Higgs bosons in supersymmetric theories

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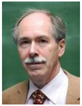
Discoveries at the LHC

Expectations (2008):



’t Hooft:
“A Higgs, or more”

Gross:

“A super world”

Veltman:

“The unexpected”

. . .

Nov. 2011

HCP 2011:
Exclusion of a wide Higgs mass range, some theorists’ thought: “complete exclusion until the end of 2011”

13 Dec. 2011

ATLAS & CMS report an excess of events:
Too early to draw conclusions

4 July 2012

ATLAS & CMS announce the discovery of a Higgs-like particle

8 Oct. 2013

Nobel prize:
for the theoret. discovery of a mechanism that contributes to our understanding of the origin of mass . . .

Is it "the" Higgs boson?

- **Mass:** free parameter in the Standard Model

  expectation from precision measurements: $\mathcal{O}$(100 GeV)
  (e.g. mass of the W boson)

  Moriond '13: CMS: $m_H = 125.7 \pm 0.3$ (stat) $\pm\, 0.3$ (syst) GeV

  ATLAS: $m_H = 125.5 \pm 0.2$ (stat) $^{+0.5}_{-0.6}$ (syst) GeV

- **Spin?** Landau-Yang theorem:

  Massive spin-1 particle cannot decay into two photons:

  Decay into photons observed $\Rightarrow$ spin $\neq 1$

  Moriond '13: spin = 2: Excluded with $>$ 99% confidence level

  spin = 0: compatible

  model dependent

- **CP?** Moriond '13: CP-even: compatible

  spin = 0

  CP-odd: Exclusion with $\gtrsim$ 98% confidence level

Is it “the” Higgs boson?

- **Couplings?** so far compatible with the Standard Model:
  - Measurement of further production und decay channels:

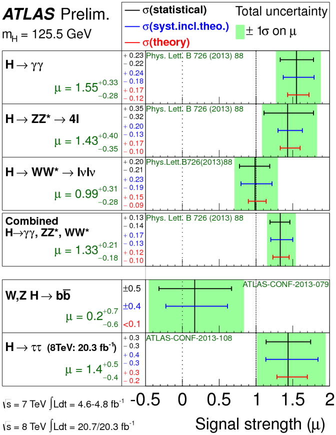
    $pp \to H \to WW$
    (compatible with SM)

    $pp \to H \to \tau\tau$ (Evidence!)

    $pp \to H \to bb$

    …
  - still relatively large errors ($\sim$ 20 %)
  - not all couplings accessible

Signal strengths:



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  … W boson)

  Moriond ’13: C… $\pm$ 0.3 (stat) $\pm$ 0.3 (syst) GeV

  ATLA… $= 125.5 \pm 0.2$ (stat) $^{+0.5}_{-0.6}$ (syst) GeV

Other models: Higgs mass can be given by other parameters.

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  spin = 0: com…atible

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- **CP?** Moriond ’13: C… atible

  CP… Exclusion with $\gtrsim$ 98% confidence level

  spin = 0

a mixture of CP-odd and -even?

Is it "the" Higgs boson?

- **Couplings?** so far compatible wit… Standard Model:
  - Measurement of furt… production und…

    Signal strengths:

    $pp \to H \to$ …
    (compatible … M)

    $pp \to H \to \tau\tau$ (Evidence!)

    $pp \to H \to bb$

    …
  - still relatively large errors ($\sim$ 20 %)
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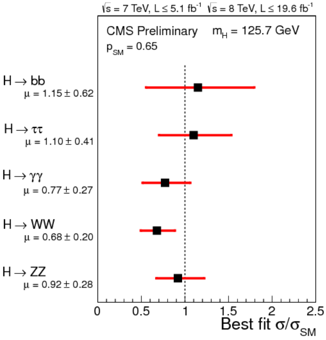
Could be affected by an extended Higgs sector or other unknown particles



Minimal Supersymmetric Standard Model (MSSM)

MSSM: ⋆ Extension of the Standard Model (SM)

⋆ Further symmetry:

Supersymmetry (SUSY):

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle, \qquad Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$

$Q =$ supersymmetry generator

Recipe:
- Standard Model particles + 2[nd] Higgs doublet (2HDM)
  (Generation of fermion masses, anomaly cancelations)
- Superpartners
- Explicit soft SUSY-breaking ⇒ many new (complex) parameters
  (Else: $\text{mass}_{\text{superpartner}} = \text{mass}_{\text{2HDM-particle}} \leftarrow$ exp. excluded)
- R-Parity: discrete symmetry

Minimal Supersymmetric Standard Model (MSSM)

Particle content:

(2HDM)-Particle	Quarks	Leptons	Gauge bosons	Higgs bosons
Superpartner	Squarks	Sleptons		Gauginos Higgsinos

Gauginos, Higgsinos ⇓ mix → Charginos, Neutralinos

- Constraints from direct searches
  one way to circumvent constraints: larger SUSY masses
- Constraints from indirect probes
  e.g. Higgs boson mass

Higgs Sector at Born Level

Higgs potential: gauge couplings H_d, H_u: Higgs doublets

$$V_{\text{Higgs}} = \frac{g^2 + g'^2}{8}(H_d^+ H_d - H_u^+ H_u)^2 + \frac{g^2}{2}|H_d^+ H_u|^2$$

$$+ |\mu|^2 (H_d^+ H_d + H_u^+ H_u)$$ μ: coupl. betw. Higgs superfields

$$+ (m_1^2 H_d^+ H_d + m_2^2 H_u^+ H_u)$$ soft breaking terms

$$+ (\epsilon_{ij} |m_{12}^2| e^{i\varphi_{m_{12}^2}} H_d^i H_u^j + h.c.)$$

- one phase in the Higgs potential: $\varphi_{m_{12}^2}$
- phase difference of Higgs doublets ξ

non-vanishing phases:
$\Rightarrow$ maybe CP- or T-violation?
(T-operator antiunitary $\Rightarrow$ complex conjugation of parameters)

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$$+ (\epsilon_{ij} |m_{12}^2| e^{i\varphi_{m_{12}^2}} H_d^i H_u^j + h.c.)$$

- one phase in the Higgs potential: $\varphi_{m_{12}^2}$
  can be rotated away
- phase difference of Higgs doublets ξ:
  vanishes because of minimum condition

} no CP violation at Born level in the Higgs sector

Higgs Sector at Born Level

Physical mass eigenstates (at Born level):

- 5 Higgs bosons: 3 neutral H, h, A; 2 charged $H^{\pm}$

Masses of the Higgs bosons:

- not all independent:

  often: Mass M_A or $M_{H^{\pm}}$ (and $\tan\beta$) as free parameter

  $\tan\beta = \frac{v_2}{v_1}$: ratio of the Higgs vac. expect. values

- lightest Higgs boson: h

  Upper theoretical Born mass bound:

  $M_h \leq M_Z = 91$ GeV

  with quantum corrections of higher orders: $M_h \lesssim 140$ GeV

  ↖ dependent on the MSSM parameters

Why a precise Higgs mass prediction?

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

- experimental measured value $\Rightarrow$ constraint on viable MSSM parameter space

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

  $\Delta M_H^{\text{exp.}} < 1$ GeV vs $\Delta M_H^{\text{theory}} \approx 3$ GeV

- In the discussion of the amount of fine-tuning of the MSSM the precise theoretical prediction of the Higgs boson mass enters.

Calculation of Higgs masses in the MSSM

Two approaches:

- Feynman diagrammatic approach

  (or effective potential approach for vanishing external momenta)

  [Brignole, Chankowski, Choi, Dabelstein, Dedes, Degrassi, Demir, Drees, Ellis, Frank, Hahn, Harlander, Heinemeyer, Hollik, Kant, Lee, Martin, Mihaila, Pilaftsis, Pokarski, Ridolfi, Rosiek, H.R., Slavich, Steinhauser, Weiglein, Zwirner, . . .]

- Renormalization group equation approach

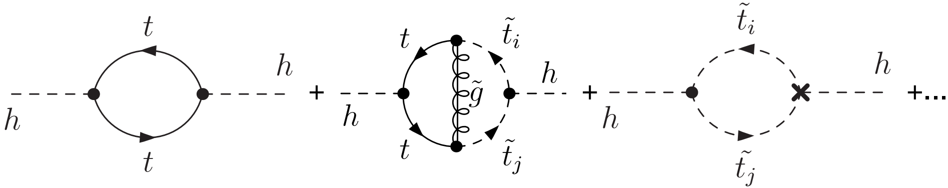
  [Carena, Draper, Espinosa, Haber, Hempfling, Hoang, Lee, Quiros, Wagner, Zhang, . . .]

  very recent [Draper, Lee, Wagner, arXiv:1312.5743]

Feynman diagrammatic approach

Calculate Feynman diagrams

which contribute to the Higgs-boson self energies $\hat{\Sigma}$:



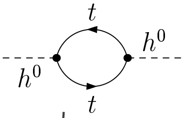
1-loop level $\mathcal{O}(\alpha_t)$ 2-loop level $\mathcal{O}(\alpha_t \alpha_s)$ Counterterm contr.

$\alpha_t \sim$ (top Yukawa coupl.)^2

Feynman diagrammatic approach

Two-point-function:

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



with the matrix:

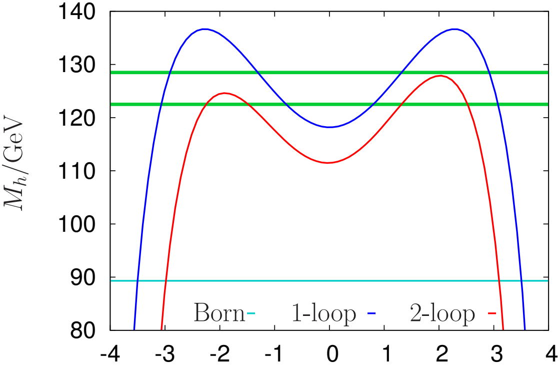
$$\mathbf{M}(\mathbf{p^2}) = \begin{pmatrix} M^2_{H^0_{\text{Born}}} - \hat{\Sigma}_{H^0H^0}(p^2) & -\hat{\Sigma}_{H^0h^0}(p^2) & -\hat{\Sigma}_{H^0A^0}(p^2) \\ -\hat{\Sigma}_{H^0h^0}(p^2) & M^2_{h^0_{\text{Born}}} - \hat{\Sigma}_{h^0h^0}(p^2) & -\hat{\Sigma}_{h^0A^0}(p^2) \\ -\hat{\Sigma}_{H^0A^0}(p^2)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

Real parameters: $\hat{\Sigma}_{H^0A^0}(p^2) = \hat{\Sigma}_{h^0A^0}(p^2) = 0$ no mixing between CP-even and CP-odd states

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

$\Rightarrow$ loop-corrected Higgs masses

Implications of a 125.5 GeV Higgs boson (MSSM)



X_t/TeV, X_t = squark mixing parameter

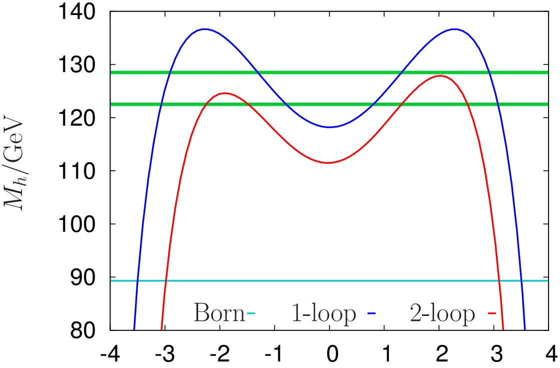
generated using `FeynHiggs` [Hahn, Heinemeyer, Hollik, H.R., Weiglein, Williams]

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; Dedes, Degrassi, Slavich]

- A 125.5 ± 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]

Implications of a 125.5 GeV Higgs boson (MSSM)



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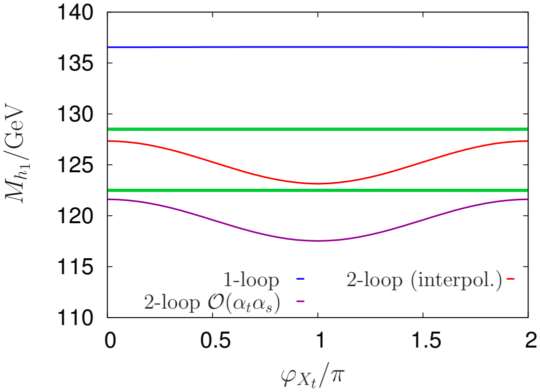
X_t/TeV, X_t = squark mixing parameter

For parameter scans, see e.g.

[Heinemeyer, Stål, Weiglein, arXiv:1112.3026;

Arbey, Battaglia, Djouadi, Mahmoudi, Quevillon, arXiv:1112.3028]

Higgs boson mass and CP-violating phases



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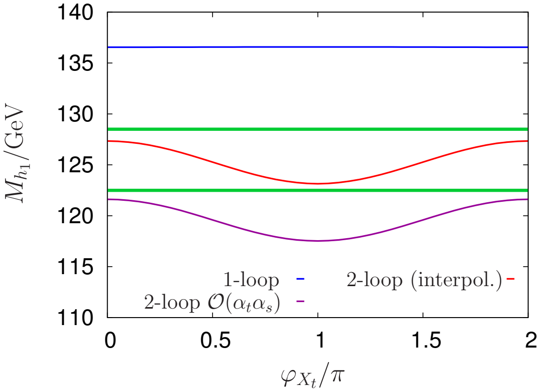
2-loop (interpol.): corrections for real parameters are interpolated [Degrassi, Slavich, Zwirner; Brignole, Degrassi, Slavich, Zwirner; Dedes, Degrassi, Slavich]

- The Higgs mass does depend on the squark mixing phase φ_{X_t}.
- For $\varphi_{X_t} \neq n\pi, n \in \mathbb{N}_0$, h_1 is not a CP-eigenstate.

Higgs boson mass and CP-violating phases



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To do: Implementation of $\mathcal{O}(\alpha_t^2)$ contr. [Hollik, Passehr, arXiv:1401.8275]

Renormalization Group Equation (RGE) approach

⋆ 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

$$M_h^2(m_t) = 2\lambda(m_t)v^2 \qquad v \approx 174 \text{ GeV}$$

Advantages

- Feynman diagrammatic approach:

  All log- and non-log terms are taken into account
  at a certain order of perturbation theory:

  Especially important for lower mass scales

- Renormalization group equation approach:

  Resummation of potentially large log-terms ($\ln \frac{M_S}{m_t}$):

  Especially important for larger mass scales

$\Rightarrow$ Combine both approaches (now: only for real parameters)

Combination

- Feynman diagrammatic part: from `FeynHiggs`
- Renormalization Group Equation (RGE) part:

  ⋆ 2-loop RGE for running for the **quartic Higgs coupling λ**, **strong coupling g_s with $\alpha_s = g_s^2/(4\pi)$**, **top Yukawa coupling y_t**

  [Espinosa, Quiros '91]

  ⋆ Matching at scale $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$: [Carena, Haber, Heinemeyer, Hollik, Wagner, Weiglein, hep-ph/0001002]

$$\lambda(M_S) = \frac{3{y_t}^4}{8\pi^2} \frac{X_t^2}{M_S^2} \left[1 - \frac{X_t^2}{M_S^2}\right]$$

$m_{\tilde{t}_i}$ = stop masses

$X_t = A_t - \mu \cot\beta$ = squark mixing parameter

$\Rightarrow$ leading + next-leading log $(\ln \frac{M_S}{m_t})$ resummation

Combination

- Combination of both approaches:

  Avoid double counting of logs

  $\Rightarrow$ Subtract logs from the Feynman diagrammatic (FD) result:

$$\Delta M_h^2 = (\Delta M_h^2)^{\text{FD}}(X_t^{\text{OS}}) - (\Delta M_h^2)^{\log}(X_t^{\text{OS}}) + (\Delta M_h^2)^{\text{RGE}}(X_t^{\overline{\text{MS}}})$$

  $\star$ Both approaches use a $\overline{\text{MS}}$ top quark mass

  $\star$ FD: X_t in on-shell scheme, RGE: X_t in $\overline{\text{MS}}$ scheme:
  Conversion needed:

$$X_t^{\overline{\text{MS}}} = X_t^{\text{OS}} \left[1 + \ln \frac{M_S^2}{m_t^2} \left(\frac{\alpha_s}{\pi} - \frac{3\alpha_t}{16\pi} \right) \right]$$

Combination

For $M_A \gg M_Z$:

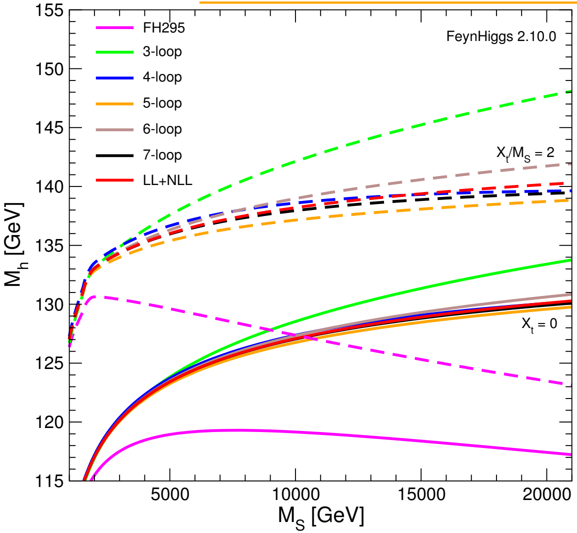
$$\hat{\Sigma}_{\phi_u\phi_u} \approx (\sin\beta)^{-2} \Delta M_h^2$$

self energy of the interaction eigenstates ϕ_u

ϕ_u couples to up-type quarks

Correction can be incorporated into the self energy matrix

Results for the combination



Comparison of:

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

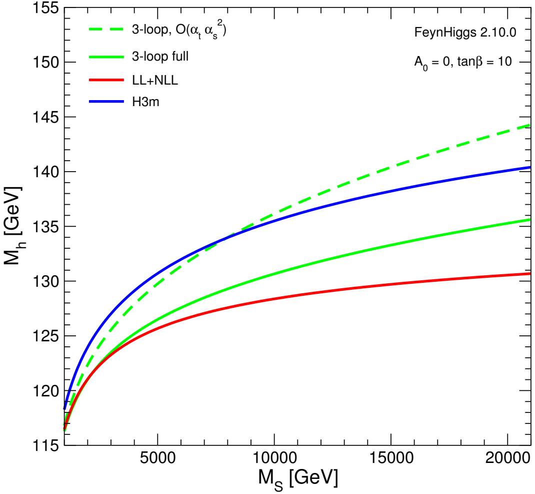
⋆ analyt. solution of RGE: 3-loop ... 7-loop level: Logs of order $\mathcal{O}(\alpha_t\alpha_s^2, \alpha_t^2\alpha_s, \alpha_t^3)$ ...

⋆ 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]

Results for the combination



Comparison with H3m:

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

3-loop: $\mathcal{O}(\alpha_t\alpha_s^2)$, $\mathcal{O}(\alpha_t^2\alpha_s)$, $\mathcal{O}(\alpha_t^3)$

- ⋆ only leading and next-to leading logs
- ⋆ single scale M_S

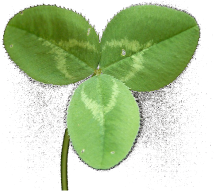
H3m: ⋆ complete $\mathcal{O}(\alpha_t\alpha_s^2)$ result

⋆ different scales

At 2-loop: different ren. schemes

CMSSM: $m_0 = m_{1/2} = 200 \ldots 15000$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$, spectra generation with SoftSUSY [Allanach, hep-ph/0104145]

More Higgs Bosons



$\longrightarrow$

[Frank Vincentz, http://de.wikipedia.org/wiki/Kleeblatt; Uwe Vogel, http://www.oldskoolman.de/]

Next-to Minimal Supersymmetric Standard Model

Field content:

NMSSM superfields = MSSM superfields + Higgs superfield singlet $\hat{S}$

Superpotential:

$$W_{\text{NMSSM}} = W_{\text{MSSM}}|_{\mu=0} - \lambda\,\hat{S}\,\hat{H}_d^1\,\hat{H}_u^2 + \lambda\,\hat{S}\,\hat{H}_d^2\,\hat{H}_u^1 + \frac{1}{3}\,\kappa\,\hat{S}^3$$

2 new coupling parameters: λ, κ ($\hat{H}_d$, $\hat{H}_u$: Higgs doublet superfields)

μ term of the MSSM: $W_{MSSM} = \ldots \mu \hat{H}_d^1\,\hat{H}_u^2 + \ldots$

$\rightarrow$ dynamically generated in the NMSSM

(scalar Higgs singlet field has a vacuum expectation value v_S)

Soft-breaking part extended: New parameters: m_S^2, A_λ, A_κ

Next-to Minimal Supersymmetric Standard Model

Higgs doublets and singlet expanded about the vacuum:

$$H_d = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + h_d + i a_d) \\ h_d^- \end{pmatrix} \qquad H_u = e^{i\varphi_u} \begin{pmatrix} h_u^+ \\ \frac{1}{\sqrt{2}}(v_u + h_u^0 + i a_u^0) \end{pmatrix}$$

$$S = \frac{e^{i\varphi_s}}{\sqrt{2}}(v_s + h_s + i a_s)$$

- three real scalar fields: h_d, h_u, h_s
- three real pseudoscalar fields: a_d, a_u, a_s
- two complex scalar fields: $h_d^\pm$, $h_u^\pm$

} no mass eigenstates

Next-to Minimal Supersymmetric Standard Model

In the MSSM: (3 neutral, 2 charged Higgs bosons, 4 neutralinos)

lightest CP-even Higgs boson:

upper theoretical mass bound:

at tree-level: $M_h \leq M_Z$

at loop-level: bound shifted to higher values: $M_h \lesssim 140$ GeV

In the NMSSM: (5 neutral, 2 charged Higgs bosons, 5 neutralinos)

extra contributions $\sim \lambda^2$

$\Rightarrow$ already at tree-level larger masses possible

+ loop corrections (possibly smaller as in the MSSM)

Status: CP-conserving NMSSM (up to 2010)

- leading one-loop contributions due to (s)top/(s)bottom loops

  [Ellwanger hep-ph/9302224; Elliott, King, White hep-ph/9302202; hep-ph/9305282; hep-ph/9308309; Pandita Z. Phys. C59, '93; Phys. Lett. B318, '93]

- one-loop leading-log contributions due to chargino, neutralino and Higgs boson loops [Ellwanger, Hugonie hep-ph/0504269]

- two-loop leading-log contributions of $\mathcal{O}(\alpha_s \alpha_{\{t,b\}})$ and $\mathcal{O}(\alpha^2_{\{t,b\}})$
  (can be adapted from the MSSM)

  [Yeghian hep-ph/9904488; Ellwanger, Hugonie, hep- ph/9909260]

- full one-loop corrections in the $\overline{\text{DR}}$-scheme

  [Degrassi, Slavich arXiv:0907.4682; Staub, Porod, Herrmann arXiv:1007.4049]

- two-loop corrections in the $\overline{\text{DR}}$-scheme of $\mathcal{O}(\alpha_s \alpha_t + \alpha_s \alpha_b)$
  (can be adapted from the MSSM)

  [Degrassi, Slavich arXiv:0907.4682]

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  (c SM)
  [Degrassi, Slavich arXiv:0907.4682]

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

SOFTSUSY
Next-to Minimal
[Allanach, hep-ph/0104145;
Allanach, Athron, Tunstall, Voigt, Williams, arXiv:1311.7659]

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

Real Parameters

Original parameter set:

soft SUSY-breaking parameters				gauge couplings		Higgs vacuum expectation values			singlet Higgs couplings		
$m_{H_d}^2$	$m_{H_u}^2$	m_S^2	A_λ	g	g'	v_u	v_d	v_s	λ	κ	A_κ

New parameter set:

t_{h_d}	t_{h_u}	t_{h_s}	$M_{H^\pm}^2$	M_W^2	M_Z^2	e	$\tan\beta$	v_s	λ	κ	A_κ
tadpole parameters			charged Higgs boson mass	gauge boson masses		electric charge	$\tan\beta = \frac{v_u}{v_d}$				

Real Parameters

CP-even Higgs boson mass matrix M_S (3×3 matrix):

$$M_S^2 = M_S^2(M_{H_\pm}^2, M_W^2, M_Z^2, \lambda, e, \tan\beta, \beta_B, t_{h_d}, t_{h_u}, t_{h_s}, \kappa, v_s, A_\kappa)$$

mixing angle of charged Higgs boson fields:
at tree level: $\beta_B = \beta$
enters M_S via replacement $A_\lambda \to M_{H^\pm}$

$t_{h_d}, t_{h_u}, t_{h_s}$: vanish at tree-level

CP-odd Higgs boson mass matrix M_P (3×3 matrix):

$$M_P^2 = M_P^2(M_{H_\pm}^2, M_W^2, M_Z^2, \lambda, e, \tan\beta, \beta_B, t_{h_d}, t_{h_u}, t_{h_s}, \kappa, v_s, A_\kappa)$$

Here: β_B also describes the tree-level mixing of the CP-odd fields yielding one Goldstone boson

Real Parameters

Renormalization procedure:

$$M_S^2 \to M_S^2(M_{H_\pm}^2,\, M_W^2,\, M_Z^2,\, \lambda,\, e,\, \tan\beta,\, \kappa,\, v_s,\, A_\kappa)$$

$$+\,\delta M_S^2(M_{H_\pm}^2,\, M_W^2,\, M_Z^2,\, \lambda,\, e,\, \tan\beta,\, \kappa,\, v_s,\, A_\kappa,\, \delta M_{H_\pm}^2,\, \delta M_W^2,\, \delta M_Z^2,$$

$$\delta\lambda,\, \delta Z_e\, e,\, \delta\tan\beta,\, \delta\kappa,\, \delta v_s,\, \delta A_\kappa,\, \delta t_{h_d},\, \delta t_{h_u},\, \delta t_{h_s})$$

linear in parameter counterterms $\delta M_{H_\pm}^2, \ldots$

Example: $M_{S_{11}}^2 = \dfrac{\sin^2\beta}{\cos^2\beta - \beta_B} M_{H^\pm}^2 + \ldots$

Replace: $M_{H_\pm}^2 \to M_{H_\pm}^2 + \delta M_{H_\pm}^2$

$\tan\beta \to tan\beta + \delta\tan\beta$

No counterterm for β_B

Expansion about counterterms:

$$\delta M_{S_{11}}^2 = \sin^2\beta\,\delta M_{H^\pm}^2 + 2\sin^2\beta\cos^3\beta\, M_{H^\pm}^2 \delta\tan\beta + \ldots$$

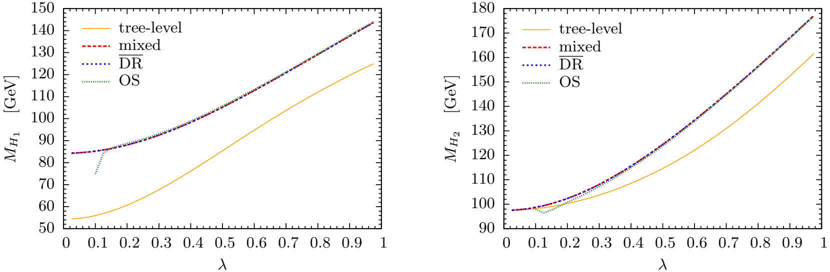
Renormalization Schemes

	mixed	$\overline{\text{DR}}$	on-shell (OS)	
t_{h_d}, t_{h_u}, t_{h_s}	"OS"	"OS"	"OS"	vanishing tadpole contr.
$M_{H^\pm}$, M_W, M_Z	OS	$\overline{\text{DR}}$	OS	
e	OS	$\overline{\text{DR}}$	OS	via $ee\gamma$ vertex in the Thomson limit
$\tan\beta$	$\overline{\text{DR}}$	$\overline{\text{DR}}$	$\overline{\text{DR}}$	
v_s, λ, κ, A_κ	$\overline{\text{DR}}$	$\overline{\text{DR}}$	OS	via chargino, neutralino and CP-odd Higgs boson masses

Main scheme (→ mixed)

Results: NMSSM with Real Parameters

Different renormalization schemes:

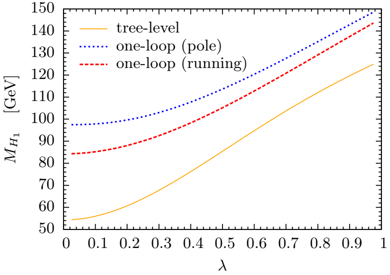


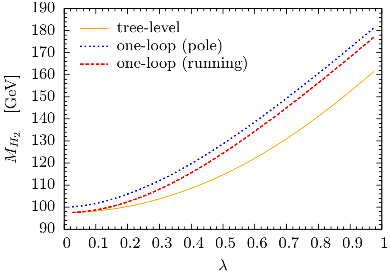
- in general good agreement between the different schemes ($\lesssim$ 1 GeV)
- for small λ: OS-scheme deviates due to finite $\frac{1}{\lambda}$ terms in the counterterms

$\kappa = \lambda/5$, $\tan\beta = 2$, $A_\lambda = 500$ GeV, $A_\kappa = -10$ GeV, $v_S = \frac{1}{\sqrt{2}}\frac{250}{\lambda}$ GeV,
$M_S = 300$ GeV, $A_t = A_b = A_\tau = -1.5 M_S$, $M_1 = M_S/3$, $M_2 = 2/3 M_S$, $M_3 = 2 M_S$

Results: NMSSM with Real Parameters

Different top quark schemes:



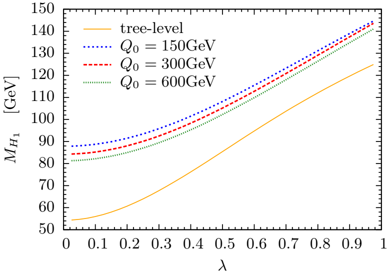


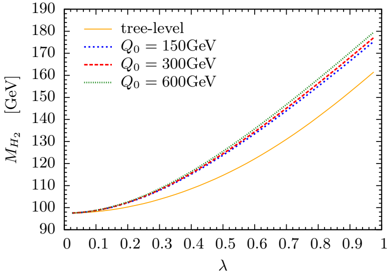
- relatively large differences between running and pole top quark mass

  2-loop contributions reduce this uncertainty (here only one-loop)

Results: NMSSM with Real Parameters

Different renormalization scales ($\overline{\text{DR}}$-scheme):





- Running top quark mass is used - changes also with the scale Q_o

  $\Rightarrow$ driving the differences

  again: 2-loop contributions reduce this uncertainty

  (here only one-loop)

Degenerate Higgs bosons

In the NMSSM:

2 Higgs bosons could be nearly degenerate with masses of $\sim$ 125 GeV

[Gunion, Jiang, Kraml, arXiv:1207.1545]

For illustration (one possibility):

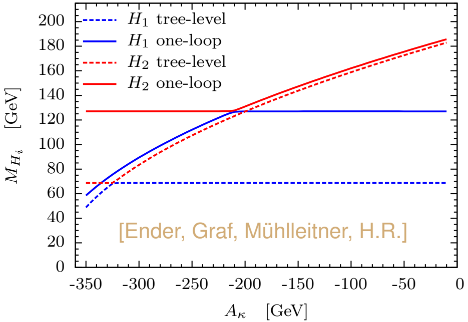


Illustration: Cross-over region of H_1 and H_2 at $A_\kappa \approx -210$ GeV:

- Masses $M_{H_i} \sim 125$ GeV
- H_1 and H_2 interchange their role

trilinear, SUSY-breaking singlet coupling

Degenerate Higgs bosons

In the NMSSM:

2 Higgs bosons could be nearly degenerate with masses of $\sim$ 125 GeV

$\Rightarrow$ Change of the effective couplings

[Gunion, Jiang, Kraml, arXiv:1207.1545]

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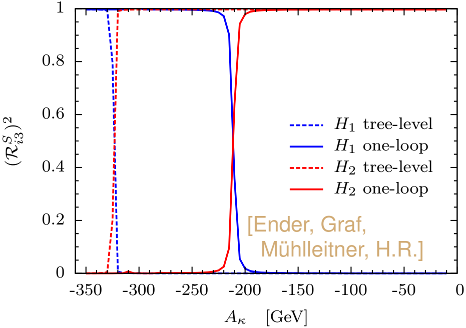

Illustration: Cross-over region of H_1 and H_2: Masses $\sim$ 125 GeV

$A_\kappa < -210$ GeV: H_1 singlet-like, H_2 non-singlet like

$A_\kappa > -210$ GeV: H_1 non-singlet like, H_2 singlet-like

Degenerate Higgs bosons

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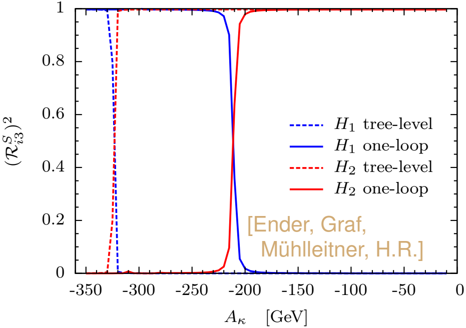

Illustration: Higher-order corrections are necessary

Status: CP-violating NMSSM (up to now)

- one-loop contributions in the effective potential approach:
  - from the third generation squark sector
    [Ham, Kim, Oh, Son hep-ph/0104144;
    Ham, Kim, Oh, Son arXiv:0708.2755]
  - and from charged particles
    [Ham, Oh, Son hep-ph/0110052]
  - and from the neutralino sector
    [Ham, Jeong, Oh hep-ph/0308264]
  - from the quark/squark sector and gauge boson sector
    [Funakubo, Tao hep-ph/0409294]
- and logarithmic two-loop contributions
  [Cheung, Hou, Lee, Senaha arXiv:1006.1458]
- full one-loop corrections in a mixed $\overline{\text{DR}}$/on-shell scheme
  ($\overline{\text{DR}}$ scheme can be easily deduced)
  [Graf, Gröber, Mühlleitner, HR, Walz arXiv:1206.6806]

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NMSSMCALC

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

Complex Parameters – Renormalization Scheme

Original parameter set:

$m^2_{H_d}$ $m^2_{H_u}$ m^2_S φ_{A_κ} φ_{A_λ} $|A_\lambda|$ g g' v_u v_d v_s φ_s φ_u $|\lambda|$ φ_λ $|\kappa|$ φ_κ $|A_\kappa|$

New parameter set:

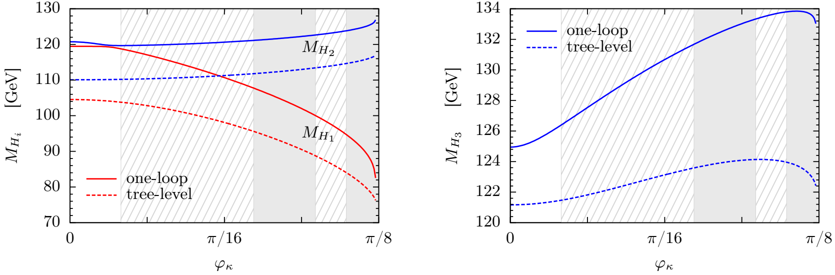
$$\underbrace{t_{h_d} \;\; t_{h_u} \;\; t_{h_s} \;\; t_{a_d} \;\; t_{a_s} \;\; M^2_{H^\pm} \;\; M^2_W \;\; M^2_Z \;\; e}_{\text{on-shell}} \;\; \underbrace{\tan\beta \;\; v_s \;\; \varphi_s \;\; \varphi_u \;\; |\lambda| \;\; \varphi_\lambda \;\; |\kappa| \;\; \varphi_\kappa \;\; |A_\kappa|}_{\overline{\text{DR}}}$$

→ generalisation of the "mixed scheme"

Remark: Counterterms of $\varphi_s, \varphi_u, \varphi_\lambda, \varphi_\kappa$ vanish in this scheme

Results: NMSSM with Complex Parameters

Higgs mass spectrum with tree-level CP-violation:



- clear dependence on φ_κ, also at tree-level
- no values for $\varphi_\kappa > \frac{\pi}{8}$: necessary minimum condition is not fulfilled

$|\lambda| = 0.72$, $|\kappa| = 0.20$, $\tan\beta = 3$, $M_{H^\pm} = 629$ GeV, $|A_\kappa| = 27$ GeV, $|v_s| = \frac{1}{\sqrt{2}} \frac{198}{|\lambda|}$ GeV

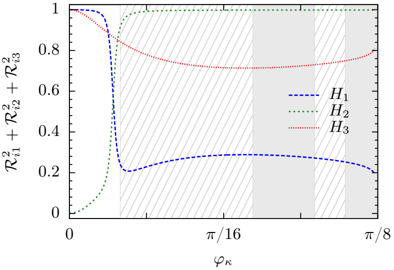
$M_{Q_3} = 490$ GeV, $M_{t_R} = 477$ GeV, $|A_b| = 963$ GeV, $|A_t| = 875$ GeV, $M_{\tilde{f} \neq \{\tilde{b},\tilde{t}\}} = A_{f \neq \{b,t\}} = 1$ TeV,

$M_1 = 145$ GeV, $M_2 = 200$ GeV, $M_3 = 600$ GeV.

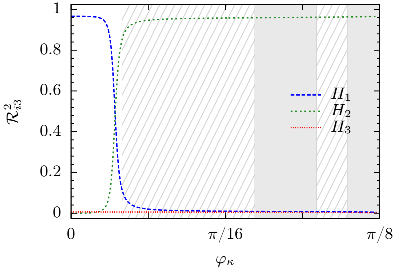
Results: NMSSM with Complex Parameters

One-loop mixing with tree-level CP-violation:

size of CP-violation:



size of CP-even singlet component:



- Size of CP-violation: Values of 0 and 1 correspond to no CP-violation. H_1 and H_3 clearly can be a mixture of CP-even and CP-odd.
- Here, no big mixture of the singlet and the other components.

NMSSMCALC

- Reads in: SusyLesHouchesAccord file:
  - ⋆ parameters in terms of real part and imaginary part
    (slightly modified renormalization scheme)
  - ⋆ the phase φ_u has to be given additionally
- Outputs a SLHA file including (besides non-Higgs parameters):
  - ⋆ Higgs boson masses
  - ⋆ Higgs boson mixings
  - ⋆ Higgs branching ratios
    (based on HDECAY [Djouadi, Kalinowski, Spira, hep-ph/9704448;
    Djouadi, Kalinowski, Mühlleitner, Spira, in arXiv:1003.1643])
    (for partial decay widths in the complex NMSSM,
    see also [Munir, Roszkowski, Trojanowski, arXiv:1305.0591; Munir, arXiv:1310.8129])

(NMSSMCALC: see http://www.itp.kit.edu/ maggie/NMSSMCALC/)

Summary

- Exciting times!
- Higg boson masses and mixings are important

  as input for cross sections and partial decay widths

  as constraints of the parameters spaces
- Improved Higgs mass prediction for the MSSM for large stop masses
- Complete one-loop Higgs mass prediction for the CP-violating NMSSM
- Further program development and improvement to come

  (for both `FeynHiggs` and `NMSSMCALC`)