Correct Treatment of Higher-Order Corrected Higgs-Bosons (in FeynHiggs2.4)

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

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:

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

with

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

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

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, $\mathcal{CP}$-even and $\mathcal{CP}$-odd fields can mix

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

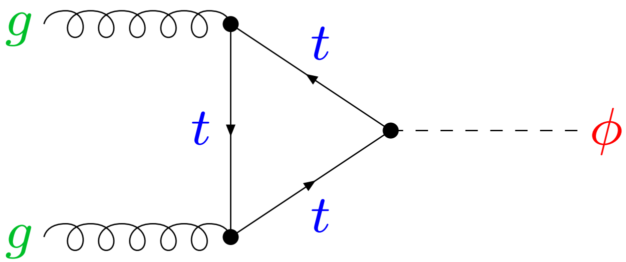
– full 1-loop: complex phases, q^2-dep., imaginary parts

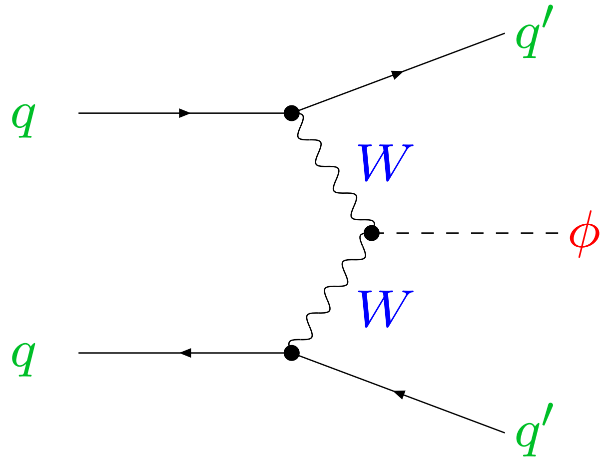
– currently implemented: cMSSM $\mathcal{O}(\alpha_t\alpha_s)$ corrections in the FD approach
rMSSM: difference between FD and RGiEP approach $\mathcal{O}$ (few GeV)

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

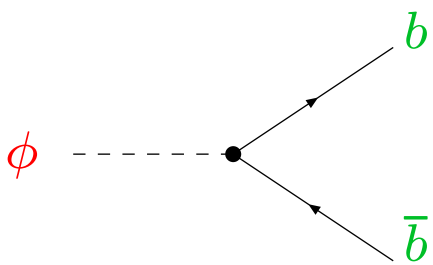
Examples for external (on-shell) Higgs bosons ($\phi = h_1, h_2, h_3$):

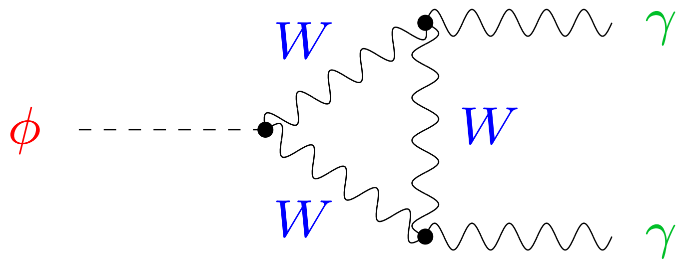
Higgs production:





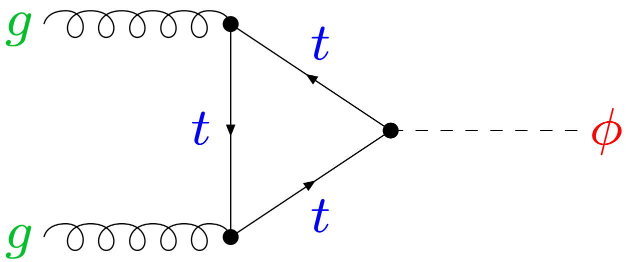
Higgs decays:

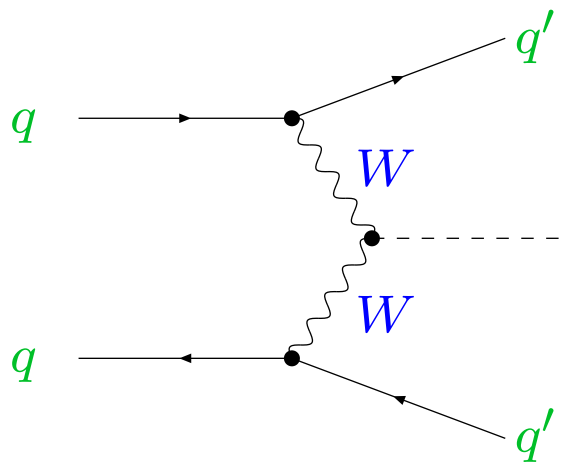




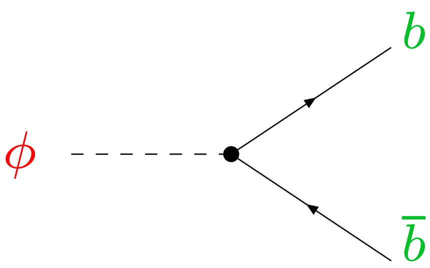
Examples for external (on-shell) Higgs bosons ($\phi = h_1, h_2, h_3$):

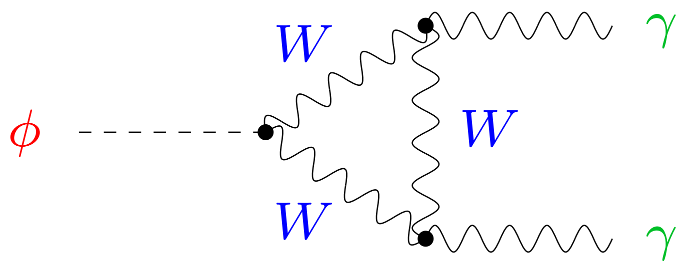
Higgs production:





Higgs decays:





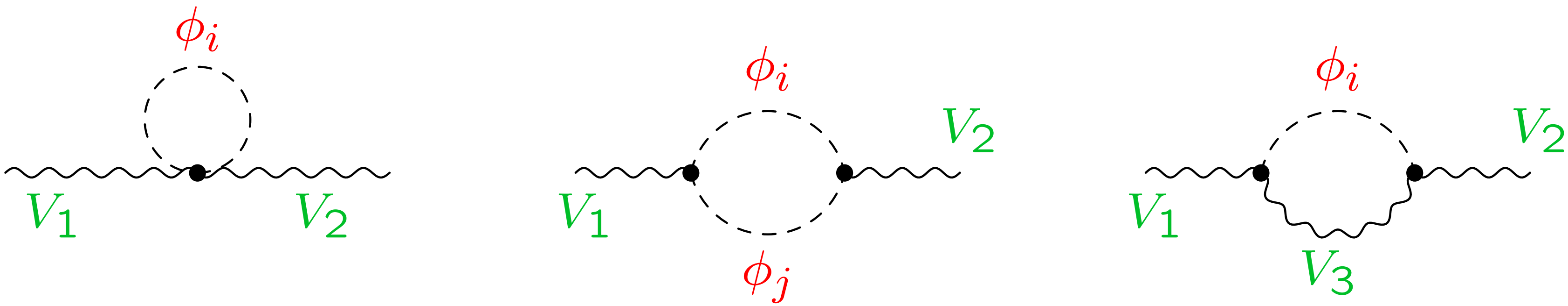
$\Rightarrow$ important to ensure on-shell properties of external Higgs boson

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

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Vector boson self-energies:

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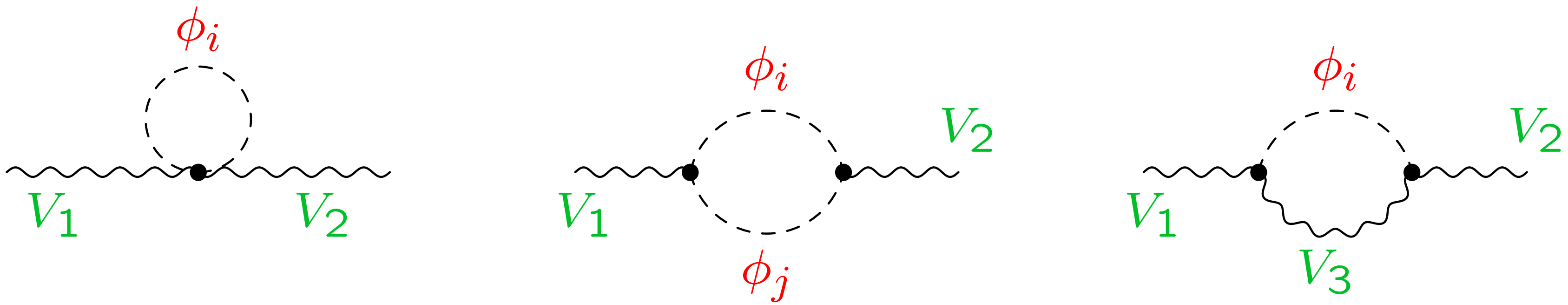


$\phi_{i,j} = h, H, A$ (tree-level states): $\Rightarrow$ ok

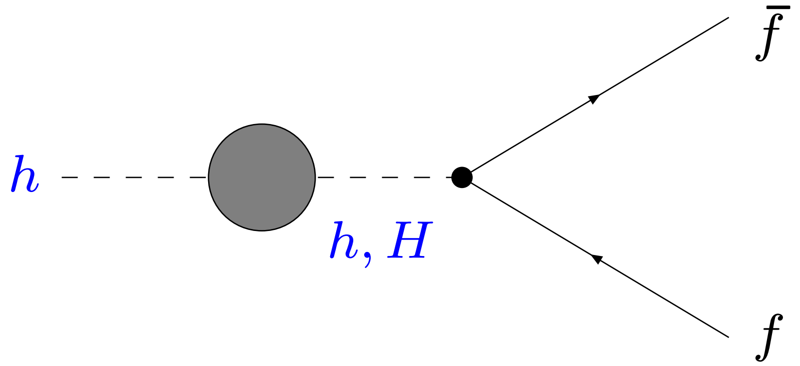
But what if $\phi_{i,j} = h_1, h_2, h_3$?

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

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

2. External (on-shell) Higgs bosons

The real case, 2×2 mixing, is known since long:



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

Amplitude:

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

$\Gamma_{h,H}$: 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 $h \to H$

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

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

$$Z_i = \left[1 + \left(\mathrm{Re}\hat{\Sigma}_{ii}^{\mathrm{eff}}\right)'(M_i^2)\right]^{-1}$$

$$\hat{\Sigma}_{ii}^{\mathrm{eff}}(p^2) = \hat{\Sigma}_{ii}(p^2) - \left(\frac{\left(\hat{\Sigma}_{ij}(p^2)\right)^2}{p^2 - m_j^2 + \hat{\Sigma}_{jj}(p^2)}\right)$$

$$Z_{ij} = -\frac{\hat{\Sigma}_{ij}(M_i^2)}{M_i^2 - m_j^2 + \hat{\Sigma}_{jj}(M_i^2)}$$

m_i: tree-level masses

M_i: higher-order corrected masses

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

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

$$Z_i = \left[1 + \left(\mathrm{Re}\hat{\Sigma}^{\mathrm{eff}}_{ii}\right)'(M_i^2)\right]^{-1}$$

$$\hat{\Sigma}^{\mathrm{eff}}_{ii}(p^2) = \hat{\Sigma}_{ii}(p^2) - \left(\frac{\left(\hat{\Sigma}_{ij}(p^2)\right)^2}{p^2 - m_j^2 + \hat{\Sigma}_{jj}(p^2)}\right)$$

$$Z_{ij} = -\frac{\hat{\Sigma}_{ij}(M_i^2)}{M_i^2 - m_j^2 + \hat{\Sigma}_{jj}(M_i^2)}$$

m_i: tree-level masses

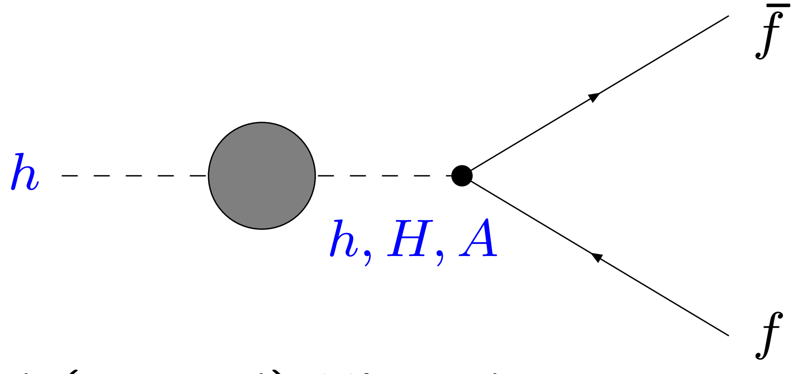
M_i: higher-order corrected masses

Limit $p^2 \to 0$:

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

$$\to \Gamma_h(\alpha \to \alpha_{\mathrm{eff}})$$

New: Extension to the 3×3 case:



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 $h \to H/A$

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

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

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

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

$$
\begin{aligned}
Z_i &= \left[1 + \left(\mathrm{Re}\hat{\Sigma}^{\mathrm{eff}}_{ii}\right)'(M_i^2)\right]^{-1} \\
\hat{\Sigma}^{\mathrm{eff}}_{ii}(p^2) &= \hat{\Sigma}_{ii}(p^2) \\
&\quad - i\frac{2\hat{\Gamma}_{ij}(p^2)\hat{\Gamma}_{jk}(p^2)\hat{\Gamma}_{ki}(p^2) - \hat{\Gamma}^2_{ki}(p^2)\hat{\Gamma}_{jj}(p^2) - \hat{\Gamma}^2_{ij}(p^2)\hat{\Gamma}_{kk}(p^2)}{\hat{\Gamma}_{jj}(p^2)\hat{\Gamma}_{kk}(p^2) - \hat{\Gamma}^2_{jk}(p^2)} \\
Z_{ij} &= \frac{\hat{\Sigma}_{ij}(M_i^2)\left(M_i^2 - m_k^2 + \hat{\Sigma}_{kk}(M_i^2)\right) - \hat{\Sigma}_{jk}(M_i^2)\hat{\Sigma}_{ki}(M_i^2)}{\hat{\Sigma}^2_{jk}(M_i^2) - \left(M_i^2 - m_j^2 + \hat{\Sigma}_{jj}(M_i^2)\right)\left(M_i^2 - m_k^2 + \hat{\Sigma}_{kk}(M_i^2)\right)} \\
\hat{\Gamma}_{ii}(p^2) &= i\left[p^2 - m_i^2 + \hat{\Sigma}_{ii}(p^2)\right] \\
\hat{\Gamma}_{ij}(p^2) &= i\,\hat{\Sigma}_{ij}
\end{aligned}
$$

m_i: tree-level masses

M_i: higher-order corrected masses

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

Limit $p^2 \to 0$:

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

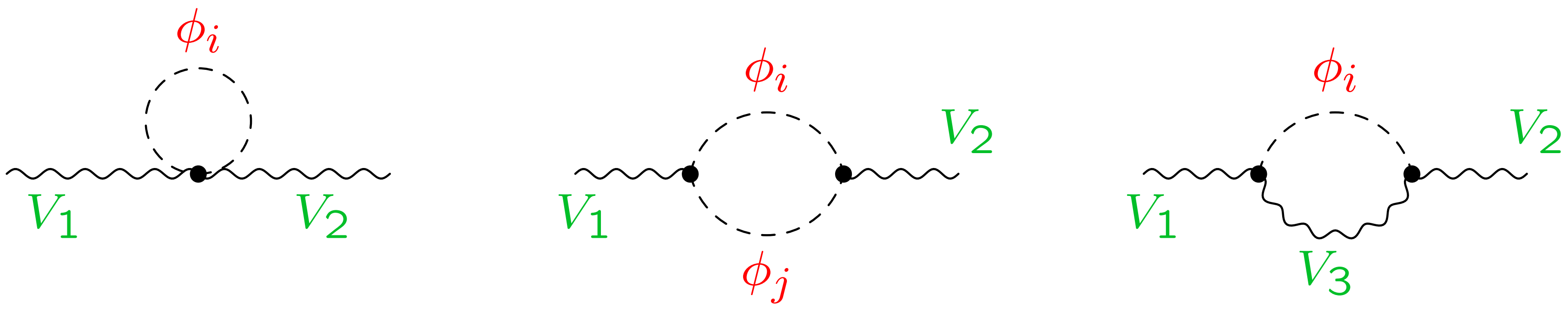
$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}_{p^2=0} = \mathbf{R} \cdot \begin{pmatrix} h \\ H \\ A \end{pmatrix}, \; \mathbf{R}\,\mathbf{M}_{hHA}(0)\,\mathbf{R}^\dagger = \begin{pmatrix} M^2_{h_1,p^2=0} & 0 & 0 \\ 0 & M^2_{h_2,p^2=0} & 0 \\ 0 & 0 & M^2_{h_3,p^2=0} \end{pmatrix}$$

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

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

3. 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" : $\mathbf{U}$

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

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

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

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

What is better?

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

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

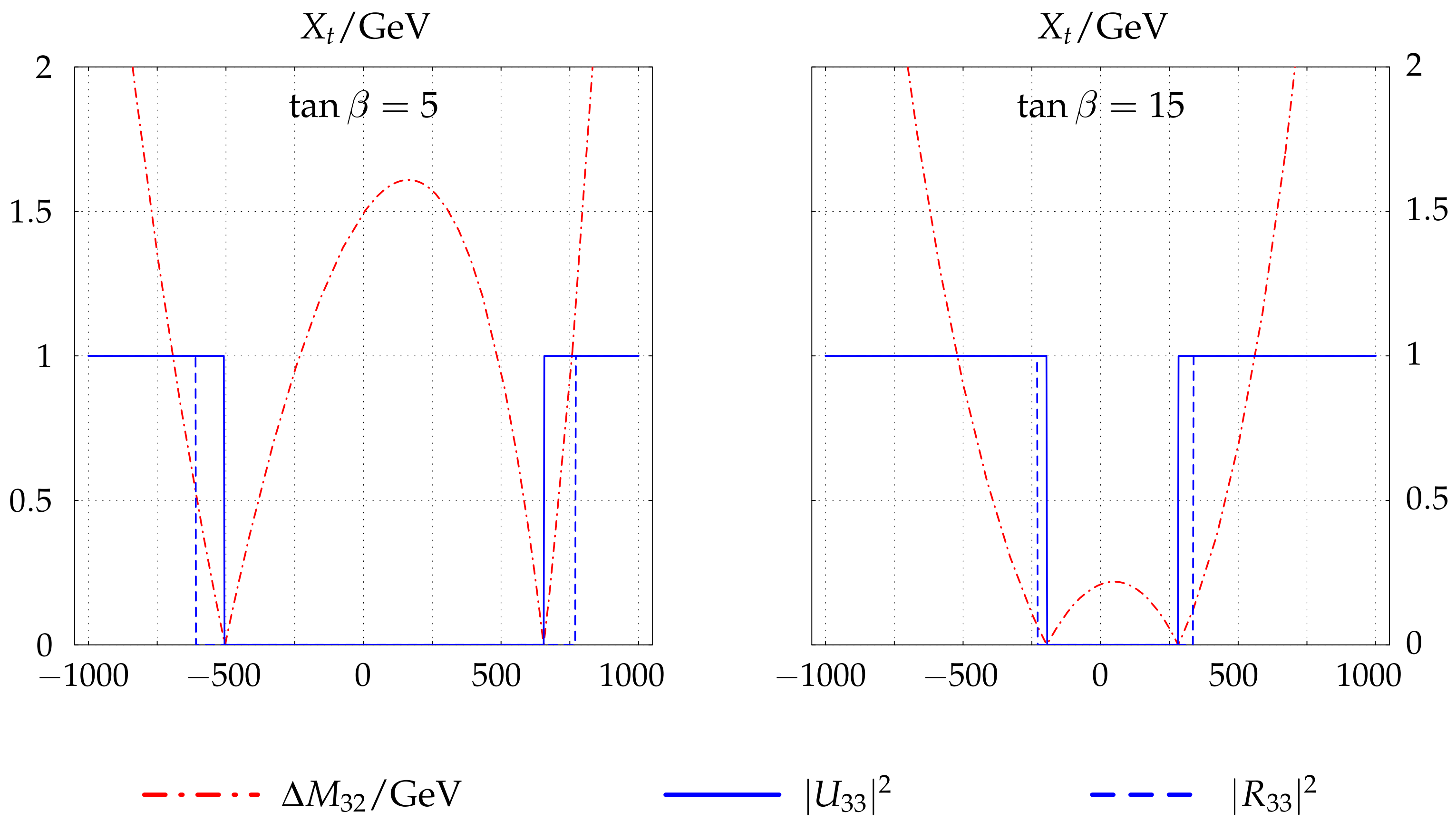
Two possible tests:

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}:

$M_{\rm SUSY} = m_{\tilde{g}} = M_2 = 500$ 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 $\mathbf{U}$:

$$C_{h_i xy} = \mathbf{U}_{ih}\, C_{hxy} + \mathbf{U}_{iH}\, C_{Hxy} + \mathbf{U}_{iA}\, C_{Axy}$$

Limit of $\hat{\Sigma}(p^2) \to \hat{\Sigma}(0)$: $\mathbf{Z} \to \mathbf{R} \neq \mathbf{U}$

4. Implementation into FeynHiggs2.4 & Numerical results

Latest version: FeynHiggs2.4.1 (06/06)

version FeynHiggs2.4.2 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

FeynHiggs2.2 $\rightarrow$ FeynHiggs2.4: main new features

- Complex contributions to Higgs mass matrix taken into account (from $\text{Im}\, B_0(\ldots) \neq 0$)
- 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 $\Rightarrow$ Higgs bosons in loops
- $\Rightarrow$ included in all Higgs production and decay
- inclusion of full one-loop NMFV effects
- Preliminary implementation of LEP Higgs exclusion bounds (to be refined)
- 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 FeynHiggs2.4 (I):

Evaluation of all Higgs boson masses and mixing angles

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

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

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

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

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

Included in FeynHiggs2.4 (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

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

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

- all channels as above

Included in FeynHiggs2.4 (III):

Evaluation of all charged Higgs boson decay channels (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

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

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

Included in FeynHiggs2.4 (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 [*LEP Higgs WG '06*]
- EDMs of electron, neutron, Hg, . . .

Planned:

- ILC production cross sections

Implementation of Z and U into FeynHiggs

Example: Command-line mode

Input File

```
MT         171.4
MB         4.7
MW         80.3
MZ         91.1
MSusy      500
Abs(At)    900
Arg(At)    1.57
Abs(M_2)   500
Abs(MUE)   2000
Abs(M_3)   1000
Arg(M_3)   1.57
MHp        200
TB         10
```

Command

FeynHiggs *file flags* →

Screen Output

```
| Mh1       =  121.663341
| Mh2       =  163.059786
| Mh3       =  194.352436
| MHp       =  200.000000
| SAeff     = -2.00000000 0.00000000
| UHiggsRe = 0.98296798 0.02245591 -0.18239977 \
|            0.17114966 0.24969051  0.95308050 \
|           -0.06694578 0.96806528 -0.24159445
| ZHiggsRe = 0.99776634 0.02058169 -0.18753478 \
|            0.15697066 0.24403177  0.93189908 \
|           -0.06892111 0.95824845 -0.23574594
| ZHiggsIm = 0.00000000 0.00015697 -0.00033670 \
|           -0.00017718 0.00108671  0.00000000 \
|           -0.00017687 0.00000000  0.00129246
  ...
%  Channel    Gamma          BR         BRSM
%| h1-b-b   = 1.729866E-02  0.866537   0.679088
  ...
%  Channel     Re Coupling    Im Coup    SM Ratio
%| C:h1-W-W = 0.000000E+00  51.4305    0.979683
  ...
%  Channel       xsection/fb      SM xsection/fb
%| Tev:b-b-h1 = 66.7766          9.83480
  ...
```

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

Other codes/calculations:

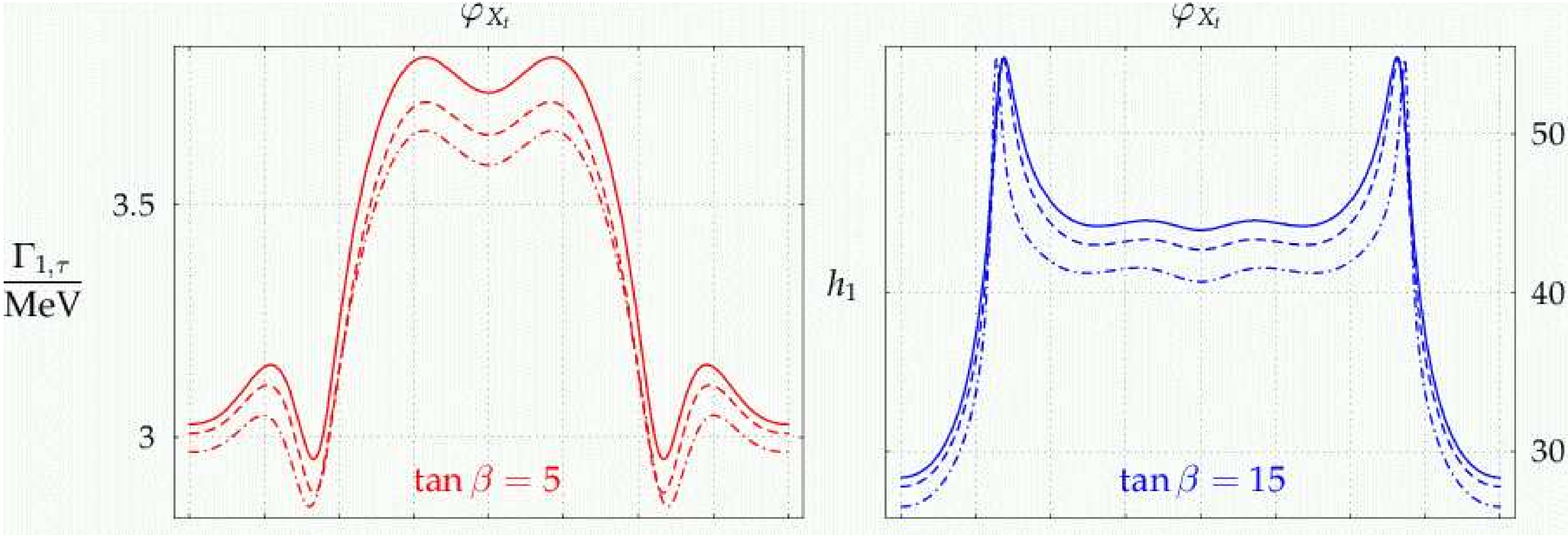
- rely on evaluation of Γ, BR with $\mathbf{R}$ (possibly with $\mathbf{U}$)
- effective potential approach corresponds to $\mathbf{R}$

$\Rightarrow$ see numerical examples for size of effects

Numerical results (I):

$M_{\text{SUSY}} = m_{\tilde{g}} = M_2 = 500$ 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: **Z** , dashed: **U** , dot-dashed: **R**

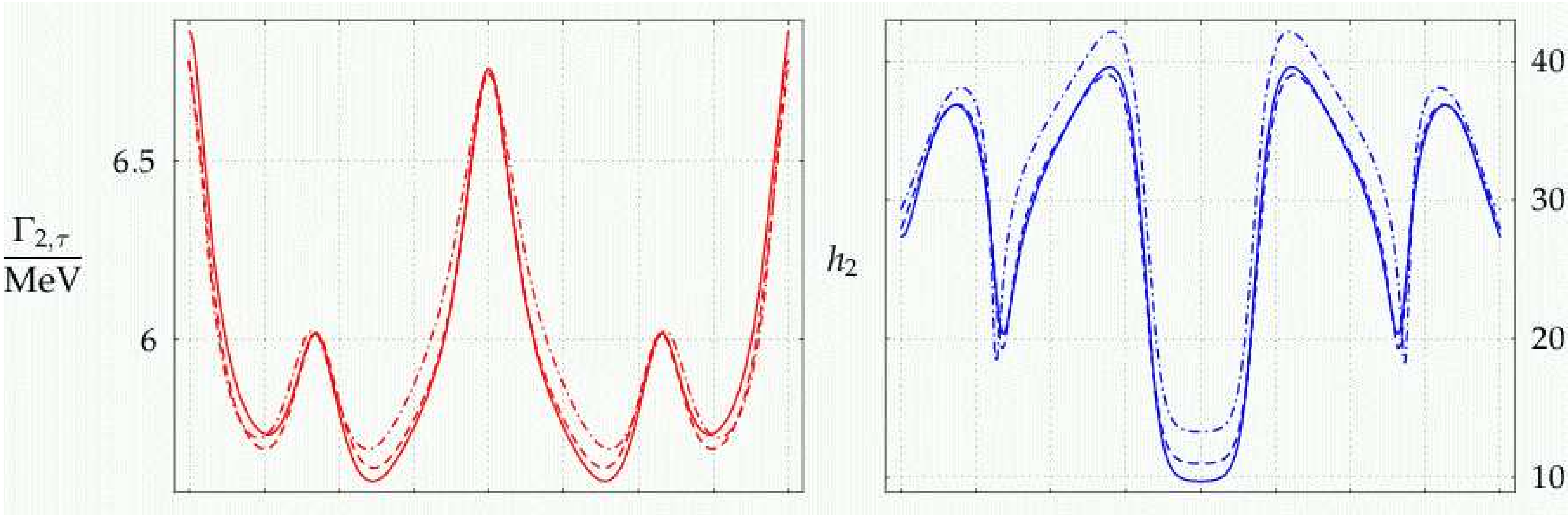
⇒ **U** gives results closer to full result than **R**

⇒ deviations at the 5-10% level

Numerical results (II):

$M_{\text{SUSY}} = m_{\tilde{g}} = M_2 = 500$ 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: **Z** , dashed: **U** , dot-dashed: **R**

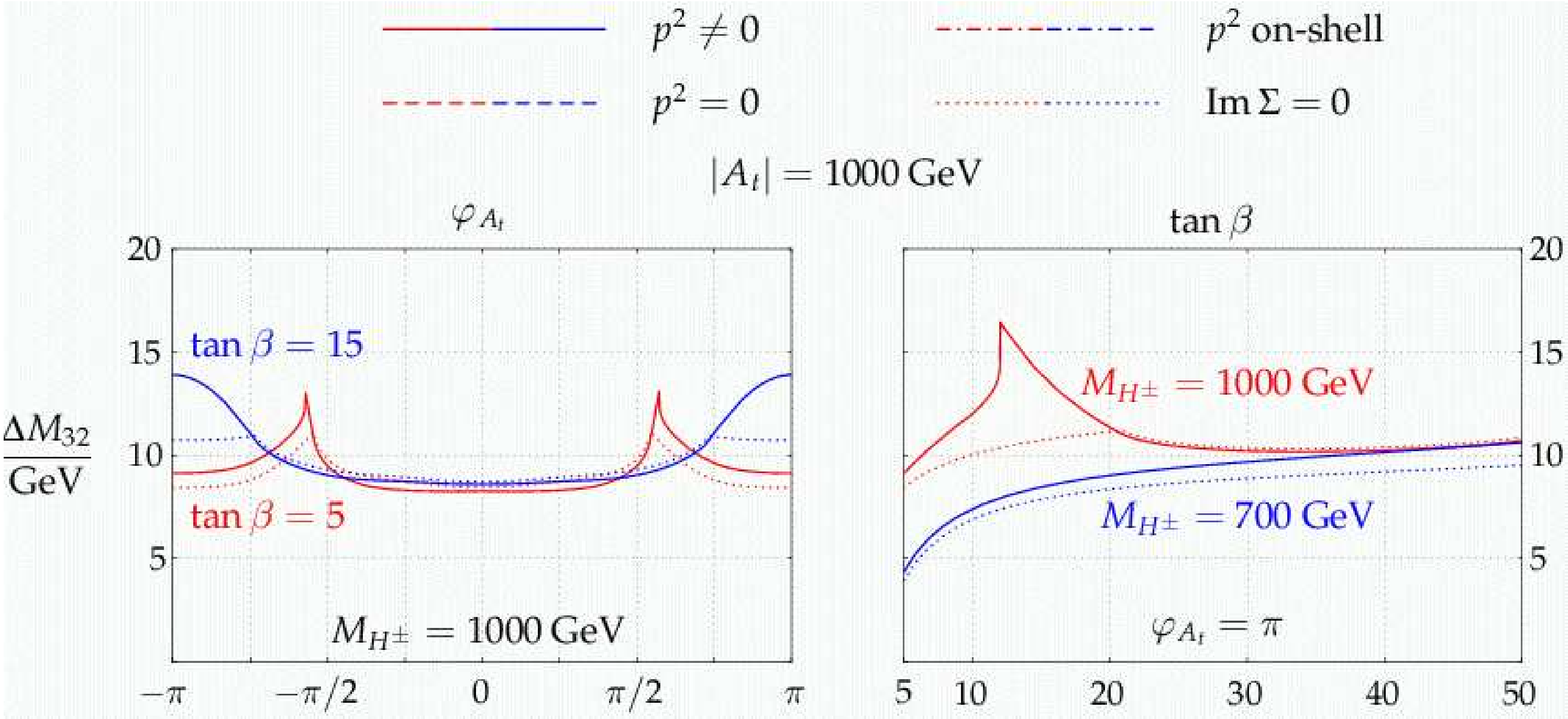
⇒ **U** gives results closer to full result than **R**

⇒ deviations at the 5-10% level

Numerical results (III):

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

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

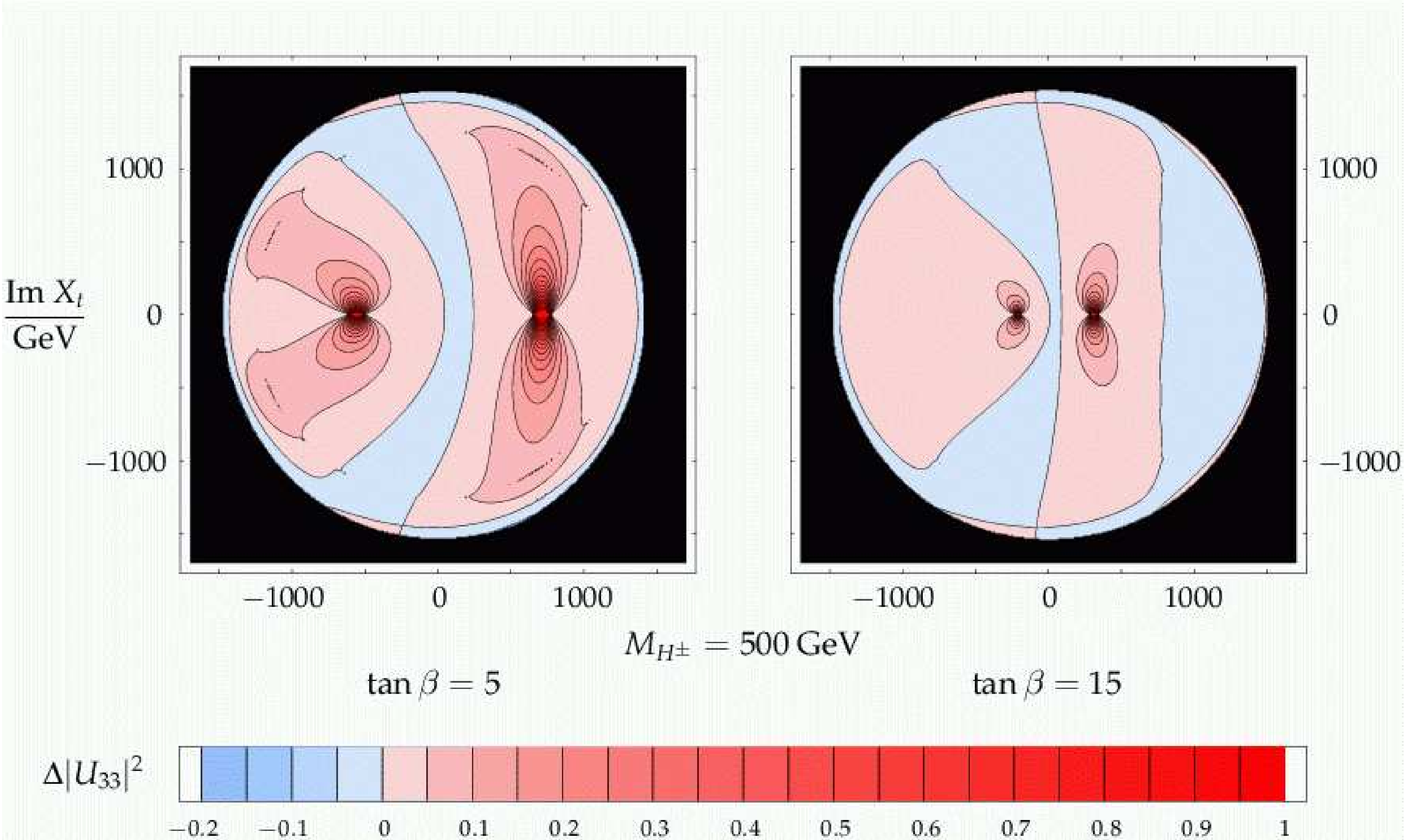


$\Rightarrow$ differences of up to 5 GeV

Numerical results (IV):

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

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

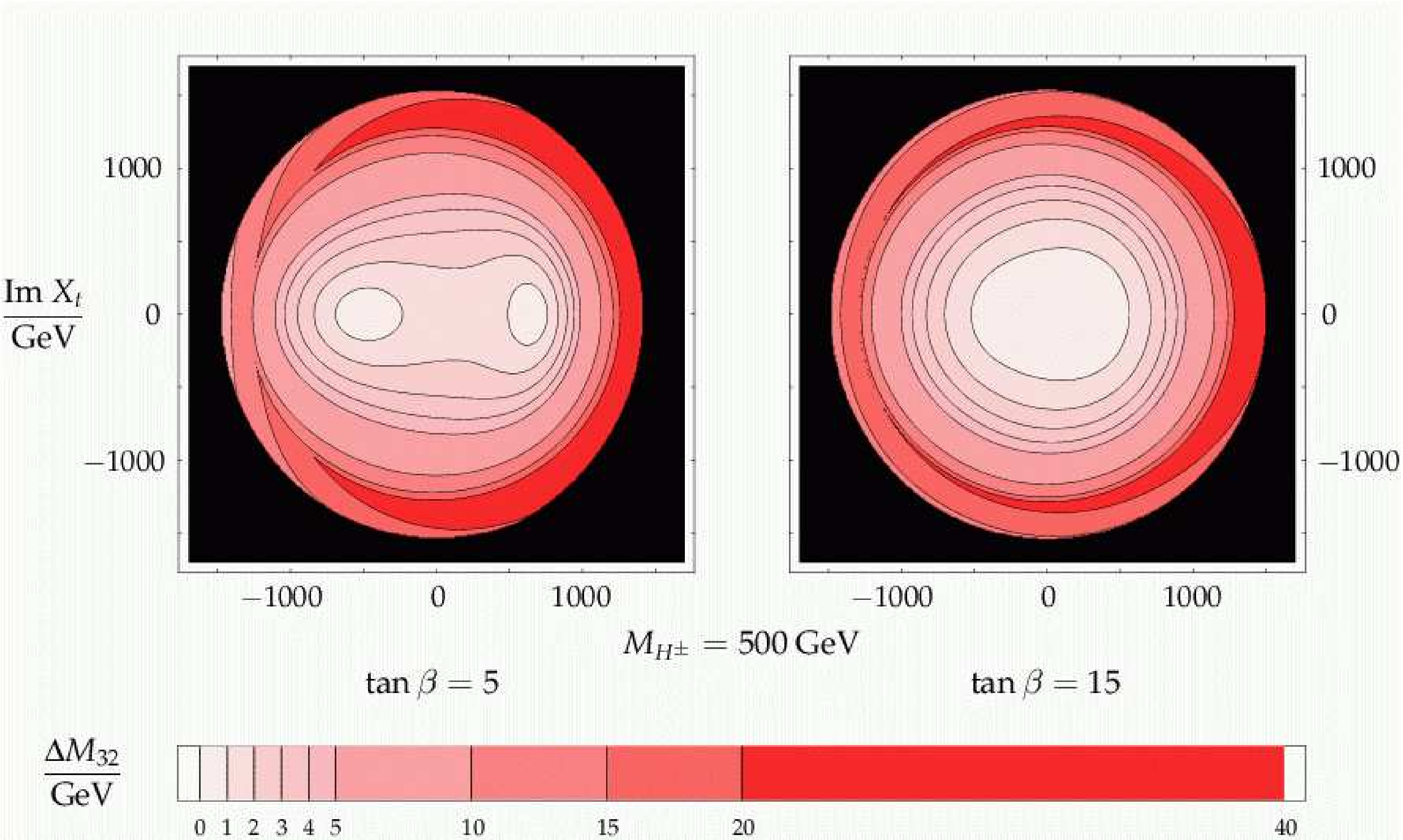


⇒ large deviations where ΔM_{32} is small

Numerical results (IV):

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

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



$\Rightarrow$ large deviations where ΔM_{32} is small

5. Conclusinos

- Very precise MSSM Higgs sector evaluation necessary to
  - 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 for Higgs in loops
- `FeynHiggs2.4` 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** consistently included for effective couplings
  ⇒ effects up to 5-10%
  – $\mathrm{Im}\,\hat{\Sigma}$ consistently included in mass and coupling calculations (only `FeynHiggs!`)
  ⇒ effects up to 5 GeV
- `FeynHiggs2.4` is available at `www.feynhiggs.de`