Introduction to SARAH

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Outline

Introduction to SARAH

→ Tutorial I

SARAH model files

→ Tutorial II

The SUSY-Toolbox and SSP

→ Tutorial III

Why it might be necessary to extend the 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 $\to$ R-parity violation or Seesaw mechanism?
- The μ problem $\to$ effective μ term?
- Parity $\to$ left-right symmetry at higher scales?
- R-symmetry $\to$ Dirac gaugino masses?
- Heavy higgs mass & diphoton rate $\to$ extended Higgs sector?

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- Heavy higgs mass & diphoton rate $\rightarrow$ extended Higgs sector?

Need to study many different models

Steps to study a new SUSY model

collider phenomenology | dark matter | low energy constraints | ...

↑ ↑ ↑ ↑

Add loop corrections to masses

↑

Calculate the mass spectrum and parameters

↑

Embed model in GUT theory like mSugra: **RGEs needed**

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Derive expressions for masses, vertices, ...

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Idea for a new model

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Idea for a new model

looks like a long and exhaustive way

Steps to study a new SUSY model

collider phenomenology	dark matter	low energy constraints	...
↑	↑	↑	↑

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Derive expressions for masses, vertices, ...

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Idea for a new model

is covered in a completely automatized way now!

SARAH

SARAH

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

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Input: Gauge Groups, Particle Content, Superpotential

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Lagrangian for Gauge Eigenstates

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Input: Gauge Groups, Particle Content, Superpotential

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Lagrangian for Gauge Eigenstates

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Input: Symmetry Breaking(s) and Rotations

↓

Final Lagrangian, Mass Matrices, Tadpole Equations

↓

Vertices, loop corrections, RGEs

Supported Models

SARAH can handle a large variety of models

Particle Content and Interactions

- 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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- 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

Implemented (public) models:

- 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, $\mu\nu$SSM
  - 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

What happens automatically:

- 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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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)

Information obtained by SARAH

Tree level relations

- Masses and tadpole equations
- All vertices

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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,Porod,FS,1107.2670]
+ Support of Dirac Gauginos [Goodsell,1206.6697]

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

One-loop tadpoles/self-energies ($\overline{\text{DR}}$-scheme, ’t Hooft gauge)

$\rightarrow$ formulas for mass spectrum at one-loop

Output

Model Files

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

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LaTeX

All derived expressions can also be exported to LaTeX files.

SARAH and SPheno

SPheno

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

- 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 $\mu \to e\gamma$, $\delta\rho$, ...

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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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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. $b \to s\gamma$, $\delta\rho$, $\mu \to 3e$) for given model with same precision as SPheno does for the MSSM
- Calculation of decay widths and branching ratios

  ($h \to \gamma\gamma$ and $h \to gg$ at full LO and partly NLO)
- Writes input files for HiggsBounds and WHIZARD

Outlook

Towards SARAH 4

- Support of non-$SU(N)$ groups: linking Susyno [with Fonseca]
- 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]

Important Commands

- 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

Tutorial I

The following topics are discussed in the following

1. Using existing models
    - Calculating mass matrices, tadpole equations and vertices
    - Writing and using Output for `FeynArts` and `CalcHep`
    - Creating source code for `SPheno`

The Next-to-Minimal Supersymmetric Standard Model

Motivation

The NMSSM solves the μ-problem of the MSSM by adding a gauge singlet S to the particle content

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Superpotential:

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

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New soft-breaking terms:

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

Higgs sector of the NMSSM

Scalar gauge singlet S receives a VEV v_s after SUSY breaking

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

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

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The Higgs sector of the NMSSM consists in total of

- Three CP-even scalar Higgs h_i
- Two physical CP-odd pseudo scalar Higgs A_i^0
- Two physical charged Higgs $H^\pm$ with $H^+ = (H^-)^*$

From MSSM to NMSSM in SARAH

- 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};
```

From MSSM to NMSSM in SARAH

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

```
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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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

From MSSM to NMSSM in SARAH

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

```
SuperPotential = {{{Yu,1},{q, Hu, u}},
        {{Yd,-1},{q, Hd, d}},{{Ye,-1},{l, Hd, e}},
        {{μ,1},{Hu, Hd}}};
```

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```
SuperPotential = {{{Yu,1},{q, Hu, u}},
        {{Yd,-1},{q, Hd, d}},{{Ye,-1},{l, Hd, e}},
        {{λ,1},{Hu, Hd, S}},
        {{κ,1/3},{S,S,S}}};
```

From MSSM to NMSSM in SARAH

- The gauge sector hasn't to be changed
- Add singlet superfield
- Change superpotential
- Give VEV to scalar singlet

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

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{SSing, {vS,1/√2},{sigmaS,I/√2},{phiS,1/√2}}};
```

From MSSM to NMSSM in SARAH

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

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DEFINITION[EWSB][MatterSector]=
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{{fB, fW0, FHd0, FHu0,FSing}, {L0, ZN}},
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```

From MSSM to NMSSM in SARAH

- The gauge sector hasn't to be changed
- Add singlet superfield
- Change superpotential
- Give VEV to scalar singlet
- Change particle mixings
- Define properties of parameters

```
{κ,{LaTeX -> "\\kappa",
    Real -> True,
    LesHouches -> {EXTPAR,62} }}
```

From MSSM to NMSSM in SARAH

- The gauge sector hasn't to be changed
- Add singlet superfield
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- Define properties of parameters

Tutorial II

- Checking the implementation of the NMSSM in `SARAH`
- Running the NMSSM in `SARAH`
- Using the `SPheno` version of the NMSSM

SUSY Toolbox ... 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]
- SPheno [Porod,hep-ph/0301101],[Porod,FS,1104.1573]
- WHIZARD [Kilian,Ohl,Reuter,0708.4233],[Moretti,Ohl,Reuter,0102195]
- HiggsBounds [Bechtle,Brein,Heinemeyer,Weiglein,Williams,1102.1898]
- CalcHep [Pukhov et. al,hep-ph/9908288
- MicrOmegas [Belanger,Boudjema,Pukhov,Semenov,hep-ph/0405253]
- MadGraph [Alwall,Herquet,Maltoni,Mattelaer,Stelzer,1106.0522]
- SSP [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

SUSY Toolbox

FS,Ohl,Porod,Speckner,1109.5147

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

```
> ./configure
> make
> ./butler B-L-SSM
```

SSP

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

SSP - SARAH Scan and Plot

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

SSP Input File

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 LaTeXlabels using `psfrag`

Tutorial III

- Running an example for SSP