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Possible pre-LEP200 SUSY threshold signals

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Abstract

If R -parity is not conserved, the SUSY-threshold production process $e^+e^- \rightarrow \chi_1^0\chi_1^0$ could be detectable with relatively low luminosity. Hence an interesting mass range for the lightest SUSY particle χ_1^0 could be explored at the CERN LEP collider during its intermediate energy development, even before the full LEP200 upgrade is completed. We present cross section formulas and discuss event rates and detection for the three distinct decay options: $\chi_1^0 \rightarrow 2 \text{ charged leptons} + \text{neutrino}$, $\chi_1^0 \rightarrow \text{lepton} + 2 \text{ quarks}$, and $\chi_1^0 \rightarrow 3 \text{ quarks}$.

The theoretical attractions of Supersymmetry (SUSY) still lack the direct experimental support that would come from discovering some of the predicted SUSY partners of Standard Model (SM) particles. Their non-appearance may be attributed to their masses being beyond the reach of experimental searches so far. Also, in the Minimal Supersymmetric Standard Model (MSSM)[1], the lightest SUSY partner (usually expected to be the lightest neutralino χ_1^0) is stable and weakly interacting so that the lowest-threshold SUSY process

$$e^+e^- \rightarrow \chi_1^0\chi_1^0 \quad (1)$$

is completely invisible. But if χ_1^0 in fact decays visibly, as can happen if the conventional assumption of R -parity conservation is relaxed[2–5,7], this process will be detectable and in fact may have an appreciable cross section, depending on the mixture of electroweak gauginos and higgsinos in χ_1^0 and on the mass of the lightest selectron. (Strictly speaking, R -parity violation (RPV) also allows single-SUSY-partner production with lower thresholds than Eq.(1), but the corresponding production cross sections depend on unknown RPV-couplings that are either constrained[4–6] or suspected to be much smaller than the gauge and Yukawa couplings controlling Eq.(1)). In the present Letter we provide cross section formulas and numerical evaluations for Eq.(1), and discuss the types of signal that would be observable in an RPV scenario where χ_1^0 is the lightest SUSY partner (LSP). We also point out that these cross sections are big enough to enable significant SUSY-RPV searches during the gradual upgrade of the CERN e^+e^- collider LEP from CM energy $\sqrt{s} \simeq 90$ GeV toward 200 GeV, even though the intermediate-energy running will not accumulate high luminosity. An experimental search has already been made for Eq.(1) at LEP[8], assuming that χ_1^0 is a pure photino and taking a specific RPV model[9]; it excludes a range of photino masses between 5 and 42 GeV in this model, provided the exchanged selectron is light enough. Also possible LEP200 τ -lepton signals from Eq.(1) have been considered in Ref.[6]. But other discussions of SUSY-RPV signals at e^+e^- colliders [2,3,10] usually neglect Eq.(1) in favor of processes such as slepton-pair or chargino-pair production, which may have larger cross sections eventually but also have higher thresholds.

With the MSSM particle content, the most general gauge- and SUSY-invariant Lagrangian includes the following Yukawa coupling terms[2,3]:

$$\mathcal{L}_{RPV} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c, \quad (2)$$

where L_i and E_i^c are the (left-handed) lepton doublet and antilepton singlet chiral superfields (with generation index i), while Q_i and U_i^c , D_i^c are the quark doublet and antiquark singlet superfields. Antisymmetry gives $\lambda_{ijk} = -\lambda_{jik}$ and $\lambda''_{ijk} = -\lambda''_{ikj}$. The LLE^c and LQD^c terms violate lepton number L while the $U^c D^c D^c$ terms violate baryon number B . In the MSSM these terms are all conventionally forbidden by a multiplicative symmetry called R -parity (R_p), with $R_p = 1$ for all SM particles and $R_p = -1$ for their SUSY partners, in order to prevent rapid proton decay. However, proton decay is prevented if *either* the L -violating *or* the B -violating terms are absent; this is an adequate restriction on RPV scenarios. Since χ_1^0 can couple to any of these superfields, each RPV term provides a possible decay channel into SM fermions (via sfermion exchanges) as follows:

$$\lambda_{ijk} \Rightarrow \chi_1^0 \rightarrow \ell_i^- \nu_j \ell_k^+, \quad (3)$$

$$\lambda'_{ijk} \Rightarrow \chi_1^0 \rightarrow \ell_i^- u_j \bar{d}_k, \nu_i d_j \bar{d}_k, \quad (4)$$

$$\lambda''_{ijk} \Rightarrow \chi_1^0 \rightarrow \bar{u}_i \bar{d}_j \bar{d}_k, \quad (5)$$

together with the charge-conjugate channels. In practical applications, it is customary to consider just one of the 45 independent couplings in Eq.(2) at a time, since it seems likely that one will be more important than the others. For example, the OPAL search[8] probed $\chi_1^0 \rightarrow e\nu_\mu\tau, \nu_e\mu\tau$ signals[9] due to λ_{123} . (More complicated situations, where several λ_{ijk} , λ'_{lmn} contributions are comparable, are discussed however in Ref.[6]). The requirement that χ_1^0 decays within the detector (typically within 1 m) translates into[3]

$$\lambda \gtrsim 5 \times 10^{-6} \sqrt{\beta\gamma} (\tilde{m}_f)^2 (m_{\chi_1^0})^{-5/2}, \quad (6)$$

where λ denotes the dominant RPV coupling, $m_{\chi_1^0}$ and \tilde{m}_f are the masses of χ_1^0 and the dominant exchanged sfermion (in GeV), while $\beta\gamma = \sqrt{s/(4m_{\chi_1^0}^2) - 1}$ is the appropriate Lorentz factor for χ_1^0 . For typical values of present interest $m_{\chi_1^0} \sim 50$, $\tilde{m}_f \sim 100$, $\beta\gamma \sim 1$, this gives a very weak lower bound $\lambda \gtrsim 3 \times 10^{-6}$. The alternative types of decay mode in Eqs.(3)–(5) give quite different final state decay signatures for Eq.(1), which we now discuss.

(a) LLE^c -mediated decays: Eq.(3). Each χ_1^0 decays to two charged plus one neutral lepton; e.g. the λ_{132} mode gives

$$\chi_1^0 \rightarrow e^- \nu_\tau \mu^+, \nu_e \tau^- \mu^+, e^+ \bar{\nu}_\tau \mu^-, \bar{\nu}_e \tau^+ \mu^-, \quad (7)$$

with equal probabilities, assuming the contributing sfermion masses do not depend on the generation. In this case all final states contain two muons; 50% contain same-sign

dimuons; 12.5% contain same-sign dimuons plus same-sign dielectrons. In other cases the lepton flavors are distributed differently, but all have missing energy-momentum and same-sign dileptons among their signatures. Because of the missing neutrinos here, one cannot directly reconstruct the χ_1^0 mass, but it can in principle be inferred from the distribution of opposite-sign-dilepton invariant mass $m(\ell^+\ell^-)$ (with four entries per event, two of which have a common χ_1^0 parent and hence $m < m_{\chi_1^0}$).

(b) LQD^c -mediated decays: Eq.(4). Each χ_1^0 decays to a charged or neutral lepton plus two quarks (i.e. potentially two jets); e.g. the λ'_{213} mode gives

$$\chi_1^0 \rightarrow \mu^- u \bar{b}, \nu_\mu d \bar{b}, \mu^+ \bar{u} b, \bar{\nu}_\mu \bar{d} b, \quad (8)$$

with comparable probabilities, that become equal if $\tilde{m}_{\mu L} = \tilde{m}_{\nu_\mu L}$, $\tilde{m}_{uL} = \tilde{m}_{dL}$ and χ_1^0 is a pure bino. In the latter case, 50% of final states have dimuons (plus jets plus no missing energy), 25% have same-sign dimuons. We can attempt to reconstruct the χ_1^0 mass as follows. We partition each $\ell jjjj$ event into $(\ell jj)_1(\ell jj)_2$ clusters, with invariant masses m_1, m_2 , in six different ways; each such partition represents a possible $(\chi_1^0)(\chi_1^0)$ reconstruction; the best reconstruction is the one with least difference between m_1 and m_2 , and the best reconstructed χ_1^0 mass is the corresponding mean value $m(\ell jj) = (m_1 + m_2)/2$, with a distribution peaked near the true value $m_{\chi_1^0}$.

(c) $U^c D^c D^c$ -mediated decays: Eq.(5). Each χ_1^0 decays to three quarks (i.e. potentially three jets) with no missing energy. There are 10 ways to partition 6 jets into two 3-jet clusters with masses m_1 and m_2 , say, to provide candidate reconstructions; as before, the best reconstruction is the one with least difference between m_1 and m_2 , and the best χ_1^0 mass estimate is the mean value $m(jjj) = (m_1 + m_2)/2$, with a distribution peaked near the true value $m_{\chi_1^0}$.

(d) Note finally that if λ happens to lie in the range $5 \times (10^{-4} - 10^{-6}) \sqrt{\beta\gamma} (\tilde{m}_f)^2 (m_{\chi_1^0})^{-5/2}$, giving mean decay lengths of order 0.1 mm–1 m, the two decay vertices will usually be detectably displaced from each other and from the beam-intersection spot, giving an important additional signature.

The cross section for Eq.(1) depends on the composition of χ_1^0 in terms of electroweak gauginos and higgsinos. The production proceeds via t - and u -channel exchanges of selectrons and an s -channel Z -pole. The couplings in the general case are

$$\mathcal{L} = e\sqrt{2}(f_L \bar{e}_L \bar{e}_L \chi_1^0 + f_R \bar{e}_R \bar{e}_R \chi_1^0 + h.c.) + ec_a Z^\mu \bar{\chi}_1^0 \gamma_\mu \gamma_5 \chi_1^0 \quad (9)$$

with the coefficients f_L , f_R and c_a determined by the gaugino and higgsino composition of the neutralino. For pure states these coefficients take the values

| χ | | f_L | f_R | c_a |
|-----------------|---------------------|-----------------------------|---------------------------|--|
| <i>photino</i> | $\tilde{\gamma}$ | 1 | 1 | 0 |
| <i>zino</i> | \tilde{Z} | g_L^e | g_R^e | 0 |
| <i>bino</i> | $\tilde{\lambda}_0$ | $\frac{1}{2 \cos \theta_w}$ | $\frac{1}{\cos \theta_w}$ | 0 |
| <i>wino</i> | $\tilde{\lambda}_3$ | $\frac{1}{2 \sin \theta_w}$ | 0 | 0 |
| <i>higgsino</i> | \tilde{h} | 0 | 0 | $-\frac{1}{4 \sin \theta_w \cos \theta_w}$ |
| <i>higgsino</i> | \tilde{h}' | 0 | 0 | $\frac{1}{4 \sin \theta_w \cos \theta_w}$ |

(10)

where $g_L^e = (1 - 2 \sin^2 \theta_w) / \sin 2\theta_w$, $g_R^e = -\tan \theta_w$, and θ_w is the usual weak angle. The weak isospins T_3 of \tilde{h} and \tilde{h}' are $\frac{1}{2}$ and $-\frac{1}{2}$ respectively. In general,

$$f_{L,R} = \sum_i f_{L,R}^i a_i \epsilon_{L,R} \quad (11)$$

$$c_a = \frac{a_{\tilde{h}'}^2 - a_{\tilde{h}}^2}{4 \sin \theta_w \cos \theta_w} \quad (12)$$

where we denote the \tilde{h} , \tilde{h}' , $\tilde{\lambda}_3$, $\tilde{\lambda}_0$ components of χ_1^0 by a_i . The phase factor ϵ_L is 1 (or i) for a positive (or negative) eigenvalue of the state χ_1^0 when the neutralino mass matrix is diagonalized. Also $\epsilon_R = \epsilon_L^*$. Our expression for c_a agrees with Ref.[11].

The cross section is evaluated in the helicity basis L, R for subsequent use in joint production and decay analysis. The production amplitudes are

$$\mathcal{M}(e_L \bar{e}_R \rightarrow \chi_L \chi_R) = -e^2 \cos^2 \theta \left[f_L^2 \left(\frac{s(1-\beta)}{t - \tilde{m}_{eL}^2} - \frac{s(1+\beta)}{u - \tilde{m}_{eL}^2} \right) + \frac{4\beta c_a g_L^e s}{s - M_Z^2 + iM_Z \Gamma_Z} \right] \quad (13)$$

$$\mathcal{M}(e_L \bar{e}_R \rightarrow \chi_R \chi_L) = -e^2 \sin^2 \theta \left[f_L^2 \left(\frac{s(1-\beta)}{u - \tilde{m}_{eL}^2} - \frac{s(1+\beta)}{t - \tilde{m}_{eL}^2} \right) + \frac{4\beta c_a g_L^e s}{s - M_Z^2 + iM_Z \Gamma_Z} \right] \quad (14)$$

$$\mathcal{M}(e_L \bar{e}_R \rightarrow \chi_L \chi_L) = -\mathcal{M}(e_L \bar{e}_R \rightarrow \chi_R \chi_R) = e^2 f_L^2 \sin \theta \frac{m_{\chi_1^0}}{\sqrt{s}} \left(\frac{s}{t - \tilde{m}_{eL}^2} - \frac{s}{u - \tilde{m}_{eL}^2} \right) \quad (15)$$

$$\mathcal{M}(e_R \bar{e}_L \rightarrow \chi_R \chi_L) = e^2 \cos^2 \theta \left[f_R^2 \left(\frac{s(1-\beta)}{t - \tilde{m}_{eR}^2} - \frac{s(1+\beta)}{u - \tilde{m}_{eR}^2} \right) - \frac{4\beta c_a g_R^e s}{s - M_Z^2 + iM_Z \Gamma_Z} \right] \quad (16)$$

$$\mathcal{M}(e_R \bar{e}_L \rightarrow \chi_L \chi_R) = e^2 \sin^2 \theta \left[f_R^2 \left(\frac{s(1-\beta)}{u - \tilde{m}_{eR}^2} - \frac{s(1+\beta)}{t - \tilde{m}_{eR}^2} \right) - \frac{4\beta c_a g_R^e s}{s - M_Z^2 + iM_Z \Gamma_Z} \right] \quad (17)$$

$$\mathcal{M}(e_R \bar{e}_L \rightarrow \chi_R \chi_R) = -\mathcal{M}(e_R \bar{e}_L \rightarrow \chi_L \chi_L) = e^2 f_R^2 \sin \theta \frac{m_{\chi_1^0}}{\sqrt{s}} \left(\frac{s}{t - \tilde{m}_{eR}^2} - \frac{s}{u - \tilde{m}_{eR}^2} \right) \quad (18)$$

where s, t, u are the usual invariant squares of CM energy and momentum transfer, θ is the polar scattering angle, and $\beta = \sqrt{1 - 4m_{\chi_1^0}^2/s}$ is the CM velocity of χ_1^0 . Note that production from $e_L\bar{e}_R$ ($e_R\bar{e}_L$) initial states involves \bar{e}_L (\bar{e}_R) exchanges; we assume no \bar{e}_L, \bar{e}_R mixing, which is expected to be an excellent approximation. The differential cross section is given by

$$\frac{d\sigma}{d\cos\theta} = \frac{\beta}{128\pi s} \sum |\mathcal{M}|^2. \quad (19)$$

Since we have identical particles in the final state, the phase space is limited to the forward hemisphere, $\cos\theta \geq 0$. In the case that χ_1^0 is a photino, we reproduce the cross section expression given in Ref.[12].

The decay amplitude is greatly simplified if we assume it is dominated by the exchange of the right-handed scalar partner. For the process $\chi_h(p) \rightarrow \mu(q)e^+(l)\bar{\nu}_\tau(k)$, the R -parity violating coupling λ_{132} gives

$$\mathcal{M} = \frac{e\sqrt{2}f_R\lambda_{132}}{(l+k)^2 - \tilde{m}_{\mu_R}^2} T_{+,h}(q,p)T_{-,+}(l,k)\sqrt{8l^0k^0q^0(p^0 - h|p|)}, \quad (20)$$

where $h = +$ or $-$ denotes the helicity, R or L , of the χ state; the spinor product T is defined in Ref.[13]. We have assumed this form in our decay calculations. Generalization of this formula is straightforward. The full amplitude to a given final state is the product of contributing production and decay amplitudes summed over intermediate χ_1^0 helicities; we have calculated distributions by Monte Carlo methods, in the narrow- χ_1^0 -width approximation.

For our discussion, we focus particular attention on one interesting example with $m_{\chi_1^0} = 48$ GeV, light sleptons $\tilde{m}_{\ell R} = 74$ GeV and $\tilde{m}_{\ell L} = 112$ GeV ($\ell = e, \mu, \tau$) plus relatively heavy squarks; this is a typical SUSY-GUT solution from Ref.[14] in the top-Yukawa fixed-point region with $\tan\beta = 1.5$, where χ_1^0 is almost a pure bino. We also focus attention on $\sqrt{s} = 140$ GeV, a likely energy for intermediate LEP running, where luminosity of order 20 pb^{-1} may be accumulated in late 1995.

Figure 1(a) gives the integrated cross section for the particular choice of energy and selectron masses above, but allowing the χ_1^0 mass and composition to vary. We see that of order twenty $e^+e^- \rightarrow \chi_1^0\chi_1^0$ events could soon be produced at $\sqrt{s} = 140$ GeV if χ_1^0 is light and bino-like (as in our example above) or photino-like or higgsino-like. Figure 1(b) illustrates the uncut angular distribution of χ_1^0 production for $m_{\chi_1^0} = 48$ GeV, with the same choice of energy and selectron masses as before. For the interesting bino-like and photino-like cases, we see that χ_1^0 production is preferentially at large polar angles θ , away

from the beam-pipe region where detection is poor; however the higgsino-like case has less favorable dependence $d\sigma/d\cos\theta \sim 1 + \cos^2\theta$, offsetting the higher integrated cross section here. Signals from LLE^c or LQD^c decay modes can in principle be detected by their exotic leptonic content (especially same-sign dileptons) and generally have small SM backgrounds [6]; a handful of such events should be enough to attract attention and provoke a detailed analysis. Six-jet signals from $U^c D^c D^c$ decays are less remarkable, since there are $e^+e^- \rightarrow q\bar{q}gggg$ and other QCD backgrounds; however, these backgrounds are expected to be of order $\alpha^2\alpha_s^4/s$ which is small compared to our illustrated signals of order $\alpha^2 s/\tilde{m}_{eR}^4 \sim \alpha^2/s$, and the signals contain a mass peak that we illustrate below. All RPV signals could also contain displaced vertices, as noted in (d) above.

To illustrate final-state invariant mass distributions, we impose gaussian smearing on energies, with $\Delta E/E = 0.8/\sqrt{E}$ for jets and $\Delta E/E = 0.2/\sqrt{E}$ for leptons, to simulate experimental resolution. We also impose loose semi-realistic cuts, requiring each of the visible leptons or quarks (=jets) to have energy $E > 6$ GeV, rapidity $|\eta| < 2$ and angular separations $\Delta\theta_{ij} > 15^\circ$. For $m_{\chi_1^0} = 48$ GeV, these cuts typically reduce the four-item (six-item) final state event rates by factors 0.53 (0.50), where item means charged lepton or jet. We then take the same energy and selectron masses as above, assume χ_1^0 to be a pure bino, and compare the case $m_{\chi_1^0} = 48$ GeV (from the SUSY-GUT example[14]) with the case $m_{\chi_1^0} = 60$ GeV, to illustrate the mass sensitivity.

Figure 2(a) illustrates the distributions of unlike-sign dilepton mass $m(\ell^+\ell^-)$ in four-lepton final states from LLE^c decays (four entries per event). The signal is at best a broad peak, because of the missing neutrino in each χ_1^0 decay, but there is also an intrinsic background here from the 50% of dilepton pairs that do not have the same χ_1^0 parent. Figure 2(b) shows the distribution of reconstructed χ_1^0 mass $m(\ell jj)$ in $\ell l j j j j$ final states from LQD^c decays; the background below the peak comes from the gaussian energy resolution, which smears the peak and also leads to some wrong choices for the best partitioning. Figure 2(c) shows the distribution of reconstructed χ_1^0 mass $m(j j j)$ in $j j j j j j$ final states from $U^c D^c D^c$ decays (in the limit of large exchanged squark mass); here too the background outside the peak is due to energy smearing. In all three of these distributions, we see there is sensitivity to the χ_1^0 mass; in the latter two cases there is a clear mass peak showing high sensitivity.

To summarize, we have shown that the SUSY threshold process Eq.(1) could be recog-

nizable and detectable at pre-LEP200 energies such as $\sqrt{s} = 140$ GeV, with modest luminosities such as 20 pb^{-1} , if R -parity is violated and χ_1^0 is the LSP. We have demonstrated that the production angular distribution may well be favorable to detection (Fig.1(b)). For the different possible RPV decay mechanisms, we have also illustrated — with semi-realistic energy resolution and acceptance — how appropriate final-state invariant mass distributions can be used to extract the χ_1^0 mass (Figs.2(a)–2(c)). Our results are complementary to those of Ref.[6], which also addressed RPV signals from Eq.(1) but calculated for $\sqrt{s} = 200$ GeV, focusing on τ -lepton channels from LLE^c and LQD^c decays, with no discussion of production angles nor final state invariant mass distributions nor possible displaced-vertex signatures.

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Figures

1. $e^+e^- \rightarrow \chi_1^0\chi_1^0$ production cross sections: (a) integrated cross section versus χ_1^0 mass $m_{\chi_1^0}$, and (b) CM differential cross section versus $|\cos\theta|$, for various cases. Solid, dashed, dot-dashed, short-long-dashed and short-short-long-dashed curves denote the cases where χ_1^0 is purely photino, bino, zino, neutral wino and higgsino, respectively. We here take CM energy $\sqrt{s} = 140$ GeV with exchanged selectron masses $\tilde{m}_{eL} = 112$ GeV and $\tilde{m}_{eR} = 74$ GeV.
2. Invariant mass distributions that can reveal the χ_1^0 mass $m_{\chi_1^0}$: (a) opposite-sign dilepton mass $m(\ell^+\ell^-)$ in four-lepton signals from LLE^c decays; (b) best-reconstructed lepton-plus-dijet mass $m(\ell jj)$ in two-lepton-plus-four-jet signals from LQD^c decays; (c) best-reconstructed trijet mass $m(jjj)$ in six-jet signals from $U^cD^cD^c$ decays. We assume the same energy and selectron masses as in Fig.1, and compare the cases $m_{\chi_1^0} = 48, 60$ GeV for a pure bino χ_1^0 .

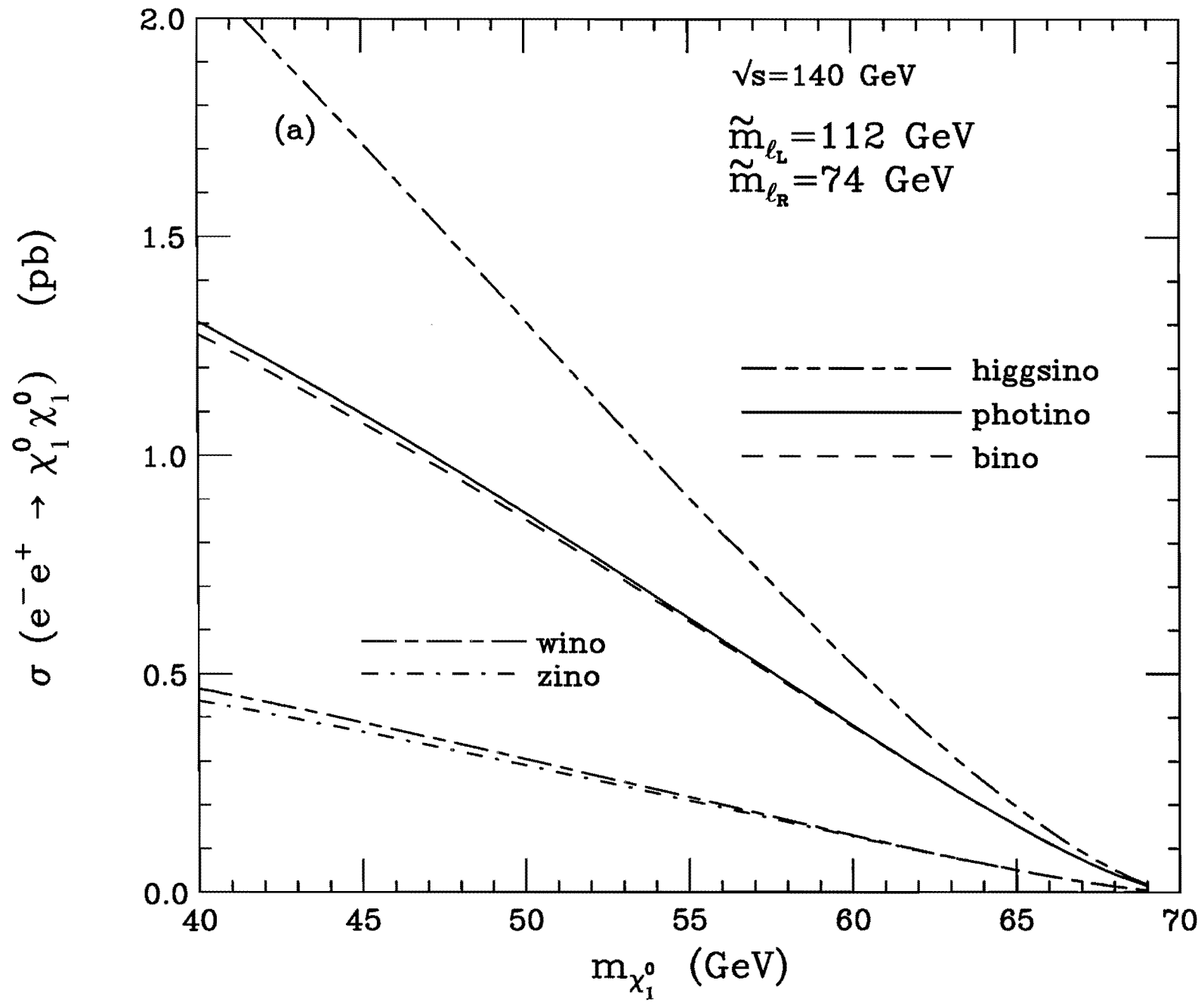


Figure 1(a)

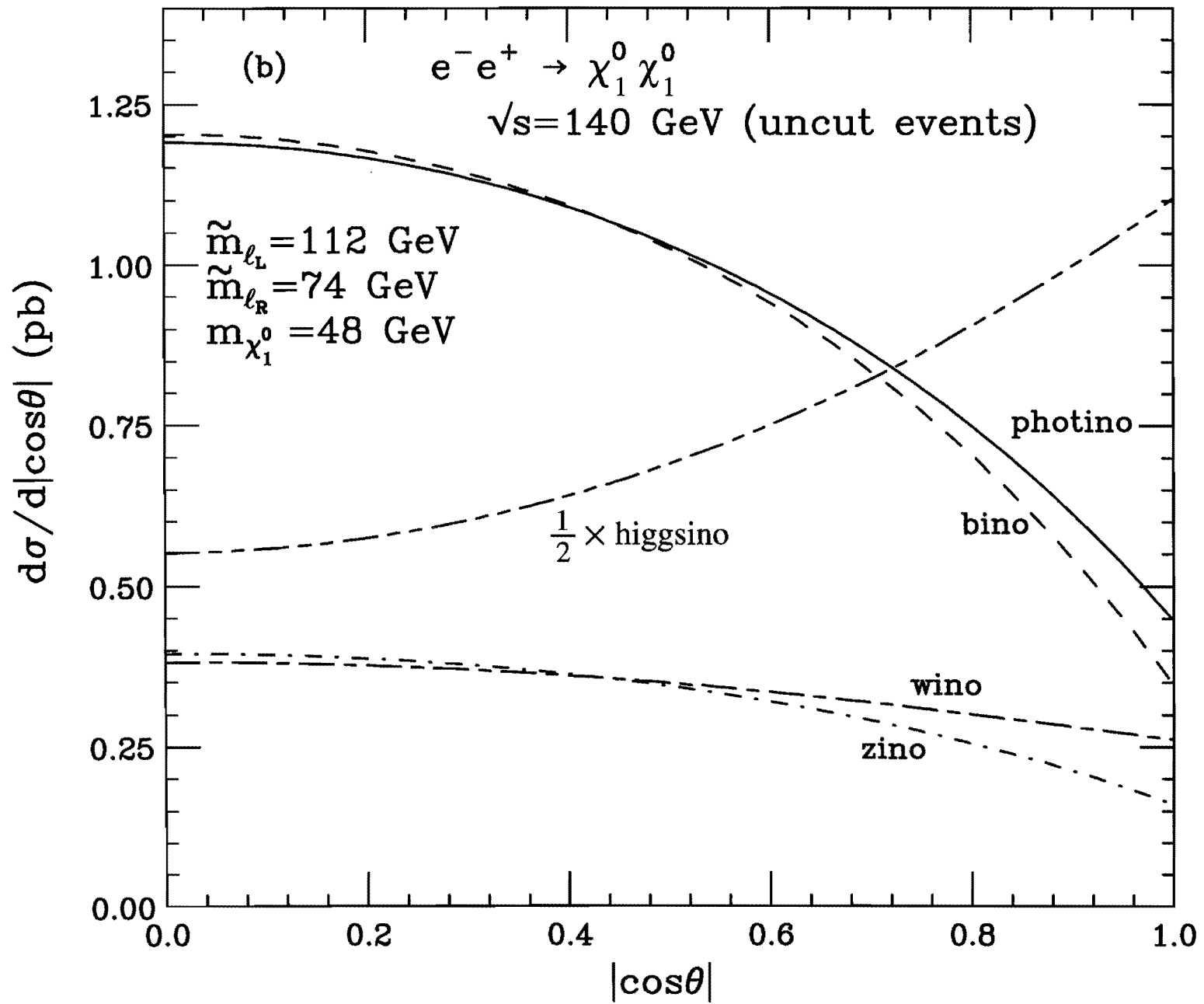


Figure 1(b)

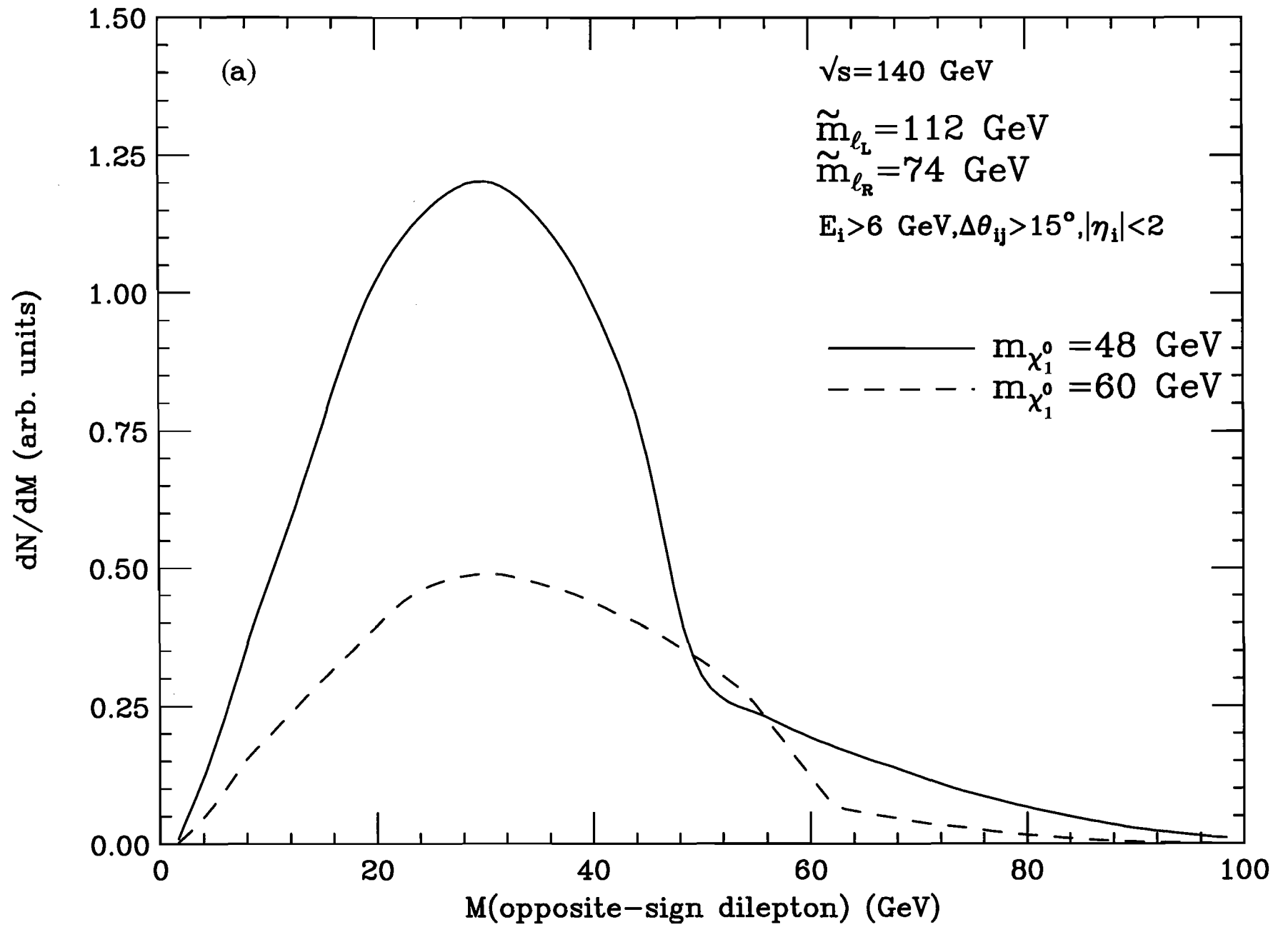


Figure 2(a)

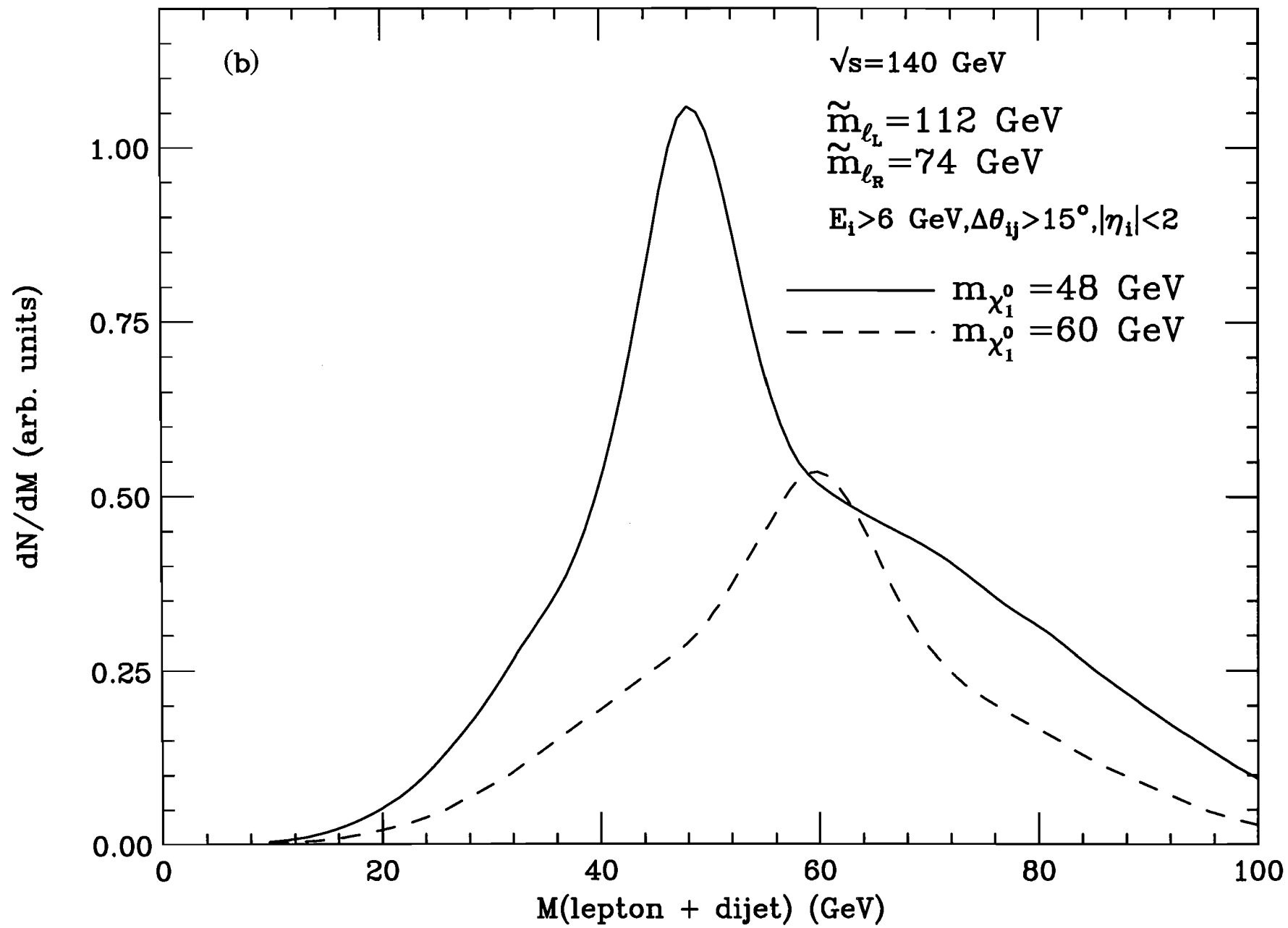


Figure 2(b)

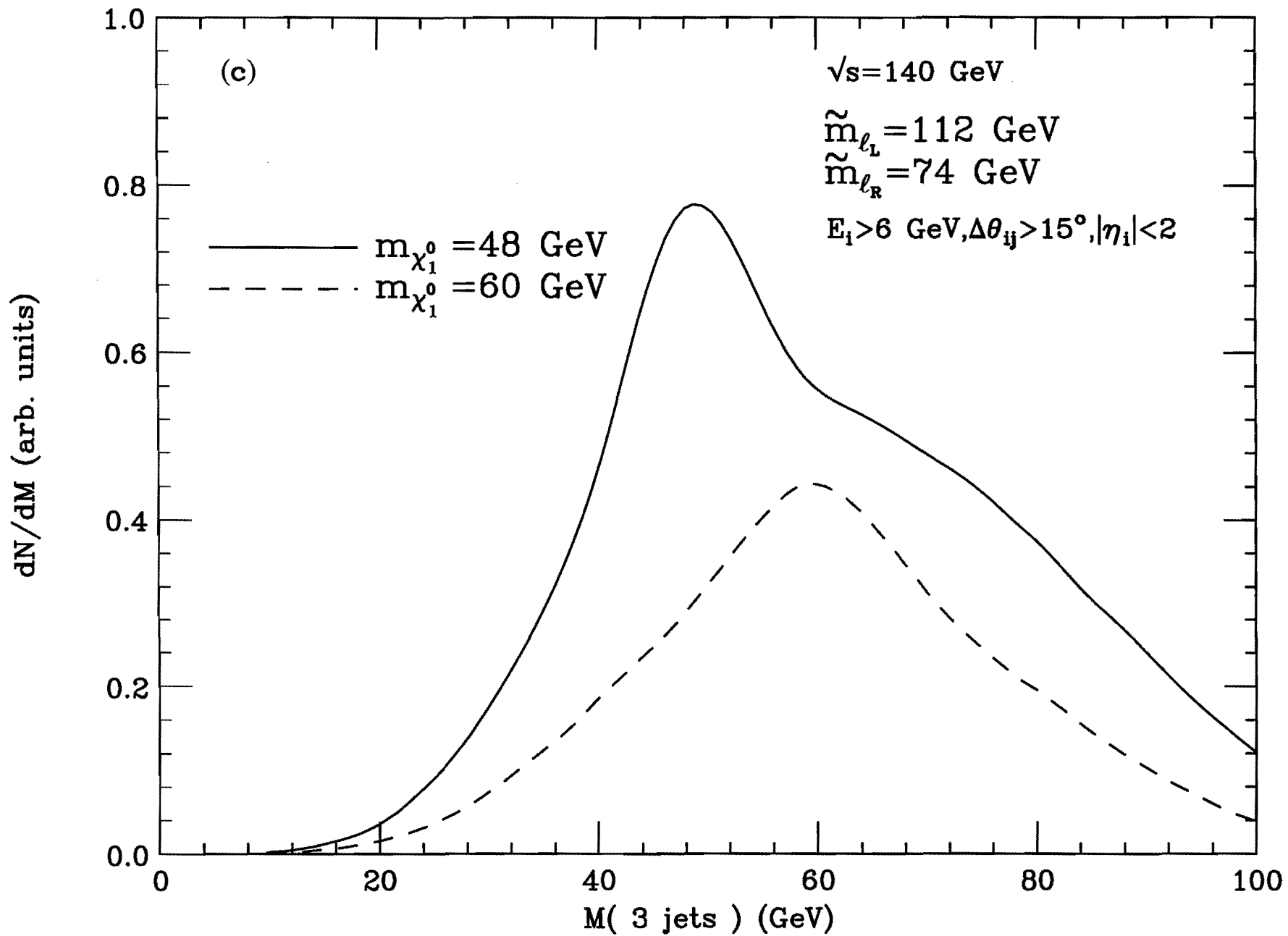


Figure 2(c)