Higgs Decays into SM particles in the NMSSM

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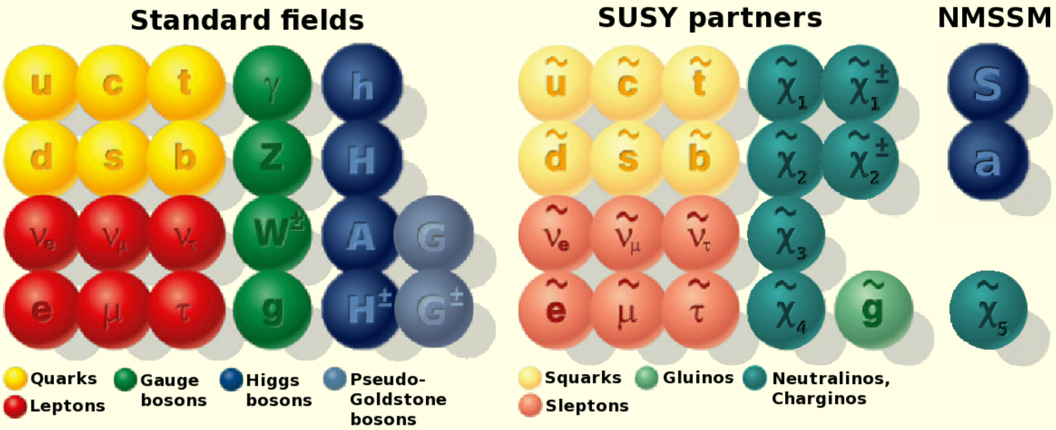
Planck 2018

Bethe Center of Theoretical Physics
Bonn, Germany
23rd of May 2018

Contents

Particle content of the NMSSM



supersymmetry $\Rightarrow$ SUSY partners

no anomalies, holomorphic superpotential $\Rightarrow$ two Higgs doublets

nice to have $\Rightarrow$ Higgs singlet

Higgs sector of the NMSSM at tree level

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

$$
\begin{aligned}
V_H^{\mathrm{NMSSM}} &= V_{\mathrm{Higgs}}^{\mathrm{NMSSM}} + V_{\mathrm{breaking}}^{\mathrm{NMSSM}} \,, \\
V_{\mathrm{Higgs}}^{\mathrm{NMSSM}} &= \tfrac{1}{8}\left(g_Y^2 + g_{\mathrm{w}}^2\right)\left(|\mathcal{H}_2|^2 - |\mathcal{H}_1|^2\right)^2 + \tfrac{1}{2}\, g_{\mathrm{w}}^2\, |\mathcal{H}_1^\dagger \mathcal{H}_2|^2 + |\lambda\, \mathcal{S}|^2 \left(|\mathcal{H}_1|^2 + |\mathcal{H}_2|^2\right) \\
&\quad + \left|\lambda\, \mathcal{H}_1 \cdot \mathcal{H}_2 + \kappa\, \mathcal{S}^2\right|^2 \,, \\
V_{\mathrm{breaking}}^{\mathrm{NMSSM}} &= \tilde{m}_1^2\, |\mathcal{H}_1|^2 + \tilde{m}_2^2\, |\mathcal{H}_2|^2 + \left(\lambda\, A_\lambda\, \mathcal{S}\, \mathcal{H}_1 \cdot \mathcal{H}_2 + \mathrm{h.\,c.}\right) \\
&\quad + \tilde{m}_S^2\, |\mathcal{S}|^2 + \left(\frac{1}{3}\, \kappa\, A_\kappa\, \mathcal{S}^3 + \mathrm{h.\,c.}\right) \,,
\end{aligned}
$$

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

$$m_h^2 = \text{complicated} \lesssim m_Z^2 \cos^2 2\beta + \lambda^2\, v^2\, \sin^2 2\beta \ \text{(assuming no mixing with singlet)}$$

additional term $\propto \lambda$ compared to MSSM

Higgs particles at higher order

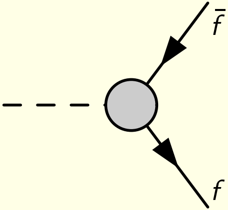
- Higgs masses are poles of propagators,
- Higgs propagators corrected by self-energies $\hat{\mathbf{\Sigma}}$:

$$\mathbf{\Delta}\left(p^2\right) = \mathbb{i}\left[p^2\,\mathbf{1} - \mathbf{M}^2_{\text{tree}} + \hat{\mathbf{\Sigma}}\left(p^2\right)\right]$$

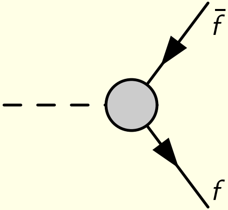
- $\hat{\mathbf{\Sigma}}$ contains mixing between tree-level eigenstates,
- no unitary matrix exists to explain transition from tree-level to higher-order mass eingenstates
- but: special non-unitary matrix $\mathbf{Z}$ can be constructed,
  see [F. Domingo, P. Drechsel, SP, arXiv:1706.00437]
  in our case: 5×5 matrix for neutral Higgs bosons

decay amplitudes of external physical Higgs bosons composed of tree-level amplitudes evaluated at $p^2 = (M_{h_i}^{\text{phys}})^2$

$$\mathcal{A}^{1\text{L}}_{\text{vert}}\left[h_i^{\text{phys}} \to f\bar{f}\right] = h_i^{\text{phys}}$$

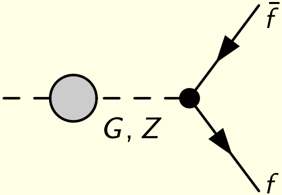


$$= \sum_j Z_{ij} \times h_j^{\text{tree}}$$



in addition: mixing with Goldstone and Z bosons (not included in our $\mathbf{Z}$ matrix)

$$\mathcal{A}^{1\text{L}}_{G,Z}\left[h_j^{\text{tree}} \to f\bar{f}\right] = h_j^{\text{tree}}$$



General framework

- similar procedure as for the MSSM [H. Rzehak, G. Weiglein, K. Williams, arXiv:1103.1335]
- Higgs masses and mixing at full one-loop order, see [F. Domingo, P. Drechsel, SP, arXiv:1706.00437], additional MSSM-like two-loop contributions with FeynHiggs:
  [S. Heinemeyer, W. Hollik, G. Weiglein, arXiv:9812320, arXiv:9812472], [G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. Weiglein, arXiv:0212020], [M. Frank, T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein, arXiv:0611326], [H. Bahl, W. Hollik, arXiv:1608.01880], [T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak, G. Weiglein, arXiv:1312.4937], [H. Bahl, S. Heinemeyer, W. Hollik, G. Weiglein, arXiv:1706.00346]
  $\mathcal{O}(\alpha_t \alpha_s)$ [S. Heinemeyer, W. Hollik, H. Rzehak, and G. Weiglein, arXiv:0705.0746], $\mathcal{O}(\alpha_t^2)$ [W. Hollik, SP, arXiv:1401.8275, arXiv:1409.1687]
- vertex corrections at full one-loop order:

$$\mathcal{A}\left[h_j^{\text{tree}} \to f\bar{f}\right] = \mathcal{A}^{\text{tree}}\left[h_j^{\text{tree}} \to f\bar{f}\right] + \mathcal{A}^{1\text{L}}_{\text{vert}}\left[h_j^{\text{tree}} \to f\bar{f}\right] + \mathcal{A}^{1\text{L}}_{G,Z}\left[h_j^{\text{tree}} \to f\bar{f}\right],$$

$$\Gamma[h_i^{\text{phys}} \to f\bar{f}] = \frac{1}{16\,\pi\, M_{h_i}} \sqrt{1 - \frac{4\, m_f^2}{M_{h_i}^2}} \sum_{\text{pol., col.}} \left|\mathcal{A}[h_i^{\text{phys.}} \to f\bar{f}]\right|^2$$

  with help of FeynArts [J. Küblbeck, M. Böhm, and A. Denner, CPC 60 (1990) 165–180], [T. Hahn, arXiv:0012260], FormCalc [T. Hahn and M. Pérez-Victoria, arXiv:9807565], LoopTools [T. Hahn and M. Pérez-Victoria, arXiv:9807565]
- general case of NMSSM with complex parameters implemented

Additional modifications

- $\overline{\text{MS}}$ quark masses with three-loop QCD at scale m_t [I. Hinchliffe, A. Manohar, arXiv:0004186]
- conversion of pole top mass with two-loop QCD and one-loop Yukawa [D. Kunz, L. Mihaila, N. Zerf, arXiv:1409.2297]
- $\tan\beta$-enhanced corrections to down-type Yukawa resummed in Δ_b (see also: [J. Baglio, R. Gröber, M. Mühlleitner, D. Nhung, H. Rzehak, M. Spira, J. Streicher, K. Walz, arXiv:1312.4788])
- restore gauge identities by proper treatment of Higgs–Goldstone couplings
- keep terms of $\mathcal{O}(1\text{L})^2$, i. e. partial two-loop order
- $h_i \to \gamma\gamma, gg$: zero at tree level $\Rightarrow$ add higher-order QCD [M. Spira, A. Djouadi, D. Graudenz, P. Zerwas, arXiv:9504378] [M. Mühlleitner, M. Spira, arXiv:0612254]
- $h_i \to q\bar{q}$: add contributions from $h_i \to g(g \to q\bar{q})$ [A. Djouadi, M. Spira, P. Zerwas, arXiv:9511344]
- $h_i \to WW, ZZ$: decays into off-shell bosons (four f final states) significant, popular approach: tree-level rescaling of SM width from e. g. `Prophecy4f` [A. Bredenstein, A. Denner, S. Dittmaier, and M. Weber, arXiv:0604011, arXiv:0607060, arXiv:0611234]

$$\mathcal{A}[h_i \to VV] = \mathcal{A}\Big[H^{\text{SM}}(M_{h_i}) \to VV\Big] \left|\frac{g^{\text{NMSSM}}_{h_i VV}}{g^{\text{SM}}_{HVV}}\right|^2$$

our approach: tree-level off-shell + one-loop on-shell

Existing tools/computations for Higgs decays in the NMSSM

- NMHDECAY/NMSSMTools [U. Ellwanger, J. Gunion and C. Hugonie, arXiv:0406215], [U. Ellwanger and C. Hugonie, arXiv:0508022], [F. Domingo, arXiv:1503.07087]

  based on HDECAY [A. Djouadi, J. Kalinowski, and M. Spira, arXiv:9704448], [The Tools and Monte Carlo Working Group, arXiv:1003.1643]
- NMSSMCALC [J. Baglio, R. Gröber, M. Mühlleitner, D. Nhung, H. Rzehak, M. Spira, J. Streicher, K. Walz, arXiv:1312.4788]

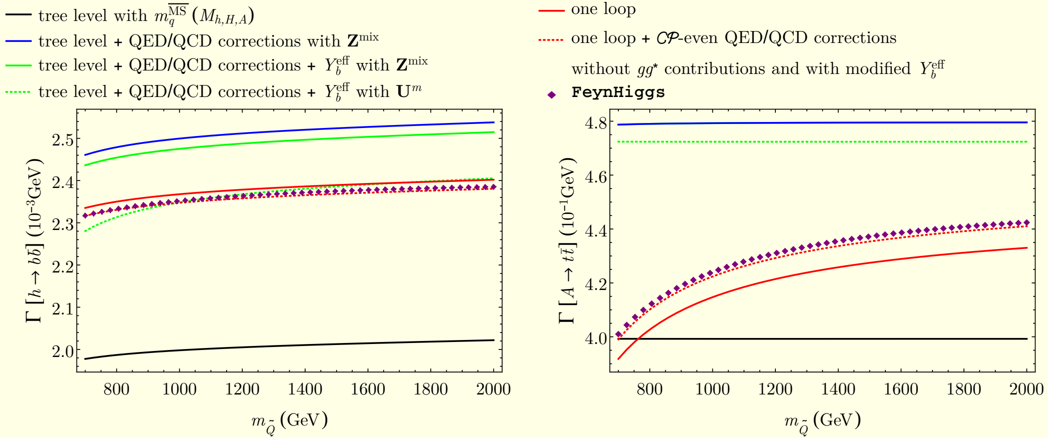
  based on HDECAY
- SloopS [G. Bélanger, V. Bizouard, G. Chalons arXiv:1402.3522], [G. Bélanger, V. Bizouard, F. Boudjema, G. Chalons, arXiv:1602.05495, arXiv:1705.02209]

  not public
- SARAH/SPheno [M. Goodsell, S. Liebler and F. Staub, arXiv:1703.09237]

  generic two-body decays
- SoftSUSY [B. Allanach and T. Cridge, arXiv:1703.09717]

  leading order or leading QCD corrections

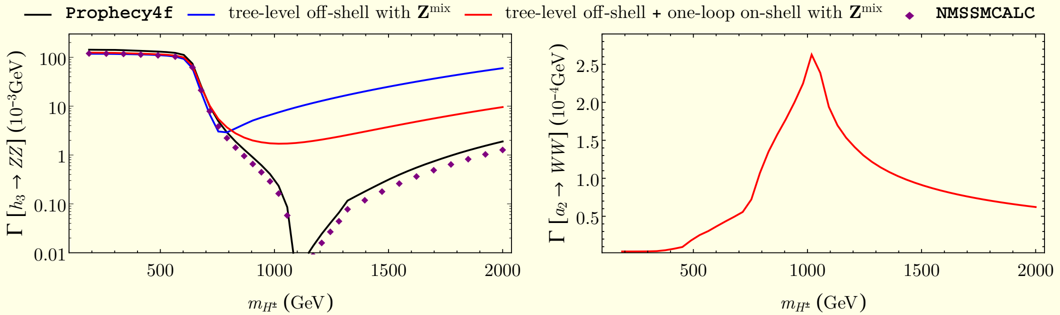
Comparison with FeynHiggs in MSSM limit $\lambda \to 0$, $\kappa/\lambda = \text{const}$



$$m_{\tilde{Q}} = 0.7 + 1.3 \cdot x,\ A_t = 1.4 + 1.6 \cdot x,\ x \in [0,1] \Rightarrow M_h \in [124, 126.5]\ \text{GeV},\ M_A \sim 997\ \text{GeV}$$

$$\lambda = 10^{-5},\ \kappa = 10^{-5},\ t_\beta = 10,\ \mu_{\text{eff}} = 250\ \text{GeV},\ m_{H^\pm} = 1\ \text{TeV},\ A_\kappa = -100\ \text{GeV},$$
$$A_b = A_t,\ 2\,M_1 = M_2 = M_3/5 = 500\ \text{GeV},\ m_{\tilde{f}} = 1.5\ \text{TeV}$$

Comparison with NMSSMCALC, real parameters

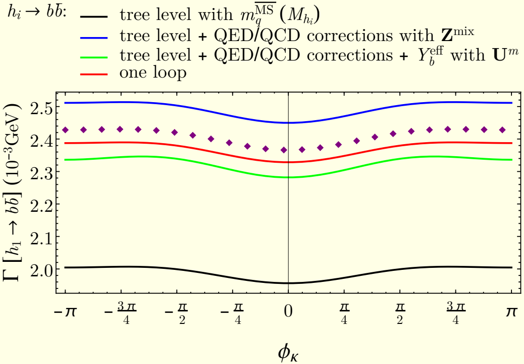


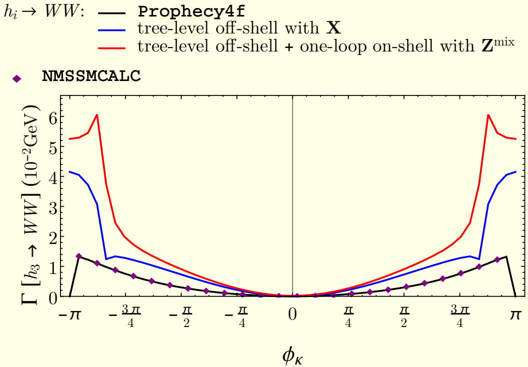
$$m_{H^\pm} = 0.15 + 1.85 \cdot x \,\text{TeV},\, x \in [0,1] \Rightarrow \begin{array}{l} M_{h_3} \sim \max\{650\,\text{GeV}, m_{H^\pm}\}, \\ M_{a_2} \sim \max\{350\,\text{GeV}, m_{H^\pm}\} \end{array}$$

$$\lambda = 0.3, \kappa = 0.4, t_\beta = 10, \mu_{\text{eff}} = 250\,\text{GeV}, A_\kappa = -100\,\text{GeV},$$
$$m_{\tilde{Q}} = 1.5\,\text{TeV}, A_t = 3\,\text{TeV}, A_b = A_t, 2\,M_1 = M_2 = M_3/5 = 500\,\text{GeV}, m_{\tilde{f}} = 1.5\,\text{TeV}$$

large loop corrections for large M_{h_i} $\Rightarrow$ might be visible despite small BR

Comparison with NMSSMCALC, complex parameters





$$\phi_\kappa = \pi(2\cdot x - 1),\, x \in [0,1] \Rightarrow M_{h_1} \sim 124.5\,\mathrm{GeV},\, M_{h_3} \sim 993\,\mathrm{GeV}$$

$$\lambda = 0.2,\, |\kappa| = 0.6,\, t_\beta = 25,\, \mu_{\mathrm{eff}} = 200\,\mathrm{GeV},\, m_{H^\pm} = 1\,\mathrm{TeV},\, A_\kappa = -750\,\mathrm{GeV},$$
$$m_{\tilde{Q}} = 1.5\,\mathrm{TeV},\, A_t = -2.5\,\mathrm{TeV},\, A_b = A_t,\, 2\,M_1 = M_2 = M_3/5 = 500\,\mathrm{GeV},\, m_{\tilde{f}} = 1.5\,\mathrm{TeV}$$

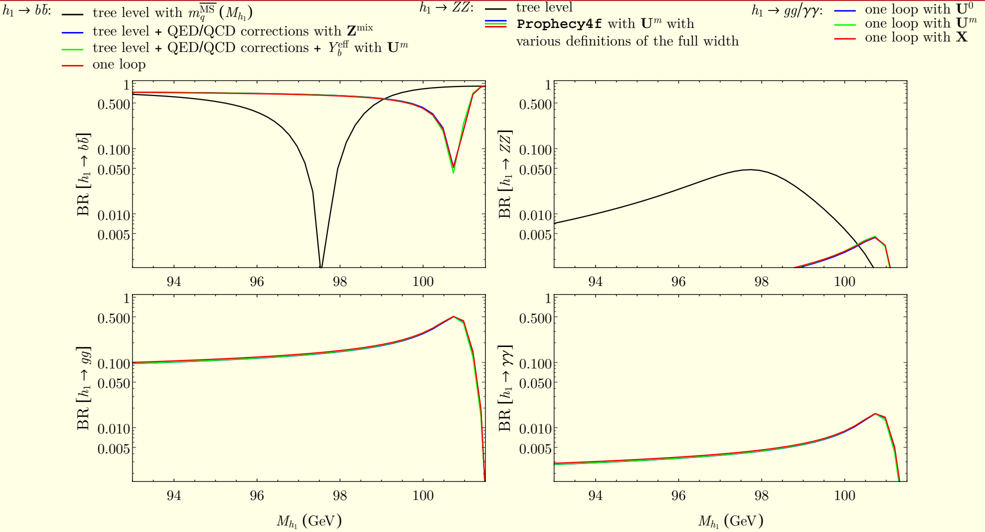
Light-Higgs signals

motivation:

- at LEP: [ALEPH, DELPHI, L3, OPAL, LEP Working Group for Higgs Boson Searches, arXiv:0306033]
  2.3 σ local excess in $e^+e^- \to Z(H \to b\bar{b})$,
  signal strength $\sim 10\%$ with respect to SM,
  consistent with Higgs of $\sim 98\,\text{GeV}$
- more recently at CMS: [CMS, CDS CMS-PAS-HIG-17-013]
  3 σ local excess in Run II (2 σ in Run I) in $H \to \gamma\gamma$ at $\sim 96\,\text{GeV}$,
  signal strength $60\% \pm 20\%$ with respect to SM

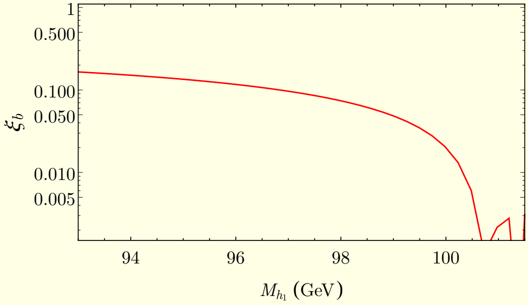
ideal candidate: light CP-even singlet-dominated Higgs in the NMSSM,
see e. g.
[R. Dermisek, J. Gunion, arXiv:0709.2269],
[U. Ellwanger, arXiv:1012.1201],
[G. Bélanger, U. Ellwanger, J. Gunion, Y. Jiang, S. Kraml, J. Schwarz, arXiv:1210.1976]

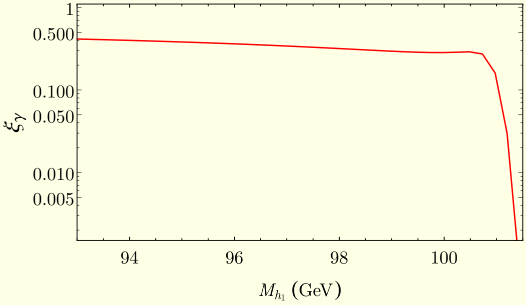
Light singlet, branching ratios



$$\lambda = 0.6,\ \kappa = 0.035,\ t_\beta = 2,\ \mu_{\mathrm{eff}} \sim 400\,\mathrm{GeV},\ m_{H^\pm} = 1\,\mathrm{TeV},\ A_\kappa = -325\,\mathrm{GeV},\ m_{\tilde{Q}} = 1\,\mathrm{TeV},\ A_t = 0$$

Light singlet, signals





$$\xi_b \equiv \frac{\Gamma[h_1 \to ZZ] \cdot \mathrm{BR}[h_1 \to b\bar{b}]}{\Gamma[H_{\mathrm{SM}}(M_{h_1}) \to ZZ] \cdot \mathrm{BR}[H_{\mathrm{SM}}(M_{h_1}) \to b\bar{b}]} \sim \frac{\sigma[e^+e^- \to Z(h_1 \to b\bar{b})]}{\sigma[e^+e^- \to Z(H_{\mathrm{SM}}(M_{h_1}) \to b\bar{b})]}$$

$$\xi_\gamma \equiv \frac{\Gamma[h_1 \to gg] \cdot \mathrm{BR}[h_1 \to \gamma\gamma]}{\Gamma[H_{\mathrm{SM}}(M_{h_1}) \to gg] \cdot \mathrm{BR}[H_{\mathrm{SM}}(M_{h_1}) \to \gamma\gamma]} \sim \frac{\sigma[gg \to h_1 \to \gamma\gamma]}{\sigma[gg \to H_{\mathrm{SM}}(M_{h_1}) \to \gamma\gamma]}$$

total width from $h_1 \to b\bar{b}, \tau^+\tau^-, c\bar{c}, WW, ZZ, gg, \gamma\gamma$

Conclusions and outlook

- Higgs decays into SM particles at full one-loop order
- Higgs mixing taken into account consistently
- partial higher-order contributions, further refinements
- more reliable prediction for decays into gauge bosons
- completely consistent with `FeynHiggs` in MSSM limit
- very good agreement with `NMSSMCALC` where expected
- use case: light singlet,
  explanation of LEP and CMS excesses possible (even simultaneously)
- implementation in upcoming extension of `FeynHiggs`
- for heavy Higgs bosons: Sudakov logarithms can become relevant
- uncertainty estimate for different decay channels