Interference effects in MSSM Higgs searches

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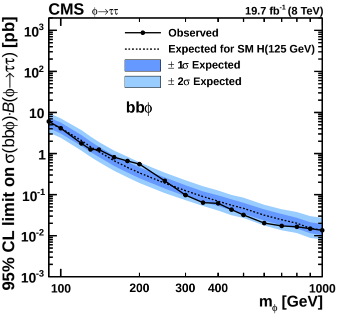
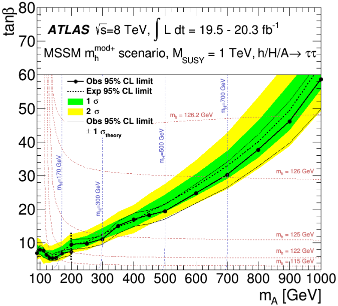
Searches for additional Higgs bosons

→ talk by G. Quast

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

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

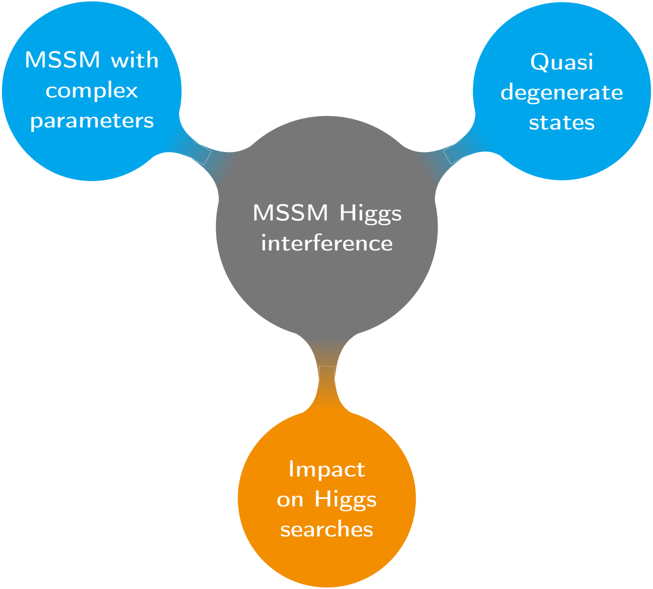




Limitation of interpretation in standard NWA

interference terms neglected, relevant especially with complex phases

Outline


MSSM with complex parameters
Quasi degenerate states
MSSM Higgs interference
Impact on Higgs searches

Complex phases in the MSSM Higgs sector

→ talk by S. Patel

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_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 $\boldsymbol{h, H, A}$ → mass eigenstates $\boldsymbol{h_1, h_2, h_3}$

Breit-Wigner approximation of full propagators

- **Breit-Wigner** (BW) propagator (mass basis) with complex pole $\mathcal{M}^2_{h_a}$

$$\Delta_a^{\mathrm{BW}}(p^2) = \frac{i}{p^2 - \mathcal{M}^2_{h_a}} = \frac{i}{p^2 - M^2_{h_a} + i M_{h_a} \Gamma_{h_a}}$$

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

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

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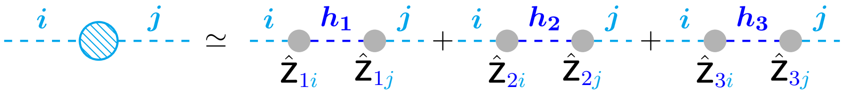
- consider all 3 complex poles $\mathcal{M}^2_a,\ a = 1,2,3$

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

[Fowler, EF, Weiglein (in preparation)]



Interference of quasi degenerate states

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

- off-shell effects
- interference
  - peak - continuum
  - 2 close-by resonances: $\Delta M \leq \Gamma_1 + \Gamma_2$

    $\hookrightarrow$ factorised interference extension of NWA [EF, Thewes, Weiglein '14]

    $\hookrightarrow$ other interference approaches

    [Cacciapaglia, Deandrea, Curtis '09] [Blas, Lizana, Perez-Victoria '12]

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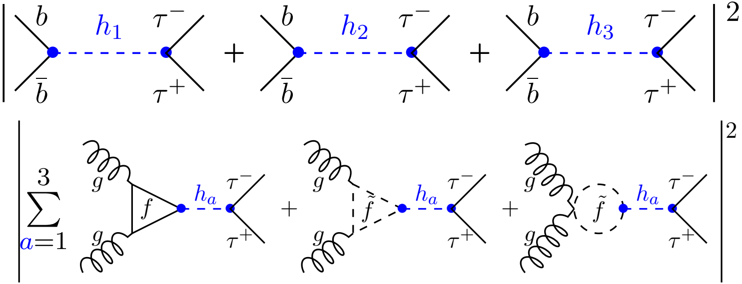
MSSM: Higgs bosons can be quasi degenerate and interfere

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

Production, decay and interference with ϕ_{A_t}

Higgs bosons as intermediate states in $\{b\bar{b}, gg\} \to h_a \to \tau\tau$



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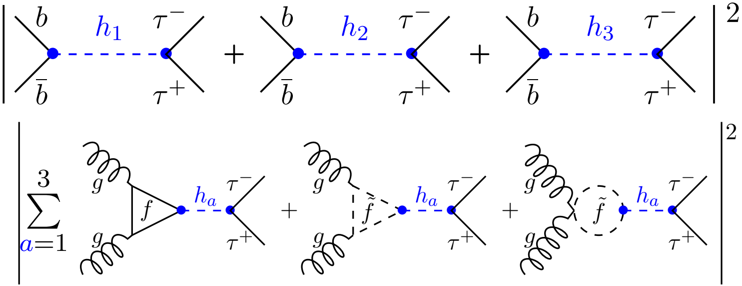


consider $\phi_{A_t} \neq 0$ in trilinear coupling $A_t = |A_t| e^{i\phi_{A_t}}, \quad A_b = A_\tau = A_t$

- impact on masses, couplings, widths, cross sections, mixing
- $\not{C}\not{P}$ H-A mixing and interference
    - full propagator mixing Δ_{hHA} vs. BW propagators$\times$on-shell $\hat{\mathbf{Z}}$-factors
    - coherent $|\sum h_a|^2$ vs. incoherent sum $\sum |h_a|^2$

$\mathcal{CP}$ benchmark scenario

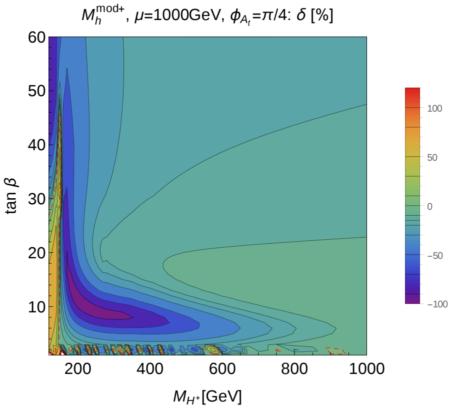
$M_h^{\mathrm{mod}+}$ scenario with $\mu = 1000\,\mathrm{GeV}$ and $\phi_{A_t} = \pi/4$

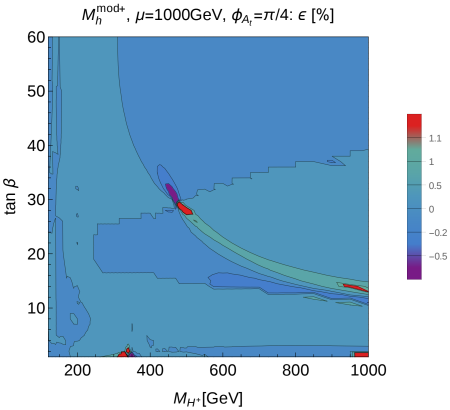
- effect of ϕ_{A_t} on cross section:

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

- Breit-Wigner approximation:

$$\boxed{\epsilon := \frac{\sigma_{\mathrm{BW}\hat{\mathbf{z}}}}{\sigma_{\mathrm{full}}} - 1}$$

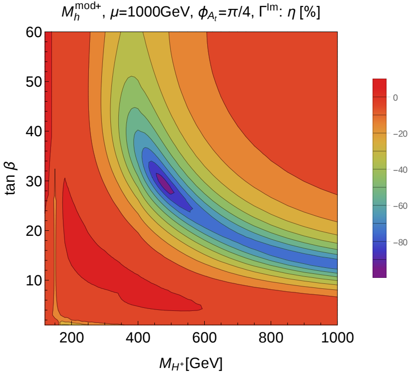




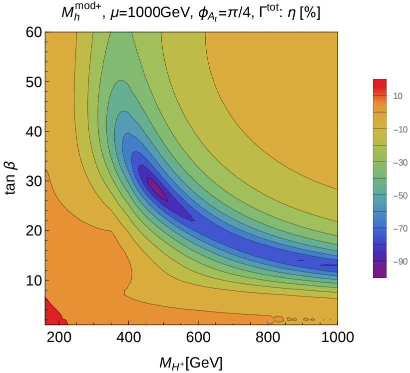
Pure interference effect in $\{b\bar{b}, gg\} \to h_a \to \tau\tau$

relative interference contribution $\boxed{\eta := \frac{\sigma_{\text{int}}(\phi_{A_t})}{\sigma_{\text{incoh}}(\phi_{A_t})}}$

$b\bar{b}h_a$ production



gluon fusion



drastic, destructive interference effect

Combination of precise building blocks

Production: cross sections of $b\bar{b} \to h_a$ and $gg \to h_a$ from `FeynHiggs`

Decay: branching ratios for $h_a \to \tau^+\tau^-$ from `FeynHiggs`

Combination of precise building blocks

Production: cross sections of $b\bar{b} \to h_a$ and $gg \to h_a$ from `FeynHiggs`

$\downarrow$

Interference incl. propagator corrections:

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

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

$\hookrightarrow$ will also be done analogously for $gg \to h_a$

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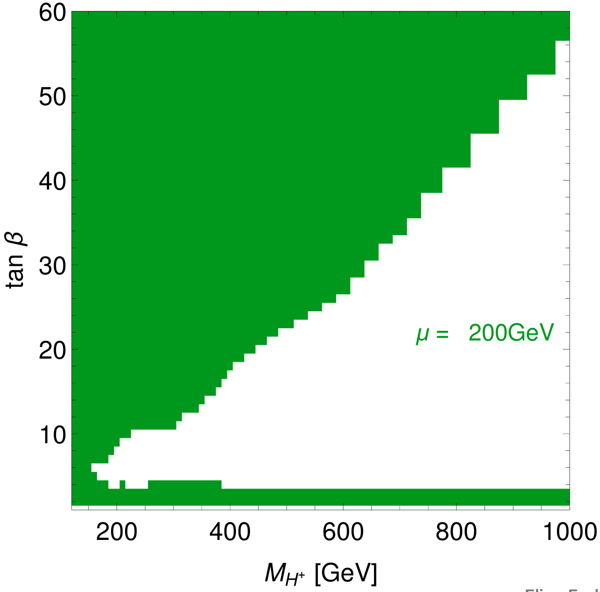
$\Downarrow$

Confront with experimental data: input for `HiggsBounds`

Impact of the interference on exclusion bounds

HiggsBounds

PRELIMINARY



default $M_h^{\mathrm{mod}+}$ scenario:
real parameters
$\mu = 200\,\mathrm{GeV}$

Impact of the interference on exclusion bounds

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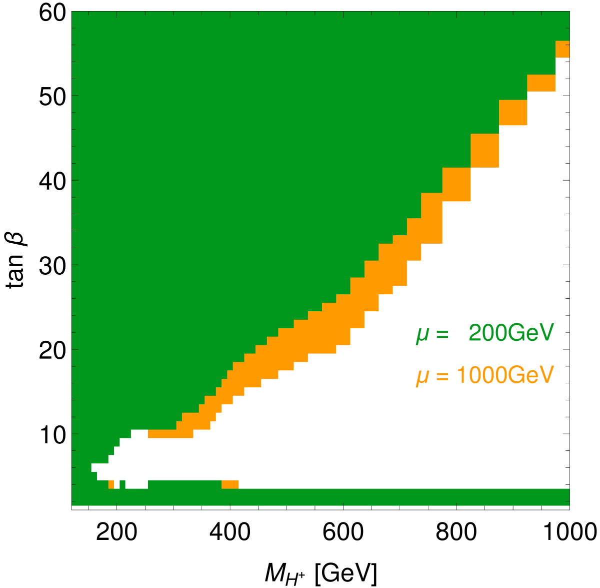
PRELIMINARY



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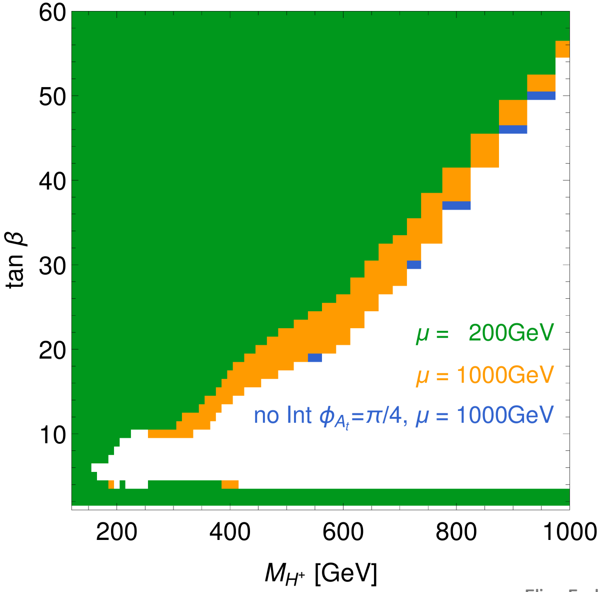
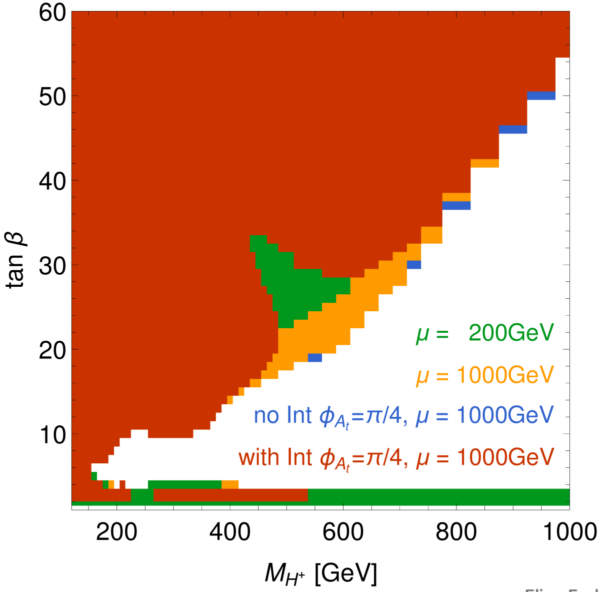


$\not{\mathcal{CP}}$ benchmark:
$M_h^{\text{mod}+}$ with $\phi_{A_t} = \pi/4$
$\mu = 1000\,\text{GeV}$
interference neglected

Impact of the interference on exclusion bounds

`HiggsBounds` with interference in $b\bar{b} \to h_a \to \tau\tau$

PRELIMINARY



$\not{C}\not{P}$ benchmark:
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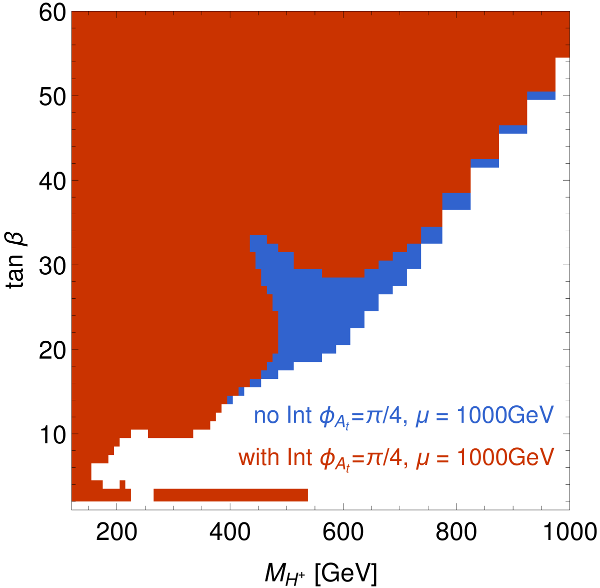

$\cancel{\mathcal{CP}}$ benchmark:
$M_h^{\text{mod}+}$ with $\phi_{A_t} = \pi/4$
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interference included
$\Rightarrow$ significant shift of exclusion bounds

Summary: Interference in MSSM Higgs searches

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- 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

- $\boldsymbol{h_2 - h_3}$ interference relevant in $\mathcal{CP}$-violating benchmark scenario
- phase $\boldsymbol{\phi_{A_t}}$ can have significant impact on exclusion limits
- Outlook:
  - include interference in gluon fusion and other phases
  - use gluon fusion cross section with complex parameters from `SusHi`
  - automatise interference calculation for `HiggsBounds`

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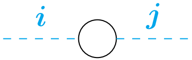
Thank you!

Backup material

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

Full mixing propagators



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

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

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

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

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

complex poles of propagators: $\boxed{\mathcal{M}_{h_a}^2 = M_{h_a}^2 - i M_{h_a} \Gamma_{h_a}}$

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

interaction eigenstates $\boldsymbol{h, H, A} \rightarrow$ mass eigenstates $\boldsymbol{h_1, h_2, h_3}$

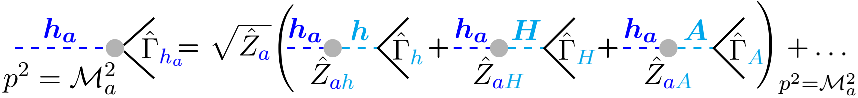
Finite wave function normalisation Z-factors

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

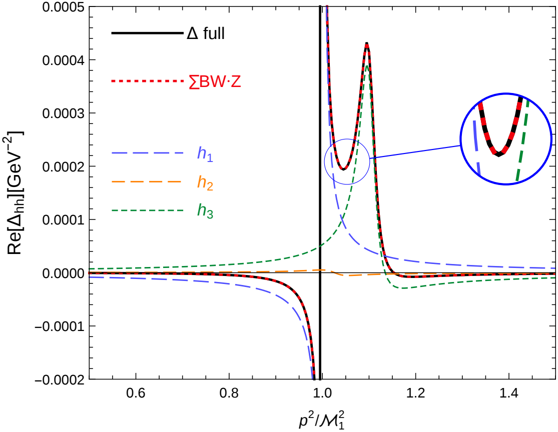
  [Chankowski, Pokorski, Rosiek '93], [Frank, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein '07], [Williams, Rzehak, Weiglein '11]...

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

$$\begin{pmatrix} \hat{\Gamma}_{h_a} \\ \hat{\Gamma}_{h_b} \\ \hat{\Gamma}_{h_c} \end{pmatrix} = \hat{\mathbf{Z}} \cdot \begin{pmatrix} \hat{\Gamma}_{h} \\ \hat{\Gamma}_{H} \\ \hat{\Gamma}_{A} \end{pmatrix}, \quad \hat{\mathbf{Z}}_{aj} = \sqrt{\hat{Z}_a}\hat{Z}_{aj}$$



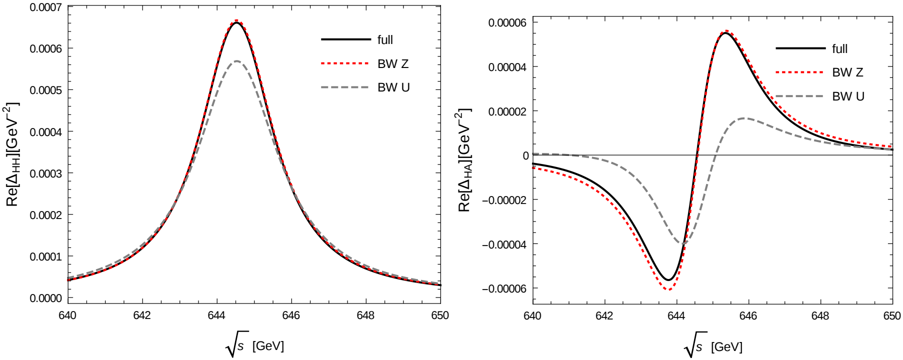
Comparison: Breit-Wigner and full propagators



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

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

$\hat{Z}$-factors vs. effective couplings

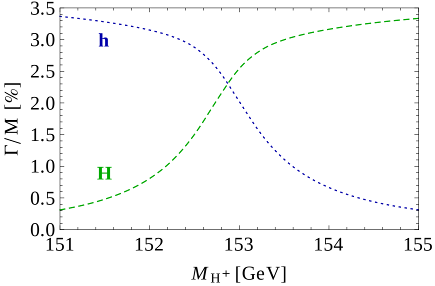


Scenario with quasi degenerate h,H

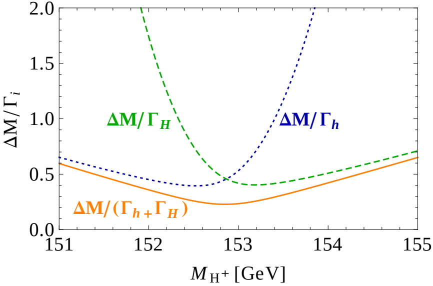
Test case: $M_h^{\max}$-like scenario with real parameters

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

Narrow width

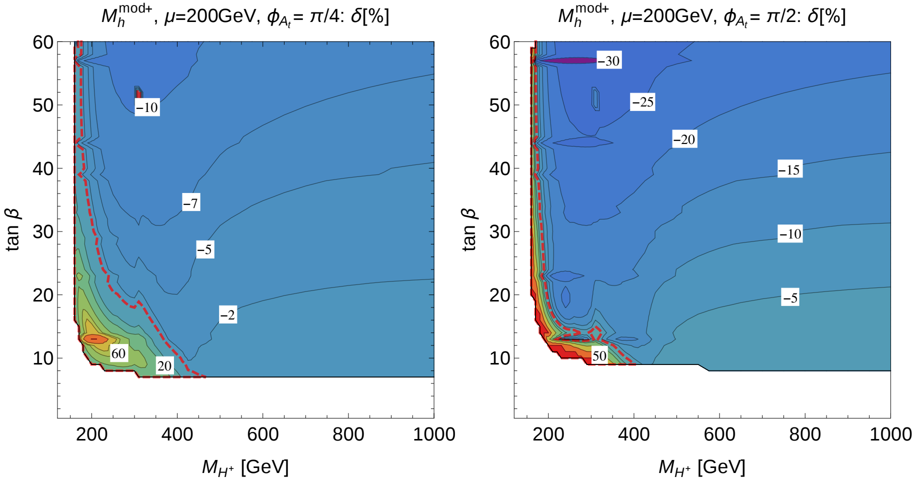


ΔM vs width



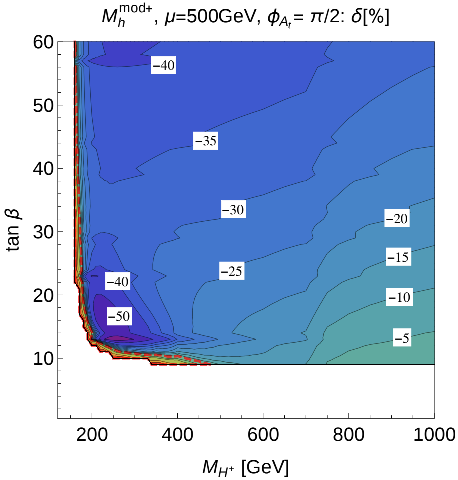
$\boxed{\text{expect sizable interference around } \Delta M_{hH} \lesssim \Gamma_{h/H}}$

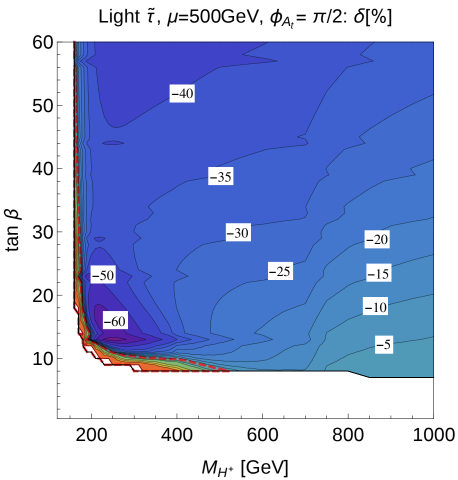
Effect of ϕ_{A_t} on cross section $b\bar{b} \to h_a \to \tau^+\tau^-$



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

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



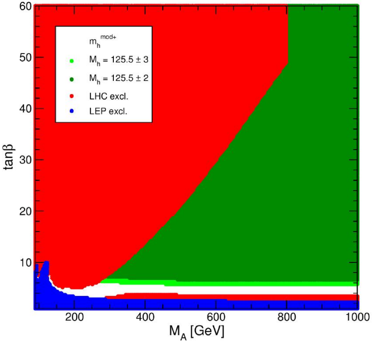


Stronger effect with larger μ

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

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

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



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