χ_0 decay in trilinear and bilinear RPV

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ABSTRACT

In this work we calculate the neutralino decay in two different scenarios. In the first case, we work in the context of trilinear R-parity violation (TRpV) and we calculate the decay to three quarks. In the second case we work with bilinear RpV and calculate the decay of the neutralino to leptons, bosons and quarks. In both cases we present a program that calculates numerically the branching ratios and final-state kinematic distribution. In the last section we show a couple of figures and a table that ilustrate the results obtained with the program.

1. χ_0 to qqq decay, trilinear case

The TRpV superpotential necessary for this calculation is the following:

$$W_{TRp} = \lambda_{ijk}\hat{L}_i\hat{L}_jE^c_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^c_k + \lambda''_{ijk}\hat{U}^c_i\hat{D}^c_j\hat{D}^c_k \tag{1}$$

We are going to work just with $\lambda'' \neq 0$. In this scenario we can calculate the $\chi_0 \to udd$ decay through a virtual squark.

The different decay rates of the Neutralino are given by a standard three-body phase factor multiplied by a squared amplitude which is averaged over the initial neutralino spin and summed over the final fermion spins.

$$\frac{\partial\Gamma}{\partial x_1\partial x_2} = \frac{m_\chi}{256\pi^3}\sum_{spins}|\mathcal{M}|^2 \tag{2}$$

$$x_{1,2} = \frac{2E_{1,2}}{m_\chi} \tag{3}$$

It is useful to write this expresion in terms of the invariant masses

$$\begin{aligned}
\frac{\partial\Gamma}{\partial m_{12}^2 \partial m_{23}^2} &= \frac{1}{(2\pi)^3 32 m_\chi^3} \sum_{spins} |\mathcal{M}|^2 && (4)\\
m_{12}^2 &= (p_1+p_2)^2 && (5)\\
m_{23}^2 &= (p_2+p_3)^2 && (6)\\
m_{13}^2 &= (p_1+p_3)^2 && (7)
\end{aligned}$$

Where $|\mathcal{M}|^2$ depends just on m_{12}^2 and m_{23}^2 as independent variables. The expresion for $\mathcal{M}$ is obtained from the following expansion of λ'' term and the lagrangian of the MSSM that contains the neutralino-squark-quark vertex [1]:

$$\begin{aligned}
\mathcal{L}_{UDD} &\ni -2\epsilon^{\alpha\beta\gamma}\lambda''_{ijk}[\tilde{u}_{Ri\alpha}\bar{\eta}^D_{j\beta}\bar{\eta}^D_{k\gamma} + \tilde{d}_{Rj\beta}\bar{\eta}^U_{i\alpha}\bar{\eta}^D_{k\gamma} + \tilde{d}_{Rk\gamma}\bar{\eta}^U_{i\alpha}\bar{\eta}^D_{j\beta}] + h.c.\\
&\ni -2\epsilon^{\alpha\beta\gamma}\lambda''_{ijk}[\Gamma^{u*}_{Rli}\tilde{u}_{l\alpha}\bar{d}^c_{j\beta}P_R d_{k\gamma} + \Gamma^{d*}_{Rlj}\tilde{d}_{l\beta}\bar{u}^c_{i\alpha}P_R d_{k\gamma}\\
&\quad +\Gamma^{d*}_{Rlk}\tilde{d}_{l\gamma}\bar{u}^c_{i\alpha}P_R d_{j\beta}] + h.c. && (8)\\
\mathcal{L}_{\chi q\tilde{q}} &\ni \bar{\chi}(g^L_{\chi q_i k}P_L + g^R_{\chi q_i k}P_R)q_{i\alpha}\tilde{q}_{k\alpha} + h.c. && (9)
\end{aligned}$$

where we have used the squark mixing matrix $\Gamma^f_{(R,L)ki}$ and

$$\begin{aligned}
\bar{\eta}_1\bar{\eta}_2 &= \bar{\psi}^c_1 P_R \psi_2 && (10)\\
\tilde{f}_{R,Li} &= \Gamma^{f*}_{R,Lki}\tilde{f}_k && (11)\\
g^A_{\chi f_i k} &= \Gamma^f_{Rki}g^{RA}_{\chi f_i} + \Gamma^f_{Lki}g^{LA}_{\chi f_i} && (12)
\end{aligned}$$

To write the matrix element we use the following convention :

$\bar{v}$ $\rightarrow$ incoming lepton
v $\rightarrow$ outcoming lepton
$\bar{u}$ $\rightarrow$ incoming anti-lepton
u $\rightarrow$ outcoming anti-lepton

and we calculate $\mathcal{M}$ from left to right. The resulting expression for $|\mathcal{M}|^2$ is

$$\begin{aligned}
\mathcal{M} &= -2\lambda''_{ijk}[\bar{v}_\chi(g^L_{\chi u_i l}P_L + g^R_{\chi u_i l}P_R)\Delta_{\tilde{u}_l}\Gamma^{u*}_{Rli}v_{u_i}\bar{u}_{d_j}P_R v_{d_k} -\\
&\quad \bar{v}_\chi(g^L_{\chi d_j l}P_L + g^R_{\chi d_j l}P_R)\Delta_{\tilde{d}_l}\Gamma^{d*}_{Rlj}v_{d_j}\bar{u}_{u_i}PRv_{d_k} +\\
&\quad \bar{v}_\chi(g^L_{\chi d_k l}P_L + g^R_{\chi d_k l}P_R)\Delta_{\tilde{d}_l}\Gamma^{u*}_{Rlk}v_{d_k}\bar{u}_{u_i}P_R v_{d_j}]
\end{aligned}$$

Next we introduce the next quantities

$$
\begin{aligned}
G_{f_i}^{AB} &= \sum_k g_{\chi f_i k}^B \Delta_{\tilde{f}_k} \Gamma_{Aki}^{d*} \\
g(a,b,c,d) &= a \cdot bc \cdot d - a \cdot cb \cdot d + a \cdot db \cdot c
\end{aligned}
\tag{13}
$$

and obtain

$$
\begin{aligned}
\sum_{spins} |\mathcal{M}|^2 &= 8c_f |\lambda ijk''|^2 \times Re\Big\{ \\
& d_j \cdot d_k [(|G_u^{RL}|^2 + |G_u^{RR}|^2)\chi \cdot u + 2G_u^{RL} G_u^{RR*} m_\chi m_u] \\
& +(u \leftrightarrow d_j) + \\
& +(u \leftrightarrow d_k) \\
& -G_u^{RR} G_{d_j}^{RR*} g(u, d_k, d_j, \chi) - G_u^{RL} G_{d_j}^{RR*} d_j \cdot d_k m_\chi m_u \\
& -G_u^{RR} G_{d_j}^{RL*} u \cdot d_k m_\chi m_{d_j} - G_u^{RL} G_{d_k}^{RR*} \chi \cdot d_k m_u m_{d_j} \\
& -(d_j \leftrightarrow d_k) \\
& -(u \leftrightarrow d_k, d_k \leftrightarrow d_j) \Big\}
\end{aligned}
\tag{14}
$$

We can rewrite this result without the squark mixing-matrix, assuming squark mass degeneraty and neglecting the quark masses, obtaining :

$$
\begin{aligned}
\sum_{spins} |\mathcal{M}|^2 &= \frac{16}{9} c_f \lambda ijk''|^2 (g' N_{\chi_1})^2 \times \Big\{ \\
& \frac{m_{23}^2 (m_\chi^2 - m_{23}^2)}{(m_{\tilde{q}}^2 - m_{23}^2)^2} + \frac{1}{4} \frac{m_{13}^2 (m_\chi^2 - m_{13}^2)}{(m_{\tilde{q}}^2 - m_{13}^2)^2} \\
& + \frac{1}{4} \frac{m_{12}^2 (m_\chi^2 - m_{12}^2)}{(m_{\tilde{q}}^2 - m_{12}^2)^2} + \frac{m_{23}^2 m_{13}^2}{(m_{\tilde{q}}^2 - m_{23}^2)(m_{\tilde{q}}^2 - m_{13}^2)} \\
& + \frac{m_{12}^2 m_{23}^2}{(m_{\tilde{q}}^2 - m_{12}^2)(m_{\tilde{q}}^2 - m_{23}^2)} - \frac{1}{2} \frac{m_{12}^2 m_{13}^2}{(m_{\tilde{q}}^2 - m_{12}^2)(m_{\tilde{q}}^2 - m_{13}^2)} \Big\}
\end{aligned}
\tag{15}
$$

with $m_{13}^2 = m_\chi^2 - m_{23}^2 - m_{12}^2$. The minimun and maximum values of the independent invariant masses are:

$$
\begin{aligned}
(m_{23}^2)_{min} &= 0 &(16)\\
(m_{23}^2)_{max} &= m_\chi^2 &(17)\\
(m_{12}^2)_{min} &= 0 &(18)\\
(m_{12}^2)_{max} &= \frac{m_\chi^2 - m_{23}^2}{2} &(19)
\end{aligned}
$$

1.1. χ_0 rest frame

In the χ_0 rest-frame we can use the following variables in analogy with [3]

$$
\begin{aligned}
x_i &= \frac{E_i}{E} = \frac{2E_i}{Q}\\
m_{ij}^2 &= m_\chi(m_\chi - 2E_k)\\
&= 4E(E - E_k)\\
&= Q^2(1 - x_k)\\
R &= \frac{m_{\tilde{q}}^2}{Q^2} \qquad (20)
\end{aligned}
$$

It is also useful to recall the following relation

$$\sum_{i=1}^{3} x_i = 2 \qquad (21)$$

with this, we can write $|\mathcal{M}|^2$ in the χ_0 rest-frame as

$$
\begin{aligned}
\sum_{spins} |\mathcal{M}|^2 = {} & \frac{16}{9} c_f |\lambda ijk''|^2 (g' N_{\chi_1})^2 \times \Bigg\{\\
& \frac{x_1(1-x_1)}{(1-x_1-R)^2} + \frac{1}{4}\frac{x_2(1-x_2)}{(1-x_2-R)^2} + \frac{1}{4}\frac{x_3(1-x_3)}{(1-x_3-R)^2} +\\
& \frac{(1-x_1)(1-x_2)}{(1-x_1-R)(1-x_2-R)} + \frac{(1-x_1)(1-x_3)}{(1-x_1-R)(1-x_3-R)} -\\
& \frac{1}{2}\frac{(1-x_2)(1-x_3)}{(1-x_2-R)(1-x_3-R)}\Bigg\} \qquad (22)
\end{aligned}
$$

We remember also that the differential decay rate can be writter in the forms

$$\frac{\partial\Gamma}{\partial m_{12}^2 \partial m_{23}^2} = \frac{\partial\Gamma}{\partial x_1 \partial x_3} \frac{1}{Q^4} \tag{23}$$

1.2. m_{23}^2 rest frame

This frame is defined by the relation $\vec{p_2} + \vec{p_3} = 0$. To describe the matrix element $\mathcal{M}$ we use the variables m_{23}^2 and $\cos\theta$ [4], where θ is the angle between the particle 1 and 2. In this context we can write the following

$$\begin{aligned} m_{12}^2 &= E_1 E_2 (1 - \cos\theta) \\ m_{13}^2 &= E_1 E_2 (1 + \cos\theta) \\ m_{23}^2 &= 2E_2^2 \end{aligned} \tag{24}$$

using 4-momentum conservation we have

$$\begin{aligned} Q^2 &= m_{12}^2 + m_{23}^2 + m_{13}^2 \\ E_1 &= \frac{Q^2 - 2E_2^2}{2E_2} \\ m_{12}^2 &= \frac{Q^2 - m_{23}^2}{2}(1 - \cos\theta) \\ m_{13}^2 &= \frac{Q^2 - m_{23}^2}{2}(1 + \cos\theta) \end{aligned} \tag{25}$$

Thus, the squared decay amplitude $|\mathcal{M}|^2$ is

$$\begin{aligned} \sum_{spins} |\mathcal{M}|^2 &= \frac{16}{9} c_f \lambda ijk''|^2 (g' N_{\chi_1})^2 \times \Big\{ \\ & \frac{m_{23}^2(Q^2 - m_{23}^2)}{(m_{\tilde{q}}^2 - m_{23}^2)} + \frac{1}{4}\frac{(Q^2 - m_{23}^2)(1+\cos\theta)(Q^2(1-\cos\theta) + m_{23}^2(1+\cos\theta))}{(2m_{\tilde{q}}^2 - (Q^2 - m_{23}^2)(1+\cos\theta))^2} \\ & + \frac{1}{4}\frac{(Q^2 - m_{23}^2)(1-\cos\theta)(Q^2(1+\cos\theta) + m_{23}^2(1-\cos\theta))}{(2m_{\tilde{q}}^2 - (Q^2 - m_{23}^2)(1-\cos\theta))^2} \end{aligned}$$

$$
\begin{aligned}
&+\frac{4m_{23}^2(Q^2-m_{23}^2)(1+\cos\theta)}{(m_{\tilde{q}}^2-m_{23}^2)(2m_{\tilde{q}}^2-(Q^2-m_{23}^2)(1+\cos\theta))}\\
&+\frac{4m_{23}^2(Q^2-m_{23}^2)(1-\cos\theta)}{(m_{\tilde{q}}^2-m_{23}^2)(2m_{\tilde{q}}^2-(Q^2-m_{23}^2)(1-\cos\theta))}\\
&-\frac{(Q^2-m_{23}^2)^2(1-(\cos\theta)^2)}{(2m_{\tilde{q}}^2-(Q^2-m_{23}^2)(1-\cos\theta))(2m_{\tilde{q}}^2-(Q^2-m_{23}^2)(1+\cos\theta))}
\end{aligned}
\tag{26}
$$

with the corresponding relution for the differential decay rate

$$
\frac{\partial\Gamma}{\partial m_{12}^2\partial m_{23}^2}=\frac{\partial\Gamma}{\partial m_{23}^2\partial\cos\theta}\frac{2}{(Q^2-m_{23}^2)}
\tag{27}
$$

2. χ_0 decay in bilineal R-Parity violation

The BRpV superpotential that we use is the following:

$$
W_{BRp}=\epsilon_i\hat{L}_i^a\hat{H}_u^b
\tag{28}
$$

In this superpotential we can see R-parity and lepton number violation in three generations.

At the end of this calculation we hope as a first goal to find the percentages that appear in the paper [6] by means of a program that we heve written in Fortran, which are necessary to simulate LHC neutralino physics. The final idea is obtain a program that lets us change the BRpV parameters Λ_i and ϵ_i and thus relates neutrino physics to LHC phenomenology.

2.1. Two-body χ_0 decay

We first calculate two-body χ_0 decay in this scenario. The process that interests us is:

$$
\chi_0\to l^{\pm}W^{\pm}
\tag{29}
$$

it, is also possible and straightforward to calculate the following two-body decays that maybe will be interesting.

$$
\chi_0 \;\to\; \nu Z
$$

$$
\begin{aligned}
Z &\rightarrow l^-l^+ \\
&\rightarrow \nu\nu \\
&\rightarrow q\bar{q} \\
W^\pm &\rightarrow \nu l^\pm \\
W^\pm &\rightarrow q\bar{q}'
\end{aligned} \tag{30}
$$

For all of these processes the forms of the decay rates are the same, the differences just appear in the calculations of the matrix element $\mathcal{M}$. In general, we find that the vertex and decay rate are:

$$
\begin{aligned}
V &= i\gamma_\mu[O_L P_L + O_R P_R] \\
\Gamma &= \frac{|\mathcal{M}|^2}{16\pi m_1^3}\lambda(m_1^2, m_2^2, m_3^2) \\
\lambda(m_1^2, m_2^2, m_3^2) &= m_1^4 + m_2^4 + m_3^4 - 2m_1^2 m_2^2 - 2m_1^2 m_3^2 - 2m_2^2 m_3^2
\end{aligned} \tag{31}
$$

In the calculation of $|\mathcal{M}|^2$ just two different options appear. One is the neutralino-lepton-boson and the other is the boson-lepton-lepton process. The corresponding results of this matrix element are:

$$
\begin{aligned}
|\mathcal{M}|^2 &= (|O_L|^2 + |O_R|^2)\{\frac{2p_1 \cdot p_3 p_2 \cdot p_3}{m_3^2} + p_1 \cdot p_2\} - 3(O_L O_R^* + O_L^* O_R)m_1 m_2 \\
|\mathcal{M}|^2 &= \frac{2}{3}(|O_L|^2 + |O_R|^2)\{\frac{2p_1 \cdot p_2 p_1 \cdot p_3}{m_1^2} + p_2 \cdot p_3\} + 2(O_L O_R^* + O_L^* O_R)m_2 m_3
\end{aligned} \tag{32}
$$

To write these results in terms of the particle's mass we choose as like reference frame the rest frame of the father particle, in which we find that:

$$
\begin{aligned}
p_1 &= (m_1, \vec{0}) \\
p_2 &= (E_2, \vec{p_2}) \\
p_3 &= (E_3, -\vec{p_2}) \\
|p_2|^2 &= \frac{\lambda^2(m_1^2, m_2^2, m_3^2)}{4m_1^2}
\end{aligned} \tag{33}
$$

In the implementation of the program, as in the three-body decay calculation we neglect the masses of SM particles.

2.2. Three-body χ_0 decay

This case is more interesting than the two-body decay case, because in this case it is necessary to calculate numericall the decay rate by means of some program. For this reason, we are just going to show the differential decay rate in terms of the invariant masses.

The kinematic form for all three-body decays is the following (as in qqq decay):

$$\begin{aligned}
\frac{\partial\Gamma}{\partial m_{12}^2 \partial m_{23}^2} &= \frac{1}{(2\pi)^3 32 m_\chi^3} \sum_{spins} |\mathcal{M}|^2 && (34)\\
m_{12}^2 &= (p_i + p_j)^2 && (35)\\
m_{23}^2 &= (p_j + p_k)^2 && (36)\\
m_{13}^2 &= (p_i + p_k)^2 && (37)
\end{aligned}$$

where the indices i, j and k identify the final-state particles.

The processes that we want to calculate are:

$$\begin{aligned}
\chi_0 &\to \nu_i l_j^{\mp} l_k^{\pm} \\
&\to \nu_i q_j \bar{q}_k \\
&\to u_i \bar{d}_j l_k^- \\
&\to \nu\nu\nu && (38)
\end{aligned}$$

All these processes have an intermediate boson or scalar particle. In the first process we have the bosons $Z, W^{\pm}, S_n^0, P_n^0, S_n^{\pm}$ as intermediate particles. In the second process we have $Z, S_n^0, P_n^0, \tilde{q}_n$. In the third process we have $W^{\pm}, S_n^{\pm}, \tilde{q}_n$ and in the last process Z, S_n^0, P_n^0. The Feynman diagrams and the details of this process appear in [2].

The next step is to calculate the squared matrix element $|\mathcal{M}|^2$ for each of these processes, including quadratic terms and cross terms between different Feynman diagrams for each process.

As in the two-body decay case, we calculate the process in general form, and in the program we write all results explicitly.

2.3. Quadratic terms, with intermediate vector bosons

We start with the quadratic term of the $\chi_0 \to l_i Z \to l_i l_j l_k$ process, where l is any fermion in the final state. The vertex and propagators have the following expressions:

$$\begin{aligned} V_1 &= i\gamma_\mu[O_L^1 P_L + O_R^1 P_R] \\ V_2 &= i\gamma_\nu[O_L^2 P_L + O_R^2 P_R] \\ \Delta_z &= \frac{1}{(p_j + p_k)^2 - m_z^2 + i m_z \Gamma_z} \end{aligned} \tag{39}$$

and the final form of $|\mathcal{M}|^2$ is:

$$\begin{aligned} |\mathcal{M}|^2 &= (|O_L^1|^2 + |O_R^1|^2)(|O_L^2|^2 + |O_R^2|^2)|\Delta_z|^2 \times \\ &\Big\{(l_i \cdot l_j)(x \cdot l_k) + (x \cdot l_j)(l_i \cdot l_k) \\ &-\frac{1}{m_z^2}[(x \cdot l_j)(x \cdot l_i)(l_j \cdot l_k) - (x \cdot l_i)(l_j \cdot l_k)(x \cdot p_z)] \\ &+\frac{1}{m_z^4}[(x \cdot l_i)(x \cdot p_z)(l_j \cdot l_k)^2 + 2(x \cdot l_i)(l_j \cdot l_k)^3)]\Big\} \end{aligned} \tag{40}$$

This result is general in the following sense. In the case of the $\chi_0 \to l_j W^+ \to l_i l_j l_k$ process, the corresponding matrix element is obtained if we change $l_i \leftrightarrow l_j$ and replace Z with W^+, in the equation shown above. We can do the same for the $\chi_0 \to l_k W^+ \to l_i l_j l_k$ process, where we must to change $l_i \leftrightarrow l_k$ and replace Z with W^- .

2.4. Quadratic terms, with intermediate scalar bosons

As before we start with the diagram that contains the neutral boson. Which in this case is the process $\chi_0 \to l_i S_n^0 \to l_i l_j l_k$. The verteices and propagators have the following expressions:

$$\begin{aligned} V_1 &= i[O_L^1 P_L + O_R^1 P_R] \\ V_2 &= i[O_L^2 P_L + O_R^2 P_R] \\ \Delta_S &= \frac{1}{(p_j + p_k)^2 - m_S^2 + i m_S \Gamma_S} \end{aligned} \tag{41}$$

and the final form of $|\mathcal{M}|^2$ is:

$$|\mathcal{M}|^2 = 2(|O_L^1|^2 + |O_R^1|^2)(|O_L^2|^2 + |O_R^2|^2)|\Delta_S|^2 \times (x \cdot l_i)(l_j \cdot l_k) \tag{42}$$

To obtain the $\chi_0 \to l_j S_n^+ \to l_i l_j l_k$ term, we must replace $l_i \leftrightarrow l_j$ and S_n^0 with S_n^+. In the $\chi_0 \to l_k S_n^- \to l_i l_j l_k$ process we replace $l_i \leftrightarrow l_k$ and S_n^0 with S_n^-. In the process $\chi_0 \to l_k \tilde{q}_n \to l_i l_j l_k$ we replace $l_i \leftrightarrow l_k$ and S_n^0 with $\tilde{q}_n$. And, in the process $\chi_0 \to l_i \tilde{q}_n \to l_i l_j l_k$ we just replace S_n^0 with $\tilde{q}_n$. The two last processes are a bit stranges but with the indicated replacements there are no problems.

2.5. Vector-Vector cross terms

Also calculating the quadratic terms, it is necessary to obtain the cross terms betwen the different diagrams that may contribute to the same decay. We chosse to start with the boson-boson cross terms. We choice start with the term $Z \times W^+$. The vertices and propagators for this term are:

$$\begin{aligned}
V_1^Z &= i\Gamma_\mu[O_L^{Z1} P_L + O_R^{Z1} P_R] \\
V_2^Z &= i\Gamma_\nu[O_L^{Z2} P_L + O_R^{Z2} P_R] \\
V_1^W &= i\Gamma_\rho[O_L^{W1} P_L + O_R^{W1} P_R] \\
V_2^W &= i\Gamma_\sigma[O_L^{W2} P_L + O_R^{W2} P_R] \\
\Delta_Z &= \frac{1}{(p_j + p_k)^2 - m_z^2 + i m_z \Gamma_z} \\
\Delta_W &= \frac{1}{(p_i + p_k)^2 - m_w^2 + i m_w \Gamma_w}
\end{aligned} \tag{43}$$

and the corresponding $|\mathcal{M}|^2$ is obtained from the following expresion:

$$\begin{aligned}
|\mathcal{M}|^2 &= \frac{1}{2}(O_L^{Z1} O_L^{Z2} O_L^{W1*} O_L^{W2*} + O_R^{Z1} O_R^{Z2} O_R^{W1*} O_R^{W2*})\Delta_Z \Delta_W^* \times \\
&\left(g^{\mu\nu} - \frac{p_z^\mu p_z^\nu}{m_z^2}\right)\left(g^{\rho\sigma} - \frac{p_w^\rho p_w^\sigma}{m_w^2}\right) x^\alpha l_j^\beta l_k^\gamma l_i^\delta Tr\{\gamma_\alpha \gamma_\rho \gamma_\beta \gamma_\nu \gamma_\gamma \gamma_\sigma \gamma_\delta \gamma_\mu\}
\end{aligned} \tag{44}$$

This expression when explicit written in terms of the four-momenta too bcomes complicated, but in the program it is writen in full. We continue with the term $Z \times W^-$, the forms of the verteices and propagators are as before, although we must note that the propagator the W^- is written in terms of the momentum $(p_i + p_j)$, for this reason just we write $|\mathcal{M}|^2$ as.

$$
\begin{aligned}
|\mathcal{M}|^2 &= \frac{1}{2}(O_L^{Z1}O_L^{Z2}O_L^{W1*}O_L^{W2*} + O_R^{Z1}O_R^{Z2}O_R^{W1*}O_R^{W2*})\Delta_Z\Delta_W^* \times \\
& \left(g^{\mu\nu} - \frac{p_z^\mu p_z^\nu}{m_z^2}\right)\left(g^{\rho\sigma} - \frac{p_w^\rho p_w^\sigma}{m_w^2}\right)x^\alpha l_j^\beta l_k^\gamma l_i^\delta Tr\{\gamma_\beta\gamma_\nu\gamma_\gamma\gamma_\rho\gamma_\alpha\gamma_\mu\gamma_\delta\gamma_\sigma\}
\end{aligned} \tag{45}
$$

To finish this section we write the expression for the $W^+ \times W^-$ term. In this case it is necessary to write the vertices and propagators again.

$$
\begin{aligned}
V_1^+ &= i\Gamma_\mu[O_L^{+1}P_L + O_R^{+1}P_R] \\
V_2^+ &= i\Gamma_\nu[O_L^{+2}P_L + O_R^{+2}P_R] \\
V_1^- &= i\Gamma_\rho[O_L^{-1}P_L + O_R^{-1}P_R] \\
V_2^- &= i\Gamma_\sigma[O_L^{-2}P_L + O_R^{-2}P_R] \\
\Delta_+ &= \frac{1}{(p_i + p_k)^2 - m_+^2 + im_+\Gamma_+} \\
\Delta_- &= \frac{1}{(p_i + p_j)^2 - m_-^2 + im_-\Gamma_-}
\end{aligned} \tag{46}
$$

and the corresponding $|\mathcal{M}|^2$ is obtained from the following expression:

$$
\begin{aligned}
|\mathcal{M}|^2 &= \frac{1}{2}(O_L^{+1}O_L^{+2}O_L^{-1*}O_L^{-2*} + O_R^{+1}O_R^{+2}O_R^{-1*}O_R^{-2*})\Delta_+\Delta_-^* \times \\
& \left(g^{\mu\nu} - \frac{p_+^\mu p_+^\nu}{m_+^2}\right)\left(g^{\rho\sigma} - \frac{p_-^\rho p_-^\sigma}{m_-^2}\right)x^\alpha l_j^\beta l_k^\gamma l_i^\delta Tr\{\gamma_\gamma\gamma_\rho\gamma_\alpha\gamma_\nu\gamma_\beta\gamma_\sigma\gamma_\delta\gamma_\mu\}
\end{aligned} \tag{47}
$$

2.6. Scalar-Scalar cross terms

We continue the calculation with the terms that include cross-terms between Feynman diagrams with scalar boson as intermediate particles. We start with the term $S_n^0 \times P_n^0$. The verteices and propagators for this term are:

$$
\begin{aligned}
V_1^S &= i[O_L^{S1} P_L + O_R^{S1} P_R] \\
V_2^S &= i[O_L^{S2} P_L + O_R^{S2} P_R] \\
V_1^P &= i[O_L^{P1} P_L + O_R^{P1} P_R] \\
V_2^P &= i[O_L^{P2} P_L + O_R^{P2} P_R] \\
\Delta_S &= \frac{1}{(p_j + p_k)^2 - m_s^2 + i m_s \Gamma_s} \\
\Delta_P &= \frac{1}{(p_j + p_k)^2 - m_p^2 + i m_p \Gamma_p}
\end{aligned}
\tag{48}
$$

and the corresponding $|\mathcal{M}|^2$ is obtained from the following expression:

$$
\begin{aligned}
|\mathcal{M}|^2 &= 8(O_L^{S1} O_L^{P1*} + O_R^{S1} O_R^{P1*})(O_L^{S2} O_L^{P2*} + O_R^{S2} O_R^{P2*}) \Delta_S \Delta_P^* \times \\
&\quad (x \cdot l_i)(l_j \cdot l_k)
\end{aligned}
\tag{49}
$$

We continue with the term $S_n^0 \times S_n^+$. Note that this term is equal to the term $P_n^0 \times S_n^+$, if we change $S_n^0 \leftrightarrow P_n^0$. The vertices and propagators are:

$$
\begin{aligned}
V_1^S &= i[O_L^{S1} P_L + O_R^{S1} P_R] \\
V_2^S &= i[O_L^{S2} P_L + O_R^{S2} P_R] \\
V_1^P &= i[O_L^{+1} P_L + O_R^{+1} P_R] \\
V_2^P &= i[O_L^{+2} P_L + O_R^{+2} P_R] \\
\Delta_S &= \frac{1}{(p_j + p_k)^2 - m_s^2 + i m_s \Gamma_s} \\
\Delta_P &= \frac{1}{(p_i + p_k)^2 - m_+^2 + i m_+ \Gamma_+}
\end{aligned}
\tag{50}
$$

and the corresponding $|\mathcal{M}|^2$ is obtained from the following expression:

$$
\begin{aligned}
|\mathcal{M}|^2 &= 8(O_L^{S1} O_L^{S2} O_L^{+1*} O_L^{+2*} + O_R^{S1} O_R^{S2} O_R^{+1*} O_R^{+2*}) \Delta_S \Delta_+^* \times \\
&\quad ((l_j \cdot l_k)(x \cdot l_i) - (l_i \cdot l_j)(x \cdot l_k) + (x \cdot l_j)(l_i \cdot l_k))
\end{aligned}
\tag{51}
$$

To obtain the term $S_n^0 \times S_n^-$ we must change in the above result the vertex terms, propagators and exchange $x \leftrightarrow l_i$. For the term $S_n^+ \times S_n^-$ we must change $l_i \leftrightarrow l_k$ and the corresponding vertices and propagators. Note that the calculation of the cross terms that involve $\tilde{q}_n$ do not introduce new terms because the calculation is equal to the cross terms with S_n^- and S_n^+ contributions.

2.7. Vector-Scalar cross term

The last kind of cross term in the calculation of the matrix elements corresponds to vector-scalar cross terms. In the aproximation of massless SM particles, the terms $Z^0 \times S_n^0(P_n^0)$, $W^+ \times S_n^+$ and $W^- \times S_n^-$ are equal to zero.

So, the first non-zero term that appears in this sector is $Z^0 \times S_n^+$. The vertices and propagators for this calculation are:

$$
\begin{aligned}
V_1^S &= i\gamma_\mu[O_L^{Z1}P_L + O_R^{Z1}P_R] \\
V_2^S &= i\gamma_\nu[O_L^{Z2}P_L + O_R^{Z2}P_R] \\
V_1^P &= i[O_L^{+1}P_L + O_R^{+1}P_R] \\
V_2^P &= i[O_L^{+2}P_L + O_R^{+2}P_R] \\
\Delta_S &= \frac{1}{(p_j+p_k)^2 - m_z^2 + im_z\Gamma_z} \\
\Delta_P &= \frac{1}{(p_i+p_k)^2 - m_+^2 + im_+\Gamma_+}
\end{aligned}
\tag{52}
$$

and the corresponding $|\mathcal{M}|^2$ is obtained from the following expression:

$$
\begin{aligned}
|\mathcal{M}|^2 = {} & 4(O_L^{Z1}O_R^{Z2}O_L^{+1*}O_R^{+2*} + O_R^{Z1}O_L^{Z2}O_R^{+1*}O_L^{+2*})\Delta_Z\Delta_+^* \times \\
& \Big\{2(x\cdot l_j)(l_i\cdot l_k) - \frac{1}{m_z^2}(z\cdot l_i)g(x,l_j,z,l_k) \\
& + \frac{1}{m_z^2}(z\cdot l_k)g(x,l_j,z,l_i) - \frac{1}{2m_z^2}(z\cdot z)g(x,l_j,l_k,l_i)\Big\}
\end{aligned}
\tag{53}
$$

To obtain the term $W^+ \times S_n^0(P_n^0)$ we change $l_i \leftrightarrow l_j$ in the last result together with the vertex terms and propagators. We continue with the term $Z^0 \times S_n^-$, but this term is equal to the term $Z^0 \times S_n^+$ if we change $x \leftrightarrow l_i$. So, the term $W^- \times S_n^0(P_n^0)$ is obtained from $Z^0 \times S_n^-$ if we change $l_i \leftrightarrow l_k$. The last term that introduces new information is $W^+ \times S_n^-$, because the term $W^- \times S_n^+$ is obtained from this one changing $x \leftrightarrow l_i$ and $l_j \leftrightarrow l_k$. Then, the vertices and propagators are:

$$
\begin{aligned}
V_1^S &= i\gamma_\mu[O_L^{W1}P_L + O_R^{W1}P_R] \\
V_2^S &= i\gamma_\nu[O_L^{W2}P_L + O_R^{W2}P_R] \\
V_1^P &= i[O_L^{-1}P_L + O_R^{-1}P_R] \\
V_2^P &= i[O_L^{-2}P_L + O_R^{-2}P_R] \\
\Delta_S &= \frac{1}{(p_i+p_k)^2 - m_w^2 + im_w\Gamma_w} \\
\Delta_P &= \frac{1}{(p_i+p_j)^2 - m_-^2 + im_-\Gamma_-}
\end{aligned}
\tag{54}
$$

and the corresponding $|\mathcal{M}|^2$ is obtained from the following expression:

$$
\begin{aligned}
|\mathcal{M}|^2 = {}& 4(O_L^{W1}O_R^{W2}O_L^{-1*}O_R^{-2*} + O_R^{W2}O_L^{W2}O_R^{-1*}O_L^{-2*})\Delta_w\Delta_-^* \times \\
& \Big\{2(x\cdot l_j)(l_i\cdot l_k) - \frac{1}{m_w^2}(w\cdot l_j)g(x,l_i,l_k,w) \\
& + \frac{1}{m_w^2}(w\cdot x)g(l_i,l_k,w,l_j) - \frac{1}{2m_w^2}(w\cdot w)g(l_i,l_k,x,l_j)\Big\}
\end{aligned}
\tag{55}
$$

Remember again that the terms that involve $\tilde{q}$ do not introduce new information. With all of these terms we chave written a program that calculates explicitly the branching ratio and final-state kinematic distributions of neutralino decays in the bilinear R-parity scenario.

3. To write the program

To write the program that caculates the different branching ratio it is necessary:

- To find the four-momentum products in terms of the invariant masses defined previously.
- To obtain the coupling constants for all the vertices.

3.1. Four-momentum products in terms of invariant masses

This exercise is straightforward, but is very important to write correctly the program. So, here we show all different four-momentum products that appear:

$$
\begin{aligned}
(l_i \cdot l_j) &= \frac{m_{12}^2}{2} = (w^- \cdot l_i) = (w^- \cdot l_j) = (w^- \cdot w^-) \\
(l_i \cdot l_k) &= \frac{m_{13}^2}{2} = (w^+ \cdot l_i) = (w^+ \cdot l_k) = (w^+ \cdot w^+) \\
(l_j \cdot l_k) &= \frac{m_{23}^2}{2} = (z \cdot l_j) = (z \cdot l_k) = (z \cdot z)
\end{aligned} \tag{56}
$$

$$
\begin{aligned}
(x \cdot l_i) &= \frac{m_\chi^2 - m_{23}^2}{2} = (x \cdot z) = (z \cdot l_i) \\
(x \cdot l_j) &= \frac{m_\chi^2 - m_{13}^2}{2} = (x \cdot w^+) = (w^+ \cdot l_j) \\
(x \cdot l_k) &= \frac{m_\chi^2 - m_{12}^2}{2} = (x \cdot w^-) = (w^- \cdot l_k)
\end{aligned} \tag{57}
$$

$$
(z \cdot w^+) = \frac{m_\chi^2}{2} = (z \cdot w^-) = (w^+ \cdot w^-) \tag{58}
$$

3.2. Coupling constants

The coupling constants necessary to calculate all these decays are given in the program coupling.f [8]. This program was written with the subroutines of the program Spheno.f [7] where the couplings appear in the convention of the papers [2] and [5]. The interesting coupling constants are:

- Neutralino-Neutralino-Z, Neutralino-Neutralino-(P)Scalar, Neutralino-Chargino-W, Neutralino-Chargino-Charged Scalar
- Chargino-Chargino-Z, Chargino-Chargino-(P)Scalar,
- Quark-Quark-Z, Quark-Quark-W, Quark-Quark-(P)Scalar, Quark-Quark-Charged Scalar, Quark-Squark-Neutralino, Quark-Squark-Chargino

4. Results

In this section we show some results obtained from the program xdecay.f [8]. We start with a figure that show the differential cross sections for four different kinds of neutralino decay.

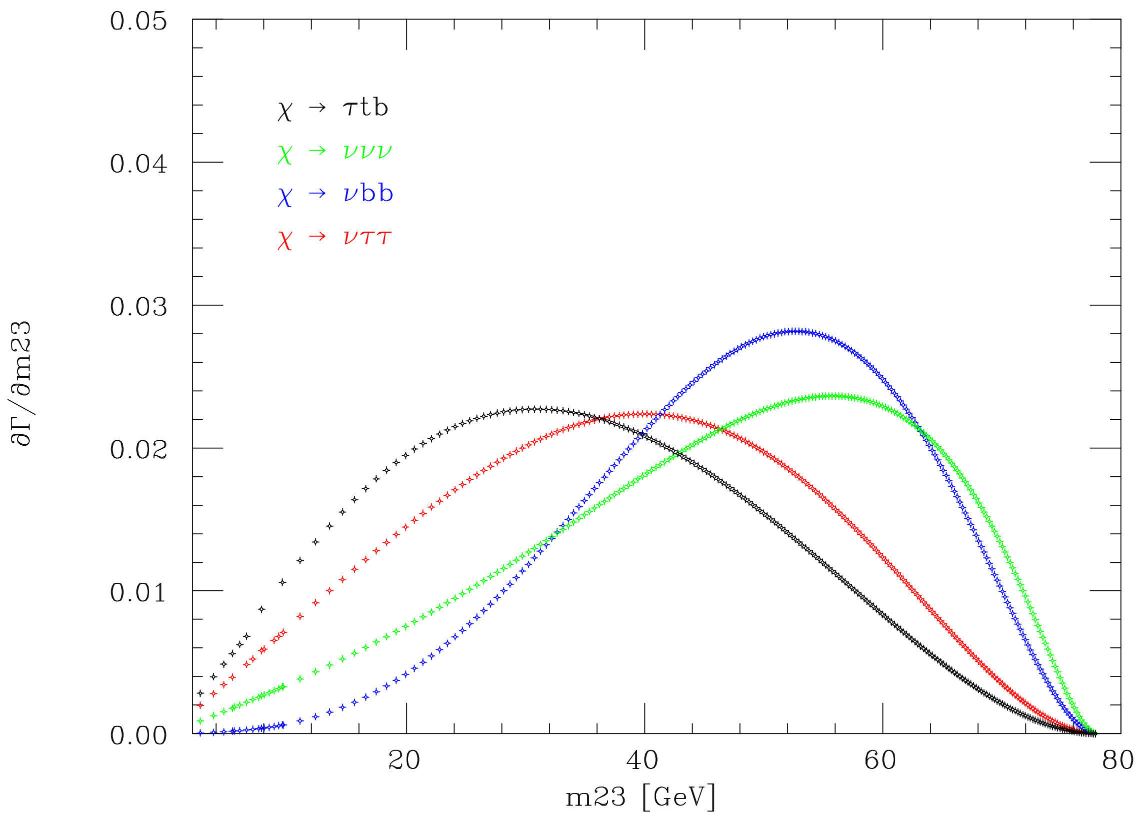

Fig. 1.— The endpoint of the curves correspond to the mass of the Neutralino, that in our case is 80.0 GeV. The forms of the curves are explained by the different boson particles in the intermediate states in each decay, which yields different forms in the products of the four-momenta of the particles. The invariant mass m_{23} correspond to the sum of four-momenta of the last two particles in each decay.

Other results that we can obtain from the program correspond to the percentages of the all decays necessary to simulate the phenomenology of the neutralino at the LHC. For example, the percentage for neutralino decays in a scenario with a sugra point like in [6] are:

$$\mathrm{BR}(W^{\pm}\mu^{\mp}) = 0.13\% \quad \mathrm{BR}(W^{\pm}\tau^{\mp}) = 0.15\% \quad \mathrm{BR}(\bar{q}q'\mu^{-}) = 0.017\%$$
$$\mathrm{BR}(\bar{q}q'\tau^{-}) = 0.016\% \quad \mathrm{BR}(q\bar{q}\nu_i) = 0.21\% \quad \mathrm{BR}(b\bar{b}\nu_i) = 1.21\%$$
$$\mathrm{BR}(e^{\pm}\tau^{\mp}\nu_i) = 7.6\% \quad \mathrm{BR}(\mu^{\pm}t^{\mp}\nu_i) = 41.7\% \quad \mathrm{BR}(\tau^{+}\tau{-}\nu_i) = 48.8\%$$

These results show numerical differences with the results from [6], because there are free parameters that may not have the same values. One of these parameters is the B_i term, from $\mathcal{L}_{Soft} = -B_i\epsilon_i\epsilon_{ab}\tilde{L}_i^a H_u^b$ [5], that in our case have a value of 20 GeV for all i. The decay length for the neutralino is $c\tau = 0.47$ mm. Further checks are in progress.

With the program is possible too obtain the distribution of the differential cross section to diffenrent masses of the neutralino.

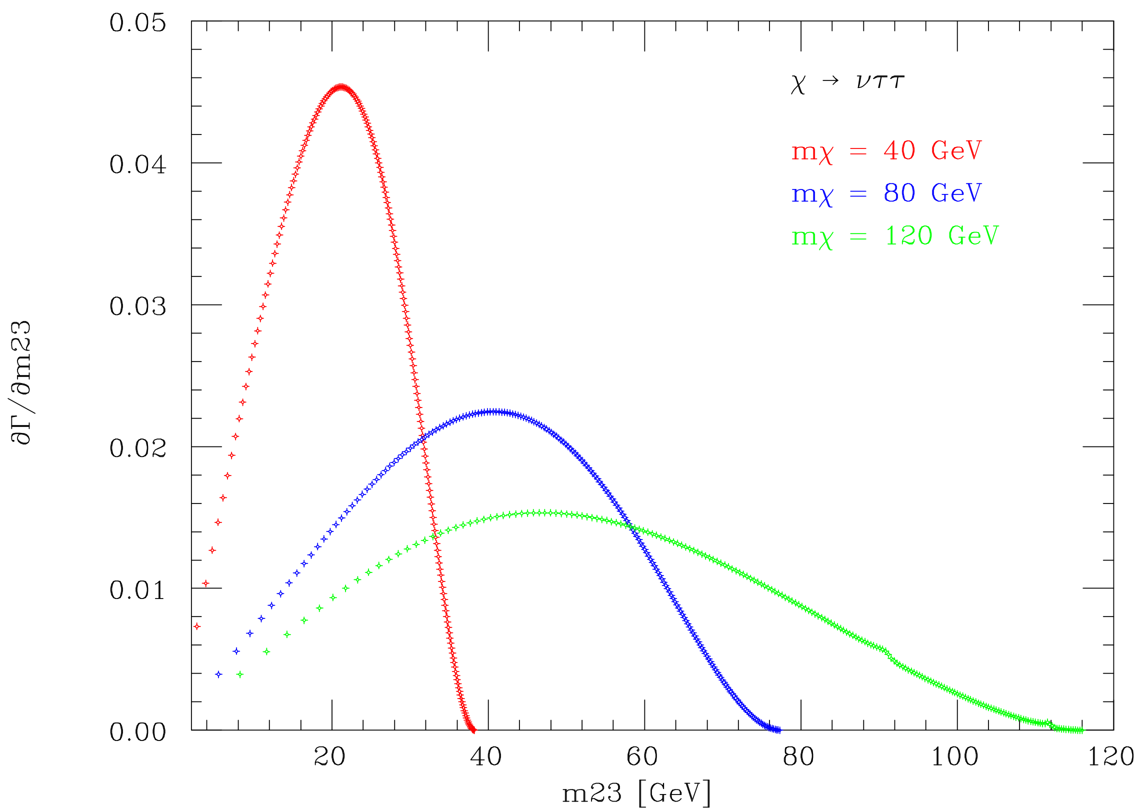

Fig. 2.— This figure show the curves of $\chi_0 \to \nu\tau\tau$ decay for different mass of neutralino. Note that both the endpoint and the pick of the distribution are dependent of the neutralino mass.

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