Precise predictions for the Higgs masses and mixings in the CP-violating (N)MSSM

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PARTICLEFACE Webinar

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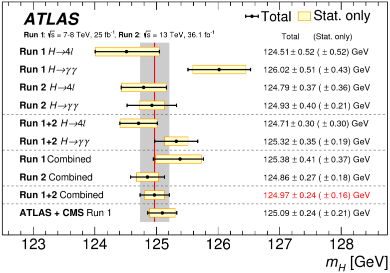
One of the best measured properties

…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
  $\rightarrow$ important for predictions of for example
  Higgs decays in the Standard Model

- In extension of the Standard Model
  $\rightarrow$ Higgs boson mass can be predicted
  for example in SUSY models

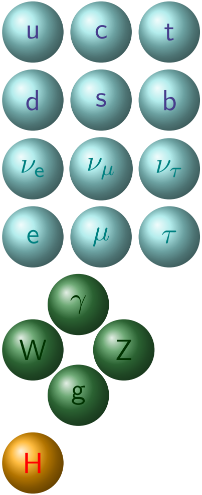


Minimal Supersymmetric Standard Model (MSSM)

Supersymmetry (SUSY):

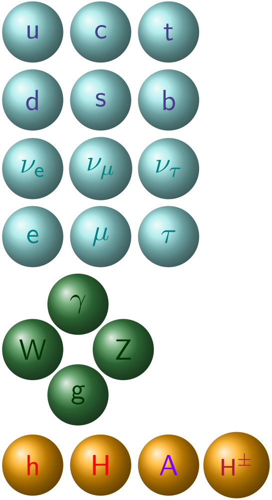
Minimal Supersymmetric Standard Model (MSSM)

Recipe: Standard Model particles



Minimal **S**upersymmetric **S**tandard **M**odel (MSSM)

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



In SUSY models needed for, e.g.:

Generation of
up- and down-type fermion masses

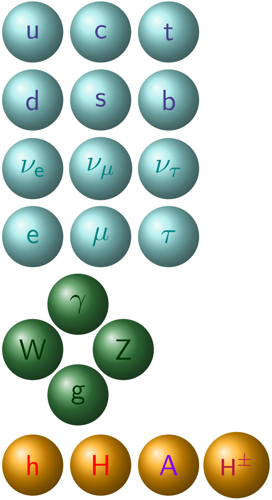
At tree-level:

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

$\Rightarrow$ Type II 2HDM

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

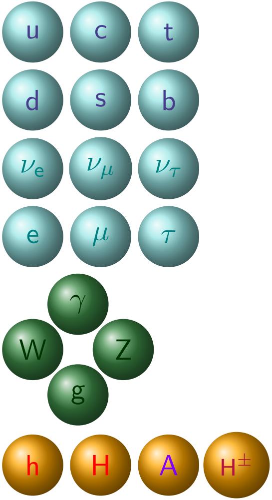
With quantum corrections:

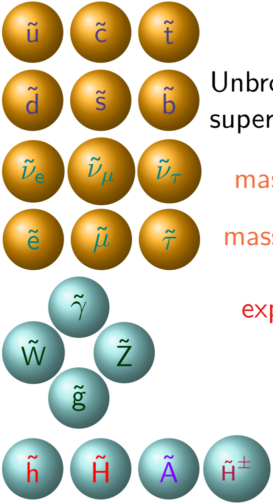
- both Higgs doublets couple to all types of fermions

$\Rightarrow$ Type III 2HDM

Minimal Supersymmetric Standard Model (MSSM)

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



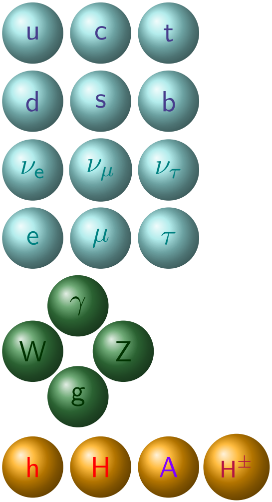


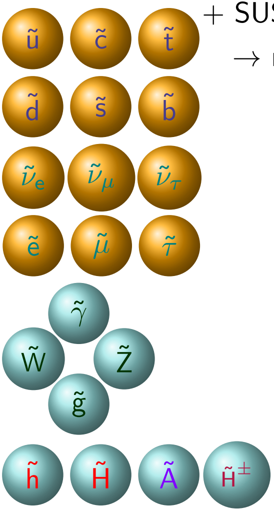
Unbroken supersymmetry:

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

Minimal Supersymmetric Standard Model (MSSM)

Recipe: Standard Model particles
+ 2^{nd} Higgs doublet (2HDM) + Superpartners
+ SUSY-breaking
→ many new parameters





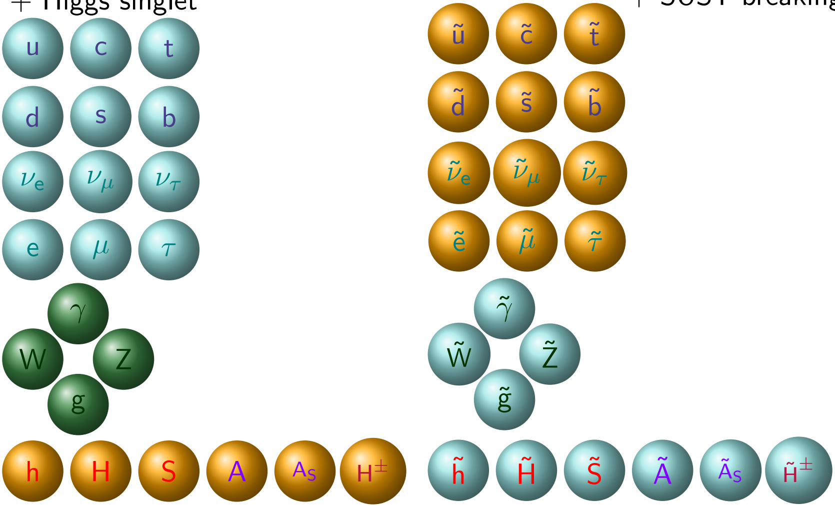
Next-to Minimal Supersymmetric Standard Model (NMSSM)

Recipe: Standard Model particles

+ 2^{nd} Higgs doublet (N2HDM) + Superpartners

+ Higgs singlet

+ SUSY-breaking



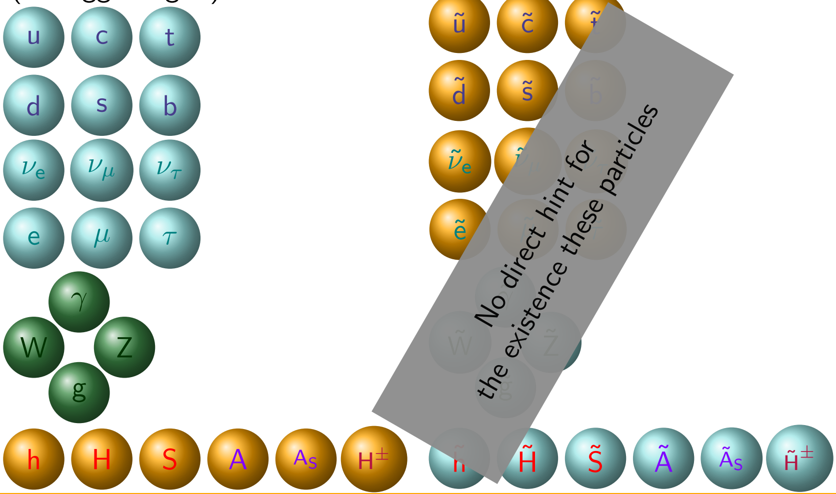
(Next-to) Minimal Supersymmetric Standard Model ((N)MSSM)

Recipe: Standard Model particles

+ 2nd Higgs doublet
(+ Higgs singlet)

+ Superpartners

+ SUSY-breaking



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:

  $$\Delta M_H^{\text{exp.}} \approx 200 \text{ MeV} \quad \text{vs} \quad \Delta M_H^{\text{theory}} \approx \mathcal{O}(\text{GeV})$$

  expected:

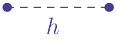
  LHC: $\Delta M_H^{\text{exp.}} = 200$ MeV,
  ILC: $\Delta M_H^{\text{exp.}} = 50$ MeV

  see discussion in:
  [Slavich et al, 2012.15629]

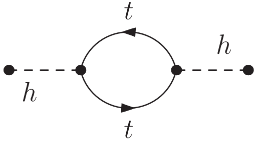
- Needed as consistent input for the calculation of cross sections and decay widths in the (N)MSSM

Contributions to the Higgs boson masses

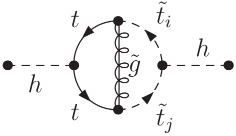
Born propagator: **Quantum corrections:**



$+$



$+ \ldots$



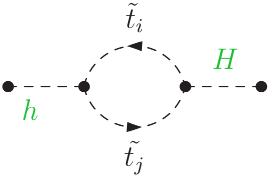
$+ \ldots$

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

One-loop level: Two-loop level

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

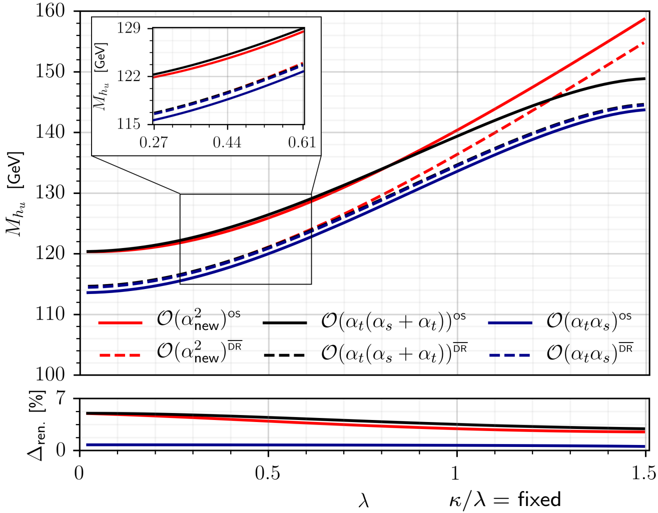
Additionally, mixing at loop level:



Contributions to the Higgs boson masses

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

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



New contribution:

$$\alpha_{\text{new}}^2 = \alpha_t\alpha_s + (\alpha_t+\alpha_\lambda+\alpha_\kappa)^2$$

$\alpha_s = \frac{g_s^2}{4\pi}$

$g_s =$ **strong gauge coupl.**

$\alpha_t = \frac{y_t^2}{4\pi}$

$y_t =$ **top Yukawa coupl.**

$\alpha_\lambda = \frac{\lambda^2}{4\pi}$, $\alpha_\kappa = \frac{\kappa^2}{4\pi}$

$\lambda =$ **Yukawa-type coupl. between Higgs doublets & singlet**

$\kappa =$ **Yukawa-type coupl. between singlets**

Contributions to the Higgs boson masses

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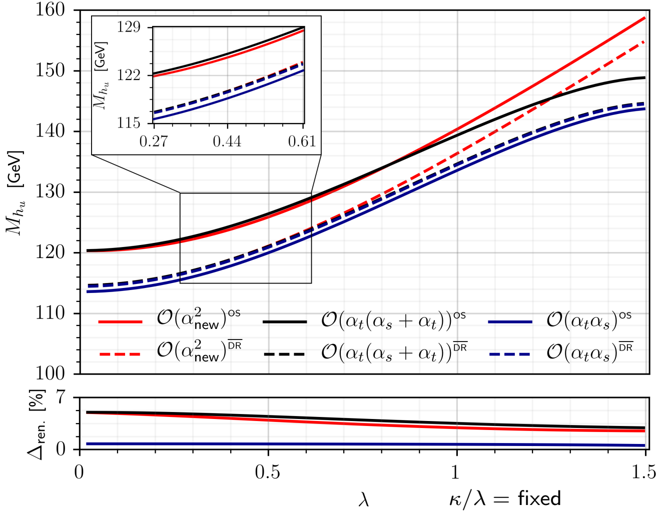

New contribution:

$$\alpha^2_{\text{new}} = \alpha_t\alpha_s + (\alpha_t + \alpha_\lambda + \alpha_\kappa)^2$$

- 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

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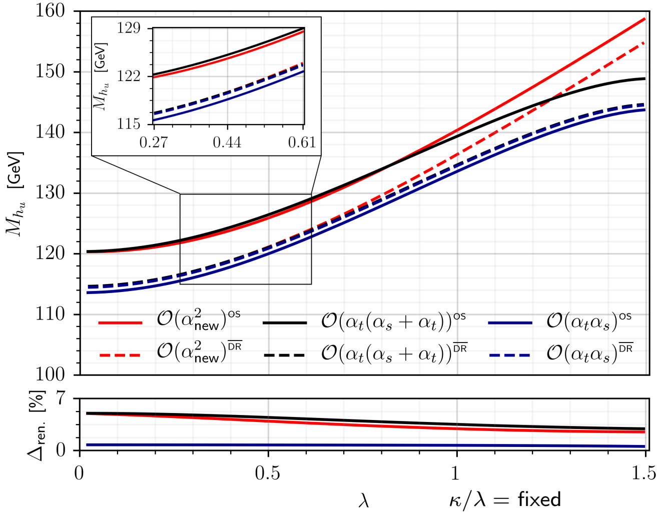


New contribution:

$$\alpha_{\text{new}}^2 = \alpha_t\alpha_s + (\alpha_t + \alpha_\lambda + \alpha_\kappa)^2$$

Here:

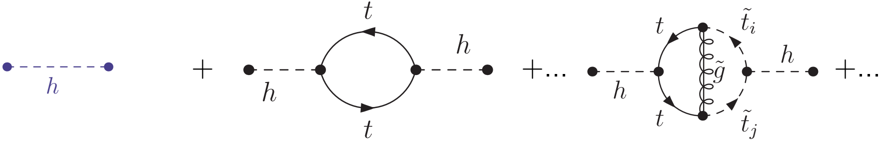
Stop masses:

$m_{\tilde{t}_1} \approx 1.0$ TeV

$m_{\tilde{t}_2} \approx 1.8$ TeV

Contributions to the Higgs boson masses

Born propagator: **Quantum corrections:**



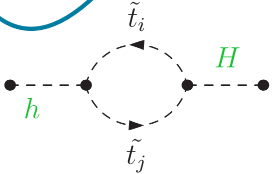
$$\frac{i}{p^2 - M_h^2}$$

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

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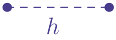

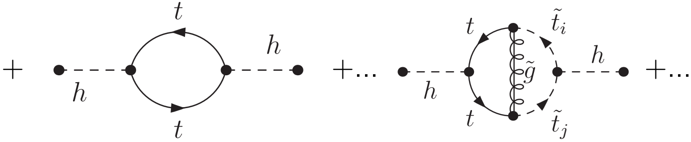

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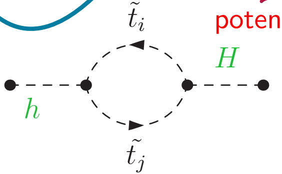
One-loop level: Two-loop level

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

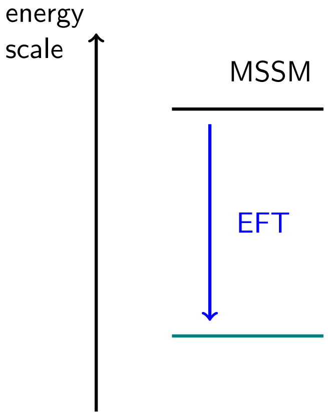
$\log\left(\frac{m_{\tilde{t}_j}}{m_t}\right)$ potentially large

Additionally, mixing at loop level:



Different approach for heavy SUSY particles

Effective Field Theories (EFT) approach:



$O^{\mathrm{MSSM}} = O^{\mathrm{EFT}}$ — **Matching of the theories**

Evolution to low scale with Renormalization Group Equations (RGE)

scale of observation (SO) — **Calculation of low-energy observables, e.g. Higgs mass**

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

Light Higgs bosons and heavy SUSY particles

Effective Field Theories (EFT) approach:

energy scale

MSSM

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

Matching of theories at one-loop level

2HDM Type III

Evolution to low scale with Renormalization Group Equations (RGE)

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

Calculation of Higgs mass spectrum and mixing

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

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

Light Higgs bosons and heavy SUSY particles

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  [Machacek, Vaughn; Kuo, Wang, Xiao; Schienbein, Staub, Steudtner, Svirina;
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Light Higgs bosons and heavy SUSY particles

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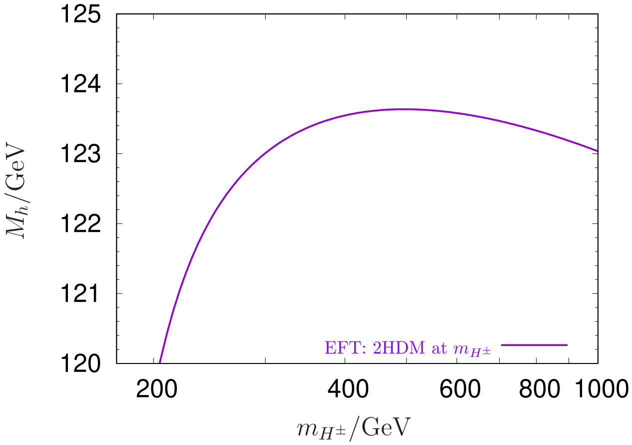
- Vanishing 1st, 2nd generation Yukawa couplings
- Calculation of masses in 2HDM: only one-loop Yukawa contributions

Mass of the lightest Higgs boson M_h

[Murphy, HR]



Here: $M_h < 124$ GeV

$m_{H^\pm}$ a good scale?

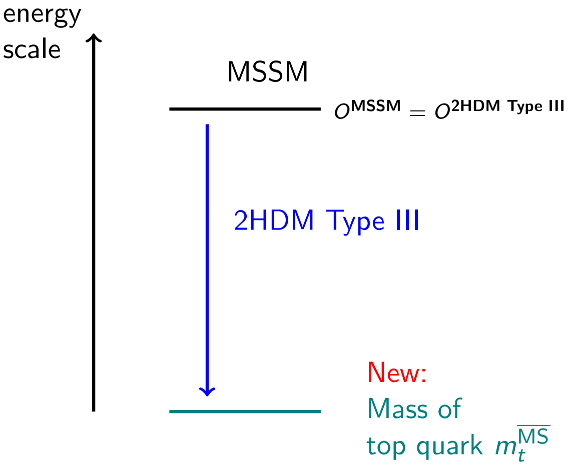
What about $m_t^{\overline{\text{MS}}}$?

$m_t^{\overline{\text{MS}}}$ = 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:



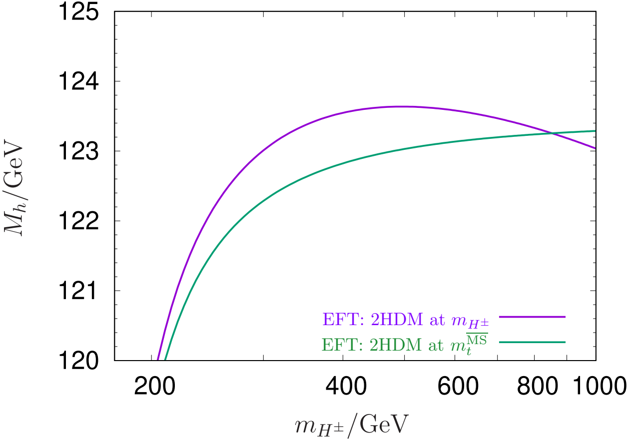
Matching of theories at one-loop level

Evolution to low scale with Renormalization Group Equations (RGE)

Calculation of Higgs mass spectrum and mixing

Mass of the lightest Higgs boson M_h

[Murphy, HR]

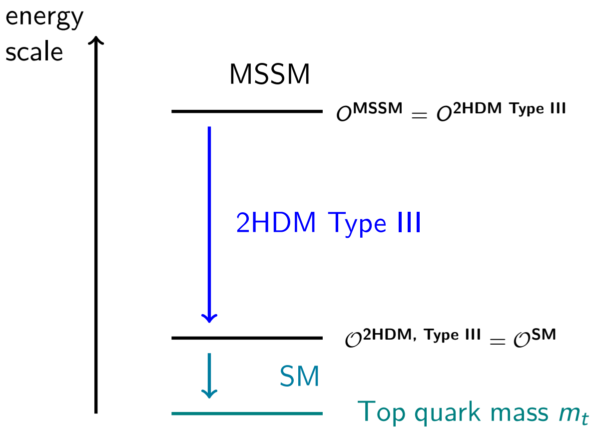


$\log(m_t/m_{H^\pm})$ important?

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

Medium-heavy Higgs bosons & heavy SUSY particles

Effective Field Theories (EFT) approach:



Matching of theories at one-loop level

Evolution to $m_{H^\pm}$ with 2HDM RGEs)

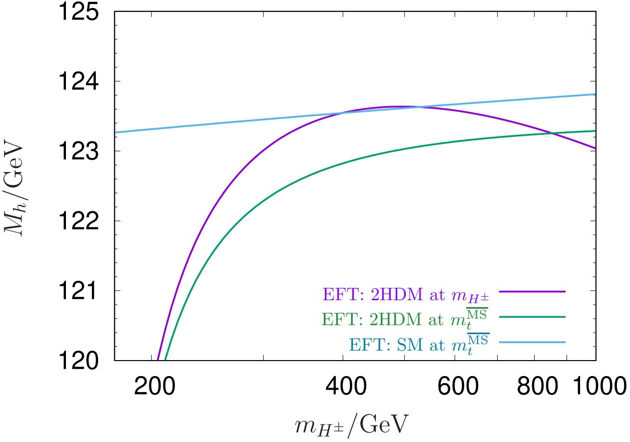
Matching of theories at tree level

Evolution to m_t with SM RGE

Calculation of Higgs mass spectrum and mixing

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 $m_{H^\pm}$

$\rightarrow$ 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

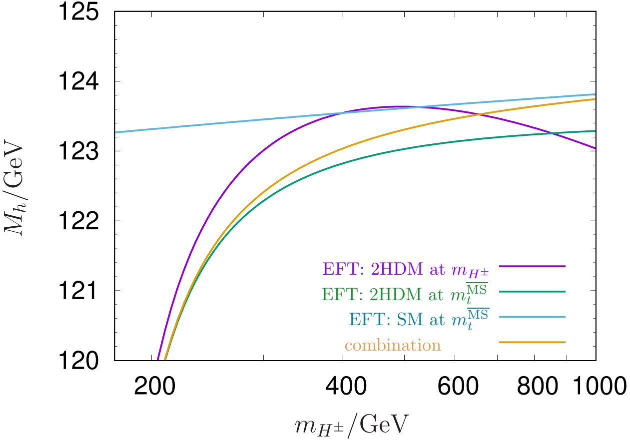
$\rightarrow$ Only H_1 has a non-vanishing vacuum expectation value v

- Identify the "SM-like" entry of $\mathcal{M}_{\text{Higgs basis}}$ with $\left(m_h^{\text{SM}}\right)^2 = \lambda^{\text{SM}} v^2$
  $\rightarrow$ 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 $\tilde{\lambda}^{\text{SM}} = \lambda^{\text{SM}}(m_t^2) - \lambda^{\text{SM}}(M_{H^+}^2)$

Mass of the lightest Higgs boson M_h

[Murphy, HR]



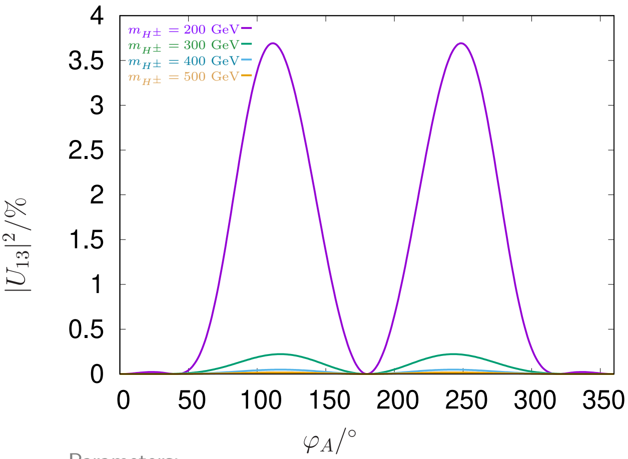
Combination:

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

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

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

Nonvanishing phases → possible CP-violation [Murphy, HR]



Only for light charged Higgs bosons:

Relatively large CP-odd admixture to SM-like Higgs boson

Parameters:

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

Approaches and advantages

Advantages of EFT approach:

- Resummation of large logarithms to all orders

$\rightarrow$ Required for heavy SUSY particles

Advantages of Fixed-order approach:

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

$\Rightarrow$ Make use of both $\rightarrow$ 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

$\rightarrow$ Need subtraction terms to avoid double counting

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

$\Rightarrow$ Two-point-vertex-function matrix Γ_{hHA}:

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

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

[Bahl, Hollik 1805.00867]

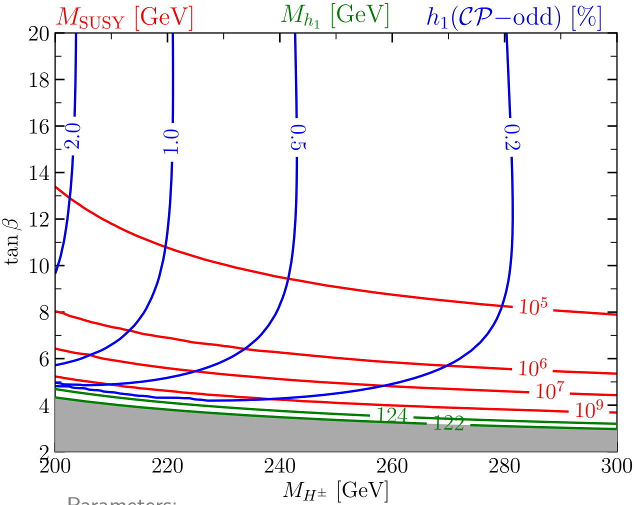
Differences in the EFT part

[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]



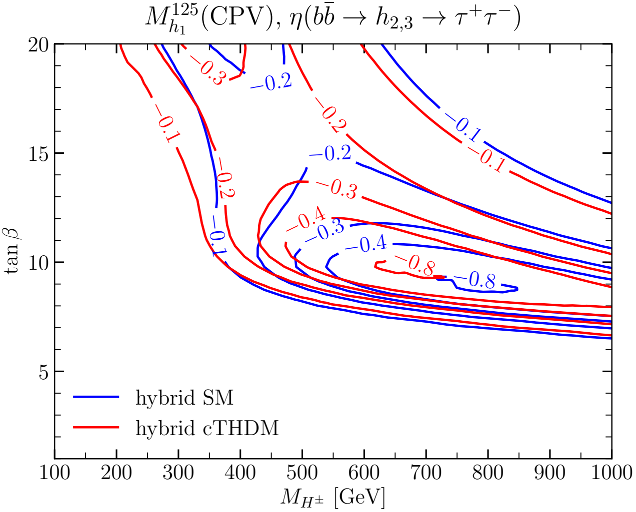
Parameters:
$|A_t| = |A_b| = |\mu| = 3M_S$, $\varphi_A = 2\pi/3$, $\varphi_{M_3} = \pi/4$

Higgs boson masses only:

$\rightarrow$ strong constraint on CP-odd admixture of light Higgs boson

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

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 of the MSSM
  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, Paßehr, 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]

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

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

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

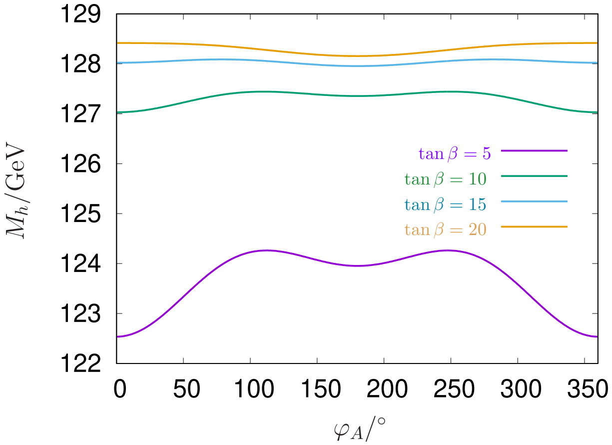
$m_{\tilde{X}\neq\tilde{Q}_3,\tilde{t}_R} = 3$ TeV, $A_t = 2$ TeV, $A_{i\neq t,\kappa} = 0$ GeV,

$|M_1| = 2|M_2| = 800$ GeV, $M_3 = 2$ TeV,

all phases $= 0$

Mass of the lightest Higgs boson M_h: EFT approach

[Murphy, HR]



Obviously,
Higgs mass depends
on phases.

Parameters:

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

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

[Bagnaschi et al 1808.07542]

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

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

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

all other phases $= 0$.