

Precise predictions of the mass of the discovered Higgs boson in supersymmetric scenarios

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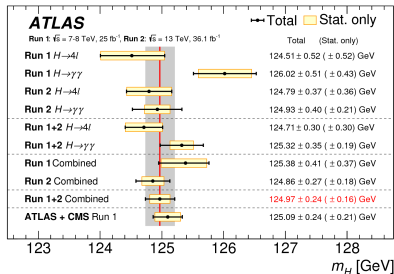
EPS-HEP 2021, 26 July 2021

One of the best measured properties

... of the discovered Higgs boson = its mass m_H

ATLAS/CMS (Run 1): $m_H = 125.09 \pm 0.21$ (stat) ± 0.11 (syst) GeV

- Free parameter in the Standard Model
→ important for predictions of for example Higgs decays in the Standard Model
- In extension of the Standard Model
→ Higgs boson mass can be predicted for example in SUSY models



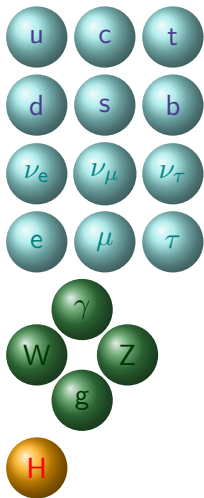
Minimal Supersymmetric Standard Model (MSSM)

Supersymmetry (SUSY):



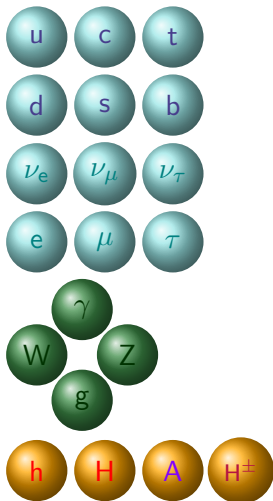
Minimal Supersymmetric Standard Model (MSSM)

Recipe: Standard Model particles



Minimal Supersymmetric Standard Model (MSSM)

Recipe: Standard Model particles (2HDM)
+ 2nd Higgs doublet



In SUSY models **needed** for, e.g.:
Generation of
up- and down-type fermion masses

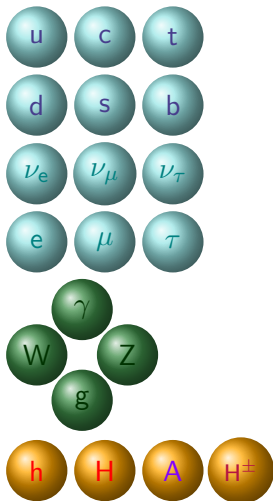
At tree-level:

- one Higgs doublet couples to down-type quarks and leptons, the other one to up-type quarks

⇒ Type II 2HDM

Minimal Supersymmetric Standard Model (MSSM)

Recipe: Standard Model particles (2HDM)
+ 2nd Higgs doublet



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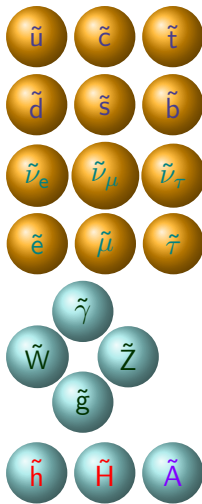
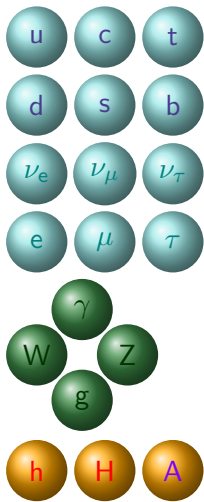
With quantum corrections:

- both Higgs doublets couple to all types of fermions

⇒ Type III 2HDM

Minimal Supersymmetric Standard Model (MSSM)

Recipe: Standard Model particles (2HDM) + Superpartners
 + 2nd Higgs doublet

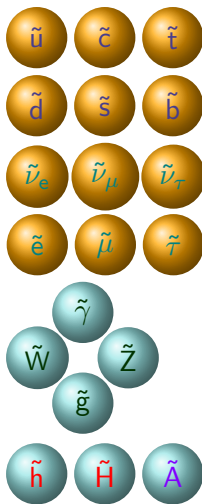
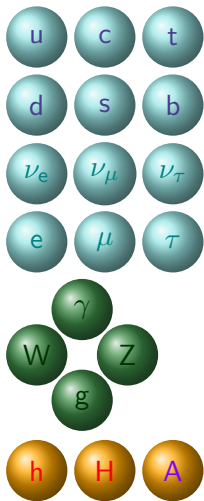


Unbroken supersymmetry:

$mass_{\text{superpartner}} = mass_{\text{2HDM-particle}}$
 \uparrow
 exp. excluded

Minimal Supersymmetric Standard Model (MSSM)

Recipe: Standard Model particles (2HDM) + Superpartners
 + 2nd Higgs doublet

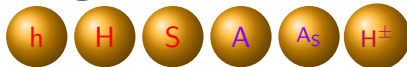
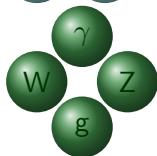
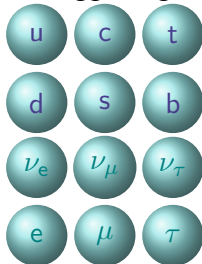


+ SUSY-breaking
 → many new parameters

Next-to Minimal Supersymmetric Standard Model (NMSSM)

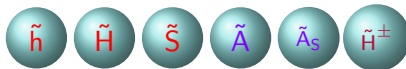
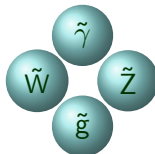
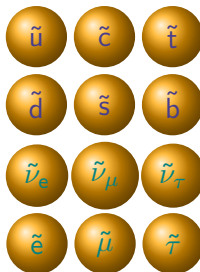
Recipe: Standard Model particles

+ 2nd Higgs doublet
+ Higgs singlet



(N2HDM) + Superpartners

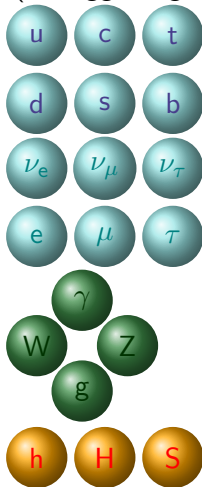
+ SUSY-breaking



(Next-to) Minimal Supersymmetric Standard Model ((N)MSSM)

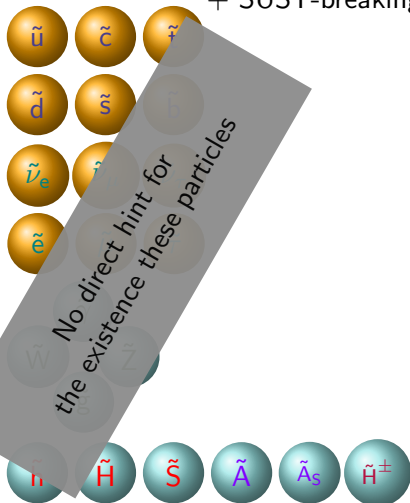
Recipe: Standard Model particles

+ 2nd Higgs doublet
(+ Higgs singlet)



+ Superpartners

+ SUSY-breaking



No direct hint for the existence these particles

Why a precise Higgs mass prediction?

experimentally
measured value



constraint on
viable (N)MSSM
parameter space

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

$$\Delta M_H^{\text{exp.}} \approx 200 \text{ MeV}$$

vs

$$\Delta M_H^{\text{theory}} \approx \mathcal{O}(\text{GeV})$$

expected:

$$\text{LHC: } \Delta M_H^{\text{exp.}} = 200 \text{ MeV,}$$

$$\text{ILC: } \Delta M_H^{\text{exp.}} = 50 \text{ MeV}$$

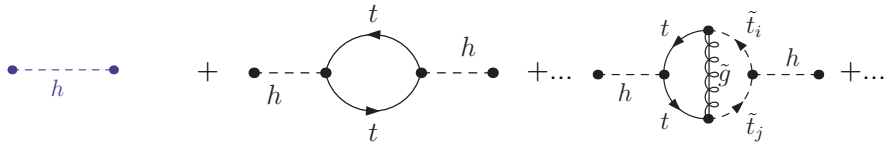
see discussion in:

[Slavich et al, 2012.15629]

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

Contributions to the Higgs boson masses

Born propagator: Quantum corrections:



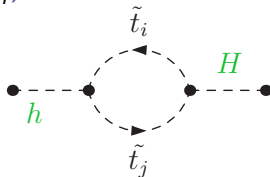
$$\frac{i}{p^2 - M_h^2}$$

One-loop level:

Two-loop level

$$\frac{i}{p^2 - (M_h^2 + \Delta M_h^2)}$$

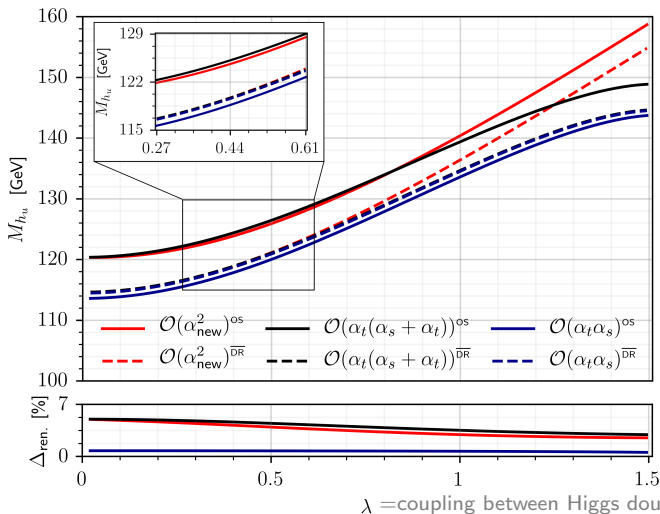
Additionally, mixing at loop level:



Contributions to the Higgs boson masses

[Dao, Gabelmann, Mühlleitner, HR 2106:06990]

Example in the NMSSM: Including different two-loop contributions:

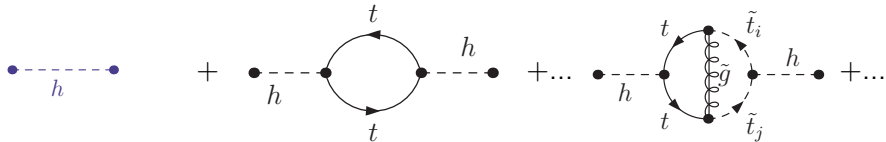


New contribution:

- important for large λ , see also [Goodsell, Nickel, Staub 1411:4665]
- implemented in NMSSMCALC [Baglio, Gabelmann, Gröber, Krause, Mühlleitner, Nhung, HR, Spira, Streicher, Walz]

Contributions to the Higgs boson masses

Born propagator: Quantum corrections:



$$\frac{i}{p^2 - M_h^2}$$

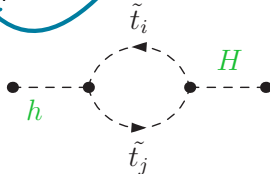
One-loop level:

Two-loop level

$$\frac{i}{p^2 - (M_h^2 + \Delta M_h^2)}$$

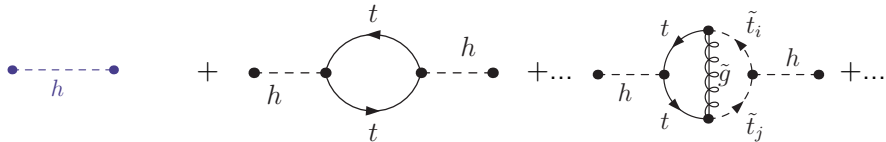
$$\log\left(\frac{m_{\tilde{t}_j}}{m_t}\right)$$

Additionally, mixing at loop level:



Contributions to the Higgs boson masses

Born propagator: Quantum corrections:



$$\frac{i}{p^2 - M_h^2}$$

One-loop level:

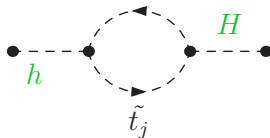
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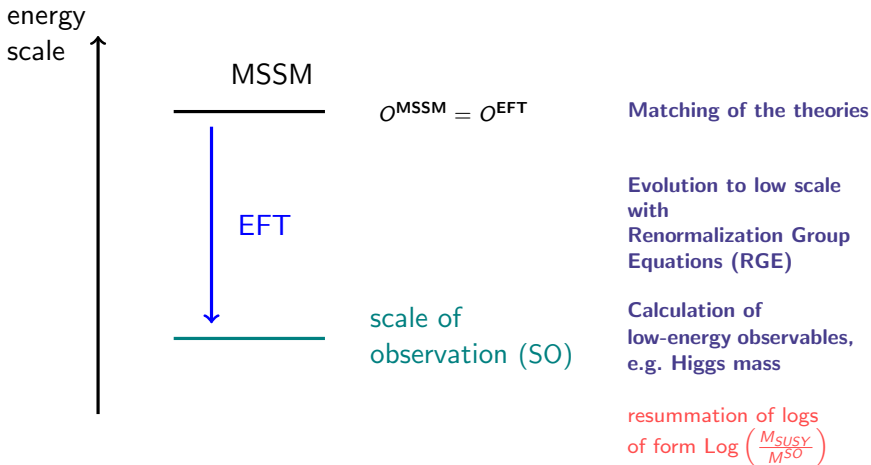
potentially large

Additionally, mixing at loop level:



Different approach for heavy SUSY particles

Effective Field Theories (EFT) approach:



Light Higgs bosons and heavy SUSY particles

Effective Field Theories (EFT) approach:

energy
scale



MSSM
— $O^{\text{MSSM}} = O^{\text{2HDM Type III}}$



2HDM Type III



Mass of charged
Higgs boson m_{H^\pm}

Matching of theories
at one-loop level

Evolution to low scale
with
Renormalization Group
Equations (RGE)

Calculation of
Higgs mass spectrum
and mixing

resummation of logs
of form $\text{Log} \left(\frac{M_{\text{SUSY}}}{M_{\text{SO}}} \right)$

Light Higgs bosons and heavy SUSY particles

Some further details:

[Murphy, HR 1909.00726]

- Non-vanishing phases allowed \rightarrow possible CP-violation

Light Higgs bosons and heavy SUSY particles

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- Non-vanishing phases allowed \rightarrow possible CP-violation
- One-loop threshold contributions to quartic couplings λ_1 to λ_7 of $\mathcal{O}(h_{\{t,b\}}^{\text{MSSM}^2} \{g^2, g_y^2, h_{\{t,b\}}^{\text{MSSM}^2}\})$

[Carena, Ellis, Lee, Pilaftsis, Wagner 1512.00437;
Haber, Hempfling hep-ph/9307201; Bahl, Hollik 1805.00867]

$h_{\{t,b\}}^{\text{MSSM}}$ = MSSM {top, bottom} Yukawa coupling,
 $g, g_y = SU(2), U(1)$ gauge couplings

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$h_{\{t,b\}}$ = 2HDM {top, bottom} Yukawa coupling,

$h'_{\{t,b\}}$ = loop-induced 2HDM {top, bottom} Yukawa coupling to 'wrong' Higgs doublet,

g_s = strong gauge coupling

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[Machacek, Vaughn; Kuo, Wang, Xiao; Schienbein, Staub, Steudtner, Svirina; Sperling, Stöckinger, Voigt; Oredsen; Thomsen]

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- Vanishing 1st, 2nd generation Yukawa couplings

Light Higgs bosons and heavy SUSY particles

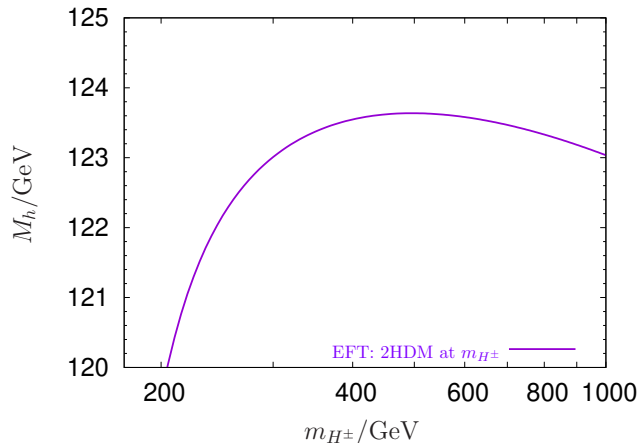
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- Vanishing 1st, 2nd generation Yukawa couplings
- Calculation of masses in 2HDM: only one-loop Yukawa contributions

Mass of the lightest Higgs boson M_h

[Murphy, HR]



Here: $M_h < 124$ GeV

m_{H^\pm} a good scale?

What about $m_t^{\overline{\text{MS}}}$?

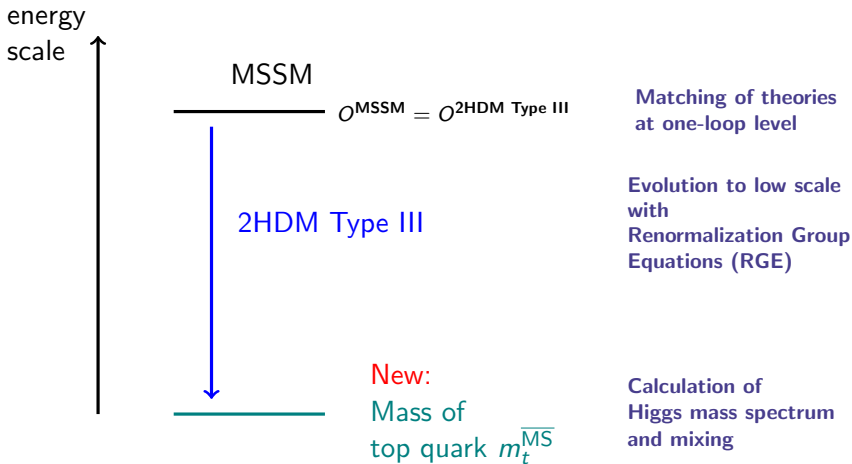
$m_t^{\overline{\text{MS}}}$ = top quark mass
in $\overline{\text{MS}}$ scheme

Parameters:

$M_S = 3$ TeV, $|A_t| = |A_b| = |\mu| = 3M_S$, $\tan \beta = 5$,
vanishing phases

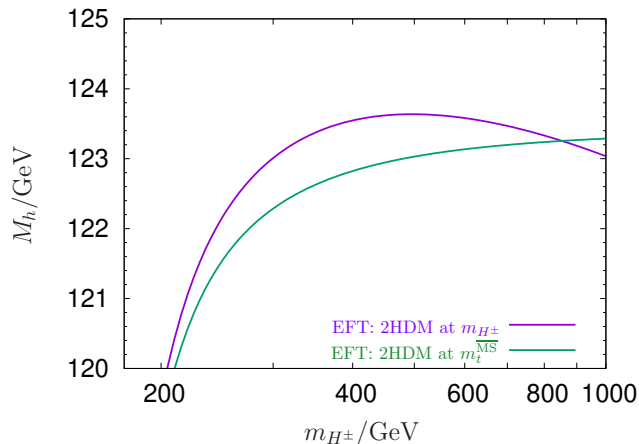
Light Higgs bosons and heavy SUSY particles

Effective Field Theories (EFT) approach:



Mass of the lightest Higgs boson M_h

[Murphy, HR]



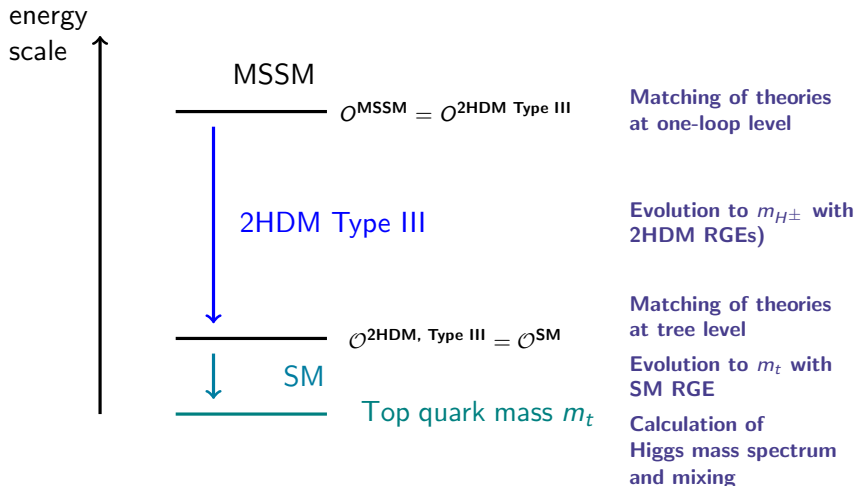
$\log(m_t/m_{H^\pm})$ important?

Parameters:

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vanishing phases

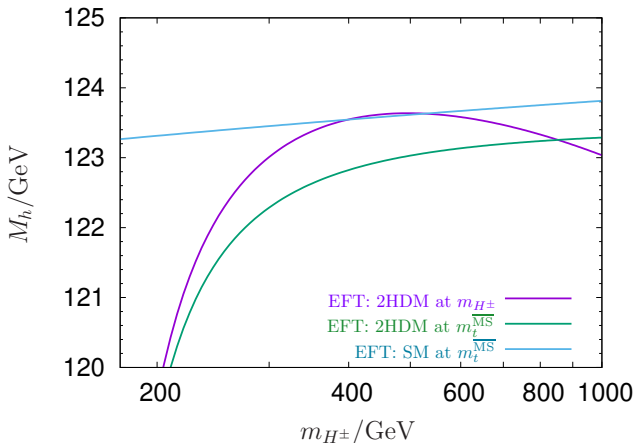
Medium-heavy Higgs bosons & heavy SUSY particles

Effective Field Theories (EFT) approach:



Mass of the lightest Higgs boson M_h

[Murphy, HR]



SM EFT:

good for large m_{H^\pm}
bad for small m_{H^\pm}

2HDM EFT:

bad for large m_{H^\pm}
good for small m_{H^\pm}

→ combining?

Combination of SM & 2HDM as low-energy EFT

[Lee, Wagner 1508.00576; Bahl, Hollik 1805.00867]

- At scale m_{H^\pm} : Go to Higgs-Basis:
$$H_1 = \cos \beta \Phi_1 + \sin \beta \Phi_2$$
$$H_2 = \cos \beta \Phi_2 - \sin \beta \Phi_1$$

$\Phi_1, \Phi_2 =$ Higgs doublets

→ Only H_1 has a non-vanishing vacuum expectation value v

- Identify the “SM-like” entry of $\mathcal{M}_{\text{Higgs}}$ basis with $(m_h^{\text{SM}})^2 = \lambda^{\text{SM}} v^2$
→ tree-level matching to SM

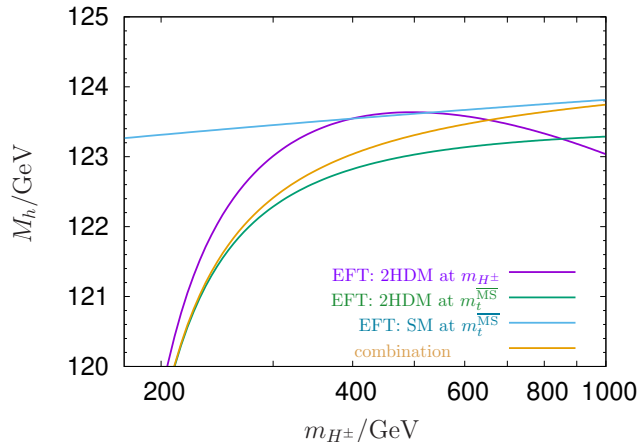
- Evolving λ^{SM} , y_t , g_s , and v down to m_t

- $\mathcal{M}_{\text{Higgs}}$ basis $\rightarrow \mathcal{M}_{\text{Higgs}}$ basis $+ v^2(m_t^2)$ $\begin{pmatrix} \tilde{\lambda}^{\text{SM}} & \frac{1}{\tan \beta} \tilde{\lambda}^{\text{SM}} & 0 & 0 \\ \frac{1}{\tan \beta} \tilde{\lambda}^{\text{SM}} & \frac{1}{\tan^2 \beta} \tilde{\lambda}^{\text{SM}} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$

with $\tilde{\lambda}^{\text{SM}} = \lambda^{\text{SM}}(m_t^2) - \lambda^{\text{SM}}(M_{H^\pm}^2)$

Mass of the lightest Higgs boson M_h

[Murphy, HR]



Combination:

For large m_{H^\pm} :
good agreement with
SM EFT

For small m_{H^\pm} :
good agreement with
2HDM EFT

Approaches and advantages

Advantages of EFT approach:

- Resummation of large logarithms to all orders
- Required for heavy SUSY particles

Advantages of Fixed-order approach:

- Complete result up to the considered order
- Takes mass differences automatically into account

⇒ Make use of both → Hybrid approach

Hybrid approach

[Bahl, Murphy, HR 2010.04711]

see also [Hahn, Heinemeyer, Hollik, HR, Weiglein 1312.4937; Bahl, Hollik 1609.00371; Staub, Porod 1703.03267; Athron, Bach, Harries, Kwasnitza, Park, Stöckinger, Voigt, Ziebell 1710.03760]

- 1) Redefine Higgs fields of fixed-order calculation to match normalization of the Higgs fields in the EFT

[Bahl, Hollik 1805.00867; Bahl 1812.06452]

- 2) Add individual results of EFT and fixed-order calculation

→ Need subtraction terms to avoid double counting

$$\hat{\Sigma}_{ij}^{\text{hybrid}}(p^2) = \hat{\Sigma}_{ij}^{\text{fixed order}}(p^2) + \Delta_{ij}^{\text{EFT}} - \Delta_{ij}^{\text{sub}}$$

⇒ Two-point-vertex-function matrix Γ_{hHA} :

$$\hat{\Gamma}_{hHA}(p^2) = i \left[p^2 \mathbb{1} - \text{diag}(m_h^2, m_H^2, m_A^2) + \hat{\Sigma}^{\text{hybrid}}(p^2) \right]$$

⇒ Pole masses = poles of inverse two-point-vertex function Γ_{hHA}^{-1}

[Bahl, Hollik 1805.00867]

Differences in the EFT part

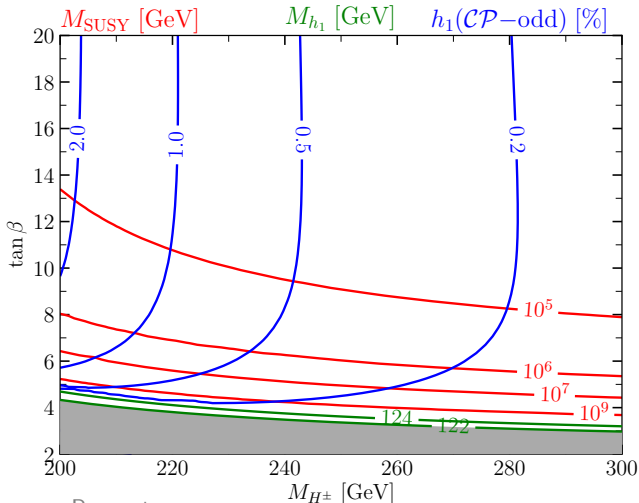
[Bahl, Murphy, HR 2010.04711]

- Additional threshold contributions for the 2HDM quartic couplings λ_1 to λ_7 :
 - ★ Purely electroweak contributions at one-loop
 - ★ $\mathcal{O}(\alpha_t \alpha_s)$ contributions

[Bahl, Sobolev, Weiglein 2009.07572; Lee, Wagner 1508.00576]
 - Electroweak contributions to the thresholds of the 2HDM Yukawa couplings
 - Full one-loop threshold between the SM and the 2HDM
 - Extraction of mass of SM-like Higgs boson
incl. full one- and two-loop order
- [Buttazzo et al 1307.3536]
- Vanishing bottom Yukawa couplings

CP-odd admixture

[Bahl, Murphy, HR 2010.04711]



Higgs boson masses only:

→ strong constraint
on CP-odd admixture
of light Higgs boson

Summary

- Higgs mass: Important constraint for the (N)MSSM
- Fixed-order approach: Complete up-to considered order:
→ here: NMSSM example incl. large λ contributions
- EFT approach: Resummation of Logs:
→ here: complex 2HDM type III as low-energy EFT
combined with SM EFT contributions
- Hybrid approach:
combines advantages of EFT and fixed-order approach
→ here: generalization of previous results to complex parameters
→ implemented into FeynHiggs
[Bahl, Hahn, Heinemeyer, Hollik, PaBehr, HR, Weiglein]
- CP-odd admixture to SM-like Higgs boson in MSSM tiny
- CP-mixing for heavy Higgs bosons possible

Parameter values for NMSSM example

[Dao, Gabelmann, Mühlleitner, HR 2106:06990]

$$\kappa = \lambda \kappa_0 / \lambda_0, \quad \lambda_0 = 0.46, \quad \kappa_0 = 0.43,$$

$$\operatorname{Re}(A_\kappa) = -4 \text{ GeV}, \quad |\mu_{\text{eff}}| = \lambda v_S / \sqrt{2} = 200 \text{ GeV}, \quad \tan \beta = \beta = 3.7$$

$$m_{H^\pm} = 640 \text{ GeV}, \quad m_{\tilde{Q}_3} = 1 \text{ TeV}, \quad m_{\tilde{t}_R} = 1.8 \text{ TeV},$$

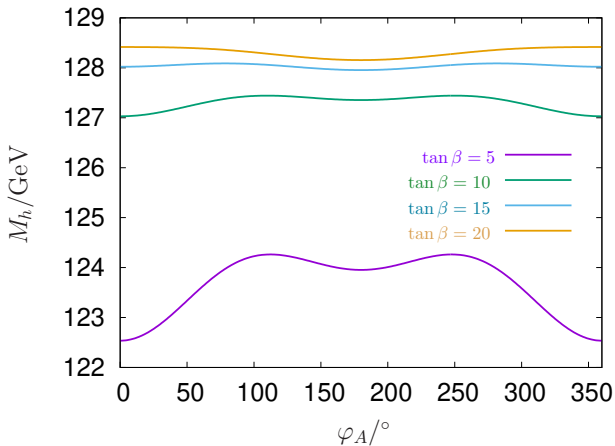
$$m_{\tilde{\chi}_{\neq \tilde{Q}_3, \tilde{t}_R}} = 3 \text{ TeV}, \quad A_t = 2 \text{ TeV}, \quad A_{i \neq t, \kappa} = 0 \text{ GeV},$$

$$|M_1| = 2|M_2| = 800 \text{ GeV}, \quad M_3 = 2 \text{ TeV},$$

all phases = 0

Mass of the lightest Higgs boson M_h : EFT approach

[Murphy, HR]



Obviously,
Higgs mass depends
on phases.

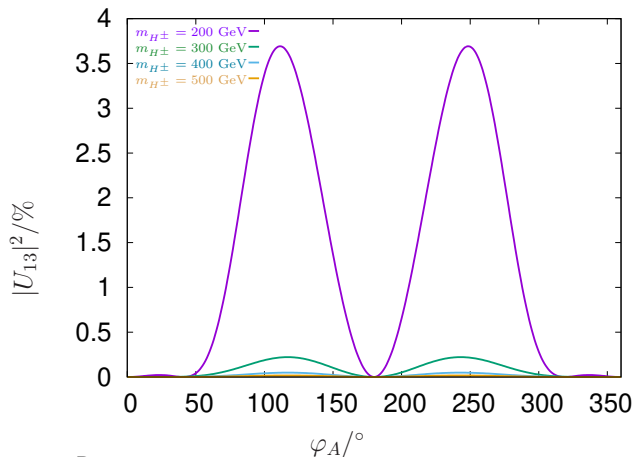
Parameters:

$$M_S = 5 \text{ TeV}, |A_t| = |A_b| = |\mu| = 2M_S, m_{H^\pm} = 500 \text{ GeV}, \varphi_\mu = \varphi_{M_3} = 0$$

CP-odd admixture $|U_{13}|^2$: EFT approach

Nonvanishing phases \rightarrow possible CP-violation

[Murphy, HR]



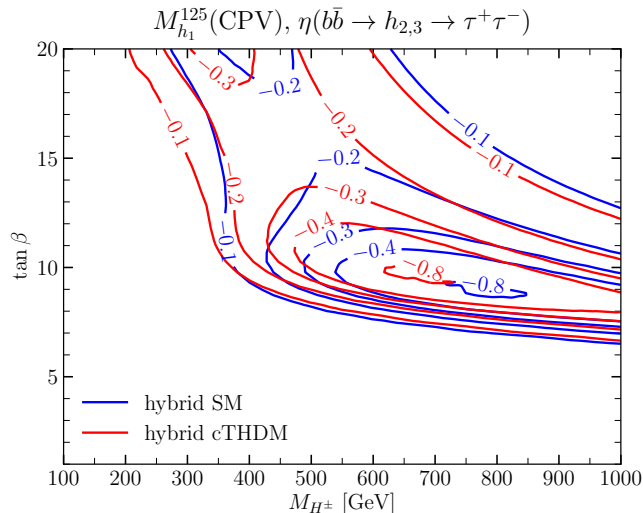
Only for light charged Higgs bosons:
Relatively large CP-odd admixture to SM-like Higgs boson

Parameters:

$$M_S = 30 \text{ TeV}, |A_t| = |A_b| = |\mu| = 3M_S, \tan\beta = 5, \varphi_\mu = \varphi_{M_3} = 0$$

CP-mixed heavy Higgs bosons: Hybrid approach

[Bahl, Murphy, HR 2010.04711]



CP-mixed heavy
Higgs bosons possible:

Benchmark scenario

[Bagnaschi et al 1808.07542]

→ exclusion bounds
change with CP-violation

With new calculation:
overall picture remains
the same
but details change

Benchmark scenario: $M_{h_1}^{125}$ (CPV) scenario

[Bagnaschi et al 1808.07542]

$$M_{Q_3} = M_{U_3} = M_{D_3} = M_{L_3} = M_{E_3} = 2 \text{ TeV},$$

$$\mu = 1.65 \text{ TeV}, M_1 = M_2 = 1 \text{ TeV}, M_3 = 2.5 \text{ TeV},$$

$$|A_t| = \mu \cot \beta + 2.8 \text{ TeV}, \phi_{A_t} = \frac{2\pi}{15}, A_b = A_\tau = |A_t|,$$

all other phases = 0.