NMSSM spectrum calculation with SoftSUSY

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NMSSM variants implemented in SoftSUSY

Z_3-symmetric NMSSM:

$$W_{Z_3} = y_e(H_d L)\bar{E} + y_d(H_d Q)\bar{D} + y_u(QH_u)\bar{U} + \lambda S(H_d H_u) + \frac{\kappa}{3}S^3$$

$$\mathcal{L}_{\text{soft},Z_3} = \mathcal{L}_{\text{soft,MSSM}}(B\mu = 0) - m_s^2|s|^2 - \left(\lambda A_\lambda s(h_d h_u) + \frac{\kappa A_\kappa}{3}s^3 + \text{h.c.}\right)$$

NMSSM variants implemented in SoftSUSY

$\not{\mathbb{Z}}_3$-NMSSM:

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

EWSB in the NMSSM

$$\langle h_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d \\ 0 \end{pmatrix}, \qquad \langle h_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix}, \qquad \langle s \rangle = \frac{1}{\sqrt{2}} v_s$$

$\Rightarrow$

3 additional parameters:

$$v_u, v_d, v_s \qquad \Leftrightarrow \qquad v = \sqrt{v_u^2 + v_d^2}, \quad \tan\beta = \frac{v_u}{v_d}, \quad v_s$$

3 EWSB conditions:

$$0 = \frac{\partial V_{\text{Higgs}}}{\partial v_i}$$

$\Rightarrow$ solve for

Z_3 :	$\{\kappa, \lvert v_s \rvert, m_s^2\}$	or	$\{m_{h_d}^2, m_{h_u}^2, m_s^2\}$
$\not{Z}_3$:	$\{\lvert\mu\rvert^2, B\mu, \xi_s\}$	or	$\{m_{h_d}^2, m_{h_u}^2, m_s^2\}$

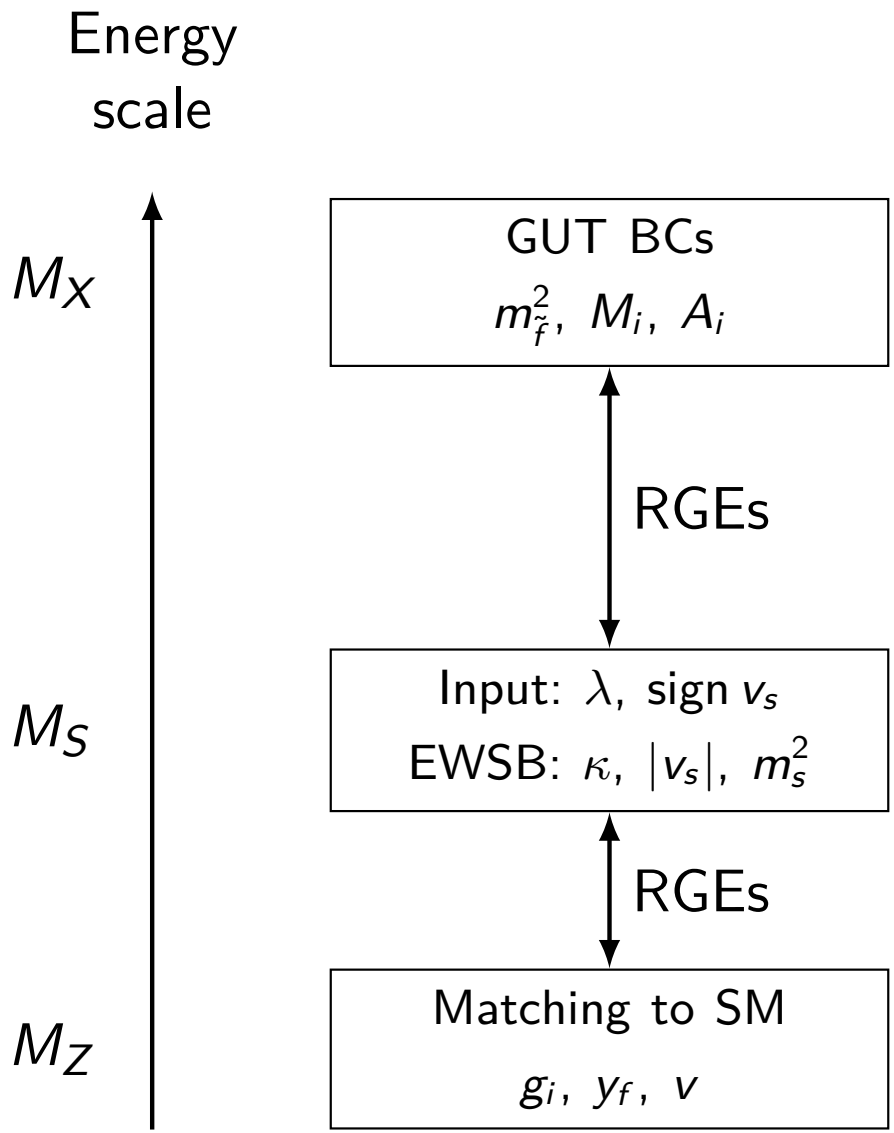
NMSSM parameters ($\overline{\text{DR}}$ scheme)

	Z_3	$\not{Z}_3$
fixed by SM	g_Y, g_2, g_3, y_u, y_d, y_e, v	g_Y, g_2, g_3, y_u, y_d, y_e, v
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, $\tan\beta$, 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, $\tan\beta$, sign μ, κ, v_s, μ', $m_s'^2$, ξ_F

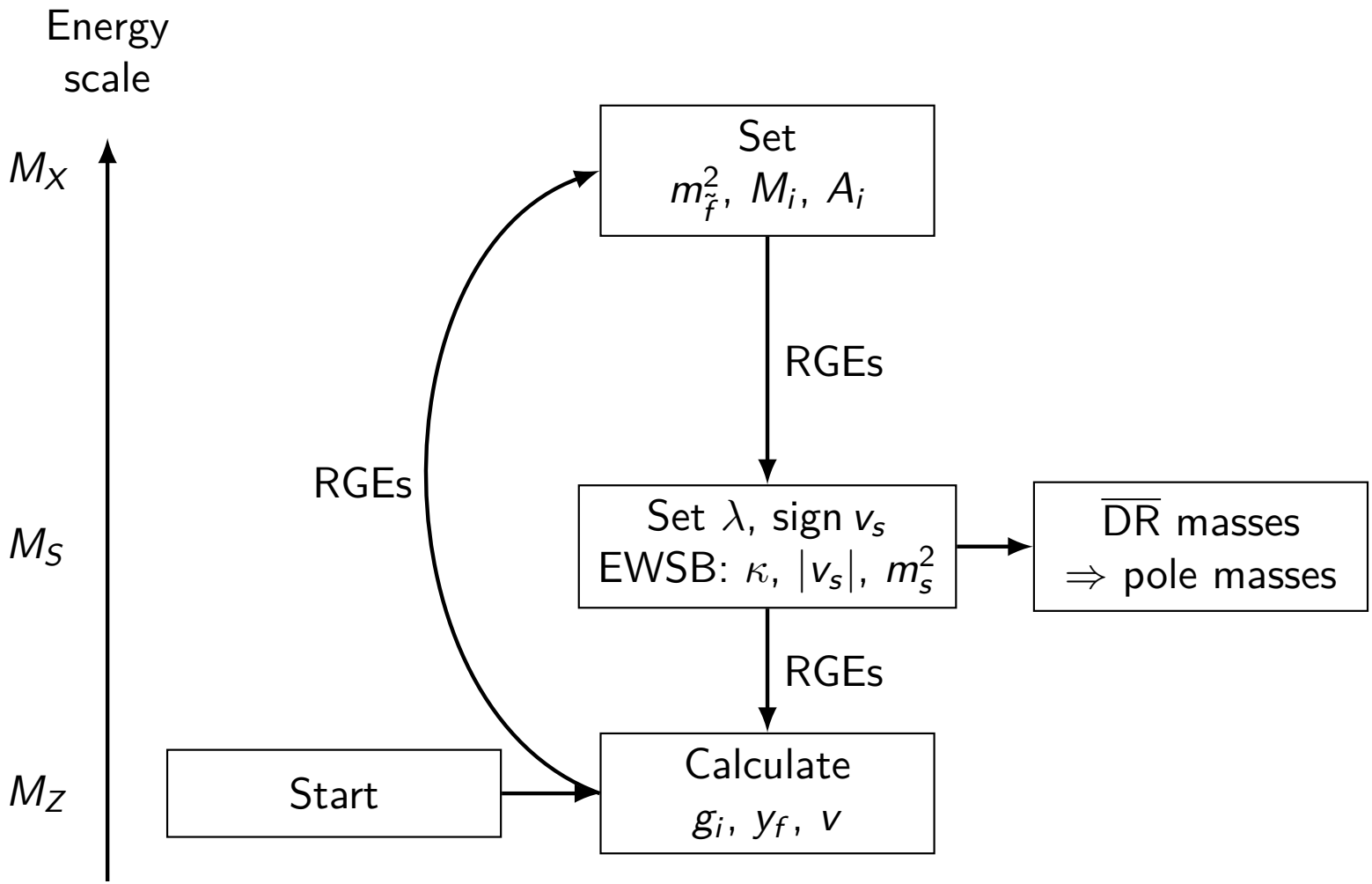
NMSSM parameters ($\overline{\text{DR}}$ scheme)

	Z_3	$\not{Z}_3$
fixed by SM	g_Y, g_2, g_3, y_u, y_d, y_e, v	g_Y, g_2, g_3, y_u, y_d, y_e, v
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, $\tan\beta$, 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, $\tan\beta$, 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 $y_t^{\overline{\rm DR}}(M_Z)$

$$y_t^{\overline{\rm DR}}(M_Z) = \frac{\sqrt{2}\, m_t^{\overline{\rm DR}}(M_Z)}{v(M_Z)/\sin\beta(M_Z)}$$

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

$$m_t^{\overline{\rm DR}} = M_t + \Sigma_t^{\text{no gluon}}(M_t) + M_t\left[\Delta m_t^{(1L),\text{gluon}} + \Delta m_t^{(2L),\text{gluon}}\right]$$

$$\Delta m_t^{(1L),\text{gluon}} = -\frac{g_3^2}{12\pi^2}\left[5 - 3\log\left(\frac{m_t^2}{\mu^2}\right)\right]$$

$$\Delta m_t^{(2L),\text{gluon}} = \left(\Delta m_t^{(1L),\text{gluon}}\right)^2 - \frac{g_3^4}{4608\pi^4}\left[396\log^2\left(\frac{m_t^2}{\mu^2}\right) - 1476\log\left(\frac{m_t^2}{\mu^2}\right) - 48\zeta(3) + 2011 + 16\pi^2(1+\log 4)\right]$$

Calculation of v

SM VEV is calculated from the running Z mass at $\mu = M_Z$:

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

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

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

Calculation of the Higgs pole mass

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

$$0 = \det\left[p^2 - m^2_h - \Delta m^2_{h,1\mathrm{L}} - \Delta m^2_{h,2\mathrm{L}}\right]$$

where

$$\Delta m^2_{h,1\mathrm{L}} = \Sigma^{(1L)}_h(p^2 = M^2_{h_i}, \mu = M_S)$$

$$\Delta m^2_{h,2\mathrm{L}} = O(\alpha_s(\alpha_t + \alpha_b), p^2 = 0) \qquad \text{NMSSM [Degrassi, Slavich, Nucl. Phys. B 825]}$$

$$+ O((\alpha_t + \alpha_b)^2 + \alpha^2_\tau, p^2 = 0) \quad \text{MSSM}$$

Features and restrictions

Restrictions:

- real parameters $\Rightarrow$ no CP violation
- no sfermion flavour violation

Features:

- Z_3- and $\not{Z}_3$-NMSSM with 2 different sets of EWSB output parameters each
- 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 $O((\alpha_t + \alpha_b)^2 + \alpha_\tau^2, p^2 = 0)$
- decays via interface to NMSDECAY
- relic density via interface to NMSSMTools/micrOMEGAS

Coming soon

- higher order corrections to g_i and y_f (late June 2015)
- higher order corrections to gluino/squark masses (2-loop QCD/3rd family y_f) (July 2015)
- decays in the MSSM and NMSSM (fall 2015)

Backup

NMSSM EWSB conditions

$$0 = m_{h_d}^2 + \frac{m_Z^2}{2}\cos 2\beta + \frac{\lambda^2}{2}v_u^2 - B\mu_{\text{eff}}\tan\beta + |\mu_{\text{eff}}|^2$$

$$0 = m_{h_u}^2 + \frac{m_Z^2}{2}\cos 2\beta + \frac{\lambda^2}{2}v_d^2 - \frac{B\mu_{\text{eff}}}{\tan\beta} + |\mu_{\text{eff}}|^2$$

$$0 = m_s^2 + \kappa^2 v_s^2 + \frac{\lambda^2}{2}v^2 - \kappa\lambda v_u v_d - \lambda A_\lambda \frac{v_u v_d}{\sqrt{2}v_s} + \kappa A_\kappa v_s + m_S'^2 + \mu'^2 - 2\kappa\xi_F + 3\kappa v_s \mu'$$

where

$$m_Z^2 = \tfrac{1}{4}(g_Y^2 + g_2^2)(v_1^2 + v_2^2)$$

$$B\mu_{\text{eff}} = \frac{\lambda v_s}{\sqrt{2}}\left(A_\lambda + \frac{\kappa v_s}{\sqrt{2}}\right) + B\mu + \lambda\left(\frac{\mu' v_s}{\sqrt{2}} + \xi_F\right)$$

$$\mu_{\text{eff}} = \mu + \frac{\lambda v_s}{\sqrt{2}}$$

SoftSUSY's Weltanschauung

- Model is defined in terms of Lagrangian parameters: g_i, y_{ij}, v, ... in the $\overline{\text{DR}}$ scheme

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

- Output parameters: m_h, M_h, Z_h, ...

Calculate spectra with NMSSM-SoftSUSY

1. Get the source code from https://softsusy.hepforge.org
2. Compile

```
$ ./configure
$ make
```

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

```
$ ./softpoint leshouches < inOutFiles/nmssmSLHAZ3Input

Block MASS                          # Mass spectrum
# PDG code      mass                particle
         25     1.06125535e+02   # h0(1)
         35     4.59247521e+02   # h0(2)
         45     5.13839234e+02   # h0(3)
         36     4.75604904e+02   # A0(1)
         46     5.17641351e+02   # A0(2)
         37     5.19730937e+02   # H+
```

SoftSUSY SLHA configuration options

```
Block SOFTSUSY   # SOFTSUSY specific inputs
     1    1e-04   # precision goal
     3    0       # printout level
#    4    1000    # EWSB scale
     5    1       # 2-loop running
     7    2       # Higgs mass loop order
    15    1       # NMSSMTools compatible output
    16    0       # Call micrOmegas (default: 0 = no,
                  # 1 = relic density only,
                  # 2 = direct detection + relic dens.,
                  # 3 = indirect detection+relic dens.,
                  # 4 = all)
    17    1       # Sparticle decays via NMSDECAY
    18    0       # soft Higgs masses as EWSB output
```