Higgs
and
supersymmetric extensions of the SM

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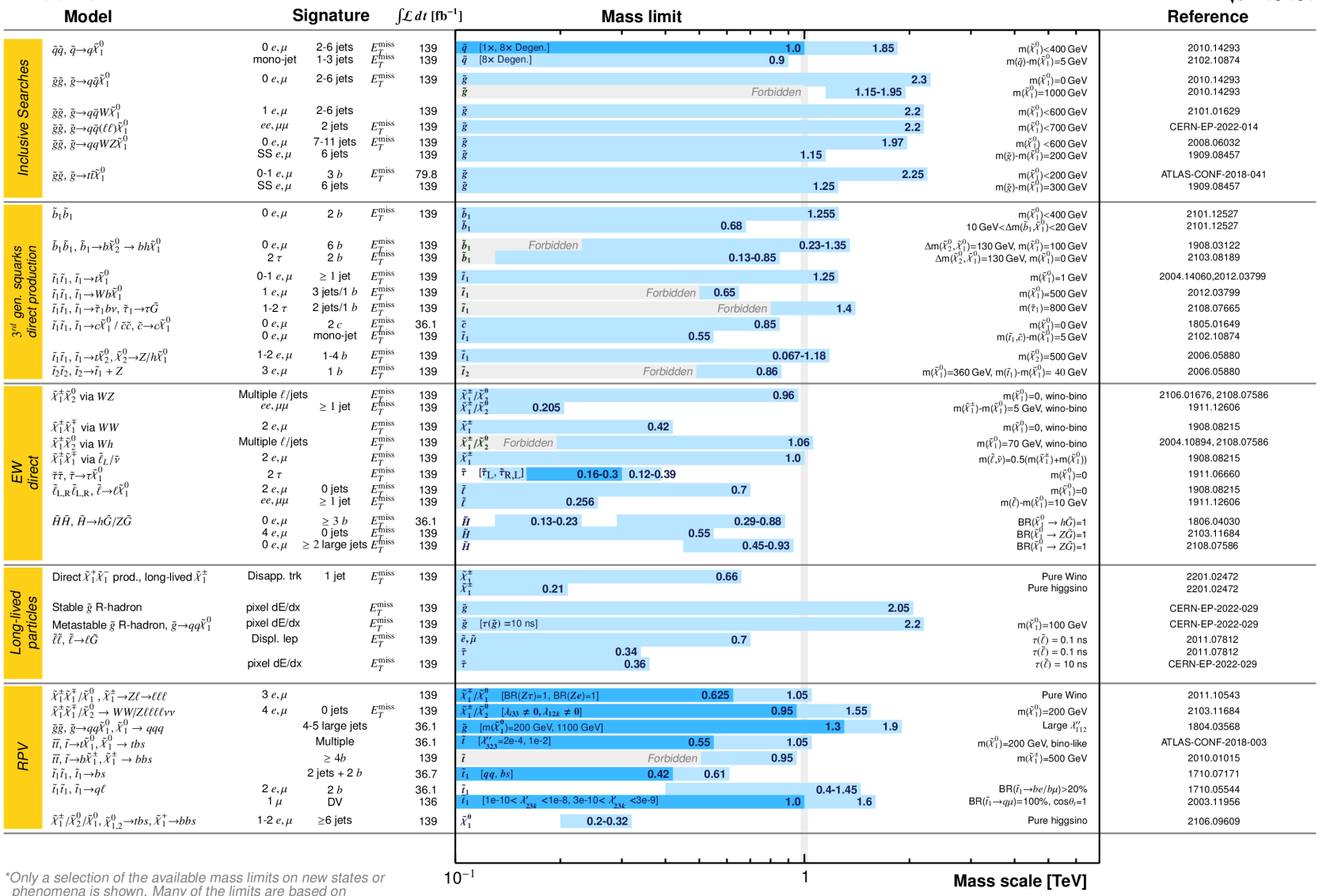
Higgs 2022, 10 November 2022

Status - Exclusion limits



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

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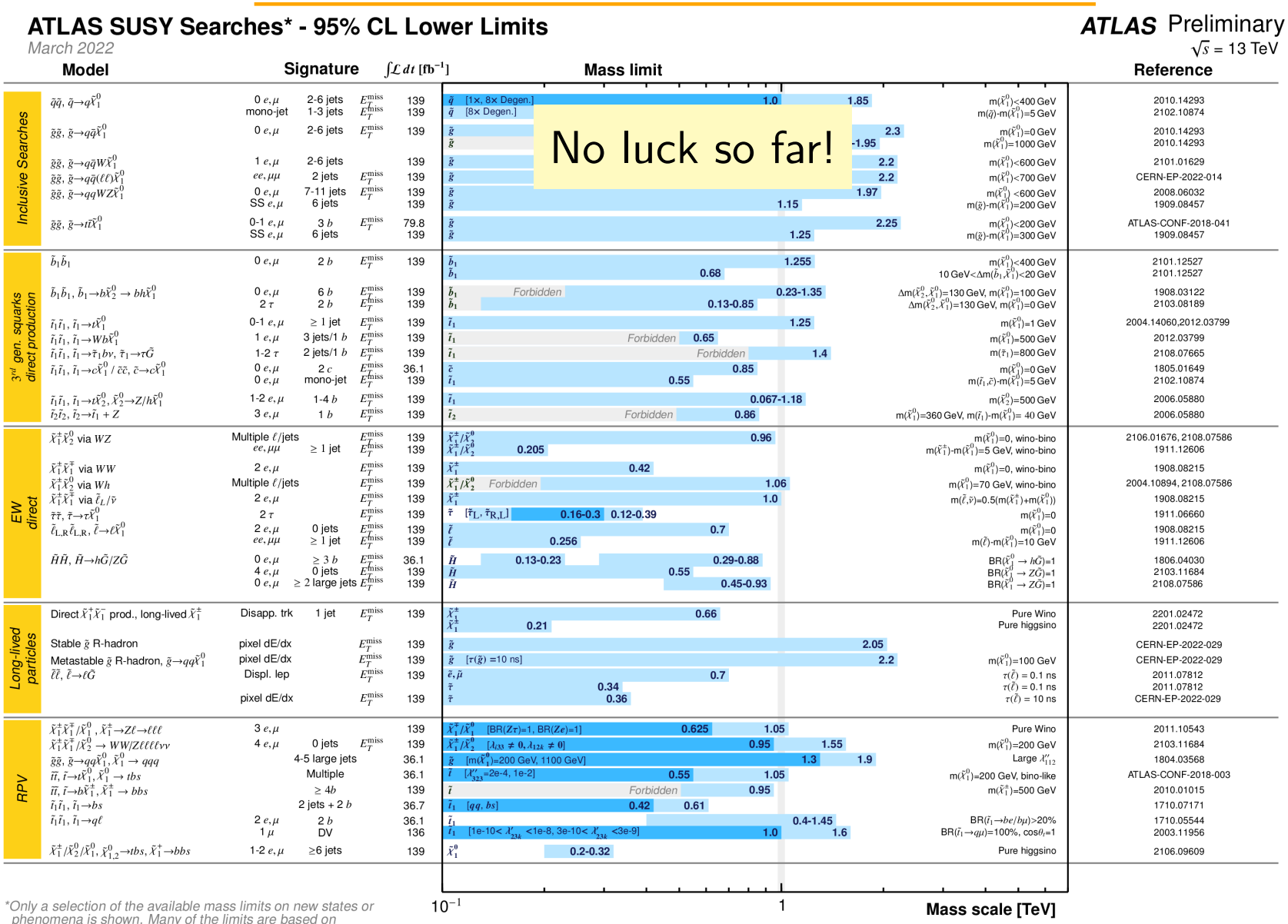

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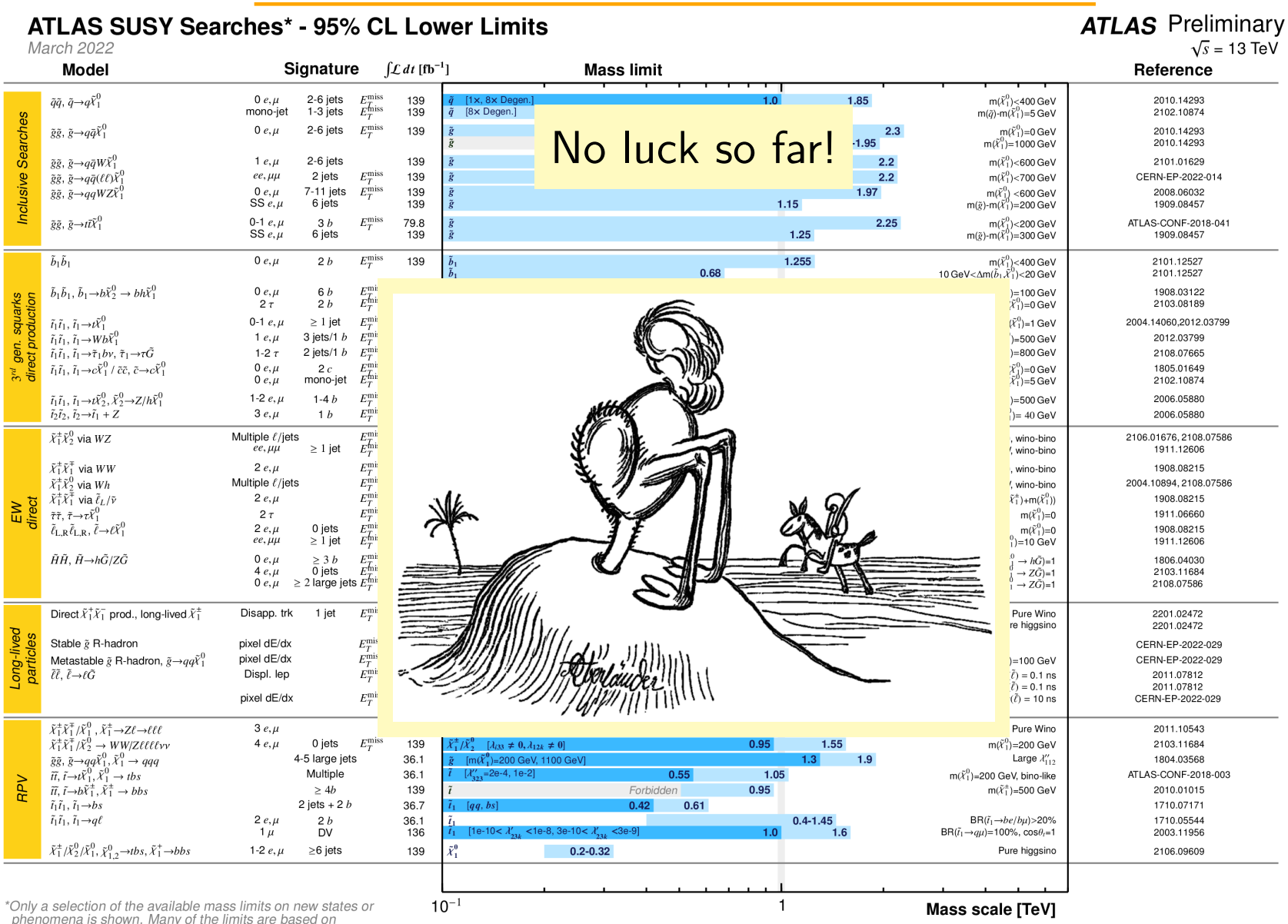

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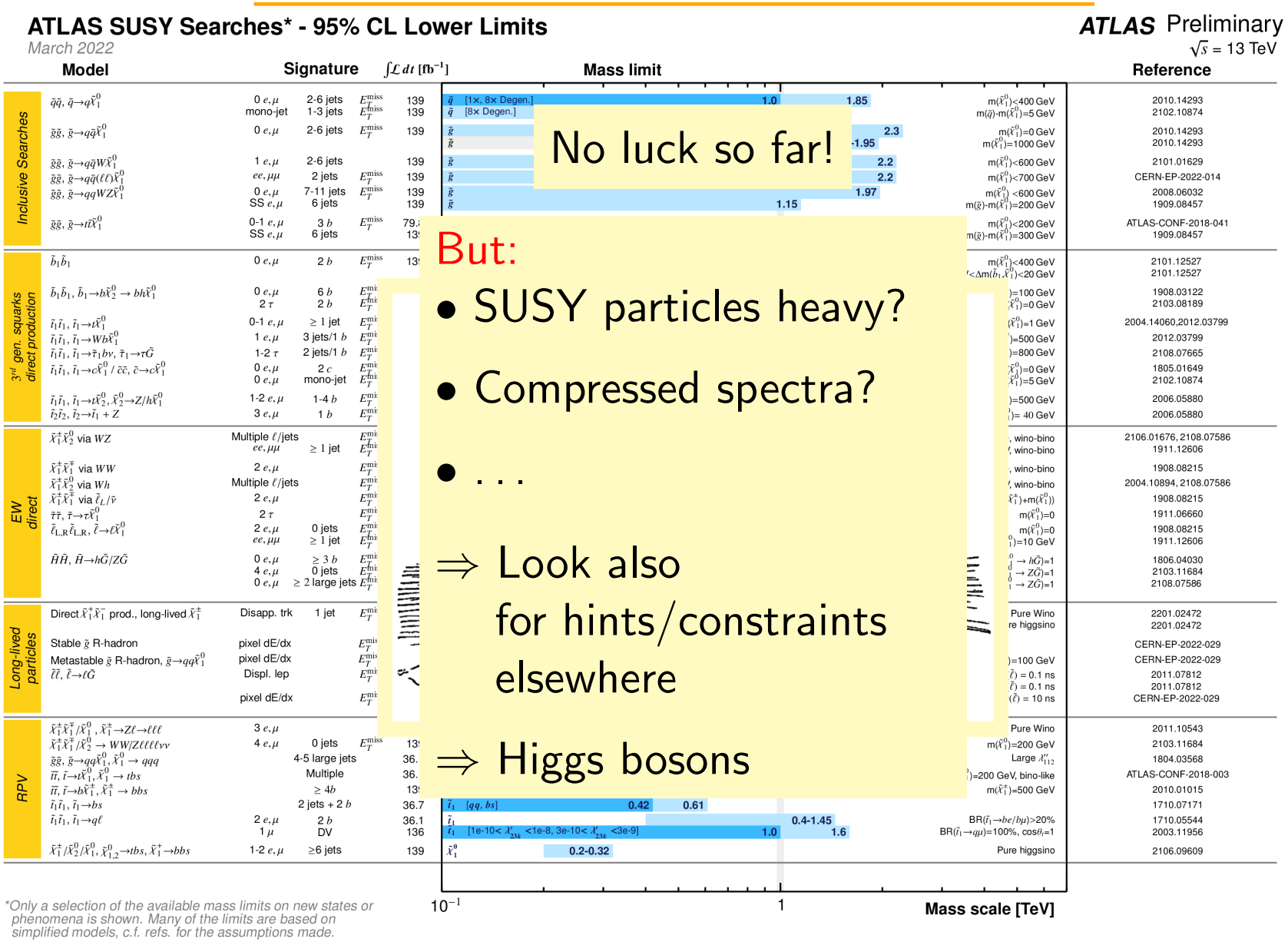


No luck so far!

But:

- SUSY particles heavy?
- Compressed spectra?
- ...

⇒ Look also for hints/constraints elsewhere

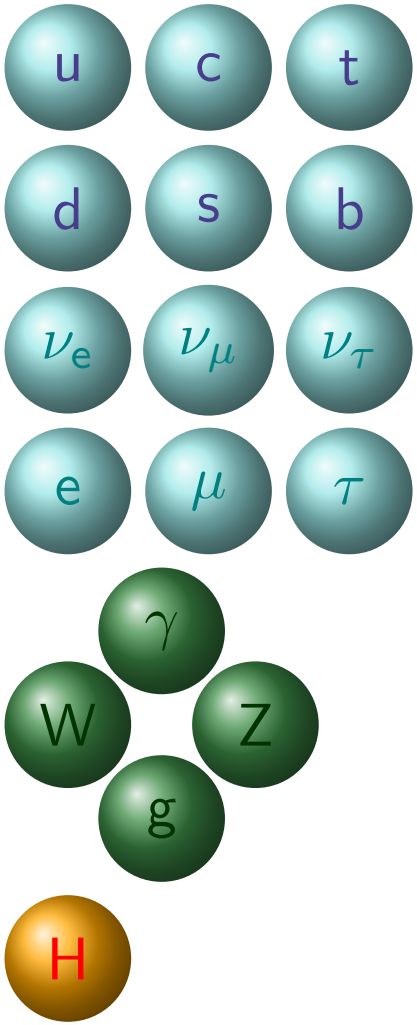
⇒ Higgs bosons

Minimal Supersymmetric Standard Model (MSSM)

Supersymmetry (SUSY):

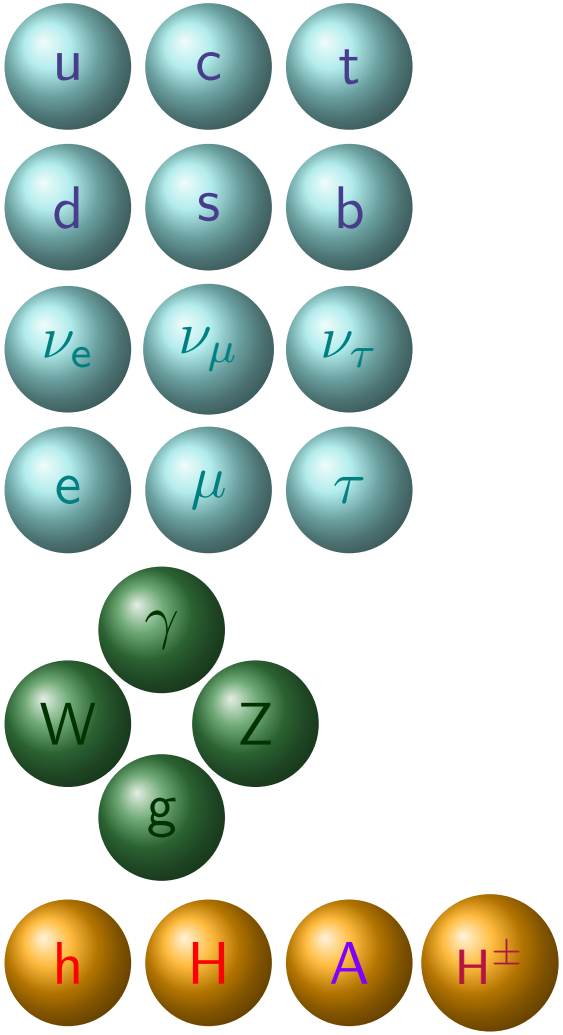
Minimal Supersymmetric Standard Model (MSSM)

Recipe: Standard Model particles



Minimal Supersymmetric Standard Model (MSSM)

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



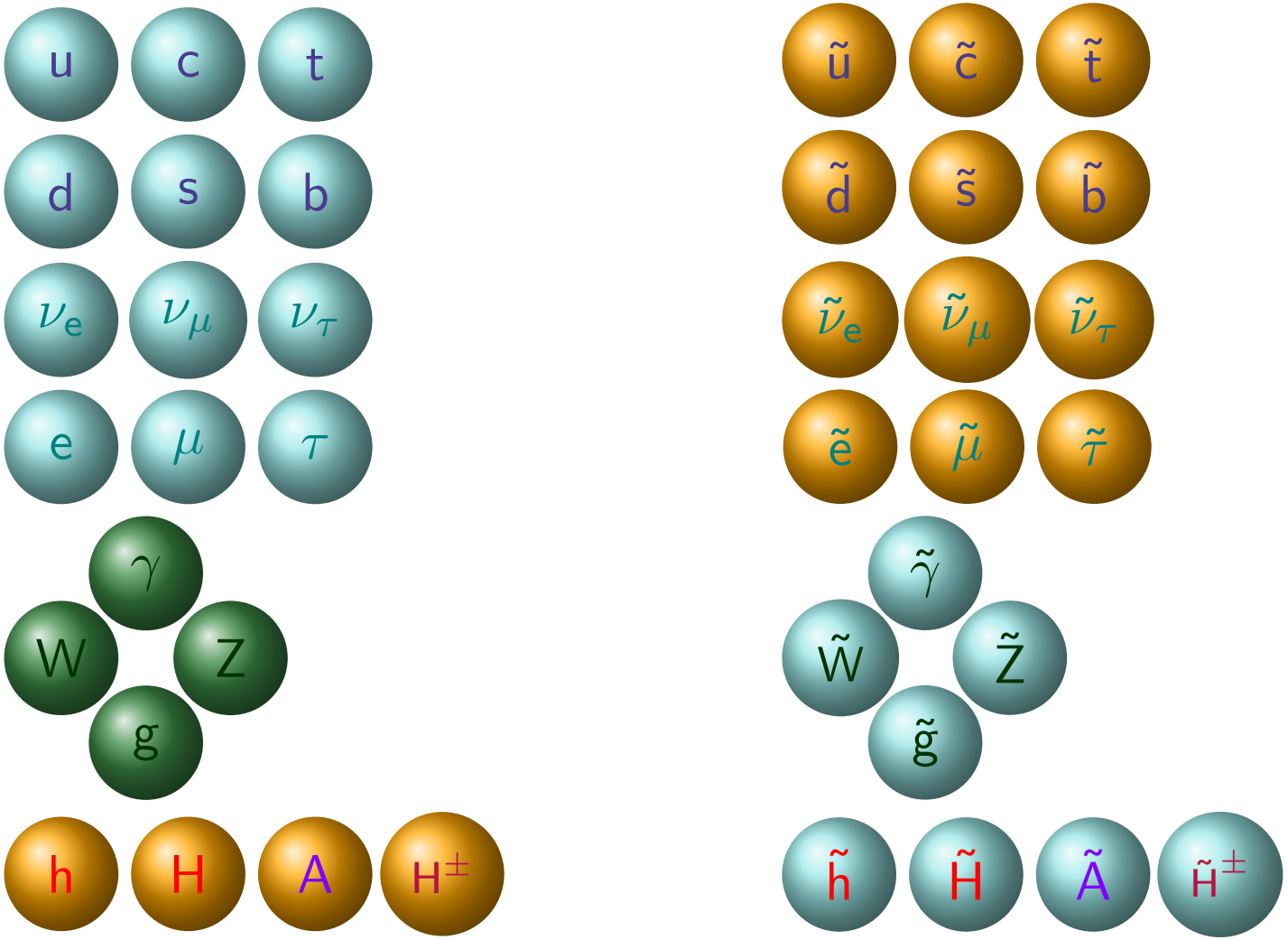
In SUSY models needed for, e.g.:

Generation of
up- and down-type fermion masses

$\Rightarrow$ Extended Higgs sector
even in minimal version

Minimal Supersymmetric Standard Model (MSSM)

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



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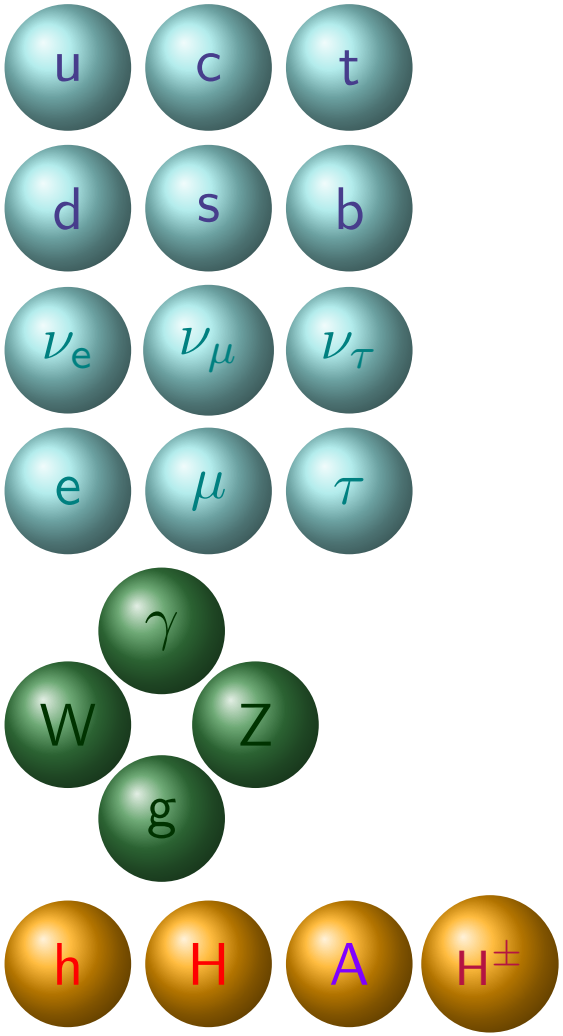

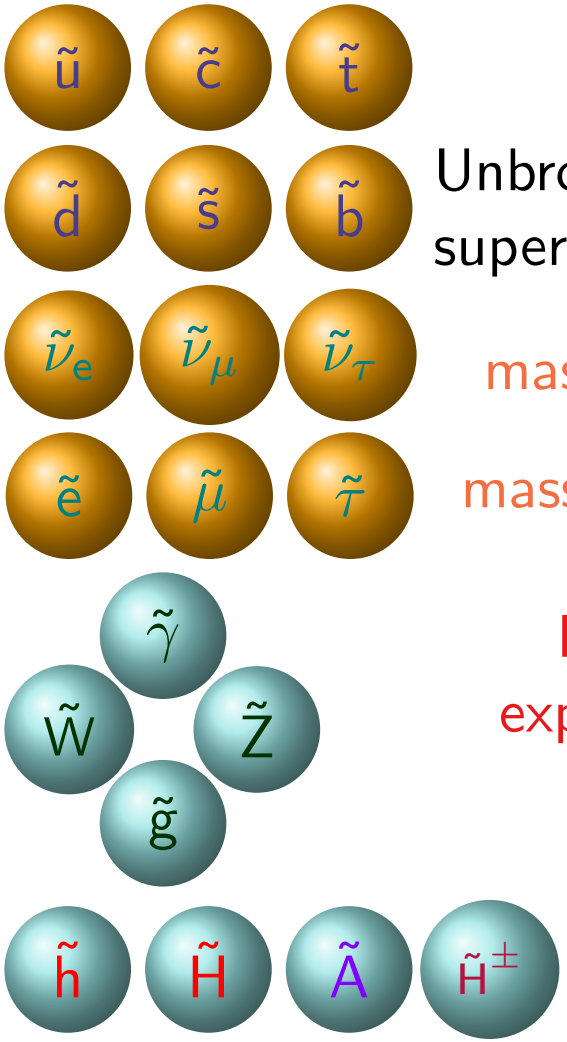

Unbroken supersymmetry:

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

$\uparrow$

Relation: exp. excluded

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Recipe: Standard Model particles (2HDM) + Superpartners
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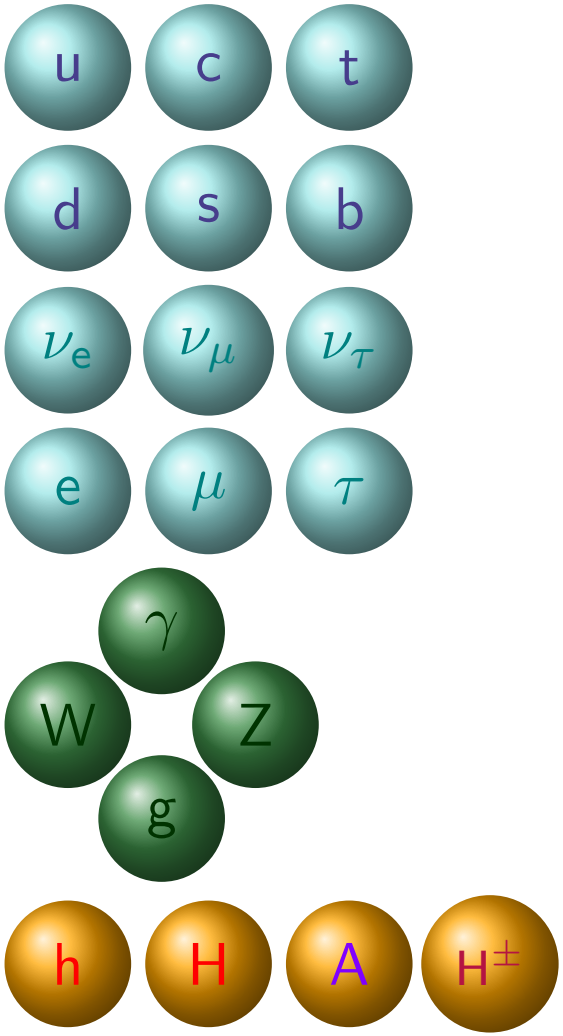

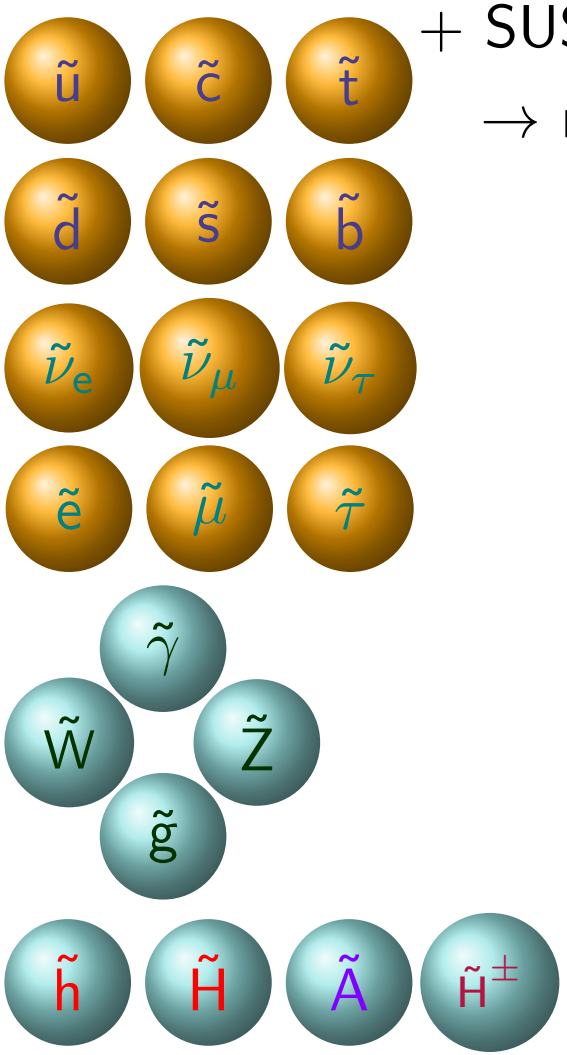

+ SUSY-breaking
$\rightarrow$ many new parameters

Minimal Supersymmetric Standard Model (MSSM)

Recipe: Standard Model particles (2HDM) + Superpartners
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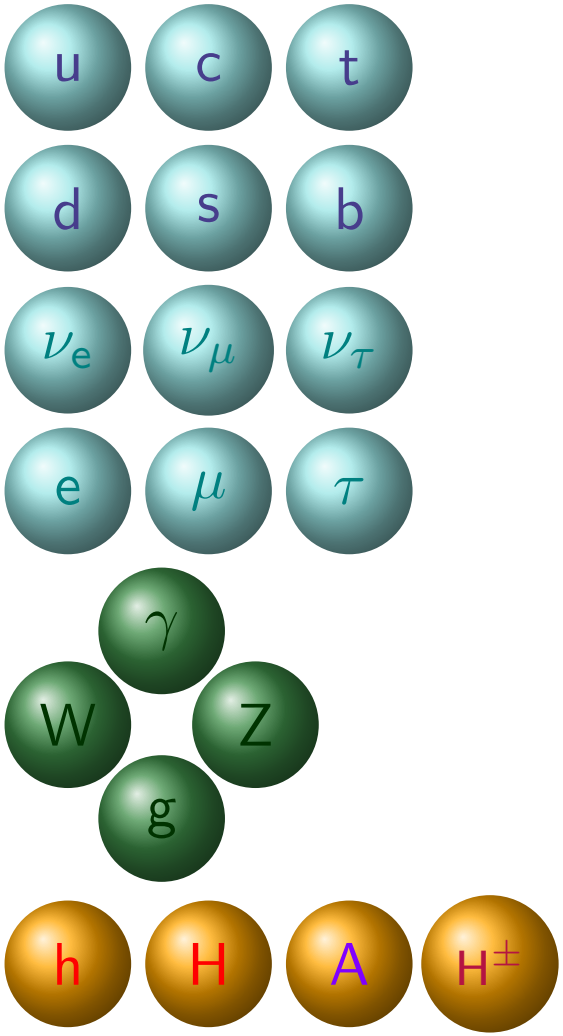

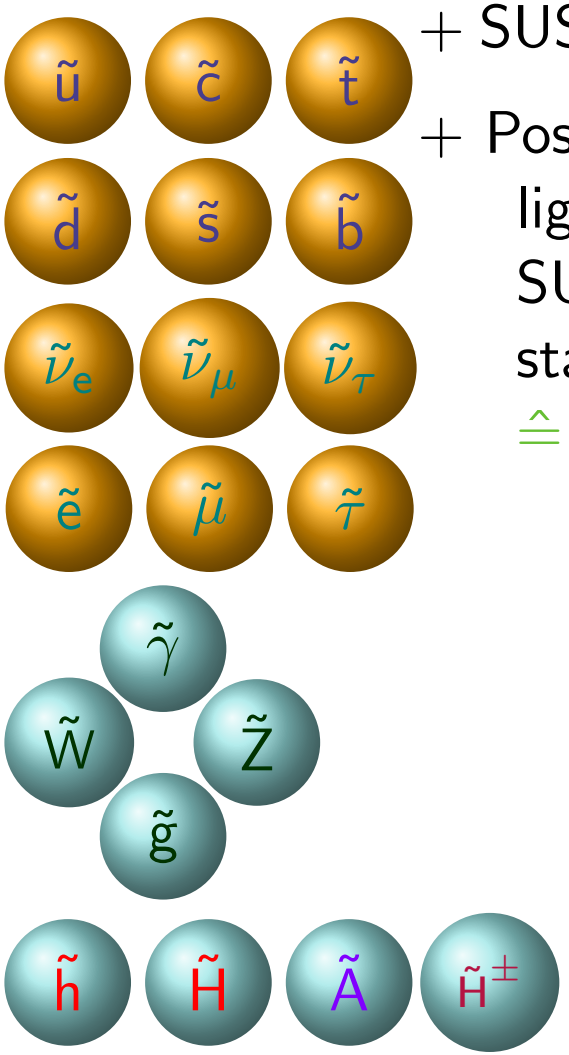

+ SUSY-breaking

+ Possible:
lightest SUSY particle stable
$\hat{=}$ dark matter candidate

Higgs sectors in SUSY models

SUSY models: At least two Higgs doublets $\rightarrow$ 2HDM+!

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- Further features:

  $\star$ At tree-level: up-type Yukawa term with Higgs doublet H_u
  down-type Yukawa term with Higgs doublet H_d
  $\Rightarrow$ 2HDM type II

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  other Yukawa terms loop-induced: 2HDM type III

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  down-type Yukawa term with Higgs doublet H_d
  $\Rightarrow$ 2HDM type II

  other Yukawa terms loop-induced: 2HDM type III

  $\star$ SUSY leads to special structure of Higgs potential:

$$V_H = \frac{1}{8}(g^2+g'^2)(|H_d|^2-|H_u{}^2|)^2+\frac{1}{2}g^2|H_d{}^\dagger H_u|^2+|\mu|^2(|H_d|^2+|H_u|^2)$$
$$+m_{H_d}^2|H_d|^2+m_{H_u}^2|H_u{}^2|-m_{H_dH_u}^2(\epsilon_{ab}H_d{}^aH_u{}^b+\mathrm{h.c.})$$

  $\rightarrow$ depends on gauge couplings g, g'

Higgs mass spectrum in the MSSM

Features:

- At tree level: $M_h \leq M_Z$

M_h = **mass of the lightest CP-even Higgs boson**
M_Z = **Z boson mass**

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- At tree level: $M_{H^\pm}^2 = M_A^2 + M_W^2$

  M_A = **mass of the CP-odd Higgs boson**
  $M_{H^\pm}$ = **mass of the charged Higgs boson**
  M_W = **W boson mass**
  M_H = **mass of the heavy CP-even Higgs boson**
  $\tan\beta = v_u/v_d$ = **ratio of Higgs vac. exp. values**

$$M_{H,h}^2 = \frac{1}{2}\left(M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 2M_Z^2 M_A^2 \cos^2 2\beta}\right)$$

$\rightarrow$ if $M_A \gg M_Z \Rightarrow M_H \sim M_A \sim M_{H^\pm}$

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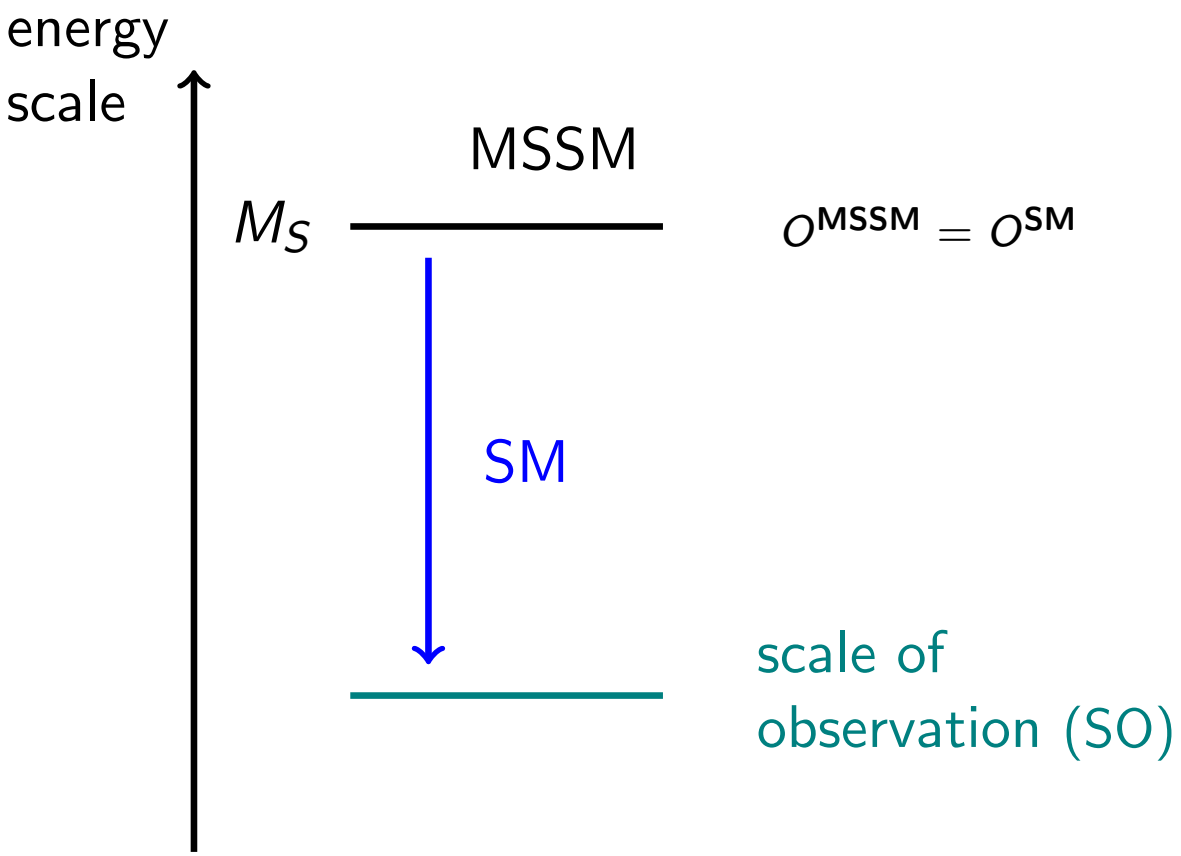
- At tree level:

  Higgs mass spectrum only depends on M_A or $M_{H^\pm}$ and $\tan\beta$

  $\rightarrow$ Difference to pure 2HDM where masses are free parameters

Heavy SUSY particles and heavy Higgs bosons

Effective Field Theories (EFT) approach:



$O^{\text{MSSM}} = O^{\text{SM}}$

Matching of the theories

Evolution to low scale with Renormalization Group Equations (RGE)

Calculation of low-energy observables, e.g. Higgs mass

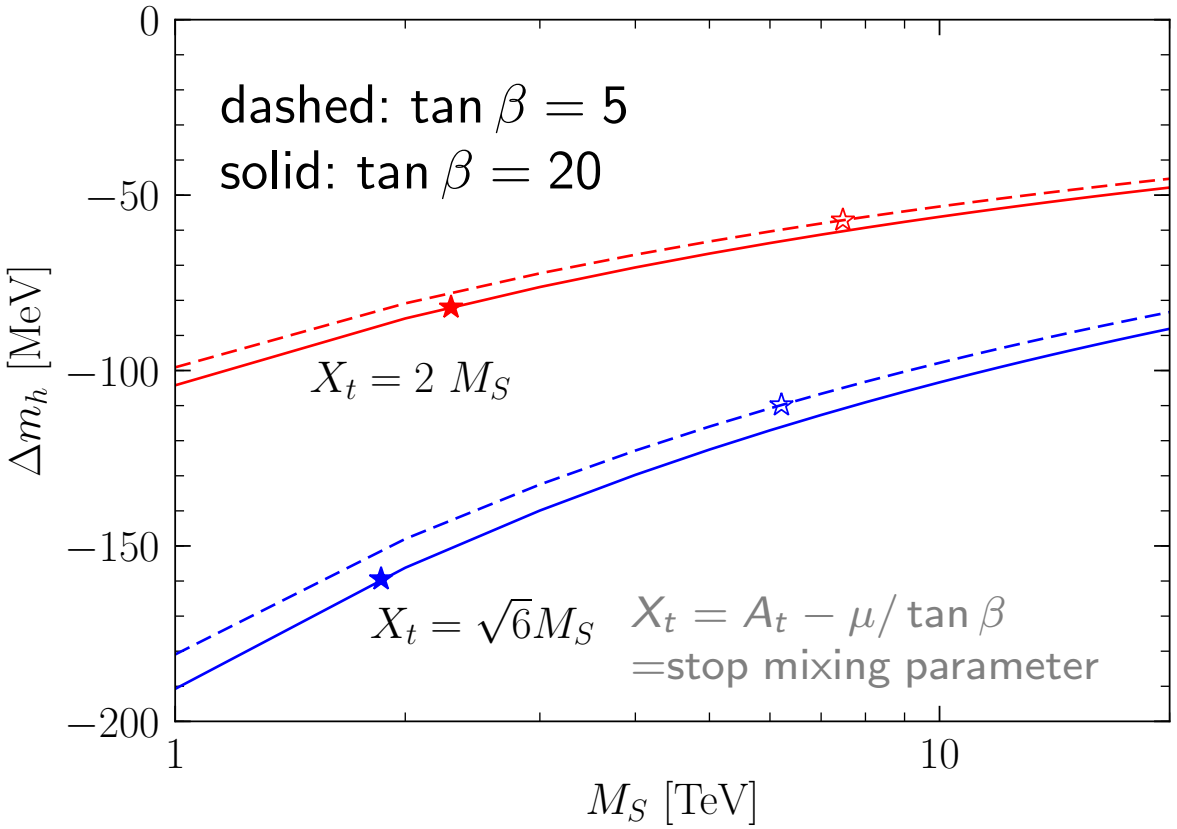
resummation of logs of form $\text{Log}\left(\frac{M_S}{M^{SO}}\right)$

Mass of the lightest Higgs boson M_h

[Bagnaschi, Degrassi, Paßehr, Slavich, 1908.01670]

Mass difference: $\Delta m_h = M_h(O^{\text{with } \mathcal{O}(\alpha_s g_x^4)}) - M_h(O^{\text{without } \mathcal{O}(\alpha_s g_x^4)})$

$\mathbf{g}_x^4 = g^2 y_{\{t,b\}}^2, g^2 g'^2, g^4, g'^4$, $\mathbf{y}_{\{t,b\}}$ = top, bottom Yukawa coupl.



$\star \mathrel{\hat{=}} M_h = 125.09$ GeV

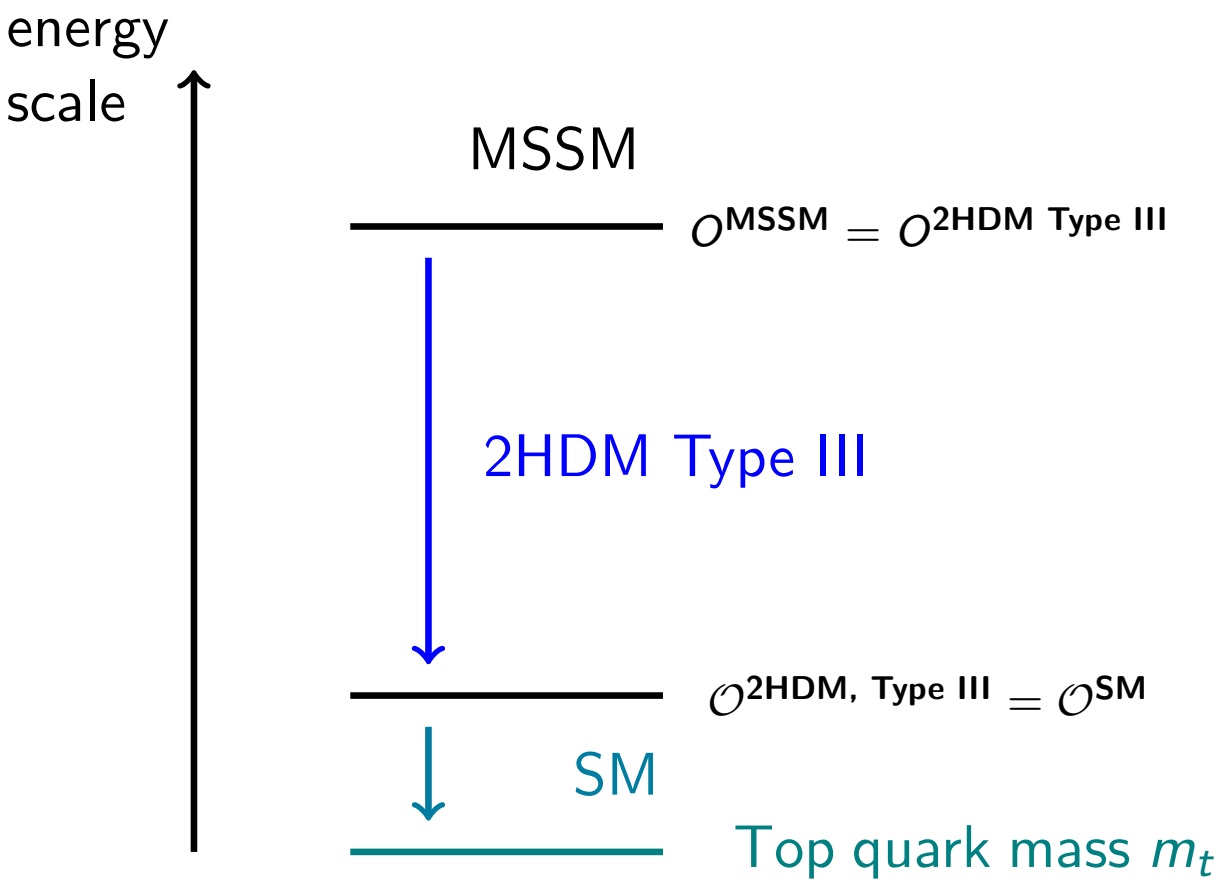
$\Rightarrow$ constraint on M_S

Additional gauge contributions in the matching

$\rightarrow \Delta m_h \sim \mathcal{O}(100 \text{ MeV})$

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

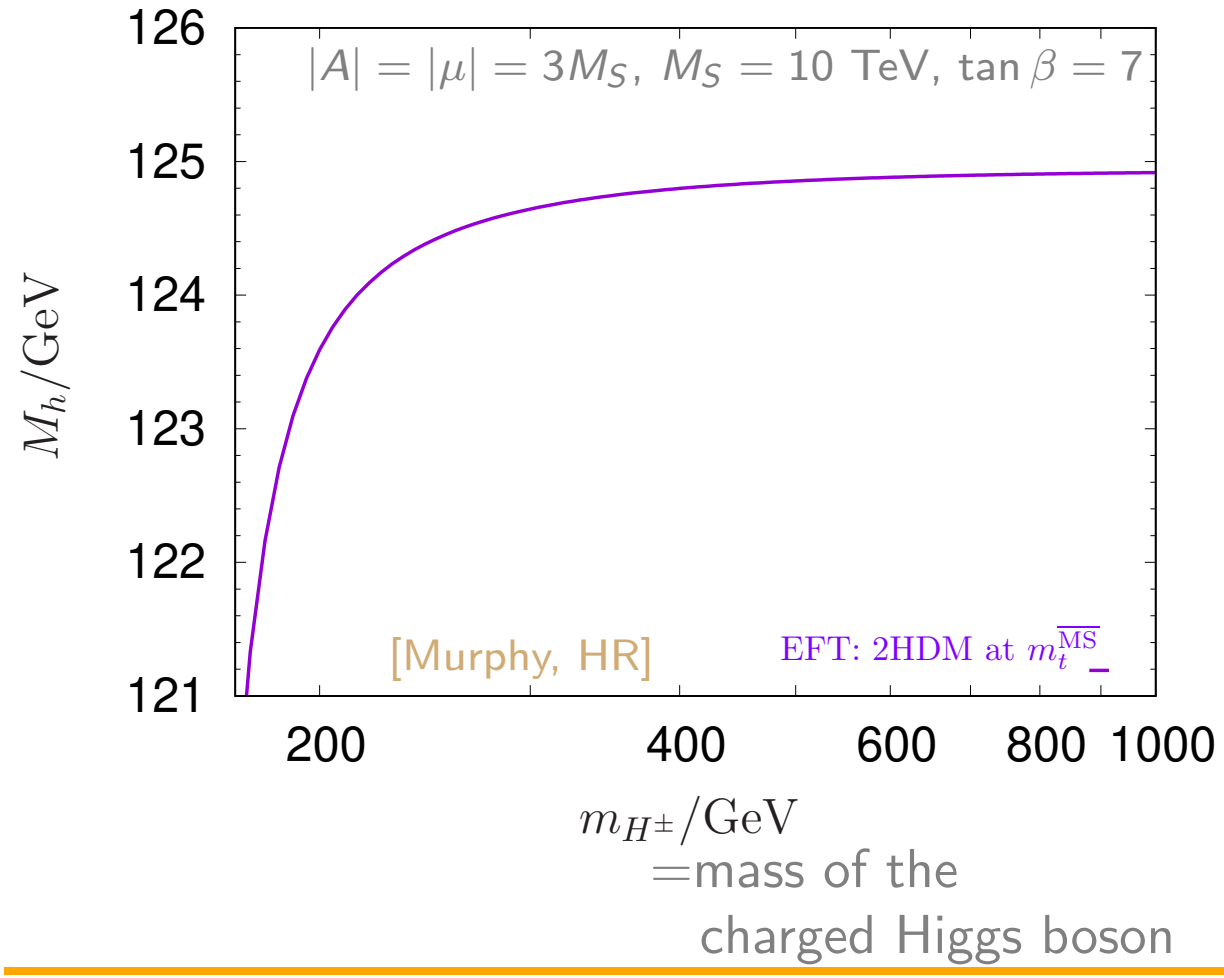
Calculation of Higgs mass spectrum and mixing

Mass of the lightest Higgs boson M_h

[Murphy, HR, 1909.00726]

Treatment of low scale:

- Lowest EFT: 2HDM

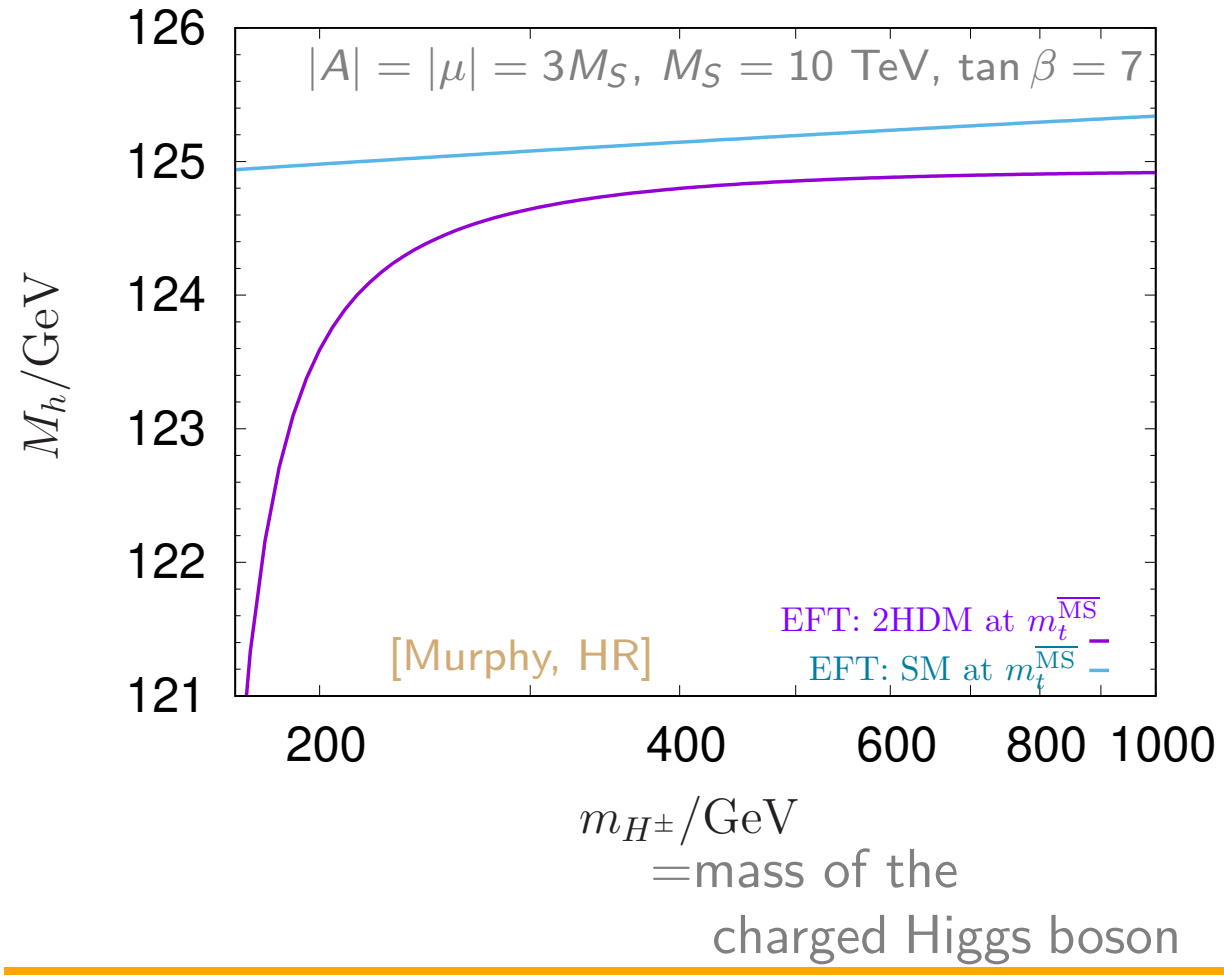


Mass of the lightest Higgs boson M_h

[Murphy, HR, 1909.00726]

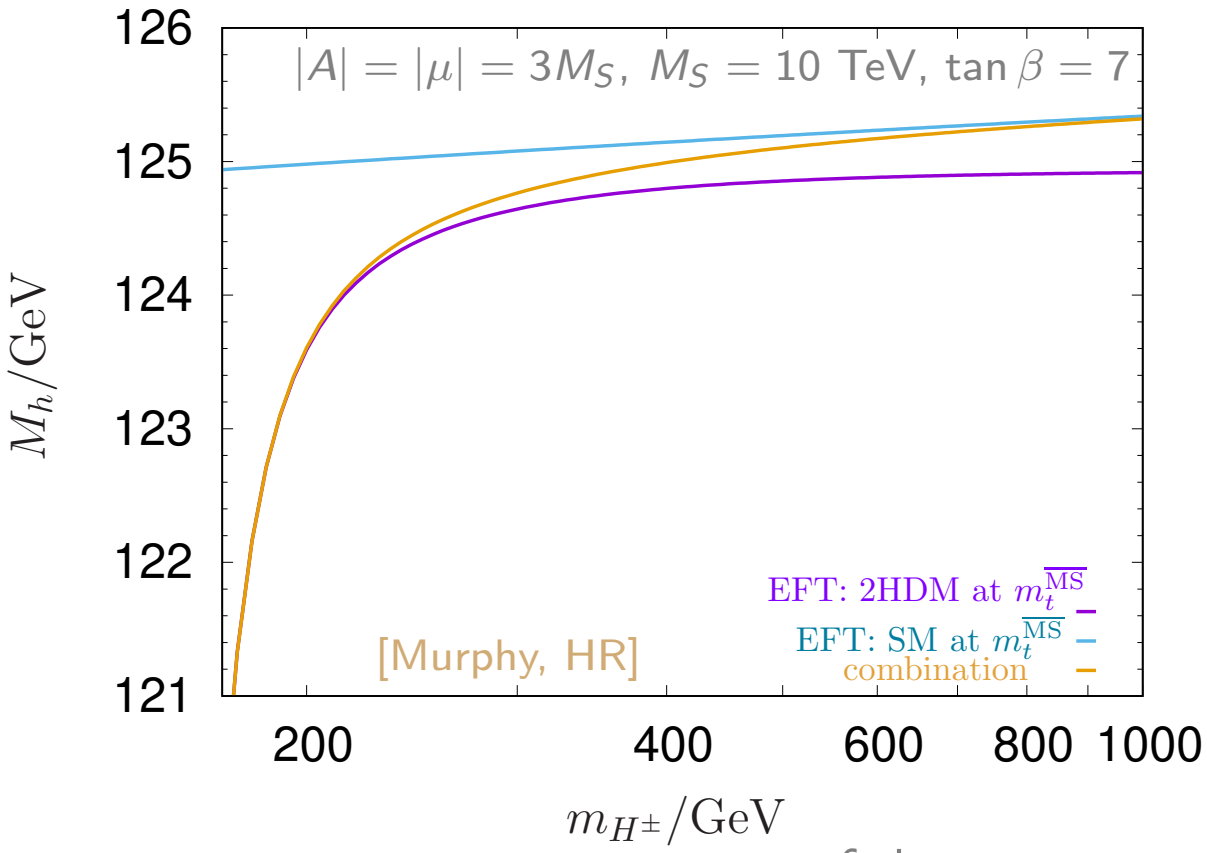
Treatment of low scale:

- Lowest EFT: 2HDM
- Lowest EFT: SM



Mass of the lightest Higgs boson M_h

[Murphy, HR, 1909.00726]

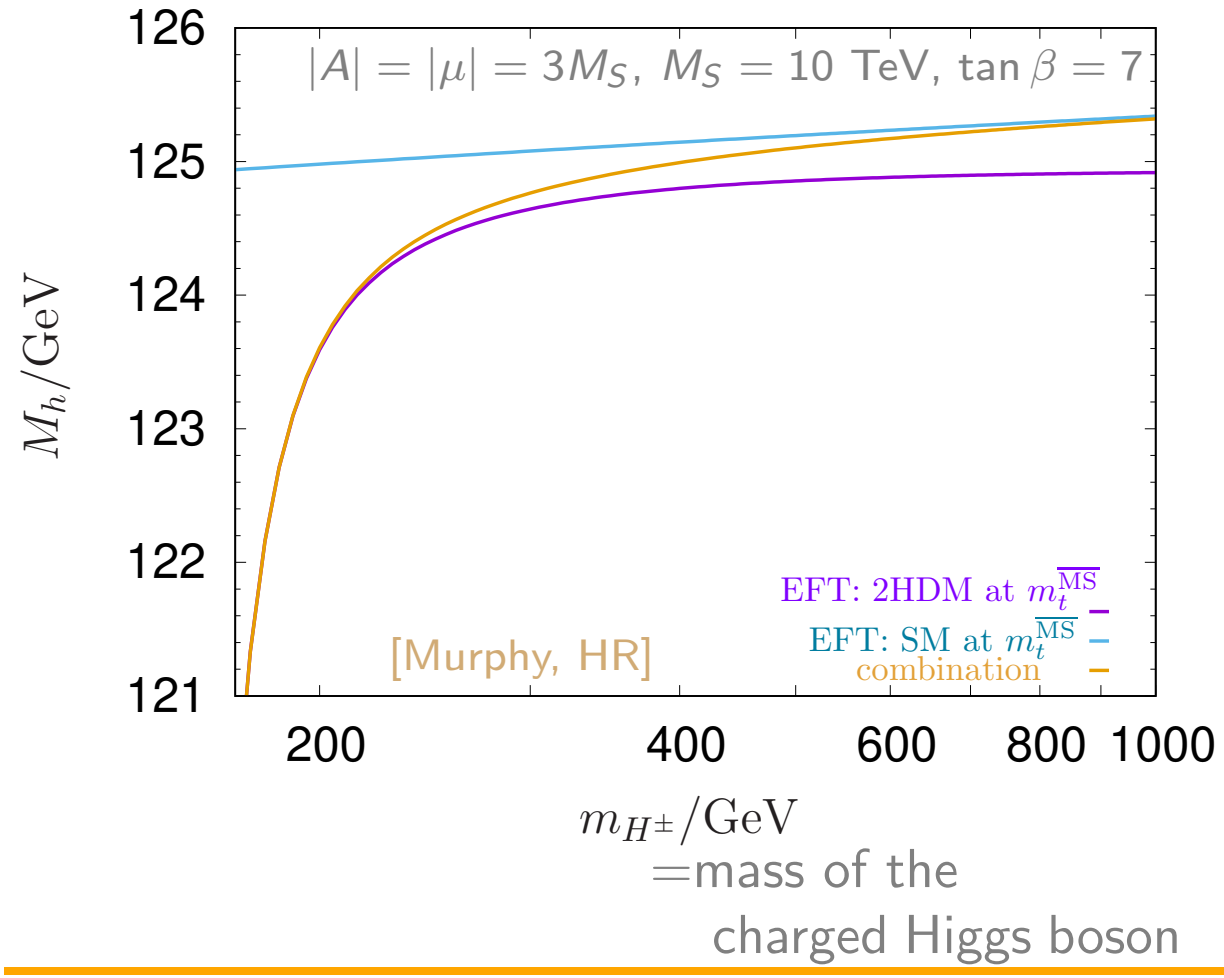


=mass of the charged Higgs boson

Treatment of low scale:

- Lowest EFT: 2HDM
- Lowest EFT: SM
- Combination

Mass of the lightest Higgs boson M_h



[Murphy, HR, 1909.00726]

Treatment of low scale:

- Lowest EFT: 2HDM
- Lowest EFT: SM
- Combination

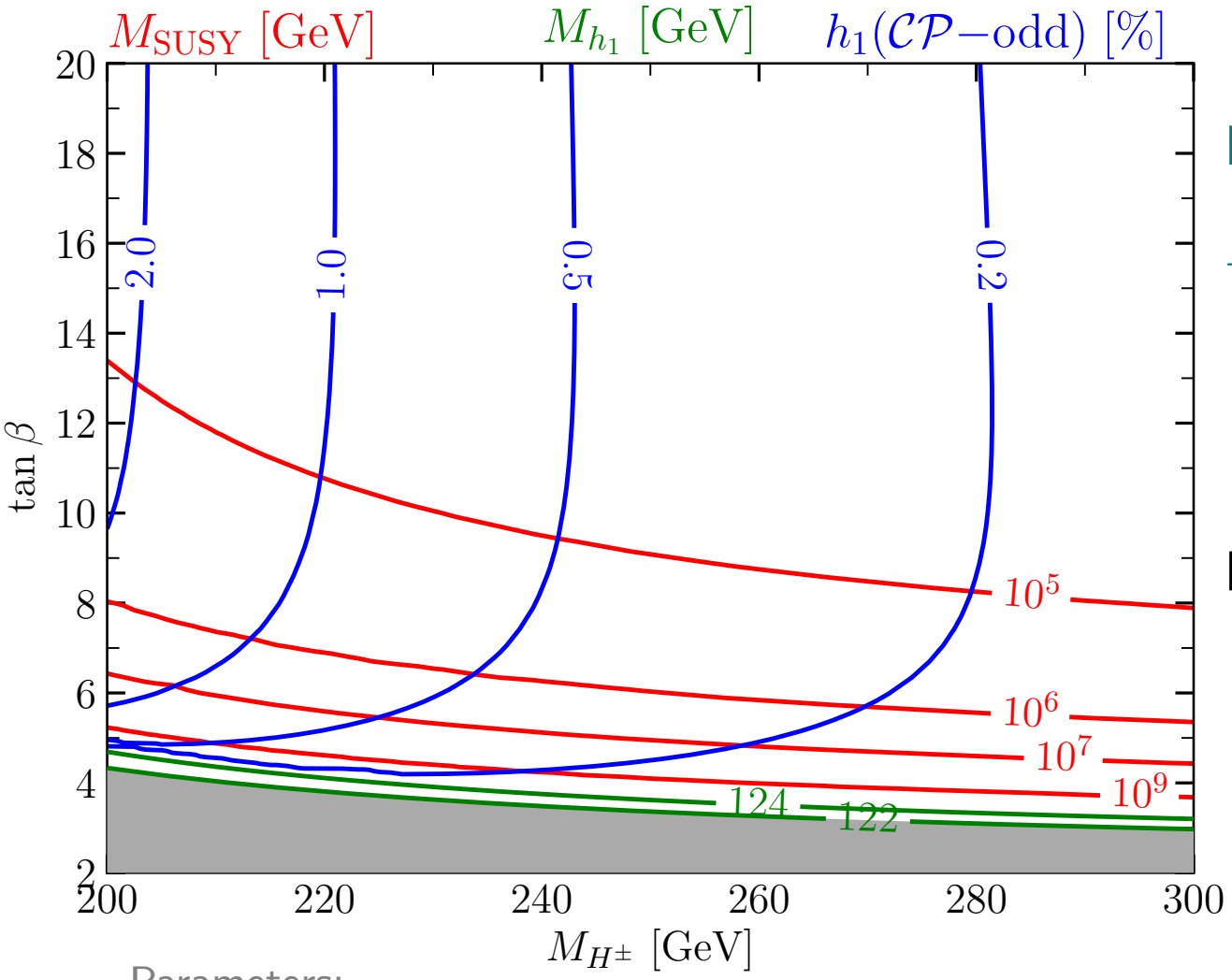
⋆ Large M_{H^+}:
SM
= appropriate lowest EFT

⋆ Small M_{H^+}:
2HDM
= appropriate lowest EFT

⋆ Good interpolation with combination

CP-odd admixture

[Bahl, Murphy, HR 2010.04711]



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

Higgs boson masses only:

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

Here: hybrid approach = fixed order + EFT

$\rightarrow$ implemented in `FeynHiggs`

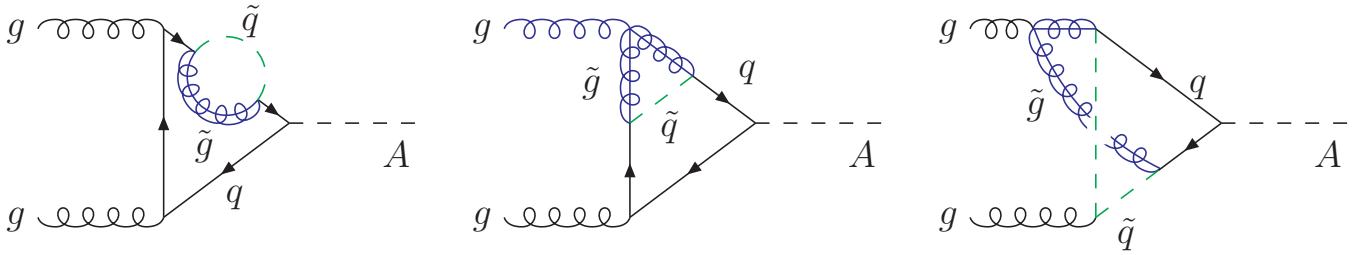
[Bahl, Hahn, Heinemeyer, Hollik, Paßehr, HR, Weiglein]

Relatively light SUSY particles

[Bagnaschi, Fritz, Liebler, Mühlleitner, Nguyen, Spira, 2207.02807]

Two-loop contribution to pseudoscalar production:

Example diagrams:



SUSY particles active:

squarks $\tilde{q}$: here: stops, sbottoms

gluinos $\tilde{g}$

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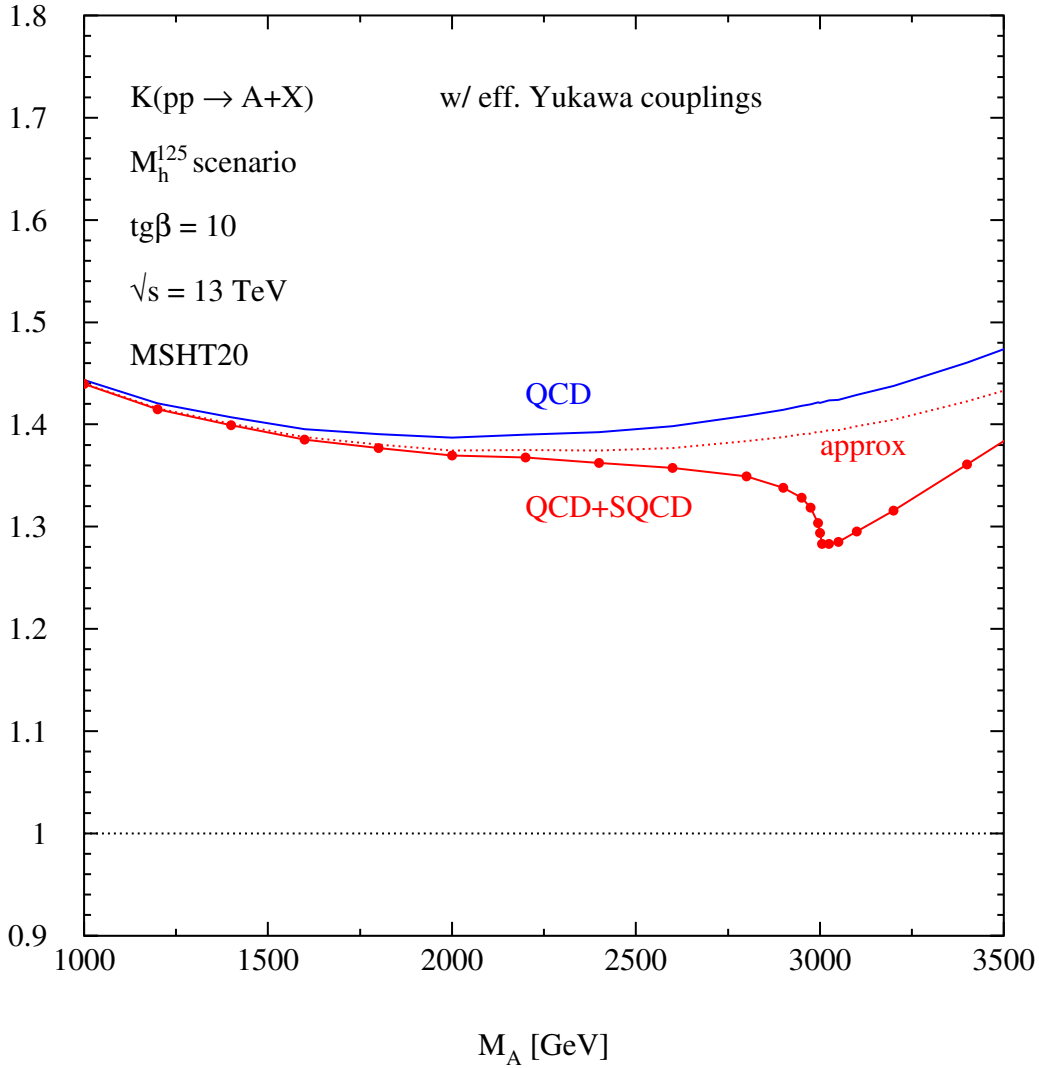
[Bagnaschi, Fritz, Liebler, Mühlleitner, Nguyen, Spira, 2207.02807]

K-factor for pseudoscalar production:



In stop/sbottom threshold regions:

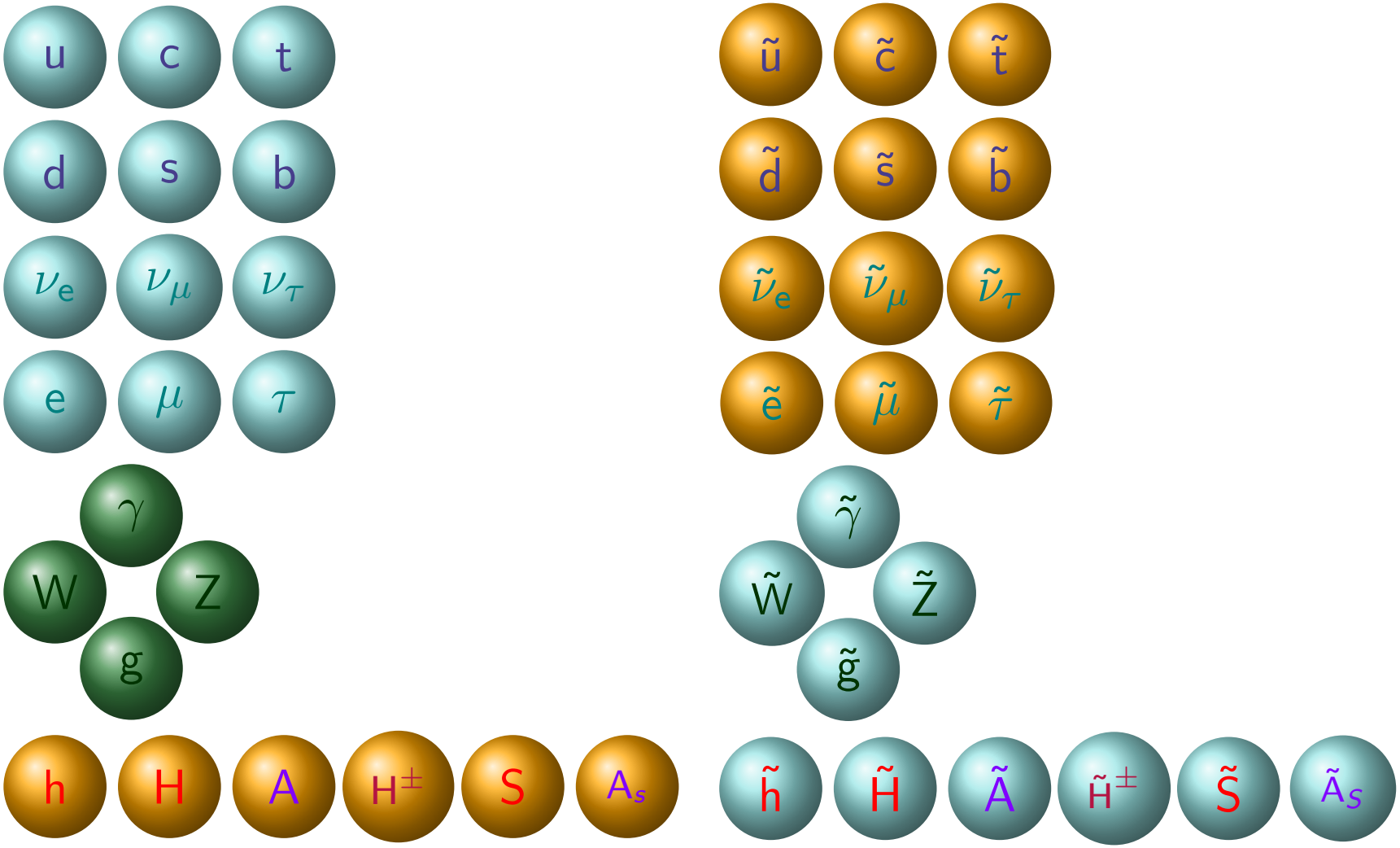
Full SUSY-QCD contribution important

Otherwise: Approximation of heavy SUSY particles: Good

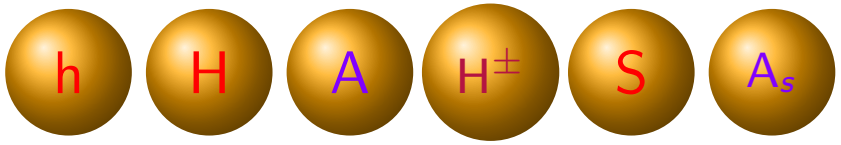
[Degrassi, Di Vita, Slavich, 1107.0914]

Next-to Minimal Supersymmetric Standard Model (NMSSM)

NMSSM = MSSM + Higgs singlet and superpartners



Features of the NMSSM

- 7 Higgs bosons 

- 5 neutralinos (4 neutralinos in the MSSM)

- Dimensionful parameter μ in the Higgs potential is generated via a vacuum expectation value explaining its size.
  (**MSSM:** $|\mu|^2(|H_d|^2 + |H_u|^2) \rightarrow$ **NMSSM:** $|\lambda\langle S\rangle|^2(|H_d|^2 + |H_u|^2)$)

- Mass of the light CP-even MSSM-like Higgs boson can be larger than in the MSSM

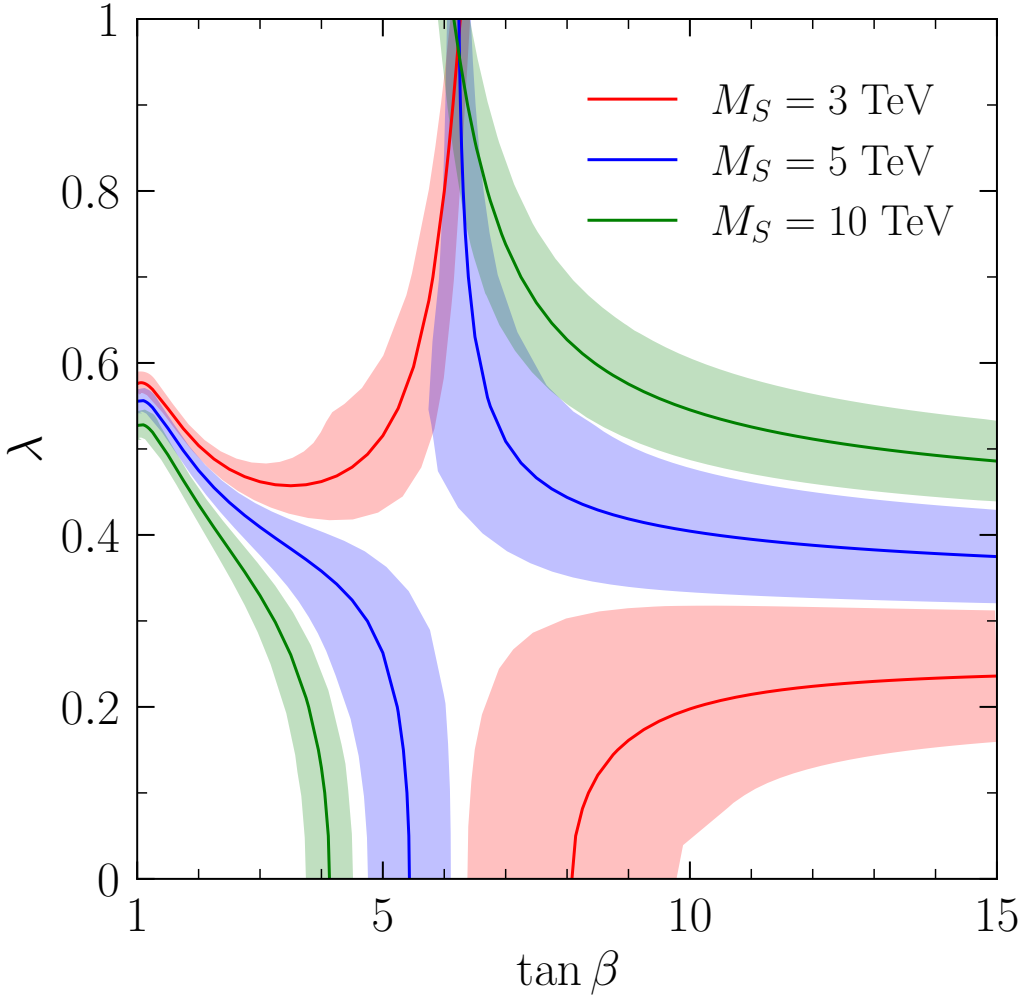
- Viable scenarios with Higgs bosons lighter than the discovered one

- CP-violation in the Higgs sector possible already at Born level

Heavy SUSY particles and heavy Higgs bosons: M_h

[Bagnaschi, Goodsell, Slavich, 2206.04618]

Mass of SM-like Higgs boson in the NMSSM with heavy non-SM particles



Regions with

$M_h = 125.25$ GeV

$\kappa = 2\lambda$

$\kappa =$ **Higgs singlet Yukawa coupling**

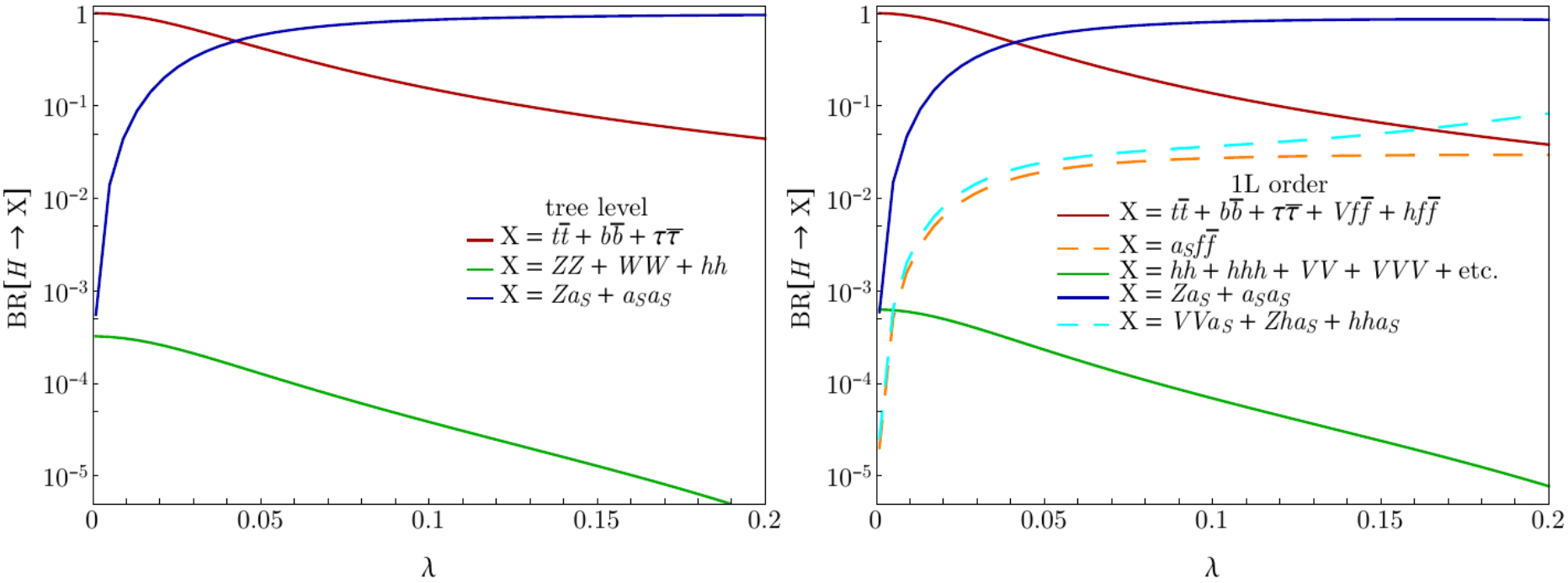
$\lambda =$ **Higgs singlet doublet Yukawa coupling**

Relatively heavy SUSY particles

[Domingo, Paßehr, 2207.05776]

Heavy CP-even Higgs boson in the NMSSM: Branching ratios

(no decays into SUSY particles possible)



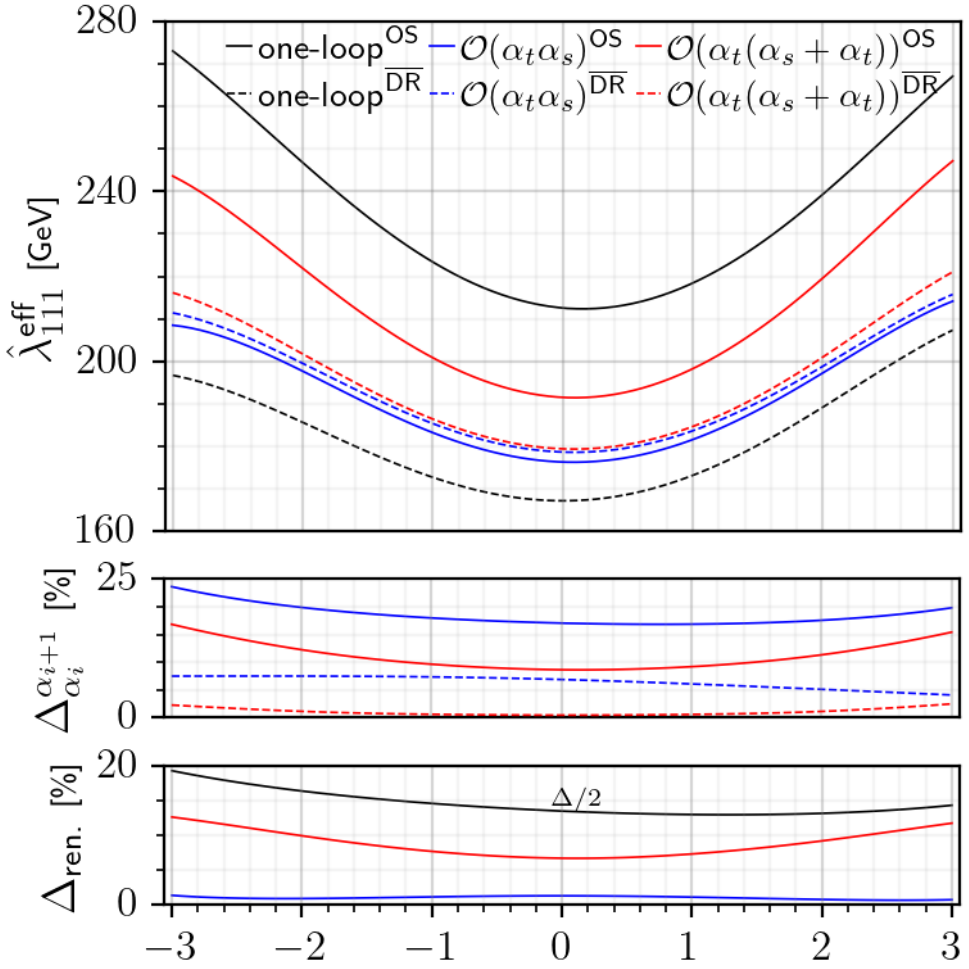
$\rightarrow$ Need to take 3-body decays into account

$\rightarrow$ compensation of IR-type corrections

Relatively light SUSY particles

[Borschensky, Dao, Gabelmann, Mühlleitner, HR, 2210.02104]

Effective trilinear Higgs coupling $\hat{\lambda}^{\text{eff}}_{111}$:



BP10 scenario $A_t^{\overline{\text{DR}}}$ [TeV] **= trilinear soft-breaking parameter**

h_1: SM-like

largest h_u component

$\rightarrow$ large coupling to top quarks

In the SM: $\lambda^{\text{SM}}_{hhh} \approx 190$ GeV

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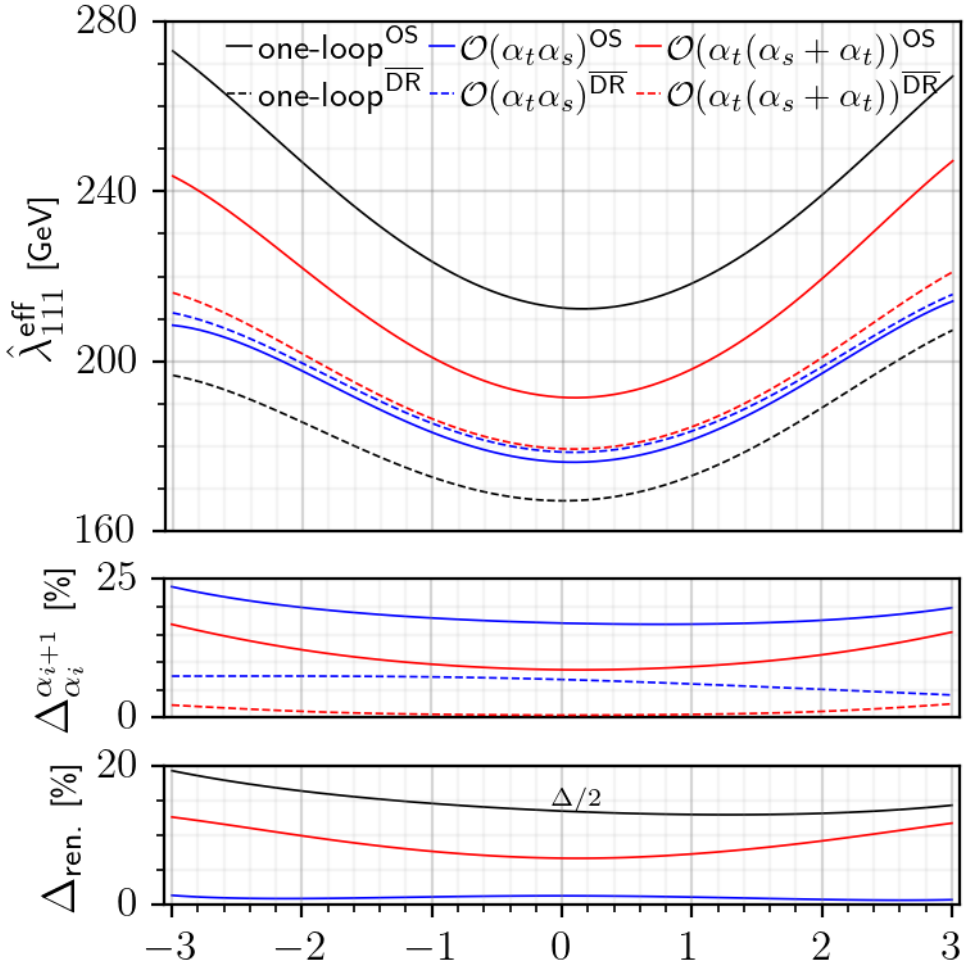

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Size of correction depends on renormalization scheme

$\rightarrow$ contribution to theory uncertainty

Beyond (N)MSSM (Examples)

- Dirac Gaugino models:
  $\rightarrow$ new scalars can mix with Higgs fields
  see e.g [Benakli, Goodsell, Maier 1104.2695; Benakli, Goodsell, Staub 1211.9552]
- $\mu\nu$SSM:
  Additional "right-handed" sneutrinos mix with Higgs fields
  see e.g. [Lopez-Fogliani, Muñoz hep-ph/0508297; Muñoz 0909.5140]
- NMSSM with Inverse Seesaw Mechanism:
  No mixing with new scalar fields,
  but new chiral fields $\rightarrow$ contribute at loop level
  see e.g. [Gogoladze, Okada, Shafi 0809.0703]

Tools for arbitrary SUSY models:

- Sarah [Staub 0806.0538]/SPheno [Porod hep-ph/0301101; Porod, Staub 1104.1573]
- Sarah/FlexibleSUSY [Athron, Park, Stöckinger, Voigt 1406.2319, Athron, Bach, Harries, Kwasnitza, Park, Stöckinger, Voigt, Ziebell 1710.03760; Athron, Büchner, Harries, Kotlarski, Stöckinger, Voigt 2106.05038]

Summary

- Supersymmetry restricts
  - ⋆ properties
  - ⋆ relations

  in the Higgs sector

- Measurements of properties of the discovered Higgs boson

  Searches for further Higgs bosons

  $\Rightarrow$ Constraints of SUSY models

  $\Rightarrow$ Hints for viable SUSY scenarios

- Higgs observables in SUSY models:

  Higher-order corrections important

  $\rightarrow$ Development of results continuing

M_h^{125} scenario

[Bagnaschi, Bahl, Fuchs, Hahn, Heinemeyer, Liebler, Patel, Slavich, Stefaniak, Wagner, Weiglein, 1808.07542]

$M_{Q_3} = M_{U_3} = M_{D_3} = 1.5$ TeV, $M_{L_3} = M_{E_3} = 2$ TeV,

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

$X_t = 2.8$ TeV, $A_b = A_\tau = X_t + \mu/\tan\beta$

For $\tan\beta = 10$:

Stop masses: $m_{\tilde{t}_1} = 1340$ GeV, $m_{\tilde{t}_2} = 1662$ GeV

Sbottom masses: $m_{\tilde{b}_1} = 1496$ GeV, $m_{\tilde{b}_2} = 1508$ GeV

Parameters for scenario: H decay in the NMSSM

$\lambda = \kappa$, $\tan\beta = 10$, $\mu = 10$ TeV, $M_{H^\pm} = 3$ TeV,

$A_\kappa = -3$ GeV $\rightarrow M_{a_s} \approx 300$ GeV,

$M_S = 10$ TeV, $|M_3| = 10.9$ GeV, $A_t = -2.5$ TeV,

$A_b = A_\tau = 1$ TeV

BP10 scenario

[Abouabid, Arhrib, Azevdo, Falaki, Ferreira, Mühlleitner, Santos, 2112.12515]

$$
\begin{aligned}
|\lambda| &= 0.65\,,\ |\kappa| = 0.65\,,\ \mathrm{Re}(A_\kappa) = -432\ \mathrm{GeV}\,,\ |\mu_{\mathrm{eff}}| = 225\ \mathrm{GeV}\,,\ \tan\beta = 2.6\,,\\
M_{H^\pm} &= 611\ \mathrm{GeV}\,,\ m_{\tilde{Q}_3} = 1304\ \mathrm{GeV}\,,\ m_{\tilde{t}_R} = 1576\ \mathrm{GeV}\,,\ m_{\tilde{X}\neq\tilde{Q}_3,\tilde{t}_R} = 3\ \mathrm{TeV}\,,\\
A_t &= 46\ \mathrm{GeV}\,,\ A_b = -1790\ \mathrm{GeV}\,,\ A_\tau = -93\ \mathrm{GeV}\,,\ A_c = 267\ \mathrm{GeV}\,,\\
A_s &= -618\ \mathrm{GeV}\,,\ A_\mu = 1851\ \mathrm{GeV}\,,\ A_u = -59\ \mathrm{GeV}\,,\ A_d = -175\ \mathrm{GeV}\,,\\
A_e &= 1600\ \mathrm{GeV}\,,\ |M_1| = 810\ \mathrm{GeV}\,,\ |M_2| = 642\ \mathrm{GeV}\,,\ M_3 = 2\ \mathrm{TeV}\,.
\end{aligned}
$$

All complex phases are set to zero.

$\rightarrow M_{h_1}^{\mathcal{O}(\alpha_t(\alpha_s+\alpha_t))} = 123.53$ GeV (on-shell scheme)

Tree-level matching: NMSSM $\leftrightarrow$ SM

[Bagnaschi, Goodsell, Slavich, 2206.04618]

$$\lambda_{\rm SM}^{\rm tree} = \underbrace{\frac{1}{4}(g^2+g'^2)\cos^2 2\beta}_{\text{MSSM contribution}} + \underbrace{\frac{1}{2}\lambda^2 \sin^2 2\beta}_{\substack{\text{NMSSM}\\ \text{specific}\\ \text{F-term}\\ \text{contribution}}} - \underbrace{\frac{\frac{\lambda}{\sqrt{2}}\left[2\lambda v_S - (A_\lambda + 2\kappa v_S)\sin 2\beta\right]}{m_S^2}}_{\substack{\text{Contribution due to decoupling}\\ \text{of the singlet scalar}}}$$

$M_S = 3$ TeV: $(\tan\beta)_{\rm MSSM} = \tan\beta(\lambda = 0)$

$\tan\beta < (\tan\beta)_{\rm MSSM} \Rightarrow$ NMSSM contr. needed for $M_h \approx 125$ GeV

$\tan\beta \uparrow \Rightarrow$ NMSSM-specific contr. $\downarrow$, since MSSM contr. $\uparrow$

(NMSSM specific contr. $\propto \lambda^2$) $\rightarrow 0$ for $\tan\beta \uparrow \Rightarrow \lambda \Uparrow$

$\tan\beta > (\tan\beta)_{\rm MSSM} \Rightarrow M_h^{\rm MSSM}$ too large $\Rightarrow$ need last negative term

Tree-level matching: NMSSM $\leftrightarrow$ SM

[Bagnaschi, Goodsell, Slavich, 2206.04618]

$$\lambda_{\rm SM}^{\rm tree} = \underbrace{\frac{1}{4}(g^2+g'^2)\cos^2 2\beta}_{\text{MSSM contribution}} + \underbrace{\frac{1}{2}\lambda^2 \sin^2 2\beta}_{\substack{\text{NMSSM}\\ \text{specific}\\ \text{F-term}\\ \text{contribution}}} - \underbrace{\frac{\frac{\lambda}{\sqrt{2}}\left[2\lambda v_S - (A_\lambda + 2\kappa v_S)\sin 2\beta\right]}{m_S^2}}_{\substack{\text{Contribution due to decoupling}\\ \text{of the singlet scalar}}}$$

$M_S = 5$ TeV, $M_S = 10$ TeV:

$\lambda_{\rm SM} < 0$ only for $\tan\beta > (\tan\beta)_{\rm MSSM}$:

$\tan\beta \to (\tan\beta)_{\rm MSSM}$ from left: $\lambda \to 0$ for for $M_h \approx 125$ GeV

gap: no values of λ leading to $M_h \approx 125$ GeV: $M_h(\lambda) > 125$ GeV

further increase of $\tan\beta$:

NMSSM contribution < 0 needed $\Rightarrow M_h \approx 125$ GeV: $\tan\beta \uparrow \Rightarrow \lambda \downarrow$