

Higgs interference effects

in the MSSM

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DESY

in collaboration with Sven Heinemeyer, Oscar Stål and Georg Weiglein

HiggsHunting

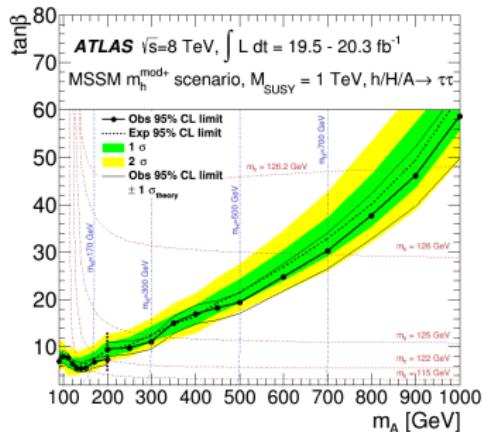
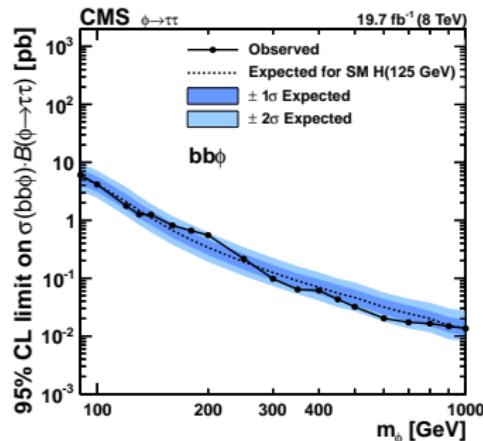
Orsay, 31 July 2015

Searches for additional Higgs bosons

→ talks by A. Caudron, M. Beckingham

Experimental searches for $\Phi = h, H, A$

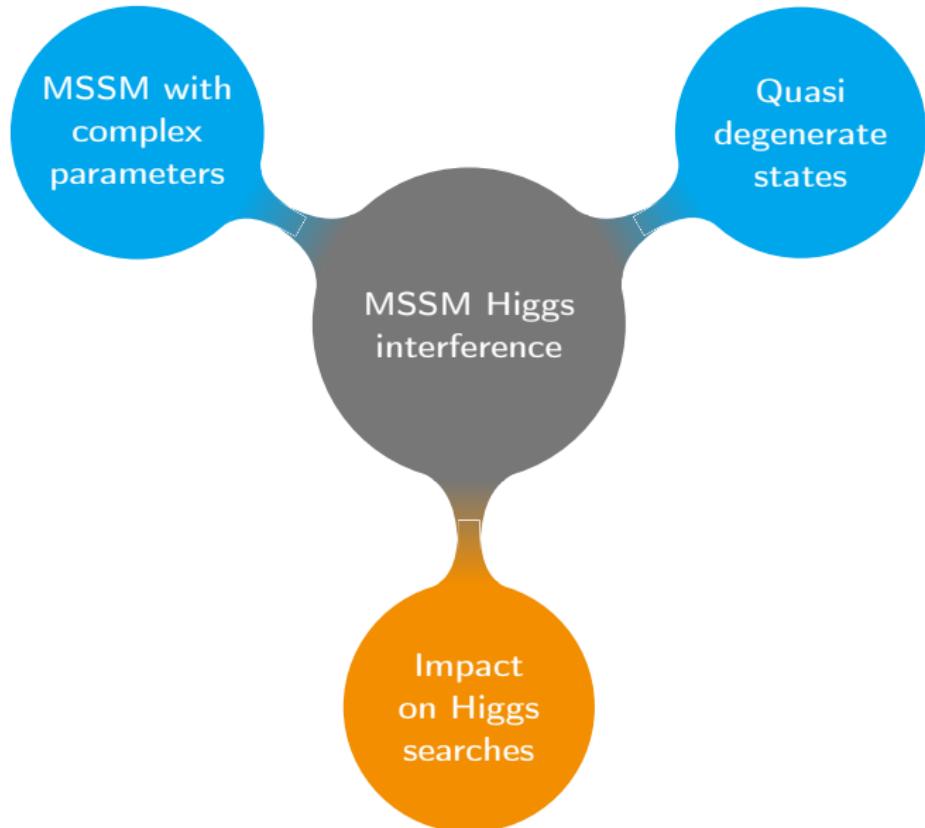
production $\{gg \rightarrow \Phi, b\bar{b}\Phi\} \times$ decay $\Phi \rightarrow \{\tau^+\tau^-, \mu^+\mu^-, b\bar{b}\}$



Limitation of interpretation in standard NWA

interference terms neglected, relevant especially with complex phases

Outline



Complex phases in the MSSM Higgs sector

Motivation

- ▶ baryon asymmetry of the universe requires BSM \mathcal{CP} -violation
- ▶ MSSM Higgs sector is \mathcal{CP} -conserving at lowest order
- ▶ parameters from **other sectors** can be **complex**
 - trilinear couplings A_f
 - higgsino mass parameter μ
 - gaugino mass parameters M_1, M_2 (rotate ϕ_{M_2} away), M_3

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Constraints from EDMs

e.g. [Barger, Falk, Han, Jiang, Li, Plehn '01], [Ellis, Lee, Pilaftsis '09], [Li, Profumo, Ramsey-Musolf '10], [Arbey, Ellis, Godbole, Mahmoudi '14]

- ▶ least constrained and most relevant in Higgs sector: $\phi_{A_{t,b}}, \phi_{M_3}$

\mathcal{CP} eigenstates $h, H, A \rightarrow$ mass eigenstates h_1, h_2, h_3

Interference of quasi degenerate states

Effects beyond standard NWA ($\sigma_{\text{prod}} \times \text{BR}$)

- ▶ off-shell effects → G. Passarino's talk
 - ▶ interference
 - peak - continuum
 - 2 close-by resonances: $\Delta M \leq \Gamma_1 + \Gamma_2$
 - ↪ systematic interference extension of NWA [EF, Thewes, Weiglein '14]
 - ↪ other interference approaches
- [Cacciapaglia, Deandrea, Curtis '09] [Blas, Lizana, Perez-Victoria '12]

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MSSM: Higgs bosons can be quasi degenerate and interfere

Parameters	Which Higgses?	Where?
\mathbb{R}	h, H	$M_h \simeq M_H$ at high $\tan \beta$, low M_A
C	h_1, h_2, h_3	$M_{h_2} \simeq M_{h_3}$ in decoupling limit

Influence of phase ϕ_{A_t}

consider $\phi_{A_t} \neq 0$ in trilinear coupling $A_t = |A_t| e^{i\phi_{A_t}}$, $A_b = A_\tau = A_t$

- ▶ impact on masses, couplings, widths, cross sections, mixing
- ▶ \mathcal{CP} H-A interference relevant in decoupling limit

$$\left| \begin{array}{c} b \\ \bar{b} \end{array} \right\rangle \begin{array}{c} h_1 \\ \tau^- \\ \tau^+ \end{array} + \left| \begin{array}{c} b \\ \bar{b} \end{array} \right\rangle \begin{array}{c} h_2 \\ \tau^- \\ \tau^+ \end{array} + \left| \begin{array}{c} b \\ \bar{b} \end{array} \right\rangle \begin{array}{c} h_3 \\ \tau^- \\ \tau^+ \end{array} \right|^2$$

- ▶ cross section σ with propagator corrections: comparison

[Fowler, EF, Weiglein (in preparation)]

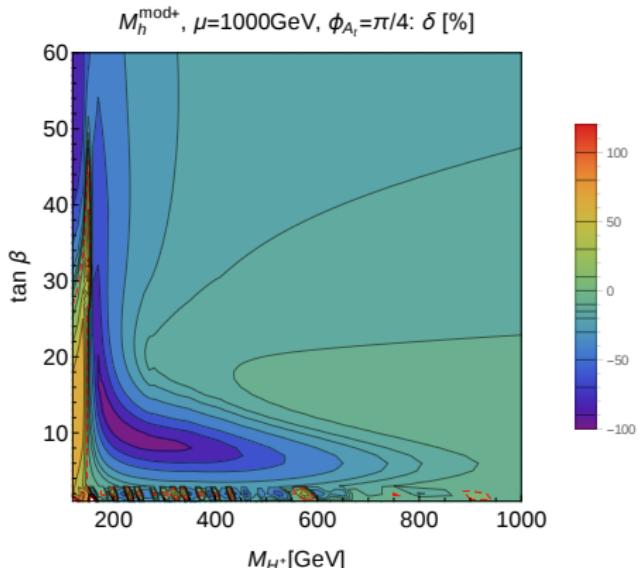
- full propagator mixing Δ_{hHA}
- Breit-Wigner propagators with on-shell $\hat{\mathbf{Z}}$ -factors

- ▶ evaluate $\sigma(\phi_{A_t})$ for $\phi_{A_t} = 0, \frac{\pi}{4}, \frac{\pi}{2}$

$M_h^{\text{mod}+}$ scenario with $\mu = 1000 \text{ GeV}$ and $\phi_{A_t} = \pi/4$

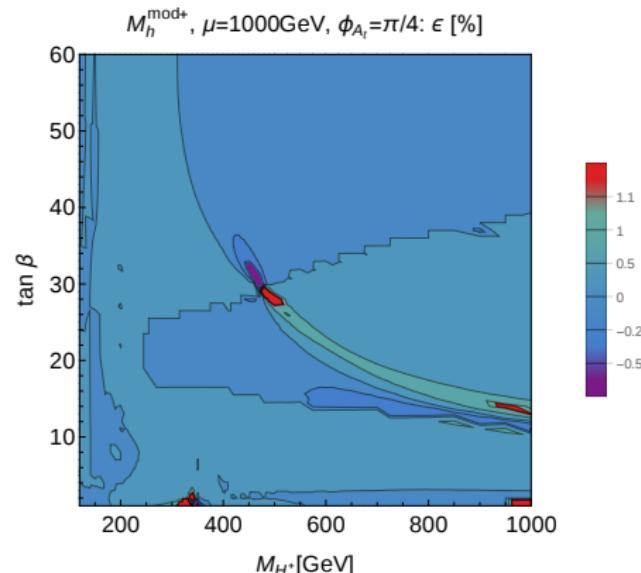
- effect of ϕ_{A_t} on cross section:

$$\delta := \frac{\sigma(\phi_{A_t})}{\sigma(0)} - 1$$



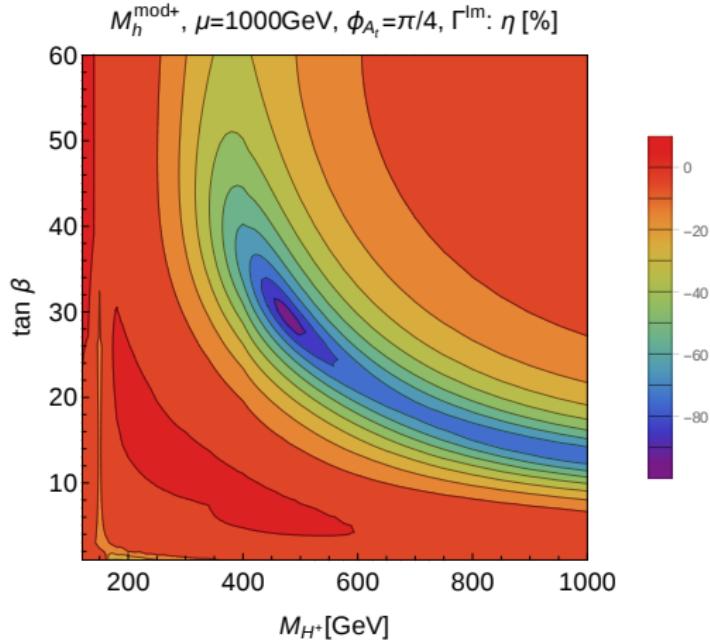
- Breit-Wigner approximation:

$$\epsilon := \frac{\sigma_{\text{BW}} \hat{z}}{\sigma_{\text{full}}} - 1$$



Pure interference effect

Disentangle overall phase effect δ from pure interference effect η



interference:

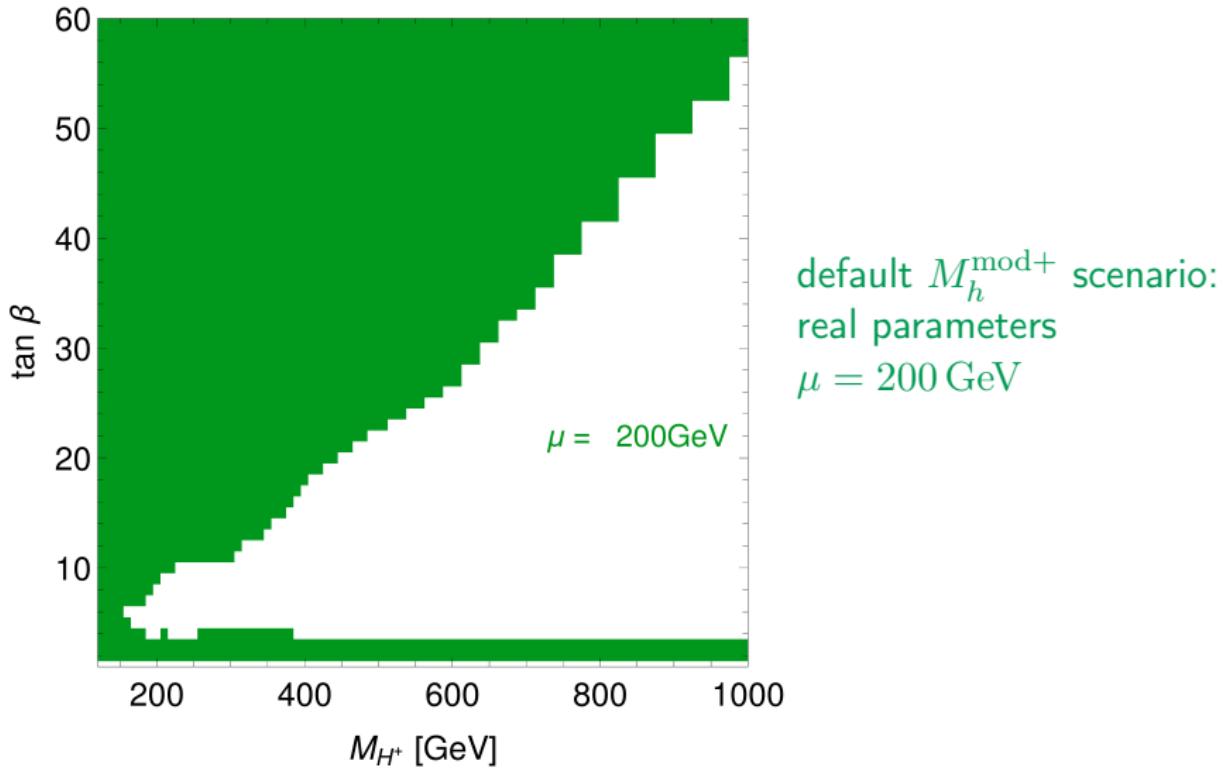
$$|h_1 + h_2 + h_3|^2 \text{ vs } |h_1|^2 + |h_2|^2 + |h_3|^2$$

$$\eta = \frac{\sigma_{\text{int}}(\phi_{A_t})}{\sigma_{\text{incoh}}(\phi_{A_t})}$$

drastic, destructive interference effect

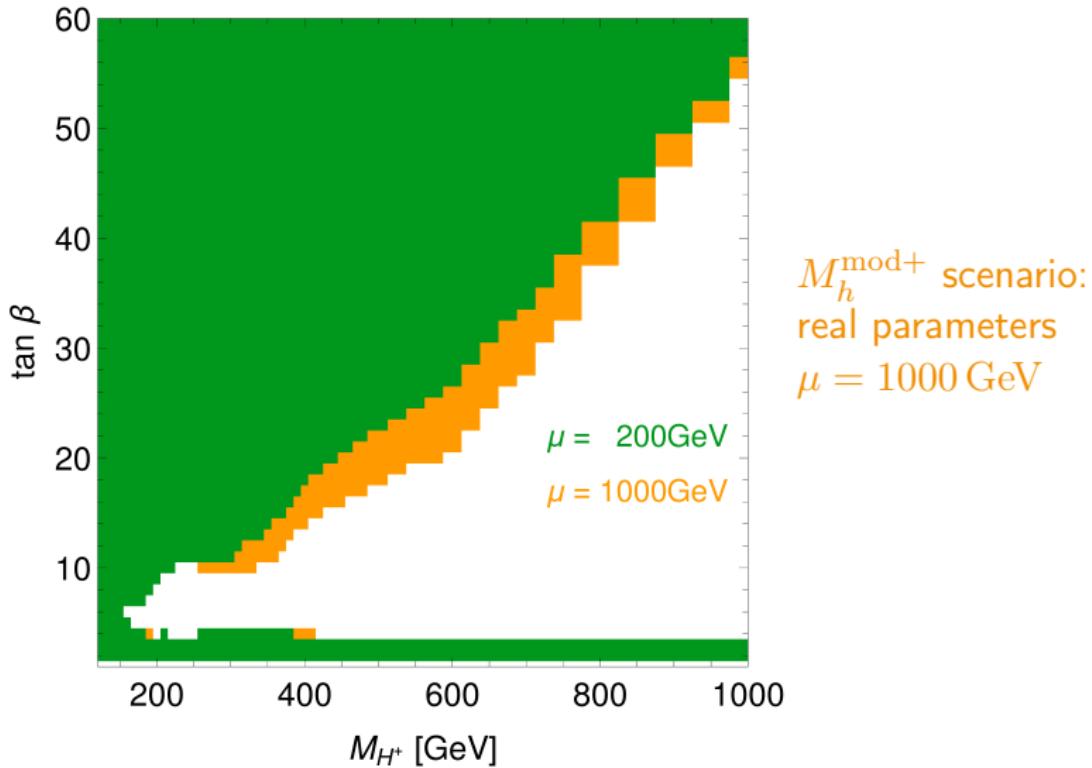
Impact of the interference on exclusion bounds

HiggsBounds



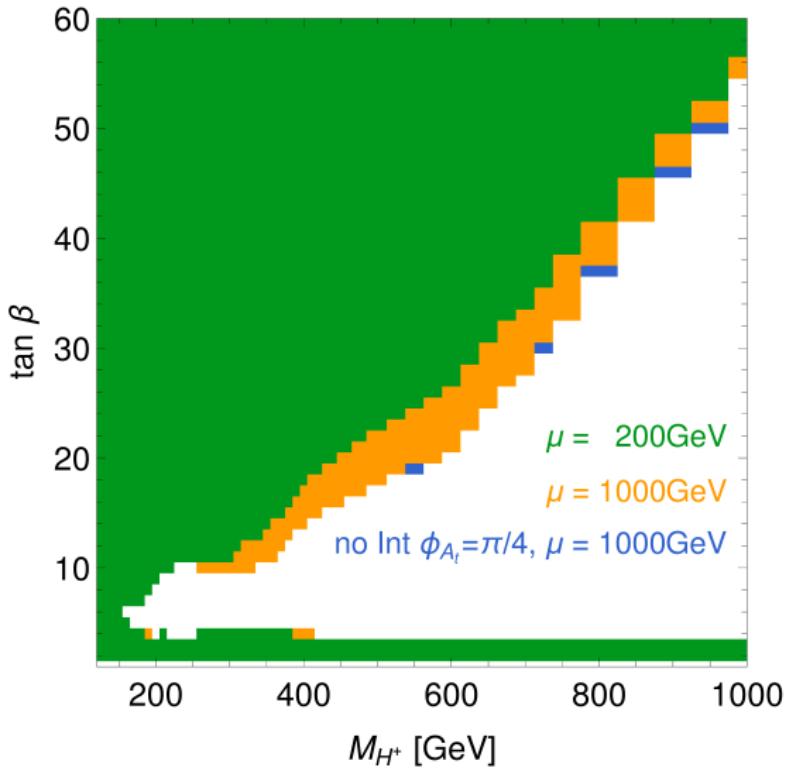
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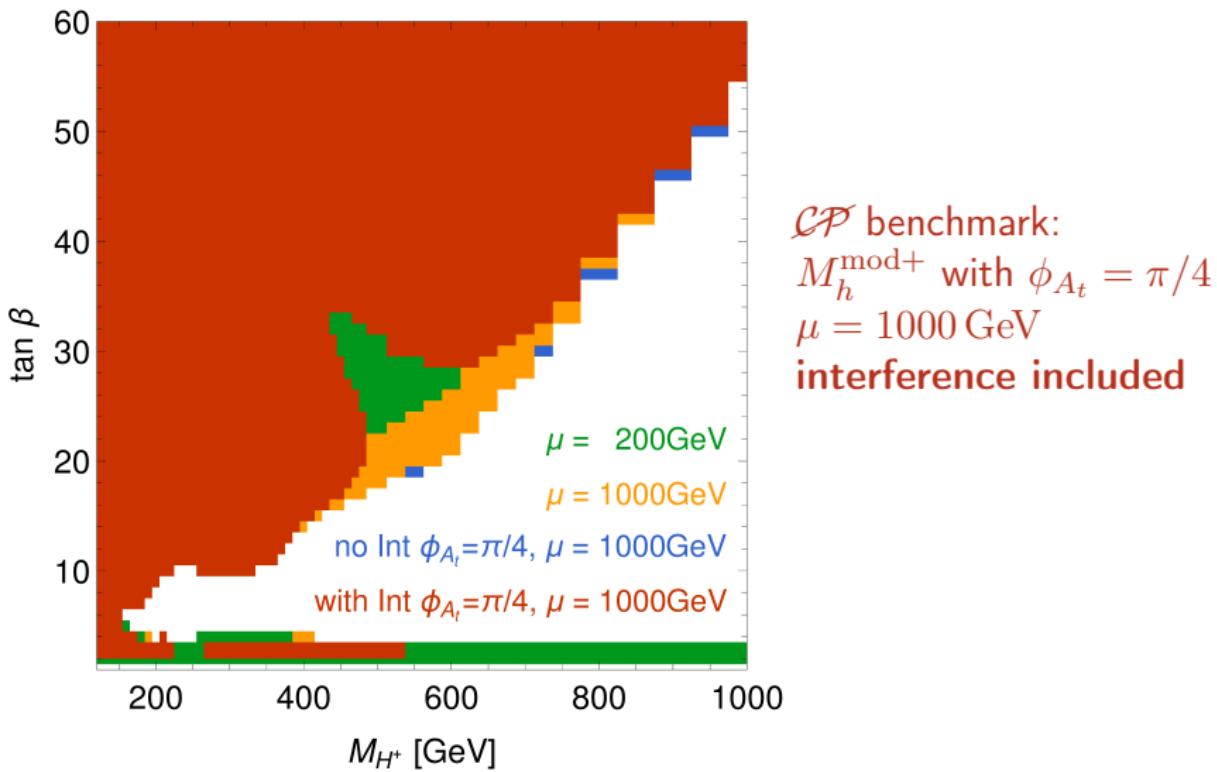
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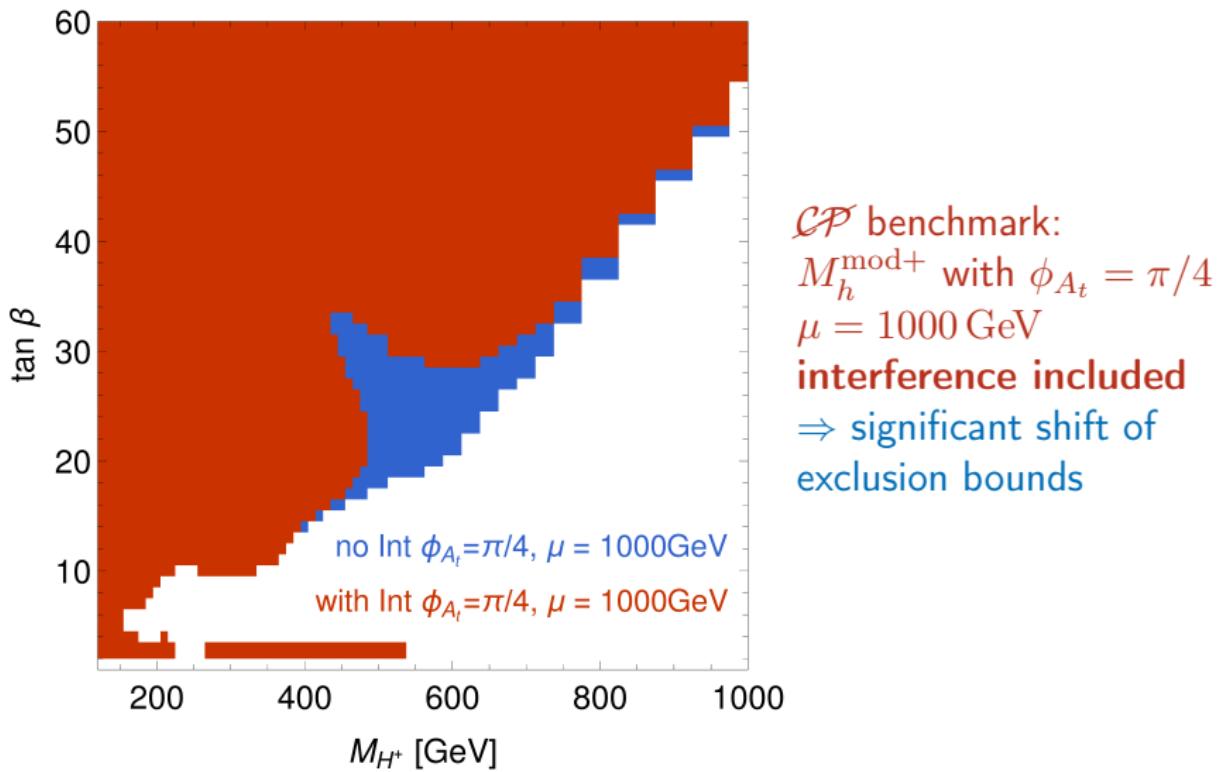
Impact of the interference on exclusion bounds

HiggsBounds with interference contribution



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Summary: Interference in MSSM Higgs searches

Interference of quasi degenerate resonances

- ▶ interference between Higgs bosons beyond standard NWA
- ▶ h_2, h_3 nearly degenerate in large parameter space

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\mathcal{CP} -violating interference in MSSM Higgs searches

- ▶ $h_2 - h_3$ interference relevant in \mathcal{CP} -violating benchmark scenario
- ▶ phase ϕ_{A_t} can have significant impact on exclusion limits
- ▶ outlook: include other phases and interference in gluon fusion

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Thank you!

Backup material

- ▶ Full Higgs propagators
- ▶ Definition of \hat{Z} -factors
- ▶ BW \hat{Z} propagator approximation I
- ▶ BW \hat{Z} propagator approximation II
- ▶ Effective couplings
- ▶ Scenario $\Delta M, \Gamma$ for $h - H$ interference
- ▶ Impact of ϕ_{A_t}
- ▶ Impact of μ
- ▶ HiggsBounds
- ▶ $M_h^{\text{mod}+}$ scenario

Full mixing propagators



mixing self-energies $\hat{\Sigma}_{ij}(p^2)$, $i, j = h, H, A$

- mass matrix $\mathbf{M}_{ij} = m_i^2 \delta_{ij} - \hat{\Sigma}_{ij}(p^2)$

2-point vertex functions: $\hat{\Gamma}_{hHA} = i [p^2 \mathbf{1} - \mathbf{M}(p^2)]$

propagator matrix: $\Delta_{hHA}(p^2) = - [\hat{\Gamma}_{hHA}(p^2)]^{-1}$

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

complex poles of propagators:

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

- higher-order masses M_{h_a} and widths Γ_{h_a} , $a = 1, 2, 3$

interaction eigenstates $\mathbf{h}, \mathbf{H}, \mathbf{A} \rightarrow$ mass eigenstates $\mathbf{h}_1, \mathbf{h}_2, \mathbf{h}_3$

Finite wave function normalisation Z-factors

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

[Chankowski, Pokorski, Rosiek '93], [Frank, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein '07],
[Williams, Rzehak, Weiglein '11]...

$$\hat{Z}_{ai} = \frac{1}{1 + \hat{\Sigma}_{ii}^{\text{eff}}'(\mathcal{M}_{h_a}^2)}, \quad \hat{Z}_{aj} = \frac{\Delta_{ij}(\mathcal{M}_{h_a}^2)}{\Delta_{ii}(\mathcal{M}_{h_a}^2)}$$

$$\begin{pmatrix} \hat{\Gamma}_{h_a} \\ \hat{\Gamma}_{h_b} \\ \hat{\Gamma}_{h_c} \end{pmatrix} = \hat{\mathbf{Z}} \cdot \begin{pmatrix} \hat{\Gamma}_h \\ \hat{\Gamma}_H \\ \hat{\Gamma}_A \end{pmatrix}, \quad \hat{\mathbf{Z}}_{aj} = \sqrt{\hat{Z}_a} \hat{Z}_{aj}$$

$$p^2 = \mathcal{M}_a^2 - \frac{\cancel{h}_a}{\hat{Z}_{ah}} \cancel{\hat{\Gamma}}_{h_a} = \sqrt{\hat{Z}_a} \left(\frac{\cancel{h}_a}{\hat{Z}_{ah}} \cancel{\hat{\Gamma}}_h + \frac{\cancel{h}_a}{\hat{Z}_{aH}} \cancel{\hat{\Gamma}}_H + \frac{\cancel{h}_a}{\hat{Z}_{aA}} \cancel{\hat{\Gamma}}_A \right) + \dots$$

Breit-Wigner approximation of full propagators

- Breit-Wigner propagator (mass basis)

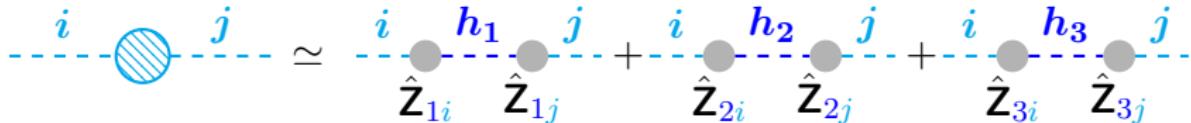
$$\Delta_a^{\text{BW}}(p^2) = \frac{i}{p^2 - M_{h_a}^2 + iM_{h_a}\Gamma_{h_a}}$$

- approximation of full propagator (interaction basis) around $p^2 \simeq \mathcal{M}_{h_a}^2$:

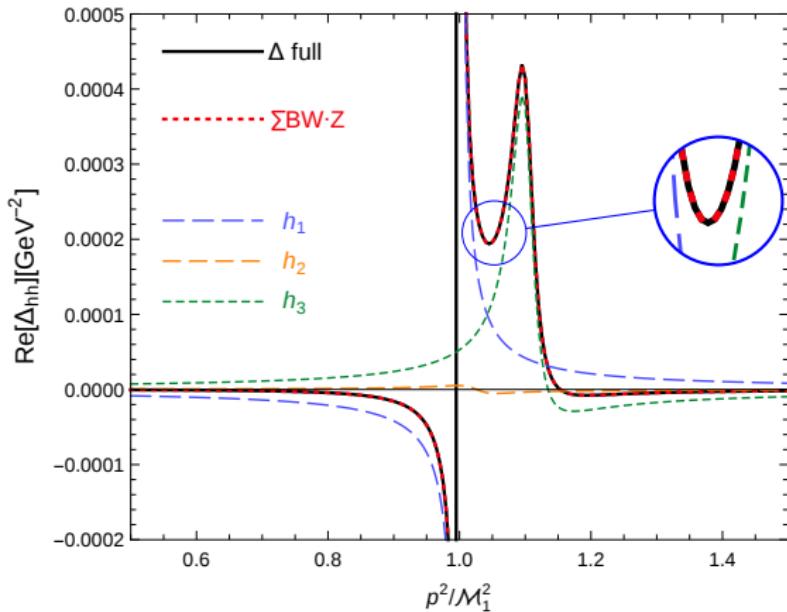
$$\Delta_{ii}(p^2) \simeq \Delta_a^{\text{BW}}(p^2) \hat{\mathbf{Z}}_{ai}^2$$

- consider all 3 complex poles \mathcal{M}_a^2 , $a = 1, 2, 3$

$$\Delta_{ij}(p^2) \simeq \sum_{a=1,2,3} \hat{\mathbf{Z}}_{ai} \Delta_a^{\text{BW}}(p^2) \hat{\mathbf{Z}}_{aj}$$



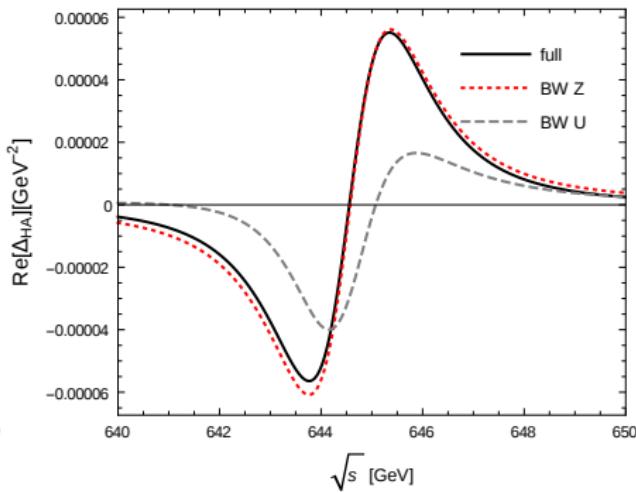
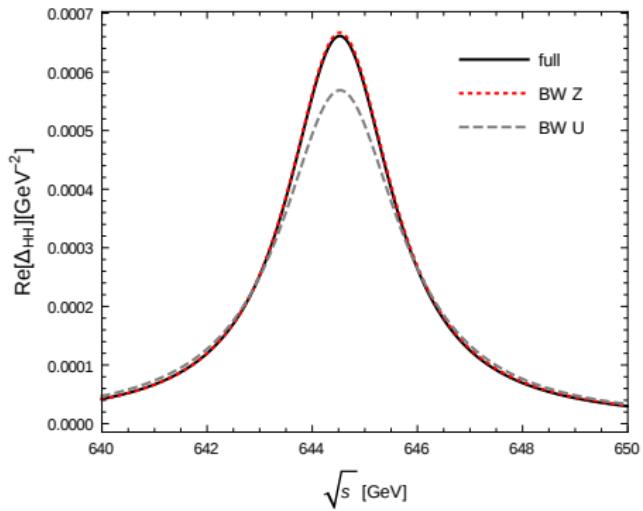
Comparison: Breit-Wigner and full propagators



- scenario with 3 light Higgs bosons \Rightarrow **overlap** of resonance regions

Δ_{ij} very well approximated by **sum** of BW propagators and \hat{Z} -factors

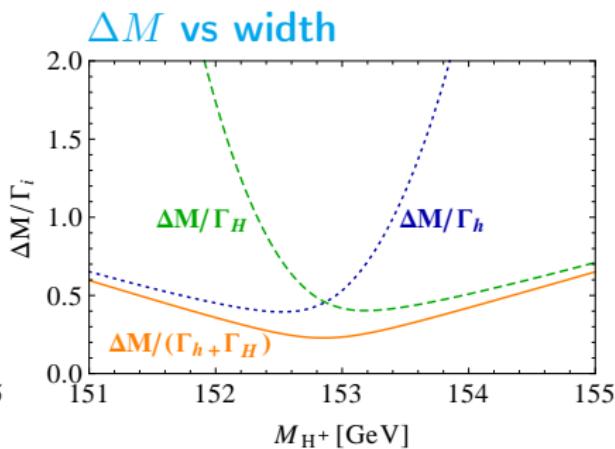
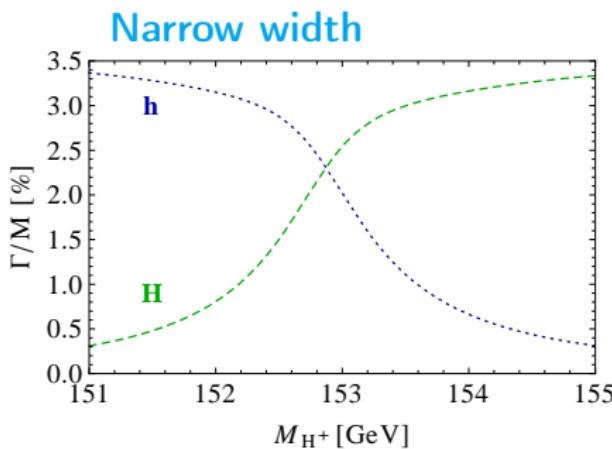
\hat{Z} -factors vs. effective couplings



Scenario with quasi degenerate h, H

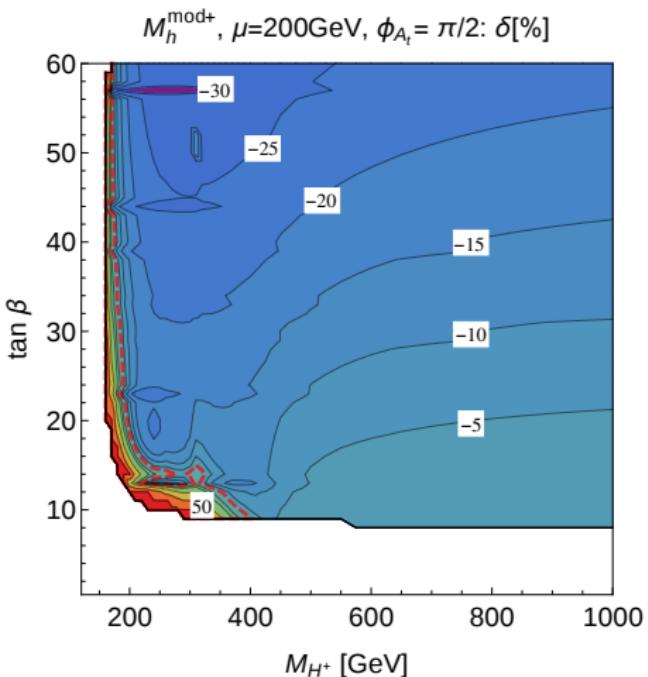
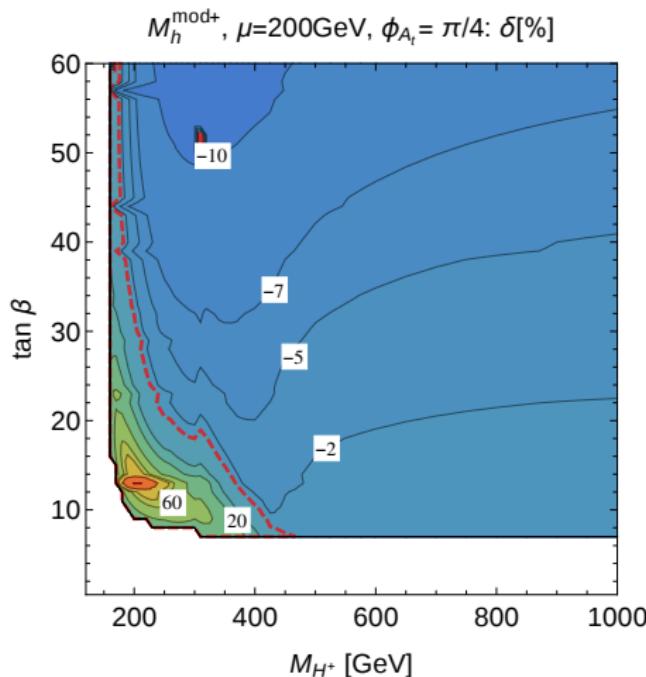
Test case: M_h^{\max} -like scenario with real parameters

- ▶ large $\tan \beta = 50$, low M_A, M_{H^\pm}
- ▶ $\Delta M = M_H - M_h$ small



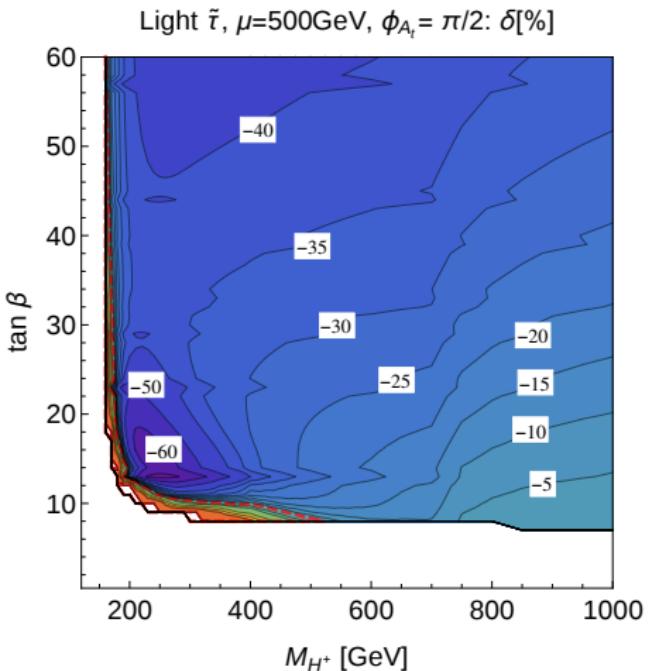
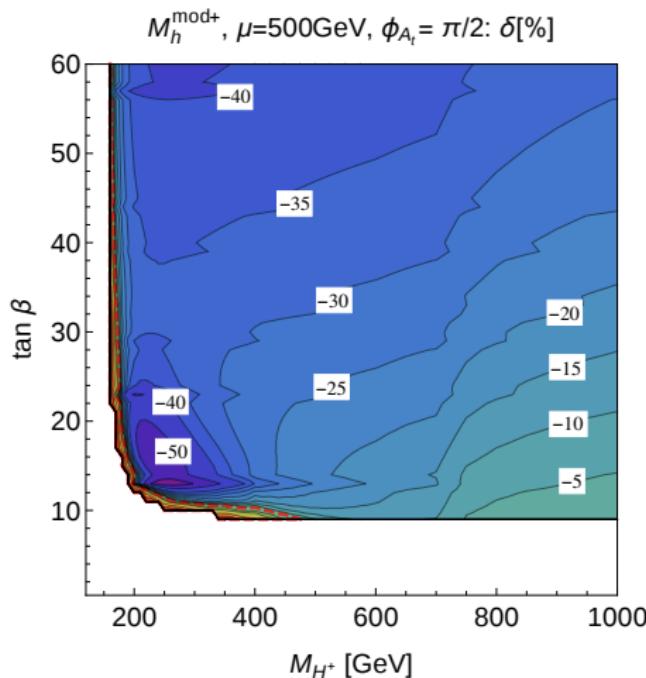
expect sizable interference around $\Delta M_{hH} \lesssim \Gamma_{h/H}$

Effect of ϕ_{A_t} on cross section $b\bar{b} \rightarrow h_a \rightarrow \tau^+\tau^-$



Mostly negative effects of δ in M_{h_1} -allowed region

Effect of ϕ_{A_t} on cross section $b\bar{b} \rightarrow h_a \rightarrow \tau^+\tau^-$



Stronger effect with larger μ

Testing Higgs model predictions against observed limits

- ▶ input: # neutral and charged Higgs bosons in the model, xs, BR, masses, widths,...
- ▶ for MSSM: can be linked to FeynHiggs
- ▶ comparison to data from LEP, Tevatron, LHC
- ▶ **based on standard NWA**
- ▶ output: if point excluded @ 95%CL

We included the interference terms
by rescaling the $b\bar{b} \rightarrow h_a$ production as input:

$$\frac{\sigma^{\text{MSSM}}(b\bar{b} \rightarrow h_a)}{\sigma^{\text{SM}}(b\bar{b} \rightarrow h)} \longrightarrow \frac{\sigma^{\text{MSSM}}(b\bar{b} \rightarrow h_a)}{\sigma^{\text{SM}}(b\bar{b} \rightarrow h)} \cdot (1 + \eta_a)$$

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

$$M_{\text{SUSY}} = 1000 \text{ GeV}$$

$$M_2 = 200 \text{ GeV}$$

$$X_t^{\text{OS}} = 1.5 M_{\text{SUSY}}$$

$$A_t = A_b = A_\tau$$

$$M_3 = 1500 \text{ GeV}$$

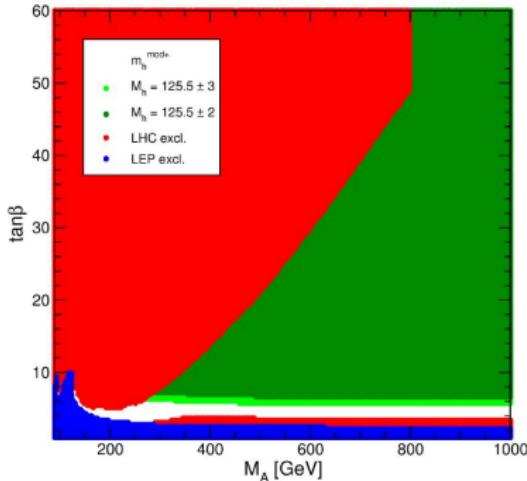
$$M_{\tilde{f}_3} = M_{\text{SUSY}}$$

$$M_{\tilde{q}_{1,2}} = 1500 \text{ GeV}$$

$$M_{\tilde{l}_{1,2}} = 500 \text{ GeV}$$

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

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



Major part of open region compatible with M_h^{exp}