Physics in the MSSM with Complex Parameters

Georg Weiglein

DESY

Bonn, 08 / 2010

Based mainly on work done in collaboration with Alison Fowler (IPPP Durham)

- Introduction
- Higgs phenomenology
- Renormalisation for complex parameters and unstable particles
- Interference effects and narrow-width approximation
- Conclusions

Introduction

Prospects for SUSY searches at the LHC:

Global χ^2 fit in the CMSSM ($m_{1/2}$, m_0, A_0 (GUT scale), $\tan\beta$, $\mathrm{sign}(\mu)$ (weak scale)) and the NUHM1 (m_H^2 as add. param.)

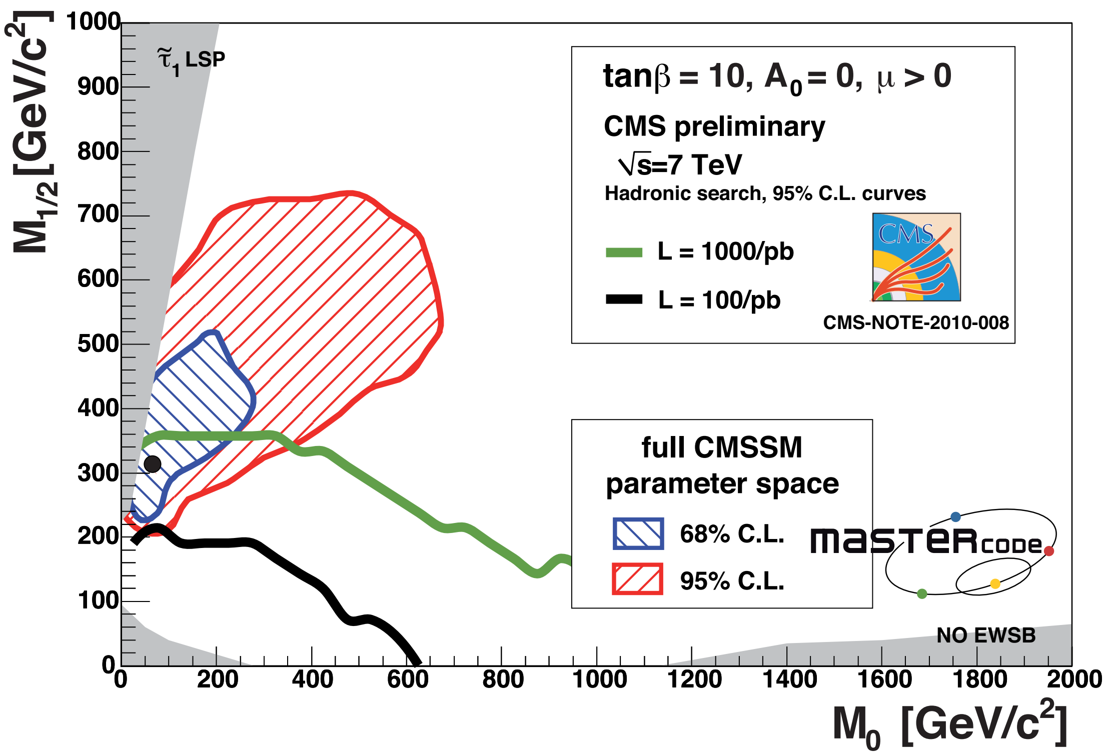
Fit includes (*MasterCode*, Markov-chain Monte Carlo sampling):
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '08*]

- Electroweak precision observables: M_W, $\sin^2\theta_\mathrm{eff}$, Γ_Z, ...
- $+$ Cold dark matter (CDM) density (WMAP, ...), $\Omega_\mathrm{CDM}\, h^2 = 0.1099 \pm 0.0062$
- $+ \ (g-2)_\mu$
- $+$ BPO: $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_\mathrm{s} \to \mu^+\mu^-)$, $\mathrm{BR}(B \to \tau\nu)$, ...
- $+$ Kaon decay data: $\mathrm{BR}(K \to \mu\nu)$, ...

Predictions for the SUSY scale from precision data: CMSSM

Comparison: preferred region in the m_0–$m_{1/2}$ plane vs. CMS 95% C.L. reach for $0.1, 1\ \mathrm{fb}^{-1}$ at $7\ \mathrm{TeV}$

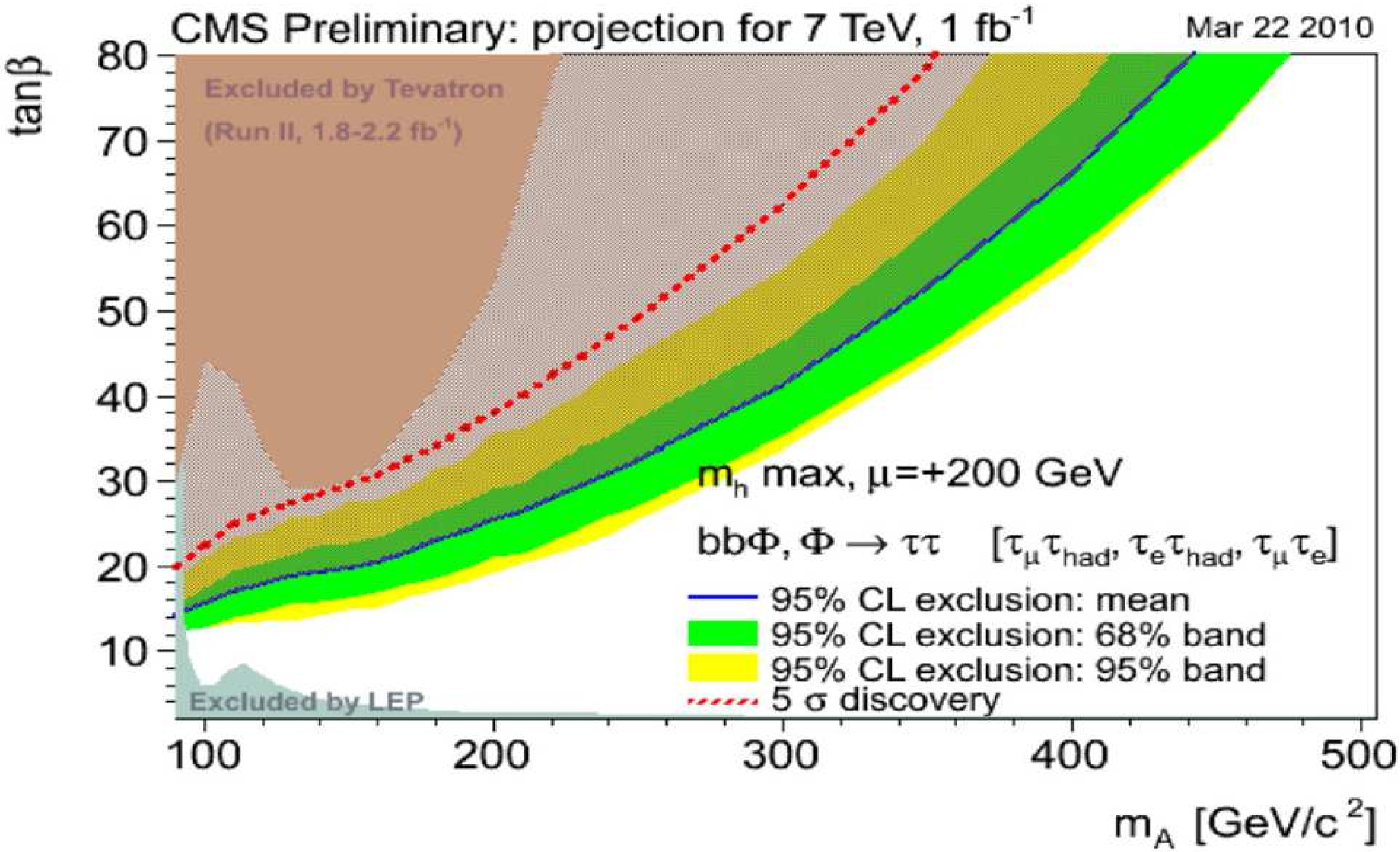
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '10*]



⇒ Good prospects for early discovery! Get hint in first run?

Prospects for SUSY Higgs search at the LHC with $1\ \text{fb}^{-1}$ at 7 TeV

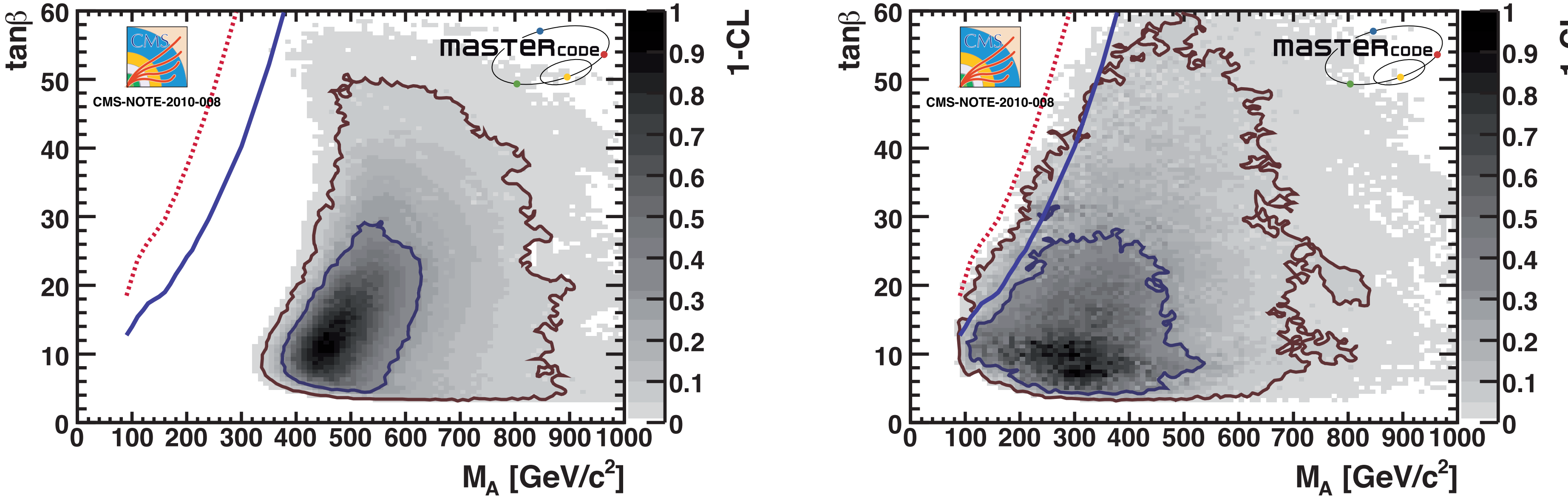
[*CMS Collaboration '10*]



⇒ Higgs searches with early LHC data have a chance to discover the heavy MSSM Higgses H, A before a light SM-like Higgs h is found

Early LHC data: sensitivity for SUSY Higgs searches vs. preferred regions in CMSSM, NUHM1

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, F. Ronga, G. W. '10*]



⇒ Not much hope in the CMSSM and NUHM1 with the first $1\ \text{fb}^{-1}$ at $7\ \text{TeV}$

⇒ A hint in early searches could point towards a non-minimal model

Beyond CMSSM, NUHM1, . . . ?

At present global SUSY fits based on present data on precision observables focus on constrained SUSY models (CMSSM, NUHM1, . . .); fits have limited sensitivity to the structure of less minimal models

Beyond CMSSM, NUHM1, . . . ?

At present global SUSY fits based on present data on precision observables focus on constrained SUSY models (CMSSM, NUHM1, . . .); fits have limited sensitivity to the structure of less minimal models

MSSM with complex parameters: additional sources for $\mathcal{CP}$-violation ($\leftrightarrow$ asymmetry between matter and anti-matter in the Universe)

Beyond CMSSM, NUHM1, . . . ?

At present global SUSY fits based on present data on precision observables focus on constrained SUSY models (CMSSM, NUHM1, . . .); fits have limited sensitivity to the structure of less minimal models

MSSM with complex parameters: additional sources for $\mathcal{CP}$-violation ($\leftrightarrow$ asymmetry between matter and anti-matter in the Universe)

Recent result on A^b_{sl} from D0?

Beyond CMSSM, NUHM1, . . . ?

At present global SUSY fits based on present data on precision observables focus on constrained SUSY models (CMSSM, NUHM1, . . .); fits have limited sensitivity to the structure of less minimal models

MSSM with complex parameters: additional sources for $\mathcal{CP}$-violation ($\leftrightarrow$ asymmetry between matter and anti-matter in the Universe)

Recent result on A^b_{sl} from D0?

Constraints on $\mathcal{CP}$ phases from electric dipole moments affect mainly first two generations; corresponding phases are tightly constrained or mass scales have to be very heavy

Much weaker bounds on 3rd generation phases, gluino phase

Higgs phenomenology

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)

  $\Leftrightarrow$ 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

Higgs physics in the MSSM with complex parameters

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

Higgs propagator-type corrections

Mixing between h, H, A

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

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

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

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

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

Determination of the masses from the complex poles

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

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

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

where

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

Expansion around the real part of the complex pole:

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

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

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

Finite wave-function normalisation factors ensure the correct on-shell properties of the S matrix

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

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

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

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

Wave function normalisation for amplitudes with external Higgs bosons

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

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

Fulfills the conditions

$$\lim_{p^2 \to \mathcal{M}_{h_a}^2} -\frac{i}{p^2 - \mathcal{M}_{h_a}^2} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_2 \cdot \hat{\mathbf{Z}}^T \right)_{hh} = 1$$

$$\lim_{p^2 \to \mathcal{M}_{h_b}^2} -\frac{i}{p^2 - \mathcal{M}_{h_b}^2} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_2 \cdot \hat{\mathbf{Z}}^T \right)_{HH} = 1$$

$$\lim_{p^2 \to \mathcal{M}_{h_c}^2} -\frac{i}{p^2 - \mathcal{M}_{h_c}^2} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_2 \cdot \hat{\mathbf{Z}}^T \right)_{AA} = 1$$

Expansion of the propagator around the complex pole

$$\Delta_{ii}(p^2) = \frac{i}{p^2 - \mathcal{M}_{h_i}^2} Z_i + \dots$$

where $\mathcal{M}_{h_i}^2 = M_i^2 - iM_i\Gamma_i$

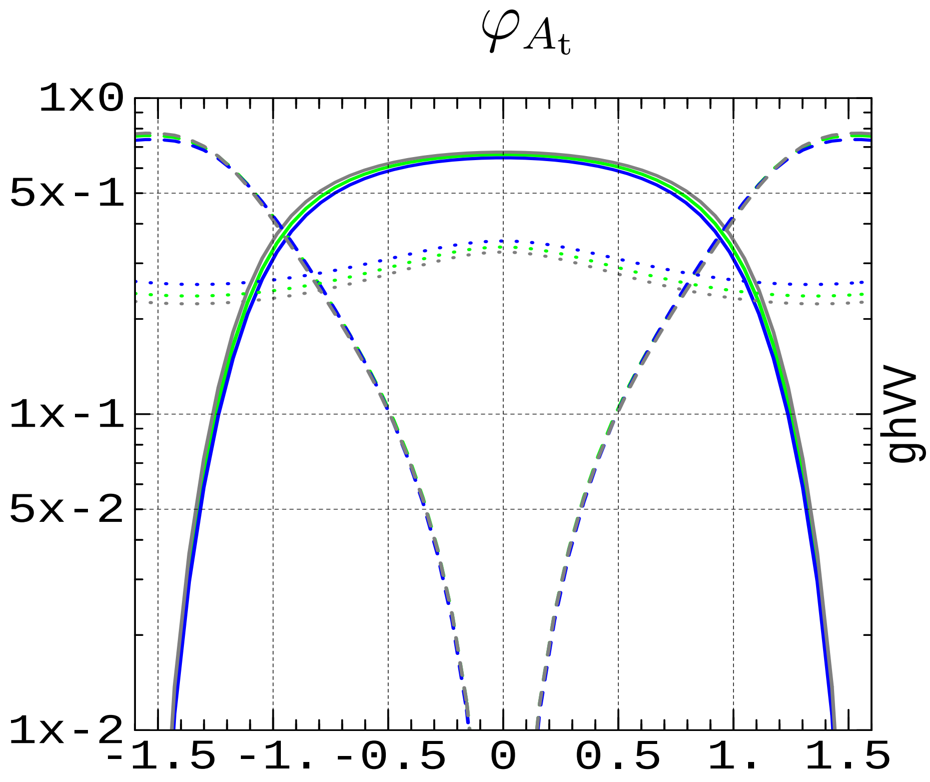
$\Rightarrow$ Propagator in the vicinity of the complex pole is given by a Breit–Wigner factor with constant width,

$$\Delta_i^{\text{BW}}(p^2) = \frac{i}{p^2 - M_i^2 + iM_i\Gamma_i}$$

weighted by a wave function normalisation factor Z_i evaluated at the complex pole

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,

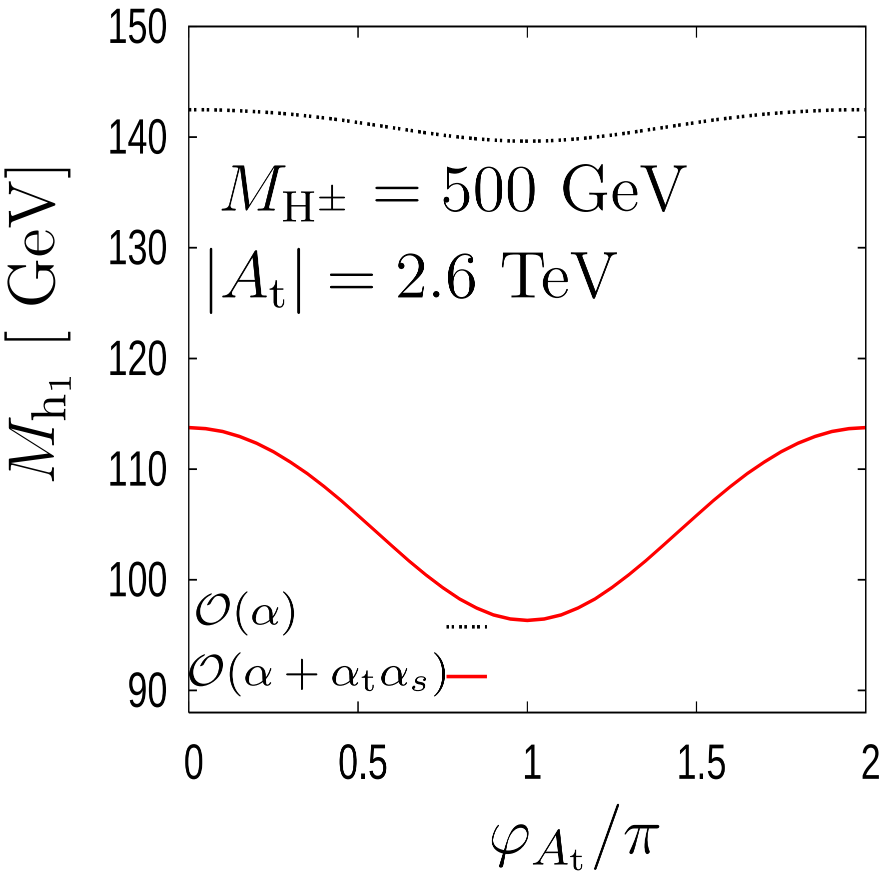
$|A_t| = 1000$ GeV,

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

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

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 $|A_t|$

MSSM with complex parameters: a very light SUSY Higgs?

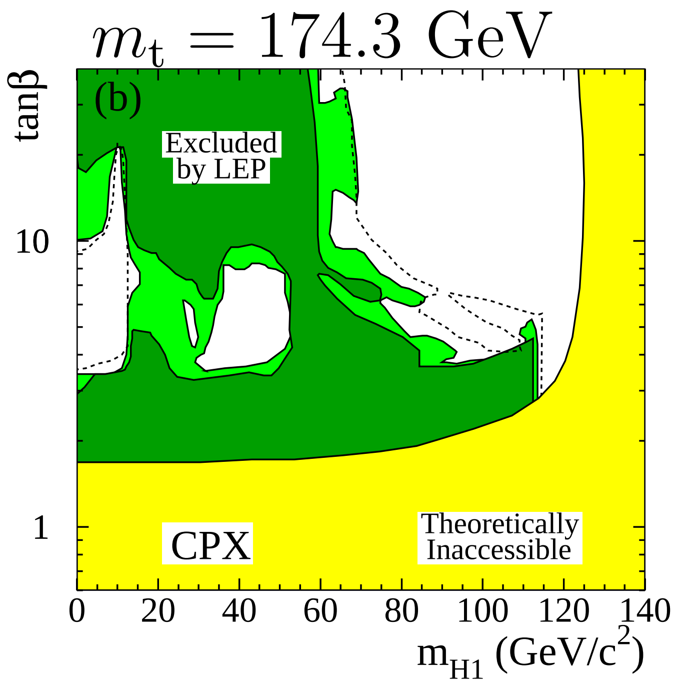
MSSM with $\mathcal{CP}$-violating phases (CPX scenario):

Light Higgs, h_1: strongly suppressed h_1VV couplings

Second-lightest Higgs, h_2, possibly 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

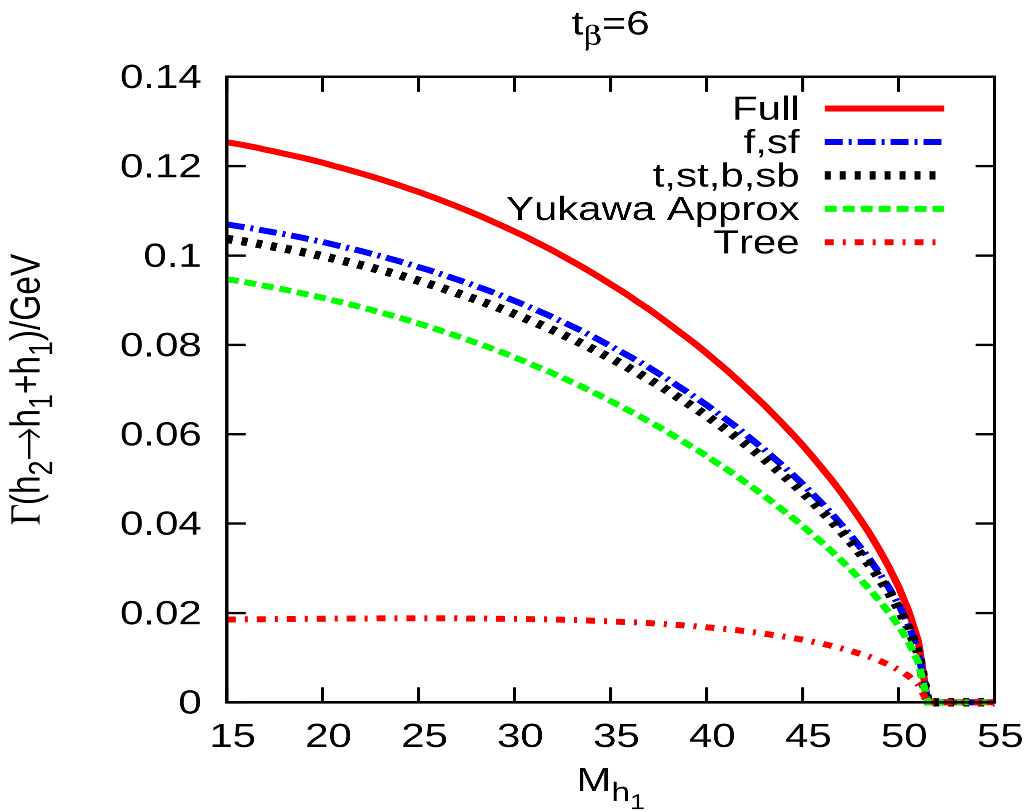
[*LEP Higgs WG '06*]



$\Rightarrow$ Light SUSY Higgs not ruled out!

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*]

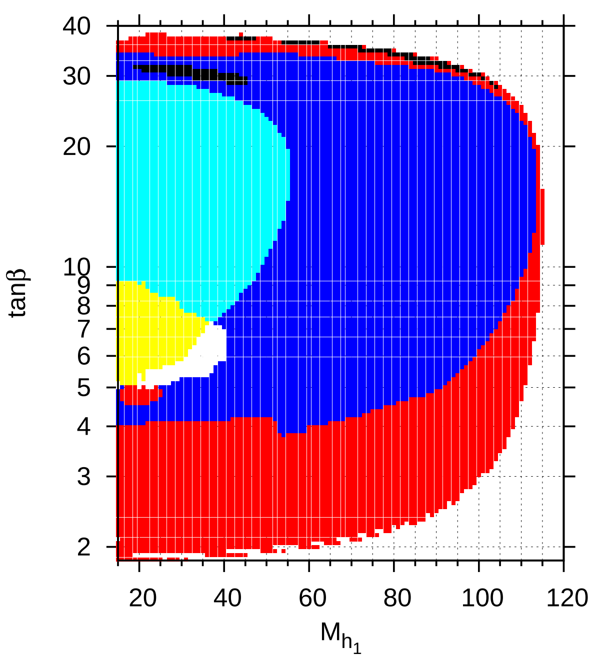


$\Rightarrow$ Huge effect from corrections to genuine $(h_2 h_1 h_1)$ vertex

Analysis of LEP coverage with improved theoretical prediction

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

Use cross section limits (expected and observed) from LEP and the Tevatron; determine for every parameter point the search channel with the highest statistical sensitivity for setting an exclusion; comparison of prediction for this channel with observed limit yields 95% C.L. exclusion contour



Channels:

(red) $= (h_1 Z) \rightarrow (b\bar{b}Z)$

(blue) $= (h_2 Z) \rightarrow (b\bar{b}Z)$

(white) $= (h_2 Z) \rightarrow (h_1 h_1 Z) \rightarrow (b\bar{b}b\bar{b}Z)$

(cyan) $= (h_2 h_1) \rightarrow (b\bar{b}b\bar{b})$

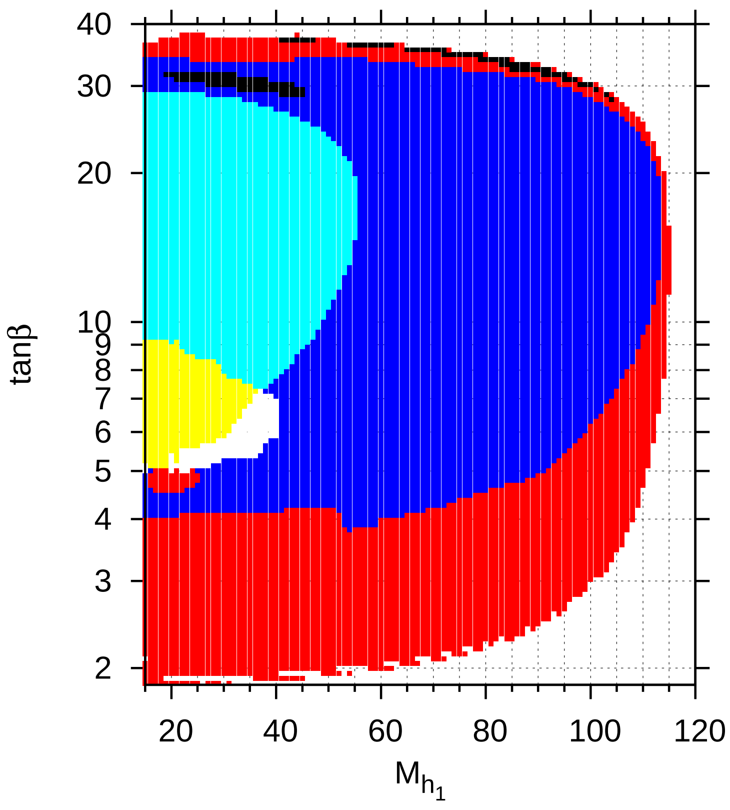
(yellow) $= (h_2 h_1) \rightarrow (h_1 h_1 h_1) \rightarrow (b\bar{b}b\bar{b}b\bar{b})$

(black) = other channels

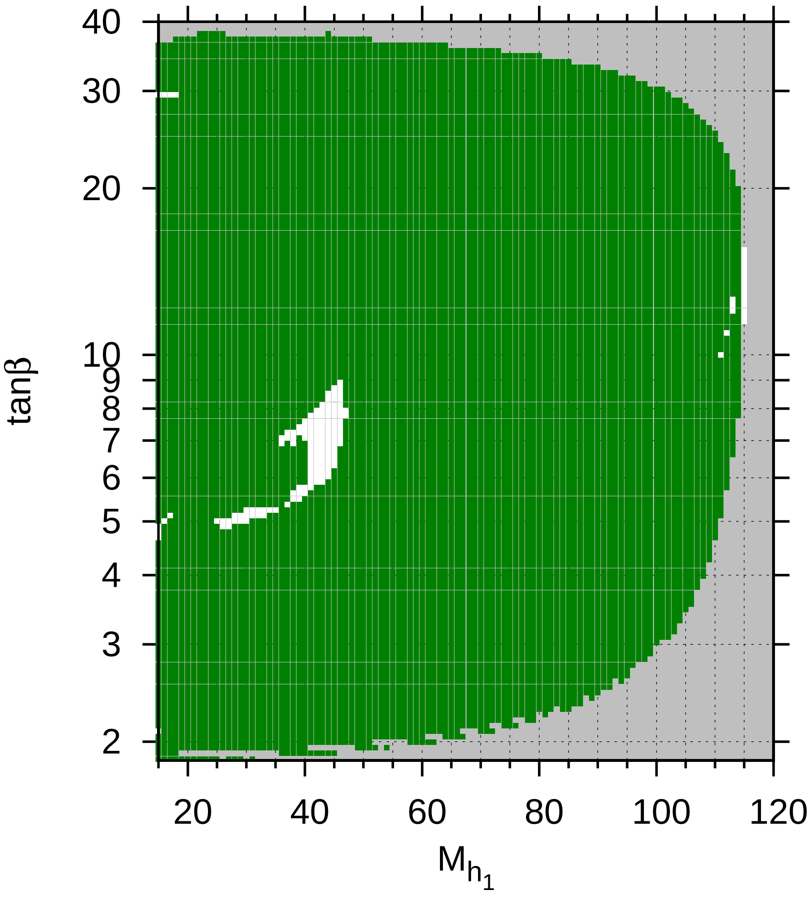
Impact on exclusion bounds from the LEP Higgs searches, CPX scenario, $m_{\mathrm{t}} = 170.9\ \mathrm{GeV}$

Channels (*HiggsBounds*)

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



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



$\Rightarrow$ Confirmation of the "hole" in the LEP coverage

$\Rightarrow$ Very light Higgs boson is not excluded

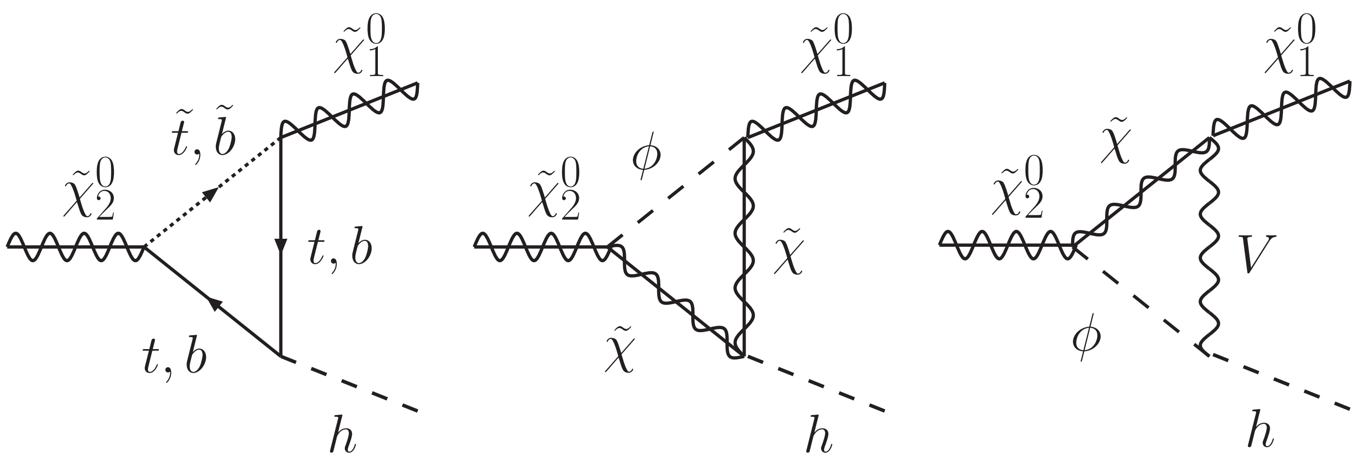
Higgs production in SUSY cascade decays

SUSY cascade decays could be a promising Higgs source

E.g. $\mathcal{CP}$-violating scenario: very light Higgs, $M_{\mathrm{h}_1} \approx 40 \text{ GeV}$ not excluded by LEP, difficult to cover with standard search channels at the LHC

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

[*A. Fowler, G. W. '09*]



$\Rightarrow$ CPX scenario: 13% of the gluinos decay into h_1

Renormalisation for complex parameters and unstable particles

Occurrence of imaginary parts:

- From complex parameters
- From absorptive parts of loop integrals
  $\leftrightarrow$ unstable particles

$\Rightarrow$ MSSM with complex parameters:
absorptive parts of loop integrals can contribute to real part of 1-loop quantities

Comparison: Standard Model case

- CKM matrix renormalisation: intense discussion in the literature (gauge invariance, . . .)
- Mass renormalisation: difference between mass renormalisation according to complex pole of the propagator / pole of the real part of the propagator occurs at 2-loop order

  Need to define the mass according to the real part of the complex pole in order to obtain a gauge-invariant mass counterterm

Renormalisation in the chargino / neutralino sector of the MSSM with complex parameters

Allow field renormalisations to be different for in- and outgoing fermions:

$$\omega_L \tilde{\chi}_i^- \to (1 + \tfrac{1}{2}\delta Z_-^L)_{ij}\,\omega_L \tilde{\chi}_j^-, \qquad \overline{\tilde{\chi}_i^-}\,\omega_R \to \overline{\tilde{\chi}_i^-}\,(1 + \tfrac{1}{2}\delta \bar{Z}_-^L)_{ij}\,\omega_R,$$
$$\omega_R \tilde{\chi}_i^- \to (1 + \tfrac{1}{2}\delta Z_-^R)_{ij}\,\omega_R \tilde{\chi}_j^-, \qquad \overline{\tilde{\chi}_i^-}\,\omega_L \to \overline{\tilde{\chi}_i^-}\,(1 + \tfrac{1}{2}\delta \bar{Z}_-^R)_{ij}\,\omega_L,$$

In $\mathcal{CP}$-conserving case: can choose a scheme where hermiticity relation holds (up to purely imaginary terms that do not contribute to squared matrix elements at 1-loop)

$$\delta \bar{Z}_{ij} = \delta Z_{ij}^\dagger$$

Decomposition of fermion self-energies:

$$\Sigma_{ij}(p^2) = \not{p}\,\omega_L \Sigma_{ij}^L(p^2) + \not{p}\,\omega_R \Sigma_{ij}^R(p^2) + \omega_L \Sigma_{ij}^{SL}(p^2) + \omega_R \Sigma_{ij}^{SR}(p^2)$$

Field renormalisation conditions (1-loop)

Vanishing of off-diagonal contributions and unit residues:

$$\hat{\Gamma}^{(2)}_{ij}\tilde{\chi}_i(p)|_{p^2=m^2_{\tilde{\chi}_j}} = 0, \quad \overline{\tilde{\chi}}_i(p)\hat{\Gamma}^{(2)}_{ij}|_{p^2=m^2_{\tilde{\chi}_i}} = 0$$

$$\lim_{p^2\to m^2_{\tilde{\chi}_i}} \frac{1}{\not{p} - m_{\tilde{\chi}_i}}\hat{\Gamma}^{(2)}_{ii}\tilde{\chi}_i(p) = i\tilde{\chi}_i, \quad \lim_{p^2\to m^2_{\tilde{\chi}_i}} \overline{\tilde{\chi}}_i(p)\hat{\Gamma}^{(2)}_{ii}\frac{1}{\not{p} - m_{\tilde{\chi}_i}} = i\overline{\tilde{\chi}}_i$$

Additional conditions needed for the general case with $\mathcal{CP}$ violation:

Loop-corrected propagator should have the same Lorentz structure in the on-shell as at tree level ($\rightarrow$ vanishing of γ_5 contributions)

$$\hat{\Sigma}^{SL}_{ii}(m^2_{\tilde{\chi}_i}) = \hat{\Sigma}^{SR}_{ii}(m^2_{\tilde{\chi}_i})$$

Exploit additional freedom: $\delta Z^R_{ii} - \delta\bar{Z}^R_{ii} = \delta\bar{Z}^L_{ii} - \delta Z^L_{ii}$

Result for chargino field renormalisation constants (left-handed, diagonal)

$$\delta Z^L_{-,ii} = -\Sigma^L_{-,ii}(m^2_{\tilde{\chi}^\pm_i}) - m^2_{\tilde{\chi}^\pm_i}\left[\Sigma^{L'}_{-,ii}(m^2_{\tilde{\chi}^\pm_i}) + \Sigma^{R'}_{-,ii}(m^2_{\tilde{\chi}^\pm_i})\right]$$
$$- m_{\tilde{\chi}^\pm_i}\left[\Sigma^{SL'}_{-,ii}(m^2_{\tilde{\chi}^\pm_i}) + \Sigma^{SR'}_{-,ii}(m^2_{\tilde{\chi}^\pm_i})\right]$$
$$+ \frac{1}{2m_{\tilde{\chi}^\pm_i}}\left[\Sigma^{SL}_{-,ii}(m^2_{\tilde{\chi}^\pm_i}) - \Sigma^{SR}_{-,ii}(m^2_{\tilde{\chi}^\pm_i}) + (V\delta X^\dagger U^T)_{ii} - (U^*\delta X V^\dagger)_{ii}\right]$$

$$\delta \bar{Z}^L_{-,ii} = -\Sigma^L_{-,ii}(m^2_{\tilde{\chi}^\pm_i}) - m^2_{\tilde{\chi}^\pm_i}\left[\Sigma^{L'}_{-,ii}(m^2_{\tilde{\chi}^\pm_i}) + \Sigma^{R'}_{-,ii}(m^2_{\tilde{\chi}^\pm_i})\right]$$
$$- m_{\tilde{\chi}^\pm_i}\left[\Sigma^{SL'}_{-,ii}(m^2_{\tilde{\chi}^\pm_i}) + \Sigma^{SR'}_{-,ii}(m^2_{\tilde{\chi}^\pm_i})\right]$$
$$- \frac{1}{2m_{\tilde{\chi}^\pm_i}}\left[\Sigma^{SL}_{-,ii}(m^2_{\tilde{\chi}^\pm_i}) - \Sigma^{SR}_{-,ii}(m^2_{\tilde{\chi}^\pm_i}) + (V\delta X^\dagger U^T)_{ii} - (U^*\delta X V^\dagger)_{ii}\right]$$

Result for chargino field renormalisation constants (left-handed, off-diagonal)

$$\delta Z^L_{-,ij} = \frac{2}{m^2_{\tilde{\chi}^\pm_i} - m^2_{\tilde{\chi}^\pm_j}} \Big[m^2_{\tilde{\chi}^\pm_j} \Sigma^L_{-,ij}(m^2_{\tilde{\chi}^\pm_j}) + m_{\tilde{\chi}^\pm_i} m_{\tilde{\chi}^\pm_j} \Sigma^R_{-,ij}(m^2_{\tilde{\chi}^\pm_j})$$

$$+ m_{\tilde{\chi}^\pm_i} \Sigma^{SL}_{-,ij}(m^2_{\tilde{\chi}^\pm_j}) + m_{\tilde{\chi}^\pm_j} \Sigma^{SR}_{-,ij}(m^2_{\tilde{\chi}^\pm_j})$$

$$- m_{\tilde{\chi}^\pm_i} \left(U^* \delta X V^\dagger\right)_{ij} - m_{\tilde{\chi}^\pm_j} \left(V \delta X^\dagger U^T\right)_{ij} \Big]$$

$$\delta \bar{Z}^L_{-,ij} = \frac{2}{m^2_{\tilde{\chi}^\pm_j} - m^2_{\tilde{\chi}^\pm_i}} \Big[m^2_{\tilde{\chi}^\pm_i} \Sigma^L_{-,ij}(m^2_{\tilde{\chi}^\pm_i}) + m_{\tilde{\chi}^\pm_i} m_{\tilde{\chi}^\pm_j} \Sigma^R_{-,ij}(m^2_{\tilde{\chi}^\pm_i})$$

$$+ m_{\tilde{\chi}^\pm_i} \Sigma^{SL}_{-,ij}(m^2_{\tilde{\chi}^\pm_i}) + m_{\tilde{\chi}^\pm_j} \Sigma^{SR}_{-,ij}(m^2_{\tilde{\chi}^\pm_i})$$

$$- m_{\tilde{\chi}^\pm_i} \left(U^* \delta X V^\dagger\right)_{ij} - m_{\tilde{\chi}^\pm_j} \left(V \delta X^\dagger U^T\right)_{ij} \Big]$$

Additional rel. for neutralinos (Majorana part.): $\delta Z^{L/R}_{0,ij} = \delta \bar{Z}^{R/L}_{0,ji}$

Chargino / neutralino field renormalisation in the MSSM with complex parameters

Chargino / neutralino field renormalisation in the MSSM with complex parameters

- In general $\delta\bar{Z}_{ij} \neq \delta Z^{\dagger}_{ij}$

  $\Rightarrow$ Hermiticity relation does not hold, but it can be shown that the CPT theorem is fulfilled

Chargino / neutralino field renormalisation in the MSSM with complex parameters

- In general $\delta \bar{Z}_{ij} \neq \delta Z_{ij}^{\dagger}$

  $\Rightarrow$ Hermiticity relation does not hold, but it can be shown that the CPT theorem is fulfilled

- If absorptive parts of the loop integrals are discarded from the field renormalisation constants

  $\Rightarrow$ Hermiticity relation is restored, but correct on-shell properties are spoiled

  $\Rightarrow$ Additional mixing contributions needed to obtain the correct on-shell properties

Numerical relevance of absorptive parts

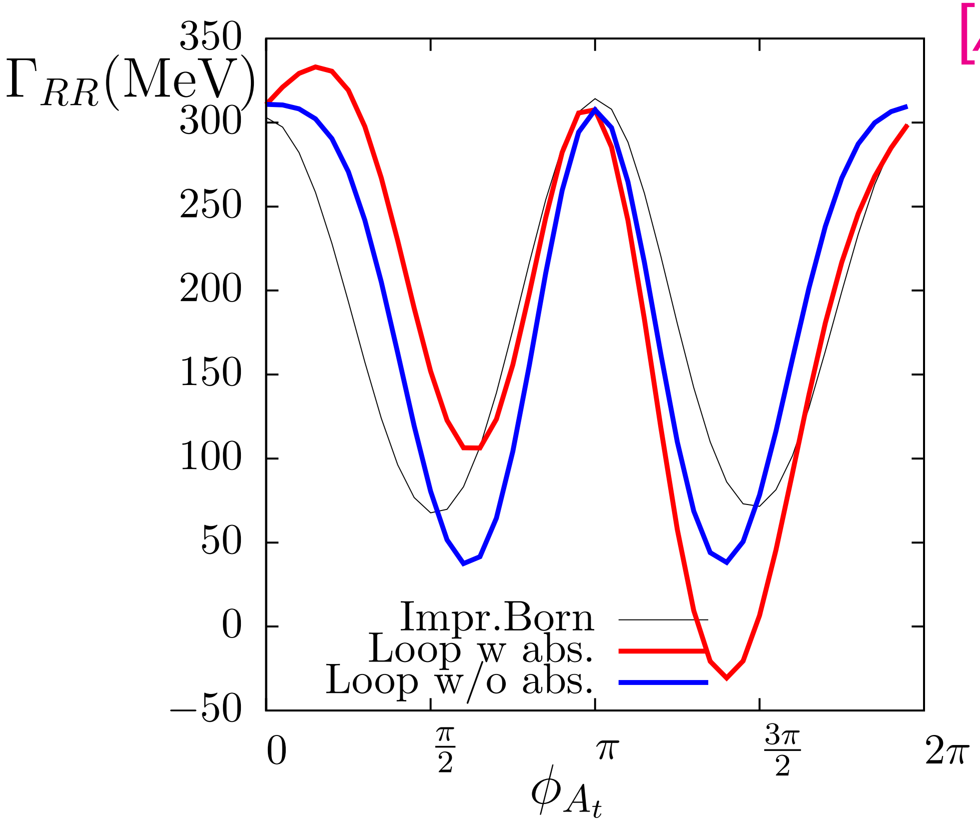
Consider Higgs decays into neutralinos at the LHC: $h_2 \to \tilde{\chi}^0_3 \tilde{\chi}^0_2$

$\Rightarrow$ Sensitivity at the LHC in search for 4-lepton final states

[*M. Bisset et al. '09*]

Partial decay width into right-handed neutralinos:

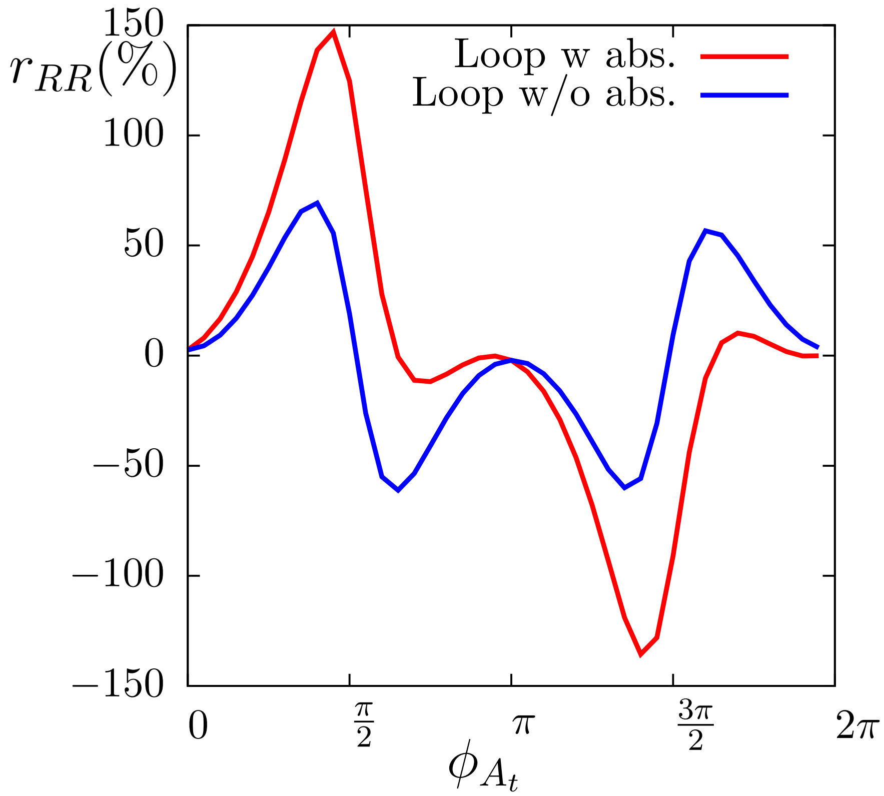
[*A. Fowler, G. W. '10*]



$\Rightarrow$ Absorptive parts have sizable effect

Relative size of the loop corrections

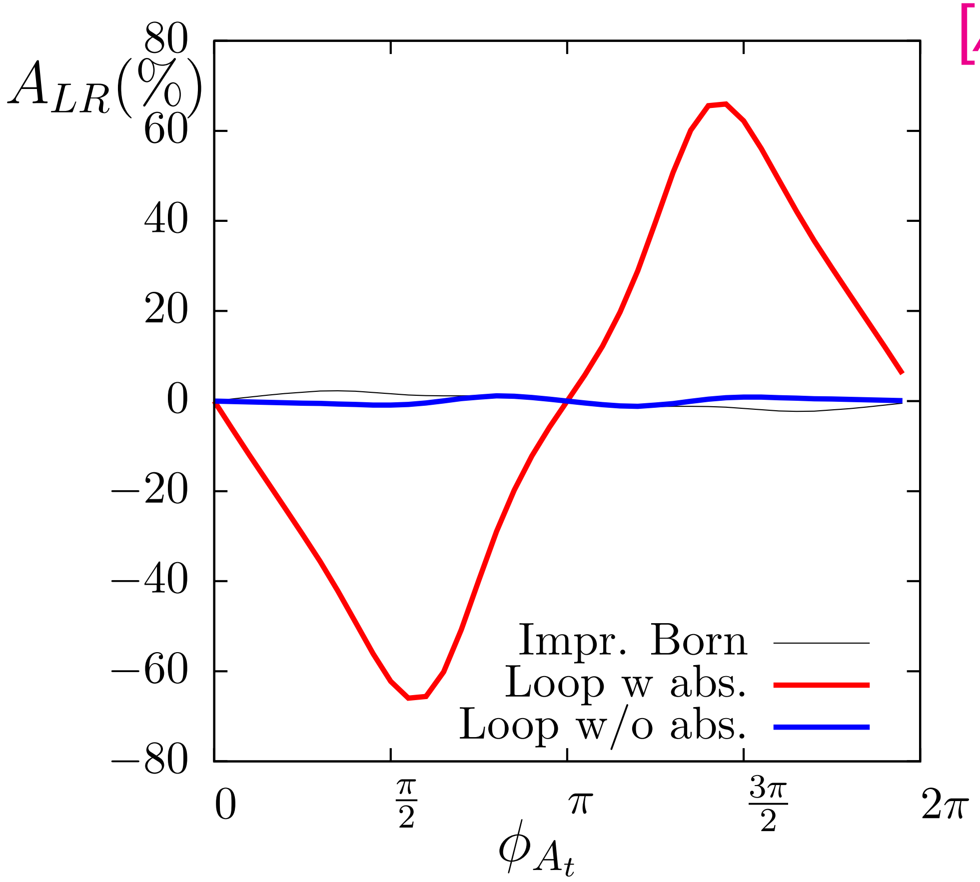
$M_{\mathrm{H}^\pm} = 800$ GeV, $\mu = 500$ GeV, $M_2 = 200$ GeV, $m_{\tilde{g}} = 1$ TeV,
$M_{\mathrm{SUSY}} = 500$ GeV, $M_{\tilde{l}} = 200$ GeV, $M_{\tilde{\tau}} = 300$ GeV,
$|A_{\mathrm{t}}| = 1200$ GeV, $\tan\beta = 20$ [*A. Fowler, G. W. '10*]



$\Rightarrow$ Genuine vertex corrections are large, incorporation of absorptive parts is crucial

$\mathcal{CP}$-violating asymmetry

[*A. Fowler, G. W. '10*]



$\Rightarrow$ Large asymmetries possible

Condition for sizable asymmetries:

$\mathcal{CP}$ violation (complex parameters) $+$ absorptive parts

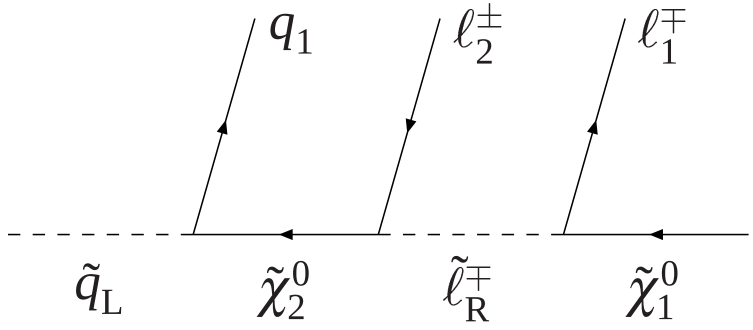
Interference effects and narrow-width approximation

The usual factorisation of processes into

(production cross section) $\times$ (branching ratio)

is based on the narrow width approximation

- $\sigma(gg \to h_i) \times \mathrm{BR}(h_i \to \tau^+\tau^-)$
- SUSY cascade decays



written as $\sigma_{\mathrm{prod}} \times \mathrm{BR}_1 \times \mathrm{BR}_2 \ldots$

- ...

Interference effects

For cases with mass degeneracies

$$|M_i - M_j| \lesssim \Gamma_i, \Gamma_j$$

$\Rightarrow$ Narrow width approximation no longer valid

Resonance-type behaviour possible

In MSSM with complex parameters: mass degeneracy between M_{h_2}, M_{h_3} occurs generically for $M_{H^\pm} \gg M_Z$, large mixing effects possible

[*A. Pilaftsis '97, '98*] [*J. Ellis, J.S. Lee, A. Pilaftsis '04*] [*S.Y. Choi, J. Kalinowski, Y. Liao, P. Zerwas '05*] [*M. Frank, T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. W. '07*] [*H. Dreiner, O. Kittel, F. von der Pahlen '07*] [*D. Berdine, N. Kauer, D. Rainwater '07*] [*M. Gigg, P. Richardson '08*] [*G. Cacciapaglia, A. Deandrea, S. De Curtis '09*] [...]

Treatment of interference effects

example: 2×2 *mixing case*

Write total matrix element in terms of production and decay matrix elements and resonant Breit–Wigner type propagators:

$$\mathcal{M}(ab \to cef) = \mathcal{M}(ab \to ch_1) \frac{1}{q^2 - M_{h_1}^2 + iM_{h_1}\Gamma_{h_1}} \mathcal{M}(h_1 \to ef) + \mathcal{M}(ab \to ch_2) \frac{1}{q^2 - M_{h_2}^2 + iM_{h_2}\Gamma_{h_2}} \mathcal{M}(h_2 \to ef)$$

$$\sigma(ab \to cef) = \frac{1}{2\pi} \frac{1}{2\lambda^{\frac{1}{2}}(s, m_a^2, m_b^2)} \int dq^2 \text{dlips}(s; p_c, q) \text{dlips}(q; p_e, p_f) \times \left(\frac{|\mathcal{M}(ab \to ch_1)|^2 \mathcal{M}(h_1 \to ef)|^2)}{(q^2 - M_{h_1}^2)^2 + M_{h_1}^2 \Gamma_{h_1}^2} + \frac{|\mathcal{M}(ab \to ch_2)|^2 |\mathcal{M}(h_2 \to ef)|^2)}{(q^2 - M_{h_2}^2)^2 + M_{h_2}^2 \Gamma_{h_2}^2} + 2\text{Re}\left[\frac{\mathcal{M}(ab \to ch_1)\mathcal{M}^*(ab \to ch_2)\mathcal{M}(h_1 \to ef)\mathcal{M}^*(h_2 \to ef)}{(q^2 - M_{h_1}^2 + iM_{h_1}\Gamma_{h_1})(q^2 - M_{h_2}^2 - iM_{h_2}\Gamma_{h_2})} \right] \right)$$

Treatment of interference effects

example: 2×2 mixing case

Observation: as long as one is sufficiently far away from thresholds, it works well to use an on-shell approximation

$$\Rightarrow \sigma(ab \to cef) \equiv \sigma_{\text{tot}} = \sigma_1 \times \text{BR}_1 + \sigma_2 \times \text{BR}_2$$
$$+ C \left(2\text{Re} \int dq^2 \frac{1}{(q^2 - M_{h_1}^2 + iM_{h_1}\Gamma_{h_1})(q^2 - M_{h_2}^2 - iM_{h_2}\Gamma_{h_2})} \right)$$

Treatment of interference effects

example: 2×2 *mixing case*

Observation: as long as one is sufficiently far away from thresholds, it works well to use an on-shell approximation

$$\Rightarrow \sigma(ab \to cef) \equiv \sigma_{\rm tot} = \sigma_1 \times {\rm BR}_1 + \sigma_2 \times {\rm BR}_2$$
$$+ C \left(2{\rm Re} \int dq^2 \frac{1}{(q^2 - M_{h_1}^2 + i M_{h_1}\Gamma_{h_1})(q^2 - M_{h_2}^2 - i M_{h_2}\Gamma_{h_2})} \right)$$

$\Rightarrow$ Interference contribution is obtained from coefficient C, which contains the dependence on the on-shell matrix elements, and a universal integral factor over Breit–Wigner propagators

Contribution of on-shell matrix elements

$$\frac{\mathcal{M}(ab \to ch_1)\mathcal{M}^*(ab \to ch_2)\mathcal{M}(h_1 \to ef)\mathcal{M}^*(h_2 \to ef)}{|\mathcal{M}(ab \to ch_1)|^2 \mathcal{M}(h_1 \to ef)|^2} = x_1$$

$$\frac{\mathcal{M}(ab \to ch_1)\mathcal{M}^*(ab \to ch_2)\mathcal{M}(h_1 \to ef)\mathcal{M}^*(h_2 \to ef)}{|\mathcal{M}(ab \to ch_2)|^2 \mathcal{M}(h_2 \to ef)|^2} = x_2$$

Contribution of on-shell matrix elements

$$\frac{\mathcal{M}(ab \to ch_1)\mathcal{M}^*(ab \to ch_2)\mathcal{M}(h_1 \to ef)\mathcal{M}^*(h_2 \to ef)}{|\mathcal{M}(ab \to ch_1)|^2 \mathcal{M}(h_1 \to ef)|^2} = x_1$$

$$\frac{\mathcal{M}(ab \to ch_1)\mathcal{M}^*(ab \to ch_2)\mathcal{M}(h_1 \to ef)\mathcal{M}^*(h_2 \to ef)}{|\mathcal{M}(ab \to ch_2)|^2 \mathcal{M}(h_2 \to ef)|^2} = x_2$$

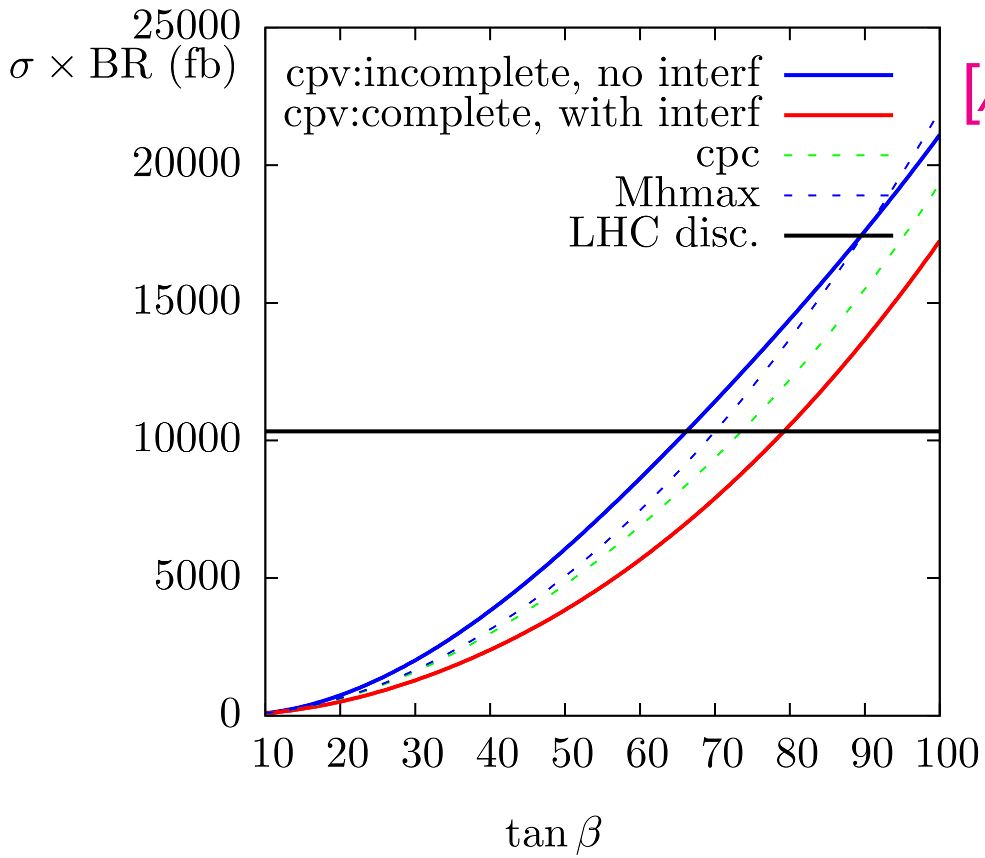
With appropriate approximation for x_1, x_2

$\Rightarrow$ Result can be expressed in terms of cross sections, branching ratios and a universal integral factor over Breit–Wigner propagators

$\Rightarrow$ Convenient way to incorporate interference effects

Impact of interference effects on Higgs production processes at Tevatron and LHC

CPV scenario: $|A_t| = 1200$ GeV, $\phi_{A_t} = \phi_{A_b} = \phi_{A_\tau} = \pi/5$, $M_{H^\pm} = 340$ GeV, $M_{SUSY} = 500$ GeV, $\mu = 200$ GeV, $M_2 = 200$ GeV, $m_{\tilde{g}} = 1$ TeV



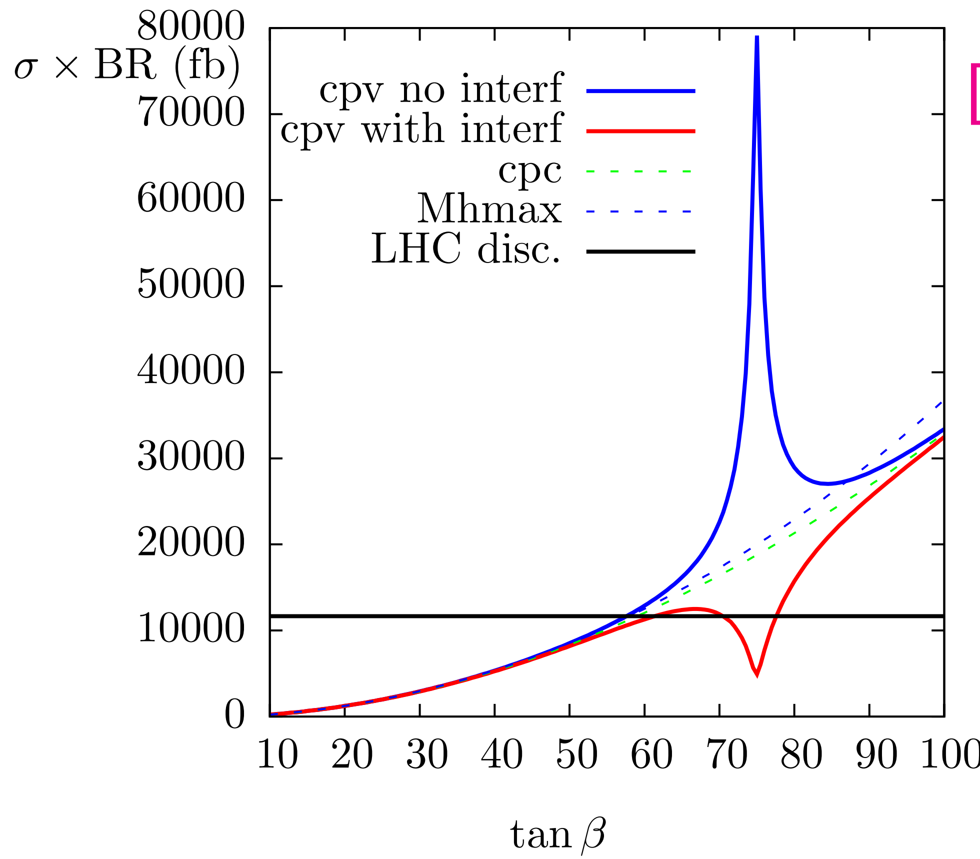
[A. Fowler, G. W. '10]

$\Rightarrow$ Interference effect yields sizable reduction of $\sigma \times \mathrm{BR}$

Can be important for interpretation of Higgs search results

"Resonance-type" scenario

CPV scenario: $|A_{\rm t}| = 800$ GeV, $\phi_{A_{\rm t}} = \phi_{A_{\rm b}} = \phi_{A_\tau} = \pi/30$, $M_{\rm H^\pm} = 300$ GeV, $M_{\rm SUSY} = 500$ GeV, $\mu = 200$ GeV, $M_2 = 200$ GeV, $m_{\tilde{g}} = 1$ TeV



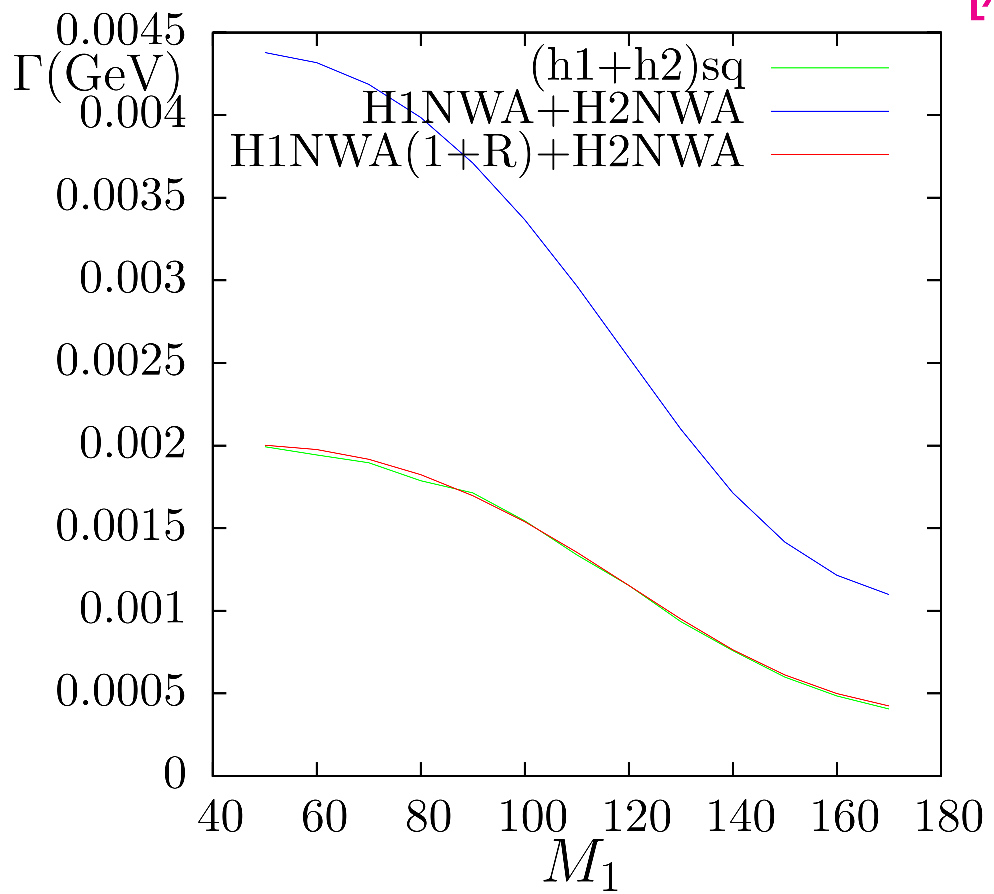
[A. Fowler, G. W. '10]

$\Rightarrow$ Large destructive interference contribution needs to be taken into account

Example of interference effect in the $\mathcal{CP}$-conserving case

Decay $\tilde{\chi}^0_4 \to \tilde{\chi}^0_1 \tau^+\tau^-$, contributions from h and H exchange, $M_h^{\max}$ scenario, $\tan\beta = 40$, $M_{H^\pm} = 170$ GeV

[A. Fowler, G. W. '10]



$\Rightarrow$ Interference effects have large impact

Conclusions

- MSSM with complex parameters offers many interesting features both conceptually and phenomenologically

Conclusions

- MSSM with complex parameters offers many interesting features both conceptually and phenomenologically
- Careful treatment of imaginary parts from complex parameters and from absorptive parts of loop integrals is necessary

  Absorptive parts play an important role in particular in $\mathcal{CP}$ asymmetries

Conclusions

- MSSM with complex parameters offers many interesting features both conceptually and phenomenologically
- Careful treatment of imaginary parts from complex parameters and from absorptive parts of loop integrals is necessary

  Absorptive parts play an important role in particular in $\mathcal{CP}$ asymmetries
- Mass degeneracies occur generically in the MSSM with or without complex parameters

  $\Rightarrow$ Interference effects can be sizable

  The narrow width approximation can be extended to incorporate interference effects