Precision predictions for the Higgs masses and mixings in the CP-violating MSSM

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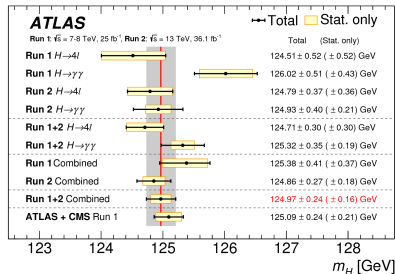in coll. with H. Bahl and N. Murphy

ParticleFace Workshop 2021, 14 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
  - $\rightarrow$ 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
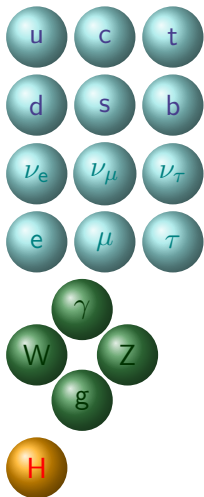   for example in the MSSM

Supersymmetry (SUSY):

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

Recipe: Standard Model particles

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

Recipe: Standard Model particles (2HDM)
$+$ 2nd Higgs doublet
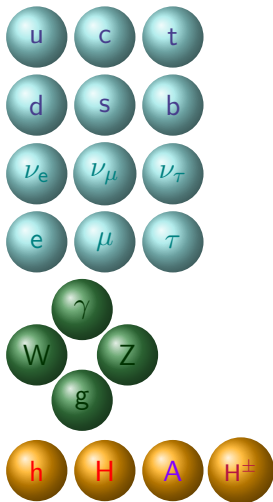
In SUSY models needed for, e.g.:

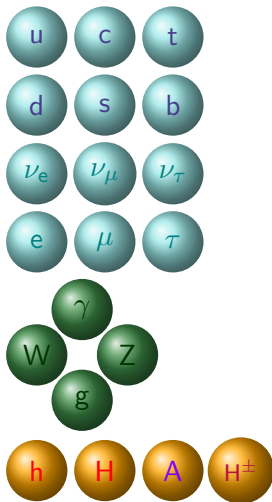Generation of
up- and down-type fermion masses

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

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

In SUSY models needed for, e.g.:

Generation of
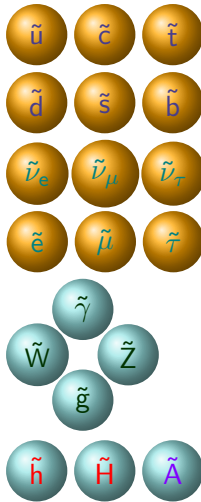up- and down-type fermion masses

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 (2HDM) + Superpartners
+ 2nd Higgs doublet
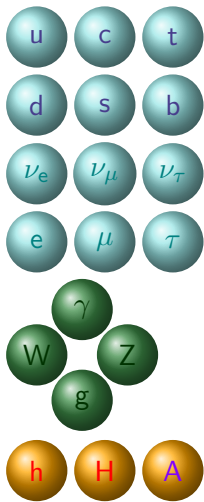
Unbroken supersymmetry:

$$\text{mass}_{\text{superpartner}} = \text{mass}_{\text{2HDM-particle}}$$

↑

exp. excluded

Minimal Supersymmetric Standard Model (MSSM)

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

+ SUSY-breaking
→ many new parameters

Minimal Supersymmetric Standard Model (MSSM)

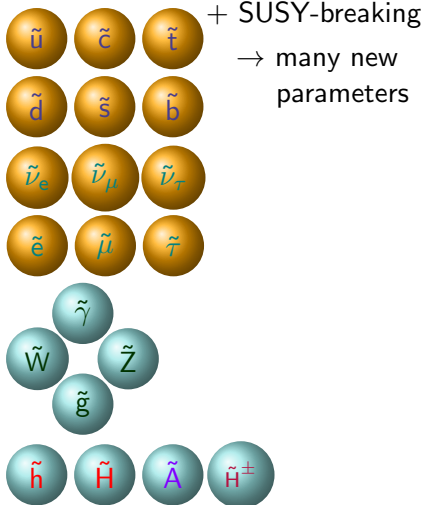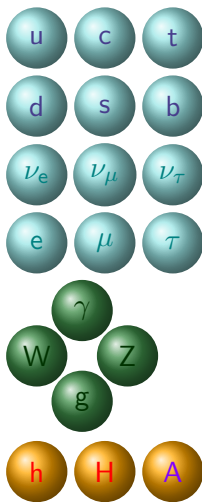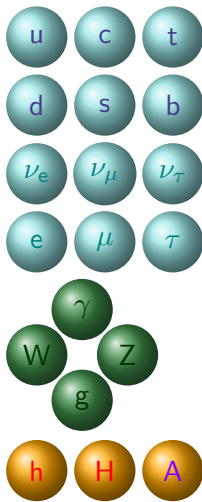**Recipe:** Standard Model particles (2HDM) + Superpartners
+ 2nd Higgs doublet

+ SUSY-breaking

No direct hint for the existence these particles

Why a precise Higgs mass prediction?

-

  experimentally measured value $\Rightarrow$ constraint on viable MSSM parameter space

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

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

  see discussion in:

  [Slavich et al, 2012.15629]

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

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

Contributions to the Higgs boson masses

Born propagator: **Quantum corrections:**
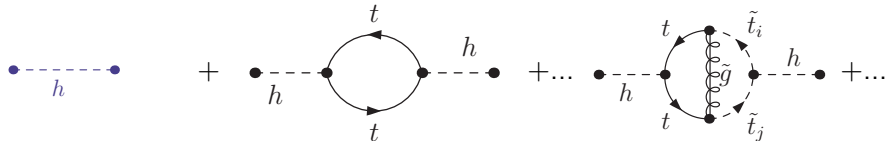
$$\frac{i}{p^2 - M_h^2}$$

One-loop level: Two-loop level

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

Additionally, mixing at loop level:
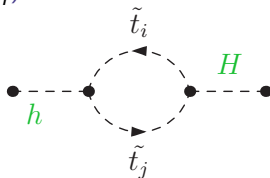
Contributions to the Higgs boson masses

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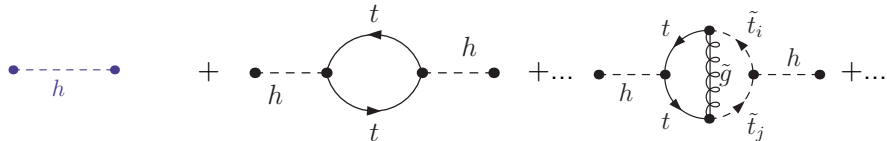
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Two-loop level

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

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

Additionally, mixing at loop level:
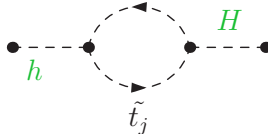
Contributions to the Higgs boson masses

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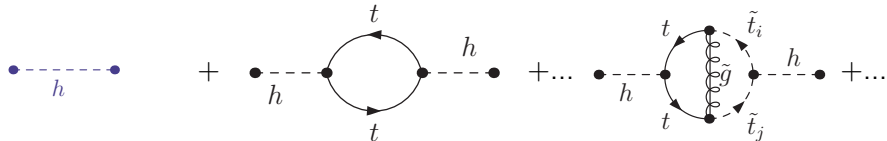
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One-loop level:

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:
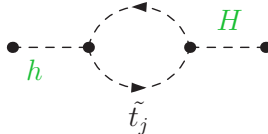
Different approach for heavy SUSY particles
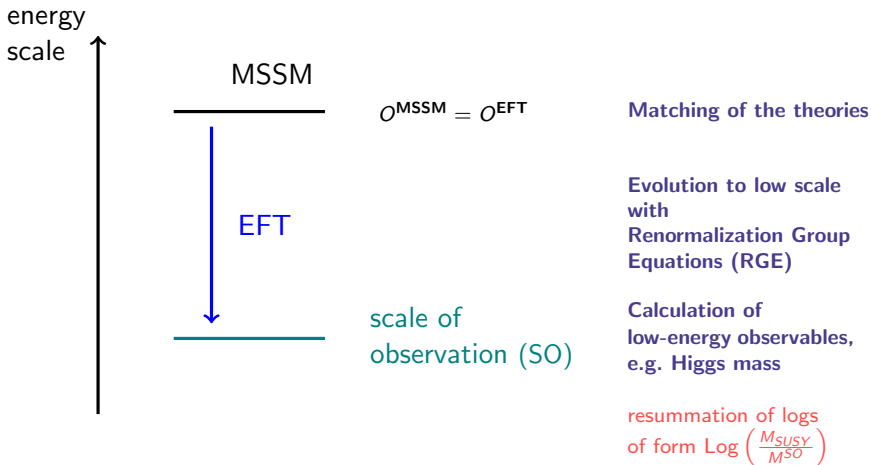
Effective Field Theories (EFT) approach:

energy scale

MSSM

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

EFT

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

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 $\text{Log} \left(\frac{M_{SUSY}}{M^{SO}} \right)$
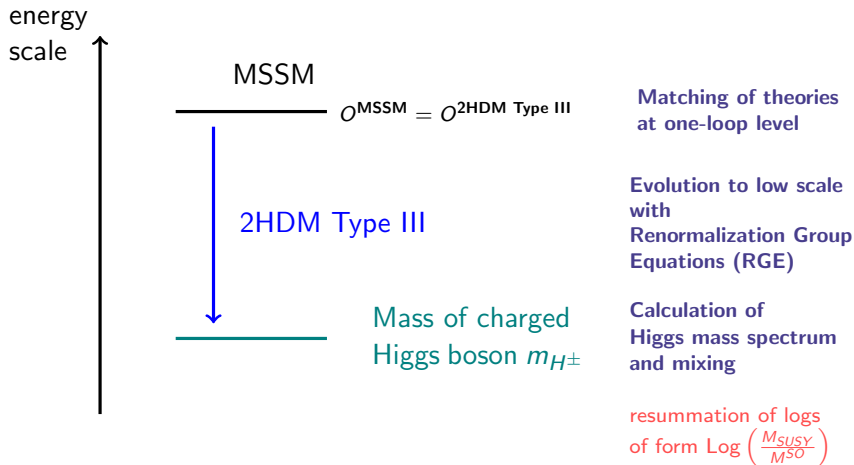
Light Higgs bosons and heavy SUSY particles

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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- One-loop threshold contributions to
  quartic couplings λ_1 to λ_7 of $\mathcal{O}(h_{\{t,b\}}^{\mathrm{MSSM}^2}\{g^2, g_y^2, h_{\{t,b\}}^{\mathrm{MSSM}^2}\})$

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

$h_{\{t,b\}}^{\mathrm{MSSM}} = $ MSSM $\{$top, bottom$\}$ Yukawa coupling,

g, $g_y = SU(2)$, $U(1)$ gauge couplings

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  see also [Gorbahn, Jäger, Nierste, Trine 0901.2065]

  $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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- Two-loop RGEs for the complex 2HDM Type III
  [Machacek, Vaughn; Kuo, Wang, Xiao; Schienbein, Staub, Steudtner, Svirina;
   Sperling, Stöckinger, Voigt; Oredsen; Thomsen]

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- Vanishing 1$^{\mathrm{st}}$, 2$^{\mathrm{nd}}$ generation Yukawa couplings

- Calculation of masses in 2HDM: only one-loop Yukawa contributions

Mass of the lightest Higgs boson M_h

[Murphy, HR]
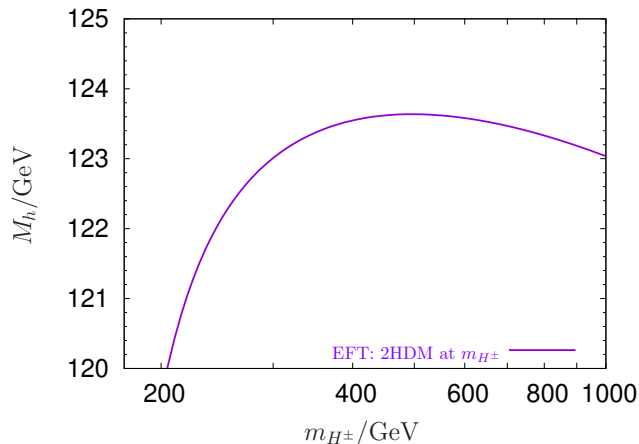
Here: $M_h < 124$ GeV

$m_{H^\pm}$ 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:

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)**

New:
Mass of
top quark $m_t^{\overline{\text{MS}}}$ **Calculation of Higgs mass spectrum and mixing**
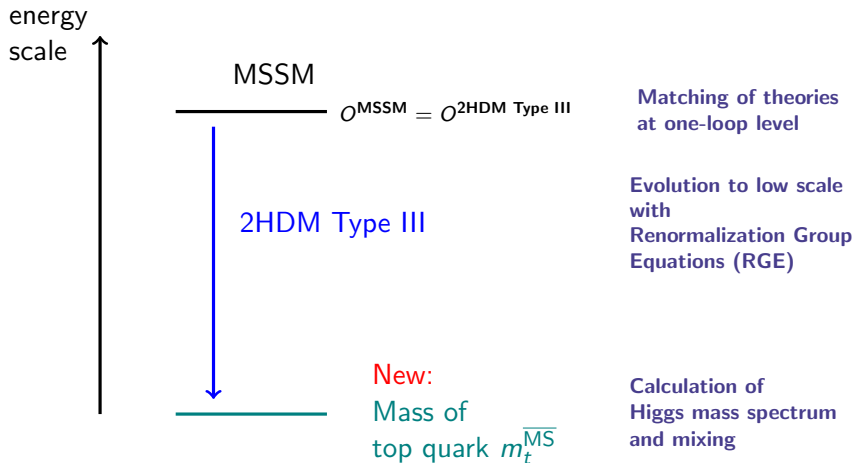
Mass of the lightest Higgs boson M_h
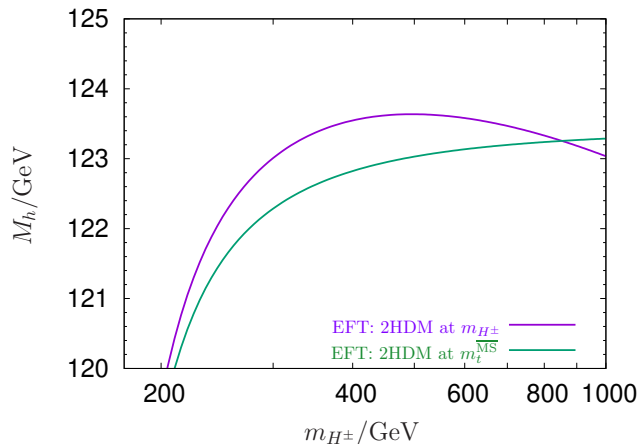
$\log(m_t/m_{H^\pm})$ important?

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

Medium-heavy Higgs bosons & heavy SUSY particles
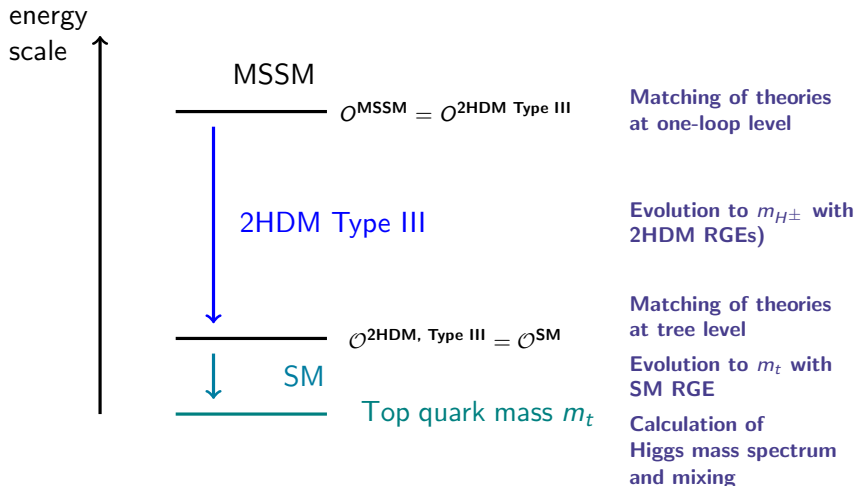
Effective Field Theories (EFT) approach:

energy scale

MSSM

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

Matching of theories at one-loop level

2HDM Type III

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

$\mathcal{O}^{\mathbf{2HDM,\ Type\ III}} = \mathcal{O}^{\mathbf{SM}}$

Matching of theories at tree level

SM

Evolution to m_t with SM RGE

Top quark mass m_t

Calculation of Higgs mass spectrum and mixing

Mass of the lightest Higgs boson M_h
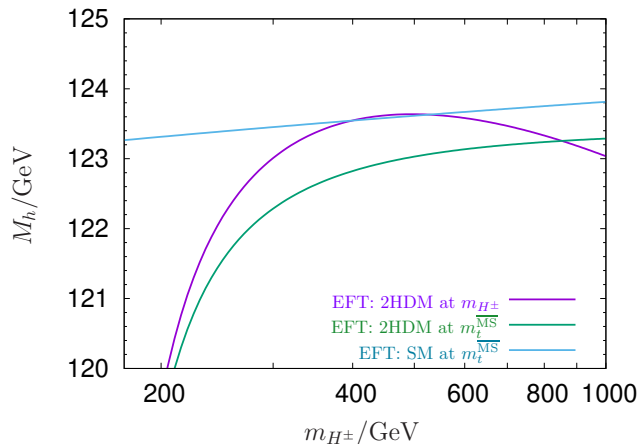
SM EFT:

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 $\left(m_h^{\text{SM}}\right)^2 = \lambda^{\text{SM}} v^2$
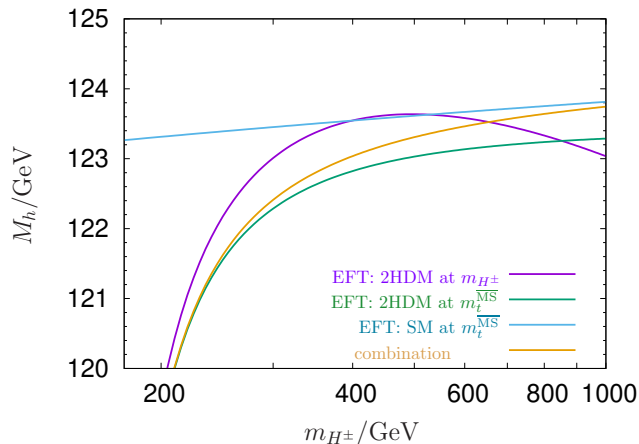 $\rightarrow$ tree-level matching to SM

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

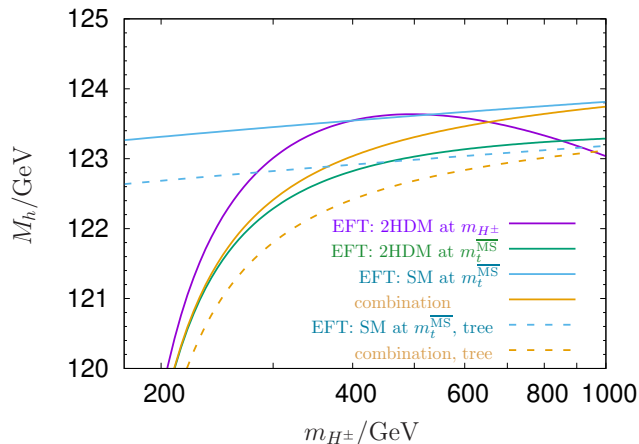# Mass of the lightest Higgs boson M_h

Combination:

For large $m_{H^\pm}$:

good agreement with SM EFT

For small $m_{H^\pm}$:

good agreement with 2HDM EFT

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

Dashed:
Pole mass calculation
at low energy without
loop contributions

The figure shows M_h/GeV on the vertical axis (120 to 125) versus $m_{H^\pm}/\text{GeV}$ on the horizontal axis (200 to 1000). Curves:
- EFT: 2HDM at $m_{H^\pm}$
- EFT: 2HDM at $m_t^{\overline{\text{MS}}}$
- EFT: SM at $m_t^{\overline{\text{MS}}}$
- combination
- EFT: SM at $m_t^{\overline{\text{MS}}}$, tree
- combination, tree

Mass of the lightest Higgs boson M_h

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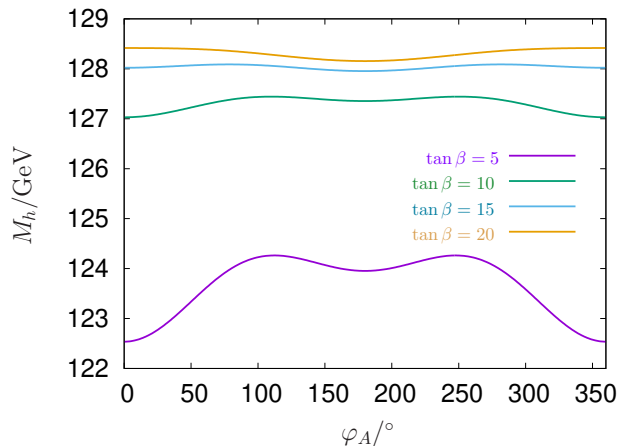
Obviously,
Higgs mass depends
on phases.

Parameters:

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

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]

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}:

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

$\Rightarrow$ 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

M_{SUSY} [GeV] M_{h_1} [GeV] $h_1(\mathcal{CP}-\mathrm{odd})$ [%]
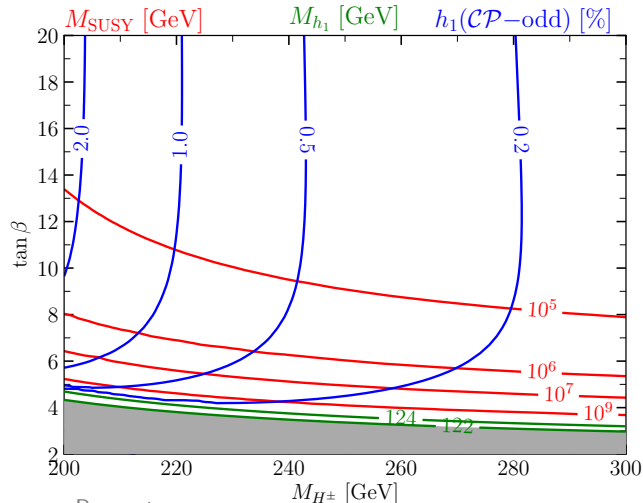
Higgs boson masses only:

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

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

CP-mixed heavy Higgs bosons

$M_{h_1}^{125}(\text{CPV})$, $\eta(b\bar{b} \to h_{2,3} \to \tau^+\tau^-)$
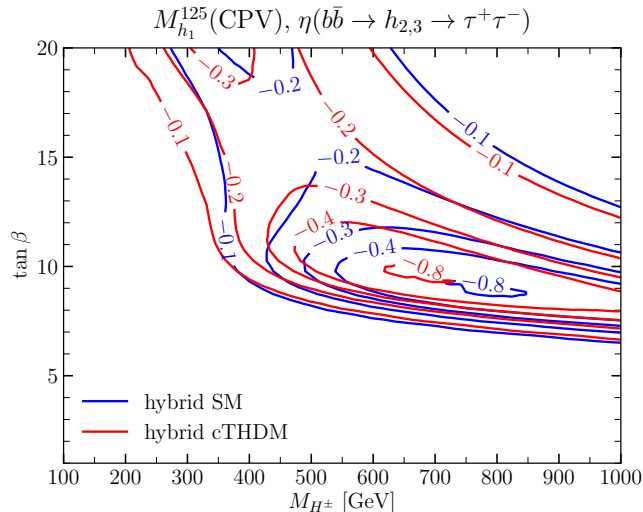
CP-mixed heavy Higgs bosons possible:

Benchmark scenario
[Bagnaschi et al 1808.07542]
$\to$ exclusion bounds change with CP-violation

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

Summary

- Higgs mass: Important constraint for the MSSM

- EFT approach: Resummation of Logs:
  - $\rightarrow$ here: complex 2HDM type III as low-energy EFT
    combined with SM EFT contributions

- Hybrid approach:
  combines advantages of EFT and fixed-order approach
  - $\rightarrow$ here: generalization of previous results to complex parameters
  - $\rightarrow$ implemented into FeynHiggs

    [Bahl, Hahn, Heinemeyer, Hollik, Paßehr, Rzehak, Weiglein]

- CP-odd admixture to SM-like Higgs boson in MSSM tiny

- CP-mixing for heavy Higgs bosons possible