CP-violating loop effects in the Higgs sector of the MSSM

Georg Weiglein

IPPP Durham

Sondershausen, 04/2008

HEPTOOLS, collab. with *A. Fowler, T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, K. Williams*

- Introduction
- Results for Higgs masses and wave function normalisations
- Higgs self-couplings and Higgs cascade decays
- Higgs production in SUSY cascade decays
- Conclusions

Introduction

MSSM Higgs potential contains two Higgs doublets:

$$V_H = m_1^2 H_{1i}^* H_{1i} + m_2^2 H_{2i}^* H_{2i} - \epsilon^{ij} (m_{12}^2 H_{1i} H_{2j} + {m_{12}^2}^* H_{1i}^* H_{2j}^*)$$

$$+ \frac{1}{8}(g_1^2 + g_2^2)(H_{1i}^* H_{1i} - H_{2i}^* H_{2i})^2 + \frac{1}{2} g_2^2 |H_{1i}^* H_{2i}|^2$$

$$\begin{pmatrix} H_{11} \\ H_{12} \end{pmatrix} = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 - i\chi_1) \\ -\phi_1^- \end{pmatrix}$$

$$\begin{pmatrix} H_{21} \\ H_{22} \end{pmatrix} = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix}$$

Complex phases $\arg(m_{12}^2)$, ξ can be rotated away

$\Rightarrow$ Higgs sector is $\mathcal{CP}$-conserving at tree level

Higher-order corrections in the MSSM Higgs sector

- Quartic couplings in the Higgs sector are given by the gauge couplings, g_1, g_2 (SM: free parameter)

  $\Rightarrow$ Upper bound on the lightest Higgs mass

- Large higher-order corrections from Yukawa sector:

  $\Rightarrow$ Leading corr.: $\Delta m_{\mathrm{h}}^2 \sim G_\mu m_{\mathrm{t}}^4$

  Can be of $\mathcal{O}(100\%)$

$\Rightarrow$ Higher-order corrections are phenomenologically very important (constraints on parameter space from search limits / possible future measurements)

Can induce $\mathcal{CP}$-violating effects

$\mathcal{CP}$ *violation in the Higgs sector*

Five physical states; tree level: $h^0, H^0, A^0, H^\pm$

Complex parameters enter via (often large) loop corrections:

– μ: Higgsino mass parameter

– $A_{t,b,\tau}$: trilinear couplings

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

– M_3: gluino mass $m_{\tilde{g}}$ + complex phase

$\Rightarrow$ $\mathcal{CP}$-violating mixing between neutral Higgs bosons h_1, h_2, h_3

Lowest-order Higgs sector has two free parameters

$\Rightarrow$ choose $\tan\beta \equiv \frac{v_2}{v_1}$, $M_{\mathrm{H}^\pm}$ as input parameters

Phenomenological constraints on complex phases

Experimental constraints from:

- Electric dipole moments of electron, neutron, deuterium, heavy quarks, ...: affect mainly first two generations, corresponding phases are tightly constrained or mass scales have to be very heavy
- $\mathcal{CP}$-violation in the b sector: much weaker bounds on 3rd generation complex phases

CPX benchmark scen.: [*M. Carena, J. Ellis, A. Pilaftsis, C. Wagner '00*]

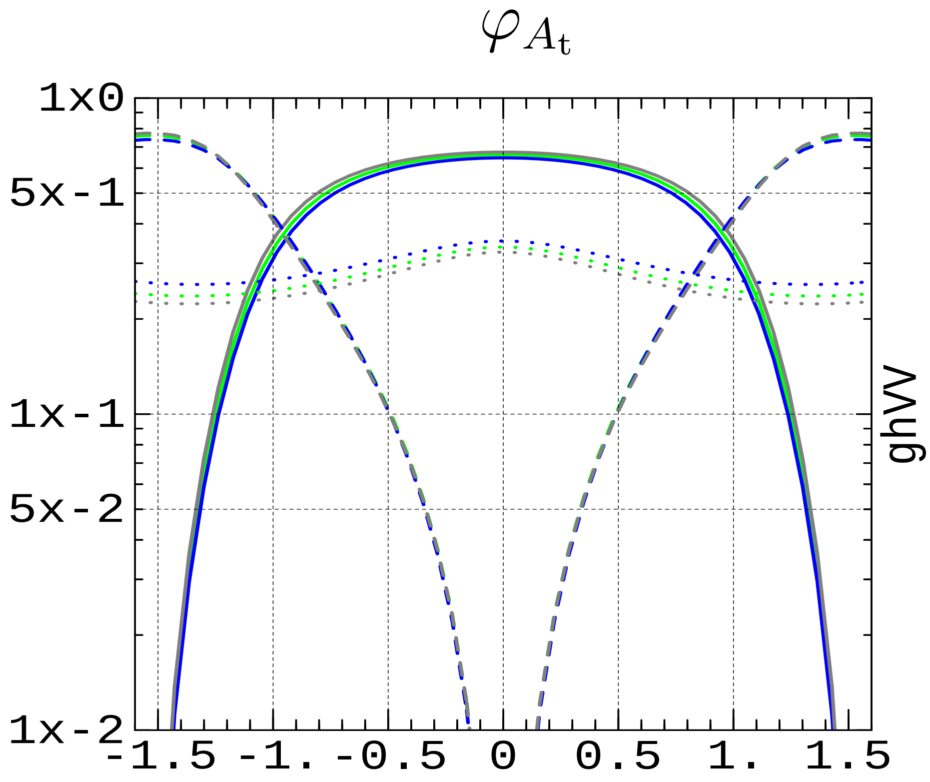
$$\varphi_{A_{\rm t}} = \varphi_{A_{\rm b}} = \varphi_{\tilde{g}} = 90^\circ,$$

$$\mu = 4 M_{\rm SUSY}, \quad |A_{\rm t}| = |A_{\rm b}| = 2 M_{\rm SUSY}, \quad m_{\tilde{\rm g}} = 1 \text{ TeV}$$

"extreme" parameter values, chosen to illustrate possible effects of complex phases

Impact of complex phases

Example: g^2_{hVV} for h_1, h_2, h_3: [*M. Frank, S. Heinemeyer, W. Hollik, G. W. '03*]



full: h_1, dashed: h_2, dotted: h_3

Parameters:

$M_{\rm SUSY} = 500$ GeV,

$M_2 = 500$ GeV,

$\mu = 2000$ GeV,

$|A_t| = 1000$ GeV,

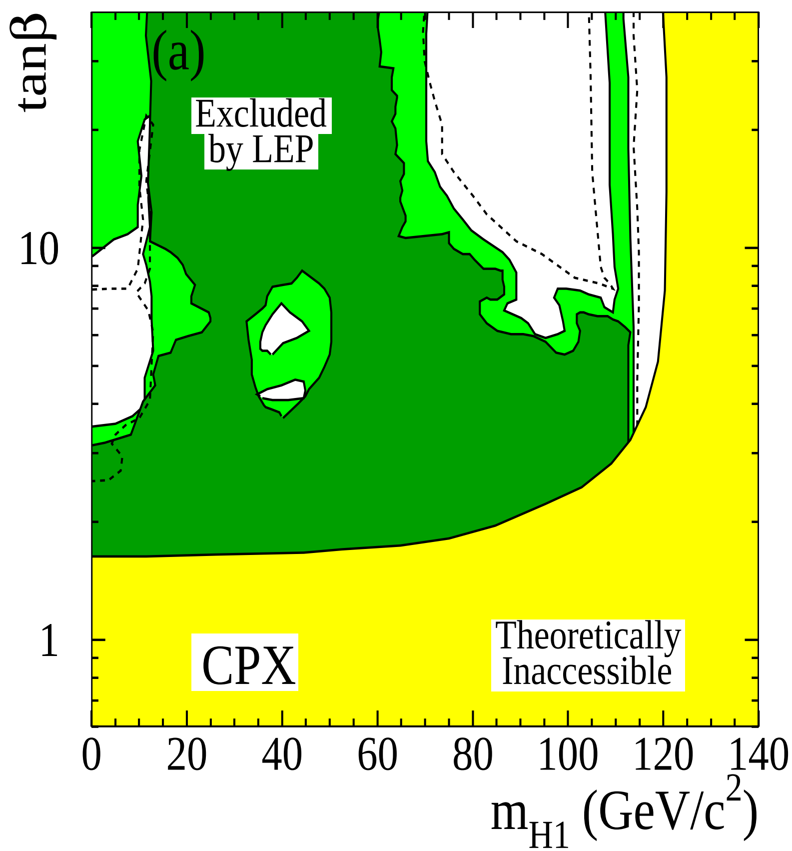
$M_{H^\pm} = 150$ GeV, $\tan\beta = 5$

$\Rightarrow$ Complex phases can have large effects on Higgs couplings

$\mathcal{CP}$-violating case (CPX benchmark scenario): LEP exclusion bounds

[LEP Higgs Working Group '06]

$m_t = 169.3$ GeV $\qquad$ $m_t = 174.3$ GeV



⇒ No lower limit on M_{h_1}: light SUSY Higgs not ruled out!

Sensitive dependence on m_t

Reason for "CPX holes"

- Suppressed coupling of light Higgs, h_1, to gauge bosons over wide regions of parameter space

- Second-lightest Higgs, h_2, may be within LEP reach (with reduced VVh_2 coupling), h_3 beyond LEP reach

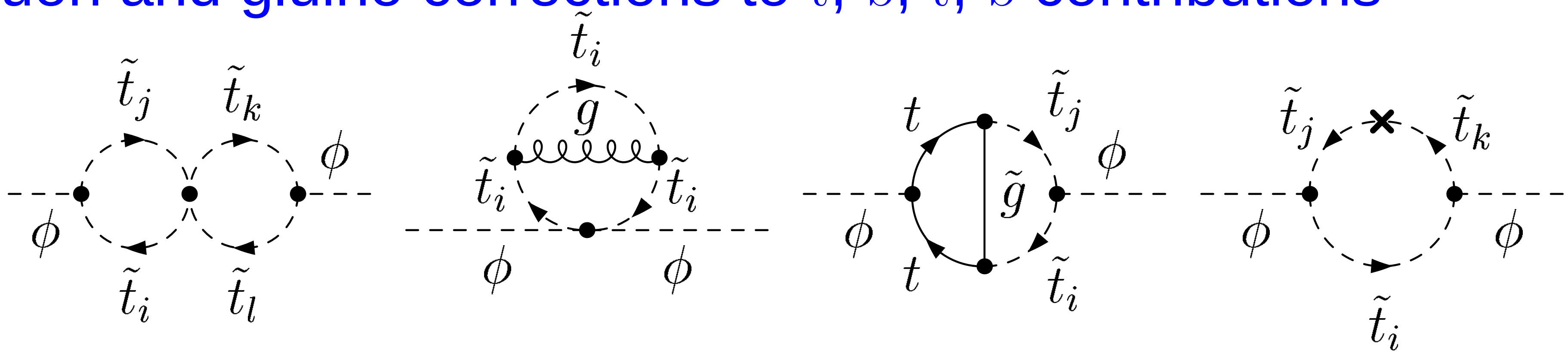
- Large $\mathrm{BR}(h_2 \to h_1 h_1) \Rightarrow$ difficult final state

$\Rightarrow$ Precise prediction for $\mathrm{BR}(h_2 \to h_1 h_1)$ needed for analysis of Higgs exclusion bounds

Results for Higgs masses and wave function normalisations

Leading two-loop QCD corrections in the Higgs sector:

Gluon and gluino corrections to t, b, $\tilde{\mathrm{t}}$, $\tilde{\mathrm{b}}$ contributions



Leading $\mathcal{O}(\alpha_\mathrm{t}\alpha_s)$ corrections: 2-loop contrib. evaluated in limit of vanishing gauge couplings, external momentum: $p^2 \to 0$

Renormalisation:

- 2-loop renormalisation in the Higgs sector, independent parameters: $M_{\mathrm{H}^\pm}$, $\tan\beta$
- 1-loop renormalisation in the $\tilde{\mathrm{t}}$, $\tilde{\mathrm{b}}$ sector, need also renormalisation of complex phase φ_{A_t}

Contributing counterterms from the two-loop renormalisation in the Higgs sector

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

$$\delta m_h^{2(2)} = c^2_{\alpha-\beta}\, \delta M^{2(2)}_{\mathrm{H}^\pm} + \frac{e\, s_{\alpha-\beta}}{4 M_Z c_W s_W}\Big[\big(s_{\alpha-2\beta} - 3 s_\alpha\big)\delta T^{(2)}_{\phi_1} + \big(c_{\alpha-2\beta} + 3 c_\alpha\big)\delta T^{(2)}_{\phi_2}\Big] ,$$

$$\delta m_{hH}^{2(2)} = \frac{s_{2\alpha-2\beta}}{2}\delta M^{2(2)}_{\mathrm{H}^\pm} + \frac{e\, c_{\alpha-\beta}}{4 M_Z c_W s_W}\Big[\big(s_{2\alpha-\beta} + c_{2\alpha-2\beta} s_\beta\big)\delta T^{(2)}_{\phi_1} - \frac{c_{2\alpha-3\beta} + 3 c_{2\alpha-\beta}}{2}\delta T^{(2)}_{\phi_2}\Big] ,$$

$$\delta m_H^{2(2)} = s^2_{\alpha-\beta}\, \delta M^{2(2)}_{\mathrm{H}^\pm} + \frac{e\, c_{\alpha-\beta}}{4 M_Z c_W s_W}\Big[\big(c_{\alpha-2\beta} - 3 c_\alpha\big)\delta T^{(2)}_{\phi_1} - \big(s_{\alpha-2\beta} + 3 s_\alpha\big)\delta T^{(2)}_{\phi_2}\Big] ,$$

$$\delta m_{AH}^{2(2)} = -\frac{e\, c_{\alpha-\beta}}{2 M_Z c_W s_W}\delta T^{(2)}_A ,$$

$$\delta m_{Ah}^{2(2)} = \frac{e\, s_{\alpha-\beta}}{2 M_Z c_W s_W}\delta T^{(2)}_A ,$$

$$\delta m_A^{2(2)} = \delta M^{2(2)}_{\mathrm{H}^\pm}$$

$s_x \equiv \sin(x)$, $c_x \equiv \cos(x)$

Stop and sbottom mass matrices

$$\mathbf{M}_{\tilde{q}} = \begin{pmatrix} M_L^2 + m_q^2 + M_Z^2 c_{2\beta}(T_q^3 - Q_q s_\mathrm{w}^2) & m_q X_q^* \\ m_q X_q & M_{\tilde{q}_R}^2 + m_q^2 + M_Z^2 c_{2\beta} Q_q s_\mathrm{w}^2 \end{pmatrix}$$

with

$$X_q = A_q - \mu^* \kappa \,, \qquad \kappa = \{\cot\beta, \tan\beta\} \quad \text{for} \quad q = t, b$$

$$\mathbf{D}_{\tilde{q}} = \mathbf{U}_{\tilde{q}}\, \mathbf{M}_{\tilde{q}}\, \mathbf{U}_{\tilde{q}}^\dagger = \begin{pmatrix} m_{\tilde{q}_1}^2 & 0 \\ 0 & m_{\tilde{q}_2}^2 \end{pmatrix}, \qquad \mathbf{U}_{\tilde{q}} = \begin{pmatrix} \cos\theta_{\tilde{q}} & e^{i\varphi_{\tilde{q}}} \sin\theta_{\tilde{q}} \\ -e^{-i\varphi_{\tilde{q}}} \sin\theta_{\tilde{q}} & \cos\theta_{\tilde{q}} \end{pmatrix}$$

$\Rightarrow$ Mass eigenvalues $m_{\tilde{q}_1}^2$, $m_{\tilde{q}_2}^2$, mixing angle $\theta_{\tilde{q}}$, phase $\varphi_{\tilde{q}}$

Mass eigenvalues $m_{\tilde{q}_1}^2$, $m_{\tilde{q}_2}^2$ depend only on $|X_q|$

Renormalisation in the sfermion sector with complex parameters

$$\delta|A_{\rm t}| = \frac{1}{m_{\rm t}}\mathrm{Re}[e^{i\varphi_{A_{\rm t}}}K_t]\ , \qquad \delta\varphi_{A_{\rm t}} = -\frac{1}{m_{\rm t}|A_{\rm t}|}\mathrm{Im}[e^{i\varphi_{A_{\rm t}}}K_t]$$

$$K_t = -\,(A_{\rm t}^* - \mu\cot\beta)\delta m_{\rm t} + U^*_{\tilde{\rm t}_{11}}U_{\tilde{\rm t}_{12}}(\delta m^2_{\tilde{\rm t}_1} - \delta m^2_{\tilde{\rm t}_2}) + U^*_{\tilde{\rm t}_{11}}U_{\tilde{\rm t}_{22}}\delta Y_t + U_{\tilde{\rm t}_{12}}U^*_{\tilde{\rm t}_{21}}\delta Y_t^*$$

$$\delta Y_{\tilde{\rm t}} = \frac{1}{2}\,[\widetilde{\mathrm{Re}}\Sigma_{\tilde{\rm t}_{12}}(m^2_{\tilde{\rm t}_1}) + \widetilde{\mathrm{Re}}\Sigma_{\tilde{\rm t}_{12}}(m^2_{\tilde{\rm t}_2})]$$

SU(2) invariance $\Rightarrow$ relation between $m_{\tilde{b}_L}$, $m_{\tilde{\rm t}_1}$, $m_{\tilde{\rm t}_2}$, $\theta_{\tilde{\rm t}}$

$$\delta m^2_{\tilde{b}_L} = |U_{\tilde{\rm t}_{11}}|^2\delta m^2_{\tilde{\rm t}_1} + |U_{\tilde{\rm t}_{12}}|^2\delta m^2_{\tilde{\rm t}_2} - U^*_{\tilde{\rm t}_{12}}U_{\tilde{\rm t}_{22}}\delta Y_t - U_{\tilde{\rm t}_{12}}U^*_{\tilde{\rm t}_{22}}\delta Y_t^* - 2m_{\rm t}\delta m_{\rm t}$$

Results for Higgs self-energies are implemented in *FeynHiggs*

[*T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. W. '08*]

Higher-order corrections to the Higgs masses

Mixing between h, H, A

$\Rightarrow$ loop-corrected masses obtained from propagator matrix

$$\Delta_{hHA}(p^2) = -\left(\hat{\Gamma}_{hHA}(p^2)\right)^{-1}, \quad \hat{\Gamma}_{hHA}(p^2) = i\left[p^2 \mathbb{1} - \mathrm{M}_{\mathrm{n}}(p^2)\right]$$

where (up to sub-leading two-loop corrections)

$$\mathrm{M}_{\mathrm{n}}(p^2) = \begin{pmatrix} m_{\mathrm{h}}^2 - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{hH}(p^2) & -\hat{\Sigma}_{hA}(p^2) \\ -\hat{\Sigma}_{hH}(p^2) & m_{\mathrm{H}}^2 - \hat{\Sigma}_{HH}(p^2) & -\hat{\Sigma}_{HA}(p^2) \\ -\hat{\Sigma}_{hA}(p^2) & -\hat{\Sigma}_{HA}(p^2) & m_{\mathrm{A}}^2 - \hat{\Sigma}_{AA}(p^2) \end{pmatrix}$$

$\Rightarrow$ Higgs propagators: $\Delta_{ii}(p^2) = \dfrac{i}{p^2 - m_i^2 + \hat{\Sigma}_{ii}^{\mathrm{eff}}(p^2)}$

Higher-order corrections to the Higgs masses

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

Complex pole $\mathcal{M}^2$ of each propagator is determined from

$$\mathcal{M}_i^2 - m_i^2 + \hat{\Sigma}^{\rm eff}_{ii}(\mathcal{M}_i^2) = 0,$$

where

$$\mathcal{M}^2 = M^2 - iM\Gamma,$$

Expansion around the real part of the complex pole:

$$\hat{\Sigma}_{jk}(\mathcal{M}^2_{h_a}) \approx \hat{\Sigma}_{jk}(M^2_{h_a}) + i\,\mathrm{Im}\left[\mathcal{M}^2_{h_a}\right]\hat{\Sigma}'_{jk}(M^2_{h_a})$$

$j, k = h, H, A$, $a = 1, 2, 3$

Impact of complex phases at the two-loop level

$\mathcal{O}(\alpha_t \alpha_s)$ corrections depend only on the phase combinations

$$\mu\, A_t\, \left(m_{12}^2\right)^* \quad \text{and} \quad A_t\, M_3^*$$

Phase of m_{12}^2 has been rotated away (see above)

$\Rightarrow$ Analyse the dependence on the phases of A_t (X_t) and M_3

Variation of φ_{A_t} for fixed μ, $\tan\beta$

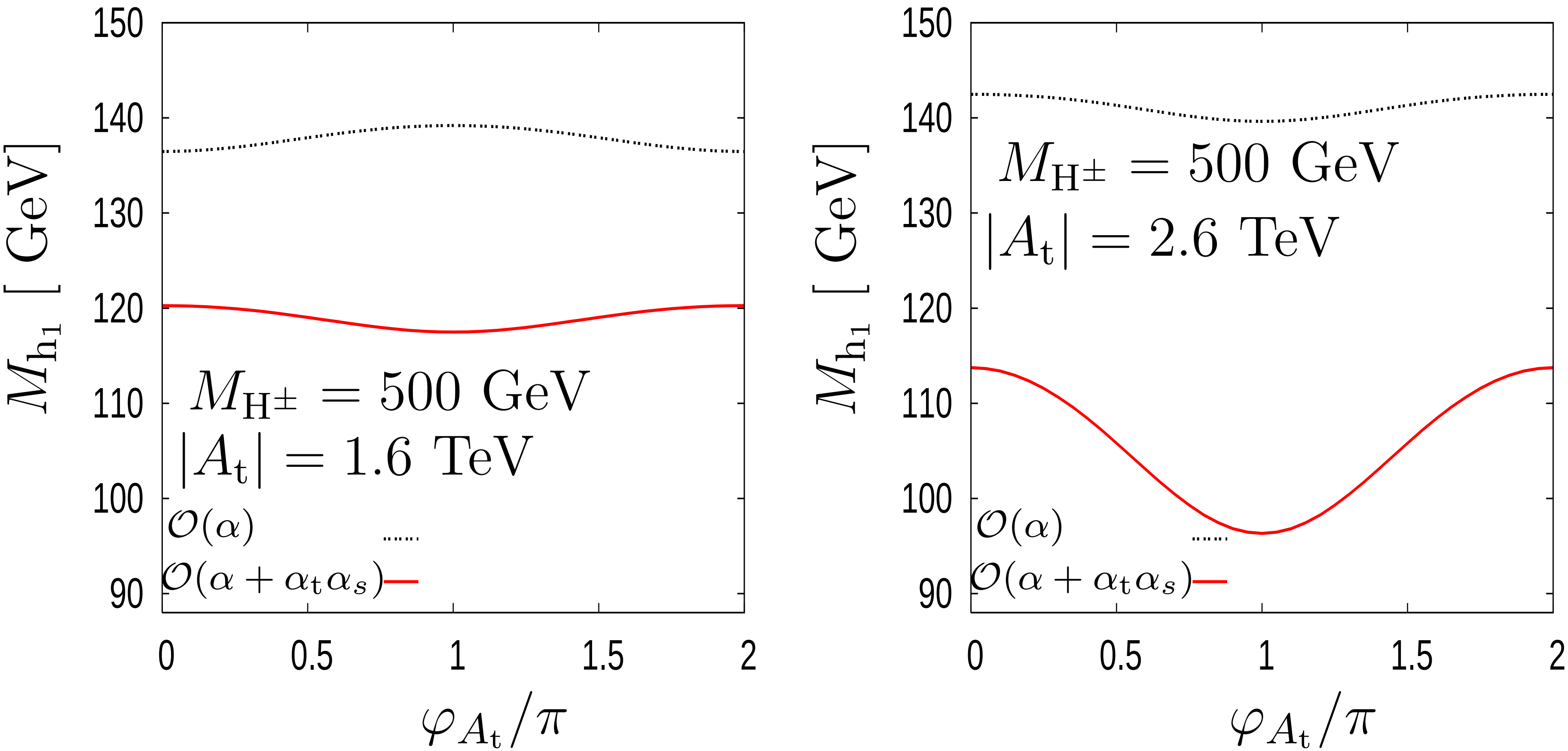
$\Rightarrow$ change of $|X_t|$ $\Rightarrow$ change of stop masses

Variation of φ_{X_t}

$\Rightarrow$ change of A_t, stop masses stay the same

Dependence of prediction for M_{h_1} on φ_{A_t}: one-loop vs. two-loop

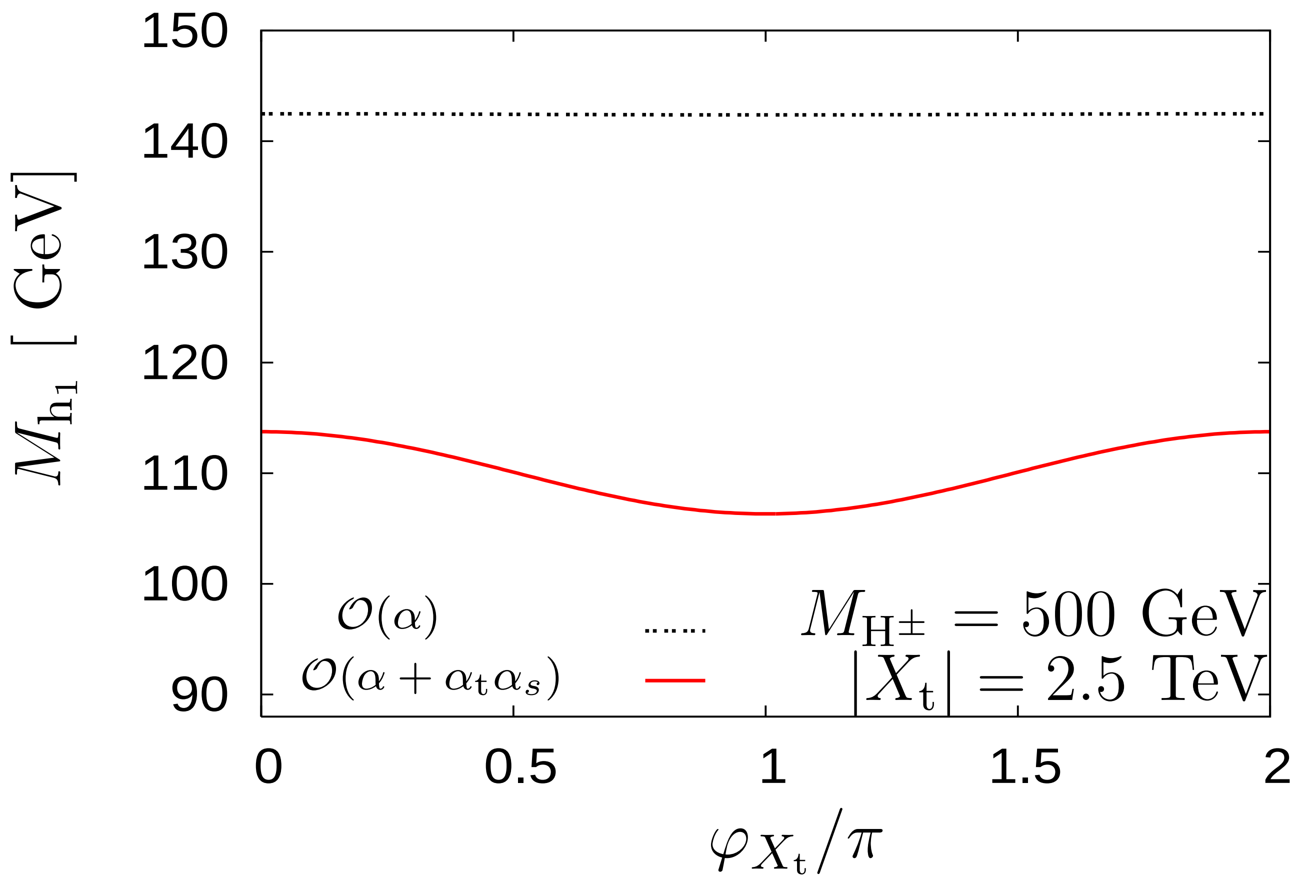
[*S. Heinemeyer, W. Hollik, H. Rzehak, G. W. '07*] $\mu = 1$ TeV, $\tan\beta = 10$



$\Rightarrow$ Two-loop corrections significantly enhance the effects of the complex phase φ_{A_t}, sizable effects for large $|A_\mathrm{t}|$

Dependence of prediction for M_{h_1} on φ_{X_t}: one-loop vs. two-loop

[*S. Heinemeyer, W. Hollik, H. Rzehak, G. W. '07*] $\mu = 1$ TeV, $\tan\beta = 10$



$\Rightarrow$ One-loop: very weak dependence on φ_{X_t}

Two-loop: large change in phase dependence

Reason for the large impact of the phase in the two-loop contribution

Leading one-loop result in the limit $M_{\mathrm{H}^\pm} \gg M_\mathrm{Z}$ depends only on the absolute value $|X_\mathrm{t}| \equiv |A_\mathrm{t} - \mu^*/\tan\beta|$

$\Leftrightarrow$ only combination $\varphi_{A_\mathrm{t}} + \varphi_\mu$ enters

$\Rightarrow$ weak dependence of one-loop result on φ_{X_t}

dependence on φ_{A_t} mainly through $|X_\mathrm{t}|$

Reason for the large impact of the phase in the two-loop contribution

Leading one-loop result in the limit $M_{\mathrm{H}^\pm} \gg M_\mathrm{Z}$ depends only on the absolute value $|X_\mathrm{t}| \equiv |A_\mathrm{t} - \mu^*/\tan\beta|$

$\Leftrightarrow$ only combination $\varphi_{A_\mathrm{t}} + \varphi_\mu$ enters

$\Rightarrow$ weak dependence of one-loop result on φ_{X_t}

dependence on φ_{A_t} mainly through $|X_\mathrm{t}|$

Two-loop level:

$\Rightarrow$ Gluino contributions introduce dependence on phase combination $A_\mathrm{t}\, M_3^*$

$\Rightarrow$ Large modification of phase dependence

Higgs mixing

- Need to establish the correct on-shell properties of processes with external Higgs bosons

  $\Rightarrow$ finite wave function normalisation factors Z_i introduced

- Unstable particles $\Rightarrow$ finite-width effects important

- h_2, h_3 are almost mass-degenerate over a large part of the parameter space

  $$M_{h_3} - M_{h_2} \sim \Gamma_{h_2}, \Gamma_{h_3}$$

  $\Rightarrow$ resonance-type effects possible

Wave function normalisation (finite) for amplitudes with external Higgs bosons

$$Z_h = \frac{1}{\frac{\partial}{\partial p^2}\left(\frac{i}{\Delta_{hh}(p^2)}\right)\Big|_{p^2=\mathcal{M}_{h_a}^2}} \qquad Z_H = \frac{1}{\frac{\partial}{\partial p^2}\left(\frac{i}{\Delta_{HH}(p^2)}\right)\Big|_{p^2=\mathcal{M}_{h_b}^2}}$$

$$Z_A = \frac{1}{\frac{\partial}{\partial p^2}\left(\frac{i}{\Delta_{AA}(p^2)}\right)\Big|_{p^2=\mathcal{M}_{h_c}^2}}$$

$$Z_{hH} = \frac{\Delta_{hH}}{\Delta_{hh}}\Big|_{p^2=\mathcal{M}_{h_a}^2} \qquad Z_{Hh} = \frac{\Delta_{hH}}{\Delta_{HH}}\Big|_{p^2=\mathcal{M}_{h_b}^2} \qquad Z_{Ah} = \frac{\Delta_{hA}}{\Delta_{AA}}\Big|_{p^2=\mathcal{M}_{h_c}^2}$$

$$Z_{hA} = \frac{\Delta_{hA}}{\Delta_{hh}}\Big|_{p^2=\mathcal{M}_{h_a}^2} \qquad Z_{HA} = \frac{\Delta_{HA}}{\Delta_{HH}}\Big|_{p^2=\mathcal{M}_{h_b}^2} \qquad Z_{AH} = \frac{\Delta_{HA}}{\Delta_{AA}}\Big|_{p^2=\mathcal{M}_{h_c}^2}$$

Wave function normalisation for amplitudes with external Higgs bosons

WF constants can be written as (non-unitary) matrix $\hat{\mathbf{Z}}$,

$$\hat{\mathbf{Z}} = \begin{pmatrix} \sqrt{Z_h} & \sqrt{Z_h} Z_{hH} & \sqrt{Z_h} Z_{hA} \\ \sqrt{Z_H} Z_{Hh} & \sqrt{Z_H} & \sqrt{Z_H} Z_{HA} \\ \sqrt{Z_A} Z_{Ah} & \sqrt{Z_A} Z_{AH} & \sqrt{Z_A} \end{pmatrix}, \qquad \begin{pmatrix} \hat{\Gamma}_{h_a} \\ \hat{\Gamma}_{h_b} \\ \hat{\Gamma}_{h_c} \end{pmatrix} = \hat{\mathbf{Z}} \cdot \begin{pmatrix} \hat{\Gamma}_h \\ \hat{\Gamma}_H \\ \hat{\Gamma}_A \end{pmatrix}$$

Fulfills the conditions

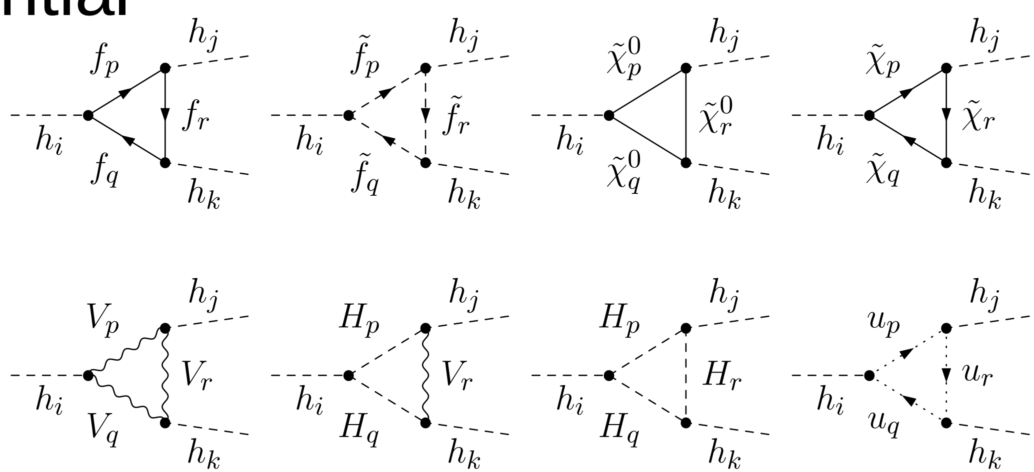
$$\begin{aligned} \lim_{p^2 \to \mathcal{M}^2_{h_a}} -\frac{i}{p^2 - \mathcal{M}^2_{h_a}} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_2 \cdot \hat{\mathbf{Z}}^T \right)_{hh} &= 1 \\ \lim_{p^2 \to \mathcal{M}^2_{h_b}} -\frac{i}{p^2 - \mathcal{M}^2_{h_b}} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_2 \cdot \hat{\mathbf{Z}}^T \right)_{HH} &= 1 \\ \lim_{p^2 \to \mathcal{M}^2_{h_c}} -\frac{i}{p^2 - \mathcal{M}^2_{h_c}} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_2 \cdot \hat{\mathbf{Z}}^T \right)_{AA} &= 1 \end{aligned}$$

Higgs cascade decays: $h_2 \to h_1 h_1$, ...

Higgs cascade decays:

- Important for Higgs searches: $h_2 \to h_1 h_1$ is in general the dominant channel where it is kinematically allowed

- Access to Higgs self-coupling $\Rightarrow$ reconstruction of the Higgs potential



Complete one-loop results in the MSSM with complex parameters $+$ two-loop propagator-type corrections

[*K. Williams, G. W. '07*]

Higgs – Goldstone mixing

Calculations in the MSSM Higgs sector are notorious for mixing different orders of perturbation theory $\Rightarrow$ need to be careful not to spoil symmetry relations, gauge cancellations

Particular care needed for treatment of mixing of Higgs bosons with Goldstone bosons

$\Rightarrow$ Treat Higgs – Goldstone mixing strictly at one-loop level to ensure the cancellation of unphysical poles

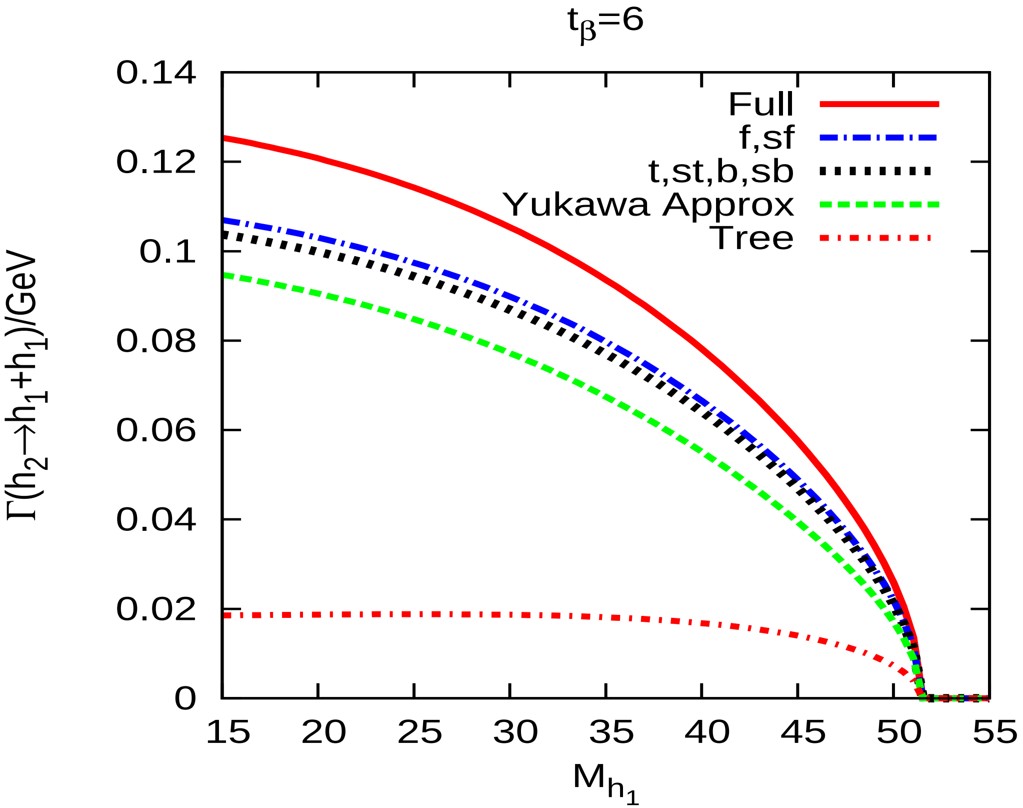
$$\Gamma^{\rm full}_{h_a h_b h_c} = \hat{\mathbf{Z}}_{ck}\hat{\mathbf{Z}}_{bj}\hat{\mathbf{Z}}_{ai}\left[\Gamma^{\rm 1PI}_{h_i h_j h_k}\left(M^2_{h_a}, M^2_{h_b}, M^2_{h_c}\right) + \underbrace{\Gamma^{\rm G,Z\,mix}_{h_i h_j h_k}\left(m^2_{h_i}, m^2_{h_j}, m^2_{h_k}\right)}\right]$$

tree-level masses, tree-level vertex, one-loop Higgs–Goldstone self-energy

Numerical effect of Higgs – Goldstone mixing is small

Impact of higher-order corrections on prediction for $\Gamma(h_2 \to h_1 h_1)$

Complete 1-loop result for $(h_2 h_1 h_1)$ vertex contribution in the MSSM with complex parameters [*K. Williams, G. W. '07*]
$+$ 2-loop propagator corrections; CPX benchmark scenario
[*S. Heinemeyer, W. Hollik, H. Rzehak, G. W. '07*]



$\Rightarrow$ Huge effect from corrections to genuine $(h_2 h_1 h_1)$ vertex

Impact on exclusion bounds from the LEP Higgs searches

Comparison of improved theory predictions with bounds on topological cross sections from LEP: [*LEP Higgs Working Group '06*]

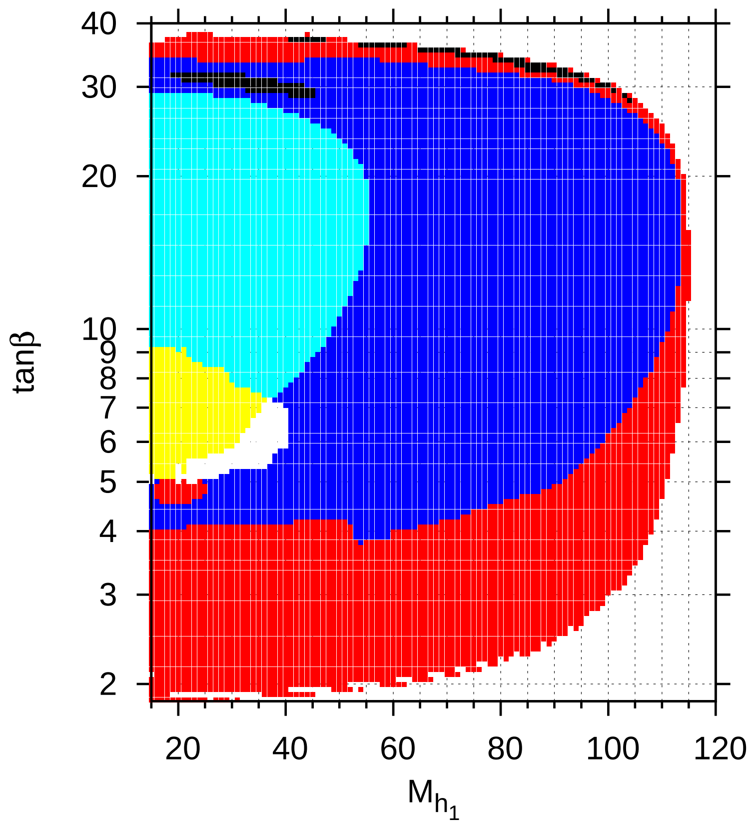
In order to obtain a correct statistical interpretation of overall exclusion limit at 95% C.L.:

Need to compare theory prediction with the single channel that has the highest statistical sensitivity for setting an exclusion limit

LEP Higgs search channels that are predicted to have the highest statistical sensitivity for setting an exclusion limit

HiggsBounds [*P. Bechtle, O. Brein, S. Heinemeyer, G. W., K. Williams '08*]

Contains LEP limits; implementation of Tevatron limits in progress



Channels:

(■) $= (h_1 Z) \to (b\bar{b}Z)$

(■) $= (h_2 Z) \to (b\bar{b}Z)$

(□) $= (h_2 Z) \to (h_1 h_1 Z) \to (b\bar{b}b\bar{b}Z)$

(■) $= (h_2 h_1) \to (b\bar{b}b\bar{b})$

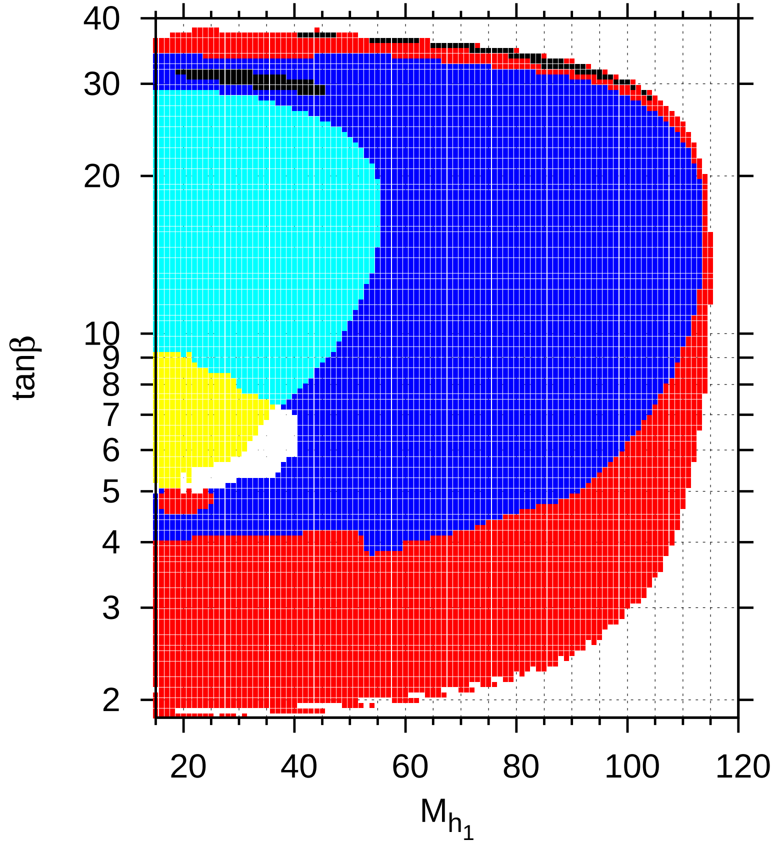
(■) $= (h_2 h_1) \to (h_1 h_1 h_1) \to (b\bar{b}b\bar{b}b\bar{b})$

(■) = other channels

Impact on exclusion bounds from the LEP Higgs searches, CPX scenario, $m_{\rm t} = 170.9$ GeV

Channels

$(\Box) : (h_2 Z) \to (h_1 h_1 Z) \to (b\bar{b}b\bar{b}Z)$

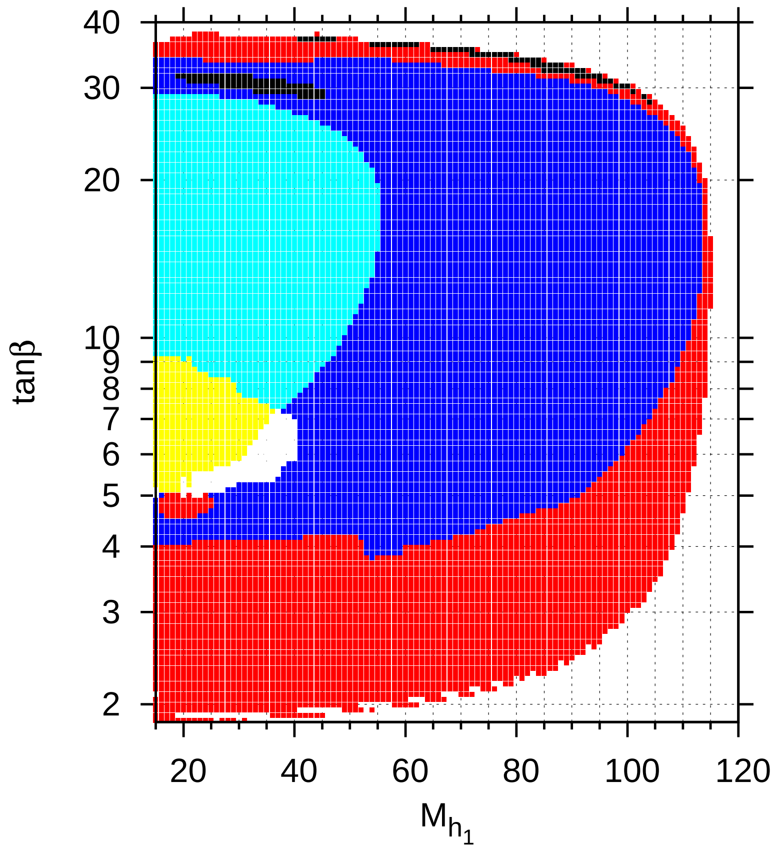


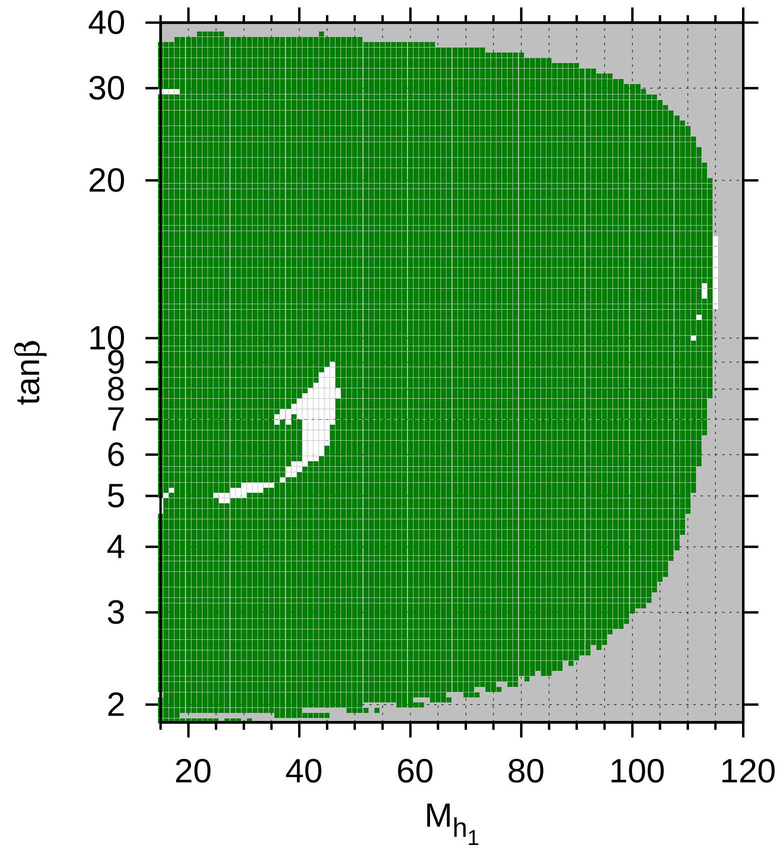
Impact on exclusion bounds from the LEP Higgs searches, CPX scenario, $m_{\rm t} = 170.9\ {\rm GeV}$

Channels

$(\Box) : (h_2 Z) \to (h_1 h_1 Z) \to (b\bar{b}b\bar{b}Z)$

Excluded region from LEP, 95% C.L. [*K. Williams, G. W. '07*]



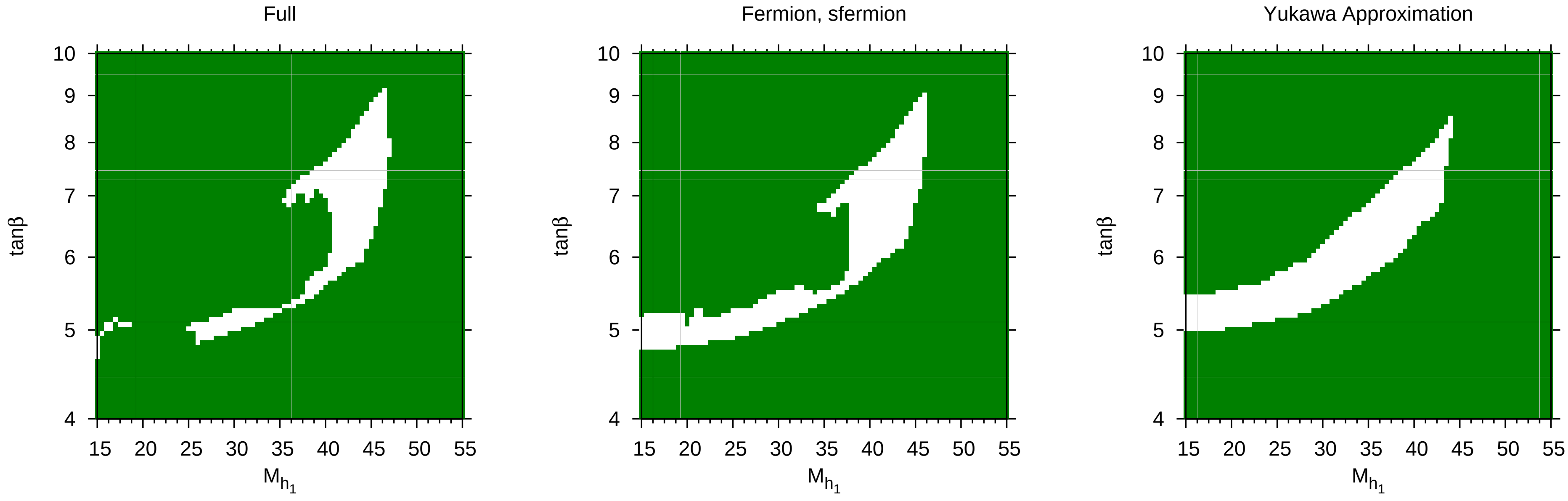


⇒ "Hole" in the LEP coverage where $h_2 \to h_1 h_1$ is dominating very light Higgs boson is not excluded

LEP coverage: comparison of complete result for genuine triple-Higgs vertex corrections with approximations

Complete result, fermion / sfermion contribution, Yukawa approximation

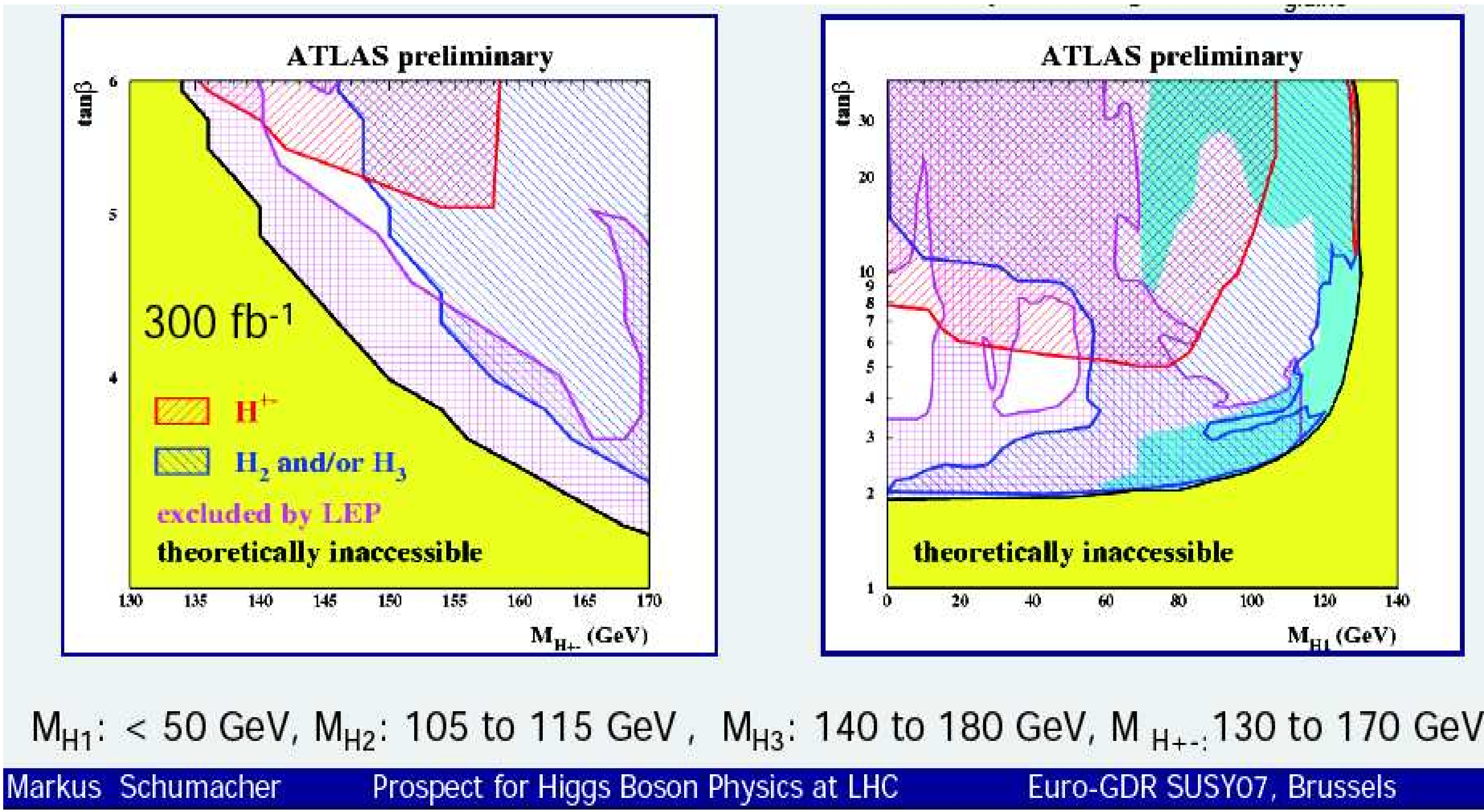
[*K. Williams, G. W. '07*]



⇒ Sub-leading contributions have sizable impact

CPX holes are also difficult to cover at the LHC

[M. Schumacher, ATLAS '07]



$\Rightarrow$ "CPX holes" cannot be covered in conventional channels

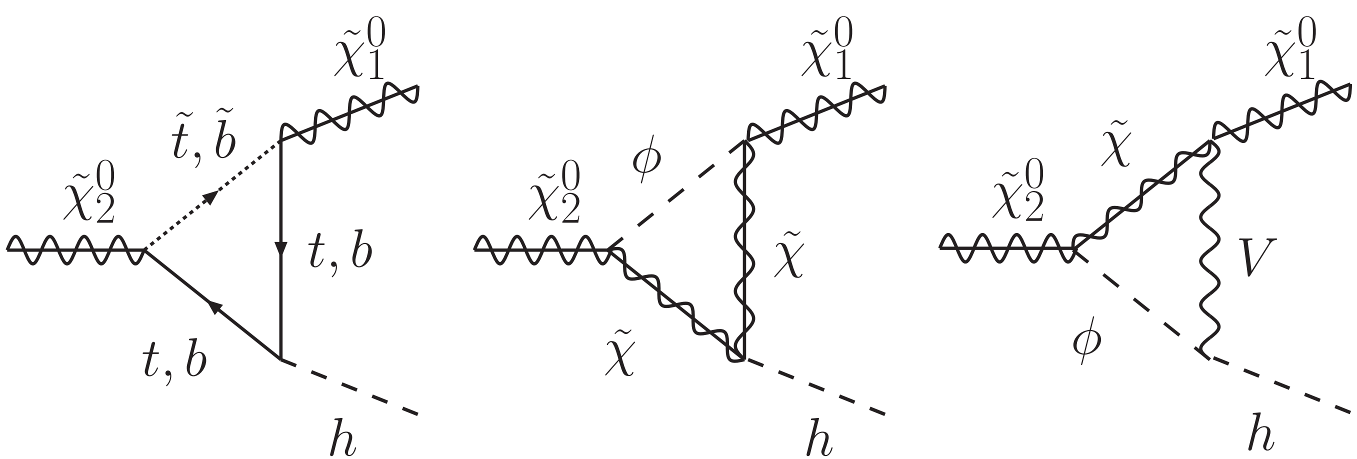
Higgs production in SUSY cascade decays

CPX holes $\Leftrightarrow$ very light Higgs

$\Rightarrow$ Can be produced in SUSY cascade decays

$\Rightarrow$ $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$ can dominate over $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 l\bar{l}$

Genuine one-loop corrections in the MSSM with complex phases



$+$ two-loop $\mathcal{O}(\alpha_t\alpha_s)$ propagator-type corrections

[*A. Fowler, G. W., preliminary, '08*]

Higher-order contributions to $\Gamma(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h)$

Chargino/neutralino ren. [*T. Fritzsche, W. Hollik '02*] [*H. Eberl et al. 02*]

Six particle masses: $m_{\tilde{\chi}^\pm_1}$ $m_{\tilde{\chi}^\pm_2}$, $m_{\tilde{\chi}^0_1}$ $m_{\tilde{\chi}^0_2}$, $m_{\tilde{\chi}^0_3}$ $m_{\tilde{\chi}^0_4}$

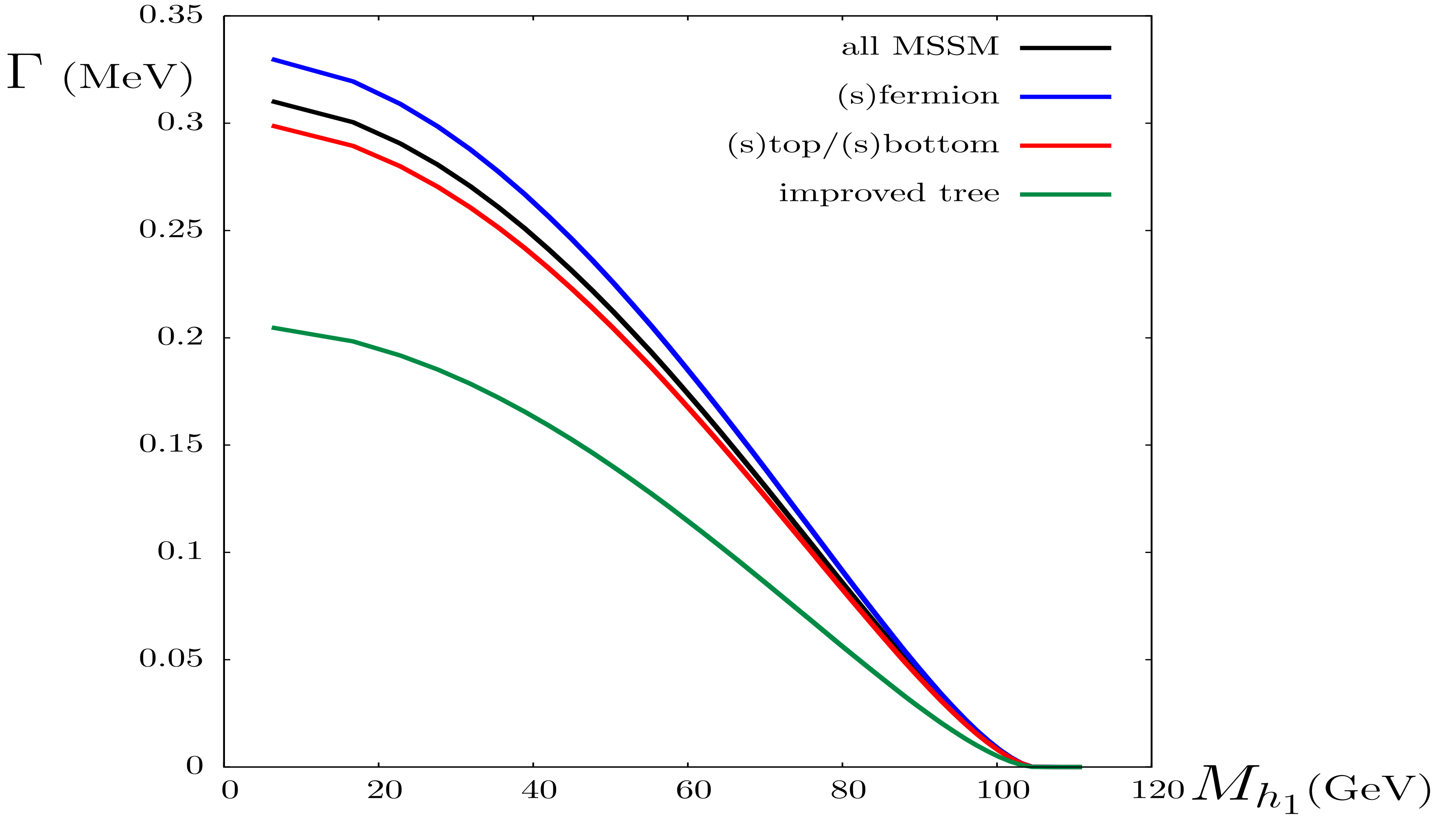
Three parameters: M_1, M_2, μ (ren. for phases in progress)

- On-shell prescription: choose three particle masses as on-shell, other mass CTs are dependent quantities
  Convenient for processes with external charginos and neutralinos
  but: asymmetric treatment: pole masses for three of the masses receive higher-order corrections
  determination of finite parts of the dependent counterterms can lead to unphysically large effects

- $\overline{\mathrm{DR}}$ prescription: simple and symmetric,
  but: all pole masses receive higher-order corrections
  potential problems with external SUSY particles

Higher-order contributions to $\Gamma(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h)$

Results in the CPX scenario [*A. Fowler, G. W., preliminary, '08*]



$\Rightarrow$ Large effect from genuine vertex corrections

Conclusions

- Results in the MSSM Higgs sector with complex param.:
  Complete one-loop results for masses, mixings,
  $\Gamma(h_2 \to h_1 h_1)$, $\Gamma(h_i \to f\bar{f})$, $\Gamma(\tilde{\chi}^0_i \to \tilde{\chi}^0_j h_k)$
  $+$ two-loop $\mathcal{O}(\alpha_t \alpha_s)$ propagator-type corrections
  Implementation into *FeynHiggs* is in progress

Conclusions

- Results in the MSSM Higgs sector with complex param.:
  Complete one-loop results for masses, mixings,
  $\Gamma(h_2 \to h_1 h_1)$, $\Gamma(h_i \to f\bar{f})$, $\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 h_k)$
  $+$ two-loop $\mathcal{O}(\alpha_t \alpha_s)$ propagator-type corrections
  Implementation into *FeynHiggs* is in progress

- Complex phases can have large impact on Higgs pheno:
  – 2-loop contrib. yield large enhancement of phase dep.
  – large effect on $\mathrm{BR}(h_2 \to h_1 h_1)$
  – Confirmation of "CPX holes":
    very light Higgs boson is not excluded

Conclusions

- Results in the MSSM Higgs sector with complex param.:
  Complete one-loop results for masses, mixings,
  $\Gamma(h_2 \to h_1 h_1)$, $\Gamma(h_i \to f\bar{f})$, $\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 h_k)$
  $+$ two-loop $\mathcal{O}(\alpha_t\alpha_s)$ propagator-type corrections
  Implementation into *FeynHiggs* is in progress

- Complex phases can have large impact on Higgs pheno:
  – 2-loop contrib. yield large enhancement of phase dep.
  – large effect on $\mathrm{BR}(h_2 \to h_1 h_1)$
  – Confirmation of “CPX holes”:
  very light Higgs boson is not excluded

- “CPX holes” could potentially be covered at the LHC with SUSY cascade decays
  Genuine $(\tilde{\chi}_i^0 \tilde{\chi}_j^0 h_k)$ vertex corrections are large