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German-Egyptian School of Particle Physics Cairo, 28. February 2013

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Outline

Introduction to SARAH

 \rightarrow Tutorial I

SARAH model files

 \rightarrow Tutorial II

The SUSY-Toolbox and SSP

 \rightarrow Tutorial III

Why it might be necessary to extend the $\ensuremath{\mathsf{MSSM}}$

The MSSM has very nice features:

- It solves the hierarchy problem
- It leads to gauge coupling unification
- It provides often a Dark Matter candidate
- ► It can explain EWSB

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However, there remain open questions which demand extensions

- ▶ Neutrino masses → R-parity violation or Seesaw mechanism?
- The μ problem \rightarrow effective μ term?
- Parity \rightarrow left-right symmetry at higher scales?
- ▶ R-symmetry → Dirac gaugino masses?
- Heavy higgs mass & diphoton rate \rightarrow extended Higgs sector?

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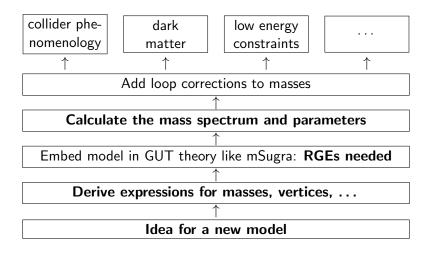
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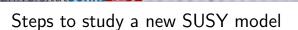
Need to study many different models



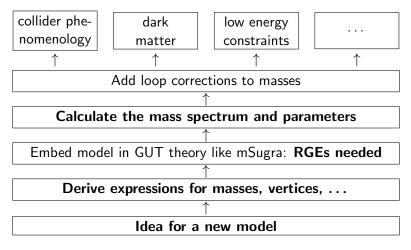
Steps to study a new SUSY model

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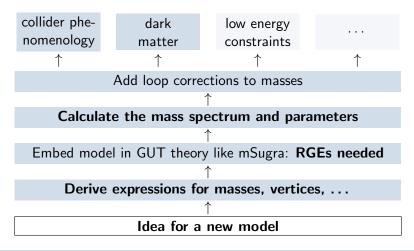
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looks like a long and exhaustive way

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Steps to study a new SUSY model



is covered in a completely automatized way now!

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SARAH

SARAH

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[FS,0806.0538],[FS,0909.2863],[FS,1002.0840],[FS,1207.0906]

Introduction to SARAH

SARAH

SARAH is a Mathematica package to get with minimal amount of information all properties of a (N = 1)-SUSY-model

SARAH

SARAH

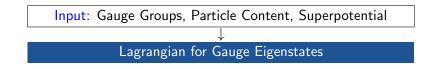
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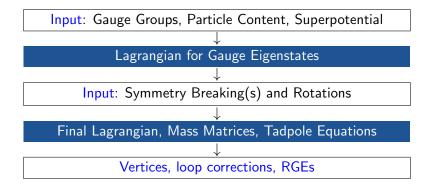
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Introduction to SARAH

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SARAH is a Mathematica package to get with minimal amount of information all properties of a (N = 1)-SUSY-model



Supported Models

SARAH can handle a large variety of models

Particle Content and Interactions

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- ► Gauge sector can be any direct product of SU(N) groups
- ► All irreducible representations of *SU*(*N*) for chiral superfields are possible
- Matter interactions are defined in a compact form by superpotential
- All gauge interactions are added automatically

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- Matter interactions are defined in a compact form by superpotential
- All gauge interactions are added automatically
- Arbitrary number of field rotations/symmetry breakings
- Dirac gauginos fully supported with version 3.2.0
- Non canonical terms can be added to the Lagrangian

Introduction to SARAH

Implemented (public) models:

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- MSSM: with/without FV or CPV
- Low scale extensions of the MSSM:
 - Singlet extensions: NMSSM, nMSSM, SMSSM (GNMSSM)
 - Triplet extensions: TMSSM, TNMSSM
 - R-parity violation: bilinear RpV, Lepton/Baryon number violation, μνSSM
 - ▶ Additional U(1)'s: UMSSM, sMSSM, B-L, $U(1)_R \times U(1)_{B-L}$
 - inverse seesaw, linear seesaw
 - Models with Dirac gauginos: MSSM+DG, MRSSM
- High scale extensions
 - Seesaw 1 3 (SU(5) version)
 - Left/right model (ΩLR)
- Non SUSY models:
 - SM
 - inert doublet model

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What happens automatically:

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- Model is checked for Gauge Anomalies and Witten anomaly
- Charge conservation of superpotential is checked
- Soft SUSY Breaking terms are added
- Complete Lagrangian is calculated for component fields
- Gauge fixing terms in R_{ξ} gauge are derived automatically
- Ghost interactions are added

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What happens automatically:

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- Model is checked for Gauge Anomalies and Witten anomaly
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- Soft SUSY Breaking terms are added
- Complete Lagrangian is calculated for component fields
- Gauge fixing terms in R_{ξ} gauge are derived automatically
- Ghost interactions are added

Further checks are possible (function CheckModel):

- Do additional fields mix?
- Are mass matrices reducible?
- Are unbroken charges are conserved in definition of mass matrices?
- Exist additional superpotential terms allowed by gauge invariance? (discrete symmetries not yet considered)

Introduction to SARAH

Information obtained by SARAH

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Tree level relations

- Masses and tadpole equations
- All vertices

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Information obtained by SARAH

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Renormalization group equations

 General 2-loop RGEs for softly broken SUSY
 [Martin,Vaughn,hep-ph/9311340]

 + Support of kinetic mixing
 [Fonseca,Malinsky,Pord,FS,1107.2670]

 + Support of Dirac Gauginos
 [Goodsell,1206.6697]

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 [Goodsell,1206.6697]

One-loop corrections

[Pierce,Bagger,Matchev,Zhang,hep-ph/9606211]

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One-loop tadpoles/self-energies (DR-scheme, 't Hooft gauge)

 \rightarrow formulas for mass spectrum at one-loop

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Output

Model Files

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Model files for CalcHep/CompHep, FeynArts/FormCalc, WHIZARD and in the UFO format can be generated.

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Output

Model Files

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Model files for CalcHep/CompHep, FeynArts/FormCalc, WHIZARD and in the UFO format can be generated.

- The UFO format is supported for instance by MadGraph 5
- The model files for CalcHep can also be used with MicrOmegas

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Output

Model Files

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- The UFO format is supported for instance by MadGraph 5
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PALEX

All derived expressions can also be exported to $\[AT_EX]$ files.

Introduction to SARAH

SARAH and SPheno

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SPheno

[Porod,hep-ph/0301101],[Porod,FS,1104.1573]

Introduction to SARAH

- Calculates SUSY spectrum based on low energy or GUT input
- Calculates two- and three body decay modes of SUSY particle as well as of Higgs bosons
- Includes production cross section in e⁺e⁻ collisions
- Calculates several low energy constraints as $\mu \to e\gamma$, $\delta\rho$, ...

SARAH and SPheno

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${\tt SPheno}$

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SPheno	SARAH
Restricted mostly to MSSM	Supports many models
RGEs, vertices, hardcoded	Calculates everything by its own
Routines for loop integrals, phase space,	Nothing like that
Numerically fast (Fortran)	Numerically slow (Mathematica)

Spectrum generator generator

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SARAH writes source-code for the model which can be compiled with SPheno.

Introduction to SARAH

Spectrum generator generator

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SARAH writes source-code for the model which can be compiled with SPheno.

Features of SPheno by SARAH

- Precise mass calculation using 2-Loop RGEs and 1-Loop corrections
- ▶ MSSM 2-Loop corrections $(O(Y^4, \alpha_S Y^2))$ can be linked.
- All SUSY thresholds at low scale included
- ► Calculation of observables (e.g. $b \rightarrow s\gamma$, $\delta\rho$, $\mu \rightarrow 3e$) for given model with same precision as SPheno does for the MSSM
- Calculation of decay widths and branching ratios

 $(h
ightarrow \gamma \gamma$ and h
ightarrow gg at full LO and partly NLO)

Writes input files for HiggsBounds and WHIZARD

Introduction to SARAH

Outlook

Towards SARAH 4

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- Support of non-SU(N) groups: linking Susyno
- Check for global minimum of the 1-loop eff. potential

[with Carmago,O'Leary,Porod; see also 1212.4146]

- Better support of Non-SUSY models:
 - Simplified input
 - Non-SUSY RGEs

[with Lyonnet,Schienbein,Wingerter]

[with Fonseca]

Important Commands

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- ShowModels: Returns a list with installed models
- Start[''Model'']: Starts the given model
- CheckModel: Performs checks of a model implementation
- MassMatrix[Particle]: Returns the mass matrix
- TadpoleEquation[Particle]: Returns the tadpole equation
- Vertex[Particles]: Calculates the vertex for given states
- MakeVertexList[Options]: Calculates all vertices
- CalcRGEs[Options]: Calculates the RGEs
- MakeFeynArts[Options]: Writes FeynArts model files
- MakeCHep[Options]: Writes CalcHep/CompHep model files
- MakeWHIZARD[Options]: Writes WHIZARD model files
- MakeUFO[Options]: Writes model files in the UFO format
- MakeTeX[Options]: Writes LATEX files
- MakeSPheno[Options]: Writes source code for SPheno

Introduction to SARAH

Tutorial I

The following topics are discussed in the following

1. Using existing models

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- Calculating mass matrices, tadpole equations and vertices
- Writing and using Output for FeynArts and CalcHep
- Creating source code for SPheno

 \rightarrow Tutorial I

Motivation

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The NMSSM solves the $\mu\text{-problem}$ of the MSSM by adding a gauge singlet S to the particle content

Motivation

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The NMSSM solves the $\mu\text{-problem}$ of the MSSM by adding a gauge singlet S to the particle content

Superpotential:

$$W_{\rm MSSM} = -\hat{H}_u \hat{q} Y_u \hat{u} + \hat{H}_d \hat{q} Y_d \hat{d} + \hat{H}_d \hat{l} Y_e \hat{e} + \mu \hat{H}_u \hat{H}_d$$

Motivation

bctp

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Superpotential:

$$W_{\text{NMSSM}} = -\hat{H}_u \hat{q} Y_u \hat{u} + \hat{H}_d \hat{q} Y_d \hat{d} + \hat{H}_d \hat{l} Y_e \hat{e} + \lambda \hat{H}_u \hat{H}_d \hat{S} + \frac{1}{3} \kappa \hat{S} \hat{S} \hat{S}.$$

Motivation

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Superpotential:

$$W_{\text{NMSSM}} = -\hat{H}_u \hat{q} Y_u \hat{u} + \hat{H}_d \hat{q} Y_d \hat{d} + \hat{H}_d \hat{l} Y_e \hat{e} + \lambda \hat{H}_u \hat{H}_d \hat{S} + \frac{1}{3} \kappa \hat{S} \hat{S} \hat{S}.$$

New soft-breaking terms:

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$$V_{SB,NMSSM} = m_S^2 |S|^2 + T_\lambda H_u H_d S + \frac{1}{3} T_\kappa SSS$$

Higgs sector of the NMSSM

bctp

Scalar gauge singlet S receives a VEV v_s after SUSY breaking

$$S = \frac{1}{\sqrt{2}} \left(\phi_s + i\sigma_s + v_s \right)$$

Higgs sector of the NMSSM

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Scalar gauge singlet S receives a VEV v_s after SUSY breaking

$$S = \frac{1}{\sqrt{2}} \left(\phi_s + i\sigma_s + v_s \right)$$

μ term

The generated μ -term is of order SUSY-breaking scale

$$\mu_{\rm eff} = \frac{1}{\sqrt{2}} \lambda v_s.$$

Higgs sector of the NMSSM

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μ term

The generated μ -term is of order SUSY-breaking scale

$$\mu_{\rm eff} = \frac{1}{\sqrt{2}} \lambda v_s.$$

The Higgs sector of the NMSSM consists in total of

- Three CP-even scalar Higgs h_i
- Two physical CP-odd pseudo scalar Higgs A⁰_i
- ▶ Two physical charged Higgs H^{\pm} with $H^+ = (H^-)^*$

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The gauge sector hasn't to be changed

```
Gauge[[1]]={B, U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left, g2,True};
Gauge[[3]]={G, SU[3], color, g3,False};
```

- The gauge sector hasn't to be changed
- Add singlet superfield

bctp

```
Fields[[1]] = {{uL,dL}, 3, q, 1/6, 2, 3};
...
Fields[[5]] = {conj[dR], 3, d, 1/3, 1, -3};
Fields[[6]] = {conj[uR], 3, u, -2/3, 1, -3};
Fields[[7]] = {conj[eR], 3, e, 1, 1, 1};
```

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bctp

```
Fields[[1]] = {{uL,dL}, 3, q, 1/6, 2, 3};
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Fields[[6]] = {conj[uR], 3, u, -2/3, 1, -3};
Fields[[7]] = {conj[eR], 3, e, 1, 1, 1};
Fields[[8]] = {Sing, 1, S, 0, 1, 1};
```

The name of the component fields will be FuL, FdL, SdL, SuL,...FSing, SSing

- The gauge sector hasn't to be changed
- Add singlet superfield

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Change superpotential

SuperPotential = {{{Yu,1},{q, Hu, u}},
{{Yd,-1},{q, Hd, d}},{{Ye,-1},{1, Hd, e}},
{{
$$\mu,1$$
},{Hu, Hd}};

- The gauge sector hasn't to be changed
- Add singlet superfield

bctp

Change superpotential

```
\begin{split} \text{SuperPotential} &= \{\{\{\text{Yu},1\},\{\text{q},\ \text{Hu},\ u\}\},\\ &\quad \{\{\text{Yd},-1\},\{\text{q},\ \text{Hd},\ d\}\},\{\{\text{Ye},-1\},\{\text{l},\ \text{Hd},\ e\}\},\\ &\quad \{\{\lambda,1\},\{\text{Hu},\ \text{Hd},\ S\}\},\\ &\quad \{\{\kappa,1/3\},\{\text{S},\text{S},\text{S}\}\}\}; \end{split}
```

- The gauge sector hasn't to be changed
- Add singlet superfield

bctp

- Change superpotential
- Give VEV to scalar singlet

```
DEFINITION [EWSB] [VEVs] = {{SHd0, {vd, 1/\sqrt{2}}, {sigmad, 1/\sqrt{2}}, {phid, 1/\sqrt{2}}, {SHu0, {vu, 1/\sqrt{2}}, {sigmau, 1/\sqrt{2}}, {phiu, 1/\sqrt{2}}};
```

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```
\begin{split} & \text{DEFINITION[EWSB][VEVs]} = \\ & \{ \{ \text{SHd0, } \{ \text{vd, } 1/\sqrt{2} \}, \{ \text{sigmad, } 1/\sqrt{2} \}, \{ \text{phid, } 1/\sqrt{2} \} \}, \\ & \{ \text{SHu0, } \{ \text{vu, } 1/\sqrt{2} \}, \{ \text{sigmau, } 1/\sqrt{2} \}, \{ \text{phiu, } 1/\sqrt{2} \} \}, \\ & \{ \text{SSing, } \{ \text{vS, } 1/\sqrt{2} \}, \{ \text{sigmaS, } 1/\sqrt{2} \}, \{ \text{phiS, } 1/\sqrt{2} \} \} \}; \end{split}
```

- The gauge sector hasn't to be changed
- Add singlet superfield

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- Change superpotential
- Give VEV to scalar singlet
- Change particle mixings

```
DEFINITION[EWSB][MatterSector]=
{{{SdL, SdR}, {Sd, ZD}},
...
{{phiu, phid}, {h, ZH}},
{{sigmau, sigmad}, {Ah, ZA}},
{{fB, fW0, FHd0, FHu0}, {L0, ZN},
{{fWm, FHdm}, {fWp, FHup}}, {{Lm,Um}, {Lp,Up}}}}
```

- The gauge sector hasn't to be changed
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```
DEFINITION[EWSB][MatterSector]=
{{{SdL, SdR}, {Sd, ZD}},
...
{{phiu, phid,phiS}, {h, ZH}},
{{sigmau, sigmad,sigmaS}, {Ah, ZA}},
{{fB, fW0, FHd0, FHu0,FSing}, {L0, ZN}},
{{fWm, FHdm}, {fWp, FHup}}, {{Lm,Um}, {Lp,Up}}}}
```

- The gauge sector hasn't to be changed
- Add singlet superfield

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- Change superpotential
- Give VEV to scalar singlet
- Change particle mixings
- Define properties of parameters

```
 \{ \kappa, \{ LaTeX \rightarrow " \setminus \ kappa", \\ Real \rightarrow True, \\ LesHouches \rightarrow \{ EXTPAR, 62 \} \} \}
```

- The gauge sector hasn't to be changed
- Add singlet superfield

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- Change superpotential
- Give VEV to scalar singlet
- Change particle mixings
- Define properties of parameters



- Checking the implementation of the NMSSM in SARAH
- Running the NMSSM in SARAH

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Using the SPheno version of the NMSSM

 \rightarrow Tutorial II

SUSY Toolbox ...

SPheno

WHIZARD

CalcHep

HiggsBounds

MicrOmegas

MadGraph

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FS,Ohl,Porod,Speckner,1109.5147

... is a collection of scripts to create an environment including

► SARAH [FS,0806.0538],[FS,0909.2863],[FS,1002.0840]

[Porod,hep-ph/0301101],[Porod,FS,1104.1573]

[Kilian,Ohl,Reuter,0708.4233],[Moretti,Ohl,Reuter,0102195]

[Bechtle, Brein, Heinemeyer, Weiglein, Williams, 1102.1898]

[Pukhov et. al,hep-ph/9908288

[Belanger,Boudjema,Pukhov,Semenov,hep-ph/0405253]

[Alwall, Herquet, Maltoni, Mattelaer, Stelzer, 1106.0522]

[FS,Ohl,Porod,Speckner,1109.5147]

and to implement new models into the other tools based on the implementation in SARAH

http://projects.hepforge.org/sarah/Toolbox.html

SSP

The SUSY-Toolbox and SSP The SUSY Toolbox

SUSY Toolbox

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FS,Ohl,Porod,Speckner,1109.5147

The SUSY-Toolbox and SSP

The SUSY Toolbox

The SUSY toolbox is a collection of scripts to create an environment including SARAH, SPheno, WHIZARD, HiggsBounds, CalcHep, MicrOmegas and SSP and to implement new models into the other tools based on the implementation in SARAH

http://projects.hepforge.org/sarah/Toolbox.html

Using the SUSY-Toolbox new models implement in all tools with 3 steps:

> ./configure

> make

> ./butler B-L-SSM



Provides an easy way to perform parameter scans using the created environment

SSP - SARAH Scan and Plot

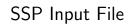
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Calls the different tools, passes information between the programs, reads the output and creates plots

- Also based on Mathematica
- Constraints can be included
- Contour scans using intrinsic Mathematica functions

The SUSY-Toolbox and SSP

The SUSY Toolbox



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- 1. Head:
 - Setting the tools which are used
 - Defining IDs for the different scans
 - Defining the kind of scan: grid, scatter, contour, (very basic MCMC)
 - Possibility to set constraints
 - Defining the different input block
- 2. Main:
 - Defining the parameter range for all input parameters
 - Possible contributions for grid: linear, log
- 3. Plots:
 - Defining which plots should be created automatically
 - Possibility to create LATEX labels using psfrag

The SUSY-Toolbox and SSP

The SUSY Toolbox



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Running an example for SSP

(bctp)

Tutorial III