NMSSM spectrum calculation with FlexibleSUSY

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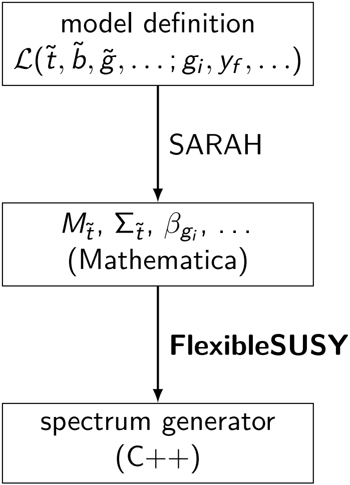
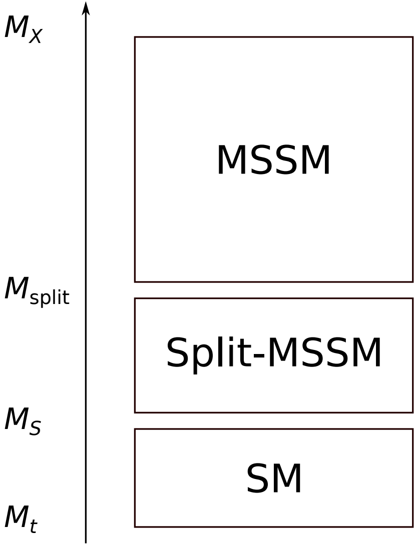
FlexibleSUSY = spectrum generator generator

FlexibleSUSY

Generating a spectrum generator



Tower of EFTs



NMSSM variants available in FlexibleSUSY

Z_3-symmetric NMSSM (called `NMSSM` in FlexibleSUSY):

$$\begin{aligned} W_{Z_3} &= y_e (H_d L)\bar{E} + y_d (H_d Q)\bar{D} + y_u (Q H_u)\bar{U} \\ &\quad + \lambda S (H_d H_u) + \frac{\kappa}{3} S^3 \\ \mathcal{L}_{\text{soft},Z_3} &= \mathcal{L}_{\text{soft,MSSM}}(B\mu = 0) \\ &\quad - m_s^2 |s|^2 - \left(\lambda A_\lambda s (h_d h_u) + \frac{\kappa A_\kappa}{3} s^3 + \text{h.c.} \right) \end{aligned}$$

NMSSM variants available in FlexibleSUSY

$\not{Z}_3$-NMSSM (called `SMSSM` in FlexibleSUSY):

$$
\begin{aligned}
W_{\not{Z}_3} &= y_e (H_d L)\bar{E} + y_d (H_d Q)\bar{D} + y_u (Q H_u)\bar{U} \\
&\quad + \lambda S (H_d H_u) + \frac{\kappa}{3} S^3 \\
&\quad + \mu (H_d H_u) + \xi_F S + \frac{\mu'}{2} S^2 \\
\mathcal{L}_{\text{soft},\not{Z}_3} &= \mathcal{L}_{\text{soft,MSSM}}(B\mu = 0) \\
&\quad - m_s^2 |s|^2 - \left(\lambda A_\lambda s (h_d h_u) + \frac{\kappa A_\kappa}{3} s^3 + \text{h.c.}\right) \\
&\quad - \xi_s s - \frac{{m_s'}^2}{2} s^2 - B\mu (h_d h_u) + \text{h.c.}
\end{aligned}
$$

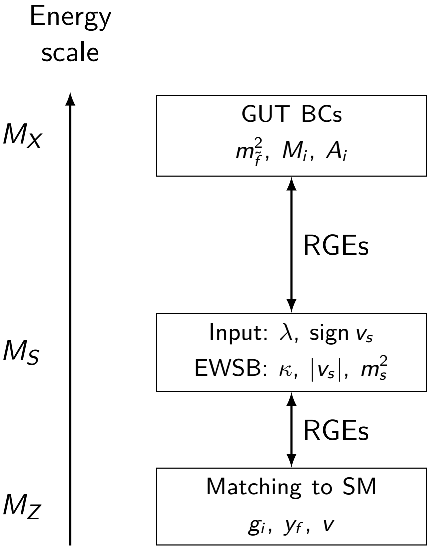
NMSSM parameters ($\overline{\text{DR}}$ scheme)

	Z_3 (NMSSM)	$\not{Z}_3$ (SMSSM)
fixed by SM	g_Y, g_2, g_3, y_u, y_d, y_e, v_u, v_d	g_Y, g_2, g_3, y_u, y_d, y_e, v_u, v_d
fixed by EWSB	κ, $\lvert v_s \rvert$, m_s^2	$\lvert\mu\rvert^2$, $B\mu$, ξ_s
User input (general)	m_q^2, m_u^2, m_d^2, m_ℓ^2, m_e^2, $m_{h_d}^2$, $m_{h_u}^2$, A_e, A_d, A_u, A_λ, A_κ, M_1, M_2, M_3, λ, sign v_s	m_q^2, m_u^2, m_d^2, m_ℓ^2, m_e^2, $m_{h_d}^2$, $m_{h_u}^2$, m_s^2, A_e, A_d, A_u, A_λ, A_κ, M_1, M_2, M_3, λ, sign μ, κ, v_s, μ', $m_s'^2$, ξ_F

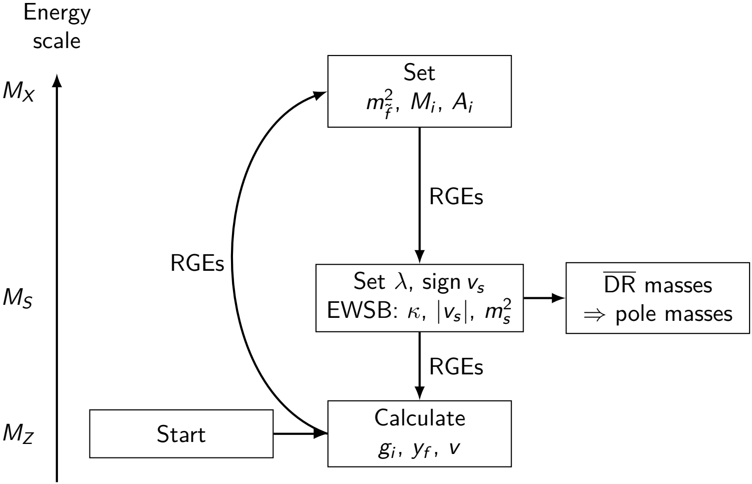
NMSSM parameters ($\overline{\text{DR}}$ scheme)

	Z_3 (NUTNMSSM)	$\not{Z}_3$ (NUTSMSSM)
fixed by SM	g_Y, g_2, g_3, y_u, y_d, y_e, v_u, v_d	g_Y, g_2, g_3, y_u, y_d, y_e, v_u, v_d
fixed by EWSB	$m_{h_d}^2$, $m_{h_u}^2$, m_s^2	$m_{h_d}^2$, $m_{h_u}^2$, m_s^2
User input (general)	m_q^2, m_u^2, m_d^2, m_ℓ^2, m_e^2, κ, $\lvert v_s \rvert$, A_e, A_d, A_u, A_λ, A_κ, M_1, M_2, M_3, λ, sign v_s	m_q^2, m_u^2, m_d^2, m_ℓ^2, m_e^2, $\lvert\mu\rvert^2$, $B\mu$, ξ_s, A_e, A_d, A_u, A_λ, A_κ, M_1, M_2, M_3, λ, sign μ, κ, v_s, μ', $m_s'^2$, ξ_F

Physical problem statement for the Z_3-NMSSM



Algorithm to calculate the model parameters consistent with all BCs



Calculation of $g_3^{\overline{\text{DR}}}(M_Z)$

Input: $\alpha_{\text{s,SM}}^{(5),\overline{\text{MS}}}(M_Z) = 0.1185$

$\rightarrow$

$$\alpha_{\text{s}}^{\overline{\text{DR}}}(M_Z) = \frac{\alpha_{\text{s,SM}}^{(5),\overline{\text{MS}}}(M_Z)}{1 - \Delta\alpha_{\text{s,SM}}(M_Z) - \Delta\alpha_{\text{s}}(M_Z)}$$

with

$$\Delta\alpha_{\text{s,SM}}(\mu) = \frac{\alpha_{\text{s}}}{2\pi}\left[-\frac{2}{3}\log\frac{m_t}{\mu}\right]$$

$$\Delta\alpha_{\text{s}}(\mu) = \frac{\alpha_{\text{s}}}{2\pi}\left[\frac{1}{2} - \sum_{\text{SUSY particle } f} T_f \log\frac{m_f}{\mu}\right]$$

$\Rightarrow$

$$g_3^{\overline{\text{DR}}}(M_Z) = \sqrt{4\pi\alpha_{\text{s}}^{\overline{\text{DR}}}(M_Z)}$$

Calculation of $y_t^{\overline{\text{DR}}}(M_Z)$

$$y_t^{\overline{\text{DR}}}(M_Z) = \frac{\sqrt{2}\, m_t^{\overline{\text{DR}}}(M_Z)}{v_u(M_Z)}$$

where the running top mass is calculated from the pole mass M_t as

$$\begin{aligned}
m_t^{\overline{\text{DR}}}(\mu) &= M_t + \operatorname{Re}\Sigma_t^S(M_t) + M_t\Big[\operatorname{Re}\Sigma_t^L(M_t) \\
&\qquad + \operatorname{Re}\Sigma_t^R(M_t) + \Delta m_t^{(1),\text{gluon}} + \Delta m_t^{(2),\text{gluon}}\Big] \\
\Delta m_t^{(1L),\text{gluon}} &= -\frac{g_3^2}{12\pi^2}\left[5 - 3\log\left(\frac{m_t^2}{\mu^2}\right)\right] \\
\Delta m_t^{(2L),\text{gluon}} &= \left(\Delta m_t^{(1L),\text{gluon}}\right)^2 \\
&\quad - \frac{g_3^4}{4608\pi^4}\left[396\log^2\left(\frac{m_t^2}{\mu^2}\right) - 1476\log\left(\frac{m_t^2}{\mu^2}\right)\right. \\
&\qquad\qquad \left. - 48\zeta(3) + 2011 + 16\pi^2(1+\log 4)\right]
\end{aligned}$$

Calculation of v_u and v_d

The VEVs are calculated from the running Z mass at $\mu = M_Z$:

$$v_u^{\overline{\text{DR}}}(M_Z) = \frac{2m_Z^{\overline{\text{DR}}}(M_Z)\sin\beta}{\sqrt{g_Y^2 + g_2^2}}$$

$$v_d^{\overline{\text{DR}}}(M_Z) = \frac{2m_Z^{\overline{\text{DR}}}(M_Z)\cos\beta}{\sqrt{g_Y^2 + g_2^2}}$$

$$m_Z^{\overline{\text{DR}}}(M_Z) = \sqrt{M_Z^2 + \Pi_Z^{(1L)}(p^2 = \mu^2 = M_Z^2)}$$

$v_u^{\overline{\text{DR}}}$ and $v_d^{\overline{\text{DR}}}$ evolve under RG running according to
[Sperling, Stöckinger, AV, 2013, 2014]

Calculation of the Higgs pole mass

For each $i = 1, \ldots, 3$: find $p^2 = M_{h_i}^2$ which satisfies

$$0 = \det\left[p^2 - m_h^2 - \Delta m_{h,1\text{L}}^2 - \Delta m_{h,2\text{L}}^2\right]$$

where

$$\begin{aligned}
\Delta m_{h,1\text{L}}^2 &= \Sigma_h^{(1L)}(p^2 = M_{h_i}^2, \mu = M_S) \\
\Delta m_{h,2\text{L}}^2 &= O(\alpha_s(\alpha_t + \alpha_b), p^2 = 0) \qquad \text{NMSSM} \\
&\quad + O((\alpha_t + \alpha_b)^2 + \alpha_\tau^2, p^2 = 0) \quad \text{MSSM}
\end{aligned}$$

[Degrassi, Slavich, Nucl. Phys. B 825]

FlexibleSUSY vs. NMSSM-SoftSUSY

NMSSM-SoftSUSY	FlexibleSUSY
Commonalities	
Z_3- and $\not{Z}_3$-NMSSM	
GUT boundary conditions	
complete $\beta^{(1L)}$ and $\beta^{(2L)}$ (incl. family mixing)	
complete $\Sigma^{(1L)}(p^2)$ $\forall$ particles	
genuine NMSSM 2-loop Higgs mass corrections $O(\alpha_s(\alpha_t + \alpha_b), p^2 = 0)$	
2-loop MSSM Higgs mass corrections $O((\alpha_t + \alpha_b)^2 + \alpha_\tau^2, p^2 = 0)$	
Differences	
Decay interface for NMSDECAY	FlexibleDecay (currently in development)
optimized couplings	automatically generated couplings
3 EWSB variants	user-defined
BCs via C++	BCs via Mathematica or C++
fast pole masses	fast RG running
stable code basis	automatically generated
few dependencies	requires Mathematica, SARAH, Boost, Eigen, GSL
G_μ input	G_μ or M_W input
no sfermion flavour violation	sfermion flavour violation possible
relic density via micrOMEGAS	–
real parameters	complex parameters (development finished, currently in testing)

Features and restrictions

Restrictions:

- gauge group restricted to $SU(3)_{\mathsf{c}} \times SU(2)_{\mathsf{L}} \times U(1)_Y \times G$
- currently only MSSM- and NMSSM Higgs 2-loop corrections
- currently no decays

Features:

- automatically generate spectrum generator for MSSM, NMSSM, USSM, MRSSM, E_6SSM, $\mu\nu$SSM, SM, THDM-II
- aim to be as precise as SoftSUSY
- modular C++ code → extensible and reusable
- easy to build towers of EFTs

Comming soon

- decays via FlexibleDecay
- $(g-2)_\mu$
- more precise Higgs pole mass calculation via EFT approach (large log resummation)
- automated creation of tower of EFTs
- alternative BVP solvers (lattice solver, semi-analytic solver)
- prediction of M_W in all models
- complex parameters $\Rightarrow$ CP violation

Backup

FlexibleSUSY's Weltanschauung

- Model is defined in terms of Lagrangian parameters:
  g_i, y_{ij}, v_i, … in the $\overline{\text{MS}}/\overline{\text{DR}}$ scheme

- Input parameters:
  $\alpha_{\text{em,SM}}^{(5),\overline{\text{MS}}}(M_Z)$, $\alpha_{\text{s,SM}}^{(5),\overline{\text{MS}}}(M_Z)$, M_Z, M_t, G_F, …

- Output parameters:
  m_h, M_h, Z_h, …

NMSSM-Spektrumgenerator in FlexibleSUSY

1. Get the source code from https://flexiblesusy.hepforge.org
2. Create a NMSSM spectrum generator:

```
$ ./install-sarah # if not already installed
$ ./createmodel --name=NMSSM
$ ./configure --with-models=NMSSM
$ make
```

3. Calculate spectrum for given parameter point (SLHA format):

```
$ ./models/NMSSM/run_NMSSM.x \
   --slha-input-file=models/NMSSM/LesHouches.in.NMSSM

Block MASS
   1000021     5.05906233E+02   # Glu
   1000024     1.46609728E+02   # Cha_1
   1000037     3.99399367E+02   # Cha_2
        37     4.33363816E+02   # Hpm_2
...
```

FlexibleSUSY SLHA configuration options

```
Block FlexibleSUSY
    0   1e-04  # precision goal
    1   0      # max. iterations (0 = automatic)
    3   0      # calculate SM pole masses
    4   2      # pole mass loop order
    5   2      # EWSB loop order
    6   2      # beta-functions loop order
    7   2      # threshold corrections loop order
    8   1      # Higgs 2-loop corrections
               # O(alpha_t alpha_s)
    9   1      # Higgs 2-loop corrections
               # O(alpha_b alpha_s)
   10   1      # Higgs 2-loop corrections
               # O((alpha_t + alpha_b)^2)
   11   1      # Higgs 2-loop corrections
               # O(alpha_tau^2)
   12   0      # force output
   13   1      # Top quark 2-loop corrections QCD
   14   1e-11  # beta-function zero threshold
```