Interference effects in BSM processes

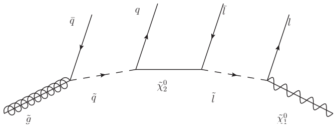
Elina Fuchs
DESY

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

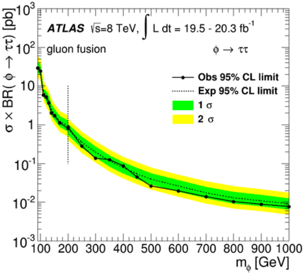
Rencontres de Blois
June 2, 2015

Useful approximation for New Physics searches

- BSM: extended spectrum $\rightarrow$ typical cascade decays
- many-particle final state difficult at higher order
- $\rightsquigarrow$ simplified by factorisation into **production**$\times$**decay**
- application in MC generators, experimental limits

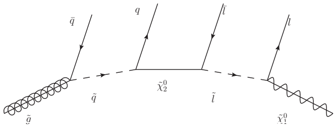


$$\sigma_{\text{production}} \times BR_1 \times BR_2 \times BR_3 \times BR_4$$

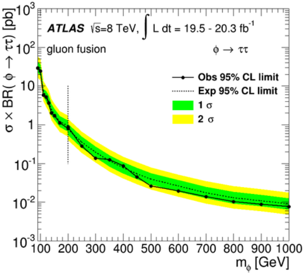


Useful approximation for New Physics searches

- BSM: extended spectrum $\rightarrow$ typical cascade decays
- many-particle final state difficult at higher order
- $\rightsquigarrow$ simplified by factorisation into production$\times$decay
- application in MC generators, experimental limits



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



Standard narrow-width approximation neglects interference term

extension necessary to combine interference and higher-order effects

Outline

1 Generalised NWA for interference effects

2 Impact of interference effects on LHC Higgs searches

Outline

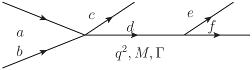
1 Generalised NWA for interference effects

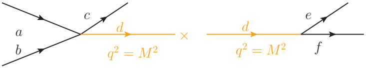
- Standard NWA
- gNWA at tree level
- gNWA at higher order

2 Impact of interference effects on LHC Higgs searches

Standard Narrow-Width Approximation (NWA)

generic example:
$ab \stackrel{d}{\to} cef$





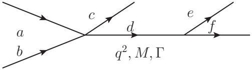
Factorisation: production × decay

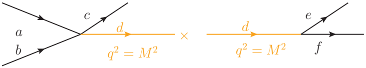
- instead of Breit-Wigner propagator $\Delta^{\rm BW}(q^2) = \frac{i}{q^2 - M^2 + iM\Gamma}$
- on-shell production and decay of particle with mass M:

$$\boxed{\sigma_{ab\to cef} \approx \sigma_{ab\to cd}(q^2 = M^2) \cdot BR_{d\to ef}}$$

Standard Narrow-Width Approximation (NWA)

generic example:
$ab \xrightarrow{d} cef$





Factorisation: production $\times$ decay

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

$$\boxed{\sigma_{ab\to cef} \approx \sigma_{ab\to cd}(q^2 = M^2) \cdot BR_{d\to ef}}$$

- narrow width $\Gamma \ll M$, otherwise off-shell effects
- production and decay sub-processes kinematically open and away from thresholds
- non-factorisable corrections small e.g. [Denner, Dittmaier, Roth '98]
- 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 Γ_i, Γ_j

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

2.) Mixing

- Matrix elements $\mathcal{M}_i, \mathcal{M}_j$
- without i-j mixing
  $\sigma_{\text{Int}} \propto 2\text{Re}[\mathcal{M}_i \mathcal{M}_j^*] = 0$

Interference of quasi degenerate resonances

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

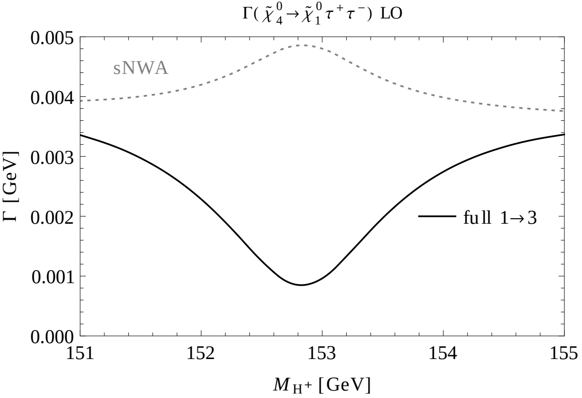
- Matrix elements $\mathcal{M}_i, \mathcal{M}_j$
- without i-j mixing
  $\sigma_{\text{Int}} \propto 2\text{Re}[\mathcal{M}_i \mathcal{M}_j^*] = 0$

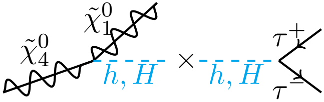
Examples of quasi degenerate states in BSM

- (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 $\rightarrow$ include in NWA!

Example: $\Gamma(\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h/H \to \tilde{\chi}_1^0 \tau^+\tau^-)$ at LO



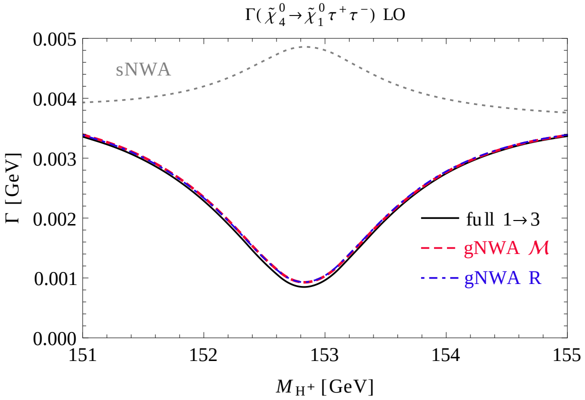


- **'full'**: $1 \to 3$ with h, H+interference, but without Z
- sNWA: $\Gamma_{P_h} \mathrm{BR}_h + \Gamma_{P_H} \mathrm{BR}_H$

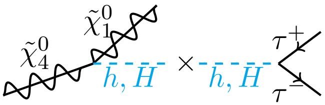
FeynArts,FormCalc,LoopTools,FeynHiggs

large discrepancy between sNWA and **full 3-body** decay width

Example: $\Gamma(\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h/H \to \tilde{\chi}_1^0 \tau^+\tau^-)$ at LO



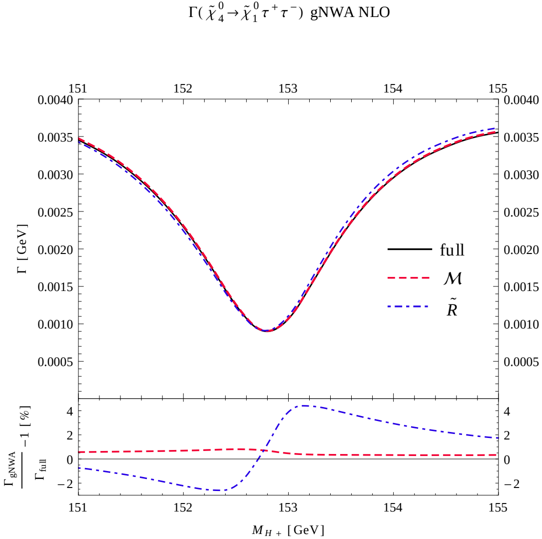
FeynArts,FormCalc,LoopTools,FeynHiggs



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

large **negative interference** effect well approximated by **gNWA**

$1 \to 3$ decay vs. gNWA at NLO



1-loop gNWA

- virtual and real corrections
- 1-loop expansion of matrix elements
- Higgs-sector: $M, \Gamma, \hat{\mathbf{Z}}$ at leading 2-loop level from `FeynHiggs`

uncertainty $< 1\%$ for on-shell approximation of interference at NLO

Outline

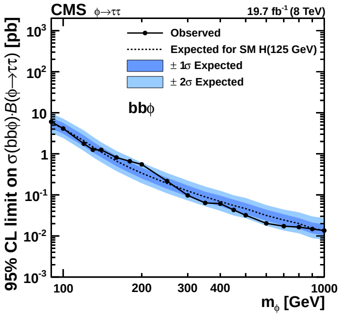
1 Generalised NWA for interference effects

2 Impact of interference effects on LHC Higgs searches
- Impact of complex parameters on Higgs cross sections
- Consequences of interference for exclusion bounds

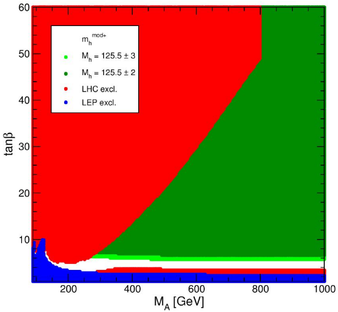
Searches for additional Higgs bosons

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

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



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



Interpretation in benchmark scenarios, here $M_h^{\text{mod}+}$ (real)

interference terms neglected, relevant especially with complex phases

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 principal be **complex**: 12
  - trilinear couplings A_f
  - higgsino mass parameter μ
  - gaugino mass parameters M_1, M_2 (rotate ϕ_{M_2} away), M_3

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 principal be **complex**: 12
  - trilinear couplings A_f
  - higgsino mass parameter μ
  - gaugino mass parameters M_1, M_2 (rotate ϕ_{M_2} away), M_3

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 $\phi_{A_{t,b}}$
- ϕ_{M_1} can be sizeable
- ϕ_{M_3} strongly constrained only if $\tilde{f}_{1,2}$ light
- ϕ_μ tight limits

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

Dependence of lightest Higgs mass on ϕ_{A_t}

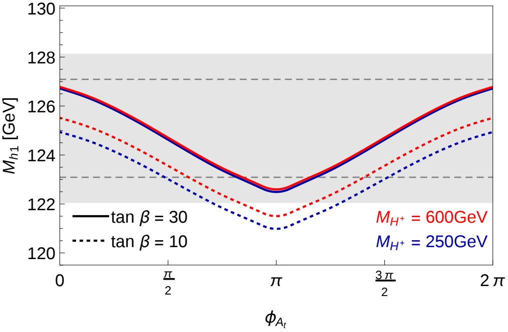
consider $\phi_{A_t} \neq 0$ in trilinear coupling $\boxed{A_t = |A_t| e^{i\phi_{A_t}},}$ $A_b = A_\tau = A_t$

- enhanced in $\mu A_{t,b}$
- impact on masses, couplings, widths, cross sections, mixing
- Higgs mixing $h, H, A \rightarrow h_1, h_2, h_3$

Dependence of lightest Higgs mass on ϕ_{A_t}

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

- enhanced in $\mu A_{t,b}$
- impact on masses, couplings, widths, cross sections, mixing
- Higgs mixing $h, H, A \rightarrow h_1, h_2, h_3$



check if $M_{h_1}(\phi_{A_t} \neq 0)$ stays in allowed mass window $M_h^{\rm exp} = 125.09 \pm 3(2)\,\mathrm{GeV}$ (theory uncertainty)

FeynHiggs

$\mathcal{CP}$-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 $\sum \sigma_\Phi \mathrm{BR}_\Phi$
- 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

$\mathcal{CP}$-violating Higgs interference

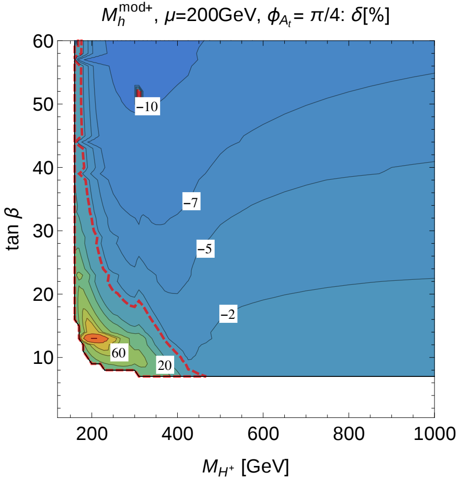
In presence of non-zero phase: change of cross section

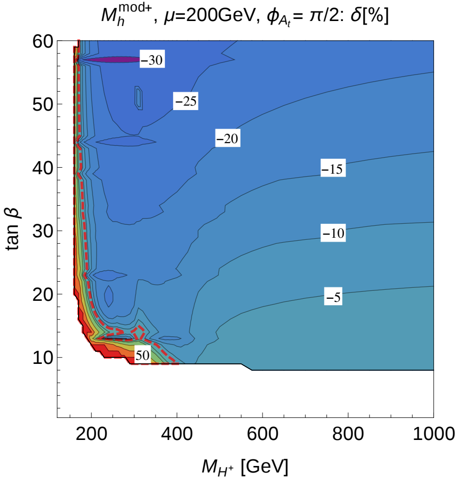
- important effect: H-A interference $\Rightarrow \sigma_{H+A} \not\approx 2\sigma_H$ or $\sum \sigma_\Phi \mathrm{BR}_\Phi$
- relevance of interference with complex parameters:
  - real case: $h - H$ interference restricted to narrow region
  - $M_{h_2} \simeq M_{h_3}$ in decoupling regime

Our approach

- full propagator mixing Δ_{ij}: $i, j = h, H, A$
  - $\phi \equiv \phi_{A_t} \neq 0$ or $\phi = 0 \longrightarrow \boxed{\delta := \frac{\sigma(\phi) - \sigma(0)}{\sigma(0)}}$
  - measures relative effect of complex phase on cross section σ
- Breit-Wigner propagators $\cdot\hat{\mathbf{Z}}$-factors with ϕ_{A_t}, with/out interference
  - measures difference between $|h_1 + h_2 + h_3|^2$ and $|h_1|^2 + |h_2|^2 + |h_3|^2$

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

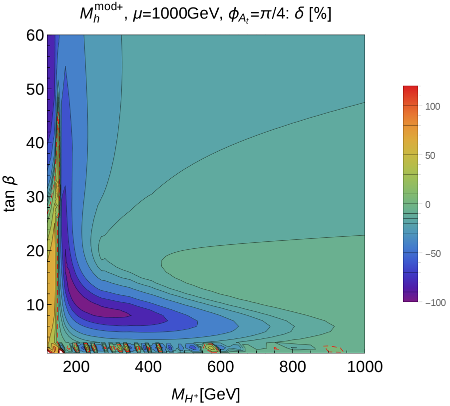




Mostly negative effects of δ in M_{h_1}-allowed region

$\mathcal{CP}$ benchmark scenario

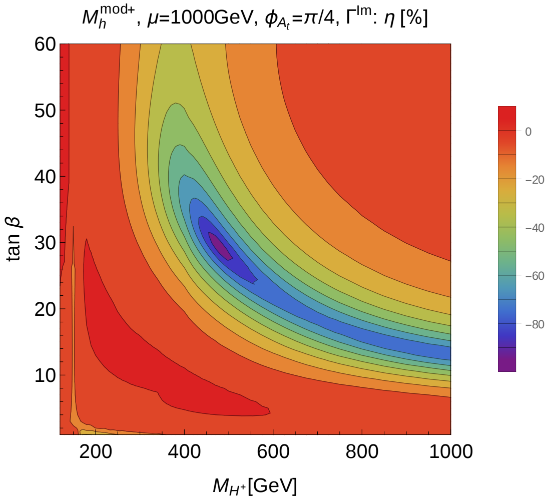
$M_h^{\text{mod}+}$ with $\mu = 1000\,\text{GeV}$ and $\phi_{A_t} = \pi/4$



Stronger phase effect with larger μ

Pure interference effect

Disentangle overall phase effect δ from pure interference effect η



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

$$\eta = \frac{\sigma_{\text{coh}}(\phi_{A_t})}{\sigma_{\text{incoh}}(\phi_{A_t})} - 1 = \frac{\sigma_{\text{int}}(\phi_{A_t})}{\sigma_{\text{incoh}}(\phi_{A_t})}$$

drastic, destructive interference effect

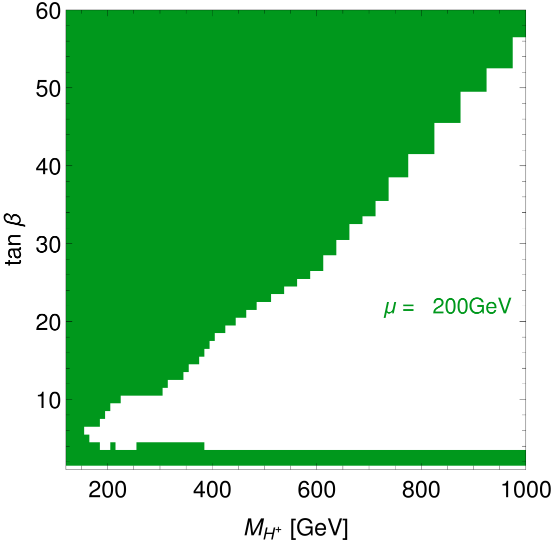
Testing Higgs model predictions against observed limits

- 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

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

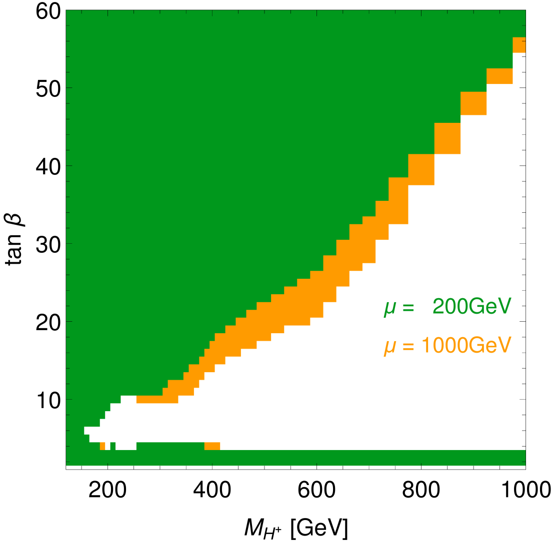
$$\frac{\sigma^{\mathrm{MSSM}}(b\bar{b} \to h_a)}{\sigma^{\mathrm{SM}}(b\bar{b} \to h)} \quad \longrightarrow \quad \frac{\sigma^{\mathrm{MSSM}}(b\bar{b} \to h_a)}{\sigma^{\mathrm{SM}}(b\bar{b} \to h)} \cdot (1 + \boldsymbol{\eta_a})$$

Impact of the interference on exclusion bounds



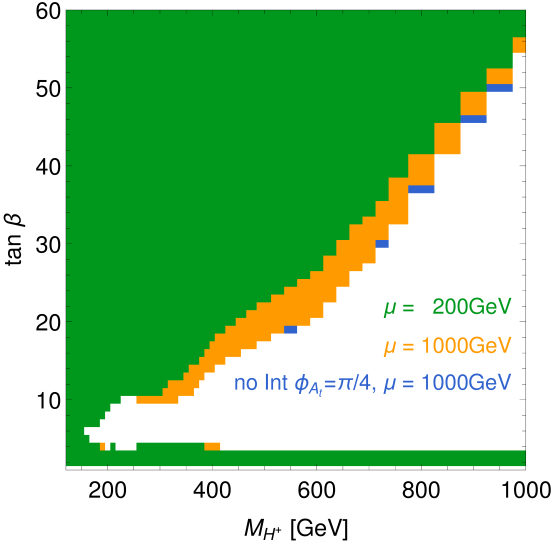
default $M_h^{\text{mod}+}$ scenario:
real parameters
$\mu = 200\,\text{GeV}$

Impact of the interference on exclusion bounds



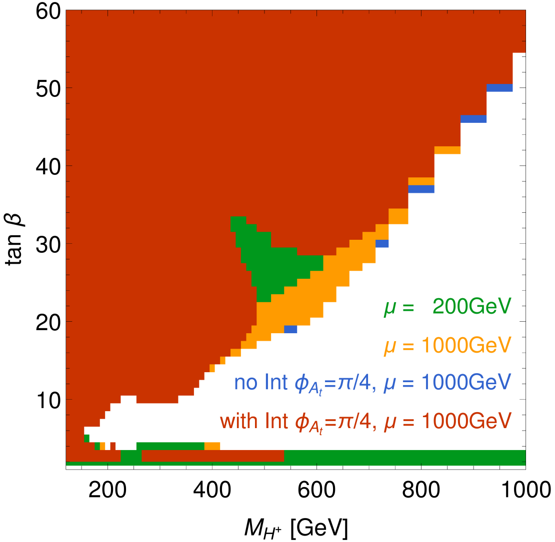
$M_h^{\mathrm{mod}+}$ scenario:
real parameters
$\mu = 1000\,\mathrm{GeV}$

Impact of the interference on exclusion bounds



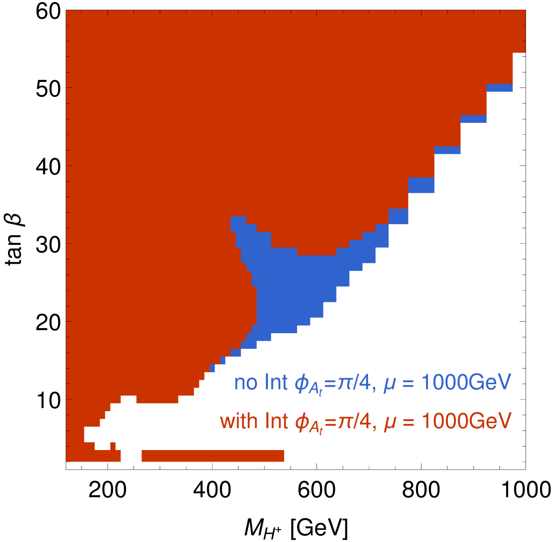
$\cancel{\mathcal{CP}}$ benchmark:
$M_h^{\mathrm{mod}+}$ with $\phi_{A_t} = \pi/4$
$\mu = 1000\,\mathrm{GeV}$
interference neglected

Impact of the interference on exclusion bounds



$\cancel{\mathcal{CP}}$ benchmark:
$M_h^{\mathrm{mod}+}$ with $\phi_{A_t} = \pi/4$
$\mu = 1000\,\mathrm{GeV}$
interference included

Impact of the interference on exclusion bounds



$\cancel{\mathcal{CP}}$ benchmark:
$M_h^{\mathrm{mod}+}$ with $\phi_{A_t} = \pi/4$
$\mu = 1000\,\mathrm{GeV}$
interference included
$\Rightarrow$ significant shift of exclusion bounds

Summary: Interference in MSSM Higgs searches

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

Summary: Interference in MSSM Higgs searches

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

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

- $h_2 - h_3$ interference relevant in $\mathcal{CP}$-violating benchmark scenario
- Non-zero phases can have significant impact on exclusion limits

Outlook: define $\mathcal{CP}$-violating benchmark scenario

- evaluate interference effect in gluon fusion
- further investigate impact of various values of μ, ϕ_{A_t}, ϕ_{M_3}
- LHC run II: Higgs searches interpreted in complex MSSM

Summary: Interference in MSSM Higgs searches

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

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

- $h_2 - h_3$ interference relevant in $\mathcal{CP}$-violating benchmark scenario
- Non-zero phases can have significant impact on exclusion limits

Outlook: define $\mathcal{CP}$-violating benchmark scenario

- evaluate interference effect in gluon fusion
- further investigate impact of various values of μ, ϕ_{A_t}, ϕ_{M_3}
- LHC run II: Higgs searches interpreted in complex MSSM

Thank you!

APPENDIX

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
- '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** $M_h \approx M_H$

accuracy vs. technical simplification of approximation

Generalised NWA with interference term

$$\sigma(ab \to cef) = \frac{1}{F} \int d\Phi \left(\frac{|\mathcal{M}(ab \to ch)|^2 |\mathcal{M}(h \to ef)|^2}{(q^2 - M_h^2)^2 + M_h^2 \Gamma_h^2} + \frac{|\mathcal{M}(ab \to cH)|^2 |\mathcal{M}(H \to ef)|^2}{(q^2 - M_H^2)^2 + M_H^2 \Gamma_H^2} \right.$$

$$\left. + 2Re \left\{ \frac{\mathcal{M}(ab \to ch)\mathcal{M}^*(ab \to cH)\mathcal{M}(h \to ef)\mathcal{M}^*(H \to ef)}{(q^2 - M_h^2 + iM_h\Gamma_h)(q^2 - M_H^2 - iM_H\Gamma_H)} \right\} \right)$$

$$\stackrel{\mathcal{M}\ on-shell}{\approx} \sigma_{ab \to ch} BR_{h \to ef} + \sigma_{ab \to cH} BR_{H \to ef}$$

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

$$\left. \left. \left[\int d\Phi_D(q^2) \mathcal{D}_1(M_1^2) \mathcal{D}_2^*(M_2^2) \right] \right) \right\}$$

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

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

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

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

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 γ

> precise $\Gamma, M, Z,$ BR (FeynHiggs)

> tree-level result without NWA

$\Longrightarrow$

combination of higher-order corrections to subprocesses in generalised NWA

On-shell interference term at NLO

Standard NWA

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

Matrix element method

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

R-factor approximation

- $\sigma_P^1 \cdot \mathrm{BR}^0$
- $\sigma_P^0 \cdot \mathrm{BR}^1$
- $\tilde{R}$-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: $\delta_{\mathrm{SB}}(q^2) \cdot \mathcal{M}_i(q^2)\mathcal{M}_j^*(q^2) \to$ mismatch with $\mathcal{D}^{\mathsf{virt}}(M^2)$! $\times$
- integrals in 1-loop matrix elements and soft-photon factor δ_{SB} need to be evaluated at the same mass $\to$ **IR-div. cancel** $\checkmark$
- 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 γs

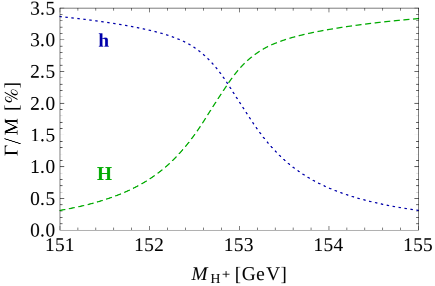
[Denner, Dittmaier, Roth, Wackeroth '00] [Grünewald, Passarino et. al. '00]

Example process with h-H interference

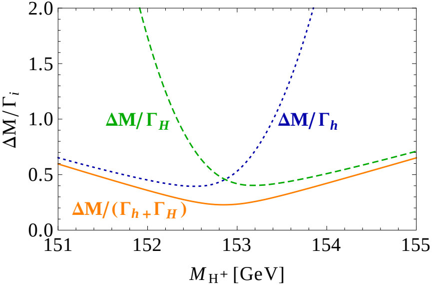
Test case: $M_h^{\max}$-like scenario with real parameters

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

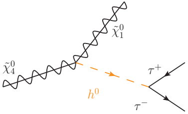
Narrow width

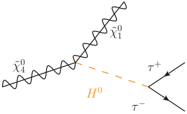


ΔM vs width

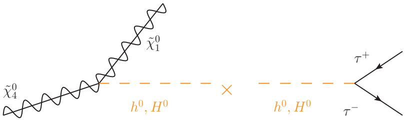


3-body decay

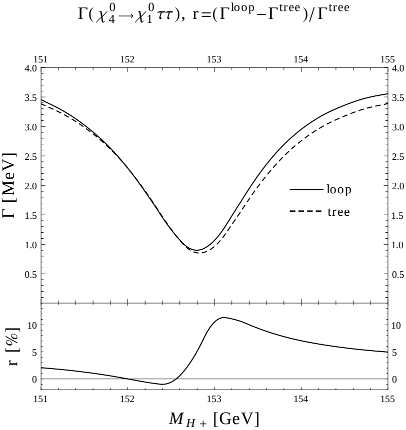




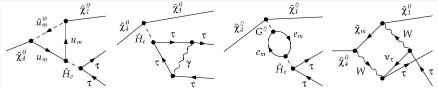
NWA: 2-body decays



$1 \to 3$ decay at NLO



1-loop calculation

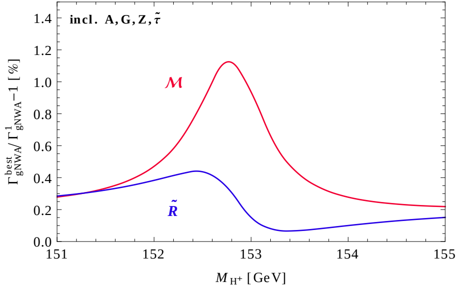


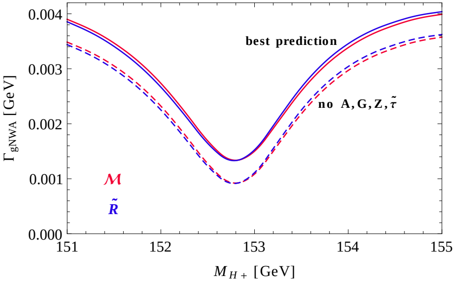
- diagrams
  - vertices
  - self-energy
  - box
  - soft photon radiation
- Higgs mixing by $\hat{\mathbf{Z}}$-factors
- manageable at 1-loop level

use process to validate gNWA at 1-loop level

gNWA with most precise subprocesses

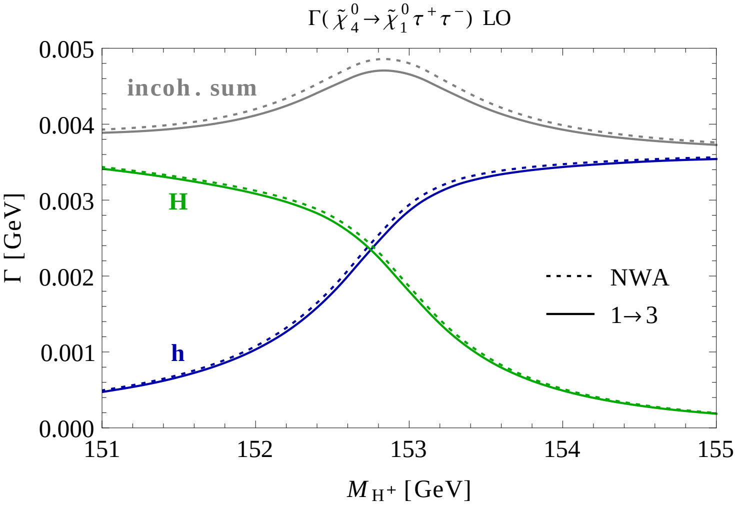
$$\sigma_{\text{gNWA}}^{\text{best}} = \sigma_{\text{full}}^{0} + \sum_{i=h,H} \left(\sigma_{P_i}^{\text{best}} \text{BR}_i^{\text{best}} - \sigma_{P_i}^{0} \text{BR}_i^{0} \right) + \sigma_{\text{gNWA}}^{\text{int1}} + \sigma_{\text{gNWA}}^{\text{int+}}$$





use **factorisation**: include σ_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
  $\rightarrow$ 3 parameters $|M_1|, |M_2|, |\mu|$ properly fixed
- otherwise: huge counterterms and unphysically large mass corrections
- here: **NNN** scheme with $\tilde{\chi}^0_{1,3,4}$ on-shell

stability of scheme (proper parameter fixing): parameter dependent

Neutralino-chargino renormalisation schemes

Renormalisation constants and ΔM 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**

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

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

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

$$\hat{Z}_a = \mathrm{Res}_{\mathcal{M}_a^2} \Delta_{ii}(p^2) = \frac{1}{1 + \hat{\Sigma}_{ii}^{\mathrm{eff}\prime}(\mathcal{M}_a^2)}, \quad \hat{Z}_{aj} = \left.\frac{\Delta_{ij}(p^2)}{\Delta_{ii}(p^2)}\right|_{p^2 = \mathcal{M}_a^2} \tag{4}$$

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

Higher-order effects in the Higgs sector

Self-energy diagrams

- significant impact on masses
- 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 contributes only at 2-loop order, but at 1-loop in correction Δ_b to bottom Yukawa coupling

Phenomenology

- loop corrected Higgs mass at 125 GeV possible in MSSM
- important loop contributions to Higgs production and decay

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

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 $\to h_1, h_2, h_3$
  - $M_{h_3} - M_{h_2} \leq \Gamma_{h_2}, \Gamma_{h_3}$ in decoupling region

Include interference term

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

Analyse interference effects in the complex MSSM!

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

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

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