

# FeynHiggs for the ILC

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DESY, 06/2007

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

1. Introduction
2. Recent theory developments → more details in talk by G. Weiglein
3. Parameter planes
4. Implementation into FeynHiggs 2.6
5. Conclusions

# 1. Introduction

Higgs potential of the **cMSSM** contains two Higgs doublets:

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 - i\chi_1)/\sqrt{2} \\ -\phi_1^- \end{pmatrix}$$
$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

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

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

2  $\mathcal{CP}$ -violating phases:  $\xi, \arg(m_{12}) \Rightarrow$  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:

- $\mu$  : 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:

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

with

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

## How to include higher-order corrections: ( $\rightarrow$ Feynman-diagrammatic approach)

Propagator / mass matrix with higher-order corrections:

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

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

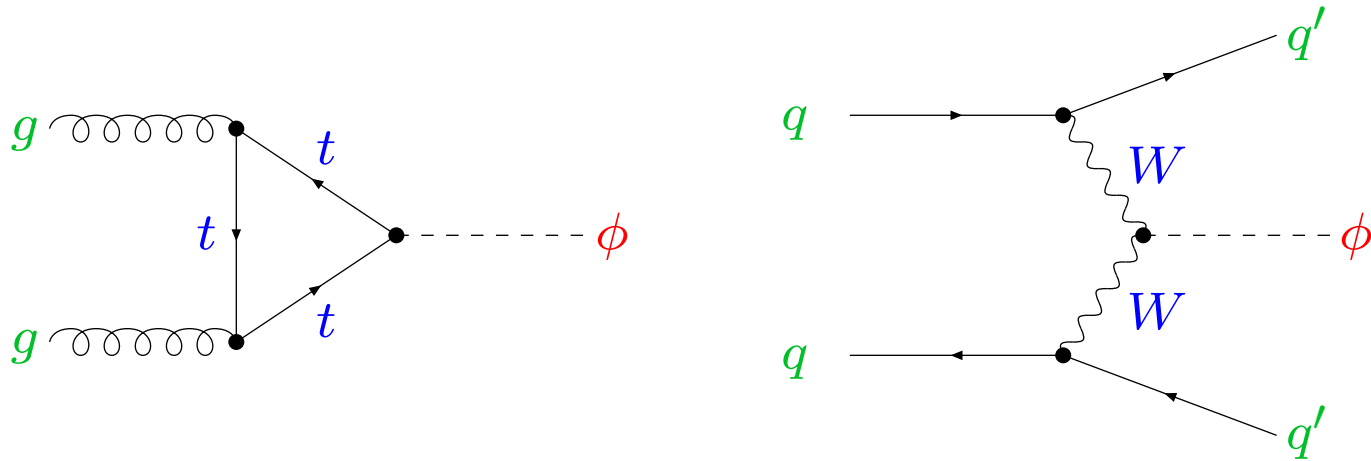
$\hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH} \neq 0 \Rightarrow \mathcal{CPV}$ ,  $\mathcal{CP}$ -even and  $\mathcal{CP}$ -odd fields can mix

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

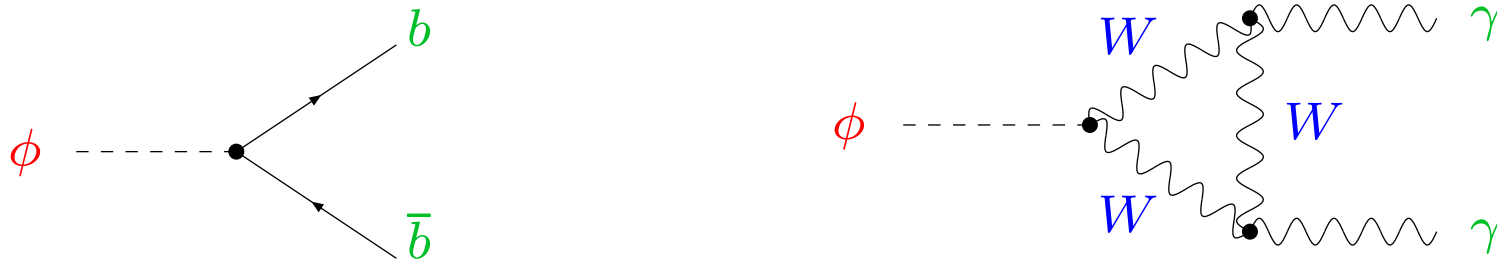
- full 1-loop: complex phases,  $q^2$ -dep., imaginary parts
  - currently implemented:  $\text{cMSSM } \mathcal{O}(\alpha_t \alpha_s)$  corrections in the FD approach  
rMSSM: difference between FD and RGiEP approach  $\mathcal{O}(\text{few GeV})$
- $\Rightarrow$  numerical search for the complex roots of  $\det(M_{hHA}^2(q^2))$

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

Higgs production:

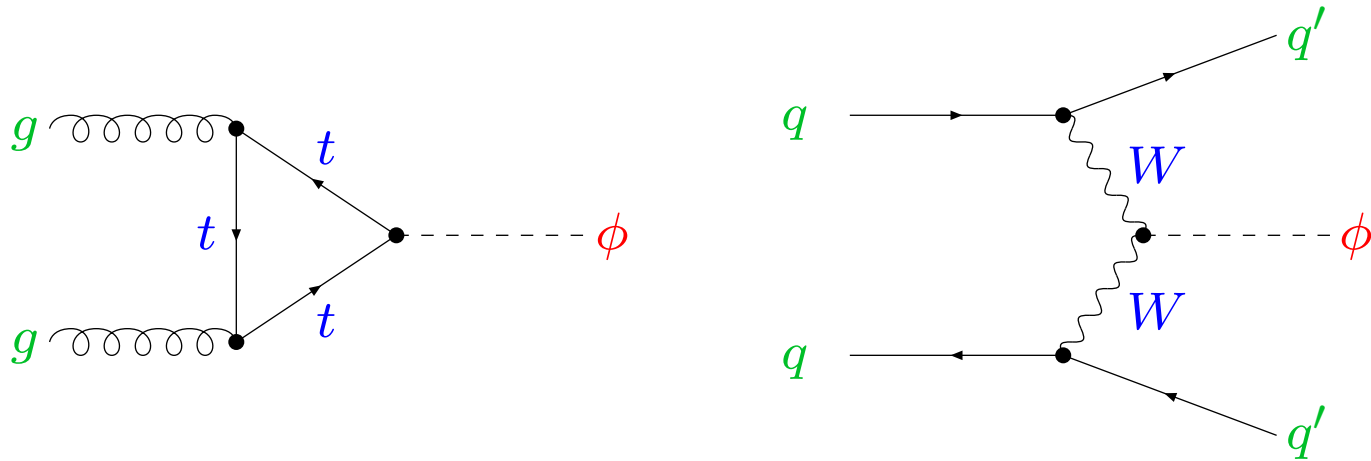


Higgs decays:



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

Higgs production:



Higgs decays:



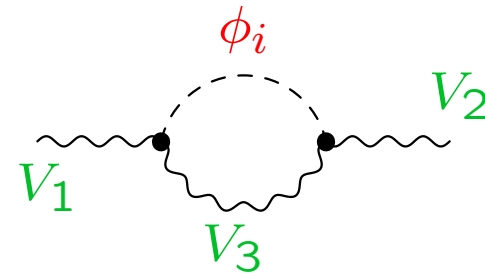
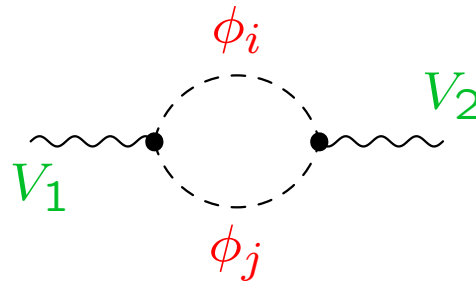
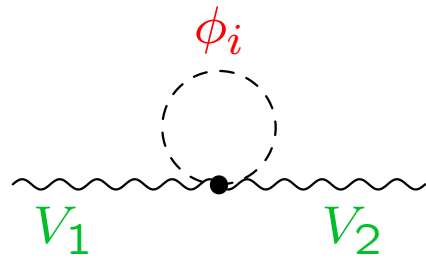
⇒ important to ensure on-shell properties of external Higgs boson

## Examples for Higgs bosons entering loop corrections:

### Vector boson self-energies:

e.g. in  $\mu$  decay, precision observables, ...

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



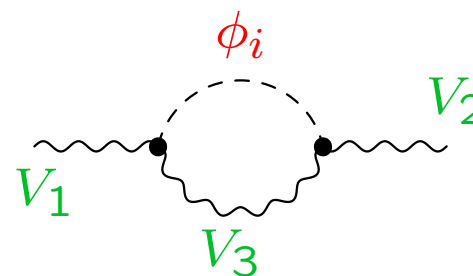
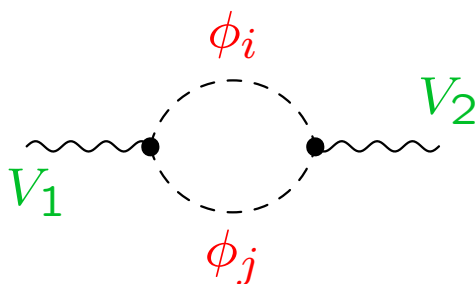
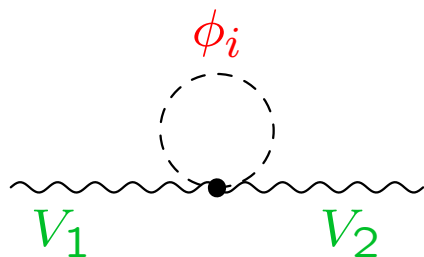
$\phi_{i,j} = h, H, A$  (tree-level states):  $\Rightarrow$  ok

## Examples for Higgs bosons entering loop corrections:

### Vector boson self-energies:

e.g. in  $\mu$  decay, precision observables, ...

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$\phi_{i,j} = h, H, A$  (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?

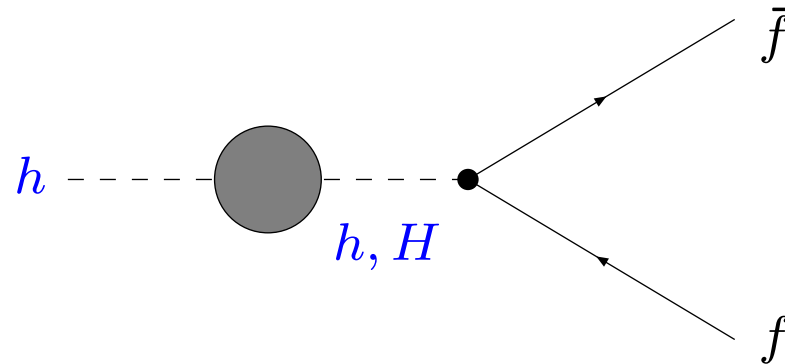
$\Rightarrow$  How to define “effective couplings” ?



## 2. Recent theory developments → more details in talk by G. Weiglein

### 2A) External (on-shell) Higgs bosons

The real case,  $2 \times 2$  mixing, is known since long:



$h, H$  : loop-corrected (neutral  $\mathcal{CP}$ -even) Higgs bosons

Amplitude:

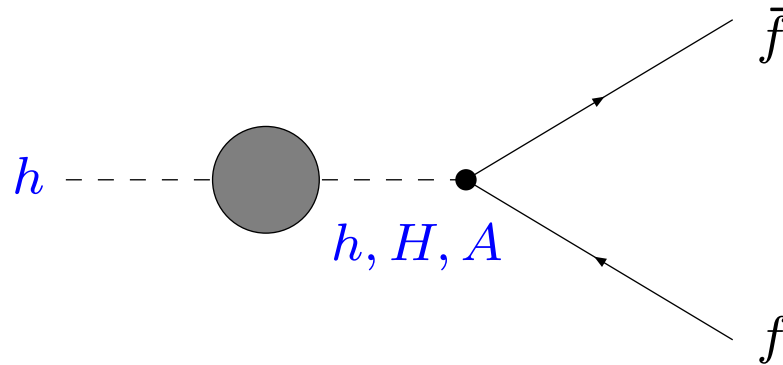
$$A(h \rightarrow f\bar{f}) = \sqrt{Z_h} (\Gamma_h + Z_{hH} \Gamma_H)$$

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

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

$Z_{hH}$  : describes the transition from  $h \rightarrow H$

New: Extension to the  $3 \times 3$  case:



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

Amplitude:

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

$\Gamma_{h,H,A}$  : 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  $h \rightarrow H/A$

But: more complicated expressions for  $Z_i, Z_{ij}$

Limit  $p^2 \rightarrow 0$ :

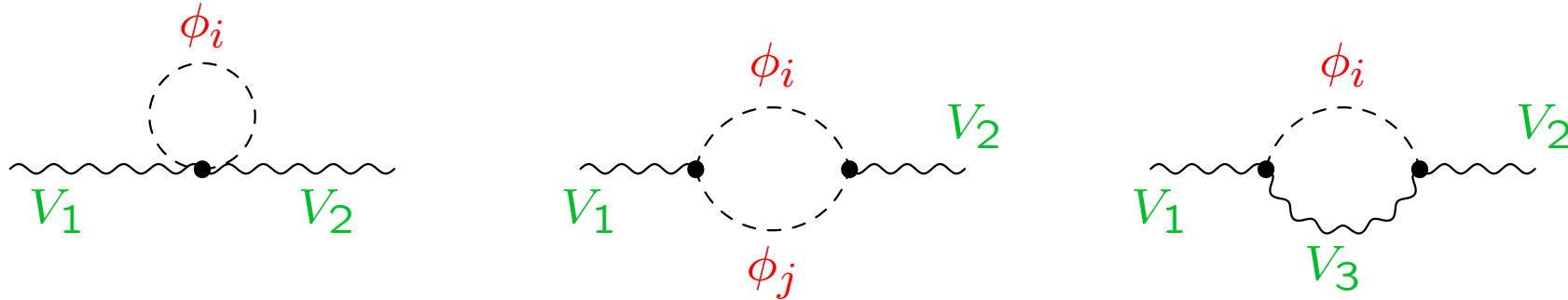
$$\mathbf{Z} \rightarrow \mathbf{R} : \quad \mathbf{R} = \begin{pmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{pmatrix}$$

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

- $\mathbf{R}$  in the  $2 \times 2$  case is exactly  $\alpha_{\text{eff}}$
- $\mathbf{R}$  corresponds to the effective potential approach

## 2B) Effective couplings

How to treat higher-order corrected Higgs bosons entering in loop diagrams?



Needed: a **unitary matrix  $\mathbf{D}$**  to rotate the Higgs bosons:

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

$\Rightarrow$  mass matrix  $\mathbf{M}$  has to be made hermitian

Two possibilities:

1.) “ $p^2$  on-shell”:  $\mathbf{U}$

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

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

2.) “ $p^2 = 0$ ”:  $\mathbf{R}$

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

## Summary: treatment of “higher-order” corrected Higgs bosons:

### 1. external/on-shell Higgs bosons

amplitude with on-shell Higgs boson  $i$ :

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

$Z_i, Z_{ij}$ : finite wave function renormalizations

Written more compact with the **Z matrix**:

$$Z_{ij} = \sqrt{Z_i} Z_{ij}$$

resulting in

$$A_{h_i xy} \sim Z_{ih} C_{hxy} + Z_{iH} C_{Hxy} + Z_{iA} C_{Axy}$$

### 2. Higgs bosons in loop corrections

rotate tree-level couplings with **U** or **R**:

$$C_{h_i xy} = U_{ih} C_{hxy} + U_{iH} C_{Hxy} + U_{iA} C_{Axy}$$

$$C_{h_i xy} = R_{ih} C_{hxy} + R_{iH} C_{Hxy} + R_{iA} C_{Axy}$$

## 2C) Inclusion of $\mathcal{O}(\alpha_t\alpha_s)$ corrections for complex parameters:

Propagator / mass matrix with higher-order corrections:

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

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

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

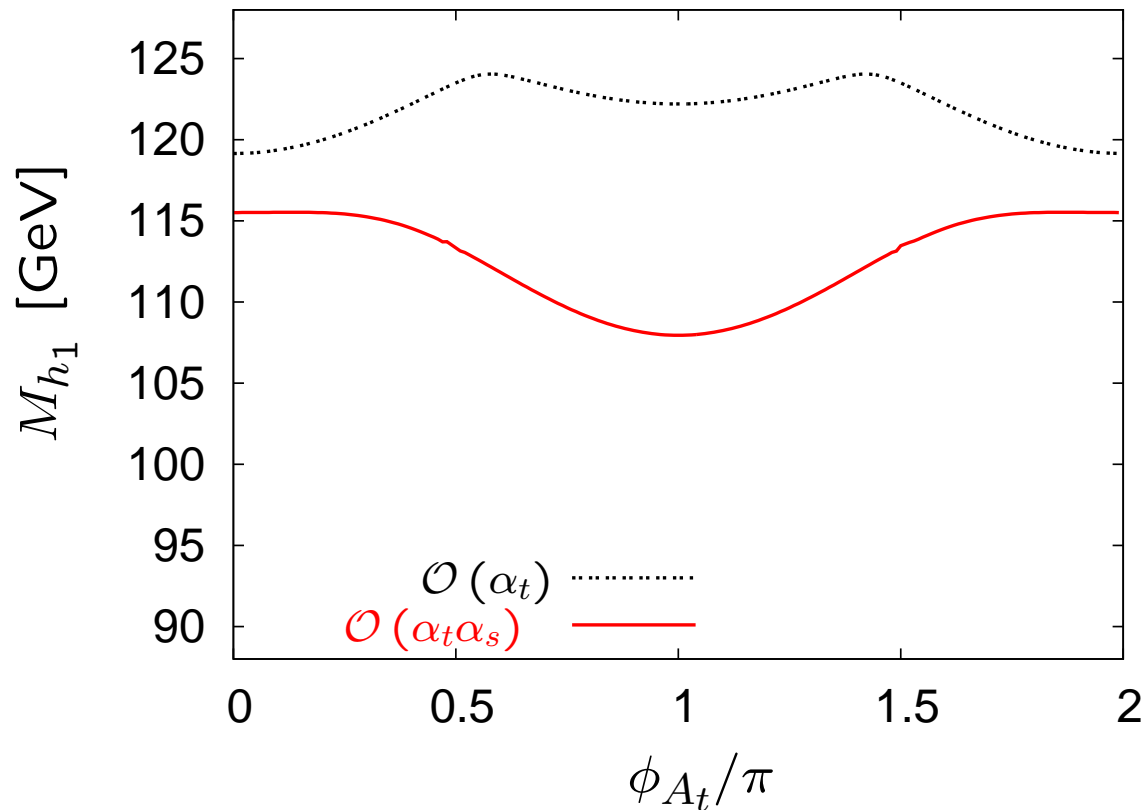
Results available for  $\hat{\Sigma}_{ij}$ :

$$\hat{\Sigma}_{ij}(q^2) = \hat{\Sigma}_{ij}^{(1)}(q^2) + \hat{\Sigma}_{ij}^{(2)}(0) + \dots$$

- full 1-loop evaluation: dependence on all possible phases included
- New:  $\mathcal{O}(\alpha_t\alpha_s)$  corrections in the FD approach  
(rMSSM: difference between FD and RGiEP approach  $\mathcal{O}(\text{few GeV})$ )

## $M_{h_1}$ as a function of $\phi_{A_t}$ :

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



$$M_{\text{SUSY}} = 1000 \text{ GeV}$$

$$|A_t| = 2000 \text{ GeV}$$

$$\tan \beta = 10$$

$$M_{H^\pm} = 150 \text{ GeV}$$

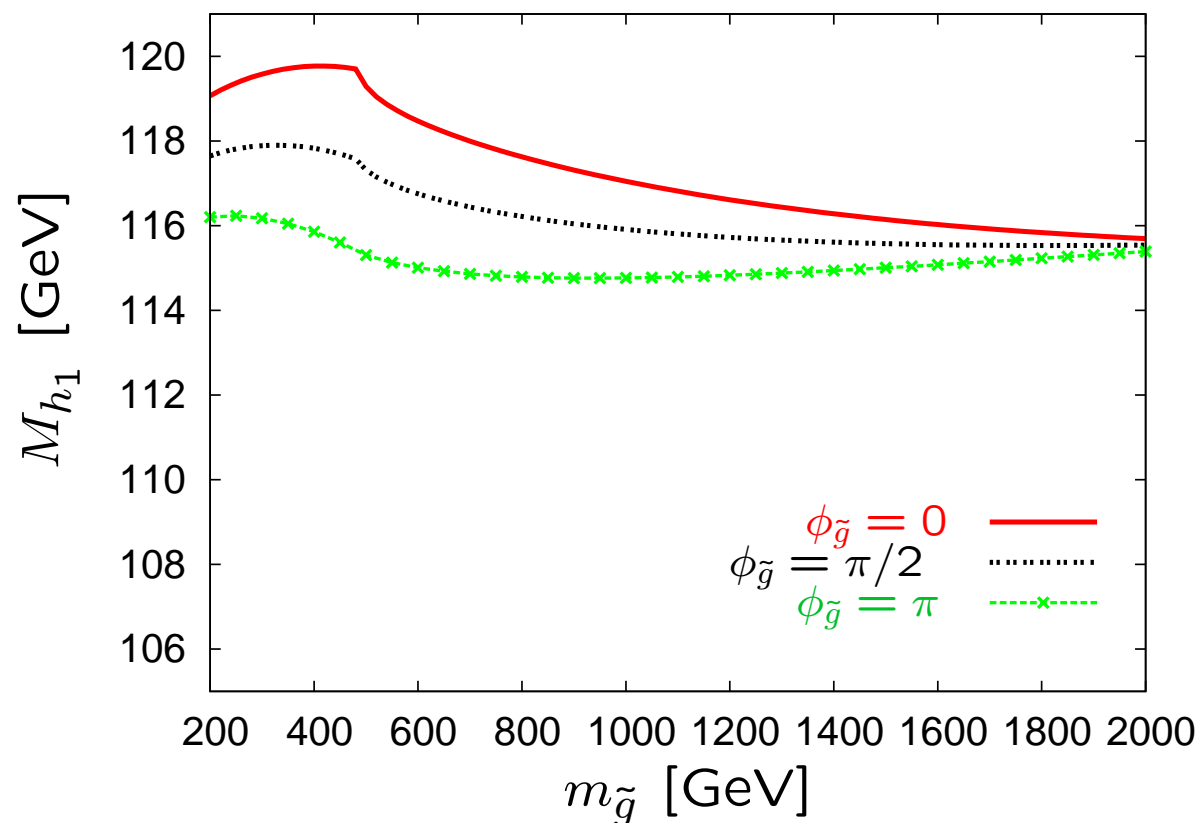
OS renormalization

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



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

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



$$M_{\text{SUSY}} = 500 \text{ GeV}$$

$$A_t = 1000 \text{ GeV}$$

$$\tan \beta = 10$$

$$M_{H^\pm} = 500 \text{ GeV}$$

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

### 3. Parameter planes

Search for the MSSM Higgs bosons:

→ investigate benchmark scenarios:

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

1.  $m_h^{\max}$  scenario:

→ obtain conservative  $\tan \beta$  exclusion bounds ( $X_t = 2 M_{\text{SUSY}}$ )

2. no-mixing scenario

→ no mixing in the scalar top sector ( $X_t = 0$ )

3. small  $\alpha_{\text{eff}}$  scenario

→  $hb\bar{b}$  coupling  $\sim \sin \alpha_{\text{eff}} / \cos \beta$  can be zero:  $\alpha_{\text{eff}} \rightarrow 0$ :  
main decay mode vanishes, important search channel vanishes

4. gluophobic Higgs scenario

→  $hgg$  coupling is small: main LHC production mode vanishes

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

→ included in FeynHiggs for a long time

## Possible external constraints:

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

⇒ so far ignored (for (good) reasons)

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

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Possible models:

### 1.) CMSSM (or mSUGRA):

⇒ Scenario characterized by

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

⇒ too restricted

## Possible external constraints:

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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

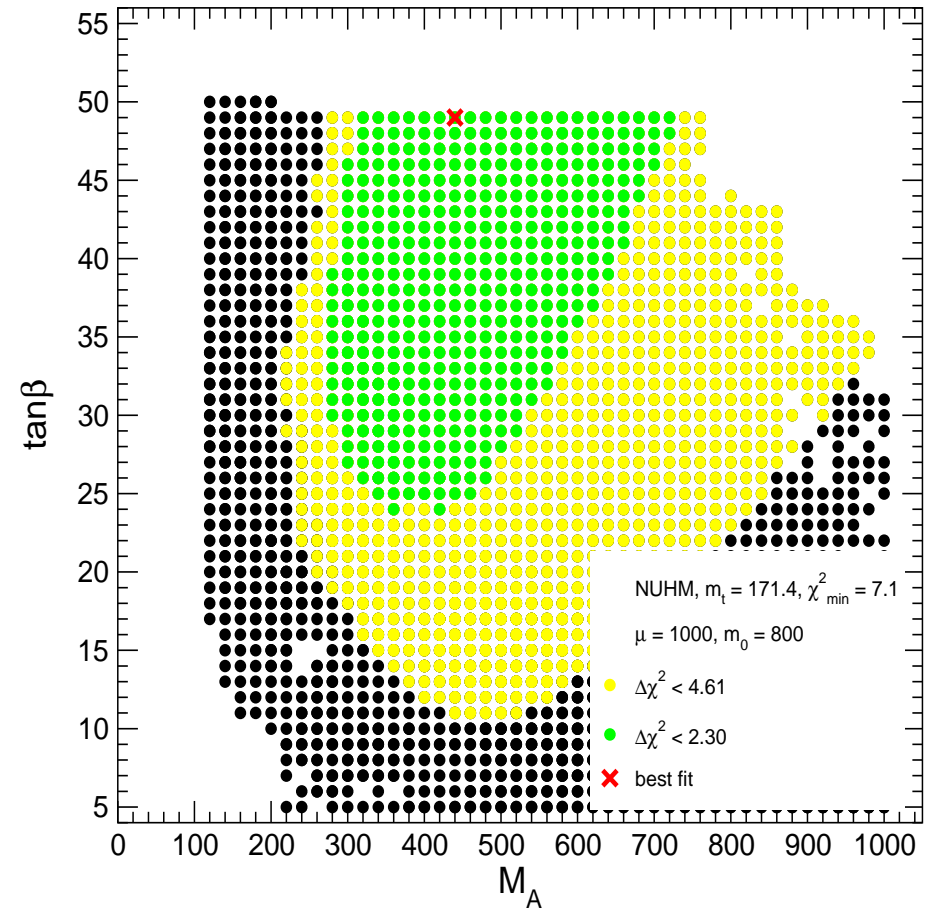
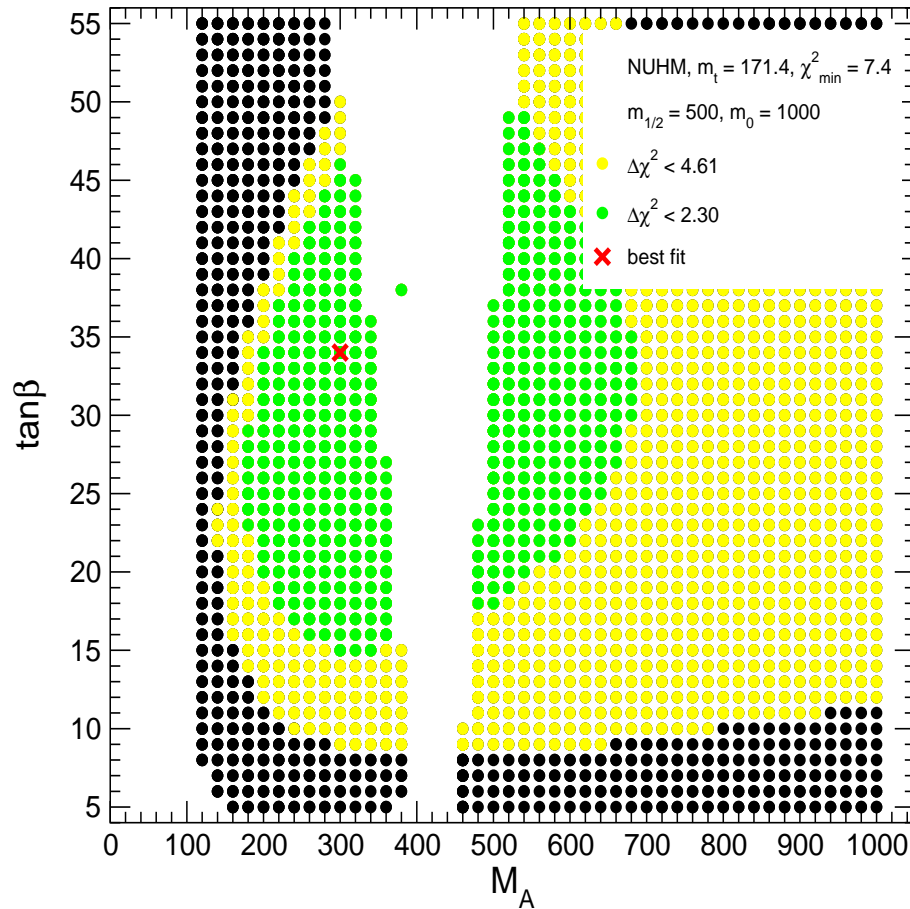
⇒ effectively  $M_A$  and  $\mu$  free parameters at the EW scale

⇒ besides the CMSSM parameters

$M_A$  and  $\mu$

## Results: NUHM: planes 2,3

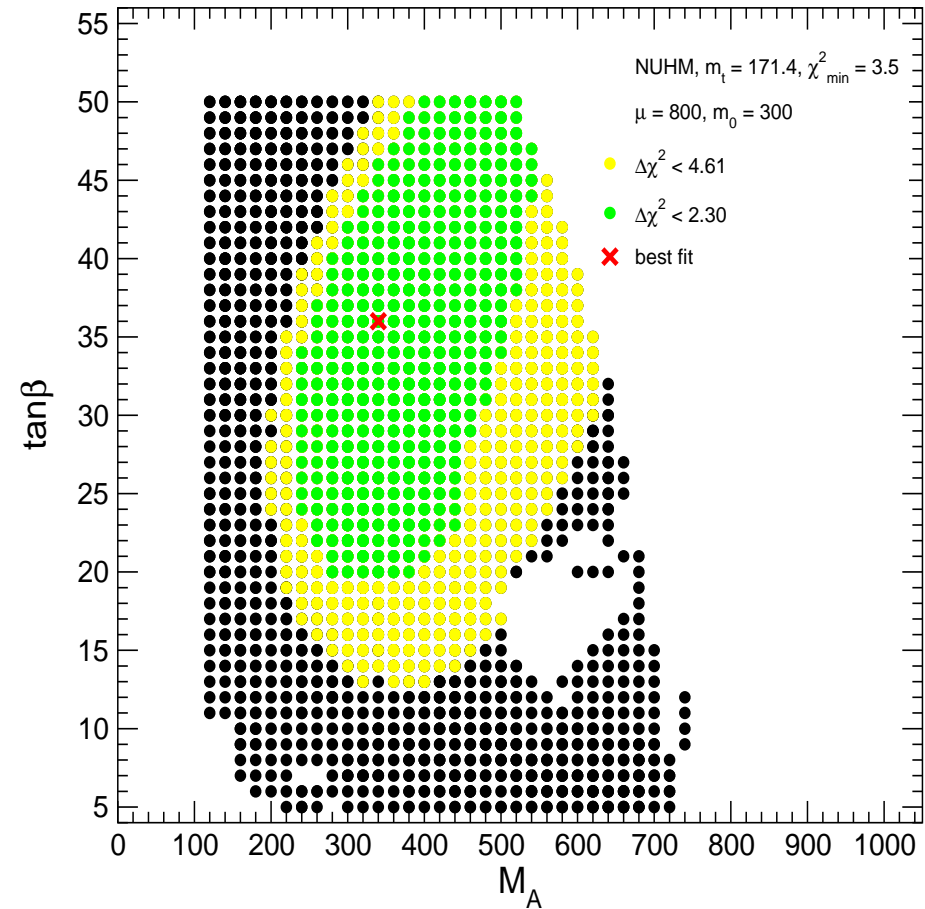
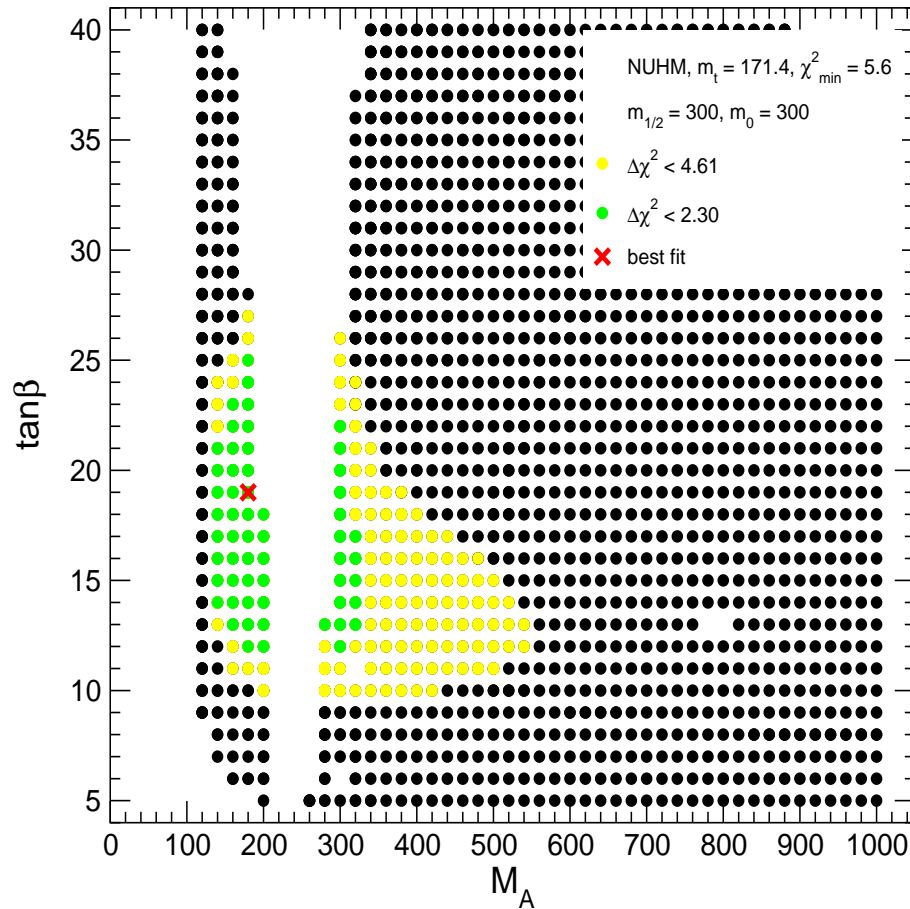
[J. Ellis, S.H., K. Olive, A.M. Weber, G. Weiglein '07]



$\Rightarrow$  good  $\chi^2$  ( $M_W$ ,  $\sin^2\theta_{\text{eff}}$ ,  $\Gamma_Z$ ,  $M_h$ ,  $(g-2)_\mu$ ,  $\text{BR}(b \rightarrow s\gamma)$  and other BPO)  
 $\Rightarrow$  larger regions o.k.

## Results: NUHM: planes 4,5

[J. Ellis, S.H., K. Olive, A.M. Weber, G. Weiglein '07]



$\Rightarrow$  good  $\chi^2$  ( $M_W$ ,  $\sin^2 \theta_{\text{eff}}$ ,  $\Gamma_Z$ ,  $M_h$ ,  $(g-2)_\mu$ ,  $\text{BR}(b \rightarrow s\gamma)$  and other BPO)  
 $\Rightarrow$  larger regions o.k.

## 4. Implementation into FeynHiggs 2.6

Latest version: FeynHiggs 2.5.1 (02/07)

version FeynHiggs 2.6 to be released within two weeks ...

real MSSM:

contains all available higher-order corrections  
to Higgs boson masses and couplings

FeynHiggs contains

- full 1 loop calculations
- all available 2 loop calculations (leading and subleading)
- very leading 3 loop contributions

complex MSSM:

contains nearly all available results  
(we are (even currently) working on the rest)

[www.feynhiggs.de](http://www.feynhiggs.de)



## FeynHiggs2.2 → FeynHiggs 2.6: main new features

- **Complex** contributions to **Higgs mass matrix** taken into account (from  $\text{Im } B_0(\dots) \neq 0$ )
- **Higgs masses** are now the **real part** of the **complex pole**
- $\Rightarrow$  **complex**  $3 \times 3$  **mixing matrix**  $Z \Rightarrow$  **external (on-shell) Higgs bosons**  
**unitary**  $3 \times 3$  **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**
- extended implementation of  $(g - 2)_\mu$ : leading SM fermion two-loop contributions [*S.H., D. Stöckinger, G. Weiglein '04*]
- **EDMs** of electron, neutron, Hg, ...

## Included in FeynHiggs 2.6 (I):

### Evaluation of all Higgs boson masses and mixing angles

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

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

- total decay width  $\Gamma_{\text{tot}}$
- $\text{BR}(h_i \rightarrow f\bar{f})$ : decay to SM fermions
- $\text{BR}(h_i \rightarrow \gamma\gamma, ZZ^{(*)}, WW^{(*)}, gg)$ : decay to SM gauge bosons
- $\text{BR}(h_i \rightarrow h_1 Z^{(*)}, h_1 h_1)$ : decay to gauge and Higgs bosons
- $\text{BR}(h_i \rightarrow \tilde{f}_i \tilde{f}_j)$ : decay to sfermions
- $\text{BR}(h_i \rightarrow \tilde{\chi}_i^\pm \tilde{\chi}_j^\pm, \tilde{\chi}_i^0 \tilde{\chi}_j^0)$ : decay to charginos, neutralinos

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

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

Included in FeynHiggs 2.6 (II):

Evaluation of all neutral Higgs boson production cross sections at Tevatron/LHC  $\Leftarrow$  with Z

SM: most up-to-date, MSSM: additional effective couplings

- $gg \rightarrow h_i$ : gluon fusion
- $WW \rightarrow h_i, ZZ \rightarrow h_i$ : gauge boson fusion
- $W \rightarrow Wh_i, Z \rightarrow Zh_i$ : Higgs strahlung
- $b\bar{b} \rightarrow b\bar{b}h_i$ : Yukawa process
- $b\bar{b} \rightarrow b\bar{b}h_i, h_i \rightarrow b\bar{b}$ , one  $b$  tagged
- $t\bar{t} \rightarrow t\bar{t}h_i$  : Yukawa process

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

- all channels as above

## Included in FeynHiggs 2.6 (III):

### Evaluation of all charged Higgs boson decay channels (rMSSM/cMSSM)

- total decay width  $\Gamma_{\text{tot}}$
- $\text{BR}(H^+ \rightarrow f\bar{f}')$ : decay to SM fermions
- $\text{BR}(H^+ \rightarrow h_i W^+)$ : decay to gauge and Higgs bosons
- $\text{BR}(H^+ \rightarrow \tilde{f}_i \tilde{f}_j')$ : decay to sfermions
- $\text{BR}(H^+ \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^+)$ : decay to charginos and neutralinos

### Evaluation of additional couplings: $\Leftarrow$ with **U** or **R**

- $g(V \rightarrow V h_i, h_i h_j)$ : coupling of gauge and Higgs bosons
- $g(h_i h_j h_k)$ : all Higgs self couplings (including charged Higgs)
- $\sigma(\gamma\gamma \rightarrow h_i)$ : Higgs production XS at a  $\gamma C$

## Included in FeynHiggs 2.6 (IV):

### Evaluation of theory error on masses and mixing

→ estimate of uncertainty in  $M_{h_i}, U_{ij}, Z_{ij}$  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]  
⇒ Connection to Flavor physics

### Evaluation of additional constraints (rMSSM/cMSSM)

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

### Planned:

- ILC production cross sections

## Comparison with other codes/calculations:

**FeynHiggs** is the only code that has

- evaluation of  $\Gamma(h_i \rightarrow \dots)$  with external Higgs, bosons on-shell  
i.e. evaluated with **Z**
- evaluation of  $\text{BR}(h_i \rightarrow \dots)$  with external Higgs, bosons on-shell  
i.e. evaluated with **Z**
- evaluation of  $\sigma_{\text{TeV,LHC}}(\dots \rightarrow h_i + X)$  with external Higgs bosons on-shell,  
i.e. evaluated with **Z**
- evaluation of effective couplings with **U** or **R**
- $\text{Im } \hat{\Sigma}$  included consistently in mass and coupling evaluation

Other codes/calculations:

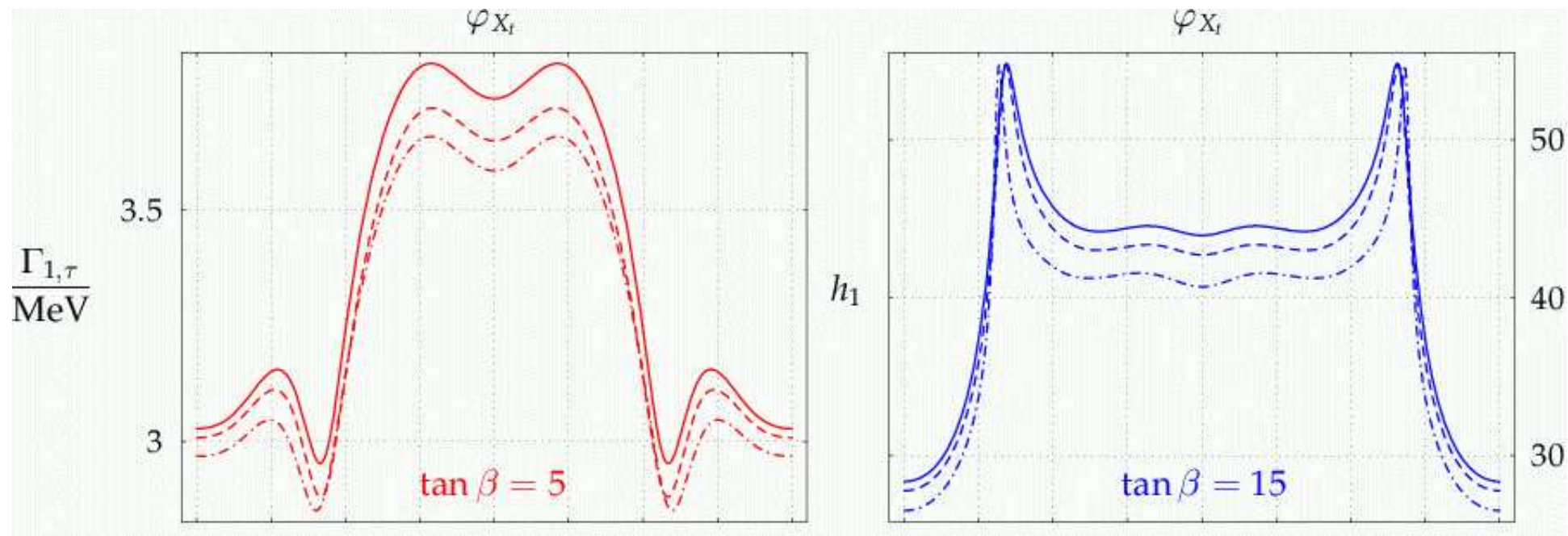
- rely on evaluation of  $\Gamma$ ,  $\text{BR}$  with **R** (possibly with **U**)
- effective potential approach corresponds to **R**

$\Rightarrow$  see numerical examples for size of effects

## Numerical results (I):

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

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



solid: **Z** ,    dashed: **U** ,    dot-dashed: **R**

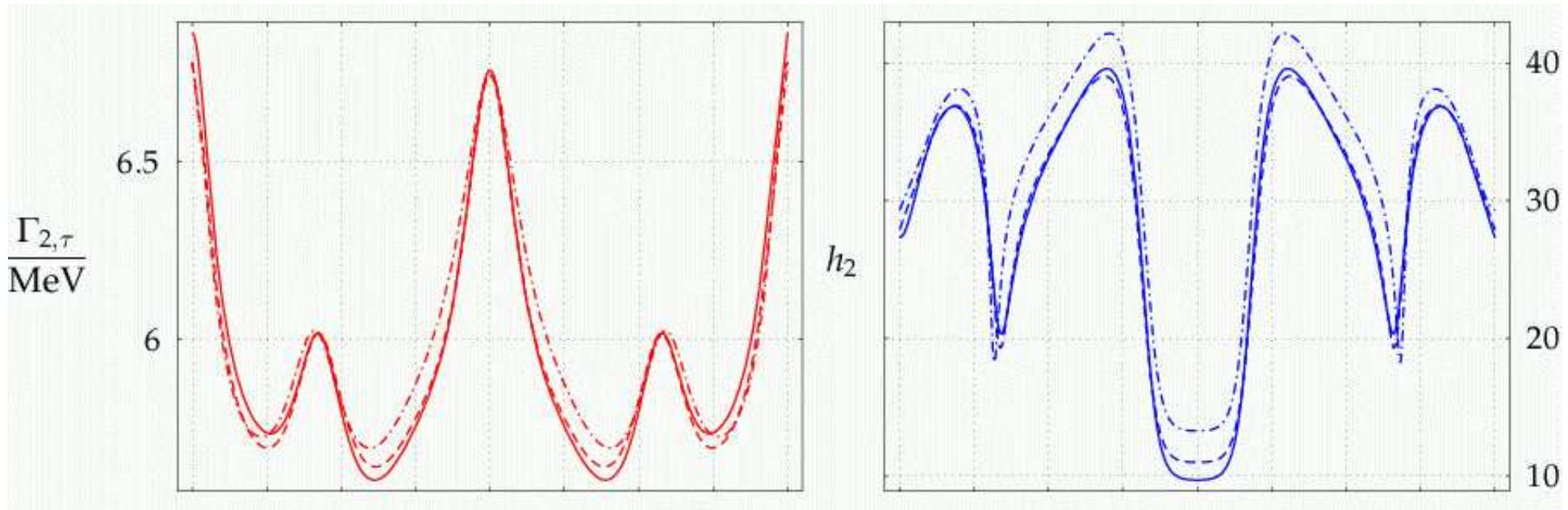
$\Rightarrow$  **U** gives results closer to full result than **R**

$\Rightarrow$  deviations at the 5-10% level

## Numerical results (II):

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

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



solid: **Z** ,    dashed: **U** ,    dot-dashed: **R**

$\Rightarrow$  **U** gives results closer to full result than **R**

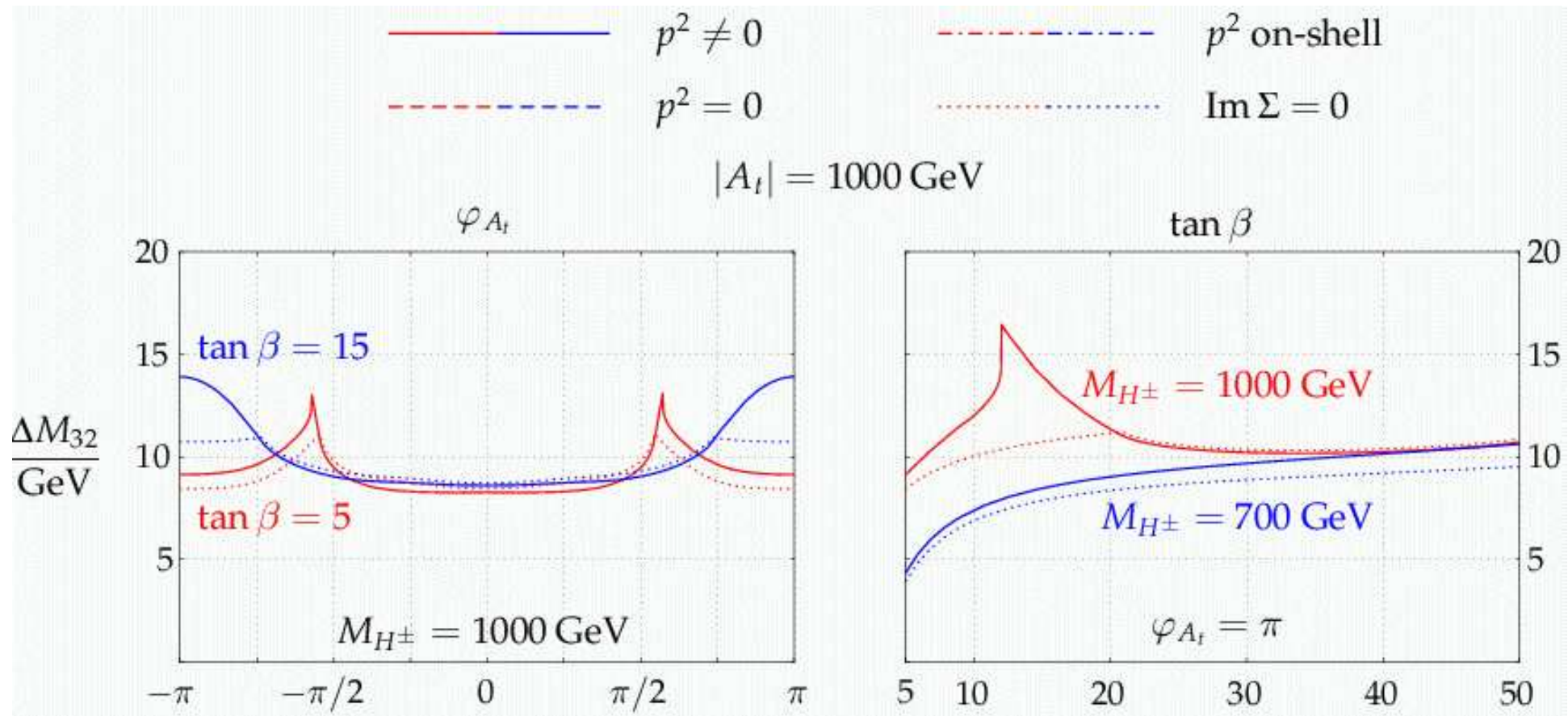
$\Rightarrow$  deviations at the 5-10% level



### Numerical results (III):

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

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



$\Rightarrow$  differences of up to 5 GeV

## 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](http://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](http://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
MAO     200
Abs(M_2) 332
Abs(MUE) 980
TB      50
Abs(At)  -300
Abs(Ab)  1500
Abs(M_3)  975
```

### Input File (“new”)

```
MT      172.7
MB      4.7
MW      80.4
MZ      91.1
MAO     200
TB      50
table ehoww.A2.dat MAO TB
```

- Loops over parameter values possible (parameter scans).

```
MAO      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  $\Rightarrow$  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(...)` :

→ 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[]** :  
→ obtain decay widths, BRs etc.



## D) WWW mode

1. The FeynHiggs User Control Center is available at  
[www.feynhiggs.de/fhucc](http://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

2. 

3. <http://www.feynhiggs.de/cgi-bin/ft>

⇒ **Flags**

⇒ Scope of the 1-loop part: full MSSM

1-loop field renormalization: MSbar

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

Solution: **Z** for external (on-shell) Higgs, **U** or **R** for Higgs in loops

- 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)
- – **Z** consistently included (only FeynHiggs!)
- – **U**, **R** consistently included for effective couplings
  - ⇒ effects up to 5-10%
- –  $\text{Im } \hat{\Sigma}$  consistently included in masses and couplings (only FeynHiggs!)
- ⇒ effects up to 5 GeV
- Correction of  $\mathcal{O}(\alpha_t \alpha_s)$  in the cMSSM included
- benchmark scenarios:  $M_A$ -tan  $\beta$  planes in agreement with CDM included