# Impact of complex phases on MSSM Higgs searches

## Interference and other $\mathcal{CP}$-violating effects.

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Higgs session

HELMHOLTZ
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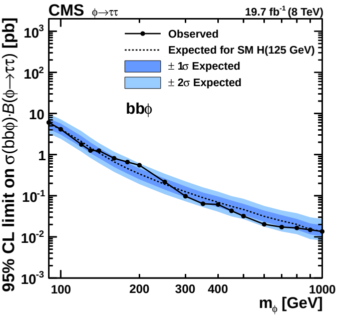
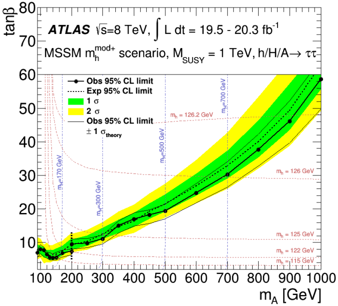
# Interpretation of MSSM Higgs searches

## Experimental searches for $\Phi = h, H, A$ $\rightarrow$ A. Gilbert's, L. Hauswald's talks

**production** $\{gg \to \Phi, \underline{b\bar{b}\Phi}\} \times$ **decay** $\Phi \to \{\underline{\tau^+\tau^-}, \mu^+\mu^-, b\bar{b}\}$




## Limitation of factorisation in standard NWA

**interference** terms neglected, relevant especially with complex phases

# Outline

# Complex phases: motivation and constraints

## Motivation

- baryon asymmetry of the universe requires more $\mathcal{CP}$-violation than in CKM matrix
- **MSSM Higgs sector is $\mathcal{CP}$-conserving at lowest order**
- parameters from **other sectors** can in principal be **complex**: 12
  - trilinear couplings $A_f$
  - higgsino mass parameter $\mu$
  - gaugino mass parameters $M_1, M_2$ (rotate $\phi_{M_2}$ away), $M_3$

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## Constraints from EDMs (Tl, Hg, n, D)

e.g. [Barger, Falk, Han, Jiang, Li, Plehn '01], [Ellis, Lee, Pilaftsis '09], [Li, Profumo, Ramsey-Musolf '10]

- $\phi_{A_{f_{1,2}}}$ more strongly constrained than $\phi_{A_{t,b}}$
- $\phi_{M_1}$ can be sizeable - large
- $\phi_{M_3}$ strongly constrained only if $\tilde{f}_{1,2}$ light
- $\phi_\mu$ tight limits

Most relevant phases in Higgs sector: $\phi_{A_{t,b}}, \phi_{M_3}$, enhanced $\mu \cdot A_t$

# Mixing of Higgs bosons

$\rightarrow$ S. Paßehr's talk

**$\mathbb{R}$eal case: $\mathcal{CP}$ conserved**

- only $\mathcal{CP}$-even states mix: $h - H$
- $M_A$ or $M_{H^\pm}$ as input mass

**$\mathbb{C}$omplex case: $\mathcal{CP}$ violated**

- all neutral states mix: $h, H, A \rightarrow h_1, h_2, h_3$
- $M_{H^\pm}$ as input mass

$\mathcal{CP}$-violating phases can cause interesting phenomenology

# Criteria for a significant interference effect

## 1.) Degeneracy

Nearby resonances

- masses $M_i, M_j$
- widths $\Gamma_i, \Gamma_j$

overlap if $\Delta M \leq \Gamma_i, \Gamma_j$

## 2.) Mixing

- Matrix elements $\mathcal{M}_i, \mathcal{M}_j$
- if $i, j$ do not mix:
  $\sigma_{\text{Int}} \propto 2\text{Re}[\mathcal{M}_i \mathcal{M}_j^*] = 0$

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## Interference in MSSM Higgs sector?

- real parameters: only $h, H$ mix
  - but $M_h \simeq M_H$ limited to narrow parameter range
- complex parameters: all neutral Higgs bosons mix $\rightarrow h_1, h_2, h_3$
  - $M_{h_3} - M_{h_2} \leq \Gamma_{h_2}, \Gamma_{h_3}$ in decoupling region

Analyse interference effects between neutral Higgs bosons!

# $\mathcal{CP}$-violating Higgs interference

## In presence of non-zero phase: change of cross section

- dominant effect: $h_2 - h_3$ interference $\Rightarrow \sigma_{H+A} \not\approx 2\sigma_H$ or $\sum \sigma_\Phi \mathrm{BR}_\Phi$
- also affected: couplings, masses, widths, mixings in/outside $\sigma_{\mathrm{int}}$

## Our approach

- full propagator mixing $\Delta_{ij}(p^2)$: $3 \times 3$ or $2 \times 2$ (no NWA)
  - $\phi \equiv \phi_{A_t} \neq 0$ or $\phi = 0 \longrightarrow \boxed{\delta := \frac{\sigma(\phi) - \sigma(0)}{\sigma(0)}}$
- measures relative effect of complex phase on cross section $\sigma$

# $\mathcal{CP}$-violating Higgs interference

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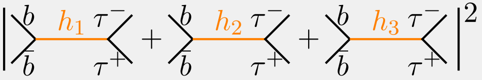
## Process: $b\bar{b} \to \tau^+\tau^-$ via $\Phi = h_1, h_2, h_3$




FeynArts,

FormCalc,

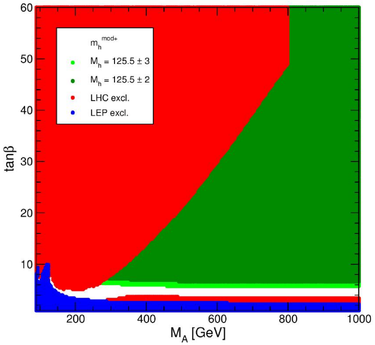
FeynHiggs

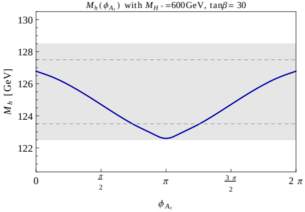
# Benchmark scenario: $M_h^{\rm mod+}$

$$
\begin{aligned}
M_{\rm SUSY} &= 1000\,\text{GeV}\\
M_2 &= 200\,\text{GeV}\\
X_t^{\rm OS} &= 1.5 M_{\rm SUSY}\\
A_t &= A_b = A_\tau\\
M_3 &= 1500\,\text{GeV}\\
M_{\tilde f_3} &= M_{\rm SUSY}\\
M_{\tilde q_{1,2}} &= 1500\,\text{GeV}\\
M_{\tilde l_{1,2}} &= 500\,\text{GeV}
\end{aligned}
$$

$$\mu = \pm 200, \pm 500, \quad \pm 1000\,\text{GeV}$$

[Carena, Heinemeyer, Stål, Wagner, Weiglein '13]



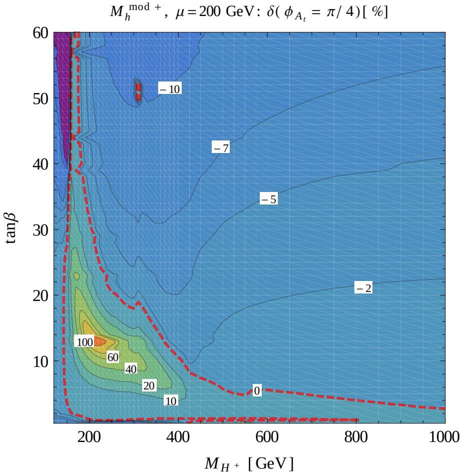



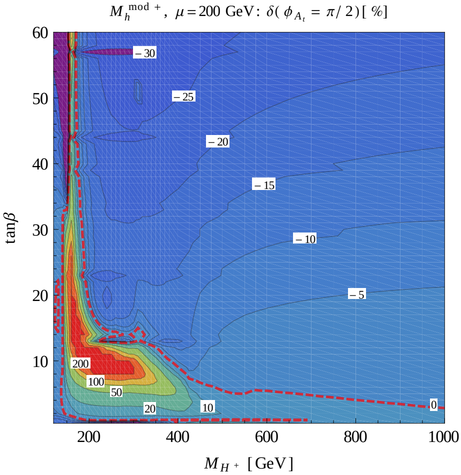

- most parameter space $M_h$−allowed
- $\phi_{A_t}$ changes $M_h$
- but $M_h$ mostly stays in allowed region

# Impact of $\phi_{A_t}$ in $M_h^{\mathrm{mod}+}$ scenario

preliminary

$\delta = \frac{\sigma_\phi - \sigma_0}{\sigma_0}$ in full plane




**Constructive and destructive effects of $\delta$**

# Impact of $\phi_{A_t}$ in $M_h^{\text{mod}+}$ scenario

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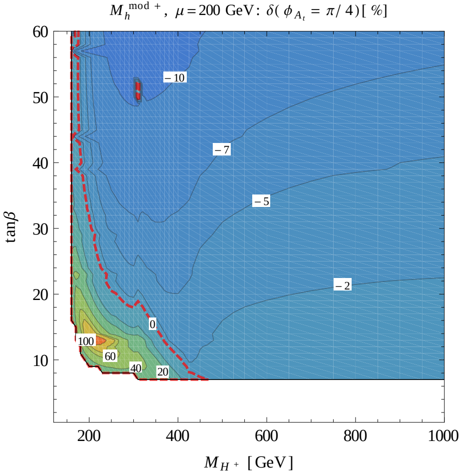
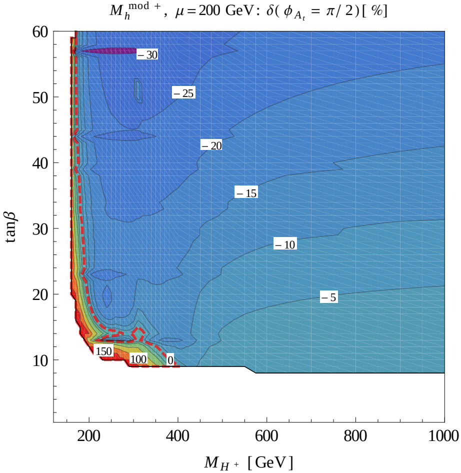
$$\delta = \frac{\sigma_\phi - \sigma_0}{\sigma_0} \text{ where } M_h = 125.5 \pm 3\,\text{GeV}$$




Mostly destructive effects of $\delta$ in $M_h$-allowed region

# Re-evaluation of the exclusion contour preliminary

**back-of-the-envelope calculation:**

- for fixed $M_A$
- $\sigma(0, \tan\beta_0) \leftrightarrow$ exclusion limit
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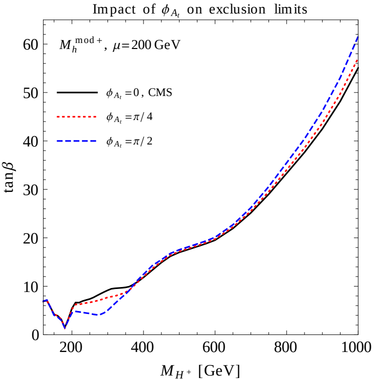
## More precise $\tan\beta$-limit

- HiggsBounds

## Comparison with CMS

24.6/fb, [1408.3316], $\tau^+\tau^-$

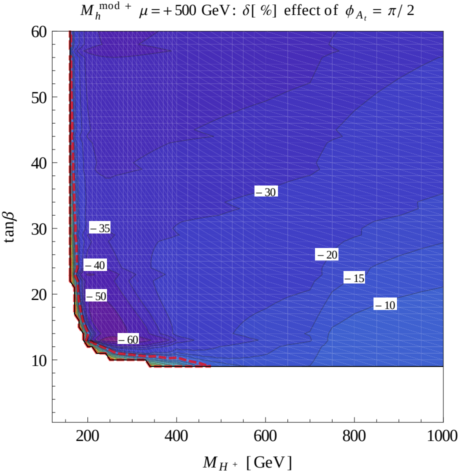


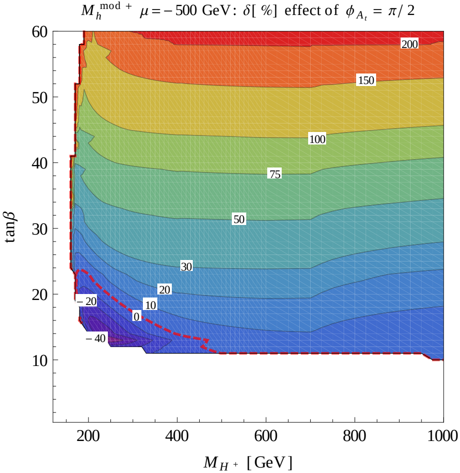

slightly weakened limit at high masses for $\phi_{A_t} \neq 0$

# Impact of $\mu$ in $M_h^{\text{mod}+}$ scenario

preliminary

$\mu = \pm 500\,\text{GeV}$: $\delta = \frac{\sigma_\phi - \sigma_0}{\sigma_0}$ where $M_h = 125.5 \pm 3\,\text{GeV}$

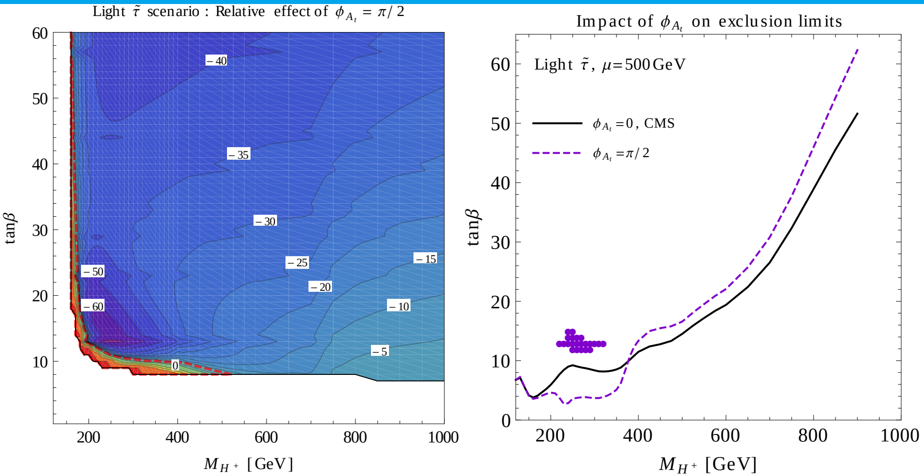



$|\mu|, \text{sgn}(\mu)$ have crucial influence on $\delta$

# $\mu = 500\,\text{GeV}$ in light-$\tilde{\tau}$ scenario

preliminary




**Unexcluded hole** of parameter points due to **strongly destructive** interference effect

# Conclusion: relevant phase effects

## Outlook

- Calculate the impact of $\phi_{A_t}$ and interference also in gluon fusion
- Study impact on experimental limits in more detail: `HiggsBounds`
- Separate interference term from other non-zero phase effects

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## Summary

- Complex phases allow for $\mathcal{CP}$-violating mixing and interference effects in the MSSM Higgs sector
  - $\mathcal{CP}$-violating case: analysis beyond *incoherent* sum $\sigma_A \mathrm{BR}_A + \sigma_H \mathrm{BR}_H$
- Extend analyses of benchmark scenarios
  - include different values of $\mu = \pm 200, \pm 500, \pm 1000\,\mathrm{GeV}$
- Non-zero phases can have significant impact on exclusion limits

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**Thank you!**

# The MSSM Higgs sector

**2 Higgs doublets** needed for holomorphic superpotential

$$\mathcal{H}_1 = \begin{pmatrix} H_{11} \\ H_{12} \end{pmatrix} = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1^0 - i\chi_1^0) \\ -\phi_1^- \end{pmatrix}$$

$$\mathcal{H}_2 = \begin{pmatrix} H_{21} \\ H_{22} \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2^0 + i\chi_2^0) \end{pmatrix} e^{i\xi}$$

**Higgs potential** with SUSY and soft ~~SUSY~~ terms

$$V_H = m_1^2 \mathcal{H}_1^\dagger \mathcal{H}_1 + m_2^2 \mathcal{H}_2^\dagger \mathcal{H}_2 - m_{12}^2 \epsilon^{ij} (\mathcal{H}_{1i}\mathcal{H}_{2j} + \text{h.c.})$$
$$+ \frac{1}{8}(g_1^2 + g_2^2)(\mathcal{H}_1^\dagger \mathcal{H}_1 - \mathcal{H}_2^\dagger \mathcal{H}_2)^2 + \frac{1}{2} g_2^2 |\mathcal{H}_1^\dagger \mathcal{H}_2|^2$$

$$m_i^2 = \tilde{m}_i^2 + |\mu|^2, \; i = 1, 2$$

$$m_{12}^2 = b\mu = |m_{12}^2| e^{i\zeta}$$

**Complex phases** $\xi, \zeta$ can be rotated away

# Relations at lowest order

Higgs sector $\mathcal{CP}$-conserving at lowest order

## Physical states

- $\mathcal{CP}$-even: $\phi_1^0, \phi_2^0 \to h, H$
- $\mathcal{CP}$-odd: $\chi_1^0, \chi_2^0 \to A, G$
- charged: $\phi_1^\pm, \phi_2^\pm \to H^\pm, G^\pm$

## Input parameters

$$\tan\beta = \frac{v_2}{v_1}, \quad m_A^2 = \frac{2|m_{12}^2|}{\sin(2\beta)}$$

**Masses** determined by $m_A, \tan\beta$

$$m_{h/H}^2 = \frac{1}{2}\left(m_A^2 + M_Z^2 \mp \sqrt{\left(m_A + M_Z^2\right)^2 - 4m_A^2 M_Z^2 \cos^2(2\beta)}\right)$$

$$\Rightarrow m_h^2 \leq M_Z^2$$

$$m_{H^\pm}^2 = m_A^2 + M_W^2$$

But higher-order corrections important

# Higher-order effects in the Higgs sector

## Self-energy diagrams

- significant impact on masses
  - mixing self-energies $\hat{\Sigma}_{ij}(p^2) \Rightarrow$ mass matrix $\mathbf{M}_{ij} = m_i^2 \delta_{ij} - \hat{\Sigma}_{ij}(p^2)$
  - higher-order masses and widths from complex poles of the propagators

$$\mathcal{M}_{h_a}^2 = M_{h_a}^2 - i M_{h_a} \Gamma_{h_a}$$

- particles and parameters from other sectors contribute, e.g.
  - sfermions: trilinear couplings $A_f$ and mixing parameters $X_{f_{u,d}} = A_{f_{u,d}} - \mu^* \{\cot\beta, \tan\beta\}$ enter at 1-loop order
  - gluino: $M_3$ contribute only at 2-loop order, but at 1-loop in correction $\Delta_b$ to bottom Yukawa coupling

## Phenomenology

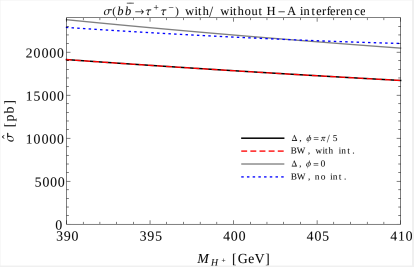
- loop corrected Higgs mass at 126 GeV possible in MSSM
- important loop contributions to Higgs production and decay

More parameters than $m_A, \tan\beta$ necessary to describe Higgs sector

# Complex parameter in $b\bar{b} \to \tau^+\tau^-$ via $\Phi = h, H, A$

## $\mathcal{CP}$-violating scenario

$\phi_{A_t} = \pi/5, |A_t| = 1200,$
$\tan\beta = 50, M_{\text{SUSY}} = 500$ GeV,
$M_{\tilde{f}} = M_{\text{SUSY}}, M_{\tilde{u}_3} = 0.8 M_{\text{SUSY}}$
$\mu = M_2 = 200$ GeV




## Comparison

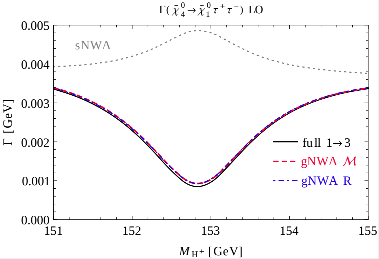
- full cross sections ($\Delta_{ij}, BW$) agree very well
- phase and interference effect similar
  - significant effects
  - dominant: interference term
- in the following:
  - full mixing propagators
  - impact of $\phi_{A_t}$ on all terms

# Example in $\mathcal{CP}$-conserving Higgs sector

## Destructive h-H interference

example process: $\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 \tau^+ \tau^-$

$\mathbb{R}$ scenario, $\tan\beta = 50$




**sNWA**: standard NWA insufficient here!

**full**: 3-body decay BW

**gNWA**: generalised NWA

## Include interference term

- **Mixing propagators**
  - full $p^2$-dependence
  - $\hat{\Sigma}_{ij}$ from `FeynHiggs`
- **Breit-Wigner propagators**
  - approximate $p^2$-dependence
  - $\hat{\mathbf{Z}}$-factors from `FeynHiggs`
- **generalised NWA**

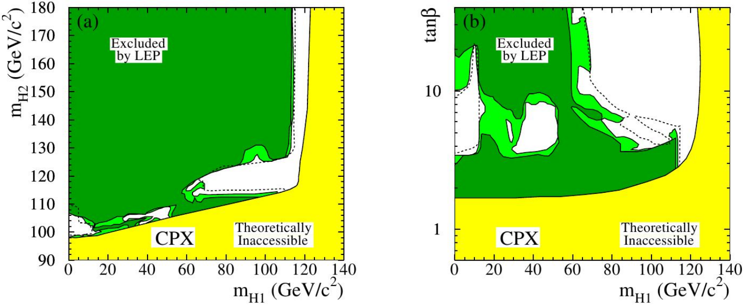
  [EF, S. Thewes, G. Weiglein '14]

  - on-shell matrix elements
  - enables factorisation into production$\times$decay

# Another complex example: CPX hole at LEP

## LEP search for neutral MSSM Higgs bosons

interpreted in **CPX scenario** with large amount of $\mathcal{CP}$-violation




## Unexcluded hole in parameter space

due to **suppressed coupling** of $h_1 ZZ$ in CPX scenario