

# Interference effects in MSSM Higgs searches

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DESY

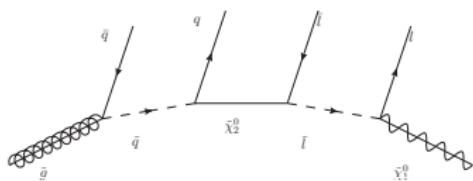
[1411.4652] with Silja Thewes and Georg Weiglein  
[work in progress] with Sven Heinemeyer, Oscar Stål and Georg Weiglein

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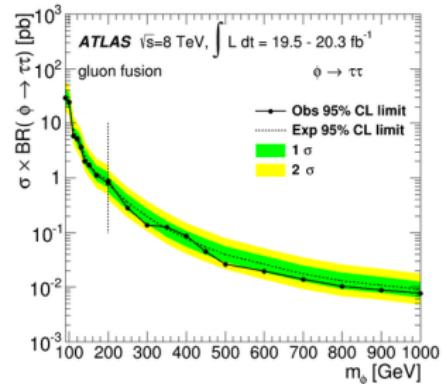


# Useful approximation for New Physics searches

- BSM: extended spectrum → typical cascade decays
- many-particle final state difficult at higher order
- ↵ simplified by factorisation into production × decay
- application in MC generators, experimental limits

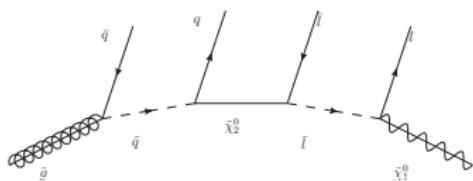


$$\sigma_{\text{production}} \times BR_1 \times BR_2 \times BR_3 \times BR_4$$

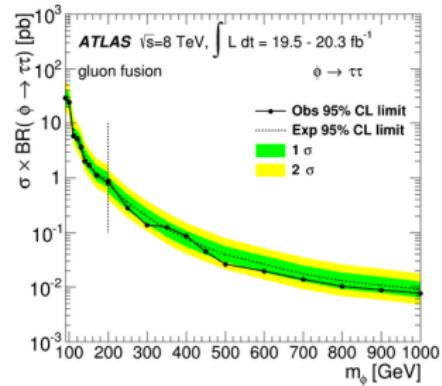


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Standard narrow-width approximation neglects interference term  
extension necessary to combine interference and higher-order effects

# Outline

- 1 Higgs mixing in MSSM with real and complex parameters
- 2 Generalised NWA for interference effects
- 3 Impact of interference effects on LHC Higgs searches



# Outline

## 1 Higgs mixing in MSSM with real and complex parameters

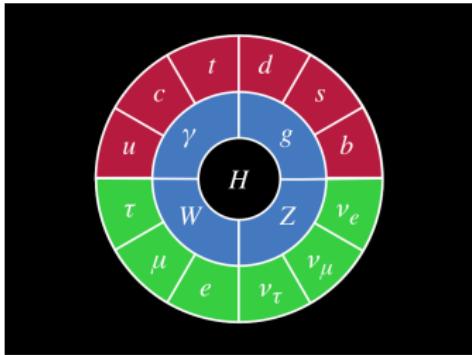
- Introduction of the MSSM
- The MSSM Higgs sector
  - with real parameters
  - with complex phases
- Breit-Wigner approximation of full Higgs propagators

## 2 Generalised NWA for interference effects

## 3 Impact of interference effects on LHC Higgs searches



# Introduction of the MSSM

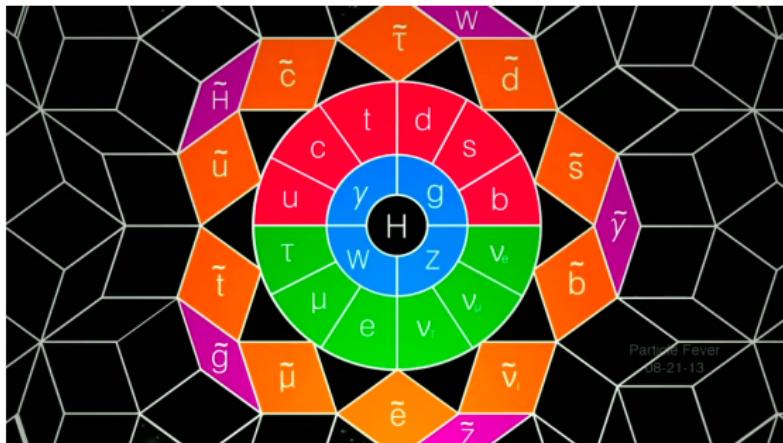


[image: *Particle Fever* movie]

## Shortcomings of the SM

- ▶ Higgs mass: hierarchy
- ▶ no DM candidate
- ▶ not sufficient  $\mathcal{CP}$
- ▶ no unification of gauge couplings

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## Minimal Supersymmetric Standard Model (MSSM): new particles

- ▶ 2nd Higgs doublet
- ▶ sfermions  $\tilde{f}$ , gluino  $\tilde{g}$
- ▶ bino, wino, higgsinos  $\rightarrow$  neutralinos  $\tilde{\chi}_i^0$ , charginos  $\tilde{\chi}_j^\pm$

# 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

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

$$m_i^2 = m_{\mathcal{H}_i}^2 + |\mu|^2, \quad i = 1, 2$$

$$m_{12}^2 = |m_{12}| e^{i\xi}$$

Complex phases  $\xi$  can be rotated away,  $\xi$  vanishes at minimum of  $V_H$



# Relations at lowest order

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

## Physical states

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

## Input parameters

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

Masses determined by  $m_A, \tan \beta$

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

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

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

But higher-order corrections important



# Complex phases: motivation and constraints

## Motivation

- ▶ baryon asymmetry of the universe requires more  $\mathcal{CP}$ -violation than in CKM matrix
- ▶ parameters from **other sectors** can in principle 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]

- ▶  $\phi_{A_{f1,2}}$  more strongly constrained than  $\phi_{A_{t,b}}$
- ▶  $\phi_{M_1}$  can be sizeable
- ▶  $\phi_{M_3}$  strongly constrained only if  $\tilde{f}_{1,2}$  light
- ▶  $\phi_\mu$  tight limits

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



# Mixing of Higgs bosons

## Real case: $\mathcal{CP}$ conserved

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

## Complex 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



# Full mixing propagators

mixing self-energies  $\hat{\Sigma}_{ij}(p^2)$

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

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



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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  $\Gamma_{h_a}$

reduce full  $6 \times 6$  ( $h, H, A, G, \gamma, Z$ ) mixing  $\rightarrow 3 \times 3$  ( $\mathbb{C}$ ) or  $2 \times 2$  ( $\mathbb{R}$ )



# 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]...

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

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

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



# Breit-Wigner approximation of full propagators

- Breit-Wigner propagator (mass basis)

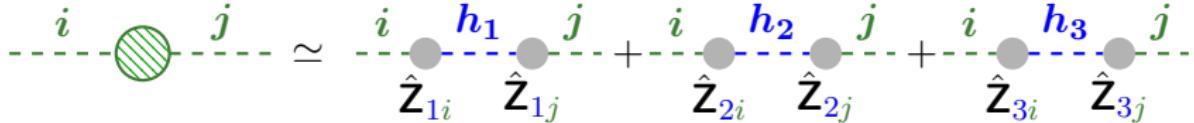
$$\Delta_a^{\text{BW}}(p^2) = \frac{i}{p^2 - M_{h_a}^2 + iM_{h_a}\Gamma_{h_a}}$$

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

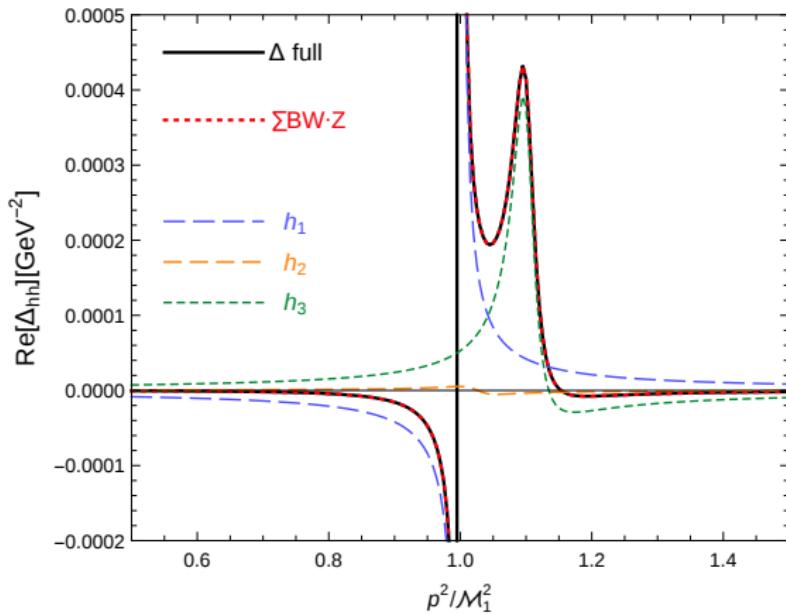
$$\Delta_{ii}(p^2) \simeq \Delta_a^{\text{BW}}(p^2) \hat{\mathbf{Z}}_{ai}^2$$

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

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



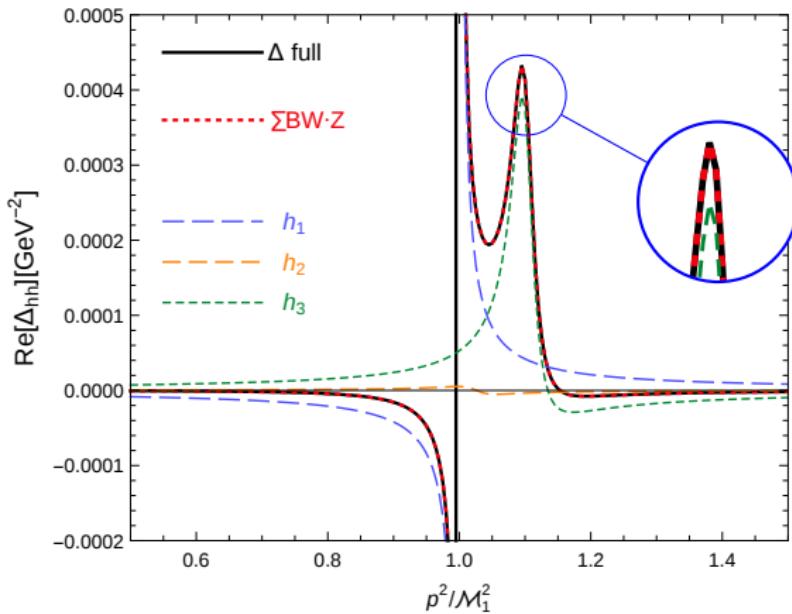
# Comparison: Breit-Wigner and full propagators



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

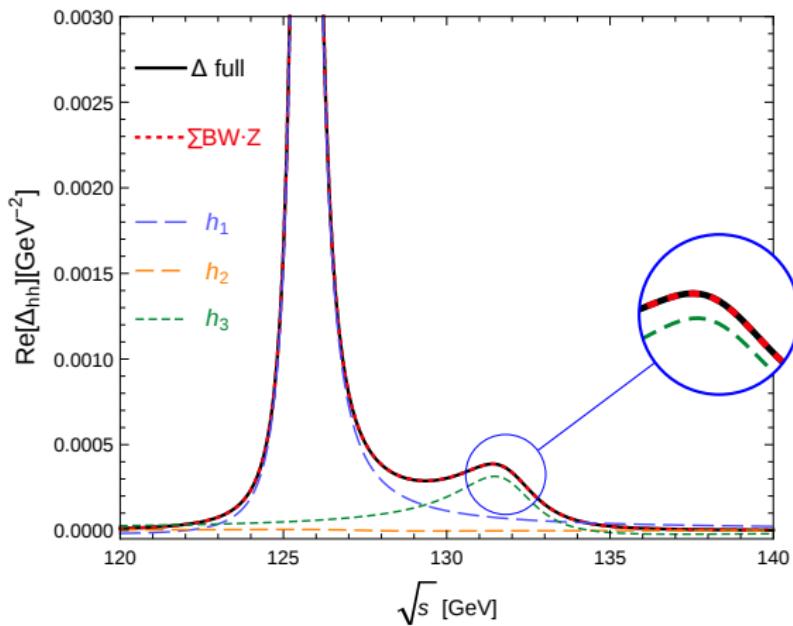


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# Breit-Wigner propagators in cross sections

- Contribution of one resonance  $h_a$

$$\hat{\Gamma}_{h_a}^X \otimes \hat{\Gamma}_{h_a}^Y = \sum_{i,j=h,H,A} \hat{\Gamma}_i^X \hat{\mathbf{z}}_{ai} \hat{\mathbf{z}}_{aj} \otimes \hat{\Gamma}_j^Y$$

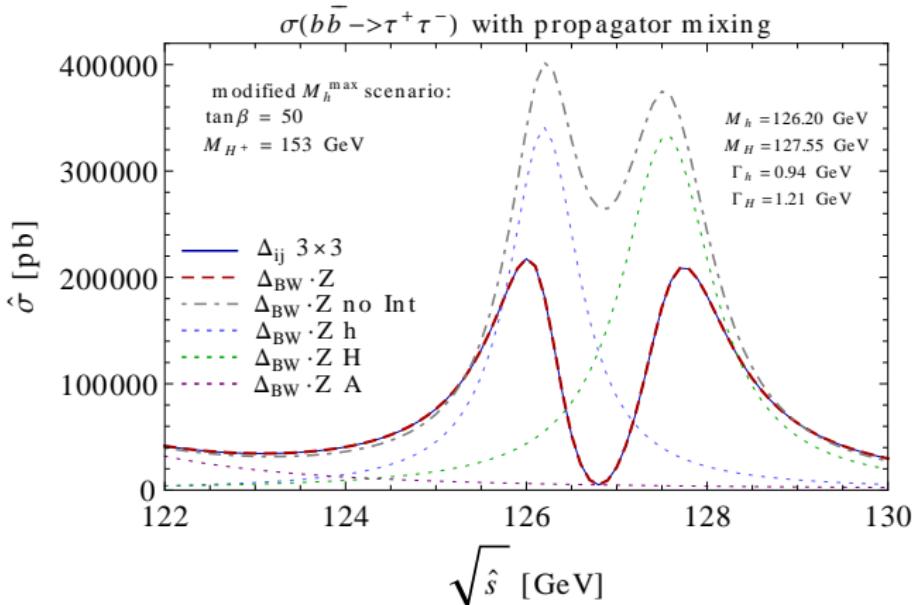
- Include all 3 resonances and their overlap

$$\sum_{i,j} \hat{\Gamma}_i^X \Delta_{ij}(p^2) \hat{\Gamma}_j^Y \simeq \sum_{a,i,j} \hat{\Gamma}_i^X \hat{\mathbf{z}}_{ai} \Delta_a^{\text{BW}}(p^2) \hat{\mathbf{z}}_{aj} \hat{\Gamma}_j^Y$$

- example process:  $b\bar{b} \rightarrow \tau^+ \tau^-$

$$\left| \hat{\Gamma}_{b\bar{b}}^X \otimes \hat{\Gamma}_{\tau^+\tau^-}^Y + \hat{\Gamma}_{b\bar{b}}^X \otimes \hat{\Gamma}_{\tau^+\tau^-}^Y + \hat{\Gamma}_{b\bar{b}}^X \otimes \hat{\Gamma}_{\tau^+\tau^-}^Y \right|^2$$

# BW approximation and interference effect



- ▶ Full propagators well approximated by sum of BW and  $\hat{Z}$ -factors
- ▶ significant **negative interference** term



# Summary I: Mixing of MSSM Higgs bosons

- ▶ Higgs sector  $\mathcal{CP}$  conserving at tree-level
- ▶ **complex parameters** can enter in loops
- ▶ interaction eigenstates  $h, H, A \rightarrow$  mass eigenstates  $h_1, h_2, h_3$
- ▶ full **mixing** well approximated by Breit-Wigner propagators and  $\hat{Z}$  factors
- ▶ **interference** can be large also in  $\mathcal{CP}$  conserving case



# Outline

## 1 Higgs mixing in MSSM with real and complex parameters

## 2 Generalised NWA for interference effects

- gNWA at tree level
  - Standard NWA
  - Approximation of the interference term
- Example process with h-H interference at LO
- gNWA at higher order

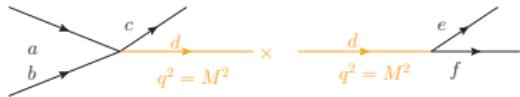
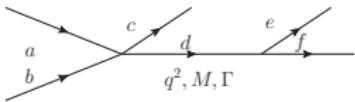
## 3 Impact of interference effects on LHC Higgs searches



# Standard Narrow-Width Approximation (NWA)

generic example:

$$ab \xrightarrow{d} cef$$



Factorisation: production  $\times$  decay

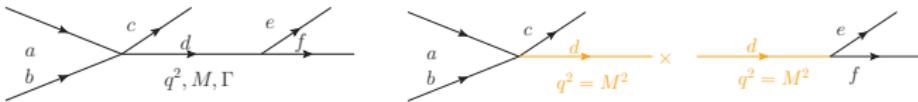
- instead of Breit-Wigner propagator  $\Delta^{\text{BW}}(q^2) = \frac{i}{q^2 - M^2 + iM\Gamma}$
- on-shell production and decay of particle with mass  $M$ :

$$\sigma_{ab \rightarrow cef} \approx \sigma_{ab \rightarrow cd}(q^2 = M^2) \cdot BR_{d \rightarrow e f}$$

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## Factorisation of the $n$ -particle phase space $d\Phi_n$

- $d\Phi_n \equiv dlips(P; p_1, \dots, p_f) = (2\pi)^4 \delta^{(4)}(P - \sum_{f=1}^n p_f) \prod_{f=1}^n \frac{d^3 p_f}{(2\pi)^3 2E_f}$
- here: kinematics of 3-body decay  $\rightarrow$  2-body  
 $d\Phi = dlips(\sqrt{s}; p_c, p_e, p_f) = dlips(\sqrt{s}; p_c, \mathbf{q}) \frac{dq^2}{2\pi} dlips(\mathbf{q}; p_e, p_f)$



# Validity and limitations of the NWA

- ▶ **narrow width**  $\Gamma \ll M$ , otherwise off-shell effects
  - uncertainty estimate  $\mathcal{O}\left(\frac{\Gamma}{M}\right)$
  - off-shell extension possible e.g. [Gigg, Richardson '08] [Kauer, Uhlemeyer '08]



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- ▶ production and decay sub-processes kinematically open
  - threshold extension e.g. [Kauer '08]
  - intermediate thresholds → off-shell effects enhanced
- ▶ **non-factorisable** corrections small
  - e.g. [Denner, Dittmaier, Roth '98] [Denner, Dittmaier, Roth, Wackerlo '00]



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e.g. [Denner, Dittmaier, Roth '98] [Denner, Dittmaier, Roth, Wackerlo '00]
- ▶ **no interference with other processes**

e.g. [Reuter '07] [Berdine, Kauer, Rainwater '07][Kalinowski, Kilian, Reuter, Robens, Rolbiecki '08]



# Interference of quasi degenerate resonances

## 1.) Degeneracy

Nearby resonances

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

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

## 2.) Simultaneous contributions

- ▶ Matrix elements  $\mathcal{M}_i, \mathcal{M}_j$
- ▶ if one of them suppressed:  
 $\sigma_{\text{Int}} \propto 2\text{Re}[\mathcal{M}_i \mathcal{M}_j^*] \simeq 0$



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## Examples of quasi degenerate states in BSM

- ▶ (N)MSSM
  - Higgs bosons
  - squarks
- ▶ 2-Higgs doublet model: Higgs bosons
- ▶ Extra dimensions: all states at one Kaluza-Klein level
- ▶ ...

Interference term can be relevant → include in NWA!



# Generalised NWA with interference term

## 2 steps for on-shell approximation of interference term

- ▶ matrix elements on-shell  $\mathcal{M}(q^2 = M^2)$ 
  - pro close to full result
  - con no automated evaluation of squared matrix elements



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- ▶ matrix elements on-shell  $\mathcal{M}(q^2 = M^2)$ 
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- ▶ 'interference weight factor'  $R$ :  $\sigma \approx \sum_i \sigma_{P_i} BR_i \cdot (1 + R_i)$ 
  - pro building blocks available as in sNWA:  $\sigma_P, \Gamma_D, \Gamma^{tot}, g_P, g_D$
  - con additional approximation  $M_h \approx M_H$



# Generalised NWA with interference term

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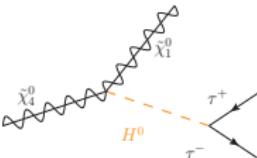
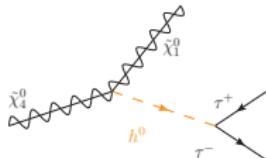
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accuracy vs. technical simplification of approximation

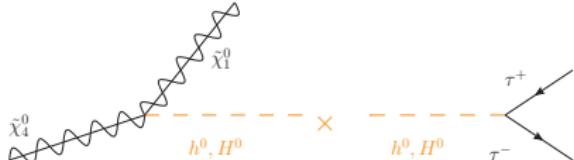


# Example process: $\Gamma(\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^0 \tau^+ \tau^-)$ via h, H

## 3-body decay



## NWA: 2-body decays



## Calculation

- decay widths: FeynArts/FormCalc/LoopTools
- tree-level amplitudes with Breit-Wigner propagators
- precise input quantities at 2-loop  $M, \Gamma, Z$ : FeynHiggs
- for consistent comparison: restricted to h,H-exchange
- interference term implemented in different approximations

# Scenario with quasi degenerate h,H

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

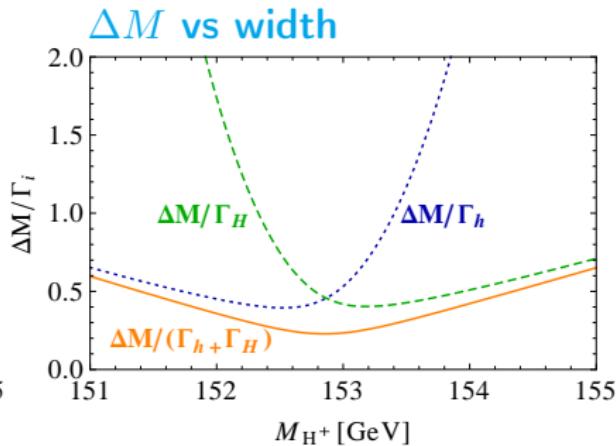
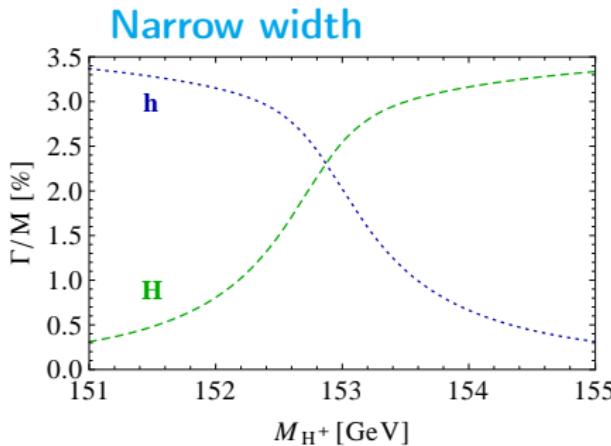
- ▶ large  $\tan \beta = 50$ , low  $M_A, M_{H^\pm}$
- ▶  $\Delta M = M_H - M_h$  small



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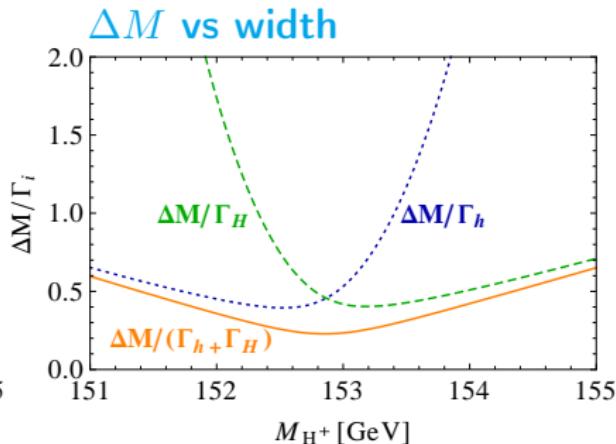
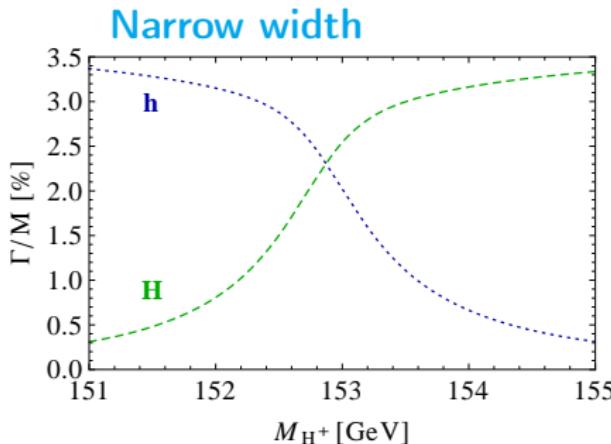
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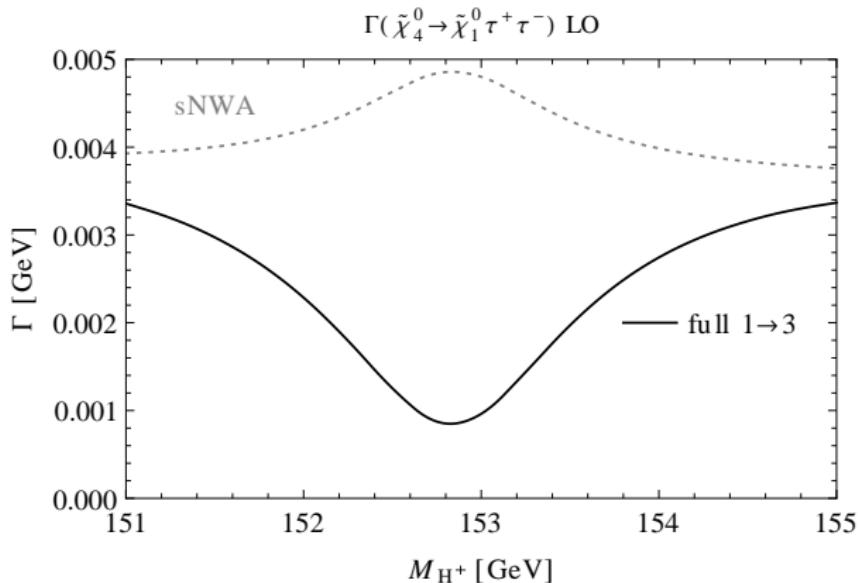
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expect sizable interference around  $\Delta M_{hH} \lesssim \Gamma_{h/H}$

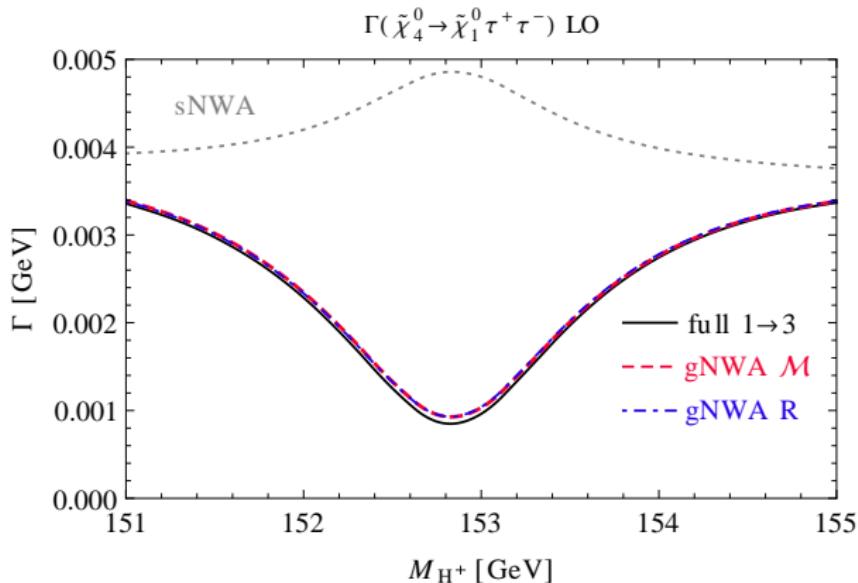
# Decay width $\Gamma(\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^0 \tau^+ \tau^-)$ at LO



- ▶ 'full':  $1 \rightarrow 3$  with  $h, H + \text{interference}$ , but without  $Z$
- ▶ sNWA:  
 $\Gamma_{P_h} \text{BR}_h + \Gamma_{P_H} \text{BR}_H$

large discrepancy between sNWA and full 3-body decay width

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- ▶ 'full':  $1 \rightarrow 3$  with  $h, H +$ interference, but without  $Z$
- ▶ sNWA:  
 $\Gamma_{P_h} \text{BR}_h + \Gamma_{P_H} \text{BR}_H$
- ▶ gNWA:  
sNWA+Int  $M/R$

large discrepancy between sNWA and full 3-body decay width

large negative interference effect well approximated by gNWA ( $M/R$ )

# Concept of gNWA at higher order

## Strategy: combination of precise partial results

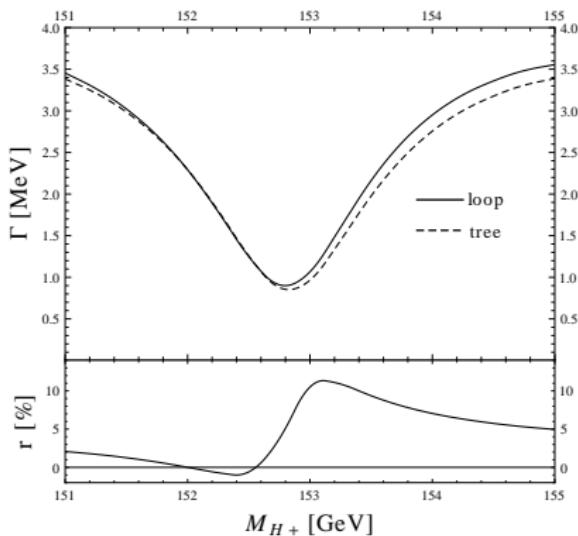
- > separate calculation of loop corrections to **production** and **decay**
- > approximation of **interference term** based on NLO matrix elements
- > IR-cancellations between on-shell matrix elements with virtual + real soft  $\gamma$
- > precise  $\Gamma, M, Z, \text{BR}$  (FeynHiggs)
- > tree-level result without NWA



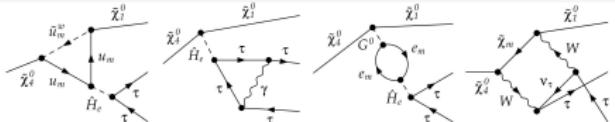
combination of higher-order corrections to subprocesses in **generalised NWA**

# $1 \rightarrow 3$ decay at NLO

$\Gamma(\chi_4^0 \rightarrow \chi_1^0 \tau\tau)$ ,  $r = (\Gamma^{\text{loop}} - \Gamma^{\text{tree}})/\Gamma^{\text{tree}}$



## 1-loop calculation



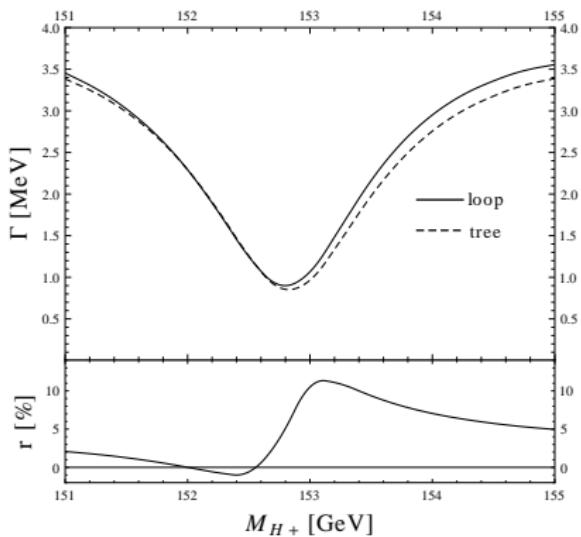
## ► diagrams

- vertices
- self-energy
- box
- soft photon radiation

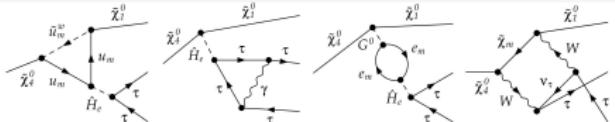
## ► Higgs mixing by $\hat{Z}$ -factors

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## 1-loop calculation



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- box
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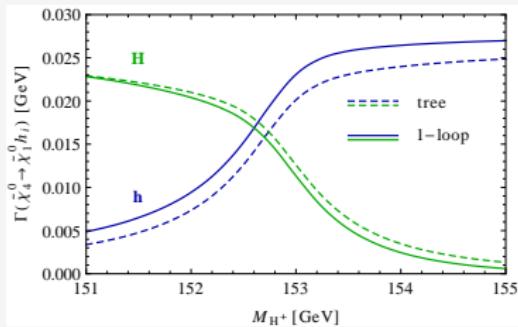
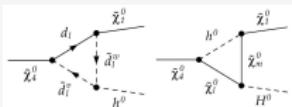
- Higgs mixing by  $\hat{Z}$ -factors
- manageable at 1-loop level

use process to validate gNWA at 1-loop level

# 2-body decays at NLO

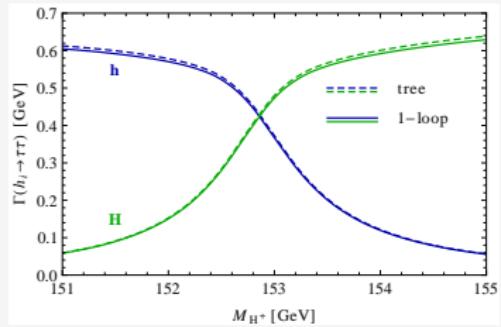
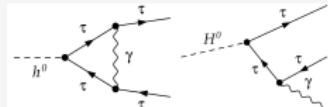
Production:  $\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^0 h/H$

e.g.



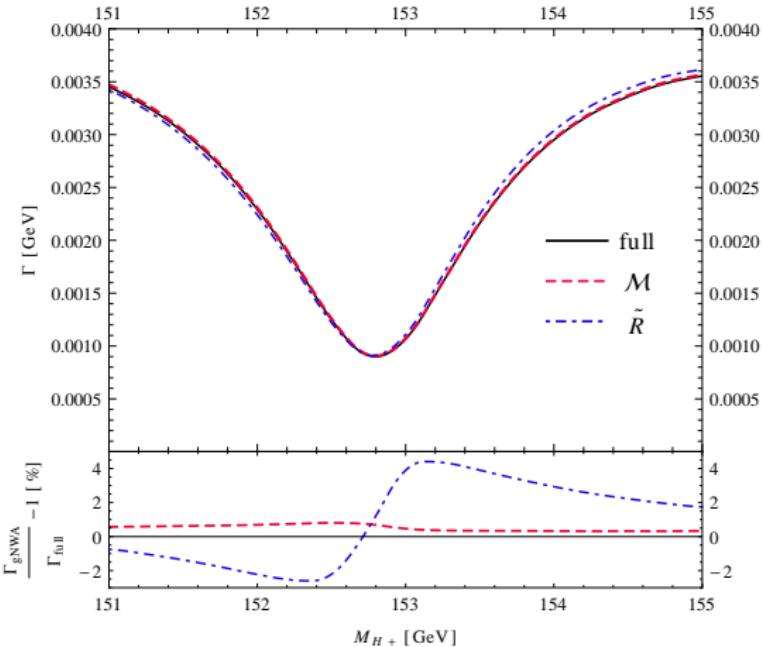
Decay:  $h/H \rightarrow \tau^+\tau^-$

e.g.



# $1 \rightarrow 3$ decay vs. gNWA at NLO

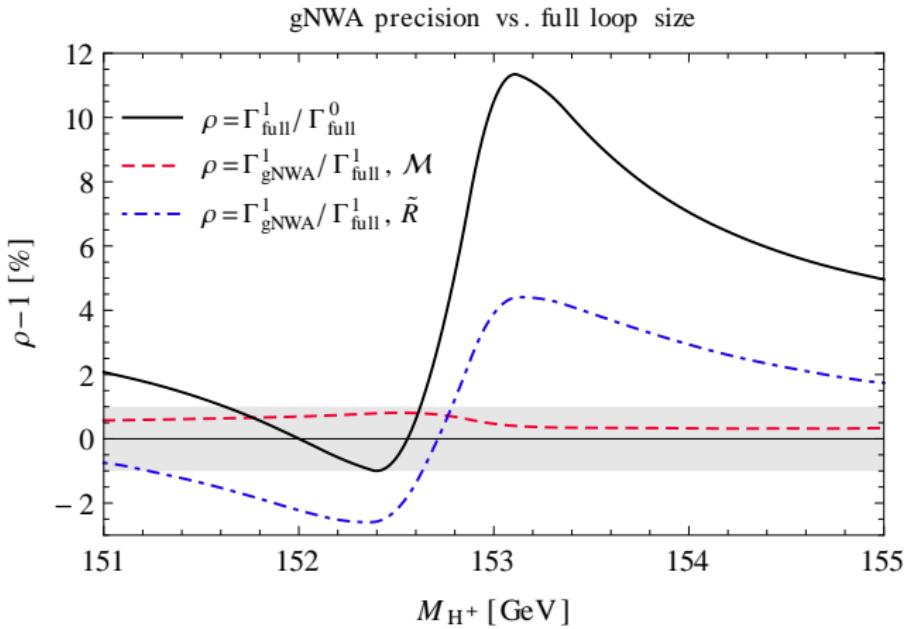
$\Gamma(\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^0 \tau^+ \tau^-)$  gNWA NLO



## 1-loop gNWA

- ▶ 1-loop expansion of matrix elements
- ▶ Higgs-sector:  $M, \Gamma, \hat{Z}$  at leading 2-loop level from FeynHiggs

# gNWA accuracy vs. relative loop contribution



uncertainty:  $M^2 < 1\% \sim \text{estimated full uncertainty}; R < 4\%$

## Summary II: Generalised NWA

- ▶ example: decay  $\tilde{\chi}_4^0 \xrightarrow{h,H} \tilde{\chi}_1^0 \tau^+ \tau^-$  with interference of Higgs bosons
- ▶ applied gNWA at loop level: inclusion of virtual and real corrections
- ▶ 1% agreement with full result
- ▶ gNWA enables factorisation into production and decay with interference and NLO effects → useful for various BSM models

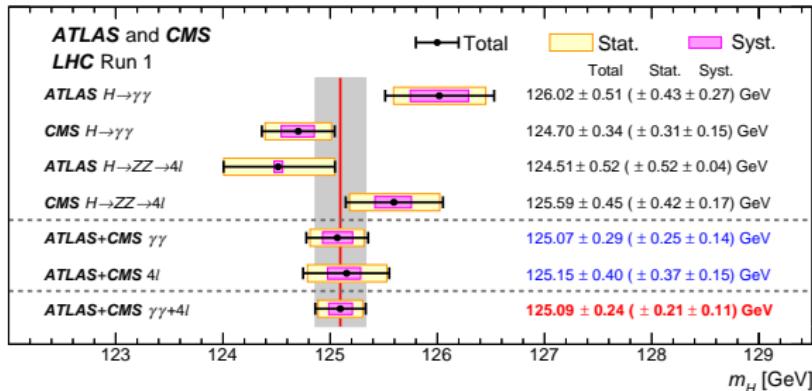
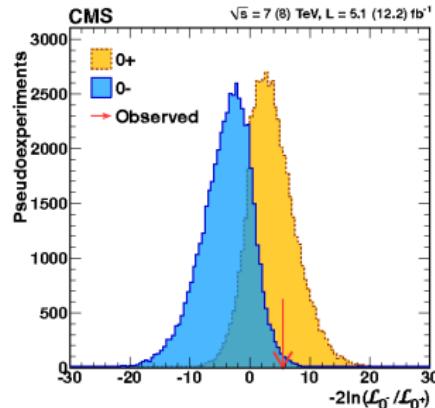


# Outline

- 1 Higgs mixing in MSSM with real and complex parameters
- 2 Generalised NWA for interference effects
- 3 Impact of interference effects on LHC Higgs searches
  - Status of Higgs searches at the LHC
  - Impact of complex parameters on Higgs cross sections
  - Consequences of interference for exclusion bounds



# Experimental status of discovered Higgs boson

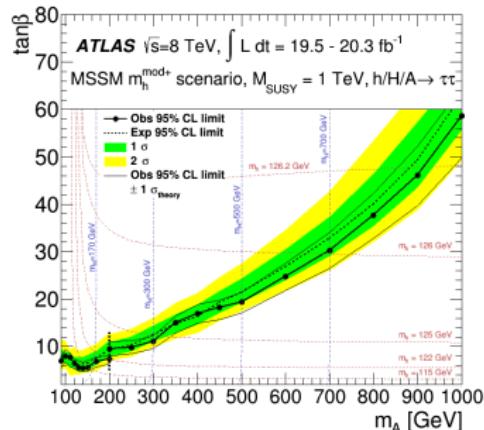
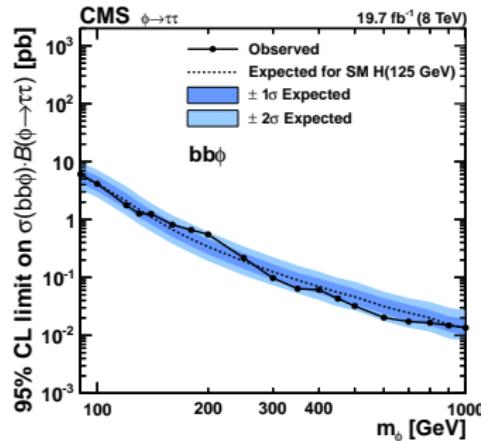


- ▶ compatible with scalar, but  $\mathcal{CP}$ -odd admixture possible
- ▶ couplings, signal strengths mostly SM-like, but deviations possible
- ▶ combined mass  $M_h^{\text{exp}} = 125.09 \pm 0.24 \text{ GeV}$

# Searches for additional Higgs bosons

## 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

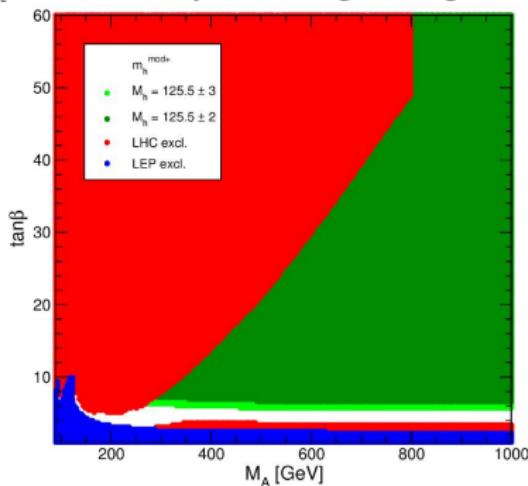
interference terms neglected, relevant especially with complex phases



# 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  $M_h^{\text{exp}}$

# Dependence of lightest Higgs mass on $\phi_{A_t}$

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



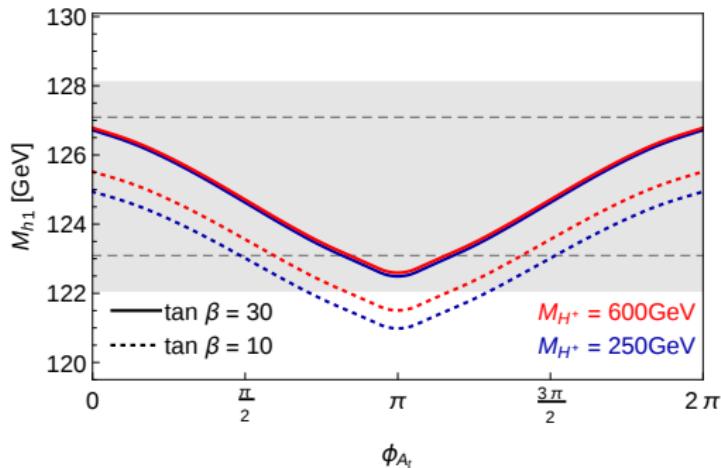
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# $\mathcal{CP}$ -violating Higgs interference

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

- ▶ important effect: **H-A interference**  $\Rightarrow \sigma_{H+A} \not\approx 2\sigma_H$  or  $\sum \sigma_\Phi \text{BR}_\Phi$
- ▶ relevance of interference with complex parameters:
  - real case:  $h - H$  interference restricted to narrow region
  - $M_{h_2} \simeq M_{h_3}$  in decoupling regime



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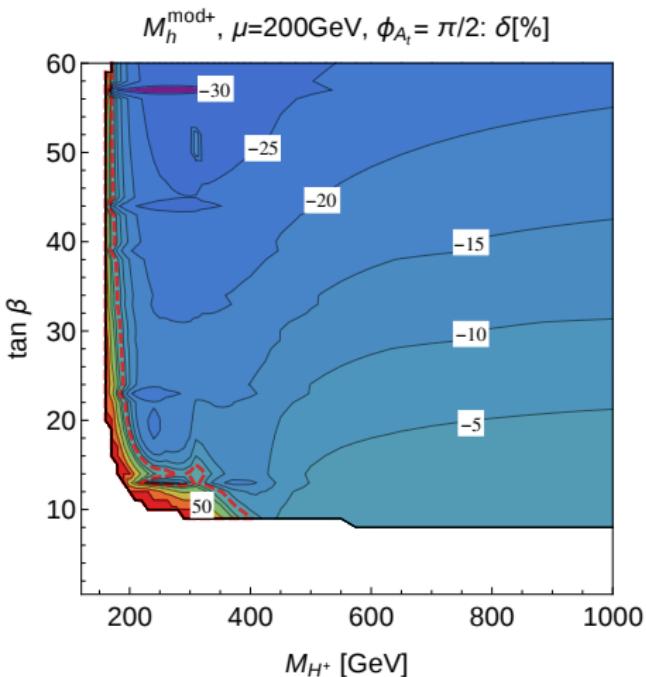
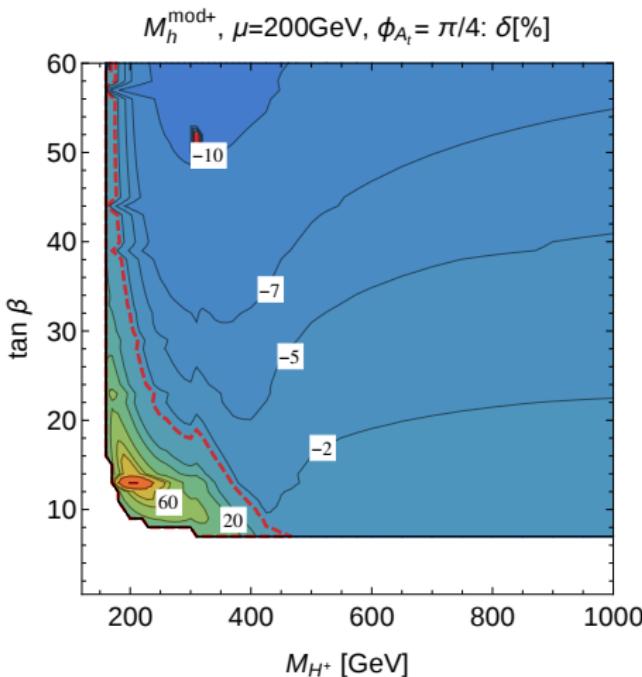
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## Our approach

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

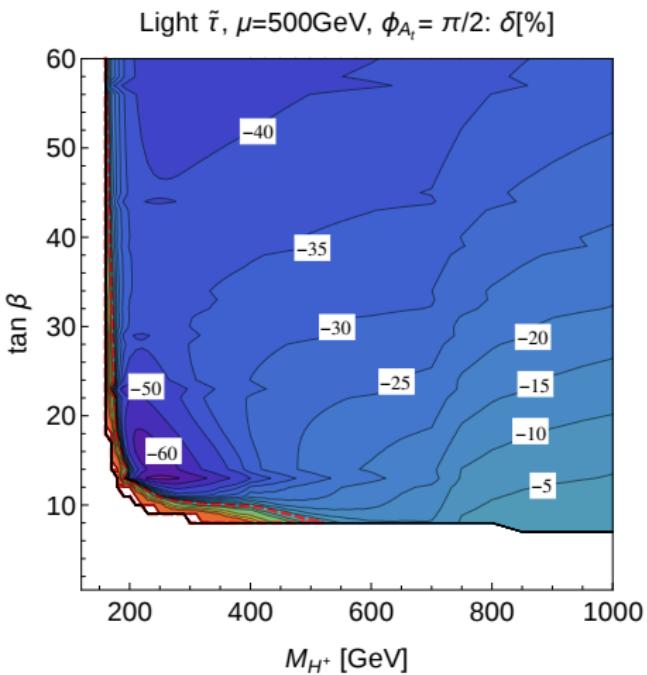
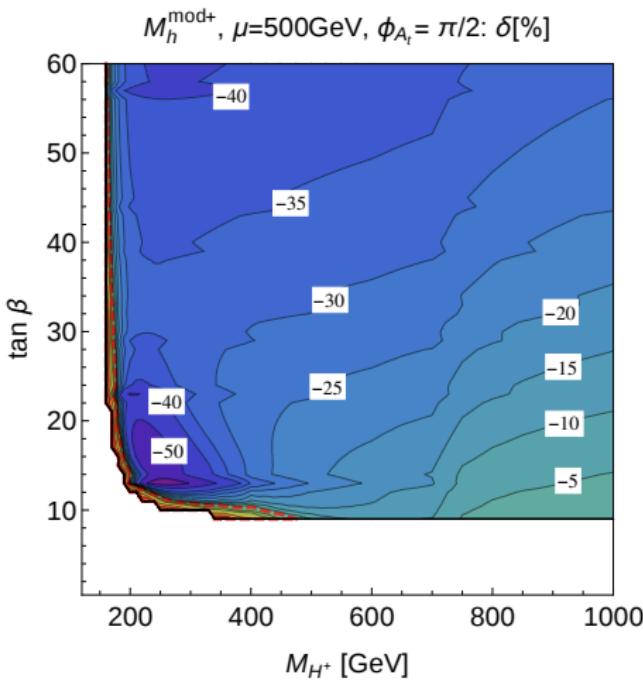


# Effect of $\phi_{A_t}$ on cross section $b\bar{b} \rightarrow h_a \rightarrow \tau^+\tau^-$



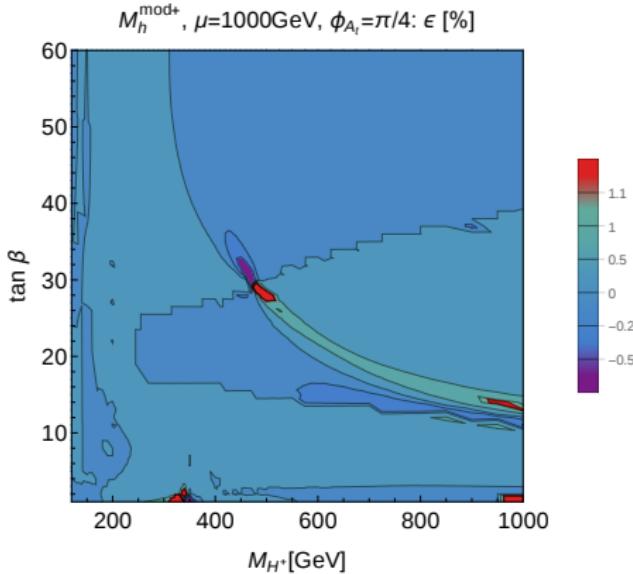
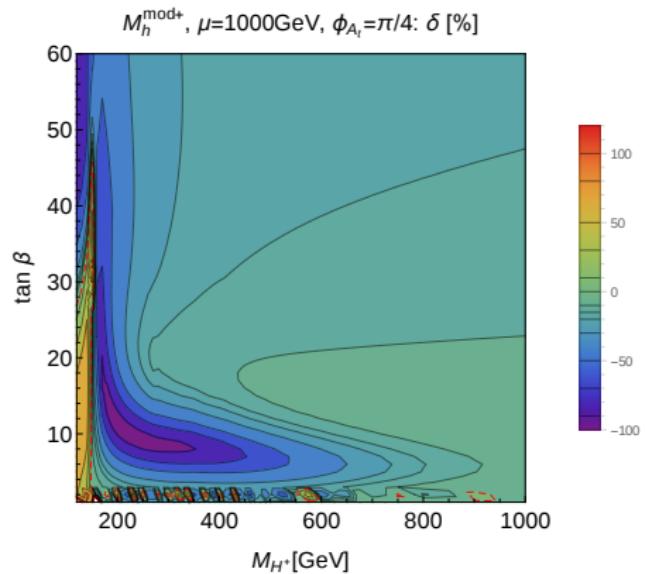
Mostly negative effects of  $\delta$  in  $M_{h_1}$ -allowed region

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



Stronger effect with larger  $\mu$

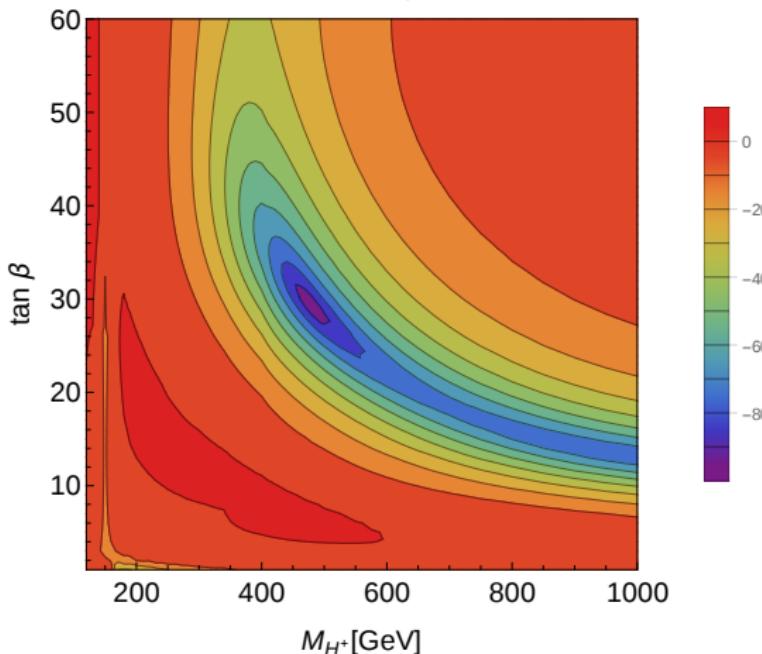
$M_h^{\text{mod+}}$  with  $\mu = 1000 \text{ GeV}$  and  $\phi_{A_t} = \pi/4$



# Pure interference effect

Disentangle overall phase effect  $\delta$  from pure interference effect  $\eta$

$M_h^{\text{mod+}}$ ,  $\mu=1000\text{GeV}$ ,  $\phi_{A_t}=\pi/4$ ,  $\Gamma^{\text{Im}}$ :  $\eta$  [%]



$$\sigma_{\text{int}} = \sigma_{\text{coh}} - \sigma_{\text{incoh}},$$

$$\begin{aligned}\eta &= \frac{\sigma_{\text{coh}}(\phi_{A_t})}{\sigma_{\text{incoh}}(\phi_{A_t})} - 1 \\ &= \frac{\sigma_{\text{int}}(\phi_{A_t})}{\sigma_{\text{incoh}}(\phi_{A_t})}.\end{aligned}$$

drastic, destructive interference effect

## 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
- ▶ output: if point excluded @ 95%CL



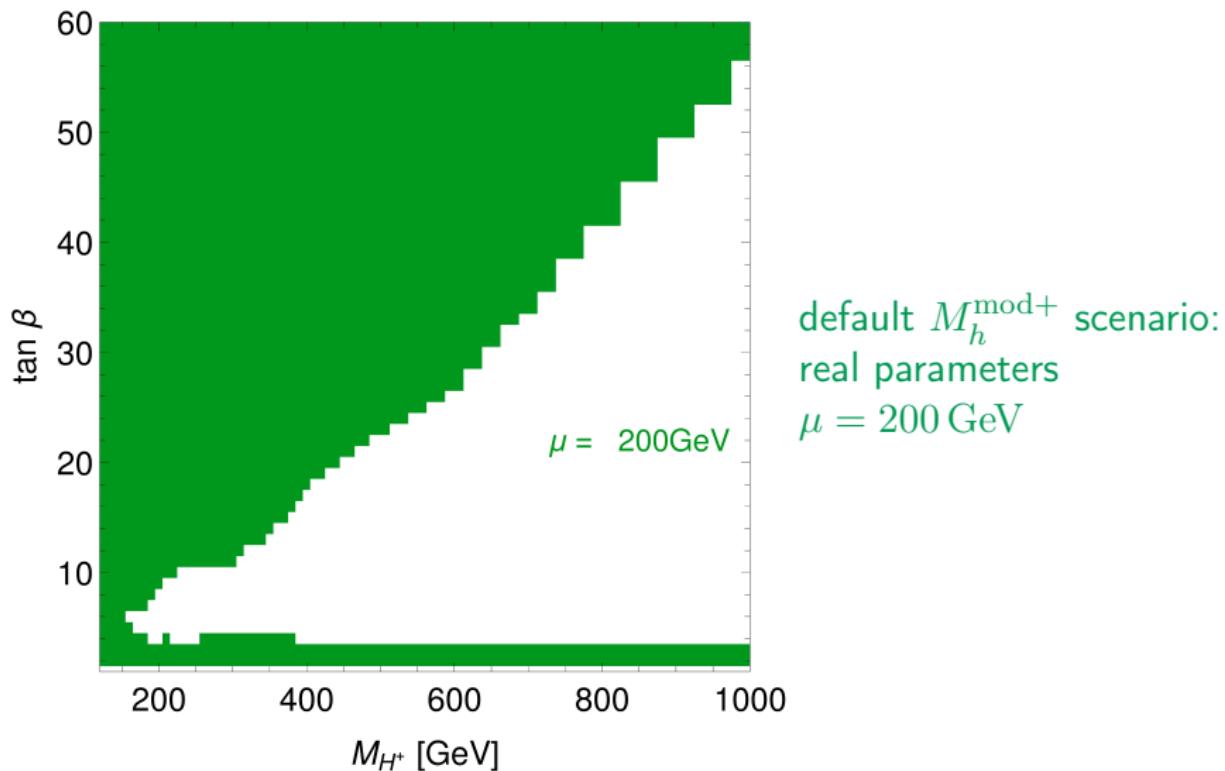
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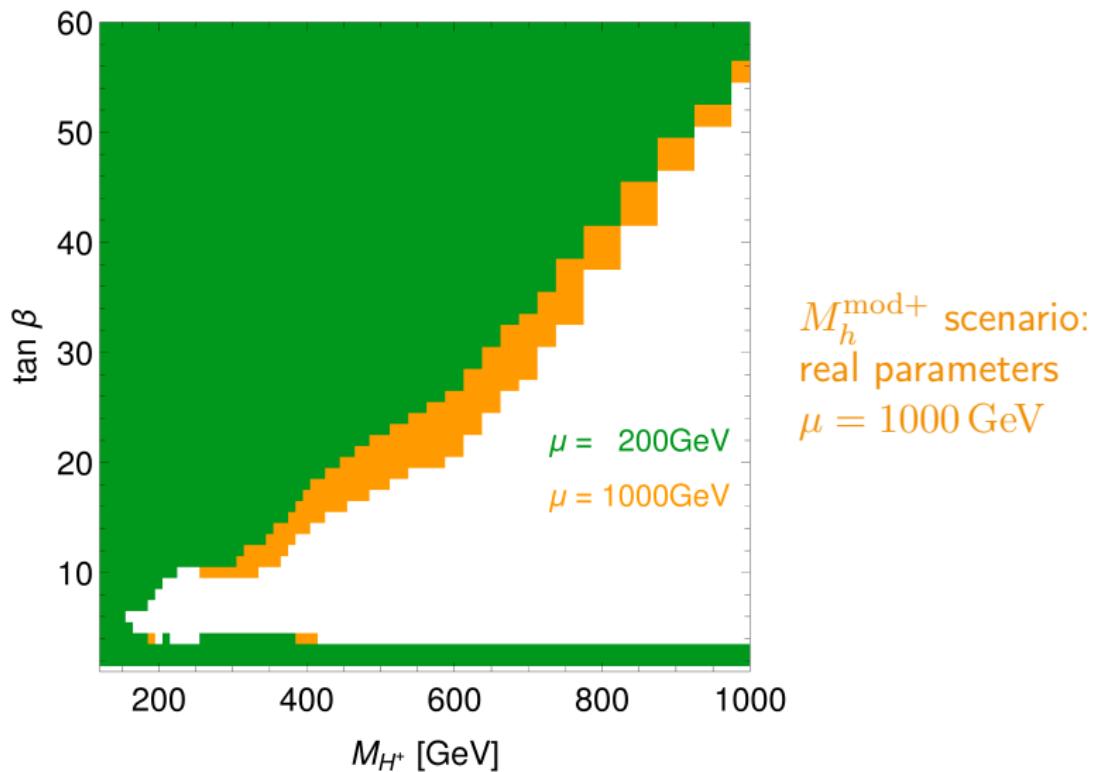
We rescaled the  $b\bar{b} \rightarrow h_a$  production as input:

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

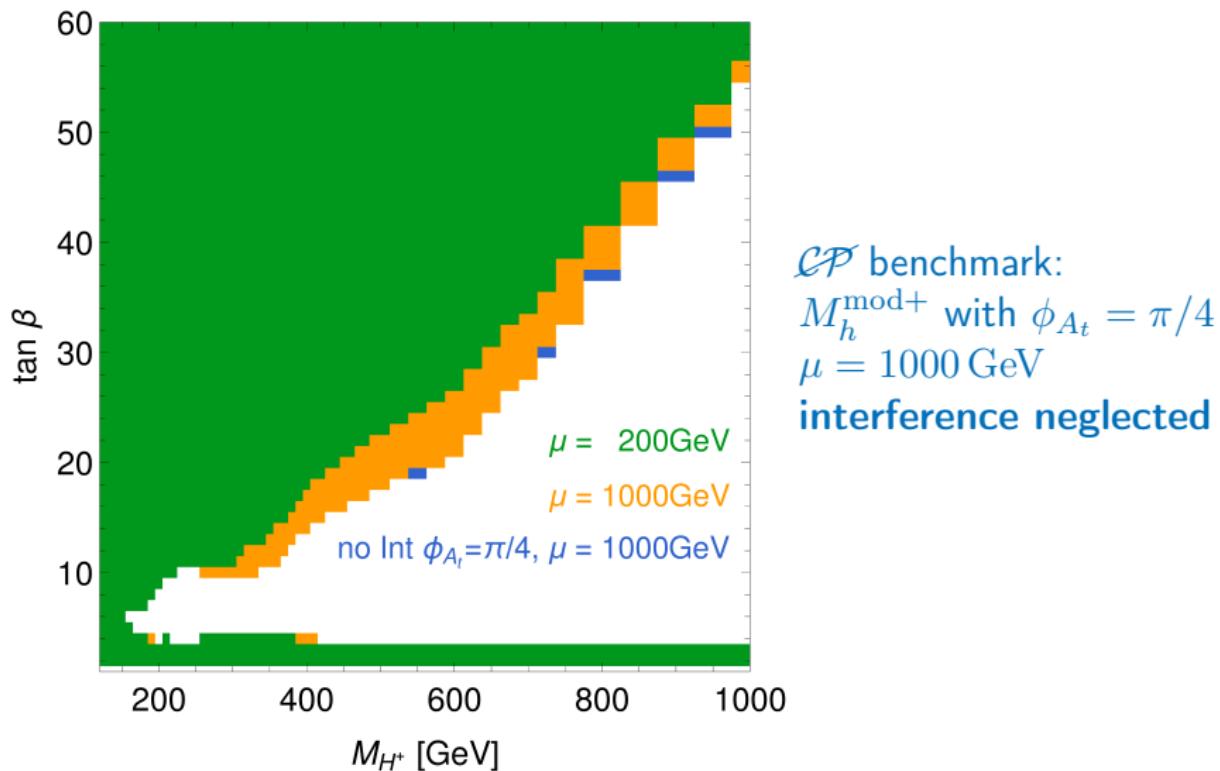
# Impact of the interference on exclusion bounds



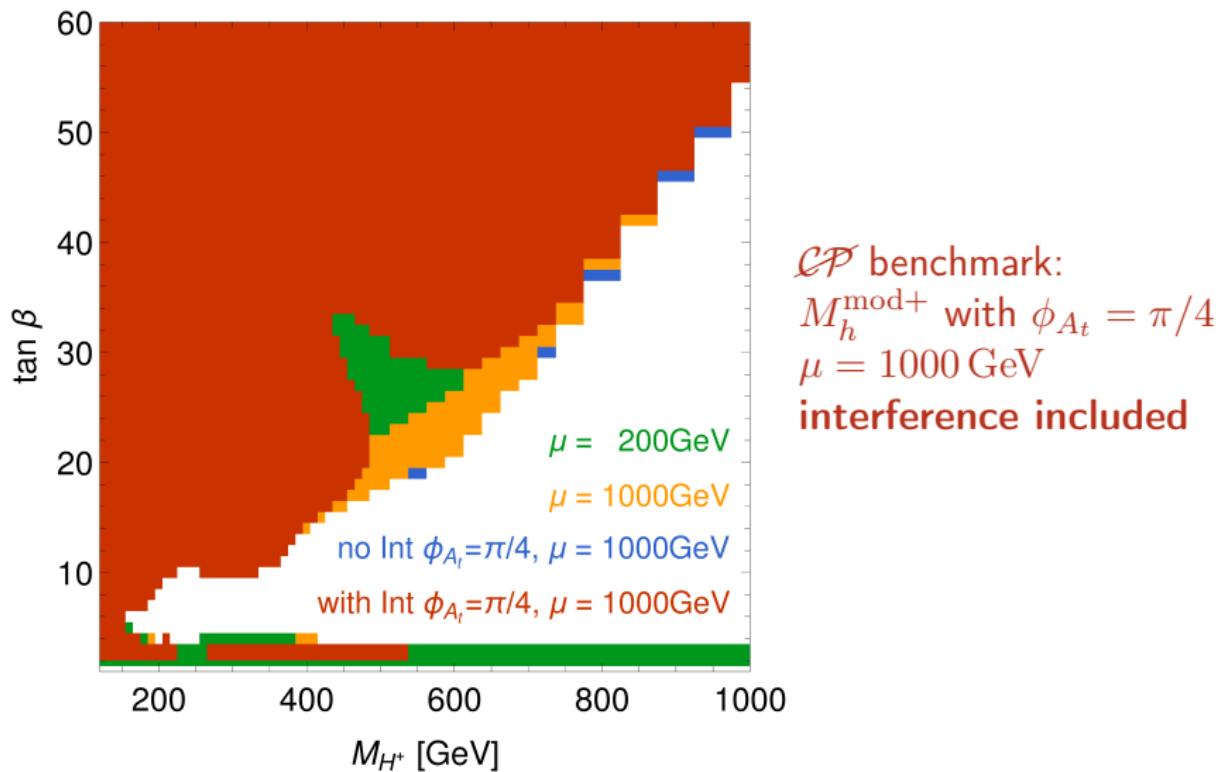
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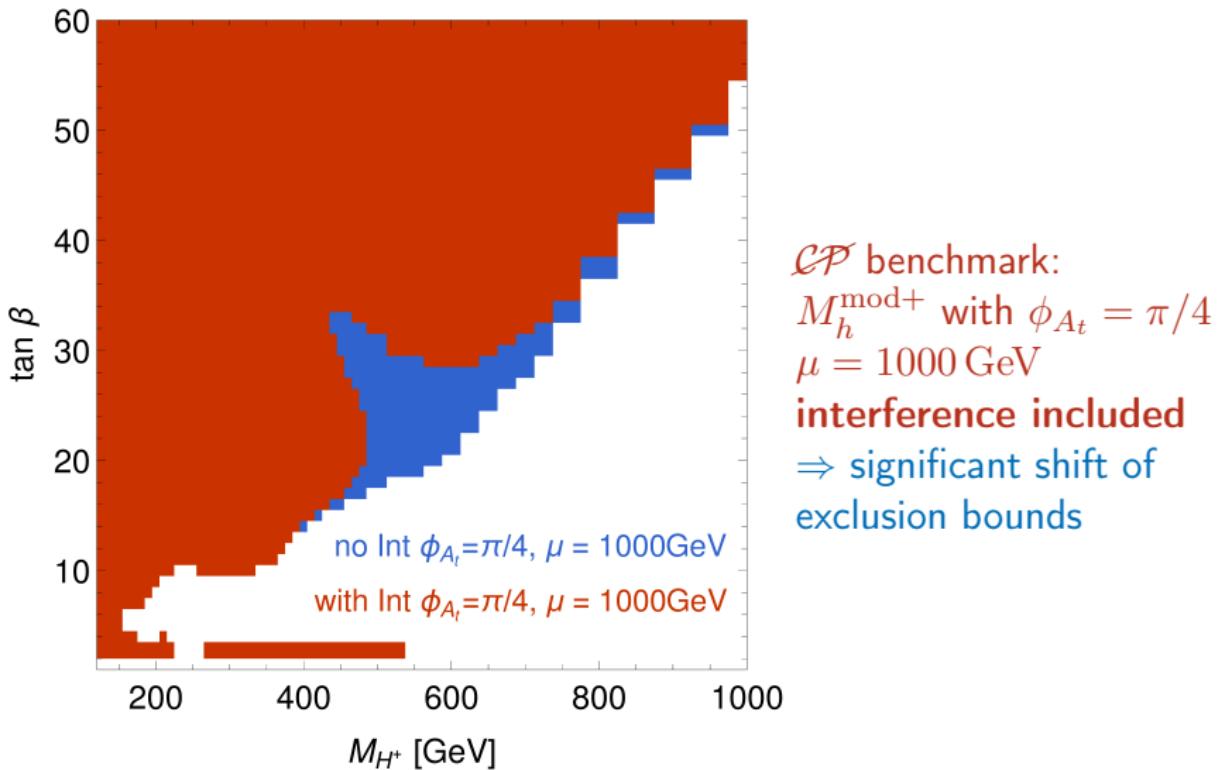
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# Impact of the interference on exclusion bounds



# Impact of the interference on exclusion bounds



# Outlook: new CPV benchmark scenario

1. include gluon fusion
2. further investigate impact of interference effects in complex MSSM on exclusion limits with `HiggsBounds`
  - various values of  $\mu$
  - dependence on  $\phi_{A_t}, \phi_{M_3}$
3. define new  $\mathcal{CP}$ -violating benchmark scenario
4. LHC run II: Higgs searches interpreted in MSSM with complex parameters



# Summary: Interference in MSSM Higgs searches

## Higgs propagator mixing with complex parameters

- ▶  $h, H, A \rightarrow h_1, h_2, h_3$
- ▶ full mixing well approximated by BW propagators and Z-factors

## Formulation of a generalised NWA

- ▶ gNWA enables factorisation into production  $\times$  decay with interference and NLO effects  $\rightarrow$  useful for various BSM models
- ▶ good agreement in  $\mathcal{CP}$ -conserving example with  $h - H$  interference



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MERCI!



# Generalised NWA with interference term

$$\sigma(ab \rightarrow cef) = \frac{1}{F} \int d\Phi \left( \frac{|\mathcal{M}(ab \rightarrow c\textcolor{blue}{h})|^2 |\mathcal{M}(\textcolor{blue}{h} \rightarrow ef)|^2}{(q^2 - M_h^2)^2 + M_h^2 \Gamma_h^2} + \frac{|\mathcal{M}(ab \rightarrow c\textcolor{blue}{H})|^2 |\mathcal{M}(\textcolor{blue}{H} \rightarrow ef)|^2}{(q^2 - M_H^2)^2 + M_H^2 \Gamma_H^2} \right. \\ \left. + 2\text{Re} \left\{ \frac{\mathcal{M}(ab \rightarrow c\textcolor{blue}{h}) \mathcal{M}^*(ab \rightarrow c\textcolor{blue}{H}) \mathcal{M}(\textcolor{blue}{h} \rightarrow ef) \mathcal{M}^*(\textcolor{blue}{H} \rightarrow ef)}{(q^2 - M_h^2 + iM_h \Gamma_h)(q^2 - M_H^2 - iM_H \Gamma_H)} \right\} \right)$$

$$\stackrel{\mathcal{M} \text{ on-shell}}{\approx} \sigma_{ab \rightarrow c\textcolor{blue}{h}} BR_{\textcolor{blue}{h} \rightarrow ef} + \sigma_{ab \rightarrow c\textcolor{blue}{H}} BR_{\textcolor{blue}{H} \rightarrow ef}$$

$$+ \frac{2}{F} \text{Re} \left\{ \int \frac{dq^2}{2\pi} \left( \Delta_1^{BW}(q^2) \Delta_2^{*BW}(q^2) \left[ \int d\Phi_P(q^2) \mathcal{P}_1(M_1^2) \mathcal{P}_2^*(M_2^2) \right] \right. \right. \\ \left. \left. \left[ \int d\Phi_D(q^2) \mathcal{D}_1(M_1^2) \mathcal{D}_2^*(M_2^2) \right] \right) \right\}$$

$$\stackrel{M_h \simeq M_H}{\approx} \sigma_{P_1} BR_1 \cdot (1 + R_1) + \sigma_{P_2} BR_2 \cdot (1 + R_2)$$

$$R_i := 2M_i \Gamma_i w_i \cdot 2\text{Re} \{x_i I\}$$

$$I := \int \frac{dq^2}{2\pi} \Delta_1^{BW}(q^2) \cdot \Delta_2^{*BW}(q^2), \quad w_i := \frac{\sigma_{P_i} BR_i}{\sigma_{P_1} BR_1 + \sigma_{P_2} BR_2}$$

$$x_i := \frac{g_{P_i} g_{P_j}^* g_{D_i} g_{D_j}^*}{|g_{P_i}|^2 |g_{D_i}|^2} \quad (g_{P/D} : \text{couplings in production/decay})$$



# On-shell interference term at NLO

## Standard NWA

$$\sigma_P \cdot \text{BR} \longmapsto \frac{\sigma_P^1 \Gamma_D^0 + \sigma_P^0 \Gamma_D^1}{\Gamma^{\text{tot}}}$$

## Matrix element method

- ▶  $\mathcal{P}_i^1 \mathcal{D}_i^0 \mathcal{P}_j^{0*} \mathcal{D}_j^{0*}$
- ▶  $\mathcal{P}_i^0 \mathcal{D}_i^1 \mathcal{P}_j^{0*} \mathcal{D}_j^{0*}$
- ▶  $\delta_{\text{SB}} \mathcal{P}_i^0 \mathcal{D}_i^0 \mathcal{P}_j^{0*} \mathcal{D}_j^{0*}$   
soft bremsstrahlung

## R-factor approximation

- ▶  $\sigma_P^1 \cdot \text{BR}^0$
- ▶  $\sigma_P^0 \cdot \text{BR}^1$
- ▶  $\tilde{R}$ -factor: only ratios of LO couplings

Expansion restricted to tree+1-loop  
for consistent comparison with full process at NLO



# Cancellation of IR-divergences

**KLN theorem** [Kinoshita '62] [Lee, Nauenberg '64]

IR-divergences from real and virtual photons cancel

**IR-divergences in on-shell matrix elements (here only decay)**

- ▶ if tree:  $\delta_{\text{SB}}(q^2) \cdot \mathcal{M}_i(q^2)\mathcal{M}_j^*(q^2) \rightarrow$  mismatch with  $\mathcal{D}^{\text{virt}}(M^2)$ ! ✗
- ▶ integrals in 1-loop matrix elements and soft-photon factor  $\delta_{\text{SB}}$  need to be evaluated at the same mass  $\rightarrow$  **IR-div. cancel ✓**
- ▶ possible to separate subsets of IR-finite and IR-divergent diagrams

**Comparison to double-pole approximation (DPA)**

[Denner, Dittmaier, Roth '98]

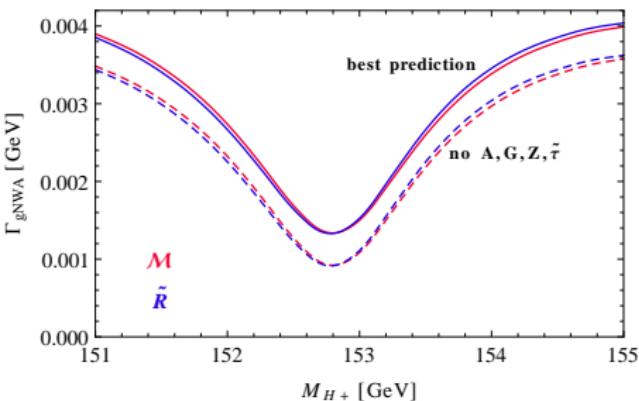
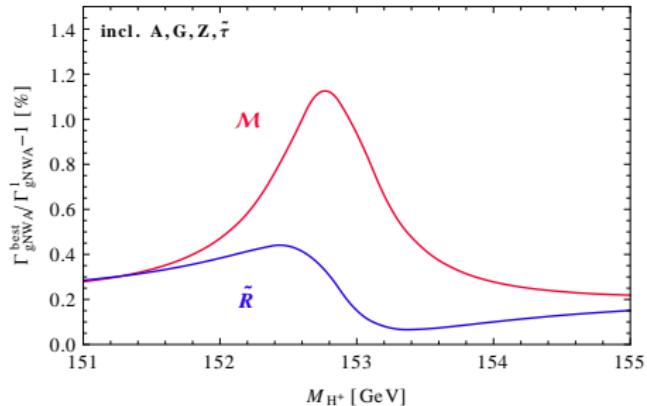
- ▶ extract singular parts from real photon contribution
- ▶ apply DPA only on terms which match singularities from virtual  $\gamma s$

[Denner, Dittmaier, Roth, Wackeroth '00] [Grünewald, Passarino et. al. '00]



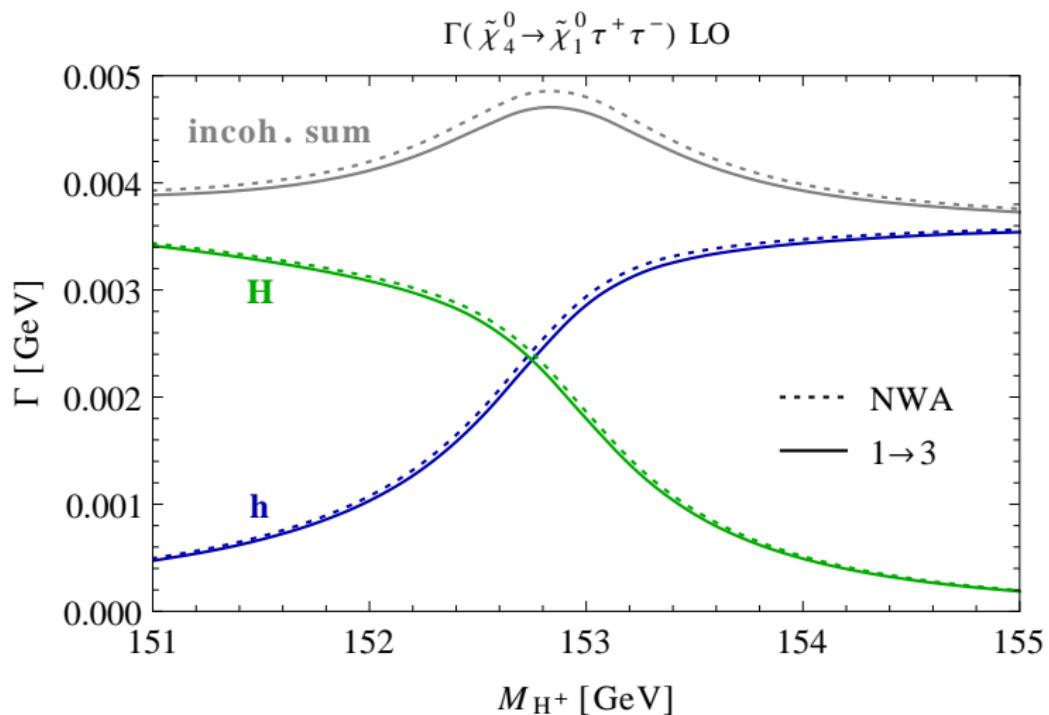
# gNWA with most precise subprocesses

$$\sigma_{\text{gNWA}}^{\text{best}} = \sigma_{\text{full}}^0 + \sum_{i=h,H} \left( \sigma_{P_i}^{\text{best}} \text{BR}_i^{\text{best}} - \sigma_{P_i}^0 \text{BR}_i^0 \right) + \sigma_{\text{gNWA}}^{\text{int1}} + \sigma_{\text{gNWA}}^{\text{int+}}$$



use **factorisation**: include  $\sigma_P$  and BR at **highest available precision** in gNWA

# Intrinsic NWA uncertainty $\sim \mathcal{O}(\Gamma/M)$



# Renormalisation of neutralino-chargino sector

## Neutralino and chargino matrices

$$Y = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{pmatrix}, \quad X = \begin{pmatrix} M_2 & \sqrt{2} M_W s_\beta \\ \sqrt{2} M_W c_\beta & \mu \end{pmatrix}$$

### Renormalisation: on-shell

[Fowler, Weiglein '09] [Bharucha, Fowler, Moortgat-Pick, Weiglein '12]

[Chatterjee, Drees, Kulkarni, Xu '11] [Bharucha, Heinemeyer, Pahlen, Schappacher '12] et al.

- ▶ 3 out of 6  $\tilde{\chi}^0, \tilde{\chi}^\pm$  masses on-shell
- ▶ choose most bino-, wino- and higgsino-like states as input  
→ 3 parameters  $|M_1|, |M_2|, |\mu|$  properly fixed
- ▶ otherwise: huge counterterms and unphysically large mass corrections
- ▶ here: NNN scheme with  $\tilde{\chi}_{1,3,4}^0$  on-shell

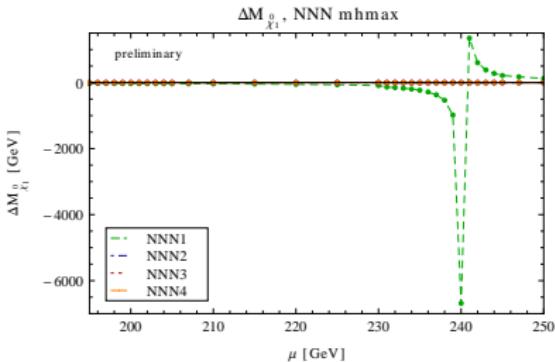
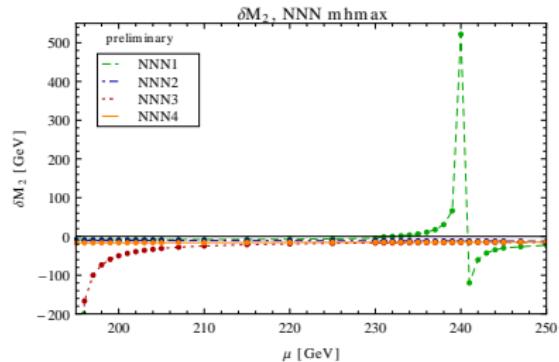
**stability of scheme (proper parameter fixing): parameter dependent**



# Neutralino-chargino renormalisation schemes

## Renormalisation constants and $\Delta M$ with 3 neutralinos on-shell

- **NNNi scheme:**  $m_{\tilde{\chi}_i^0}$  and  $m_{\tilde{\chi}_{1,2}^\pm}$  receive loop correction
- scenario with  $\mu = M_2 = 200 \text{ GeV}$
- stable schemes: here NNN2, NNN4 with  $\tilde{\chi}_2^0/\tilde{\chi}_4^0$  shifted



# Definition and use of the Z-factors

- ▶ ensure **correct normalisation** of S-matrix with external Higgs bosons
- ▶  $\hat{\mathbf{Z}}$  with  $\hat{\mathbf{Z}}_{aj} = \sqrt{\hat{Z}_a} \hat{Z}_{aj}$  is **not unitary**

$$\lim_{p^2 \rightarrow \mathcal{M}_a^2} -\frac{i}{p^2 - \mathcal{M}_a^2} \left( \hat{\mathbf{Z}} \cdot \hat{\Gamma}_{hHA} \cdot \hat{\mathbf{Z}}^T \right)_{hh} = 1, \quad (1)$$

$$\lim_{p^2 \rightarrow \mathcal{M}_b^2} -\frac{i}{p^2 - \mathcal{M}_b^2} \left( \hat{\mathbf{Z}} \cdot \hat{\Gamma}_{hHA} \cdot \hat{\mathbf{Z}}^T \right)_{HH} = 1, \quad (2)$$

$$\lim_{p^2 \rightarrow \mathcal{M}_c^2} -\frac{i}{p^2 - \mathcal{M}_c^2} \left( \hat{\mathbf{Z}} \cdot \hat{\Gamma}_{hHA} \cdot \hat{\mathbf{Z}}^T \right)_{AA} = 1 \quad (3)$$

$$\hat{Z}_a = \text{Res}_{\mathcal{M}_a^2} \Delta_{ii}(p^2) = \frac{1}{1 + \hat{\Sigma}_{ii}^{\text{eff}'}(\mathcal{M}_a^2)}, \quad \hat{Z}_{aj} = \frac{\Delta_{ij}(p^2)}{\Delta_{ii}(p^2)} \Big|_{p^2 = \mathcal{M}_a^2} \quad (4)$$

$$\begin{pmatrix} \hat{\Gamma}_{h_1} \\ \hat{\Gamma}_{h_2} \\ \hat{\Gamma}_{h_3} \end{pmatrix} = \hat{\mathbf{Z}} \cdot \begin{pmatrix} \hat{\Gamma}_h \\ \hat{\Gamma}_H \\ \hat{\Gamma}_A \end{pmatrix} \quad (5)$$



# Interference effects in real/complex Higgs sector

## MSSM Higgs interference?

- ▶ **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

## Include interference term

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

Analyse interference effects in the complex MSSM!

