Precise Higgs mass prediction in SUSY and non-SUSY models

Alexander Voigt

Aachen–Bonn–Heidelberg–Mainz research group meeting
"The Future of Searches for Invisible Particles"

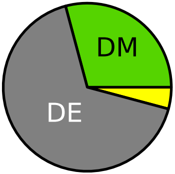
14.12.2017

RWTH AACHEN UNIVERSITY

Contents

Contents

Why to search for physics beyond the SM?

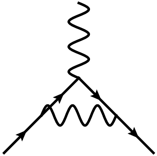


Questions:

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

Many proposed BSM models to address some of these questions:
Supersymmetry, Dark Matter models, extra dimensions, . . .

Why to search for physics beyond the SM?

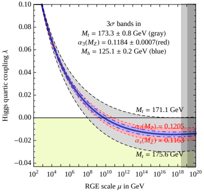


Questions:

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

Many proposed BSM models to address some of these questions: Supersymmetry, Dark Matter models, extra dimensions, ...

Why to search for physics beyond the SM?



Questions:

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

Many proposed BSM models to address some of these questions: Supersymmetry, Dark Matter models, extra dimensions, ...

Why to search for physics beyond the SM?

$$\boxed{M_h^2 = \lambda v^2 + \cdots}$$

Questions:

- What does Dark Matter consist of?
- What causes the deviation of $(g-2)_\mu$?
- Is the vacuum stable up to M_{Pl}?
- Why is $M_h = 125\,\text{GeV}$?
- Can the SM Yukawa couplings be predicted?
- Is there a solution to the hierarchy problem?
- Can the SM and gravity be unified?

Many proposed BSM models to address some of these questions: Supersymmetry, Dark Matter models, extra dimensions, . . .

Why to search for physics beyond the SM?

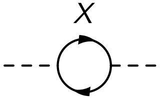
$$\boxed{\mathcal{L} = y_{ij}\phi\psi_i\psi_j + \cdots}$$

Questions:

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

Many proposed BSM models to address some of these questions:
Supersymmetry, Dark Matter models, extra dimensions, . . .

Why to search for physics beyond the SM?

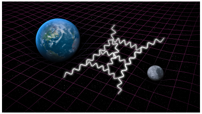


Questions:

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

Many proposed BSM models to address some of these questions: Supersymmetry, Dark Matter models, extra dimensions, ...

Why to search for physics beyond the SM?

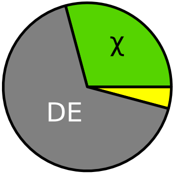

[SLAC]

Questions:

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

Many proposed BSM models to address some of these questions: Supersymmetry, Dark Matter models, extra dimensions, . . .

Supersymmetry



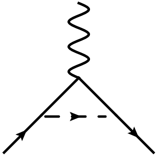
Still an attractive extension of the Standard Model!
But not necessarily minimal Supersymmetry.

Features:

- can provide a Dark Matter candidate
- can explain deviation of $(g-2)_\mu$
- can stabilize the electroweak vacuum (see later)
- can predict the SM-like Higgs mass (see later)
- can predict the SM Yukawa couplings
- can solve the hierarchy problem
- possible connection to super-gravity models and String Theory

Problem: LHC has not found any SUSY particles so far ⇒ SUSY particles are probably heavy

Supersymmetry



Still an attractive extension of the Standard Model!
But not necessarily minimal Supersymmetry.

Features:

- can provide a Dark Matter candidate
- can explain deviation of $(g-2)_\mu$
- can stabilize the electroweak vacuum (see later)
- can predict the SM-like Higgs mass (see later)
- can predict the SM Yukawa couplings
- can solve the hierarchy problem
- possible connection to super-gravity models and String Theory

Problem: LHC has not found any SUSY particles so far ⇒ SUSY particles are probably heavy

Supersymmetry

Still an attractive extension of the Standard Model!
But not necessarily minimal Supersymmetry.

$$\boxed{\lambda = \frac{1}{4}(g_Y^2 + g_2^2)c_{2\beta}^2}$$

Features:

- can provide a Dark Matter candidate
- can explain deviation of $(g-2)_\mu$
- can stabilize the electroweak vacuum (see later)
- can predict the SM-like Higgs mass (see later)
- can predict the SM Yukawa couplings
- can solve the hierarchy problem
- possible connection to super-gravity models and String Theory

Problem: LHC has not found any SUSY particles so far ⇒ SUSY particles are probably heavy

Supersymmetry

Still an attractive extension of the Standard Model!
But not necessarily minimal Supersymmetry.

$$\boxed{M_h^2 = m_Z^2 c_{2\beta}^2}$$

Features:

- can provide a Dark Matter candidate
- can explain deviation of $(g-2)_\mu$
- can stabilize the electroweak vacuum (see later)
- can predict the SM-like Higgs mass (see later)
- can predict the SM Yukawa couplings
- can solve the hierarchy problem
- possible connection to super-gravity models and String Theory

Problem: LHC has not found any SUSY particles so far ⇒ SUSY particles are probably heavy

Supersymmetry

Still an attractive extension of the Standard Model!
But not necessarily minimal Supersymmetry.

$$\boxed{\mathcal{L} = \Delta_{27,ij}\phi\psi_i\psi_j}$$

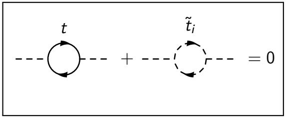
Features:

- can provide a Dark Matter candidate
- can explain deviation of $(g-2)_\mu$
- can stabilize the electroweak vacuum (see later)
- can predict the SM-like Higgs mass (see later)
- can predict the SM Yukawa couplings
- can solve the hierarchy problem
- possible connection to super-gravity models and String Theory

Problem: LHC has not found any SUSY particles so far ⇒ SUSY particles are probably heavy

Supersymmetry

Still an attractive extension of the Standard Model!
But not necessarily minimal Supersymmetry.



Features:

- can provide a Dark Matter candidate
- can explain deviation of $(g-2)_\mu$
- can stabilize the electroweak vacuum (see later)
- can predict the SM-like Higgs mass (see later)
- can predict the SM Yukawa couplings
- can solve the hierarchy problem
- possible connection to super-gravity models and String Theory

Problem: LHC has not found any SUSY particles so far ⇒ SUSY particles are probably heavy

Supersymmetry

Still an attractive extension of the Standard Model!
But not necessarily minimal Supersymmetry.

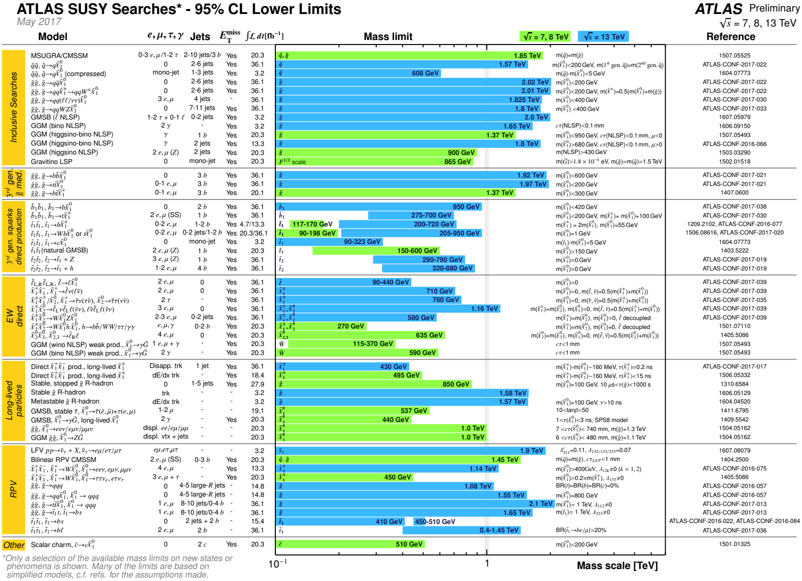
$\boxed{E_8 \times E_8 \to E_6 \to G_{\mathrm{SM}}}$

Features:

- can provide a Dark Matter candidate
- can explain deviation of $(g-2)_\mu$
- can stabilize the electroweak vacuum (see later)
- can predict the SM-like Higgs mass (see later)
- can predict the SM Yukawa couplings
- can solve the hierarchy problem
- possible connection to super-gravity models and String Theory

Problem: LHC has not found any SUSY particles so far ⇒ 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 TeV

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

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	🟩 $\tilde{q}, \tilde{g}$ 1.85 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	🟦 $\tilde{q}$ 1.57 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	🟦 $\tilde{q}$ 608 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0)$<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	🟦 $\tilde{g}$ 2.02 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}_1^{\pm}\rightarrow qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	🟦 $\tilde{g}$ 2.01 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	36.1	🟦 $\tilde{g}$ 1.825 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2017-030
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	🟦 $\tilde{g}$ 1.8 TeV	$m(\tilde{\chi}_1^0)$ <400 GeV	ATLAS-CONF-2017-033
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	🟦 $\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	🟦 $\tilde{g}$ 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	🟩 $\tilde{g}$ 1.37 TeV	$m(\tilde{\chi}_1^0)$<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	🟦 $\tilde{g}$ 1.8 TeV	$m(\tilde{\chi}_1^0)$>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	🟩 $\tilde{g}$ 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	🟩 $F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	🟦 $\tilde{g}$ 1.92 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	🟦 $\tilde{g}$ 1.97 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	🟩 $\tilde{g}$ 1.37 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	🟦 $\tilde{b}_1$ 950 GeV	$m(\tilde{\chi}_1^0)$<420 GeV	ATLAS-CONF-2017-038
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	1 b	Yes	36.1	🟦 $\tilde{b}_1$ 275-700 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_1^0)$+100 GeV	ATLAS-CONF-2017-030
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow b\tilde{\chi}_1^{\pm}$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 🟩 117-170 GeV 🟦 200-720 GeV	$m(\tilde{\chi}_1^{\pm}) = 2m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$ 🟩 90-198 GeV 🟦 205-950 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	🟦 $\tilde{t}_1$ 90-323 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	🟩 $\tilde{t}_1$ 150-600 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	36.1	🟦 $\tilde{t}_2$ 290-790 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2017-019
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1+h$	1-2 e,μ	4 b	Yes	36.1	🟦 $\tilde{t}_2$ 320-880 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2017-019
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	36.1	🟦 $\tilde{\ell}$ 90-440 GeV	$m(\tilde{\chi}_1^0)$=0	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	36.1	🟦 $\tilde{\chi}_1^{\pm}$ 710 GeV	$m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\rightarrow\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	🟦 $\tilde{\chi}_1^{\pm}$ 760 GeV	$m(\tilde{\chi}_1^0)$=0, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	36.1	🟦 $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 1.16 TeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	36.1	🟦 $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 580 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\rightarrow b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	🟩 $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 270 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\rightarrow\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}_{2,3}^0$ 635 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$	1 $e,\mu+\gamma$	-	Yes	20.3	🟩 $\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$	2 γ	-	Yes	20.3	🟩 $\tilde{W}$ 590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	🟦 $\tilde{\chi}_1^{\pm}$ 430 GeV	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	ATLAS-CONF-2017-017
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	🟩 $\tilde{\chi}_1^{\pm}$ 495 GeV	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	🟩 $\tilde{g}$ 850 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	🟦 $\tilde{g}$ 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	🟦 $\tilde{g}$ 1.57 TeV	$m(\tilde{\chi}_1^0)$=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\rightarrow\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	🟩 $\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	🟩 $\tilde{\chi}_1^0$ 440 GeV	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\rightarrow ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	🟩 $\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\rightarrow Z\tilde{G}$	displ. vtx + jets	-	-	20.3	🟩 $\tilde{\chi}_1^0$ 1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\rightarrow e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	🟦 $\tilde{\nu}_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	🟩 $\tilde{q}, \tilde{g}$ 1.45 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	🟦 $\tilde{\chi}_1^{\pm}$ 1.14 TeV	$m(\tilde{\chi}_1^0)$>400GeV, $\lambda_{12k}\neq0$ ($k=1,2$)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\tau\tau\nu_e, e\tau\nu_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	🟩 $\tilde{\chi}_1^{\pm}$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$ 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$ 1.55 TeV	$m(\tilde{\chi}_1^0)$=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	🟦 $\tilde{g}$ 2.1 TeV	$m(\tilde{\chi}_1^0)$= 1 TeV, $\lambda_{112}\neq0$	ATLAS-CONF-2017-013
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow\tilde{t}_1t$, $\tilde{t}_1\rightarrow bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	🟦 $\tilde{g}$ 1.65 TeV	$m(\tilde{t}_1)$= 1 TeV, $\lambda_{323}\neq0$	ATLAS-CONF-2017-013
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow bs$	0	2 jets + 2 b	-	15.4	🟦 $\tilde{t}_1$ 410 GeV 🟦 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow b\ell$	2 e,μ	2 b	-	36.1	🟦 $\tilde{t}_1$ 0.4-1.45 TeV	BR($\tilde{t}_1\rightarrow be/\mu$)>20%	ATLAS-CONF-2017-036
Other	Scalar charm, $\tilde{c}\rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	🟩 $\tilde{c}$ 510 GeV	$m(\tilde{\chi}_1^0)$<200 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.*

Higgs sectors in (B)SM models

Model	Higgs representations $SU(3)_{\mathsf{c}} \times SU(2)_{\mathsf{L}} \times U(1)_Y \times X$
SM	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$
2HDM	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$, $(\mathbf{1}, \mathbf{2}, \frac{1}{2})$
SSM	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$, $(\mathbf{1}, \mathbf{1}, 0)$
MSSM	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$, $(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
NMSSM	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$, $(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$, $(\mathbf{1}, \mathbf{1}, 0)$
MRSSM	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$, $(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$, $(\mathbf{1}, \mathbf{1}, 0)$, $(\mathbf{1}, \mathbf{3}, 0)$
E_6SSM	$(\mathbf{1}, \mathbf{2}, \frac{1}{2}, -\frac{2}{\sqrt{40}})$, $(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, -\frac{3}{\sqrt{40}})$, $(\mathbf{1}, \mathbf{1}, 0, \frac{5}{\sqrt{40}})$
...	

Feature of SUSY models: The mass of the SM-like Higgs is a prediction!

Higgs masses in the SM

Higgs potential

$$V_{\text{Higgs}} = -\mu^2|\Phi|^2 + \frac{1}{2}\lambda|\Phi|^4$$

Decompose Φ as

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

$\Rightarrow$ mass of the Higgs after EWSB

$$m_h^2 = \lambda v^2 \qquad \text{(tree-level)}$$

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

$$\begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \to \begin{pmatrix} h \\ H \end{pmatrix}, \begin{pmatrix} G^0 \\ A \end{pmatrix}, \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}$$

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

$\Rightarrow$ **prediction** (if $m_A \gg m_Z$):

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

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

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

Because of large loop corrections Δm_h^2:

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

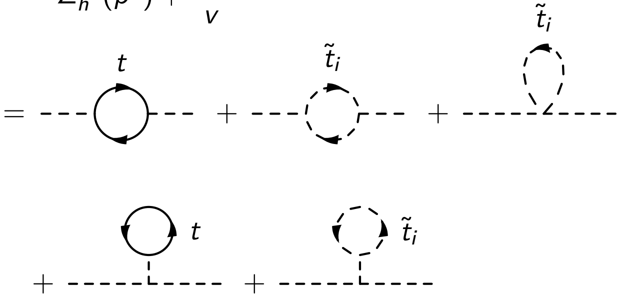
$$\Delta M_h^{\text{exp}} = 0.24\,\mathrm{GeV}$$ [PDG-2017]

Contents

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

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

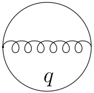
$X_t = A_t - \mu/t_\beta =$ stop mixing parameter, $M_S = (m_Q)_{33} = (m_U)_{33}$

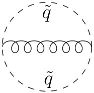
Observations:

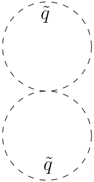
- logarithmically enhanced by M_S/m_t
- maximal for $X_t \approx \sqrt{6} M_S$
- high sensitivity on m_t, due to prefactor $m_t^2 y_t^2 = 2m_t^4/v^2$
- ambiguity of definition of m_t: pole mass or $\overline{\text{DR}}$ mass?
  $M_t \approx 173.3\,\text{GeV}$, $m_t^{\overline{\text{DR}}} \approx 165\,\text{GeV}$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

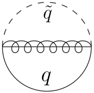
Higgs mass at 2-loop level

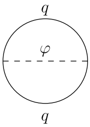
Known contributions: $O(\alpha_s(\alpha_t+\alpha_b)+(\alpha_t+\alpha_b)^2+\alpha_\tau^2)$ for $p^2=0$ [hep-ph/0105096, hep-ph/0112177]

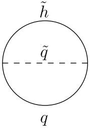


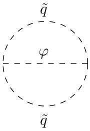


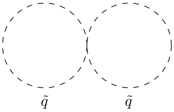


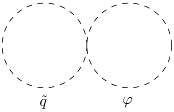












Higgs mass at 2-loop level

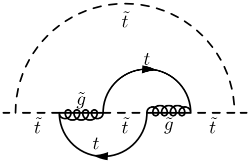
$$(\Delta m_h^2)^{2L} \approx \frac{m_t^2 y_t^4}{(4\pi)^4} \left(c_1 \ln^2 \frac{M_S^2}{m_t^2} + c_2 \ln \frac{M_S^2}{m_t^2} + c_3 \right) + \frac{m_t^2 y_t^2 g_3^2}{(4\pi)^4} \left(c_4 \ln^2 \frac{M_S^2}{m_t^2} + c_5 \ln \frac{M_S^2}{m_t^2} + c_6 \right)$$

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, 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)
  recall: $M_h^{\text{exp}} = (125.09 \pm 0.24)\,\text{GeV}$

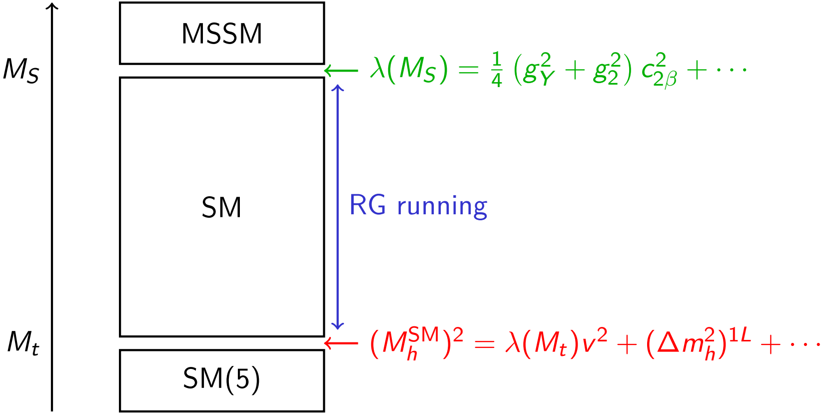
Note: 3-loop MSSM calculation implemented in `FS+H` [1708.05720]

Contents

1. BSM Physics and extended Higgs sectors
2. Higgs mass calculation
   - at fixed loop order
   - in an EFT
   - in a mixed approach
3. Current status of Higgs mass prediction in the MSSM
4. Summary

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.



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

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

EFT avoids large logarithmic corrections

1. Calculate λ from the condition ($p^2 = v^2 = 0$):

$$\partial_{p^2}^{(k)} \Gamma_{h,\ldots,h}^{\text{MSSM},(n)} = \partial_{p^2}^{(k)} \Gamma_{h,\ldots,h}^{\text{SM},(n)}$$

$\Rightarrow$

$$\begin{aligned}\lambda(Q) &= \frac{1}{4}\left[g_Y^2 + g_2^2\right] c_{2\beta}^2 + \Delta\lambda^{1L} + \Delta\lambda^{2L} + \cdots \\ &= \frac{1}{4}\left[g_Y^2 + g_2^2\right] c_{2\beta}^2 + \frac{12 m_t^2 y_t^2}{(4\pi)^2 v^2}\left[\ln\frac{M_S^2}{Q^2} + \frac{X_t^2}{M_S^2} - \frac{X_t^4}{12 M_S^4}\right] + \cdots\end{aligned}$$

$\Rightarrow$ no large logs for $Q \approx M_S$

2. RG running of λ from $Q = M_S \to M_t$.

   $\Rightarrow$ logs are resummed to all orders

3. Calculate M_h in the SM at $Q = M_t$:

$$(M_h^{\text{SM}})^2 = \lambda(Q) v^2 + \frac{12 m_t^2 y_t^2}{(4\pi)^2 v^2} \ln\frac{Q^2}{m_t^2} + \cdots$$

$\Rightarrow$ no large logs for $Q \approx M_t$

Summary of EFT approach

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

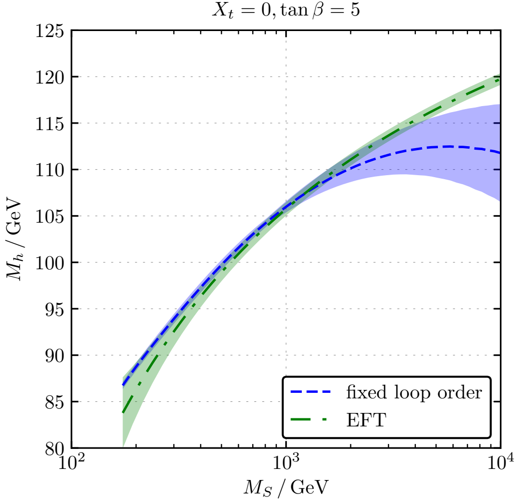
$$\begin{aligned} M_h &= m_h + \Delta m_h^{1L} + \Delta m_h^{2L} + \Delta m_h^{3L} + \cdots \\ &\approx [O(124) + O(0.5\ldots1) + O(0.1\ldots0.2) + O(0.02\ldots0.04)]\,\text{GeV} \end{aligned}$$

Advantages:

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

Disadvantage: 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



Summary of fixed-order and EFT approaches

	low M_S $M_S \lesssim 2\,\text{TeV}$	high M_S $M_S \gtrsim 2\,\text{TeV}$
fixed-order	✓	✗
EFT	✗	✓
? mixed	✓	✓

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

A: Yes! [1312.4937, 1609.00371, 1710.03760]

Contents

Mixed fixed-order and EFT approaches

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

Two known approaches:

- FeynHiggs [1312.4937]: Replace logs from fixed-order calculation by resummed logs

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

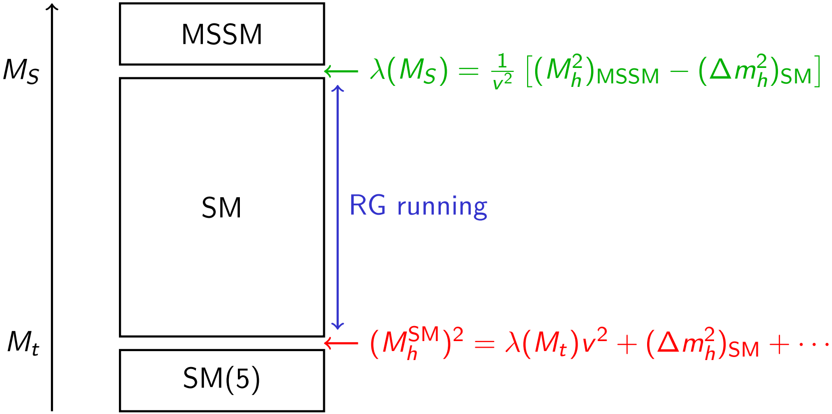
- FlexibleEFTHiggs [1609.00371, 1710.03760]: Incorporate $O(v^2/M_S^2)$ terms into λ by using the matching condition

$$(M_h^2)_{\text{SM}} \overset{!}{=} (M_h^2)_{\text{MSSM}} \qquad \text{at 1L level at } Q = M_S$$

FlexibleEFTHiggs approach [1609.00371, 1710.03760]

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

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



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

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

FlexibleEFTHiggs – EFT equivalence

Proof of equivalence: Start with matching condition:

$$\begin{aligned} (M_h^2)_{\mathrm{SM}} &= (M_h^2)_{\mathrm{MSSM}} \qquad \text{1L}, \; Q = M_S \\ \lambda v^2 + (\Delta m_h^2)_{\mathrm{SM}}^{1L} &= (M_h^2)_{\mathrm{MSSM}} \end{aligned}$$

$\Rightarrow$

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

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

FlexibleEFTHiggs – EFT equivalence

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

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

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

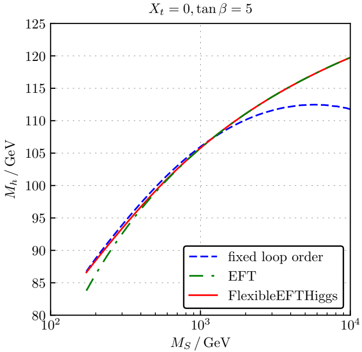
FlexibleEFTHiggs – EFT equivalence

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

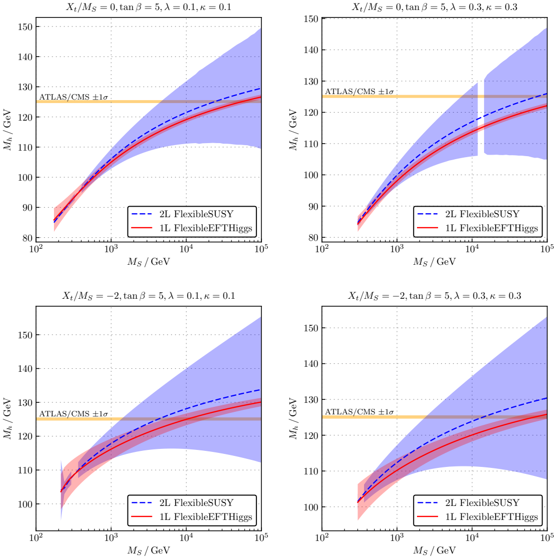
$$\begin{aligned}
\lambda(M_S) &= \frac{1}{4}(g_Y^2+g_2^2)c_{2\beta}^2 - 12\frac{m_t^2(y_t^{\text{SM}})^2}{(4\pi)^2 v^2} B_0(m_h^2, M_S^2, M_S^2) \\
&= \frac{1}{4}(g_Y^2+g_2^2)c_{2\beta}^2 - 12\frac{m_t^2(y_t^{\text{SM}})^2}{(4\pi)^2 v^2}\left[-\log\frac{M_S^2}{Q^2} + \frac{m_h^2}{6M_S^2} + O\Big(\frac{m_h^4}{M_S^4}\Big)\right]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

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

Comparison of the three approaches in the MSSM



Comparison of the three approaches in the NMSSM



Summary FlexibleEFTHiggs approach

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

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 λ

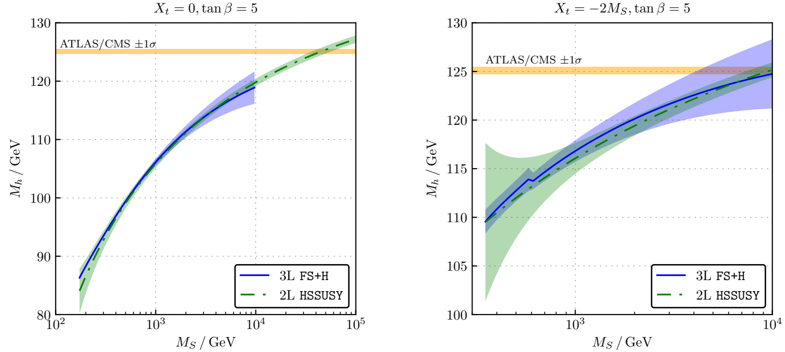
⇒ FlexibleEFTHiggs leads to a correct Higgs mass prediction at the full 1-loop level (including suppressed terms) with additional NLL resummation.

Disadvantage:

- tricky to extend to 2-loop accuracy (work in progress)

Current status of high precision calculation in the MSSM

Currently most precise tools: `FS+H` (3-loop fixed order [1708.05720]), `HSSUSY` (2-loop EFT [1710.03760]), `FeynHiggs` (2-loop mixed [1312.4937, 1608.01880, 1706.00346]), `SPheno` (2-loop* mixed [1703.03267])



$M_S \lesssim 2\,\text{TeV} \Rightarrow$ `FS+H` more accurate than `HSSUSY`

$M_S \gtrsim 2\,\text{TeV} \Rightarrow$ `FS+H` less accurate than `HSSUSY`

Summary

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

Approaches to calculate M_h:

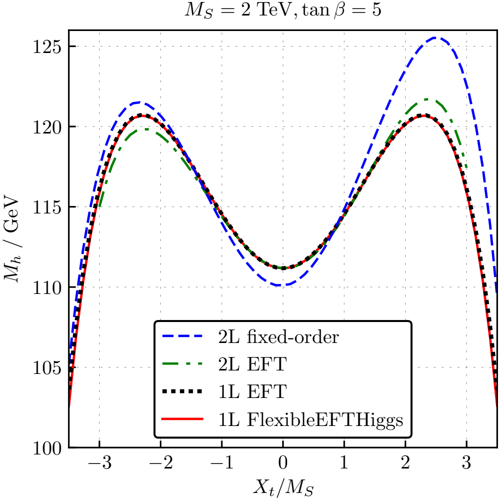
	low M_S $M_S \lesssim 2\,\text{TeV}$	high M_S $M_S \gtrsim 2\,\text{TeV}$
fixed-order	✓	✗
EFT	✗	✓
mixed (FlexibleEFTHiggs)	✓	✓

FlexibleEFTHiggs:

- full NLO + NLL resummation
- can be applied to **any** BSM model (SUSY or non-SUSY)
- can be easily automatized
- tricky to extend to 2-loop level (work in progress)

Backup

Comparison of the three approaches



Higgs mass uncertainty estimate

FS+H:

- $|M_h^{3L}(Q_\text{pole} = M_S/2) - M_h^{3L}(Q_\text{pole} = 2M_S)|$
- $|M_h^{2L}(\alpha_s^{1L}) - M_h^{2L}(\alpha_s^{2L})|$

EFT (HSSUSY):

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

FlexibleEFTHiggs:

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