

Mass spectrum prediction in non-minimal supersymmetric models

Alexander Voigt

DESY Hamburg

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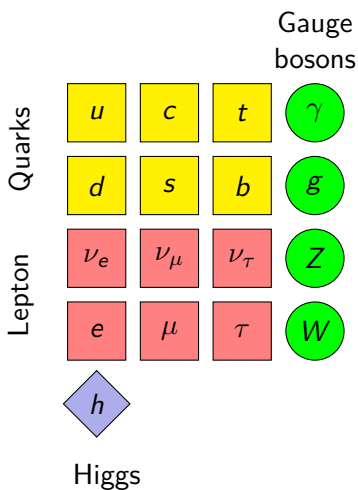
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The Standard Model of particle physics



Describes

- Quarks, Leptons, Higgs
- electromagnetic, strong, weak interactions

Problems:

- no gravitation
- no dark matter

Weaknesses:

- no unification of gauge couplings
- hierarchy problem
- prediction of $(g - 2)_\mu$

Hierarchy problem

Higgs pole mass:

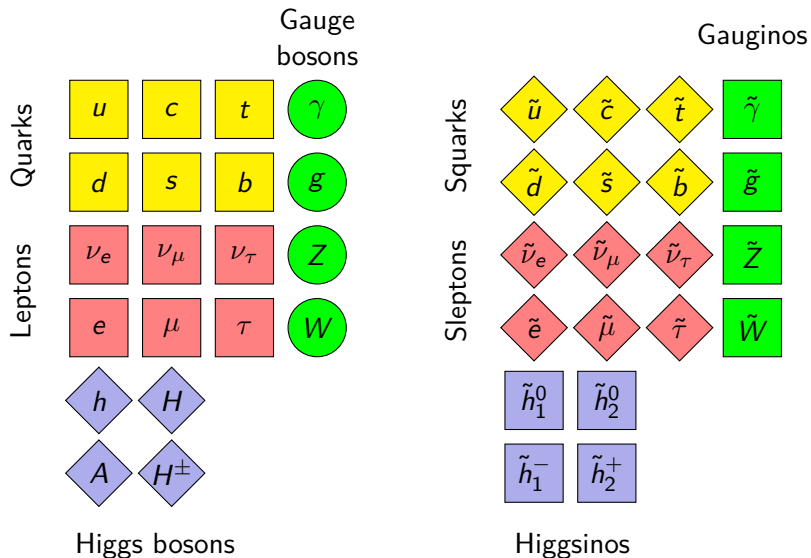
$$(m_h^{\text{pole}})^2 = (m_h^{\text{tree}})^2 + \Delta m_h^2$$

$$\Delta m_h^2 = \text{---} \overset{h}{\bullet} \text{---} \begin{array}{c} \text{---} \overset{t}{\curvearrowright} \text{---} \\ \text{---} \underset{t}{\curvearrowleft} \text{---} \end{array} \text{---} \\ + \text{---} \overset{h}{\bullet} \text{---} \begin{array}{c} \text{---} \overset{\tilde{t}_i}{\curvearrowright} \text{---} \\ \text{---} \underset{\tilde{t}_i}{\curvearrowleft} \text{---} \end{array} \text{---} + \text{---} \begin{array}{c} \text{---} \overset{\tilde{t}_i}{\curvearrowright} \text{---} \\ \text{---} \underset{\tilde{t}_i}{\curvearrowleft} \text{---} \end{array} \text{---} = 0$$

if $m_t = m_{\tilde{t}_i}$ and appropriate couplings $\Gamma_{h\tilde{t}_i\tilde{t}_i^*}$ and $\Gamma_{hh\tilde{t}_i\tilde{t}_i^*}$

\Rightarrow **supersymmetry**

Minimal Supersymmetric Standard Model (MSSM)



Minimal Supersymmetric Standard Modell (MSSM)

Field	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$SU(5)$
$Q_i = (Q_{u_i} \quad Q_{d_i})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})_i$	} $(\mathbf{10})_i$
\bar{U}_i	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})_i$	
\bar{E}_i	$(\mathbf{1}, \mathbf{1}, 1)_i$	
\bar{D}_i	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})_i$	} $(\bar{\mathbf{5}})_i$
$L_i = (L_{\nu_i} \quad L_{e_i})$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})_i$	
	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$	} $(\bar{\mathbf{5}})$
$H_1 = (H_1^0 \quad H_1^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	
	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$	} $(\mathbf{5})$
$H_2 = (H_2^+ \quad H_2^0)$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	
V_g^a	$(\mathbf{8}, \mathbf{1}, 0)$	$\ni (\mathbf{24})$
V_W^i	$(\mathbf{1}, \mathbf{3}, 0)$	$\ni (\mathbf{24})$
V_Y	$(\mathbf{1}, \mathbf{1}, 0)$	$\ni (\mathbf{24})$

Minimal Supersymmetric Standard Modell (MSSM)

$$\mathcal{W}_{\text{MSSM}} = \mu(H_1 H_2) - y_{ij}^e(H_1 L_i)\bar{E}_j - y_{ij}^d(H_1 Q_i)\bar{D}_j - y_{ij}^u(Q_i H_2)\bar{U}_j$$

Breaking of Supersymmetry

Soft breaking of supersymmetry

$$\mathcal{L}_{\text{soft}} = -m_{ij}^2 \phi_i^* \phi_j - \frac{1}{2} (M_a \lambda_a \lambda_a + \text{h.c.}) \\ + \left(\frac{1}{3!} A_{ijk} \phi_i \phi_j \phi_k - \frac{1}{2} B_{ij} \phi_i \phi_j + C_i \phi_i + \text{h.c.} \right)$$

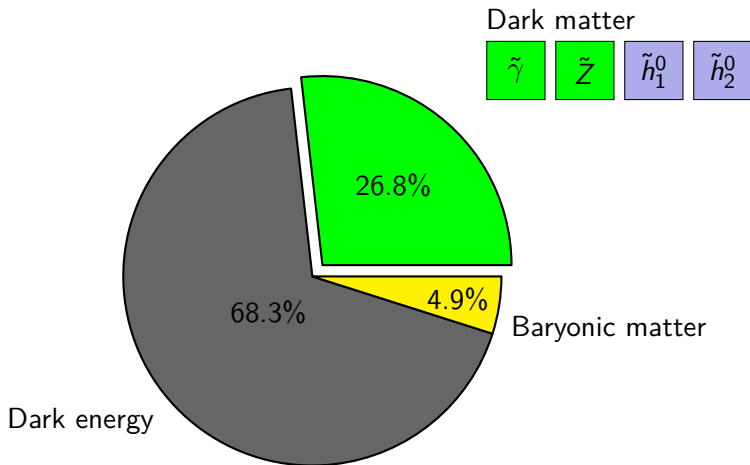
\Rightarrow

$$m_{\tilde{t}_i} \gtrsim m_t \\ m_{\tilde{V}_i} > 0$$

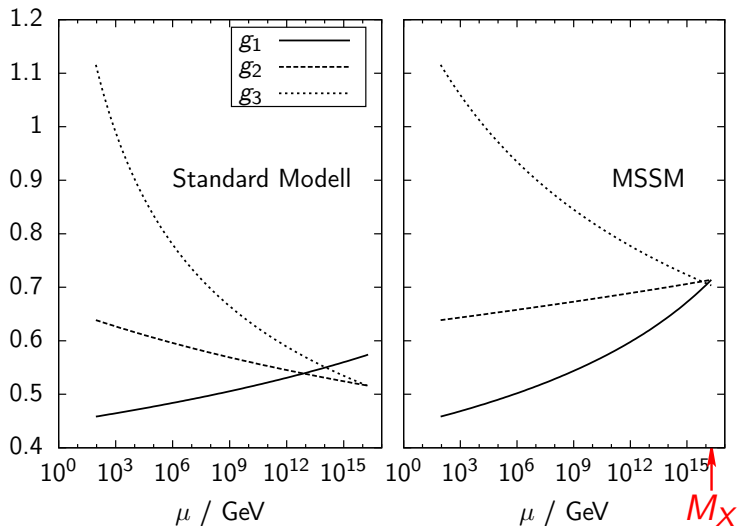
mSUGRA constraint:

$$m_{ij}^2(M_X) = m_0^2 \delta_{ij} \\ A_{ij}(M_X) = A_0 \\ M_a(M_X) = M_{1/2}$$

Advantage of the MSSM: Dark Matter Candidate



Advantage of the MSSM: Gauge Coupling Unification



Weakness of the MSSM: Fine-tuning problem

$$(m_h^{\text{pole}})^2 \approx m_Z^2 \cos^2 2\beta + \Delta m_h^2,$$

$$m_h^{\text{pole}} \approx 125 \text{ GeV}$$

$$m_Z \approx 91 \text{ GeV}$$

$$\Rightarrow \Delta m_h \gtrsim 87 \text{ GeV}$$

\Rightarrow large splitting between m_t and $m_{\tilde{t}_i}$

\Rightarrow large SUSY breaking terms

\Rightarrow spoils SUSY's solution to hierarchy problem

Weakness of the MSSM: μ -Problem

$$\mathcal{W}_{\text{MSSM}} = \mu(H_1 H_2) + \dots$$

On the one hand:

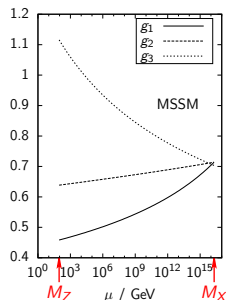
μ has its origin at the GUT scale M_X

$$\Rightarrow \mu \sim M_X \sim 10^{16} \text{ GeV}$$

On the other hand:

μ fixed by EWSB at M_Z

$$\Rightarrow \mu \sim M_Z \sim 10^2 \text{ GeV}$$



Solution: introduce new Higgs singlet S with VEV v_s

\Rightarrow Next-to Minimal Supersymmetric Standard Modell
(NMSSM)

Next-to-MSSM (NMSSM)

Field	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$SU(5)$
$Q_i = (Q_{u_i} \quad Q_{d_i})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})_i$	} $(\mathbf{10})_i$
\bar{U}_i	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})_i$	
\bar{E}_i	$(\mathbf{1}, \mathbf{1}, 1)_i$	
\bar{D}_i	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})_i$	} $(\bar{\mathbf{5}})_i$
$L_i = (L_{\nu_i} \quad L_{e_i})$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})_i$	
	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$	} $(\bar{\mathbf{5}})$
$H_1 = (H_1^0 \quad H_1^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	
	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$	} $(\mathbf{5})$
$H_2 = (H_2^+ \quad H_2^0)$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	
S	$(\mathbf{1}, \mathbf{1}, 0)$	$(\mathbf{1})$
V_g^a	$(\mathbf{8}, \mathbf{1}, 0)$	$\ni (\mathbf{24})$
V_W^i	$(\mathbf{1}, \mathbf{3}, 0)$	$\ni (\mathbf{24})$
V_Y	$(\mathbf{1}, \mathbf{1}, 0)$	$\ni (\mathbf{24})$

Next-to-MSSM (NMSSM)

$$\begin{aligned}\mathcal{W}_{\text{MSSM}+S} = & \lambda S(H_1 H_2) + \frac{\kappa}{3} S^3 + \frac{\mu'}{2} S^2 + \xi_F S \\ & + \mu(H_1 H_2) - y_{ij}^e(H_1 L_i)\bar{E}_j - y_{ij}^d(H_1 Q_i)\bar{D}_j - y_{ij}^u(Q_i H_2)\bar{U}_j\end{aligned}$$

Next-to-MSSM (NMSSM)

$$\mathcal{W}_{\text{MSSM}+S} = \lambda S(H_1 H_2) + \frac{\kappa}{3} S^3 + \frac{\mu'}{2} S^2 + \xi_F S \\ + \mu(H_1 H_2) - y_{ij}^e(H_1 L_i)\bar{E}_j - y_{ij}^d(H_1 Q_i)\bar{D}_j - y_{ij}^u(Q_i H_2)\bar{U}_j$$

Impose Z_3 symmetry to forbid dimensionful couplings and solve the μ -problem

\Rightarrow

$$\mathcal{W}_{\text{NMSSM}} = \lambda S(H_1 H_2) + \frac{\kappa}{3} S^3 \\ - y_{ij}^e(H_1 L_i)\bar{E}_j - y_{ij}^d(H_1 Q_i)\bar{D}_j - y_{ij}^u(Q_i H_2)\bar{U}_j$$

Advantage of the NMSSM: Reduced m_h Fine-tuning

$$(m_h^{\text{pole}})^2 \approx \underbrace{m_Z^2 \cos^2 2\beta}_{\text{MSSM}} + \frac{\lambda^2 v^2}{2} \sin^2 2\beta + \Delta m_h^2$$

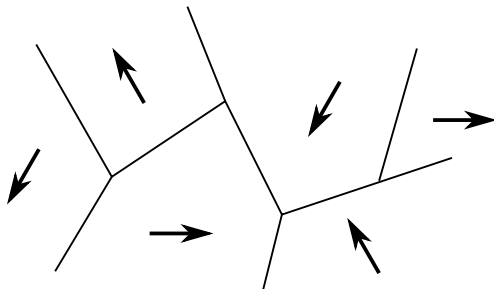
NMSSM

$$\Rightarrow \Delta m_h \gtrsim 55 \text{ GeV}$$

$$\text{MSSM: } \Delta m_h \gtrsim 87 \text{ GeV}$$

Problem of the NMSSM: Domain Walls

Problem: $\mathcal{W}_{\text{NMSSM}}$ has a *discrete* Z_3 symmetry.
 \Rightarrow domain walls



Solution: new *continuous* gauge symmetry $U(1)'$

$\Rightarrow U(1)'$ -extended Supersymmetric Standard Modell (USSM)

$U(1)'$ -extended Supersymmetric Standard Modell (USSM)

Field	$G_{\text{SM}} \times U(1)'$	$SU(5) \times U(1)'$
$Q_i = (Q_{u_i} \quad Q_{d_i})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6}, N_Q)_i$	} $(\mathbf{10}, N_{10})_i$
\bar{U}_i	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}, N_U)_i$	
\bar{E}_i	$(\mathbf{1}, \mathbf{1}, 1, N_E)_i$	
\bar{D}_i	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}, N_D)_i$	} $(\bar{\mathbf{5}}, N_{\bar{\mathbf{5}}})_i$
$L_i = (L_{\nu_i} \quad L_{e_i})$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, N_L)_i$	
	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}, N_X)$	} $(\bar{\mathbf{5}}, N_{\bar{\mathbf{5}}})$
$H_1 = (H_1^0 \quad H_1^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, N_{H_1})$	
	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3}, N_X)$	} $(\mathbf{5}, N_{\mathbf{5}})$
$H_2 = (H_2^+ \quad H_2^0)$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2}, N_{H_2})$	
S	$(\mathbf{1}, \mathbf{1}, 0, N_S)$	$(\mathbf{1}, N_1)$
V_g^a	$(\mathbf{8}, \mathbf{1}, 0, 0)$	$\ni (\mathbf{24}, 0)$
V_W^i	$(\mathbf{1}, \mathbf{3}, 0, 0)$	$\ni (\mathbf{24}, 0)$
V_Y	$(\mathbf{1}, \mathbf{1}, 0, 0)$	$\ni (\mathbf{24}, 0)$
V_N	$(\mathbf{1}, \mathbf{1}, 0, 0)$	$\ni (\mathbf{1}, 0)$

$U(1)'$ -extended Supersymmetric Standard Modell (USSM)

If $N_S \neq 0$ and $N_S + N_{H_1} + N_{H_2} = 0$
 \Rightarrow all S^n terms forbidden

$$\mathcal{W}_{\text{USSM}} = \lambda S(H_1 H_2) - y_{ij}^e(H_1 L_i) \bar{E}_j - y_{ij}^d(H_1 Q_i) \bar{D}_j - y_{ij}^u(Q_i H_2) \bar{U}_j$$

Advantage of the USSM: Reduced m_h Fine-tuning

$$(m_h^{\text{pole}})^2 = (m_h^{\text{tree}})^2 + \Delta m_h^2$$

$$(m_h^{\text{tree}})^2 \approx \underbrace{m_Z^2 \cos^2 2\beta}_{\text{MSSM}} + \underbrace{\frac{\lambda^2 v^2}{2} \sin^2 2\beta}_{\text{NMSSM}} + \frac{m_Z^2}{4} \left(1 + \frac{1}{4} \cos 2\beta\right)^2$$

USSM

$$\Rightarrow \Delta m_h \gtrsim 32 \text{ GeV}$$

MSSM: $\Delta m_h \gtrsim 87 \text{ GeV}$

NMSSM: $\Delta m_h \gtrsim 55 \text{ GeV}$

Problem of the USSM: Anomalies

Problem: $U(1)'$ -charges are arbitrary
(as long as $\mathcal{W}_{\text{USSM}}$ is gauge invariant)
 \Rightarrow unsuitable choice can lead to gauge anomalies:

$$\sum_f Z' \text{ (triangle diagram)} = \infty$$

Solution: anomaly-free gauge group, e.g. $SO(10)$ or E_6

\Rightarrow Exceptional Supersymmetric Standard Modell ($E_6\text{SSM}$)

Exceptional Supersymmetric Standard Modell (E_6 SSM)

Field	$G_{SM} \times U(1)_N$	$SU(5) \times U(1)_N$	E_6
$Q_i = (Q_{u_i} \quad Q_{d_i})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6}, 1)_i$	$(\mathbf{10}, 1)_i$	$(\mathbf{27})_i$
\bar{U}_i	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}, 1)_i$		
\bar{E}_i	$(\mathbf{1}, \mathbf{1}, 1, 1)_i$		
\bar{D}_i	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}, 2)_i$	$(\bar{\mathbf{5}}, 2)_i$	
$L_i = (L_{\nu_i} \quad L_{e_i})$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 2)_i$		
\bar{X}_i	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}, -3)_i$	$(\bar{\mathbf{5}}, -3)_i$	
$H_{1i} = (H_{1i}^0 \quad H_{1i}^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, -3)_i$		
X_i	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3}, -2)_i$	$(\mathbf{5}, -2)_i$	
$H_{2i} = (H_{2i}^+ \quad H_{2i}^0)$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2}, -2)_i$		
S_i	$(\mathbf{1}, \mathbf{1}, 0, 5)_i$	$(\mathbf{1}, 5)_i$	
\bar{N}_i	$(\mathbf{1}, \mathbf{1}, 0, 0)_i$	$(\mathbf{1}, 0)_i$	
$H' = (H'^0 \quad H'^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 2)$	$\ni (\bar{\mathbf{5}}, 2)'$	$\ni (\mathbf{27})'$
$\bar{H}' = (\bar{H}'^+ \quad \bar{H}'^0)$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2}, -2)$	$\ni (\mathbf{5}, -2)'$	$\ni (\bar{\mathbf{27}})'$
V_g^a	$(\mathbf{8}, \mathbf{1}, 0, 0)$	$\ni (\mathbf{24}, 0)$	$\ni (\mathbf{78})$
V_W^i	$(\mathbf{1}, \mathbf{3}, 0, 0)$	$\ni (\mathbf{24}, 0)$	$\ni (\mathbf{78})$
V_Y	$(\mathbf{1}, \mathbf{1}, 0, 0)$	$\ni (\mathbf{24}, 0)$	$\ni (\mathbf{78})$
V_N	$(\mathbf{1}, \mathbf{1}, 0, 0)$	$\ni (\mathbf{1}, 0)$	$\ni (\mathbf{78})$

Exceptional Supersymmetric Standard Modell (E₆SSM)

$$\begin{aligned}\mathcal{W}_{E_6SSM} = & \lambda_3 S_3(H_{13}H_{23}) \\ & - y_{ij}^e(H_{13}L_i)\bar{E}_j - y_{ij}^d(H_{13}Q_i)\bar{D}_j - y_{ij}^u(Q_iH_{23})\bar{U}_j \\ & + \kappa_{ij} S_3(X_i\bar{X}_j) + \lambda_{\alpha\beta} S_3(H_{1\alpha}H_{2\beta}) + \mu'(H'\bar{H}')\end{aligned}$$

Summary Supersymmetry

Supersymmetric Models are attractive extensions of the SM.

Advantages:

- Solution of the hierarchy problem
- Dark matter candidate particles
- Gauge coupling unification
- Correct prediction of $(g - 2)_\mu$
- Closer connection to supergravity models



Contents

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Standard Modell

Supersymmetric extensions

② Calculation of mass spectra

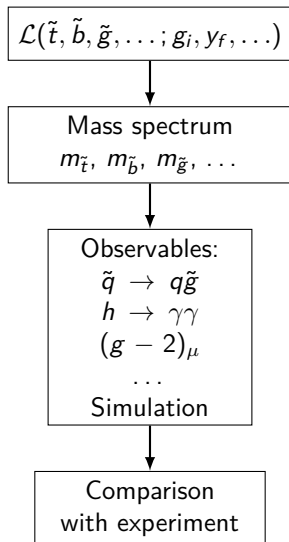
Physical problem statement

FlexibleSUSY: a SUSY spectrum generator generator

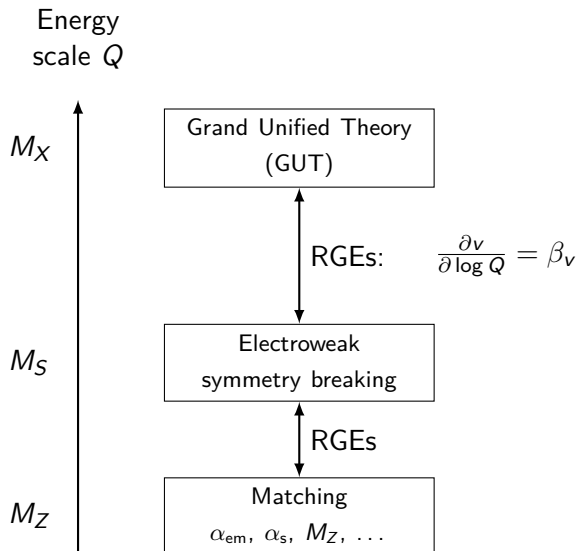
Algorithm to calculate the mass spectrum

③ Parameters scans in the CMSSM, NMSSM, USSM, E_6 SSM

Why calculate the mass spectrum?



Physical problem statement



Publicly available SUSY spectrum generators

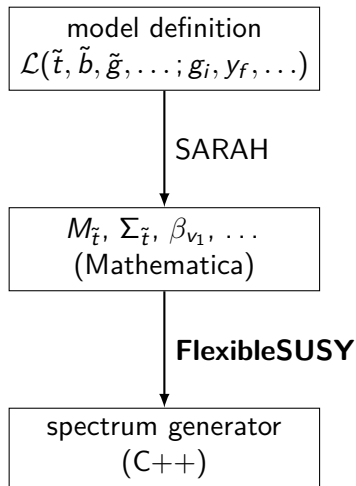
Model	spectrum generator
MSSM	ISASUSY, SOFTSUSY, SPheno, SuSeFlav, SuSpect
NMSSM	NMSPEC, SOFTSUSY
USSM	–
CE ₆ SSM	CE6SSMSpecGen
any SUSY-Modell	SARAH, FlexibleSUSY

FlexibleSUSY: a SUSY spectrum generator generator

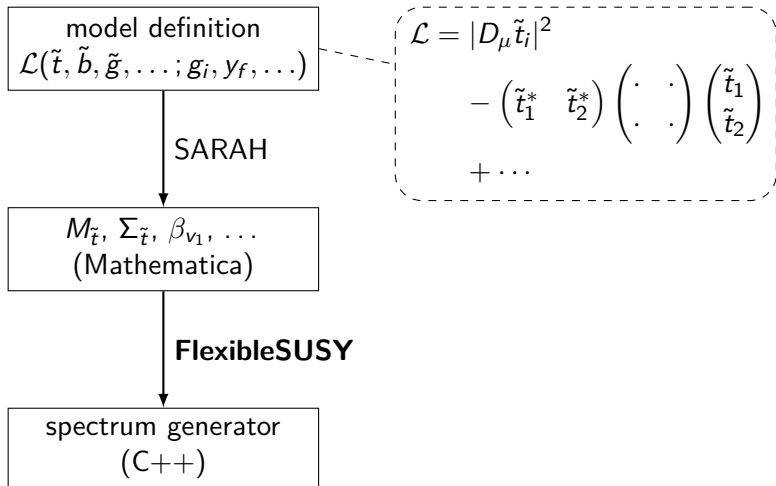
FlexibleSUSY



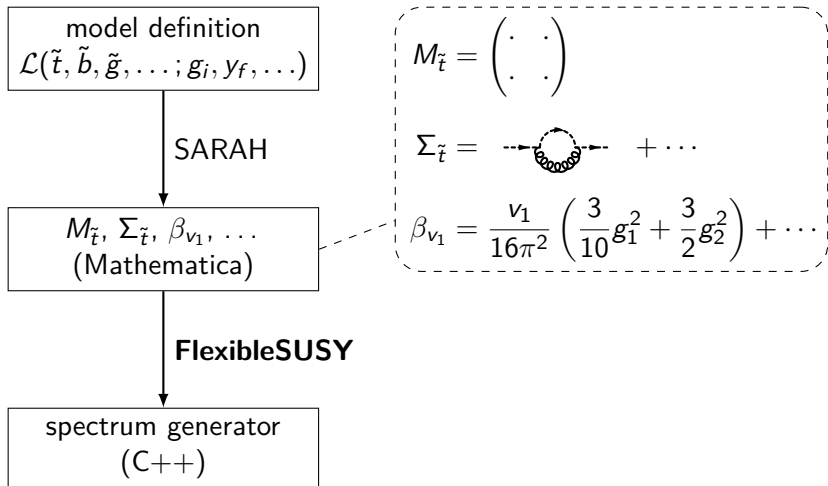
How a spectrum generator is generated



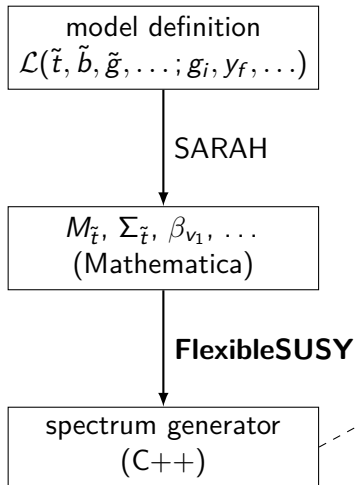
How a spectrum generator is generated



How a spectrum generator is generated



How a spectrum generator is generated



```
Matrix<2,2> get_mass_matrix_St() {  
    Matrix<2,2> mass_matrix;  
  
    mass_matrix(0,0) = ...;  
    mass_matrix(0,1) = ...;  
    mass_matrix(1,0) = ...;  
    mass_matrix(1,1) = ...;  
  
    return mass_matrix;  
}  
  
complex<double> self_energy_St() {  
    complex<double> self_energy;  
  
    self_energy += ...;  
    self_energy += ...;  
    self_energy += ...;  
  
    return self_energy;  
}  
  
double beta_v1() {  
    double beta_v1;  
  
    beta_v1 = v1*(0.3*Sqr(g1)  
        + 1.5*Sqrt(g2))/(16.*Sqr(Pi) + ...;  
  
    return beta_v1;  
}
```

FlexibleSUSY Design Goals

- **Modular, well readable C++ code**

Reason: large variety of SUSY models

→ User intervention likely

- **High precision**

Reason: Higgs mass measurement with $\sigma \approx 0.4$ GeV

(leading 2-loop m_h , $y_{t,b}$; full 2-loop β_i , 1-loop Σ_i)

- **different RGE+BC solvers**

Reason: convergence problems in some regions

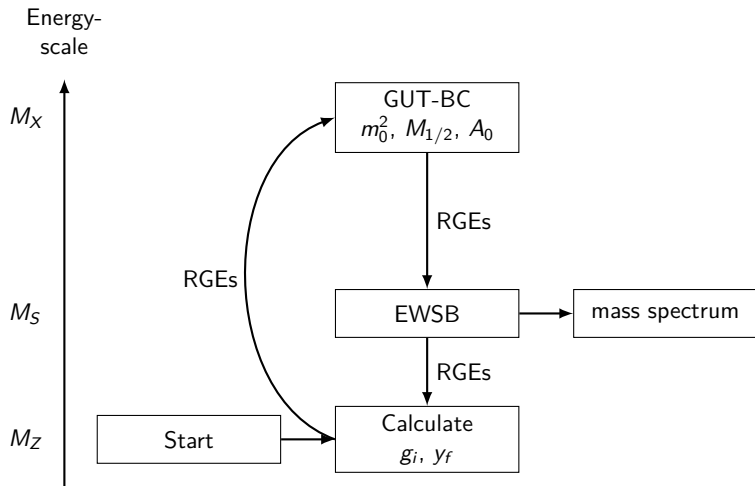
(Two-scale, Lattice, ...)

- **High speed**

Reason: many model parameters

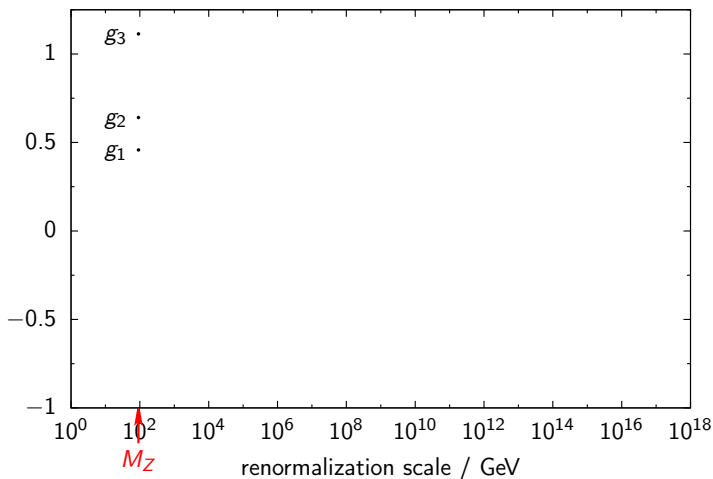
(C++ expression templates, multi-threading)

Algorithm to calculate the mass spectrum



Algorithm to calculate the mass spectrum

Iteration step 1: calculate gauge couplings $g_i^{\overline{\text{DR}}}(M_Z)$



Calculate gauge coupling $g_3^{\overline{\text{DR}}}(M_Z)$

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

→

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

with

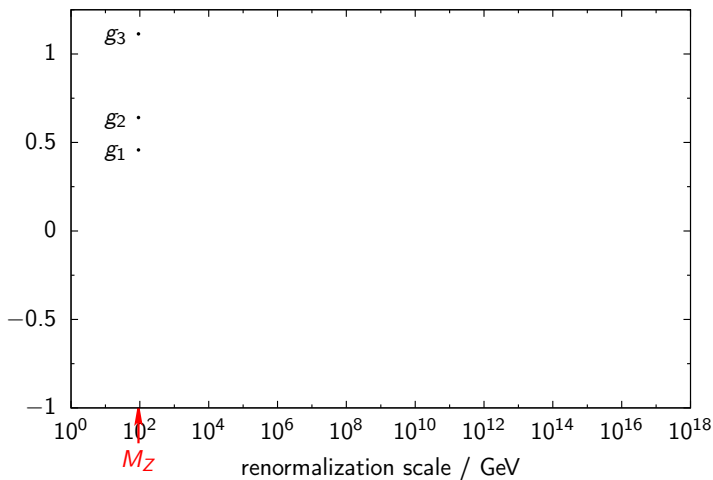
$$\Delta\alpha_{s,\text{SM}}(\mu) = \frac{\alpha_s}{2\pi} \left[-\frac{2}{3} \log \frac{m_t}{\mu} \right]$$
$$\Delta\alpha_s(\mu) = \frac{\alpha_s}{2\pi} \left[\frac{1}{2} - \sum_{\text{SUSY particle } f} T_f \log \frac{m_f}{\mu} \right]$$

⇒

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

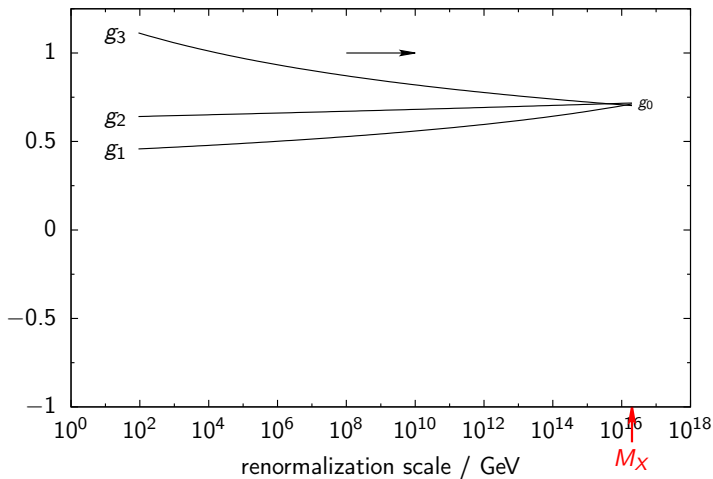
Algorithm to calculate the mass spectrum

Iteration step 1: calculate gauge couplings $g_i^{\overline{\text{DR}}}(M_Z)$



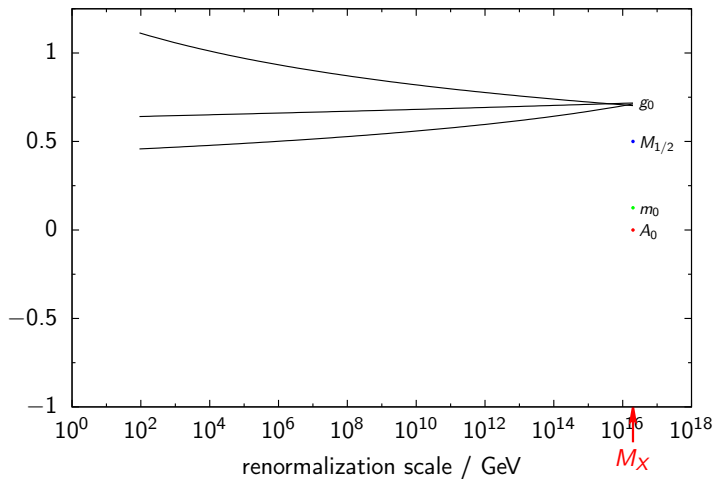
Algorithm to calculate the mass spectrum

Iteration step 1: RG running of gauge couplings to M_X



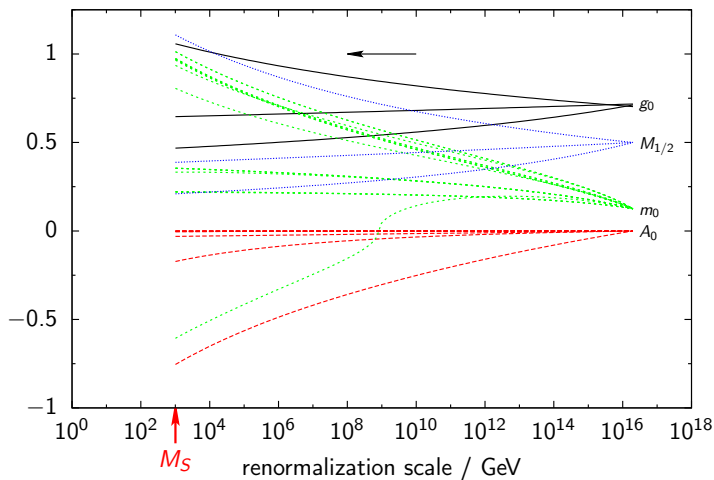
Algorithm to calculate the mass spectrum

Iteration step 1: impose boundary conditions at M_X



Algorithm to calculate the mass spectrum

Iteration step 1: RG running to M_S , impose EWSB conditions



Solve EWSB conditions

Solve EWSB conditions by fixing N model parameters (p_1, \dots, p_N) :

$$0 = \frac{\partial V^{\text{tree}}}{\partial v_i} - t_i(m_f) \quad (i = 1, \dots, N)$$

For example: CMSSM solve for $(\mu, B\mu)$

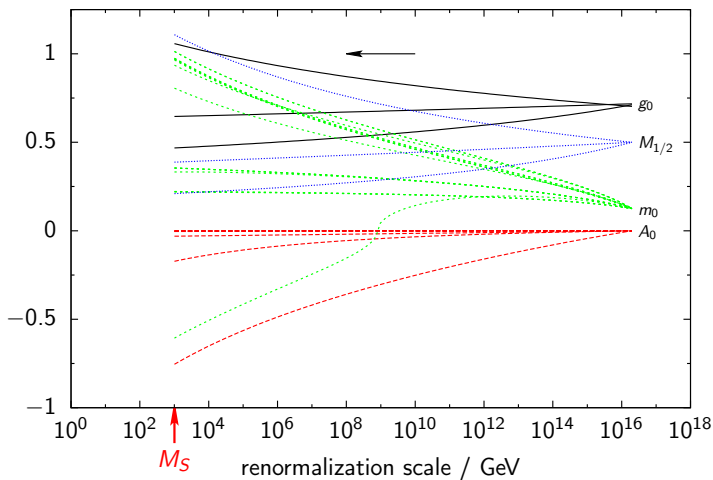
$$0 = m_{h_1}^2 v_1 + |\mu|^2 v_1 - B\mu v_2 + \frac{\bar{g}^2}{8} (v_1^2 - v_2^2) v_1 - t_1(m_f)$$

$$0 = m_{h_2}^2 v_2 + |\mu|^2 v_2 - B\mu v_1 - \frac{\bar{g}^2}{8} (v_1^2 - v_2^2) v_2 - t_2(m_f)$$

where $\bar{g}^2 = g_Y^2 + g_2^2$

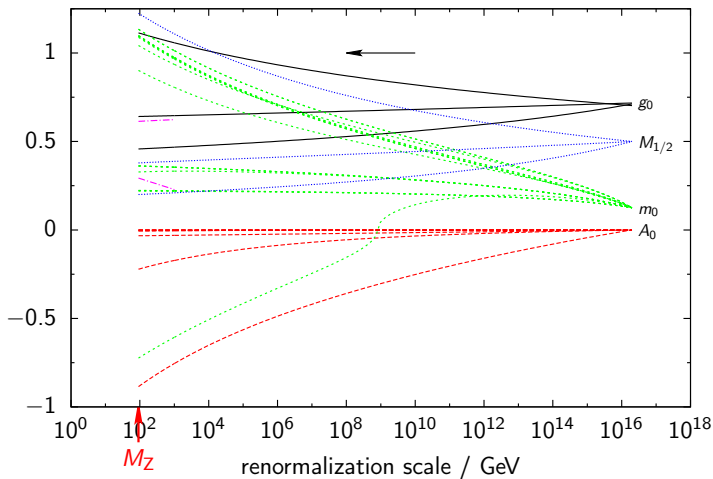
Algorithm to calculate the mass spectrum

Iteration step 1: RG running to M_S , impose EWSB on $(\mu, B\mu)$



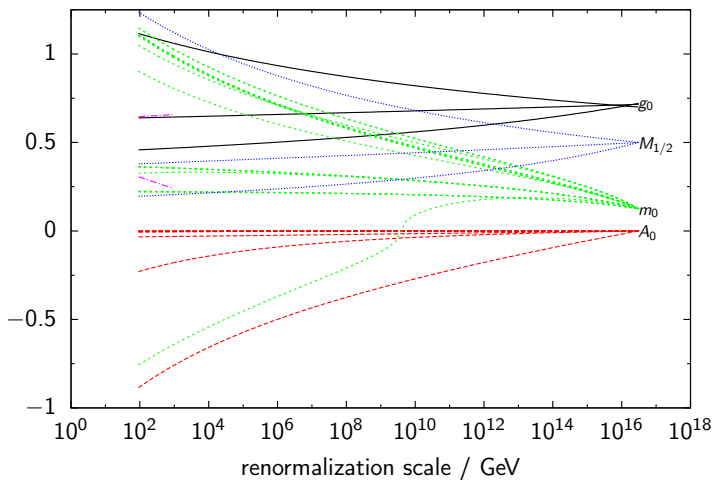
Algorithm to calculate the mass spectrum

Iteration step 1: RG running to M_Z



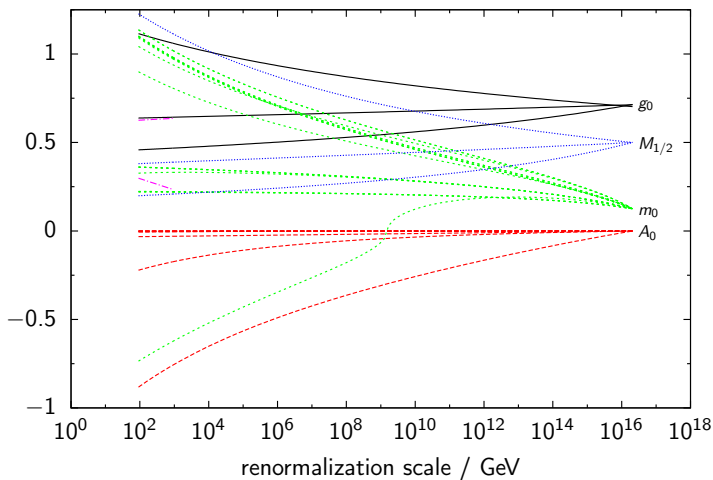
Algorithm to calculate the mass spectrum

Iteration step 2:



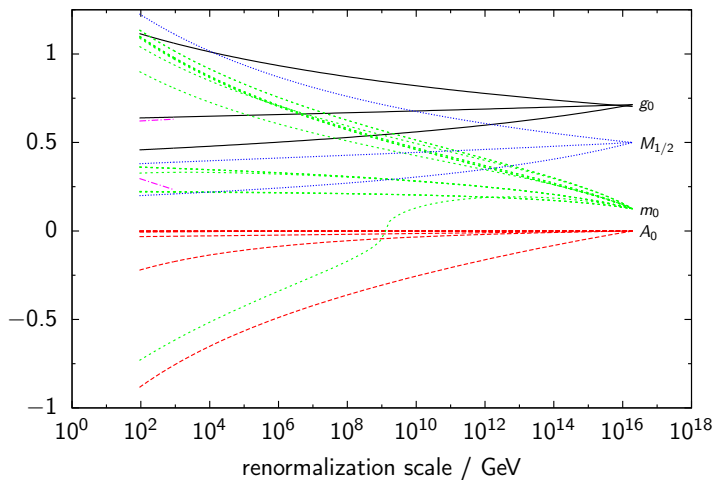
Algorithm to calculate the mass spectrum

Iteration step 3:

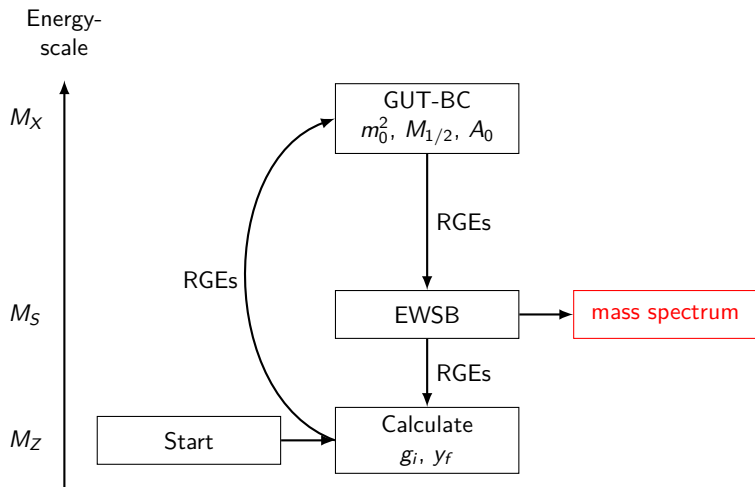


Algorithm to calculate the mass spectrum

Iteration step 8: convergence



Algorithm to calculate the mass spectrum



Calculate the pole mass spectrum

Solve for each particle f :

$$0 = \det \left[p^2 \mathbf{1} - M_f + \hat{\Sigma}_f(p^2) \right]$$

For example $f = \text{Higgs}$:

$$M_h = \begin{pmatrix} (M_h)_{11} & (M_h)_{12} \\ (M_h)_{12} & (M_h)_{22} \end{pmatrix}$$

$$(M_h)_{11} = m_{h_1}^2 + |\mu|^2 + \frac{1}{8}(g_Y^2 + g_2^2)(3v_1^2 - v_2^2)$$

$$(M_h)_{12} = -\frac{1}{2}(B\mu + B\mu^*) - \frac{1}{4}v_2 v_1 (g_Y^2 + g_2^2)$$

$$(M_h)_{22} = m_{h_2}^2 + |\mu|^2 + \frac{1}{8}(g_Y^2 + g_2^2)(3v_2^2 - v_1^2)$$

$$\hat{\Sigma}_h(p^2) = \Sigma_h(p^2) - \delta M_h^2 + (p^2 \mathbf{1} - M_h^2) \delta Z_h,$$

$$\delta M_h^2 = \Sigma_h(p^2) \Big|_{\Delta}, \quad \delta Z_h = -\Sigma'_h(p^2) \Big|_{\Delta}$$

Contents

① Introduction

Standard Modell

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Physical problem statement

FlexibleSUSY: a SUSY spectrum generator generator

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③ Parameters scans in the CMSSM, NMSSM, USSM, E₆SSM

Parameters scans in the CMSSM, NMSSM, USSM, E₆SSM

Models: CMSSM, NMSSM, USSM, E₆SSM

mSUGRA-inspired GUT scale BCs:

$$(m_{\tilde{f}}^2)_{ij}(M_X) = m_0^2 \delta_{ij}$$

$$A_{ij}^f(M_X) = A_0$$

$$M_i(M_X) = M_{1/2}$$

parameters fixed by EWSB conditions at M_S :

CMSSM: $\mu, B\mu$

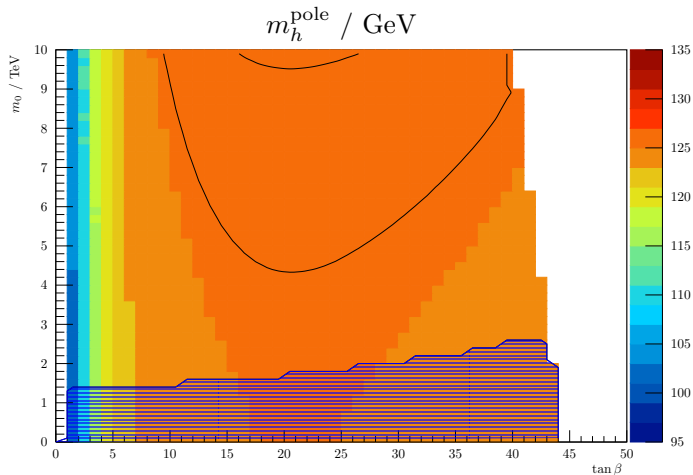
NMSSM: κ, v_S, m_S^2

USSM: $m_{h_1}^2, m_{h_2}^2, m_S^2$

E₆SSM: $m_{h_1}^2, m_{h_2}^2, m_S^2$

2-dimensional scan over: $m_0, \tan \beta = v_2/v_1$

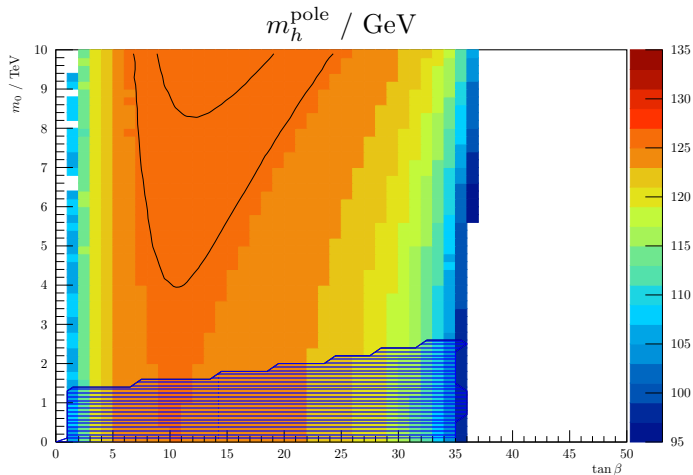
CMSSM parameter scan



$M_{1/2} = A_0 = 5 \text{ TeV}, \text{sign } \mu = +1$

Higgs mass contours at $m_h^{\text{pole}} = (125.7 \pm 0.4) \text{ GeV}$

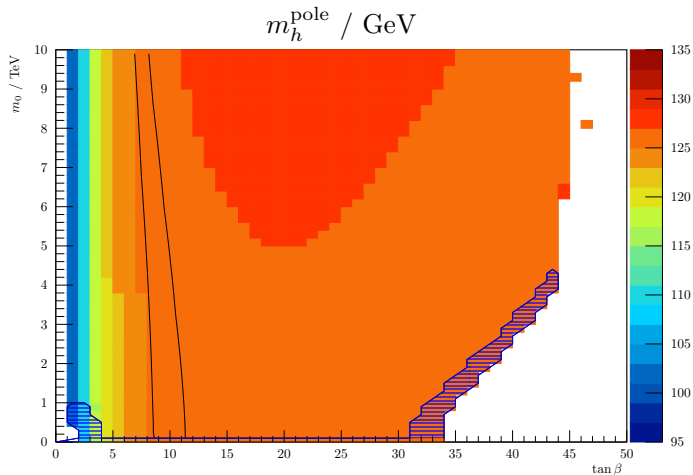
NMSSM parameter scan



$M_{1/2} = -A_0 = 5 \text{ TeV}, \lambda(M_X) = 0.1, \text{sign } v_s = +1$

Higgs mass contours at $m_h^{\text{pole}} = (125.7 \pm 0.4) \text{ GeV}$

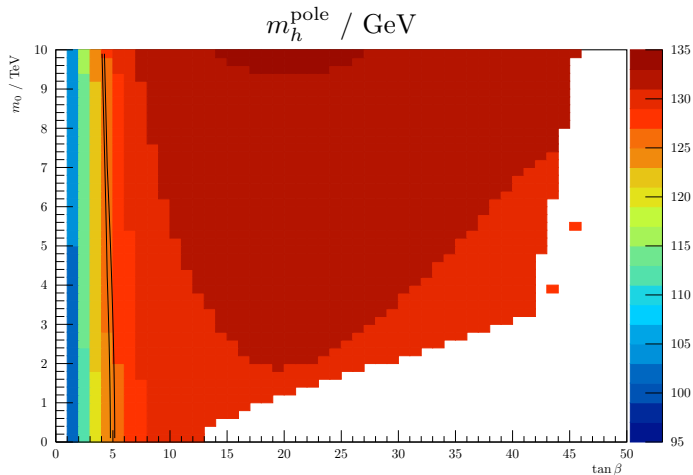
USSM parameter scan



$M_{1/2} = A_0 = 5 \text{ TeV}, \lambda(M_X) = 0.1, v_s = 10 \text{ TeV}$

Higgs mass contours at $m_h^{\text{pole}} = (125.7 \pm 0.4) \text{ GeV}$

E_6 SSM parameter scan



$M_{1/2} = A_0 = 5 \text{ TeV}, \lambda(M_X) = \kappa(M_X) = 0.1, v_s = 10 \text{ TeV}$
Higgs mass contours at $m_h^{\text{pole}} = (125.7 \pm 0.4) \text{ GeV}$

Conclusions

Non-minimal SUSY models are attractive extensions of the SM.

Advantages:

- Solution of the hierarchy problem
- Solution of the μ -problem of the MSSM
- Dark matter candidate particles
- Gauge coupling unification
- Correct prediction of $(g - 2)_\mu$
- Closer connection to supergravity models possible

FlexibleSUSY: general SUSY spectrum generator

Supported models:

- MSSM, CMSSM, NUH-MSSM, NMSSM, SMSSM, USSM, NUHM-E₆SSM, MRSSM, TMSSM, $\mu\nu$ SSM, ...

<https://flexiblesusy.hepforge.org>

Future plans for FlexibleSUSY

- More applications!
(currently studied: MRSSM, E_6 SSM, NE_6 SSM)
- support non-SUSY models (currently developed)
- 2-loop m_h from RGEs (currently developed)
- decays ($h \rightarrow \gamma\gamma, \dots$)
- some observables ($(g-2)_\mu, \dots$)
- interface to HiggsBounds
- *automatic* tower of effective field theories
- complex parameters (to study CP violation, etc.)
- ...

Thank you!



Backup

little Hierarchy problem

$$(m_h^{\text{pole}})^2 = (m_h^{\text{tree}})^2 + \Delta m_h^2 = (125.7 \text{ GeV})^2$$

$$(m_h^{\text{tree}})^2 \approx \underbrace{m_Z^2 \cos^2 2\beta}_{\text{MSSM}} + \underbrace{\frac{\lambda^2 v^2}{2} \sin^2 2\beta}_{\text{NMSSM}} + \frac{m_Z^2}{4} \left(1 + \frac{1}{4} \cos 2\beta\right)^2$$

$\underbrace{\hspace{15em}}_{\text{USSM, E}_6\text{SSM}}$

\Rightarrow

$$\Delta m_h^2 \geq \begin{cases} (87 \text{ GeV})^2 & \text{MSSM} & \Rightarrow m_{\tilde{t}} \gg \gg m_t \\ (55 \text{ GeV})^2 & \text{NMSSM} & \Rightarrow m_{\tilde{t}} \gg m_t \\ (32 \text{ GeV})^2 & \text{UMSSM, E}_6\text{SSM} & \Rightarrow m_{\tilde{t}} > m_t \end{cases}$$

Renormierung von v

Allgemeine Renormierungstransformation:

$$(\phi + v) \rightarrow \sqrt{Z}\phi + v + \delta v$$

$$\text{oder } (\phi + v) \rightarrow \sqrt{Z}(\phi + v + \delta\bar{v})$$

Mit $\sqrt{Z} = 1 + \frac{1}{2}\delta Z$ folgt:

$$\delta v = \frac{1}{2}\delta Z v + \delta\bar{v}$$

Trick: Hintergrundfeld einführen

$$\phi \rightarrow \phi_{\text{eff}} = \phi + \hat{\phi} + \hat{v}$$

$$\phi_{\text{eff}} \rightarrow \sqrt{Z} \left[\phi + \sqrt{\hat{Z}} (\hat{\phi} + \hat{v}) \right]$$

Damit folgt für $\hat{\phi} = 0$

$$\delta v = \frac{1}{2} (\delta Z + \delta\hat{Z}) v$$

$$\beta_v = (\gamma + \hat{\gamma})v$$

Berechnung von β_v

Allgemeine Eichtheorie:

$$\beta_v = (\gamma + \hat{\gamma})v$$

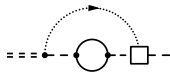
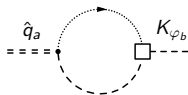
γ ... anomale Dimension des Higgsfeldes

[Machacek, Vaughn (1983)]

$\hat{\gamma}$... anomale Dimension eines Hintergrundfeldes

unbekannt!

Berechnung von β_V



\Rightarrow

$$\hat{\gamma}^{(1)} = \frac{\xi}{(4\pi)^2} 2g^2 C^2(S)$$

$$\hat{\gamma}^{(2)} = \frac{\xi}{(4\pi)^4} 2g^2 C^2(S)$$

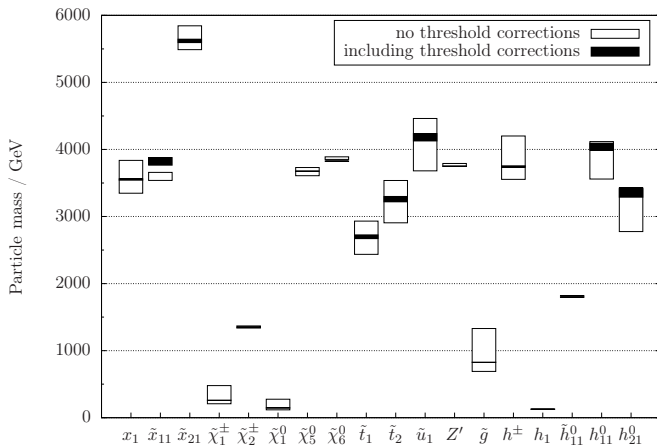
$$\times \left[g^2 (1 + \xi) C^2(S) + g^2 \frac{7 - \xi}{4} C_2(G) - Y^2(S) \right]$$

E₆SSM-Schwellenkorrekturen

$$g_i^{\overline{\text{DR}}, E_6 \text{SSM}}(Q) = g_i^{\overline{\text{MS}}, \text{SM}}(Q) + \Delta g_i(Q) \quad (i = 1, 2, 3),$$

$$\Delta g_3(Q) = \frac{g_3^3}{(4\pi)^2} \left[\frac{1}{2} - 2 \log \frac{m_{\tilde{g}}}{Q} - \frac{1}{6} \sum_{\tilde{q} \in \{\tilde{u}, \tilde{d}\}} \sum_{i=1}^3 \sum_{k=1}^2 \log \frac{m_{\tilde{q}_{ik}}}{Q} \right. \\ \left. - \frac{2}{3} \sum_{i=1}^3 \log \frac{m_{X_i}}{Q} - \frac{1}{6} \sum_{i=1}^3 \sum_{k=1}^2 \log \frac{m_{\tilde{X}_{ik}}}{Q} \right]$$

CE₆SSM-Massenspektrum

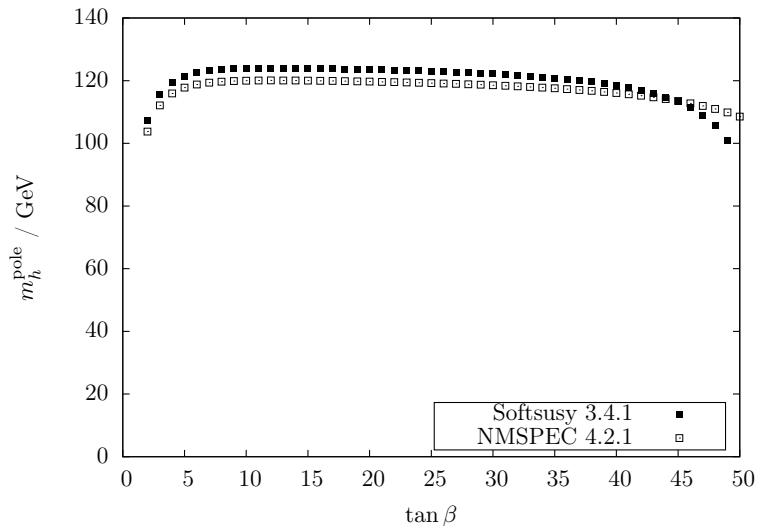


$$\tan \beta = 35, \quad \lambda_{1,2,3} = \kappa_{1,2,3} = 0.2, \quad v_s = 10 \text{ TeV},$$

$$\mu' = m_{h'} = m_{\bar{h}'} = 10 \text{ TeV}, \quad B\mu' = 0,$$

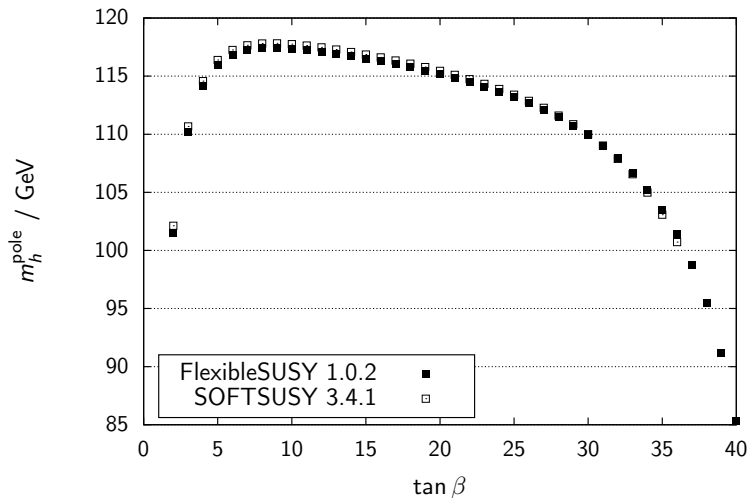
$$T_{\text{match}} = \frac{1}{2} T_0 \dots 2 T_0, \quad T_0 = 1.9 \text{ TeV}$$

NMSSM Higgs-Masse SOFTSUSY vs. NMSPEC



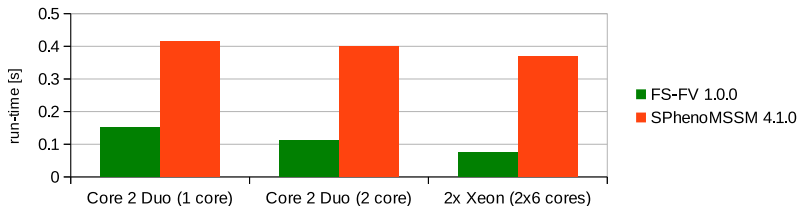
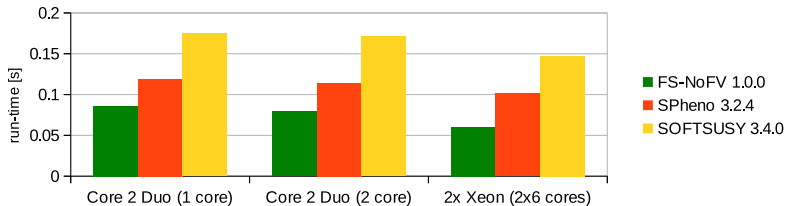
$$m_0 = M_{1/2} = -A_0 = 5 \text{ TeV}, \lambda(M_S) = 0.1, \text{sign } v_s = +1$$

NMSSM Higgs-Masse FlexibleSUSY vs. SOFTSUSY



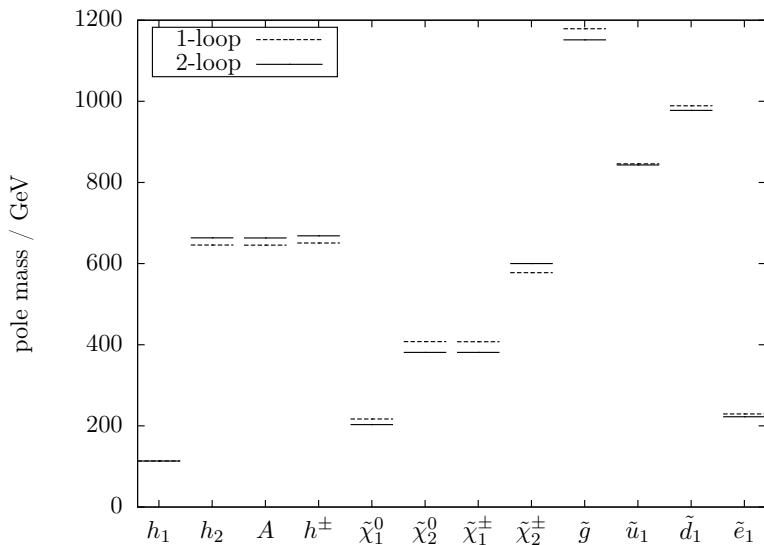
$$m_0 = M_{1/2} = -A_0 = 1 \text{ TeV}, \lambda(M_X) = 0.1, \text{sign } v_s = +1$$

CMSSM-Laufzeitvergleich

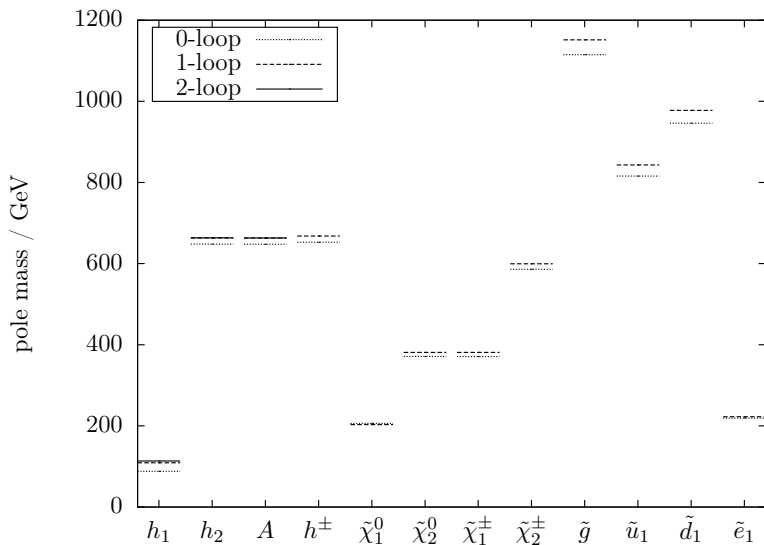


g++ 4.8.0, ifort 13.1.3 20130607

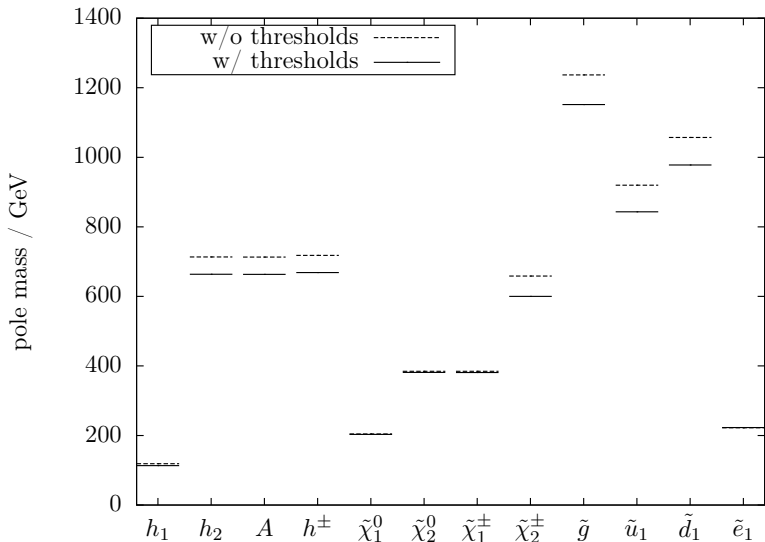
Einfluss der β -Funktionen-Loop-Ordnung (MSSM)



Einfluss der Selbstenergie-Loop-Ordnung (MSSM)



Einfluss der Schwellenkorrekturen-Loop-Ordnung (MSSM)



NMSSM-SOFTSUSY vs. NMSSM-FlexibleSUSY

NMSSM-SOFTSUSY	NMSSM-FlexibleSUSY
Decay interface for NMHDECAY	FlexibleDecay
optimized couplings	automatically generated couplings
2 EWSB variants	user-defined
BCs via C++	BCS via Mathematica
fast pole masses	fast RGE running
stable code basis	automatically generated
few dependencies	requires Mathematica, SARAH, Boost, etc.
G_{μ} input	M_W input

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
  ...
```

Definition der NMSSM-Randbedingungen

```
$ cat models/NMSSM/FlexibleSUSY.m
```

```
FSModelName = "NMSSM";

MINPAR = { {1, m0}, {2, m12}, {3, TanBeta}, {5, Azero} };

EXTPAR = { {61, LambdaInput} };

EWSBOutputParameters = { \[Kappa], vS, ms2 };

SUSYScale = Sqrt[M[Su[1]]*M[Su[6]]];

HighScale = g1 == g2;

HighScaleInput = {
    {mHd2, m0^2}, {mHu2, m0^2}, {mq2, UNITMATRIX[3] m0^2},
    ...
};

LowScale = SM[MZ];

LowScaleInput = { ... };
```

Generated NMSSM spectrum generator C++ code

```
typedef Two_scale T; // or Lattice
NMSSM<T> nmssm;
NMSSM_input_parameters input;
QedQcd qedqcd;

// create BCs
std::vector<Constraint<T>*> constraints = {
    new NMSSM_low_scale_constraint<T>(input, qedqcd),
    new NMSSM_susy_scale_constraint<T>(input),
    new NMSSM_high_scale_constraint<T>(input)
};

// solve RG eqs. with the above BCs
RGFlow<T> solver;
solver.add_model(&nmssm, constraints);
solver.solve();

nmssm.calculate_spectrum();
```

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\mathcal{W}_{\text{MSSM}} = \mu(H_1 H_2) - y_{ij}^e(H_1 L_i)\bar{E}_j - y_{ij}^d(H_1 Q_i)\bar{D}_j - y_{ij}^u(Q_i H_2)\bar{U}_j$$

$$h_1^0 \rightarrow \frac{v_1}{\sqrt{2}} + h_1^0,$$

$$h_2^0 \rightarrow \frac{v_2}{\sqrt{2}} + h_2^0,$$

mSUGRA GUT constraint:

$$(m_{\bar{f}}^2)_{ij}(M_X) = m_0^2 \delta_{ij} \quad (f = q, \ell, u, d, e, h_1, h_2),$$

$$A_{ij}^f(M_X) = A_0, \quad (f = u, d, e),$$

$$M_i(M_X) = M_{1/2} \quad (i = 1, 2, 3).$$

EWSB output: $\mu(M_S), B\mu(M_S)$

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\mathcal{W}_{\text{NMSSM}} = \lambda S(H_1 H_2) - y_{ij}^e(H_1 L_i)\bar{E}_j - y_{ij}^d(H_1 Q_i)\bar{D}_j - y_{ij}^u(Q_i H_2)\bar{U}_j + \frac{\kappa}{3} S^3$$

$$h_1^0 \rightarrow \frac{v_1}{\sqrt{2}} + h_1^0, \quad h_2^0 \rightarrow \frac{v_2}{\sqrt{2}} + h_2^0, \quad s \rightarrow \frac{v_s}{\sqrt{2}} + s$$

mSUGRA-inspired GUT constraint:

$$\begin{aligned} (m_f^2)_{ij}(M_X) &= m_0^2 \delta_{ij} & (f = q, \ell, u, d, e, h_1, h_2), \\ A_{ij}^f(M_X) &= A_0, & (f = u, d, e, \lambda, \kappa), \\ M_i(M_X) &= M_{1/2} & (i = 1, 2, 3). \end{aligned}$$

EWSB output: $\kappa(M_S)$, $v_s(M_S)$, $m_s^2(M_S)$

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$$

$$\mathcal{W}_{\text{USSM}} = \lambda S(H_1 H_2) - y_{ij}^e (H_1 L_i) \bar{E}_j - y_{ij}^d (H_1 Q_i) \bar{D}_j - y_{ij}^u (Q_i H_2) \bar{U}_j$$

$$h_1^0 \rightarrow \frac{v_1}{\sqrt{2}} + h_1^0, \quad h_2^0 \rightarrow \frac{v_2}{\sqrt{2}} + h_2^0, \quad s \rightarrow \frac{v_s}{\sqrt{2}} + s$$

mSUGRA-inspired GUT constraint:

$$\begin{aligned} (m_{\tilde{f}}^2)_{ij}(M_X) &= m_0^2 \delta_{ij} & (f = q, \ell, u, d, e), \\ A_{ij}^f(M_X) &= A_0, & (f = u, d, e, \lambda), \\ M_i(M_X) &= M_{1/2} & (i = 1, 2, 3, 4). \end{aligned}$$

EWSB output: $m_{h_1}^2(M_S), m_{h_2}^2(M_S), m_s^2(M_S)$

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_N$$

$$\begin{aligned} \mathcal{W}_{E_6SSM} = & \lambda_3 \mathcal{S}_3(H_{13}H_{23}) - y_{ij}^e(H_{13}L_i)\bar{E}_j - y_{ij}^d(H_{13}Q_i)\bar{D}_j - y_{ij}^u(Q_iH_{23})\bar{U}_j \\ & + \kappa_{ij} \mathcal{S}_3(X_i\bar{X}_j) + \lambda_{\alpha\beta} \mathcal{S}_3(H_{1\alpha}H_{2\beta}) + \mu'(H'\bar{H}') \end{aligned}$$

$$h_1^0 \rightarrow \frac{v_1}{\sqrt{2}} + h_1^0, \quad h_2^0 \rightarrow \frac{v_2}{\sqrt{2}} + h_2^0, \quad s \rightarrow \frac{v_s}{\sqrt{2}} + s$$

mSUGRA-inspired GUT constraint:

$$\begin{aligned} (m_f^2)_{ij}(M_X) &= m_0^2 \delta_{ij} & (\forall \text{ scalars, except } h_1, h_2, s), \\ A_{ij}^f(M_X) &= A_0, & (f = u, d, e, \lambda, \kappa), \\ M_i(M_X) &= M_{1/2} & (i = 1, 2, 3, 4). \end{aligned}$$

EWSB output: $m_{h_1}^2(M_S), m_{h_2}^2(M_S), m_s^2(M_S)$

Brechung der E_6

het. Stringtheorie: $E_8 \times E'_8$

↓

SUSY-Eichtheorie: $E_6 \rightarrow SO(10) \times U(1)_\psi$

$$\hookrightarrow SU(5) \times U(1)_\chi$$

$$\hookrightarrow SU(3)_c \times \underbrace{SU(2)_L \times U(1)_Y}_{\rightarrow U(1)_{em}}$$

het. Stringtheorie: $SO(32)$

↓

SUSY-Eichtheorie: $SO(10) \times U(1)_\psi$

$$\hookrightarrow SU(5) \times U(1)_\chi$$

$$\hookrightarrow SU(3)_c \times SU(2)_L \times U(1)_Y$$

Brechung der E_6

Zerlegung der E_6 bezüglich $SO(10) \times U(1)_\psi$:

$$(27)_{E_6} \rightarrow (\mathbf{16}, 1) + (\mathbf{10}, -2) + (\mathbf{1}, 4)$$

$$(78)_{E_6} \rightarrow (\mathbf{45}, 0) + (\mathbf{16}, -3) + (\overline{\mathbf{16}}, 3) + (\mathbf{1}, 0)$$


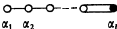
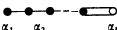
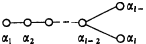



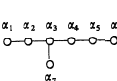
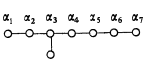
Zerlegung der $SO(10)$ bezüglich $SU(5) \times U(1)_\chi$:

$$(\mathbf{10})_{SO(10)} \rightarrow (\mathbf{5}, -2) + (\overline{\mathbf{5}}, 2)$$

$$(\mathbf{45})_{SO(10)} \rightarrow (\mathbf{24}, 0) + (\mathbf{10}, -4) + (\overline{\mathbf{10}}, 4) + (\mathbf{1}, 0)$$

$$(\mathbf{16})_{SO(10)} \rightarrow (\mathbf{10}, 1) + (\overline{\mathbf{5}}, -3) + (\mathbf{1}, 5)$$

Dynkin-Diagramme halbeinfacher Lie-Algebren

Order	Cartan's Notation	Group	Dynkin Diagram	Solutions
$l(l+2)$	A_l	$SU(l+1)$		$e_i - e_j (i, j = 1, \dots, l+1)$
$l(2l+1)$ $l \geq 2$	B_l	$SO(2l+1)$		$\pm e_i$ and $\pm e_i \pm e_j (i, j = 1, \dots, l)$
$l(2l+1)$ $l \geq 3$	C_l	$Sp(2l)$		$\pm 2e_i$ and $\pm e_i \pm e_j (i, j = 1, \dots, l)$
$l(2l-1)$ $l \geq 4$	D_l	$SO(2l)$		$\pm e_i \pm e_j (i, j = 1, \dots, l)$
14	G_2	G_2		$e_i - e_j (i, j = 1, 2, 3; i \neq j)$ $\pm 2e_i \mp e_j \mp e_k (i, j, k = 1, 2, 3, i \neq j \neq k)$
52	F_4	F_4		As for B_4 plus the 16 solutions $\frac{1}{2}(\pm e_1 \pm e_2 \pm e_3 \pm e_4)$
78	E_6	E_6		As for A_5 plus solutions $\pm \sqrt{2}e_7$ and $\frac{1}{2}(\pm e_1 \pm e_2 \pm e_3 \pm e_4 \pm e_5 \pm e_6) \pm e_7/\sqrt{2}$ (an arbitrary choice of 3 "+" and 3 "-" signs for the terms in parentheses)
133	E_7	E_7		As for A_6 plus the solutions $\frac{1}{2}(\pm e_1 \pm e_2 \pm e_3 \pm e_4 \pm e_5 \pm e_6 \pm e_7 \pm e_8)$ (an arbitrary choice of 4 "+" and 4 "-" signs for the terms in parentheses)
248	E_8	E_8		As for D_8 plus the solutions $\frac{1}{2}(\pm e_1 \pm e_2 \pm e_3 \pm e_4 \pm e_5 \pm e_6 \pm e_7 \pm e_8)$ with an even number of plus signs.

$$U(1) \subset SU(2) \subset SU(3) \subset SU(4) \subset SU(5) \subset SO(10) \subset E_6 \subset E_7 \subset E_8$$

E₆SSM EWSB-Gleichungen (tree-level)

$$0 = \frac{\partial V}{\partial v_1} = m_{h_{13}}^2 v_1 - \frac{\lambda_3 A_{\lambda_3}}{\sqrt{2}} v_s v_2 + \frac{\lambda_3^2}{2} (v_2^2 + v_s^2) v_1 + \frac{\bar{g}^2}{8} (v_1^2 - v_2^2) v_1$$
$$+ \frac{g_N^2}{2} \left(\frac{N_{H_{13}}}{2} v_1^2 + \frac{N_{H_{23}}}{2} v_2^2 + \frac{N_{S_3}}{2} v_s^2 \right) \frac{N_{H_{13}}}{2} v_1$$

$$0 = \frac{\partial V}{\partial v_2} = m_{h_{23}}^2 v_2 - \frac{\lambda_3 A_{\lambda_3}}{\sqrt{2}} v_s v_1 + \frac{\lambda_3^2}{2} (v_1^2 + v_s^2) v_2 + \frac{\bar{g}^2}{8} (v_2^2 - v_1^2) v_2$$
$$+ \frac{g_N^2}{2} \left(\frac{N_{H_{13}}}{2} v_1^2 + \frac{N_{H_{23}}}{2} v_2^2 + \frac{N_{S_3}}{2} v_s^2 \right) \frac{N_{H_{23}}}{2} v_2$$

$$0 = \frac{\partial V}{\partial v_s} = m_{s_3}^2 v_s - \frac{\lambda_3 A_{\lambda_3}}{\sqrt{2}} v_1 v_2 + \frac{\lambda_3^2}{2} (v_1^2 + v_2^2) v_s$$
$$+ \frac{g_N^2}{2} \left(\frac{N_{H_{13}}}{2} v_1^2 + \frac{N_{H_{23}}}{2} v_2^2 + \frac{N_{S_3}}{2} v_s^2 \right) \frac{N_{S_3}}{2} v_s$$

mit $\bar{g}^2 = g_Y^2 + g_2^2$

Gravity Mediated SUSY Breaking (PMSB)

Superpotential includes effective gravitational interactions:

$$\mathcal{W} = \mathcal{W}_{\text{MSSM}} - \frac{1}{M_{\text{Pl}}} \left[y^{Xijk} X \Phi_i \Phi_j \Phi_k + \mu^{Xij} X \Phi_i \Phi_j + \dots \right]$$
$$K = \Phi_i^\dagger \Phi_i + \frac{1}{M_{\text{Pl}}} \left[n^{ij} X + \bar{n}^{ij} X^\dagger \right] \Phi_i^\dagger \Phi_j - \frac{1}{M_{\text{Pl}}^2} k^{ij} X X^\dagger \Phi_i^\dagger \Phi_j$$

X and X^\dagger break SUSY via an F -term VEV:

$$X \rightarrow \theta \theta \langle F \rangle \qquad X^\dagger \rightarrow \bar{\theta} \bar{\theta} \langle F \rangle^*$$

Integrate X out \Rightarrow

$$-\mathcal{L}_{\text{soft}} = \frac{\langle F \rangle}{M_{\text{Pl}}} \left[f_A \lambda^A \lambda^A + g^{ijk} \phi_i \phi_j \phi_k + h^{ij} \phi_i \phi_j + k^i \phi_i + \text{h.c.} \right]$$
$$+ \frac{|\langle F \rangle|^2}{M_{\text{Pl}}^2} m^{ij} \phi_i^* \phi_j$$

Gauge Mediated SUSY Breaking (GMSB)

Messenger Superfields transform under $SU(3)_c \times SU(2)_L \times U(1)_Y$:

$$Q = (\mathbf{3}, \mathbf{1}, -1/3), \quad \ell = (\mathbf{1}, \mathbf{2}, 1/2), \quad \bar{Q}, \quad \bar{\ell}$$

Coupled to a gauge singlet S in the messenger sector:

$$\mathcal{W}_{\text{mess}} = y_2 S \ell \bar{\ell} + y_3 S Q \bar{Q}$$

Scalar and F -component of S get VEVs $\langle S \rangle$ and $\langle F_S \rangle$

\Rightarrow SUSY broken in messenger sector

SUSY breaking is communicated to the MSSM via loop diagrams:

$$\bar{B}, \bar{W}, \bar{g} \sim \frac{g_i^2}{(4\pi)^2} \frac{\langle F_S \rangle}{\langle S \rangle} \lambda_i \lambda_i$$

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

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

	Model	$\epsilon, \mu, \tau, \gamma$	Jets	E_{miss}^T	$\int \mathcal{L} d\tau [fb^{-1}]$	Mass limit		Reference	
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	#	1.7 TeV	$m(\tilde{g})=m(\tilde{t})$	1405.7875
	MSUGRA/CMSSM	1 ϵ, μ	3-6 jets	Yes	20.3	#	1.2 TeV	any $m(\tilde{g})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	#	1.1 TeV	any $m(\tilde{g})$	1308.1841
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}\tilde{q} \rightarrow \tilde{g}W^+W^-\tilde{t}$	0	2-6 jets	Yes	20.3	#	850 GeV	$m(\tilde{t}_1^0)=0 \text{ GeV}, m(\tilde{t}_2^0)=m(\tilde{g}), m(\tilde{q})=m(\tilde{q}^c)$	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}\tilde{q} \rightarrow \tilde{g}W^+W^-\tilde{t}$	0	2-6 jets	Yes	20.3	#	1.33 TeV	$m(\tilde{t}_1^0)=0 \text{ GeV}$	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}\tilde{q} \rightarrow \tilde{g}W^+W^-\tilde{t}$	1 ϵ, μ	3-6 jets	Yes	20.3	#	1.18 TeV	$m(\tilde{t}_1^0)=200 \text{ GeV}, m(\tilde{t}_2^0)=0.5(m(\tilde{t}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}\tilde{q} \rightarrow \tilde{g}W^+W^-\tilde{t}$	2 ϵ, μ	0-3 jets	Yes	20.3	#	1.12 TeV	$m(\tilde{t}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2013-089
	GMSB (\tilde{t} NLSP)	2 ϵ, μ	2-4 jets	Yes	4.7	#	1.24 TeV	$\tan\beta=15$	1208.4688
	GMSB (\tilde{t} NLSP)	1.2 $\tau, \mu + 0.1 \tilde{t}$	0-2 jets	Yes	20.3	#	1.6 TeV	$\tan\beta > 20$	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	#	1.28 TeV	$m(\tilde{t}_1^0)=50 \text{ GeV}$	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $\epsilon, \mu + \gamma$	-	Yes	4.8	#	619 GeV	$m(\tilde{t}_1^0)=50 \text{ GeV}$	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	0	γ	1-3 jets	Yes	4.8	900 GeV	$m(\tilde{t}_1^0)=220 \text{ GeV}$	1211.1167
GGM (higgsino NLSP)	2 ϵ, μ (Z)	0-3 jets	Yes	4.8	#	690 GeV	$m(\text{NLSP})=200 \text{ GeV}$	ATLAS-CONF-2012-152	
Gravitino LSP	0	mono-jet	Yes	10.5	#	645 GeV	$m(\tilde{t}_1^0)=10^{-1} \text{ eV}$	ATLAS-CONF-2012-147	
3rd gen. \tilde{t} med.	$\tilde{g}\tilde{g}, \tilde{g}\tilde{t}_1^0$	0	3-6 jets	Yes	20.3	#	1.25 TeV	$m(\tilde{t}_1^0)=400 \text{ GeV}$	1407.0600
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{t}_1^0$	0	7-10 jets	Yes	20.3	#	1.1 TeV	$m(\tilde{t}_1^0) < 350 \text{ GeV}$	1308.1841
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{t}_1^0$	0-1 ϵ, μ	3-6 jets	Yes	20.1	#	1.34 TeV	$m(\tilde{t}_1^0) < 400 \text{ GeV}$	1407.0600
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{t}_1^0$	0-1 ϵ, μ	3-6 jets	Yes	20.1	#	1.3 TeV	$m(\tilde{t}_1^0) < 300 \text{ GeV}$	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\tilde{t}_1^0, \tilde{b}_1\tilde{t}_1^0$	0	2 b	Yes	20.1	\tilde{b}_1	100-620 GeV	$m(\tilde{t}_1^0)=90 \text{ GeV}$	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\tilde{t}_1^0, \tilde{b}_1\tilde{t}_1^0$	2 ϵ, μ (SS)	0-3 b	Yes	20.3	\tilde{b}_1	275-440 GeV	$m(\tilde{t}_1^0)=2 m(\tilde{t})$	1404.2500
	$\tilde{t}_1^0\tilde{t}_1^0$ (light), $\tilde{t}_1^0\tilde{t}_1^0 \rightarrow W\tilde{b}_1^0$	1-2 ϵ, μ	1-2 b	Yes	4.7	\tilde{t}_1^0	110-167 GeV	$m(\tilde{t}_1^0)=55 \text{ GeV}$	1208.4305, 1209.2102
	$\tilde{t}_1^0\tilde{t}_1^0$ (medium), $\tilde{t}_1^0\tilde{t}_1^0 \rightarrow W\tilde{b}_1^0$	2 ϵ, μ	0-2 jets	Yes	20.3	\tilde{t}_1^0	130-210 GeV	$m(\tilde{t}_1^0)=m(\tilde{g}), m(\tilde{W})=50 \text{ GeV}, m(\tilde{b}_1^0) < m(\tilde{t}_1^0)$	1403.4853
	$\tilde{t}_1^0\tilde{t}_1^0$ (heavy), $\tilde{t}_1^0\tilde{t}_1^0 \rightarrow W\tilde{b}_1^0$	2 ϵ, μ	2 jets	Yes	20.3	\tilde{t}_1^0	215-530 GeV	$m(\tilde{t}_1^0)=1 \text{ GeV}$	1403.4853
	$\tilde{t}_1^0\tilde{t}_1^0$ (heavy), $\tilde{t}_1^0\tilde{t}_1^0 \rightarrow W\tilde{b}_1^0$	1 ϵ, μ	1 b	Yes	20.1	\tilde{t}_1^0	150-580 GeV	$m(\tilde{t}_1^0)=200 \text{ GeV}, m(\tilde{t}_1^0)=m(\tilde{g})+5 \text{ GeV}$	1308.2631
	$\tilde{t}_1^0\tilde{t}_1^0$ (heavy), $\tilde{t}_1^0\tilde{t}_1^0 \rightarrow W\tilde{b}_1^0$	0	2 b	Yes	20.3	\tilde{t}_1^0	210-640 GeV	$m(\tilde{t}_1^0)=0 \text{ GeV}$	1407.0583
	$\tilde{t}_1^0\tilde{t}_1^0, \tilde{t}_1^0\tilde{t}_1^0$	0	2 b	Yes	20.1	\tilde{t}_1^0	250-640 GeV	$m(\tilde{t}_1^0)=0 \text{ GeV}$	1406.1122
	$\tilde{t}_1^0\tilde{t}_1^0, \tilde{t}_1^0\tilde{t}_1^0$	0	mono-jet+tag	Yes	20.3	\tilde{t}_1^0	90-240 GeV	$m(\tilde{t}_1^0)=m(\tilde{t}_2^0)=85 \text{ GeV}$	1407.0606
	$\tilde{t}_1^0\tilde{t}_1^0$ (natural GMSB)	2 ϵ, μ (Z)	1 b	Yes	20.3	\tilde{t}_1^0	150-580 GeV	$m(\tilde{t}_1^0)=150 \text{ GeV}$	1403.5232
	$\tilde{t}_2^0\tilde{t}_2^0, \tilde{t}_2^0\tilde{t}_2^0 + Z$	3 ϵ, μ (Z)	1 b	Yes	20.3	\tilde{t}_2^0	290-600 GeV	$m(\tilde{t}_1^0)=200 \text{ GeV}$	1403.5232
	EW direct	$\tilde{t}_1^0\tilde{t}_1^0, \tilde{t}_1^0\tilde{t}_1^0, \tilde{t}_1^0\tilde{t}_1^0$	2 ϵ, μ	0	Yes	20.3	\tilde{t}_1^0	90-325 GeV	$m(\tilde{t}_1^0)=0 \text{ GeV}$
$\tilde{t}_1^0\tilde{t}_1^0, \tilde{t}_1^0\tilde{t}_1^0, \tilde{t}_1^0\tilde{t}_1^0$		2 ϵ, μ	0	Yes	20.3	\tilde{t}_1^0	140-405 GeV	$m(\tilde{t}_1^0)=0 \text{ GeV}, m(\tilde{t}_2^0)=0.5(m(\tilde{t}_1^0)+m(\tilde{t}_2^0))$	1403.5294
$\tilde{t}_1^0\tilde{t}_1^0, \tilde{t}_1^0\tilde{t}_1^0 \rightarrow \tilde{t}_1^0\tilde{t}_1^0$		2 τ	-	Yes	20.3	\tilde{t}_1^0	100-350 GeV	$m(\tilde{t}_1^0)=0 \text{ GeV}, m(\tilde{t}_2^0)=0.5(m(\tilde{t}_1^0)+m(\tilde{t}_2^0))$	1407.0350
$\tilde{t}_1^0\tilde{t}_1^0, \tilde{t}_1^0\tilde{t}_1^0 \rightarrow \tilde{t}_1^0\tilde{t}_1^0$		3 ϵ, μ	0	Yes	20.3	$\tilde{t}_1^0, \tilde{t}_2^0$	700 GeV	$m(\tilde{t}_1^0)=m(\tilde{t}_2^0), m(\tilde{t}_1^0)=0, m(\tilde{t}_2^0)=0.5(m(\tilde{t}_1^0)+m(\tilde{t}_2^0))$	1402.7029
$\tilde{t}_1^0\tilde{t}_1^0, \tilde{t}_1^0\tilde{t}_1^0 \rightarrow W\tilde{b}_1^0, Z\tilde{b}_1^0$		2-3 ϵ, μ	0	Yes	20.3	$\tilde{t}_1^0, \tilde{t}_2^0$	420 GeV	$m(\tilde{t}_1^0)=m(\tilde{t}_2^0), m(\tilde{t}_1^0)=0, \text{ sleptons decoupled}$	1403.5294, 1402.7029
$\tilde{t}_1^0\tilde{t}_1^0, \tilde{t}_1^0\tilde{t}_1^0 \rightarrow W\tilde{b}_1^0, Z\tilde{b}_1^0$		1 ϵ, μ	2 b	Yes	20.3	$\tilde{t}_1^0, \tilde{t}_2^0$	285 GeV	$m(\tilde{t}_1^0)=m(\tilde{t}_2^0), m(\tilde{t}_1^0)=0, \text{ sleptons decoupled}$	ATLAS-CONF-2013-093
$\tilde{t}_1^0\tilde{t}_1^0, \tilde{t}_1^0\tilde{t}_1^0 \rightarrow W\tilde{b}_1^0, Z\tilde{b}_1^0$	4 ϵ, μ	0	Yes	20.3	$\tilde{t}_1^0, \tilde{t}_2^0$	620 GeV	$m(\tilde{t}_1^0)=m(\tilde{t}_2^0), m(\tilde{t}_1^0)=0, m(\tilde{t}_2^0)=0.5(m(\tilde{t}_1^0)+m(\tilde{t}_2^0))$	1405.5086	
Long-lived particles	Direct $\tilde{t}_1^0\tilde{t}_1^0$ prod., long-lived \tilde{t}_1^0	Disapp. trk	1 jet	Yes	20.3	\tilde{t}_1^0	270 GeV	$m(\tilde{t}_1^0)=m(\tilde{t}_2^0)=160 \text{ MeV}, \tau(\tilde{t}_1^0)=0.2 \text{ ns}$	ATLAS-CONF-2013-069
	Stable, stopped \tilde{t}_1^0 R-hadron	0	1-5 jets	Yes	27.9	\tilde{t}_1^0	832 GeV	$m(\tilde{t}_1^0)=10 \text{ GeV}, 10 \mu\text{sec} < \tau < 1000 \text{ s}$	1310.6584
	GMSB, stable $\tilde{t}_1^0, \tilde{t}_1^0 \rightarrow \tilde{t}_1^0, \tilde{b}_1^0 + \nu(\epsilon, \mu)$	1-2 μ	-	Yes	15.9	\tilde{t}_1^0	475 GeV	10-tagged-50	ATLAS-CONF-2013-058
	GMSB, $\tilde{t}_1^0 \rightarrow \tilde{G}$, long-lived \tilde{t}_1^0	2 γ	-	Yes	4.7	\tilde{t}_1^0	230 GeV	$0.4 < \tau < 156 \text{ nm}, \text{BR}(\tilde{t}_1^0 \rightarrow \tilde{t}_1^0)=108 \text{ GeV}$	1304.8910
$\tilde{g}\tilde{g}, \tilde{g}\tilde{g} \rightarrow \tilde{g}W^+W^-\tilde{t}$	1 μ , displ. vtx	-	-	20.3	\tilde{t}_1^0	1.0 TeV	-	ATLAS-CONF-2013-092	
RPV	LFV $\tilde{p}\tilde{p} \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e\mu + \tau$	2 ϵ, μ	-	-	4.6	$\tilde{\nu}_e$	1.61 TeV	$A_{111}=0.10, A_{120}=0.05$	1212.1272
	LFV $\tilde{p}\tilde{p} \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e\mu + \tau$	1 $\epsilon, \mu + \tau$	-	-	4.6	$\tilde{\nu}_e$	1.1 TeV	$A_{111}=0.10, A_{120}=0.05$	1212.1272
	Bilinear RPV CMSSM	2 ϵ, μ (SS)	0-3 b	Yes	20.3	\tilde{g}, \tilde{t}_1^0	1.35 TeV	$m(\tilde{g})=m(\tilde{t}_1^0), \tau_{RPV} < 1 \text{ nm}$	1404.2500
	$\tilde{t}_1^0\tilde{t}_1^0, \tilde{t}_1^0\tilde{t}_1^0 \rightarrow W\tilde{b}_1^0, Z\tilde{b}_1^0$	0 ϵ, μ	-	Yes	20.3	\tilde{t}_1^0	750 GeV	$m(\tilde{t}_1^0)=0.2 m(\tilde{t}_2^0), \tilde{t}_1^0, \tilde{t}_2^0=0$	1405.5086
	$\tilde{t}_1^0\tilde{t}_1^0, \tilde{t}_1^0\tilde{t}_1^0 \rightarrow W\tilde{b}_1^0, Z\tilde{b}_1^0$	3 $\epsilon, \mu + \tau$	-	Yes	20.3	\tilde{t}_1^0	450 GeV	$m(\tilde{t}_1^0)=2.2 m(\tilde{t}_2^0), \tilde{t}_1^0, \tilde{t}_2^0=0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\tilde{g}$	0	6-7 jets	Yes	20.3	\tilde{t}_1^0	916 GeV	$\text{BR}(\tilde{t}_1^0 \rightarrow \tilde{b}_1^0) = \text{BR}(\tilde{t}_1^0 \rightarrow \tilde{c}_1^0) = 50\%$	ATLAS-CONF-2013-091
$\tilde{g}\tilde{g}, \tilde{g}\tilde{g}$	2 ϵ, μ (SS)	0-3 b	Yes	20.3	\tilde{t}_1^0	890 GeV	-	1404.2500	
Other	Scalar gluon pair, sgluon $\rightarrow \tilde{q}\tilde{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon $\rightarrow \tilde{t}\tilde{t}$	2 ϵ, μ (SS)	2 b	Yes	14.3	sgluon	350-600 GeV	-	ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	\tilde{M}^{SUSY}	704 GeV	$m(\tilde{t}_1^0)=80 \text{ GeV}, \text{limit of } \tilde{c}\tilde{c} \text{ for D8}$	ATLAS-CONF-2012-147

$\sqrt{s} = 7 \text{ TeV}$ full data partial data $\sqrt{s} = 8 \text{ TeV}$ full data

10⁻¹ 1 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncertainty.

