Precise Higgs mass calculations in BSM models in light of the recent LHC results

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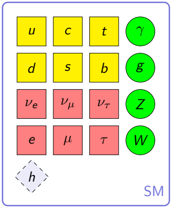
RWTH AACHEN UNIVERSITY

Contents

Open questions before/after the Higgs discovery



Open questions:

- Does the Higgs exist?
- What does DM consist of?
- What causes the deviation of $(g-2)_\mu$?
- Is the vacuum stable up to M_{Pl}?
- Why is $M_h = 125\,\mathrm{GeV}$?
- Is there a solution to the hierarchy problem?
- Can QFT and gravity be unified?

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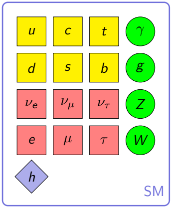

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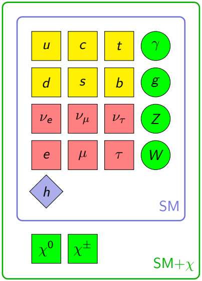

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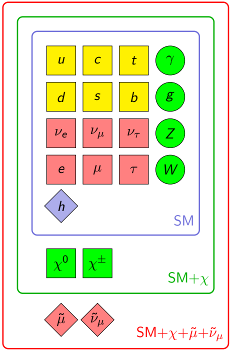

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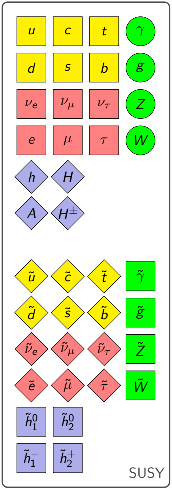

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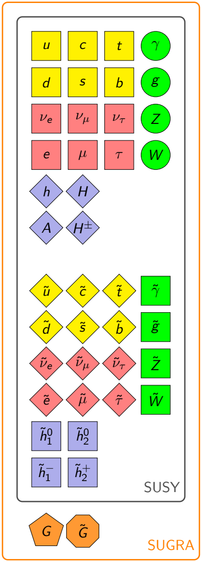

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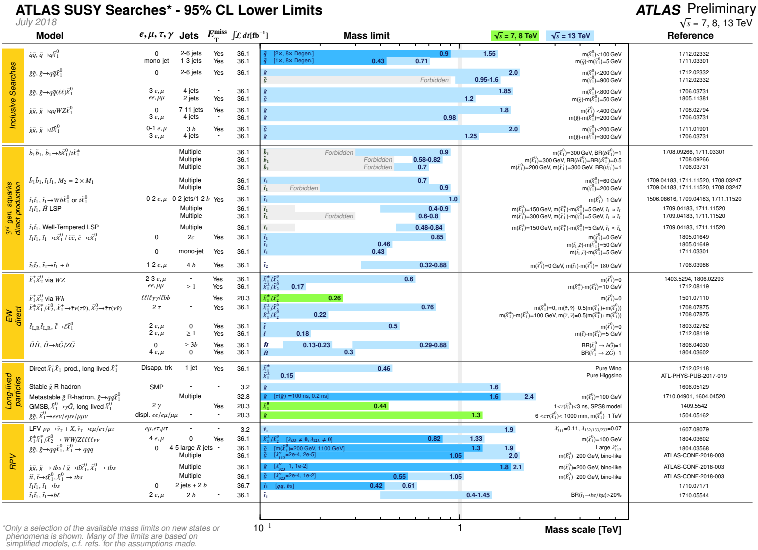
Problem 1: no SUSY particles observed



ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ [2×, 8× Degen.] 0.9 1.55	m($\tilde{\chi}_1^0$)<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
						$\tilde{g}$ Forbidden 0.95-1.6	m($\tilde{\chi}_1^0$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.85	m($\tilde{\chi}_1^0$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	Yes	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 0.98	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}_1^0$)<200 GeV	1711.01901
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1706.03731
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.7	m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1, M_2 = 2\times M_1$		Multiple		36.1	$\tilde{t}_1$ 0.7	m($\tilde{\chi}_1^0$)=60 GeV	1709.04183, 1711.11520, 1708.03247
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.9	m($\tilde{\chi}_1^0$)=200 GeV	1709.04183, 1711.11520, 1708.03247
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$ 1.0	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$ 0.4-0.9	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.6-0.8	m($\tilde{\chi}_1^0$)=300 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}_1^0$	0	2c	Yes	36.1	$\tilde{t}_1$ 0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$ 0.43	m($\tilde{t}_1,\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$ 0.32-0.88	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e,μ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.6	m($\tilde{\chi}_1^0$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.17	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=10 GeV	1712.08119
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.26	m($\tilde{\chi}_1^0$)=0	1501.07110
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.76	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
						$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.22	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=100 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$ 0.5	m($\tilde{\chi}_1^0$)=0	1803.02762
		2 e,μ	≥ 1	Yes	36.1	$\tilde{\ell}$ 0.18	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0	Yes	36.1	$\tilde{H}$ 0.3	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$ 1.6		1606.05129
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4	m($\tilde{\chi}_1^0$)=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 0.44	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$ 1.3	6 <$c\tau(\tilde{\chi}_1^0)$< 1000 mm, m($\tilde{\chi}_1^0$)=1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.82 1.33	m($\tilde{\chi}_1^0$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}, \tilde{g}\to tbs$ / $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8 2.1	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544

**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.*

Problem 2: Tree-level Higgs mass too small

(minimal) SUSY **predicts** at tree-level:

$$m_h = m_Z |\cos 2\beta| \leq m_Z$$

But from experiment we know:

$$M_h \approx 125.09\,\text{GeV}$$
$$M_Z \approx 91.2\,\text{GeV}$$

$\Rightarrow$ **large loop corrections** required!

$$M_h^2 = m_h^2 + \Delta m_h^2 \qquad \Rightarrow \qquad \Delta m_h^2 \geq (85\,\text{GeV})^2$$

How can we test a SUSY model?

Idea:

❶ Calculate M_h as precisely as possible in the SUSY model:

$$M_h^2 = m_h^2 + \Delta m_h^2$$

❷ Constrain the parameter space by requiring:

$$M_h \overset{!}{=} 125.09\,\text{GeV} \pm \Delta M_h^{\text{exp}} \pm \Delta M_h^{\text{theo}}$$

Problem: because of large loop corrections Δm_h^2:

$$\Delta M_h^{\text{theo}} \gtrsim (1\ldots 2)\,\text{GeV} \quad \text{at least!}$$
$$\Delta M_h^{\text{exp}} = 0.24\,\text{GeV}$$

[PDG-2017]

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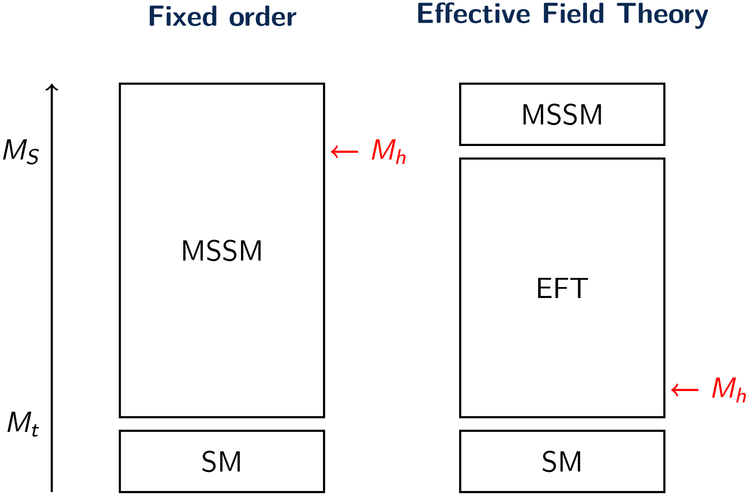
Approaches to predict M_h



Fixed order

Effective Field Theory

M_S

M_t

MSSM

SM

$\leftarrow M_h$

MSSM

EFT

SM

$\leftarrow M_h$

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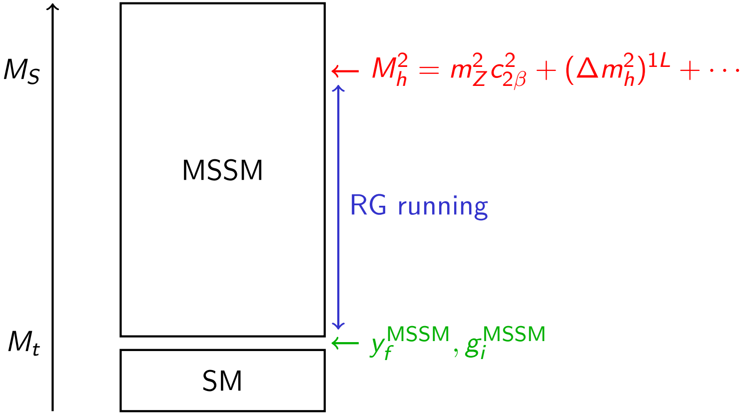
Fixed-order calculation

Input: α_{em}, α_s, G_F, M_Z, M_t, m_b, ...



M_S

$\leftarrow M_h^2 = m_Z^2 c_{2\beta}^2 + (\Delta m_h^2)^{1L} + \cdots$

MSSM

RG running

M_t

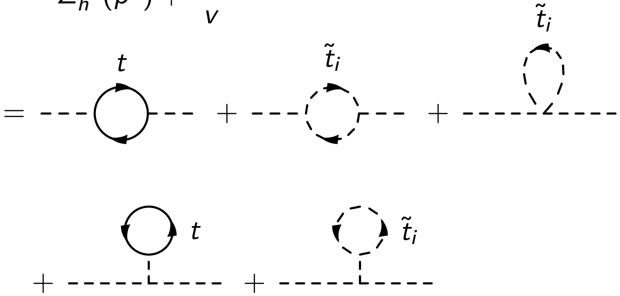
$\leftarrow y_f^{\text{MSSM}}, g_i^{\text{MSSM}}$

SM

Fixed loop order calculation

Dominant contribution to M_h at the 1-loop level:

$$(\Delta m_h^2)^{1L} = -\Sigma_h^{1L}(p^2) + \frac{t_h^{1L}}{v}$$



$$\approx \frac{12 m_t^2 y_t^2}{(4\pi)^2} \left(\ln \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} - \frac{X_t^4}{12 M_S^4} \right) + O(p^2)$$

Higgs mass at 1-loop level

$$(\Delta m_h^2)^{1L} \approx \frac{12 m_t^2 y_t^2}{(4\pi)^2} \left(\ln \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} - \frac{X_t^4}{12 M_S^4} \right) + O(p^2)$$

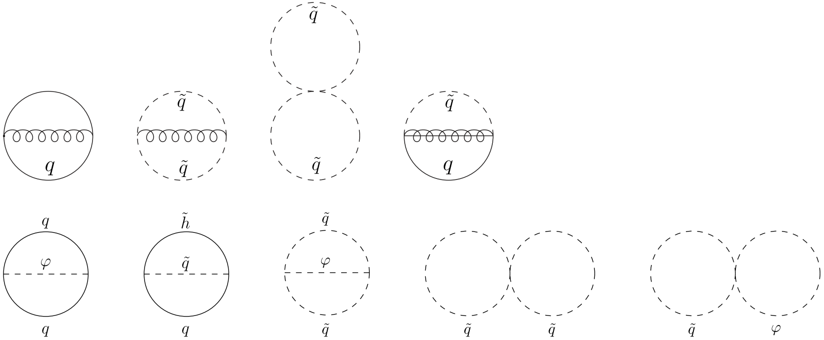
$X_t = A_t - \mu/t_\beta =$ stop mixing parameter, $M_S = (m_Q)_{33} = (m_U)_{33}$

Observations:

- logarithmically enhanced by M_S/m_t
- maximal for $X_t \approx \sqrt{6} M_S$
- high sensitivity on m_t, due to prefactor $m_t^2 y_t^2 = 2 m_t^4 / v^2$
- ambiguity of definition of m_t: pole mass or $\overline{\text{DR}}$ mass?
  $M_t \approx 173.3\,\text{GeV}$, $m_t^{\overline{\text{DR}}} \approx 165\,\text{GeV}$
  $\Rightarrow$ huge theoretical uncertainty!
  $\Rightarrow$ 2-loop calculation needed to resolve this ambiguity
- $M_h \approx 125\,\text{GeV}$ requires $M_S \gtrsim 5\,\text{TeV}$

Higgs mass at 2-loop level

Known contributions: $O(\alpha_s(\alpha_t + \alpha_b) + (\alpha_t + \alpha_b)^2 + \alpha_\tau^2)$ for $p^2 = 0$ [hep-ph/0105096, hep-ph/0112177]



Higgs mass at 2-loop level

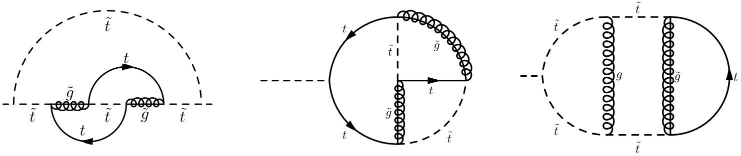
$$
\begin{aligned}
(\Delta m_h^2)^{2L} \approx{}& \frac{m_t^2 y_t^4}{(4\pi)^4} \left(c_1 \ln^2 \frac{M_S^2}{m_t^2} + c_2 \ln \frac{M_S^2}{m_t^2} + c_3 \right) \\
&+ \frac{m_t^2 y_t^2 g_3^2}{(4\pi)^4} \left(c_4 \ln^2 \frac{M_S^2}{m_t^2} + c_5 \ln \frac{M_S^2}{m_t^2} + c_6 \right)
\end{aligned}
$$

Observations:

- logarithmically enhanced by M_S/m_t
- still high sensitivity on m_t
- ambiguity of definition of m_t is resolved ✓
- ambiguity of definition of α_s: $\alpha_s^{\text{SM}}(M_Z)$, $\alpha_s^{\text{MSSM}}(M_S)$, …?
  $\Rightarrow$ 3-loop calculation needed to resolve this ambiguity

Higgs mass at 3-loop level

Known contributions: $O(\alpha_t \alpha_s^2)$ for $p^2 = 0$ [1005.5709]



$$(\Delta m_h^2)^{3L} \approx \frac{m_t^2 y_t^2 g_3^4}{(4\pi)^6} \left(c_7 \ln^3 \frac{M_S^2}{m_t^2} + c_8 \ln^2 \frac{M_S^2}{m_t^2} + c_9 \ln \frac{M_S^2}{m_t^2} + c_{10} \right)$$

Observations:

- logarithmically enhanced by M_S/m_t
- still high sensitivity on m_t
- ambiguity of definition of m_t is resolved ✓
- ambiguity of definition of α_s is resolved ✓

Summary of fixed loop order calculation

Typical order of magnitude of loop contributions (depends on parameter scenario):

$$\begin{aligned} M_h &= m_h + \Delta m_h^{1L} + \Delta m_h^{2L} + \Delta m_h^{3L} + \cdots \\ &\approx [91 + O(20\ldots30) + O(2\ldots4) + O(1\ldots2)]\,\text{GeV} \end{aligned}$$

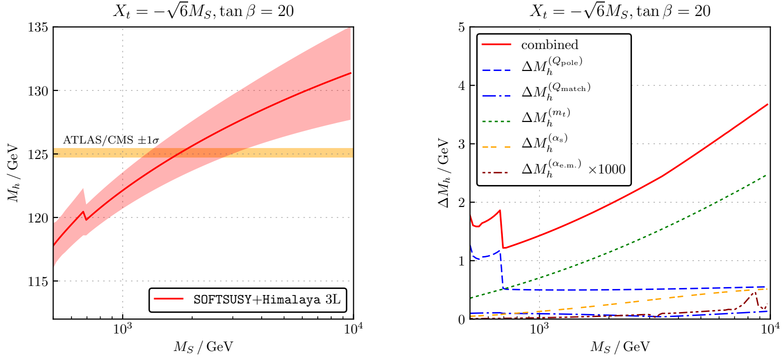
Advantages:

- includes logarithmic and non-logarithmic contributions
- precise prediction if $M_S \sim m_t$

Problem:

- large logarithmic corrections, if $M_S \gg m_t$
  $\Rightarrow$ slow convergence of perturbation series
  $\Rightarrow$ large theoretical uncertainty, (1–2 GeV, or more)

Uncertainty estimate of the fixed-order $\overline{\text{DR}}'$ calculation



[1804.09410]

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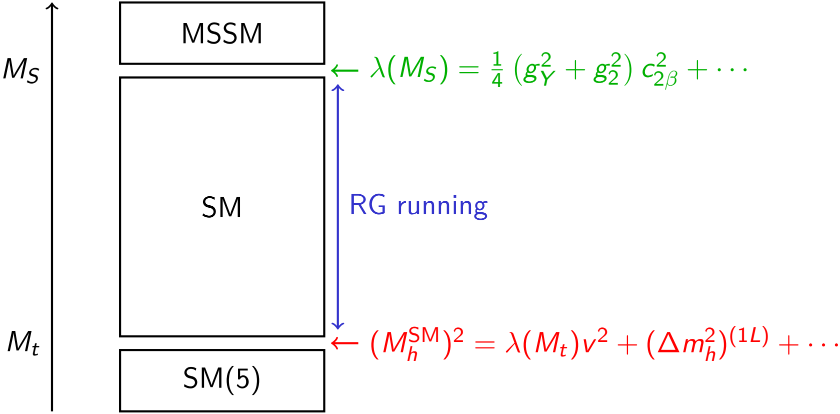
Higgs mass calculation in an EFT

Idea: Decouple SUSY particles at M_S (expand in v^2/M_S^2)
$\Rightarrow \lambda(M_S)$ is fixed by the MSSM



$\leftarrow \lambda(M_S) = \frac{1}{4}\left(g_Y^2 + g_2^2\right) c_{2\beta}^2 + \cdots$

$\leftarrow (M_h^{\text{SM}})^2 = \lambda(M_t) v^2 + (\Delta m_h^2)^{(1L)} + \cdots$

Summary of EFT approach

Typical order of magnitude of loop contributions (depends on parameter scenario, here $X_t = 0$, $M_S = 20\,\text{TeV}$):

$$\begin{aligned} M_h &= m_h + \Delta m_h^{1L} + \Delta m_h^{2L} + \Delta m_h^{3L} + \cdots \\ &\approx [O(124) + O(0.5 \ldots 1) + O(0.1 \ldots 0.2) + O(0.02 \ldots 0.04)]\,\text{GeV} \end{aligned}$$

Advantages:

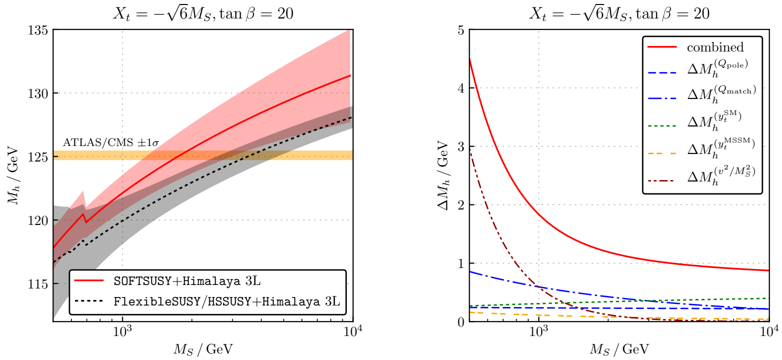
- large logarithmic fixed order loop corrections are avoided
- large logarithms $\propto \ln(M_S/M_t)$ are resummed to all orders

Disadvantage: terms of $O(v^2/M_S^2)$ are neglected

$\Rightarrow$ imprecise when $v \sim M_S$

$\Rightarrow$ large theoretical uncertainty when $v \sim M_S$

Comparison of fixed-order and EFT calculation



$$\Delta M_h^{(\text{FO})} \overset{!}{=} \Delta M_h^{(\text{EFT})}$$

$$\Rightarrow M_S^\text{equal} = 1.0\text{–}1.3\,\text{TeV for small/large } \tan\beta \text{ and/or } X_t$$

[1804.09410]

Summary of fixed-order and EFT approaches

	low M_S $M_S \lesssim 1\,\text{TeV}$	high M_S $M_S \gtrsim 1\,\text{TeV}$
fixed-order	✓	✗
EFT	✗	✓
? mixed	✓	✓

Q: Can the fixed-order and EFT approaches be combined?

A: Yes! [1312.4937, 1609.00371, 1710.03760]

Contents

Hybrid fixed-order/EFT calculation

Goal: resum large logarithms **and** include suppressed $O(v^2/M_S^2)$ terms

Idea I: (“FeynHiggs approach” [1312.4937, 1706.00346, 1805.00867])
Replace logs from fixed-order calculation by resummed logs:

$$M_h^2 = (M_h^2)_{\text{fixed-order}} - (M_h^2)_{\text{logs}} + (M_h^2)_{\text{resummed logs}}$$

Pro:

- ✓ approach applicable to any BSM model
- ✓ any EFT can be used

Contra:

- ✗ requires knowledge of fixed-order and EFT expressions
- ✗ care must be taken to avoid double counting

Hybrid fixed-order/EFT calculation

Idea II: ("FlexibleEFTHiggs" [1609.00371, 1710.03760])
Incorporate $O(v^2/M_S^2)$ terms into λ by using the matching condition

$$\begin{aligned}(M_h^2)_{\text{SM}} &\overset{!}{=} (M_h^2)_{\text{BSM}} \qquad \text{at } Q = M_S \\ \lambda(M_S)v^2 + (\Delta m_h^2)_{\text{SM}} &= (M_h^2)_{\text{BSM}}\end{aligned}$$

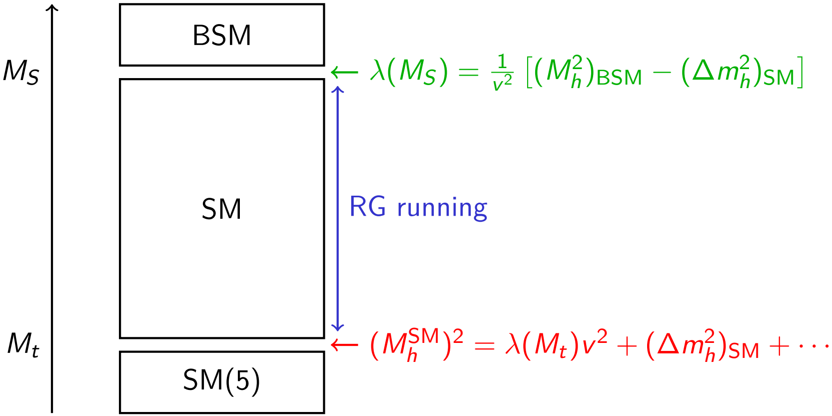
$\Rightarrow$

$$\lambda(M_S) = \frac{1}{v^2}\left[(M_h^2)_{\text{BSM}} - (\Delta m_h^2)_{\text{SM}}\right]$$

Continue as in in the EFT calculation ...

FlexibleEFTHiggs approach

Continue as in the EFT calculation:



$\leftarrow \lambda(M_S) = \frac{1}{v^2}\left[(M_h^2)_{\text{BSM}} - (\Delta m_h^2)_{\text{SM}}\right]$

$\leftarrow (M_h^{\text{SM}})^2 = \lambda(M_t) v^2 + (\Delta m_h^2)_{\text{SM}} + \cdots$

FlexibleEFTHiggs approach

Matching condition:

$$(M_h^2)_{\text{SM}} \overset{!}{=} (M_h^2)_{\text{BSM}}$$

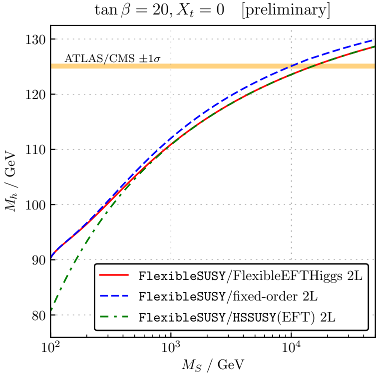
Pro:

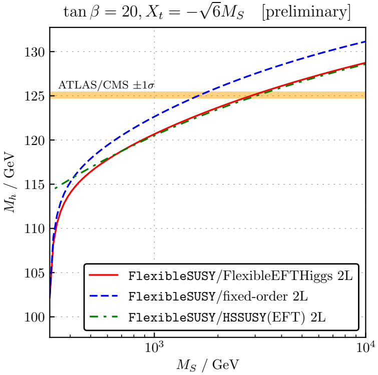
- ✓ approach applicable to any BSM model
- ✓ very simple → easy to automate
- ✓ only BSM fixed-order expressions required

Contra:

- ✗ difficult to extend to other EFTs beyond the SM (2HDM, ...)
- – tricky to reach 2-loop accuracy
  (requires careful treatment of parameter matching)

Comparison of the three approaches in the MSSM





Preliminary work by Thomas Kwasnitza, Dominik Stöckinger, AV

Contents

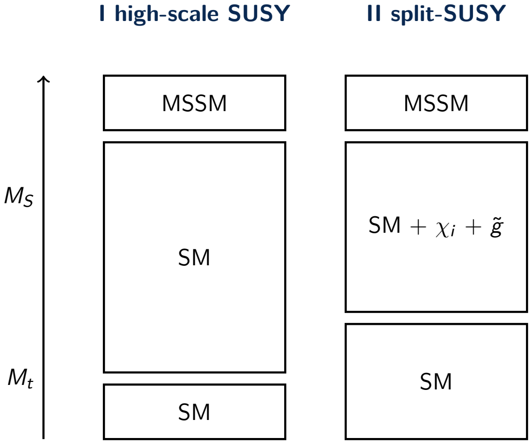
Where is SUSY?

Difficult question!

→ Need to make precise predictions for all parameter scenarios

→ Need to consider all different kinds of EFTs!

Scenarios with 1 light Higgs doublet



I high-scale SUSY

II split-SUSY

MSSM

SM

SM

MSSM

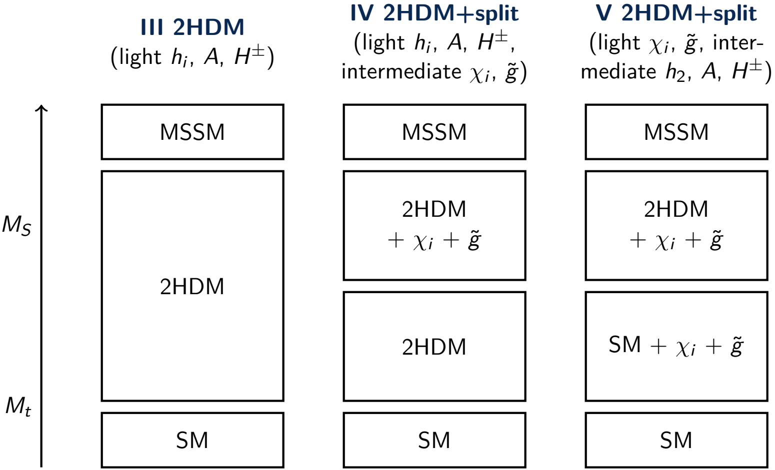
SM + χ_i + $\tilde{g}$

SM

M_S

M_t

Scenarios with 2 light/intermediate Higgs doublets



M_S

M_t

III 2HDM
(light h_i, A, $H^{\pm}$)

MSSM

2HDM

SM

IV 2HDM+split
(light h_i, A, $H^{\pm}$,
intermediate χ_i, $\tilde{g}$)

MSSM

2HDM
$+\ \chi_i + \tilde{g}$

2HDM

SM

V 2HDM+split
(light χ_i, $\tilde{g}$, intermediate h_2, A, $H^{\pm}$)

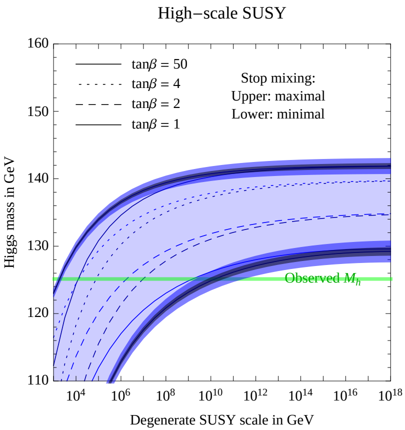
MSSM

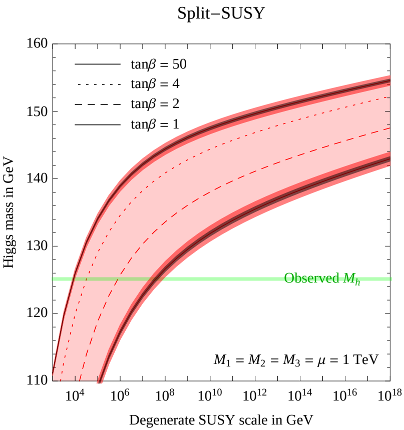
2HDM
$+\ \chi_i + \tilde{g}$

SM $+\ \chi_i + \tilde{g}$

SM

Where is SUSY?





[1407.4081]

Summary

Supersymmetry is still attractive and viable, but $M_S \gtrsim 1\,\text{TeV}$ required in the MSSM to get $M_h = 125.09\,\text{GeV}$.

Higgs mass prediction can be used to constrain SUSY parameter space.

When to use fixed-order/EFT calculation?

- $M_S \lesssim 1\,\text{TeV} \Rightarrow$ use fixed-order
- $M_S \gtrsim 1\,\text{TeV} \Rightarrow$ use EFT

Recent advances in EFT calculations:

Model → EFT	Accuracy	Program
MSSM → SM	$\text{N}^3\text{LO} + \text{N}^3\text{LL}$	FS
MSSM → split-SUSY	$\text{N}^2\text{LO} + \text{NLL}$	FS, FH
MSSM → 2HDM(+split)	$\text{N}^2\text{LO} + \text{NLL}$	FS, FH
any BSM → SM	NLO + NLL	FS, SP*
any BSM → any EFT	NLO + NLL	SP

Prospects

large zoo of models $\Rightarrow$ automation necessary!

Backup

Higgs masses in the SM

Higgs potential

$$V_{\text{Higgs}} = -\mu^2 |\Phi|^2 + \frac{\lambda}{2}|\Phi|^4 = -\frac{\mu^2}{2}(v+h)^2 + \frac{\lambda}{8}(v+h)^4 + \cdots$$

where

$$\Phi = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h) \end{pmatrix}$$

After eliminating μ^2:

$$V_{\text{Higgs}} = \lambda v^2 \frac{h^2}{2} + \cdots \qquad \Rightarrow \qquad m_h^2 = \lambda v^2 \qquad \text{(tree-level)}$$

Until 2012: $M_h = \,? \Leftrightarrow \lambda = \,?$
Since 2012: $M_h \approx 125\,\text{GeV} \Rightarrow \lambda \approx 0.26$

Higgs masses in the (real) MSSM

Higgs potential:

$$V_{\text{Higgs}} = \frac{1}{8}(g_Y^2 + g_2^2)(|h_1|^2 - |h_2|^2)^2 + \frac{g_2^2}{2}|h_1^\dagger h_2|^2 + \cdots$$

where

$$h_1 = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_1 + h_1^0) \\ 0 \end{pmatrix}, \qquad h_2 = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v_2 + h_2^0) \end{pmatrix}$$

After EWSB (if $m_A \gg m_Z$):

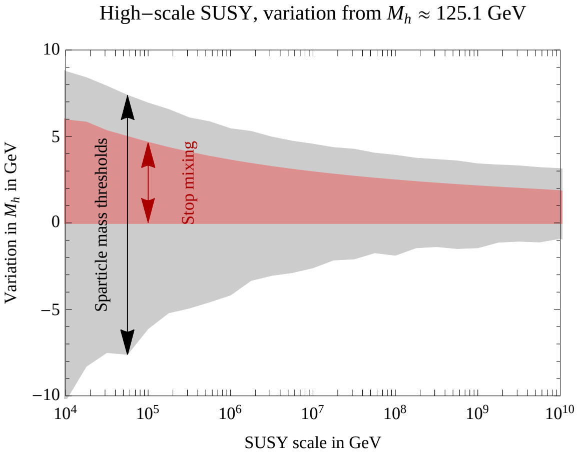
$$V_{\text{Higgs}} \approx \frac{1}{4}(g_Y^2 + g_2^2)v^2 c_{2\beta}^2 \frac{h^2}{2} + \cdots = m_Z^2 c_{2\beta}^2 \frac{h^2}{2} + \cdots$$

⇒ **prediction**:

$$m_h^2 = m_Z^2 \cos^2 2\beta \leq m_Z^2 \approx (91.2\,\text{GeV})^2 \qquad \text{(tree-level)}$$

Where is SUSY?

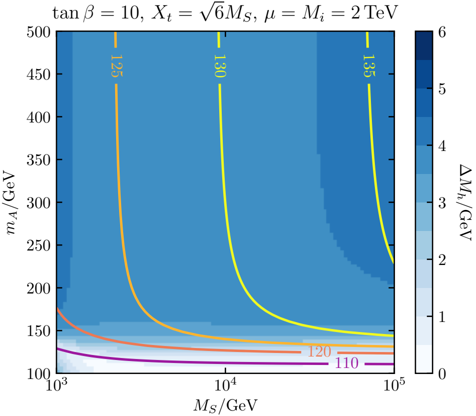
I high-scale SUSY



[1407.4081]

Where is SUSY?

IV THDM+split



Current status of (N)MSSM spectrum generators

MSSM

Spectrum generator	fixed order	EFT	hybrid
`FeynHiggs`	2L	2L	NNLO + NNLL
`FlexibleSUSY`	3L	3L	NNLO + NNLL[†]
`SOFTSUSY`	3L	–	–
`SARAH/SPheno`	2L	–	NNLO + LL

NMSSM

Spectrum generator	fixed order	EFT	hybrid
`FeynHiggs`	–	–	–
`FlexibleSUSY`	2L*	–	NNLO + NNLL[†]
`SOFTSUSY`	2L*	–	–
`SARAH/SPheno`	2L	1L	NNLO + LL

[†] in preparation

[*] $O(\alpha_t^2)$ corrections in the MSSM limit, no $O(\alpha_t \lambda^2)$ corrections

Uncertainty estimate of the fixed-order $\overline{\mathrm{DR}}'$ calculation

Calculation of m_t in two different ways as proposed in [1609.00371]:

$$\begin{aligned}
m_t^{[1]} &= M_t + \widetilde{\Sigma}_t^{(1L),S} + M_t\left[\widetilde{\Sigma}_t^{(1L),L} + \widetilde{\Sigma}_t^{(1L),R}\right] \\
&\quad + M_t\left[\widetilde{\Sigma}_t^{(1L),\mathrm{SQCD}} + \widetilde{\Sigma}_t^{(2L),\mathrm{SQCD}} + \left(\widetilde{\Sigma}_t^{(1L),\mathrm{SQCD}}\right)^2\right] \\
m_t^{[2]} &= M_t + \widetilde{\Sigma}_t^{(1L),S} + m_t\left[\widetilde{\Sigma}_t^{(1L),L} + \widetilde{\Sigma}_t^{(1L),R}\right] \\
&\quad + m_t\left[\widetilde{\Sigma}_t^{(1L),\mathrm{SQCD}} + \widetilde{\Sigma}_t^{(2L),\mathrm{SQCD}}\right]
\end{aligned}$$

Calculation of α_s and α_{em} in two different ways:

$$\begin{aligned}
\alpha_s^{[1]} &= \frac{\alpha_s^{\mathrm{SM}(5)}}{1 - \Delta^{(1L)}\alpha_s - \Delta^{(2L)}\alpha_s} \\
\alpha_s^{[2]} &= \alpha_s^{\mathrm{SM}(5)}\left[1 + \Delta^{(1L)}\alpha_s + (\Delta^{(1L)}\alpha_s)^2 + \Delta^{(2L)}\alpha_s\right]
\end{aligned}$$

Uncertainty estimate of FlexibleEFTHiggs-1L

$$\Delta M_h^{(Q_\text{pole})} = \max_{Q_\text{pole}\in[M_t/2,2M_t]} |M_h(Q_\text{pole}) - M_h(M_t)|$$ [1609.00371]

$$\Delta M_h^{(Q_\text{match})} = \max_{Q_\text{match}\in[M_S/2,2M_S]} |M_h(Q_\text{match}) - M_h(M_S)|$$ [1407.4081]

$$\Delta M_h^{(y_t^\text{SM})} = \left|M_h(y_t^{\text{SM},(2L)}(M_Z)) - M_h(y_t^{\text{SM},(3L)}(M_Z))\right|$$ [1504.05200]

$$\Delta M_h^{(v^2/M_S^2)} = 0 \quad \text{(has no EFT uncertainty!)}$$ [1609.00371]

Uncertainty estimate of fixed-order $\overline{\text{DR}}'$ calculation

In [1804.09410] 5 sources of uncertainty were combined:

$$\Delta M_h^{(Q_\text{pole})} = \max_{Q_\text{pole}\in[M_S/2,2M_S]} |M_h(Q_\text{pole}) - M_h(M_S)|$$ [1609.00371]

$$\Delta M_h^{(Q_\text{match})} = \max_{Q_\text{match}\in[M_Z/2,2M_Z]} |M_h(Q_\text{match}) - M_h(M_Z)|$$ [1804.09410]

$$\Delta M_h^{(m_t)} = \left|M_h(m_t^{[1]}) - M_h(m_t^{[2]})\right|$$ [1609.00371]

$$\Delta M_h^{(\alpha_s)} = \left|M_h(\alpha_s^{[1]}) - M_h(\alpha_s^{[2]})\right|$$ [1804.09410]

$$\Delta M_h^{(\alpha_\text{em})} = \left|M_h(\alpha_\text{em}^{[1]}) - M_h(\alpha_\text{em}^{[2]})\right|$$ [1804.09410]

Combination:

$$\Delta M_h^{(\text{FO})} = \Delta M_h^{(Q_\text{pole})} + \Delta M_h^{(Q_\text{match})} + \Delta M_h^{(m_t)} + \Delta M_h^{(\alpha_s)} + \Delta M_h^{(\alpha_\text{em})}$$

Uncertainty estimate of the EFT calculation

In [1804.09410] 5 sources of uncertainty were combined:

$$\Delta M_h^{(Q_{\text{pole}})} = \max_{Q_{\text{pole}} \in [M_t/2, 2M_t]} \left| M_h(Q_{\text{pole}}) - M_h(M_t) \right|$$ [1609.00371]

$$\Delta M_h^{(Q_{\text{match}})} = \max_{Q_{\text{match}} \in [M_S/2, 2M_S]} \left| M_h(Q_{\text{match}}) - M_h(M_S) \right|$$ [1407.4081]

$$\Delta M_h^{(y_t^{\text{SM}})} = \left| M_h(y_t^{\text{SM},(2L)}(M_Z)) - M_h(y_t^{\text{SM},(3L)}(M_Z)) \right|$$ [1504.05200]

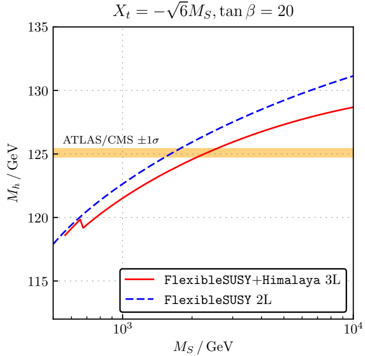
$$\Delta M_h^{(v^2/M_S^2)} = \left| M_h - M_h(v^2/M_S^2) \right|$$ [1504.05200]

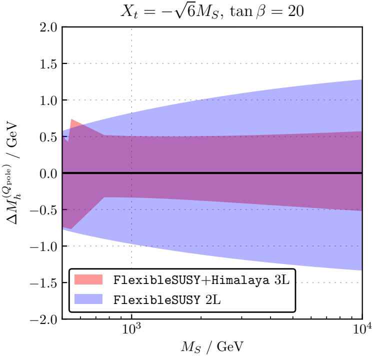
$$\Delta M_h^{(y_t^{\text{MSSM}})} = \left| M_h - M_h(y_t^{\text{MSSM}}(M_S)) \right|$$ [Bagnaschi,AV,Weiglein]

Combination:

$$\Delta M_h^{(\text{EFT})} = \Delta M_h^{(Q_{\text{pole}})} + \Delta M_h^{(Q_{\text{match}})} + \Delta M_h^{(y_t^{\text{SM}})} + \Delta M_h^{(y_t^{\text{MSSM}})} + \Delta M_h^{(v^2/M_S^2)}$$

Effect of the 3-loop $O(\alpha_t\alpha_s^2)$ corrections to M_h

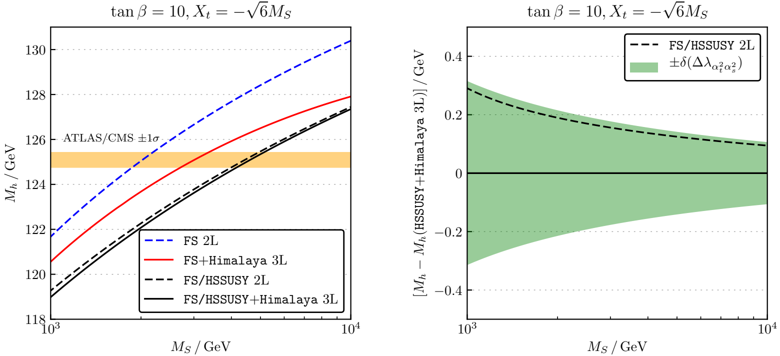




[1708.05720]

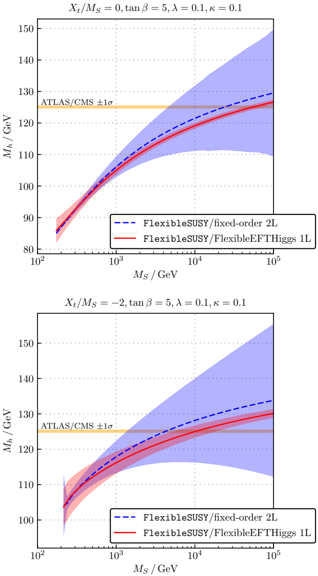
Effect of the 3-loop corrections to $\lambda(M_S)$

3-loop corrections to $\lambda(M_S)$ allow for an N^{3}LL resummation of strong corrections $O(\alpha_t^2\alpha_s^2)$:



[1807.03509]

Fixed-order vs. hybrid calculation in the NMSSM



Gauge Coupling Unification