Precise Higgs mass calculations in models beyond the Standard Model

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HEP Webinar Monash University

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



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Many extensions of the Standard Modell must be studied



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FlexibleSUSY – a spectrum generator generator



Spectrum generator setup in FlexibleSUSY



Example spectrum generator: MSSM



Features for all models (SUSY and non-SUSY)

Observables

 $egin{aligned} & M_h, \ M_W, \ {
m BSM} \ {
m masses}, \ & (g-2)_\mu, \ {
m EDMs}, \ & h o \gamma\gamma, \ h o gg \end{aligned}$

Flexibility

multipe BVP solvers, user-defined BCs, modular C++ code, SLHA input/output, Mathematica input/output, SQLite output

High precision

2L RGEs + 1L self energies (via SARAH) + 1L thresholds, NLL resummation for M_h (FlexibleEFTHiggs)

High speed

multi-threading, self-optimizing linear algebra, lazy evaluation

Additional model-specific precision corrections

MSSM

3L RGEs, 3L M_h , 2L $M_{H,A,H^{\pm}}$, 2L $(g - 2)_{\mu}$, 2L thresholds

NMSSM

2L M_h , 2L $M_{H,A,H^{\pm}}$, 2L thresholds

Split-MSSM

3L M_h , 2L thresholds for y_t , 2L thresholds for λ , \tilde{g}_{ip} the MSSM

SM

4L RGEs, 4L M_h , 4L thresholds for α_s , y_t , 3L thresholds for λ to the MSSM (HSSUSY)

THDM-II

2L thresholds for λ_i to the MSSM

THDM-II + $\tilde{h} + \tilde{g}$

1L thresholds for λ_i to the MSSM

FlexibleSUSY resources



FlexibleSUSY reference manuals:

[1406.2319], [1710.03760]

Software download:

flexiblesusy.hepforge.org github.com/FlexibleSUSY

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Prediction of the Higgs boson mass in supersymmetry

SM: Higgs potential (ad-hoc):

 \Rightarrow

 \Rightarrow

$$V(\phi) = \frac{\lambda}{8}\phi^4 - \frac{\mu^2}{2}\phi^2$$

$$m_h^2 = \frac{\lambda}{v^2}$$

MSSM: Higgs potential (required by SUSY):

$$V(\phi) = \frac{1}{8} \frac{1}{4} \left(g_Y^2 + g_2^2 \right) \cos^2(2\alpha) \phi^4 + \cdots$$

$$m_h^2 = \frac{1}{4} \left(g_Y^2 + g_2^2 \right) \cos^2(2\alpha) v^2$$
$$= m_Z^2 \cos^2(2\alpha)$$
$$\leq m_Z^2$$

Problem: Is the predicted Higgs mass too small?

MSSM **predicts** at tree-level:

$$m_h^2 = m_Z^2 \cos^2 2\alpha \le m_Z^2$$

But from experiment we know [PDG]:

$$M_h = (125.10 \pm 0.14) \, \text{GeV}$$

 $M_Z = (91.1876 \pm 0.0021) \, \text{GeV}$

 \Rightarrow large loop corrections required!

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

Use the Higgs mass to put constraints on a SUSY model

Idea:

() Calculate M_h as precisely as possible in the SUSY model:

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

2 Constrain the parameter space by requiring:

$$M_h \stackrel{!}{=} (125.10 \pm 0.14) \,\mathrm{GeV} \pm \Delta M_h^{\mathrm{theo}}$$

Problem: because of large loop corrections Δm_h^2 :

$$\Delta M_h^{
m theo} \sim 1 \, {
m GeV} \ igodots \ \Delta M_h^{
m exp} = 0.14 \, {
m GeV} \ {}_{
m [PDG-2019]}$$

 \rightarrow Theorists must increase their precision!

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Fixed-order calculation

Input: $\alpha_{em}(M_Z)$, $\alpha_s(M_Z)$, G_F , M_Z , M_t , $m_b(m_b)$, SUSY parameters, ...



Fixed-order calculation

Dominant contribution to M_h at the 1-loop level:



Higgs mass at 1-loop level

$$(\Delta m_h^2)^{1L} \approx \frac{6y_t^4 v^2}{(4\pi)^2} \left(\log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} - \frac{X_t^4}{12M_S^4} \right) + \mathcal{O}\left(\frac{v^2}{M_S^2}\right)$$

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

Observations:

- logarithmically enhanced by $\log(M_S/m_t)$
- maximal for $X_t/M_S \approx \sqrt{6}$
- high sensitivity on m_t , due to prefactor $y_t = \sqrt{2}m_t/v$
- 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
- $M_h pprox 125 \, {
 m GeV}$ requires $M_S \gtrsim 5 \, {
 m TeV}$

Higgs mass at 2-loop level

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



Higgs mass at 2-loop level

$$(\Delta m_h^2)^{2L} \approx rac{y_t^6 v^2}{(4\pi)^4} \left(c_1 \log^2 rac{M_S^2}{m_t^2} + c_2 \log rac{M_S^2}{m_t^2} + c_3
ight) \ + rac{y_t^4 g_3^2 v^2}{(4\pi)^4} \left(c_4 \log^2 rac{M_S^2}{m_t^2} + c_5 \log rac{M_S^2}{m_t^2} + c_6
ight)$$

Observations:

- logarithmically enhanced by $\log^2(M_S/m_t)$
- still high sensitivity on m_t
- ambiguity of definition of m_t is resolved \checkmark
- ambiguity of definition of α_s : $\alpha_s^{SM}(M_Z)$, $\alpha_s^{MSSM}(M_S)$, ...? \Rightarrow 3-loop calculation needed to resolve this ambiguity

Higgs mass at 3-loop level

Known contributions: $\mathcal{O}(\alpha_t \alpha_s^2)$ for $p^2 = 0$ [1005.5709,1708.05720]



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

Observations:

- logarithmically enhanced by $\log^3(M_S/m_t)$
- still high sensitivity on m_t
- ambiguity of definition of m_t is resolved \checkmark
- ambiguity of definition of α_{s} is resolved \checkmark

Summary of fixed loop order calculation

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

$$M_h = m_h + \Delta m_h^{1L} + \Delta m_h^{2L} + \Delta m_h^{3L} + \cdots$$

$$\approx [91 + \mathcal{O}(20\dots 30) + \mathcal{O}(2\dots 4) + \mathcal{O}(1\dots 2)] \text{ GeV}$$

Advantages:

- ✓ includes logarithmic, non-logarithmic and suppressed terms of $\mathcal{O}((v^2/M_S^2)^\infty)$ at fixed loop order
- ✓ precise prediction if $M_S \sim m_t$ (then log $(M_S/m_t) \approx 0$)

Disadvantages:

- × 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]

Additional problem: no SUSY particles observed so far

July 2019								$\sqrt{s} = 13 \text{ TeV}$		
	Model	Signa	ture	∫£ dt [fb⁻	") Ma	ass limit				Reference
Inclusive Searches	$\bar{q}\bar{q},\bar{q}{\rightarrow}q\bar{t}_{1}^{0}$	0 r.μ 2-6 mono-jet 1-3	ets E_T^{min} ets E_T^{min}	36.1 36.1	₽ [2x, 8x Depen.] ₽ [1x, 8x Depen.]	0.43 0.	0.9 71	1.55	m((t))<100 GeV m((j)-m((t))=5 GeV	1712.02332 1711.03301
	$\bar{g}\bar{g}, \bar{g} \rightarrow g\bar{g}\bar{\ell}_1^0$	0 e, µ 2-6	ets E_T^{min}	36.1	5		Forbidden	2.0 0.95-1.6	m(t))<200 GeV m(t)):900 GeV	1712.02332 1712.02332
	$\hat{g}\hat{g}, \hat{g} \rightarrow g\hat{q}(\ell\ell)\hat{R}_{1}^{0}$	3 e.μ 4 ja ee.μμ 2 ja	its E_T^{min}	36.1 36.1	8			1.85	m(t^0)=800 GeV m(t)=m(t^0)=50 GeV	1705.03731 1805.11381
	$gg, g \rightarrow ggWZ \tilde{\xi}_1^0$	0 e,μ 7-11 SS e,μ 6 je	jets E _T its	36.1 139	8		1	.15	$m(\tilde{t}_1^0) \sim 400 \text{ GeV}$ $m(\tilde{t}) = 200 \text{ GeV}$	1708.02794 ATLAS-CONF-2019-015
	$gg, g \rightarrow a \tilde{\kappa}_1^0$	0-1 e.μ 3 SS e.μ 6 je	b E _T min	79.8 139	8			1.25	5 m(t ² ₁)-200 GeV m(t ²)-m(t ² ₁)=300 GeV	ATLAS-CONF-2018-041 ATLAS-CONF-2019-015
3" ⁴ gen. squarks drect production	$\hat{b}_1\hat{b}_1,\hat{b}_1{\rightarrow}b\hat{\eta}_1^0/t\hat{\chi}_1^*$	Mult Mult	iple iple iple	36.1 36.1 139	51 Forbidden 51 51	Forbidden 0.5	0.9 i8-0.82 1.74	m(x ²)	m(t ²)=300 GeV, BP(16t ²)=1 m(t ²)=300 GeV, BP(16t ²)=BP(16t ²)=0.5 =200 GeV, m(t ²)=300 GeV, BP(16t ²)=1	1708.09255, 1711.02301 1708.09255 ATLAS-CONF-2019-015
	$b_1b_1, b_1 \rightarrow b \dot{\ell}_2^0 \rightarrow b b \dot{\ell}_1^0$	0 e.µ 6	$b = E_T^{min}$	139	δ ₁ Forbidden δ ₁	0.23-0.48	0	23-1.35	$\begin{array}{l} \Delta m(\hat{k}_{2}^{0},\hat{k}_{1}^{0})\!=\!130\mathrm{GeV}, m(\hat{\ell}_{1}^{0})\!=\!100\mathrm{GeV} \\ \Delta m(\hat{\ell}_{2}^{0},\hat{\ell}_{1}^{0})\!=\!130\mathrm{GeV}, m(\hat{\ell}_{1}^{0})\!=\!0\mathrm{GeV} \end{array}$	SUSY-2018-31 SUSY-2018-31
	$\begin{array}{l} \bar{n}_1\bar{r}_1,\;\bar{n}_1{\rightarrow}Wb\bar{k}_1^0\; {\rm or}\; s\bar{k}_1^0\\ \bar{n}_1\bar{r}_1,\;\bar{r}_1{\rightarrow}Wb\bar{k}_1^0\\ \bar{n}_1\bar{r}_1,\;\bar{n}_1{\rightarrow}\bar{\pi}_1 {\rm or}\; \bar{r}_1{\rightarrow}\bar{\pi}G\\ \bar{n}_1\bar{r}_1,\;\bar{n}_1{\rightarrow}c\bar{k}_1^0\;/\bar{\pi}\bar{r},\;\bar{r}{\rightarrow}c\bar{k}_1^0 \end{array}$	$\begin{array}{ccc} 0.2 e, \mu & 0.2 \mathrm{jets} \\ 1 e, \mu & 3 \mathrm{jets} \\ 1 \tau + 1 e, \mu, \tau & 2 \mathrm{jets} \\ 0 e, \mu & 2 \end{array}$	$(1-2) = E_T^{min}$ $(1-b) = E_T^{min}$ $(1-b) = E_T^{min}$ $(1-b) = E_T^{min}$ $c = E_T^{min}$	36.1 139 36.1 36.1	11 11 11 12 11	0.44-0.59	1.0 1 0.85	.16	m(t ²)=1 GeV m(t ²)=400 GeV m(t ²)=800 GeV m(t ²)=80 GeV m(t ²)=80 GeV m(t ²)=80 GeV	1505.08516, 1703.04183, 1711.11520 ATLAS-CONF-2019-017 1803.10178 1805.01549 1805.01549
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$ $\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	0 e,μ mon 1-2 e,μ 4 3 e,μ 1	$b = E_T^{min}$ $b = E_T^{min}$ $b = E_T^{min}$	36.1 36.1 139	71 72 72	0.43 Forbidden	0.32-0.88		$\begin{split} m(\tilde{r}_1,\tilde{r})\!=\!m(\tilde{r}_1^0)\!=\!5~\text{GeV}\\ m(\tilde{r}_1^0)\!=\!0~\text{GeV}, m(\tilde{r}_1)\!=\!m(\tilde{r}_1^0)\!=\!100~\text{GeV}\\ m(\tilde{r}_1^0)\!=\!360~\text{GeV}, m(r_1)\!=\!m(\tilde{r}_1^0)\!=\!40~\text{GeV} \end{split}$	1711.03301 1705.03986 ATLAS-CONF-2019-016
	$\hat{x}_1^* \hat{x}_2^0$ via WZ	2-3 e,μ ee,μμ ≥	E_T^{min} 1 E_T^{min}	36.1 139	$\frac{\hat{x}_{1}^{*}/\hat{x}_{2}^{*}}{\hat{x}_{1}^{*}/\hat{x}_{2}^{*}} = 0.205$	0.6			$m(\hat{r}_{1}^{0})=0$ $m(\hat{r}_{1}^{0})=m(\hat{r}_{1}^{0})=5 \text{ GeV}$	1403.5294, 1805.02293 ATLAS-CONF-2019-014
EW direct	$\hat{\chi}_{1}^{+} \hat{\chi}_{1}^{+} \text{ via } WW$ $\hat{\chi}_{1}^{+} \hat{\chi}_{2}^{0} \text{ via } Wh$ $\hat{\chi}_{1}^{+} \hat{\chi}_{1}^{+} \text{ via } \hat{\ell}_{L}/\bar{r}$	2 e,μ 0-1 e,μ 2 bl 2 e,μ	E_T^{min} $2 \gamma = E_T^{min}$ E_T^{min}	139 139 139	\hat{x}_1^{\dagger} $\hat{x}_1^{\dagger} \beta \hat{x}_2^{\dagger}$ Forbidden \hat{x}_1^{\dagger}	0.42	1.74		$m(\hat{\epsilon}_{1}^{0})=0$ $m(\hat{\epsilon}_{2}^{0})=70 \text{ GeV}$ $m(\hat{\epsilon}_{1}^{0})=0.5(m(\hat{\epsilon}_{1}^{0})+m(\hat{\epsilon}_{1}^{0}))$	ATLAS-CONF-2019-008 ATLAS-CONF-2019-019, ATLAS-CONF-2019-XY ATLAS-CONF-2019-008
	$\tau \tau$, $\tau \rightarrow \tau \tilde{\chi}_1^0$ $\tilde{\ell}_{L,R} \tilde{\ell}_{L,R}$, $\tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	2 τ 2 ε,μ 0 μ 2 ε,μ ≥	E_T^{min} its E_T^{min} 1 E_T^{min}	139 139 139	7 [7L.7R.L] 0.16-0.3 7 7 0.256	0.12-0.39	.7		$m(\hat{\xi}_{1}^{0})=0$ $m(\hat{\xi}_{1}^{0})=0$ $m(\hat{\xi}_{1})=10 \text{ GeV}$	ATLAS-CONF-2019-018 ATLAS-CONF-2019-008 ATLAS-CONF-2019-014
	$\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/Z\hat{G}$	$\begin{array}{ccc} 0 e, \mu & \geq 3 \\ 4 e, \mu & 0 \mu \end{array}$	the E_T^{min} its E_T^{min}	36.1 36.1	й 0.13-0.23 И 0.3		0.29-0.88		$BR(\hat{\tau}_1^0 \rightarrow \lambda \hat{G})=1$ $BR(\hat{\tau}_1^0 \rightarrow Z \hat{G})=1$	1805.04030 1804.03502
g-lived ticles	Direct $\hat{x}_1^* \hat{x}_1^-$ prod., long-lived \hat{x}_1^*	Disapp. trk 1 j	et E ^{gino}	36.1	£* £* 0.15	0.46			Pure Wno Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
Lon Dar	Metastable ġ R-hadron, ġ→qqi ⁰	Mult	iple	36.1	* 2 [r(2) = 10 ns, 0.2 ns]		_	2.05	2.4 m(\hat{c}_1^0)::100 GeV	1710.04901,1808.04095
RPV	LFV $pp \rightarrow \bar{v}_{\tau} + X, \bar{v}_{\tau} \rightarrow equ/e\tau/\mu\tau$ $\tilde{X}_{1}^{+} \tilde{X}_{1}^{+} / \tilde{X}_{2}^{0} \rightarrow WW/Z\ell\ell\ell\ell\nu\tau$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qg\bar{q}\tilde{\chi}_{1}^{+}, \tilde{X}_{1}^{0} \rightarrow qgq$ $= z \rightarrow z\theta \rightarrow \theta$	eμ.er.μτ 4.e.μ 0 ji 4-5 larg Mult Mult	its E _T a-Rjets iple	3.2 36.1 36.1 36.1	7, $\left[\hat{x}_{1}^{2} / \hat{x}_{2}^{2} - [A_{00} \neq 0, A_{120} \neq 0] \right]$ $\hat{x}_{1}^{2} = [m (\hat{x}_{1}^{2}) - 200 \text{ GeV}, 1100 \text{ GeV}]$ $\hat{y}_{1}^{2} = [\hat{x}_{12}^{2} - 204, 20-5]$ $\hat{y}_{2}^{2} = [\hat{x}_{12}^{2} - 204, 10-3]$		0.82	1.9 1.33 1.3 1.9 2.0	$\lambda'_{111} = 0.11, \lambda_{132/133/233} = 0.07$ $m(k_1^2) = 100 \text{ GeV}$ Large λ''_{112} $m(k_1^2) = 200 \text{ GeV}$, thro-like	1607.08079 1804.03502 1804.03568 ATLAS-CONF-2016-003
	$H_i I \rightarrow \ell \ell i_1, \chi_1 \rightarrow \ell b x$ $\tilde{i}_1 \tilde{i}_1, \tilde{i}_1 \rightarrow b x$ $\tilde{i}_1 \tilde{i}_1, \tilde{i}_1 \rightarrow q \ell$	2 jets 2 r,μ 2 1 μ D	+ 2 b b V	36.7 36.1 136	$ \begin{array}{c} s & (r_{122}, r_{223}, r_{233}, r_{233},$	0.33 0.42 0.61	1.0	0.4-1.45 1.6	BR(2)→2x00 GPV, BINS-R68 BR(2)→2x75, BR(2)→3x9)=100%, cos8+1	ATLAS-CONF-2019-003 1710.07171 1710.05544 ATLAS-CONF-2019-005
							· · · ·]
Cony a selection of the available mass limits on new states or 10										

ATLAS SUSY Searches* - 95% CL Lower Limits

phenomena is shown. Many of the limits are based on simplified models. c.f. refs. for the assumptions made.

ATLAS Preliminary

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Higgs mass calculation in an Effective Field Theory

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



Resummation of large logarithms in an EFT

System of coupled DEQs ($t = \log(Q)$, $\kappa = 1/(4\pi)^2$):

$$\frac{\mathrm{d}\lambda}{\mathrm{d}t} = \beta_{\lambda} \approx -12\kappa y_t^4, \qquad \frac{\mathrm{d}y_t}{\mathrm{d}t} \approx -8\kappa y_t g_3^2, \qquad \frac{\mathrm{d}g_3}{\mathrm{d}t} \approx -7\kappa g_3^3$$

Solution $(L = \log(M_S/M_t))$:

$$\lambda(M_t) = \lambda(M_S) - \frac{2y_t^4}{3g_3^2} \left[\left(1 + 14g_3^2 \kappa L \right)^{-9/7} - 1 \right]$$

Insert in $M_h^2 = \lambda(M_t)v^2$, with $\lambda(M_S) = m_Z^2 c_{2\beta}^2/v^2$:

$$M_{h}^{2} = m_{Z}^{2} c_{2\beta}^{2} - \frac{2y_{t}^{4} v^{2}}{3g_{3}^{2}} \left[\left(1 + 14g_{3}^{2} \kappa L \right)^{-9/7} - 1 \right]$$

= $m_{Z}^{2} c_{2\beta}^{2} + 12y_{t}^{4} v^{2} \left[\kappa L - 16g_{3}^{2} \kappa^{2} L^{2} + \frac{736}{3} g_{3}^{4} \kappa^{3} L^{3} + \mathcal{O}(\kappa^{4} L^{4}) \right]$

 $\Rightarrow M_h^2$ contains **infinite series** of $(\kappa L)^n$ terms in an EFT

Summary of EFT approach

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

$$M_h = \sqrt{\lambda(M_t)} v + \Delta m_h^{1L} + \Delta m_h^{2L} + \Delta m_h^{3L} + \cdots$$

$$\approx [\mathcal{O}(124) + \mathcal{O}(0.5...1) + \mathcal{O}(0.1...0.2) + \mathcal{O}(0.02...0.04)] \text{ GeV}$$

Advantages:

- ✓ large corrections of $\log^n(M_S/M_t)$ at fixed order n are avoided
- ✓ large logarithms $\propto \log^{\infty}(M_S/M_t)$ are resummed to all orders **Disadvantage:**
 - **X** Terms of $\mathcal{O}(v^2/M_5^2)$ are (typically) neglected
 - \Rightarrow imprecise when $M_S \sim v$ (relevant?)
 - \Rightarrow large theoretical uncertainty when $\mathit{M_S} \sim \mathit{v}$

Comparison of fixed-order and EFT calculation



$$\Delta M_h^{({\sf FO})} \stackrel{!}{=} \Delta M_h^{({\sf EFT})}$$

 $\Rightarrow M_S^{
m equal} \sim 1 \,{
m TeV}$ for small/large tan eta and/or X_t

[1804.09410]

Summary of fixed-order and EFT approaches

	low M_S	high <i>M_S</i>
	$M_{\mathcal{S}} \lesssim 1{ m TeV}$	$M_{\mathcal{S}}\gtrsim 1{ m TeV}$
fixed-order	1	×
EFT	×	✓
? hybrid	1	\checkmark

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

A: Yes! [1312.4937, 1609.00371, 1710.03760, 1910.03595, 2003.04639]

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Hybrid calculation – FeynHiggs approach

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

Idea I: ("FeynHiggs approach" [1312.4937, 1706.00346, 1805.00867, 1910.03595]) Replace logs from fixed-order calculation by resummed logs:

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

Advantages:

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

Disadvantages:

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

FeynHiggs approach in FlexibleSUSY at 3-loop



[1910.03595]

Hybrid calculation – FlexibleEFTHiggs

Idea II: ("FlexibleEFTHiggs" [1609.00371, 1710.03760, 2003.04639]) Incorporate all $\mathcal{O}((v^2/M_5^2)^{\infty})$ terms into λ by using the matching condition for the FO calculations:

$$(M_h^2)_{\mathrm{SM}} \stackrel{!}{=} (M_h^2)_{\mathrm{BSM}}$$
 at $Q = M_S$
 $\lambda(M_S)v^2 + (\Delta m_h^2)_{\mathrm{SM}} = (M_h^2)_{\mathrm{BSM}}$

 \Rightarrow

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

Continue as in the EFT calculation ...

Hybrid calculation – FlexibleEFTHiggs

Continue as in the EFT calculation:



Proof: FlexibleEFTHiggs \rightarrow EFT for $v^2 \ll M_S^2$

Consider the matching condition:

$$\lambda(M_{S}) = rac{1}{v^{2}} \left[(M_{h}^{2})_{\mathsf{MSSM}} - (\Delta m_{h}^{2})_{\mathsf{SM}}
ight]$$

where at $\mathcal{O}(y_t^4)$:

$$(\Delta m_h^2)_{\text{SM}} = -\Sigma_h^{\text{SM}} - 6\kappa y_t^2 A_0(m_t)$$
$$(M_h^2)_{\text{MSSM}} = m_Z^2 c_{2\alpha}^2 + \left[-\Sigma_h^{\text{SM}} - 6\kappa y_t^2 A_0(m_t) \right] \frac{c_\alpha^2}{s_\beta^2}$$
$$- 6\kappa y_t^4 v^2 \frac{c_\alpha^2}{s_\beta^2} B_0(M_S, M_S)$$

Proof: FlexibleEFTHiggs \rightarrow EFT for $v^2 \ll M_S^2$

$$\begin{split} \lambda(M_S) &= \frac{1}{v^2} \left[(M_h^2)_{\mathsf{MSSM}} - (\Delta m_h^2)_{\mathsf{SM}} \right] \\ &= \frac{m_Z^2}{v^2} c_{2\alpha}^2 + \frac{1}{v^2} \left[-\sum_h^{\mathsf{SM}} - 6\kappa y_t^2 \mathcal{A}_0(m_t) \right] \left(\frac{c_\alpha^2}{s_\beta^2} - 1 \right) \\ &- 6\kappa y_t^4 \frac{c_\alpha^2}{s_\beta^2} \mathcal{B}_0(M_S, M_S) \end{split}$$

In the limit $v^2 \ll M_{\cal S}^2$: $c_{lpha}^2 o s_{eta}^2$, $c_{2lpha}^2 o c_{2eta}^2 \Rightarrow$

$$\begin{split} \lambda(M_S) &= \frac{1}{4} (g_Y^2 + g_2^2) c_{2\beta}^2 - 6\kappa y_t^4 B_0(M_S, M_S) \\ &= \frac{1}{4} (g_Y^2 + g_2^2) c_{2\beta}^2 - 6\kappa y_t^4 \Big[-\log \frac{M_S^2}{Q^2} + \frac{p^2}{6M_S^2} + \mathcal{O}\Big(\frac{p^4}{M_S^4}\Big) \Big] \end{split}$$

Summary of FlexibleEFTHiggs hybrid calculation

Matching condition:

$$(M_h^2)_{\rm SM} \stackrel{!}{=} (M_h^2)_{\rm BSM}$$

Advantages:

- ✓ includes all power-suppressed terms at *n*-loop order $(v^2/M_S^2)^{\infty}[c + \log^n(M_S/Q) + \log^n(M_S/m_t)]$
- ✓ resumms large non-suppressed logarithms $c \log^{\infty}(M_S/m_t)$
- \checkmark approach applicable to any BSM model
- ✓ only 1- and 2-point fixed-order expressions required → easy to automate (e.g. SARAH/FlexibleSUSY)

Disadvantages:

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

Interpolation behaviour of FlexibleEFTHiggs in the MSSM

Interpolation behaviour between FO and EFT calculation:



[plots along the lines of 2003.04639]

Hybrid calculation – FlexibleEFTHiggs



[2003.04639]

Theory uncertainty $\Delta M_h \lesssim 1 \,\text{GeV}$ in relevant degenerate SUSY scenarios.

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Further improvements: x_t resummation

Large stop mixing, $x_t \equiv X_t/M_S \approx \pm \sqrt{6}$, is an attractive scenario for low-scale supersymmetry.

However: "With large stop mixing comes large uncertainty." — P. Slavich



Recap: $\tan \beta$ resummation in m_b

Relation between running m_b in the MSSM and m_b^{EFT} in the EFT:

$$m_b^{\mathsf{EFT}} = m_b(1+\Delta m_b)$$

where Δm_b is expressed in terms of MSSM parameters.

Theorem (hep-ph/9912516)

There are no contributions to Δm_b of $\mathcal{O}((\alpha_s \tan \beta)^n)$ for $n \ge 2$.

 \Rightarrow All higher-order MSSM contributions in m_b of $\mathcal{O}((\alpha_s \tan \beta)^n)$ can be resummed by writing:

$$m_b = rac{m_b^{\mathsf{EFT}}}{1 + \Delta m_b} = m_b^{\mathsf{EFT}} \sum_{n=0}^{\infty} (-\Delta m_b)^n$$

x_t resummation

Relation between running y_t in the MSSM and y_t^{EFT} in the EFT:

$$y_t^{\mathsf{EFT}} = y_t s_eta + \Delta y_t$$

where Δy_t is expressed in terms of MSSM parameters.

Theorem (Kwasnitza, Stöckinger (2003.04639)) There are no unsuppressed contributions to Δy_t of $\mathcal{O}(\alpha_s^n x_t^{>1})$ for $n \ge 1$.

 \Rightarrow All higher-order MSSM contributions in y_t of $\mathcal{O}(\alpha_s^n x_t^{>1})$ can be resummed by writing:

$$y_t = rac{y_t^{\mathsf{EFT}}}{1 + \Delta y_t / (y_t s_eta)}$$

x_t resummation

⇒ by expressing $\lambda(M_S)$ in terms of **MSSM parameters** (y_t , m_b , ...), certain higher-order contributions can be resummed to all orders



[2003.04639]

Summary and Conclusions

Precise prediction of the Higgs boson mass in supersymmetric models allows to constrain the model parameter space

Effective field theory and resummation methods necessary for a precise prediction (resummation of large logarithms and x_t^{∞} corrections)

 \Rightarrow

Current precision in the MSSM in relevant parameter space: $\Delta M_h \lesssim 1 \, {\rm GeV}$

Stop quarks must be heavy, $M_S \gtrsim 2 \text{ TeV}$, in the MSSM for correct prediction of $M_h \approx 125 \text{ GeV}$

Outlook

Large zoo of SUSY models \Rightarrow automation important!



Outlook

Thank you for your attention!



Backup

Status of Higgs mass calculations

	FO	EFT	hybrid
MSSM			
FeynHiggs	2L	2L	2L
FlexibleSUSY	3L	3L	3L‡
SARAH	2L	2L	2L*
SOFTSUSY	3L	_	_
SPheno	2L	—	2L*
generic			
FlexibleSUSY	1L	_	$1L^\dagger$
SARAH/SPheno	2L	1L	2L*

- [‡]: in preparation, including x_t resummation
- *: NNLO + LL resummation
- [†]: NLO + NLL resummation

Maximum stop masses in the MSSM

Maximum stop mass scenario with $\tan \beta = 1$:



Dark region: charge and color breaking minima Hatched region: unbounded Higgs potential, $\lambda(M_S) < 0$

Scenarios with 1 light Higgs doublet



Scenarios with 2 light/intermediate Higgs doublets

