

Higgs-boson decays into Standard Model particles in the NMSSM with complex parameters

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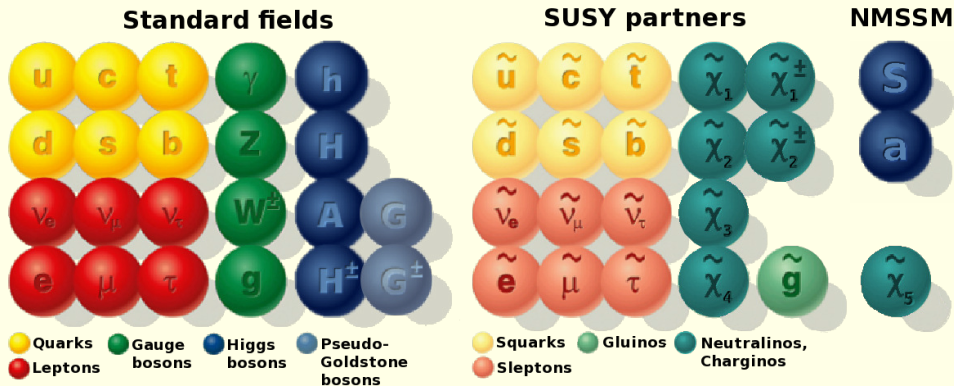
B9 Higgs Meeting

DESY Hamburg, Germany
25th of September 2017



- ① The NMSSM
- ② Higgs mixing in the NMSSM at higher orders
- ③ Higgs decays
 - Higgs decays into fermions
 - Higgs decays into vector bosons
- ④ Conclusions and outlook

- extension of the Standard Model by Supersymmetry
- two Higgs doublets, one Higgs singlet



non-kinetic part of the Lagrangian involving only Higgs fields:

$$V_H^{\text{NMSSM}} = V_{\text{Higgs}}^{\text{NMSSM}} + V_{\text{breaking}}^{\text{NMSSM}} ,$$

$$V_{\text{Higgs}}^{\text{NMSSM}} = \frac{1}{8} \left(g_Y^2 + g_w^2 \right) \left(|\mathcal{H}_2|^2 - |\mathcal{H}_1|^2 \right)^2 + \frac{1}{2} g_w^2 |\mathcal{H}_1^\dagger \mathcal{H}_2|^2 + |\lambda \mathcal{S}|^2 \left(|\mathcal{H}_1|^2 + |\mathcal{H}_2|^2 \right) \\ + \left| \lambda \mathcal{H}_1 \cdot \mathcal{H}_2 + \kappa \mathcal{S}^2 \right|^2 ,$$

$$V_{\text{breaking}}^{\text{NMSSM}} = \tilde{m}_1^2 |\mathcal{H}_1|^2 + \tilde{m}_2^2 |\mathcal{H}_2|^2 + (\lambda A_\lambda \mathcal{S} \mathcal{H}_1 \cdot \mathcal{H}_2 + \text{h. c.}) \\ + \tilde{m}_S^2 |\mathcal{S}|^2 + \left(\frac{1}{3} \kappa A_\kappa \mathcal{S}^3 + \text{h. c.} \right) ,$$

minimization of potential relates bilinear and quartic terms $\Rightarrow$ mass prediction

see talk from LHC Physics Discussions, 11.09.2017,

[Florian Domingo and Peter Drechsel, SP, arXiv:1706.00437]

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two point vertex function at one-loop order

$$\det \left[\widehat{\Gamma}_h(p^2) \right]_{p^2 = x_i^2} = 0, \quad m_{H_i}^2 = \Re[x_i^2], \quad i \in \{1, 2, 3, 4, 5\},$$

$\Rightarrow$ physical mass eigenstates: $H_1, \dots, H_5$ with masses $m_{H_1}, \dots, m_{H_5}$

relation between tree level h_i and loop level H_i :

$$\text{since } \widehat{\Sigma}_h^{(1)}(m_{H_j}^2 - i \Gamma_{H_j} m_{H_j}) \not\propto \widehat{\Sigma}_h^{(1)}(m_{H_k}^2 - i \Gamma_{H_k} m_{H_k}), j \neq k$$
$$\nexists \text{ unitary } \mathbf{U} \mid (H_1, H_2, H_3, H_4, H_5) = \mathbf{U} (h_1, h_2, h_3, h_4, h_5)$$

i. e. no unitary $\mathbf{U}$ diagonalizes $\widehat{\Gamma}_h^{(1)}(p^2)$ for all p^2

however, for each p^2 we can find unitary $\mathbf{U}^{p^2}$ which diagonalizes $\widehat{\Gamma}_h^{(1)}(p^2)$

particularly: determine $\mathbf{U}^{m_{H_1}^2}, \dots, \mathbf{U}^{m_{H_5}^2}$

construct matrix

$$\mathbf{Z}^{\text{mix}} = (1, 0, 0, 0, 0) \mathbf{U}^{m_{H_1}^2} + \dots + (0, 0, 0, 0, 1) \mathbf{U}^{m_{H_5}^2}$$

indeed:

$$\left[\mathbf{M}_h^{(1)} \left(m_{H_i}^2 - i \Gamma_{H_i} m_{H_i} \right) \right]_{kl} \mathbf{Z}_{il}^{\text{mix}} = \left(m_{H_i}^2 - i \Gamma_{H_i} m_{H_i} \right) \mathbf{Z}_{ik}^{\text{mix}}$$

possible approximation:

determine orthogonal $\mathbf{U}^0$ by neglecting p^2 in $\widehat{\Sigma}_h$

Z matrix, normalization

kinetic term of effective Lagrangian for loop-corrected Higgs bosons:

$$\mathbf{Z}_{il} \left[\mathbf{1} + \frac{d\hat{\Sigma}_h^{(1)}}{dp^2} \bigg|_{p^2 = m_{H_i}^2 - i \Gamma_{H_i} m_{H_i}} \right]_{kl} \mathbf{Z}_{ik} \stackrel{!}{=} \mathbf{1}$$

$$\Rightarrow \mathbf{Z}_i^{\text{fac}} = \left\{ \mathbf{Z}_{il}^{\text{mix}} \left[\mathbf{1} + \frac{d\hat{\Sigma}_h^{(1)}}{dp^2} \bigg|_{p^2 = m_{H_i}^2 - i \Gamma_{H_i} m_{H_i}} \right]_{kl} \mathbf{Z}_{ik}^{\text{mix}} \right\}^{-1}$$

we derive the $\mathbf{Z}$ matrix

$$\mathbf{Z}_{il} = \sqrt{\mathbf{Z}_i^{\text{fac}}} \mathbf{Z}_{il}^{\text{mix}}$$

further reading [Florian Domingo and Peter Drechsel, SP, arXiv:1706.00437]

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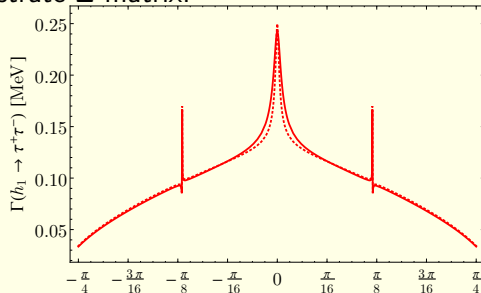
framework:

- similar procedure as for the MSSM [H. Rzehak, G. Weiglein, K. Williams, arXiv:1103.1335]
- full one-loop order, i. e. including $\mathbf{Z}$ matrix
- additional correction factors of higher order
- inclusion in future version of FeynHiggs
- future reading [F. Domingo, S. Heinemeyer, SP, G. Weiglein, in preparation]

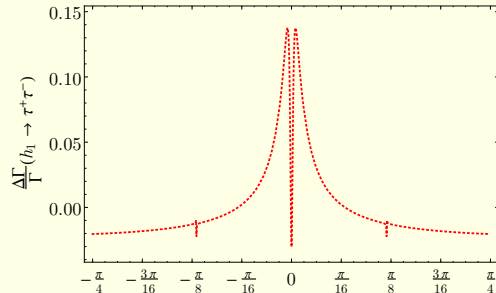
existing codes for the NMSSM:

- NMHDECAY [U. Ellwanger, J. Gunion and C. Hugonie, hep-ph/0406215, U. Ellwanger and C. Hugonie, hep-ph/0508022, F. Domingo, arXiv:1503.07087]
- NMSSMCalc [J. Baglio, R. Gröber, M. Mühlleitner, D. Nhung, H. Rzehak, M. Spira, J. Streicher, K. Walz, arXiv:1312.4788]
- SloopS [G. Belanger, V. Bizouard, F. Boudjema and G. Chalons, arXiv:1602.05495, arXiv:1705.02209]
- SARAH/SPheno [M. Goodsell, S. Liebler and F. Staub, arXiv:1703.09237]
- SoftSUSY [B. C. Allanach and T. Cridge, arXiv:1703.09717]

illustrate **Z** matrix:



dotted: approximation by $\mathbf{U}^0$ matrix
solid: full **Z** matrix



difference of both normalized to full result

if external mixing neglected $\rightarrow$ prediction completely off
additional mixing in production $\rightarrow$ further shift

- $$\mathcal{M}(H_i \rightarrow ff) = \mathbf{Z}_{ij} \mathcal{M}(h_j \rightarrow ff)_{m_{h_j} \rightarrow m_{H_i}}$$

⇒ take Higgs–Goldstone/Z mixing into account via wave function normalization

$$\mathcal{M}_{\text{wfn}} = \text{---} \underset{h_i}{\bullet} \text{---} \text{---} \underset{G, Z}{\bullet} \text{---} f + \text{---} \underset{h_i}{\times} \text{---} \underset{G, Z}{\bullet} \text{---} f$$

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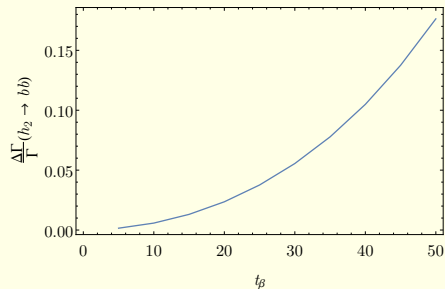
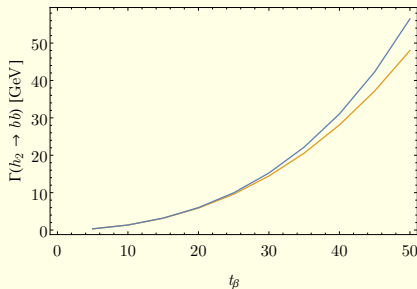
Higgs decays into vector bosons

④ Conclusions and outlook

Δb effect, $H_i \rightarrow bb$

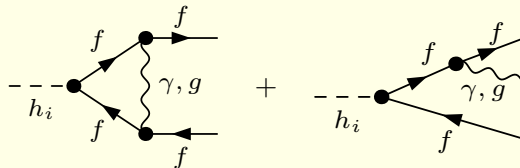
sizable corrections for large $t_\beta \rightarrow$ resummation
description through effective coupling from

$$\mathcal{L}_{\text{eff}} = -Y_b \bar{b} \left[H_d^0 + \frac{\Delta b}{\tan \beta} \left(\frac{\lambda}{\mu_{\text{eff}}} S H_u^0 \right)^* \right] P_L b + \text{h.c.}$$



QCD and QED corrections for $H_i \rightarrow f\bar{f}$

vertex corrections with massless propagators,



require adding real emission (otherwise IR divergent)

our choice:

- remove γ, g from vertex corrections
- include correction factor for QED and QCD:

$$\Gamma(H_i \rightarrow f\bar{f}) = \Gamma(H_i \rightarrow f\bar{f})_{\text{without } \gamma, g} \left(\frac{m_b^{\overline{\text{MS}}}(m_{H_i})}{m_b} \right)^2 (1 + f_{\text{QED}} + f_{\text{QCD}})$$

[E. Braaten, J. Leveille (1980); M. Drees, K. Hikasa (1990)]

total factor $\approx \frac{1}{2}$

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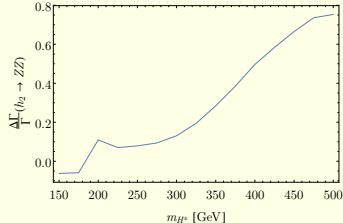
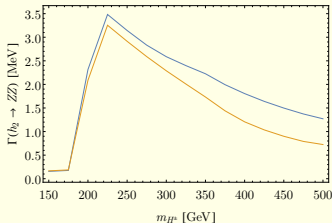
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off-shell effects, $H_i \rightarrow WW/ZZ$

decays into on-shell WW/ZZ easily computable,
usual understanding of WW/ZZ final states includes off-shell effects,

our approach I: full SM result from Prophecy4f,
rescaling to NMSSM Higgs by squared ratio of tree-level couplings,
justified for SM-like Higgs; wrong one-loop correction

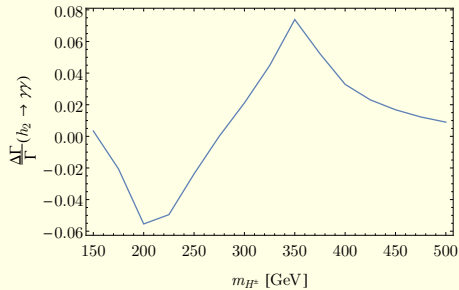
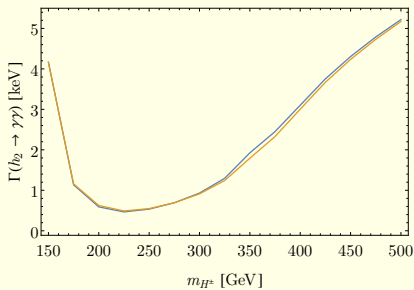
our approach II: one-loop calculation of decay into on-shell WW/ZZ ,
include tree-level off-shell effects,
justified for heavy Higgs with mass far above WW/ZZ threshold



decay width equal to zero at tree level,
leading order equal to one-loop order,
large higher-order QCD corrections to quark and squark loops,

taken into account numerically at the level of amplitudes: factors $c \left(\frac{M_{H_i}^2}{4 m_q^2} \right)$

[M. Spira, A. Djouadi, D. Graudenz, and P. Zerwas, hep-ph/9504378, M. Mühlleitner and M. Spira, hep-ph/0612254]



decay width equal to zero at tree level,
leading order equal to one-loop order,
large higher-order QCD corrections to quark and squark loops,
include virtual corrections, but also real radiation of quarks/gluons,
numerical implementation of results in the large-mass limit [M. Spira, arXiv:1612.07651]
subtract di-quark radiation and assign it to $H_i \rightarrow qq$ [A. Djouadi, M. Spira, and P. M. Zerwas, hep-ph/9511344]

trilinear couplings $h_i GG$, $h_i h_j G$ (analogous for charged $H^\pm$, $G^\pm$) are $\propto m_{h_i}^2$,
we use external Higgs with physical (loop corrected) mass M_{H_i} ,
→ gauge identities broken, but actually just higher-order effect

- Ward identity in $H_i \rightarrow \gamma\gamma$ not satisfied
- IR divergence in $H_i \rightarrow WW$ does not cancel with $H_i \rightarrow WW\gamma$
- $H_i \rightarrow f\bar{f}$ evaluated in R_ξ gauge depends on gauge-fixing parameter

remove inconveniences by using M_{H_i} inside tree-level couplings of Goldstone bosons

mixing:

- loop corrections induce mixing of tree-level states
- in general no unitary matrix to describe mixing
- full treatment is important for Higgs couplings (production, decay)

decays:

- full one-loop amplitude
- down-type Yukawa resummation
- factorization of QED and QCD corrections for $H_i \rightarrow f\bar{f}$
- additional mixing with Goldstone and Z
- off-shell effects for $H_i \rightarrow WW/ZZ$
- higher-order QCD corrections for $H_i \rightarrow \gamma\gamma$
- approximated higher-order QCD corrections for $H_i \rightarrow gg$
- proper assignment of di-quark radiation in $H_i \rightarrow gg$

results will become publicly available via FeynHiggs