Precise Higgs mass calculations in models beyond the Standard Model

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Monash University

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Hochschule Flensburg
University of Applied Sciences

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2. BSM phenomenology with FlexibleSUSY
3. Higgs mass calculations in BSM models
   - Fixed order
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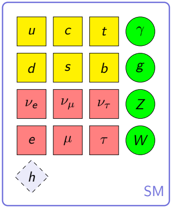
4. x_t resummation
5. Summary and conclusions

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 $M_{\rm Pl}$?
- 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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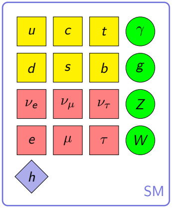

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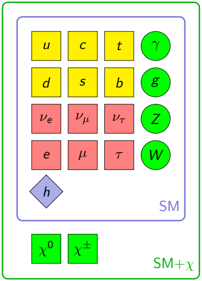

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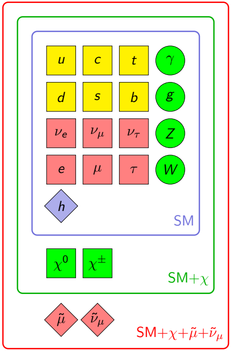

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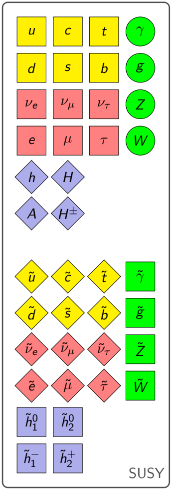

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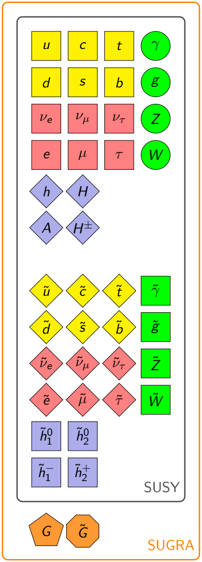

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Many extensions of the Standard Modell must be studied

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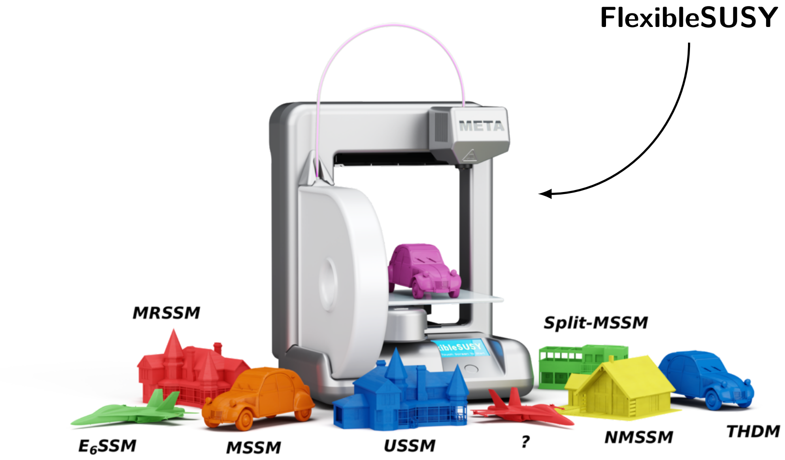

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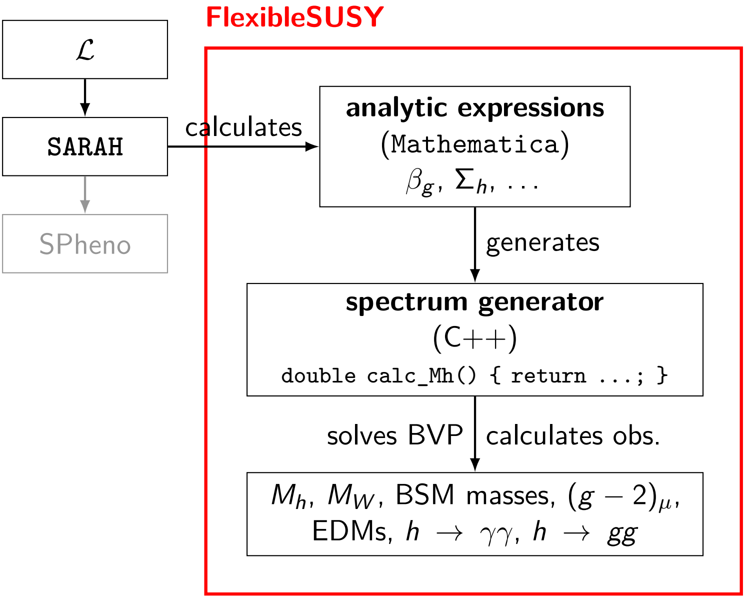
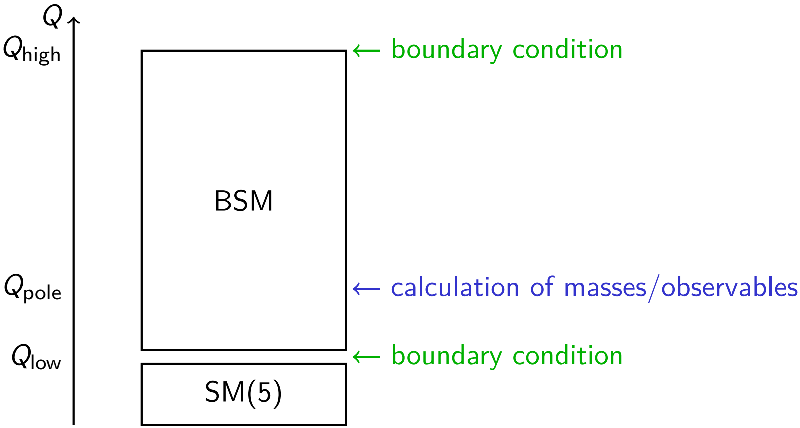
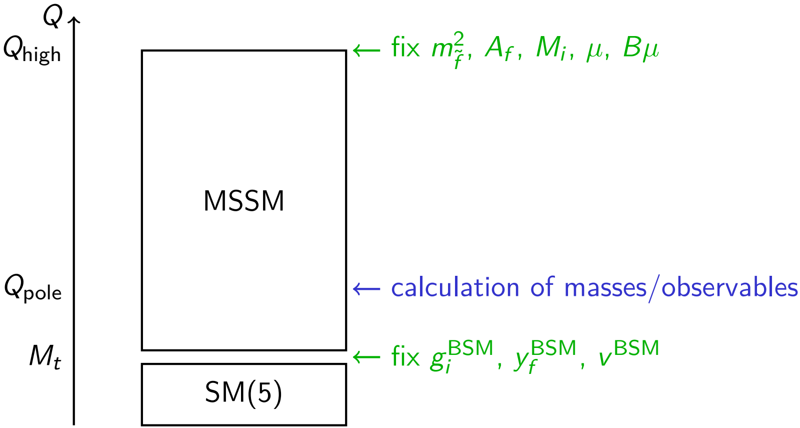
FlexibleSUSY – a spectrum generator generator



Spectrum generator setup in FlexibleSUSY



Example spectrum generator: MSSM



Features for all models (SUSY and non-SUSY)

Observables

M_h, M_W, BSM masses, $(g-2)_\mu$, EDMs, $h \to \gamma\gamma$, $h \to gg$

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):

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

$\Rightarrow$

$$m_h^2 = \lambda v^2$$

MSSM: Higgs potential (required by SUSY):

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

$\Rightarrow$

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

Problem: Is the predicted Higgs mass too small?

MSSM **predicts** at tree-level:

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

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!

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

Use the Higgs mass to put constraints on a SUSY model

Idea:

1. 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:

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

Problem: because of large loop corrections Δm_h^2:

$$\Delta M_h^{\text{theo}} \sim 1\,\text{GeV} \quad ☹$$
$$\Delta M_h^{\text{exp}} = 0.14\,\text{GeV} \quad \text{[PDG-2019]}$$

→ Theorists must increase their precision!

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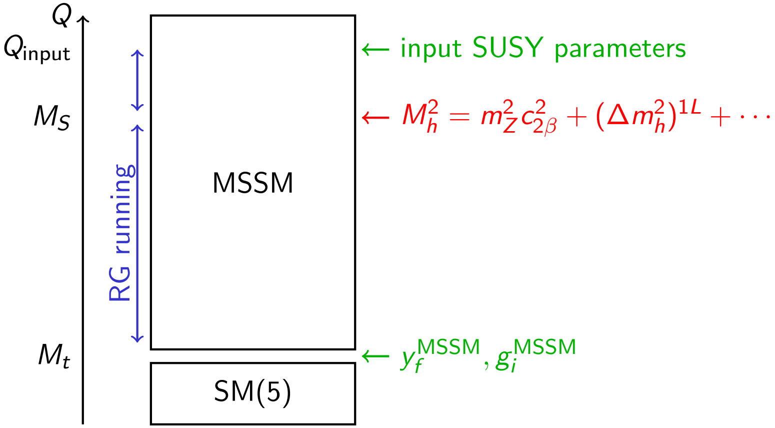
Fixed-order calculation

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

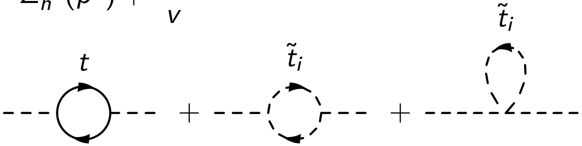


Fixed-order calculation

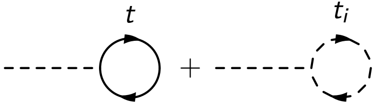
Dominant contribution to M_h at the 1-loop level:

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

$=$



$+ \ \frac{1}{v} \Big($



$\Big)$

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

Higgs mass at 1-loop level

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

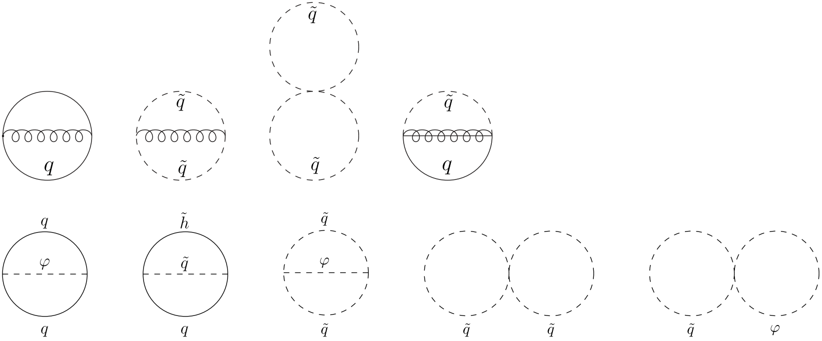
$X_t = A_t - \mu / t_\beta =$ stop mixing parameter, $M_S = (m_Q)_{33} = (m_U)_{33}$

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
- $M_h \approx 125\,\text{GeV}$ requires $M_S \gtrsim 5\,\text{TeV}$

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

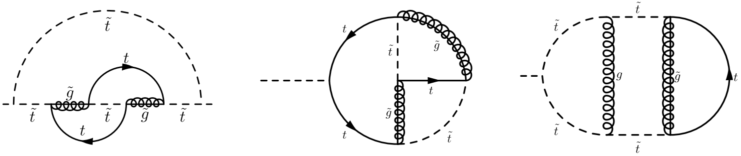
$$(\Delta m_h^2)^{2L} \approx \frac{y_t^6 v^2}{(4\pi)^4}\left(c_1 \log^2 \frac{M_S^2}{m_t^2} + c_2 \log \frac{M_S^2}{m_t^2} + c_3\right) + \frac{y_t^4 g_3^2 v^2}{(4\pi)^4}\left(c_4 \log^2 \frac{M_S^2}{m_t^2} + c_5 \log \frac{M_S^2}{m_t^2} + c_6\right)$$

Observations:

- logarithmically enhanced by $\log^2(M_S/m_t)$
- 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: $\mathcal{O}(\alpha_t \alpha_s^2)$ 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 ✓
- 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):

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

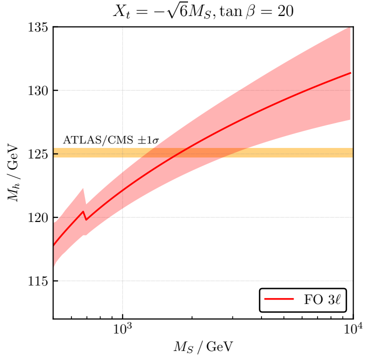
Advantages:

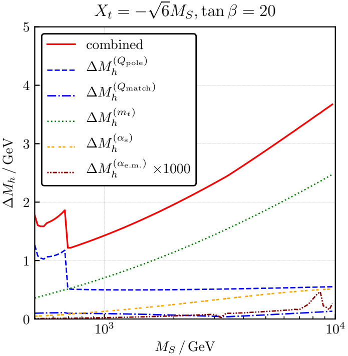
- ✓ includes logarithmic, non-logarithmic and suppressed terms of $\mathcal{O}((v^2/M_S^2)^\infty)$ at fixed loop order
- ✓ precise prediction if $M_S \sim m_t$ (then $\log(M_S/m_t) \approx 0$)

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)

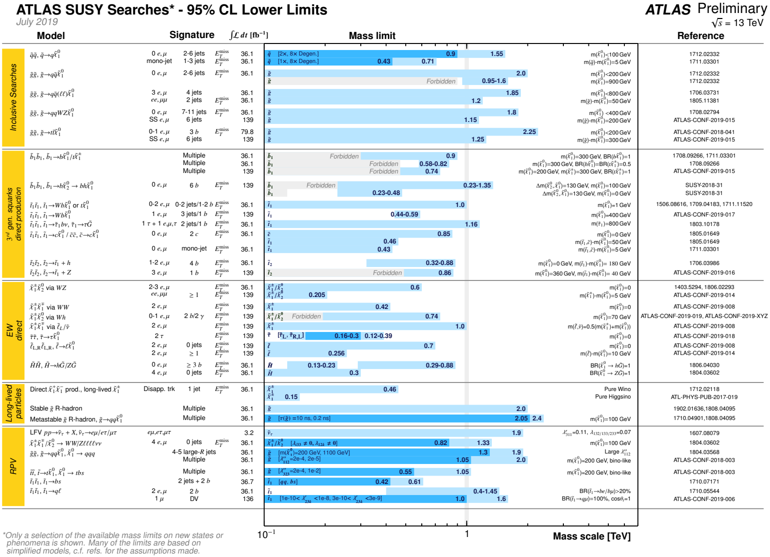
Uncertainty estimate of the fixed-order $\overline{\text{DR}}'$ calculation





[1804.09410]

Additional problem: no SUSY particles observed so far



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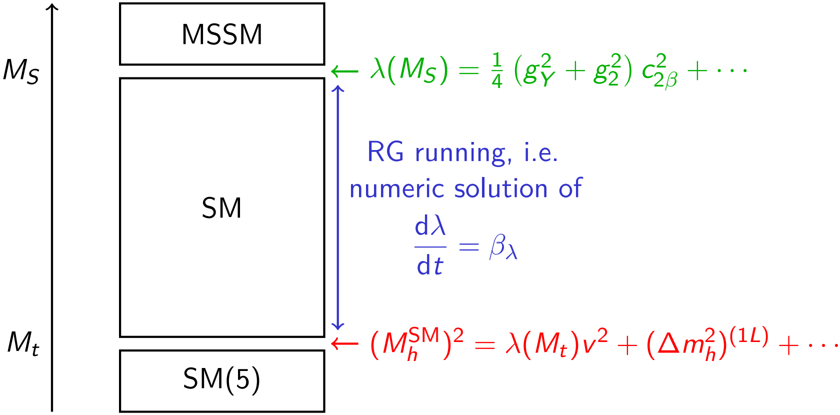
Higgs mass calculation in an Effective Field Theory

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 $\lambda(M_S) = m_Z^2 c_{2\beta}^2/v^2$:

$$\begin{aligned} M_h^2 &= m_Z^2 c_{2\beta}^2 - \frac{2y_t^4 v^2}{3g_3^2}\left[\left(1 + 14g_3^2\kappa L\right)^{-9/7} - 1\right] \\ &= m_Z^2 c_{2\beta}^2 + 12y_t^4 v^2\left[\kappa L - 16g_3^2\kappa^2 L^2 + \frac{736}{3}g_3^4\kappa^3 L^3 + \mathcal{O}(\kappa^4 L^4)\right] \end{aligned}$$

$\Rightarrow$ 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 $X_t = 0$, $M_S = 20\,\text{TeV}$):

$$M_h = \sqrt{\lambda(M_t)}\, v + \Delta m_h^{1L} + \Delta m_h^{2L} + \Delta m_h^{3L} + \cdots$$
$$\approx [\mathcal{O}(124) + \mathcal{O}(0.5\ldots1) + \mathcal{O}(0.1\ldots0.2) + \mathcal{O}(0.02\ldots0.04)]\,\text{GeV}$$

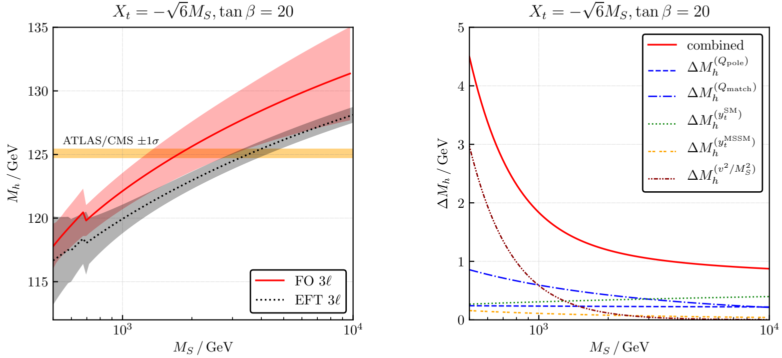
Advantages:

- ✓ 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:

- ✗ Terms of $\mathcal{O}(v^2/M_S^2)$ are (typically) neglected
  $\Rightarrow$ imprecise when $M_S \sim v$ (relevant?)
  $\Rightarrow$ large theoretical uncertainty when $M_S \sim v$

Comparison of fixed-order and EFT calculation



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

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

[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	✗	✓
? hybrid	✓	✓

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:

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

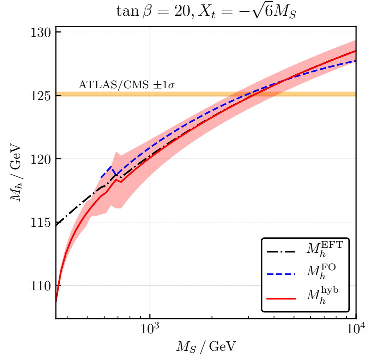
Advantages:

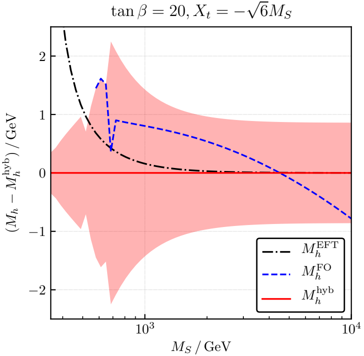
- ✓ approach applicable to any BSM model
- ✓ any EFT can be used

Disadvantages:

- ✗ requires knowledge of fixed-order and EFT expressions
- ✗ 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 $\mathcal{O}((v^2/M_S^2)^\infty)$ terms into λ by using the matching condition for the FO calculations:

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

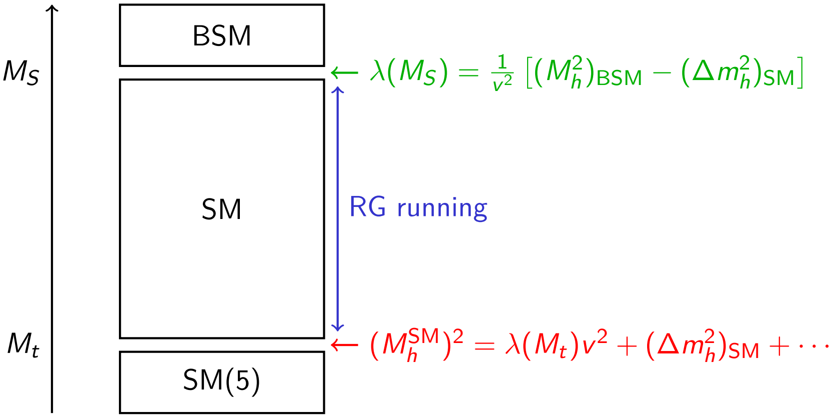
$\Rightarrow$

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

Continue as in the EFT calculation ...

Hybrid calculation – FlexibleEFTHiggs

Continue as in the EFT calculation:



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

Consider the matching condition:

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

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 $\to$ EFT for $v^2 \ll M_S^2$

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

$$= \frac{m_Z^2}{v^2} c_{2\alpha}^2 + \frac{1}{v^2}\Big[-\Sigma_h^{\text{SM}} - 6\kappa y_t^2 A_0(m_t)\Big]\left(\frac{c_\alpha^2}{s_\beta^2} - 1\right)$$

$$- 6\kappa y_t^4 \frac{c_\alpha^2}{s_\beta^2} B_0(M_S, M_S)$$

In the limit $v^2 \ll M_S^2$: $c_\alpha^2 \to s_\beta^2$, $c_{2\alpha}^2 \to c_{2\beta}^2 \Rightarrow$

$$\lambda(M_S) = \frac{1}{4}(g_Y^2 + g_2^2) c_{2\beta}^2 - 6\kappa y_t^4 B_0(M_S, M_S)$$

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

Summary of FlexibleEFTHiggs hybrid calculation

Matching condition:

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

Advantages:

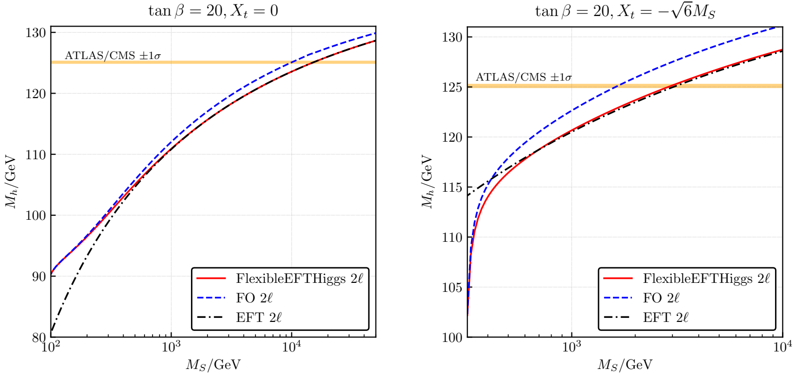
- ✓ includes all power-suppressed terms at n-loop order $(v^2/M_S^2)^\infty[c + \log^n(M_S/Q) + \log^n(M_S/m_t)]$
- ✓ resumms large non-suppressed logarithms $c\log^\infty(M_S/m_t)$
- ✓ approach applicable to any BSM model
- ✓ only 1- and 2-point fixed-order expressions required $\rightarrow$ easy to 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)

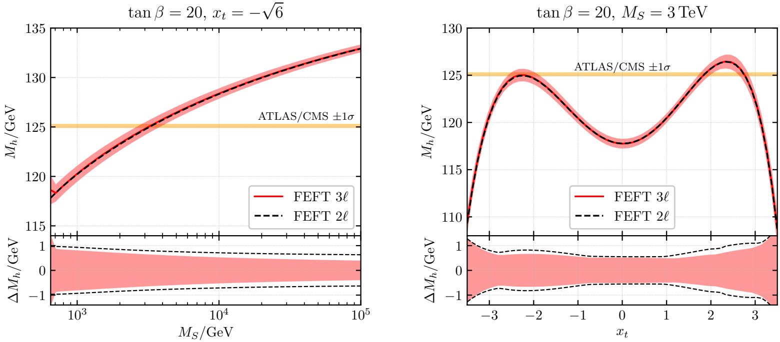
Interpolation behaviour of FlexibleEFTHiggs in the MSSM

Interpolation behaviour between FO and EFT calculation:



[plots along the lines of 2003.04639]

Hybrid calculation – FlexibleEFTHiggs



[2003.04639]

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

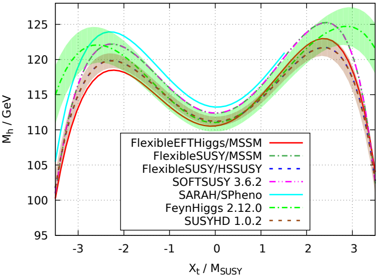
Contents

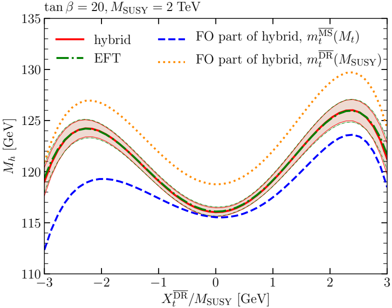
1. Introduction
2. BSM phenomenology with FlexibleSUSY
3. Higgs mass calculations in BSM models
   - Fixed order
   - Effective Field Theory
   - Hybrid
4. x_t resummation
5. Summary and conclusions

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





[1609.00371, 1912.10002]

Recap: $\tan\beta$ resummation in m_b

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

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

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 $n \geq 2$.

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

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

x_t resummation

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

$$y_t^{\text{EFT}} = y_t s_\beta + \Delta y_t$$

where Δy_t is expressed in terms of MSSM parameters.

Theorem (Kwasnitza, Stöckinger (2003.04639))

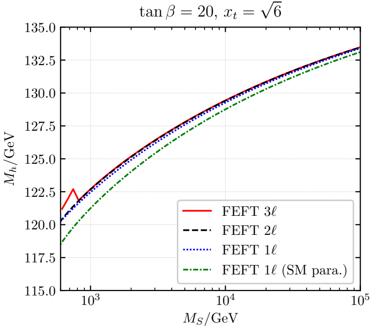
There are no unsuppressed contributions to Δy_t of $\mathcal{O}(\alpha_s^n x_t^{>1})$ for $n \geq 1$.

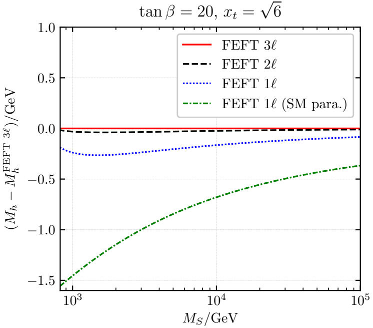
$\Rightarrow$ All higher-order MSSM contributions in y_t of $\mathcal{O}(\alpha_s^n x_t^{>1})$ can be resummed by writing:

$$y_t = \frac{y_t^{\text{EFT}}}{1 + \Delta y_t / (y_t s_\beta)}$$

x_t resummation

$\Rightarrow$ 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)

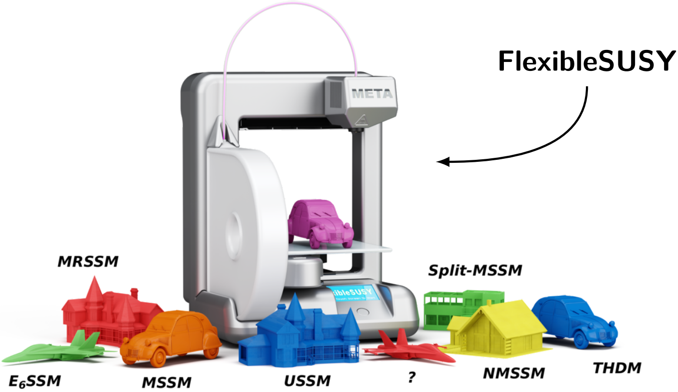
$\Rightarrow$

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

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

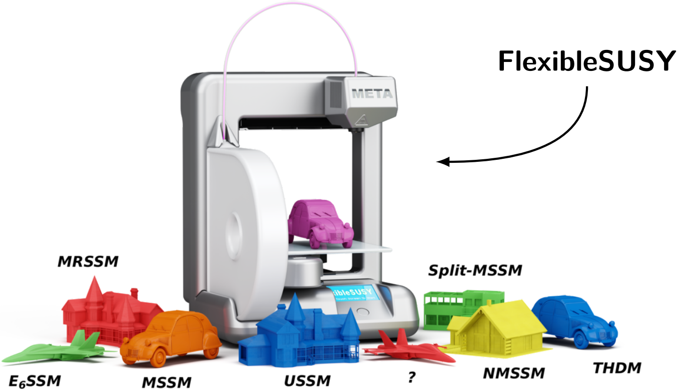
Outlook

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†
SARAH/SPheno	2L	1L	2L*

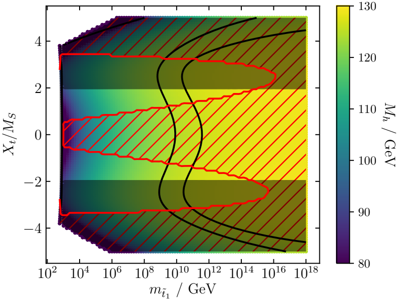
‡: in preparation, including x_t resummation

*: NNLO + LL resummation

†: NLO + NLL resummation

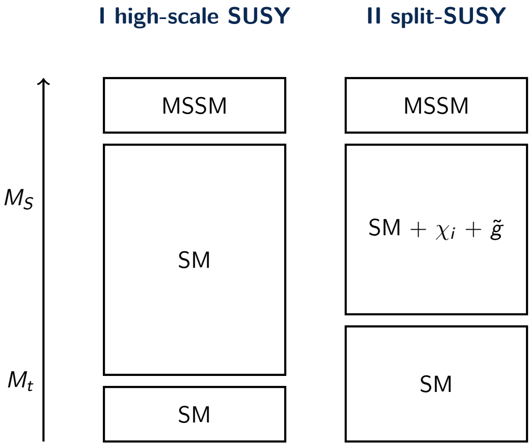
Maximum stop masses in the MSSM

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