SPheno 3.1: extensions including flavour, CP-phases and models beyond the MSSM

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Outline

Introduction

- The first version of `SPheno` has been published 2003
- From the beginning written in Fortran 95
- Optimized for a fast calculation of the MSSM mass spectrum neglecting flavor mixing and CP violation
- Routines for SUSY decays and SUSY production at e^+e^- already included

Introduction

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SPheno 3

`SPheno` 3 provides many new features: possibility of CP phases, flavor mixing, calculation of low-energy observables and models beyond the MSSM. It can be downloaded from

`http://projects.hepforge.org/spheno/`

Calculation of the mass spectrum

The SUSY masses in the MSSM as well as in extensions are calculated with a high precision

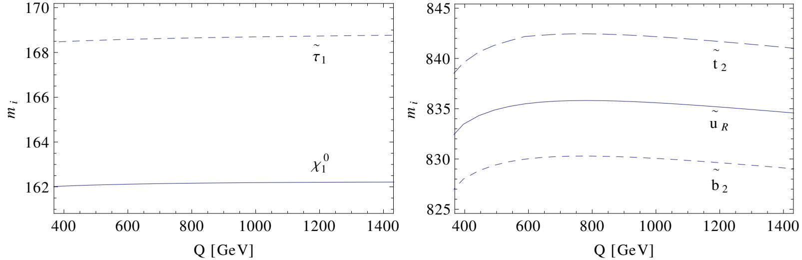
Mass spectrum calculation

- 2-loop RGEs including all CP phases and full flavor structure are used
- All thresholds of SUSY particles at EW scale taken into account
- The 1-loop corrections to all SUSY masses include the dependence on the external momenta ('t Hooft gauge, $\overline{DR}$ scheme)
- Complete 1-loop corrections to the Higgs masses and dominant 2-loop corrections $\mathcal{O}(\alpha_S^2, Y_i^2\alpha_S, Y_i^2 Y_j^2)$, $i, j = t, b, \tau$

Mixing between CP even and odd Higgs fields not yet implemented.

Scale dependence

$M_{1/2} = 400$ GeV, $m_0 = 90$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$



Variation of Q gives impression of theoretical uncertainty:

- Charginos, neutralinos and sleptons: few per-mile
- Squarks: roughly factor 2 larger
- Gluino: up to 2 per-cent
- Higgs: 1-2 per-cent

Decays of SUSY particle

For all the decays the complete flavor and CP structure is taken into account

Sparticle decays

- All two-body decay modes of all SUSY particles are calcualted at tree-level
- In addition, 1-loop decays are included
  - $\tilde{\chi}^0_i \to \tilde{\chi}^0_j \gamma$
  - $\tilde{g} \to \tilde{\chi}^0_i g$
- Three body decays of all SUSY fermions in fermionic final states calculated
- Three body decays of stops are included

General agreement with SDECAY and WHIZARD

Routines for 3-body scalar decays exists and are tested

Higgs decays

Also for Higgs decays the CP phases and possible flavor mixing is included

Higgs decays

- All two body decays at tree level but in quarks
- The two body decays in quarks include gluonic 1-loop corrections
- 1-loop induced decays $\phi \to gg$ and $\phi \to \gamma\gamma$ ($\phi = h, H, A^0$)
- Possible decays in a real and a virtual gauge boson are added ($h \to ZZ^*/W^+W^{-,*}/W^-W^{+,*}$)

- Mostly agreement with other codes
- For $\phi \to gg$ QCD corrections are missing which are included e.g. in `FeynHiggs`, `HDECAY` or `HFOLD`

Low-energy observables

(semi-) hadronic observables

- Radiative decays: $BR(b \to s\gamma)$
- bottom decays: $BR(b \to s\mu^+\mu^-)$, $BR(b \to s\sum_i \nu_i\nu_i)$
- B-meson decays: $BR(B_d^0 \to \mu^+\mu^-)$, $BR(B_s^0 \to \mu^+\mu^-)$, $BR(B_u \to \tau^+\nu)$
- B-mixing: $\Delta M_{B_s^0}$ and $\Delta M_{B_d^0}$

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leptonic observables

- electric dipole moments (EDMs) of the leptons
- two body decays $\mu \to e\gamma$, $\tau \to e\gamma$ and $\tau \to \mu\gamma$
- three body decays $\mu \to ee^+e^-$, $\tau \to ee^+e^-$ and $\tau \to \mu\mu^+\mu^-$
- Z decays, $Z \to e^\pm\mu^\mp$, $Z \to e^\pm\tau^\mp$ and $Z \to \mu^\pm\tau^\mp$

Comparison with other flavor codes

Other public code for the calculation of flavor observabales:

SUSY_FLAVOUR , SusyBSG , SuperIso , Micromegas

Good agreement

In general there is a good agreement between SPheno and the other tools

→ detailed comparison by L. Hofer and W. Porod in preparation

In- and Output

- SPheno fully supports SLHA 2 conventions for the MSSM and bilinear RpV
- Many features can be swichted on/off or adjusted with the LesHouches input file (numerical precision, loop level, ...)
- If necessary, SLHA 1 can be used for the output
- For seesaw models the proposals of the 2011 LH working group are used
- Support of FLHA for the output of the low energy observables partly included and going to be extended
- Additional blocks for HiggsBounds are included

  $\rightarrow$ Spectrum file can directly be used to check Higgs constraints

MSSM

Several GUT boundary conditions in case of the MSSM can be used

GUT Boundary conditions

- CMSSM (mSugra): m_0, $M_{1/2}$, $\tan\beta$, sign(μ), A_0
- NUHM: CMSSM + $m^2_{H_d}$, $m^2_{H_u}$ or μ, m_A
- GMSB: Λ, M_{Mess}, $\tan\beta$, sign(μ), n_5, c_g

  $\rightarrow$ Gravitino included in decays
- AMBS: m_0, $M_{3/2}$, $\tan\beta$, sign(μ)

- In case of CMSSM also othter GUT parameters can defined independently using `EXTPAR`
- In addition, also a SUSY scale input is possible.

Seesaw models

Seesaw I: up to three generations of gauge singlets

$$W^{I} = Y_{\nu}\,\hat{N}\,\bar{5}_{M}\,5_{H} + \frac{1}{2}\hat{N}M_{N}\hat{N}\ .$$

Seesaw models

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Seesaw II: either two complete $SU(5)$ 15-plets or only triplets

$$\begin{aligned} W^{II} &= \frac{1}{\sqrt{2}} \left(Y_T \, \hat{l} \, \hat{T} \, \hat{l} + Y_S \, \hat{d} \, \hat{S} \, \hat{d} \right) + Y_Z \, \hat{d} \, \hat{Z} \, \hat{l} + \frac{1}{\sqrt{2}} \lambda_1 \hat{H}_d \hat{T} \hat{H}_d \\ & + \frac{1}{\sqrt{2}} \lambda_2 \hat{H}_u \hat{\bar{T}} \hat{H}_u + M_T \hat{T} \hat{\bar{T}} + M_Z \hat{Z} \hat{\bar{Z}} + M_S \hat{S} \hat{\bar{S}} \; . \end{aligned}$$

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Seesaw III: up to three generations of $SU(5)$ 24-plets

$$\begin{aligned} W^{III} &= + \hat{H}_u (\hat{W}_M Y_N - \sqrt{\frac{3}{10}} \hat{B}_M Y_B) \hat{L} + \hat{H}_u \hat{\bar{X}}_M Y_X \hat{D}^c \\ &+ \frac{1}{2} (\hat{B}_M M_B \hat{B}_M + \hat{G}_M M_G \hat{G}_M + \hat{W}_M M_W \hat{W}_M) + \hat{X}_M M_X \hat{\bar{X}}_M \end{aligned}$$

More about seesaw

Boundary conditions

The GUT conditions for the seesaw parameters are chosen to be $SU(5)$ invariant:

- Seesaw I: M_R, Y_ν
- Seesaw II: M_{15}, Y_{15}, λ_1, λ_2
- Seesaw III: M_{24}, Y_{24}

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Each generation of heavy multiplets is integrated out at a separate threshold scale:

- 1-loop boundary conditions for gauge couplings and gauginos included
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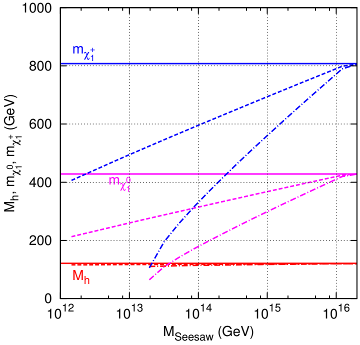
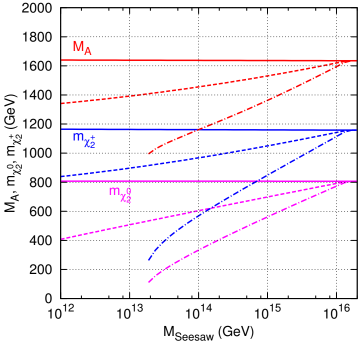
For the Weinberg operator also 2-loop RGEs are used and the neutrino masses are calculated at 1-loop

Masses in Seesaw I – III

[Esteves,Hirsch,Porod,Romao,FS,1010.6000]

$m_0 = M_{1/2} = 1$ TeV, $\tan\beta = 10, \mu > 0$



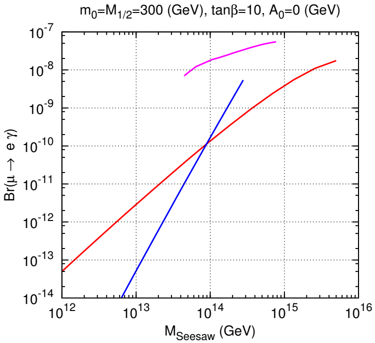


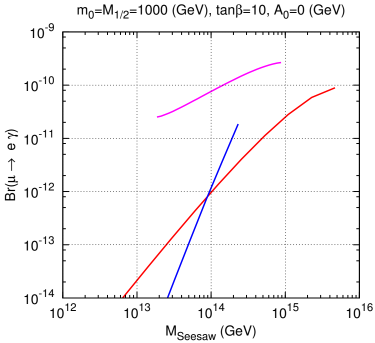
$M_h, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^+}$ $\quad$ $M_A, m_{\chi_2^0}, m_{\tilde{\chi}_2^+}$

full lines: type-I, dashed lines: type-II, dash-dotted lines: type-III

$\text{Br}(\mu \to e\gamma)$ in Seesaw I – III

[Esteves,Hirsch,Porod,Romao,FS,1010.6000]





red lines: type-I, blue lines: type-II, magenta lines: type-III

R-parity violation

Bilinear RpV

$$W = W_{MSSM} + \epsilon_i \hat{l}_i \hat{H}_u$$

R-parity violation

Bilinear RpV

$$W = W_{MSSM} + \epsilon_i \hat{l}_i \hat{H}_u$$

- Soft-breaking terms B_{ϵ_i} and Vacuum expectation values v_L^i of sneutrinos included
- All possible mixings are taken into account:
  - 7×7 neutralino/neutrino matrix
  - 5×5 chargino/lepton matrix
  - 8×8 charged Higgs/slepton matrix
  - two 5×5 Higgs/sneutrino matrices
- Routines for decay modes and e^+e^- scattering adjusted accordingly

Implementation of other models

A large variety of other models can be implemented by the user using the Mathematica package SARAH:

SPheno and SARAH

- Model is defined in a short form in SARAH
- SARAH calculates the RGEs, vertices, mass matrices and expressions for loop corrections
- This information is used by SARAH to generates Fortran code
- The code can be compiled together with SPheno

→ Creates a precision spectrum generator for a new model with nearly the same features as SPheno provides for the MSSM

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See also the talk about SARAH from Monday

Tested SPheno modules

So far SPheno modules by SARAH have been intensively tested for several models:

- MSSM: Cross checked with SPheno and other spectrum calculators (1109.5147)
- Seesaw I–III: cross checked with SPheno implementations (1109.5147)
- NMSSM: Cross checked with NMSSM-Tools (1007.4049)
- Lepton number violating, trilinear RpV (1204.5925)
- $SU(2)_L \times SU(2)_R$ with two intermediated scales (1011.0348,1109.6478)
- Model with additional $B - L$ gauge group (1112.4600)
- Model with $U(1)_R \times U(1)_{B-L}$ gauge sector (1110.3037)

Other models (e.g, linear seesaw, inverse seesaw, E6SSM,. . .) are used and tested at the moment.

$U(1)_R \times U(1)_{B-L}$ - The model

[Hirsch,Malinsky,Porod,Reichert,FS,1110.3037],[Hirsch,Porod,Reichert,FS,1206.XXXX]

- Gauge sector: Motivated by $SO(10)$:

$$SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$$

$SU(2)_L \times U(1)_R \times U(1)_{B-L} \to U(1)_{em}$ at the TeV scale

- Particle content: 3 Generations of $SO(10)$ 16-plets and ...

Superfield	$SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$
$\hat{H}_u$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2}, 0)$
$\hat{H}_d$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 0)$
$\hat{\chi}_R$	$(\mathbf{1}, \mathbf{1}, +\frac{1}{2}, -\frac{1}{2})$
$\hat{\bar{\chi}}_R$	$(\mathbf{1}, \mathbf{1}, -\frac{1}{2}, +\frac{1}{2})$

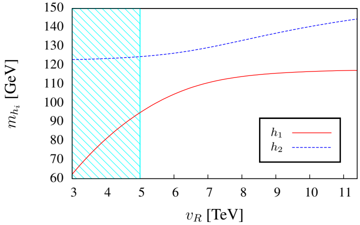
- Superpotential

$$W = Y_u \hat{u}^c \hat{Q} \hat{H}_u - Y_d \hat{d}^c \hat{Q} \hat{H}_d + Y_\nu \hat{\nu}^c \hat{L} \hat{H}_u - Y_e \hat{e}^c \hat{L} \hat{H}_d + \mu \hat{H}_u \hat{H}_d$$
$$- \mu_R \hat{\bar{\chi}}_R \hat{\chi}_R + Y_s \hat{\nu}^c \hat{\chi}_R \hat{S}$$

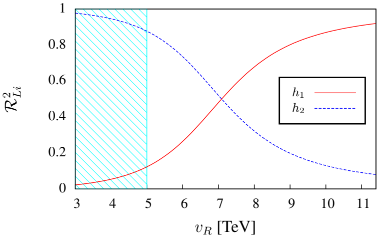
- Mass eigenstates: 4 CP even Higgs, 2 CP odd Higgs, 9 neutrinos, 9 sneutrinos, γ, Z, Z'. Charged sector MSSM-like.

$U(1)_R \times U(1)_{B-L}$ - Results for Higgs sector I

[Hirsch,Malinsky,Porod,Reichert,FS,1110.3037],[Hirsch,Porod,Reichert,FS,1206.XXXX]



masses of the two lightest scalars



$SU(2)_L$ doublet fraction $R^2_{i1} + R^2_{i2}$

Shaded blue area excluded by Z' searches
Mass spectrum based on parameters: $M_{1/2} = 800$ GeV, $m_0 = 250$ GeV, $A_0 = 0$, $\tan\beta = 10$.
Higgs Sector: $M_{A_R} = 2.35$ TeV, $\mu_R = 800$ GeV $\tan\beta_R = 0.94$

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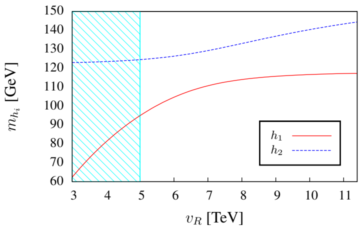

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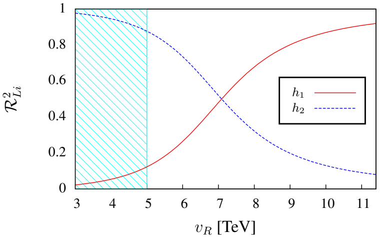

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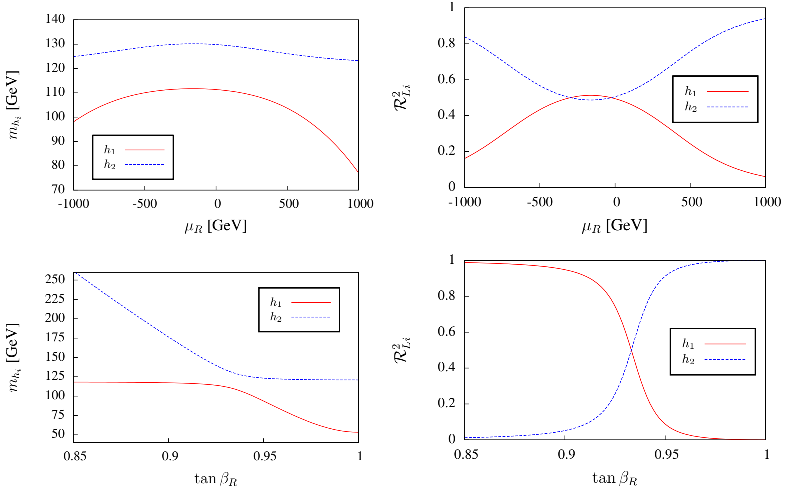
Increased MSSM Higgs mass

Near and below the level crossing the mass of the MSSM-like Higgs is significantly increased

$U(1)_R \times U(1)_{B-L}$ - Results for Higgs sector II

$m_0 = 0.25$ TeV, $A_0 = 0$, $M_{1/2} = 0.8$ TeV, $\tan\beta = 10$, $v_R = 6$ TeV, $M_{A_R} = 2.35$ TeV



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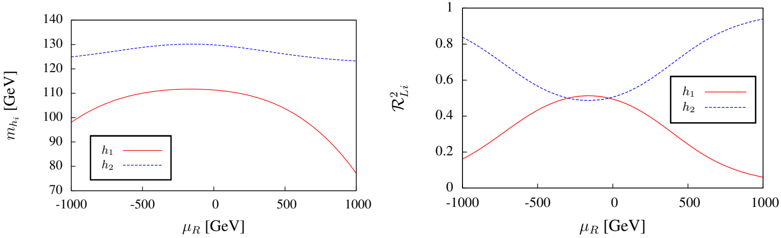

- Only small ranges for $\tan\beta_R$ possible (D-flatness) because of contributions to sfermion masses due to D-terms:

$$D \simeq \pm g_{BL}^2 (v_{\chi_R}^2 - v_{\bar{\chi}_R}^2) + g_R^2 (v_u^2 - v_d^2)$$

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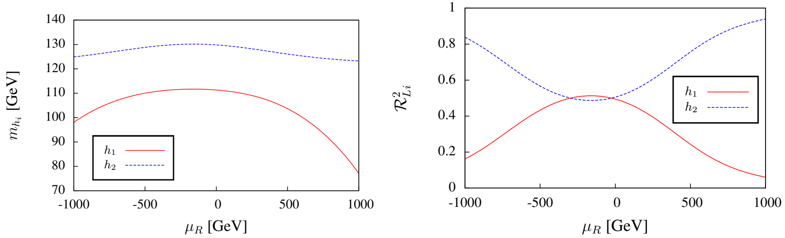

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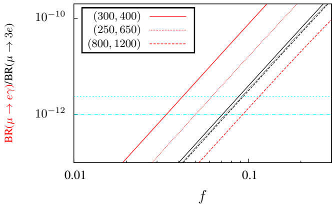
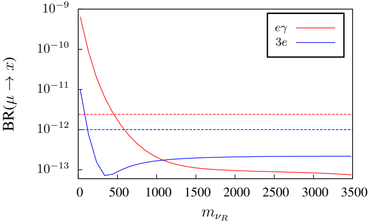
- Higgs masses of 125 GeV can easily be reached
- Very light, right-handed Higgs pass all constraints

$U(1)_R \times U(1)_{B-L}$ - Results for LFV

Large neutrino Yukawa couplings are possible but constraint by lepton flavor observables





New features in contrast to high scale seesaw

- It can be $\text{Br}(\mu \to 3e) > \text{Br}(\mu \to e\gamma)$ for a heavy spectrum because of Z^0 penguins
- W^+ loop with heavy neutrinos can be very important

Summary

- SPheno 3.1 extends the possibilites to study the MSSM by including of CP phases and flavor mixing
- A set of important flavor observables is calculated and in good agreement with other codes
- Seesaw models and bilinear RpV fully implemented
- Other models beyond the MSSM can easily be added by using SARAH