Precision for New Physics

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Necessities

- Precise understanding of the Standard Model processes
  - $\star$ Precise predictions
  - $\star$ Good understanding of detector and of the modeling
  - $\star$ ...

  $\rightarrow$ many talks and discussions here

- New Physics processes: Need for precise predictions?

Need for precise BSM predictions?

- For finding a deviation: no?
- For interpretation, including testing and limit setting: yes?

LHC: Discovery of a Higgs boson

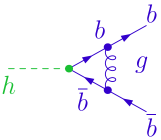
- roughly SM like

- could be embedded in an enlarged Higgs sector

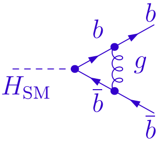
  (2HDM, Singlet extension,. . .)

Precision for a Higgs boson

- QCD corrections (no new coloured particles):
  - ⋆ can be partly taken over from the Standard Model



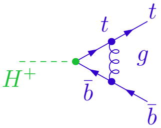
$= \frac{C_{hbb}}{C_{hbb}^{SM}} \cdot$



easily implementable, see e.g. sHDECAY

[Costa, Mühlleitner, Sampaio, Santos, arXiv:1512.05355]

  - ⋆ additional corrections for new types of particles



Precision for a Higgs boson

- Electroweak corrections: cannot be extracted from SM ones

  ⇒ calculate:

  ⋆ perform renormalization:

  – choice of set of independent input parameters

  – choice of renormalization conditions

  help: `NLOCT` based on `FeynArts` and `FeynRules`

  [Degrande] [Hahn; Küblbeck, Böhm, Denner] [Alloul, Christensen, Degrande, Duhr, Fuks]

  ⋆ calculate diagrams

  help: `FeynArts/FormCalc`, `GoSam`, `MadGraph5_aMC@NLO`, ...

  [Hahn; Hahn, Perez-Victoria] [Cullen, van Deurzen, Greiner, Heinrich, Luisoni, Mastrolia, Mirabella, Ossola, Peraro, Reiter, Schlenk, von Soden-Fraunhofen, Tramontano] [Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro]

Example: Higgs decay to 4 leptons in the 2HDM

Higgs potential:

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

- CP conserving
- invariant under $\Phi_1 \to -\Phi_1$

Example: Higgs decay to 4 leptons in the 2HDM

Original parameters:

$$m_{11}^2 \quad m_{22}^2 \quad m_{12}^2 \quad \lambda_1 \quad \lambda_2 \quad \lambda_4 \quad \overbrace{g \quad g'}^{\text{gauge couplings}} \quad \overbrace{v_1 \quad v_2}^{\text{vacuum expectation values}} \quad \lambda_3 \quad \lambda_5$$

Chosen set of independent input parameters:

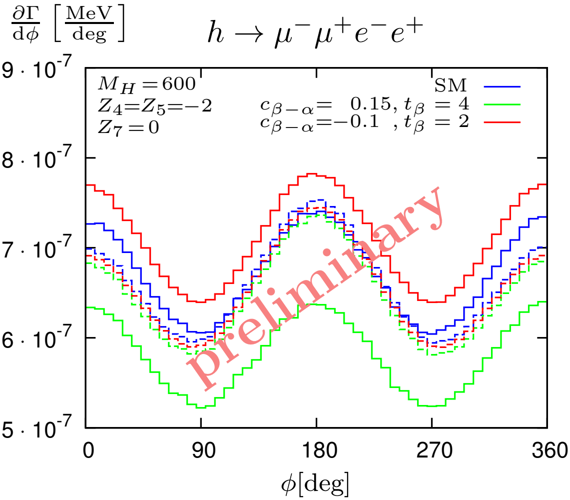
$$\underbrace{\overbrace{t_h \quad t_H}^{\text{tadpole parameters}} \quad \overbrace{M_h \quad M_H \quad M_A \quad M_{H^\pm}}^{\text{Higgs masses}} \quad \overbrace{e}^{\text{electric charge}} \quad \overbrace{M_W \quad M_Z}^{\text{gauge boson masses}}}_{\text{on-shell}} \underbrace{\overbrace{\tan\beta}^{=\frac{v_2}{v_1}} \quad \lambda_3 \quad \lambda_5}_{\overline{\text{MS}}}$$

Example: Higgs decay to 4 leptons in the 2HDM

- `FeynRules` for the creation of the model file
- Matrix element generation with `FeynArts/FormCalc`
- Implementation into `PropHecy4f` [Bredenstein, Denner, Dittmaier, Mück, Weber]

Example: Higgs decay to 4 leptons in the 2HDM

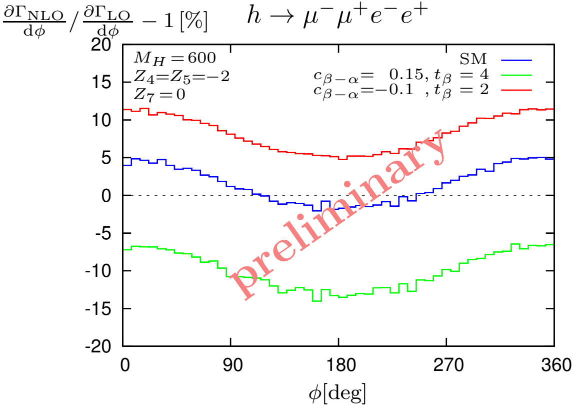
Azimuthal angle distribution: [Altenkamp, Dittmaier, HR]



- Differences at LO (dashed) rather small
- NLO corrections sizeable
- For scenarios, see [Haber, Stål, arXiv:1507.04281]

Example: Higgs decay to 4 leptons in the 2HDM

Azimuthal angle distribution (relative correction): [Altenkamp, Dittmaier, HR]



- Shape differences between LO/NLO similar to SM

New coloured particles

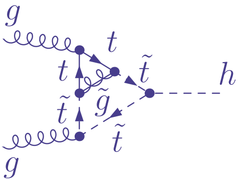
QCD corrections have to be reevaluated:

- For Higgs boson production and decay within the MSSM:

  a lot of work has been done

  see e.g. `HDECAY` [Djouadi, Kalinowski, Mühlleitner, Spira]

  `SusHi` [Harlander, Liebler, Mantler]



  Small remark:

  For Higgs boson production via VBF in the MSSM:

  SUSY electroweak effects are larger than SUSY QCD effects,

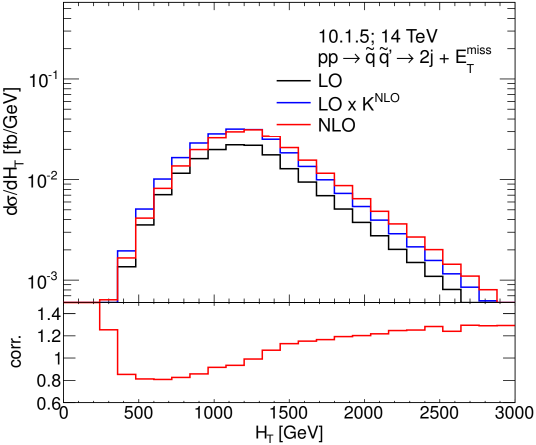
  [Hollik, Plehn, Rauch, HR, arXiv:0804.2676; Figy, Palmer, Weiglein, arXiv:1012.4789]

New coloured particles

QCD corrections for processes with new coloured particles:

Example: Squark production and decay:

[Hollik, Lindert, Pagani, arXiv:1207.1071]



$m_0 = 175$ GeV,

$m_{1/2} = 700$ GeV,

$A_0 = 0$ GeV,

$\tan\beta = 10$,

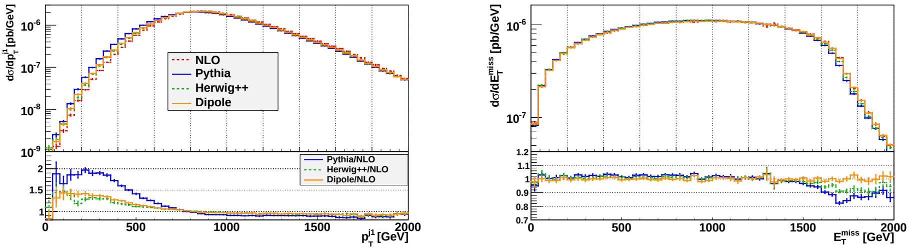
$\mathrm{sign}(\mu) = +$

see also [Gonçalves-Netto, López-Val, Mawatari, Plehn, Wigmore, arXiv:1211.0286]

New coloured particles

QCD corrections for processes with new coloured particles:

Example: Squark production and decay with parton shower:



[Gavin, Hangst, Krämer, Mühlleitner, Pellen, Popenda, Spira, arXiv:1305.4061]

$m_{1/2} = 550$ GeV, $m_0 = 825$ GeV, $A_0 = 0$ GeV, $\tan(\beta) = 10$, $\mathrm{sgn}(\mu) = +1$

Precision input and precision observable

Example: Higgs physics:

In the Standard Model:

The Higgs boson mass is a free parameter.

In extensions of the Standard Model:

The Higgs boson mass can depend on
other parameters of the theory,
e.g. in the (Next) Minimal Supersymmetric Standard Model.

Precision input and precision observable

- Needed as consistent input for the calculation of cross sections and decay widths in the (N)MSSM

- The experimental measured value

  ATLAS/CMS: $m_H = 125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})$ GeV

  constrains the viable parameter space of the MSSM:

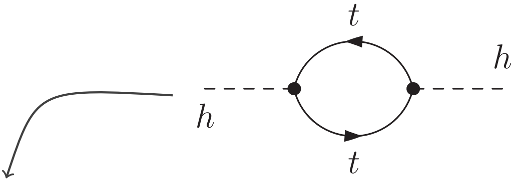
  A precise theoretical prediction is needed to fully exploit this constraint.

Higgs boson masses at higher orders

Two-point-function:

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

with the matrix:



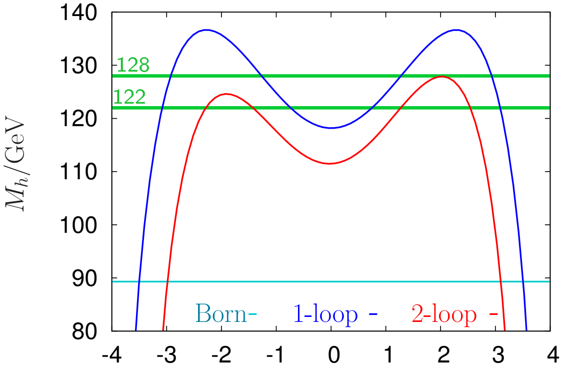
$$\mathbf{M}(\mathbf{p^2}) = \begin{pmatrix} M^2_{h_{\text{Born}}} - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{Hh}(p^2) \\ -\hat{\Sigma}_{Hh}(p^2) & M^2_{H_{\text{Born}}} - \hat{\Sigma}_{HH}(p^2) \end{pmatrix}$$

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

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

$\Rightarrow$ loop-corrected Higgs masses

Implications of a 125 GeV Higgs boson (MSSM)



X_t/TeV, X_t = stop mixing parameter

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]

Remark about renormalization

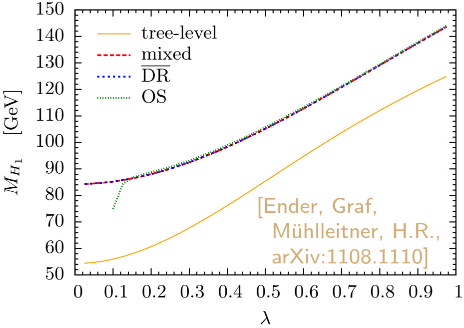
In the calculation: choice of independent input parameters
and of the renormalization scheme

Criteria:

- observables ↔ parameters
  (e.g. choice of mass parameters
  which can be related to masses)
- respect symmetry relations
- avoid unphysically large corrections

For illustration:

Mass of lightest CP-even NMSSM Higgs boson



⋆ Different schemes can give an error estimate.

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

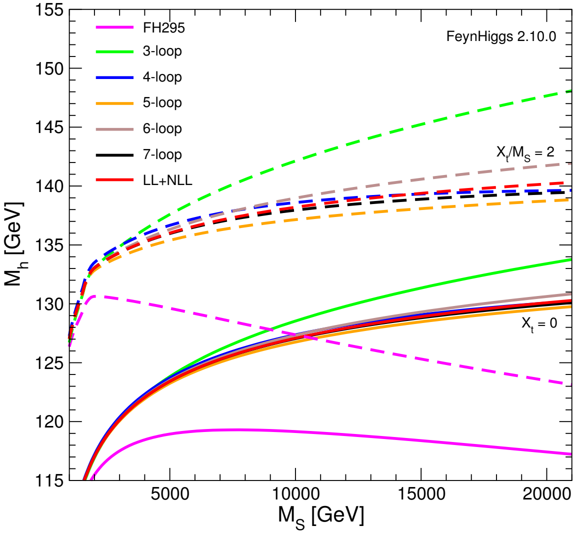
⋆ evolve λ to lower scale using Standard Model running (RGE)

⋆ 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, $\tan\beta = 10$

[T. Hahn, S. Heinemeyer, W. Hollik, H.R., G. Weiglein, arXiv:1312.4937]

Higgs mixings

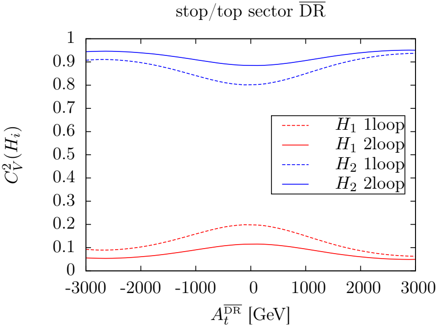
Quantum corrections can change the mixing of Higgs bosons

⇒ induce changes of couplings

Needed for predictions of Higgs decay widths

NMSSM example:

Coupling to vector bosons squared:
(normalized wrt Standard Model)



[Mühlleitner, Nhung, H.R., Walz, arXiv:1412.0918]

Tools

	fix. order	RL	scheme	CPV?	RPV?	BMSSM?
SUSPECT [1]	2L	—	$\overline{\text{DR}}$	—	—	(gen.)
SPheno [2]	2L	—	$\overline{\text{DR}}$	✓	✓	gen.
SoftSUSY [3]	2L	—	$\overline{\text{DR}}$	—	✓	NMSSM
CPsuperH [4]	2L	—	$\overline{\text{MS}}$	✓	—	—
FeynHiggs [5]	2L	2L	mixed	✓	—	(NMSSM)
SUSYHD [6]	—	3L	$\overline{\text{DR}}$	✓	—	—
H3m [7]	3L	—	$\overline{\text{DR}}$ /mixed	—	—	—
NMSSMTools [8]	2L	—	$\overline{\text{DR}}$	(✓)	—	NMSSM
NMSSMCalc [9]	2L	—	$\overline{\text{DR}}$/mixed	✓	—	NMSSM
FlexibleSUSY [10]	2L	—	$\overline{\text{DR}}$	—	—	gen.

see [Draper, HR, arXiv:1601.01890]

Tools

[1] [Djouadi, Kneur, Moultaka, hep-ph/0211331]

[2] [Porod, hep-ph/0301101; Porod, Staub, arXiv:1104.1573]

[3] [Allanach, hep-ph/0104145; Allanach, Athron, Tunstall, Lewis, Voigt, Williams, arXiv:1311.7659; Allanach, Bednyakov, Ruiz de Austri, arXiv:1407.6130]

[4] [Lee, Pilaftsis, Carena, Choi, Drees, Ellis, Wagner, hep-ph/0307377; Lee, Carena, Ellis, Pilaftsis, Wagner, arXiv:0712.2360; arXiv:1208.2212]

[5] [Heinemeyer, Hollik, Weiglein, hep-ph/9812472; hep-ph/9812320; Degrassi, Heinemeyer, Hollik, Slavich, Weiglein, hep-ph/0212020; Frank, Hahn, Heinemeyer, hep-ph/0611326; Hollik, HR, Weiglein, Hahn, Heinemeyer, Hollik, HR, Weiglein, arXiv:1312.4937]

[6] [Vega, Villadoro, arXiv:1504.05200]

[7] [Kant, Harlander, Mihaila, Steinhauser, arXiv:1005.5709]

[8] [Ellwanger, Gunion, Hugonie, hep-ph/0406215; Ellwanger, Hugonie, hep-ph/0508022]

[9] [Baglio, Gröber, Mühlleitner, Nhung, HR, Spira, Streicher, Walz, arXiv:1312.4788]

[10] [Athron, Park, Stöckinger, Voigt, arXiv:1406.2319]

Conclusion

For testing new physics:

Higher-order corrections can be important for the interpretation:

- NLO corrections for production and decay processes (QCD and electroweak)
- Higher-order corrections for masses and mixings

Outlook

PhD Scholarship in Higgs Physics and
Physics beyond the Standard Model

At CP3-Origins and the Department of Physics, Chemistry and Pharmacy at the University of Southern Denmark in Odense

Application deadline: May 31, 2016

`http://jobbank.sdu.dk/en/job/837488/syddansk-universitet/phd-scholarship-in-higgs-physi`

Definition of the Zs

$$Z_4 = \frac{1}{4}\sin^2(2\beta)\left[\lambda_1 + \lambda_2 - 2(\lambda_3 + \lambda_4 + \lambda_5)\right] + \lambda_4$$

$$Z_5 = \frac{1}{4}\sin^2(2\beta)\left[\lambda_1 + \lambda_2 - 2(\lambda_3 + \lambda_4 + \lambda_5)\right] + \lambda_5$$

$$Z_7 = -\frac{1}{2}\sin(2\beta)\left[\lambda_1 \sin^2\beta - \lambda_2 \cos^2\beta + (\lambda_3 + \lambda_4 + \lambda_5)\cos(2\beta)\right]$$

MSSM example: Parameters

$m_t = 173.2$ GeV, $M_{\text{SUSY}} = 1000$ GeV,

$|\mu| = 1000$ GeV, $\tan\beta = 10$, $M_A = 500$ GeV,

$|M_2| = 200$ GeV, $|M_3| = 1500$ GeV

NMSSM parameters for one-loop example

$\kappa = \lambda/5$, $\tan\beta = 2$, $A_\lambda = 500$ GeV, $A_\kappa = -10$ GeV,

$v_S = \frac{1}{\sqrt{2}}\frac{250}{\lambda}$ GeV, $M_S = 300$ GeV, $A_t = A_b = A_\tau = -1.5 M_S$,

$M_1 = M_S/3$, $M_2 = 2/3 M_S$, $M_3 = 2 M_S$,

$m_t = 173.3$ GeV, $\mu_{\text{ren}} = M_S$

NMSSM parameters for 2-loop example

$|\lambda| = 0.65$, $|\kappa| = 0.33$, $\tan\beta = 1.94$, $M_{H^\pm} = 420.9$ GeV,

$|A_\kappa| = 37.9$ GeV, $\mathrm{Re}(A_\kappa) < 0$, $|v_s| = \sqrt{2}\frac{193}{|\lambda|}$ GeV

$M_{Q_3} = 557$ GeV, $M_{t_R} = 709$ GeV, $M_{\tilde{f}\neq\{\tilde{b},\tilde{t}\}} = 3$ TeV,

$|A_b| = 963$ GeV, $\varphi_{A_b} = 0$, $|A_t| = 1441$ GeV, $\varphi_{A_t} = \pi$,

$M_1 = 855$ GeV, $M_2 = 269$ GeV, $M_3 = 2794$ GeV, $m_t = 173.5$ GeV,

$\mu_{\mathrm{ren}} = \sqrt{M_{Q_3} M_{t_R}}$