Higher-order corrections to decays and masses of charged Higgs bosons

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Corrections to the mass of the charged Higgs boson

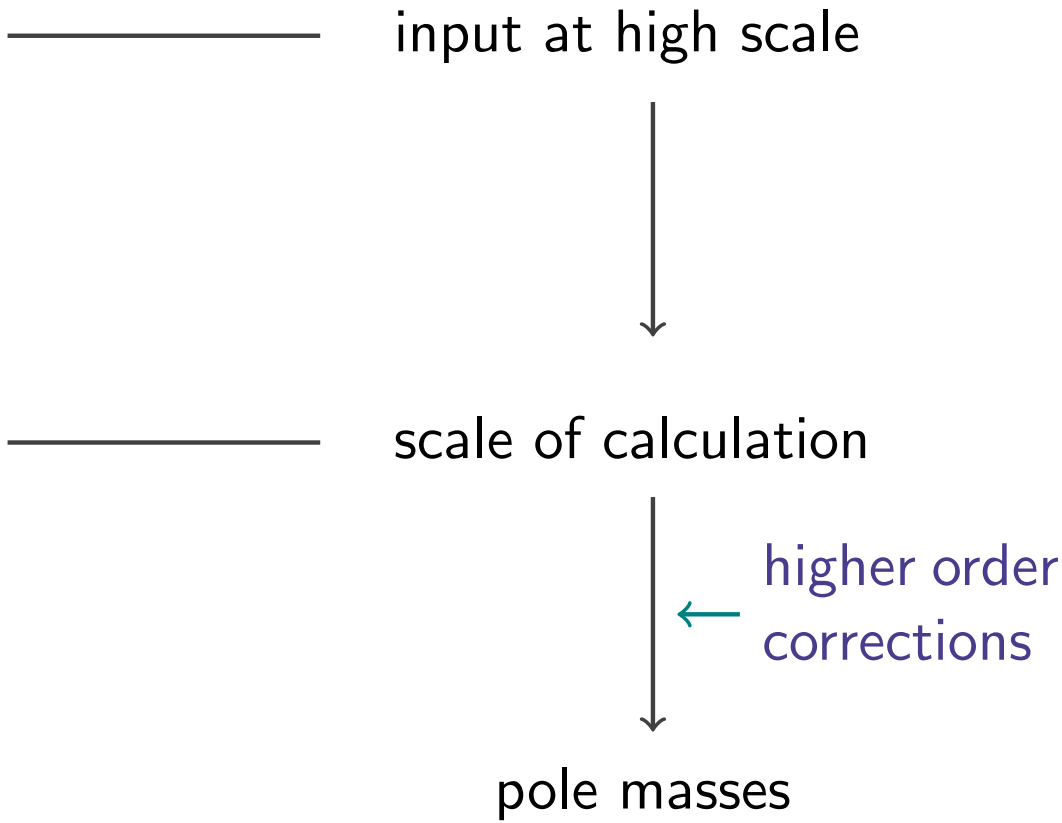
Mass of the charged Higgs boson:

- Pole/on-shell mass is input in calculations of
  - production cross sections
  - partial decay widths
- In perturbative calculations:

  Renormalization schemes dependences

Choice of renormalization schemes

- Running parameters ($\overline{\text{MS}}$ or $\overline{\text{DR}}$)



- On-shell parameters (pole masses, etc.)

input parameters $\longleftrightarrow$ physical observables

Two-Higgs-Doublet Model

Higgs potential:

$$
\begin{aligned}
V = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) \\
& + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\
& + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right]
\end{aligned}
$$

- CP conserving
- invariant under $\Phi_1 \to -\Phi_1$
- m_{11}^2, m_{22}^2 fixed by minimum condition
  m_{12}^2, λ_1, ..., λ_5 free parameters

$\Rightarrow$ enough free parameters to define all Higgs masses independently

$\Rightarrow$ all Higgs masses can be chosen as pole masses (on-shell)

MSSM

Higgs potential:

$$V = (m_1^2 + |\mu|^2)\Phi_1^\dagger\Phi_1 + (m_2^2 + |\mu|^2)\Phi_2^\dagger\Phi_2 + m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.})$$
$$+\frac{g^2 + g'^2}{8}(\Phi_1^\dagger\Phi_1)^2 + \frac{g^2 + g'^2}{8}(\Phi_2^\dagger\Phi_2)^2 - \frac{g^2 + g'^2}{4}(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$
$$+\frac{g^2}{2}(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$

- $m_1^2 + |\mu|^2$, $m_2^2 + |\mu|^2$ fixed by minimum condition

  g, g' gauge couplings (fixed in gauge sector)

  m_{12}^2 free parameter

$\Rightarrow$ too few free parameters to define all Higgs masses independently

$\Rightarrow$ only one mass can be chosen independently

(and $\tan\beta$ = ratio of vac. expect. values)

MSSM

Choices:

- CP-conserving MSSM:

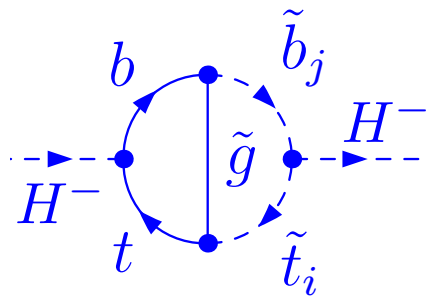
  often CP-odd Higgs boson mass as free parameter

  $\Rightarrow$ all other masses can be calculated

  relations change due to quantum corrections

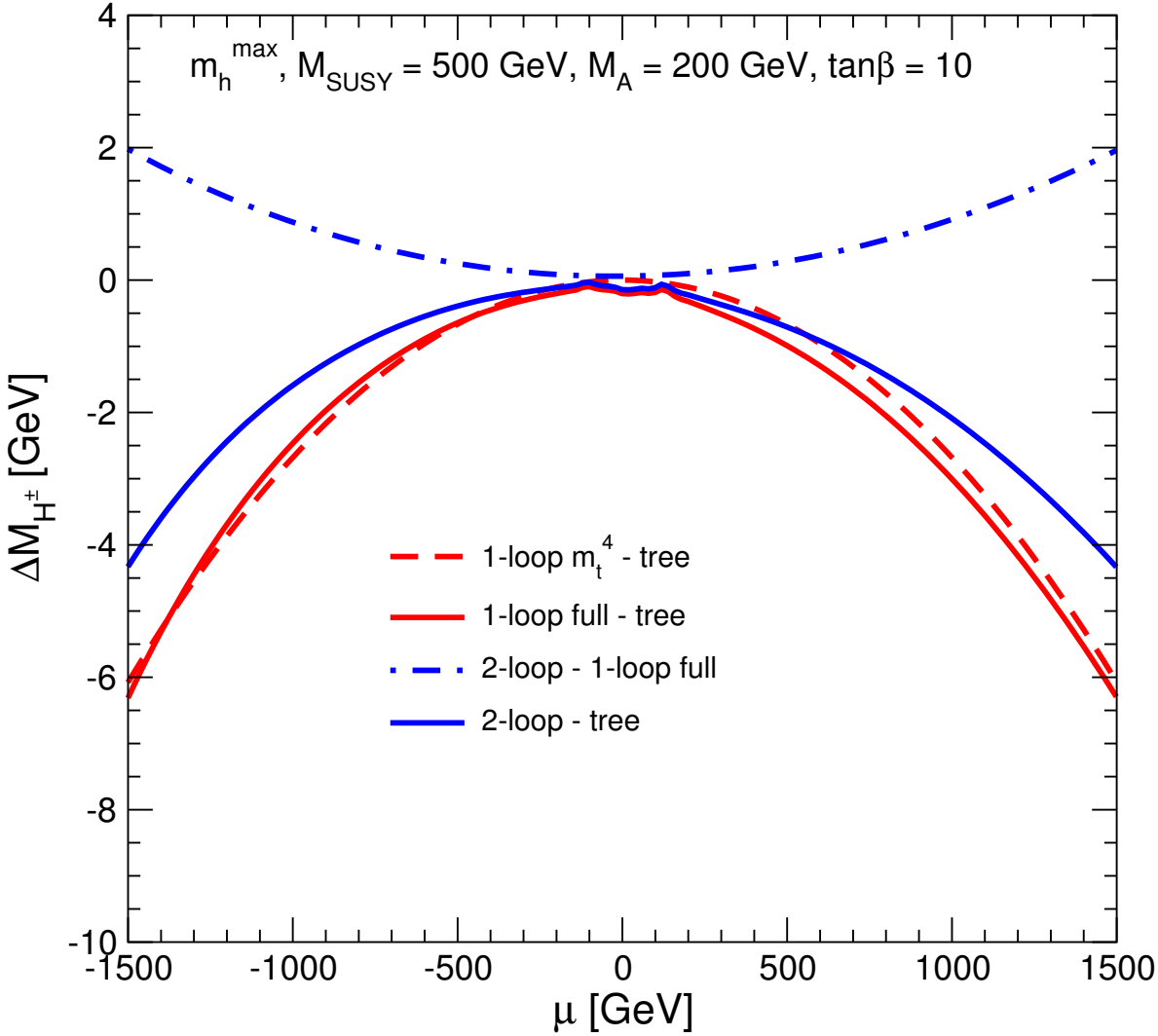
Charged Higgs mass:

$$M^2_{H^\pm} = \underbrace{M^2_A + M^2_W}_{=M^2_{H^\pm\,\text{tree}}} - \hat{\Sigma}_{H^+H^-}$$



MSSM

Corrections to the mass of the charged Higgs boson up to $\mathcal{O}(\alpha_t\alpha_s)$:



- comparison at one-loop:

  $\frac{m_t^4}{M_W^2}$ terms: good approx.

- 2-loop corrections:

  * relevant part
  * $\sim$ up to 2 GeV in example

[Frank, Galeta, Hahn, Heinemeyer, Hollik, H.R., Weiglein, arXive:1306.1156]

MSSM

Choices:

- CP-violating MSSM:

  neutral Higgs bosons: Loop-corrected mass matrix:

$$\mathbf{M}(\mathbf{p}^2) = \begin{pmatrix} M^2_{H^0_{\text{tree}}} - \hat{\Sigma}_{H^0H^0}(p^2) & -\hat{\Sigma}_{H^0h^0}(p^2) & -\hat{\Sigma}_{H^0A^0}(p^2) \\ -\hat{\Sigma}_{H^0h^0}(p^2) & M^2_{h^0_{\text{tree}}} - \hat{\Sigma}_{h^0h^0}(p^2) & -\hat{\Sigma}_{h^0A^0}(p^2) \\ -\hat{\Sigma}_{H^0A^0}(p^2) & -\hat{\Sigma}_{h^0A^0}(p^2) & M^2_{A^0_{\text{tree}}} - \hat{\Sigma}_{A^0A^0}(p^2) \end{pmatrix}$$

  all neutral Higgs bosons mix

  $\Rightarrow$ choose charged Higgs boson as input parameter

  $\Rightarrow$ can be fixed as pole mass (no quantum corrections)

  (CP-odd Higgs boson mass will receive corrections)

NMSSM

- Additional Higgs singlet superfield

  $\Rightarrow$ an additional CP-even and CP-odd Higgs boson

- Additional parameters (+ 3 to 4 complex parameters)

- Even in CP-conserving case:

  mixing effects for CP-even and CP-odd Higgs bosons

  $\Rightarrow$ choose at least charged Higgs boson as free parameter

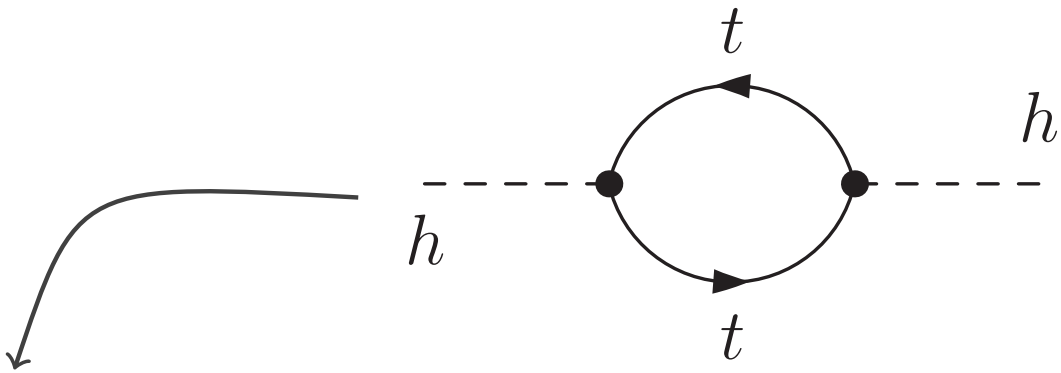
  $\Rightarrow$ can be fixed as pole mass (no quantum corrections)

Side remark: Higgs boson masses at higher orders

Two-point-function:

$$-i\hat{\Gamma}(p^2) = p^2 - \mathbf{M}(\mathbf{p^2})$$

with the matrix:



$$\mathbf{M}(\mathbf{p^2}) = \begin{pmatrix} M^2_{h_{\text{Born}}} - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{Hh}(p^2) \\ -\hat{\Sigma}_{Hh}(p^2) & M^2_{H_{\text{Born}}} - \hat{\Sigma}_{HH}(p^2) \end{pmatrix}$$

(CP-conserving MSSM case: mixing only betw. CP-even Higgs bosons h, H)

Calculate the zeros of the determinant of $\hat{\Gamma}$

$\Rightarrow$ loop-corrected Higgs masses

Higgs boson mass for large stop masses

Prediction obtained via Feynman diagrammatic approach:

\+ all log and non-log terms are taken into account
at a certain order of perturbation theory

\- possible appearance of large logs:

$$\Delta M_h \sim \log \frac{M_S}{m_t}$$

$M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$: SUSY particle mass scale

$m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$: scalar top quark masses

m_t: top quark mass

$\Rightarrow$ • good prediction for lower SUSY mass scales

• no reliable prediction for large SUSY mass scales

Higgs boson mass for large stop masses

Other approach: Renormalization Group Equation (RGE) approach:

see e.g. [Draper, Lee, Wagner, 1312.5743; Vega, Villadoro, arXiv:1504.05200; Lee, Wagner, arXiv:1508.00576]

⋆ assume: all SUSY particles are heavy of order $\sim M_S$:

above M_S: MSSM → match at scale M_S:

$\lambda^{\text{MSSM}}(M_S) = \lambda^{\text{Standard Model}}(M_S)$

below M_S: Standard Model (as effective theory)

quartic Higgs coupling

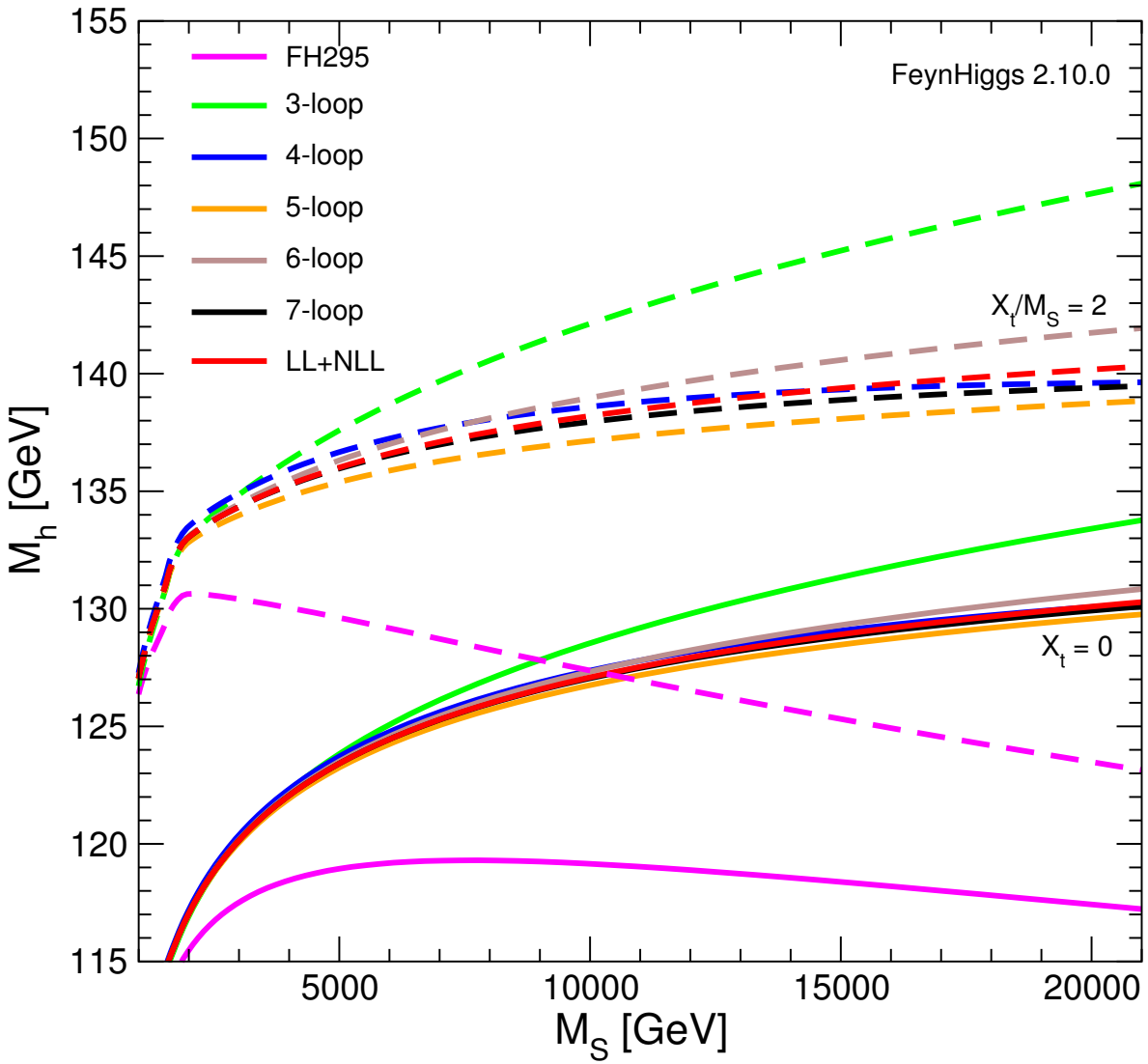
⋆ evolve λ to lower scale using Standard Model running (RGE)

⋆ the Higgs mass^2 is then $M_h^2(m_t) = 2\lambda(m_t)v^2$ $\quad v \approx 174$ GeV

⇒ logs resummed to all orders: good prediction for large SUSY masses

→ Combine both approaches

Higgs boson mass for large stop masses



Comparison of:

⋆ old FeynHiggs
reliable up to
$M_s = \mathcal{O}(1\text{TeV})$

⋆ analyt. solution of RGE:
3-loop ... 7-loop level:
Logs of order
$\mathcal{O}(\alpha_t\alpha_s^2, \alpha_t^2\alpha_s, \alpha_t^3)$ ...

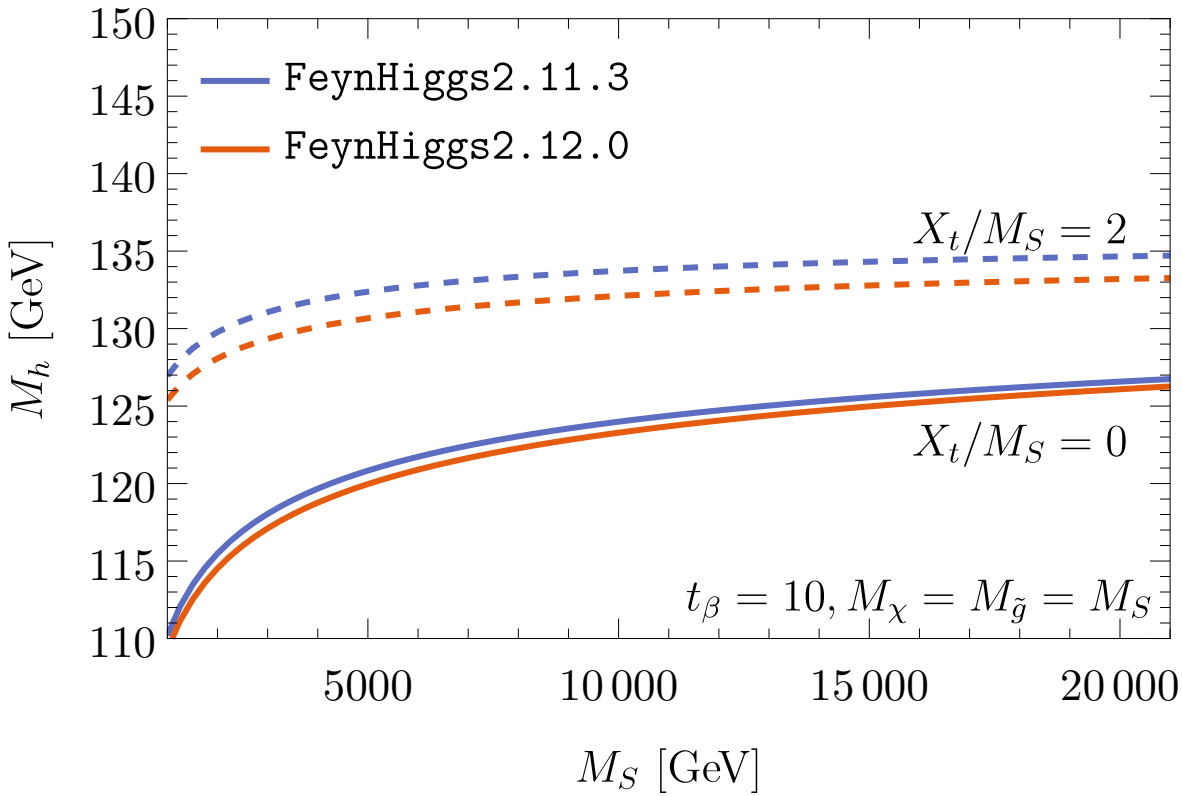
⋆ numerical solution:
LL+NLL:
logs resummed
to all orders

$M_A = M_2 = \mu = 1$ TeV, $m_{\tilde{g}} = 1.6$ TeV, $\tan\beta = 10$

[Hahn, Heinemeyer, Hollik, H.R., Weiglein, arXiv:1312.4937]

Higgs boson mass for large stop masses

Improvements:



[Bahl, Hollik, arXiv:1608.01880]

- EW LL, NLL contributions
- $\mathcal{O}(\alpha_s, \alpha_t)$ NNLL contributions

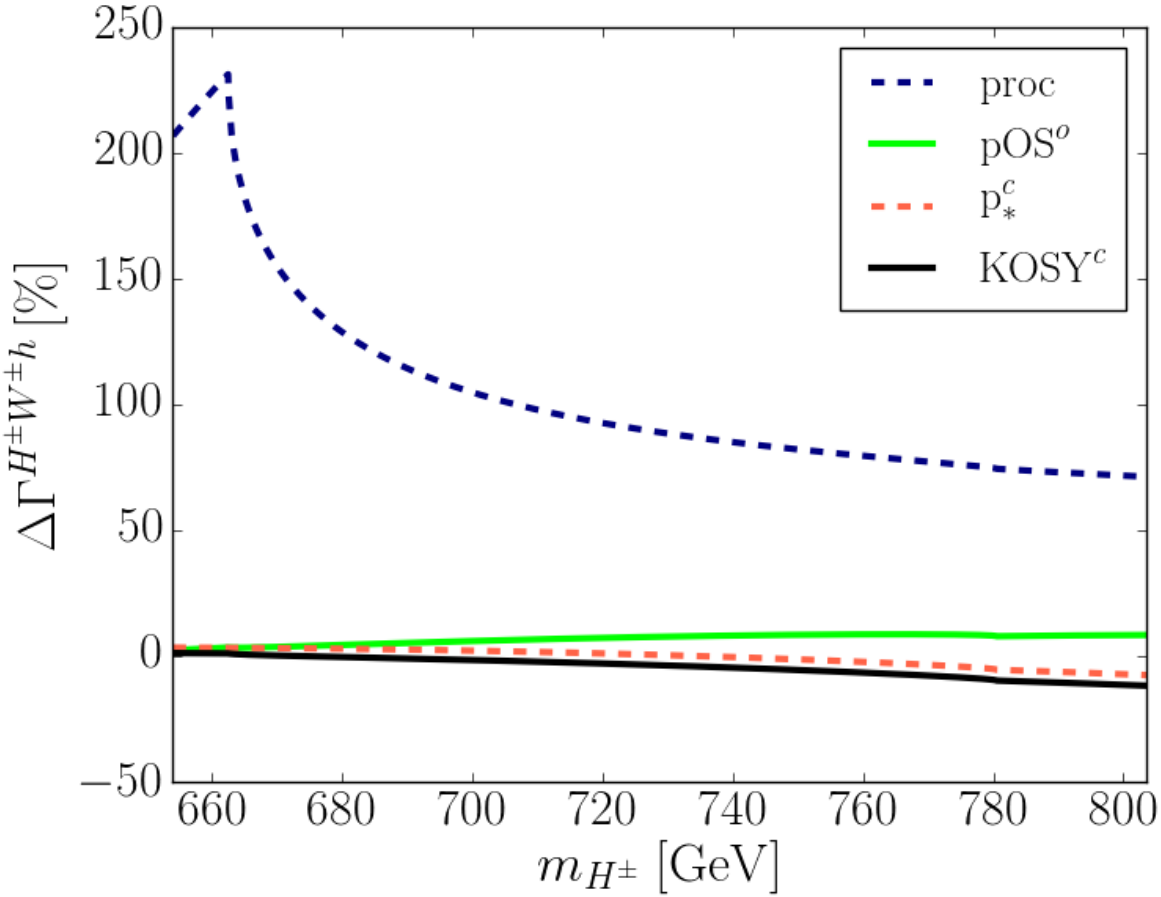
Charged Higgs decays

QCD corrections and dominant electroweak effects:

known for a while, here for $H^+ \to t\bar{b}$:

- 2HDM: e.g. [Coarasa Perez, Guasch, Hollik, Sola, hep-ph/9808278]
- MSSM: e.g. [Coarasa Perez, Garcia, Guasch, Jimenez, Sola, hep-ph/9711472; Carena, Garcia, Nierste, Wagner, hep-ph/9912516]

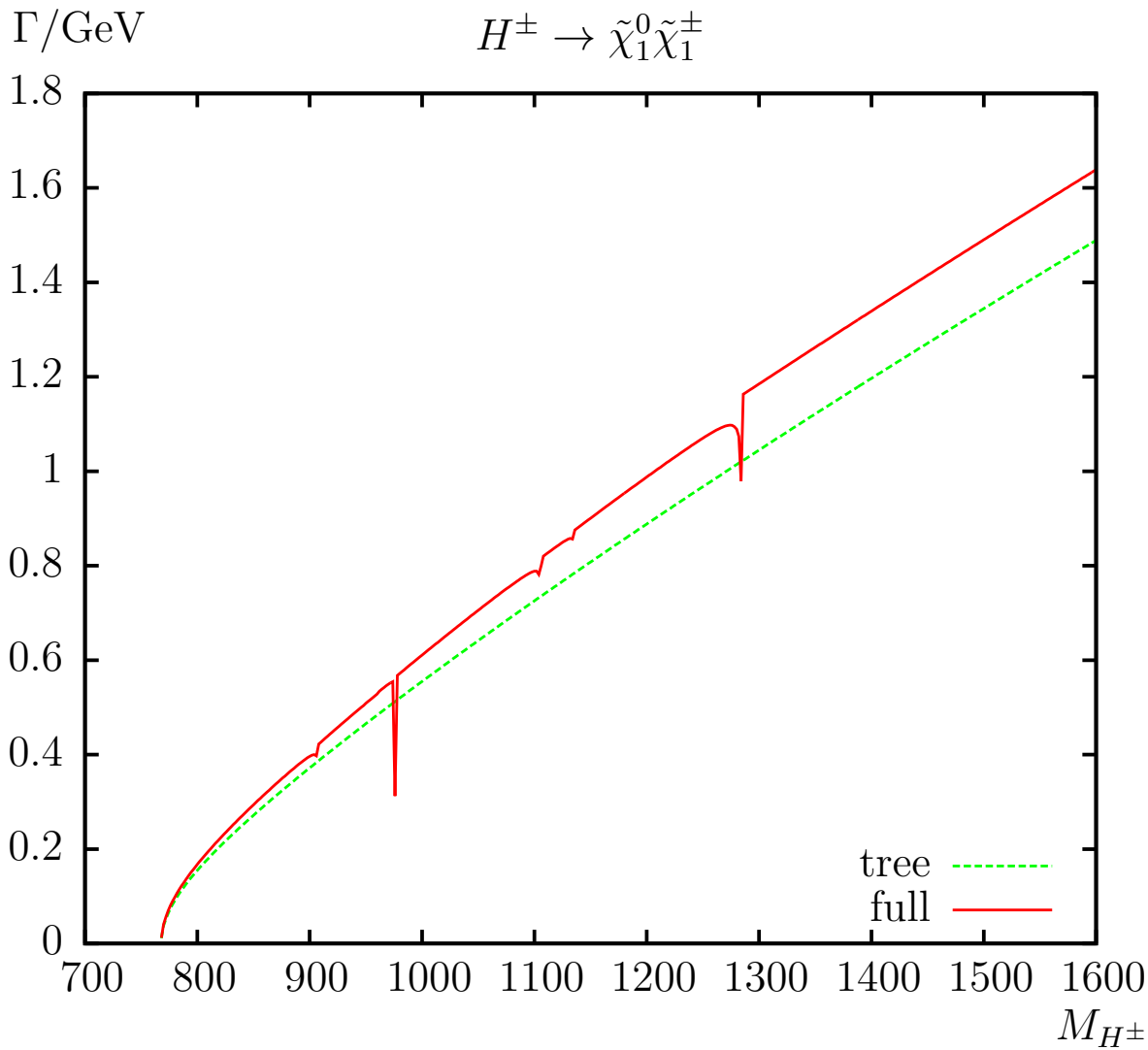
Recent work in 2HDM: $H^+ \to hW^+$



- complete EW contributions
- different renormalization schemes

[Krause, Lorenz, Mühlleitner, Santos, Ziesche, arXiv:1608.01880]

Recent work in MSSM: $H^+ \to \chi^0\chi^+$



[Heinemeyer, Schappacher, arXiv:1503.02996]

- complete EW contributions
- dips = threshold effects
- compare also to `HFOLD`

[Eberl, Frisch, Hlucha, arXiv:1012.5025]

NMSSM

- NMHDECAY (decay part based on HDECAY [Djouadi, Kalinowski, (Mühlleitner,) Spira, hep-ph/9704448])

  [Ellwanger, Gunion, Hugonie, hep-ph/0406215]

- NMSSMCALC (decay part based on HDECAY)

  [Baglio, Gröber, Mühlleitner, Nhung, H.R., Spira, Streicher, Walz, arXiv:1312.4788]

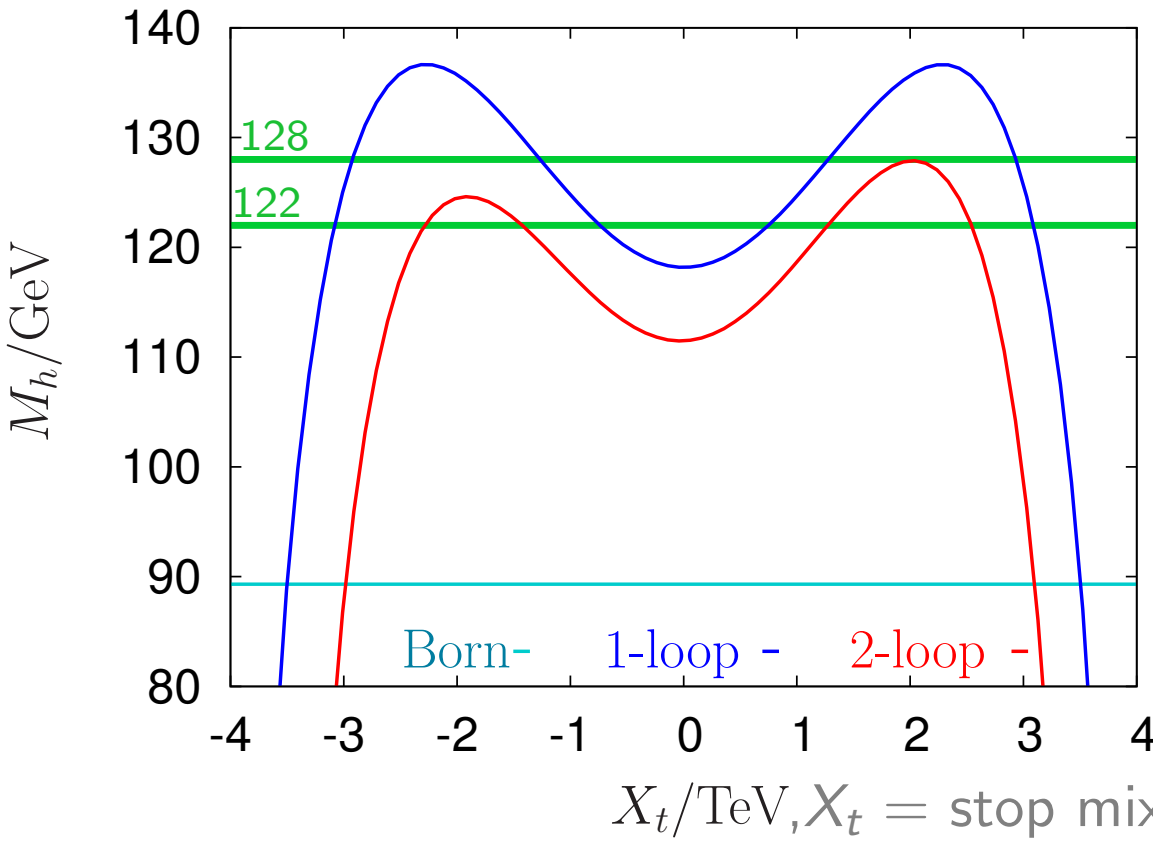
  $\rightarrow$ QCD effects and Δb type effects included

Summary

- Corrections to the mass of the charged Higgs boson:
  - non - if mass chosen as input and fixed as pole mass
  - otherwise: need to take corrections into account
- For 2HDM, MSSM, NMSSM:

  framework ready to do complete EW corrections

Implications of a 125 GeV Higgs boson (MSSM)



generated using FeynHiggs
[Hahn, Heinemeyer, Hollik, H.R., Weiglein, Williams]

1-loop [Frank, Hahn, Heinemeyer, Hollik, H.R., Weiglein]

2-loop $\mathcal{O}(\alpha_{\{t,b\}}\alpha_s, \alpha^2_{\{t,b\}}, \alpha_t\alpha_b)$
[Degrassi, Slavich, Zwirner; Brignole, Degrassi, Slavich, Zwirner; Heinemeyer, Hollik, H.R., Weiglein; Dedes, Degrassi, Slavich]

- A 125 ± 3 GeV mass constrains the parameter space but does not exclude the MSSM. (theory uncertainty ≈ 3 GeV)
- here: no known 3-loop contributions included [Martin; Harlander, Kant, Mihaila, Steinhauser]

Higgs-boson self energies in the MSSM

	real parameters				complex parameters	
	$\overline{\text{DR}}$ scheme		OS/mixed schemes		OS/mixed schemes	
	$p^2 = 0$	$p^2 \neq 0$	$p^2 = 0$	$p^2 \neq 0$	$p^2 = 0$	$p^2 \neq 0$
one-loop				✓		✓
two-loop						
$\mathcal{O}(\alpha_t\alpha_s)$	✓	✓	✓	✓	✓	
$\mathcal{O}(\alpha_t^2)$			✓		✓	
$\mathcal{O}(\alpha_b\alpha_s)$			✓			
$\mathcal{O}(\alpha_t\alpha_b, \alpha_b^2, \alpha_\tau^2)$			✓			
$\mathcal{O}(\alpha_\tau\alpha_b)$			✓			
full	✓					
1st 5 rows above		✓				
three-loop						
$O(\alpha_t\alpha_s^2)$			✓			

Higher orders: "only" logarithmic contributions known

Higgs-boson self energies in the MSSM

[Chankowski, Pokorski, Rosiek, 92; hep-ph/9303309; Dabelstein hep-ph/9409375]

[Frank, Hahn, Heinemeyer, Hollik, HR, Weiglein, hep-ph/0611326]

[Zhang, hep-ph/9808299; Degrassi, Slavich, Zwirner, hep-ph/0105096]

[Degrassi, Di Vita, Slavich, arXiv:1410.3432]

[Heinemeyer, Hollik, Weiglein, hep-ph/9812472; Degrassi, Slavich, Zwirner, hep-ph/0105096]

[Borowka, Hahn, Heinemeyer, Heinrich, Hollik, arXiv:1404.7074, arXiv:1505.03133;
Degrassi, Di Vita, Slavich, arXiv:1410.3432]

[Heinemeyer, Hollik, HR, Weiglein, arXiv:0705.0746]

[Brignole, Degrassi, Slavich, Zwirner, hep-ph/0112177]

[Hollik, Paßher, arXiv:1401.8275; arXiv:1409.1687]

[Brignole, Degrassi, Slavich, Zwirner, hep-ph/0206101;
Heinemeyer, Hollik, HR, Weiglein, hep-ph/0411114]

[Dedes, Degrassi, Slavich, hep-ph/0305127]

[Allanach, Djouadi, Kneur, Porod, Slavich, hep-ph/0406166]

[Martin, hep-ph/0211366]

[Martin, hep-ph/0405022]

[Harlander, Kant, Mihaila, Steinhauser, arXiv:0803.0672; arXiv:1005.5709]