A comprehensive analysis of new SUSY models using SARAH, SPheno and WHIZARD

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in collaboration with

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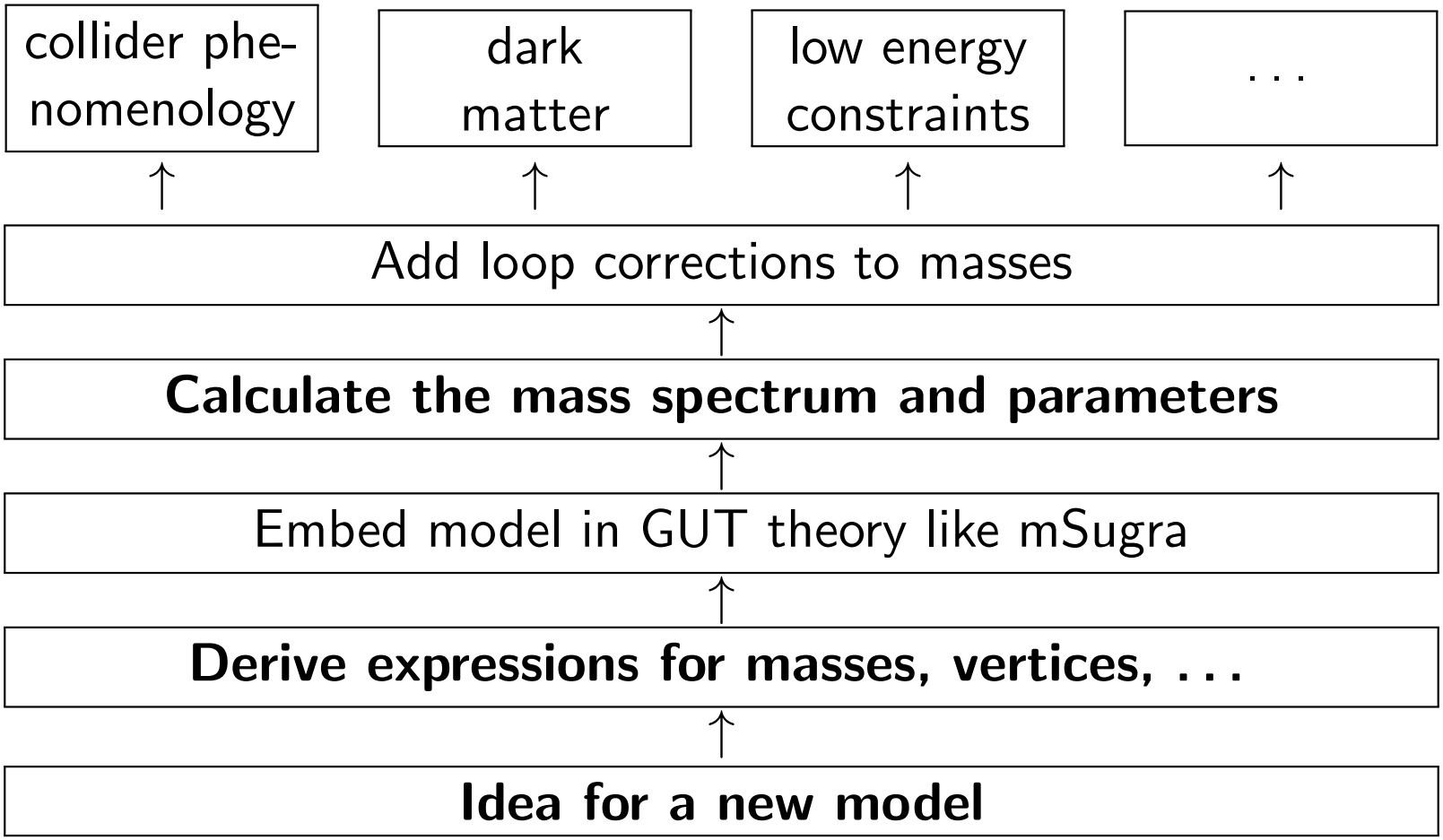
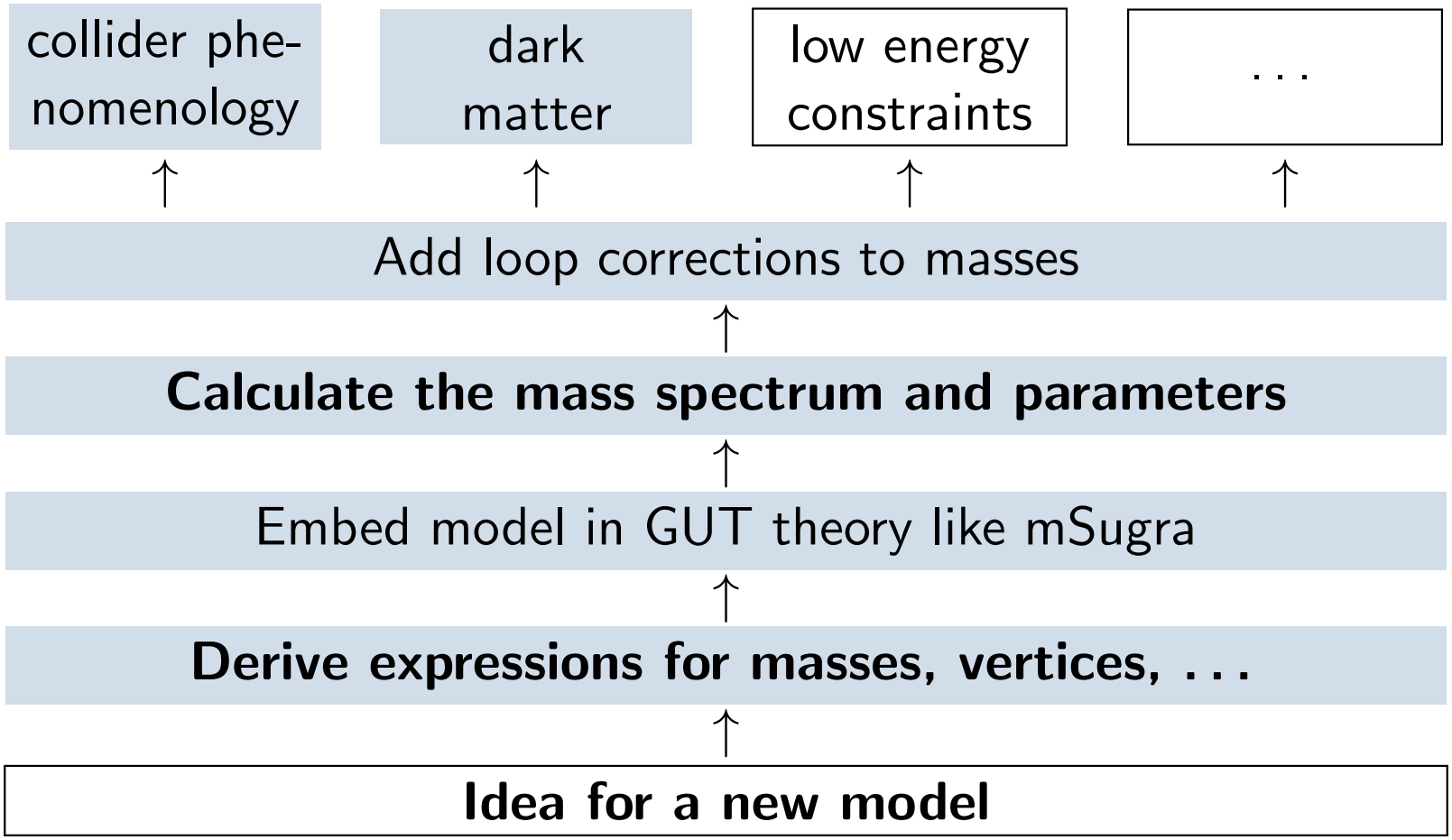
Outline

Steps to study a new SUSY model



looks like a long and exhaustive way

Steps to study a new SUSY model



is covered in a completely automatized way now!

Just as reminder ...

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
- Checks several low energy constraints as $\mu \to e\gamma$, $\delta\rho$, ...

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WHIZARD

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

- Parton level MC event generator for LHC, ILC, CLIC, ...
- Designed for the efficient calculation of multi-particle scattering cross sections and simulated event samples
- Tree-level matrix elements are generated by using the Optimizing Matrix Element Generator O'Mega.

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

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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

↓

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

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- Arbitrary number of field rotations/symmetry breakings
- Gauge fixing terms can be specified in R_ξ gauge
- Non canonical terms can be added in component fields

Information obtained by SARAH

SARAH derives the analytical expressions for ...

Tree level relations

- Masses and tadpole equations
- All vertices

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One-loop corrections

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

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

SARAH and SPheno

The analytical expression can be used to generate Fortran source code for SPheno

→ Possibility to implement new models in SPheno

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Features of the new SPheno modules

- Calculation of all masses using two-loop RGEs and one-loop corrections
- two- and three-body decays of sparticles/Higgs fields
- Heavy superfields can be integrated out
  - → one-loop corrections to gauge couplings and gauginos at thresholds
  - → initialization and running of effective operators
- Scales of gauge symmetry breaking can be included

→ Possibility to study GUT theories

SARAH and SPheno II

The fit to electroweak data in SPheno is adjusted to the new model

- New contributions to SM gauge bosons and fermions included
- New contributions to $\mu \to e\bar{\nu}_e\nu_\mu$ included

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The user has full control of the evaluation of the model in SPheno

- Boundary conditions at EW-, SUSY-, GUT- and threshold scales can be defined
- Free parameters (MINPAR, EXTPAR) can be defined in SARAH

SARAH and WHIZARD

New Model files for WHIZARD

SARAH can write model files for WHIZARD using the expressions of the vertices (interface based on [Christensen,Duhr,Fuks,Reuter,Speckner,1010.3251])

- Gauge can be chosen
- Relations between parameters can be defined inside SARAH

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Linking SPheno and WHIZARD

- SPheno and WHIZARD based on SARAH use exactly the same conventions
  → Easy to transfer information
- SPheno writes additionally output file with parameter information in WHIZARD format
  → Can be included in WHIZARD input files

We compared a MSSM module of SARAH with SPheno 3.1, e.g.

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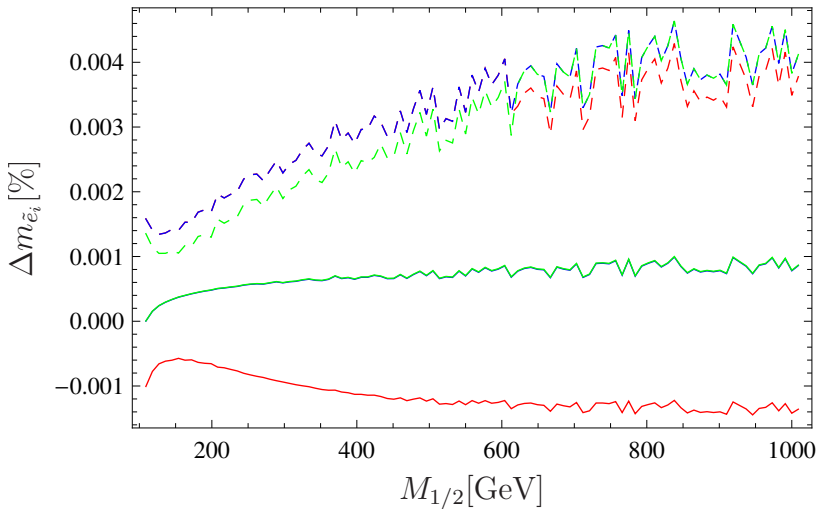
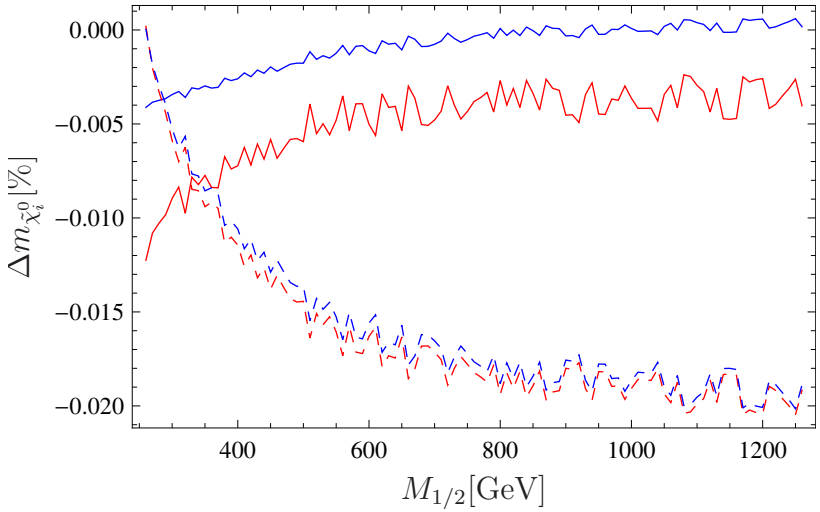
Masses:





$M_0 = 250$ GeV, $A_0 = 0$ GeV, $\tan\beta = 30$, sign$\mu = 1$.

SPheno 3.1 without two-loop corrections to Higgs masses.

→ Good agreement, origin of small differences understood

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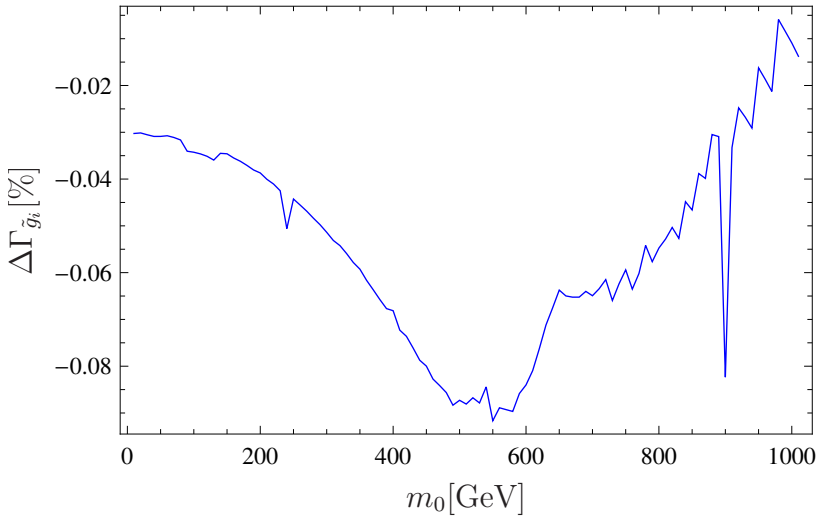
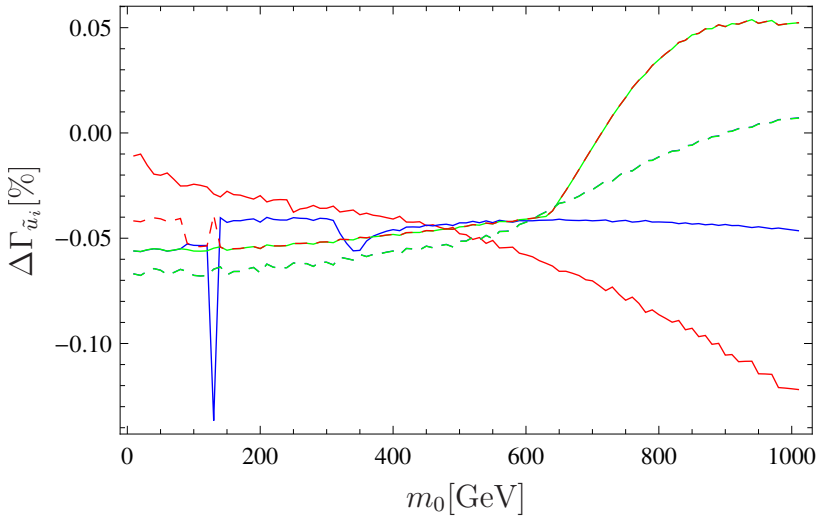
Decay Widths:





$M_{1/2} = 500$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$, sign$\mu = 1$.

SPheno 3.1 without two-loop corrections to Higgs masses.

→ Good agreement, origin of small differences understood

Check of the NMSSM output of SARAH

- Complete agreement of Higgs self-energies with results of Slavich & Degrassi [Degrassi,Slavich, 0907.4682]
- Neutralino/Chargino masses consistent with results of NMSSM-tools [Ellwanger,Hygonie,hep-ph/0612134],[FS,Herrmann,Porod,1007.4049]

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SPheno modules can be created for a large variety of models

- MSSM with Seesaw I–III ($\rightarrow$ checked against SPheno 3.1)
- Left-right model [Esteves,Hirsch,Porod,Romao,FS,Vicente,1011.0348]
- nMSSM, SMSSM, UMSSM, $\mu\nu$SSM, B-L-MSSM, ...

Validation of WHIZARD model files

Check against standard WHIZARD files

- 250 $2 \to 2$ processes for the MSSM
- 50 $2 \to 2$ processes for the SM

$\to$ All appearing vertices covered

Complete agreement

For all processes, the difference was always smaller than the numerical error

Some examples

Process	σ_S [fb]	δ_S [%]	σ_W [fb]	δ_W [%]
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to hA^0$	3.917×10^{-1}	4.04×10^{-2}	3.913×10^{-1}	4.78×10^{-2}
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to ZZ$	1.227×10^{-1}	1.19×10^{-1}	1.227×10^{-1}	1.2×10^{-1}
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0$	2.543×10^{-2}	6.54×10^{-2}	2.541×10^{-2}	6.14×10^{-2}
$e\bar{e} \to ZZ$	2.326	4.93×10^{-2}	2.326	5.39×10^{-2}
$e\bar{e} \to \tilde{t}_1\tilde{t}_1^*$	3.693	7.9×10^{-3}	3.694	7.97×10^{-3}
$e\bar{e} \to \tilde{t}_2\tilde{t}_2^*$	3.091	9.08×10^{-3}	3.091	6.61×10^{-3}
$e\bar{e} \to \tilde{\tau}_1\tilde{\tau}_2$	1.561×10^{-1}	9.63×10^{-3}	1.561×10^{-1}	7.14×10^{-3}
$\tau\bar{\tau} \to \tilde{\chi}_3^0\tilde{\chi}_3^0$	1.806×10^{-2}	5.86×10^{-2}	1.807×10^{-2}	5.12×10^{-2}
$\tau\bar{\tau} \to \tilde{\chi}_4^0\tilde{\chi}_4^0$	8.167×10^{-2}	5.04×10^{-2}	8.169×10^{-2}	6.13×10^{-2}
$d\bar{d} \to \tilde{\chi}_2^+\tilde{\chi}_2^-$	1.532	4.74×10^{-2}	1.53	4.88×10^{-2}
$d\bar{d} \to \tilde{\chi}_4^0\tilde{\chi}_4^0$	2.998×10^{-2}	6.14×10^{-2}	2.996×10^{-2}	5.44×10^{-2}
$d\bar{d} \to \tilde{b}_1\tilde{b}_2^*$	1.715×10^{-1}	1.48×10^{-2}	1.715×10^{-1}	6.82×10^{-3}
$d\bar{d} \to \tilde{t}_1\tilde{t}_1^*$	1.493×10^{2}	8.46×10^{-3}	1.493×10^{2}	8.12×10^{-3}
$d\bar{d} \to \tilde{g}\tilde{g}$	4.942×10^{2}	4.35×10^{-2}	4.94×10^{2}	5.36×10^{-2}
$\gamma\gamma \to H^-H^+$	8.99	4.24×10^{-2}	8.983	4.38×10^{-2}
$\gamma\gamma \to W^-W^+$	3.213×10^{2}	4.4×10^{-2}	3.211×10^{2}	6.91×10^{-2}
$\gamma\gamma \to \tilde{\chi}_2^+\tilde{\chi}_2^-$	3.695×10^{1}	4.71×10^{-2}	3.696×10^{1}	4.45×10^{-2}
$\gamma\gamma \to d\bar{d}$	1.21	7.26×10^{-2}	1.213	5.52×10^{-2}

What else works already

Model files for CalcHep/CompHep

[Pukhov et. al,hep-ph/9908288

Easy to get information from SPheno using SLHA+ functions of CalcHep

[Belanger,Christensen,Pukhov,Semenov,1008.0181]

→ Another way for collider studies

→ Works with MircOmegas for dark matter studies

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Other output of SARAH

- Model files for FeynArts/FormCalc

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

→ Loop calculations

- LaTeX output of all equations

→ Gives an exhaustive and easy readable overview the model

Outlook

SSP - SARAH Scan and Plot

- Also based on Mathematica
- Should provide an easy way to perform parameter scans
- Constraints can be included
- Parameter space sampling using intrinsic Mathematica functions
- Beta-version might be published within the next weeks

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

- SPheno calculates already most of the information needed by HiggsBounds
- However, some parts are missing, like $h \to Z\gamma$

Summary

- SUSY models can implemented easily in SARAH
- SARAH derives all necessary, analytical expressions for the model
- Creation of SPheno source code and WHIZARD model files

Combining all programs

→ Automatized way from model building to phenomenology

→ Works for a large variety of SUSY models

→ Precision comparable to the MSSM (just two-loop effects in Higgs sector missing)