

Determination of the Higgs mass in the MSSM with heavy superparticles

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SUSY 2018 – Barcelona, 23-27 July 2018

The Higgs sector of the MSSM

Two complex doublets H_1 and H_2 , five physical states after EWSB: h, H, A, H^\pm

A SUSY peculiarity: the Higgs quartic couplings are not free parameters as in SM / THDM

$$V_{\text{SM}} \supset \frac{\lambda}{2} |\phi|^4, \quad V_{\text{MSSM}} \supset \frac{1}{8}(g^2 + g'^2) (|H_1^0|^2 - |H_2^0|^2)^2$$

At tree-level, the CP-even masses can be expressed in terms of M_Z , M_A and $\tan\beta = v_2/v_1$

$$M_{h,H}^2 = \frac{1}{2} \left(M_Z^2 + M_A^2 \mp \sqrt{(M_Z^2 + M_A^2)^2 - 4 M_Z^2 M_A^2 \cos^2 2\beta} \right)$$

For $M_A \gg M_Z$ (*decoupling limit*) the lightest scalar h has SM-like couplings to fermions and gauge bosons; the other Higgses are mass-degenerate, decoupled from gauge-boson pairs, and their couplings to up-type (down-type) SM fermions are suppressed (enhanced) by $\tan\beta$

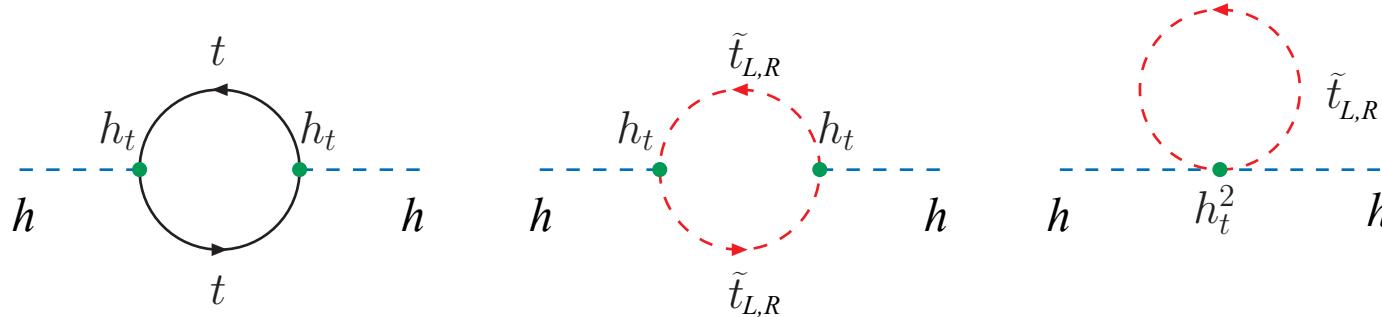
(in)famous upper bound on the tree-level mass: $M_h^{\text{tree}} < M_Z |\cos 2\beta|$

Large radiative corrections
to obtain $M_h \approx 125 \text{ GeV}$:

$$(125 \text{ GeV})^2 = (M_h^{\text{tree}})^2 + \Delta M_h^2 \approx 2 \times (M_h^{\text{tree}})^2$$

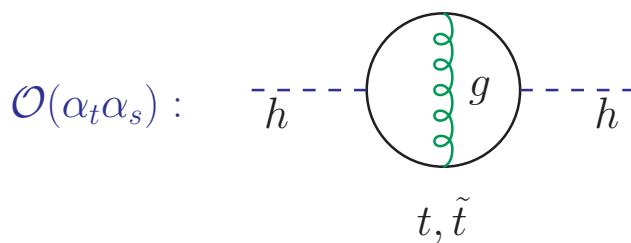
Radiative corrections to the light-Higgs mass in the MSSM

The dominant 1-loop corrections to the Higgs masses are due to the particles with the strongest couplings to the Higgs bosons: the top (and bottom) quarks and squarks

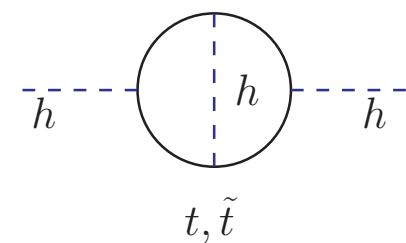


When loop corrections are large, it is vital to include higher orders

2-loop:



$\mathcal{O}(\alpha_t^2)$:



A quarter-century of calculations gave us full 1-loop, almost-full 2-loop and partial 3-loop results

Public codes for the 2- or 3-loop calculation
of the Higgs-boson masses in the MSSM:

**CPsuperH, FeynHiggs, H3m,
SPheno, SoftSUSY, SuSpect ...**

Also, public codes for 1- or 2-loop calculations in
“generic” models (applicable Beyond MSSM)

SARAH, FlexibleSUSY

Dominant 1-loop corrections to the light-Higgs mass from top/stop and sbottom loops:

$$(\Delta M_h^2)^{\text{1-loop}} \simeq \frac{3 M_t^4}{2 \pi^2 v^2} \left(\ln \frac{M_S^2}{M_t^2} + \frac{X_t^2}{M_S^2} - \frac{X_t^4}{12 M_S^4} \right) - \frac{y_b^4 \mu^4 \tan^4 \beta v^2}{32 \pi^2 M_S^4}$$

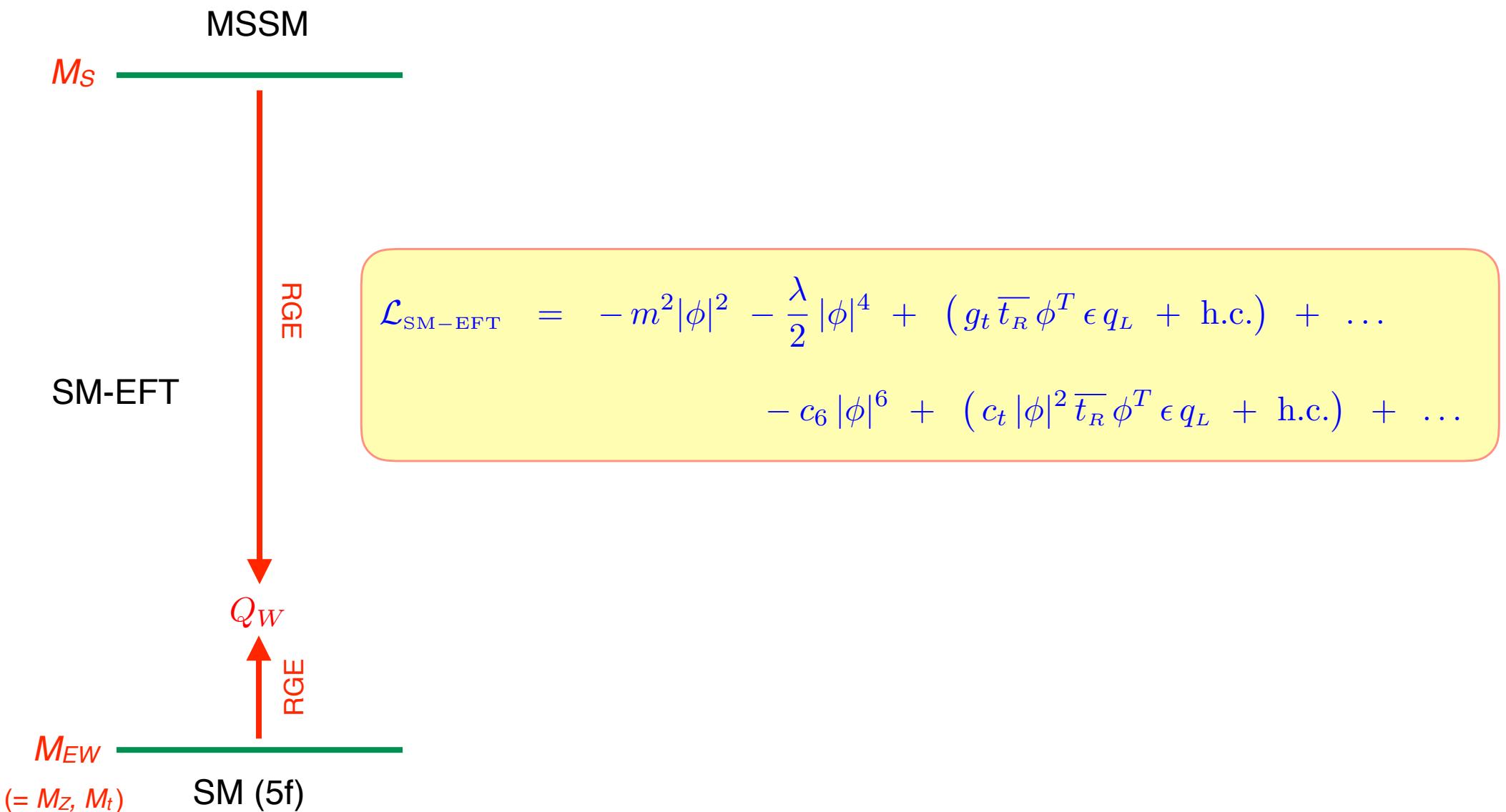
(decoupling limit, M_S = average stop mass, $X_t = A_t - \mu \cot\beta$ = L-R stop mixing)

- “Maximal-mixing” scenarios ($X_t \approx \sqrt{6} M_S$) can work with stops around the TeV (but only if $\tan\beta$ and M_A are large enough that $M_h \approx M_Z$ at tree level)
- Small-mixing ($X_t \ll M_S$) or small $\tan\beta$ (or M_A) require multi-TeV stop masses to reach $M_h \approx 125$ GeV via the large logarithmic term

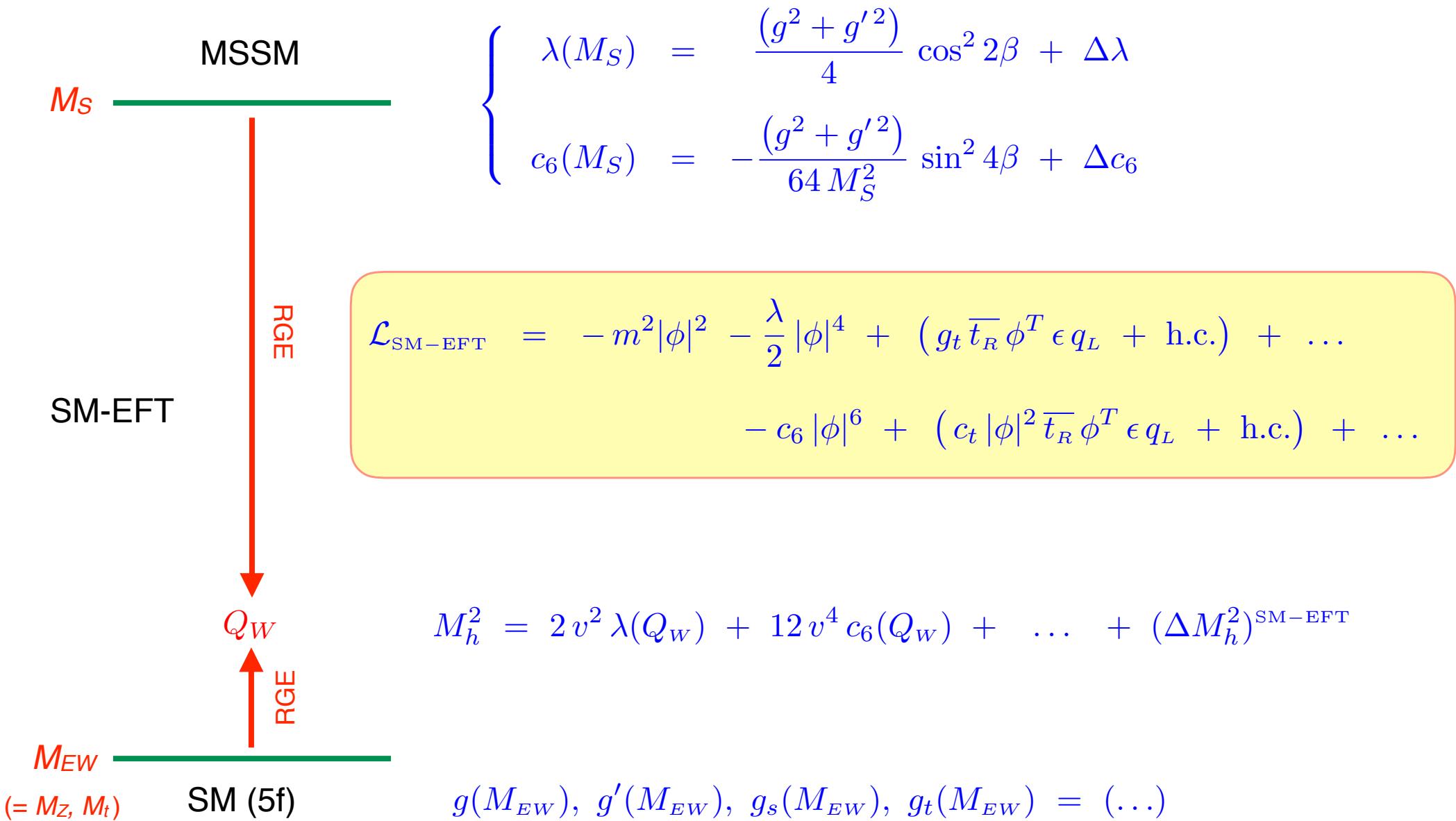
n-loop corrections to the Higgs masses contain terms enhanced by $\ln(M_S/M_{EW})^n$!!!

For multi-TeV SUSY masses, such terms must be resummed in an EFT approach

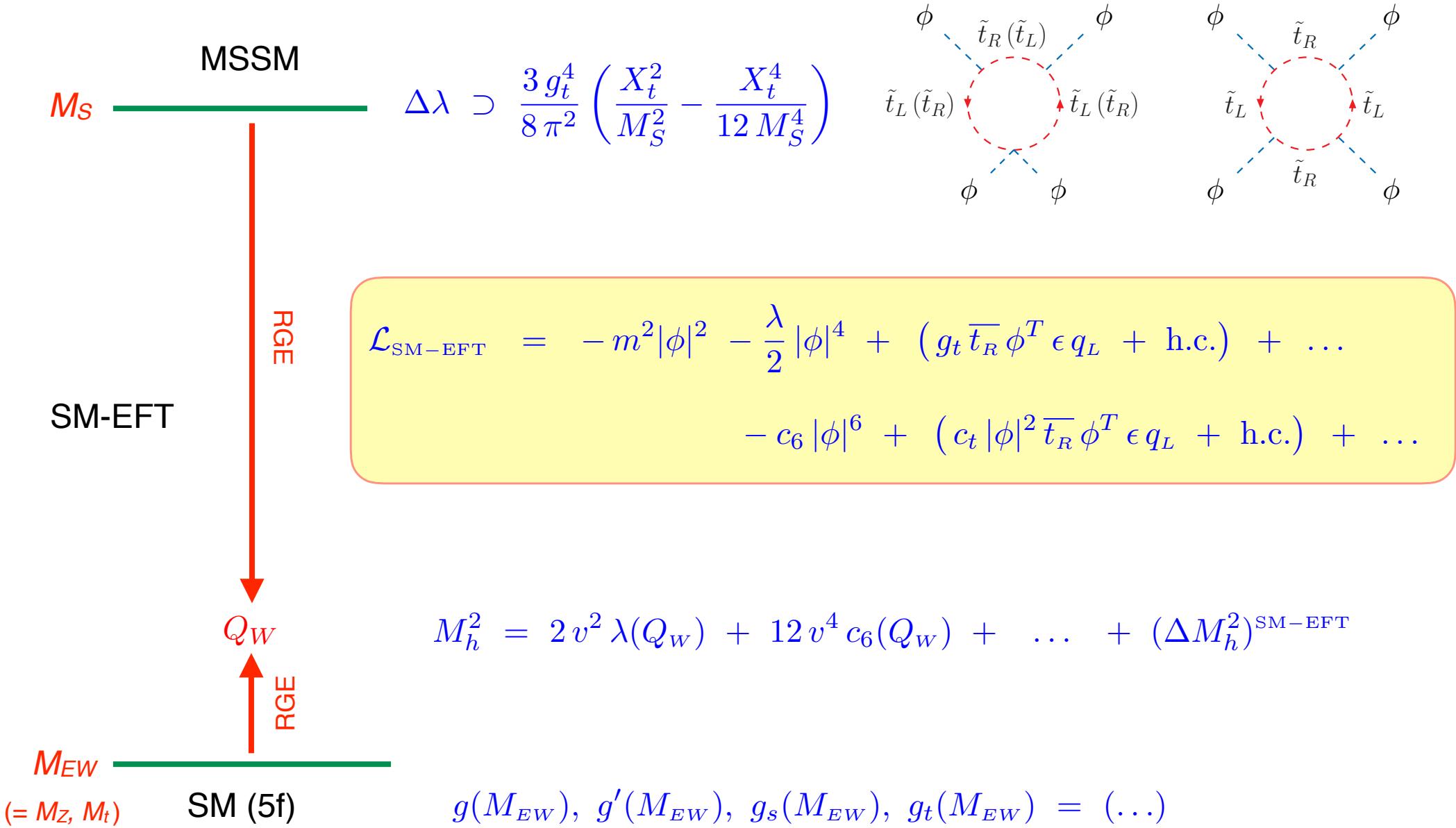
The simplest scenario: all SUSY particles are heavy, with masses around M_S



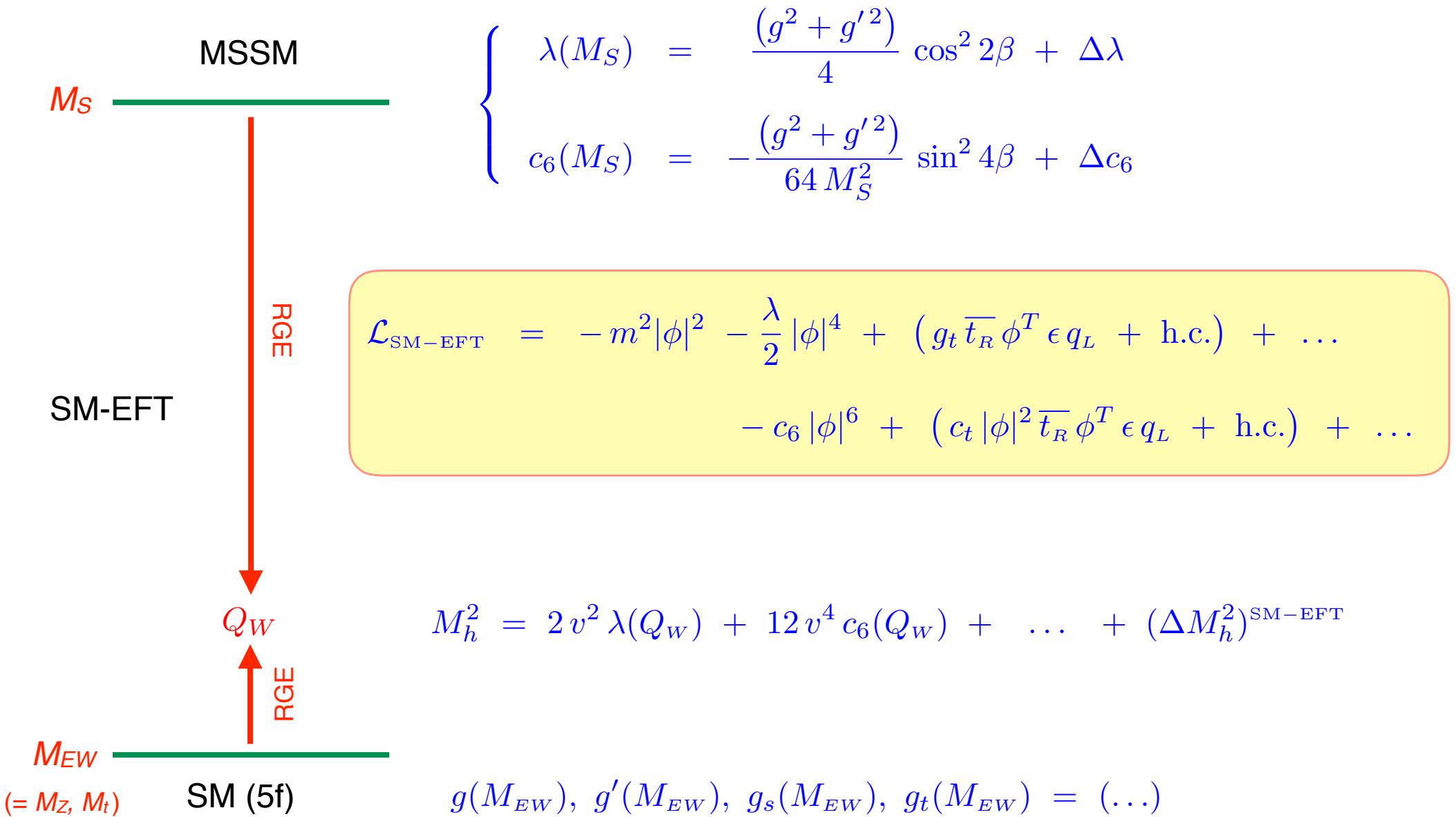
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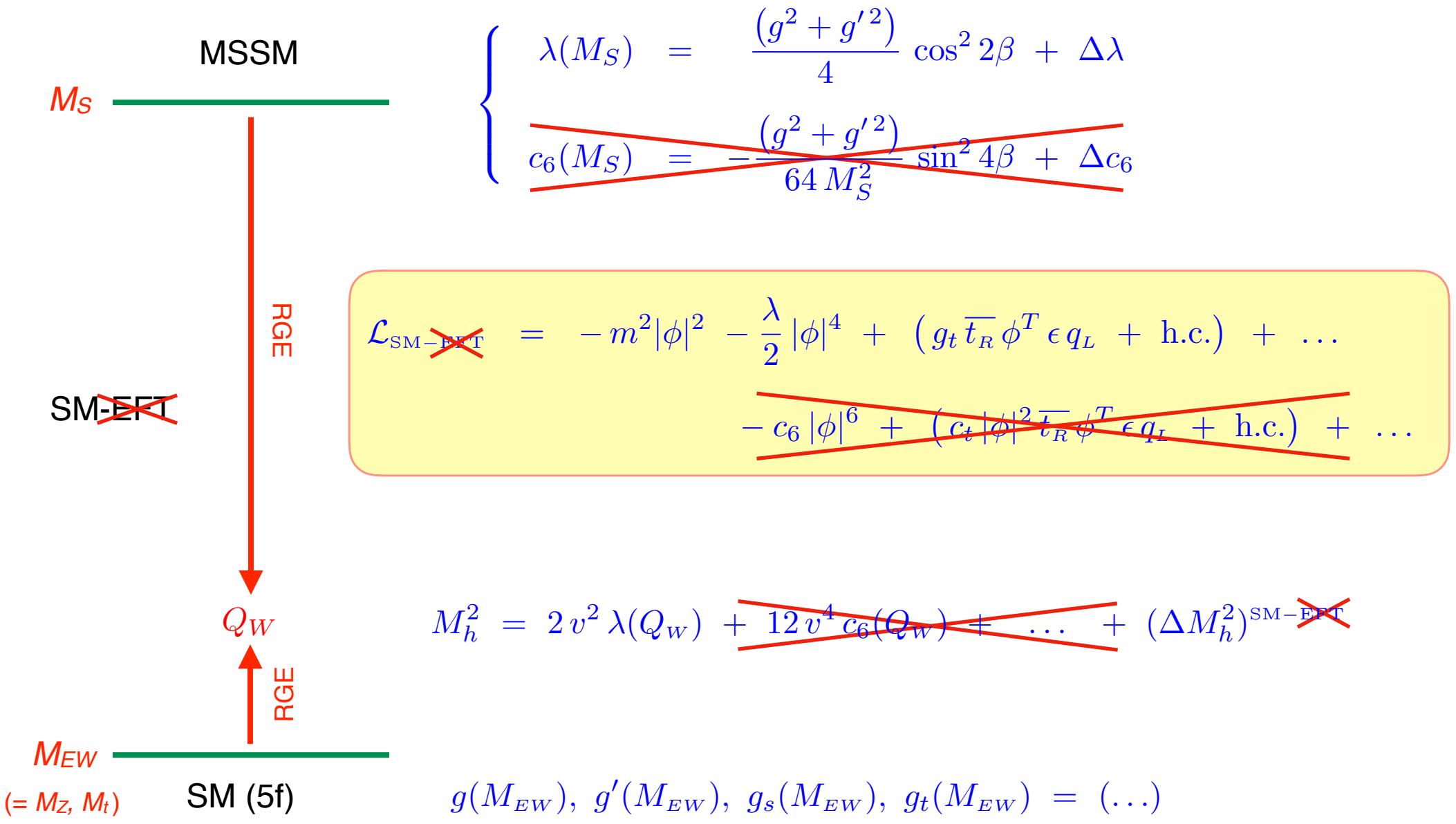
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Using the “pure” SM as EFT resums the large logarithms, but neglects effects of $\mathcal{O}(v^2/M_S^2)$

Reminder: N^n LL resummation of large logs requires n -loop matching and $(n+1)$ -loop RGE

$$\begin{array}{ccccccccc}
 & 0 & \alpha^0 & & & & & & \\
 & 1 & \alpha \log & + & \alpha & & & & (\alpha = \text{generic loop factor}) \\
 & 2 & \alpha^2 \log^2 & + & \alpha^2 \log & + & \alpha^2 & & \\
 & \vdots & \vdots & & \vdots & & \vdots & & \\
 & n & \alpha^n \log^n & + & \alpha^n \log^{n-1} & + & \alpha^n \log^{n-2} & + & (\dots) + \alpha^n \\
 & \vdots & \vdots & & \vdots & & \vdots & & \vdots \\
 & \text{LL} & \text{NLL} & & \text{NNLL} & & (\dots) & & \text{N}^n\text{LL} \\
 & & & & & & & & \\
 & & & & & & & & (\log \text{order})
 \end{array}$$

Status of the calculation in the simplest heavy-SUSY scenario: *full NLL and partial NNLL*

- SUSY-scale boundary conditions: full 1-loop + 2-loop in the “gaugeless limit” ($g, g' = 0$)
[\[Bagnaschi, Giudice, P.S. & Strumia, 1407.4081\]](#) + [\[Bagnaschi, Pardo-Vega & P.S., 1703.08166\]](#)
- Evolution between the SUSY and EW scales: full 3-loop RGE of the SM
[\[as collected in Buttazzo *et al.*, 1307.3536v4\]](#)
- EW-scale (=SM) boundary conditions: full 2-loop + 3-loop QCD for g_t
[\[interpolating formulae from Buttazzo *et al.*, 1307.3536v4 – see also Kniehl *et al.*, 1503.02138\]](#)

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(*) see Alexander’s talk for a brand-new partial N^3 LL calculation [Harlander *et al.*, 1807.03509]

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Sources of theoretical uncertainty in the EFT calculation

- “SUSY uncertainty” :
Incomplete calculation of the threshold corrections to the SM parameters at the SUSY matching scale
- “SM uncertainty” :
Incomplete determination of the SM parameters and of the pole Higgs mass at the weak scale
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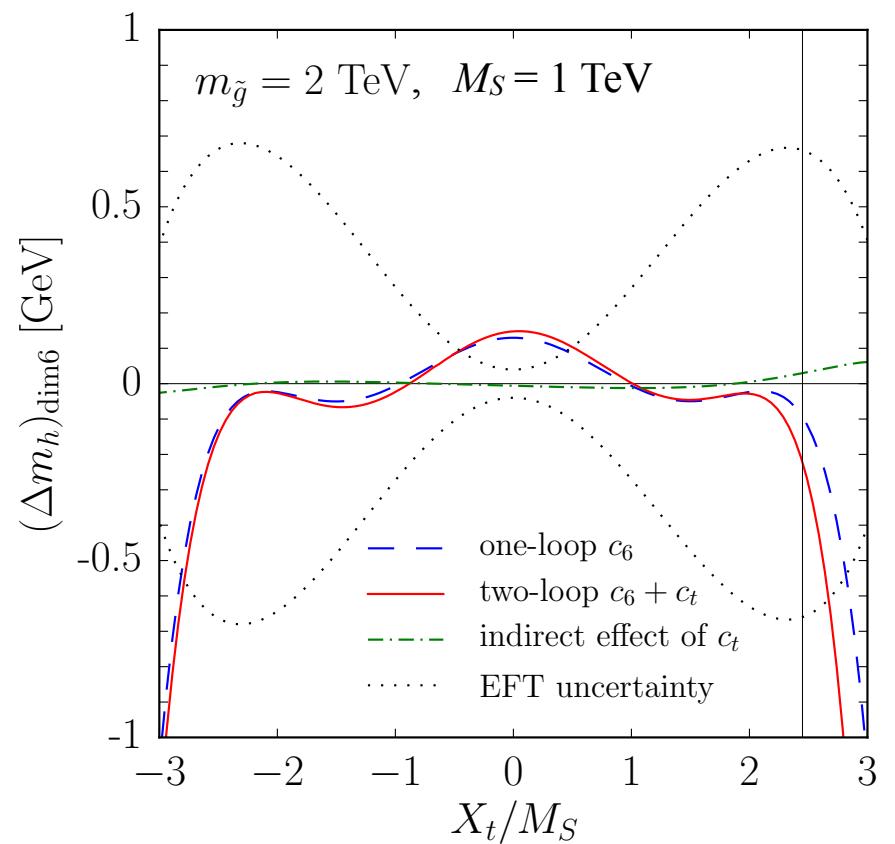
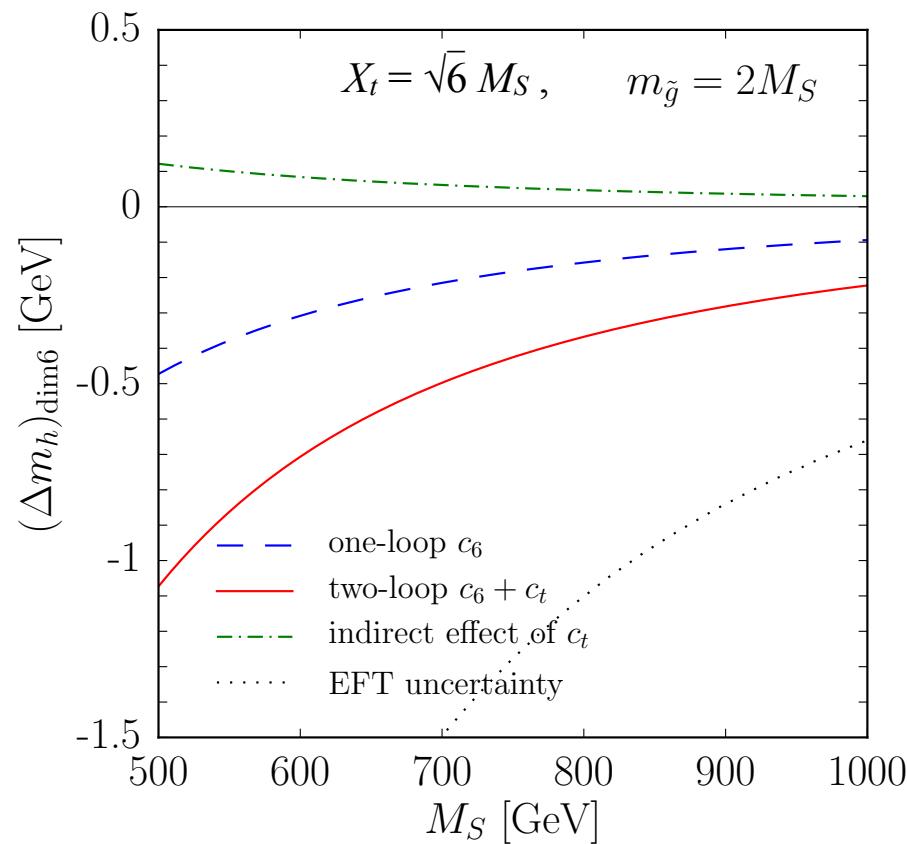
estimated by rescaling $\Delta\lambda \rightarrow \Delta\lambda (1 \pm 2v^2/M_S^2)$
(too crude?)

Effects of dim-6 operators on the dominant one- and two-loop corrections to the Higgs mass

[Bagnaschi, P.S. & Pardo-Vega, 1703.08166]

$$\mathcal{L}_{\text{SM-EFT}} = -m^2|\phi|^2 - \frac{\lambda}{2}|\phi|^4 - c_6|\phi|^6 + (g_t \bar{t}_R \phi^T \epsilon q_L + \text{h.c.}) + (c_t |\phi|^2 \bar{t}_R \phi^T \epsilon q_L + \text{h.c.})$$

$$g_t(Q_w) = \frac{\bar{m}_t}{v} - c_t v^2, \quad M_h^2 = 2v^2 \lambda(Q_w) + 12v^4 c_6(Q_w) + (\Delta M_h^2)^{\text{SM-EFT}}$$

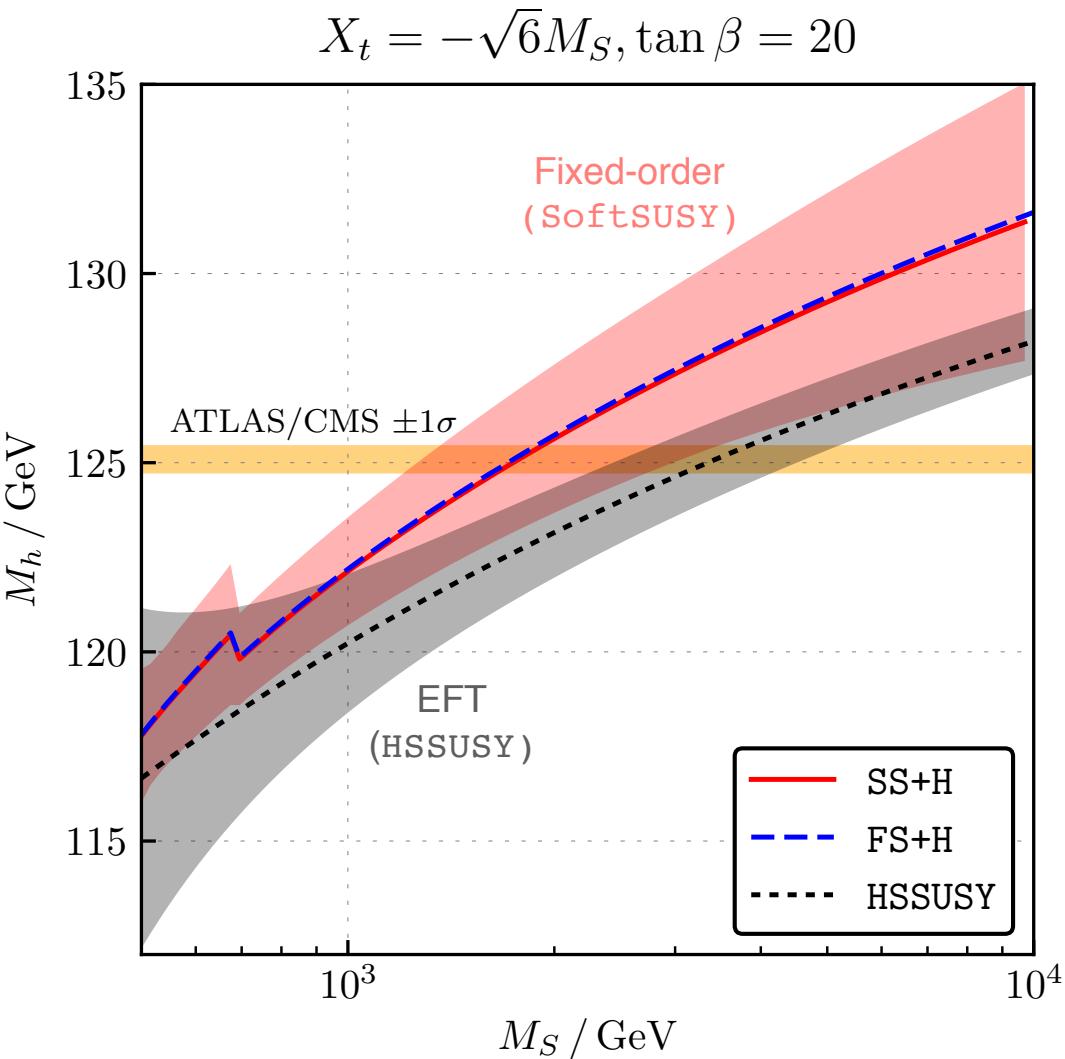


For $M_S \sim \text{TeV}$ and “maximal” X_t the naive estimate of the “EFT uncertainty” is quite generous

Fixed-order vs EFT calculation: who wins for $M_S \sim \text{TeV}$?

[e.g. Allanach & Voigt, 1804.09410 – see Alexander's talk]

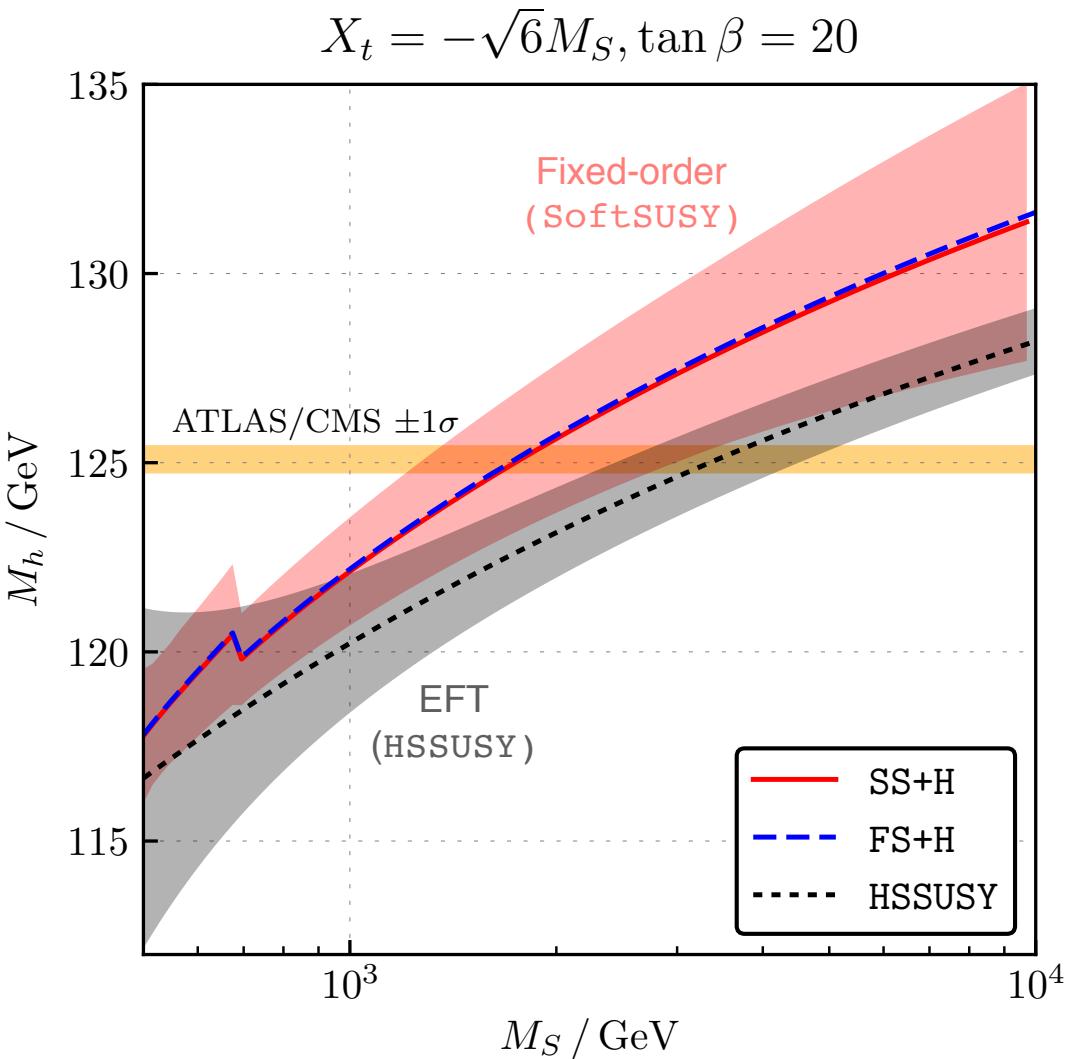
- In general, $(M_h)^{\text{EFT}} < (M_h)^{\text{f.o.}}$
- The fixed-order calculation loses accuracy for $M_S \sim \text{few TeV}$ (large logs)
- The EFT calculation loses accuracy for $M_S \gtrsim 1 \text{ TeV}$ (v^2/M_S^2 terms)
- In this example, the observed value of M_h corresponds to $M_S \approx 2\text{-}3 \text{ TeV}$



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The EFT result seems more precise there, but some ambiguity remains

“Hybrid” calculations: combining fixed-order and EFT

- **FeynHiggs** ≥ 2.10 [Hahn *et al.*, 1312.4937 + Bahl & Hollik, 1608.01880 + Bahl *et al.*, 1706.00346]

$$M_h^2 = (M_h^2)^{\text{FH}} + [(M_h^2)^{\text{EFT}} - (\Delta M_h^2)^{\text{dblcount}}]$$

- **FlexibleEFTHiggs** [Athron *et al.*, 1609.00371 + 1710.03760] ,
SPPheno/SARAH [Porod & Staub, 1703.03267] (applicable also to
BMSSM models)

$$\lambda(M_S) = \frac{1}{v^2} [(M_h^2)^{\text{MSSM}} - (\Delta M_h^2)_{Q=M_S}^{\text{SM}}] \quad + \quad \text{standard EFT calculation below } M_S$$

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fixed-order:
full 1-loop, partial 2-loop

full NLL
partial NNLL

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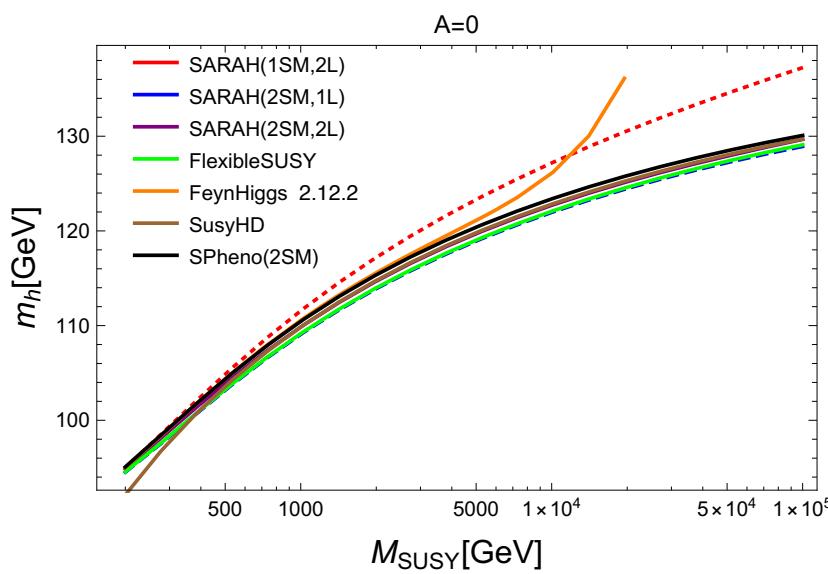
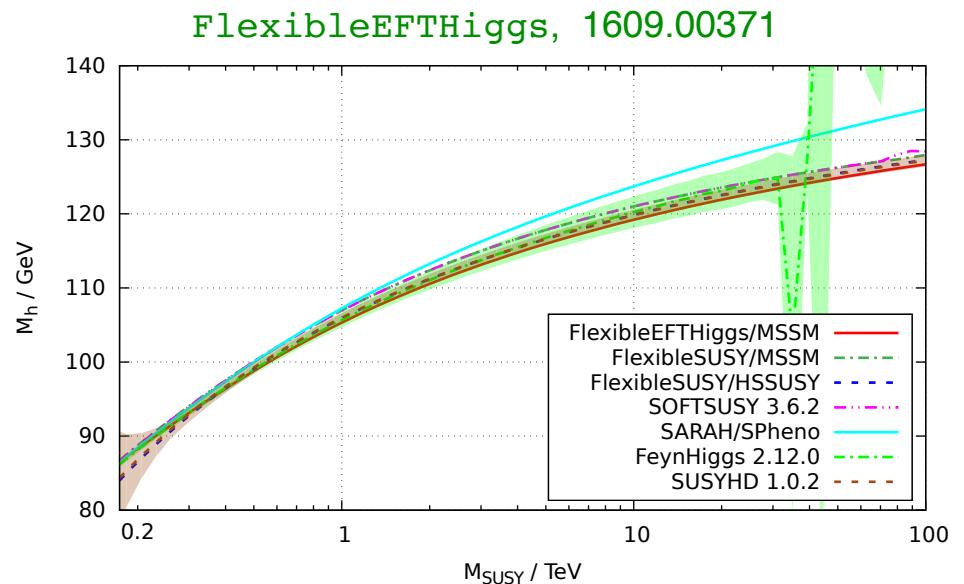
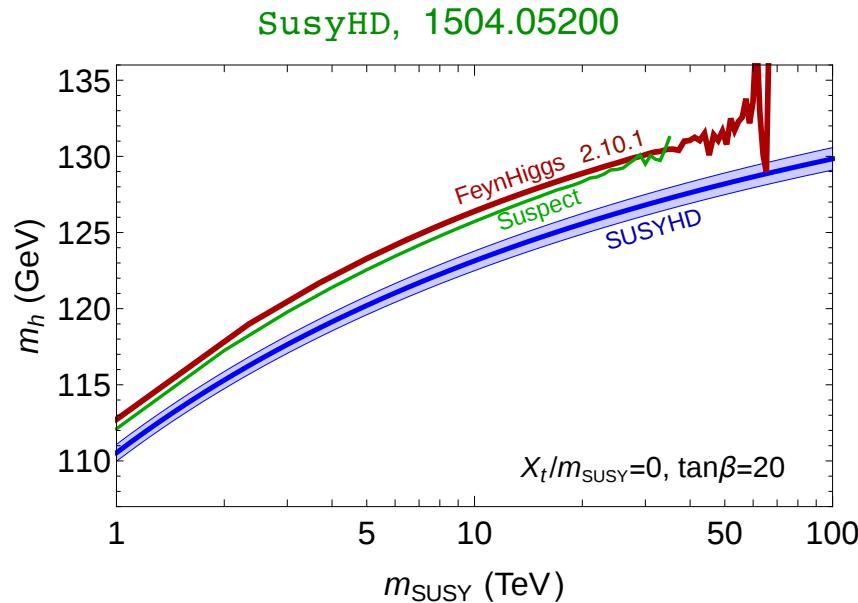
fixed-order as in SoftSUSY (or SPheno/SARAH)
full 1-loop (+ partial 2-loop)

+ standard EFT calculation
below M_S

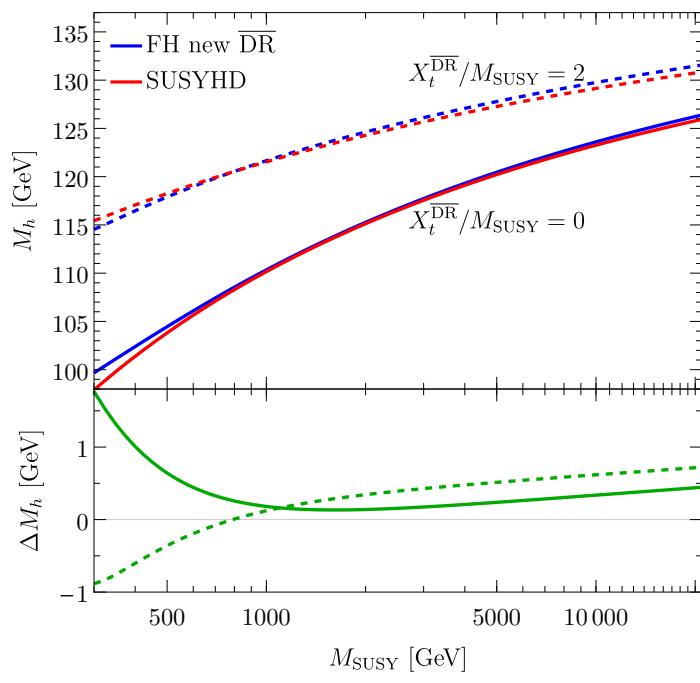
(N)LL resummation
of large logarithms

(Both approaches require non-trivial manipulations to avoid double counting of large logs)

Battle of the Codes: hybrid vs pure EFT

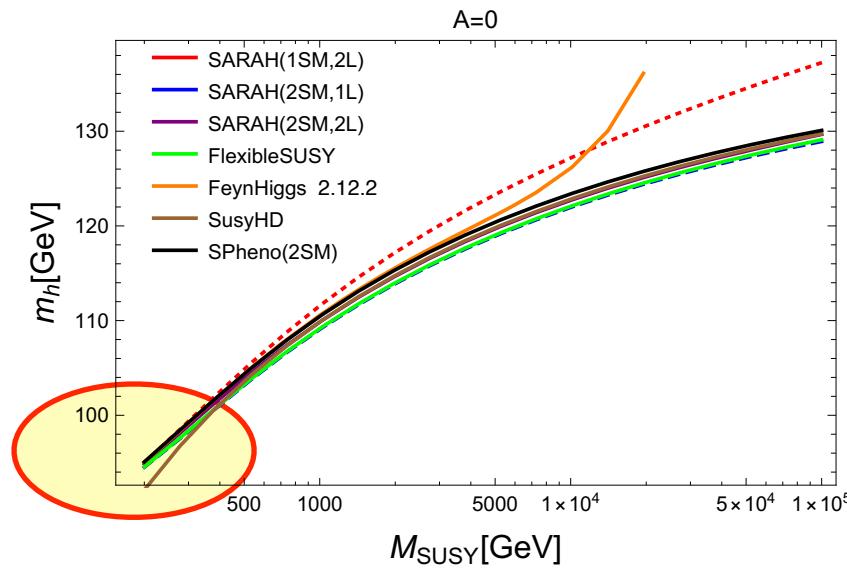
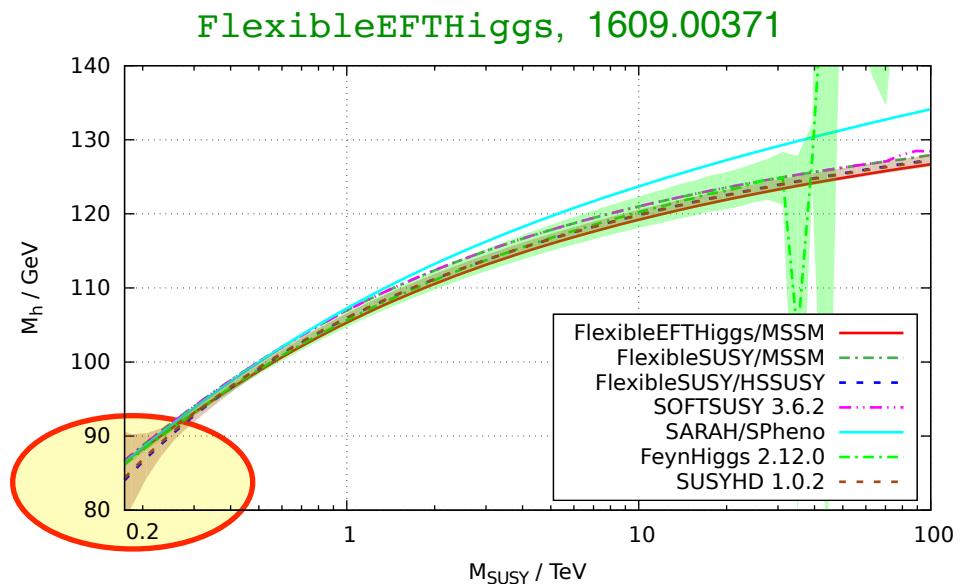
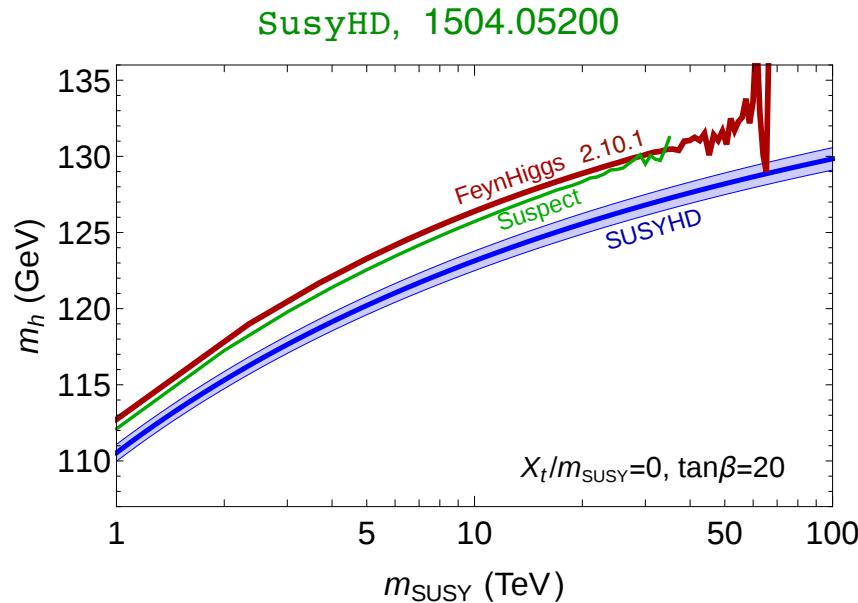


SPheno/SARAH, 1703.03267

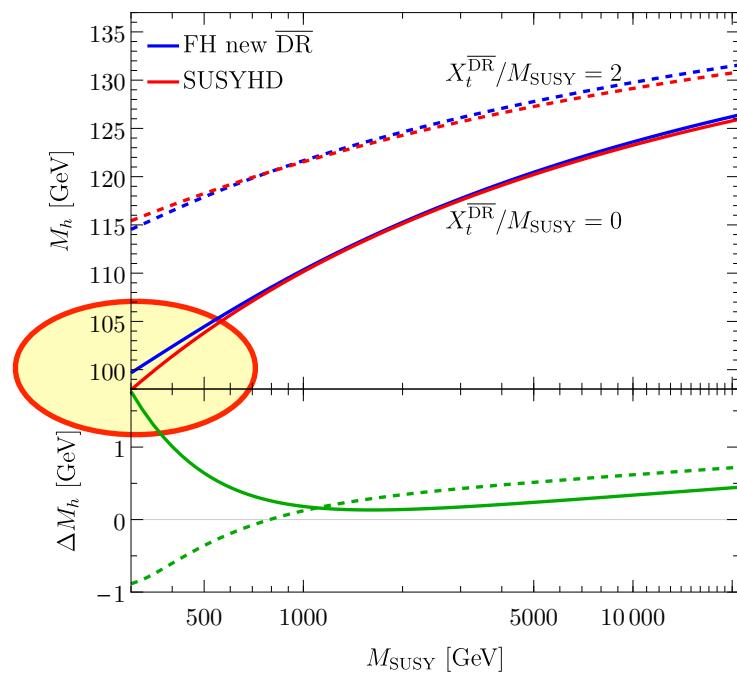


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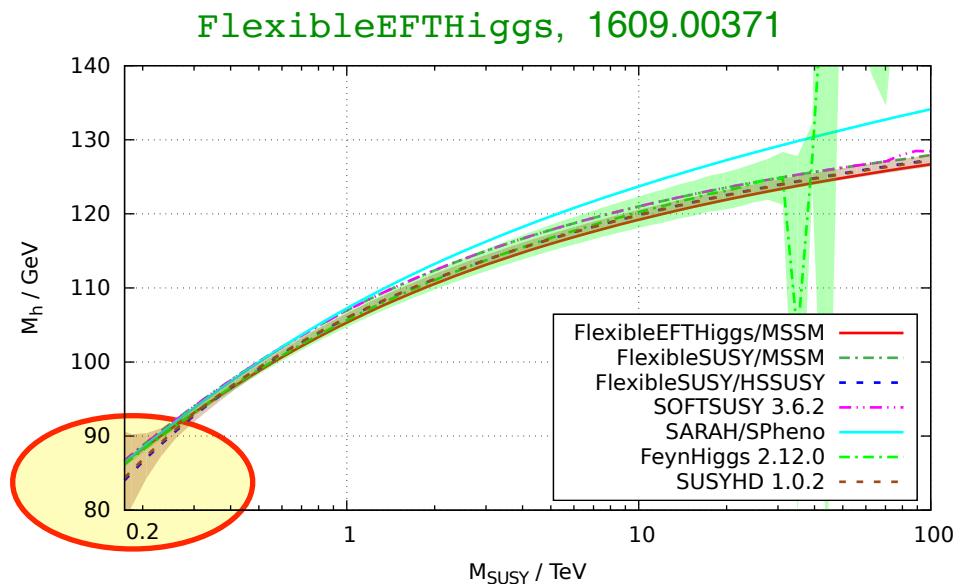
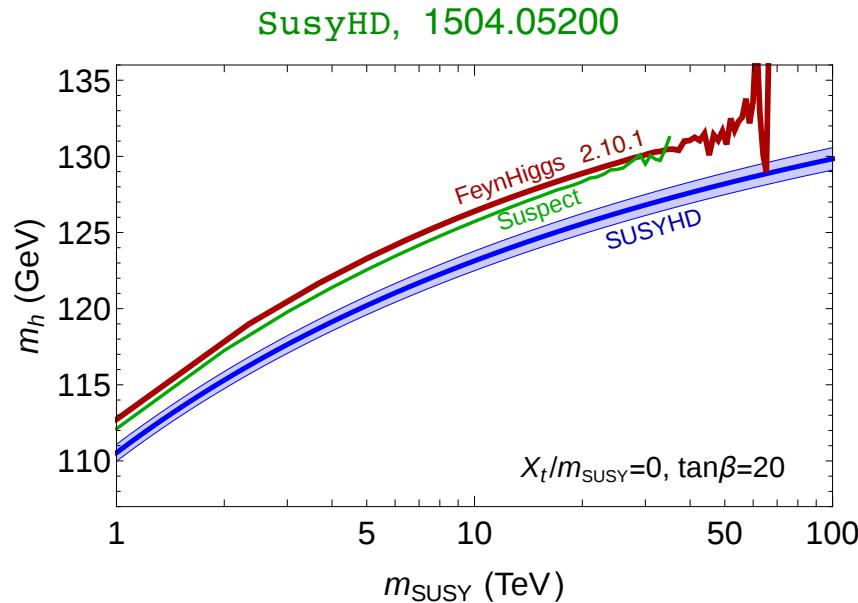


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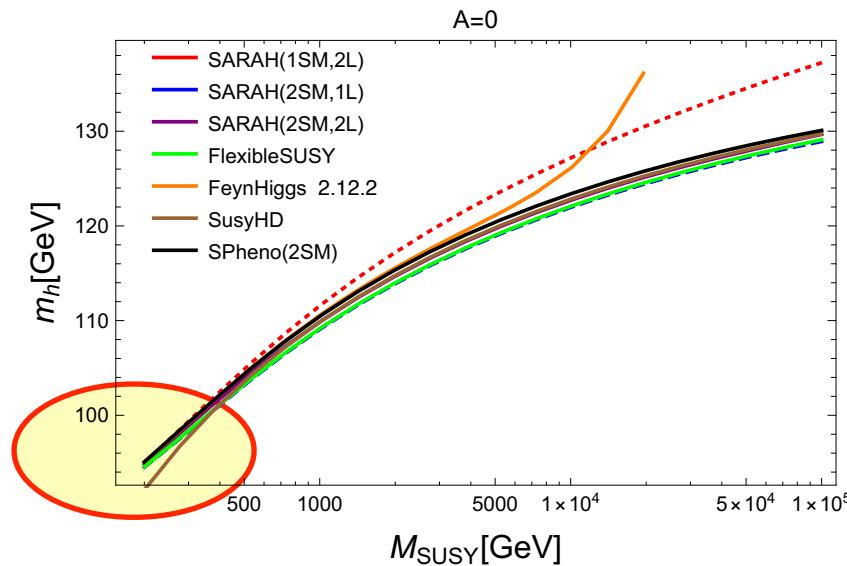


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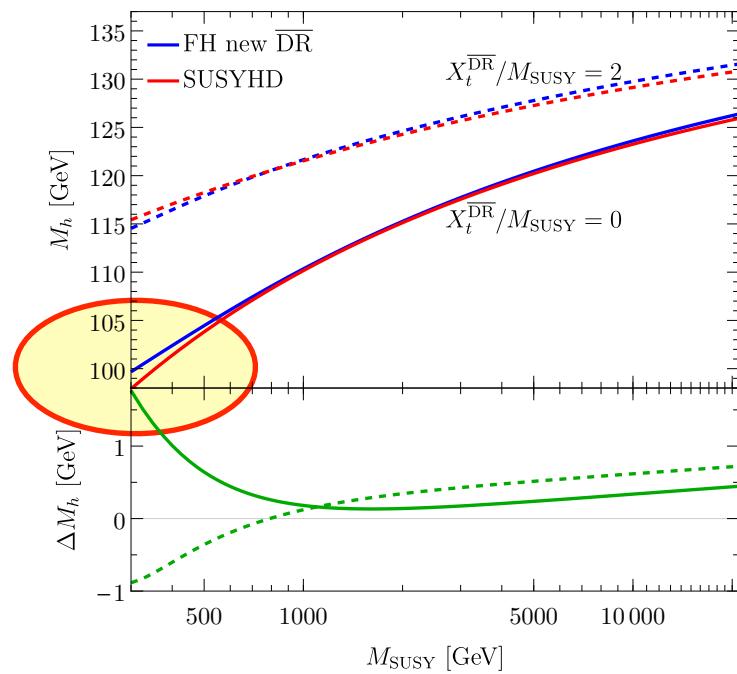
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Relevant mostly for
 $M_h \ll 125 \text{ GeV} \dots$

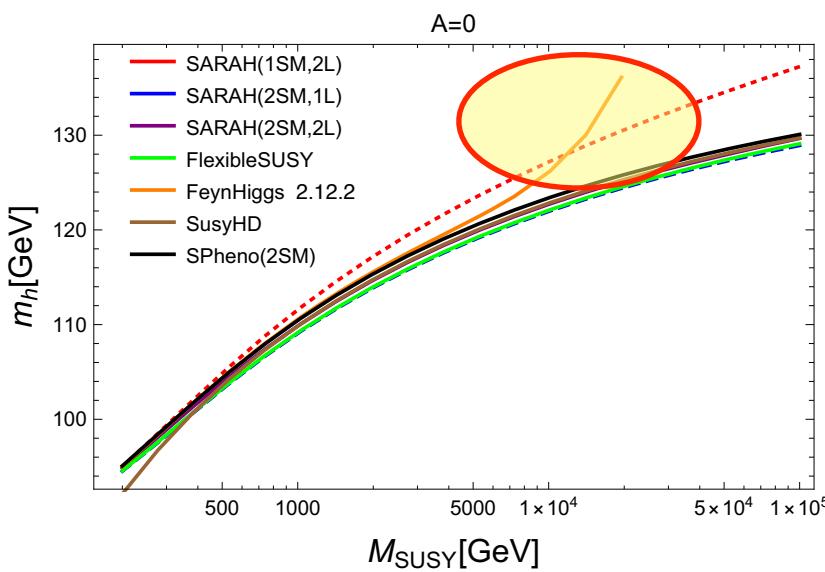
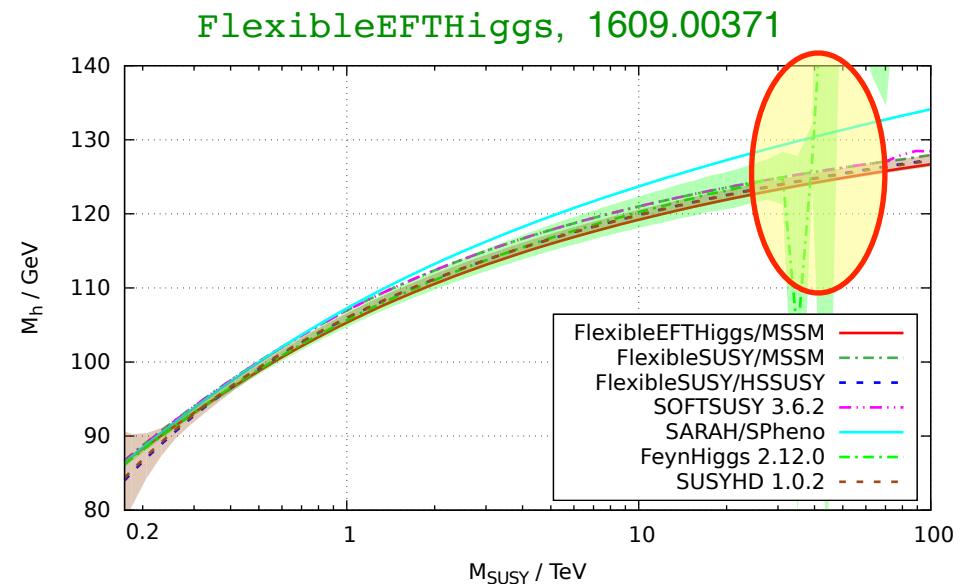
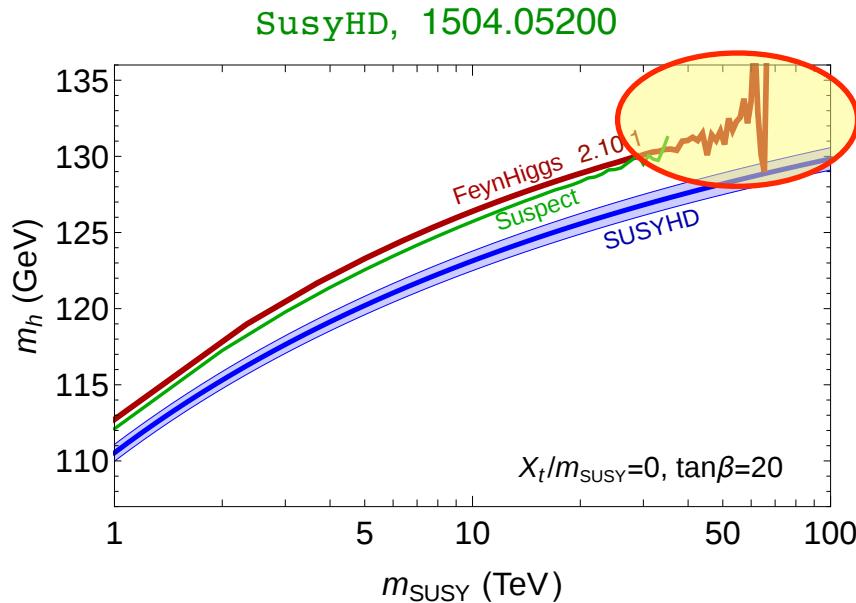


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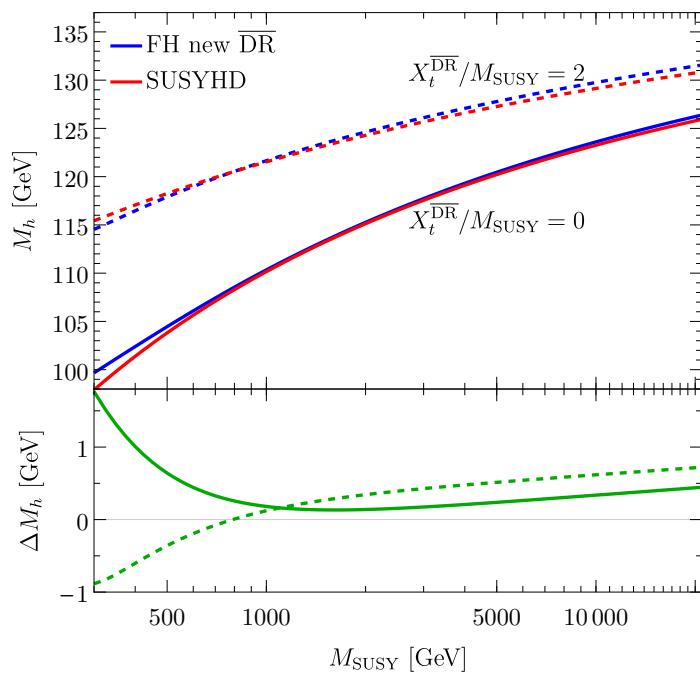


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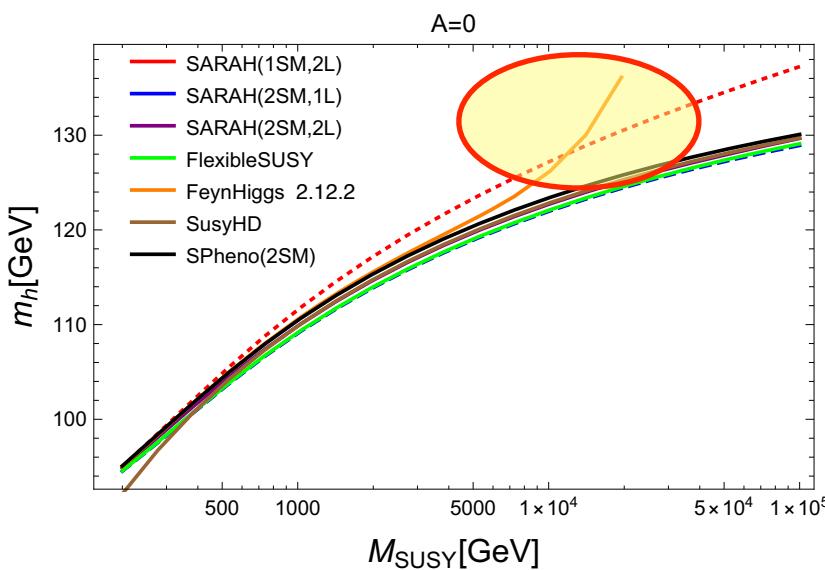
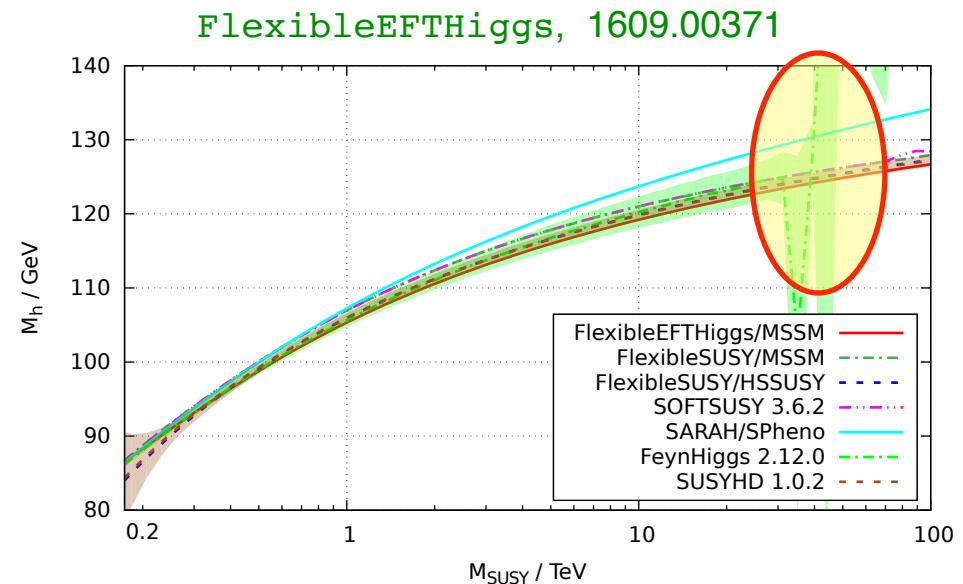
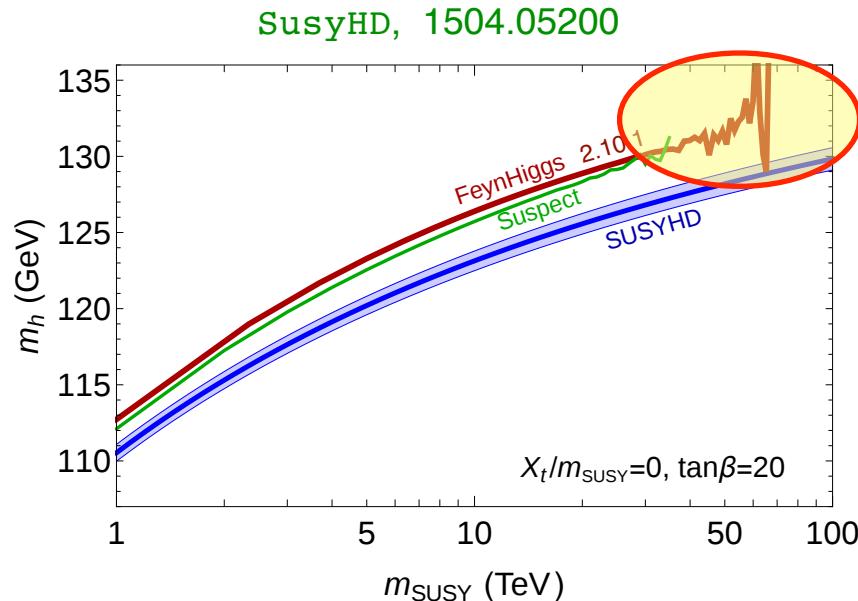


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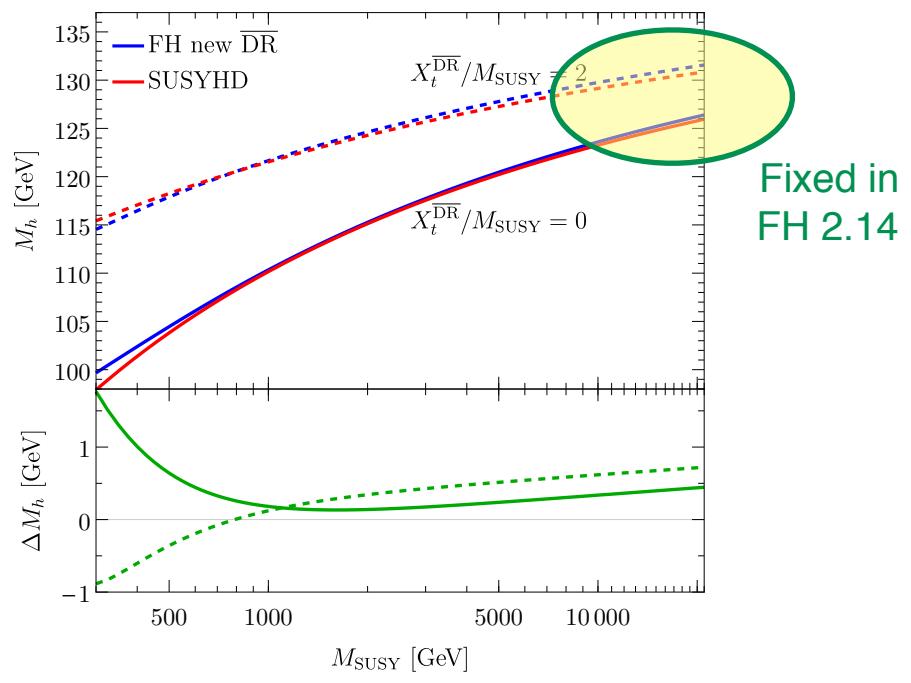


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Beyond the simplest heavy-SUSY scenario

“Split SUSY”

“THDM”

“THDM+Split (1)”

“THDM+Split (2)”

MSSM

MSSM

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 $\tilde{b}, \tilde{w}, \tilde{g},$
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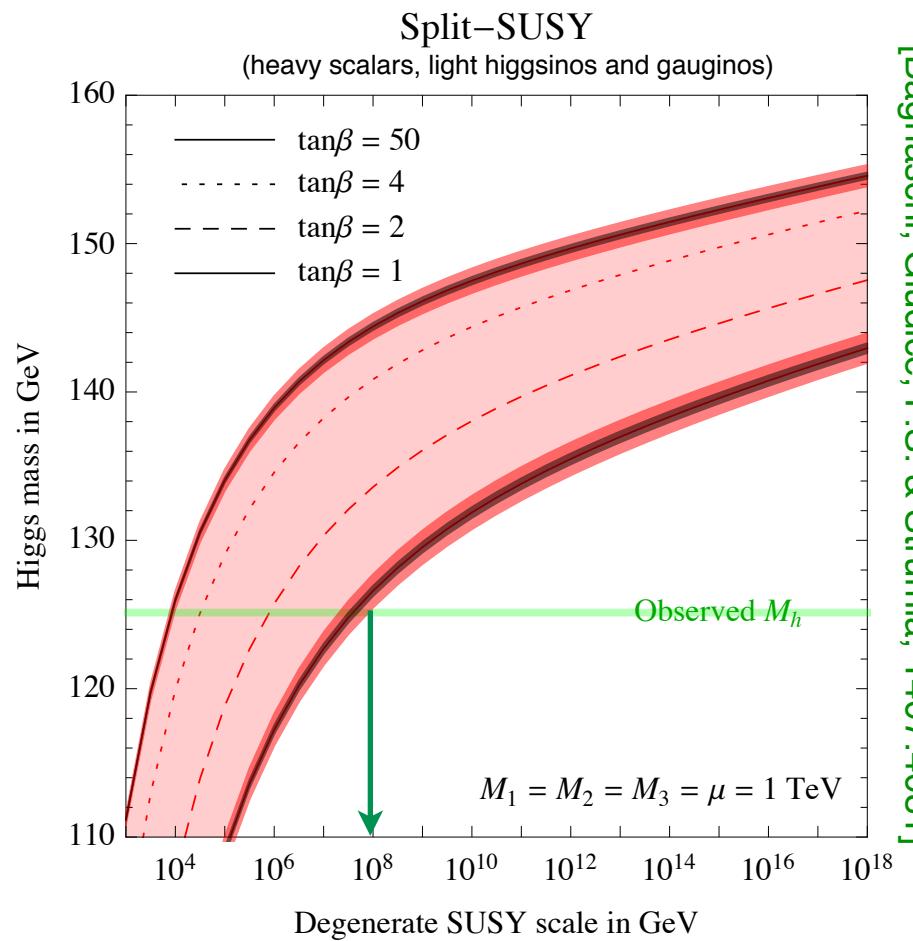
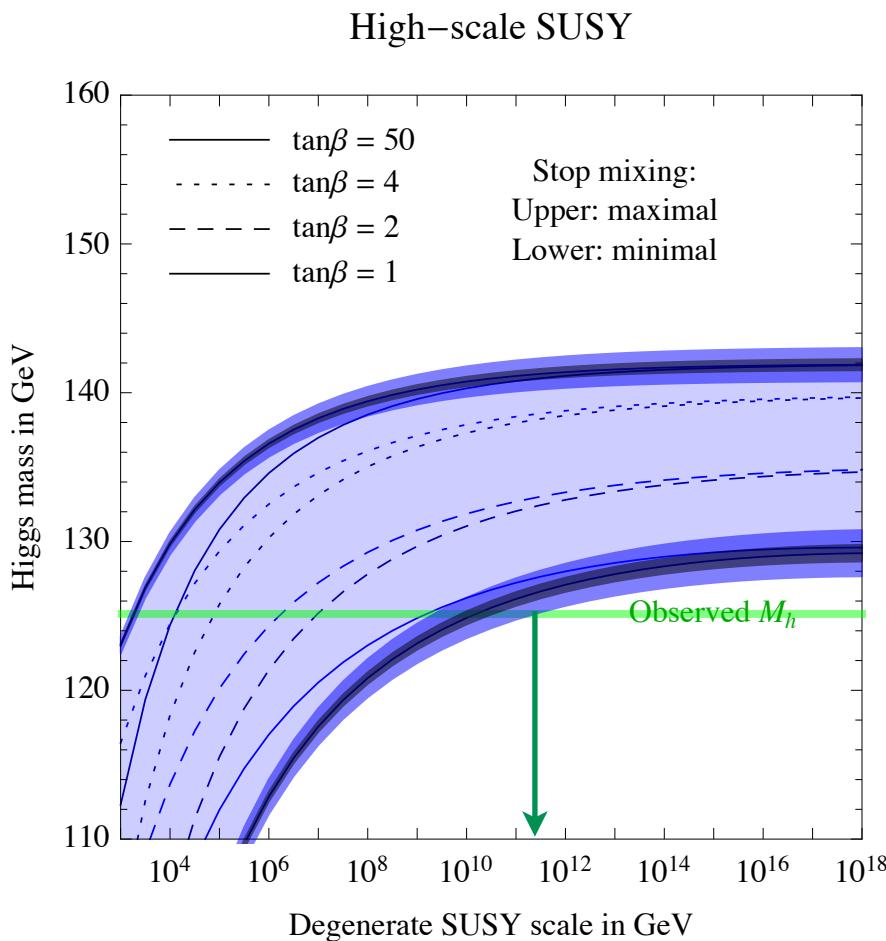
SM

SM

So far, accuracy of large-log resummation is only NLL (2-loop RGEs, matching mostly 1-loop)

The use of “generic” calculations helps cover the plethora of possible mass hierarchies

Pushing un-naturalness: High-scale SUSY vs Split SUSY



[Bagnaschi, Giudice, P.S. & Strumia, 1407.4081]

- The prediction depends on the high-scale parameter $\tan\beta$ (and X_t in HSS)
- The observed M_h determines an **upper bound** on the SUSY-breaking scale

Effective THDM with heavy SUSY

[Haber & Hempfling, early 90s, (...), Lee & Wagner, 1508.00576, Bagnaschi, Voigt *et al.*, 1512.07761, Bahl & Hollik, 1805.00867]

$$\begin{aligned}
 V = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] \\
 & + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
 & + \left\{ \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2) \right] (\Phi_1^\dagger \Phi_2) + \text{h.c.} \right\}
 \end{aligned}$$

1) SUSY boundary conditions at the scale M_S :

$$\begin{aligned}
 \lambda_1 &= \lambda_2 = -(\lambda_3 + \lambda_4) = \frac{1}{4} (g^2 + g'^2) , & (\text{NOTE: loop corrections}) \\
 \lambda_4 &= -\frac{g^2}{2} , \quad \lambda_5 = \lambda_6 = \lambda_7 = 0
 \end{aligned}$$

- 2) RG evolution of all seven lambdas from M_S to the weak scale;
 3) scalar mass matrix in terms of the weak-scale lambdas:

$$M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix} \quad \begin{aligned}
 L_{11} &= \lambda_1 c_\beta^2 + 2 \lambda_6 s_\beta c_\beta + \lambda_5 s_\beta^2 \\
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$$\begin{aligned}
\lambda_1 &= \frac{1}{4}(g^2 + g'^2) + \frac{2 N_c}{(4\pi)^2} \left(y_b^4 \frac{A_b^2}{M_S^2} \left(1 - \frac{A_b^2}{12M_S^2} \right) - y_t^4 \frac{\mu^4}{12M_S^4} \right) \\
\lambda_2 &= \frac{1}{4}(g^2 + g'^2) + \frac{2 N_c}{(4\pi)^2} \left(y_t^4 \frac{A_t^2}{M_S^2} \left(1 - \frac{A_t^2}{12M_S^2} \right) - y_b^4 \frac{\mu^4}{12M_S^4} \right) \\
\lambda_3 &= \frac{1}{4}(g^2 - g'^2) + \frac{2 N_c}{(4\pi)^2} \left(y_b^2 y_t^2 \frac{A_{tb}}{2} + y_t^4 \left(\frac{\mu^2}{4M_S^2} - \frac{\mu^2 A_t^2}{12M_S^4} \right) + y_b^4 \left(\frac{\mu^2}{4M_S^2} - \frac{\mu^2 A_b^2}{12M_S^4} \right) \right) \\
\lambda_4 &= -\frac{1}{2} g^2 + \frac{2 N_c}{(4\pi)^2} \left(-y_b^2 y_t^2 \frac{A_{tb}}{2} + y_t^4 \left(\frac{\mu^2}{4M_S^2} - \frac{\mu^2 A_t^2}{12M_S^4} \right) + y_b^4 \left(\frac{\mu^2}{4M_S^2} - \frac{\mu^2 A_b^2}{12M_S^4} \right) \right) \\
\lambda_5 &= -\frac{2 N_c}{(4\pi)^2} \left(y_t^4 \frac{\mu^2 A_t^2}{12M_S^4} + y_b^4 \frac{\mu^2 A_b^2}{12M_S^4} \right), \\
\lambda_6 &= \frac{2 N_c}{(4\pi)^2} \left(y_b^4 \frac{\mu A_b}{M_S^2} \left(-\frac{1}{2} + \frac{A_b^2}{12M_S^2} \right) + y_t^4 \frac{\mu^3 A_t}{12M_S^4} \right), \\
\lambda_7 &= \frac{2 N_c}{(4\pi)^2} \left(y_t^4 \frac{\mu A_t}{M_S^2} \left(-\frac{1}{2} + \frac{A_t^2}{12M_S^2} \right) + y_b^4 \frac{\mu^3 A_b}{12M_S^4} \right),
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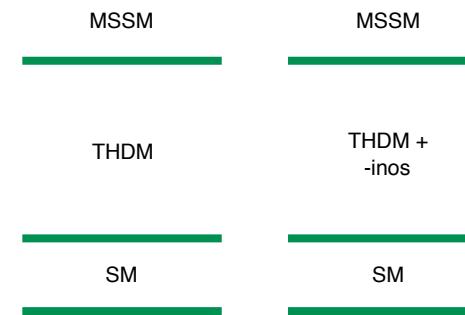
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 \end{aligned}$$

Public codes for the effective THDM

- **MhEFT** [Lee & Wagner, 1508.00576]

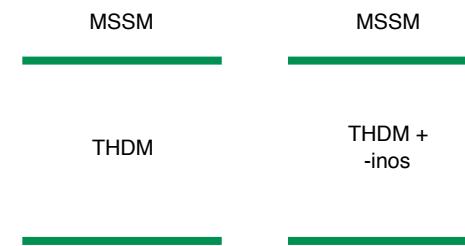
Partial 1- / 2-loop thresholds at M_S ;
2-loop RGE for THDM (*partial* for -inos);
usual SM calculation below $Q = M_A$



- **FlexibleSUSY/FlexibleBSM** [Atron et al., 1710.03760, see also Bagnaschi et al., 1512.07761]

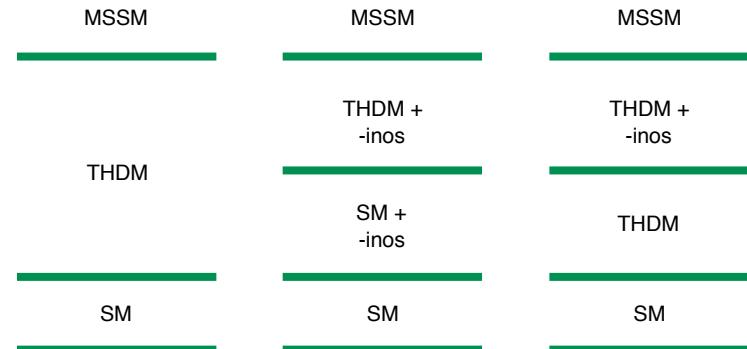
Partial 1- / 2-loop thresholds at M_S ;
Full 2-loop RGE for THDM (& -inos)

[Coming soon: *Full* 1-loop thresholds,
independent matching scale for -inos]

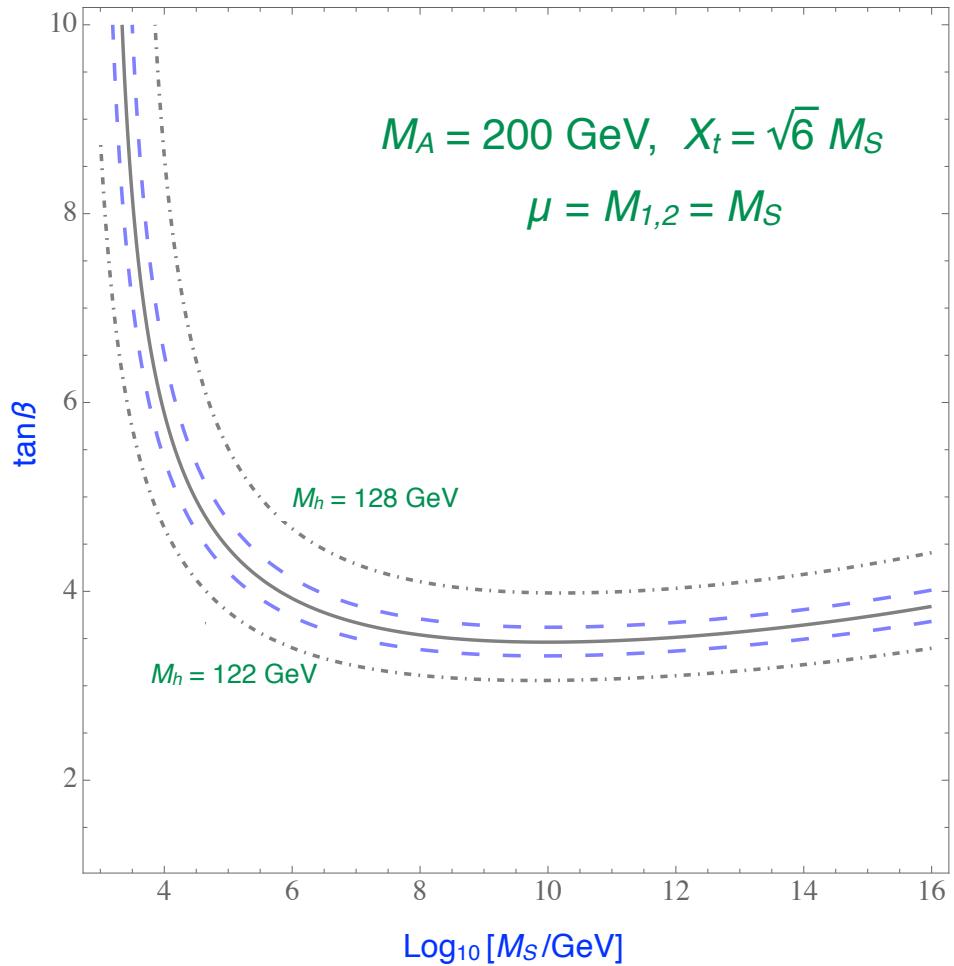


- Coming soon: effective THDM in **FeynHiggs** [see Bahl & Hollik, 1805.00867]

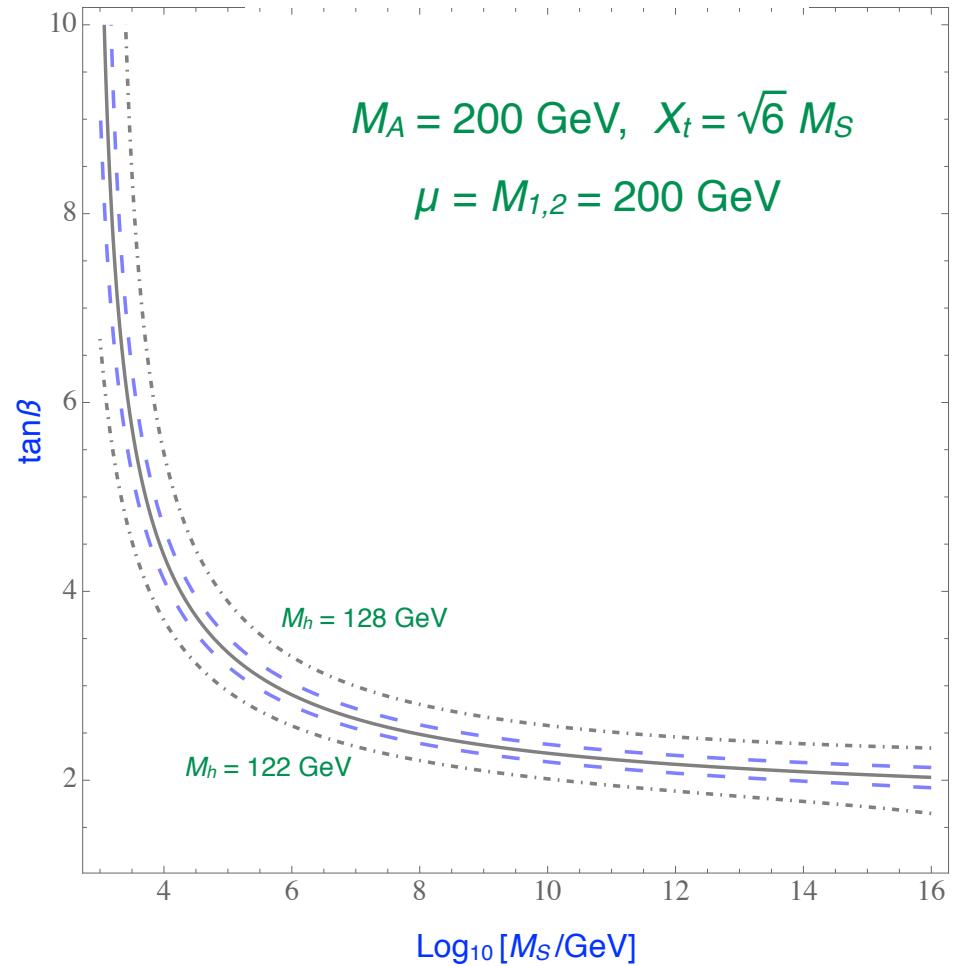
Full 1-loop (+partial 2-loop) thresholds;
Full 2-loop RGE for THDM (& -inos);
multiple matching scales;
“hybrid” calculation (combined with fixed-order)



Light THDM (MhEFT)

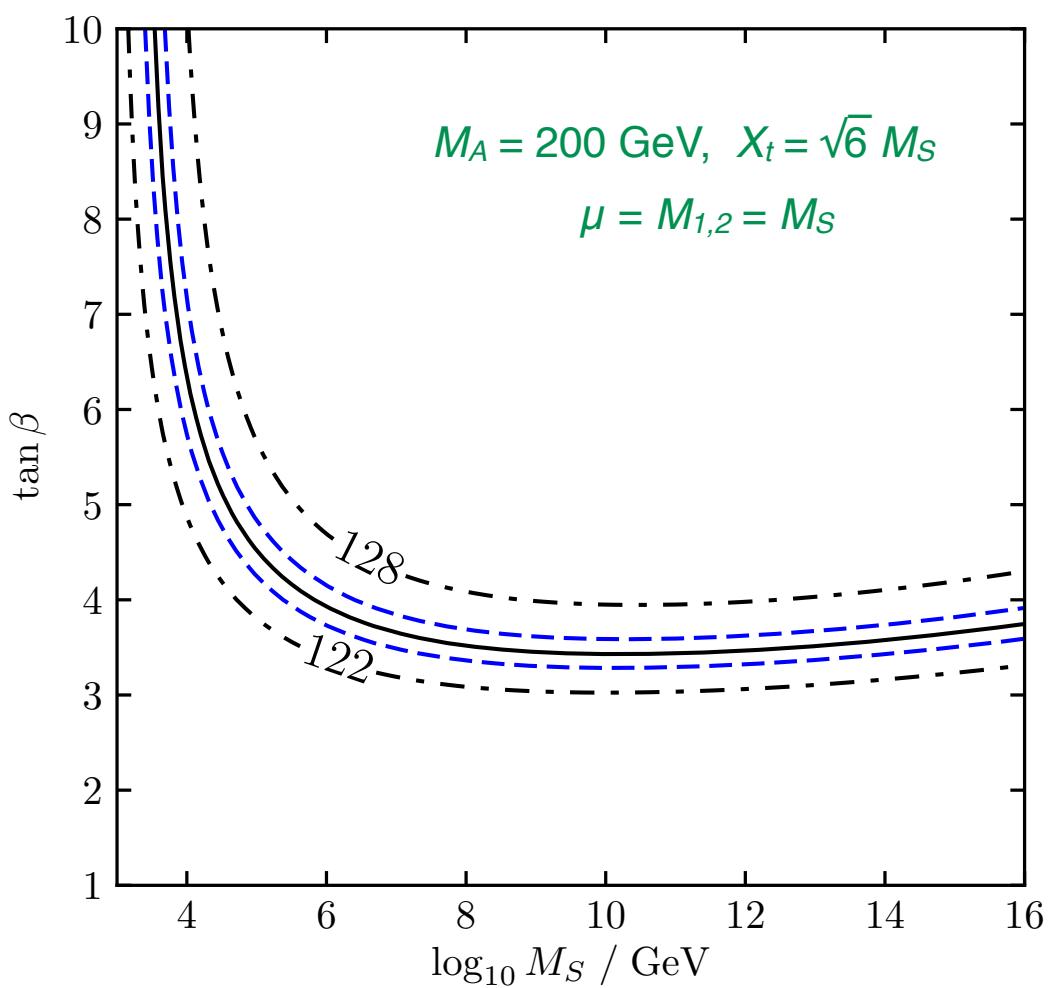


Light THDM + EW-inos (MhEFT)

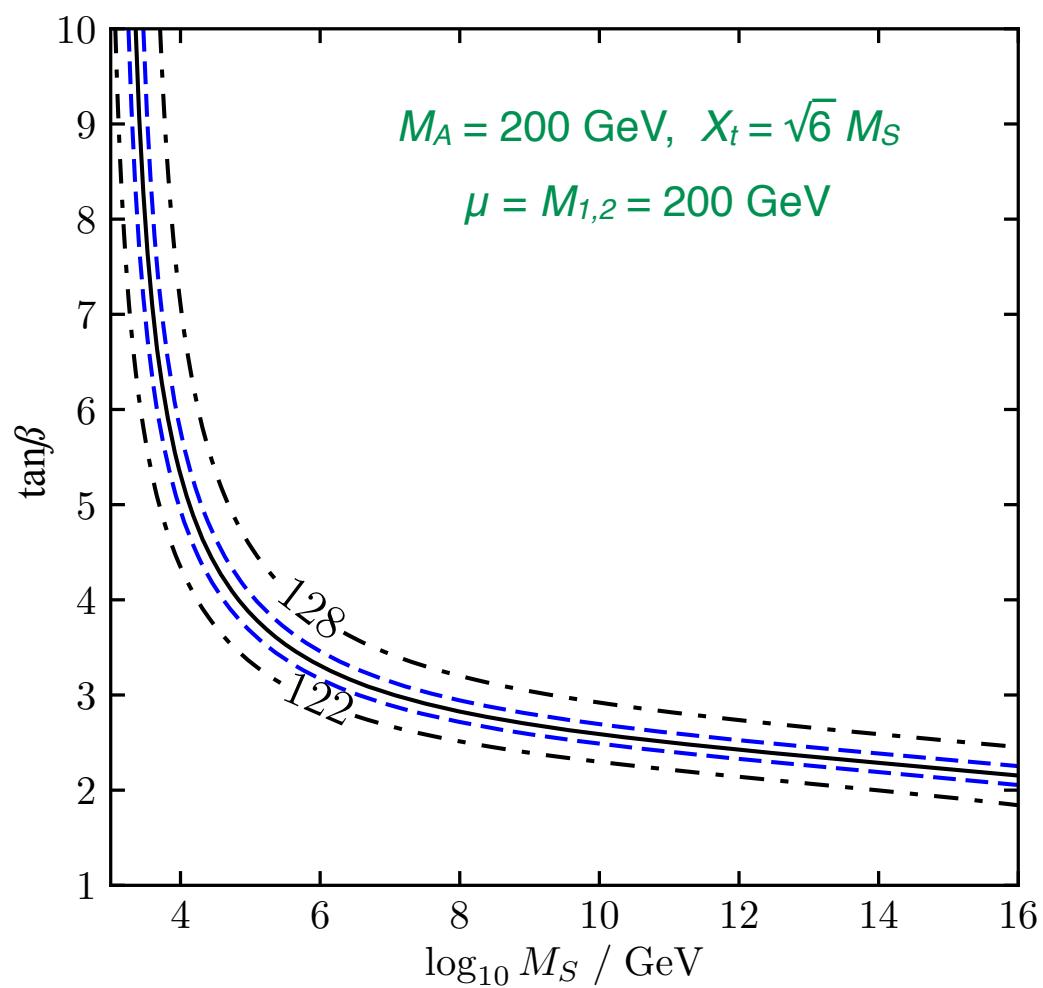


NOTE: can $M_h = 125 \text{ GeV}$ be reached at all for very low M_A and $\tan\beta$?

Light THDM (FlexibleSUSY)

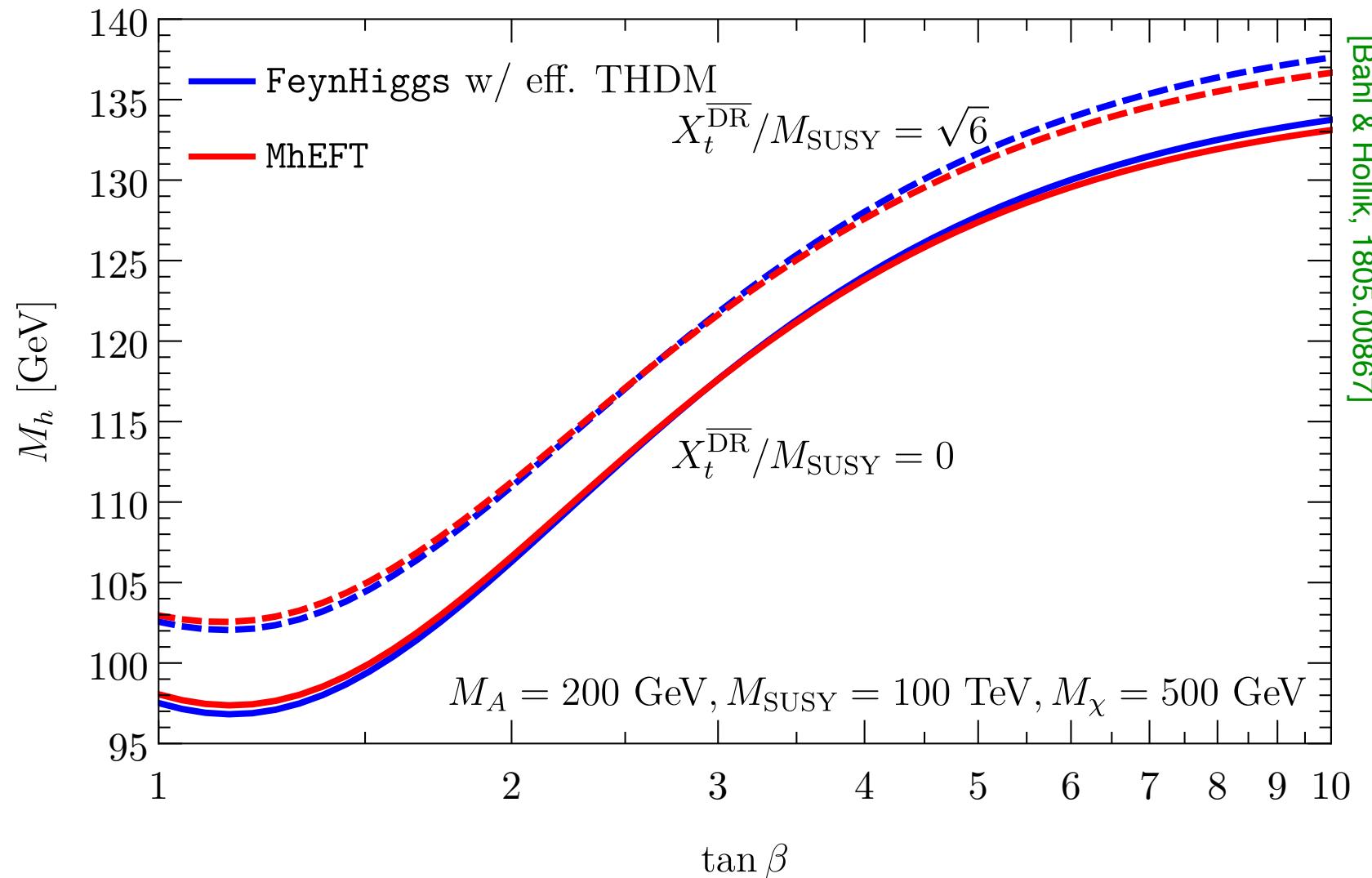


Light THDM + EW-inos (FlexibleSUSY)



NOTE: can $M_h = 125 \text{ GeV}$ be reached at all for very low M_A and $\tan\beta$?

FeynHiggs vs MhEFT



[Bahl & Holl k, 1805.00867]

The small differences are likely due to the improvements of the FeynHiggs calculation
(full 1-loop thresholds and full 2-loop RGEs)

Summary:

Status of the Higgs-mass calculation in the MSSM with heavy SUSY

- The simplest MSSM scenario with all large masses around M_S is well under control
(Full NLL, partial NNLL, partial N^3LL , dim-6 operators, uncertainty estimates...)
- The focus for the MSSM has shifted towards more-complicated mass hierarchies:
Light THDM, light gauginos, light higgsinos and all combinations thereof
(NLL resummation at best – anyway, >2-loop RGEs will be a bottleneck)
- BMSSM scenarios with heavy SUSY have been tackled only by “generic” calculators
(LL resummation in SARAH , NLL resummation in FlexibleEFTHiggs)

Katharsis of Ultimate Theory Standards

9th meeting: 16.-18. July 2018 (Wurzburg Univ.)

Precise Calculation of

(N)

Higgs Boson masses

Organized by:

M. Carena, H. Haber

R. Harlander, S. Heinemeyer

W. Hollik, P. Slavich, G. Weiglein

Local organizer: W. Porod

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Precise Calculations

Next: Dresden, April 2019

(N)

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