NMSSM in WHIZARD

Joined verification of WHIZARD, MadGraph and CalcHep in collaboration with B. Fuks and J.Reuter

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Next-to-Minimal Supersymmetric SM

- Motivated by the $\mu \sim 1$ TeV problem
- Introduce SM singlet S
- Neglecting linear and bilinear terms in S, the superpotential reads:

$$W_{\text{NMSSM}} = \epsilon^{ab} \left(Y^e \, H_1^a L^b e^c + Y^d \, H_1^a Q^b d^c \right.$$
$$\left. + Y^u \, H_2^b Q^a u^c - \lambda \, S H_1^a H_2^b + \frac{1}{3} \kappa \, S^3 \right)$$

- Condensation of S generates effective μ parameter:

$$\mu_{\text{eff}} = \lambda \langle S \rangle$$

Next-to-Minimal SSM

Phenomenological consequences:
Extended Higgs and Neutralino Sector

- Three scalar Higgs fields (CP conserving)

$$(h_1^0, h_2^0, h_3^0)^T = \mathsf{Re}\,(H_1^0, H_2^0, S)^T\, U_S^T$$

- Two pseudo scalar Higgs fields

$$(A_1^0, A_2^0)^T = \mathsf{Im}\,(H_1^0, H_2^0, S)^T\, U_P^T$$

- Five neutralinos

$$(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0)^T = (-i\tilde{b}, -i\tilde{w}^3, \tilde{h}_1, \tilde{h}_2, \tilde{s})^T\, U_N^T$$

The need for automatization

1) Softly broken SUSY models have high dimensional space of free parameters

$\longrightarrow$ Tools that solve RGEs, calculate spectra, check for consistency with experimental bounds. Monte-Carlo Markow-Chains to explore the parameter space

e.g NMSSMTools by U. Ellwanger, J. F. Gunion, C. Hugonie

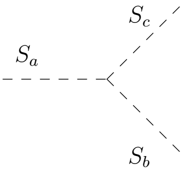
2) Variety of new particles and couplings make calculation of processes cumbersome (even at tree-level!!)

$\longrightarrow$ Event generators build up all the diagrams contributing to a given process; calculate amplitudes; sample the phase space and calculate cross sections; (shower, hadronization)

- Most event generators have the MSSM built in, but not the NMSSM

The need for automatization!!!

- NMSSM, like many BSM models, imposes discrete Symmetry
  - ⇒ Pair production
  - ⇒ Decay chains
  - ⇒ Multi-particle final states
- Combinatorics and Feynman rules in the Higgs and neutralino sector become more difficult...



$$
\begin{aligned}
&-\tfrac{3}{2}\, i\, \tfrac{g^2+g'^2}{2}\, v \left(\cos\beta\, U^S_{a1}U^S_{b1}U^S_{c1} + \sin\beta\, U^S_{a2}U^S_{b2}U^S_{c2}\right)\\
&+i\left(\tfrac{g^2+g'^2}{4}-\lambda^2\right) v\cos\beta \left(U^S_{a1}U^S_{b2}U^S_{c2} + U^S_{a2}U^S_{b1}U^S_{c2} + U^S_{a2}U^S_{b2}U^S_{c1}\right)\\
&+i\left(\tfrac{g^2+g'^2}{4}-\lambda^2\right) v\sin\beta \left(U^S_{a1}U^S_{b1}U^S_{c2} + U^S_{a1}U^S_{b2}U^S_{c1} + U^S_{a2}U^S_{b1}U^S_{c1}\right)\\
&+i\left(\lambda k v\sin\beta - \lambda^2 v\cos\beta\right)\left(U^S_{a1}U^S_{b3}U^S_{c3} + U^S_{a3}U^S_{b1}U^S_{c3} + U^S_{a3}U^S_{b3}U^S_{c1}\right)\\
&+i\left(\lambda k v\cos\beta - \lambda^2 v\sin\beta\right)\left(U^S_{a2}U^S_{b3}U^S_{c3} + U^S_{a3}U^S_{b2}U^S_{c3} + U^S_{a3}U^S_{b3}U^S_{c2}\right)\\
&-i\lambda^2 x\left(U^S_{a1}U^S_{b1}U^S_{c3} + U^S_{a1}U^S_{b3}U^S_{c1} + U^S_{a3}U^S_{b1}U^S_{c1}\right.\\
&\qquad\qquad \left. + U^S_{a2}U^S_{b2}U^S_{c3} + U^S_{a2}U^S_{b3}U^S_{c2} + U^S_{a3}U^S_{b2}U^S_{c2}\right)\\
&+i\lambda\left(\tfrac{A_\lambda}{\sqrt{2}} + kx\right)\left(U^S_{a1}U^S_{b2}U^S_{c3} + U^S_{a1}U^S_{b3}U^S_{c2} + U^S_{a2}U^S_{b1}U^S_{c3}\right.\\
&\qquad\qquad \left. + U^S_{a2}U^S_{b3}U^S_{c1} + U^S_{a3}U^S_{b1}U^S_{c2} + U^S_{a3}U^S_{b2}U^S_{c1}\right)\\
&-i\left(\sqrt{2}kA_k + 6\sqrt{2}k^2\right) U^S_{a3}U^S_{b3}U^S_{c3}
\end{aligned}
$$

The WHIZARD Event Generator

Kilian/Ohl/Reuter, 0708.4233

Current versions:

WHIZARD 1.9x   latest release v1.93: 2009, April, 15th

Web address:

`http://whizard.event-generator.org`
`http://projects.hepforge.org/whizard`

Major upgrade   WHIZARD 2.0 (more later)

The WHIZARD team

W. Kilian, T. Ohl, H.-W. Poschmann, J. Reuter, F. Braam, S. Schmidt, C. Speckner, D. Wiesler

WHIZARD: Prerequisites

Prerequisites:

- Standard tools: (like `make, sed, grep, Perl5 etc.`)
- O'Caml (Objective Caml) compiler (Version $\geq$ 3.04)
- Fortran 95/03 compiler
  gfortran (v$\geq$4.3.0), Intel (v$\geq$10.0), NAG, Lahey, g95,
  still problematic: Portland pgf
- LHAPDF library for PDFs
- PYTHIA/HERWIG for showering/hadronization

  Optional:

  - LaTeX and MetaPost for on-line generation of histograms and plots
  - for support, contact the authors

WHIZARD: Installation

WHIZARD 1: Installation

- Download tar-ball from `http:whizard.event-generator.org`
- unpack
- do `configure FC=<your compiler>`
- `make install` that's it!
  - → O'Mega builds up all matrix elements contributing to the processes specified in `conf/whizard.prc` in a highly efficient way
  - → All process files are generated `processes-src/`
  - → `whizard` executable is build
- By running `./whizard` the cross sections for the processes selected in `results/whizard.in` are calculated (various options and cuts possible)

Sample files

```
# Process file for 2->2 NMSSM comparison

model NMSSM

#################################################
# tautau channels
#################################################
##SM-like processes
# lepton pairs
tautau     tau+,tau-        tau+,tau-       omega
# Slepton pairs
stau12    tau+,tau-        stau1-,stau2+   omega
# Squark pairs
st12    tau+,tau-        st1,st2c        omega
# Gaugino pairs
nn35    tau+,tau-        neu3,neu5       omega
# Higgs pairs
h1h3       tau+,tau-        h01,h03         omega
a1a2       tau+,tau-        A01,A02         omega
```

```
!!whizard.in file

 &process_input

 process_id = "tautau"

 sqrts = 3000
 luminosity = 0
 polarized_beams = F
 structured_beams = F
 input_file = "nmssm"
 input_slha_format = T
  /

 &integration_input
 calls = 1 20000 1 20000 3
 stratified = F
```

O'Mega

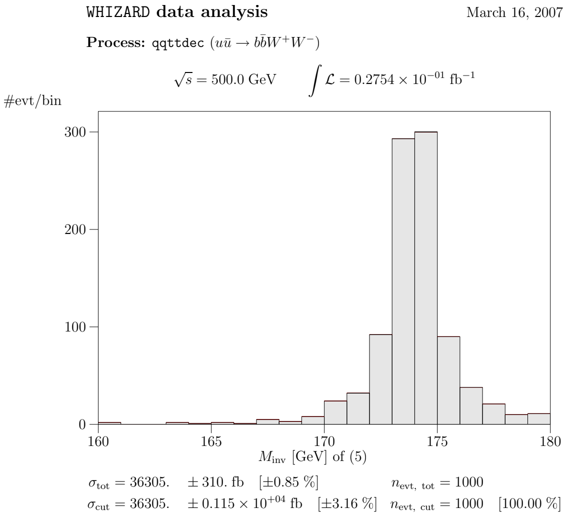
- optimized matrix elements (same complexity class as Alpgen(ALPHA) and HELAC, but symbolic expressions are available for further manipulation)
- algorithm checked for vertices with arbitrary(!) many legs
- rich set set of Lorentz structures for vertices (will become completely general in 2.0)
- algorithm completely different from Madgraph, allows meaningful cross checks. Numeric support library also developed independently
- matrix element code is structured to take advantage of gauge cancellations
- matrix element code can be instrumented for automatic gauge invariance checks

WHIZARD – Overview over BSM Models

MODEL TYPE	with CKM matrix	trivial CKM
QED with e, μ, τ, γ	–	`QED`
QCD with d, u, s, c, b, t, g	–	`QCD`
Standard Model	`SM_CKM`	`SM`
SM with anomalous gauge couplings	`SM_ac_CKM`	`SM_ac`
SM with anomalous top couplings	`SMtop_CKM`	`SMtop`
SM with K matrix	—	`SM_KM`
MSSM	`MSSM_CKM`	`MSSM`
MSSM with gravitinos	—	`MSSM_Grav`
NMSSM	`NMSSM_CKM`	`NMSSM`
extended SUSY models	—	`PSSSM`
Littlest Higgs	—	`Littlest`
Littlest Higgs with ungauged $U(1)$	—	`Littlest_Eta`
Littlest Higgs with T parity	—	`Littlest_Tpar`
Simplest Little Higgs (anomaly-free)	—	`Simplest`
Simplest Little Higgs (universal)	—	`Simplest_univ`
3-site model (inoff.)	—	`TSM`
UED	—	`UED`
SUSY Xdim. (inoff.)	—	`SED`
Noncommutative SM (inoff.)	—	`NCSM`
SM with Z'	—	`Zprime`
SM with gravitino and photino	—	`GravTest`
Augmentable SM template	—	`Template`

WHIZARD analysis package

Own WHIZARD graphics analysis package
(NOTE: New completely general cut syntax in v2.0)



The NMSSM: Implementation and conventions

- SLHA2 conventions Allanach et al., arXiv:0801.0045

$\longrightarrow$ fixes signs and phases:

$$W_{NMSSM} = W_{MSSM} - \epsilon_{ab}\lambda S H_1^a H_2^b + \frac{1}{3}\kappa S^3 \left[+\mu' S^2 + \xi_F S\right]$$

$$V_{\rm soft} = V_{2,MSSM} + V_{3,MSSM} + m_{\rm S}^2|S|^2 + (-\epsilon_{ab}\lambda A_\lambda S H_1^a H_2^b + \frac{1}{3}\kappa A_\kappa S^3 \left[+m_S'^2 S^2 + \xi_S S\right] + \text{h.c.})$$

- Parameter input via SLHA2 file (as obtained from NMSSMTools)
- full CKM matrix, L/R sfermion mixing (all generations)
- No sfermion generation mixing
- Generalization to CP non-conserving case easily possible

The NMSSM: Implementation and conventions

Parameters to specify NMSSM spectrum in WHIZARD:

- Lagrangian parameters in Higgs-sector:
  $\tan\beta,\ \mu_{\text{eff}},\ \lambda,\ \kappa,\ A_\lambda,\ A_\kappa$
- Higgs masses and full mixing matrices $U_S(3\times 3)$, $U_P(2\times 3)$

$$(h_1^0, h_2^0, h_3^0)^T \;=\; \mathsf{Re}\,(H_1^0, H_2^0, S)^T\, U_S^T$$

$$(A_1^0, A_2^0)^T \;=\; \mathsf{Im}\,(H_1^0, H_2^0, S)^T\, U_P^T$$

- Naming scheme for Higgs particles changed from MSSM to NMSSM (not in the manual, yet):

$h,\, H \;\to\; h01,\, h02,\, h03;\qquad\qquad A \;\to\; A01,\, A02$

$\longrightarrow$ See sample files
`conf/whizard.*.test-NMSSM`

The NMSSM: Implementation and conventions

- Neutralino masses and mixing matrix $U_{\tilde{\chi}^0}(5 \times 5)$.

$$(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0)^T = (-i\tilde{b}, -i\tilde{w}^3, \tilde{h}_1, \tilde{h}_2, \tilde{s})^T U_N^T$$

  - WHIZARD only digests real mixing matrices $\rightarrow m_{\tilde{\chi}^0} < 0$
  - Internally, they will be converted to $m_{\tilde{\chi}^0} > 0$ with appropriate factors of i in $U_{\tilde{\chi}^0}$
- Trilinear soft SUSY breaking parameters have no tensorial structure
- SM Yukawa couplings are calculated from tree level relation

$$Y_i = \frac{g\, m_i}{\sqrt{2} M_W c/s(\beta)}$$

Consistency Checks

- Verified correct MSSM limit
  $(\kappa \to 0,\ \lambda \to 0,\ \langle S \rangle \to 0:\ \mu_{\text{eff}} \neq 0)$
  in $2 \to 2$ processes using sps1a scenario at 500 GeV and 2 TeV

- Comparison of WHIZARD, MadGraph and CalcHep for various $2 \to 2$ NMSSM processes:
  e^+e^-, $\tau^+\tau^-$, $\nu_e\bar{\nu}_e$, $\nu_\tau\bar{\nu}_\tau$, W^+W^-, W^-Z, $W^-\gamma$, ZZ,
  $Z\gamma$, $\gamma\gamma$, $g\gamma$, Zg, W^-g, gg, $u\bar{u}$, $d\bar{d}$, $b\bar{b}$, $b\bar{t}$, qg
  at 3 TeV and 5 TeV (in order to make all channels accessible)

- Independence of implementation (FeynRules vs. manually implemented FR) make remaining bugs unlikely.

Consistency Checks

- Results $u\bar{u} \rightarrow 2$
- All results agree within MC error

Process	MG-FR	CH-FR	WO-ST	Comparison
u,u~>mu+,mu-	2.20046×10^{-3}	2.1997×10^{-3}	2.20045×10^{-3}	δ = 0.0346614 %
u,u~>e+,e-	2.19981×10^{-3}	2.1997×10^{-3}	2.20117×10^{-3}	δ = 0.0667913 %
u,u~>tau+,tau-	2.2008×10^{-3}	2.1997×10^{-3}	2.20011×10^{-3}	δ = 0.0499452 %
u,u~>ve,ve~	1.0292×10^{-3}	1.0293×10^{-3}	1.02955×10^{-3}	δ = 0.0340321 %
u,u~>vm,vm~	1.02947×10^{-3}	1.0293×10^{-3}	1.02967×10^{-3}	δ = 0.0361345 %
u,u~>vt,vt~	1.02855×10^{-3}	1.0293×10^{-3}	1.02947×10^{-3}	δ = 0.0894189 %
u,u~>u,u~	3.75261×10^{4}	3.7456×10^{4}	3.74598×10^{4}	δ = 0.186942 %
u,u~>t,t~	5.58697×10^{-1}	5.5755×10^{-1}	5.57366×10^{-1}	δ = 0.238383 %
u,u~>d,d~	4.93614×10^{1}	4.9354×10^{1}	4.94249×10^{1}	δ = 0.143466 %
u,u~>b,b~	5.56529×10^{-1}	5.564×10^{-1}	5.56346×10^{-1}	δ = 0.0328797 %
u,u~>W+,W-	1.49927×10^{-1}	1.511×10^{-1}	1.51099×10^{-1}	δ = 0.779563 %
u,u~>Z,Z	1.51094×10^{-2}	1.5162×10^{-2}	1.51638×10^{-2}	δ = 0.359061 %
u,u~>Z,a	1.77311×10^{-2}	1.7718×10^{-2}	1.77595×10^{-2}	δ = 0.234097 %
u,u~>sl2-,sl2+	3.61052×10^{-4}	3.6106×10^{-4}	3.61183×10^{-4}	δ = 0.0362422 %
u,u~>sl5-,sl5+	7.08717×10^{-4}	7.0878×10^{-4}	7.09027×10^{-4}	δ = 0.0437042 %
u,u~>sl4-,sl4+	7.08879×10^{-4}	7.0892×10^{-4}	7.08899×10^{-4}	δ = 0.00583665 %
u,u~>sl3-,sl3+	3.60938×10^{-4}	3.6098×10^{-4}	3.60494×10^{-4}	δ = 0.134671 %
u,u~>sl1-,sl1+	4.09102×10^{-4}	4.0907×10^{-4}	4.09637×10^{-4}	δ = 0.138445 %
u,u~>sl6-,sl6+	4.10651×10^{-4}	4.106×10^{-4}	4.0965×10^{-4}	δ = 0.244088 %
u,u~>sl6-,sl1+	1.25113×10^{-4}	1.2512×10^{-4}	1.25206×10^{-4}	δ = 0.0744907 %
u,u~>sv3,sv3~	5.01803×10^{-4}	5.018×10^{-4}	5.01571×10^{-4}	δ = 0.0460586 %
u,u~>sv2,sv2~	5.01849×10^{-4}	5.018×10^{-4}	5.00921×10^{-4}	δ = 0.185193 %
u,u~>sv1,sv1~	5.01852×10^{-4}	5.018×10^{-4}	5.01279×10^{-4}	δ = 0.114289 %

Process	MG-FR	CH-FR	WO-ST	Comparison
u,u~>su5,su5~	5.5328×10^{-2}	5.5316×10^{-2}	5.53278×10^{-2}	δ = 0.0216838 %
u,u~>su2,su2~	5.58696×10^{-2}	5.587×10^{-2}	5.58427×10^{-2}	δ = 0.0489381 %
u,u~>su4,su4~	4.0155×10^{-1}	4.0165×10^{-1}	4.01839×10^{-1}	δ = 0.0720309 %
u,u~>su3,su3~	3.86654×10^{-1}	3.8666×10^{-1}	3.87441×10^{-1}	δ = 0.203531 %
u,u~>su3,su4~	2.67839×10^{-1}	2.6786×10^{-1}	2.6822×10^{-1}	δ = 0.142065 %
u,u~>su1,su1~	8.45695×10^{-2}	8.4556×10^{-2}	8.46839×10^{-2}	δ = 0.151129 %
u,u~>su6,su6~	2.82535×10^{-2}	2.825×10^{-2}	2.82445×10^{-2}	δ = 0.0321519 %
u,u~>su1,su6~	1.53401×10^{-4}	1.5335×10^{-4}	1.53375×10^{-4}	δ = 0.033135 %
u,u~>sd5,sd5~	5.47202×10^{-2}	5.4691×10^{-2}	5.46881×10^{-2}	δ = 0.0587442 %
u,u~>sd4,sd4~	5.55289×10^{-2}	5.5531×10^{-2}	5.54786×10^{-2}	δ = 0.0944729 %
u,u~>sd6,sd6~	5.45744×10^{-2}	5.4576×10^{-2}	5.45003×10^{-2}	δ = 0.138754 %
u,u~>sd3,sd3~	5.51033×10^{-2}	5.5093×10^{-2}	5.5051×10^{-2}	δ = 0.0948878 %
u,u~>sd1,sd1~	5.57401×10^{-2}	5.5745×10^{-2}	5.57062×10^{-2}	δ = 0.0696179 %
u,u~>sd2,sd2~	5.50781×10^{-2}	5.5093×10^{-2}	5.5149×10^{-2}	δ = 0.12864 %
u,u~>sd1,sd6~	1.5208×10^{-4}	1.5212×10^{-4}	1.52169×10^{-4}	δ = 0.0580328 %
u,u~>n1,n1	4.69292×10^{-4}	4.6921×10^{-4}	4.69051×10^{-4}	δ = 0.0514149 %
u,u~>n1,n2	6.40293×10^{-5}	6.4056×10^{-5}	6.40453×10^{-5}	δ = 0.0416152 %
u,u~>n1,n3	1.65452×10^{-5}	1.6554×10^{-5}	1.65399×10^{-5}	δ = 0.0849581 %
u,u~>n1,n4	7.85102×10^{-6}	7.8524×10^{-6}	7.85524×10^{-6}	δ = 0.0537784 %
u,u~>n1,n5	2.52547×10^{-5}	2.5226×10^{-5}	2.52306×10^{-5}	δ = 0.113727 %
u,u~>n2,n2	7.25971×10^{-6}	7.2595×10^{-6}	7.25741×10^{-6}	δ = 0.0317515 %
u,u~>n2,n3	2.51478×10^{-4}	2.514×10^{-4}	2.51409×10^{-4}	δ = 0.0308572 %
u,u~>n2,n4	8.89804×10^{-5}	8.9048×10^{-5}	8.90646×10^{-5}	δ = 0.0945389 %
u,u~>n2,n5	1.58612×10^{-5}	1.5868×10^{-5}	1.58663×10^{-5}	δ = 0.043149 %
u,u~>n3,n3	1.60291×10^{-3}	1.6022×10^{-3}	1.6021×10^{-3}	δ = 0.0502345 %
u,u~>n3,n4	4.76011×10^{-5}	4.7593×10^{-5}	4.76017×10^{-5}	δ = 0.0183624 %
u,u~>n3,n5	2.42284×10^{-5}	2.4267×10^{-5}	2.4267×10^{-5}	δ = 0.159336 %
u,u~>n4,n4	1.57016×10^{-6}	1.5707×10^{-6}	1.57118×10^{-6}	δ = 0.064398 %
u,u~>n4,n5	1.91263×10^{-3}	1.9138×10^{-3}	1.91315×10^{-3}	δ = 0.0611379 %
u,u~>n5,n5	4.43224×10^{-6}	4.4287×10^{-6}	4.42896×10^{-6}	δ = 0.0797914 %
u,u~>x1+,x1-	4.99931×10^{-3}	4.9998×10^{-3}	5.00068×10^{-3}	δ = 0.02739 %
u,u~>x2+,x2-	2.69535×10^{-3}	2.7004×10^{-3}	2.70036×10^{-3}	δ = 0.18715 %
u,u~>x1+,x2-	1.98745×10^{-4}	1.9866×10^{-4}	1.98532×10^{-4}	δ = 0.107185 %
u,u~>go,go	6.49632×10^{-1}	6.5018×10^{-1}	6.50399×10^{-1}	δ = 0.117994 %
u,u~>Z,h01	5.04822×10^{-4}	5.0483×10^{-4}	5.04335×10^{-4}	δ = 0.0980176 %
u,u~>Z,h02	1.08105×10^{-5}	1.0811×10^{-5}	1.08122×10^{-5}	δ = 0.0158944 %
u,u~>Z,h03	1.46235×10^{-10}	1.4623×10^{-10}	1.46098×10^{-10}	δ = 0.0936432 %

WHIZARD 2.0

- Core completely reprogrammed in object oriented way (Fortran 2003) (back validation almost complete)
- Much better structured (use of libtool, automake etc.), central installation and user work space completely split
- All interface code and system calls from the core code, no scripts any more
- General decay cascades (allows also for inclusive processes!) (with full flavor, color, spin correlations)
- WHIZARD's own interpreter language; generally usable for
  - arbitrary event-dependent scales for PDFs, shower etc.
  - arbitrary cuts and kinematical variables
  - versatile analysis options

WHIZARD 2.0

- several WHIZARD-own parton shower options, MLM and CKKW matching
- FeynRules interface for the official version
- Root interface for more general analysis
- new optimizations in phase space, flavor sums, helicity selection rules
- more BSM models
- new manual!!!
- now processes from different models can be run in parallel

Coming soon: more features like MPI module, GUI and automatic Catani-Seymour dipole subtraction, etc.

Summary

- Whizard is a highly efficient tool to study BSM collider phenomelogogy
- NMSSM implementation is complete and tested

$\Rightarrow$ Ready to be used

- Whizard 2.0 brings major upgrades
  - $\longrightarrow$ Re-organized and optimized
  - $\longrightarrow$ FeynRules interface, will allow for easier implementation of new models
  - $\longrightarrow$ Parton shower