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Les Houches Squared Event Generator for the NMSSM

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Abstract
We present a generic framework for event generation in the Next-to-Minimal Supersymmetric Standard Model (NMSSM), including the full chain of production process, resonance decays, parton showering, hadronization, and hadron decays. The framework at present uses NMHDECAY to compute the NMSSM spectrum and resonance widths, CALCHEP for the generation of hard scattering processes, and PYTHIA for resonance decays and fragmentation. The interface between the codes is organized by means of two Les Houches Accords, one for supersymmetric mass and coupling spectra (SLHA,2003) and the other for the event generator interface (2000).

1. Introduction

With the Tevatron in operation and with the advent of a new generation of colliders on the horison, the LHC and ILC, the exploration of the TeV scale is close at hand. Among the attractive opportunities for a discovery of physics beyond the Standard Model (SM), would be the observation of heavy particles predicted by supersymmetric extensions of the SM (for reviews, see e.g. [1, 2]). The Minimal Supersymmetric Standard Model (MSSM) has been extensively studied, both theoretically and experimentally. Non-minimal SUSY extensions, however, have received less attention. The simplest of them, the Next-to-Minimal Supersymmetric Standard Model (NMSSM, see e.g. [3]), contains one additional supermultiplet, which is a singlet under all the Standard Model gauge groups. From the theoretical point of view the NMSSM solves the naturalness problem, or μ problem, which plagues the MSSM [4]. From the experimental point of view the NMSSM gives us one additional heavy neutralino and two additional Higgs particles. Moreover, in particular for Higgs physics, the NMSSM can imply quite different ranges of allowed mass values [5] as well as different experimental signatures [6], as compared to the MSSM.

2. NMSSM in CalcHEP

CALCHEP version 2.4 can be download from

`http://theory.sinp.msu.ru/~pukhov/calchep.html`

It contains an implementation of the NMSSM [7] and also the NMHDECAY code [8, 9]. Apart from the normal range of MSSM parameters (given at the weak scale) the model contains five additional parameters λ, κ, A_λ, A_κ, and $\mu_{\text{eff}} = \lambda \langle S \rangle$ which describe the Higgs sector, see [8]. For particle codes etc we adopt the conventions of NMHDECAY [8]. These conventions are also being adopted for the extension of the SUSY Les Houches Accord [10, 11], reported on elsewhere in these proceedings [12].

CALCHEP [13] is an interactive menu driven program. It allows the user to specify processes, generate and compile the corresponding matrix elements, and to launch the obtained executable. In the given case, CALCHEP launches the `nmhdecay_slha` code which reads the SLHA input parameter file `slhainp.dat`, preliminarily prepared by CALCHEP, then calculates the spectrum and writes the SLHA output to a file, `spectr.dat`. The original SLHA input and output conventions [10] have in this case been suitably extended to include the NMSSM, see [8, 9, 12].

Finally, the program allows to check the spectrum against a large variety of experimental constraints, using NMHDECAY. Any constraints that are not satisfied are listed in `BLOCK SPINFO` in the output `spectr.dat` file mentioned above. The CALCHEP variable `NMHok` also displays the number of broken constraints.

3. The Event Generation Framework

3.1 Hard Scattering

Partonic $2 \to N$ events can be generated by CalcHEP using its menu system, and can be stored in a file, by default called `events_N.txt`. This file contains information about total cross section, Monte Carlo numbers of particles involved, initial energies of beams, partonic distribution functions, and color flows for each event. The first step is thus to generate such a file, containing a number of partonic events for subsequent further processing by a parton shower and hadronisation generator, in our case PYTHIA [14, 15]. For the interface, we make use of the Les Houches generator accord [16] — see below for details on the implementation.

3.2 Resonance Decays

If the partonic final state passed to PYTHIA contains heavy unstable particles, a (series of) resonance decay(s) should then follow. However, since PYTHIA does not internally contain any of the matrix elements relevant to decays involving the new NMSSM states, these partial widths must also first be calculated by some other program, and then be passed to PYTHIA together with the event file. For this purpose, we use the SUSY Les Houches Accord [10–12], which includes a possibility to specify decay tables, whereby information on the total width and decay channels of any given particle can be transferred between codes.

Both CALCHEP and NMHDECAY can be used to generate such decay tables. For NMHDECAY, this file `decay.dat` is generated automatically, but at present it is limited to the widths and branchings for the Higgs sector only. In the case of CALCHEP the user should start a new session to generate the SLHA file. Here the types of particles are not restricted, but since CALCHEP works exclusively at tree level, Higgs decays to gg and $\gamma\gamma$ are absent.

Using the externally calculated partial widths (see below for details on the implementation), we then use the phase space generator inside PYTHIA, for a particle with appropriate spin, but using an otherwise flat phase space.

3.3 Interface to PYTHIA

After generating the LHA partonic event file and the SLHA spectrum and decay file, the final step is thus reading this into PYTHIA and start generating events. The `utile\` directory of CALCHEP contains an example *main* program `callPYTH.f` which shows how to use CALCHEP's `event2pyth.c` routine for reading the event files into PYTHIA. The most important statements to include are:

```
C...Specify LHA event file and SLHA spectrum+decay file
```

```
      eventFile='events_1.txt'
      slhafile='decay.dat'
C...Set up PYTHIA to use SLHA input.
      IMSS(1)=11
C...Open SLHA file
      OPEN(77,FILE=slhafile,STATUS='OLD',ERR=100)
C...Tell PYTHIA which unit it is on, both for spectrum and decays
      IMSS(21)=77
      IMSS(22)=77
C...Switch on NMSSM
      IMSS(13)=1
C...Initialize
      NEVMAX=initEvents(eventFile)
      CALL PYINIT('USER',' ',' ',0D0)
```

To compile everything together, use a linking like the following:

```
  cc -c event2pyth.c
  f77 -o calcpyth callPYTH.f event2pyth.o pythia6326.f
```

3.4 Parton Showering, Hadronisation, and Underlying Event

After resonance decays, the event generation proceeds inside PYTHIA completely as for any other process, i.e. controlled by the normal range of switches and parameters relevant for external processes, see e.g. the recent brief overview in [17]. Specifically, two different shower models are available for comparison, one a virtuality-ordered parton shower and the other a more recently developed transverse-momentum-ordered dipole shower, with each accompanied by its own distinct underlying-event model, see [18,19] and [20,21], respectively, and references therein.

At the end of the perturbative stage, at a typical resolution scale of about $1\mathrm{GeV}$, the parton shower activity is cut off, and a transition is made to a non–perturbative description of hadronisation, the PYTHIA one being based on the Lund string model (see [22]). Finally, any unstable hadrons produced in the fragmentation are decayed, at varying levels of sophistication, but again with the possibility of interfacing external packages for specific purposes, such as τ and B decays.

4. Practical Demonstration

For illustration, we consider Higgs strahlung at the ILC, i.e. the process $\mathrm{e^+e^-} \to \mathrm{ZH_1^0}$. We concentrate on the difficult scenario discussed in [23], where the lightest Higgs decays mainly to pseudoscalars, and where the pseudoscalars are so light that they cannot decay to b quarks. As a concrete example of such a scenario, we take “point 1” in [6], with slight modifications so as to give the same phenomenology with NMHDECAY version 2.0, with the parameters and masses given in Tab. 1. We use CALCHEP to compute the basic $\mathrm{e^+e^-} \to \mathrm{ZH_1^0}$ scattering, NMHDECAY to calculate the $\mathrm{H_1^0}$ and $\mathrm{A_1^0}$ decay widths, and PYTHIA for generating the $\mathrm{Z^0}$, $\mathrm{H_1^0}$, and $\mathrm{A_1^0}$ decays as well as for subsequent τ decays, bremsstrahlung, and hadronisation.

We generate 30000 events at the $\mathrm{e^+e^-} \to \mathrm{Z^0H_1^0}$ level, at $\sqrt{s} = 500$ GeV corresponding to about $500\ \mathrm{fb}^{-1}$ of integrated luminosity. Out of these, we select events with 4 tauons in the final state (with $p_\perp > 5$ GeV) and where the Z does not decay to neutrinos. The plot in Fig. 1 shows simultaneously the invariant mass distributions of $\tau^+\tau^-$ (solid, green) $\tau^+\tau^-\tau^+\tau^-$ (dot-dashed,

pars:	$m_{\rm t}$	$\mu_{\rm eff}$	λ	κ	$\tan\beta$	m_0	M_1	M_2	M_3	$A_{\rm b,t,\tau}$	A_λ	A_κ
[GeV]*	175	-520	0.22	-0.1	5	1000	100	200	700	1500	-700	-2.8

spectrum:	$m_{\rm A_1^0}$	$m_{\rm H_1^0}$	$m_{\tilde\chi_1^0}$	$m_{\tilde\chi_2^0,\tilde\chi_1^+}$	$m_{\tilde\chi_3^0}$	$m_{\rm A_2^0}$	$m_{\tilde\chi_4^0,\tilde\chi_2^+}$	$m_{\tilde\chi_5^0}$	$m_{\tilde{\rm g}}$	rest
[GeV]	9.87	89.0	101	200	459	477	530	540	789	$\sim$ 1000

BR's:	$\rm H_1^0\to$	$\rm A_1^0A_1^0$	$\rm b\bar b$	$\tau^+\tau^-$	$\gamma\gamma$	$\rm A_1^0\to$	$\tau^+\tau^-$	gg	$\rm c\bar c$	$\rm s\bar s$
		0.92	0.07	0.006	8×10^{-6}		0.76	0.21	0.02	0.01

Table 1: Parameters, mass spectrum, and $\rm H_1^0/A_1^0$ branching ratios larger than 1%, for an NMSSM benchmark point representative of the phenomenology discussed in [23], using NMHDECAY 2.0. * : in appropriate power of GeV.

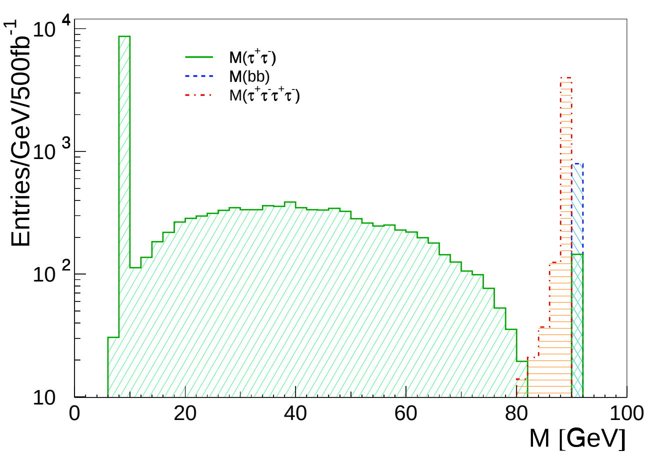

Figure 1: Invariant masses for 2-τ (solid, green), $\rm b\bar b$ (dashed, blue), and 4-τ (dot-dashed, red) combinations in $\rm e^+e^-\to H_1^0Z^0$ events at $\sqrt{s}=500$ GeV, requiring 4 tauons with $p_\perp>5$ GeV in the final state and $\rm Z^0\to$ visible.

red), and $\mathrm{b\bar{b}}$ (dashed, blue) for these events. Of course, experiments do not observe tauons and b quarks directly; this plot is merely meant to illustrate that the expected resonance peaks appear where they should: firstly, a large $\tau^+\tau^-$ peak at the A^0 mass, and a smaller one at the Z^0 mass. Secondly, a $\mathrm{b\bar{b}}$ peak also at the Z^0 mass and finally the 4-τ peak at the H_1^0 mass.

5. Conclusion

We present a framework intended for detailed studies of the collider phenomenology of NMSSM models. We combine three codes developed independently to obtain a full-fledged event generator for the NMSSM, including hard scattering, resonance decays, parton showering, and hadronisation. The interface itself is fairly straightforward, relying on standards developed at previous Les Houches workshops.

Moreover, it seems clear that this application should only be perceived as a first step. With slight further developments, a more generic framework seems realisable, which could greatly facilitate the creation of tools for a much broader range of beyond the Standard Model physics scenarios. In particular we would propose to extend the SLHA spectrum and decay file structures to include all the information that defines a particle — specifically its spin, colour and electric quantum numbers, in addition to its mass and decay modes. This would make it possible for a showering generator to handle not just the particles it already knows about, but also more generic new states.

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