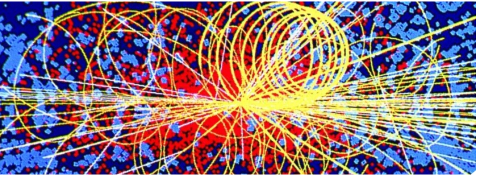
Interference Effects of Higgs Bosons in the MSSM

A Generalised Narrow-Width Approximation.



Elina Fuchs
DESY

in collaboration with
Silja Thewes and Georg Weiglein

DPG Mainz, March 2014

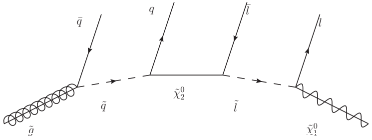
BSM Phenomenology

HELMHOLTZ GEMEINSCHAFT

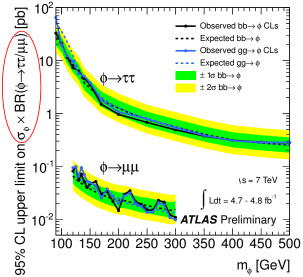
DESY

Useful approximation for New Physics searches

- NP: 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

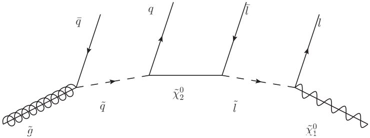


$$\sigma_{production} \times BR_1 \times BR_2 \times BR_3 \times BR_4$$

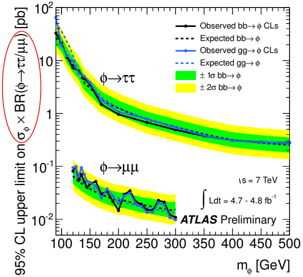


Useful approximation for New Physics searches

- NP: 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



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



Extension necessary!

combine interference and higher-order effects

Outline

> Motivation

> **Generalised Narrow-Width Approximation (NWA)**
- Standard NWA
- Generalised NWA (gNWA) including interference term

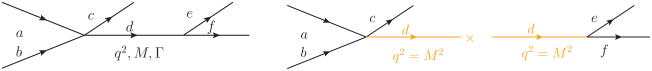
> Example process $\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 \tau^+ \tau^-$ at LO

> Comparison of full 1-loop result with gNWA
- Higgs and neutralino sector at 1-loop
- Full $1 \to 3$ decay at NLO
- gNWA at NLO

> Conclusion

Standard NWA: Conditions and limitations

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



Factorisation: production × decay

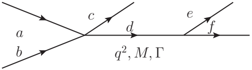
- instead of Breit-Wigner propagator $\frac{1}{q^2 - M^2 + iM\Gamma}$
- on-shell production and decay of particle with mass M:

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

- accurate up to $\mathcal{O}\left(\frac{\Gamma}{M}\right)$ [Uhlemann, Kauer '09]

Standard NWA: Conditions and limitations

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



Factorisation: production $\times$ decay

- instead of Breit-Wigner propagator $\frac{1}{q^2 - M^2 + iM\Gamma}$
- on-shell production and decay of particle with mass M:

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

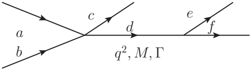
- accurate up to $\mathcal{O}\left(\frac{\Gamma}{M}\right)$ [Uhlemann, Kauer '09]

Validity

- narrow width $\Gamma \ll M$
- kinematically open, away from thresholds [Kauer '08]
- no interference with other processes

Standard NWA: Conditions and limitations

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



Factorisation: production × decay

- instead of Breit-Wigner propagator $\frac{1}{q^2 - M^2 + iM\Gamma}$
- on-shell production and decay of particle with mass M:

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

- accurate up to $\mathcal{O}\left(\frac{\Gamma}{M}\right)$ [Uhlemann, Kauer '09]

Validity

- narrow width $\Gamma \ll M$
- kinematically open, away from thresholds [Kauer '08]
- no interference with other processes

Relevance of interference term

Cross section with full interference term

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

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

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

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

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 term as R-factors: $\sigma \approx \sum_i \sigma_{P_i} BR_i \cdot (1 + R_i)$
  - 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

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 term as R-factors: $\sigma \approx \sum_i \sigma_{P_i} BR_i \cdot (1 + R_i)$
  - 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

Outline

> **Motivation**

> **Generalised Narrow-Width Approximation (NWA)**

- Standard NWA
- Generalised NWA (gNWA) including interference term

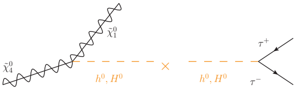
> **Example process $\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 \tau^+ \tau^-$ at LO**

> **Comparison of full 1-loop result with gNWA**

- Higgs and neutralino sector at 1-loop
- Full $1 \to 3$ decay at NLO
- gNWA at NLO

> **Conclusion**

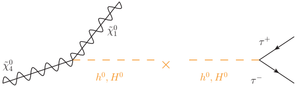
Example process: $\Gamma(\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 \tau^+ \tau^-)$

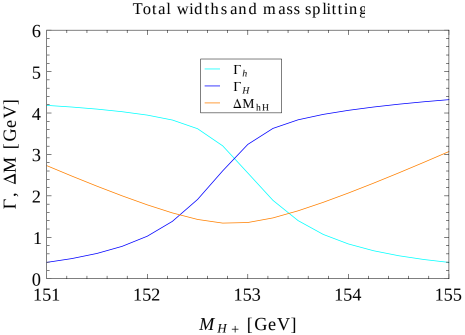


Scenario

- $\mathrm{MSSM}_{\mathbb{R}}(\mathcal{CP}) : h^0 - H^0$
- small $\Delta M = M_H - M_h$

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

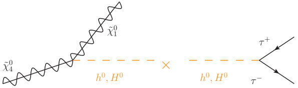


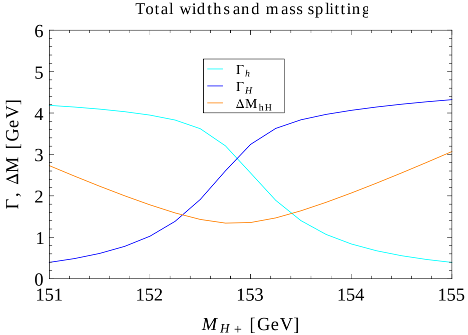


expect sizable interference around $\Delta M_{hH} \lesssim \Gamma_{h/H}$

Scenario

- $\mathrm{MSSM}_{\mathbb{R}}(\mathcal{CP}) : h^0 - H^0$
- small $\Delta M = M_H - M_h$





Scenario

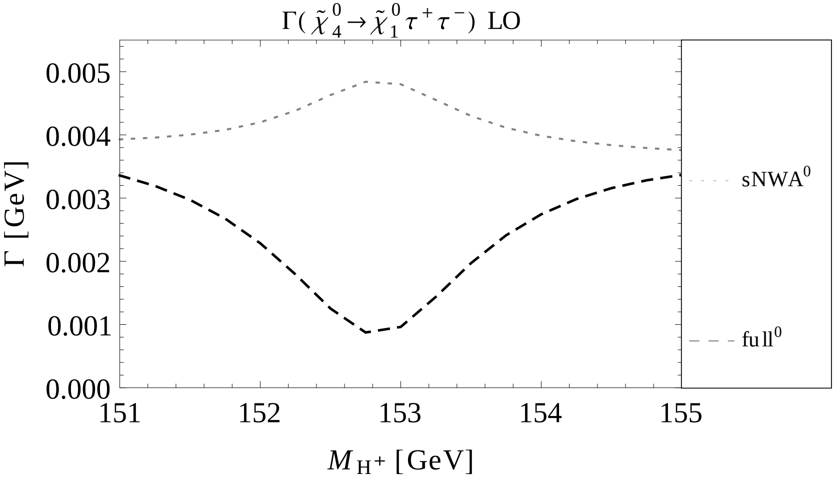
- $\mathrm{MSSM}_{\mathbb{R}}(\mathcal{CP}) : h^0 - H^0$
- small $\Delta M = M_H - M_h$

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

Calculation

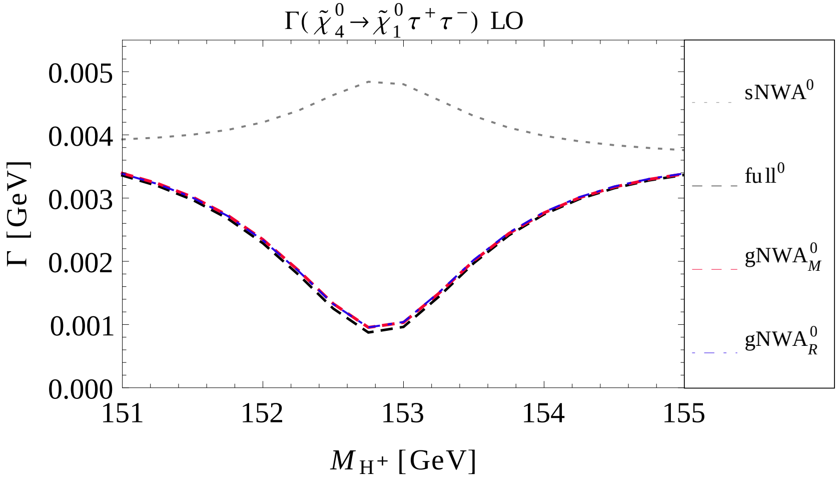
- decay widths: FeynArts/FormCalc/LoopTools
- precise input quantities at 2-loop M, Γ, Z: FeynHiggs
- interference term implemented in different approximations

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



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

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



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

Outline

> **Motivation**

> **Generalised Narrow-Width Approximation (NWA)**
- Standard NWA
- Generalised NWA (gNWA) including interference term

> **Example process $\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 \tau^+ \tau^-$ at LO**

> **Comparison of full 1-loop result with gNWA**
- Higgs and neutralino sector at 1-loop
- Full $1 \to 3$ decay at NLO
- gNWA at NLO

> **Conclusion**

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

3×3 mixing (approximation of 6×6)

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

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

3×3 mixing (approximation of 6×6)

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

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

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

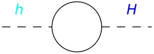
3×3 mixing (approximation of 6×6)

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

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

Z-factors

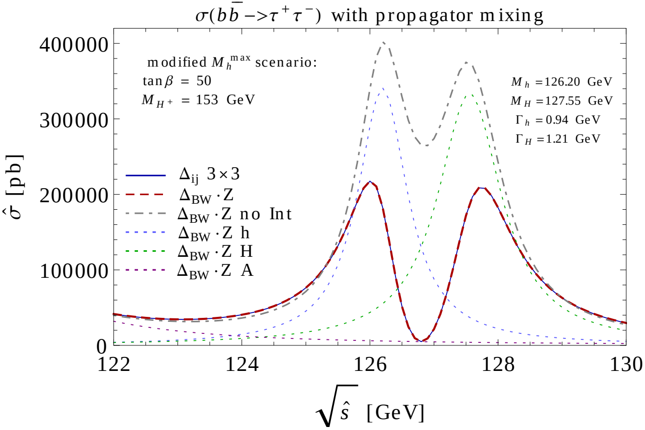
- correct on-shell properties of external Higgs bosons with mixing: $\hat{Z}_{ij}$



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

Higgs propagator mixing: BW approximation

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



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

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

Renormalisation: neutralino sector on-shell

Neutralino and chargino matrices

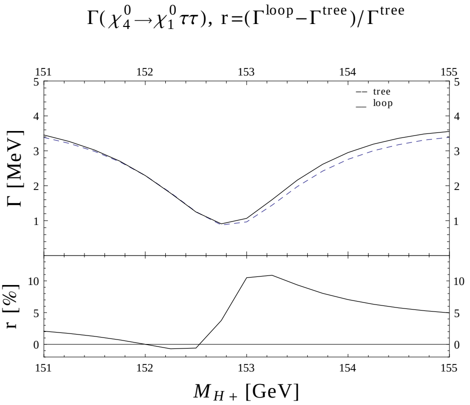
$$Y = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{pmatrix}, \quad X = \begin{pmatrix} M_2 & \sqrt{2} M_W s_\beta \\ \sqrt{2} M_W c_\beta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

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
  $\rightarrow$ 3 parameters $|M_1|, |M_2|, |\mu|$ properly fixed

stable scheme choice depends on scenario

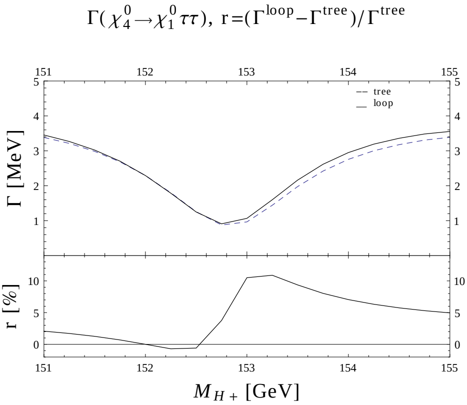
Full $1 \to 3$ decay at NLO



Full 1-loop calculation

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

Full $1 \to 3$ decay at NLO



Full 1-loop calculation

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

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 $\mathcal{O}(-4\%)$
- **Higgs propagator:** self-energy mixing by $\hat{Z}$-factors

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 $\mathcal{O}(-4\%)$
- **Higgs propagator:** self-energy mixing by $\hat{Z}$-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

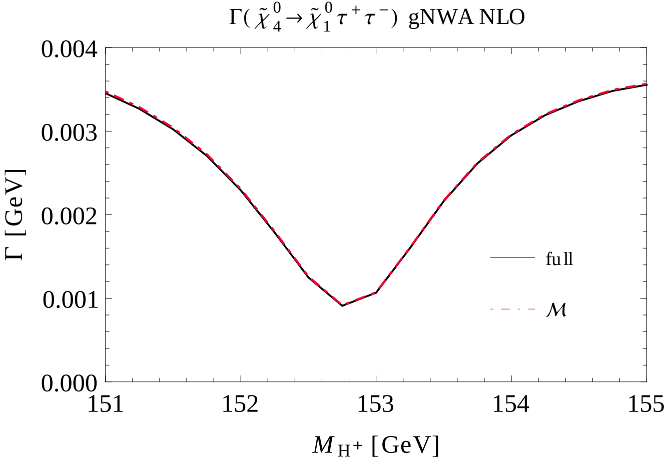
> IR-cancellations between on-shell matrix elements with virtual + real soft γ

> precise Γ, M, Z (FeynHiggs)

$\Longrightarrow$

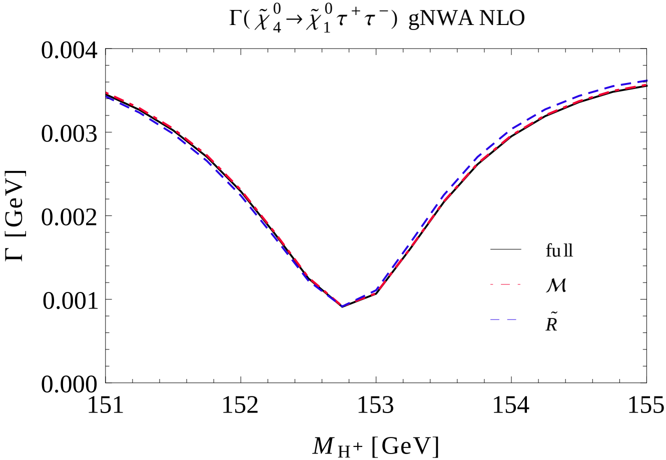
combination of higher-order corrections to sub-processes in **generalised NWA**

Full decay vs. gNWA at NLO



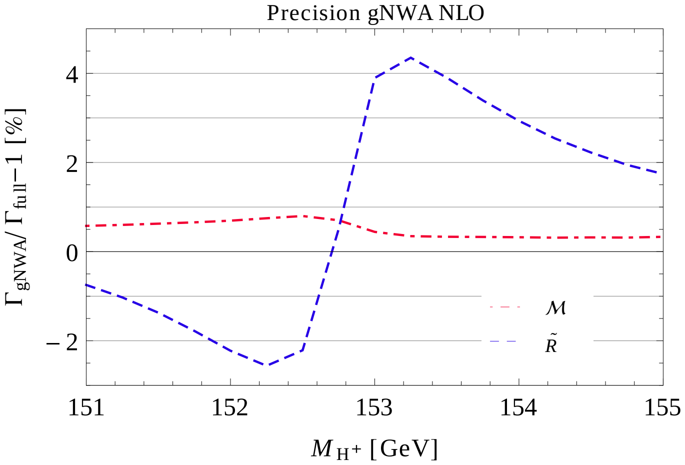
Full tree-level + 1-loop on-shell matrix elements

Full decay vs. gNWA at NLO



Full tree-level + 1-loop R-factors based on tree-level couplings and 1-loop Γ_P, Γ_D

Full decay vs. gNWA at NLO



$\mathcal{M}$atrix elements: 1% accuracy; R-factor: less precise, but simpler

Outline

> **Motivation**

> **Generalised Narrow-Width Approximation (NWA)**
- Standard NWA
- Generalised NWA (gNWA) including interference term

> **Example process $\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 \tau^+ \tau^-$ at LO**

> **Comparison of full 1-loop result with gNWA**
- Higgs and neutralino sector at 1-loop
- Full $1 \to 3$ decay at NLO
- gNWA at NLO

> **Conclusion**

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

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

Conclusion

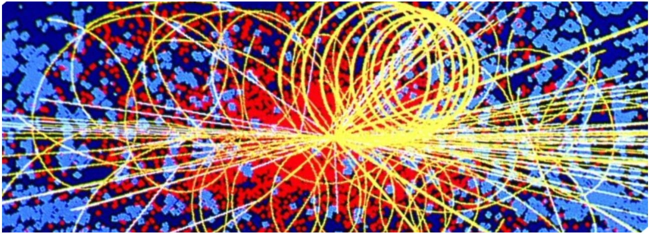
Summary: interference and NLO effects in generalised NWA

- example: decay $\tilde{\chi}_4^0 \stackrel{h^0,H^0}{\to} \tilde{\chi}_1^0 \tau^+\tau^-$ 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 $\to$ useful for various BSM models

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

- $\mathrm{MSSM}_{\mathbb{C}}$: $\cancel{\mathcal{CP}} \Rightarrow H^0 - A^0$ interference
  - $b\bar{b}\,(h/H/A \to \tau^+\tau^-/b\bar{b})$
  - $gg \to h/H/A \to \tau^+\tau^-/\mu^+\mu^-$
- negative interference terms could relax limits on σ
- impact on experimental parameter limits?

Thank you for your attention!



Do you have any questions?

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 $\to$ 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×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:
  $$\boxed{\sigma_{ab\to cef} \approx \sigma_{ab\to cd}(q^2 = M^2) \cdot BR_{d\to ef}}$$
- accurate up to $\mathcal{O}\left(\frac{\Gamma}{M}\right)$ [Uhlemann, Kauer '09]

Generalised NWA with interference term

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

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

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

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

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

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

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

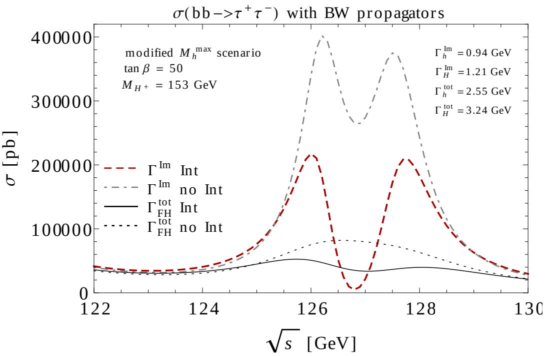
$$w_i := \frac{\sigma_{P_i}\, BR_i}{\sigma_{P_1}\, BR_1 + \sigma_{P_2}\, BR_2}$$

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

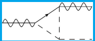
Breit-Wigner propagators: total width

- Higgs mass matrix with mixing self-energies

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

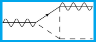


- larger **total widths** from `FeynHiggs` reduce cross section
- 2 resonances **overlap** in 1 broad peak

Vertex corrections to $\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h$ e.g. 

Renormalisation schemes with on-shell neutralinos

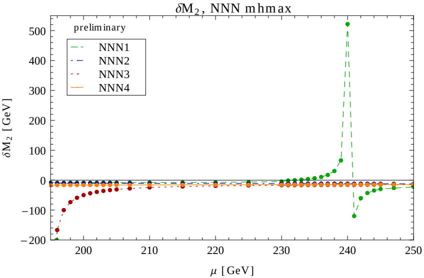
NNNi scheme: $m_{\tilde{\chi}_i^0}$ and $m_{\tilde{\chi}_{1,2}^\pm}$ receive loop correction

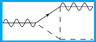
Vertex corrections to $\tilde{\chi}^0_4 \to \tilde{\chi}^0_1 h$ e.g. 

Renormalisation schemes with on-shell neutralinos

NNNi scheme: $m_{\tilde{\chi}^0_i}$ and $m_{\tilde{\chi}^\pm_{1,2}}$ receive loop correction

Parameter dependence

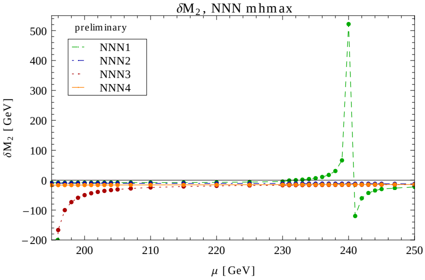


Vertex corrections to $\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h$ e.g. 

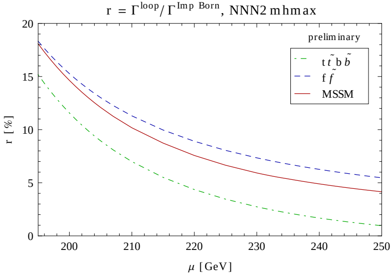
Renormalisation schemes with on-shell neutralinos

NNNi scheme: $m_{\tilde{\chi}_i^0}$ and $m_{\tilde{\chi}_{1,2}^\pm}$ receive loop correction

Parameter dependence



$\Gamma(\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h)$: loop effect

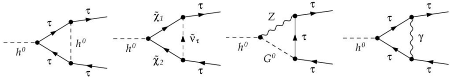


significant loop corrections to Higgs production in $\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h$ in a stable scheme

Virtual and real corrections to $h \to \tau^+\tau^-$

[Dabelstein '95] [Denner '07] [Williams, Rzehak, Weiglein '11], ...

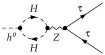
Triangle diagrams and soft γ-emission

e.g. 

UV-finite with CTs

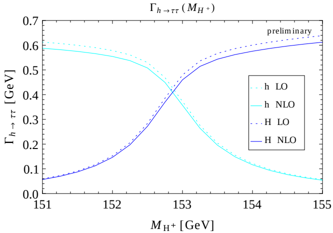
IR-finite: $\Gamma_{soft} = \delta_{soft} \cdot \Gamma_0$

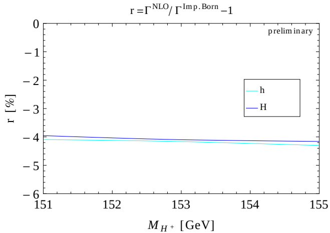
Selfenergy mixing

e.g. 

small, but sizable $h_i - h_j$ mixing approximated by Z-factors

Loop effect in $h_i \to \tau^+\tau^-$

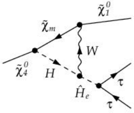


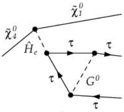


$1 \rightarrow 3$ decay at 1-loop

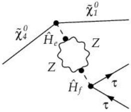
Factorisable contributions as in NWA

- vertices, e.g





- self-energy mixing, e.g.



Non-factorisable in addition to NWA

- boxes, e.g.