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R–Parity Violating Signals for Chargino Production at LEP II

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Abstract

We study chargino pair production at LEP II in supersymmetric models with spontaneously broken R–parity. We perform signal and background analyses, showing that a large region of the parameter space of these models can be probed through chargino searches at LEP II. In particular, we determine the attainable limits on the chargino mass as a function of the magnitude of the effective bilinear R–parity violation parameter ϵ, demonstrating that LEP II is able to unravel the existence of charginos with masses almost up to its kinematical limit even in the case of R–parity violation. This requires the study of several final state topologies since the usual MSSM chargino signature is recovered as $\epsilon \to 0$. Moreover, for sufficiently large ϵ values, for which the chargino decay mode $\chi^\pm \to \tau^\pm J$ dominates, we find through a dedicated Monte Carlo analysis that the $\chi^\pm$ mass bounds are again very close to the kinematic limit. Our results establish the robustness of the chargino mass limit, in the sense that it is basically model-independent. They also show

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that LEP II can establish the existence of spontaneous R–parity violation in a large region of parameter space should charginos be produced.

I. INTRODUCTION

In the *Minimal Supersymmetric Standard Model* (MSSM) the conservation of a discrete symmetry called R–parity is imposed [1]. R–parity is related to the particle spin (S), lepton number (L), and baryon number (B) through $R = (-1)^{(3B+L+2S)}$, being all the standard model particles R–even while their superpartners are R–odd. From this it follows that supersymmetric particles must be produced only in pairs, with the lightest one being stable. So far, most searches for supersymmetric particles have assumed conservation of R–parity, however, neither gauge invariance nor supersymmetry (SUSY) require its conservation. In general, we can build models exhibiting R–parity violation which may be explicit [2] or spontaneous [3], or even the residual effect of a more fundamental unified theory [4].

One possible scenario for spontaneous R–parity breaking is that it takes place through nonzero vacuum expectation values (VEVs) of scalar neutrinos [5]. In this case there are two distinct possibilities depending whether lepton number is a gauge symmetry or not. If lepton number is part of the gauge symmetry there is an additional gauge boson which acquires mass via the Higgs mechanism. Therefore, there is no physical Goldstone boson and the scale of R–parity violation, in the TeV range, also characterizes the new gauge interaction [6,7]. In this work, we consider the alternative scenario where spontaneous R–parity violation occurs in the absence of an additional gauge symmetry, so that there is a physical massless Nambu-Goldstone boson, called Majoron [8–13] [1]. In this model, the Majoron remains massless and stable in the absence of further explicit R–parity violating terms that might arise, for instance from gravitational effects [15,16]. Thus, it will lead to a missing energy signal at high energy accelerators.

In Majoron models, the neutralino is unstable and for moderate strengths of the R–parity violating interactions, it will decay inside the detector, either via

$$\begin{aligned} &\chi^0 \to \nu_\tau Z^\star \to \nu_\tau \nu\nu \ , \ \nu_\tau \ell^+ \ell^- \ , \ \nu_\tau q\bar{q} \ ; \\ &\chi^0 \to \tau W^\star \to \tau \nu_i \ell_i \ , \ \tau q \bar{q}' \ ; \end{aligned} \qquad (1)$$

or through Majoron emission

$$\chi^0 \to \nu J \ . \qquad (2)$$

[1] There are many models where neutrinos get mass from spontaneous breaking of lepton number [14]. In the present context the Majoron appears also because the (tau) neutrino mass arises as a result of the spontaneous violation of lepton number implied by the nonzero sneutrino VEVs.

Note this decay mode is R–parity conserving, since the Majoron is mainly R-odd (see Eq. (6)).

In the first case the neutralino gives rise to visible signals, except for the 3 ν decay mode. In the case of Eq. (2) the neutralino decay leads to a missing energy signature, exactly as the stable MSSM neutralino.

In this work, we study the implications of R–parity breaking SUSY models with a Majoron for chargino searches at LEP II. In this case, in addition to the conventional MSSM chargino decay mode

$$\chi^+ \to W^+ \chi^0 \ , \tag{3}$$

where the W can be real or virtual depending on the chargino and neutralino masses, there is a new R–parity conserving two-body decay mode

$$\chi^\pm \to \tau^\pm J \ , \tag{4}$$

As in Eq. (2) the decay in Eq. (4) is R–parity conserving it can therefore be quite sizeable.

Note that R–parity violating decays $\chi^+ \to W^+ \nu_\tau$ and $\chi^\pm \to Z \tau^\pm$ are typically negligible compared to the above decay modes, as shown explicitly in ref. [17].

We evaluate the LEP II potential for probing the R–parity violating SUSY parameter space through the study of new signatures arising from chargino pair production and its corresponding cascade decay. We determine the limits on the chargino mass (m_{χ^+}) for different values of the R–parity violating interactions. In our analyses, we recover the MSSM chargino mass limit, which is close to the kinematic limit, for sufficiently small strengths of the R–parity violating interactions. As the magnitude of R–parity violation becomes larger, new final state topologies become available. By performing a Monte Carlo analysis we show that these new topologies also lead to bounds on the chargino mass close to the kinematical limit. Assuming unification of the gaugino mass parameters we also determine the corresponding neutralino mass limit.

II. BASIC FRAMEWORK

We adopted the conceptually simplest model for the spontaneous violation of R proposed in Ref. [8] in which, by construction, neutrinos are massless before breaking of R–parity. As a result all R–parity violating observables are directly correlated to the mass of the tau neutrino with the magnitude of this correlation depending upon the choice of the

R–parity SUSY parameters. Apart from the theoretical attractive of giving a dynamical origin for the violation of R–parity and neutrino mass, these models offer the possibility of realizing a radiative scenario for the breaking of R–parity, similar to that of electroweak breaking [18].

In order to set up our notation, we first recall some basic ingredients. The superpotential, which conserves *total* lepton number and R, is given by

$$h_u Q H_u u^c + h_d H_d Q d^c + h_e \ell H_d e^c + (h_0 H_u H_d - \epsilon'^2)\Phi + h_\nu \ell H_u \nu^c + h \Phi S \nu^c + \text{h.c.} \ , \tag{5}$$

where the couplings h_u, h_d, h_e, h_ν, h are arbitrary matrices in generation space. The additional chiral superfields (Φ, ${\nu^c}_i$, S_i) are singlets under $SU(2) \otimes U(1)$ and carry a conserved lepton number assigned as $(0, -1, 1)$ respectively. Note that terms such as Φ^2 and Φ^3 are in principle allowed and have been discussed in earlier papers. For example a Φ^2 term was included in ref. [13] and a Φ^3 has been included in a recent formulation of the theory with radiative symmetry breaking [18]. However the presence of the Φ field is not essential in the formulation of the theory. In schemes with radiative breaking one may simply add bare mass terms $\mu H_u H_d$ and $M S \nu^c$ without adding the Φ field. From the point of view of our analysis the presence of Φ has basically no effect, as it relies mainly on the chargino sector.

The superfields ν^c, S [19] and Φ [20] are required to drive the spontaneous violation of R–parity in an acceptable way, so that the Majoron is mostly a singlet, that is given by the imaginary part of [8]

$$\frac{v_L^2}{V v^2}(v_u H_u - v_d H_d) + \frac{v_L}{V}\tilde{\nu_\tau} - \frac{v_R}{V}\tilde{\nu^c}_\tau + \frac{v_S}{V}\tilde{S_\tau} \ , \tag{6}$$

where the isosinglet VEVs

$$v_R = \langle \tilde{\nu}_{R\tau} \rangle \ , \ v_S = \left\langle \tilde{S_\tau} \right\rangle \ , \tag{7}$$

and $V = \sqrt{v_R^2 + v_S^2}$ characterizes R or lepton number breaking. The isodoublet VEVs

$$v_u = \langle H_u \rangle \ , \ v_d = \langle H_d \rangle \tag{8}$$

are responsible for the breaking of the electroweak symmetry and the generation of fermion masses with the combination $v^2 = v_u^2 + v_d^2$ being fixed by the W, Z masses. Finally, there is a small seed of R–parity breaking in the doublet sector, *i.e.,*

$$v_L = \langle \tilde{\nu}_{L\tau} \rangle \tag{9}$$

whose magnitude is now related to the Yukawa coupling h_ν. Since this vanishes as $h_\nu \to 0$, we can naturally satisfy the limits originating from stellar energy loss [21]. Note that, unlike the standard seesaw model, the neutral leptons members of the singlet superfields ${\nu^c}_i$ and S_i are given only Dirac-type masses.

Notice that we have assumed R–parity violating VEVs only for the third generation. This is the theoretically well-motivated choice if one has in mind a radiatively induced symmetry breaking mechanism [18,22], since the largest Yukawa couplings are those of the third generation [2]. For future use we define an effective parameter $\epsilon_i \equiv h_{\nu ij} v_{Rj}$, which measures the violation of R–parity now expressed as an effective bilinear superpotential term which breaks R–parity explicitly. Together with the standard MSSM μ parameter it will affect the fermion mass matrices given below.

The form of the chargino mass matrix is common to a wide class of $SU(2) \otimes U(1)$ SUSY models with spontaneously broken R–parity and is given by

$$\begin{array}{c|ccc} & e^+_j & \tilde{H}^+_u & -i\tilde{W}^+ \\ \hline e_i & h_{eij} v_d & -h_{\nu ij} v_{Rj} & \sqrt{2} g_2 v_{Li} \\ \tilde{H}^-_d & -h_{eij} v_{Li} & \mu & \sqrt{2} g_2 v_d \\ -i\tilde{W}^- & 0 & \sqrt{2} g_2 v_u & M_2 \end{array} \quad . \tag{10}$$

Two matrices U and V are needed to diagonalise the 5×5 (non-symmetric) chargino mass matrix

$$\chi^+_i = V_{ij} \psi^+_j \quad , \tag{11}$$

$$\chi^-_i = U_{ij} \psi^-_j \quad , \tag{12}$$

where the indices i and j run from 1 to 5, $\psi^+_j = (e^+_1, e^+_2, e^+_3, \tilde{H}^+_u, -i\tilde{W}^+)$ and $\psi^-_j = (e^-_1, e^-_2, e^-_3, \tilde{H}^-_d, -i\tilde{W}^-)$.

If the singlet superfield mass terms are large one can truncate the neutralino mass matrix so as to obtain an effective 7×7 matrix of the following form [8]

$$\begin{array}{c|ccccc} & \nu_i & \tilde{H}_u & \tilde{H}_d & -i\tilde{W}_3 & -i\tilde{B} \\ \hline \nu_i & 0 & h_{\nu ij} v_{Rj} & 0 & g_2 v_{Li} & -g_1 v_{Li} \\ \tilde{H}_u & h_{\nu ij} v_{Rj} & 0 & -\mu & -g_2 v_u & g_1 v_u \\ \tilde{H}_d & 0 & -\mu & 0 & g_2 v_d & -g_1 v_d \\ -i\tilde{W}_3 & g_2 v_{Li} & -g_2 v_u & g_2 v_d & M_2 & 0 \\ -i\tilde{B} & -g_1 v_{Li} & g_1 v_u & -g_1 v_d & 0 & M_1 \end{array} \tag{13}$$

[2] Some of the effects in such a complete dynamical scheme get communicated through mixing to the lightest generations. See, for example, ref. [12].

where $M_{1(2)}$ denote the supersymmetry breaking gaugino mass parameters and $g_{1(2)}$ are the $SU(2) \otimes U(1)$ gauge couplings divided by $\sqrt{2}$. Moreover, we assumed the canonical GUT relation $M_1/M_2 = \frac{5}{3}\tan^2\theta_W$. We have however included the full neutral mass matrix, including the singlet sector, and diagonalized it numerically in order to determine, for example, the ν_τ mass and to identify the physical mass eigenstates. In any case the singlets are hardly relevant for our present analysis, as they appear in the chargino mass matrix only through the effective bilinear parameters$\epsilon_i \equiv h_{\nu ij} v_{Rj}$, which measures the violation of R–parity and the usual MSSM μ parameter.

The matrix (13) is diagonalised by a 7×7 unitary matrix N,

$$\chi_i^o = N_{ij} \psi_j^o \ , \tag{14}$$

where $\psi_j^0 = (\nu_i, \tilde{H}_u, \tilde{H}_d, -i\tilde{W}_3, -i\tilde{B})$, with ν_i denoting the three weak-eigenstate neutrinos.

In our analyses, we considered typical values for the SUSY parameters μ, M_2 that can be covered by chargino production at LEP II:

$$\begin{array}{rcll} -200 & \leq \ \mu & \leq 200 & [\text{GeV}] \ , \\ 40 & \leq \ M_2 & \leq 400 & [\text{GeV}] \ . \end{array} \tag{15}$$

We also varied $\tan\beta$ in the range

$$2 \leq \ \tan\beta = \frac{v_u}{v_d} \leq 40 \ . \tag{16}$$

This is a standard choice for the ranges of the SUSY parameters which generously accounts for chargino masses within the kinematical reach of LEP I. This range has only been used in order to have an overview of parameter space in the first two figures of our paper (see below). Note that we have explicitly limited $\tan\beta$ to values that are consistent with supergravity versions with perturbative Yukawa couplings up to the GUT scale, excluding, for example $\tan\beta = 1$. No essential change would result if lower $\tan\beta$ values were included. In the analysis of the signals we have simply fixed $\tan\beta$ at the two illustrative values used by the DELPHI collaboration.

As we can see from the neutralino and chargino mass matrices, the ϵ parameter gives the main contribution to the mixing between charged (neutral) leptons and the charginos (neutralinos) and also leads to R violating gauge couplings.

We have required the parameters $h_{\nu i,3}$ and the expectation values lie in the ranges

$$10^{-10} \leq h_{\nu 13}, h_{\nu 23} \leq 10^{-1} \qquad 10^{-5} \leq h_{\nu 33} \leq 10^{-1} \tag{17}$$

$$
\begin{aligned}
v_L = v_{L3} = 100 \ \text{MeV} \\
50 \ \text{GeV} \leq v_R = v_{R3} \leq 1000 \ \text{GeV} \\
50 \ \text{GeV} \leq v_S = v_{S3} = v_R \leq 1000 \ \text{GeV}
\end{aligned}
\tag{18}
$$

For definiteness we have set $v_{L1} = v_{L2} = 0$ and $v_{R1} = v_{R2} = 0$.

The above range for the R–parity breaking parameters is quite reasonable and generous, and has been used widely in previous papers e.g. [7,13]. There are many restrictions on the parameters in broken R models which follow from laboratory experiments related to neutrino physics, weak interactions, cosmology, and astrophysics [5,14]. The most relevant constraints come from neutrino-less double beta decay and neutrino oscillation searches, direct searches for anomalous peaks at π and K meson decays, the limit on the tau neutrino mass [23], and cosmological limits on the ν_τ lifetime and mass, as well as limits on muon and tau lifetimes, on lepton flavour violating decays, and universality violation. These constraints have been taken into account in several previous papers [12,13]. Here we have just included an updated version.

The model described above constitutes a very useful way to parametrise the physics of R violation, due to the strict correlation between the magnitude of R violating phenomena and the resulting ν_τ mass. In other words, neutrinos are strictly massless before breaking R, therefore all R violating observables, such as the lightest neutralino decay rate Γ_χ, are directly correlated to the mass of the tau neutrino. In fact, the τ neutrino mass may be written schematically as $m_{\nu_\tau} \sim \xi\epsilon^2/m_{\chi^+}$, where ξ is some effective parameter given as a function of M_2, μ, $\tan\beta$, etc [3]. This establishes a correlation between the violation of R and the ν_τ mass showing explicitly how the broken R-model provides an interesting mechanism to understand the origin of neutrino mass without invoking physics at very high energy scales [24].

In Fig. 1, we exhibit the tau neutrino mass as a function of ϵ, showing in light grey the region in the (m_{ν_τ},ϵ) plane which is compatible with the tau neutrino mass limit from LEP. We also present in this figure the region in which the charginos can be pair produced at LEP, which corresponds to a smaller range of ϵ values (dark zone). As we can see, for $\tan\beta < 10$, the maximum value of ϵ that can be probed through chargino pair production at LEP II is around 20 GeV and it increases for larger $\tan\beta$. For definiteness we fixed the value of ϵ in our analysis.

In the following section we describe the most relevant chargino and neutralino decay

[3] For a more complete discussion see the second paper in Ref. [18,22]

modes for this work. A complete list of the decay widths and couplings can be found in [17] or [25].

III. SIGNALS AND BACKGROUNDS

A. Chargino Production

At LEP II the lightest chargino may be pair produced via

$$e^+e^- \to \gamma, Z, \tilde{\nu} \to \chi^+\chi^- \quad . \tag{19}$$

In this work we assumed that the sneutrinos are so heavy that only the γ and Z s-channels contribute to the cross section; see, for instance, Refs. [26] and [27]. In fact, the contribution of the t-channel to the total cross section is completely negligible for sneutrinos heavier than 500 GeV. Fig. 2 shows a scatter plot of the allowed values of the $e^+e^- \to \chi^+\chi^-$ total cross section versus the chargino mass for $\sqrt{s} = 172$ GeV, when the parameters are varied as in Eq. (15) and Eq. (16). As one can see, this cross section varies between 2 and 10 pb for almost all kinematically allowed chargino masses.

Although, our model allows the single R–parity-violating chargino production

$$e^+e^- \to \chi^\pm\tau^\mp \quad , \tag{20}$$

we only considered in this paper the pair-production of charginos, as in the MSSM, since the cross section for the single chargino production at LEP II is too small to be observed [28].

B. Neutralino and Chargino Decays

The breaking of R–parity not only opens new decay channels for the chargino but also allows the lightest neutralino to decay. Therefore, there are new signatures for SUSY, some of them being very striking. In order to simplify the analysis, we assumed that all sfermions are sufficiently heavy not to influence the physics at LEP II, *i.e.* we neglected their effects in the chargino production as well as in their decays. In the present model, the lightest neutralino (χ^0) can decay invisibly $\chi^0 \to \nu J$, as in Eq. (2), as well as into R–parity violating channels

$$\chi^0 \to \nu_\tau Z^\star \to \nu_\tau \nu\nu \ , \ \nu_\tau \ell^+ \ell^- \ , \ \nu_\tau q\bar{q} \ ; \tag{21}$$

$$\chi^0 \to \tau W^\star \to \tau \nu_i \ell_i \ , \ \tau q \bar{q}' \ . \tag{22}$$

For the chargino masses accessible at LEP II, the above W and Z are off-shell and the neutralino has only two-body majoron decays and the above three-body modes. A complete description of neutralino decay modes as a function of the model parameters and masses can be found in Ref. [17].

It is interesting to notice that all three-body decay channels of the lightest neutralino are *visible*, except for the neutral current one leading to 3 neutrinos. In the parameter space regions where most of neutralino decays are *visible*, the strategies to search for SUSY particles are considerably modified with respect to ones used in the MSSM. The MSSM is recovered as a special limit of this class of models, when the lightest neutralino decays outside the detector because R–parity violation is not strong enough. Notwithstanding, χ^0 decays can also lead to missing momentum due to the presence of neutrinos or Majorons. It is important to notice that, the neutralino of a spontaneously broken R–parity model fakes the MSSM one when the invisible decay given in Eq. (2) dominates since its decay products escape undetected.

In R–parity breaking models, the decays of the lightest chargino, denoted by $\chi^\pm$, are modified by the existence of new channels. In models with a majoron, the lightest chargino ($\chi^\pm$) exhibits the two-body decay mode $\chi^\pm \to \tau^\pm J$ of Eq. (4), in addition to the channels[4]

$$\chi^\pm \to \nu_\tau W^\star \to \nu_\tau q \bar{q}' \ , \ \nu_\tau \ell_i^\pm \nu_i \ , \tag{23}$$

$$\chi^\pm \to \tau^\pm Z^\star \to \tau^\pm q\bar{q} \ , \ \tau^\pm \ell^+ \ell^- \ , \ \tau^\pm \nu\bar{\nu} \ , \tag{24}$$

$$\chi^\pm \to \chi^0 W^\star \to \chi^0 q\bar{q}' \ , \ \chi^0 \ell_i^\pm \nu_i \ , \tag{25}$$

where we again assumed that the sfermions are heavy. In the framework of the MSSM only the last decay channel is present, however, with the χ^0 being stable. Therefore, the breaking of R–parity can modify substantially the signature of charginos.

For the sake of illustration we exhibit in Fig. 3 typical values of the branching ratios of charginos and neutralinos, when we vary ϵ for $\mu = 150$ GeV, $M_2 = 100$ GeV, and $\tan\beta = 35$. For neutralinos we exhibit its total visible and invisible branching ratios, where we included

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[4]Notice that there is the possibility of a chargino decaying into the second lightest neutralino plus a W^+, which conserves R–parity. However, for the parameter range considered, the second lightest neutralino mass is around the chargino mass, so that this decay is forbidden or kinematically suppressed.

in the invisible width the contributions coming from the neutrino plus majoron channel ($\chi^0 \to \nu$J), as well as from the neutral current channel when the Z decays into a pair of neutrinos ($\chi^0 \to 3\nu$).

For small ϵ values (up to 10^{-4} GeV) the neutralino will decay outside the detector (since its lifetime is larger than 10^{-6} s) so that it leaves no visible track. In this case it is effectively stable and the MSSM limit is restored. In this region the invisible component of the neutralino decay is associated only to the $\chi^0 \to 3\nu$ channel. When the ϵ parameter grows up to the order of 1 GeV the decay channels get mixed and both neutralinos as well as charginos have R–parity violating decays at the same level as the standard MSSM ones. As expected, above $\epsilon \sim 1$ GeV or so $\chi^\pm$ and χ^0 decay predominantly into majorons, that is, the invisible channel dominates the decay of the neutralino and the main chargino decay mode is $\tau^+ J$.

C. Signatures for chargino pair production

At LEP II, there is a variety of topologies associated to the production of lightest chargino pairs. We classified the possible signatures into four categories which contain almost all the final states allowed in R–parity violating models.

- *MSSM topologies:* This class includes the following topologies

$$\begin{aligned} \chi^+\chi^- &\to 4 \text{ jets } + \not{p}_{\mathrm{T}} \ , \\ \chi^+\chi^- &\to 2 \text{ jets } + \ell^\pm + \not{p}_{\mathrm{T}} \ , \\ \chi^+\chi^- &\to \ell^+\ell^- + \not{p}_{\mathrm{T}} \ , \end{aligned}$$

  where $\ell^\pm$ stands for $e^\pm$ or $\mu^\pm$. These are the channels used in the chargino searches within the framework of the MSSM. In majoron models, such topologies are obtained by charged-current decays into $\nu_\tau W^*$ or $\chi^0 W^*$, with the χ^0 decaying invisibly. As we can see from Fig. 3, these topologies are expected to be important for very small values of ϵ since this is the region where $\chi^\pm$ decays predominantly into $W^*\chi^0$ and the neutralino has such a long life-time and it is not observed in the detector. These topologies also play an important rôle for moderate values of ϵ (e.g. $\simeq 0.1$) where the invisible decay of the neutralino is dominant and the chargino still decays into a $\chi^0 W^*$.

- *Multi-fermion (exotic) topologies:* When the neutralino decays visibly, almost all the three-body channels of the chargino lead to at least 3 charged leptons or jets. Again, this occurs for small values of ϵ, where the chargino decays predominantly into $\chi^0 W^*$.

Therefore, the pair production of charginos can give rise to events with a large multiplicity of leptons and/or jets in this region of the parameter space. This is a striking signature of new physics. We focussed our attention on final states with 5 or more charged leptons and/or jets that also present missing energy.

- $\tau^\pm$ with 2 jets topology: For moderate values of ϵ the neutralino decays invisibly and the chargino either into $\tau^\pm J$ or into $\chi^0 W^*$. An important topology to analyze for this range of parameters is

$$\chi^+\chi^- \to \tau^\pm + 2 \text{ jets } + \not{p}_T \ , \tag{26}$$

which arises when one of the charginos decays to $\tau^\pm J$ while the other one decays to $\chi^0 W^*$.

- $\tau^+\tau^-\not{p}_T$: For large values of ϵ, the chargino decay is dominated by $\chi^\pm \to \tau^\pm J$, therefore, the signal arising from its pair production is

$$\chi^+\chi^- \to \tau^+\tau^-\not{p}_T \ . \tag{27}$$

In this case the signal for charginos in majoron models is the same of stau production in the MSSM framework [29].

D. Standard Model Backgrounds and Respective Cuts

Our goal is to evaluate the potential of LEP II to unravel the existence of supersymmetry with spontaneous R–parity violation. In order to do so, we studied the signals and backgrounds, choosing the cuts to enhance the former. The main background for the above topologies are:

- *MSSM topologies:* The background for these signals has been studied at length by several groups, including the experimental collaborations [27]. The main sources of background for these topologies are $e^+e^- \to f\bar{f}$ $(n\gamma)$ ($f = q$ or $\ell^\pm$), W^+W^-, $(Z/\gamma)^\star(Z/\gamma)^*$, $We\nu_e$, and Ze^+e^-. The total cross sections of the backgrounds and respective cuts for the three MSSM topologies, after the cuts imposed by DELPHI in their analysis, are given in [27]. Moreover, we can easily obtain the signal cross sections in models with R–parity violation by evaluating the cross section for chargino pair production and multiplying it by the appropriate branching ratios and experimental detection efficiencies – that is, we basically re-scale the DELPHI analysis to our scenario. These efficiencies are a function of the mass difference between the chargino and the lightest neutralino, with a small fluctuation due to the the statistical error in the simulation as well as an intrinsic dependence on the chargino mass. To be conservative, we have considered the lowest value of these efficiencies for each mass difference.

- *Multi-fermion (exotic) topologies:* At the parton level, these events exhibit 5 or more fermions. For instance, we can have final states $\ell_i^+ \ell_i^- q \bar{q}' \ell^\pm + \not{p}_{\rm T}$, or six charged leptons and missing p_T, or 8 jets and missing p_T. The Standard Model (SM) contributions to these events originate only from higher orders in perturbation theory, and consequently they have negligible cross sections. In our analysis, we assumed that there is no SM background and a conservative detection efficiency of 30%.

- $\tau^\pm$ plus 2 jets topology: The SM processes that can give rise to this topology are $e^+e^- \to W^+W^-$, $(Z/\gamma)^\star (Z/\gamma)^\star$, which also contribute to the $jj\ell$ MSSM topology background. At the parton level the cross sections of these process are the same for $\ell^\pm = e^\pm$, $\mu^\pm$, or $\tau^\pm$. Therefore, we evaluated the size of this background by multiplying the DELPHI's result for $\sigma_{SM}(jj\mu^\pm + \not{p}_{\rm T})$ by a τ identification efficiency, which we have taken as 80%.

- $\tau^+\tau^- + \not{p}_{\rm T}$: This is the main signal of R–parity violation models over a large ϵ range. It happens to be the same signal which would arise from the pair-production of staus in the MSSM framework. We have constructed an event generator to simulate the pair-production of charginos as well as their decays within the framework of R–parity violating models. The SM backgrounds were studied using the event generator PYTHIA [30]. We considered the following SM processes, taking into account the QED (QCD) initial and final state radiation, as well as fragmentation and τ decay:

$$e^+e^- \to W^+W^- \to \ell^+\ell^- \not{p}_{\rm T} \; , \tag{28}$$

$$e^+e^- \to (Z/\gamma)^\star (Z/\gamma)^\star \to \ell^+\ell^- \not{p}_{\rm T} \; , \tag{29}$$

$$e^+e^- \to (Z/\gamma)^\star \to \ell^+\ell^- \not{p}_{\rm T} \; , \tag{30}$$

$$e^+e^- \to [e^+e^-]\gamma\gamma \to \ell^+\ell^- \not{p}_{\rm T} \; . \tag{31}$$

In order to reduce these backgrounds, we applied a series of cuts similar to the ones used by DELPHI and ALEPHI for the stau search [31]. Initially we kept only the events presenting "two jets", which might be leptons, with a visible mass larger than 6 GeV. We also vetoed events exhibiting photons with more than 4 GeV whose angle with each jet is greater than 10° and whose invariant mass with the jets is greater than 2 GeV. The two-photon background is eliminated efficiently by requiring the missing transverse momentum to be larger than 6% of the center-of-mass energy in events with a visible mass smaller than

30 GeV. We also imposed that the polar angle of the missing momentum lies between 30° and 150°.

A very useful variable is defined by the following procedure [31]: first, we projected the jet momenta into the plane perpendicular to the beam axis. Then we evaluated the thrust from the projected momenta, and defined δ as the scalar sum of the transverse components of the projected momenta with respect to this thrust axis. We also defined the acoplanarity A as the angle in the plane perpendicular to the beam between the 2 jets. With these quantities we can reduce considerably the fermion pair background ($Z^*/\gamma^* \to \ell^+\ell^-$) by rejecting the events that lead to $17.1\ \delta + 120 - A < 0$. This cut eliminates a large fraction of the fermion pair events since these tend to exhibit back-to-back jets with a rather small δ.

The WW background is similar to the signal. However, we can discard a large fraction of the $W^\pm \to \nu e^\pm$ or $\nu\mu^\pm$ events remembering that the $e^\pm$ or $\mu^\pm$ originating from W's are more energetic than the ones coming from $\tau^\pm$ decays. This is accomplished by requiring the largest lepton momentum to be smaller than 22 GeV. If both W's decay leptonically, we also demanded the second lepton to have a momentum smaller than 15 GeV.

After applying the above cuts and for center-of-mass energy of 172 GeV, the $\gamma\gamma$ background is completely eliminated. On the other hand, the cross section for fermion pair production is reduced to 13 fb, while the ZZ background has a cross section of 4 fb. Most of the background events originate from WW pairs whose cross section is 60 fb. Nevertheless, the signal possesses an efficiency of 30–40% depending on the chargino mass.

IV. RESULTS

For the sake of definiteness we considered a center-of-mass energy of 172 GeV and a total integrated luminosity of 300 pb^{-1}, according to LEP II design expectations [32]. However, our results should be a conservative estimate of the LEP II potentiality even for actual energies and luminosities. In analogy to the usual analyses performed for the MSSM, we present the 95% CL excluded regions of the (μ, M_2) SUSY parameter space for different values of $\tan\beta$ and ϵ, assuming that the number of observed events is equal to the expected one for the background [32]. First of all, we obtained bounds for $\epsilon = v_R = v_L = 0$, which should reproduce the MSSM results. We show in Fig. 4 that we indeed obtain exactly the same limits found in the MSSM analyses [27], for both $\tan\beta = 2$ and 35. This shows that we are consistent.

For relatively small values of the R–parity violation parameter ϵ the most important topologies are the MSSM and the exotic multi-fermion ($\tau^\pm$ plus 2 jets) one for small (large) values of $\tan\beta$. We can see from Fig. 5, for $\epsilon = 0.1$ GeV and $\tan\beta = 2$, that the main constraints still come from the MSSM final states while the exotic multi-fermion channels are irrelevant to the final limits. This result can be understood by looking at Fig. 3, since for this choice of parameters the neutralino decays mostly to νJ, remaining undetected and thus giving the conventional MSSM missing momentum signal. As $\tan\beta$ increases the importance of the multi-fermion channel diminishes while the channel $\tau^\pm$ plus 2 jets starts to become important. We present in Fig. 6 the 95% CL excluded regions in the plane (μ, M_2) for $\epsilon = 0.1$ GeV and $\tan\beta = 35$, which clearly shows that the MSSM and $\tau^\pm$ plus 2 jets topologies lead to similar bounds.

For larger values of ϵ, the neutralino decays mostly invisibly while the chargino presents a sizeable τJ branching ratio; see Fig. 3. Therefore, we expect that the 2 jets$\,+\,\tau$ and $\tau\tau JJ$ signatures contribute significantly to the chargino mass bound, while the importance of the MSSM topologies becomes smaller. In fact, Fig. 7 shows for $\tan\beta = 2$ and $\epsilon = 1$ GeV that the most important channel for these parameters is 2 jets + τ in a large fraction of the parameter space. However, for this value of $\tan\beta$, the MSSM final states still lead to important bounds for small values of M_2. Moreover, for larger values of $\tan\beta$ the 2 jets$\,+\,\tau$ mode dominates in all points in SUSY parameter space; see Fig. 8.

Finally, for $\tan\beta = 35$ and $\epsilon = 10$ GeV, only the channels involving chargino to tau–majoron play a significant rôle, and consequently the MSSM topologies cannot give any information. In other words, in this case the main contributions to the chargino mass constraints, as seen from Fig. 9, come from $\tau\tau \not{p}_T$ and 2 jets$\,+\,\tau$ topologies. In this range of parameters, LEP II is also able to probe chargino masses almost up to the kinematical limit despite the presence of the irreducible WW background; see section III D. Furthermore, for such a large value of ϵ and smaller values of $\tan\beta$, the chargino masses compatible with the limits on the ν_τ mass are not accessible at LEP II energies, as can be seen in Fig. 1.

We summarize our results in Table I where we show the 95% CL chargino mass limits, that can be obtained in the absence of any signal at LEP II, for different values of the effective bilinear R–parity violation parameter ϵ and two representative values of $\tan\beta$. These bounds are the weakest constraints that can be obtained when we vary the parameters in the ranges given by Eqs. (17) and (18), and they resulted from the analysis of each topology separately, as well as from the combined results. In the case where no limit was quoted in Table I, the bound obtained was lower than 45 GeV, the kinematical limit for LEP I, although the corresponding result was used in the combined bound. As we can see, the *combined* constraints are almost independent of $\tan\beta$, and of the R–parity breaking parameter ϵ. For small values of ϵ, as expected, the chargino mass bounds reach up to the kinematical limit, recovering exactly the MSSM results for vanishing ϵ and v_L. For large ϵ, they come solely from $\tau\tau JJ$. For intermediate values, $\epsilon \approx 1$ GeV or so, the combination of channels is necessary, mainly $\tau\tau\not{p}_{\rm T}$ and 2 jets + τ topologies.

Assuming unification of the gaugino mass parameters, we can derive bounds on the neutralino mass from the limits on the chargino mass. We obtained a neutralino mass limit of 38 GeV for $\tan\beta = 2$ and 48 GeV for $\tan\beta = 35$, when ϵ has the values given in Table I.

V. COMMENTS AND CONCLUSIONS

We studied chargino pair production and decay at LEP II ($\sqrt{s} = 172$ GeV) in SUSY models with spontaneously broken R–parity, characterized by the existence of the Majoron. We performed detailed signal and background analysis in order to determine the LEP II potential in probing physical parameters such as chargino or neutralino masses, m_{χ^+} or m_{χ^0}. We found that for most of the R–parity violating SUSY parameter space the chargino signal can be seen up to chargino masses close to the kinematical limit. We explicitly verified that, as $\epsilon \to 0$ one recovers the MSSM chargino mass limit. Moreover, in analogy with standard practice, we assumed unification of the gaugino mass parameters in order to determine the corresponding neutralino mass limit. To improve this limit it is important to realize that a dedicated neutralino analysis is really needed, more so than in the corresponding MSSM case since the neutralino may exhibit visible decays.

Our analysis show that LEP II is able to discriminate between the MSSM and a model presenting spontaneous R–parity breaking in a large region of the SUSY parameter space, if charginos are indeed observed! For small values of $\epsilon(\simeq 0.1$ GeV) and $\tan\beta(\simeq 2)$, the exotic multi-fermion channel can be seen and therefore used to look for R–parity violation when the MSSM topology is the dominant one; see Fig. 5. For larger of ϵ and $\tan\beta$, the chargino decay into τJ becomes important, and consequently, the 2 jets + τ and $\tau\tau\not{p}_{\rm T}$ topologies should provide an undeniable signal for spontaneous breaking of R–parity; see Figs. 6 to 9.

As a final remark, we have assumed in our calculations that the whole integrated luminosity was collected at 172 GeV. Nevertheless, LEP II has already started running at 183 GeV. This increase in energy will enlarge the excluded area shown in our exclusion plots. However, we leave for the experimentalists the task of doing a more detailed analysis.

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TABLES

ϵ (GeV)	$\tan\beta$	MSSM channels	$\tau\tau + \not{p}_T$	Exotic channels	dijet+$\tau + \not{p}_T$	Combined results
0	2	86	–	–	–	86
	35	86	–	–	–	86
0.1	2	84.6	–	–	–	86
	35	84	–	–	61	86
1	2	–	60	–	63.7	84.2
	35	–	80	–	77	86
10	35	-	86	-	-	86

TABLE I. 95% CL chargino mass limits in GeV that can be derived from negative searches at LEP II.

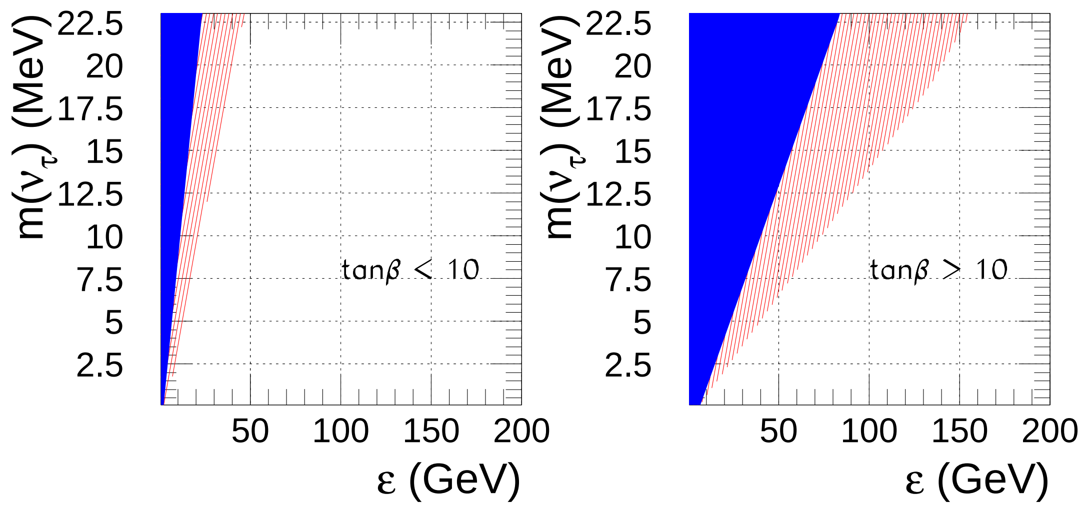


FIG. 1. The value of the predicted tau neutrino mass in our model is compatible with the LEP experimental limits in the light shaded area. Within the dark shaded area, chargino masses are such that they can be produced at $\sqrt{s} = 172$ GeV.

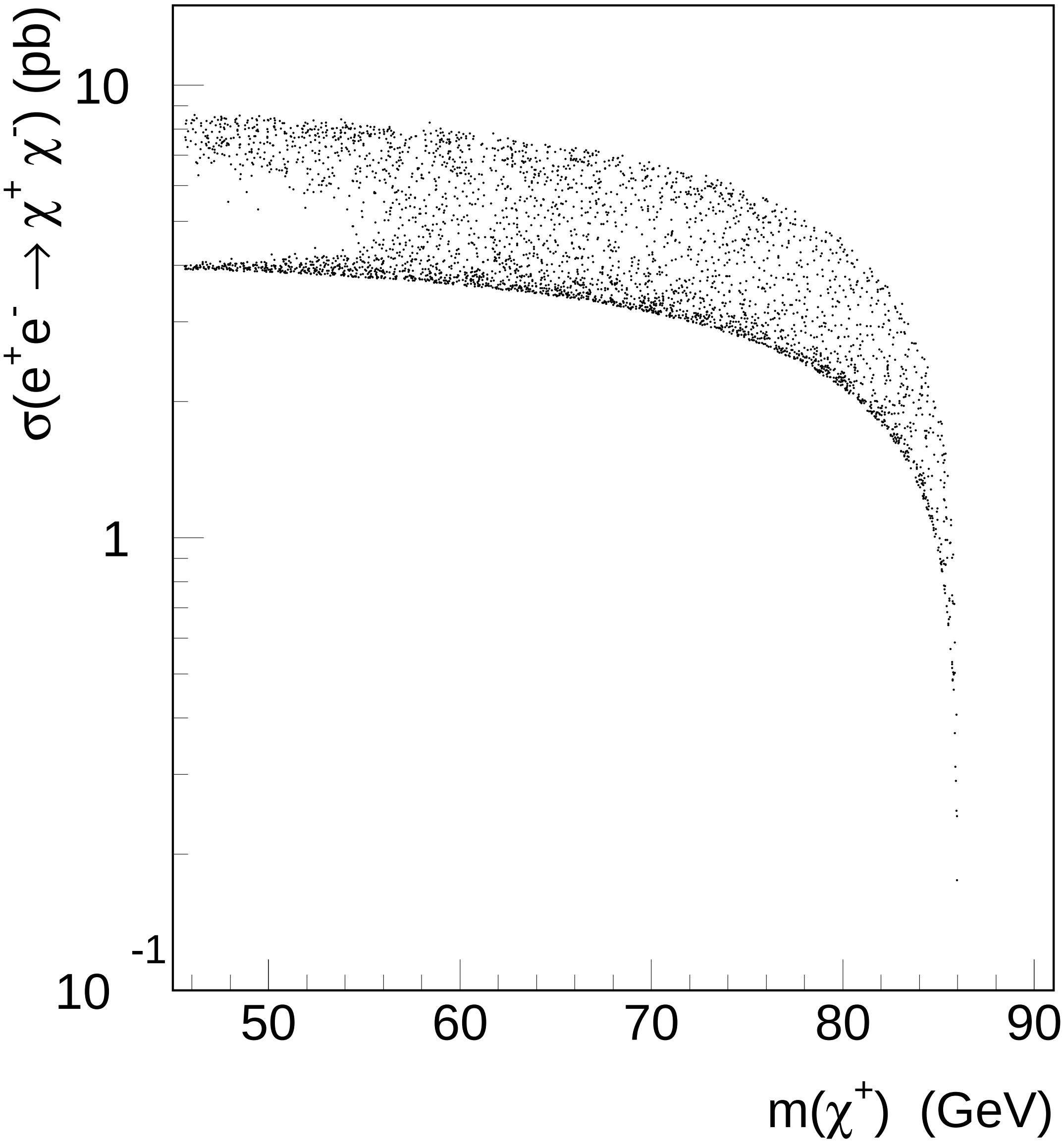


FIG. 2. $e^+e^- \to \chi^+\chi^-$ cross section, in the large $m_{\tilde{\nu}}$ limit, versus chargino mass for the parameter region defined in Eqs. (17) and (18) and $\sqrt{s} = 172$ GeV. The upper and lower limiting curves of this plot define the range of LEPII chargino pair production cross section for our parameter space.

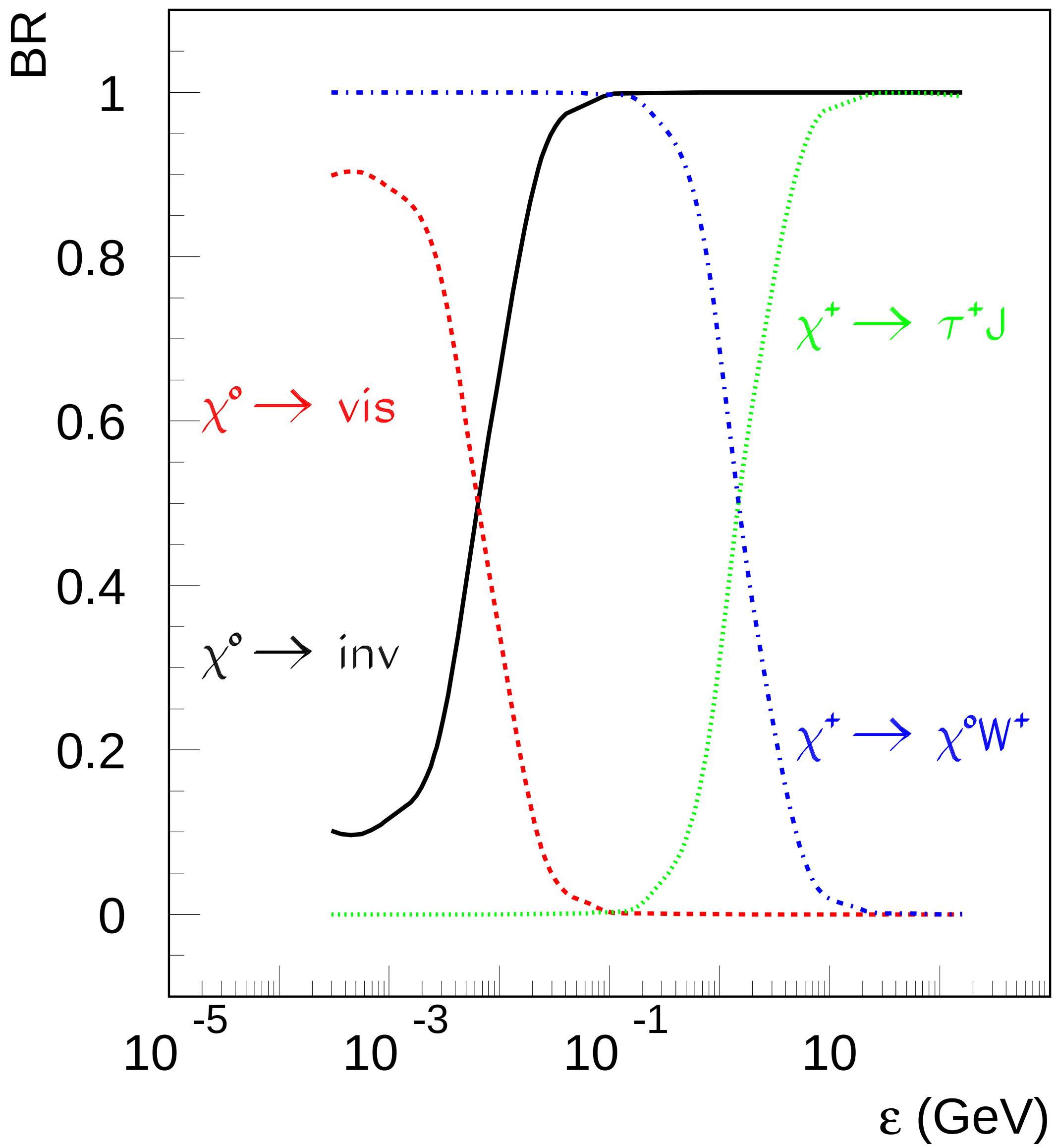
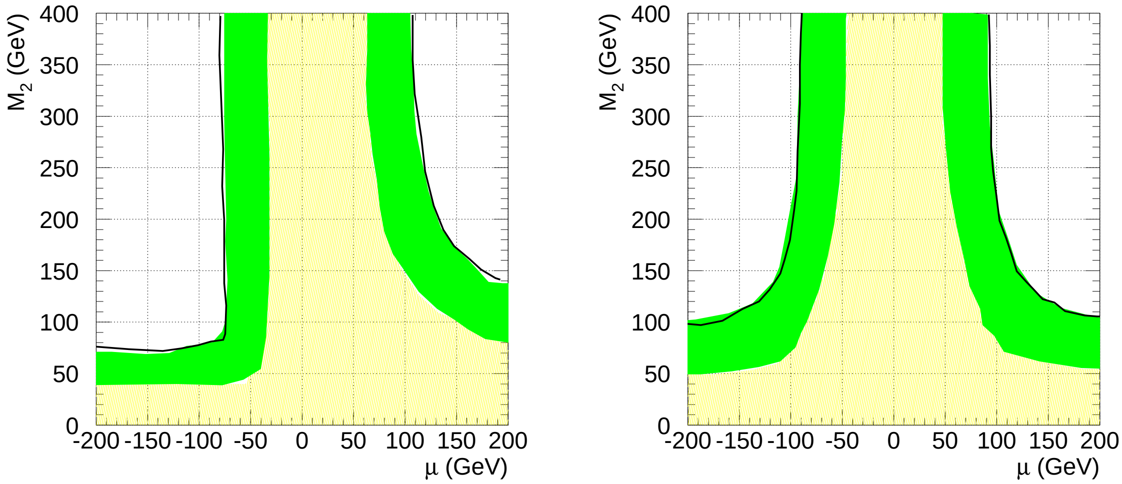


FIG. 3. Typical neutralino and chargino decay branching ratios as a function of ϵ for $\mu = 150$ GeV, $M_2 = 100$ GeV, and $\tan\beta = 35$.



(a) **(b)**

FIG. 4. 95% CL excluded region in the (μ, M_2) plane (dark shaded area) in the MSSM limit $\epsilon = v_L = 0$ for $\tan\beta = 2$ (a) [$\tan\beta = 35$ (b)], $\sqrt{s} = 172$ GeV, and an integrated luminosity of 300 pb^{-1}. The light shaded zone is excluded in the MSSM limit by LEP I while the solid curve denotes the LEP II kinematical limit.

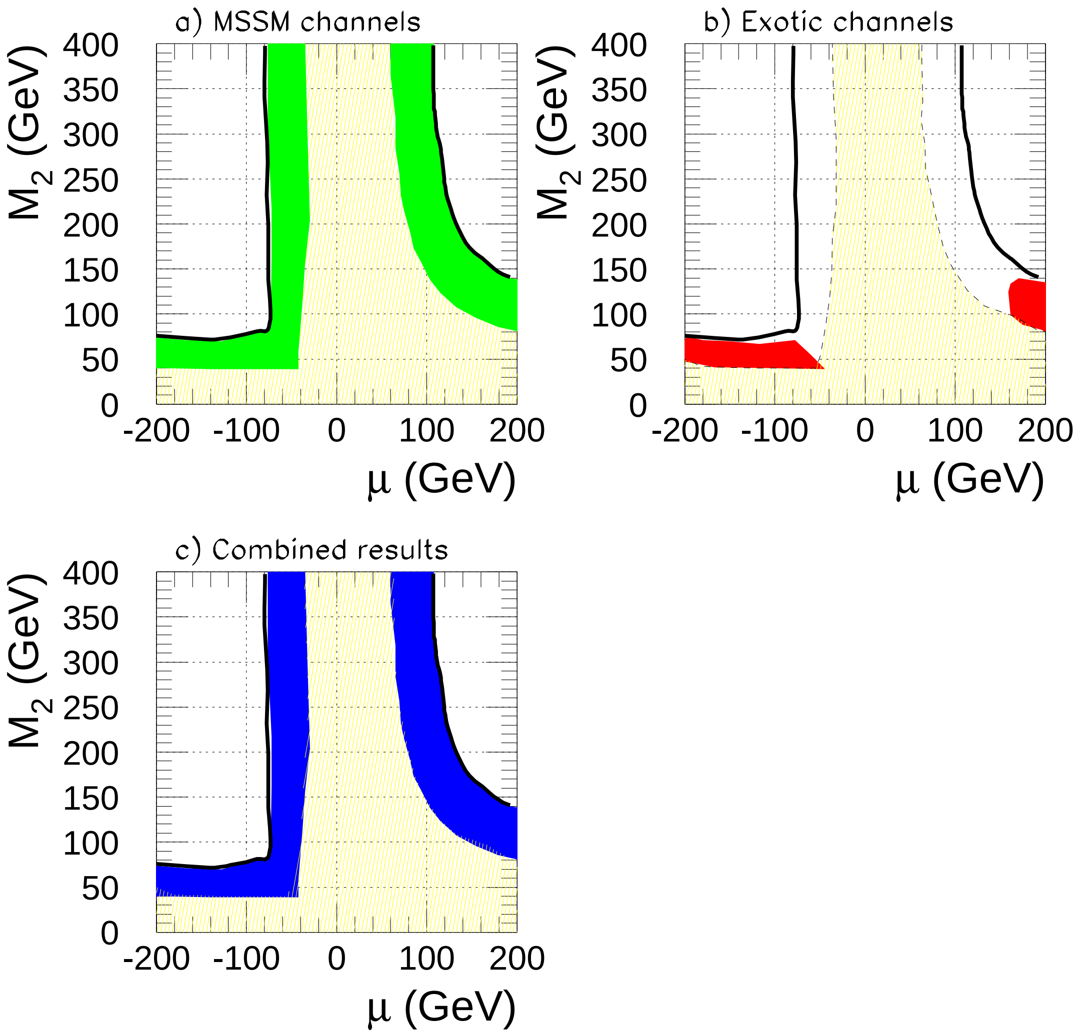


FIG. 5. 95% CL excluded region in the (μ, M_2) plane (dark shaded areas) by the analyses of the MSSM (a) and exotic (b) channels, as well as the combined excluded region (c). We assumed $\tan\beta = 2$, $\epsilon = 0.1$ GeV, $\sqrt{s} = 172$ GeV, and an integrated luminosity of 300 pb^{-1}.

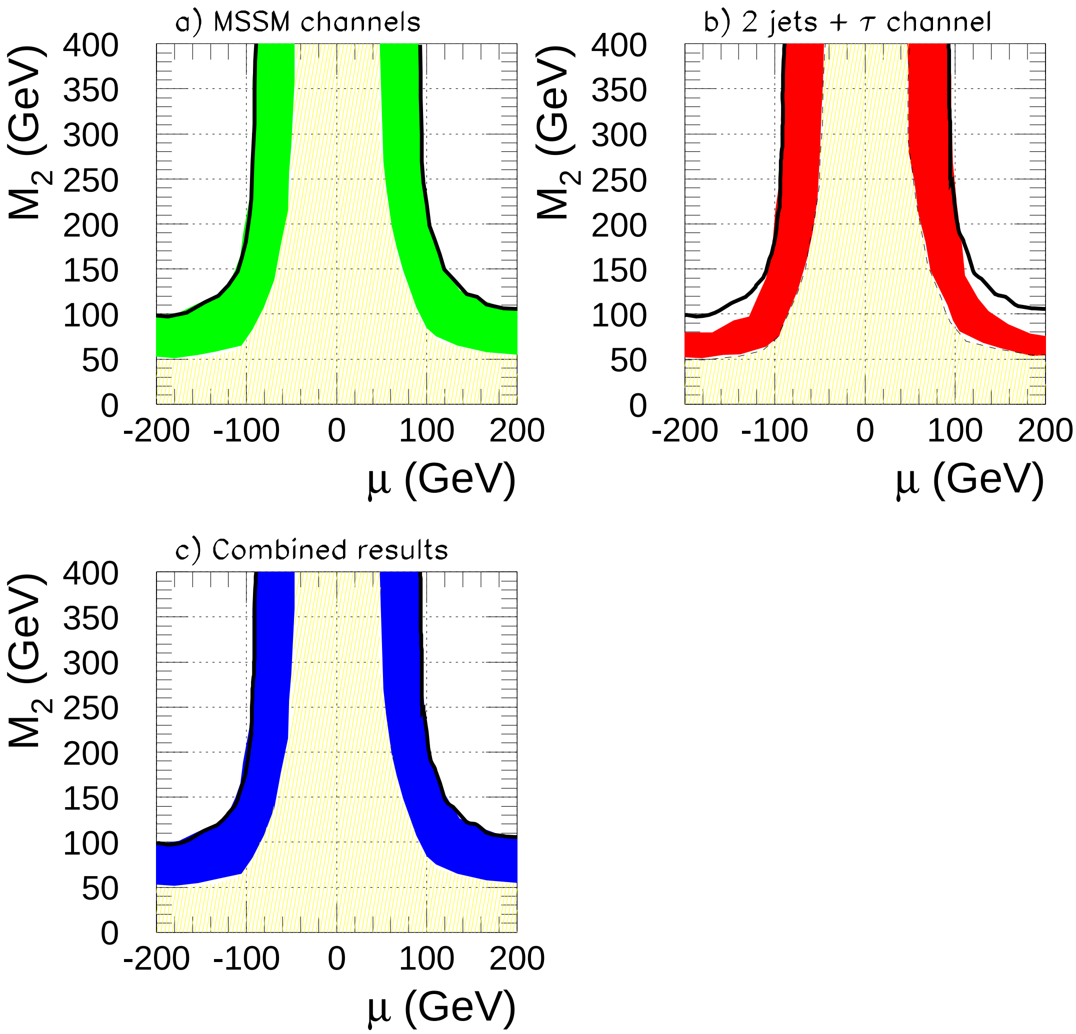


FIG. 6. 95% CL excluded region in the (μ, M_2) plane (dark shaded areas) by the analyses of the MSSM (a) and 2 jets $+\tau$ (b) channels, as well as the combined excluded region (c). We assumed $\tan\beta = 35$, $\epsilon = 0.1$ GeV, $\sqrt{s} = 172$ GeV, and an integrated luminosity of 300 pb^{-1}.

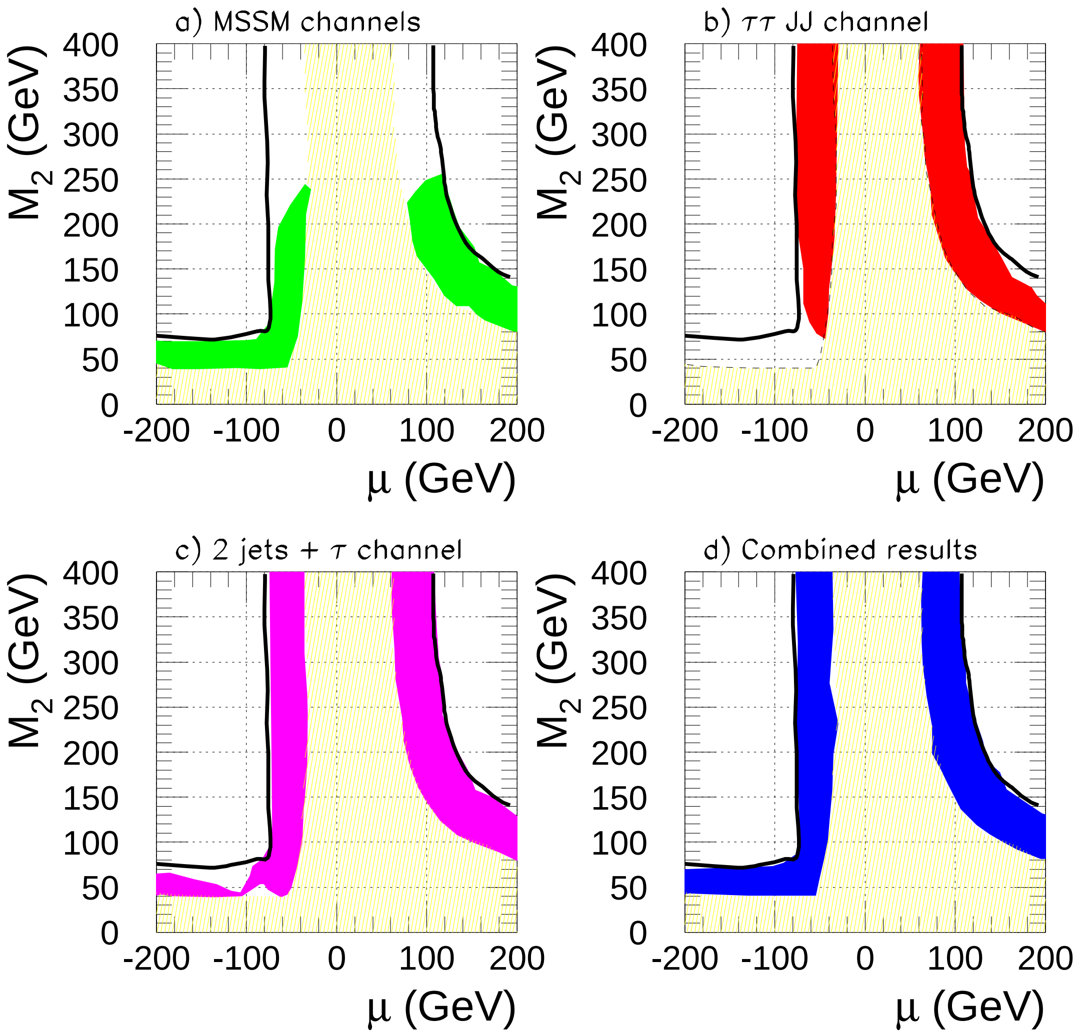


FIG. 7. 95% CL excluded region in the (μ, M_2) plane (dark shaded areas) by the analyses of the MSSM (a), $\tau\tau JJ$ (b), and 2 jets $+\tau$ (c) channels, as well as the combined excluded region (d). We assumed $\tan\beta = 2$, $\epsilon = 1$ GeV, $\sqrt{s} = 172$ GeV, and an integrated luminosity of 300 pb^{-1}.

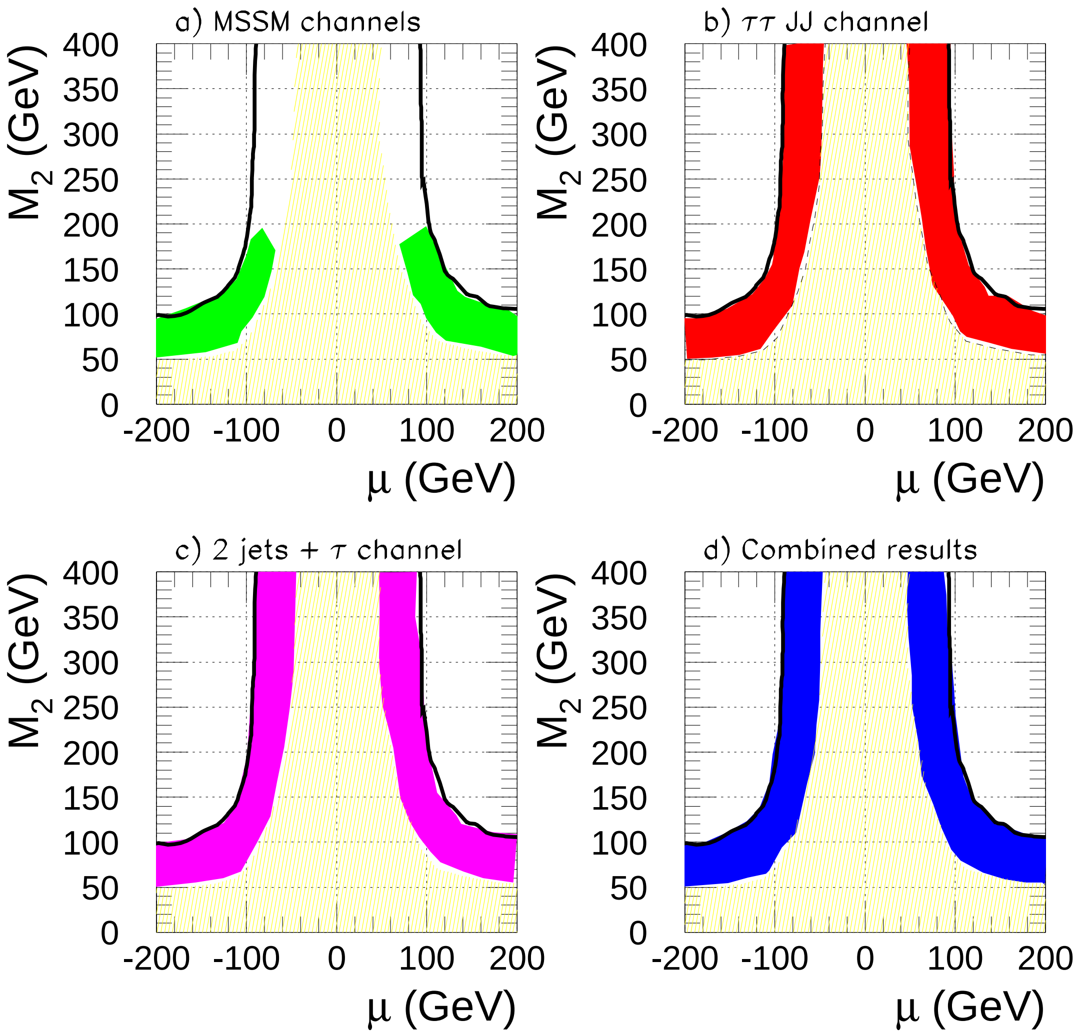


FIG. 8. 95% CL excluded region in the (μ, M_2) plane (dark shaded areas) by the analyses of the MSSM (a), $\tau\tau JJ$ (b), and 2 jets $+\tau$ (c) channels, as well as the combined excluded region (d). We assumed $\tan\beta = 35$, $\epsilon = 1$ GeV, $\sqrt{s} = 172$ GeV, and an integrated luminosity of 300 pb^{-1}.

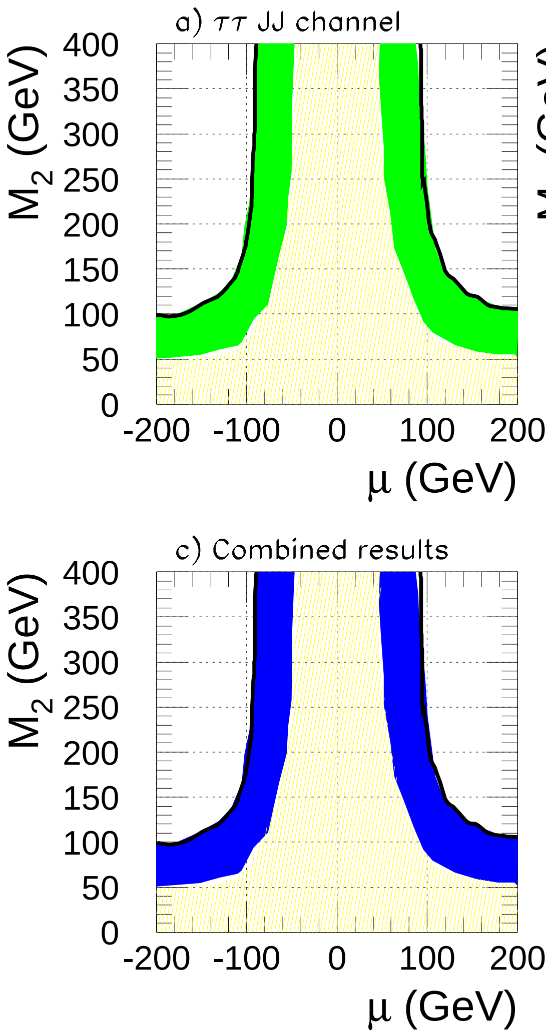


FIG. 9. 95% CL excluded region in the (μ, M_2) plane (dark shaded areas) by the analyses of the $\tau\tau JJ$ (a) and 2 jets $+\tau$ (b) channels, as well as the combined excluded region (c). We assumed $\tan\beta = 35$, $\epsilon = 10$ GeV, $\sqrt{s} = 172$ GeV, and an integrated luminosity of 300 pb^{-1}.