

Precise calculations of the Higgs mass in supersymmetric models

Thomas Kwasnitza

3rd December 2020

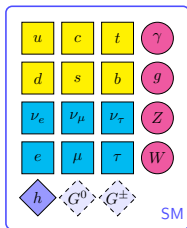
based on: [TK, D. Stöckinger, A. Voigt 20]



**TECHNISCHE
UNIVERSITÄT
DRESDEN**

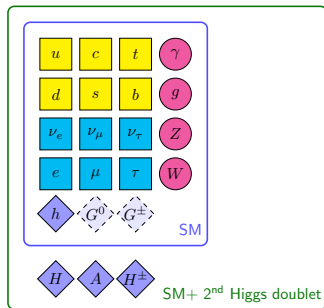


**INSTITUTE OF
NUCLEAR AND
PARTICLE PHYSICS**

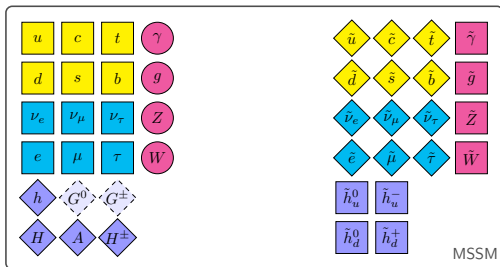


- Supersymmetry is a new fundamental spacetime symmetry

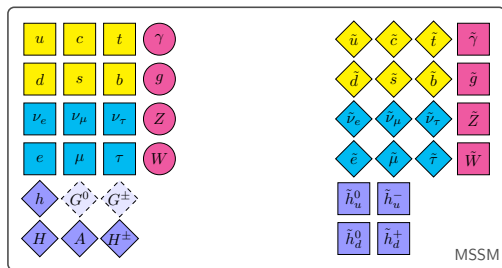
SUSY



- Supersymmetry is a new fundamental spacetime symmetry

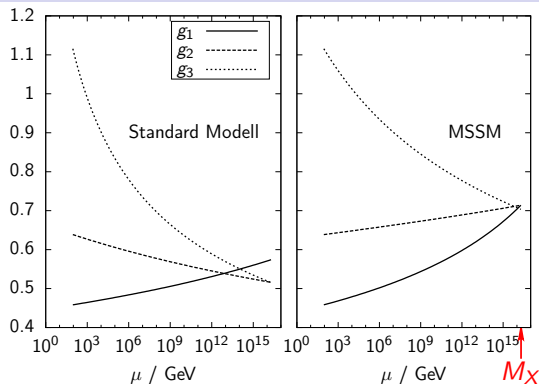


- Supersymmetry is a new fundamental spacetime symmetry



- Supersymmetry is a new fundamental spacetime symmetry
- Advantages for physics close to the EW scale
 - ▶ Dark matter
 - ▶ $g - 2$ of the muon
 - ▶ Dynamical breaking of EW symmetry ($\mu^2 < 0$)
 - ▶ Predicts one light Higgs boson

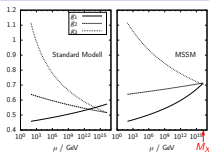
SUSY and Grand Unification



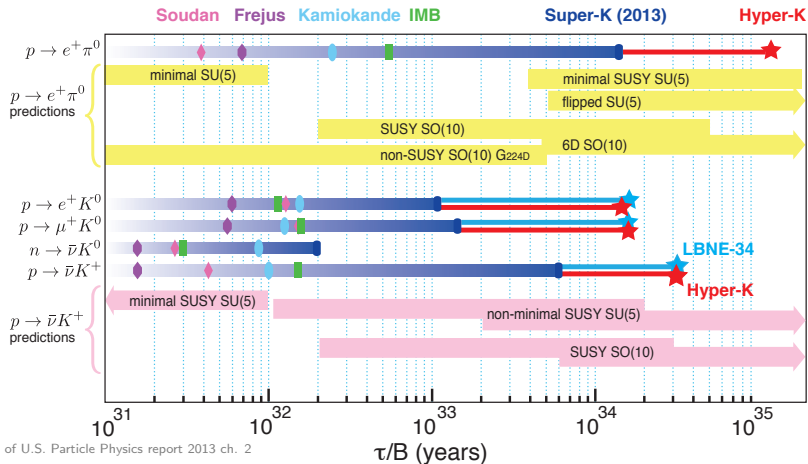
generated by FS A. Voigt

→ improved unification of gauge couplings

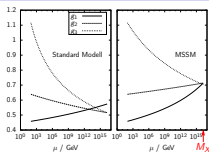
SUSY and Grand Unification



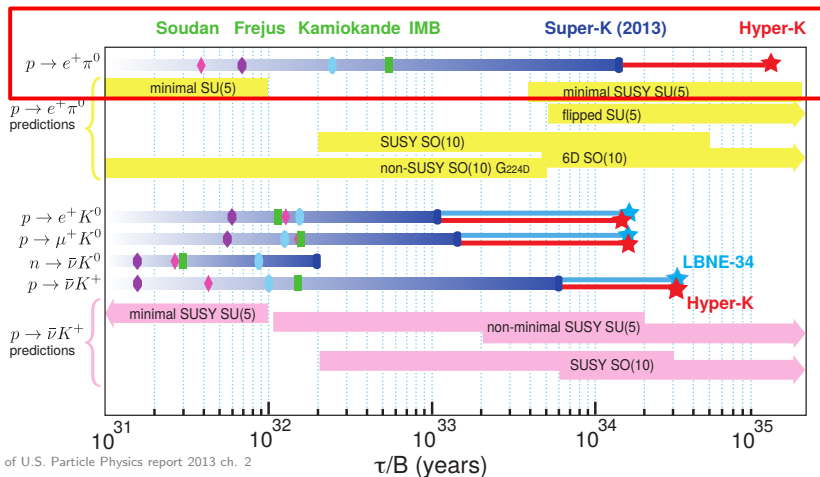
→ improved unification of gauge couplings



SUSY and Grand Unification



→ improved unification of gauge couplings



Features of Supersymmetry

Theorem in QFT (Weinberg Witten)

No massless spin $s > 2$ particle can couple consistently to massless particles with $s \leq 2$

see: Prof. Dominik Stöckinger RQFT WS19/20 Lecture 21 - 23

Poincaré + Unitarity \implies the menu of **elementary** particles is given by

massive case.: N. Arkani-Hamed, T. Huang, Y. Huang 2017

$$s \in \left\{ 0, \quad \frac{1}{2}, \quad 1, \quad \frac{3}{2}, \quad 2 \right\}$$

Features of Supersymmetry

Theorem in QFT (Weinberg Witten)


No massless spin $s > 2$ particle can couple consistently to massless particles with $s \leq 2$

see: Prof. Dominik Stöckinger RQFT WS19/20 Lecture 21 - 23

Poincaré + Unitarity \implies the menu of **elementary** particles is given by

massive case.: N. Arkani-Hamed, T. Huang, Y. Huang 2017

$$s \in \left\{ 0, \quad \frac{1}{2}, \quad \color{green}{1}, \quad \frac{3}{2}, \quad 2 \right\}$$

described by gauge theories 

Features of Supersymmetry

Theorem in QFT (Weinberg Witten)

No massless spin $s > 2$ particle can couple consistently to massless particles with $s \leq 2$

see: Prof. Dominik Stöckinger RQFT WS19/20 Lecture 21 - 23

Poincaré + Unitarity \implies the menu of **elementary** particles is given by

massive case.: N. Arkani-Hamed, T. Huang, Y. Huang 2017

$$s \in \left\{ 0, \quad \frac{1}{2}, \quad 1, \quad \frac{3}{2}, \quad \overset{\uparrow}{2} \right\}$$

unique gravity

[Eppley, Hannah 76]

Features of Supersymmetry

Theorem in QFT (Weinberg Witten)

No massless spin $s > 2$ particle can couple consistently to massless particles with $s \leq 2$

see: Prof. Dominik Stöckinger RQFT WS19/20 Lecture 21 - 23

Poincaré + Unitarity \implies the menu of **elementary** particles is given by

massive case.: N. Arkani-Hamed, T. Huang, Y. Huang 2017

$$s \in \left\{ 0, \quad \frac{1}{2}, \quad 1, \quad \frac{3}{2}, \quad 2 \right\}$$

described by local SUSY 

Features of Supersymmetry

Theorem in QFT (Weinberg Witten)

No massless spin $s > 2$ particle can couple consistently to massless particles with $s \leq 2$

see: Prof. Dominik Stöckinger RQFT WS19/20 Lecture 21 - 23

Poincaré + Unitarity \implies the menu of **elementary** particles is given by

massive case.: N. Arkani-Hamed, T. Huang, Y. Huang 2017

$$s \in \left\{ 0, \quad \frac{1}{2}, \quad 1, \quad \frac{3}{2}, \quad 2 \right\}$$

Features of Supersymmetry

Theorem in QFT (Weinberg Witten)

No massless spin $s > 2$ particle can couple consistently to massless particles with $s \leq 2$

see: Prof. Dominik Stöckinger RQFT WS19/20 Lecture 21 - 23

Poincaré + Unitarity \implies the menu of **elementary** particles is given by

massive case.: N. Arkani-Hamed, T. Huang, Y. Huang 2017

$$s \in \left\{ 0, \quad \frac{1}{2}, \quad 1, \quad \frac{3}{2}, \quad 2 \right\}$$

- Relation to (quantum) gravity: SUGRA, string theory, matrix models, ...

Nicht ohne SUSY

Die Superstringtheorie er
trisch ist – ein weiterer An
Physiker auf die Entdecku

Higgs mass in the MSSM

- SUSY extension **predicts** one light Higgs

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

$$m_h^2 \approx m_Z^2 c_{2\beta}^2 \leq m_Z^2, \quad m_H^2 \approx M_S^2$$

- Pole masses are PDG 2018

$$M_h = \sqrt{m_h^2 + \Delta m_h^2} \approx 125.1 \text{ GeV}$$

$$M_Z \approx 91.2 \text{ GeV}$$

Higgs mass in the MSSM

- SUSY extension **predicts** one light Higgs

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

$$m_h^2 \approx m_Z^2 c_{2\beta}^2 \leq m_Z^2, \quad m_H^2 \approx M_S^2$$

- Pole masses are PDG 2018

$$M_h = \sqrt{m_h^2 + \Delta m_h^2} \approx 125.1 \text{ GeV}$$

$$M_Z \approx 91.2 \text{ GeV}$$

- Anatomy of radiative contributions

$$\Delta m_h^2 = v^2 \kappa^n \left[\log \frac{M_S}{v} + C_0 + C_1 \frac{v^2}{M_S^2} \right]$$

→ **Use** $[M_h \stackrel{!}{=} 125.1 \text{ GeV}]$ **as a constraint on new parameters**

Higgs mass in the MSSM

$$\Delta m_h^2 = v^2 \kappa^n \left[\log \frac{M_S}{v} + C_0 + C_1 \frac{v^2}{M_S^2} \right]$$

- Q: Which parameter can be constrained?

$$\left\{ M_S, \quad \tan \beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}, \quad \begin{array}{l} x_t \text{ mixing parameter} \\ M_t^2 = \left(\begin{array}{cc} M_S^2 & x_t m_t M_S \\ (x_t m_t M_S)^* & M_S^2 \end{array} \right), \dots \end{array} \right\}$$

- MSSM is consistent iff **large** radiative corrections exist:

$$(86 \text{ GeV})^2 \leq \Delta m_h^2 \leq (125 \text{ GeV})^2$$

Higgs mass in the MSSM

$$\Delta m_h^2 = v^2 \kappa^n \left[\log \frac{M_S}{v} + C_0 + C_1 \frac{v^2}{M_S^2} \right]$$

- Q: Which parameter can be constrained?

$$\left\{ M_S, \quad \tan \beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}, \quad \overset{x_t \text{ mixing parameter}}{M_t^2} = \begin{pmatrix} M_S^2 & \\ (x_t m_t M_S)^* & M_S^2 \end{pmatrix}, \dots \right\}$$

- MSSM is consistent iff **large** radiative corrections exist:

$$(86 \text{ GeV})^2 \leq \Delta m_h^2 \leq (125 \text{ GeV})^2$$

- ▶ $\log \frac{M_S}{v}$: typical feature of SUSY, M_S **cannot be arbitrarily high!**

Exception: FSSM K. Benakli et al. 2013

Higgs mass in the MSSM

$$\Delta m_h^2 = v^2 \kappa^n \left[\log \frac{M_S}{v} + C_0 + C_1 \frac{v^2}{M_S^2} \right]$$

- Q: Which parameter can be constrained?

$$\left\{ M_S, \quad \tan \beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}, \quad x_t \text{ mixing parameter}, \quad M_t^2 = \begin{pmatrix} M_S^2 & x_t m_t M_S \\ (x_t m_t M_S)^* & M_S^2 \end{pmatrix}, \dots \right\}$$

- MSSM is consistent iff **large** radiative corrections exist:

$$(86 \text{ GeV})^2 \leq \Delta m_h^2 \leq (125 \text{ GeV})^2$$

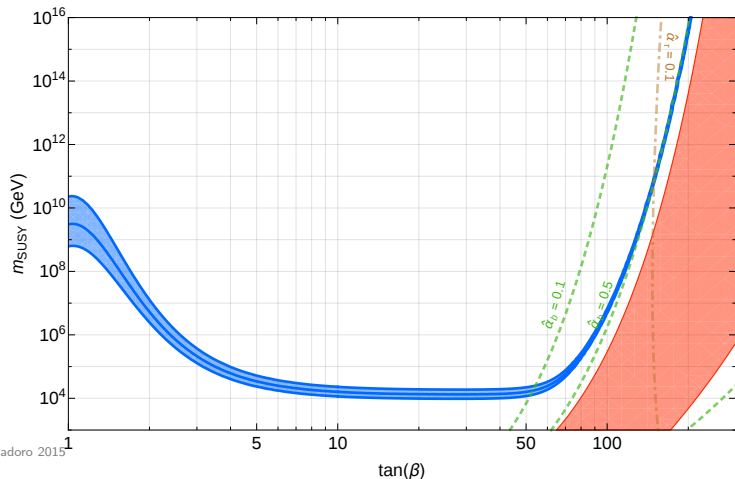
- ▶ $\log \frac{M_S}{v}$: typical feature of SUSY, M_S **cannot be arbitrarily high!**

Exception: FSSM K. Benakli et al. 2013

- Conclusive constraint requires low uncertainty
 - ▶ **Good**: experimental uncertainty $\Delta M_h^{\text{exp}} \approx 0.14 \text{ GeV}$
 - ▶ **Problem**: theory uncertainty $\Delta M_h^{\text{th}} \approx 1\text{-}3 \text{ GeV}$

Higgs mass in the MSSM

$$\left[M_h \stackrel{!}{=} 125.1 \pm 1.5 \text{ GeV} \right] \text{ solved for } M_S$$



J.Vega, G. Villadoro 2015

→ Need for a high precision calculation!

Contents

- 1 Radiative corrections to the Higgs boson mass
- 2 Trick 1: Resummation of large logarithms
- 3 Trick 2: Hybrid calculation FlexibleEFTHiggs
- 4 Trick 3: Resummation of leading x_t powers
- 5 Uncertainty of FlexibleEFTHiggs at 3-loop
- 6 Summary

Radiative corrections to the Higgs boson mass

$$\Delta m_h^2 \supset h \text{---} \text{---} \text{---} \text{---} h + h \text{---} \text{---} \text{---} \text{---} h + h \text{---} \text{---} \text{---} \text{---} h + \dots$$

- Leading loop (in SM parameters) contributions at NLO

$$\Delta m_h^2 = \kappa y_t^2 m_t^2 \left[24 \log \frac{M_S}{m_t} - x_t^4 + 12x_t^2 + \frac{m_t^2}{M_S^2} \frac{15}{4} + \dots \right]$$

Radiative corrections to the Higgs boson mass

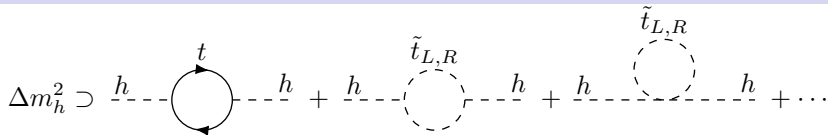
$$\Delta m_h^2 \supset \text{---} h \text{---} \text{---} \text{---} \text{---} \text{---} h \text{---} + \text{---} h \text{---} \text{---} \text{---} \text{---} \text{---} h \text{---} + \text{---} h \text{---} \text{---} \text{---} \text{---} \text{---} h \text{---} + \dots$$

- Leading loop (in SM parameters) contributions at NNLO

$$\Delta m_h^2 = \kappa y_t^2 m_t^2 \left[24 \log \frac{M_S}{m_t} \quad -x_t^4 + 12x_t^2 + \frac{m_t^2}{M_S^2} \frac{15}{4} + \dots \right]$$

$$+ \kappa^2 g_3^2 y_t^2 m_t^2 \left[k_{(2,2)} \log^2 \frac{M_S}{m_t} + \dots \quad + b_2 x_t^5 + \dots + \mathcal{O} \left(\frac{m_t^2}{M_S^2} \right) \right]$$

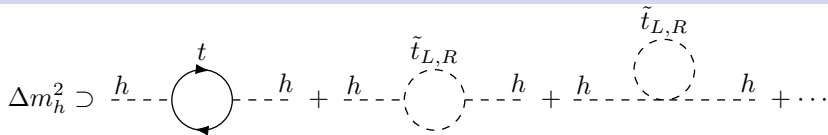
Radiative corrections to the Higgs boson mass



- Leading loop (in SM parameters) contributions at NNNLO

$$\begin{aligned}
 \Delta m_h^2 = & \kappa y_t^2 m_t^2 \left[24 \log \frac{M_S}{m_t} \quad -x_t^4 + 12x_t^2 + \frac{m_t^2}{M_S^2} \frac{15}{4} + \dots \right] \\
 & + \kappa^2 g_3^2 y_t^2 m_t^2 \left[k_{(2,2)} \log^2 \frac{M_S}{m_t} + \dots \quad + b_2 x_t^5 + \dots + \mathcal{O} \left(\frac{m_t^2}{M_S^2} \right) \right] \\
 & + \kappa^3 g_3^4 y_t^2 m_t^2 \left[k_{(3,3)} \log^3 \frac{M_S}{m_t} + \dots \quad + b_3 x_t^6 + \dots + \mathcal{O} \left(\frac{m_t^2}{M_S^2} \right) \right] \\
 & + \dots
 \end{aligned}$$

Radiative corrections to the Higgs boson mass



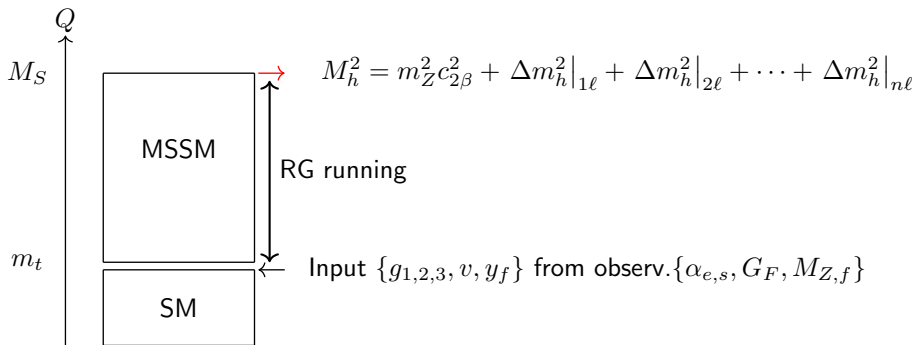
- Leading loop (in SM parameters) contributions at NNNLO

$$\begin{aligned}
 \Delta m_h^2 = & \kappa y_t^2 m_t^2 \left[24 \log \frac{M_S}{m_t} \quad -x_t^4 + 12x_t^2 + \frac{m_t^2}{M_S^2} \frac{15}{4} + \dots \right] \\
 & + \kappa^2 g_3^2 y_t^2 m_t^2 \left[k_{(2,2)} \log^2 \frac{M_S}{m_t} + \dots \quad + b_2 x_t^5 + \dots + \mathcal{O} \left(\frac{m_t^2}{M_S^2} \right) \right] \\
 & + \kappa^3 g_3^4 y_t^2 m_t^2 \left[k_{(3,3)} \log^3 \frac{M_S}{m_t} + \dots \quad + b_3 x_t^6 + \dots + \mathcal{O} \left(\frac{m_t^2}{M_S^2} \right) \right] \\
 & + \dots
 \end{aligned}$$

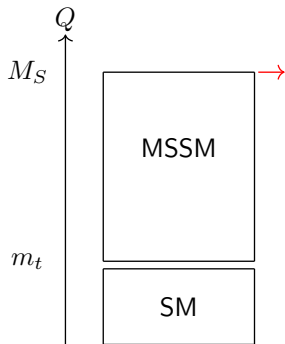
- Large loop corrections for:

- ▶ large mass gap $M_S \gg m_t$
- ▶ large off-diagonal element in the stop mass matrix: $|x_t| \approx \sqrt{6}$

Fixed-order calculation



Fixed-order calculation

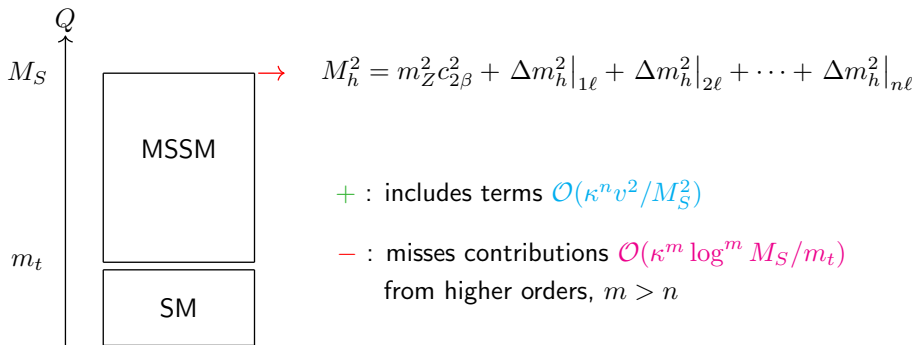


$$M_h^2 = m_Z^2 c_{2\beta}^2 + \Delta m_h^2|_{1\ell} + \Delta m_h^2|_{2\ell} + \dots + \Delta m_h^2|_{n\ell}$$

+ : includes terms $\mathcal{O}(\kappa^n v^2/M_S^2)$

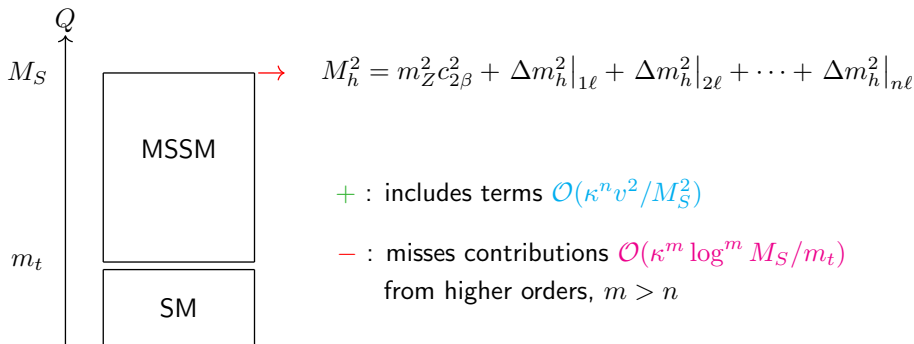
- : misses contributions $\mathcal{O}(\kappa^m \log^m M_S/m_t)$
from higher orders, $m > n$

Fixed-order calculation



- **Good:** gives reliable predictions if M_S and m_t are not too far apart

Fixed-order calculation

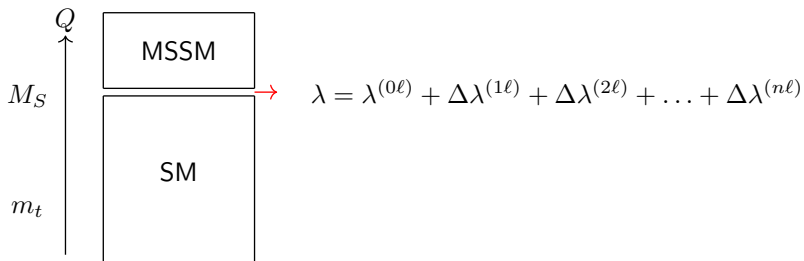


- **Good:** gives reliable predictions if M_S and m_t are not too far apart
- **Problem:** if $M_S \gg m_t \Rightarrow$ perturbative expansion converges slow

$$M_h = m_h + \Delta m_h^{1\ell} + \Delta m_h^{2\ell} + \Delta m_h^{3\ell} + \dots$$
$$\approx [91 + \mathcal{O}(20 \dots 30) + \mathcal{O}(2 \dots 5) + \mathcal{O}(1 \dots 2)] \text{ GeV}$$

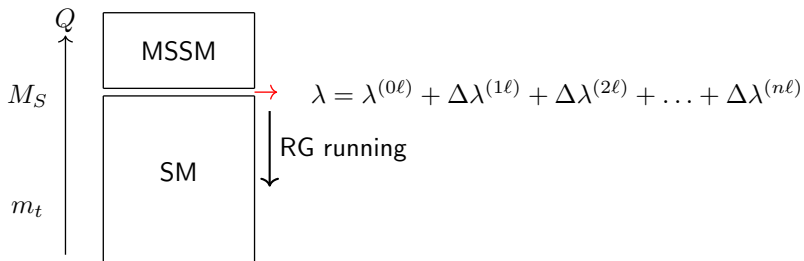
Trick 1: Resummation of large logarithms

Effective field theory approach [$\lim(v/M_S) \rightarrow 0$]



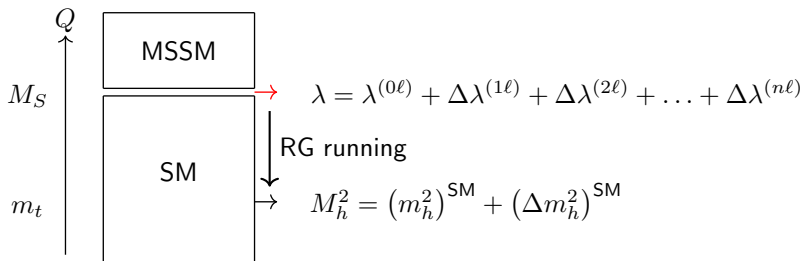
Trick 1: Resummation of large logarithms

Effective field theory approach [$\lim(v/M_S) \rightarrow 0$]



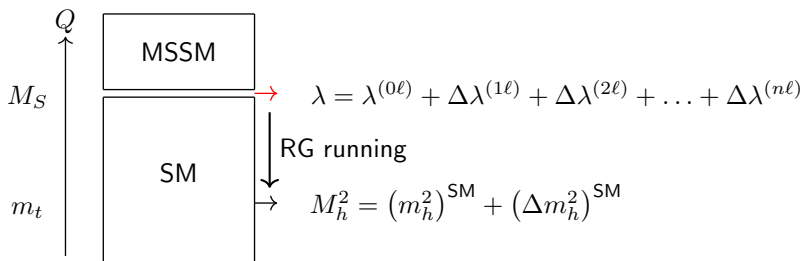
Trick 1: Resummation of large logarithms

Effective field theory approach [$\lim(v/M_S) \rightarrow 0$]



Trick 1: Resummation of large logarithms

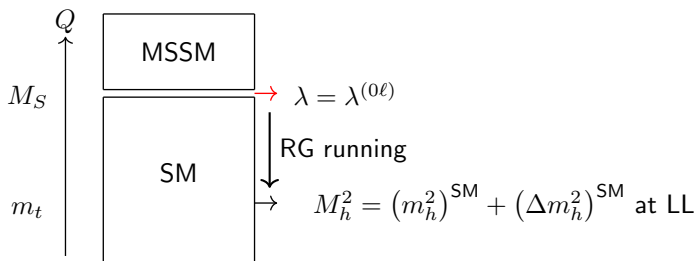
Effective field theory approach [$\lim(v/M_S) \rightarrow 0$]



$$\begin{aligned} \frac{(m_h^2)^{\text{SM}}}{m_t^2} &\supset y_t^2 \left(C_0^{1\ell} + k_{(1,1)} \log \frac{M_S}{m_t} \right) \\ &+ y_t^2 g_3^2 \left(C_0^{2\ell} + k_{(1,2)} \log \frac{M_S}{m_t} + k_{(2,2)} \log^2 \frac{M_S}{m_t} \right) \\ &+ y_t^2 g_3^4 \left(C_0^{3\ell} + k_{(1,3)} \log \frac{M_S}{m_t} + k_{(2,3)} \log^2 \frac{M_S}{m_t} + k_{(3,3)} \log^3 \frac{M_S}{m_t} \right) \\ &+ \dots \end{aligned}$$

Trick 1: Resummation of large logarithms

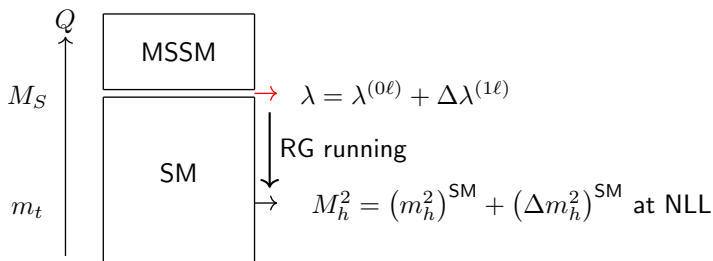
Effective field theory approach [$\lim(v/M_S) \rightarrow 0$]



$$\begin{aligned} \frac{(m_h^2)^{\text{SM}}}{m_t^2} &\supset y_t^2 \left(C_0^{1\ell} + k_{(1,1)} \log \frac{M_S}{m_t} \right) \\ &+ y_t^2 g_3^2 \left(C_0^{2\ell} + k_{(1,2)} \log \frac{M_S}{m_t} + k_{(2,2)} \log^2 \frac{M_S}{m_t} \right) \\ &+ y_t^2 g_3^4 \left(C_0^{3\ell} + k_{(1,3)} \log \frac{M_S}{m_t} + k_{(2,3)} \log^2 \frac{M_S}{m_t} + k_{(3,3)} \log^3 \frac{M_S}{m_t} \right) \\ &+ \dots \end{aligned}$$

Trick 1: Resummation of large logarithms

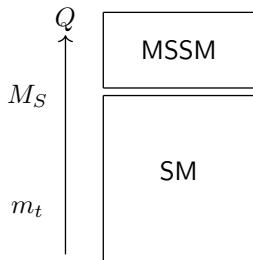
Effective field theory approach [$\lim(v/M_S) \rightarrow 0$]



$$\begin{aligned}
 \frac{(m_h^2)^{\text{SM}}}{m_t^2} &\supset y_t^2 \left(C_0^{1\ell} + k_{(1,1)} \log \frac{M_S}{m_t} \right) \\
 &+ y_t^2 g_3^2 \left(C_0^{2\ell} + k_{(1,2)} \log \frac{M_S}{m_t} + k_{(2,2)} \log^2 \frac{M_S}{m_t} \right) \\
 &+ y_t^2 g_3^4 \left(C_0^{3\ell} + k_{(1,3)} \log \frac{M_S}{m_t} + k_{(2,3)} \log^2 \frac{M_S}{m_t} + k_{(3,3)} \log^3 \frac{M_S}{m_t} \right) \\
 &+ \dots
 \end{aligned}$$

Trick 1: Resummation of large logarithms

Effective field theory approach [$\lim(v/M_S) \rightarrow 0$]



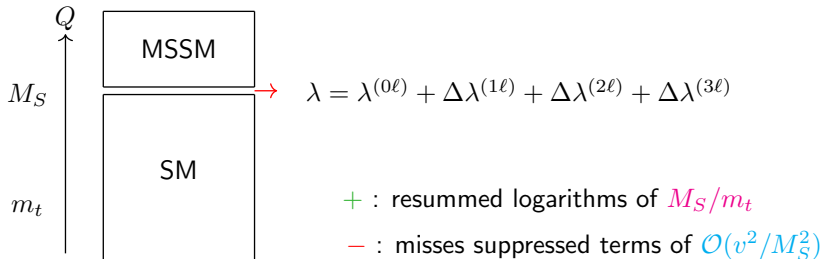
$$\lambda = \lambda^{(0\ell)} + \Delta\lambda^{(1\ell)} + \Delta\lambda^{(2\ell)} + \Delta\lambda^{(3\ell)}$$

+ : resummed logarithms of M_S/m_t

- : misses suppressed terms of $\mathcal{O}(v^2/M_S^2)$

Trick 1: Resummation of large logarithms

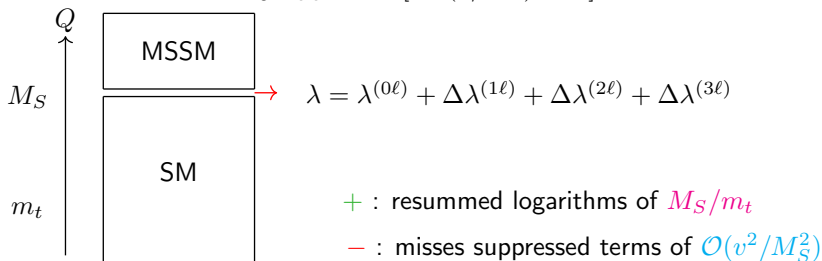
Effective field theory approach [$\lim(v/M_S) \rightarrow 0$]



- **Good:** Predicts Higgs mass reliably for large separation of m_t and M_S
- **Problem:** for $M_S \simeq m_t \Rightarrow$ large uncertainty

Trick 1: Resummation of large logarithms

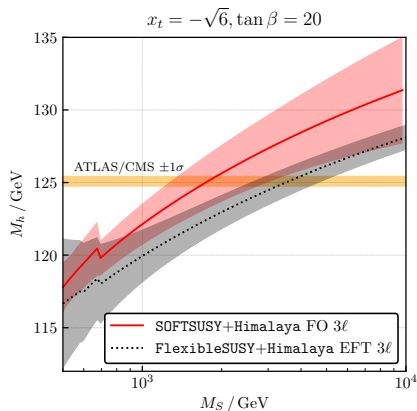
Effective field theory approach [$\lim(v/M_S) \rightarrow 0$]



- **Good:** Predicts Higgs mass reliably for large separation of m_t and M_S
- **Problem:** for $M_S \simeq m_t \Rightarrow$ large uncertainty
- convergence rate of perturbative expansion
($x_t = -\sqrt{6}$, $\tan\beta = 20$, $M_S = 3$ TeV)

$$M_h = m_h + \Delta m_h^{1\ell} + \Delta m_h^{2\ell} + \Delta m_h^{3\ell}$$
$$\approx [\mathcal{O}(117) + \mathcal{O}(7) + \mathcal{O}(1) + \mathcal{O}(0.2)] \text{ GeV}$$

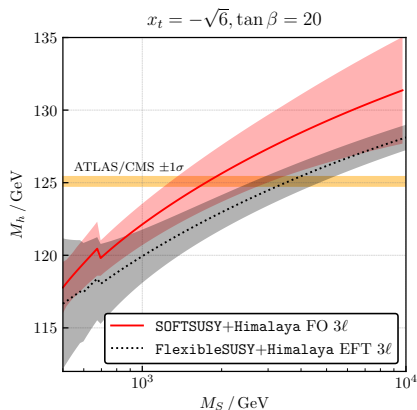
Comparison of M_h calculations



B. Allanach, A. Voigt 2018

	low M_S $M_S \lesssim 1.3 \text{ TeV}$	high M_S $M_S \gtrsim 1.3 \text{ TeV}$
fixed-order (FO)	✓	✗
EFT	✗	✓

Comparison of M_h calculations

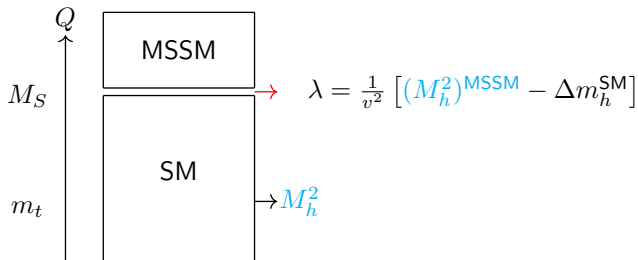


B. Allanach, A. Voigt 2018

	low M_S $M_S \lesssim 1.3 \text{ TeV}$	high M_S $M_S \gtrsim 1.3 \text{ TeV}$
fixed-order (FO)	✓	✗
EFT	✗	✓
Q: FO and EFT combined?	✓	✓


Trick 2: Hybrid calculation

A: Yes e.g. FlexibleEFTHiggs [P. Athron et al. 2016], [P. Athron et al. 2017], [TK et al. 2020]



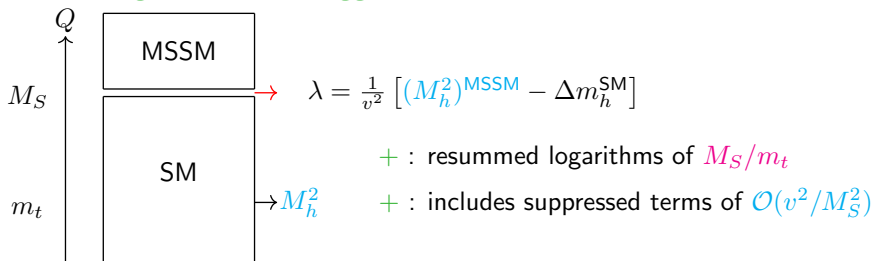
- Obtain λ from pole mass matching

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

- Ensure that $\log(M_S/m_t)$ cancel in λ 


Trick 2: Hybrid calculation

A: Yes e.g. FlexibleEFTHiggs [P. Athron et al. 2016], [P. Athron et al. 2017], [TK et al. 2020]



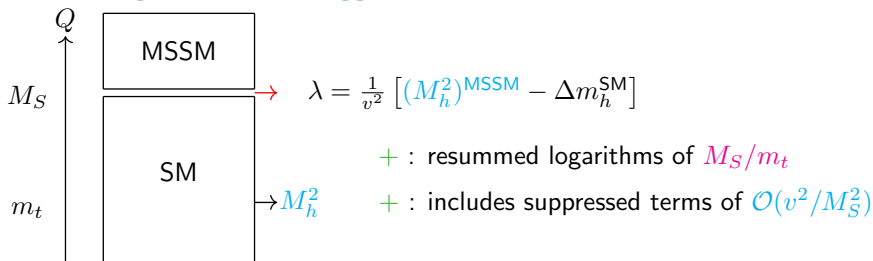
- Obtain λ from pole mass matching

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

- Ensure that $\log(M_S/m_t)$ cancel in λ 


Trick 2: Hybrid calculation

A: Yes e.g. FlexibleEFTHiggs [P. Athron et al. 2016], [P. Athron et al. 2017], [TK et al. 2020]

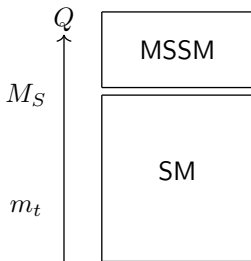


- Obtain λ from pole mass matching

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

- Ensure that $\log(M_S/m_t)$ cancel in λ 
- **Good:**
 - ▶ Valid at all scales
 - ▶ Automated derivation of $\Delta\lambda$ from self energies and tadpoles

Hybrid calculation FlexibleEFTHiggs at N³LO and N³LL



M_h^2 at 3ℓ

$$\mathcal{O}(1\ell + (\alpha_t + \alpha_b)\alpha_s + (\alpha_t + \alpha_b + \alpha_\tau)^2 + \alpha_s^2\alpha_t)$$

[0105096, 0112177, 0212132, 0206101, 0305127, 1205.6497, 1407.4336, 1708.05720]

RGE at 4ℓ [1201.5868, 1205.2892, 1212.6829, 1303.4364, 1604.00853]

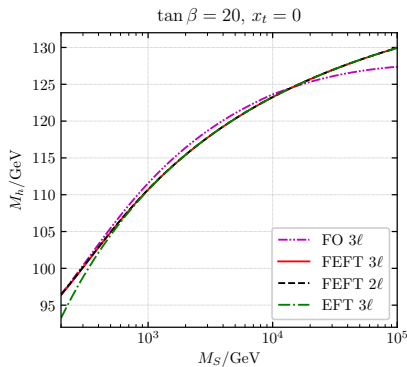
$\alpha_s^{\text{SM}(5)}$ at 2ℓ [9305305, 9707474]

M_t at 3ℓ $\mathcal{O}(\alpha_s^2 + \alpha_s^3)$ [9912391, 0507139, 9912391]

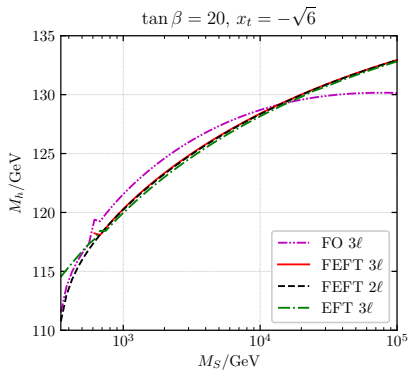
- 3L self energy from FlexibleSUSY+Himalaya obtained without terms of $\mathcal{O}(\kappa^3 v^2 / M_S^2)$

Hybrid calculation FlexibleEFTHiggs at N³LO and N³LL

- Interpolation of Hybrid FEFT between FO and EFT:



for $x_t = 0$ exact



for $x_t = -\sqrt{6}$ discrepancy

- Discrepancy is dominated by highest power x_t contributions included in FEFT

Trick 3: Resummation of leading x_t powers

- **Observation 1:** the presented EFT calc. and FlexibleEFTHiggs work in different parametrizations!

⇒ expand both matching conditions to 2-loop

$$\Delta\lambda^{\text{FEFT}} = \kappa(y_t^{\text{MSSM}})^4 \left[6x_t^2 - \frac{1}{2}x_t^4 \right] + \mathcal{O}\left(\frac{m_t^2}{M_S^2}\right) \\ + \kappa^2 g_3^2 (y_t^{\text{MSSM}})^4 \left[c_{(0,2)} + c_{(1,2)}x_t + \dots + c_{(4,2)}x_t^4 \right] + \mathcal{O}\left(\frac{m_t^2}{M_S^2}\right)$$

$$\Delta\lambda^{\text{EFT}} = \kappa(y_t^{\text{SM}})^4 \left[6x_t^2 - \frac{1}{2}x_t^4 \right] \\ + \kappa^2 g_3^2 (y_t^{\text{SM}})^4 \left[\tilde{c}_{(0,2)} + \tilde{c}_{(1,2)}x_t + \dots + \tilde{c}_{(4,2)}x_t^4 + \tilde{c}_{(5,2)}x_t^5 \right]$$

- **Q:** How is the x_t^5 term reproduced in FEFT?

Trick 3: Resummation of leading x_t powers

- **Observation 1:** the presented EFT calc. and FlexibleEFTHiggs work in different parametrizations!

⇒ expand both matching conditions to 2-loop

$$\begin{aligned}\Delta\lambda^{\text{FEFT}} &= \kappa(y_t^{\text{MSSM}})^4 \left[6x_t^2 \right. && \left. - \frac{1}{2}x_t^4 \right] + \mathcal{O}\left(\frac{m_t^2}{M_S^2}\right) \\ &+ \kappa^2 g_3^2 (y_t^{\text{MSSM}})^4 \left[c_{(0,2)} + c_{(1,2)}x_t + \dots \right. && \left. + c_{(4,2)}x_t^4 \right] + \mathcal{O}\left(\frac{m_t^2}{M_S^2}\right) \\ \Delta\lambda^{\text{EFT}} &= \kappa(y_t^{\text{SM}})^4 \left[6x_t^2 \right. && \left. - \frac{1}{2}x_t^4 \right] \\ &+ \kappa^2 g_3^2 (y_t^{\text{SM}})^4 \left[\tilde{c}_{(0,2)} + \tilde{c}_{(1,2)}x_t + \dots \right. && \left. + \tilde{c}_{(4,2)}x_t^4 + \tilde{c}_{(5,2)}x_t^5 \right]\end{aligned}$$

- **Q:** How is the x_t^5 term reproduced in FEFT?
- **A:** The reparametrization of y_t contains contributions $\Delta_t \propto g_3^2 x_t$

$$y_t^{\text{SM}} = y_t^{\text{MSSM}} [1 - \Delta_t^{1\ell}] \quad \Rightarrow \quad y_t^{\text{MSSM}} \approx y_t^{\text{SM}} [1 + \Delta_t^{1\ell}]$$

Parametrizations are equivalent at 2-loop!

Trick 3: Resummation of leading x_t powers

- **Observation 2:** Use the exact (implemented) relation

$$y_t^{\text{MSSM}} = \frac{y_t^{\text{SM}}}{[1 - \Delta_t^{1\ell}]} = y_t^{\text{SM}} \sum_n (\Delta_t^{1\ell})^n$$

$$\begin{aligned} (\Delta\lambda^{\text{FEFT}})^{(1\ell)} &= \kappa (y_t^{\text{MSSM}})^4 \left[6x_t^2 \quad -\frac{1}{2}x_t^4 \right] \\ &= \kappa (y_t^{\text{SM}})^4 \left[6x_t^2 \quad -\frac{1}{2}x_t^4 \right] \\ &\quad + \kappa^2 g_3^2 (y_t^{\text{SM}})^4 \left[\dots \quad +\hat{c}_{(4,2)}x_t^4 + \hat{c}_{(5,2)}x_t^5 \right] \\ &\quad + \kappa^3 g_3^4 (y_t^{\text{SM}})^4 \left[\dots \quad +\hat{c}_{(4,3)}x_t^4 + \hat{c}_{(5,3)}x_t^5 + \hat{c}_{(5,3)}x_t^6 \right] \\ &\quad \dots \end{aligned}$$

Trick 3: Resummation of leading x_t powers

- **Observation 2:** Use the exact (implemented) relation

$$y_t^{\text{MSSM}} = \frac{y_t^{\text{SM}}}{[1 - \Delta_t^{1\ell}]} = y_t^{\text{SM}} \sum_n (\Delta_t^{1\ell})^n$$

$$\begin{aligned}(\Delta\lambda^{\text{FEFT}})^{(1\ell)} &= \kappa (y_t^{\text{MSSM}})^4 \left[6x_t^2 \quad -\frac{1}{2}x_t^4 \right] \\ &= \kappa (y_t^{\text{SM}})^4 \left[6x_t^2 \quad -\frac{1}{2}x_t^4 \right] \\ &\quad + \kappa^2 g_3^2 (y_t^{\text{SM}})^4 \left[\dots \quad +\hat{c}_{(4,2)}x_t^4 + \hat{c}_{(5,2)}x_t^5 \right] \\ &\quad + \kappa^3 g_3^4 (y_t^{\text{SM}})^4 \left[\dots \quad +\hat{c}_{(4,3)}x_t^4 + \hat{c}_{(5,3)}x_t^5 + \hat{c}_{(5,3)}x_t^6 \right] \\ &\quad \dots\end{aligned}$$

- Direct calculation reveals
 - ▶ $\hat{c}_{(5,2)}x_t^5 = \tilde{c}_{(5,2)}x_t^5$ ✓
 - ▶ $\hat{c}_{(4,2)}x_t^4$ ✗, gets contributions from 2-loop Feynman diagrams
- **Q: What can be said about higher orders?**

Trick 3: Resummation of leading x_t powers

A: An inspection of multi-loop diagrams reveals that the highest power contributions x_t^{\max} receive no further corrections

Theorem TK, D. Stöckinger

In MSSM parameters: $\Delta\lambda \not\propto (y_t^{\text{MSSM}})^4 g_3^{2n} x_t^{(5 \text{ or higher})}$ for $n \geq 0$.

$$\begin{aligned} \frac{\Delta\lambda}{(y_t^{\text{SM}})^4} &\supset \kappa g_3^2 \left(\propto x_t^{\leq 4} + c_{(4+1,1)} x_t^{4+1} \right) \\ &+ \kappa^2 g_3^4 \left(\propto x_t^{\leq 4} + c_{(4+1,2)} x_t^{4+1} + c_{(4+2,2)} x_t^{4+2} \right) \\ &+ \kappa^3 g_3^6 \left(\propto x_t^{\leq 4} + c_{(4+1,3)} x_t^{4+1} + c_{(4+2,3)} x_t^{4+2} + c_{(4+3,3)} x_t^{4+3} \right) \\ &+ \dots \end{aligned}$$

- Constraint can be extended to orders with combinations of g_3 with other couplings, i.e. $\Delta\lambda = y_t^2 g_{1,2}^2 g_3^{2n} + y_t^6 g_3^{2n}$
- Predicted correctly $\Delta\lambda = y_t^2 g_{1,2}^2 g_3^2 x_t^3$ contribution from Bagnaschi et al. 2019

Trick 3: Resummation of leading x_t powers

A: An inspection of multi-loop diagrams reveals that the highest power contributions x_t^{\max} receive no further corrections

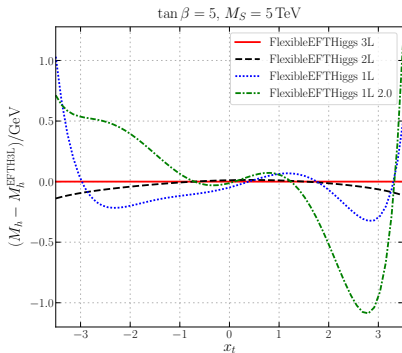
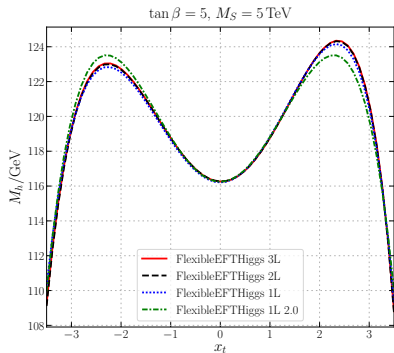
Theorem TK, D. Stöckinger

In MSSM parameters: $\Delta\lambda \not\propto (y_t^{\text{MSSM}})^4 g_3^{2n} x_t^{(5 \text{ or higher})}$ for $n \geq 0$.

$$\begin{aligned} \frac{\Delta\lambda}{(y_t^{\text{SM}})^4} &\supset \kappa g_3^2 \left(\propto x_t^{\leq 4} + c_{(4+1,1)} x_t^{4+1} \right) \\ &+ \kappa^2 g_3^4 \left(\propto x_t^{\leq 4} + c_{(4+1,2)} x_t^{4+1} + c_{(4+2,2)} x_t^{4+2} \right) \\ &+ \kappa^3 g_3^6 \left(\propto x_t^{\leq 4} + c_{(4+1,3)} x_t^{4+1} + c_{(4+2,3)} x_t^{4+2} + c_{(4+3,3)} x_t^{4+3} \right) \\ &+ \dots \end{aligned}$$

- Constraint can be extended to orders with combinations of g_3 with other couplings, i.e. $\Delta\lambda = y_t^2 g_{1,2}^2 g_3^{2n} + y_t^6 g_3^{2n}$
- Predicted correctly $\Delta\lambda = y_t^2 g_{1,2}^2 g_3^2 x_t^3$ contribution from Bagnaschi et al. 2019

Impact of x_t resummation

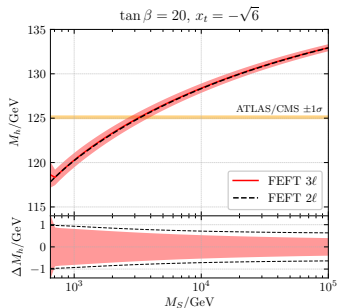
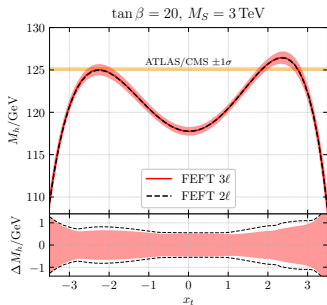
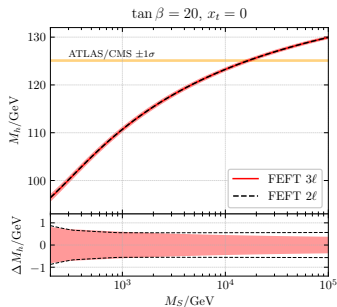


- **Good:** fast convergence of perturbation theory for all $x_t \in [-3, 3]$

$$|M_h^{\text{FEFT 1L}} - M_h^{\text{FEFT 3L}}| \lesssim 0.35 \text{ GeV}$$

$$|M_h^{\text{FEFT 2L}} - M_h^{\text{FEFT 3L}}| \lesssim 0.05 \text{ GeV}$$

Uncertainty of FlexibleEFTHiggs at 3-loop



- Low uncertainty: $\Delta M_h^{\text{th}} \lesssim 1\text{ GeV}$

Summary

- **FlexibleEFTHiggs** 3-loop ($N^3LL + N^3LO$) a state-of-the-art calculation valid for all scales M_S
- Hybrid approach is elegant and can be applied to other BSM
- **New resummation technique developed:** It is possible to resum squark mixing parameter $x_f \in \{\tan \beta, x_t\}$ in the Higgs mass through 1-loop threshold corrections
⇒ Resummation accounts for 500 MeV in realistic scenarios
- Theoretical uncertainty reduced to $\Delta M_h^{\text{th}} \lesssim 1 \text{ GeV}$ in single-scale scenarios
- Agreement with $M_h = 125.1 \text{ GeV}$ requires $M_S > 1 \text{ TeV}$
- **Outlook:**
 - ▶ Application to non-minimal SUSY extensions of the SM

Backup

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

ATLAS Preliminary

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

Model	$\epsilon, \mu, \tau, \gamma$	Jets	E_{miss}^{min}	$\int \mathcal{L} d\mathcal{L} (\text{fb}^{-1})$	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$	Reference			
Inclusive Searches	$\tilde{g}\tilde{g}, \tilde{q}\rightarrow q\tilde{g}$	0	2-6 jets	Yes	36.1	\tilde{g} [100, 100 GeV]	0.9	1.55	$m(\tilde{g}) > 100 \text{ GeV}$ $m(\tilde{q}) - m(\tilde{q}') > 50 \text{ GeV}$	1712.02332 1711.03301	
	mono-jet	1-3 jets	Yes	36.1	\tilde{g} [100, 100 GeV]	0.43	0.71	2.0	$m(\tilde{g}) > 200 \text{ GeV}$ $m(\tilde{q}') > 900 \text{ GeV}$	1712.02332 1712.02332	
	$\tilde{g}\tilde{g}, \tilde{q}\rightarrow q\tilde{g}$	0	2-6 jets	Yes	36.1	\tilde{g}	Forbidden	0.95-1.6	1.85	$m(\tilde{g}) > 800 \text{ GeV}$ $m(\tilde{q}) - m(\tilde{q}') > 50 \text{ GeV}$	1708.03731 1805.11381
	$\tilde{g}\tilde{g}, \tilde{q}\rightarrow q\tilde{g}, \ell\ell\tilde{g}$	3 ϵ, μ ev, μ	4 jets 2 jets	Yes Yes	36.1 36.1	\tilde{g}	Forbidden	1.2	1.85	$m(\tilde{g}) > 400 \text{ GeV}$ $m(\tilde{q}) - m(\tilde{q}') > 50 \text{ GeV}$	1708.02794 1708.03731
	$\tilde{g}\tilde{g}, \tilde{q}\rightarrow q\tilde{g}, WZ\tilde{g}$	0	7-11 jets	Yes	36.1	\tilde{g}	Forbidden	1.8	0.98	$m(\tilde{g}) > 400 \text{ GeV}$ $m(\tilde{q}) - m(\tilde{q}') > 200 \text{ GeV}$	1708.02794 1708.03731
	3 ϵ, μ	4 jets	-	36.1	\tilde{g}	Forbidden	1.25	2.0	$m(\tilde{g}) > 200 \text{ GeV}$ $m(\tilde{q}) - m(\tilde{q}') > 300 \text{ GeV}$	1711.01901 1708.03731	
	$\tilde{g}\tilde{g}, \tilde{q}\rightarrow q\tilde{g}$	0-1 ϵ, μ 3 ϵ, μ	3 b 4 jets	- -	36.1 36.1	\tilde{g}	Forbidden	1.25	2.0	$m(\tilde{g}) > 200 \text{ GeV}$ $m(\tilde{q}) - m(\tilde{q}') > 300 \text{ GeV}$	1711.01901 1708.03731
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\rightarrow b\tilde{g}/\tilde{t}_1^*$	Multiple Multiple	Multiple Multiple	Yes Yes	36.1 36.1	\tilde{b}_1 \tilde{b}_1	Forbidden Forbidden	0.9 0.58-0.82	$m(\tilde{b}_1) > 300 \text{ GeV}, \text{BR}(\tilde{b}_1 \rightarrow \tilde{t}_1^*) = 1$ $m(\tilde{b}_1) > 300 \text{ GeV}, \text{BR}(\tilde{b}_1 \rightarrow \tilde{t}_1^*) = \text{BR}(\tilde{b}_1 \rightarrow \tilde{t}_1^*) = 0.5$ $m(\tilde{b}_1) > 200 \text{ GeV}, m(\tilde{b}_1) > 300 \text{ GeV}, \text{BR}(\tilde{b}_1 \rightarrow \tilde{t}_1^*) = 1$	1708.09296, 1711.03301 1708.09296 1708.03731	
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1, M_2 = 2 \times M_1$	Multiple Multiple	Multiple Multiple	- -	36.1 36.1	\tilde{b}_1 \tilde{t}_1	Forbidden	0.7 0.9	$m(\tilde{b}_1) > 60 \text{ GeV}$ $m(\tilde{t}_1) > 200 \text{ GeV}$	1709.04183, 1711.11520, 1708.03247 1709.04183, 1711.11520, 1708.03247	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow Wb\tilde{t}_1^*$ or \tilde{t}_1^*	0-2 ϵ, μ	0-2 jets/1-2 b	Yes	36.1	\tilde{t}_1	Forbidden	1.0	$m(\tilde{t}_1) > 1 \text{ GeV}$	1506.08616, 1709.04183, 1711.11520	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \text{ LSP}$	Multiple Multiple	Multiple Multiple	- -	36.1 36.1	\tilde{t}_1 \tilde{t}_1	Forbidden	0.4-0.9 0.6-0.8	$m(\tilde{t}_1) > 150 \text{ GeV}, m(\tilde{t}_1) > m(\tilde{t}_1^*) > 5 \text{ GeV}, \tilde{t}_1 = \tilde{t}_1$ $m(\tilde{t}_1) > 300 \text{ GeV}, m(\tilde{t}_1) > m(\tilde{t}_1^*) > 5 \text{ GeV}, \tilde{t}_1 = \tilde{t}_1$	1709.04183, 1711.11520 1709.04183, 1711.11520	
	$\tilde{t}_1\tilde{t}_1, \text{Well-Tempered LSP}$	Multiple	Multiple	-	36.1	\tilde{t}_1	Forbidden	0.48-0.84	$m(\tilde{t}_1) > 150 \text{ GeV}, m(\tilde{t}_1) > m(\tilde{t}_1^*) > 5 \text{ GeV}, \tilde{t}_1 = \tilde{t}_1$	1709.04183, 1711.11520	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow c\tilde{t}_1^*/\tilde{c}, \tilde{t}_1\rightarrow c\tilde{t}_1^*$	0 2 ϵ, μ	2 ϵ, μ Yes	36.1 36.1	\tilde{t}_1 \tilde{t}_1	Forbidden	0.45 0.85	$m(\tilde{t}_1) > 0 \text{ GeV}$ $m(\tilde{t}_1) > 50 \text{ GeV}$	1805.01649 1805.01649		
	0	mono-jet	Yes	36.1	\tilde{t}_1	Forbidden	0.43	0.7	$m(\tilde{t}_1) > m(\tilde{t}_1^*) > 5 \text{ GeV}$	1711.03301	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow c\tilde{t}_1^*/\tilde{c}, \tilde{t}_1\rightarrow c\tilde{t}_1^*$	0	2 ϵ, μ	Yes	36.1	\tilde{t}_1	Forbidden	0.45	0.85	$m(\tilde{t}_1) > 0 \text{ GeV}$ $m(\tilde{t}_1) > 50 \text{ GeV}$	1805.01649 1805.01649
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow c\tilde{t}_1^*/\tilde{c}, \tilde{t}_1\rightarrow c\tilde{t}_1^*$	0	2 ϵ, μ	Yes	36.1	\tilde{t}_1	Forbidden	0.45	0.85	$m(\tilde{t}_1) > 0 \text{ GeV}$ $m(\tilde{t}_1) > 50 \text{ GeV}$	1805.01649 1805.01649
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow c\tilde{t}_1^*/\tilde{c}, \tilde{t}_1\rightarrow c\tilde{t}_1^*$	0	2 ϵ, μ	Yes	36.1	\tilde{t}_1	Forbidden	0.45	0.85	$m(\tilde{t}_1) > 0 \text{ GeV}$ $m(\tilde{t}_1) > 50 \text{ GeV}$	1805.01649 1805.01649
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\rightarrow c\tilde{t}_1^*/\tilde{c}, \tilde{t}_1\rightarrow c\tilde{t}_1^*$	0	2 ϵ, μ	Yes	36.1	\tilde{t}_1	Forbidden	0.45	0.85	$m(\tilde{t}_1) > 0 \text{ GeV}$ $m(\tilde{t}_1) > 50 \text{ GeV}$	1805.01649 1805.01649	
EW direct	$\tilde{t}_1\tilde{t}_1^*$ via WZ	2-3 ϵ, μ ev, μ	- Yes	36.1 36.1	$\tilde{t}_1\tilde{t}_1^*$ $\tilde{t}_1\tilde{t}_1^*$	0.17	0.6	$m(\tilde{t}_1) > 0$ $m(\tilde{t}_1) > m(\tilde{t}_1^*) > 10 \text{ GeV}$	1403.5294, 1806.02293 1712.05119		
	$\tilde{t}_1\tilde{t}_1^*$ via Wb	2-3 ϵ, μ ev, μ	- Yes	20.3 36.1	$\tilde{t}_1\tilde{t}_1^*$ $\tilde{t}_1\tilde{t}_1^*$	0.26	0.76	$m(\tilde{t}_1) > 0$ $m(\tilde{t}_1) > m(\tilde{t}_1^*) > 10 \text{ GeV}$	1501.07110 1708.07875		
	$\tilde{t}_1\tilde{t}_1^*$ via Wb	2-3 ϵ, μ ev, μ	- Yes	20.3 36.1	$\tilde{t}_1\tilde{t}_1^*$ $\tilde{t}_1\tilde{t}_1^*$	0.22	0.76	$m(\tilde{t}_1) > 0, m(\tilde{t}_1) > 0.5m(\tilde{t}_1^*) + m(\tilde{b}_1)$ $m(\tilde{t}_1) > 100 \text{ GeV}, m(\tilde{t}_1) > 0.5m(\tilde{t}_1^*) + m(\tilde{b}_1)$	1708.07875 1708.07875		
	$\tilde{t}_1\tilde{t}_1^*$ via Wb	2-3 ϵ, μ ev, μ	- Yes	20.3 36.1	$\tilde{t}_1\tilde{t}_1^*$ $\tilde{t}_1\tilde{t}_1^*$	0.22	0.76	$m(\tilde{t}_1) > 0, m(\tilde{t}_1) > 0.5m(\tilde{t}_1^*) + m(\tilde{b}_1)$ $m(\tilde{t}_1) > 100 \text{ GeV}, m(\tilde{t}_1) > 0.5m(\tilde{t}_1^*) + m(\tilde{b}_1)$	1708.07875 1708.07875		
	$\tilde{t}_1\tilde{t}_1^*$ via Wb	2-3 ϵ, μ ev, μ	- Yes	20.3 36.1	$\tilde{t}_1\tilde{t}_1^*$ $\tilde{t}_1\tilde{t}_1^*$	0.22	0.76	$m(\tilde{t}_1) > 0, m(\tilde{t}_1) > 0.5m(\tilde{t}_1^*) + m(\tilde{b}_1)$ $m(\tilde{t}_1) > 100 \text{ GeV}, m(\tilde{t}_1) > 0.5m(\tilde{t}_1^*) + m(\tilde{b}_1)$	1708.07875 1708.07875		
	$\tilde{t}_1\tilde{t}_1^*$ via Wb	2-3 ϵ, μ ev, μ	- Yes	20.3 36.1	$\tilde{t}_1\tilde{t}_1^*$ $\tilde{t}_1\tilde{t}_1^*$	0.22	0.76	$m(\tilde{t}_1) > 0, m(\tilde{t}_1) > 0.5m(\tilde{t}_1^*) + m(\tilde{b}_1)$ $m(\tilde{t}_1) > 100 \text{ GeV}, m(\tilde{t}_1) > 0.5m(\tilde{t}_1^*) + m(\tilde{b}_1)$	1708.07875 1708.07875		
Long-lived particles	$\tilde{R}, \tilde{R} \rightarrow \tilde{g}\tilde{g}, \tilde{Z}\tilde{Z}$	0	$\geq 3b$	Yes	36.1	\tilde{R}	0.13-0.23	0.29-0.68	$\text{BR}(\tilde{R} \rightarrow \tilde{g}\tilde{g}) > 1$ $\text{BR}(\tilde{R} \rightarrow \tilde{Z}\tilde{Z}) > 1$	1808.04030 1804.03602	
	$\tilde{R}, \tilde{R} \rightarrow \tilde{g}\tilde{g}, \tilde{Z}\tilde{Z}$	4 ϵ, μ	0	Yes	36.1	\tilde{R}	0.3	0.3	$\text{BR}(\tilde{R} \rightarrow \tilde{g}\tilde{g}) > 1$ $\text{BR}(\tilde{R} \rightarrow \tilde{Z}\tilde{Z}) > 1$	1808.04030 1804.03602	
	Direct $\tilde{t}_1\tilde{t}_1^*$ prod., long-lived \tilde{t}_1^*	Disapp. trk	1 jet	Yes	36.1	\tilde{t}_1^*	0.15	0.46	Pure Wino Pure Higgsino	1712.02118 ATL-Physics-PLB-2017-019	
	Stable \tilde{g} R hadron	SMP	-	-	3.2	\tilde{g}	1.6	1.6	$m(\tilde{g}) > 100 \text{ GeV}$	1608.05129	
Metastable \tilde{g} R hadron, $\tilde{g}\rightarrow q\tilde{g}$	Multiple	-	-	32.8	\tilde{g} ($m(\tilde{g}) \geq 100 \text{ ns}, 0.2 \text{ ns}$)	1.6	2.4	$m(\tilde{g}) > 100 \text{ GeV}$	1710.04901, 1604.04520		
GMSE, $\tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}, \text{long-lived } \tilde{t}_1^*$	2 γ	-	Yes	20.3	\tilde{t}_1^*	0.44	1.3	$m(\tilde{t}_1^*) > 3 \text{ ns}, \text{SPS8 model}$	1409.542		
$\tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}$	disp. ev/eq/qq	-	-	20.3	\tilde{g}	1.3	1.3	$6 < m(\tilde{t}_1^*) < 1000 \text{ nm}, m(\tilde{t}_1^*) > 1 \text{ TeV}$	1504.05162		
RPV	$\tilde{L}\tilde{V} \rightarrow \tilde{g}\tilde{g}, \tilde{X}, \tilde{X}_i \rightarrow \tilde{g}\tilde{g}, \tilde{e}\tilde{t}/\tilde{\nu}\tilde{t}$	ev, ν, μ, τ	-	-	3.2	\tilde{L}	0.82	1.33	$X_{111} < 0.11, X_{121}, X_{131} > 0.07$	1607.06079	
	$\tilde{t}_1\tilde{t}_1^*, \tilde{t}_1\tilde{t}_1^* \rightarrow WZ\ell\ell\tilde{t}_1\tilde{t}_1^*$	4 ϵ, μ	0	Yes	36.1	$\tilde{t}_1\tilde{t}_1^*$ ($k_{\text{eff}} \leq 6, k_{\text{eff}} \leq 6$)	0.82	1.33	$m(\tilde{t}_1) > 100 \text{ GeV}$	1804.03602	
	$\tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}$	4-5 large R jets	-	36.1	\tilde{g} ($m(\tilde{g}) > 200 \text{ GeV}, 1100 \text{ GeV}$)	1.3	1.9	Large X_{122}	1804.03602		
	$\tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}$	4-5 large R jets	-	36.1	\tilde{g} ($m(\tilde{g}) > 200 \text{ GeV}, 1100 \text{ GeV}$)	1.05	1.05	2.0	$m(\tilde{g}) > 200 \text{ GeV}, \text{bino-like}$	ATLAS-CONF-2018-003	
	$\tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}$	Multiple	-	36.1	\tilde{g} ($m(\tilde{g}) > 100 \text{ GeV}$)	1.8	2.1	2.1	$m(\tilde{g}) > 200 \text{ GeV}, \text{bino-like}$	ATLAS-CONF-2018-003	
	$\tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}$	Multiple	-	36.1	\tilde{g} ($m(\tilde{g}) > 100 \text{ GeV}$)	1.8	2.1	2.1	$m(\tilde{g}) > 200 \text{ GeV}, \text{bino-like}$	ATLAS-CONF-2018-003	
	$\tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}$	Multiple	-	36.1	\tilde{g} ($m(\tilde{g}) > 100 \text{ GeV}$)	1.8	2.1	2.1	$m(\tilde{g}) > 200 \text{ GeV}, \text{bino-like}$	ATLAS-CONF-2018-003	
$\tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}$	0	2 jets + 2 b	-	36.7	\tilde{g} ($m(\tilde{g}) > 4, 14-20$)	0.55	1.05	$m(\tilde{g}) > 200 \text{ GeV}, \text{bino-like}$	ATLAS-CONF-2018-003		
$\tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}$	0	2 jets + 2 b	-	36.7	\tilde{g} ($m(\tilde{g}) > 4, 14-20$)	0.55	1.05	$m(\tilde{g}) > 200 \text{ GeV}, \text{bino-like}$	ATLAS-CONF-2018-003		
$\tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}, \tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{g}\tilde{g}$	2 ϵ, μ	2 b	-	36.1	\tilde{g} ($m(\tilde{g}) > 4, 14-20$)	0.42	0.61	0.4-1.45	1710.07171 1710.05544		

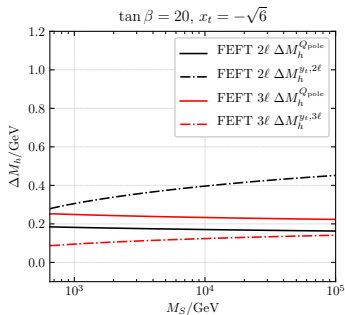
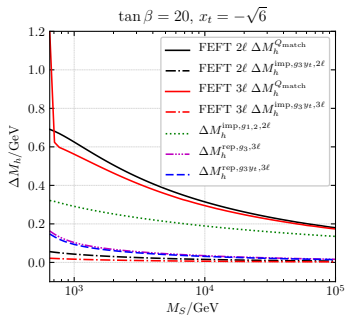
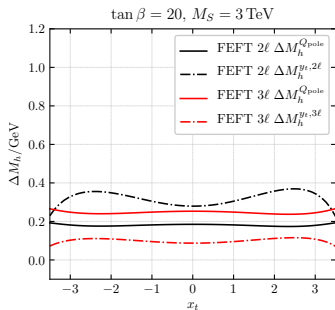
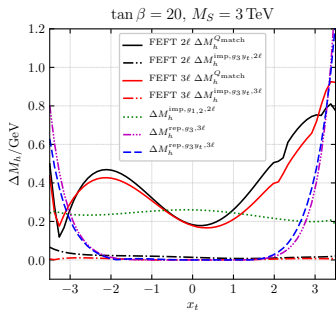
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10⁻¹

1

Mass scale [TeV]

Uncertainty M_S



Uncertainty M_S

