SIMULATING SUPERSYMMETRY WITH
ISAJET 7.0 / ISASUSY 1.0

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ABSTRACT

We review the physics assumptions and input used in ISAJET 7.0 / ISASUSY 1.0 that are relevant for simulating fundamental processes within the framework of the Minimal Supersymmetric Standard Model (MSSM) at pp and pp colliders. After a brief discussion of the underlying MSSM framework, we discuss event simulation and list the sparticle production processes and decay modes that have been incorporated into our calculations. We then describe how to set up and run an ISAJET / ISASUSY job and the user input and output formats. The ISAJET program is sufficiently flexible that some non-minimal supersymmetry scenarios may be simulated as well. Finally, plans for future upgrades which include the extension to $e^+e^-$ collisions, are listed.

1. Introduction

There are many reasons for believing that supersymmetry — a symmetry between fermionic and bosonic degrees of freedom — may be an actual symmetry of nature[1]. One reason, in particular, is that in the Standard Model (SM), the
instability of elementary scalar fields to radiative corrections leads to the well known fine-tuning problem. Supersymmetry (SUSY) provides the only known framework that allows for the introduction of elementary scalar fields, essential for the breaking of electroweak symmetry, into the theory, without the need for fine tuning parameters to uncanny accuracy. This, however, requires that the SUSY breaking scale is $\mathcal{O}(1 \text{ TeV})$, so that the supersymmetric partners of known particles should be accessible at high energy hadron colliders.

How does one make contact between the theoretical ideas of supersymmetry and gauge theories of quarks and leptons on the one hand, and the observation of real particles such as $\pi$’s, $K$’s, $e$’s, $\mu$’s and $\gamma$’s in complicated collider experiments on the other? A crucial bridge of this gap has been provided by the development of event generation and simulation programs\cite{4} such as ISAJET\cite{3}. Such programs merge perturbatively calculable hard scattering processes with approximate all-orders QCD corrections and non-perturbative models for the hadronization of quarks, gluons and beam fragments. Programs have been developed to simulate essentially all lowest order and some higher order SM processes along with a few processes arising from physics beyond the SM. The capacity to simulate production of supersymmetric particles, however, has been included only at an elementary level in some of the generators reviewed in Ref. \cite{2}. Motivated by both theoretical as well as aesthetic considerations, we have made a concerted effort to include a more realistic simulation of supersymmetry in ISAJET version 7.0, so that the experimental consequences of supersymmetry can be explicitly viewed in the environment of a collider detector.

In this report, we describe the theoretical structure of supersymmetry incorporated into ISAJET 7.0, and we explain how to set up and run the program, so that users may simulate production and decays of supersymmetric particles of the Minimal Supersymmetric Model\cite{1} at hadron colliders. We hope that this will provide a new tool for analysis of experimental data from Tevatron experiments as well as for the development of strategies for the detection of supersymmetry in experiments at supercolliders.

1.1 The Minimal Supersymmetric Model Framework

The exploration of strategies by which sparticles might be detected at high energy hadron colliders, of course, entails a knowledge of sparticle production cross sections and their decay patterns. The cross sections for the pair production of sparticles are essentially determined by their gauge interactions. Thus, aside from model-dependent mixing angles, these cross sections are fixed by their $SU(3) \times SU(2)_L \times U(1)_Y$ quantum numbers. As a result, the production cross sections for gluinos, sleptons and squarks are independent of the details of any model. This is not the case for the production of charginos and neutralinos which are model-dependent mixtures of gauginos and Higgsinos. Sparticle decay modes depend on masses, mixings and kinematically allowed modes, and so are generally also model dependent.
Here, we adopt the MSSM as a guide to sparticle masses and mixing angles\[1\]. The MSSM is the simplest supersymmetric extension of the SM. It contains the minimal number of new particles and interactions consistent with phenomenology. Corresponding to each chiral matter fermion multiplet there is a spin zero sfermion multiplet with the same internal quantum numbers. The superpartners of the Yang-Mills gauge bosons are the spin $\frac{1}{2}$ Majorana gauginos in the adjoint representation of the gauge group. Finally, any SUSY model requires at least two Higgs boson doublets to cancel anomalies and to give mass to both $T_3 = \frac{1}{2}$ and $T_3 = -\frac{1}{2}$ fermions: the SUSY partners of these are two spin $\frac{1}{2}$ doublets of Higgsinos. The gauge interactions of the model automatically conserve a discrete quantum number, the R-parity, which is $+1$ ($-1$) for ordinary (supersymmetric) particles. We assume that this is a symmetry of the complete Lagrangian so that R-parity violating Yukawa type interactions (which necessarily violate baryon or lepton number) are absent. Optimally, one would like to include all possible interactions (including R-parity violating ones) consistent with gauge symmetry. This is phenomenologically unacceptable since it leads to catastrophic proton decay which can only be avoided by assuming that at least one of baryon number, lepton number or R-parity is conserved. We assume the discrete symmetry is R-parity. The most important consequence of this is that sparticles can only decay into other sparticles until the decay cascade terminates in the lightest supersymmetric particle (LSP) which is stable. Because of cosmological considerations, the LSP is expected to be a weakly interacting neutral. Hence it is expected to escape detection in the experimental apparatus, leading to the classic $E_T$ signature for supersymmetry. In ISAJET 7.0, the lightest neutralino $\tilde{Z}_1$ is assumed to be the LSP; the other possible LSP candidate, the sneutrino $\tilde{\nu}$, is heavily disfavored by a combination of constraints from LEP and dark matter searches\[4\] if we further assume that the LSP forms the galactic dark matter.

The supersymmetric particles, i.e. the mass eigenstates of the MSSM, include the gluinos $\tilde{g}$, which being color octet fermions cannot mix with anything since $SU(3)_C$ is unbroken, and the spin-zero sfermion partners $\tilde{f}_L$ and $\tilde{f}_R$ of the left- and right-handed fermions, whose mixing is proportional to the corresponding fermion mass and hence is negligible for all but the top squarks. Finally, the gauginos and Higgsinos with the same electric charge mix once $SU(2)_L \times U(1)_Y$ is broken to form two Dirac charginos $\tilde{W}_1$ and $\tilde{W}_2$ ($m_{\tilde{W}_1} < m_{\tilde{W}_2}$) and four Majorana neutralinos $\tilde{Z}_1, \tilde{Z}_2, \tilde{Z}_3, \tilde{Z}_4$ (in order of increasing mass). In addition, there are five physical spin zero bosons associated with the Higgs sector: these are the light and heavy neutral scalars $H_1$ and $H_2$, a pseudoscalar, $H_p$ (the terms scalar and pseudoscalar refer to their couplings to matter fermions) and a pair of charged scalars $H^\pm$.

Most of the sparticle interactions relevant to collider phenomenology are fixed by the corresponding interaction of their SM partners. Only one new parameter $(\mu)\[5\]$, which corresponds to a supersymmetric mixing between the two Higgs doublet fields can be introduced. The remaining supersymmetric interactions can be written in terms of the coupling constants of the gauge and Yukawa interactions.
that are already present in the SM. Supersymmetry cannot be exact if it has to be phenomenologically relevant. Further, if SUSY is to be the resolution of the gauge hierarchy problem, supersymmetry breaking effects can all be parametrized by soft SUSY breaking interactions (these are interactions whose introduction does not lead to the reappearance of quadratic divergences) all of which have been classified in Ref. [6]. For our purposes, it is sufficient to know that both scalar and gaugino mass terms are soft. We can thus parametrize the breaking of supersymmetry in terms of these SUSY breaking masses which break the degeneracy between the fermions and their supersymmetric partners. There are other SUSY breaking interactions such as the trilinear scalar interaction which is responsible for \( \tilde{t}_L - \tilde{t}_R \) mixing; these will be incorporated into later versions of the program. It is important to stress that SUSY breaking does not alter the gauge interactions of the sparticles so that there are observable consequences of the underlying (softly broken) supersymmetry.

As discussed in Ref. [7], the SUSY breaking masses for each SM multiplet can be independent. This results in a proliferation of free parameters that make any phenomenological analyses intractable. Motivated by supergravity models[8] in which supersymmetry breaking effects in a hidden sector are communicated to the observable sector by universal gravitational interactions, we assume here that all the matter sfermions have a common mass at the unification scale. Thus, supersymmetry fixes the Lagrangian at the unification scale in terms of just a few parameters. In order for us to use this Lagrangian for perturbative calculations at the 100 GeV scale relevant to experiment today, these have to be evolved down to the low energy scale using the renormalization group[9]. The \( SU(2)_L \) and \( U(1)_Y \) gaugino masses are then fixed by the gluino mass by the well known unification condition[10]. The renormalization group evolution also splits the degeneracy between the various sfermions. The biggest effect is due to color interactions so that the largest splitting occurs between squarks and sleptons, with smaller splittings between the doublet and singlet sfermions. In our analysis, we have ignored mass splittings between the various squarks. This is a good approximation except for the third generation sfermions where the corresponding Yukawa interactions (which, for instance, cause \( \tilde{t}_L - \tilde{t}_R \) mixing) can be important. It is primarily for this reason that \( \tilde{t} \) squarks have not yet been incorporated into the program. The slepton masses are also determined by the common scalar mass, and so are fixed in terms of \( m_{\tilde{q}} \). Since light sleptons can have a significant impact on neutralino decay patterns, the D-terms responsible for mass splittings can play an important role. Although ISAJET / ISASUSY allows one to input \( m_{\tilde{l}_L}, m_{\tilde{l}_R} \) and \( m_{\tilde{\nu}} \) independently, it is quite straightforward to fix these as in the MSSM framework. Finally, the Higgs sector of the MSSM is strongly constrained so that it can be specified by just one additional parameter (which we take to be the mass of \( H_p \)) which we will assume is independent of the sfermion mass.

To recapitulate, we see that with the assumptions outlined above, the masses and couplings of all the sparticles are determined in terms of just a few parameters which may be taken to be, (i) the gluino mass which is assumed to determine the other
gaugino masses; (ii) the squark mass and slepton masses; (iii) the supersymmetric Higgsino mass ($\mu$); (iv) $\tan \beta = v/v'$, the ratio of the vacuum expectation values of the Higgs fields that couple to $T_3 = \frac{1}{2}$ and $T_3 = -\frac{1}{2}$ fermions. In addition, $m_{H_u}$ fixes the tree level masses and couplings of the five Higgs bosons of the MSSM. Radiative corrections\cite{10} due to top quark Yukawa interactions which substantially alter their masses and mixing patterns (so that these acquire a dependence on the top quark mass as well as on the other SUSY parameters) have also been incorporated.

The MSSM thus provides a framework for studying SUSY signals in experiments at current and future colliders. It should be regarded as an effective low energy theory obtained under certain reasonable assumptions, which may in the future be derived from a deeper underlying theory. It should be kept in mind that the six parameters introduced above may, in fact, be related as, for instance, in supergravity models with radiative electroweak symmetry breaking\cite{11}. The resulting sparticle spectrum can be directly incorporated into the program. Predictions of No Scale models and flipped models can also be obtained as special cases of the general parametrization of our program. It should be kept in mind that the predictions of the MSSM should primarily be used to guide our thinking about strategies for the detection of supersymmetric particles. While we expect that the qualitative features of the MSSM predictions are almost certain to be reliable (unless R-parity is violated), it should be kept in mind that the actual signals may differ in detail even if nature indeed proves to be supersymmetric. It is worth remarking that R-parity violating signals from an unstable LSP can also be studied using this code by forcing the decay of the LSP as discussed in Sec. 5.

2. Physics Content of ISAJET / ISASUSY

2.1 Event simulation with ISAJET 7.0

ISAJET\cite{4} is a Monte Carlo program which simulates $pp$, $p\bar{p}$ and to a lesser extent $e^+e^-$ interactions at high energy. Much of the simulation is based upon perturbative leading-log QCD, along with phenomenological models for non-perturbative aspects such as hadronization and beam jet evolution. Event simulation is carried out by the following steps:

- calculation of hard scattering subprocess Feynman diagrams,
- convolution with $Q^2$ dependent parton distribution functions,
- implementation of approximate all orders QCD corrections via final and initial state parton showers\cite{12},
- implementation of predicted particle and sparticle decays, along with parton radiation and independent quark and gluon hadronization\cite{13}.
suitable modelling of the underlying event structure and beam jet evolution\[14\].

More detailed aspects of the above steps are described in Ref. \[15\].

To incorporate supersymmetric processes into ISAJET, the appropriate sparticle subprocess production cross-sections and the corresponding sparticle decay modes as predicted within the MSSM framework are needed. Both production and decay processes depend in general on the parameter set \(m_{\tilde{g}}, m_{\tilde{q}}, \mu, \tan \beta, m_{H^0}, \) and \(m_t\). Other elements of the simulation are essentially unchanged. The complete spectrum of MSSM sparticle states have been defined within ISAJET, with accompanying identification codes. The supersymmetric particle IDENT codes distinguish between the partners of left and right handed fermions and include the Higgs sector of the minimal supersymmetric model:

- \(\text{UPSSL, DNSSL, STSSL, CHSSL, BTSSL, TPSSL} = 21,22,23,24,25,26\)
- \(\text{NUEL, EL-, NUML, MUL-, NULT, Taul-} = 31,32,33,34,35,36\)
- \(\text{UPSSR, DNSSR, STSSR, CHSSR, BTSSR, TPSSR} = 41,42,43,44,45,46\)
- \(\text{NUER, ER-, NUMR, MUR-, NUTR, TAUR-} = 51,52,53,54,55,56\)
- \(\text{GLSS} = 29\)
- \(\text{Z1SS, Z2SS, Z3SS, Z4SS} = 30,40,50,60\)
- \(\text{W1SS+, W2SS+} = 39,49\)
- \(\text{HL0} = 81\)
- \(\text{HH0} = 82\)
- \(\text{H0} = 83\)
- \(\text{H+} = 85\)

Anti-particle states of the above are referred to by negative IDENT codes. The right sneutrino states of course do not enter the MSSM, and the left- and right- stop states may be changed in the future to light and heavy stop mass eigenstates. The \(\text{HA0}\) state refers to the pseudoscalar Higgs boson; other particle labels ought to be self-evident.

### 2.2 Sparticle production processes

The \(O(\alpha_s^2)\) hard scattering subprocesses included in ISAJET 7.0 are,

\[
\begin{align*}
gg & \rightarrow \tilde{g}\tilde{g}, & (1) \\
\bar{q}q & \rightarrow \tilde{g}\tilde{g}, & (2) \\
gg & \rightarrow \tilde{q}_i\tilde{q}_j, & (3) \\
gg & \rightarrow \tilde{u}\tilde{d}_j, & (4) \\
q\bar{q} & \rightarrow \tilde{q}_i\tilde{d}_j, & (5) \\
q\bar{q} & \rightarrow \tilde{q}_i\tilde{q}_j. & (6)
\end{align*}
\]

Since the decay patterns of left- and right-squark types are different, ISAJET keeps track of squark flavour and type (denoted by the subscripts \(i\) and \(j\)). The production cross sections may be found, for example, in Ref. \[16\]. All squark types are currently assumed to be degenerate in mass. Top squark pair production is not yet
included at this time, so ISAJET 7.0 generates only 5 flavors of squarks, although it requires input of $\tilde{t}_L$ and $\tilde{t}_R$ masses for calculation of various loop decays and radiative corrections.

The $\mathcal{O}(\alpha\alpha_s)$ subprocesses which generate squarks or gluinos in association with charginos or neutralinos are also included in ISAJET 7.0. The cross sections for the associated production processes are as given in [17]. The subprocesses, which occur via squark exchange, are

\begin{align}
gq & \rightarrow \tilde{q}\tilde{W}_i, \quad (7) \\
gq & \rightarrow \tilde{q}\tilde{Z}_i, \quad (8) \\
q\bar{q} & \rightarrow \tilde{g}\tilde{W}_i, \quad (9) \\
q\bar{q} & \rightarrow \tilde{g}\tilde{Z}_i. \quad (10)
\end{align}

Finally, pair production of charginos with neutralinos and chargino pair production are included. These subprocesses currently contain only $W$ or $\gamma/Z$ s-channel graphs, which should be the most important ones in the mass range relevant to the Tevatron. The subprocesses are,

\begin{align}
q\bar{q} & \rightarrow \tilde{W}_i\tilde{Z}_j, \quad (11) \\
q\bar{q} & \rightarrow \tilde{W}_i\tilde{W}_j. \quad (12)
\end{align}

Explicit formulae can be readily obtained by modifications of the formulae in Ref. [18]. Neutralino pair production occurs typically at low rates, and will be included in the future.

The desired subprocesses are chosen by using the ISAJET \texttt{JETTYPEi} keyword commands. The default choice is to generate all allowed reactions in the appropriate proportions. This may not be the best idea, however, since a large amount of CPU time can be used trying to sort through the various subprocesses, especially the various squark pair reactions.

2.3 Sparticle decay modes

The signals for the production of supersymmetric particles obviously depend on how these decay. As is well known by now[19], heavy sparticles generically decay into lighter sparticles with the decay cascade terminating in the (stable) LSP. The branching ratios for the various sparticle decays as given by the MSSM are computed in the set of routines labelled ISASUSY.

Since all the sfermions (squarks and sleptons) have non-trivial gauge interactions, they can decay into all the neutralinos that are kinematically accessible in the decays,

\[ \tilde{f} \rightarrow f + \tilde{Z}_i. \] (13)
The $SU(2)$ doublet sfermions, $\tilde{f}_L$ can also decay via,

$$\tilde{f}_L \rightarrow f' + \tilde{W}_i.$$  

(14)

These decays are forbidden for the singlet sfermions in the limit that their Yukawa interactions are negligible. The squarks can also decay by strong interactions via $\tilde{q} \rightarrow q + \tilde{g}$. This decay dominates if it is not kinematically suppressed. Since the LSP is assumed to be the lightest neutralino, the two body decay, $\tilde{f} \rightarrow f + \tilde{Z}_1$ is always accessible.

The gluinos, being electroweak singlets, can only decay via

$$\tilde{g} \rightarrow \tilde{q} + q$$  

(15)

provided this decay is kinematically allowed; otherwise, the gluino decays via a virtual squark into a 3-body mode:

$$\tilde{g} \rightarrow q\bar{q} + \tilde{Z}_i$$  

(16)

or,

$$\tilde{g} \rightarrow q\bar{q}' + \tilde{W}_i.$$  

(17)

Explicit partial widths are given in Ref. [20]. In the computation of the decay widths for $\tilde{g} \rightarrow t\bar{t}\tilde{Z}_i$ and $\tilde{g} \rightarrow t\bar{b}\tilde{W}_i$, we have used the formulae in Ref. [21, 22] where the effects of the top family Yukawa interactions are included. Notice that the decay $\tilde{g} \rightarrow q\bar{q} + \tilde{Z}_1$ is always allowed. Finally, we note that we have also included the two body decay,

$$\tilde{g} \rightarrow g + \tilde{Z}_i$$  

(18)

which can be important [21] in certain regions of the parameter space.

The charginos and neutralinos, if they are heavy enough, can decay via two body modes,

$$\tilde{W}_i \rightarrow \tilde{Z}_j + (W \text{ or } H^\pm),$$  

(19)

$$\tilde{W}_2 \rightarrow \tilde{W}_1 + (Z \text{ or } H_{t, h, p}),$$  

(20)

$$\tilde{Z}_i \rightarrow \tilde{Z}_j + (Z \text{ or } H_{t, h, p}),$$  

(21)

and,

$$\tilde{Z}_i \rightarrow \tilde{W}_j + (W \text{ or } H^\pm).$$  

(22)

If sfermions are light enough, the decays

$$\tilde{Z}_i \rightarrow \tilde{f}_j + \tilde{f}_j$$  

(23)
and

\[ \tilde{W}_i \rightarrow \tilde{f}_L + \tilde{f}'_L \]  

(24)

may also be kinematically accessible. Here, we have, as before, assumed that Yukawa interactions are negligible; otherwise chargino decays to \( \tilde{f}_R \) would also be possible, as would be decays to Higgs bosons. Charginos and neutralinos will also decay via a variety of three body modes,

\[ \tilde{W}_i \rightarrow f \tilde{f}' \tilde{Z}_j, \]  

(25)

\[ \tilde{Z}_i \rightarrow f \tilde{f} \tilde{Z}_j. \]  

(26)

that are mediated by virtual \( W \) or \( Z \) bosons and virtual sfermions. It is worth noting that the inclusion of sfermion mediated neutralino decay amplitudes including mass splittings between squarks and sleptons can be very important for neutralino decay patterns because the \( Z \tilde{Z}_i \tilde{Z}_j \) coupling can be dynamically suppressed. Finally, we have also incorporated the decays,

\[ \tilde{Z}_i \rightarrow \tilde{W}_1 f \tilde{f}' \]  

(27)

into the program.

Although the direct production of the Higgs bosons has not yet been incorporated into ISAJET, these can be produced via the cascade decays of sparticles as discussed above. The charged Higgs boson can also be produced via the decay \( t \rightarrow bH^+ \) whenever it is kinematically accessible. In order to provide a complete simulation of SUSY events, the various decay modes of the MSSM Higgs bosons have, therefore, been included into ISASUSY. In our computation, we have included the effects of radiative corrections due to top quark Yukawa couplings using the formulae in Ref. \[24\]; we have not yet included radiative corrections from the bottom quark Yukawa interactions (which only become important for very large values of \( \tan \beta \gg 1 \)) or from gauge interactions. We have included the tree level decays of neutral Higgs bosons to SM particles,

\[ H_I, H_h \text{ or } H_p \rightarrow f \tilde{f}, \]  

(28)

\[ H_I, H_h \rightarrow VV \text{ or } VV^*, \ (V = W, Z) \]  

(29)

as well as the one loop decays,

\[ H_I, H_h, H_p \rightarrow \gamma\gamma \text{ or } gg. \]  

(30)

In addition, we have included decays to chargino and neutralino pairs,

\[ H_I, H_h \text{ or } H_p \rightarrow \tilde{Z}_i \tilde{Z}_j \text{ or } \tilde{W}_i \tilde{W}_i \]  

(31)
whenever these are kinematically allowed, as well as the decays,

\[ \begin{align*}
H_h & \rightarrow H^+H^- , \ H_i H_l , \ H_p H_p \text{ or } H_p Z , \\
H_p & \rightarrow H_l Z , \\
H_l & \rightarrow H_p H_p .
\end{align*} \tag{32} \tag{33} \tag{34} \]

of MSSM Higgs bosons into lighter Higgs bosons.
For the charged Higgs bosons, we have incorporated the decays,

\[ H^\pm \rightarrow f \bar{f}^\prime , \ W H_l \text{ or } \tilde{W}_i \tilde{Z}_j \tag{35} \]

into ISASUSY. The decays of both charged and neutral Higgs bosons into sfermion pairs have yet to be incorporated.

3. Setting up and running ISAJET 7.0 / ISASUSY 1.0

3.1 ISAJET 7.0

The ISAJET package has been encoded using the PATCHY code management system developed at CERN. The file ISAJET.CAR containing source code and PATCHY commands is available by copying directly from the Brookhaven VAX. For instance, on VMS

\$\text{copy BNLCL6:}$\$2\$DUA14:[ISAJET.ISALIBRARY]ISAJET.CAR *

can be used to obtain the source code. Ample disk space should be procured beforehand since the code is \(\sim 36,000\) lines long.

Simple programs using PATCHY commands can then be used to assemble the appropriate FORTRAN files, decay table and documentation. For example, on a VAX, running a .COM file including the following commands

\$\text{YTOBIN}$

\$\text{ISAJET ISAJET -- YTOBIN .GO}$

\$\text{YPATCHY}$

\$\text{ISAJET ISATEXT.TXT TTY YPATCHY .GO}$

+USE,*ISATEXT,VAX
+EXE
+PAM
+QUIT

\$\text{YPATCHY}$

\$\text{ISAJET ISAJET TTY YPATCHY .GO}$

+USE,*ISAJET,VAX
+USE,*ISAPLT
+USE,IMPNONE,NOCERN
will assemble the appropriate ISAJET.FOR file, the decay table, and the ISAJET documentation file. The ISAJET files may then be inserted into a library to be linked with main calling programs. To assemble ISAJET on other machines, or to assemble patches such as ISAZEB or ISAPLT, see Ref. [15] and the generic UNIX Makefile MAKEFILE.UNIX available from BNLCL6.

A main program to run ISAJET can be simply constructed:

```
PROGRAM MSSM
 OPEN(UNIT=1,FILE='ISADECAY.DAT',STATUS='OLD',FORM='FORMATTED')
 OPEN(UNIT=2,FILE='ISAJET.DAT',STATUS='NEW',FORM='UNFORMATTED')
 OPEN(UNIT=3,FILE='ISAJET.PAR',STATUS='OLD',FORM='FORMATTED')
 CALL ISAJET(-1,2,3,6)
 STOP
END
```

After compiling, one may link with the ISAJET library of routines, using for VMS

```
$ LINK MSSM,ISAJET/LIB/INCL=ALDATA
```

To run with the above main program, the decay table ISADECAY.DAT created above must be included in the user’s directory, as well as a file of commands ISAJET.PAR, which specifies crucial input commands.

An example of an ISAJET.PAR file is

```
SAMPLE CHARGINO PAIR JOB AT TEVATRON
1800,1000,2,500/
SUPERSYM
BEAMS
 'P','AP'/
MSSM1
200,250,250,250,250,250,250/
MSSM2
2,500,-100/
JETTYPE1
```
In the above file, the first line is simply the program title. The second line contains the machine energy ($E_{cm}$), the number of events to be generated ($N_{event}$), the number of events to be output to screen ($N_{print}$), and how many events to skip before printing another event to screen ($N_{jump}$). The first event is always printed if $N_{print}$ is greater than zero. The third line specifies the reaction type, which for supersymmetry is always SUPERSYM, although many other non-supersymmetric options are available (see Ref. [15].) Next come double lines containing a keyword and then input. First, we specify beam types proton and anti-proton. We next specify the keywords MSSM1 and MSSM2. The input for MSSM1 is $m_{\tilde{g}}, m_{\tilde{q}}, m_{\tilde{t}_L}, m_{\tilde{t}_R}, m_{\tilde{l}_L}, m_{\tilde{l}_R}$, and $m_{\tilde{\nu}_L}$. The input for MSSM2 is $\tan \beta, m_{H_u}$ and $\mu$. All mass dimension parameters are in GeV units. Invoking the MSSM1 and MSSM2 keywords causes the ISASUSY decay package to be called, so that all sparticle masses, decays modes and branching fractions are calculated, and entered into ISAJET's internal decay table. Note both MSSM1 and MSSM2 must be specified to use ISASUSY.

Next, one must specify the two final state particles of the $2 \rightarrow 2$ hard scattering. These are specified by the keywords JETTYPE1 and JETTYPE2, using A8 input format in single quotes. Currently available possibilities include:

'GLSS',
'UPSSL', 'UBSSL', 'DNSSL', 'DBSSL', 'STSSL', 'SBSSL', 'CHSSL', 'CBSSL',
'BTSSL', 'BBSSL', 'TPSSL', 'TBSSL',
'UPSSR', 'UBSSR', 'DNSSR', 'DBSSR', 'STSSR', 'SBSSR', 'CHSSR', 'CBSSR',
'BTSSR', 'BBSSR', 'TPSSR', 'TBSSR',
'W1SS+', 'W1SS-', 'W2SS+', 'W2SS-', 'Z1SS', 'Z2SS', 'Z3SS', 'Z4SS',
'SQUARKS', 'GAUGINOS'.

The last two generate respectively all allowed combinations of squarks and antisquarks and all combinations of charginos and neutralinos, with proportions as given by the MSSM. Care must be taken in specifying JETTYPE1. For instance, in the above example, the output total cross-section would correspond to the expected total cross-section for chargino pair production. If we had instead specified

JETTYPE1
'W1SS-'/
JETTYPE2
'W1SS+/'
the final cross-section tally would be only half the total cross-section, although all events and distributions would be correctly generated. The other half of the cross section would be obtained by interchanging the two JETTYPEi arguments. Finally, in the above example, the $p_T$ limits of the final state particles of the $2 \to 2$ hard scattering subprocess are specified as $(p_{T1} (\text{min}), p_{T1} (\text{max}), p_{T2} (\text{min}), p_{T2} (\text{max}))$. For more on keyword options, see Ref. [15].

### 3.2 ISASUSY 1.0

ISASUSY 1.0 — now a subset of ISAJET 7.0 — is used to calculate sparticle masses, mixings and branching fractions. ISASUSY 1.0 is automatically called by ISAJET 7.0 whenever the **MSSM1** and **MSSM2** keywords are used. In this case, ISASUSY fills an internal ISAJET decay table with the appropriate decay modes and branching fractions; the modes themselves are not printed since output consists of many pages. The user may however run ISASUSY 1.0 as a separate package to generate a file of all calculated masses and decay modes, partial widths and branching fractions.

To assemble ISASUSY.FOR for independent runs, the following VMS command file can be used:

```
$ YTOBIN
ISAJET ISAJET - - YTOBIN .GO
$ YPATCHY
ISAJET ISASUSY TTY YPATCHY .GO
+USE,*ISASUSY
+USE,VAX,IMPNONE,NOCERN
+EXE
+PAM
+QUIT
```

Compiling and linking are straightforward, since ISASUSY doesn’t need to be linked with any other files.

When running ISASUSY, the program will ask for an output filename in single quotes. After entering, ISASUSY asks for the same parameter set as ISAJET: $m_{\tilde{q}}, m_{\tilde{t}_L}, m_{\tilde{t}_R}, m_{\tilde{l}_L}, m_{\tilde{l}_R}, m_{\tilde{\nu}_L}, \tan \beta, m_{H^+_u}, \mu, m_t$. Output will then be written to the specified file for viewing or printing.

It should be noted that some choices of parameters will result in $m_{\tilde{W}_1} < m_{\tilde{Z}_1}$, violating the assumption that $\tilde{Z}_1$ is the LSP. In this case, ISASUSY replies with a warning, and terminates execution. Other choices of parameters can be in regions already excluded by LEP constraints. At present, no warnings are issued for this case.

### 4. ISAJET Output

Upon generating events, ISAJET fills various COMMON blocks listed in Ref. [15].
Explicit output of all beginning run information, all the events, and end run information is stored in the file ISAJET.DAT in the sample program given in Sec. 3. To access this information, one can read the file ISAJET.DAT using the RDTAPE subroutine of ISAJET. For instance, the following program

```fortran
PROGRAM READ
  COMMON /RECTP/ IRECTP,IREC
  COMMON/ITAPES/ ITDKY,ITEVT,ITCOM,ITLIS
  ITLIS=6
  OPEN(UNIT=1,NAME='ISAJET.DAT',TYPE='OLD',FORM='UNFORMATTED')
  CALL RDTAPE(1,IFL)
  IF (IFL.NE.0) GO TO 20
  IF (IRECTP.EQ.100) THEN
    CALL PRTEVT(0)
  END IF
  GO TO 10
20 STOP
END
```

will open and read the file ISAJET.DAT, and restore event information to the ISAJET common blocks so that it can be manipulated, if the user inserts the appropriate common blocks. This program also prints the event information to the terminal screen. Information on the final total cross section can be found in common block /FINAL/.

5. Extensions and Future Improvements

ISAJET 7.0 contains sufficient flexibility that some scenarios for non-minimal SUSY can also be studied. For instance, R-violating models with an unstable $\tilde{Z}_1$ can be easily simulated by using the ISAJET FORCE keyword command to force the desired $\tilde{Z}_1$ decay. FORCE can also be used to override ISASUSY generated decays, or to select specific decay modes for certain sparticles. In addition, the unification condition on gaugino masses can be relaxed if desired. This can be done by a simple modification of the FORTRAN code in subroutine SSMASS. Some modifications, such as added Higgs singlets which can also enlarge the neutralino sector, are more difficult to include, and would require a more substantial code revision.

ISAJET 7.0 can also be used to simulate top squark events even before stops are officially included. For instance, by setting the JETTYPEi to be bottom squarks, one generates nearly the same cross-section as for top squarks. Then the user may use the FORCE command to force the generated squarks to decay into the desired modes, such as $\tilde{t}_1 \rightarrow c\tilde{Z}_1$ or $\tilde{t}_1 \rightarrow b\tilde{W}_1$ (see Ref. [26]).

There are still many aspects of MSSM sparticle production that are not included in the current version of ISAJET, but will hopefully be included in future versions. A partial list includes the following:
• top squark production and decay;
• slepton pair production processes;
• a subroutine to notify if the parameters are in violation of LEP limits;
• direct MSSM Higgs boson production mechanisms;
• neutralino pair production processes;
• Higgs decays to sfermion pairs;
• further breaking of sfermion degeneracies, especially for the third generation;
• improved calculations of radiative corrections to the Higgs sector;
• $e^+e^-$ production of SUSY particles.

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