Higgs masses and decay widths satisfying the symmetries in the (N)MSSM

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Extended Higgs sectors

motivation:

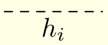
- Higgs-boson properties are/become precision observables
- high-precision theory predictions necessary
- ample scope for BSM theories with extended Higgs sector

extended Higgs sector:

- multiple scalar fields ϕ_i (after EWSB) with same quantum numbers
- gauge eigenstates ϕ_i mix into mass eigenstates $h_i \equiv$ physical states
- compute high-precision predictions for masses and decays of physical states (in the following consider only neutral scalars)

Masses and decays at tree level

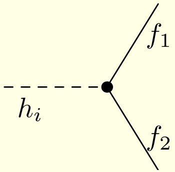
- masses (including possible vevs): $\mathcal{L} \ni m^2_{ij}\,\phi_i\,\phi_j \stackrel{!}{=} m^2_{h_i}\,h_i^2$
  eigenvalues $m^2_{h_i}$ of matrix m^2 are poles of propagators



$$\equiv \frac{i}{p^2 - m^2_{h_i}}$$

- two-body decays of h_i into fields f_1 and f_2: $\mathcal{L} \ni g_{h_i f_1 f_2}\,h_i\,f_1\,f_2$
  widths are given by $\Gamma\big[h_i \to f_1\,f_2\big] = c_{\text{kin}} \sum_{\text{pol,col}} \big|\mathcal{A}\big[h_i \to f_1\,f_2\big]\big|^2$ with amplitude

$$\mathcal{A}\big[h_i \to f_1\,f_2\big] = \mathcal{A}^{\text{tree}}\big[h_i \to f_1\,f_2\big] \equiv$$

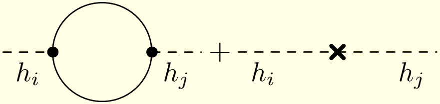


$\Rightarrow$ rotation into mass eigenbasis sufficient for consistent calculations

Masses and decays at loop order

- masses: matrix of propagators $\frac{i}{p^2\,\mathbb{1} - \text{diag}\, m^2_{h_i} + \hat{\Sigma}_{h_i h_j}\left(p^2\right)}$ via renormalized self-energies

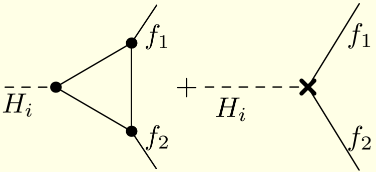
$$\hat{\Sigma}_{h_i h_j}(p^2) \equiv$$



induces new physical (loop-corrected) fields H_i, formally, mass $M^2_{H_i} = \mathfrak{Re}\left[\mathcal{M}^2_{H_i}\right]$ of H_i via solution of $\det\left[\mathcal{M}^2_{H_i} - m^2_{h_i} + \hat{\Sigma}_{h_i h_j}(\mathcal{M}^2_{H_i})\right] = 0$

- two-body decays: symbolically, look for width $\Gamma\left[H_i \to f_1\, f_2\right]$ with amplitude

$$\mathcal{A}^{1\text{L}}\left[H_i \to f_1\, f_2\right] \sim$$



Predictions for observables

- observables are measurable quantities
- theoretical predictions of observables should
  not depend on unphysical parameters
  (more strictly: results that depend on pure theory parameters are wrong)
- in the following aim for masses and decay widths in the (N)MSSM that are
  - independent of gauge-fixing parameters
  - independent of field parametrization

  some contributions to these topics:
  [Williams, Rzehak, Weiglein arXiv:1103.1335], [Goodsell, Liebler, Staub arXiv:1703.09237],
  [Domingo, Heinemeyer, SP, Weiglein arXiv:1807.06322], [Bahl arXiv:1812.06452],
  [Baglio, Dao, Mühlleitner arXiv:1907.12060],
  [Dao, Fritz, Krause, Mühlleitner, Patel arXiv:1911.07197] [Domingo, SP, arXiv:2007.11010]

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One-loop masses, field dependence

- inverse propagator matrix at one-loop order:

$$p^2\,\mathbb{1} - \mathrm{diag}\, m_{h_i}^2 + \hat{\Sigma}_{h_i h_j}(p^2) = p^2\,\mathbb{1} - \mathrm{diag}\, m_{h_i}^2 + \Sigma_{h_i h_j}(p^2) - \delta m_{h_i h_j}^2 + \left[p^2 - \frac{1}{2}\left(m_{h_i}^2 + m_{h_j}^2\right)\right]\delta Z_{h_i h_j}$$

- field renormalization (assumed to be $\overline{\mathrm{DR}}$ throughout this talk):

$$h_i \to \left(\mathbb{1} + \frac{1}{2}\,\delta Z_{h_i h_j}\right) h_j$$

- $\delta Z_{h_i h_j}$ drops out of $\hat{\Sigma}_{h_i h_j}$ if $p^2 = \frac{1}{2}\left(m_{h_i}^2 + m_{h_j}^2\right)$

One-loop masses, electroweak gauge symmetry

unphysical contributions by charged current to self-energies:

$$16\,\pi^2\,\hat{\Sigma}_{h_i h_j}(p^2) \supset c_1 \left(p^4 - m_{h_i}^2\, m_{h_j}^2\right) B_0\left(p^2, \xi\, M_W^2, \xi\, M_W^2\right)$$
$$+ c_2 \left[p^4 - m_{h_i}^2\, m_{h_j}^2 - m_{H^\pm} \left(2\,p^2 - m_{h_i}^2 - m_{h_j}^2\right)\right] B_0\left(p^2, m_{H^\pm}^2, \xi\, M_W^2\right)$$
$$+ c_3 \left(2\,p^2 - m_{h_i}^2 - m_{h_j}^2 + \tilde{C}_A\right) A_0\left(\xi\, M_W^2\right)$$

with gauge-fixing parameter ξ and couplings c_1, c_2, c_3

- in physical renormalization scheme: $\tilde{C}_A = 0$
- diagonal terms: ξ-dependence drops out at $p^2 = m_{h_i}^2$,
  different momenta generate ξ-dependent higher-order term

$$\mathcal{M}_{h_i}^2 = m_{h_i}^2 - \hat{\Sigma}_{h_i h_i}(\mathcal{M}_{h_i}^2) \approx m_{h_i}^2 - \hat{\Sigma}_{h_i h_i}(m_{h_i}^2) + \hat{\Sigma}_{h_i h_i}(m_{h_i}^2)\, \frac{d\hat{\Sigma}_{h_i h_i}}{dp^2}(m_{h_i}^2)$$

- off-diagonal terms: ξ-dependence generally **cannot** drop out

One-loop masses, non-degenerate case

- eigenvalue perturbation and momentum expansion yield

$$\mathcal{M}^2_{h_i} = m^2_{h_i} - \hat{\Sigma}_{h_i h_i}(\mathcal{M}^2_{h_i}) + \sum_{j\neq i} \frac{\hat{\Sigma}_{h_i h_j}(\mathcal{M}^2_{h_i})\,\hat{\Sigma}_{h_j h_i}(\mathcal{M}^2_{h_i})}{\mathcal{M}^2_{h_i} - m^2_{h_j}} + \cdots$$

$$\approx m^2_{h_i} - \hat{\Sigma}_{h_i h_i}(m^2_{h_i}) + \underbrace{\hat{\Sigma}_{h_i h_i}(m^2_{h_i})\,\frac{d\hat{\Sigma}_{h_i h_i}}{dp^2}(m^2_{h_i}) + \sum_{j\neq i} \frac{\hat{\Sigma}_{h_i h_j}(m^2_{h_i})\,\hat{\Sigma}_{h_j h_i}(m^2_{h_i})}{m^2_{h_i} - m^2_{h_j}}}_{\text{two-loop order}}$$

- one-loop prediction $M^2_{h_i} = m^2_{h_i} - \mathfrak{Re}\left[\hat{\Sigma}_{h_i h_i}(m^2_{h_i})\right]$ is consistent: free of $\delta Z_{h_i h_i}$ and free of ξ
- non-perturbative, iterative solution $\mathcal{M}^2_{h_i}$ generates ξ-dependent higher-order terms and field-renormalization dependence

One-loop masses, near-degenerate case

- off-diagonal elements of $\hat{\Sigma}_{h_ih_j}$ normally appear as two-loop contribution

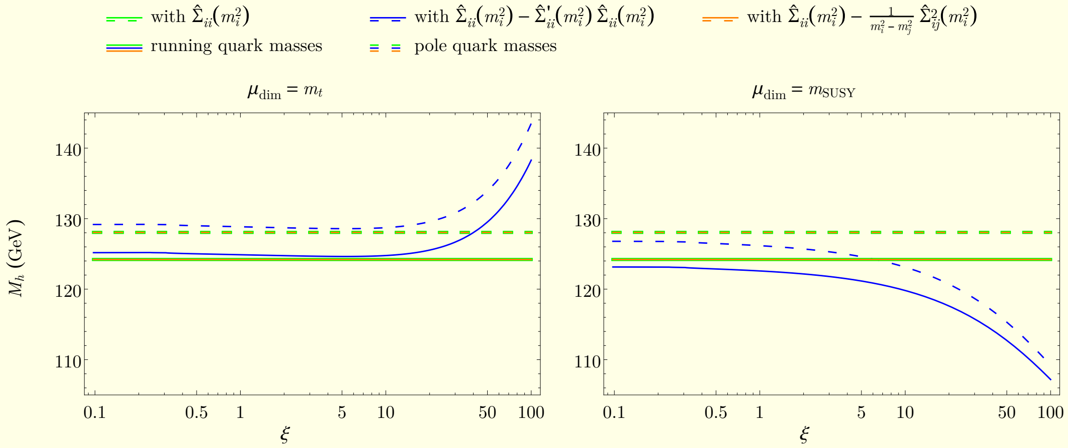
$$\sum_{j\neq i} \frac{\hat{\Sigma}_{h_ih_j}\left(m^2_{h_i}\right)\hat{\Sigma}_{h_jh_i}\left(m^2_{h_i}\right)}{m^2_{h_i}-m^2_{h_j}}$$

- but, if $\left|m^2_{h_i}-m^2_{h_j}\right| \sim \left|\hat{\Sigma}_{h_ih_j}\left(m^2_{h_i}\right)\right|$ then off-diagonal term matters at one loop
- diagonalization only in degenerate subsystem:
  - construct (symmetric) effective self-energy matrix $\hat{\Sigma}^{\text{eff}}_{h_ih_j} = \hat{\Sigma}_{h_ih_j}\left(\frac{1}{2}\left(m^2_{h_i}+m^2_{h_j}\right)\right)$
  - compute eigenvalues $M^2_{h_k}$ and eigenvectors $H_k = S^*_{ki}\, h_i$ of

$$M^{2\,\text{eff}} = \operatorname{diag} m^2_{h_i} - \hat{\Sigma}^{\text{eff}}_{h_ih_j}$$

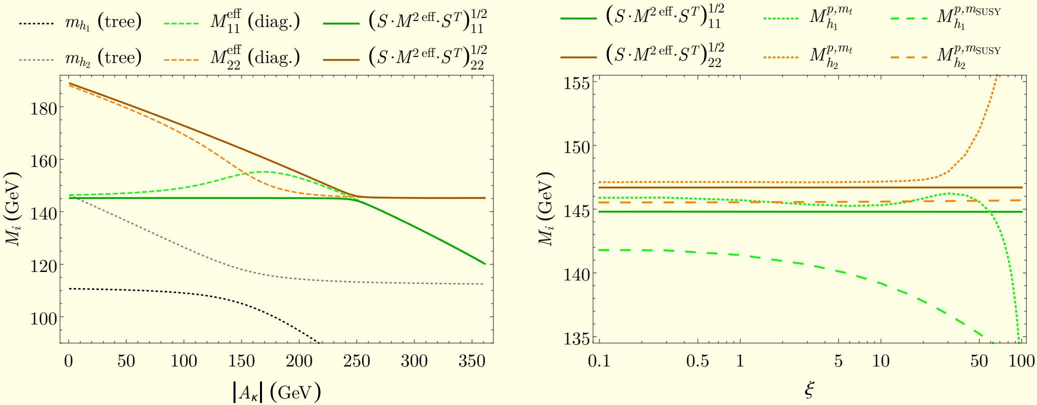
  - field renormalization drops out of $\hat{\Sigma}^{\text{eff}}_{h_ih_j}$
  - remaining ξ-dependence in off-diagonal elements $\propto \left(m^2_{h_i}-m^2_{h_j}\right)^2$, since $\left|m^2_{h_i}-m^2_{h_j}\right| = \mathcal{O}(1\text{L})$, remaining ξ-dependence of three-loop order

non-degenerate example in MSSM



- **large** power-law dependence on ξ in diagonal shift
- **negligible** off-diagonal contribution due to $m_H \approx 1\,\text{TeV} \gg m_h \approx 90\,\text{GeV}$
- **large** unphysical scale dependence in iterative diagonal shift

near-degenerate example in NMSSM



- large singlet–doublet mixing, right: $|A_\kappa| = 243\,\text{GeV}$
- **no** field-renormalization and **negligible** ξ-dependence in our solution
- **large** unphysical scale and ξ-dependence in iterative solution

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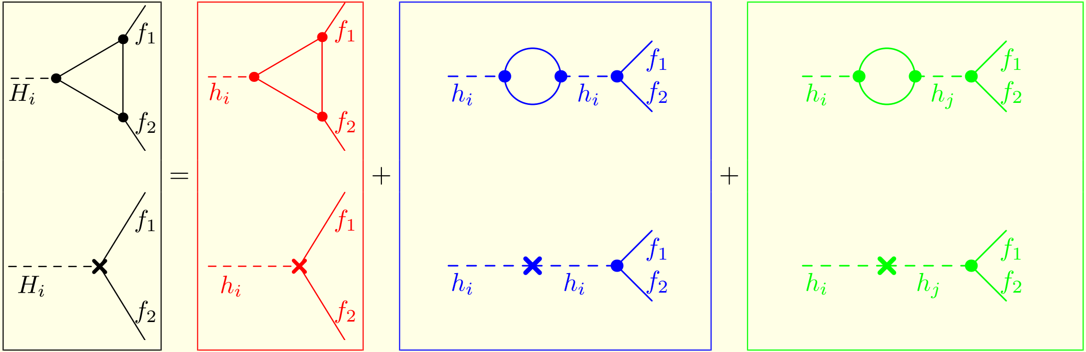
One-loop decays, perturbative expansion

in agreement with LSZ reduction formula:

$$\Gamma\left[H_i \to f_1\, f_2\right] = \Gamma^{\text{tree}}\left[h_i \to f_1\, f_2\right] + c_{\text{kin}} \sum_{\text{pol,col}} 2\,\Re\left[\left(\mathcal{A}^{\text{tree}}\left[h_i \to f_1\, f_2\right]\right)^* \mathcal{A}^{\text{1L}}\left[H_i \to f_1\, f_2\right]\right]$$

$$\mathcal{A}^{\text{1L}}\left[H_i\to f_1\, f_2\right] = \mathcal{A}^{\text{vert}}\left[h_i\to f_1\, f_2\right] + \mathcal{A}^{\text{mix}}\left[h_i\to f_1\, f_2\right]$$

$$= \mathcal{A}^{\text{vert}}\left[h_i\to f_1\, f_2\right] - \frac{d\hat{\Sigma}_{h_i h_i}}{dp^2}\left(m^2_{h_i}\right) \mathcal{A}^{\text{tree}}\left[h_i\to f_1\, f_2\right] - \sum_{j\neq i} \frac{\hat{\Sigma}_{h_i h_j}\left(m^2_{h_i}\right)}{m^2_{h_i} - m^2_{h_j}} \mathcal{A}^{\text{tree}}\left[h_j\to f_1\, f_2\right]$$



One-loop decays, electroweak gauge symmetry

- unphysical contributions by charged current to decay $H_i \to b\,\bar{b}$:

$$\mathcal{A}^{\text{vert}}\left[h_i \to b\,\bar{b}\right] \supset \bar{u}_b \left[\left(p^2 - m_{h_i}^2\right) \mathfrak{A}_1^{\text{vert}} + \left(p^2 - m_{H^\pm}^2\right) \mathfrak{A}_2 + \mathfrak{A}_3\right] v_{\bar{b}}\,,$$
$$\mathcal{A}^{\text{mix}}\left[h_i \to b\,\bar{b}\right] \supset \bar{u}_b \left[\left(p^2 - m_{h_i}^2\right) \mathfrak{A}_1^{\text{mix}} - \left(p^2 - m_{H^\pm}^2\right) \mathfrak{A}_2 - \mathfrak{A}_3\right] v_{\bar{b}}$$

  cancellation requires identical parameters and loop orders in $\mathcal{A}^{\text{vert}}$ and $\mathcal{A}^{\text{mix}}$,
  ξ-dependent remainder $\propto \left(p^2 - m_{h_i}^2\right)$
- additional ξ-dependence from mixing of h_i with G^0 and Z also $\propto \left(p^2 - m_{h_i}^2\right)$
- field-renormalization dependence drops out in a similar way

if p^2 is set to loop-corrected mass $\Rightarrow$ gauge-violating remainder of higher order,
note: kinematical masses in c_{kin} continue to be free parameters!

One-loop decays, near-degenerate case

- reminder: if $|m^2_{h_i} - m^2_{h_j}| \sim |\hat{\Sigma}_{h_i h_j}(m^2_{h_i})|$, then for degenerate subspace

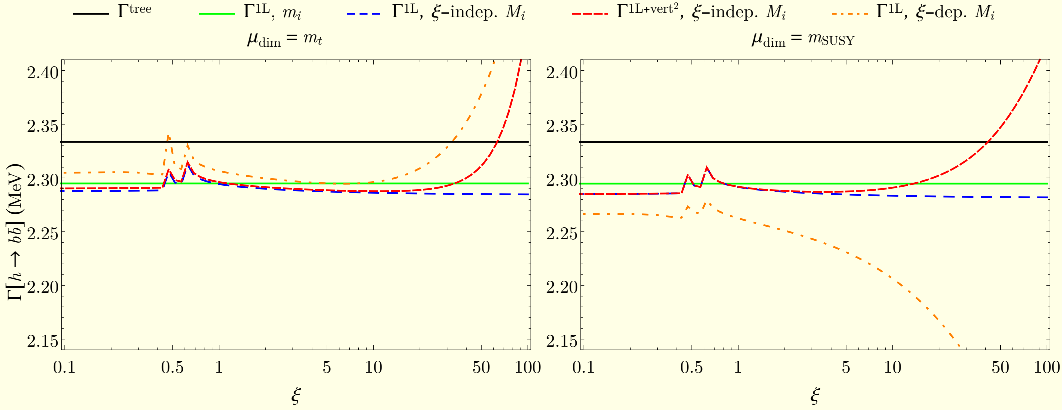
$$\left(M^2_{h_k}, H_k = S^*_{ki}\, h_i\right) \text{ eigensystem of } M^{2\,\text{eff}} = \operatorname{diag} m^2_{h_i} - \hat{\Sigma}^{\text{eff}}_{h_i h_j}\,,$$

$$\hat{\Sigma}^{\text{eff}}_{h_i h_j} = \hat{\Sigma}_{h_i h_j}\left(\tfrac{1}{2}\left(m^2_{h_i} + m^2_{h_j}\right)\right)$$

- decays of $H_k \in$ degenerate subspace:

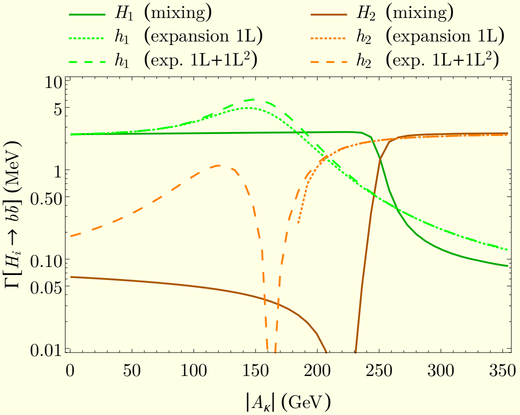
$$\mathcal{A}^{1\text{L}}\left[H_k \to f_1\, f_2\right] = S_{ki}\left\{\mathcal{A}^{\text{vert}}\left[h_i \to f_1\, f_2\right] - \frac{d\hat{\Sigma}_{h_i h_i}}{dp^2}\left(m^2_{h_i}\right)\mathcal{A}^{\text{tree}}\left[h_i \to f_1\, f_2\right] - \sum_{j \neq i} \frac{\hat{\Sigma}_{h_i h_j}\left(m^2_{h_i}\right) - \hat{\Sigma}^{\text{eff}}_{h_i h_j}}{m^2_{h_i} - m^2_{h_j}}\,\mathcal{A}^{\text{tree}}\left[h_j \to f_1\, f_2\right]\right\}$$

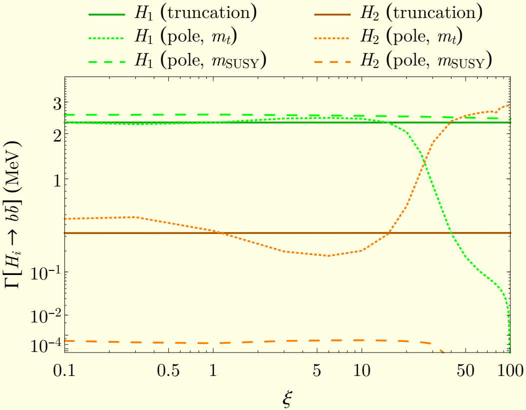
with $\hat{\Sigma}^{\text{eff}}_{h_i h_j} = 0$ if i, j **not** near-degenerate
(i. e. leading wrong one-loop term in mixing is replaced by correct one;
remaining wrong higher-order terms in S_{ki})



- **no** scale and ξ-dependence with tree-level mass
- **mild** scale and ξ-dependence with ξ-independent loop mass
- **large** ξ-dependence with ξ-dependent loop mass
- **large** ξ-dependence with vertex-squared term

} **large** scale dependence





- $H_1 \to b\,\bar{b}$, $H_2 \to b\,\bar{b}$ } near-degenerate method
- $h_1 \to b\,\bar{b}$, $h_2 \to b\,\bar{b}$ } non-degenerate method
- $H_1 \to b\,\bar{b}$, $H_2 \to b\,\bar{b}$ } perturbative expansion (our method)
- $h_1 \to b\,\bar{b}$, $h_2 \to b\,\bar{b}$ } iterative method (**Z** matrix)

Summary and outlook

for consistent higher-order predictions:

- in general, use strict perturbative expansion
- in near-degenerate scenarios:
  special treatment of masses in degenerate subspace,
  approximate restoration of physical behaviour in decays
- use tree-level masses in loop functions
- use identical parameters in whole calculation
- if partial higher-order terms are necessary (e. g. $H \to VV$),
  then ensure preservation of symmetries

outlook:

- field-independent two-loop mass predictions
- consistent two-loop gauge contributions to masses
- consistent two-loop decays

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Decoupling limit

Higgs doublet exactly $SU(2)_\mathrm{L}$ symmetric at $v = 0$,
in decoupling limit:

- $SU(2)_\mathrm{L}$-violating terms $\propto v$ and suppressed by $\frac{v}{M_{H^\pm}}$,
- $M_H \sim M_A \sim M_{H^\pm}$, $\Gamma_H \sim \Gamma_A \sim \Gamma_{H^\pm}$,
  but individual terms are $SU(2)_\mathrm{L}$ violating,
  $\rightarrow$ $SU(2)_\mathrm{L}$ invariance is powerful check of consistency
- in particular: $\ln \frac{M^2_{H^\pm}}{M^2_\mathrm{EW}}$ coincide at order $\mathcal{O}\left(\left(\frac{M_{H^\pm}}{v}\right)^0\right)$ and above
- example: SM Yukawa corrections to renormalized self-energies at one loop

$$\hat\Sigma_{HH}(p^2) \sim \hat\Sigma_{AA}(p^2) \sim \hat\Sigma_{H^\pm H^\pm}(p^2) \sim -\frac{3}{16\,\pi^2}\left(Y_t^2\, c_\beta^2 + Y_b^2\, s_\beta^2\right)\left(p^2 - m^2_{H^\pm}\right) \ln\frac{p^2}{M^2_\mathrm{EW}}\,,$$

$$\left|\hat\Sigma_{Hh}(p^2)\right| \sim \left|\hat\Sigma_{AG}(p^2)\right| \sim \left|\hat\Sigma_{H^\pm G^\mp}(p^2)\right| \sim \frac{3}{16\,\pi^2}\left(Y_t^2 - Y_b^2\right) s_\beta\, c_\beta\, p^2 \ln\frac{p^2}{M^2_\mathrm{EW}}\,.$$

Yukawa corrections of third generation to heavy masses in decoupling limit,
SUSY also decoupled at scale above heavy Higgs masses

- here: impose on-shell condition on charged Higgs,
- due to approximate $SU(2)_{\mathrm{L}}$ symmetry

at one-loop order: diagonal self-energies at $p^2 \sim m^2_{H^\pm}$ free of terms $\propto M^2_{H^\pm}\left\{1, \ln\frac{M^2_{H^\pm}}{M^2_{EW}}\right\}$, no off-diagonal terms

at two-loop order: $h_i \in \{H, A, H^\pm\}$,

$$M^2_{h_i} = m^2_{h_i} - \Re\mathfrak{e}\left[\hat\Sigma^{1\mathrm{L}}_{h_ih_i}(m^2_{h_i}) + \hat\Sigma^{2\mathrm{L}}_{h_ih_i}(m^2_{h_i}) - \hat\Sigma^{1\mathrm{L}}_{h_ih_i}(m^2_{h_i})\frac{d\hat\Sigma^{1\mathrm{L}}_{h_ih_i}}{dp^2}(m^2_{h_i}) - \sum_{j\neq i}\frac{\hat\Sigma^{1\mathrm{L}}_{h_ih_j}(m^2_{h_i})\,\hat\Sigma^{1\mathrm{L}}_{h_jh_i}(m^2_{h_i})}{m^2_{h_i}-m^2_{h_j}}\right],$$

each term $\propto M^2_{H^\pm}\left\{1, \ln\frac{M^2_{H^\pm}}{M^2_{EW}}, \ln^2\frac{M^2_{H^\pm}}{M^2_{EW}}\right\}$
in propagator expansion must be cancelled

- renormalized two-loop self-energy $\hat{\Sigma}^{2L}_{ii}\left(m^2_{h_i}\right) \sim \Sigma^{2L}_{ii}\left(m^2_{h_i}\right) - \delta^{2L} m^2_{H^\pm}$
- charged Higgs-mass counterterm

$$\delta^{2L} m^2_{H^\pm} = \Re\mathfrak{e}\left[\Sigma^{2L}_{H^+H^-}\left(m^2_{H^\pm}\right) - \hat{\Sigma}^{1L}_{H^+H^-}\left(m^2_{H^\pm}\right)\frac{d\hat{\Sigma}^{1L}_{H^+H^-}}{dp^2}\left(m^2_{H^\pm}\right) - \frac{\hat{\Sigma}^{1L}_{H^+G^-}\left(m^2_{H^\pm}\right)\hat{\Sigma}^{1L}_{G^+H^-}\left(m^2_{H^\pm}\right)}{m^2_{H^\pm} - m^2_{G^\pm}}\right]$$

- individual cancellations in matching terms of propagator expansion:

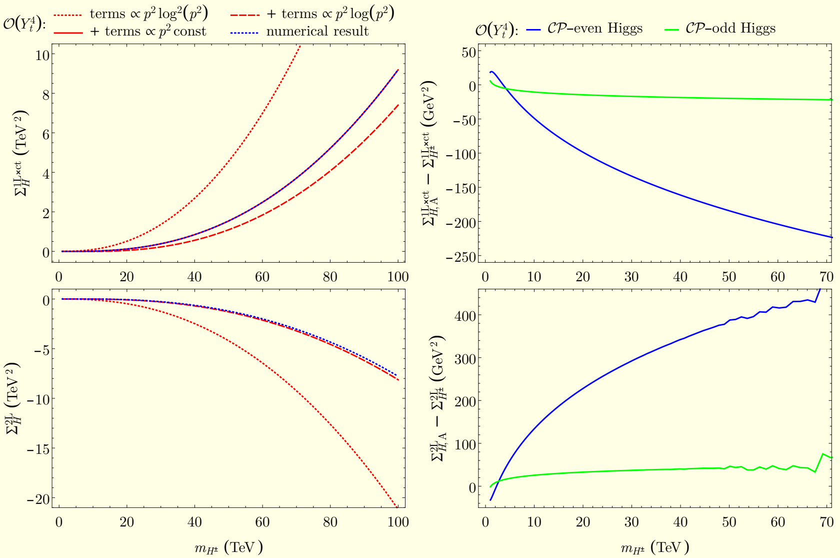
a) $$\Sigma^{2L}_{h_ih_i}\left(m^2_{h_i}\right) - \Sigma^{2L}_{H^+H^-}\left(m^2_{H^\pm}\right),$$

b) $$-\hat{\Sigma}^{1L}_{h_ih_i}\left(m^2_{h_i}\right)\frac{d\hat{\Sigma}^{1L}_{h_ih_i}}{dp^2}\left(m^2_{h_i}\right) + \hat{\Sigma}^{1L}_{H^+H^-}\left(m^2_{H^\pm}\right)\frac{d\hat{\Sigma}^{1L}_{H^+H^-}}{dp^2}\left(m^2_{H^\pm}\right),$$

c) $$-\sum_{j\neq i}\frac{\hat{\Sigma}^{1L}_{h_ih_j}\left(m^2_{h_i}\right)\hat{\Sigma}^{1L}_{h_jh_i}\left(m^2_{h_i}\right)}{m^2_{h_i} - m^2_{h_j}} + \frac{\hat{\Sigma}^{1L}_{H^+G^-}\left(m^2_{H^\pm}\right)\hat{\Sigma}^{1L}_{G^+H^-}\left(m^2_{H^\pm}\right)}{m^2_{H^\pm} - m^2_{G^\pm}}.$$

b) and c) clear from one-loop analysis of $SU(2)_L$ symmetry,
unmatched terms, e. g. by iterative pole search, strongly break symmetry

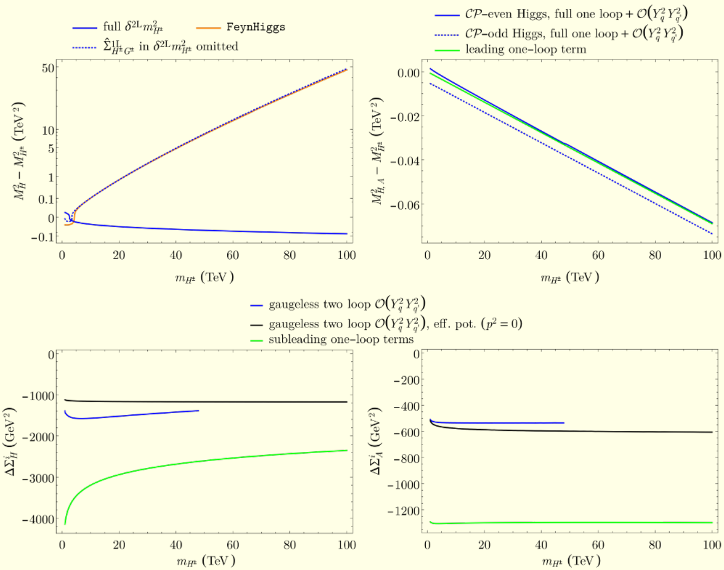
Mass corrections III



two-loop order (no SUSY):

- large terms $\propto p^2 \sim m_{H^\pm}^2$ in self-energies (momentum dependence essential)
- cancellation of all large terms in renormalized self-energies
- remainder of electroweak size
- numerical instabilities in `TSIL` at large p^2

Mass corrections IV



two-loop order:

- FeynHiggs misses off-diagonal term of propagator expansion in counterterm
- correct result dominated by one-loop gauge term $\propto \alpha\, M_Z\, m_{H^\pm}$
- $\Delta\Sigma^{2L}_{H,A} = \Sigma^{2L}_{H,A} - \Sigma^{2L}_{H^\pm}$ small (including SUSY), in particular: $\mathcal{O}(\alpha_t^2)$ subleading
- remaining momentum dependence subdominant

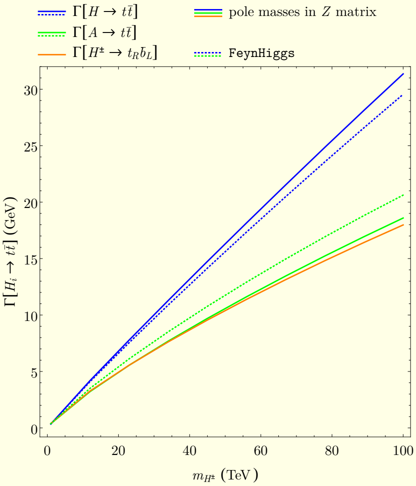
Decays into quarks I

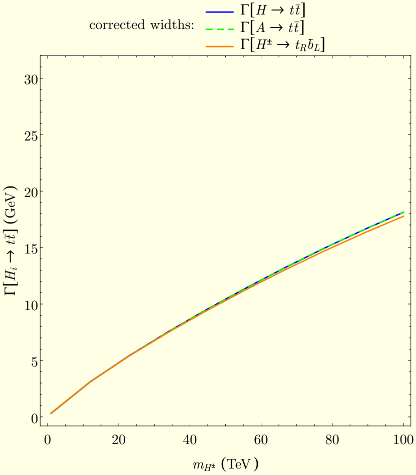
Yukawa contributions in decoupling limit (SUSY also decoupled):

$$\frac{\mathcal{A}^{1L}\left[H \to t\,\bar{t}\right]}{\mathcal{A}^{\text{tree}}\left[H \to t\,\bar{t}\right]} \simeq \frac{\mathcal{A}^{1L}\left[A \to t\,\bar{t}\right]}{\mathcal{A}^{\text{tree}}\left[A \to t\,\bar{t}\right]} \simeq \frac{\mathcal{A}^{1L}\left[H^+ \to t_R\,\bar{b}_L\right]}{\mathcal{A}^{\text{tree}}\left[H^+ \to t_R\,\bar{b}_L\right]} \simeq 1 + \frac{1}{32\,\pi^2}\left[3\,Y_t^2\left(1+s_\beta^2\right) - Y_b^2\left(2+s_\beta^2\right)\right]\ln\frac{m_{H^\pm}^2}{M_{\text{EW}}^2}$$

- results should agree at $m_{H^\pm} \gg M_{\text{EW}}$
- requires strict loop expansion:
  no resummation in Z matrix,
  no (uncontrolled) $|\mathcal{A}^{\text{vert}}|^2$ terms
- requires the same parameters in Higgs mixing and vertex corrections,
  e. g. pole/running quark masses
  (QCD analysis of vertex corrections suggests use of running masses)

Decays into quarks II





left:

- large difference of $H \to t\bar{t}$ due to pole quark masses in Z matrix
- difference to **FeynHiggs**: higher-order effects, e. g. resummation in Z matrix

right:

- running quark masses
- strict loop expansion
- physical meaningful remaining difference

Decays into electroweak gauge bosons I

$$\mathcal{A}^{\text{vert}}[H \to VV] + \mathcal{A}^{\text{mix}}[H \to VV] \simeq 0\,,$$
$$\mathcal{A}^{\text{vert}}[A \to VV] + \mathcal{A}^{\text{mix}}[A \to VV] \simeq 0\,,$$
$$\mathcal{A}^{\text{vert}}[H^+ \to W^+ Z] + \mathcal{A}^{\text{mix}}[H^+ \to W^+ Z] \simeq 0\,,$$

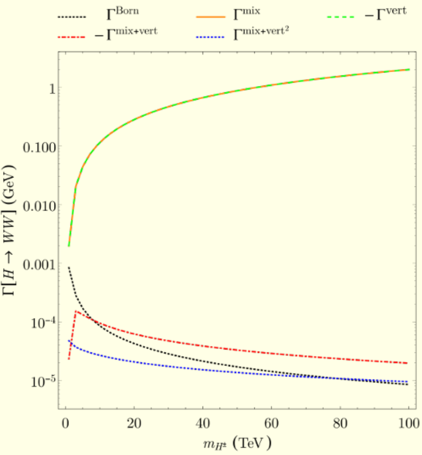
$\nexists$ $SU(2)_{\text{L}}$-conserving operator connecting one doublet scalar and two singlet/triplet vectors

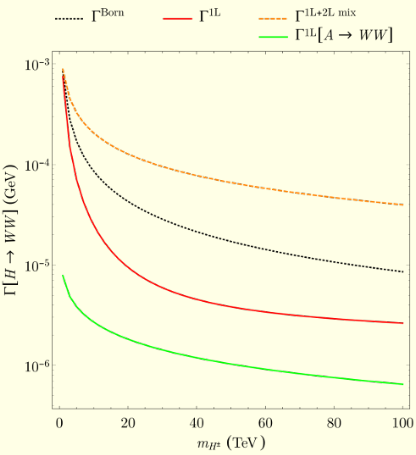
e. g. Yukawa contributions in decoupling limit

$$\mathcal{A}^{\text{vert}}[H \to VV] \simeq +\frac{3}{16\,\pi^2}\left(Y_t^2 - Y_b^2\right) s_\beta\, c_\beta \ln\frac{m_{H^\pm}^2}{M_{\text{EW}}^2}\, \mathcal{A}^{\text{tree}}[h \to VV]\,,$$
$$\mathcal{A}^{\text{mix}}[H \to VV] \simeq -\frac{3}{16\,\pi^2}\left(Y_t^2 - Y_b^2\right) s_\beta\, c_\beta \ln\frac{m_{H^\pm}^2}{M_{\text{EW}}^2}\, \mathcal{A}^{\text{tree}}[h \to VV]\,.$$

- $SU(2)_{\text{L}}$-violating channels $\propto v$ are suppressed for $m_{H^\pm} \gg M_{\text{EW}}$
- requires strict loop expansion:
  no resummation in Z matrix,
  careful treatment of $|\mathcal{A}^{\text{vert}}|^2$ terms
- requires the same parameters in Higgs mixing and vertex corrections,
  e. g. pole/running quark masses

Decays into electroweak gauge bosons II





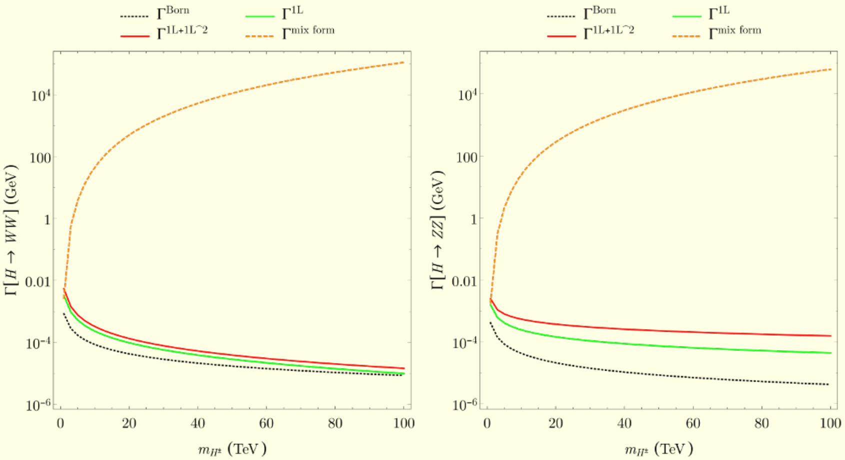
Yukawa corrections:

left:

- tiny tree level
- fine cancellation of mixing and vertex corrections
- inclusion of $|\mathcal{A}^{\text{mix+vert}}|^2$ terms for $\Gamma > 0$

right:

- inclusion of two-loop terms in Z matrix leads to artificial factor 10 enhancement



full one loop:

- suppressed widths in strict loop expansion and with consistent parametrization
- resummed Z matrix causes imperfect cancellation and large result that strongly violates $SU(2)_{\rm L}$ symmetry