Interference Effects of neutral MSSM Higgs Bosons

with a Generalised Narrow-Width Approximation.

Elina Fuchs
DESY/ CERN

in collaboration with
Silja Thewes and Georg Weiglein

Cargèse, July 2014

Student talk

HELMHOLTZ
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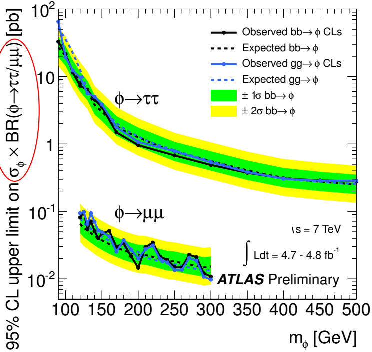
Useful approximation for New Physics searches

- NP: many-particle final state difficult at higher order
- $\rightsquigarrow$ simplified by factorisation into **production**$\times$**decay**



Narrow-width approximation (NWA)

$$\sigma \approx \sigma_{\text{prod}}(q^2 = M^2) \cdot \text{BR}_{\text{dec}}$$

- narrow width $\Gamma \ll M$
- kinematically open, away from thresholds
- non-factorisable corrections small
- no interference with other processes

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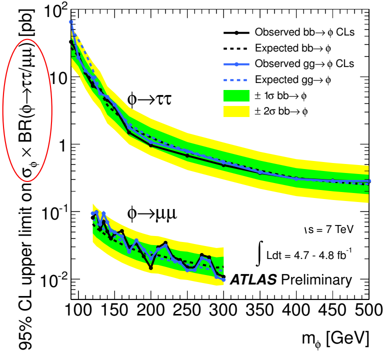

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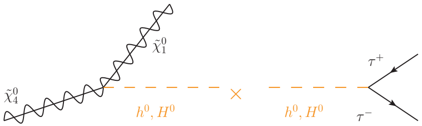
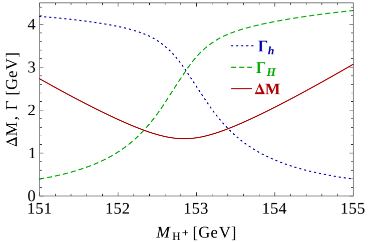
Mass degeneracy: interference term significant

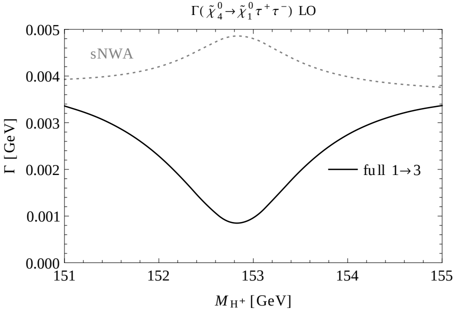
- NWA not applicable for $|M_i - M_j| \lesssim \Gamma_i, \Gamma_j$ $\rightarrow$ **generalised NWA**

Example process: $\Gamma(\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 \tau^+\tau^-)$ at leading order





Scenario: small $\Delta M = M_H - M_h$



On-shell interference term

- '**full**': $1 \to 3$ with h, H+Int
- **sNWA**: $\Gamma_{P_h}\mathrm{BR}_h + \Gamma_{P_H}\mathrm{BR}_H$

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

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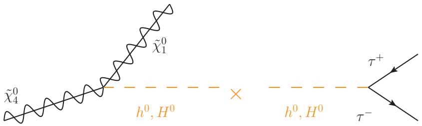

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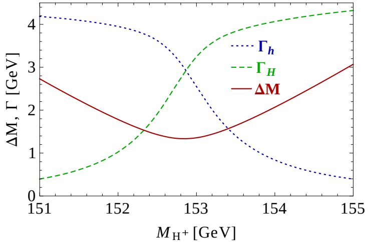
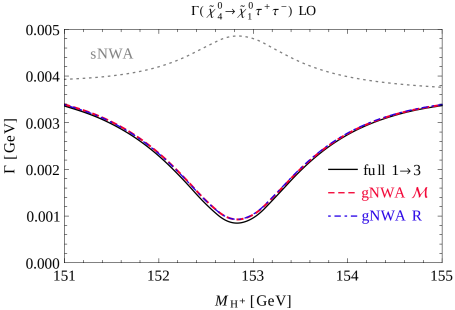




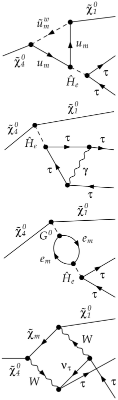
On-shell interference term

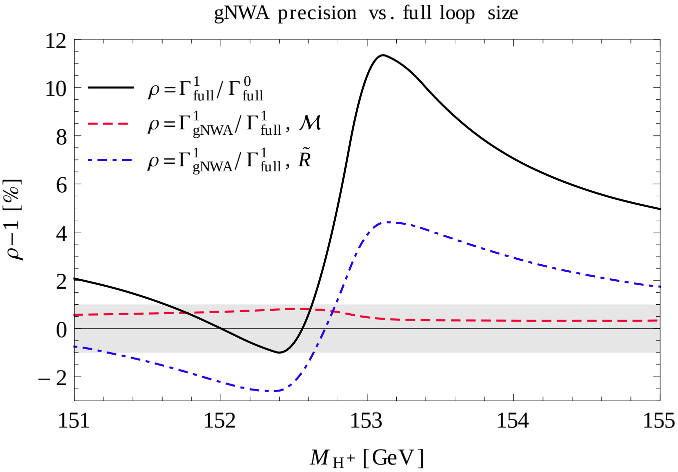
- **'full'**: $1 \to 3$ with h, H+Int
- **sNWA**: $\Gamma_{P_h}\mathrm{BR}_h + \Gamma_{P_H}\mathrm{BR}_H$
- **gNWA**: sNWA+Int$_{\text{on-shell}}$

large **negative interference** effect well approximated by **gNWA** ($\mathcal{M}$/ R)

Accuracy of gNWA at 1-loop order

Comparison with 3-body decay:





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

Conclusion

Summary: interference and NLO effects in generalised NWA

- example: decay $\tilde{\chi}_4^0 \overset{h^0,H^0}{\rightarrow} \tilde{\chi}_1^0 \tau^+ \tau^-$ with interference of Higgs bosons
- demonstrated how gNWA can be applied at the loop level: inclusion of virtual and real corrections, cancellations of IR-divergences preserved
  - on-shell matrix elements: 1% agreement with full result
  - R-factor: 4% agreement with full result, but technically easier
- gNWA enables factorisation into production and decay with interference and NLO effects $\rightarrow$ useful for various BSM models

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Ongoing: $\mathcal{CP}$-violating mixing

- $\mathrm{MSSM}_{\mathbb{C}}: \; \not{\mathcal{CP}} \Rightarrow H^0 - A^0$ interference
  - $b\bar{b}\,(h/H/A \rightarrow \tau^+\tau^-/b\bar{b})$
  - $gg \rightarrow h/H/A \rightarrow \tau^+\tau^-/\mu^+\mu^-$
- negative interference terms could relax limits on σ
- impact on experimental parameter limits?

Thank you!

Do you have any questions?

Studienstiftung des deutschen Volkes

PIER

PIER Helmholtz Graduate School A Graduate Education Program of Universität Hamburg in Cooperation with DESY

CERN

NWA basics

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

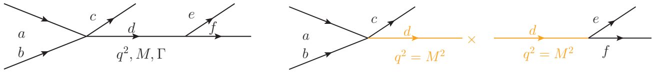
- $d\Phi_n \equiv dlips\,(P; p_1, ..., p_f) = (2\pi)^4 \delta^{(4)}(P - \sum_{f=1}^{n} p_f) \prod_{f=1}^{n} \frac{d^3 p_f}{(2\pi)^3 2E_f}$
- here: kinematics of 3-body decay $\rightarrow$ 2-body
  $d\Phi = dlips(\sqrt{s}; p_c, p_e, p_f) = dlips(\sqrt{s}; p_c, q) \frac{dq^2}{2\pi} dlips(q; p_e, p_f)$

Production$\times$decay

- instead of Breit-Wigner propagator $\frac{1}{q^2 - M^2 + iM\Gamma}$
- on-shell production of particle with mass M, and subsequent decay:
  $$\sigma_{ab\rightarrow cef} \approx \sigma_{ab\rightarrow cd}(q^2 = M^2) \cdot BR_{d\rightarrow ef}$$
- uncertainty of $\mathcal{O}\left(\frac{\Gamma}{M}\right)$

Standard NWA: Conditions and limitations

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



Validity

- narrow width $\Gamma \ll M$, otherwise off-shell effects e.g. [Gigg, Richardson '08]
- kinematically open, away from thresholds e.g. [Kauer '08]
- 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]

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

Relevance of interference term

Cross section with full interference term

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

Mass degeneracy: interference term significant [Fowler, PhD Thesis '10]

- NWA not applicable for $|M_i - M_j| \lesssim \Gamma_i, \Gamma_j$ (Breit-Wigner overlap)
- e.g. MSSM: for some parameters, h^0, H^0, A^0 have similar masses
- also relevant for other models

Generalised NWA with interference term

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

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

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

$$+ \frac{2}{F}\mathrm{Re}\left\{ \int \frac{dq^2}{2\pi} \left(\Delta_1^{BW}(q^2)\Delta_2^{*BW}(q^2) \left[\int d\Phi_P(q^2)\mathcal{M}_{P_1}(M_1^2)\mathcal{M}^*_{P_2}(M_2^2) \right] \right.\right.$$

$$\left.\left. \left[\int d\Phi_D(q^2)\mathcal{M}_{D_1}(M_1^2)\mathcal{M}^*_{D_2}(M_2^2) \right] \right) \right\}$$

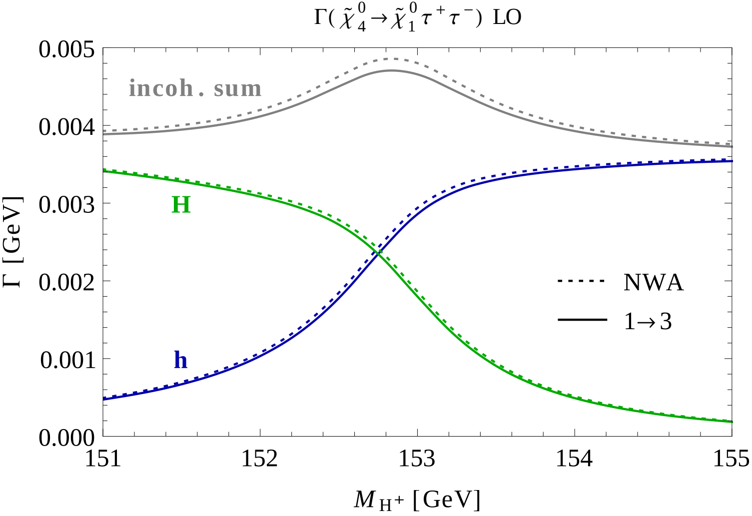
$$\overset{M_h \simeq M_H}{\approx} \sigma_{P_1}\, BR_1 \cdot (1 + R_1) + \sigma_{P_2}\, BR_2 \cdot (1 + R_2)$$

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

$$w_i := \frac{\sigma_{P_i}\, BR_i}{\sigma_{P_1}\, BR_1 + \sigma_{P_2}\, BR_2}$$

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

Uncertainty of the sNWA at tree level



Higgs propagator mixing [Frank, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein '07]

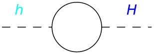
3×3 mixing (approximation of 6×6) $\to 2 \times 2$ for $\mathcal{CP}$

- mixing self-energies $\Rightarrow$ mass matrix (m_{tree}, M_{loop})

- masses and widths from complex pole $\mathcal{M}_i^2 = M_i^2 - iM_i\Gamma_i$
- diagonal propagator $\Delta_{ii} = \frac{i}{p^2 - m_i^2 + \hat{\Sigma}_{ii}^{\text{eff}}(p^2)} \overset{p^2 \simeq \mathcal{M}_i^2}{\longrightarrow} \Delta_i^{BW} \cdot \hat{\mathbf{Z}}$

Finite wave function normalisation factors (Z-factors)

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

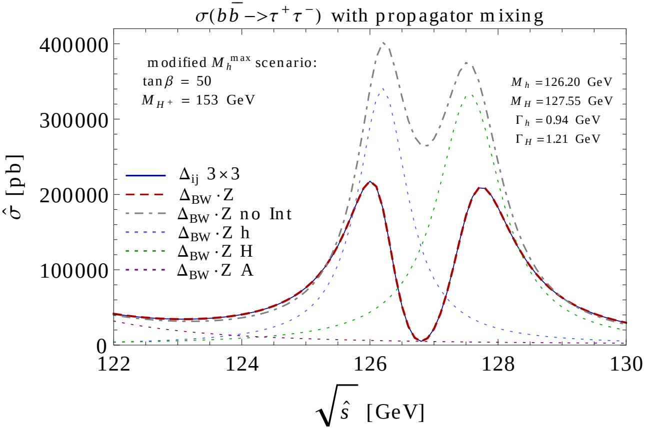


$$\Gamma_{h_i}^{(Z)} = \hat{Z}_{h_i h}\Gamma_h + \hat{Z}_{h_i H}\Gamma_H + \ldots$$

$\longrightarrow$ FeynHiggs

Higgs propagator mixing: BW approximation

- simple example process $b\bar{b} \to \tau^+\tau^-$ to study propagator mixing effects

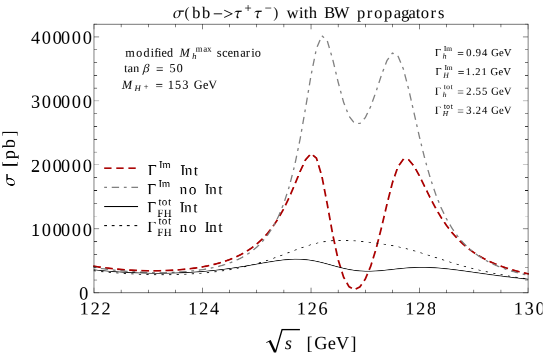


- mixing propagators well approximated by $\hat{Z} \cdot \Delta^{BW}$
- sensitive to exact values of total widths

Breit-Wigner propagators: total width

- Higgs mass matrix with mixing self-energies

$$\mathbf{M}_0(p^2) = \begin{pmatrix} m_h^2 - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{hH}(p^2) & -\hat{\Sigma}_{hA}(p^2) \\ \hat{\Sigma}_{Hh}(p^2) & m_H^2 - \hat{\Sigma}_{HH}(p^2) & -\hat{\Sigma}_{HA}(p^2) \\ \hat{\Sigma}_{Ah}(p^2) & -\hat{\Sigma}_{AH}(p^2) & m_A^2 - \hat{\Sigma}_{AA}(p^2) \end{pmatrix}$$



- larger **total widths** from `FeynHiggs` reduce cross section
- 2 resonances **overlap** in 1 broad peak

Renormalisation: neutralino sector on-shell

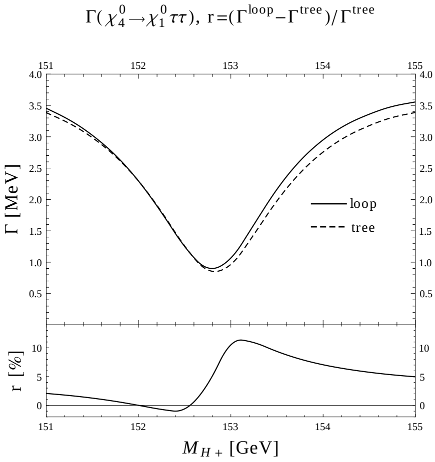
Neutralino and chargino matrices

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

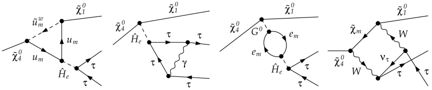
On-shell conditions [Fowler, Weiglein '09] [Bharucha, Fowler, Moortgat-Pick, Weiglein '12] [Chatterjee, Drees, Kulkarni, Xu '11] [Bharucha, Heinemeyer, Pahlen, Schappacher '12],...

- 3 out of 6 $\tilde{\chi}^0, \tilde{\chi}^\pm$ masses on-shell
- choose most bino-, wino- and higgsino-like states as input
  $\to$ 3 parameters $|M_1|, |M_2|, |\mu|$ properly fixed

stable scheme choice depends on scenario



1-loop calculation



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

use process to validate gNWA at 1-loop level

Higher-order corrections in the generalised NWA

Loop corrections to sub-processes of $\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 \tau^+ \tau^-$

- **Production:** full vertex corrections $\mathcal{O}(15\%)$
- **Decay:** virtual contributions and real γ-emission $\mathcal{O}(-1\%)$
- **Higgs propagator:** self-energy mixing by $\hat{\mathbf{Z}}$-factors

Strategy: combination of precise partial results

> separate calculation of loop corrections to production and decay

> approximation of interference term based on NLO matrix elements

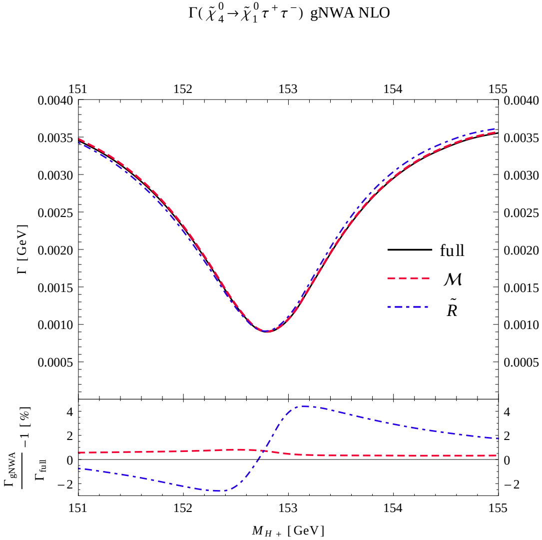
> IR-cancellations between on-shell matrix elements with virtual + real soft γ

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

$\Longrightarrow$

combination of higher-order corrections to sub-processes in **generalised NWA**

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

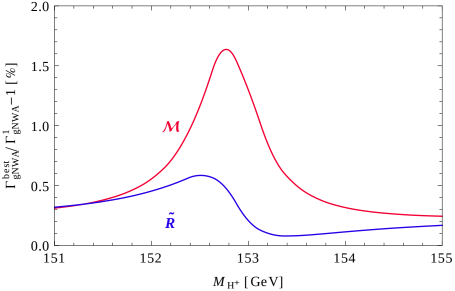


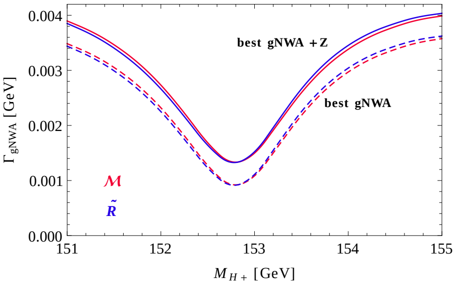
1-loop gNWA

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

gNWA with most precise subprocesses

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





use **factorisation**: include σ_P and BR at **highest available precision** in gNWA

Relation of masses and total widths