Impact of complex phases on MSSM Higgs searches

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

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BSM Higgs searches

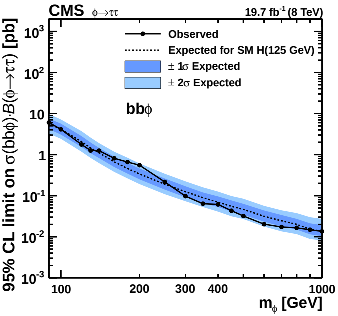
HELMHOLTZ GEMEINSCHAFT

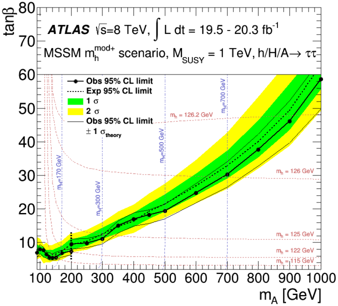
DESY

Motivation: BSM Higgs searches

Experimental searches for $\Phi = h, H, A$ → A. Nikitenko's talk

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





Limitation of factorisation in standard NWA

interference terms neglected, relevant especially with complex phases

Outline

Complex phases in the MSSM Higgs sector

→ S. Heinemeyer's talk

- MSSM Higgs sector $\mathcal{CP}$-conserving at tree-level
- phases from other MSSM sectors enter through loops
  - trilinear couplings A_f
  - gluino mass parameter M_3
  - higgsino mass parameter μ
  - gaugino mass parameters M_1, M_2 (only one phase physical)
- dominant: phase ϕ_{A_t} at 1-loop order
  - if μ small: $\phi_{A_t} \simeq \phi_{X_t}$
- phase ϕ_{M_3} only at 2-loop order,
  but at 1-loop in correction Δ_b to bottom Yukawa coupling

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

Full mixing propagators

3×3 mixing (approximation of 6×6) $\rightarrow 2 \times 2$ for $\mathbb{R}$eal parameters

- 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
  $\boxed{M_{c_i}^2 = M_i^2 - iM_i\Gamma_i}$
- diagonal propagator $\Delta_{ii}(p^2) = \frac{i}{p^2 - m_i^2 + \hat{\Sigma}_{ii}^{\text{eff}}(p^2)}$

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Finite wave function normalisation factors (Z-factors)

- correct on-shell properties of external Higgs bosons with mixing: $\hat{\mathbf{Z}}_{ij}$

$\hat{Z}_{ii} = \frac{1}{1+\hat{\Sigma}_{ii}^{\text{eff}\prime}(M_{c_i}^2)}, \quad \hat{Z}_{ij} = \frac{\Delta_{ij}(M_{c_i}^2)}{\Delta_{ii}(M_{c_i}^2)}$ [Frank, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein '07]

- Breit-Wigner-approximation at $p^2 \simeq M_{c_i}^2$: [A. Fowler, PhD thesis]

$$\sum_{i,j} \hat{\Gamma}_i^{\text{A}} \Delta_{ij}(p^2) \hat{\Gamma}_j^{\text{B}} \simeq \sum_{\alpha,i,j} \hat{\Gamma}_i^{\text{A}} \hat{\mathbf{Z}}_{\alpha i} \Delta_\alpha^{\text{BW}}(p^2) \hat{\mathbf{Z}}_{\alpha j} \hat{\Gamma}_j^{\text{B}}$$

Criteria for a significant interference effect

1.) Degeneracy

Nearby resonances

- masses M_i, M_j
- widths Γ_i, Γ_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

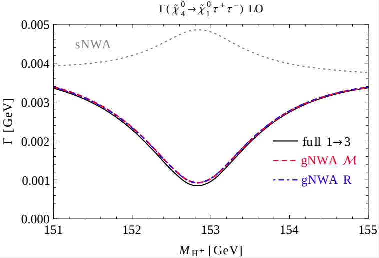
Analyse interference effects between neutral Higgs bosons!

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

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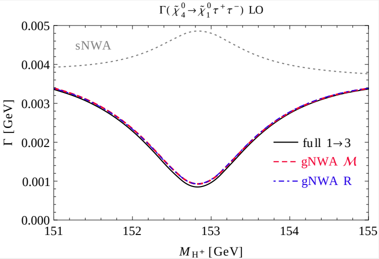

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Include interference term

- **Mixing propagators**
  - full p^2-dependence
  - $\hat{\Sigma}_{ij}$ from FeynHiggs
- **Breit-Wigner propagators**
  - approximate p^2-dependence
  - Z-factors from FeynHiggs
- **generalised NWA**
  - on-shell matrix elements
  - enables factorisation into production×decay

$\mathcal{CP}$-violating Higgs interference

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

- dominant effect: H-A 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 σ_{int}

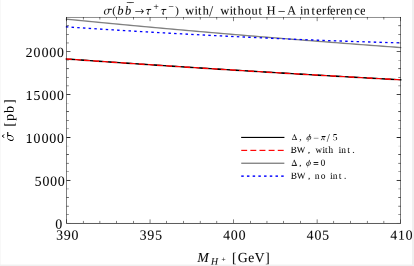
Our approach

- full propagator mixing Δ_{ij}: 3×3 or 2×2
  - $\phi \equiv \phi_{A_t} \neq 0$ or $\phi = 0 \longrightarrow$ $\boxed{\delta := \frac{\sigma(\phi) - \sigma(0)}{\sigma(0)}}$
  - measures relative effect of complex phase
- BW*Z-factors with $\phi_{A_t} \neq 0$, with/without interference
  - measures difference between $|h_1 + h_2 + h_3|^2$ and $|h_1|^2 + |h_2|^2 + |h_3|^2$

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

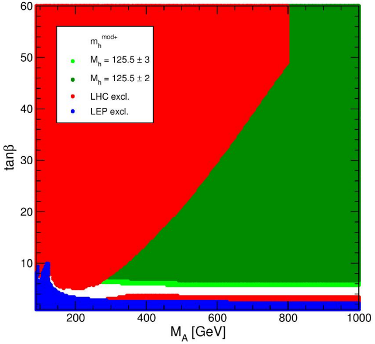
- full cross sections (Δ_{ij}, BW) agree very well
- phase and interference effect similar
  - significant effects
  - dominant: interference term
- in the following:
  - full mixing propagators
  - impact of ϕ_{A_t} on all terms

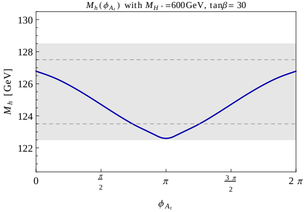
Benchmark: $M_h^{\text{mod}+}$

→ O. Stål's talk

$$
\begin{aligned}
M_{\text{SUSY}} &= 1000\,\text{GeV} \\
M_2 &= 200\,\text{GeV} \\
X_t^{\text{OS}} &= 1.5 M_{\text{SUSY}} \\
A_t &= A_b = A_\tau \\
M_3 &= 1500\,\text{GeV} \\
M_{\tilde{f}_3} &= M_{\text{SUSY}} \\
M_{\tilde{q}_{1,2}} &= 1500\,\text{GeV} \\
M_{\tilde{l}_{1,2}} &= 500\,\text{GeV} \\
\mu = \pm 200, \pm 500, &\quad \pm 1000\,\text{GeV}
\end{aligned}
$$

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



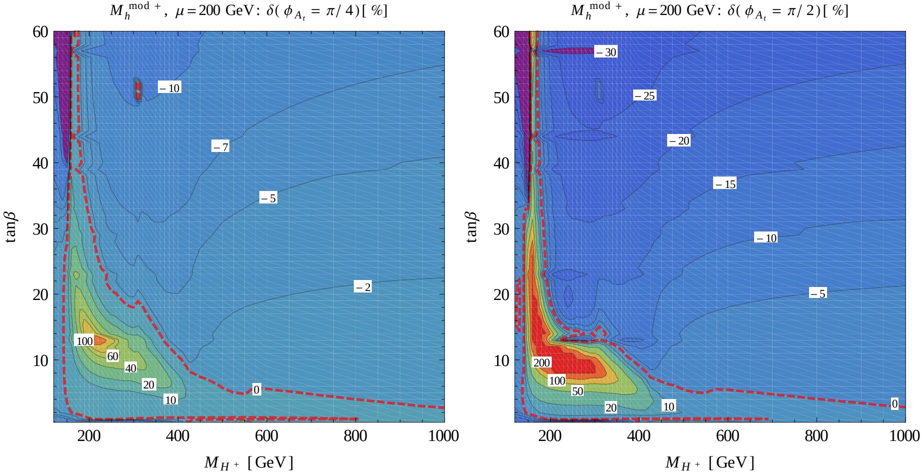


- most parameter space M_h-allowed
- ϕ_{A_t} changes M_h
- but M_h mostly stays in allowed region

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

preliminary

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

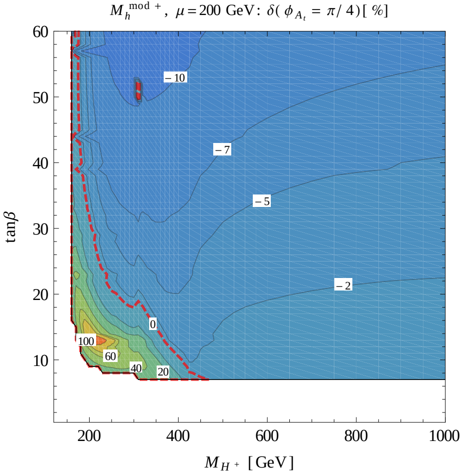


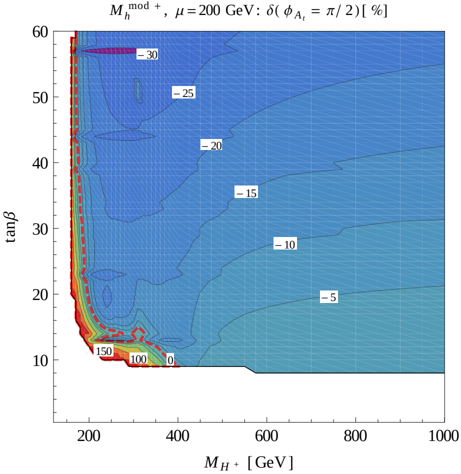
Constructive and destructive effects of δ

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

preliminary

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





Mostly destructive effects of δ in M_h-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
- $\sigma(\phi, \tan\beta_0) = (1 + \delta)\sigma(0, \tan\beta_0)$

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- $\sigma(\tan\beta) \propto \tan\beta^2$
- $$\boxed{\tan\beta_\phi \simeq \frac{\tan\beta_0}{\sqrt{(1+\delta)}}}$$

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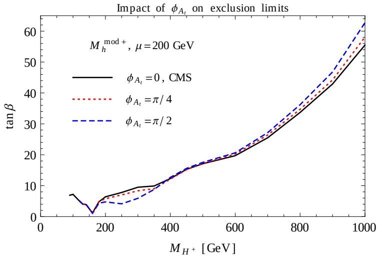
More precise $\tan\beta$-limit

- HiggsBounds

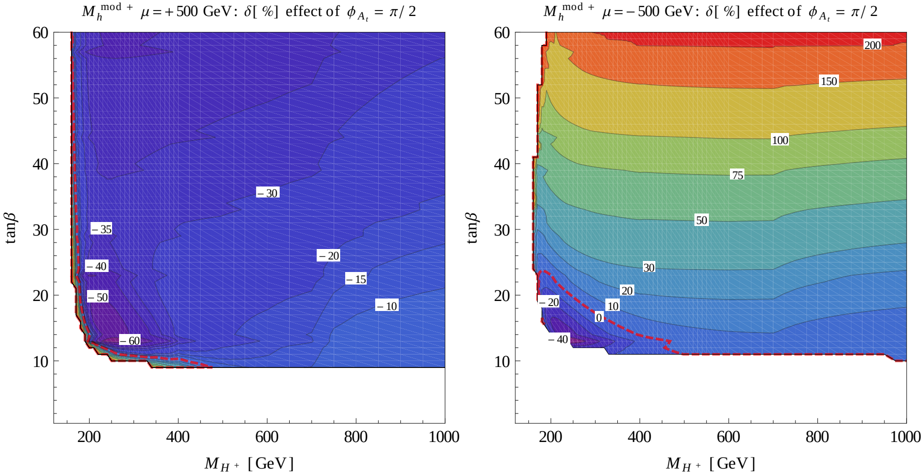
Comparison with CMS

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



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

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

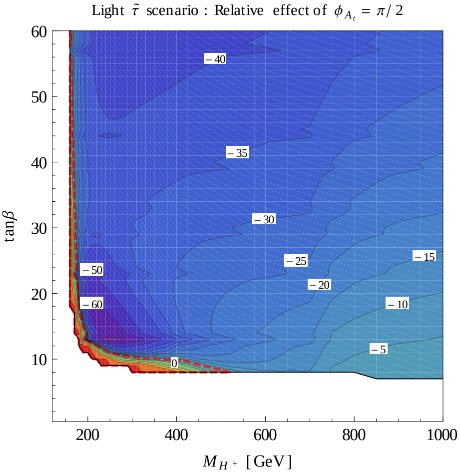


$|\mu|, \text{sgn}(\mu)$ have crucial influence on $\delta \Rightarrow$ on limits

Impact of μ in light-$\tilde{\tau}$ scenario

preliminary

$\mu = 500\,\text{GeV}$



Large μ enhances effect of complex phase ϕ_{A_t}

Conclusion: relevant interference effects

Outlook

- More detailed parameter scan: $\phi_{A_t},\ \mu$ in different benchmark scenarios
- Study impact on experimental limits in more detail
- 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
  - For benchmark scenarios with $\mu = \pm 200, \pm 500, \pm 1000\,\mathrm{GeV}$
  - Non-zero phases can have significant impact on exclusion limits

Thank you!