Mass spectrum prediction in non-minimal supersymmetric models

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TECHNISCHE UNIVERSITÄT DRESDEN

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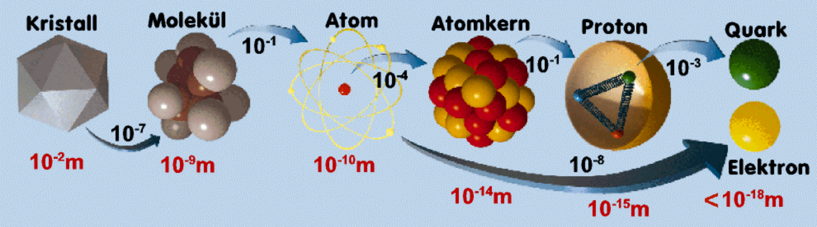
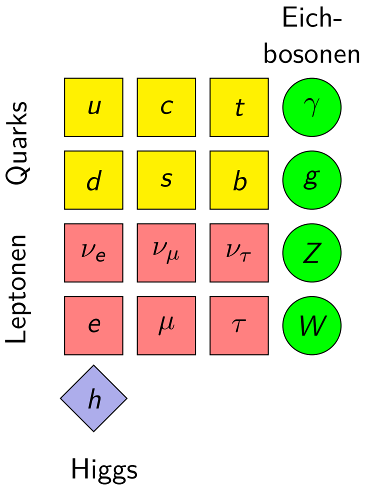
Die Bausteine der Natur



Das Standardmodell der Teilchenphysik



Beschreibt

- Quarks, Leptonen
- elektromagnetische, starke und schwache WW
- Higgsboson

Probleme:

- keine Gravitation
- keine Dunkle Materie

Schwachstellen:

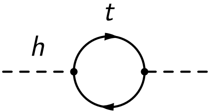
- keine Vereinigung der WW
- Hierarchieproblem

Hierarchieproblem

Higgs-Masse:

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

$$\Delta m_h^2 =$$



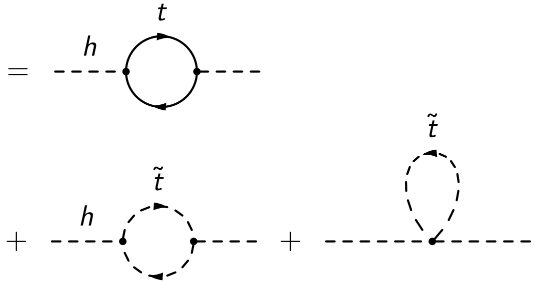
groß!

Hierarchieproblem

Higgs-Masse:

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

$\Delta m_h^2 =$

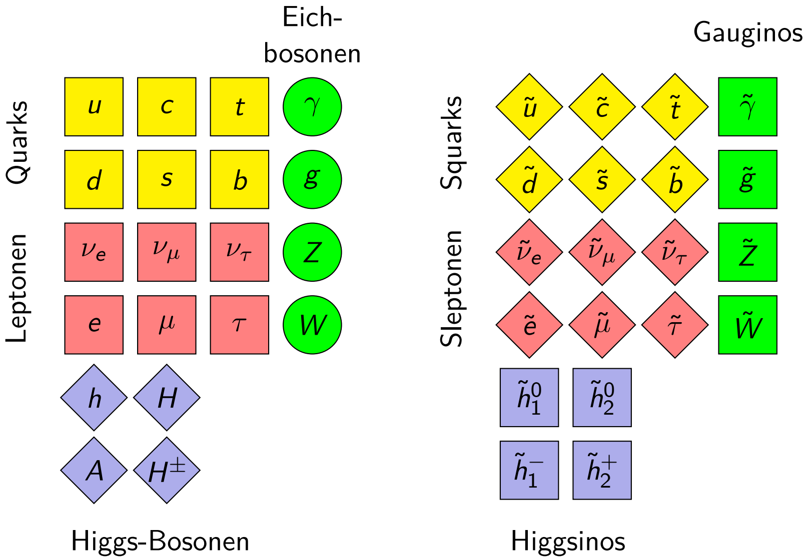


$= 0$

falls $m_t = m_{\tilde{t}},\ Q_t = Q_{\tilde{t}},\ I_t = I_{\tilde{t}},\ T_t = T_{\tilde{t}}$

$\Rightarrow$ **Supersymmetrie**

Minimales Supersymmetrisches Standardmodell (MSSM)



Brechung der Supersymmetrie

Problem: SUSY-Partner bisher nicht gefunden

$$\Downarrow$$

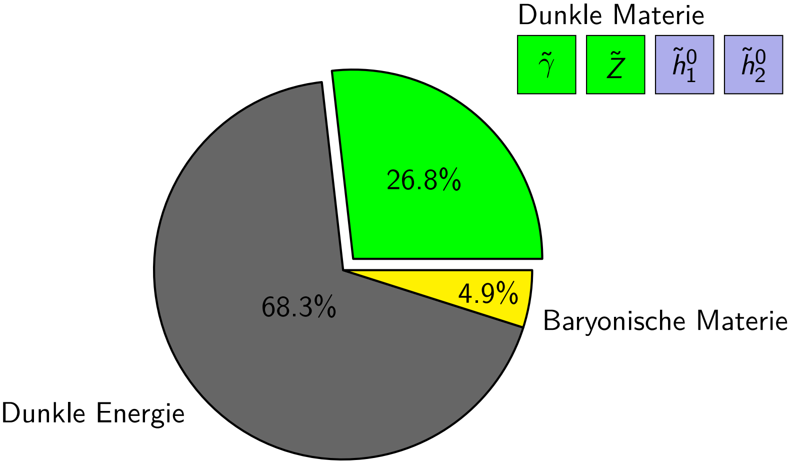
Supersymmetrie muss gebrochen sein!

$$m_{\tilde{t}} \gtrsim m_t$$

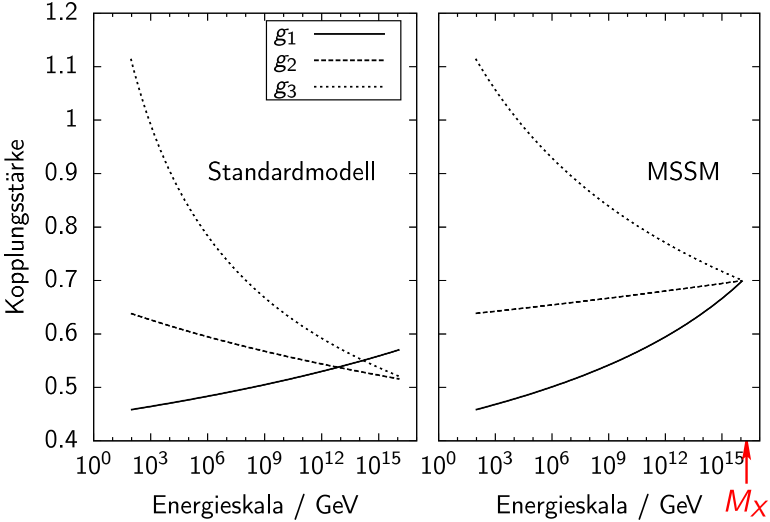
Stärke der Brechung parametrisiert durch:

$$m_0^2, \quad M_{1/2}, \quad A_0$$

Vorteil des MSSM: Dunkle Materie-Kandidat



Vorteil des MSSM: Eichkopplungsvereinigung



Schwachstelle des MSSM: μ-Problem

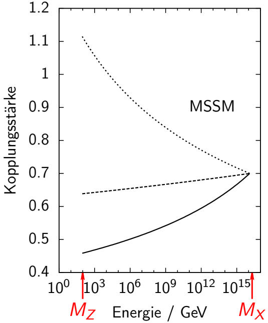
$$\mathcal{L}_{\text{MSSM}} = \mathcal{L}_{\text{Eich-WW}} + \int d^2\theta \Big[\mu (H_1 H_2) + \text{Yukawa} \Big]$$

μ hat seinen Ursprung an GUT-Skala

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

Aber andererseits: μ festgelegt durch Elektroschwache Symmetriebrechung (EWSB) an M_Z-Skala

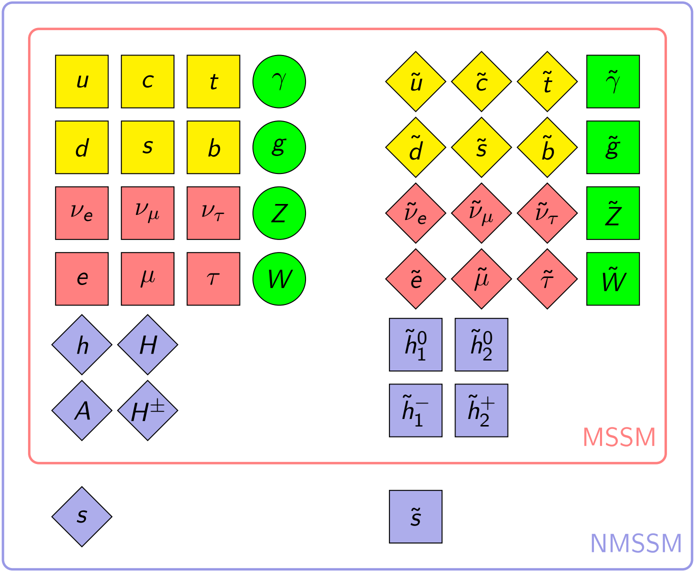
$$\Rightarrow \mu \sim M_Z \sim 10^{2}\ \text{GeV}$$



Lösung: μ ersetzen durch neues Higgs-Boson s

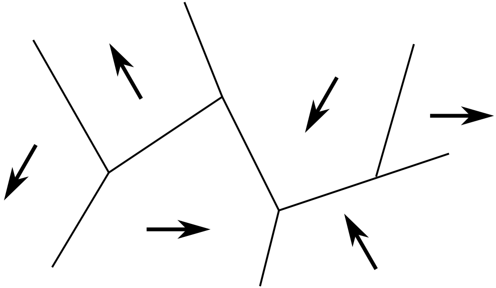
$\Rightarrow$ Nächst-Minimales Supersymmetrisches Standardmodell (NMSSM)

Next-to-MSSM (NMSSM)



Problem des NMSSM: Domänenwände

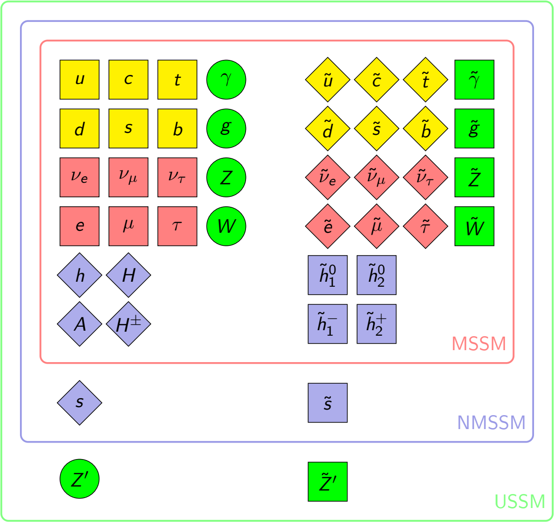
Problem: diskrete Rotationssymmetrie um 120°
$\Rightarrow$ Domänenwände



Lösung: neue kontinuierliche Eichsymmetrie $U(1)'$

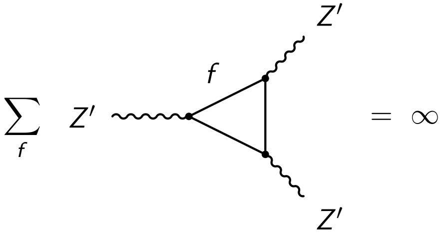
$\Rightarrow$ $U(1)'$-erweitertes Supersymmetrisches Standardmodell (USSM)

$U(1)'$-erweitertes Supersymmetrisches Standardmodell (USSM)



Problem des USSM: Anomalien

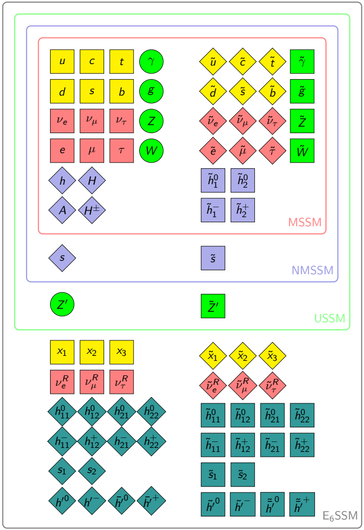
Problem: $U(1)'$-Ladungen sind beliebig.
$\Rightarrow$ Ungeschickte Wahl kann zu Anomalien führen:



Lösung: anomaliefreie Eichgruppe, z.B. $SO(10)$ oder E_6

$\Rightarrow$ Exzeptionelles Supersymmetrisches Standardmodell (E_6SSM)

Exzeptionelles Supersymmetrisches Standardmodell (E_6SSM)



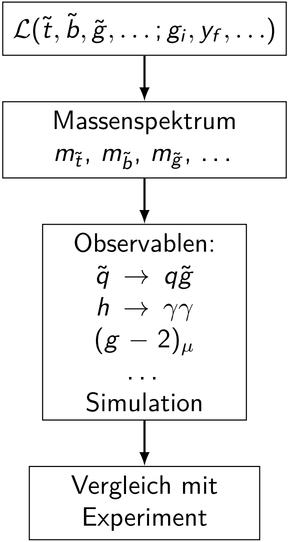
Zusammenfassung Supersymmetrie

Supersymmetrische Modelle sind attraktive Erweiterungen des SM.

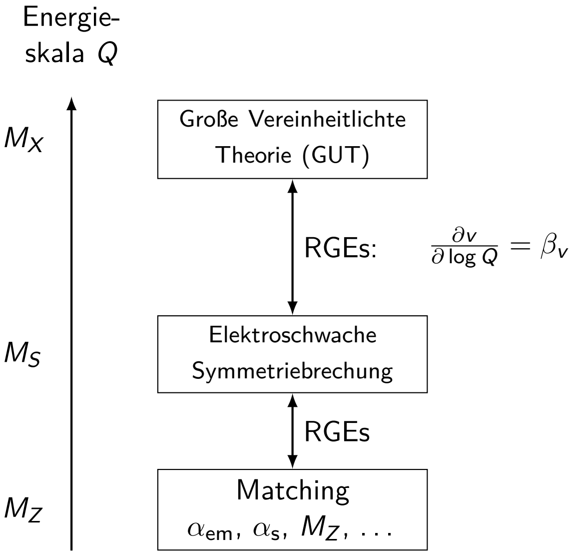
Vorteile:

- Lösung des Hierarchieproblems
- Dunkle Materie
- Eichkopplungsvereinigung
- Verbindung zu Supergravitations-Modellen

Warum Berechnung des Massenspektrums?

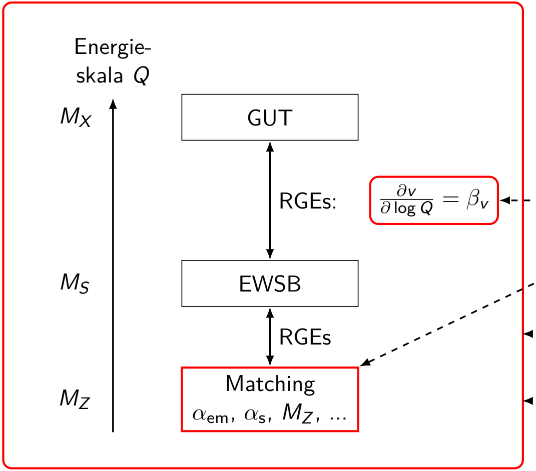


Physikalische Problemstellung



Ziel dieser Promotion

Präzise Berechnung von Massenspektren in SUSY-Modellen



Dazu:

1. Berechnung von β_v in allg. SUSY-Modell
2. Genaueres Matching im E_6SSM
3. Neuer NMSSM-Spektrumgenerator
4. Allg. SUSY-Spektrumgenerator

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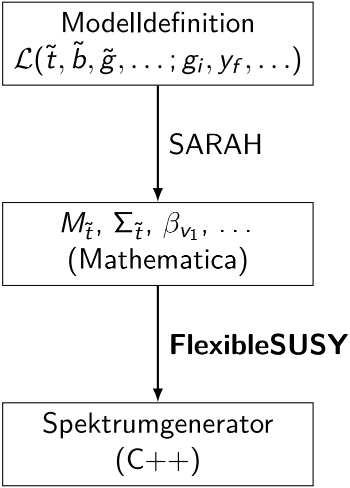
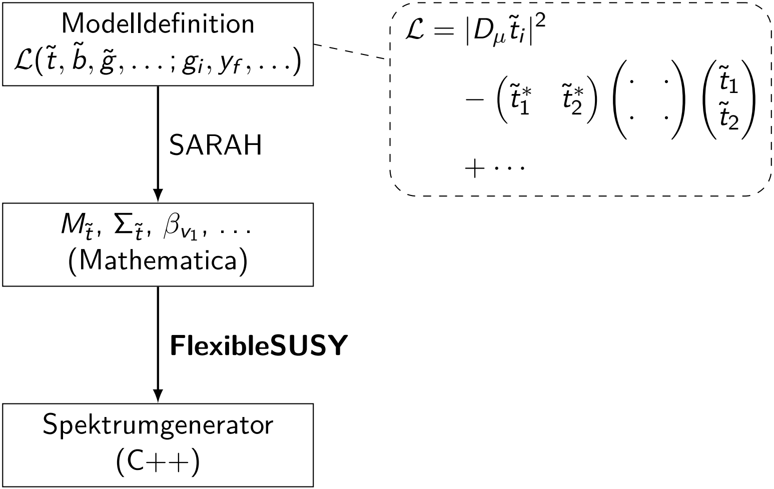
Allgemeiner SUSY-Spektrumgenerator-Generator

FlexibleSUSY

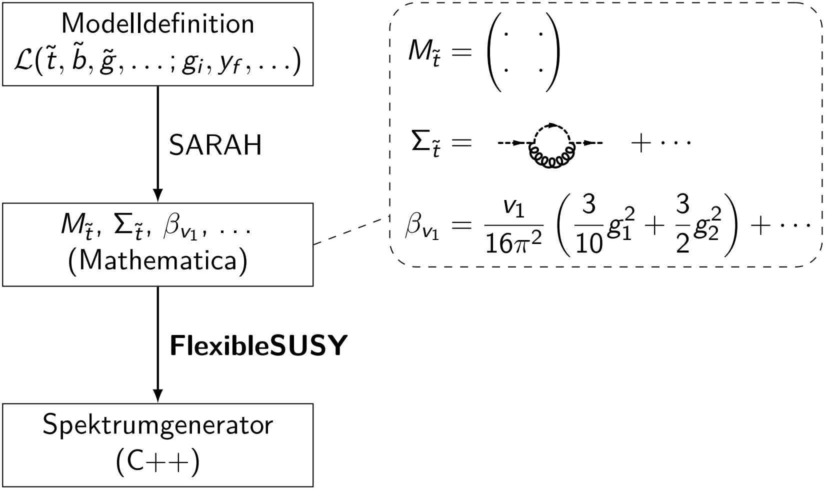
Erzeugung eines Spektrumgenerators



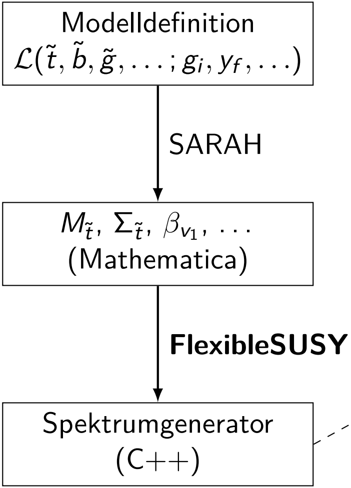
Erzeugung eines Spektrumgenerators



Erzeugung eines Spektrumgenerators

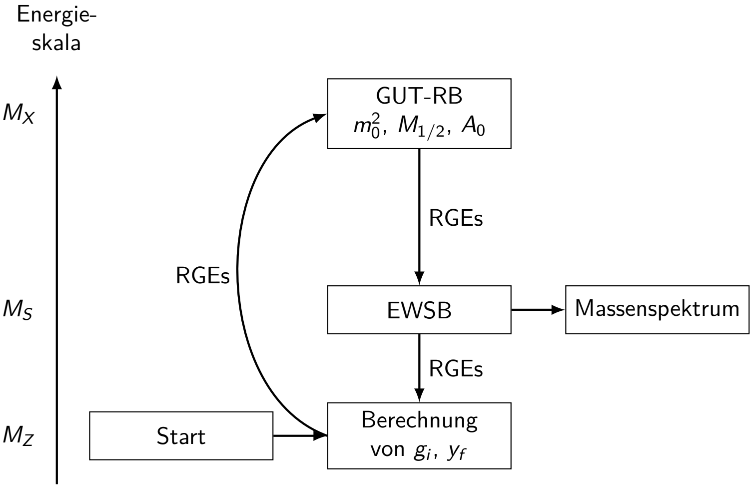


Erzeugung eines Spektrumgenerators



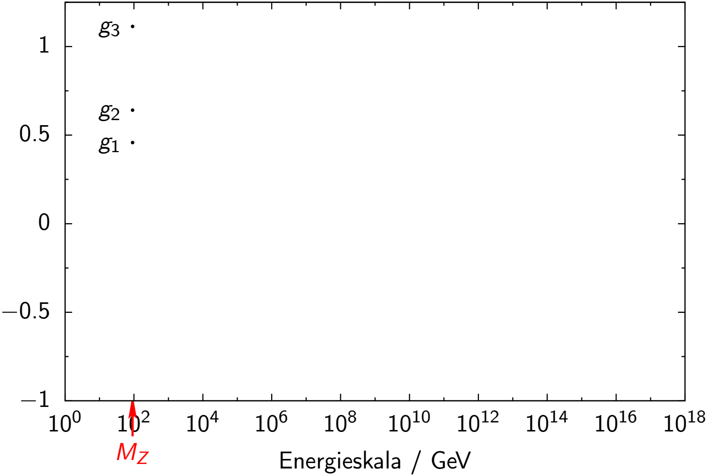

```
Matrix<2,2> get_mass_matrix_St() {
  Matrix<2,2> mass_matrix;

  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;
}
```

Algorithmus zur Berechnung des Massenspektrums



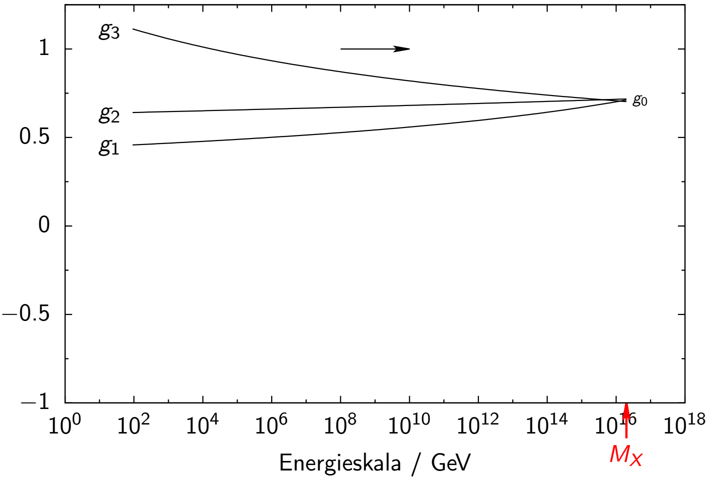
Algorithmus zur Berechnung des Massenspektrums

Iterationsschritt 1: Eichkopplungen an M_Z



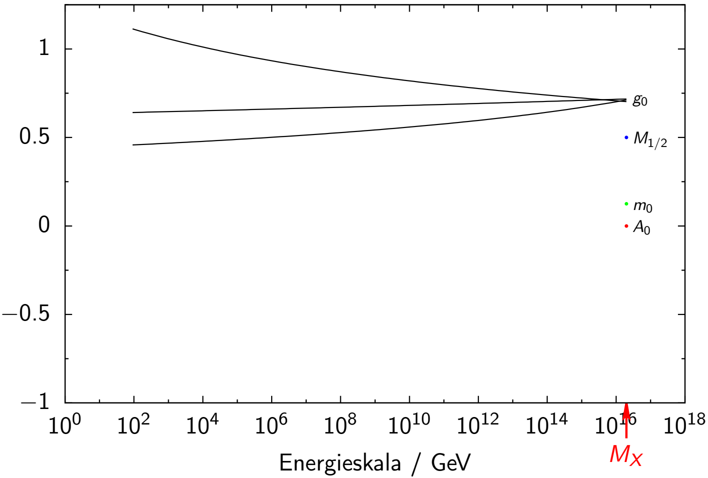
Algorithmus zur Berechnung des Massenspektrums

Iterationsschritt 1: RG-Laufen der Eichkopplungen zu M_X



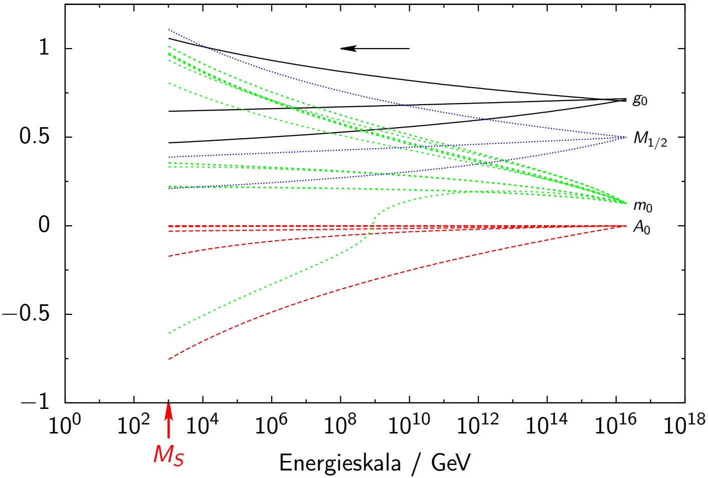
Algorithmus zur Berechnung des Massenspektrums

Iterationsschritt 1: Randbedingungen setzen an M_X



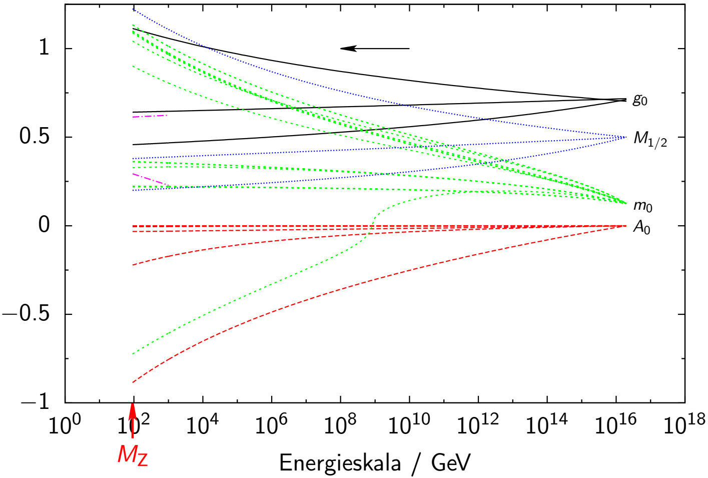
Algorithmus zur Berechnung des Massenspektrums

Iterationsschritt 1: RG-Laufen zu M_S, EWSB



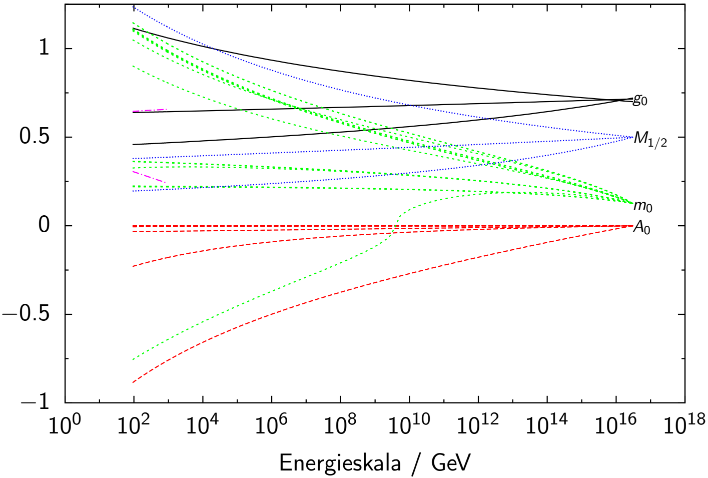
Algorithmus zur Berechnung des Massenspektrums

Iterationsschritt 1: RG-Laufen zu M_Z



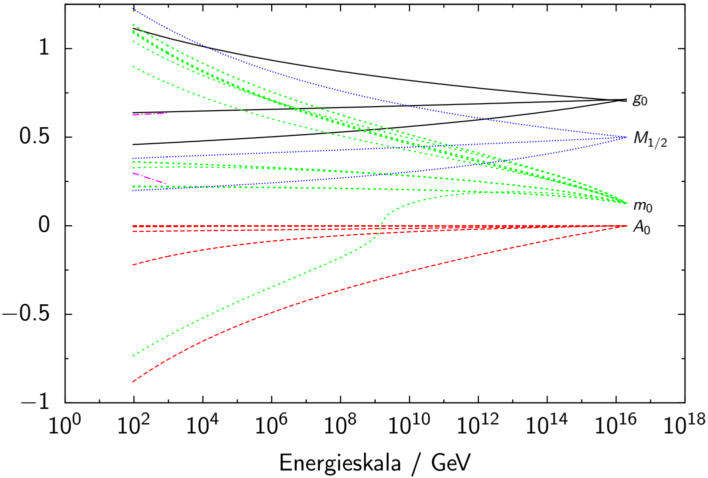
Algorithmus zur Berechnung des Massenspektrums

Iterationsschritt 2:



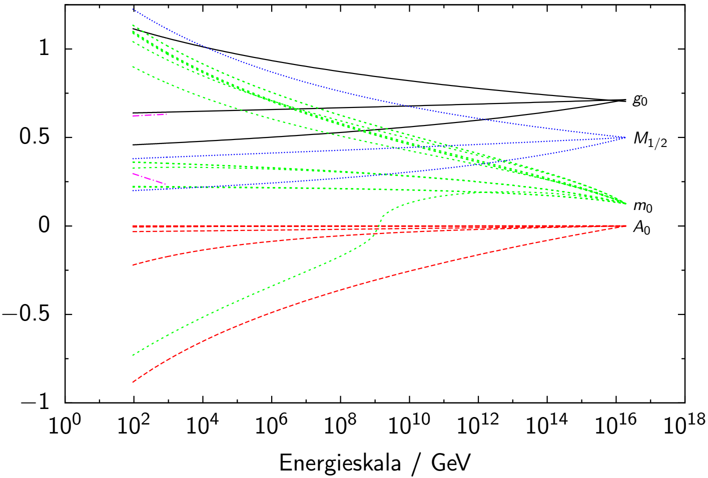
Algorithmus zur Berechnung des Massenspektrums

Iterationsschritt 3:

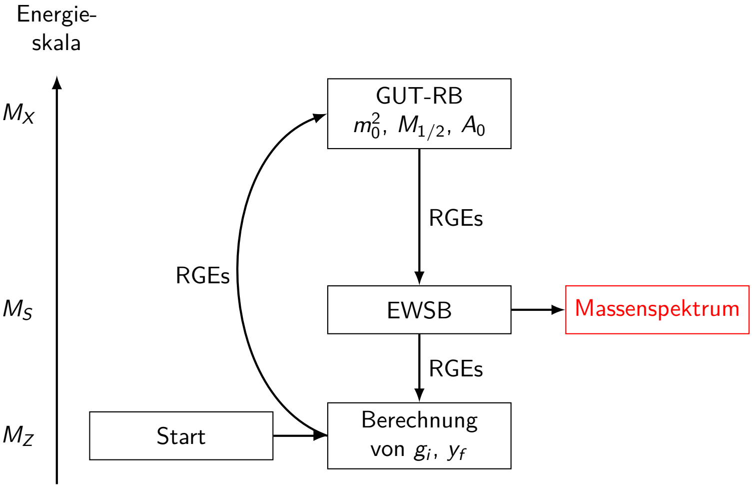


Algorithmus zur Berechnung des Massenspektrums

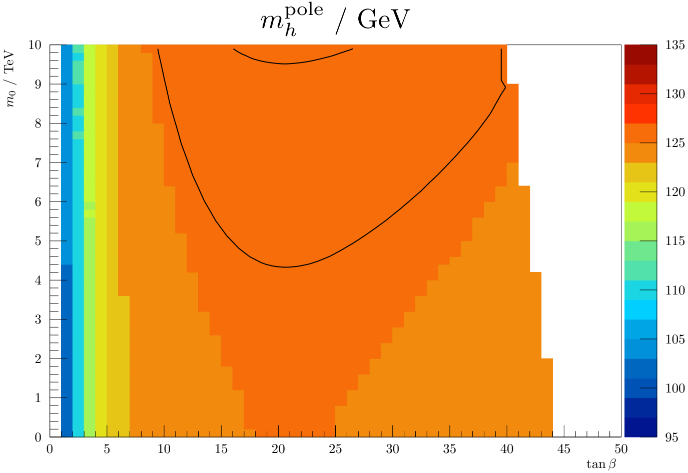
Iterationsschritt 8: Konvergenz



Algorithmus zur Berechnung des Massenspektrums



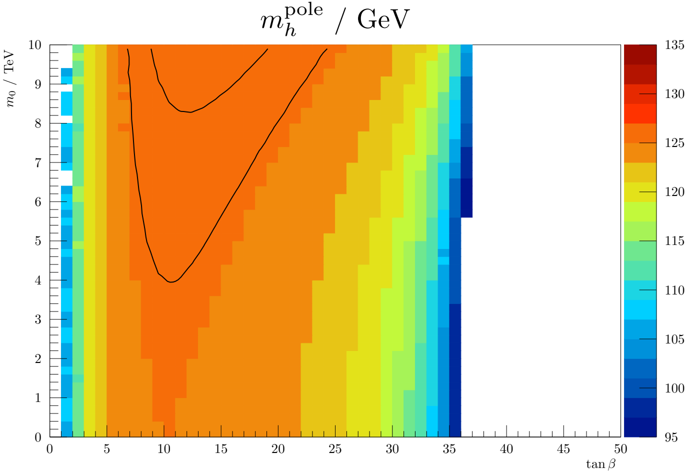
MSSM-Parameterscan



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

Higgs-Massenkonturen bei $m_h^{\mathrm{pole}} = (125.7 \pm 0.4)\,\mathrm{GeV}$

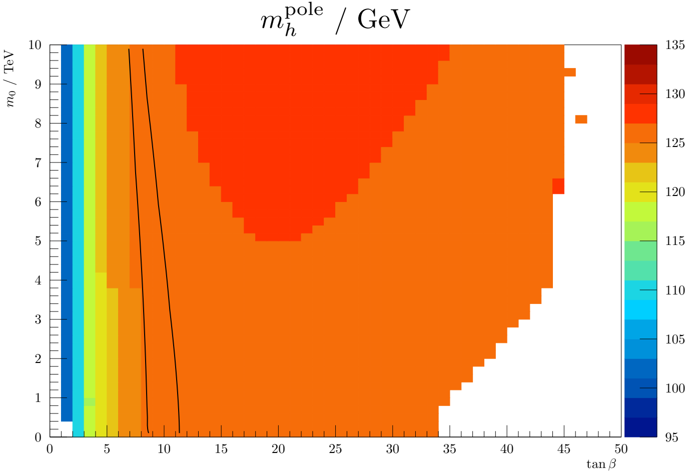
NMSSM-Parameterscan



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

Higgs-Massenkonturen bei $m_h^{\mathrm{pole}} = (125.7 \pm 0.4)\,\mathrm{GeV}$

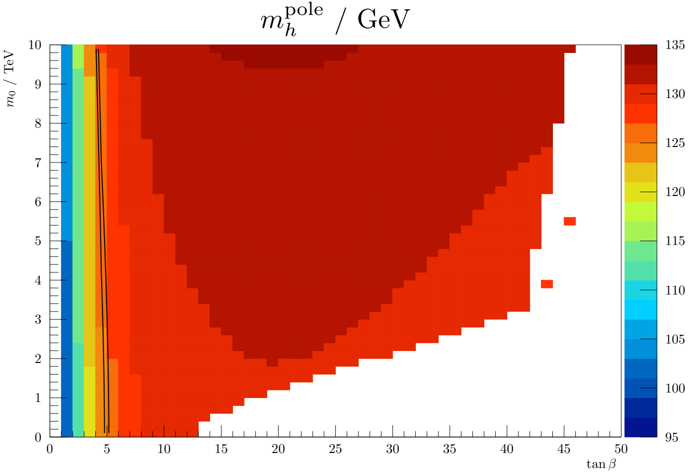
USSM-Parameterscan



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

Higgs-Massenkonturen bei $m_h^{\text{pole}} = (125.7 \pm 0.4)\,\text{GeV}$

E_6SSM-Parameterscan



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

Higgs-Massenkonturen bei $m_h^{\text{pole}} = (125.7 \pm 0.4)\,\text{GeV}$

Zusammenfassung

Ziel dieser Promotion:
Präzise Berechnung von Massenspektren in SUSY-Modellen

Dazu:

- Berechnung von β_v auf 1- und 2-Loop-Niveau

  [Sperling, Stöckinger, AV, JHEP 1307 (2013), JHEP 1401 (2014)]

- E_6SSM-Spektrumgenerator mit genauerem Matching (CE6SSMSpecGen)

  [Athron, Stöckinger, AV, Phys.Rev. D86 (2012)]

- Neuer NMSSM-Spektrumgenerator (NMSSM-SOFTSUSY)

  [Allanach, Athron, Tunstall, AV, Williams, Comput.Phys.Comm. 185 (2014)]

- Allgemeiner, automatischer SUSY-Spektrumgenerator-Generator (FlexibleSUSY)

  [Athron, Park, Stöckinger, AV, arXiv:1406.2319 (2014)]

Vielen Dank!

Backup

Kleines Hierarchieproblem

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

$$(m_h^{\text{tree}})^2 \;\approx\; \underbrace{\underbrace{\underbrace{m_Z^2 \cos^2 2\beta}_{\text{MSSM}} + \frac{\lambda^2 v^2}{2}\sin^2 2\beta}_{\text{NMSSM}} + \frac{m_Z^2}{4}\left(1 + \frac{1}{4}\cos 2\beta\right)^2}_{\text{USSM,E}_6\text{SSM}}$$

$\Rightarrow$

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

Berechnung der Higgs-Masse im MSSM

$$M_h^2 = \begin{pmatrix} (M_h^2)_{11} & (M_h^2)_{12} \\ (M_h^2)_{12} & (M_h^2)_{22} \end{pmatrix}$$

$$(M_h^2)_{11} = m_{h_d}^2 + |\mu|^2 + \frac{1}{8}(g_Y^2 + g_2^2)(3v_d^2 - v_u^2)$$

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

$$(M_h^2)_{22} = m_{h_u}^2 + |\mu|^2 + \frac{1}{8}(g_Y^2 + g_2^2)(3v_u^2 - v_d^2)$$

Higgs-Massen sind Nullstellen von

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

mit

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

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

MSSM EWSB-Gleichungen (tree-level)

$$0 = \frac{\partial V}{\partial v_d} = m_{h_d}^2 v_d + |\mu|^2 v_d - B\mu v_u + \frac{\bar{g}^2}{8}(v_d^2 - v_u^2) v_d$$
$$0 = \frac{\partial V}{\partial v_u} = m_{h_u}^2 v_u + |\mu|^2 v_u - B\mu v_d - \frac{\bar{g}^2}{8}(v_d^2 - v_u^2) v_u$$

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

Renormierung von v

Allgemeine Renormierungstransformation:

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

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

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

Trick: Hintergrundfeld einführen

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

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:

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

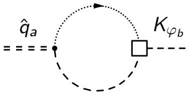
$\gamma \ldots$ anomale Dimension des Higgsfeldes

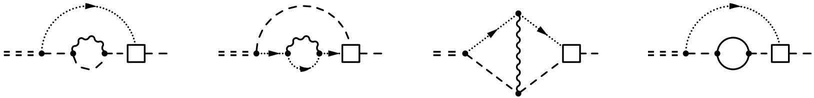
[Machacek, Vaughn (1983)]

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

unbekannt!

Berechnung von β_v





$\Rightarrow$

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

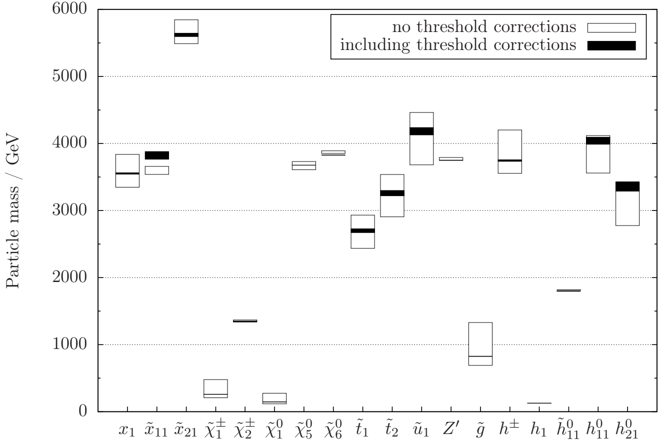
$$\hat{\gamma}^{(2)} = \frac{\xi}{(4\pi)^4} 2g^2 C^2(\mathsf{S}) \times \left[g^2 (1+\xi)\, C^2(\mathsf{S}) + g^2 \frac{7-\xi}{4} C_2(\mathsf{G}) - Y^2(\mathsf{S}) \right]$$

E_6SSM-Schwellenkorrekturen

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

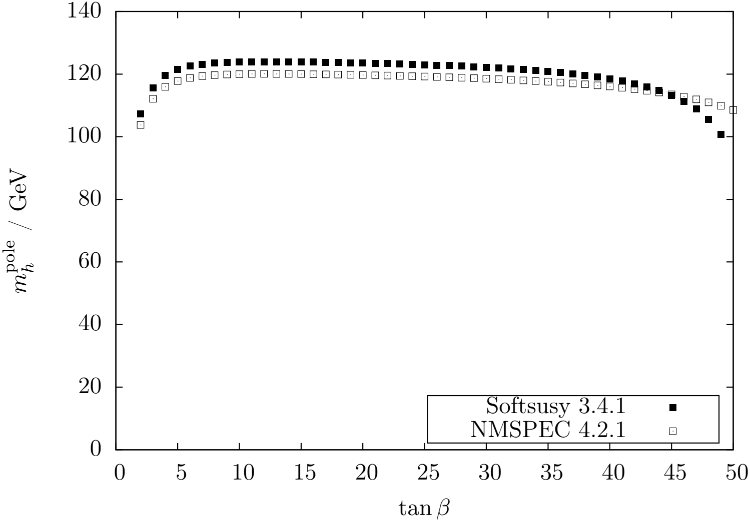
$$\Delta g_3(Q) = \frac{g_3^3}{(4\pi)^2}\left[\frac{1}{2} - 2\log\frac{m_{\tilde{g}}}{Q} - \frac{1}{6}\sum_{\tilde{q}\in\{\tilde{u},\tilde{d}\}}\sum_{i=1}^{3}\sum_{k=1}^{2}\log\frac{m_{\tilde{q}_{ik}}}{Q} - \frac{2}{3}\sum_{i=1}^{3}\log\frac{m_{x_i}}{Q} - \frac{1}{6}\sum_{i=1}^{3}\sum_{k=1}^{2}\log\frac{m_{\tilde{x}_{ik}}}{Q}\right]$$

CE$_6$SSM-Massenspektrum



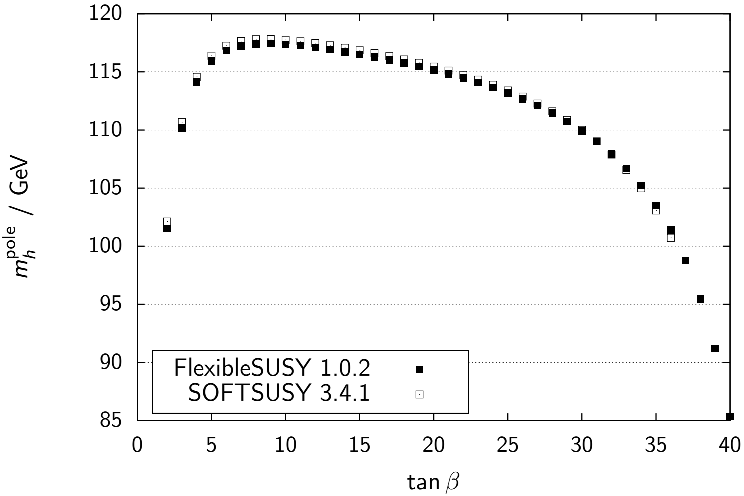
$$\tan\beta = 35, \quad \lambda_{1,2,3} = \kappa_{1,2,3} = 0.2, \quad v_s = 10\,\text{TeV},$$
$$\mu' = m_{h'} = m_{\bar{h}'} = 10\,\text{TeV}, \quad B\mu' = 0,$$
$$T_\text{match} = \tfrac{1}{2}\,T_0 \ldots 2\,T_0, \quad T_0 = 1.9\,\text{TeV}$$

NMSSM Higgs-Masse SOFTSUSY vs. NMSPEC



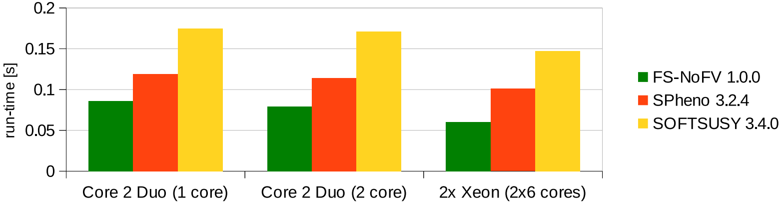
$m_0 = M_{1/2} = -A_0 = 5\,\text{TeV}, \lambda(M_S) = 0.1, \text{sign}\ v_s = +1$

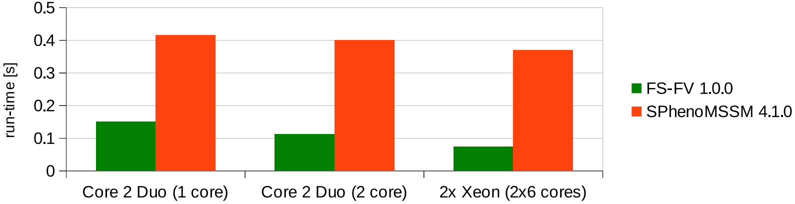
NMSSM Higgs-Masse FlexibleSUSY vs. SOFTSUSY



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

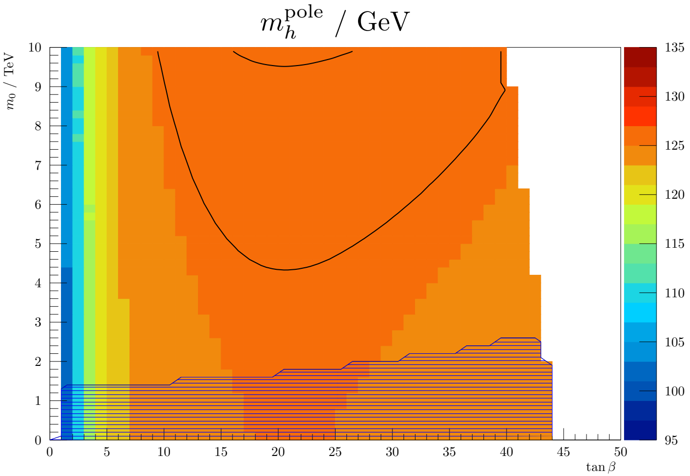
CMSSM-Laufzeitvergleich





g++ 4.8.0, ifort 13.1.3 20130607

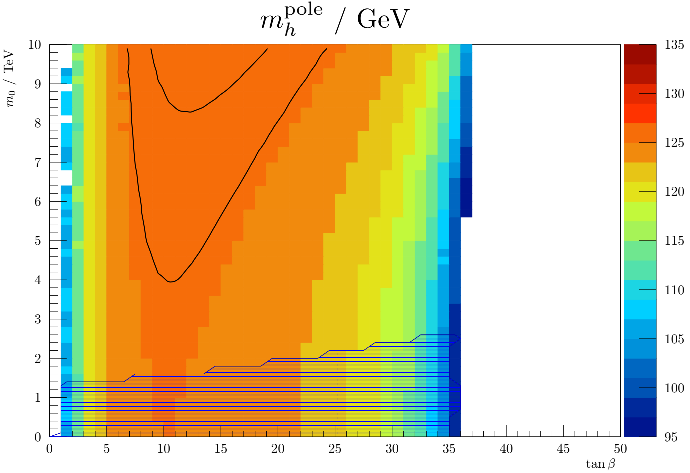
MSSM-Parameterscan



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

Higgs-Massenkonturen bei $m_h^{\text{pole}} = (125.7 \pm 0.4)\,\text{GeV}$

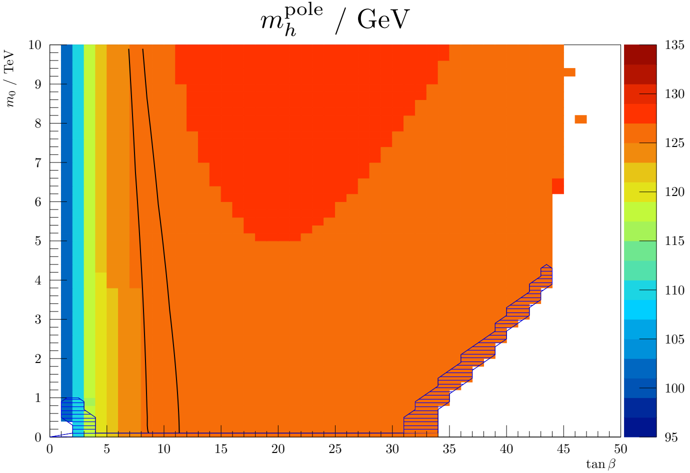
NMSSM-Parameterscan



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

Higgs-Massenkonturen bei $m_h^{\text{pole}} = (125.7 \pm 0.4)\,\text{GeV}$

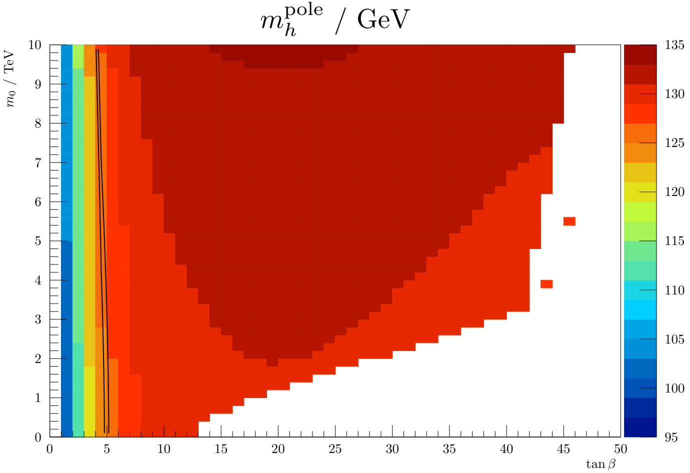
USSM-Parameterscan



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

Higgs-Massenkonturen bei $m_h^{\text{pole}} = (125.7 \pm 0.4)\,\text{GeV}$

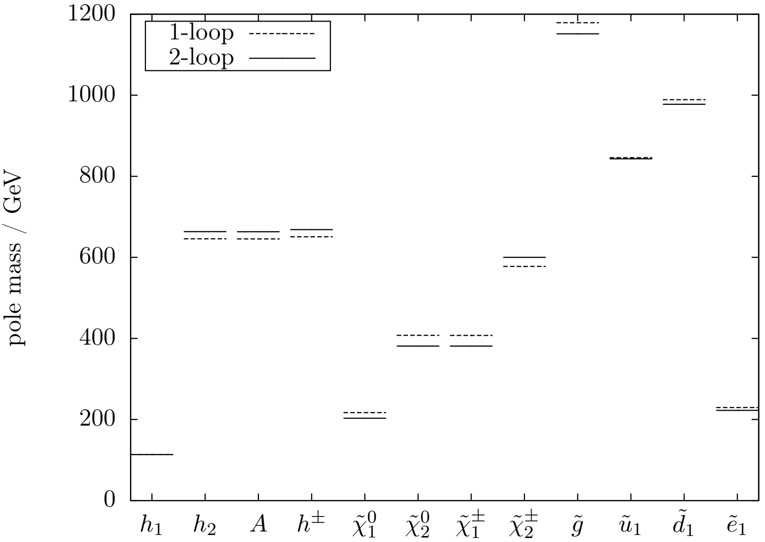
E_6SSM-Parameterscan



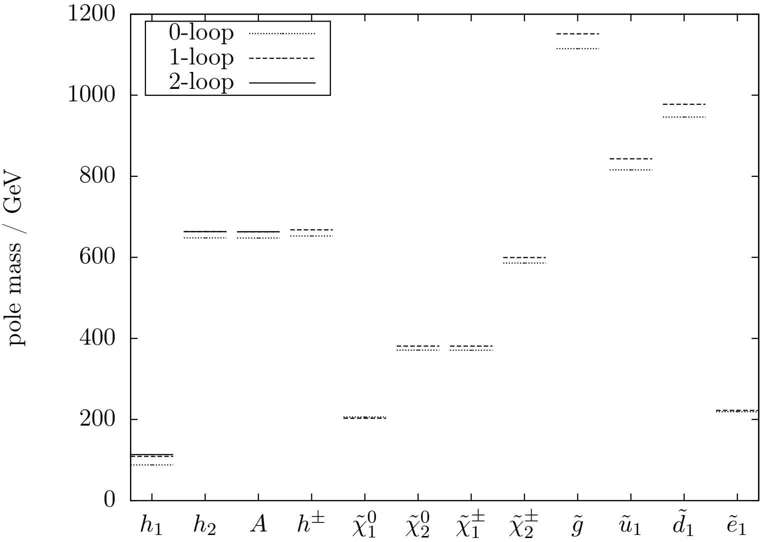
$M_{1/2} = A_0 = 5\,\text{TeV}, \lambda(M_X) = \kappa(M_X) = 0.1, v_s = 10\,\text{TeV}$

Higgs-Massenkonturen bei $m_h^{\text{pole}} = (125.7 \pm 0.4)\,\text{GeV}$

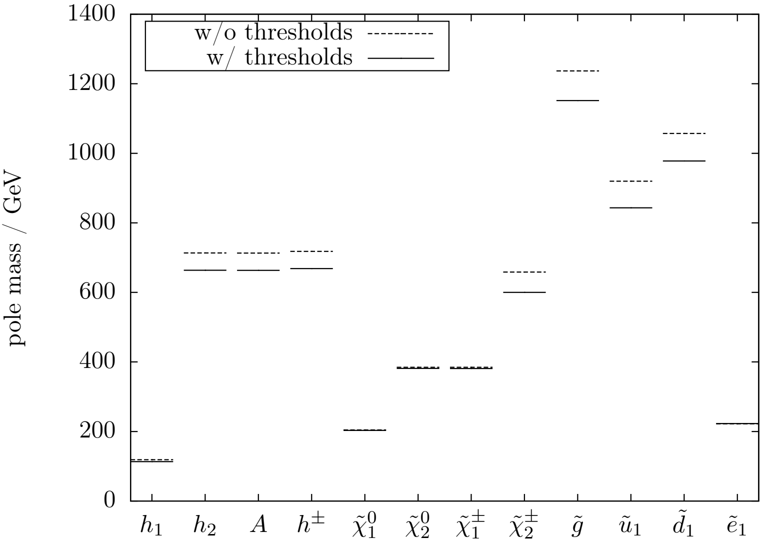
Einfluss der β-Funktionen-Loop-Ordnung (MSSM)



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

Verfügbare SUSY-Spektrumgeneratoren

Modell	Spektrumgenerator
MSSM	ISASUSY, SOFTSUSY, SPheno, SuSeFlav, SuSpect
NMSSM	NMSPEC, SOFTSUSY
USSM	–
CE_6SSM	CE6SSMSpecGen
beliebiges SUSY-Modell	SARAH, FlexibleSUSY

FlexibleSUSY Design-Ziele

- **modularer, gut lesbarer C++-Code**
  Grund: große Vielfalt an SUSY-Modellen
  $\rightarrow$ Benutzereingriff wahrscheinlich
- **hohe Rechengenauigkeit**
  Grund: Higgsmasse gemessen mit $\sigma \approx 0.4\,\text{GeV}$
  (führende 2-Loop m_h, $y_{t,b}$; volle 2-Loop β_i, 1-Loop Σ_i)
- **verschiedene RGE+RB-Lösungsalgorithmen**
  Grund: Konvergenzprobleme
  (Two-scale, Lattice, ...)
- **hohe Rechengeschwindigkeit**
  Grund: viele freie Modellparameter
  (C++ expression templates, multithreading, ...)

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

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

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

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

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

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

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

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

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

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

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

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

mSUGRA-inspired GUT constraint:

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

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

E_6SSM

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

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

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

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

E_6SSM-Teilcheninhalt

Feld	$G_{\text{SM}} \times U(1)_N$	$SU(5) \times U(1)_N$	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^a_g	$(\mathbf{8}, \mathbf{1}, 0, 0)$	$\ni (\mathbf{24}, 0)$	$\ni (\mathbf{78})$
V^i_W	$(\mathbf{1}, \mathbf{3}, 0, 0)$	$\ni (\mathbf{24}, 0)$	$\ni (\mathbf{78})$
V_Y	$(\mathbf{1}, \mathbf{1}, 0, 0)$	$\ni (\mathbf{24}, 0)$	$\ni (\mathbf{78})$
V_N	$(\mathbf{1}, \mathbf{1}, 0, 0)$	$\ni (\mathbf{1}, 0)$	$\ni (\mathbf{78})$

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

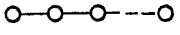
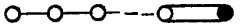
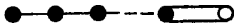
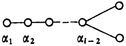
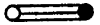
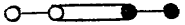
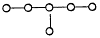
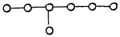
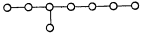
Zerlegung der E_6 bezüglich $SO(10) \times U(1)_\psi$:

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

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	$SU(l+1)$		$e_i - e_j (i, j = 1, \ldots, l+1)$
$l(2l+1)$ $l \geq 2$	B_l	$SO(2l+1)$		$\pm e_i$ and $\pm e_i \pm e_j\ (i, j = 1, \ldots, l)$
$l(2l+1)$ $l \geq 3$	C_l	$Sp(2l)$		$\pm 2e_i$ and $\pm e_i \pm e_j\ (i, j = 1, \ldots, l)$
$l(2l-1)$ $l \geq 4$	D_l	$SO(2l)$		$\pm e_i \pm e_j\ (i, j = 1, \ldots, l)$
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)

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

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

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

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

Sanfte Supersymmetrie-Brechung

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

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)

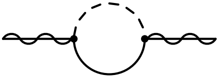
Messenger Superfields transform under $SU(3)_c \times SU(2)_L \times U(1)_Y$:

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

Coupled to a gauge singlet S in the messenger sector:

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

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:



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

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

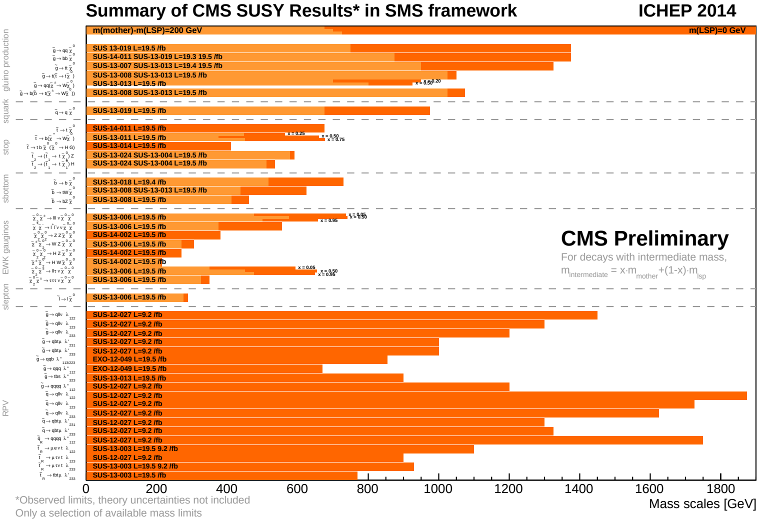
$\sqrt{s}$ = 7, 8 TeV

Category	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde q,\tilde g$ 1.7 TeV	$m(\tilde q)=m(\tilde g)$	1405.7875
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde g$ 1.2 TeV	any $m(\tilde q)$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde g$ 1.1 TeV	any $m(\tilde q)$	1308.1841
	$\tilde q\tilde q$, $\tilde q\to q\tilde\chi_1^0$	0	2-6 jets	Yes	20.3	$\tilde q$ 850 GeV	$m(\tilde\chi_1^0)$=0 GeV, m(1st gen. $\tilde q$)=m(2nd gen. $\tilde q$)	1405.7875
	$\tilde g\tilde g$, $\tilde g\to q\bar q\tilde\chi_1^0$	0	2-6 jets	Yes	20.3	$\tilde g$ 1.33 TeV	$m(\tilde\chi_1^0)$=0 GeV	1405.7875
	$\tilde g\tilde g$, $\tilde g\to qq\tilde\chi_1^\pm\to qqW^\pm\tilde\chi_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde g$ 1.18 TeV	$m(\tilde\chi_1^0)$<200 GeV, $m(\tilde\chi^\pm)=0.5(m(\tilde\chi_1^0)+m(\tilde g))$	ATLAS-CONF-2013-062
	$\tilde g\tilde g$, $\tilde g\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde\chi_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde g$ 1.12 TeV	$m(\tilde\chi_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde\ell$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde g$ 1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde\ell$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde g$ 1.6 TeV	$\tan\beta$>20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde g$ 1.28 TeV	$m(\tilde\chi_1^0)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 e,μ + γ	-	Yes	4.8	$\tilde g$ 619 GeV	$m(\tilde\chi_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde g$ 900 GeV	$m(\tilde\chi_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde g$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde G)>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde g$ med.	$\tilde g\to b\bar b\tilde\chi_1^0$	0	3 b	Yes	20.1	$\tilde g$ 1.25 TeV	$m(\tilde\chi_1^0)$<400 GeV	1407.0600
	$\tilde g\to t\bar t\tilde\chi_1^0$	0	7-10 jets	Yes	20.3	$\tilde g$ 1.1 TeV	$m(\tilde\chi_1^0)$ <350 GeV	1308.1841
	$\tilde g\to t\bar t\tilde\chi_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde g$ 1.34 TeV	$m(\tilde\chi_1^0)$<400 GeV	1407.0600
	$\tilde g\to b\bar t\tilde\chi_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde g$ 1.3 TeV	$m(\tilde\chi_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde b_1\tilde b_1$, $\tilde b_1\to b\tilde\chi_1^0$	0	2 b	Yes	20.1	$\tilde b_1$ 100-620 GeV	$m(\tilde\chi_1^0)$<90 GeV	1308.2631
	$\tilde b_1\tilde b_1$, $\tilde b_1\to t\tilde\chi_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde b_1$ 275-440 GeV	$m(\tilde\chi_1^\pm)$=2 $m(\tilde\chi_1^0)$	1404.2500
	$\tilde t_1\tilde t_1$(light), $\tilde t_1\to b\tilde\chi_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde t_1$ 110-167 GeV	$m(\tilde\chi_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde t_1\tilde t_1$(light), $\tilde t_1\to Wb\tilde\chi_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde t_1$ 130-210 GeV	$m(\tilde\chi_1^0)=m(\tilde t_1)-m(W)$-50 GeV, $m(\tilde t_1)<<m(\tilde\chi_1^\pm)$	1403.4853
	$\tilde t_1\tilde t_1$(medium), $\tilde t_1\to t\tilde\chi_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde t_1$ 215-530 GeV	$m(\tilde\chi_1^0)$=1 GeV	1403.4853
	$\tilde t_1\tilde t_1$(medium), $\tilde t_1\to b\tilde\chi_1^\pm$	0	2 b	Yes	20.1	$\tilde t_1$ 150-580 GeV	$m(\tilde\chi_1^0)$<200 GeV, $m(\tilde\chi_1^\pm)-m(\tilde\chi_1^0)$=5 GeV	1308.2631
	$\tilde t_1\tilde t_1$(heavy), $\tilde t_1\to t\tilde\chi_1^0$	1 e,μ	1 b	Yes	20	$\tilde t_1$ 210-640 GeV	$m(\tilde\chi_1^0)$=0 GeV	1407.0583
	$\tilde t_1\tilde t_1$(heavy), $\tilde t_1\to t\tilde\chi_1^0$	0	2 b	Yes	20.1	$\tilde t_1$ 260-640 GeV	$m(\tilde\chi_1^0)$=0 GeV	1406.1122
	$\tilde t_1\tilde t_1$, $\tilde t_1\to c\tilde\chi_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde t_1$ 90-240 GeV	$m(\tilde t_1)-m(\tilde\chi_1^0)$<85 GeV	1407.0608
	$\tilde t_1\tilde t_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde t_1$ 150-580 GeV	$m(\tilde\chi_1^0)$>150 GeV	1403.5222
	$\tilde t_2\tilde t_2$, $\tilde t_2\to\tilde t_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde t_2$ 290-600 GeV	$m(\tilde\chi_1^0)$<200 GeV	1403.5222
EW direct	$\tilde\ell_{L,R}\tilde\ell_{L,R}$, $\tilde\ell\to\ell\tilde\chi_1^0$	2 e,μ	0	Yes	20.3	$\tilde\ell$ 90-325 GeV	$m(\tilde\chi_1^0)$=0 GeV	1403.5294
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+\to\tilde\ell\nu(\ell\tilde\nu)$	2 e,μ	0	Yes	20.3	$\tilde\chi_1^\pm$ 140-465 GeV	$m(\tilde\chi_1^0)$=0 GeV, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi_1^\pm)+m(\tilde\chi_1^0))$	1403.5294
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+\to\tilde\tau\nu(\tau\tilde\nu)$	2 τ	-	Yes	20.3	$\tilde\chi_1^\pm$ 100-350 GeV	$m(\tilde\chi_1^0)$=0 GeV, $m(\tilde\tau,\tilde\nu)=0.5(m(\tilde\chi_1^\pm)+m(\tilde\chi_1^0))$	1407.0350
	$\tilde\chi_1^\pm\tilde\chi_2^0\to\tilde\ell_L\nu\tilde\ell_L\ell(\tilde\nu\nu)$, $\ell\tilde\nu\tilde\ell_L\ell(\tilde\nu\nu)$	3 e,μ	0	Yes	20.3	$\tilde\chi_1^\pm,\tilde\chi_2^0$ 700 GeV	$m(\tilde\chi_1^\pm)=m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)$=0, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi_1^\pm)+m(\tilde\chi_1^0))$	1402.7029
	$\tilde\chi_1^\pm\tilde\chi_2^0\to W\tilde\chi_1^0Z\tilde\chi_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde\chi_1^\pm,\tilde\chi_2^0$ 420 GeV	$m(\tilde\chi_1^\pm)=m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde\chi_1^\pm\tilde\chi_2^0\to W\tilde\chi_1^0h\tilde\chi_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde\chi_1^\pm,\tilde\chi_2^0$ 285 GeV	$m(\tilde\chi_1^\pm)=m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde\chi_2^0\tilde\chi_3^0$, $\tilde\chi_{2,3}^0\to\tilde\ell_R\ell$	4 e,μ	0	Yes	20.3	$\tilde\chi_{2,3}^0$ 620 GeV	$m(\tilde\chi_2^0)=m(\tilde\chi_3^0)$, $m(\tilde\chi_1^0)$=0, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi_2^0)+m(\tilde\chi_1^0))$	1405.5086
Long-lived particles	Direct $\tilde\chi_1^+\tilde\chi_1^-$ prod., long-lived $\tilde\chi_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde\chi_1^\pm$ 270 GeV	$m(\tilde\chi_1^\pm)-m(\tilde\chi_1^0)$=160 MeV, $\tau(\tilde\chi_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde g$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde g$ 832 GeV	$m(\tilde\chi_1^0)$=100 GeV, 10 $\mu s<\tau(\tilde g)<$1000 s	1310.6584
	GMSB, stable $\tilde\tau$, $\tilde\chi_1^0\to\tilde\tau(\tilde e,\tilde\mu)+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde\chi_1^0$ 475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde\chi_1^0\to\gamma\tilde G$, long-lived $\tilde\chi_1^0$	2 γ	-	Yes	4.7	$\tilde\chi_1^0$ 230 GeV	0.4<$\tau(\tilde\chi_1^0)$<2 ns	1304.6310
	$\tilde q\tilde q$, $\tilde\chi_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde q$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde\chi_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde\nu_\tau+X$, $\tilde\nu_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde\nu_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde\nu_\tau+X$, $\tilde\nu_\tau\to e(\mu)+\tau$	1 e,μ + τ	-	-	4.6	$\tilde\nu_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde q,\tilde g$ 1.35 TeV	$m(\tilde q)=m(\tilde g)$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+\to W\tilde\chi_1^0$, $\tilde\chi_1^0\to ee\tilde\nu_\mu, e\mu\tilde\nu_e$	4 e,μ	-	Yes	20.3	$\tilde\chi_1^\pm$ 750 GeV	$m(\tilde\chi_1^0)$>0.2×$m(\tilde\chi_1^\pm)$, $\lambda_{121}\neq0$	1405.5086
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+\to W\tilde\chi_1^0$, $\tilde\chi_1^0\to\tau\tau\tilde\nu_e, e\tau\tilde\nu_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde\chi_1^\pm$ 450 GeV	$m(\tilde\chi_1^0)$>0.2×$m(\tilde\chi_1^\pm)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde g\to qqq$	0	6-7 jets	-	20.3	$\tilde g$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde g\to\tilde t_1 t$, $\tilde t_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde g$ 850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\to q\bar q$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar t$	2 e,μ (SS)	2 b	Yes	14.3	sgluon 350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

10^{-1} 1 **Mass scale [TeV]**

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

*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.



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