

# Precise Higgs mass calculations in supersymmetry

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- ① Supersymmetry and the Higgs sector
- ② Higgs mass calculation in the MSSM
  - at fixed loop order
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# Supersymmetry

Still an attractive extension of the Standard Model!

## Features:

- can predict the SM-like Higgs mass (see later)
- gauge coupling unification at  $\sim 10^{16}$  GeV (due to extra matter)
- possible connection to super-gravity models and string theory ( $E_6$ SSM, MRSSM)
- can explain deviation of  $(g - 2)_\mu$
- can stabilize the electroweak vacuum (see later)

**Problem:** LHC has not found any SUSY particles so far  $\Rightarrow$  SUSY particles are probably heavy

# Current limits on SUSY particle masses

## ATLAS SUSY Searches\* - 95% CL Lower Limits

May 2017

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13 \text{ TeV}$

Model	$\epsilon, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$[\mathcal{L} \text{ d}t(\text{fb}^{-1})]$	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$	Reference	
Inclusive Searches	MSUGRA/CMSSM	$0.3, \mu, 1.2, \tau$	2-10 jets/3 b	Yes	20.3	#	1.85 TeV	$m(\tilde{g})=m(\tilde{u})$ 1507.05525	
	$\tilde{g}, \tilde{u}, \tilde{d}$	0	2 jets	Yes	36.1	#	1.57 TeV	$m(\tilde{g})=200 \text{ GeV}, m(\tilde{t}^*) \text{ gen. q}(m, \eta)(m(\tilde{t}^*) \text{ gen. q})$ 1604.07773	
	$\tilde{g}, \tilde{u}, \tilde{d}$ (compressed)	mono-jet	1-3 jets	Yes	3.2	#	908 GeV	$m(\tilde{g})=m(\tilde{t}^*)=5 \text{ GeV}$ ATLAS-CONF-2017-022	
	$\tilde{g}, \tilde{u}, \tilde{d}$	0	2-6 jets	Yes	36.1	#	2.02 TeV	$m(\tilde{g})=200 \text{ GeV}$ ATLAS-CONF-2017-022	
	$\tilde{g}, \tilde{u}, \tilde{d}$	0	2-6 jets	Yes	36.1	#	2.01 TeV	$m(\tilde{g})=200 \text{ GeV}, m(\tilde{t}^*)=0.5 \text{ GeV}, m(\tilde{b}^*)=m(\tilde{g})$ ATLAS-CONF-2017-022	
	$\tilde{g}, \tilde{u}, \tilde{d}$	3	4 jets	Yes	36.1	#	1.825 TeV	$m(\tilde{g})=400 \text{ GeV}$ ATLAS-CONF-2017-030	
	$\tilde{g}, \tilde{u}, \tilde{d}$	0	7-11 jets	Yes	36.1	#	1.8 TeV	$m(\tilde{g})=400 \text{ GeV}$ ATLAS-CONF-2017-033	
	$\tilde{g}, \tilde{u}, \tilde{d}$	1-2 $\tau + 0, 1 \ell$	0-2 jets	Yes	3.2	#	2.0 TeV	$m(\tilde{g})=200 \text{ GeV}$ 1607.05979	
	GMSB (if NLSP)	2 $\gamma$	-	Yes	3.2	#	1.65 TeV	$\tau \rightarrow \text{NLSP} < 0.1 \text{ mm}$ 1606.09150	
	GGM (Higgsino-bino NLSP)	7	1 jet	Yes	20.3	#	1.37 TeV	$m(\tilde{g})=950 \text{ GeV}, m(\text{NLSP}) < 0.1 \text{ mm}, \mu < 0$ ATLAS-CONF-2016-066	
	GGM (Higgsino-bino NLSP)	7	2 jets	Yes	13.8	#	1.8 TeV	$m(\tilde{g})=950 \text{ GeV}, m(\text{NLSP}) < 0.1 \text{ mm}, \mu < 0$ 1503.03390	
	GGM (Higgsino NLSP)	2 $\nu, \mu$ (Z)	2 jets	Yes	20.3	#	900 GeV	$m(\tilde{g})=430 \text{ GeV}$ 1502.01518	
Gravitino LSP	0	mono-jet	Yes	20.3	# <sup>1)</sup>	865 GeV	$m(\tilde{G}) > 1.8 \times 10^{-11} \text{ eV}, m(\tilde{g})=m(\tilde{g})=1.5 \text{ TeV}$		
if $\tilde{g}$ gen. squarks are not	$\tilde{g}, \tilde{u}, \tilde{d}$	0	3 b	Yes	36.1	#	1.92 TeV	$m(\tilde{g})=800 \text{ GeV}$ ATLAS-CONF-2017-021	
	$\tilde{g}, \tilde{u}, \tilde{d}$	0-1 $\nu, \mu$	3 b	Yes	36.1	#	1.97 TeV	$m(\tilde{g})=200 \text{ GeV}$ ATLAS-CONF-2017-021	
	$\tilde{g}, \tilde{u}, \tilde{d}$	0-1 $\nu, \mu$	3 b	Yes	20.1	#	1.37 TeV	$m(\tilde{g})=300 \text{ GeV}$ 1407.8600	
if $\tilde{g}$ gen. squarks are not	$\tilde{g}, \tilde{u}, \tilde{d}$	0	2 b	Yes	36.1	#	990 GeV	$m(\tilde{g})=420 \text{ GeV}$ ATLAS-CONF-2017-038	
	$\tilde{g}, \tilde{u}, \tilde{d}$	2 $\nu, \mu$ (SS)	1 b	Yes	36.1	#	275-700 GeV	$m(\tilde{g})=200 \text{ GeV}, m(\tilde{t}^*)=m(\tilde{b}^*)=100 \text{ GeV}$ ATLAS-CONF-2017-030	
	$\tilde{g}, \tilde{u}, \tilde{d}$	0-2 $\nu, \mu$	1-2 b	Yes	4, 713.3	#	117-170 GeV	$m(\tilde{g})=200 \text{ GeV}, m(\tilde{t}^*)=200-720 \text{ GeV}$ 1309.2102, ATLAS-CONF-2016-077	
	$\tilde{g}, \tilde{u}, \tilde{d}$	0-2 $\nu, \mu$	0-2 jets/1-2 b	Yes	20, 3, 36.1	#	90-196 GeV	$m(\tilde{g})=200 \text{ GeV}, m(\tilde{t}^*)=55 \text{ GeV}$ 1506.08616, ATLAS-CONF-2017-020	
	$\tilde{g}, \tilde{u}, \tilde{d}$	0	mono-jet	Yes	3.2	#	90-323 GeV	$m(\tilde{g})=100 \text{ GeV}$ 1604.07773	
	$\tilde{g}, \tilde{u}, \tilde{d}$ (natural GMSB)	2 $\nu, \mu$ (Z)	1 b	Yes	20.3	#	150-600 GeV	$m(\tilde{g})=150 \text{ GeV}$ 1403.5222	
	$\tilde{g}, \tilde{u}, \tilde{d}$	3 $\nu, \mu$ (Z)	1 b	Yes	36.1	#	290-790 GeV	$m(\tilde{g}) > 0 \text{ GeV}$ ATLAS-CONF-2017-019	
	$\tilde{g}, \tilde{u}, \tilde{d}$	1-2 $\nu, \mu$	4 b	Yes	36.1	#	320-850 GeV	$m(\tilde{g}) > 0 \text{ GeV}$ ATLAS-CONF-2017-019	
	$\tilde{g}, \tilde{u}, \tilde{d}$	2 $\nu, \mu$	0	Yes	36.1	#	90-440 GeV	$m(\tilde{g})=0$ ATLAS-CONF-2017-039	
	$\tilde{g}, \tilde{u}, \tilde{d}$	2 $\nu, \mu$	0	Yes	36.1	#	719 GeV	$m(\tilde{g})=0, m(\tilde{t}^*)=0.5 m(\tilde{t}^*)=m(\tilde{t}^*)$ ATLAS-CONF-2017-038	
	$\tilde{g}, \tilde{u}, \tilde{d}$	2 $\nu, \mu$	0	Yes	36.1	#	760 GeV	$m(\tilde{g})=0, m(\tilde{t}^*)=0.5 m(\tilde{t}^*)=m(\tilde{t}^*)$ ATLAS-CONF-2017-035	
	$\tilde{g}, \tilde{u}, \tilde{d}$	2 $\nu, \mu$	0	Yes	36.1	#	1.16 TeV	$m(\tilde{g})=0, m(\tilde{t}^*)=0.5 m(\tilde{t}^*)=m(\tilde{t}^*)$ ATLAS-CONF-2017-039	
EW direct	$\tilde{g}, \tilde{u}, \tilde{d}$	3 $\nu, \mu$	0-2 jets	Yes	36.1	#	580 GeV	$m(\tilde{g})=m(\tilde{t}^*), m(\tilde{t}^*)=0, m(\tilde{b}^*)=0.5 m(\tilde{b}^*)=m(\tilde{b}^*)$ ATLAS-CONF-2017-039	
	$\tilde{g}, \tilde{u}, \tilde{d}$	2-3 $\nu, \mu$	0-2 jets	Yes	36.1	#	270 GeV	$m(\tilde{g})=m(\tilde{t}^*), m(\tilde{t}^*)=0, \tilde{f}$ decoupled ATLAS-CONF-2017-039	
	$\tilde{g}, \tilde{u}, \tilde{d}$	3 $\nu, \mu$	0	Yes	20.3	#	635 GeV	$m(\tilde{g})=m(\tilde{t}^*), m(\tilde{t}^*)=0, m(\tilde{b}^*)=0.5 m(\tilde{b}^*)=m(\tilde{b}^*)$ 1405.5086	
	GGM (wino NLSP) weak prod., $\tilde{t}^* \rightarrow \tilde{t}^* \tilde{G}$	1 $\nu, \mu + \gamma$	-	Yes	20.3	#	115-370 GeV	$\tau < 1 \text{ mm}$ 1507.05493	
	GGM (bino NLSP) weak prod., $\tilde{t}^* \rightarrow \tilde{t}^* \tilde{G}$	2 $\gamma$	-	Yes	20.3	#	590 GeV	$\tau < 1 \text{ mm}$ 1507.05493	
	Long-lived particles	Direct $\tilde{t}^* \tilde{t}^*$ prod., long-lived $\tilde{t}^*$	Disapp. trk	1 jet	Yes	36.1	#	430 GeV	$m(\tilde{g})=m(\tilde{t}^*)=160 \text{ MeV}, \tau(\tilde{t}^*) > 2 \text{ ns}$ ATLAS-CONF-2017-017
		Direct $\tilde{t}^* \tilde{t}^*$ prod., long-lived $\tilde{t}^*$	dE/dx trk	-	Yes	18.4	#	405 GeV	$m(\tilde{g})=m(\tilde{t}^*)=180 \text{ MeV}, \tau(\tilde{t}^*) > 15 \text{ ns}$ 1506.09332
		Stable $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	#	850 GeV	$m(\tilde{g})=100 \text{ GeV}, 10 \mu\text{s} < \tau < 1000 \text{ s}$ 1309.25684
		Metastable $\tilde{g}$ R-hadron	trk	-	3.2	#	-	1.58 TeV	$m(\tilde{g})=100 \text{ GeV}, \tau > 10 \text{ ns}$ 1606.05129
		Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	3.2	#	-	1.57 TeV	$m(\tilde{g})=100 \text{ GeV}, \tau > 10 \text{ ns}$ 1604.04520
		GMSB, stable $\tilde{f}, \tilde{t}^* \rightarrow (\tilde{f}, \tilde{b}^*) + (\nu, \mu)$	1-2 $\mu$	-	Yes	19.1	#	537 GeV	$10 < \text{cmap} < 50$ 1411.6795
		GMSB, $\tilde{t}^* \rightarrow \tilde{t}^* \tilde{G}$ , long-lived $\tilde{t}^*$	2 $\gamma$	-	Yes	20.3	#	440 GeV	$1 < \tau(\tilde{t}^*) < 2 \text{ ns}, \text{SPS8 model}$ 1409.5042
GGM $\tilde{g}, \tilde{t}^* \rightarrow \tilde{t}^* \tilde{G}$		displ. vtx $\mu$ / $\mu$ / $\mu$	-	Yes	20.3	#	1.0 TeV	$7 < \tau(\tilde{t}^*) < 740 \text{ mm}, m(\tilde{t}^*)=1.3 \text{ TeV}$ 1504.05162	
GGM $\tilde{g}, \tilde{t}^* \rightarrow \tilde{t}^* \tilde{G}$		displ. vtx $\mu$ - jets	-	Yes	20.3	#	1.0 TeV	$6 < \tau(\tilde{t}^*) < 480 \text{ mm}, m(\tilde{t}^*)=1.1 \text{ TeV}$ 1504.05162	
RPV		LFV $\tilde{g} \tilde{g} \tilde{g} + X, \tilde{t}^* \rightarrow \tilde{t}^* \nu \tau / \mu \tau$	$\nu \mu, \nu \tau$	-	Yes	3.2	#	1.9 TeV	$A_{12} < 0.11, A_{13} < 0.0000007$ 1607.28079
		Bilinear RPV CMSSM	2 $\nu, \mu$ (SS)	0-3 b	Yes	20.3	#	1.45 TeV	$m(\tilde{g})=m(\tilde{t}^*), \tau_{\text{RPV}} < 1 \text{ mm}$ 1404.2500
		$\tilde{g}, \tilde{u}, \tilde{d}$	4 $\nu, \mu + \tau$	-	Yes	13.3	#	1.14 TeV	$m(\tilde{g})=400 \text{ GeV}, A_{13, \mu \tau} > 0 (\mu = 1, 2)$ ATLAS-CONF-2016-075
	$\tilde{g}, \tilde{u}, \tilde{d}$	3 $\nu, \mu + \tau$	-	Yes	20.3	#	450 GeV	$m(\tilde{g}) > 0.2 \text{ mm}, A_{13, \mu \tau} > 0$ 1405.5086	
	$\tilde{g}, \tilde{u}, \tilde{d}$	0	4-5 large- $\theta$ jets	-	14.8	#	1.08 TeV	$\text{BR}(\tilde{g} \rightarrow \text{RPV}) < \text{BR}(\tilde{g} \rightarrow \text{SM})$ ATLAS-CONF-2016-057	
	$\tilde{g}, \tilde{u}, \tilde{d}$	1 $\nu, \mu$	8-10 jets/0-4 b	-	36.1	#	1.55 TeV	$m(\tilde{g})=800 \text{ GeV}$ ATLAS-CONF-2016-057	
	$\tilde{g}, \tilde{u}, \tilde{d}$	1 $\nu, \mu$	8-10 jets/0-4 b	-	36.1	#	2.1 TeV	$m(\tilde{g})=1 \text{ TeV}, A_{12, \mu \tau} > 0$ ATLAS-CONF-2017-013	
	$\tilde{g}, \tilde{u}, \tilde{d}$	1 $\nu, \mu$	8-10 jets/0-4 b	-	15.4	#	1.65 TeV	$m(\tilde{g})=1 \text{ TeV}, A_{12, \mu \tau} > 0$ ATLAS-CONF-2017-013	
	$\tilde{g}, \tilde{u}, \tilde{d}$	0	2 jets + 2 b	-	15.4	#	410 GeV	$\text{BR}(\tilde{g} \rightarrow \text{RPV}) < 20\%$ ATLAS-CONF-2016-022, ATLAS-CONF-2016-084	
	$\tilde{g}, \tilde{u}, \tilde{d}$	2 $\nu, \mu$	2 b	-	36.1	#	0.4-1.45 TeV	$m(\tilde{g})=200 \text{ GeV}$ ATLAS-CONF-2017-036	
	Other	Scalar charm, $\tilde{c} \rightarrow c \tilde{t}^*$	0	2 $\nu$	Yes	20.3	#	510 GeV	$m(\tilde{g})=200 \text{ GeV}$ 1501.01325

\*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.

10<sup>-1</sup> 1 Mass scale [TeV]

## CP-even Higgs masses in the real MSSM

$$(\text{Im } H_d^0, \text{Im } H_u^0) \xrightarrow{\beta} (G^0, A), \quad (\text{Re } H_d^0, \text{Re } H_u^0) \xrightarrow{\alpha} (h, H):$$

$$m_{h,H}^2 = \frac{1}{2} \left[ m_Z^2 + m_A^2 \mp \sqrt{(m_Z^2 + m_A^2)^2 - 4m_Z^2 m_A^2 c_{2\beta}^2} \right]$$

If  $m_A \gg m_Z \Rightarrow$

$$m_h^2 \approx m_Z^2 c_{2\beta}^2 \leq (91.2 \text{ GeV})^2 \quad (\text{tree-level})$$

$\Rightarrow M_h \approx 125 \text{ GeV}$  requires **large loop corrections!**

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

Because of large loop corrections  $\Delta m_h^2$ :

$$\Delta M_h^{\text{theo}} \gtrsim (1 \dots 2) \text{ GeV} \quad \text{at least!}$$

$$\Delta M_h^{\text{exp}} = 0.24 \text{ GeV} \quad [\text{PDG-2017}]$$

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# Fixed loop order calculation

Dominant contribution to  $M_h$  at the 1-loop level:

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

$$= \text{---} \text{---} \text{---} + \text{---} \text{---} \text{---} + \text{---} \text{---} \text{---}$$

$$+ \text{---} \text{---} \text{---} + \text{---} \text{---} \text{---}$$

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



# Summary of fixed loop order calculation

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

$$\begin{aligned} M_h &= m_h + \Delta m_h^{1L} + \Delta m_h^{2L} + \Delta m_h^{3L} + \dots \\ &\approx [91 + O(20 \dots 30) + O(2 \dots 4) + O(1 \dots 2)] \text{ GeV} \end{aligned}$$

## Advantages:

- includes logarithmic, non-logarithmic and suppressed terms of the order  $O(v^2/M_S^2)$  at fixed loop order
- 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)
- $$M_h^{\text{exp}} = (125.09 \pm 0.24) \text{ GeV}$$

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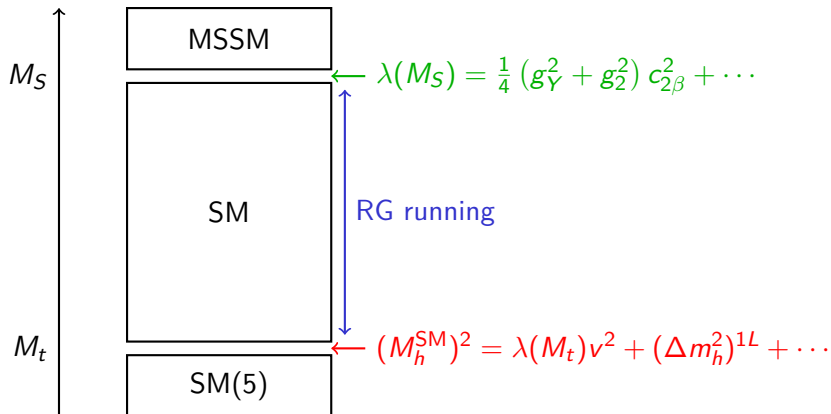
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# Higgs mass calculation in an EFT

**Idea:** Integrate out SUSY particles at  $M_S$  (expand in  $v^2/M_S^2$ )

$\Rightarrow \lambda(M_S)$  is fixed by the MSSM

$\Rightarrow$  effectively: separation of scales  $M_S$  and  $M_t$ .



# Summary of EFT approach

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

$$M_h = m_h + \Delta m_h^{1L} + \Delta m_h^{2L} + \Delta m_h^{3L} + \dots$$
$$\approx [O(124) + O(0.5 \dots 1) + O(0.1 \dots 0.2) + O(0.02 \dots 0.04)] \text{ GeV}$$

## Advantages:

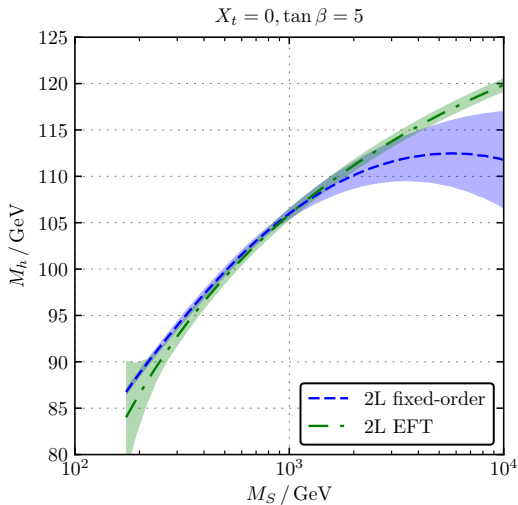
- large logarithmic fixed order loop corrections are avoided
- large logarithms  $\propto \ln(M_S/M_t)$  are resummed to all orders

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

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

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

# Comparison of fixed-order and EFT approaches



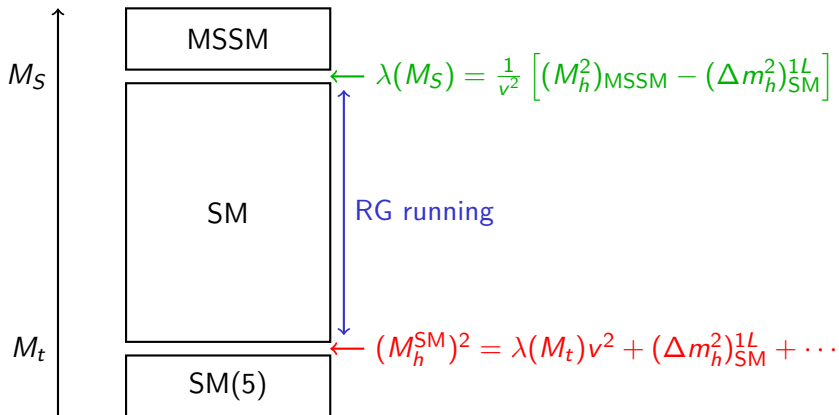
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# FlexibleEFTHiggs approach [arXiv:1609.00371]

**Idea:** Determine  $\lambda(M_S)$  from the condition

$$(M_h^2)_{\text{SM}} \equiv \lambda(M_S)v^2 + (\Delta m_h^2)_{\text{SM}}^{1L} \stackrel{!}{=} (M_h^2)_{\text{MSSM}} \quad 1L, Q = M_S$$



# Summary FlexibleEFTHiggs approach

$$(M_h^2)_{\text{SM}} = (M_h^2)_{\text{MSSM}} \quad 1\text{L}, Q = M_S$$

## Advantages:

- large logarithms  $\propto \ln(M_S/M_t)$  are resummed to all orders
- all suppressed terms  $O(v^2/M_S^2)$  are incorporated in  $\lambda$

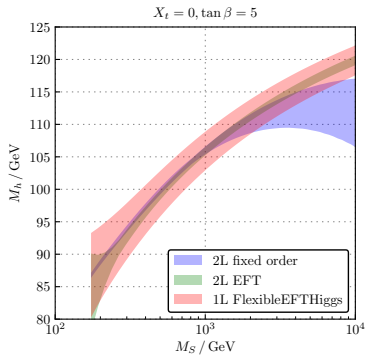
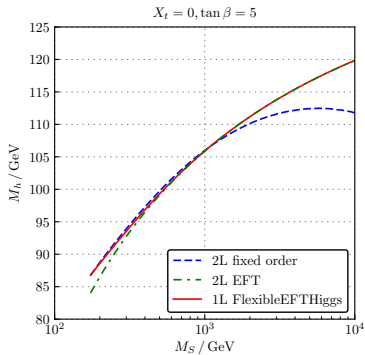
⇒ FlexibleEFTHiggs leads to a correct Higgs mass prediction at the full 1-loop level (including suppressed terms) with additional (N)LL resummation.

## Disadvantage:

- tricky to extend to 2-loop accuracy



# Comparison of the three approaches



# Summary

**Supersymmetry** is still viable, but LHC continuously excludes light SUSY scenarios

**Approaches to calculate  $M_h$ :**

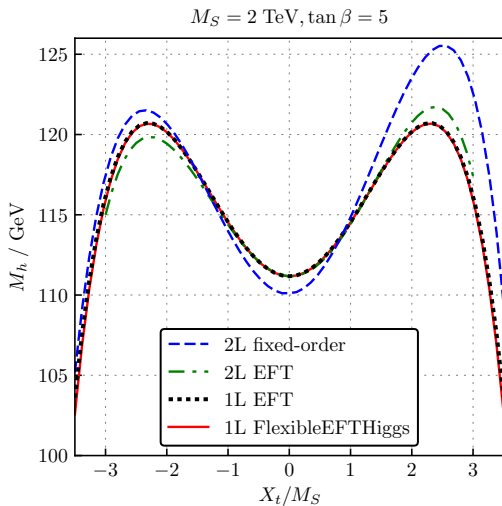
	low $M_S$ $M_S \lesssim 2 \text{ TeV}$	high $M_S$ $M_S \gtrsim 2 \text{ TeV}$
fixed-order	✓	✗
EFT	✗	✓
mixed (FlexibleEFTHiggs)	✓	✓

**FlexibleEFTHiggs:**

- full NLO + (N)LL resummation
- can be applied to **any** BSM model (SUSY or non-SUSY)
- can be easily automatized

# Backup

# Comparison of the three approaches



# FlexibleEFT Higgs – EFT equivalence

**Proof of equivalence:** Start with matching condition:

$$(M_h^2)_{\text{SM}} = (M_h^2)_{\text{MSSM}} \quad 1L, Q = M_S$$
$$\lambda v^2 + (\Delta m_h^2)_{\text{SM}}^{1L} = (M_h^2)_{\text{MSSM}}$$

$\Rightarrow$

$$\begin{aligned} \lambda(M_S) &= \frac{1}{v^2} \left[ (M_h^2)_{\text{MSSM}} - (\Delta m_h^2)_{\text{SM}}^{1L} \right] \\ &= \frac{1}{v^2} \left[ (m_h^2)_{\text{MSSM}} + (\Delta m_h^2)_{\text{MSSM}}^{1L} - (\Delta m_h^2)_{\text{SM}}^{1L} \right] \end{aligned}$$

Now insert  $(m_h^2)_{\text{MSSM}}$  and  $(\Delta m_h^2)_{\text{MSSM}}^{1L} \dots$

# FlexibleEFTHiggs – EFT equivalence

Inserting  $(m_h^2)_{\text{MSSM}}$  and  $(\Delta m_h^2)_{\text{MSSM}}^{1L}$  for  $X_t = 0$ :

$$\lambda(M_S) = \frac{1}{v^2} \left[ \frac{1}{4} (g_Y^2 + g_2^2) v^2 c_{2\beta}^2 + \frac{c_\alpha^2}{s_\beta^2} (\Delta m_h^2)_{\text{SM}}^{1L} - \frac{c_\alpha^2}{s_\beta^2} \frac{12 (y_t^{\text{SM}})^2 m_t^2}{(4\pi)^2} B_0(m_h^2, M_S^2, M_S^2) - (\Delta m_h^2)_{\text{SM}}^{1L} \right]$$

Now go to the decoupling limit  $c_\alpha^2/s_\beta^2 \rightarrow 1 \dots$

## FlexibleEFTHiggs – EFT equivalence

In the decoupling limit  $c_\alpha^2/s_\beta^2 \rightarrow 1$ :

$$\begin{aligned}\lambda(M_S) &= \frac{1}{4}(g_Y^2 + g_2^2)c_{2\beta}^2 - 12 \frac{m_t^2(y_t^{\text{SM}})^2}{(4\pi)^2 v^2} B_0(m_h^2, M_S^2, M_S^2) \\ &= \frac{1}{4}(g_Y^2 + g_2^2)c_{2\beta}^2 - 12 \frac{m_t^2(y_t^{\text{SM}})^2}{(4\pi)^2 v^2} \left[ -\log \frac{M_S^2}{Q^2} + \frac{m_h^2}{6M_S^2} + O\left(\frac{m_h^4}{M_S^4}\right) \right] \\ &= \frac{1}{4}(g_Y^2 + g_2^2)c_{2\beta}^2 + 12 \frac{m_t^2(y_t^{\text{SM}})^2}{(4\pi)^2 v^2} \left[ \log \frac{M_S^2}{Q^2} \right] + O\left(\frac{v^2}{M_S^2}\right) \\ &= \lambda^{\text{EFT,tree}} + \Delta\lambda^{\text{EFT,1L}} + O\left(\frac{v^2}{M_S^2}\right)\end{aligned}$$

In the decoupling limit  $\lambda(M_S)$  in the FlexibleEFTHiggs approach is equivalent to the EFT approach at 1-loop, up to suppressed terms  $O(v^2/M_S^2)$

# Higgs mass uncertainty estimate

## fixed-order:

- $|M_h^{2L}(Q_{\text{pole}} = M_S/2) - M_h^{2L}(Q_{\text{pole}} = 2M_S)|$
- $|M_h^{2L}(y_t^{1L}) - M_h^{2L}(y_t^{2L})|$

## EFT (SUSYHD):

- $|M_h^{2L}(Q_{\text{pole}} = M_t/2) - M_h^{2L}(Q_{\text{pole}} = 2M_t)|$
- $|M_h^{2L}(y_t^{2L}) - M_h^{2L}(y_t^{3L})|$
- $|M_h^{2L}(Q_{\text{match}} = M_S/2) - M_h^{2L}(Q_{\text{match}} = 2M_S)|$
- $|M_h^{2L} - M_h^{2L}(\lambda \rightarrow \lambda(1 + v^2/M_S^2))|$

## FlexibleEFTHiggs:

- $|M_h^{2L}(Q_{\text{pole}} = M_t/2) - M_h^{2L}(Q_{\text{pole}} = 2M_t)|$
- $|M_h^{2L}(y_t^{2L}) - M_h^{2L}(y_t^{3L})|$
- $|M_h^{2L}(Q_{\text{match}} = M_S/2) - M_h^{2L}(Q_{\text{match}} = 2M_S)|$



# Incorrect 2L logs in original FlexibleEFTHiggs-1L

Matching condition:

$$\lambda \leftarrow \frac{1}{v^2} \left[ (m_h^{\text{SM}})^2 + (M_h^{\text{MSSM}})^2 - (M_h^{\text{SM}})^2 \right]$$

Expansion of momentum iteration up to 1L level:

$$\lambda = \frac{1}{v^2} \left[ (m_h^{\text{MSSM}})^2 + \Delta m_{h,\text{MSSM}}^2 - \Delta m_{h,\text{SM}}^2 + \mathcal{O}(\hbar^2) \right]$$

with

$$\begin{aligned} \Delta m_{h,\text{MSSM}}^2 &= -\Sigma_{\text{MSSM}}^{1L} + t_{\text{MSSM}}^{1L}/v_{\text{MSSM}} \\ \Delta m_{h,\text{SM}}^2 &= -\Sigma_{\text{SM}}^{1L} + t_{\text{SM}}^{1L}/v_{\text{SM}} \end{aligned}$$

# Incorrect 2L logs in original FlexibleEFTHiggs-1L

**Problem:**  $y_t^{\text{MSSM}} = y_t^{\text{SM}}/s_\beta[1 + O(\hbar)]$

$\Rightarrow$

$$\begin{aligned}\Delta m_{h,\text{MSSM}}^2 - \Delta m_{h,\text{SM}}^2 &\propto \hbar \left[ (y_t^{\text{MSSM}} s_\beta)^4 \log \frac{m_t}{M_S} - (y_t^{\text{SM}})^4 \log \frac{m_t}{M_S} \right] \\ &= \hbar \left[ 0 + \propto \hbar y_t^4 \log \frac{m_t}{M_S} + O(\hbar^2) \right] \\ &= O(\hbar^2 y_t^4 \log \frac{m_t}{M_S})\end{aligned}$$

$\Rightarrow$

incorrect 2L logs remain in FlexibleEFTHiggs-1L