Mass spectrum prediction in non-minimal supersymmetric models

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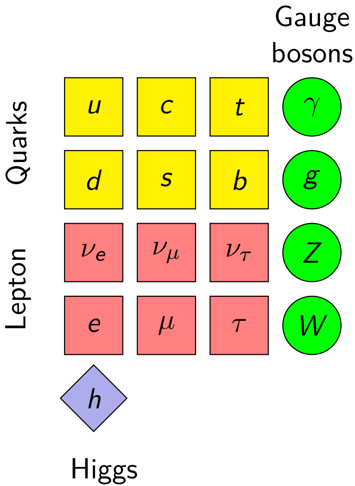
Contents

The Standard Modell of particle physics



Describes

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

Problems:

- no gravitation
- no dark matter

Weaknesses:

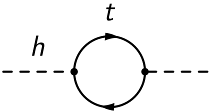
- no unification of gauge couplings
- hierarchy problem
- prediction of $(g-2)_\mu$

Hierarchy problem

Higgs pole mass:

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

$\Delta m_h^2 \;=$

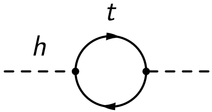


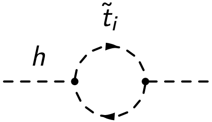
$\overset{p \ll m_t}{\sim} \; -m_t^2 \left(1 - \log \frac{m_t^2}{\mu^2}\right)$ large!

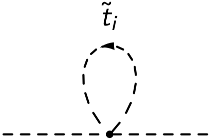
Hierarchy problem

Higgs pole mass:

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

$\Delta m_h^2 =$ 

$+$ 

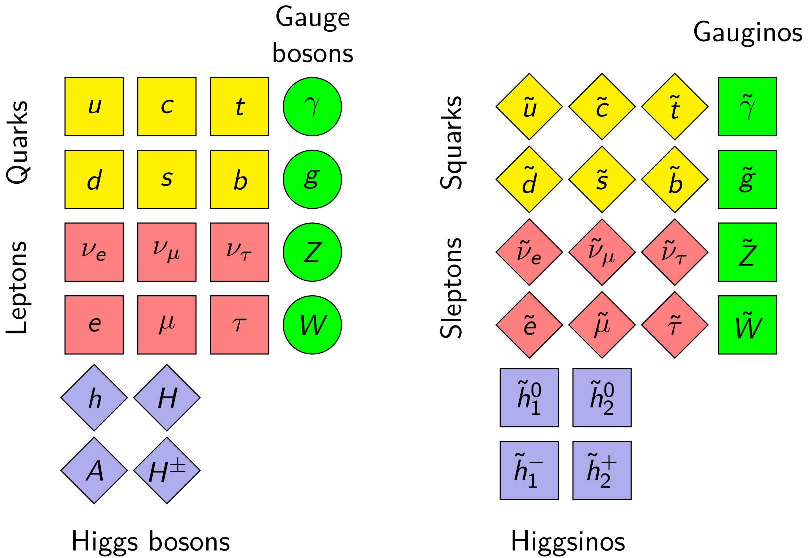
$+$ 

$= 0$

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 Modell (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)

$$\mathcal{W}_{\text{MSSM}} = \mu(H_1 H_2) - y^e_{ij}(H_1 L_i)\bar{E}_j - y^d_{ij}(H_1 Q_i)\bar{D}_j - y^u_{ij}(Q_i H_2)\bar{U}_j$$

Breaking of Supersymmetry

Soft breaking of supersymmetry

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

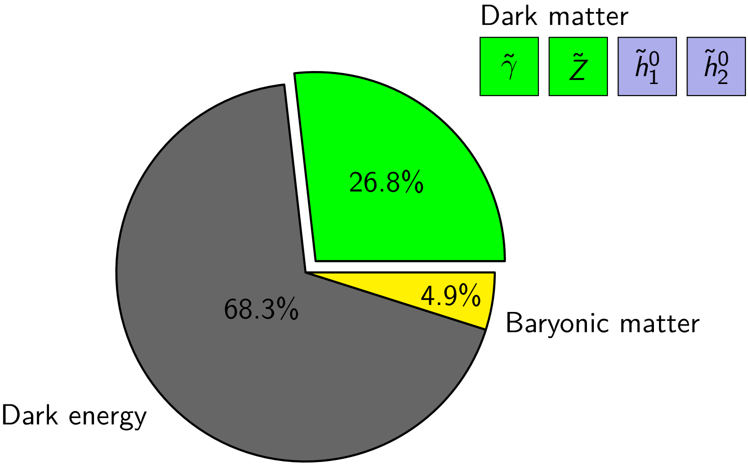
$\Rightarrow$

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

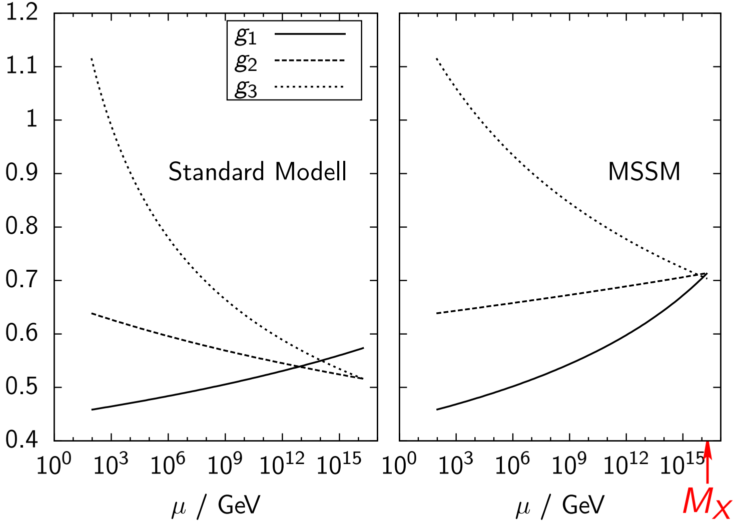
mSUGRA constraint:

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

Advantage of the MSSM: Dark Matter Candidate



Advantage of the MSSM: Gauge Coupling Unification



Weakness of the MSSM: Fine-tuning problem

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

$$\begin{aligned} m_h^{\text{pole}} &\approx 125\,\text{GeV} \\ m_Z &\approx 91\,\text{GeV} \\ \Rightarrow \Delta m_h &\gtrsim 87\,\text{GeV} \end{aligned}$$

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

⇒ large SUSY breaking terms

⇒ spoils SUSY's solution to hierarchy problem

Weakness of the MSSM: μ-Problem

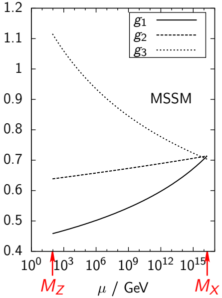
$$\mathcal{W}_{\text{MSSM}} = \mu(H_1 H_2) + \cdots$$

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	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$SU(5)$
$Q_i = (Q_{u_i} \;\; Q_{d_i})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})_i$	$(\mathbf{10})_i$
$\bar{U}_i$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})_i$	
$\bar{E}_i$	$(\mathbf{1}, \mathbf{1}, 1)_i$	
$\bar{D}_i$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})_i$	$(\bar{\mathbf{5}})_i$
$L_i = (L_{\nu_i} \;\; L_{e_i})$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})_i$	
	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$	$(\bar{\mathbf{5}})$
$H_1 = (H_1^0 \;\; H_1^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	
	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$	$(\mathbf{5})$
$H_2 = (H_2^+ \;\; H_2^0)$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	
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)

$$\mathcal{W}_{\mathrm{MSSM}+S} = \lambda S(H_1 H_2) + \frac{\kappa}{3}S^3 + \frac{\mu'}{2}S^2 + \xi_F S$$
$$+ \mu(H_1 H_2) - y^e_{ij}(H_1 L_i)\bar{E}_j - y^d_{ij}(H_1 Q_i)\bar{D}_j - y^u_{ij}(Q_i H_2)\bar{U}_j$$

Next-to-MSSM (NMSSM)

$$\mathcal{W}_{\mathrm{MSSM}+S} = \lambda S(H_1 H_2) + \frac{\kappa}{3} S^3 + \frac{\mu'}{2} S^2 + \xi_F S$$
$$+ \mu(H_1 H_2) - y^e_{ij}(H_1 L_i)\bar{E}_j - y^d_{ij}(H_1 Q_i)\bar{D}_j - y^u_{ij}(Q_i H_2)\bar{U}_j$$

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

$$\mathcal{W}_{\mathrm{NMSSM}} = \lambda S(H_1 H_2) + \frac{\kappa}{3} S^3$$
$$- y^e_{ij}(H_1 L_i)\bar{E}_j - y^d_{ij}(H_1 Q_i)\bar{D}_j - y^u_{ij}(Q_i H_2)\bar{U}_j$$

Advantage of the NMSSM: Reduced m_h Fine-tuning

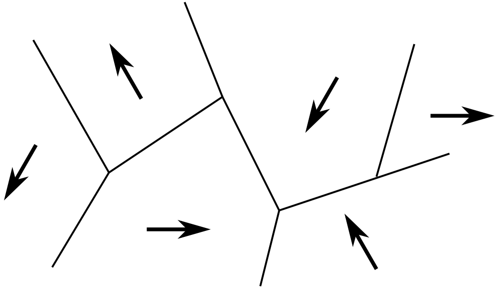
$$(m_h^{\text{pole}})^2 \approx \underbrace{\underbrace{m_Z^2 \cos^2 2\beta}_{\text{MSSM}} + \frac{\lambda^2 v^2}{2} \sin^2 2\beta}_{\text{NMSSM}} + \Delta m_h^2$$

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

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	$G_{\mathrm{SM}} \times U(1)'$	$SU(5) \times U(1)'$
$Q_i = (Q_{u_i} \quad Q_{d_i})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6}, N_Q)_i$	
$\bar{U}_i$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}, N_U)_i$	$(\mathbf{10}, N_{10})_i$
$\bar{E}_i$	$(\mathbf{1}, \mathbf{1}, 1, N_E)_i$	
$\bar{D}_i$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}, N_D)_i$	$(\bar{\mathbf{5}}, N_{\bar{5}})_i$
$L_i = (L_{\nu_i} \quad L_{e_i})$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, N_L)_i$	
	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}, N_X)$	$(\bar{\mathbf{5}}, N_{\bar{5}})$
$H_1 = (H_1^0 \quad H_1^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, N_{H_1})$	
	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3}, N_X)$	$(\mathbf{5}, N_5)$
$H_2 = (H_2^+ \quad H_2^0)$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2}, N_{H_2})$	
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

$$\mathcal{W}_{\text{USSM}} = \lambda S(H_1 H_2) - y^e_{ij}(H_1 L_i)\bar{E}_j - y^d_{ij}(H_1 Q_i)\bar{D}_j - y^u_{ij}(Q_i H_2)\bar{U}_j$$

Advantage of the USSM: Reduced m_h Fine-tuning

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

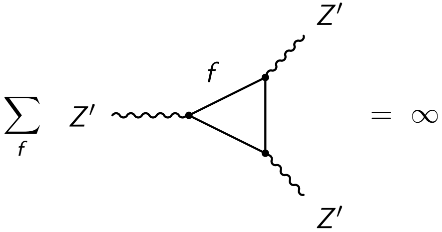
$$(m_h^{\text{tree}})^2 \approx \underbrace{\underbrace{\underbrace{m_Z^2 \cos^2 2\beta}_{\text{MSSM}} + \frac{\lambda^2 v^2}{2} \sin^2 2\beta}_{\text{NMSSM}} + \frac{m_Z^2}{4}\left(1 + \frac{1}{4}\cos 2\beta\right)^2}_{\text{USSM}}$$

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

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:



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

$\Rightarrow$ Exceptional Supersymmetric Standard Modell (E_6SSM)

Exceptional Supersymmetric Standard Modell (E_6SSM)

Field	$G_{SM} \times U(1)_N$	$SU(5) \times U(1)_N$	E_6
$Q_i = (Q_{u_i} \quad Q_{d_i})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6}, 1)_i$	$(\mathbf{10}, 1)_i$	$(\mathbf{27})_i$
$\bar{U}_i$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}, 1)_i$		
$\bar{E}_i$	$(\mathbf{1}, \mathbf{1}, 1, 1)_i$		
$\bar{D}_i$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}, 2)_i$	$(\bar{\mathbf{5}}, 2)_i$	
$L_i = (L_{\nu_i} \quad L_{e_i})$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 2)_i$		
$\bar{X}_i$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}, -3)_i$	$(\bar{\mathbf{5}}, -3)_i$	
$H_{1i} = (H^0_{1i} \quad H^-_{1i})$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, -3)_i$		
X_i	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3}, -2)_i$	$(\mathbf{5}, -2)_i$	
$H_{2i} = (H^+_{2i} \quad H^0_{2i})$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2}, -2)_i$		
S_i	$(\mathbf{1}, \mathbf{1}, 0, 5)_i$	$(\mathbf{1}, 5)_i$	
$\bar{N}_i$	$(\mathbf{1}, \mathbf{1}, 0, 0)_i$	$(\mathbf{1}, 0)_i$	
$H' = (H'^0 \quad H'^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 2)$	$\ni (\bar{\mathbf{5}}, 2)'$	$\ni (\mathbf{27})'$
$\bar{H}' = (\bar{H}'^+ \quad \bar{H}'^0)$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2}, -2)$	$\ni (\mathbf{5}, -2)'$	$\ni (\overline{\mathbf{27}})'$
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 (E_6SSM)

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

Summary Supersymmetry

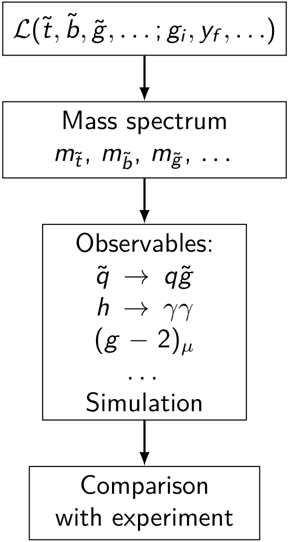
Supersymmetric Modells are attractive extensions of the SM.

Advantages:

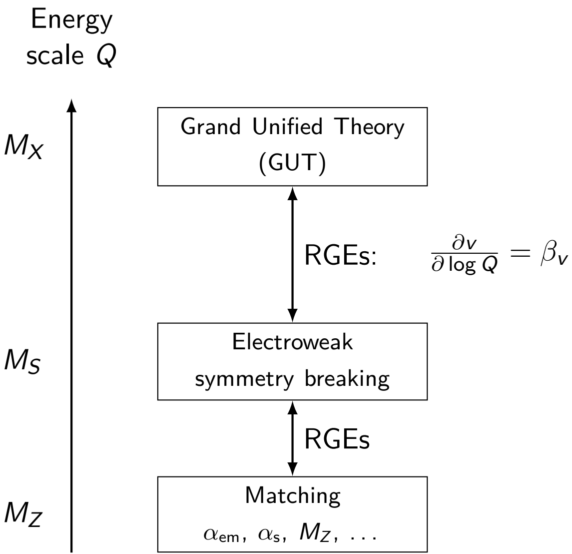
- Solution of the hierarchy problem
- Dark matter candidate particles
- Gauge coupling unification
- Correct prediction of $(g-2)_\mu$
- Closer connection to supergravity models

Contents

Why calculate the mass spectrum?



Physical problem statement



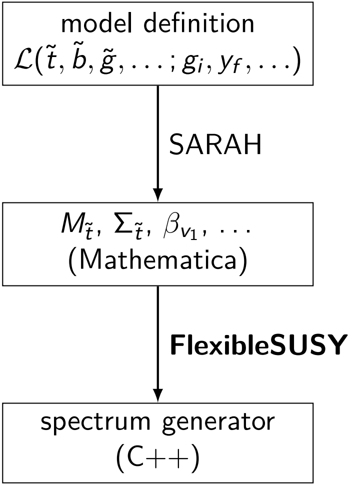
Publicly available SUSY spectrum generators

Model	spectrum generator
MSSM	ISASUSY, SOFTSUSY, SPheno, SuSeFlav, SuSpect
NMSSM	NMSPEC, SOFTSUSY
USSM	–
CE_6SSM	CE6SSMSpecGen
any SUSY-Modell	SARAH, **FlexibleSUSY**

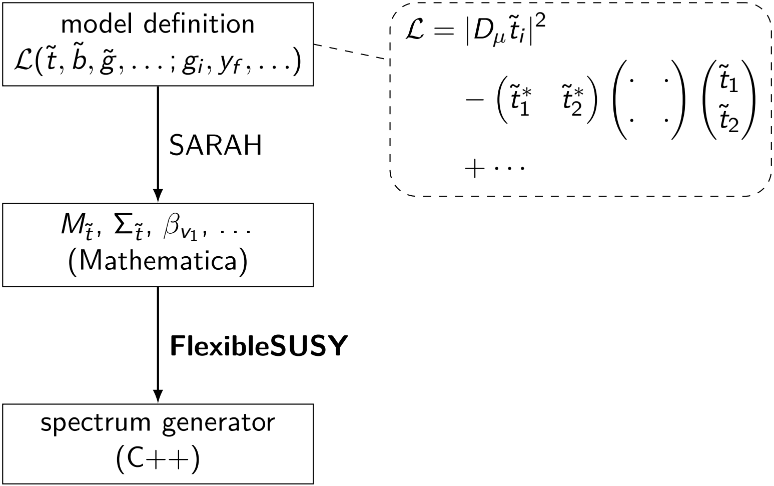
FlexibleSUSY: a SUSY spectrum generator generator

FlexibleSUSY

How a spectrum generator is generated



How a spectrum generator is generated



How a spectrum generator is generated

model definition
$\mathcal{L}(\tilde{t}, \tilde{b}, \tilde{g}, \ldots; g_i, y_f, \ldots)$

↓ SARAH

$M_{\tilde{t}}$, $\Sigma_{\tilde{t}}$, β_{v_1}, ...
(Mathematica)

↓ **FlexibleSUSY**

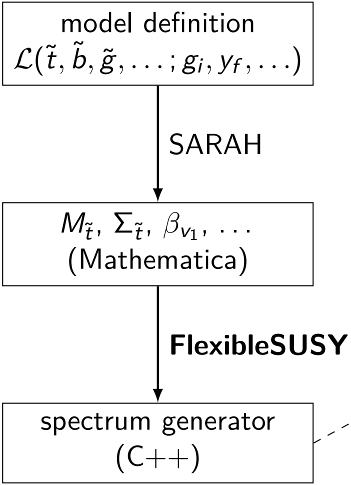
spectrum generator
(C++)

$$M_{\tilde{t}} = \begin{pmatrix} \cdot & \cdot \\ \cdot & \cdot \end{pmatrix}$$

$\Sigma_{\tilde{t}} =$  $+ \cdots$

$$\beta_{v_1} = \frac{v_1}{16\pi^2}\left(\frac{3}{10}g_1^2 + \frac{3}{2}g_2^2\right) + \cdots$$

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

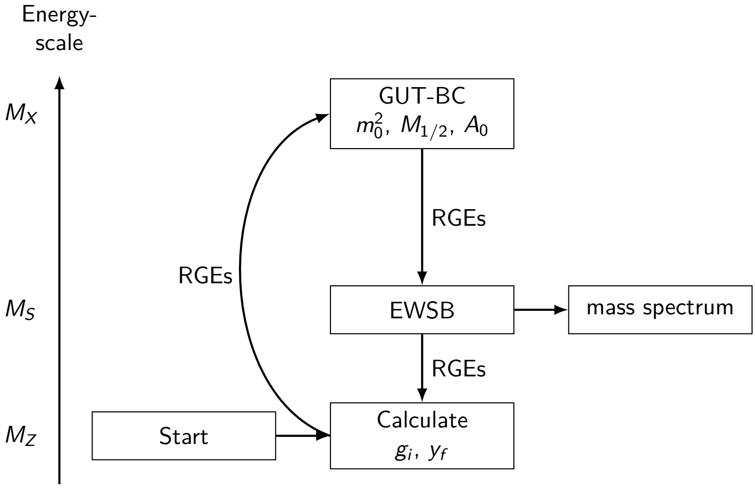
- **Modular, well readable C++ code**
  Reason: large variety of SUSY models
  $\rightarrow$ User intervention likely

- **High precision**
  Reason: Higgs mass measurement with $\sigma \approx 0.4\,\text{GeV}$
  (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, ...)

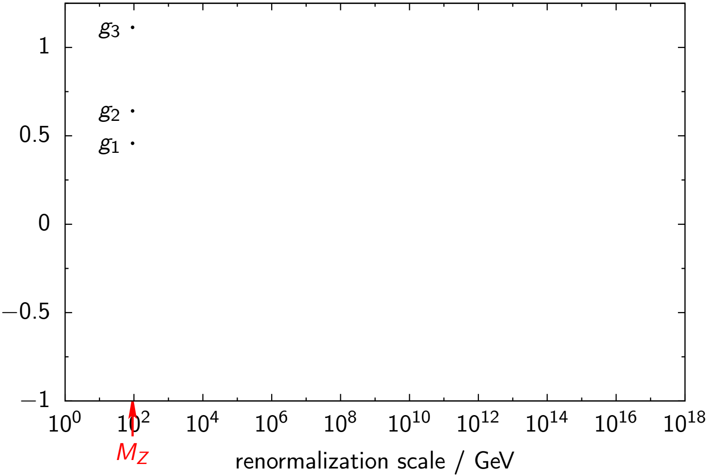
- **High speed**
  Reason: many model parameters
  (C++ expression templates, multi-threading)

Algorithm to calculate the mass spectrum



Algorithm to calculate the mass spectrum

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



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

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

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

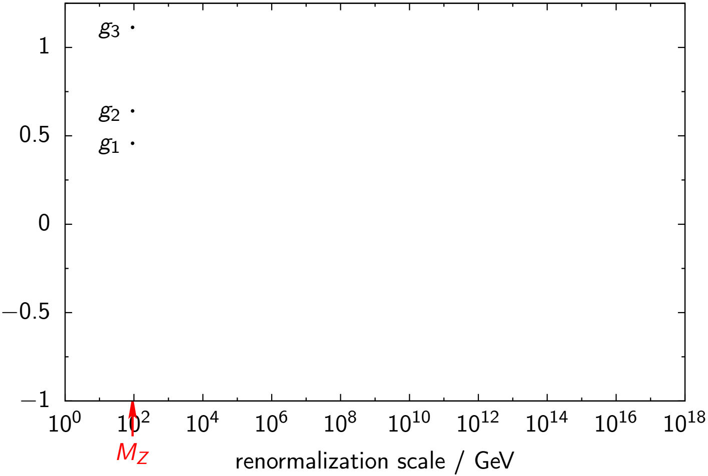
$$\Delta\alpha_{\text{s}}(\mu) = \frac{\alpha_{\text{s}}}{2\pi}\left[\frac{1}{2} - \sum_{\text{SUSY particle } f} T_f \log\frac{m_f}{\mu}\right]$$

$\Rightarrow$

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

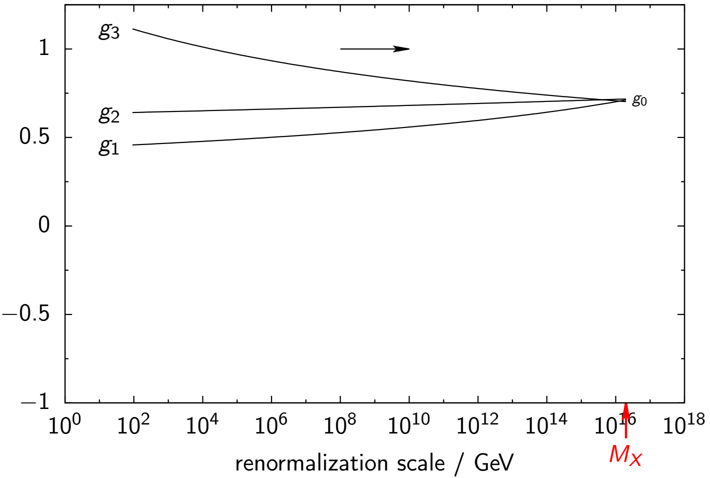
Algorithm to calculate the mass spectrum

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



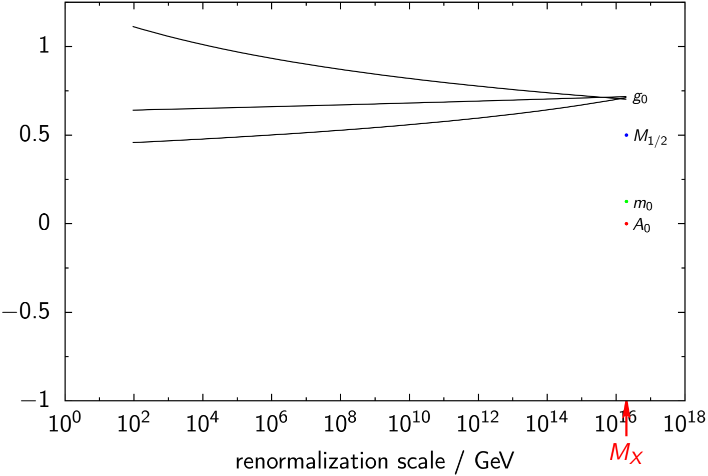
Algorithm to calculate the mass spectrum

Iteration step 1: RG running of gauge couplings to M_X



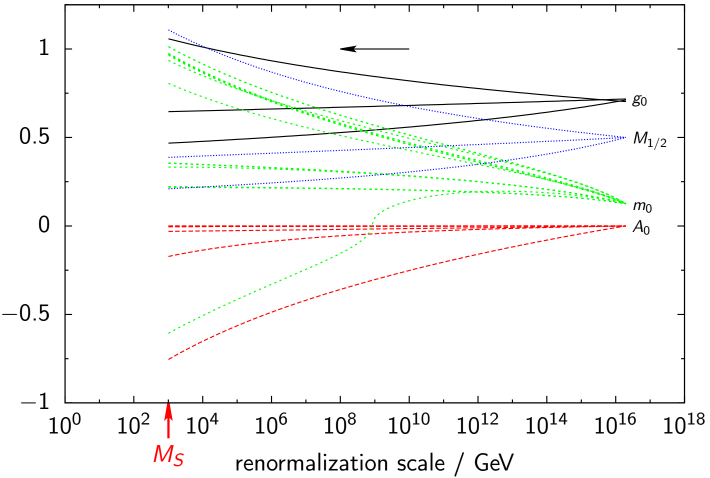
Algorithm to calculate the mass spectrum

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 $(p_1, \ldots, p_N)$:

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

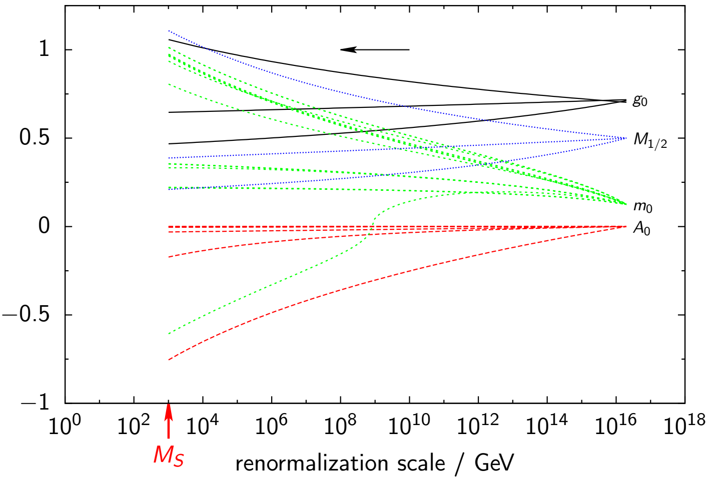
For example: CMSSM solve for $(\mu, B\mu)$

$$0 = m_{h_1}^2 v_1 + |\mu|^2 v_1 - B\mu v_2 + \frac{\bar{g}^2}{8}(v_1^2 - v_2^2)v_1 - t_1(m_f)$$
$$0 = m_{h_2}^2 v_2 + |\mu|^2 v_2 - B\mu v_1 - \frac{\bar{g}^2}{8}(v_1^2 - v_2^2)v_2 - t_2(m_f)$$

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

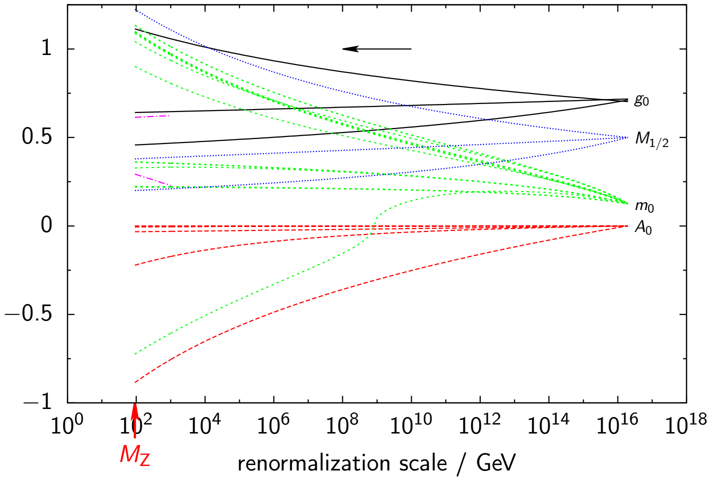
Algorithm to calculate the mass spectrum

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



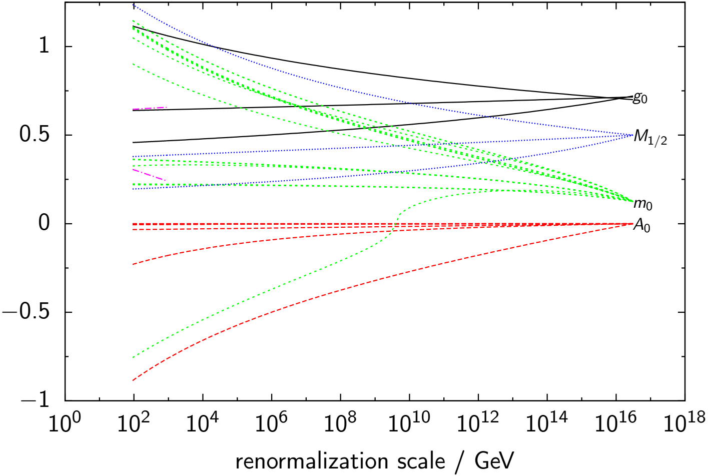
Algorithm to calculate the mass spectrum

Iteration step 1: RG running to M_Z



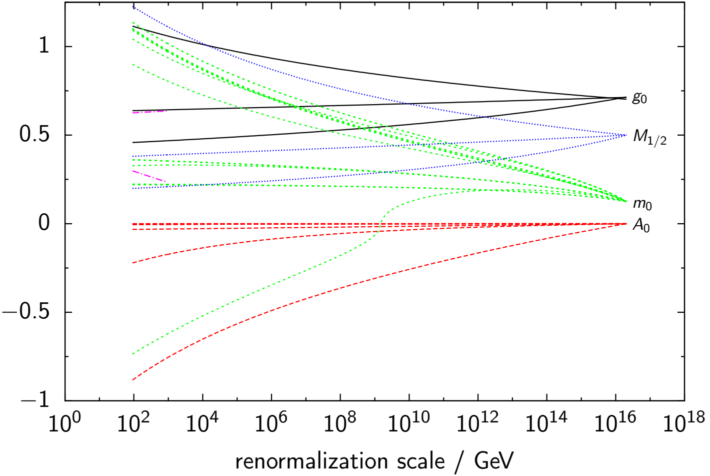
Algorithm to calculate the mass spectrum

Iteration step 2:



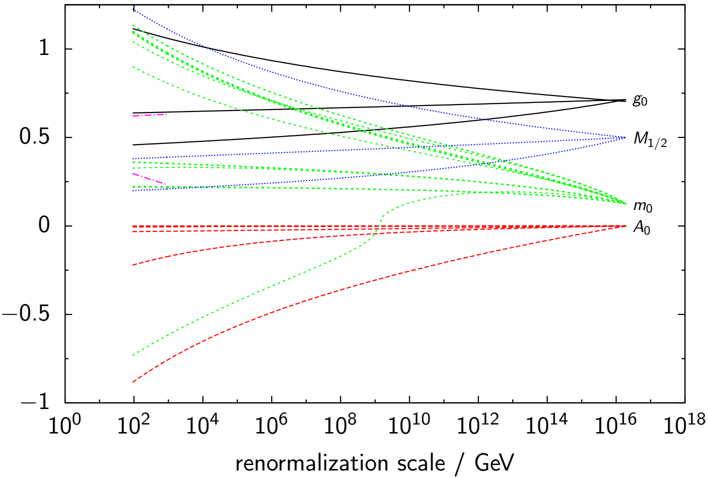
Algorithm to calculate the mass spectrum

Iteration step 3:

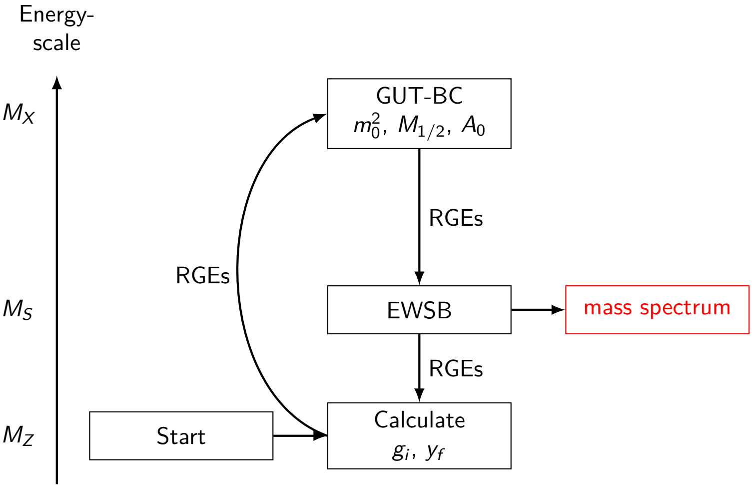


Algorithm to calculate the mass spectrum

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 = Higgs:

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

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

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

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

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

$$\delta M_h^2 = \Sigma_h(p^2)\Big|_\Delta, \qquad \delta Z_h = -\Sigma_h'(p^2)\Big|_\Delta$$

Contents

Parameters scans in the CMSSM, NMSSM, USSM, E_6SSM

Models: CMSSM, NMSSM, USSM, E_6SSM

mSUGRA-inspired GUT scale BCs:

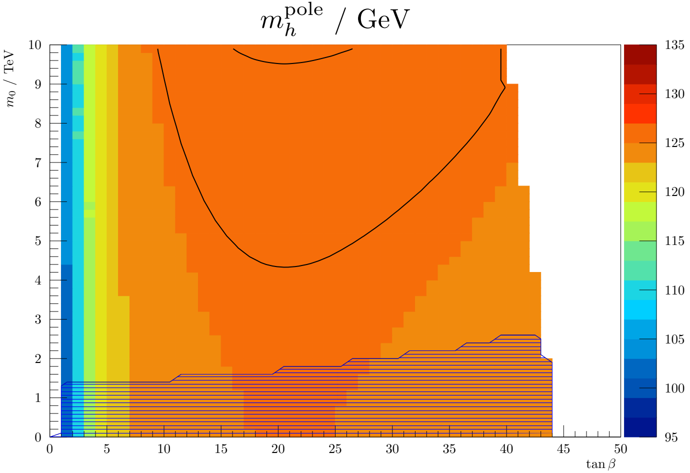
$$(m_f^2)_{ij}(M_X) = m_0^2 \delta_{ij}$$
$$A_{ij}^f(M_X) = A_0$$
$$M_i(M_X) = M_{1/2}$$

parameters fixed by EWSB conditions at M_S:

CMSSM: $\mu, B\mu$
NMSSM: κ, v_s, m_s^2
USSM: $m_{h_1}^2, m_{h_2}^2, m_s^2$
E_6SSM: $m_{h_1}^2, m_{h_2}^2, m_s^2$

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

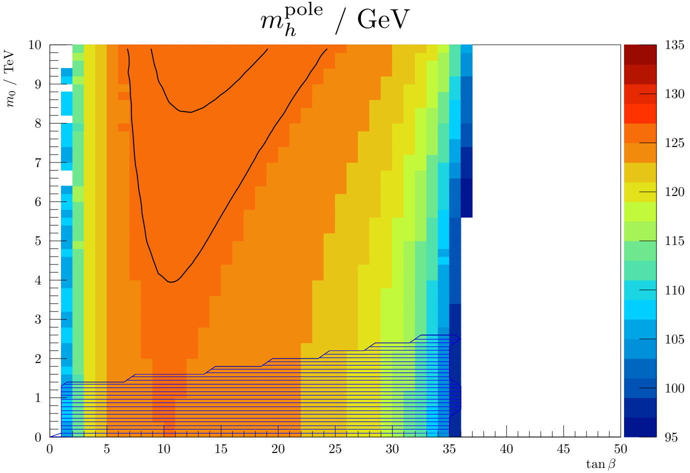
CMSSM parameter scan



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

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

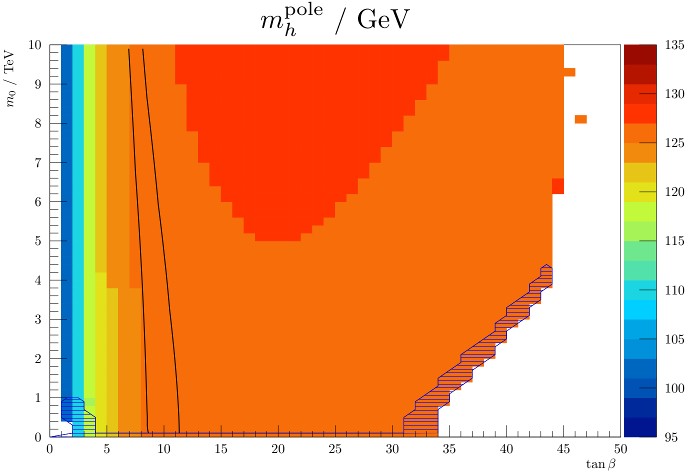
NMSSM parameter scan



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

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

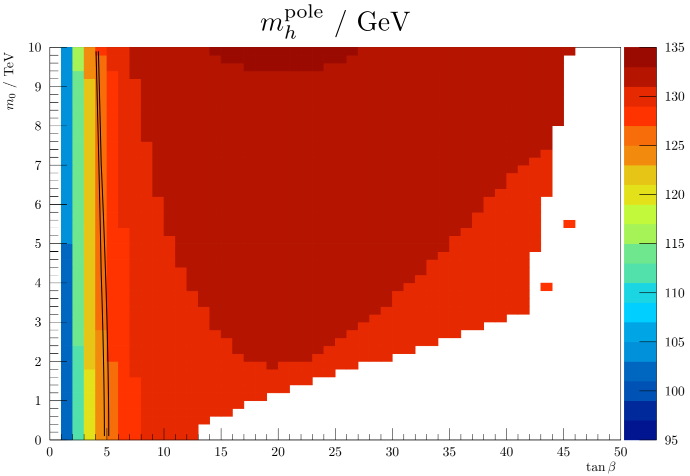
USSM parameter scan



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

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

E_6SSM 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 generator

Supported models:

- MSSM, CMSSM, NUH-MSSM, NMSSM, SMSSM, USSM, NUHM-E_6SSM, MRSSM, TMSSM, $\mu\nu$SSM, ...

https://flexiblesusy.hepforge.org

Future plans for FlexibleSUSY

- More applications!
  (currently studied: MRSSM, E_6SSM, NE_6SSM)
- support non-SUSY models (currently developed)
- 2-loop m_h from RGEs (currently developed)
- decays ($h \to \gamma\gamma, \ldots$)
- some observables ($(g-2)_\mu, \ldots$)
- interface to HiggsBounds
- *automatic* tower of effective field theories
- complex parameters (to study CP violation, etc.)
- ...

Thank you!

Backup

little Hierarchy problem

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

$$(m_h^{\text{tree}})^2 \;\approx\; \underbrace{\underbrace{\underbrace{m_Z^2 \cos^2 2\beta}_{\text{MSSM}} + \frac{\lambda^2 v^2}{2}\sin^2 2\beta}_{\text{NMSSM}} + \frac{m_Z^2}{4}\left(1 + \frac{1}{4}\cos 2\beta\right)^2}_{\text{USSM,}\mathrm{E_6}\text{SSM}}$$

$\Rightarrow$

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

Renormierung von v

Allgemeine Renormierungstransformation:

$$\begin{aligned} (\phi + v) &\to \sqrt{Z}\phi + v + \delta v \\ \text{oder} \quad (\phi + v) &\to \sqrt{Z}(\phi + v + \delta \bar{v}) \end{aligned}$$

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

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

Trick: Hintergrundfeld einführen

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

Damit folgt für $\hat{\phi} = 0$

$$\delta v = \frac{1}{2}\left(\delta Z + \delta \hat{Z}\right) v$$
$$\beta_v = (\gamma + \hat{\gamma}) v$$

Berechnung von β_v

Allgemeine Eichtheorie:

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

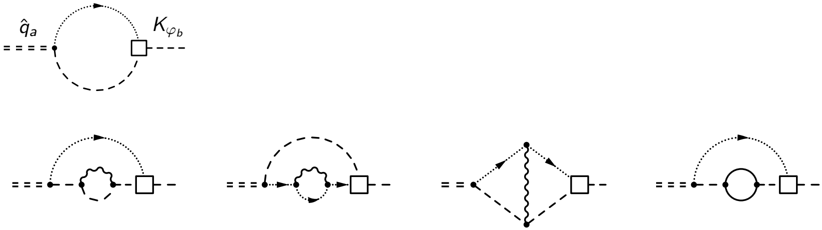
γ . . . anomale Dimension des Higgsfeldes

[Machacek, Vaughn (1983)]

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

unbekannt!

Berechnung von β_v



$\Rightarrow$

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

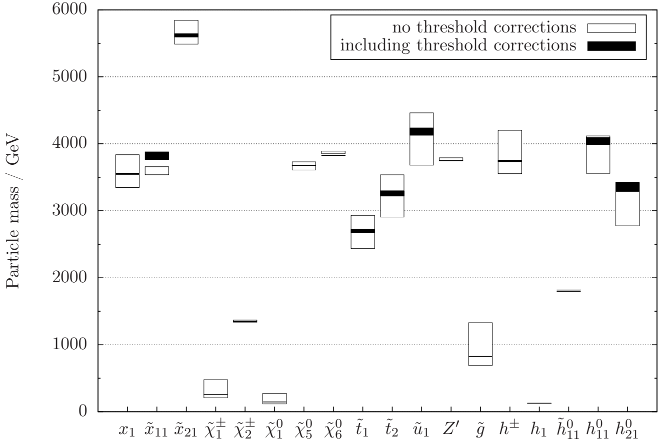
$$\hat{\gamma}^{(2)} = \frac{\xi}{(4\pi)^4} 2g^2 C^2(\mathrm{S}) \times \left[g^2 (1+\xi) \, C^2(\mathrm{S}) + g^2 \frac{7-\xi}{4} C_2(\mathrm{G}) - Y^2(\mathrm{S}) \right]$$

E_6SSM-Schwellenkorrekturen

$$g_i^{\overline{\text{DR}},\text{E}_6\text{SSM}}(Q) = g_i^{\overline{\text{MS}},\text{SM}}(Q) + \Delta g_i(Q) \qquad (i = 1, 2, 3),$$

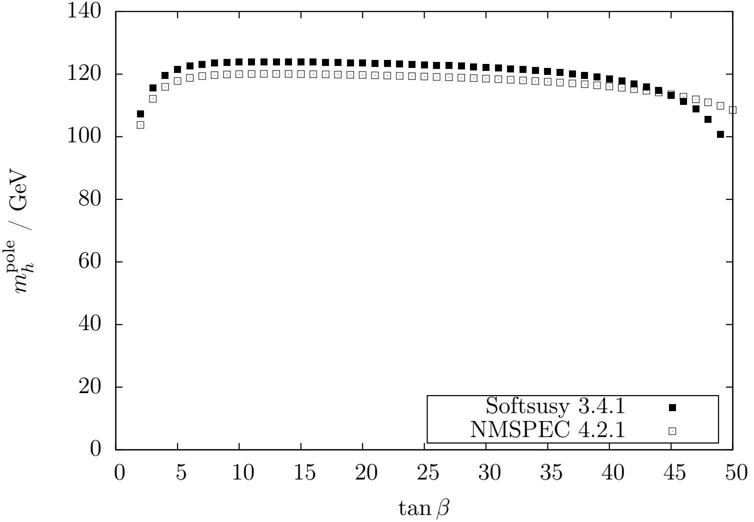
$$\Delta g_3(Q) = \frac{g_3^3}{(4\pi)^2}\left[\frac{1}{2} - 2\log\frac{m_{\tilde{g}}}{Q} - \frac{1}{6}\sum_{\tilde{q}\in\{\tilde{u},\tilde{d}\}}\sum_{i=1}^{3}\sum_{k=1}^{2}\log\frac{m_{\tilde{q}_{ik}}}{Q}\right.$$
$$\left. - \frac{2}{3}\sum_{i=1}^{3}\log\frac{m_{x_i}}{Q} - \frac{1}{6}\sum_{i=1}^{3}\sum_{k=1}^{2}\log\frac{m_{\tilde{x}_{ik}}}{Q}\right]$$

CE_6SSM-Massenspektrum



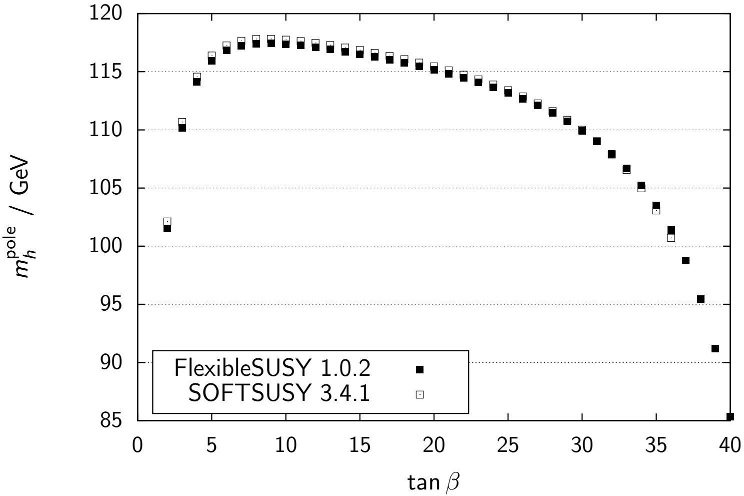
$$\tan\beta = 35, \quad \lambda_{1,2,3} = \kappa_{1,2,3} = 0.2, \quad v_s = 10\,\text{TeV},$$
$$\mu' = m_{h'} = m_{\bar{h}'} = 10\,\text{TeV}, \quad B\mu' = 0,$$
$$T_{\text{match}} = \tfrac{1}{2}\,T_0 \ldots 2\,T_0, \quad T_0 = 1.9\,\text{TeV}$$

NMSSM Higgs-Masse SOFTSUSY vs. NMSPEC



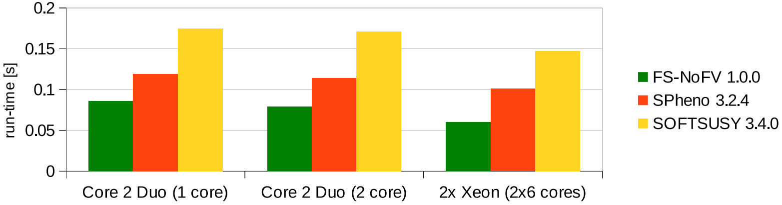
$m_0 = M_{1/2} = -A_0 = 5\,\text{TeV}, \lambda(M_S) = 0.1, \text{sign}\ v_s = +1$

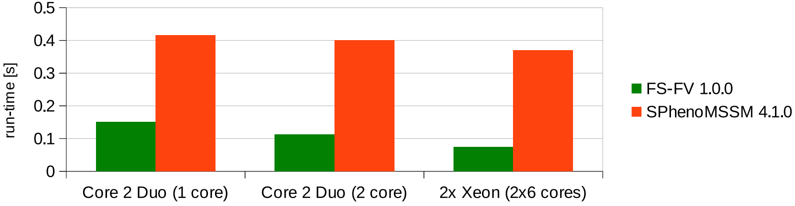
NMSSM Higgs-Masse FlexibleSUSY vs. SOFTSUSY



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

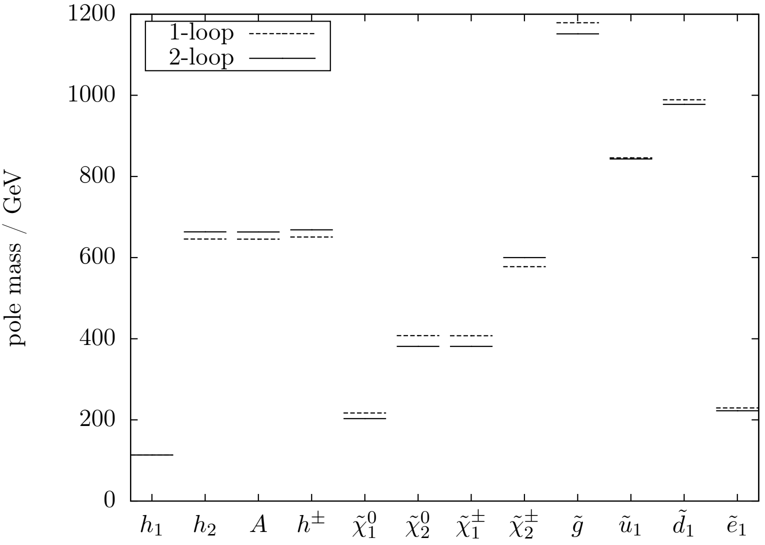
CMSSM-Laufzeitvergleich



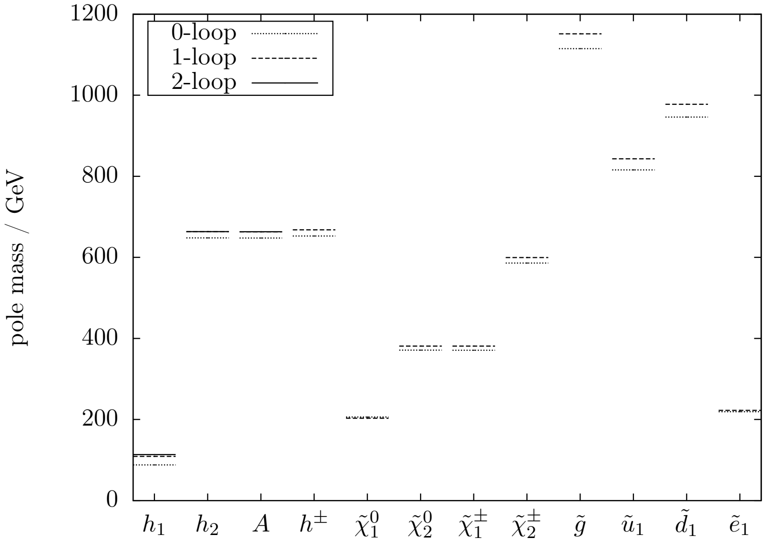


g++ 4.8.0, ifort 13.1.3 20130607

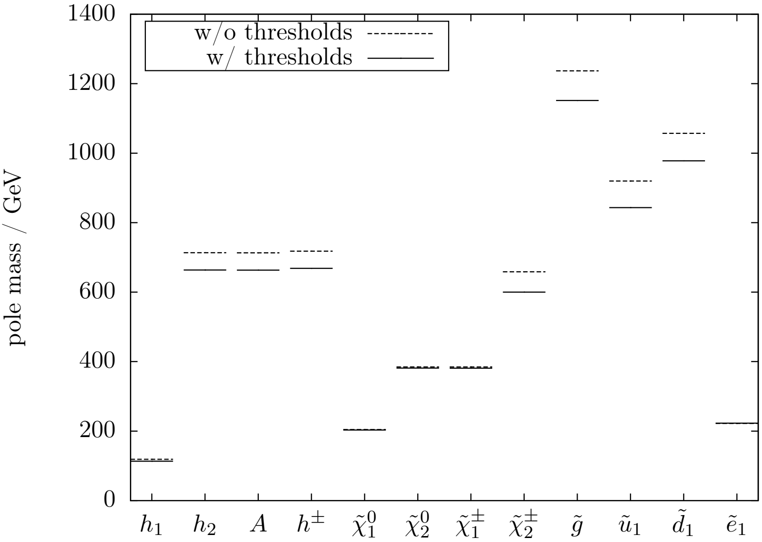
Einfluss der β-Funktionen-Loop-Ordnung (MSSM)



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-Randbedinungen

```
$ 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();
```

MSSM

$$SU(3)_{\text{c}} \times SU(2)_{\text{L}} \times U(1)_Y$$

$$\mathcal{W}_{\text{MSSM}} = \mu(H_1 H_2) - y^e_{ij}(H_1 L_i)\bar{E}_j - y^d_{ij}(H_1 Q_i)\bar{D}_j - y^u_{ij}(Q_i H_2)\bar{U}_j$$

$$h^0_1 \to \frac{v_1}{\sqrt{2}} + h^0_1, \qquad h^0_2 \to \frac{v_2}{\sqrt{2}} + h^0_2,$$

mSUGRA GUT constraint:

$$\begin{aligned} (m^2_f)_{ij}(M_X) &= m^2_0 \delta_{ij} && (f = q, \ell, u, d, e, h_1, h_2), \\ A^f_{ij}(M_X) &= A_0, && (f = u, d, e), \\ M_i(M_X) &= M_{1/2} && (i = 1, 2, 3). \end{aligned}$$

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

NMSSM

$$SU(3)_\text{c} \times SU(2)_\text{L} \times U(1)_Y$$

$$\mathcal{W}_\text{NMSSM} = \lambda S(H_1 H_2) - y^e_{ij}(H_1 L_i)\bar{E}_j - y^d_{ij}(H_1 Q_i)\bar{D}_j - y^u_{ij}(Q_i H_2)\bar{U}_j + \frac{\kappa}{3} S^3$$

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

mSUGRA-inspired GUT constraint:

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

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

USSM

$$SU(3)_{\mathrm{c}} \times SU(2)_{\mathrm{L}} \times U(1)_Y \times U(1)'$$

$$\mathcal{W}_{\mathrm{USSM}} = \lambda S(H_1 H_2) - y^e_{ij}(H_1 L_i)\bar{E}_j - y^d_{ij}(H_1 Q_i)\bar{D}_j - y^u_{ij}(Q_i H_2)\bar{U}_j$$

$$h^0_1 \to \frac{v_1}{\sqrt{2}} + h^0_1, \qquad h^0_2 \to \frac{v_2}{\sqrt{2}} + h^0_2, \qquad s \to \frac{v_s}{\sqrt{2}} + s$$

mSUGRA-inspired GUT constraint:

$$\begin{aligned} (m^2_f)_{ij}(M_X) &= m^2_0 \delta_{ij} && (f = q, \ell, u, d, e), \\ A^f_{ij}(M_X) &= A_0, && (f = u, d, e, \lambda), \\ M_i(M_X) &= M_{1/2} && (i = 1, 2, 3, 4). \end{aligned}$$

EWSB output: $m^2_{h_1}(M_S), m^2_{h_2}(M_S), m^2_s(M_S)$

E_6SSM

$$SU(3)_{\mathrm{c}} \times SU(2)_{\mathrm{L}} \times U(1)_Y \times U(1)_N$$

$$\mathcal{W}_{\mathrm{E_6SSM}} = \lambda_3 S_3 (H_{13} H_{23}) - y^e_{ij} (H_{13} L_i) \bar{E}_j - y^d_{ij} (H_{13} Q_i) \bar{D}_j - y^u_{ij} (Q_i H_{23}) \bar{U}_j$$
$$+ \kappa_{ij} S_3 (X_i \bar{X}_j) + \lambda_{\alpha\beta} S_3 (H_{1\alpha} H_{2\beta}) + \mu' (H' \bar{H}')$$

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

mSUGRA-inspired GUT constraint:

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

EWSB output: $m^2_{h_1}(M_S), m^2_{h_2}(M_S), m^2_s(M_S)$

Brechung der E_6

het. Stringtheorie: $E_8 \times E_8'$

$$\downarrow$$

SUSY-Eichtheorie:

$$E_6 \to SO(10) \times U(1)_\psi$$
$$\hookrightarrow SU(5) \times U(1)_\chi$$
$$\hookrightarrow SU(3)_c \times \underbrace{SU(2)_L \times U(1)_Y}_{\to U(1)_{em}}$$

het. Stringtheorie: $SO(32)$

$$\downarrow$$

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

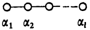
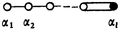
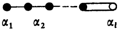
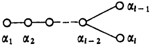
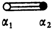
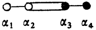
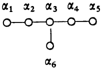
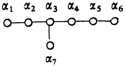
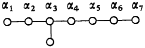
Zerlegung der E_6 bezüglich $SO(10) \times U(1)_\psi$:

$$(\mathbf{27})_{E_6} \to (\mathbf{16}, 1) + (\mathbf{10}, -2) + (\mathbf{1}, 4)$$
$$(\mathbf{78})_{E_6} \to (\mathbf{45}, 0) + (\mathbf{16}, -3) + (\overline{\mathbf{16}}, 3) + (\mathbf{1}, 0)$$

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

$$(\mathbf{10})_{SO(10)} \to (\mathbf{5}, -2) + (\overline{\mathbf{5}}, 2)$$
$$(\mathbf{45})_{SO(10)} \to (\mathbf{24}, 0) + (\mathbf{10}, -4) + (\overline{\mathbf{10}}, 4) + (\mathbf{1}, 0)$$
$$(\mathbf{16})_{SO(10)} \to (\mathbf{10}, 1) + (\overline{\mathbf{5}}, -3) + (\mathbf{1}, 5)$$

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_7 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.

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

E_6SSM 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:

$$\mathcal{W} = \mathcal{W}_{\text{MSSM}} - \frac{1}{M_{\text{Pl}}}\left[y^{Xijk}X\Phi_i\Phi_j\Phi_k + \mu^{Xij}X\Phi_i\Phi_j + \cdots\right]$$

$$K = \Phi_i^\dagger\Phi_i + \frac{1}{M_{\text{Pl}}}\left[n^{ij}X + \bar{n}^{ij}X^\dagger\right]\Phi_i^\dagger\Phi_j - \frac{1}{M_{\text{Pl}}^2}k^{ij}XX^\dagger\Phi_i^\dagger\Phi_j$$

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

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

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)

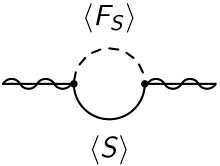
Messenger Superfields transform under $SU(3)_{\mathsf{c}} \times SU(2)_{\mathsf{L}} \times U(1)_Y$:

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

Coupled to a gauge singlet S in the messenger sector:

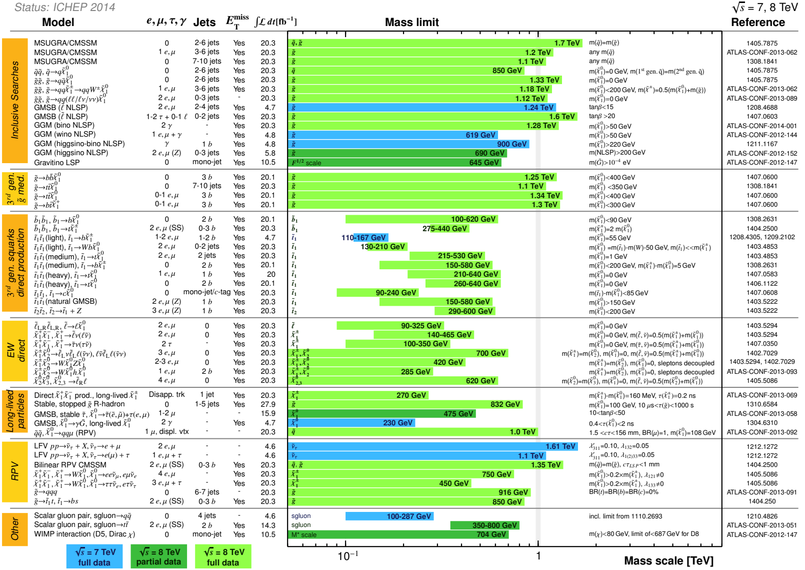
$$\mathcal{W}_{\mathsf{mess}} = y_2 S \ell \bar{\ell} + y_3 S \mathcal{Q} \overline{\mathcal{Q}}$$

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:

$\bar{B}, \bar{W}, \bar{g}$ 

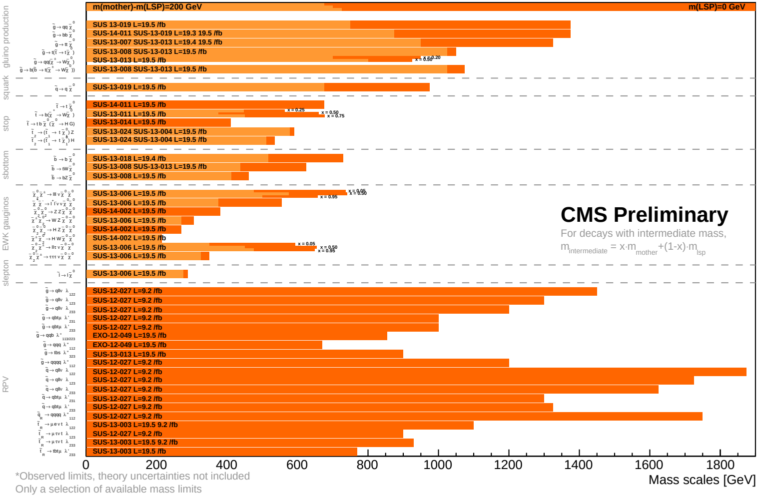
$$\sim \frac{g_i^2}{(4\pi)^2} \frac{\langle F_S \rangle}{\langle S \rangle} \lambda_i \lambda_i$$

ATLAS SUSY Searches* - 95% CL Lower Limits



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

Summary of CMS SUSY Results* in SMS framework   ICHEP 2014



*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit