# SARAH: Spectrum-Generator-Generator and more

Florian Staub

BCTP Bonn

Tools 2012
Stockholm, 18. June 2012

universitätbonn bctp

# Outline

# New SUSY models

A few reasons why people might to go beyond the MSSM:

- Increase Higgs mass at tree level $\rightarrow$ New D- or F-term contributions?
- Neutrino masses $\rightarrow$ R-parity violation or Seesaw mechanism?
- Strong CP problem $\rightarrow$ Peccei-Quinn symmetry?
- The $\mu$ problem $\rightarrow$ effective $\mu$ term?
- Parity $\rightarrow$ left-right symmetry at higher scales?
- ...

# New SUSY models

A few reasons why people might to go beyond the MSSM:

- Increase Higgs mass at tree level $\rightarrow$ New D- or F-term contributions?
- Neutrino masses $\rightarrow$ R-parity violation or Seesaw mechanism?
- Strong CP problem $\rightarrow$ Peccei-Quinn symmetry?
- The $\mu$ problem $\rightarrow$ effective $\mu$ term?
- Parity $\rightarrow$ left-right symmetry at higher scales?
- ...

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**

↑

**Derive expressions for masses, vertices, . . .**

↑

**Idea for a new model**

# 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**

↑

**Derive expressions for masses, vertices, . . .**

↑

**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 | ... |
|---|---|---|---|
| ↑ | ↑ | ↑ | ↑ |

Add loop corrections to masses

↑

**Calculate the mass spectrum and parameters**

↑

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

↑

**Derive expressions for masses, vertices, ...**

↑

**Idea for a new model**

is covered in an automatized way now!

# SARAH

## SARAH

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

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

# SARAH

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

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

Input: Gauge Groups, Particle Content, Superpotential

$\downarrow$

Lagrangian for Gauge Eigenstates

# SARAH

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

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

Input: Gauge Groups, Particle Content, Superpotential

↓

Lagrangian for Gauge Eigenstates

↓

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 automatically added
- Gauge fixing terms in $R_\xi$ gauge automatically added

# 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 automatically added
- Gauge fixing terms in $R_\xi$ gauge automatically added

- Gauge kinetic mixing fully supported
- Arbitrary number of field rotations/symmetry breakings
- Non canonical terms can be added in component fields

What happens automatically:

- Model checked for Gauge Anomalies and Witten anomaly
- Charge conservation of superpotential checked
- Soft SUSY Breaking terms are added
- Complete Lagrangian is calculated for component fields
- Ghost interactions are added

What happens automatically:

- Model checked for Gauge Anomalies and Witten anomaly
- Charge conservation of superpotential checked
- Soft SUSY Breaking terms are added
- Complete Lagrangian is calculated for component fields
- Ghost interactions are added

Further checks are possible (`CheckModel`):

- Exist additional superpotential terms allowed by gauge invariance?
- Do additional fields mix?
- Are mass matrices reducible?
- Check of internal consistency of input files.

# Example: Model file for the NMSSM

- Input to get the entire Lagrangian for gauge eigenstates

# Example: Model file for the NMSSM

- Input to get the entire Lagrangian for gauge eigenstates
  - Vector superfields

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

# Example: Model file for the NMSSM

- Input to get the entire Lagrangian for gauge eigenstates
  - Vector superfields
  - Chiral superfields

```
Fields[[1]] = {{uL,dL}, 3, q, 1/6, 2, 3};
Fields[[2]] = {{vL, eL}, 3, l, -1/2, 2, 1};
Fields[[3]] = {{Hd0, Hdm}, 1, Hd, -1/2, 2, 1};
Fields[[4]] = {{Hup, Hu0}, 1, Hu, 1/2, 2, 1};
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};
Fields[[8]] = {S, 1, s, 0, 1, 1};
```

# Example: Model file for the NMSSM

- Input to get the entire Lagrangian for gauge eigenstates
  - Vector superfields
  - Chiral superfields
  - Superpotential

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

# Example: Model file for the NMSSM

- Input to get the entire Lagrangian for gauge eigenstates
  - Vector superfields
  - Chiral superfields
  - Superpotential
- Input to break gauge symmetry

# Example: Model file for the NMSSM

- Input to get the entire Lagrangian for gauge eigenstates
  - Vector superfields
  - Chiral superfields
  - Superpotential
- Input to break gauge symmetry
  - Define VEVs

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

# Example: Model file for the NMSSM

- Input to get the entire Lagrangian for gauge eigenstates
  - Vector superfields
  - Chiral superfields
  - Superpotential
- Input to break gauge symmetry
  - Define VEVs
  - Rotate Gauge bosons and gauginos

```
DEFINITION[EWSB][GaugeSector]=
{ {{VB,VWB[3]},{VP,VZ},ZZ},
{{VWB[1],VWB[2]},{VWm,conj[VWm]},ZW},
{{fWB[1],fWB[2],fWB[3]},{fWm,fWp,fWO},ZfW}};
```

# Example: Model file for the NMSSM

- Input to get the entire Lagrangian for gauge eigenstates
  - Vector superfields
  - Chiral superfields
  - Superpotential
- Input to break gauge symmetry
  - Define VEVs
  - Rotate Gauge bosons and gauginos
  - Rotate matter fields

```
DEFINITION[EWSB][MatterSector]=
{{{SdL, SdR}, {Sd, ZD}},
{{{SuL, SuR}, {Su, ZU}},
{{{SeL, SeR}, {Se, ZE}},
{{phiu, phid,phiS}, {h, ZH}},
{{sigmau, sigmad,sigmaS}, {Ah, ZA}},
{{fB, fW0, FHd0, FHu0,FS}, {L0, ZN}},
{{{fWm, FHdm}, {fWp, FHup}}, {{Lm,Um}, {Lp,Up}}}};
```

# Example: Model file for the NMSSM

- Input to get the entire Lagrangian for gauge eigenstates
  - Vector superfields
  - Chiral superfields
  - Superpotential
- Input to break gauge symmetry
  - Define VEVs
  - Rotate Gauge bosons and gauginos
  - Rotate matter fields
- From Weyl to Dirac spinors

```
DEFINITION[EWSB][DiracSpinors]={
Fd ->{ FDL, conj[FDR]}, Fe ->{ FEL, conj[FER]},
Fu ->{ FUL, conj[FUR]}, Fv ->{ FvL, 0},
Chi ->{ L0, conj[L0]}, Cha ->{ Lm, conj[Lp]},
Glu ->{ fG, conj[fG]} };
```

# Example: Model file for the NMSSM

- Input to get the entire Lagrangian for gauge eigenstates
  - Vector superfields
  - Chiral superfields
  - Superpotential
- Input to break gauge symmetry
  - Define VEVs
  - Rotate Gauge bosons and gauginos
  - Rotate matter fields
- From Weyl to Dirac spinors
- Provide optionally additional information about parameters and particles
  - Parameters: LaTeX code, LesHouches block, dependences among parameters, real/complex, ...
  - Particles: PDGs, LaTeX code, name used in output, ...

# Non-SUSY

In principle, also non-Susy models can be studied with SARAH

**Implementation of Non-SUSY model**

- Define the SUSY particle content
- Remove all unnecessary fields using the DeleteParticle command
- Suppress the F- and D-terms with the corresponding command
- Define the matter interactions by the Lagrangian instead the superpotential

Note, the RGEs are only valid for SUSY models!

Implemented (public) models:

- MSSM: with/without FV and/or CPV
- Susy scale extensions of the MSSM:
  - Singlet extensions: NMSSM (CPC and CPV), nMSSM, SMSSM
  - Triplet extensions: TMSSM, TNMSSM
  - R-parity violation: bilinear RpV, trilinear RpV, Lepton/Baryon NV, $\mu\nu$SSM
  - Additional $U(1)'s$: UMSSM, sMSSM, B-L-SSM, singlet extended B-L, $U(1)_R \times U(1)_{B-L}$
  - SUSY scale seesaw: inverse seesaw, linear seesaw, singlet extended inverse seesaw, B-L with inverse seesaw
- High scale extensions
  - Seesaw I – III ($SU(5)$ version)
  - Left/right model ($\Omega$LR)
- Non SUSY models:
  - SM
  - inert doublet model

# Information obtained by SARAH

SARAH derives the analytical expressions for ...

## Tree level relations

- Masses and tadpole equations
- All vertices

# Information obtained by SARAH

SARAH derives the analytical expressions for ...

## Tree level relations

- Masses and tadpole equations
- All vertices

## Renormalization group equations

Two-loop RGEs with full CP and flavor structure

[Martin,Vaughn,hep-ph/9311340]

Full support of several $U(1)'s$ [Fonseca,Malinsky,Porod,FS,1107.2670]

# Information obtained by SARAH

SARAH derives the analytical expressions for . . .

## Tree level relations

- Masses and tadpole equations
- All vertices

## Renormalization group equations

Two-loop RGEs with full CP and flavor structure

[Martin,Vaughn,hep-ph/9311340]

Full support of several $U(1)'s$ [Fonseca,Malinsky,Porod,FS,1107.2670]

## One-loop corrections

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

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

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

# Model files

## FeynArts/FormCalc

[Hahn, hep-ph/0012260],[Hahn,Perez-Victoria,hep-ph/9807565]

# Model files

## FeynArts/FormCalc

[Hahn, hep-ph/0012260],[Hahn,Perez-Victoria,hep-ph/9807565]

## CalcHep/CompHep

[Pukhov et. al,hep-ph/9908288]

- Unitary and Feynman gauge supported
- Auxiliary fields for splitting of vertices with 4 colored
- Works also MicrOmegas

# Model files

## FeynArts/FormCalc

[Hahn, hep-ph/0012260],[Hahn,Perez-Victoria,hep-ph/9807565]

## CalcHep/CompHep

[Pukhov et. al,hep-ph/9908288]

- Unitary and Feynman gauge supported
- Auxiliary fields for splitting of vertices with 4 colored
- Works also MicrOmegas

## WHIZARD/ O'MEGA

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

- Support of different gauges
- Possibility to disable generic vertices like SSSS and SSVV

# Model files

## FeynArts/FormCalc

[Hahn, hep-ph/0012260],[Hahn,Perez-Victoria,hep-ph/9807565]

## CalcHep/CompHep

[Pukhov et. al,hep-ph/9908288]

- Unitary and Feynman gauge supported
- Auxiliary fields for splitting of vertices with 4 colored
- Works also MicrOmegas

## WHIZARD/ O'MEGA

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

- Support of different gauges
- Possibility to disable generic vertices like SSSS and SSVV

## MadGraph 5

[Alwall et. al,1106.0522]

Based on the UFO format

## SARAH and SPheno

SPheno is a well tested and widely used spectrum generator, however ...

| 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) |

## SARAH and SPheno

SPheno is a well tested and widely used spectrum generator, however ...

| 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

SARAH writes source-code using the obtained information about a model which can be compiled with SPheno.

$\rightarrow$ Implementation of new models in SPheno in a modular way without the need to write any line of source code by hand.

# Spectrum generator generator

## Features of SPheno modules written by SARAH

- Precise mass calculation using 2-loop RGEs and full 1-loop mass corrections
- MSSM 2-loop Higgs mass corrections can be linked.
- All SUSY thresholds at low scale included
- Threshold scales possible:
  - Effective operators can be initialized
  - Shifts in gauge couplings/gaugino masses automatically included
- Calculation of flavor observables including all additional states like $\mu \to e\gamma$, $b \to s\gamma$ and $\mu \to 3e$
- Calculation of decay widths and branching ratios
- Writes input files for HiggsBounds and WHIZARD

## SPheno properties

The properties of the SPheno version are defined in SARAH

- Input parameters (e.g. content of MINPAR, EXTPAR)
- Boundary conditions (at GUT-, SUSY-, EW- as well as possible threshold scales)
- Condition to find GUT scale (e.g. gauge unification, Yukawa unification)
- Parameters fixed by the tadpole equations during numerical evaluation

## SPheno properties

The properties of the SPheno version are defined in SARAH

- Input parameters (e.g. content of MINPAR, EXTPAR)
- Boundary conditions (at GUT-, SUSY-, EW- as well as possible threshold scales)
- Condition to find GUT scale (e.g. gauge unification, Yukawa unification)
- Parameters fixed by the tadpole equations during numerical evaluation

For more information about SPheno see also the talk tomorrow

# Combining SPheno with MC tools

**No problems with conventions!**

The implementation in SPheno as well as in CalcHep, WHIZARD or MadGraph are based on one the implementation in SARAH

→ Spectrum calculator and Monte Carlo tool uses for sure the same conventions

The SPheno output can directly be used with the other tools

- CalcHep and MadGraph are able to read the SLHA file also for BMSSM models
- SPheno writes an additional output file in the WHIZARD formats

## 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]
- MadGraph [Alwall et. al,1106.0522]
- CalcHep [Pukhov et. al,hep-ph/9908288
- MicrOmegas [Belanger,Boudjema,Pukhov,Semenov,hep-ph/0405253]
- 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

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

Using the SUSY-Toolbox all tools are downloaded, configured and installed just by:

```
> ./configure
> make
```

Afterwards, a model is implemented in all tools at once by:

```
> ./butler NMSSM
```

## SUSY Toolbox

FS,Ohl,Porod,Speckner,1109.5147

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

Using the SUSY-Toolbox all tools are downloaded, configured and installed just by:

```
> ./configure
> make
```

Afterwards, a model is implemented in all tools at once by:

```
> ./butler NMSSM
```

SSP uses the provided infrastructure to perform parameter scans

# Running time

Time needed for the different calculations in SARAH (on X220, i7, 2.7GHz)

| Command | Times [s] |
|---|---|
| `Start[''NMSSM'']` | 10.3 |
| `CalcRGEs[]` | 15.8 |
| `MakeVertexList[EWSB]` | 63.2 |
| `MakeCHep[]` | 13.0 |
| `MakeFeynArts[]` | 0.7 |
| `MakeUFO[]` | 67.8 |
| `MakeWHIZARD[]` | 1072.9 |
| `MakeLaTeX[]` | 5.6 |
| `MakeSPheno[]` | 161.3 |

# Running time

Time needed for the different calculations in SARAH (on X220, i7, 2.7GHz)

| Command | Times [s] |
|---|---|
| `Start[''NMSSM'']` | 10.3 |
| `CalcRGEs[]` | 15.8 |
| `MakeVertexList[EWSB]` | 63.2 |
| `MakeCHep[]` | 13.0 |
| `MakeFeynArts[]` | 0.7 |
| `MakeUFO[]` | 67.8 |
| `MakeWHIZARD[]` | 1072.9 |
| `MakeLaTeX[]` | 5.6 |
| `MakeSPheno[]` | 161.3 |

$\rightarrow$ The butler script takes roughly an hour (including compilation) to implement the NMSSM in all tools

# Summary

- SARAH is a Mathematica package optimized for the comprehensive study of SUSY models but supports also Non-SUSY models
- The input of SARAH supports a large variety of models and is done in an intuitive and short form
- All group theoretical considerations as well as dealing with gauge fixing terms are done by SARAH
- SARAH can write model files for FeynArts/FormCalc, CalcHep/CompHep, WHIZARD/OMEGA and MadGraph (UFO format)
- SARAH can create modules for SPheno to get a high-precision spectrum generator for a given model
- The SUSY toolbox is a collection of scripts to combine powerful and well-tested tools to a handy environment for the study of models beyond the MSSM based on the SARAH

## Setting up the SPheno properties

The basic properties of SPheno are defined in a separate input file

# Setting up the SPheno properties

The basic properties of SPheno are defined in a separate input file

- The input parameters

```
MINPAR={ {1,m0},
         {2,m12},
         {3,TanBeta},
         {4,SignumMu},
         {5,Azero} };
EXTPAR={ {61,LambdaInput},
         {62,KappaInput},
         {63,ALambdaInput},
         {64,AKappaInput},
         {65,vSinput} };
```

# Setting up the SPheno properties

The basic properties of SPheno are defined in a separate input file

- The input parameters
- Definition for GUT scale

```
ConditionGUTscale = g1 == g2;
```

# Setting up the SPheno properties

The basic properties of SPheno are defined in a separate input file

- The input parameters
- Definition for GUT scale
- The boundary conditions

```
BoundarySUSYScale= {
       {lambda, LambdaInput},{kappa,KappaInput},
       {vS, vSinput} };
```

# Setting up the SPheno properties

The basic properties of SPheno are defined in a separate input file

- The input parameters
- Definition for GUT scale
- The boundary conditions

```
BoundaryHighScale= {
       {MassB, m12},{MassWB, m12},{MassG, m12},
       {mq2, DIAGONAL m0^2}, ...
       {T[Ye], Azero*Ye}, ...
       {T[lambda], Alambda*lambda},
{T[kappa],Akappa*kappa}};
```

# Setting up the SPheno properties

The basic properties of SPheno are defined in a separate input file

- The input parameters
- Definition for GUT scale
- The boundary conditions
- The parameters fixed by the tadpole equations

```
ParametersToSolveTadpoles = {mHd2,mHu2,mS2};
```

# Setting up the SPheno properties

The basic properties of SPheno are defined in a separate input file

- The input parameters
- Definition for GUT scale
- The boundary conditions
- The parameters fixed by the tadpole equations
- The renormalization scale

```
RenormalizationScale = MSu[1]*MSu[6];
```

# Setting up the SPheno properties

The basic properties of SPheno are defined in a separate input file

- The input parameters
- Definition for GUT scale
- The boundary conditions
- The parameters fixed by the tadpole equations
- The renormalization scale
- Particles, for which the decays should be calculated

```
ListDecayParticles = Automatic;
ListDecayParticles3B = Automatic;
```