` :
  → specification of accuracy etc.

  `FHSetPara[...]` :
  → specify input parameters

  `FHGetPara[]` :
  → obtain derived parameters

  `FHHiggsCorr[]` :
  → obtain Higgs boson masses and mixings

  `FHUncertainties[]` :
  → obtain theory error on Higgs boson masses and mixings from unknown higher-order corrections

  `FHCouplings[], FHHiggsProds[], ...` :
  → obtain decay widths, BRs etc.

D) WWW mode

1. The FeynHiggs User Control Center is available at
   www.feynhiggs.de/fhucc

2. Enter you parameters on-line in the web page

3. Obtain your results with a mouse click

⇒ for single points and checks of your downloaded version of FeynHiggs
⇒ always the latest version

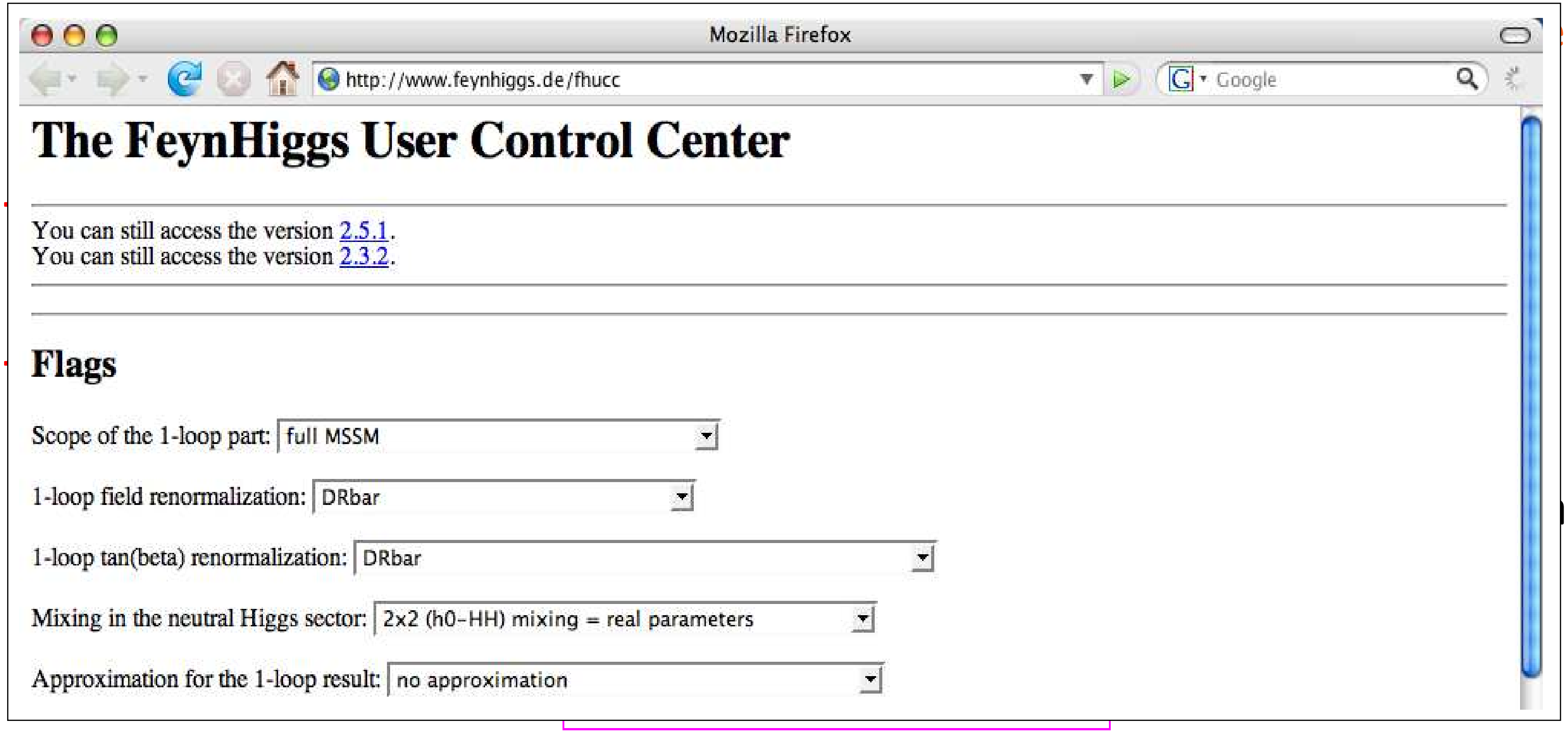
⇒ online presentation

Also man pages are available on-line

D) WWW mode

1. The FeynHiggs User Control Center is available at

/fhucc



2.

3.

⇒ Higgs

⇒

Also man pages are available on-line

5. Conclusinos

- Precise MSSM Higgs sector evaluation necessary to
  – do phenomenological analyses at the Tevatron and the LHC
  – exploit anticipated ILC precision, be sensitive to small deviations

- FeynHiggs 2.6 provides Higgs boson masses, mixing angles, couplings, branching ratios, Tev/LHC XS, etc.
  in the MSSM with/without complex parameters (and for NMFV)

- Correction of $\mathcal{O}(\alpha_t\alpha_s)$ in the cMSSM included

- Important to treat higher-order corrected Higgs bosons correctly:
  – external (on-shell) Higgs
  – Higgs in loop diagrams

  Solution: $\mathbf{Z}$ for external (on-shell) Higgs, $\mathbf{U}$ or $\mathbf{R}$ for Higgs in loops

- – $\mathbf{Z}$ consistently included (only FeynHiggs!)
  – $\mathbf{U}$, $\mathbf{R}$ consistently included for effective couplings
  $\Rightarrow$ effects up to 5-10%
  – Im $\hat{\Sigma}$ consistently included in masses and couplings (only FeynHiggs!)
  $\Rightarrow$ effects up to 5 GeV

- benchmark scenarios: M_A–$\tan\beta$ planes in agreement with CDM included

5. Conclusinos

- Precise MSSM Higgs sector evaluation necessary to
  - do phenom ... and the LHC
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    ⇒ effects up to 5 GeV
- benchmark scenarios: M_A–$\tan\beta$ planes in agreement with CDM included

www.feynhiggs.de

6. Back-up

$\sqrt{Z_i}$: ensures that the residuum of the external Higgs boson is set to 1

Z_{ij} : describes the transition from $i \to j$

$$Z_i = \left[1 + \left(\hat{\Sigma}^{\rm eff}_{ii}\right)'(\mathcal{M}_i^2)\right]^{-1}$$

$$\hat{\Sigma}^{\rm eff}_{ii}(p^2) = \hat{\Sigma}_{ii}(p^2) - i\frac{2\hat{\Gamma}_{ij}(p^2)\hat{\Gamma}_{jk}(p^2)\hat{\Gamma}_{ki}(p^2) - \hat{\Gamma}^2_{ki}(p^2)\hat{\Gamma}_{jj}(p^2) - \hat{\Gamma}^2_{ij}(p^2)\hat{\Gamma}_{kk}(p^2)}{\hat{\Gamma}_{jj}(p^2)\hat{\Gamma}_{kk}(p^2) - \hat{\Gamma}^2_{jk}(p^2)}$$

$$Z_{ij} = \left.\frac{\Delta_{ij}(p^2)}{\Delta_{ii}(p^2)}\right|_{p^2=\mathcal{M}_i^2}$$

$$\hat{\Gamma}(p^2) = iM^2_{hHA}(p^2)$$

$$\Delta(p^2) = \left(-\Gamma(p^2)\right)^{-1}$$

m_i: tree-level masses

M_i: higher-order corrected masses

Limit $p^2 \to 0$:

$$\mathbf{Z} \;\to\; \mathbf{R} \;: \qquad \mathbf{R} = \begin{pmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{pmatrix}$$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}_{p^2=0} = \mathbf{R} \cdot \begin{pmatrix} h \\ H \\ A \end{pmatrix}, \; \mathbf{R}\,\mathbf{M}_{hHA}(0)\,\mathbf{R}^\dagger = \begin{pmatrix} M^2_{h_1,p^2=0} & 0 & 0 \\ 0 & M^2_{h_2,p^2=0} & 0 \\ 0 & 0 & M^2_{h_3,p^2=0} \end{pmatrix}$$

– $\mathbf{R}$ in the 2×2 case is exactly α_{eff}

– $\mathbf{R}$ corresponds to the effective potential approach

What is better?

1.) "p^2 on-shell": $\mathbf{U}$

2.) "$p^2 = 0$": $\mathbf{R}$

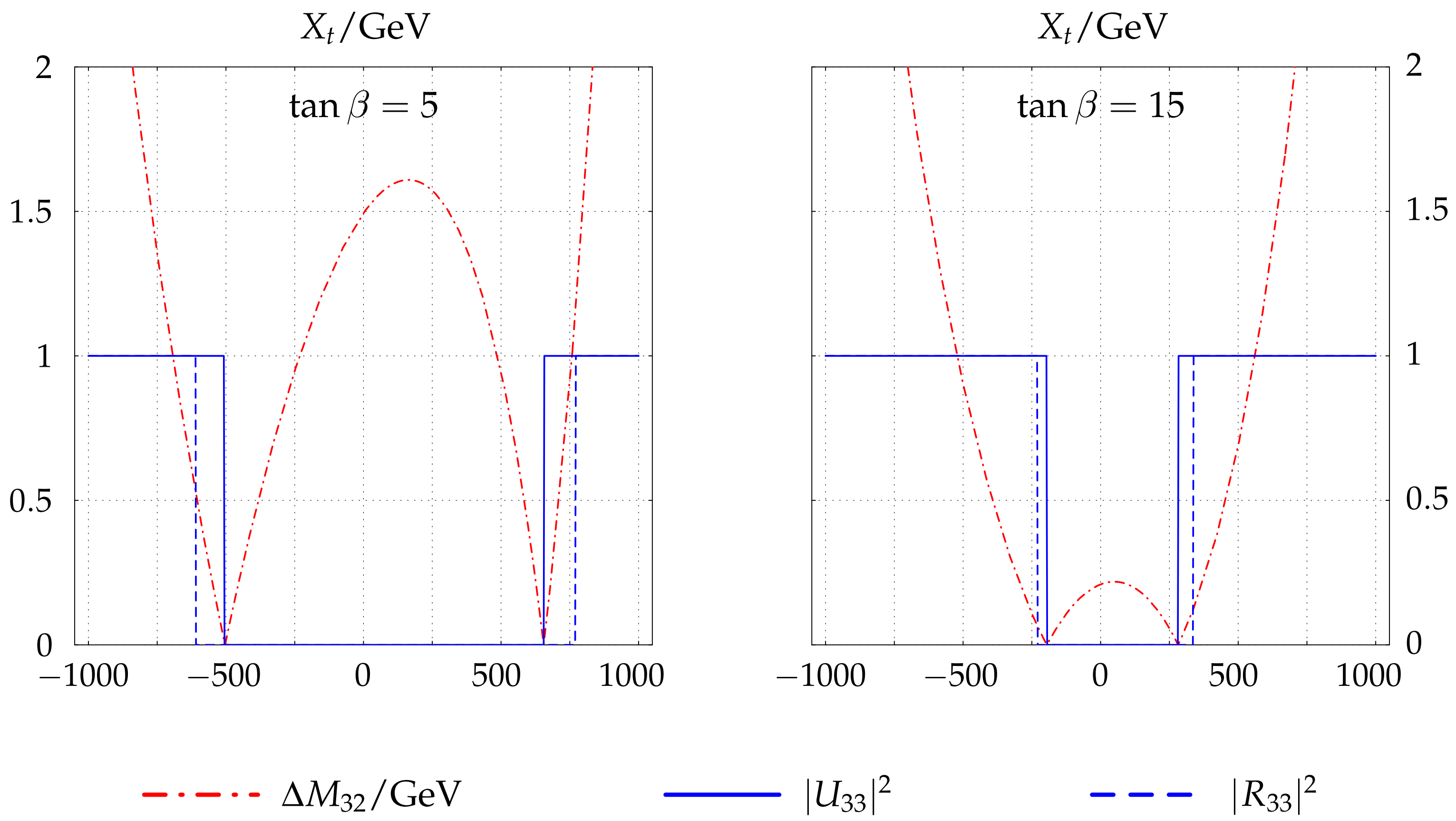
Two possible tests:

1. Compare full decay width, evaluated with $\mathbf{Z}$, with approximations, evaluated with $\mathbf{U}$ or $\mathbf{R}$
   $\rightarrow$ see later in "Numerical examples"

2. $\mathbf{U}_{33}^2$ and $\mathbf{R}_{33}^2$ correspond to the $\mathcal{CP}$-odd part of h_3
   In the rMSSM: $\mathbf{U}_{33}^2$, $\mathbf{R}_{33}^2 = 0$ or 1 (depending on mass ordering)
   Switch-over from 0 to 1 should happen for $\Delta M_{32} := M_{h_3} - M_{h_2} = 0$
   $\rightarrow$ compare switch-over with ΔM_{32}

→ Compare switch-over with ΔM_{32}:

$M_{\text{SUSY}} = m_{\tilde{g}} = M_2 = 500$ GeV, $\mu = 1000$ GeV, $M_{H^\pm} = 150$ GeV



⇒ **U** gives the better results

⇒ use **U** for effective couplings

Summary: treatment of "higher-order" corrected Higgs bosons:

1. external/on-shell Higgs bosons

   amplitude with on-shell Higgs boson i:

$$A_{h_i xy} \sim \sqrt{Z_i} \left(Z_{ih} C_{hxy} + Z_{iH} C_{Hxy} + Z_{iA} C_{Axy} \right)$$

   Z_i, Z_{ij}: finite wave function renormalizations

   Written more compact with the $\mathbf{Z}$ matrix:

$$\mathbf{Z}_{ij} = \sqrt{Z_i}\, Z_{ij}$$

   resulting in

$$A_{h_i xy} \sim \mathbf{Z}_{ih}\, C_{hxy} + \mathbf{Z}_{iH}\, C_{Hxy} + \mathbf{Z}_{iA}\, C_{Axy}$$

2. Higgs bosons in loop corrections

   rotate tree-level couplings with $\mathbf{U}$ or $\mathbf{R}$:

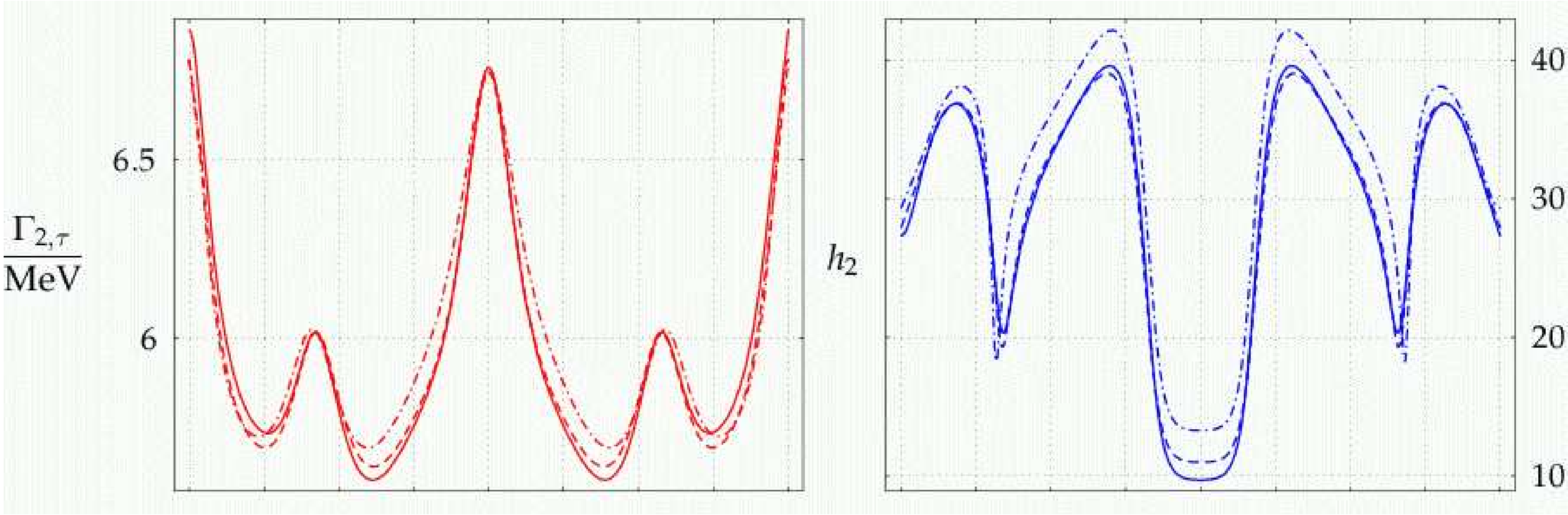
$$\begin{aligned} C_{h_i xy} &= \mathbf{U}_{ih}\, C_{hxy} + \mathbf{U}_{iH}\, C_{Hxy} + \mathbf{U}_{iA}\, C_{Axy} \\ C_{h_i xy} &= \mathbf{R}_{ih}\, C_{hxy} + \mathbf{R}_{iH}\, C_{Hxy} + \mathbf{R}_{iA}\, C_{Axy} \end{aligned}$$

Numerical results (II):

[*M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06*]

$M_{\text{SUSY}} = m_{\tilde{g}} = M_2 = 500$ GeV, $A_t = 1000$ GeV, $\mu = 1000$ GeV, $M_{H^\pm} = 150$ GeV

$\Gamma(h_1 \to \tau^+\tau^-)$ as a function of ϕ_{X_t}



solid: $\mathbf{Z}$, dashed: $\mathbf{U}$, dot-dashed: $\mathbf{R}$

⇒ $\mathbf{U}$ gives results closer to full result than $\mathbf{R}$

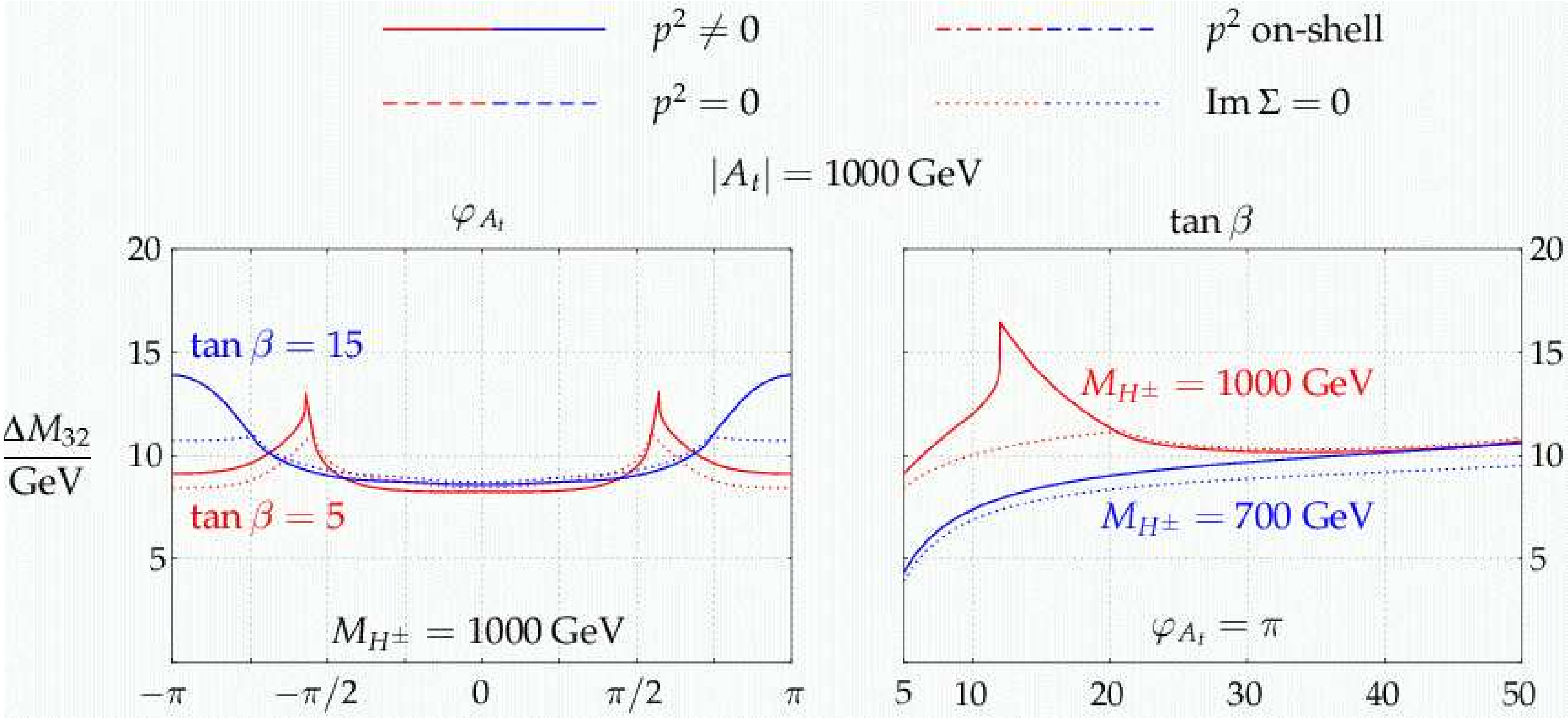
⇒ deviations at the 5-10% level

Numerical results (III):

[*M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06*]

$M_{\rm SUSY} = m_{\tilde g} = M_2 = 500$ GeV, $|A_t| = 1000$ GeV, $\mu = 1000$ GeV, $M_{H^\pm} = 1000$ GeV

Effects of $\mathrm{Im}\,\hat\Sigma$ on $\Delta M_{32} := M_{h_3} - M_{h_2}$

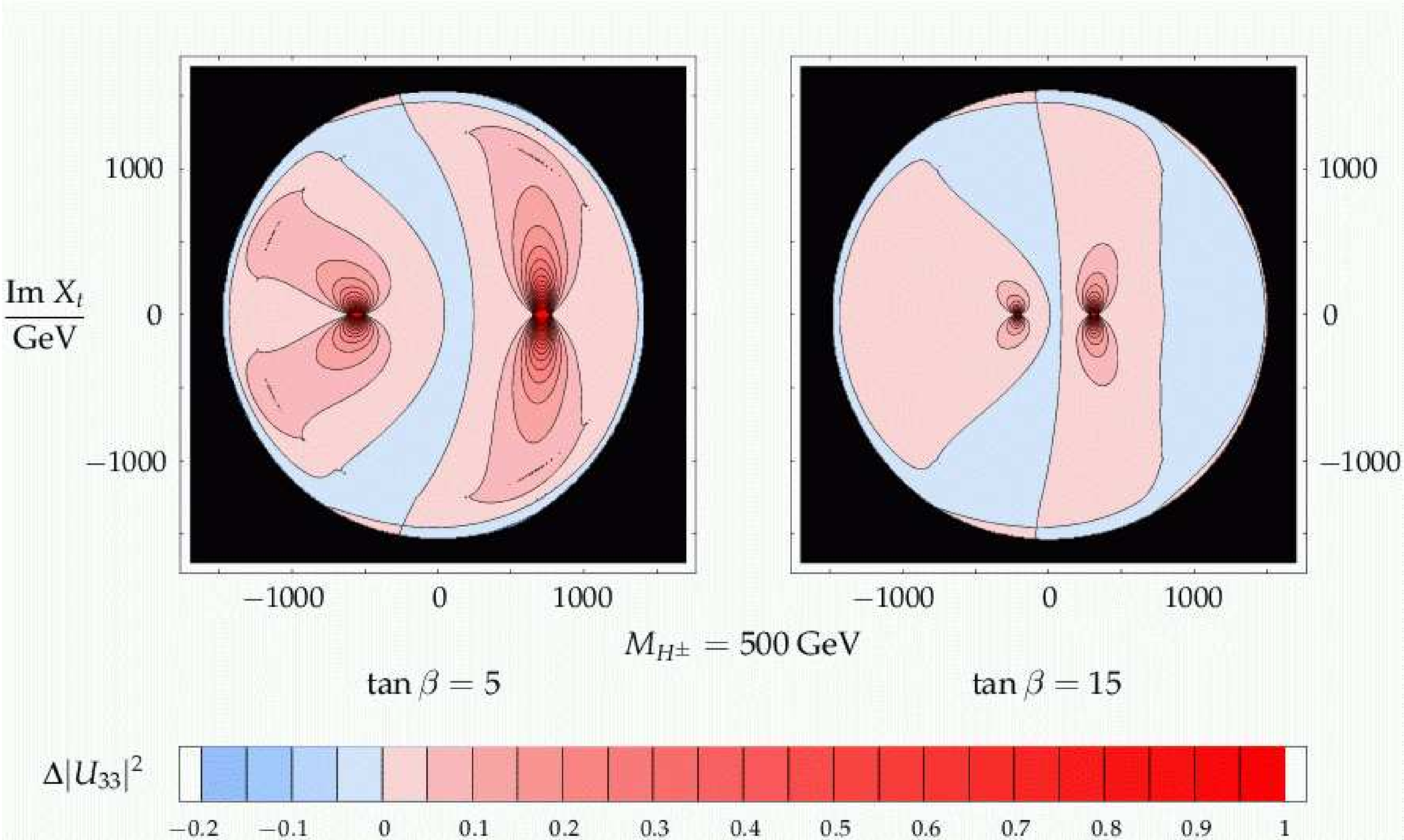


$\Rightarrow$ differences of up to 5 GeV

Numerical results (IV): [M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06]

$M_{\text{SUSY}} = m_{\tilde{g}} = M_2 = 500$ GeV, $\mu = 1000$ GeV, $M_{H^\pm} = 150$ GeV

Difference between $\mathbf{U}^2_{33}$ and $\mathbf{R}^2_{33}$:

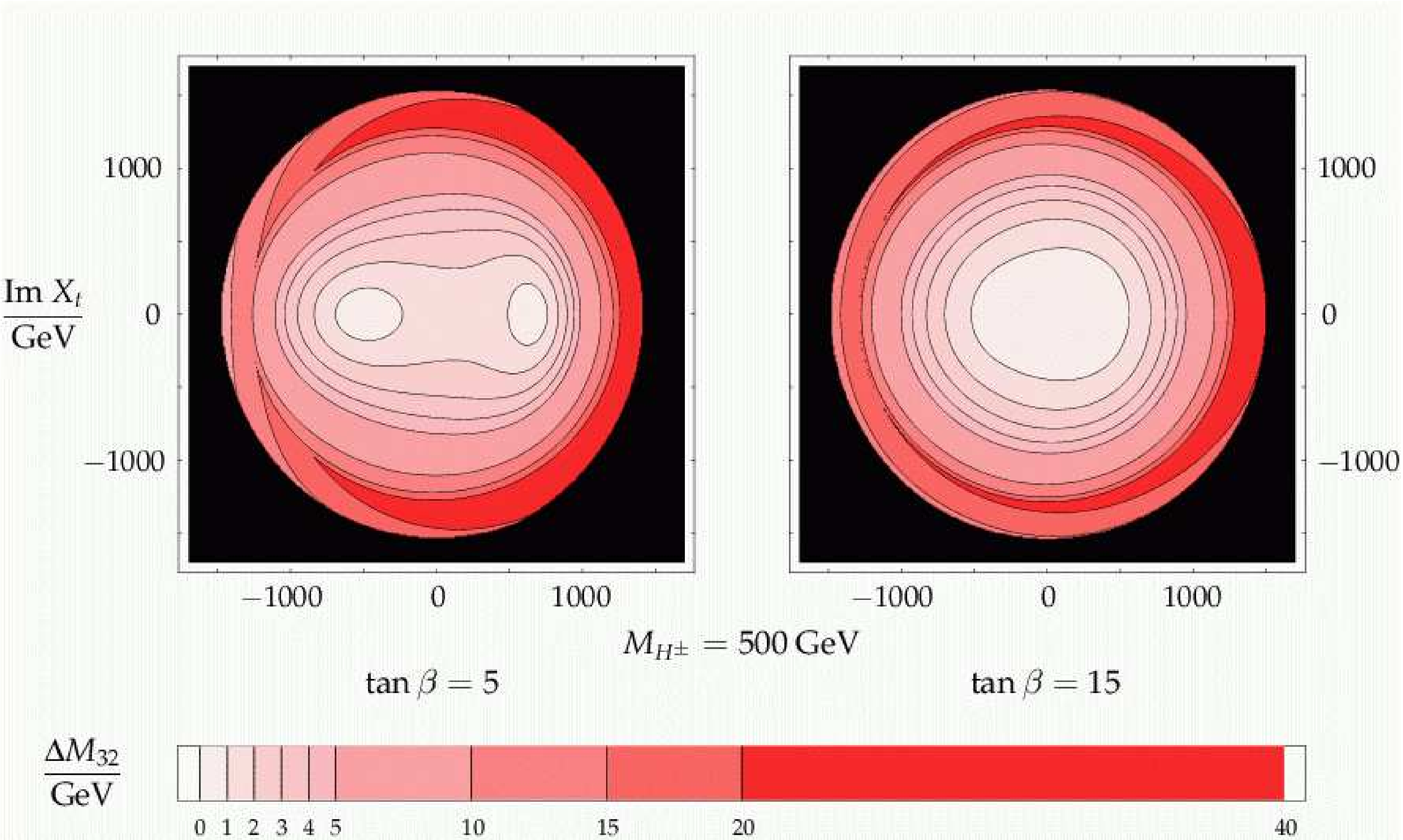


⇒ large deviations where ΔM_{32} is small

Numerical results (IV): [M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06]

$M_{\rm SUSY} = m_{\tilde{g}} = M_2 = 500$ GeV, $\mu = 1000$ GeV, $M_{H^\pm} = 150$ GeV

Difference between $\mathbf{U}_{33}^2$ and $\mathbf{R}_{33}^2$:



⇒ large deviations where ΔM_{32} is small