

The generic approach to Higgs mass calculations

Florian Staub | MU Programtag 2016, 12th December 2016

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Minimal supersymmetry (**MSSM**) is the **best studied extension**

- Solves the hierarchy problem
- Predicts gauge coupling unification
- Provides a dark matter candidate
- Relates EWSB and large top mass
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Public tools to study SUSY

The tools used so far (*SoftSusy, Suspect, Isajet, Superiso, Susy_Flavor, FeynHiggs, NMSSMTools, ...*) can handle only **very few models**.

The problems of minimal supersymmetry

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Golden era of model building?

Many more BSM models are studied than before the LHC was turned on

Extended Higgs/Gauge sector

For instance in singlet/triplet extensions, gauge extensions, or R -symmetric models.

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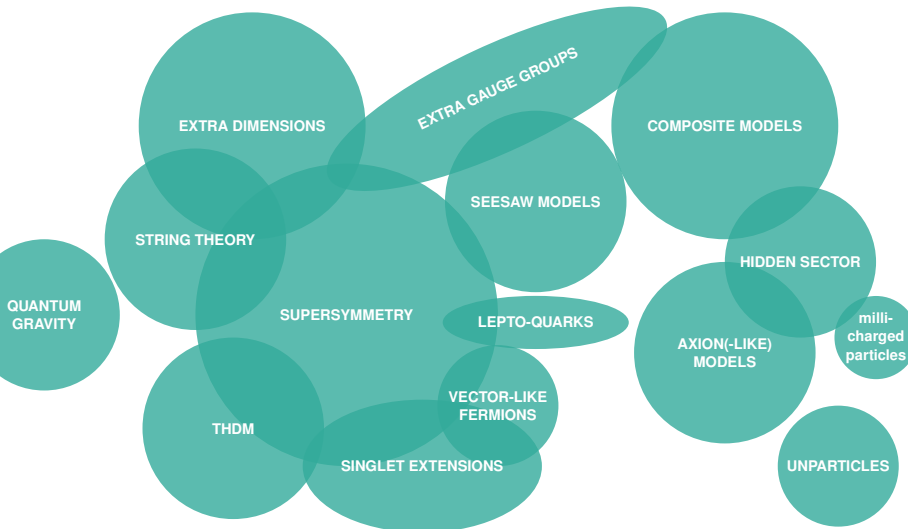
Extended Matter sector

For instance in vector-like extensions

- New loop corrections to Higgs mass

Many ideas exist to go beyond the SM

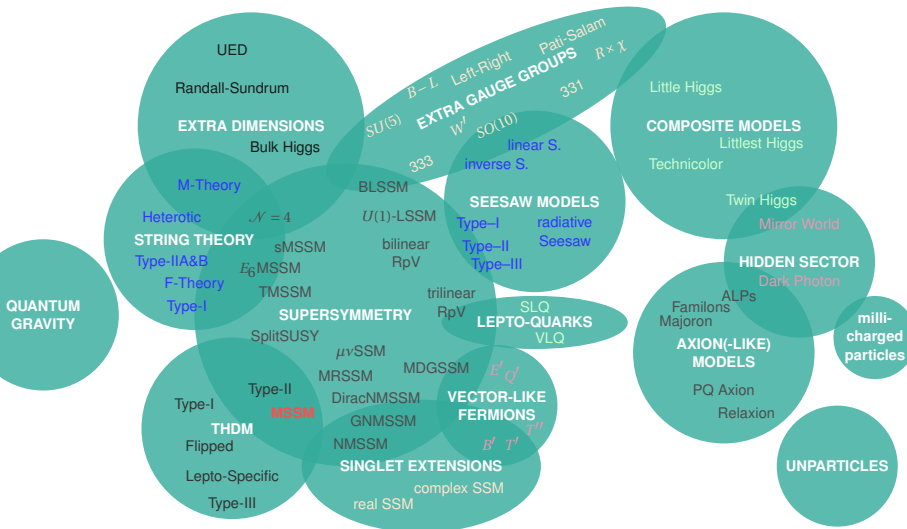
(without any claim to completeness)



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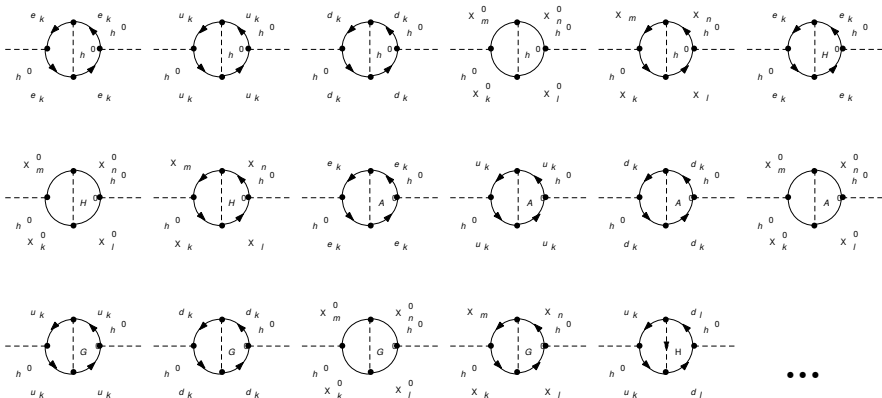
..., but precision calculations for them rarely exist:

→ **uncertainty in Higgs mass prediction usually much bigger than in MSSM**

→ **A new approach was needed to confront many BSM models with the Higgs (mass) measurements**

Generic Higgs mass calculations

Thousands of Feynman diagrams are needed to be calculated:



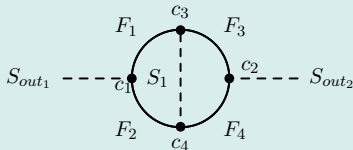
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Generic expressions



Generic expression $f(m_{out_i}, m_S, m_{F_i}, c_i)$ are

- **Valid for any model** and **for any real scalar**

→ **Disentangle** the calculation of ...

... **loop amplitudes** (difficult) and **masses & couplings** (easy)

Fully automatised two-loop calculations

The combination [SARAH/SPheno](#) provides a **fully automatised two-loop calculation** of the Higgs mass in SUSY models.

Approach

[Goodsell,Nickel,FS,1411.0675,1503.03098]

- Generic one- and two-loop calculations which are matched on concrete models.
- Auto-generated Fortran code for numerical evaluation

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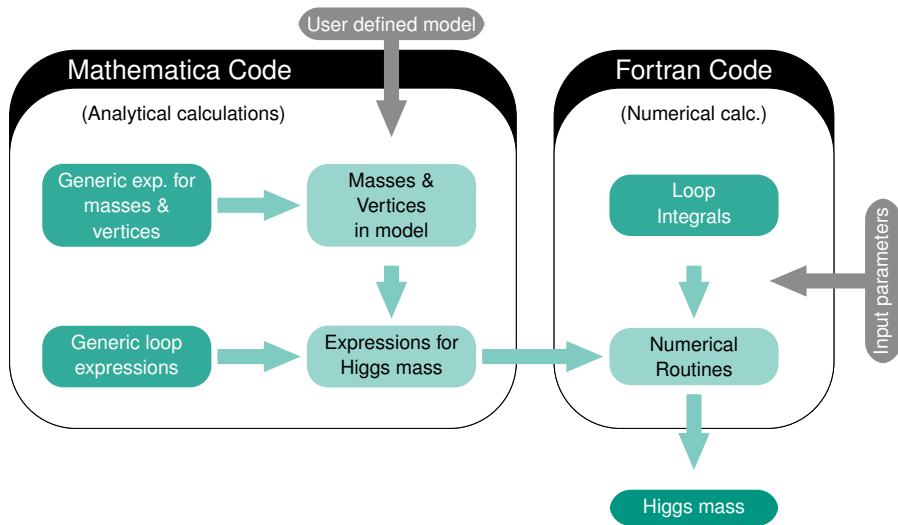
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Approximations @2-loop: gaugeless limit ($g_1 = g_2 = 0$), $p^2 = 0$:

- similar precision as most public tools provide for MSSM
- All available ($\overline{\text{DR}}$) **two-loop results** (MSSM, NMSSM) are **exactly reproduced!**
- CP violation possible

[Goodsell,FS,1604.05335]

The setup



Generic approach

New results for the Higgs mass

The setup was used to calculate many new two-loop results:

- Contributions from trilinear RpV [Dreiner,Nickel,FS,1411.3731]
- Missing corrections in the NMSSM [Goodsell,Nickel,FS,1411.4665]
- CP violating NMSSM beyond $O(\alpha_s \alpha_t)$ [Goodsell,FS, 1604.05335]
- Contributions from non-holomorphic soft-terms [Ün, Tanyildizi,Kerman Solmaz,1412.1440]
- MRSSM [Diessner,Kalinowski,Kotlarski,Stöckinger,1504.05386]
- Contributions from vectorlike (s)tops [Nickel,FS,1505.06077]
- Other vector-like states [Basirnia, Macaluso, Shih, 1605.08442]
- The MSSM beyond MFV [Goodsell,Nickel,FS,1511.01904]
- ...

The Higgs mass in non-minimal SUSY models

The MSSM beyond MFV

The **soft-breaking Lagrangian** provides in general **many new couplings**

$$\mathcal{L}_{SB} = \dots + T_u^{ij} \tilde{u}_i^* \tilde{q}_j H_u + T_d^{ij} \tilde{d}_i^* \tilde{q}_j H_d + T_e^{ij} \tilde{e}_i^* \tilde{l}_j H_d + \text{h.c.}$$

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What happens at two-loop?

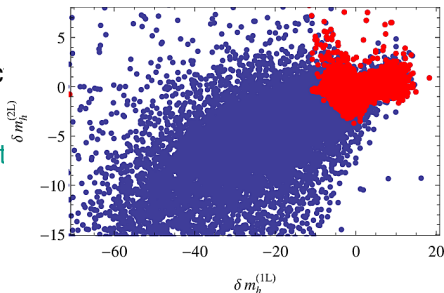
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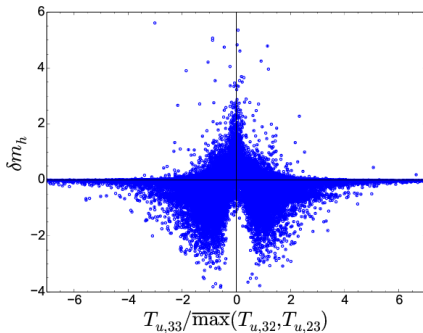
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The Higgs mass in non-minimal SUSY models

When are the two-loop effects large?

[Goodsell,Nickel,FS,1511.01904]



Important effects of several GeV in case of ...

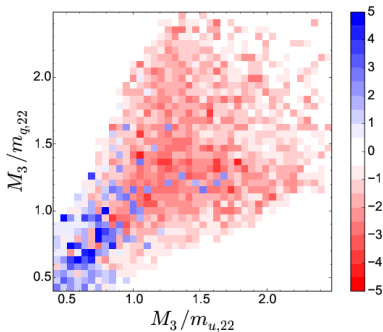
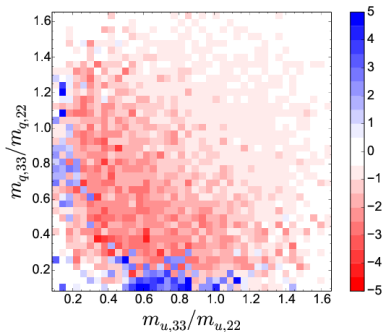
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Bounds from Vacuum stability and flavour constraints included

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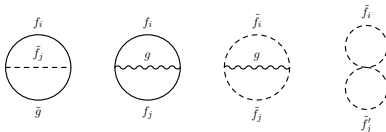
- ... specific ratios of T-terms
- ... hierarchy between soft masses

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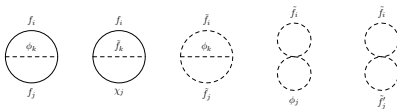
The Higgs mass in non-minimal SUSY models

Two-loop corrections in the NMSSM

$\alpha_S(\alpha_b + \alpha_t)$ (known before)

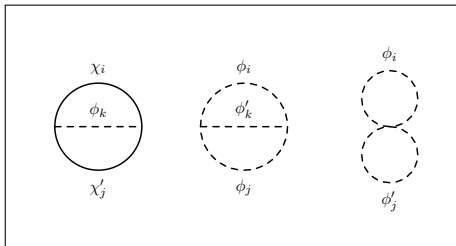


MSSM-like



NMSSM-specific

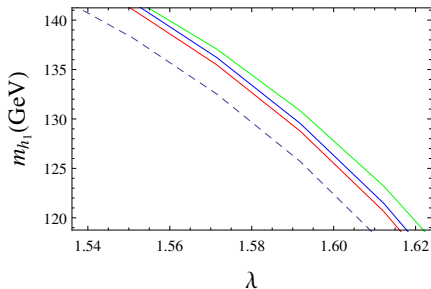
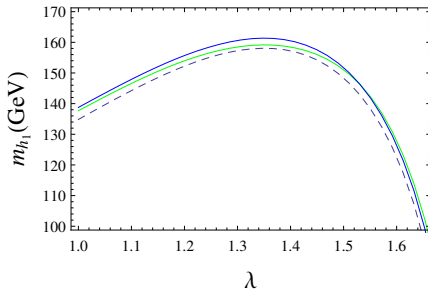
(available for first time!)



The Higgs mass in non-minimal SUSY models

NMSSM results I: heavy singlet & large λ

$$\begin{array}{llllll} \kappa = 1.6 & \tan\beta = 3 & T_\lambda = 600 \text{ GeV} & T_\kappa = -2650 \text{ GeV} & \mu_{\text{eff}} = 614 \text{ GeV} & \\ m_f^2 = 2 \cdot 10^6 \text{ GeV}^2 & T_i = 0 & M_1 = 200 \text{ GeV} & M_2 = 400 \text{ GeV} & M_3 = 2000 \text{ GeV} & \end{array}$$



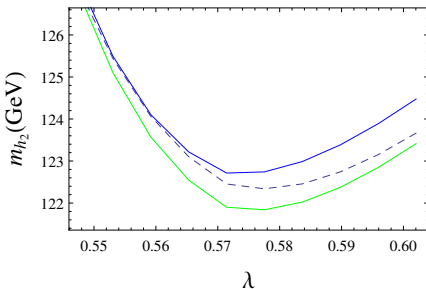
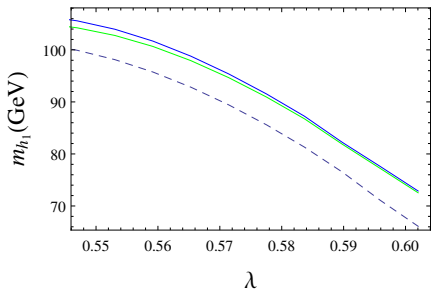
1-loop / $\alpha_S(\alpha_b + \alpha_t)$ / full / MSSM approx.

- Additional corrections crucial for (very) large λ
- Using MSSM results not a good approximation anymore

The Higgs mass in non-minimal SUSY models

NMSSM results II: light singlet

$$\begin{aligned} \kappa &= 0.596 & T_\lambda &= -27 \text{ GeV} & T_\kappa &= -240 \text{ GeV} & \mu_{eff} &= 130 \text{ GeV} \\ T_t &= -3050 \text{ GeV} & T_b = T_\tau &= -1000 \text{ GeV} & m_{t_L}^2 &= 9.0 \cdot 10^5 \text{ GeV}^2 & m_{t_R}^2 &= 1.05 \cdot 10^6 \text{ GeV}^2 \end{aligned}$$



1-loop / $\alpha_S(\alpha_b + \alpha_t)$ / full

- Corrections can be larger than the ones $\sim \alpha_S$
- Again, **MSSM approximations fail**

The Higgs mass in non-minimal SUSY models

MSSM with vectorlike top partners

$$W = W_{MSSM} + Y_{t'}^i Q_i T' H_u + M_{T'} T' \bar{T}' + m_{t'}^i U_i \bar{T}'.$$

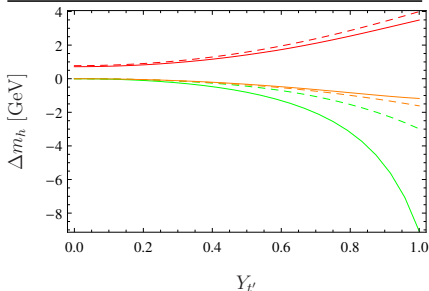
→ Only 1-loop eff. pot results available before

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Impact of additional corrections:



$B_{T'} = 0$ (dashed), $B_{T'} = (1.5 \text{ TeV})^2$ (full), $\tan \beta = 3$, $M_{T'} = 1.0 \text{ TeV}$

shifts by momentum dependence, one-loop thresholds to Y_{top} , two-loop corrections

The Higgs mass in non-minimal SUSY models

Models with Dirac gauginos have nice features:

- Suppressed flavour constraints
- Suppressed production of coloured SUSY states at the LHC
- Running of $m_{H_u}^2$ independent of gluino mass

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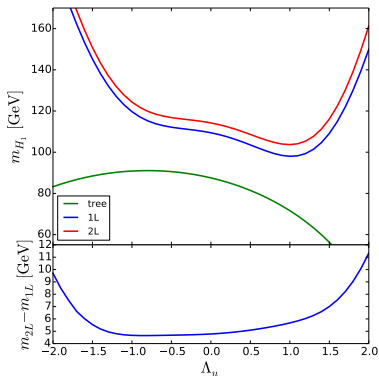
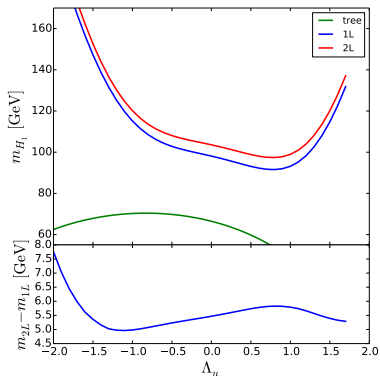
The effects on the Higgs mass are very different compared to the MSSM:

- Tree-level Higgs mass is usually suppressed
- No A -terms: stop corrections are suppressed
- New sgluon corrections at two-loop
- Other, potentially large couplings (depending on the model)

$$W = W_Y + \mu_D \hat{R}_d \hat{H}_d + \mu_U \hat{R}_u \hat{H}_u + \hat{S}(\lambda_d \hat{R}_d \hat{H}_d + \lambda_u \hat{R}_u \hat{H}_u) + \Lambda_d \hat{R}_d \hat{T} \hat{H}_d + \Lambda_u \hat{R}_u \hat{T} \hat{H}_u .$$

- New superpotential terms to increase Higgs mass

[Diessner, Kalinowski, Kotlarski, Stöckinger, 1504.05386]

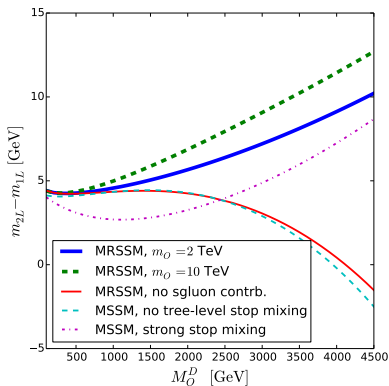
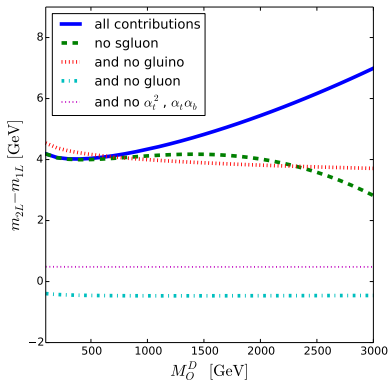


The Higgs mass in non-minimal SUSY models

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- New superpotential terms to increase Higgs mass
- New coloured corrections

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Most extensions of the SM or MSSM have a large impact on the Higgs sector:

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→ **Generic calculations are needed to confront many models with the Higgs measurements**

- The combination **SARAH/SPheno** are the only available tools to get **two-loop Higgs masses for many different models**