

## Erratum: Nonstandard string-SUSY scenario and its phenomenological implications [Phys. Rev. D 55, 330 (1997)]

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Our treatment of exclusive hadronic chargino decays in this and the companion paper (Ref. [1]) was incorrect. In particular, decays into final states containing an odd number of pions are not suppressed. Correct expressions for the corresponding partial widths are given below; these replace and complete the incorrect Eq. (A2) in Appendix A:

$$\Gamma(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \pi^-) = \frac{f_\pi^2 G_F^2 |\vec{k}_\pi|}{4\pi \tilde{m}_-^2} \{ (O_{11}^L + O_{11}^R)^2 [(\tilde{m}_-^2 - \tilde{m}_0^2)^2 - m_\pi^2 (\tilde{m}_- - \tilde{m}_0)^2] + (O_{11}^L - O_{11}^R)^2 [(\tilde{m}_-^2 - \tilde{m}_0^2)^2 - m_\pi^2 (\tilde{m}_- + \tilde{m}_0)^2] \}; \quad (\text{A2a})$$

$$\Gamma(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \pi^- \pi^0) = \frac{G_F^2}{192\pi^3 \tilde{m}_-^3} \int_{4m_\pi^2}^{(\Delta m_{\tilde{\chi}_1})^2} dq^2 |F(q^2)|^2 \left(1 - \frac{4m_\pi^2}{q^2}\right)^{3/2} \lambda^{1/2}(\tilde{m}_-, \tilde{m}_0^2, q^2) \\ \times \{ [(O_{11}^L)^2 + (O_{11}^R)^2] [q^2(\tilde{m}_-^2 + \tilde{m}_0^2 - 2q^2) + (\tilde{m}_-^2 - \tilde{m}_0^2)^2] - 12O_{11}^L O_{11}^R q^2 \tilde{m}_- \tilde{m}_0 \}; \quad (\text{A2b})$$

$$\Gamma(\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 3\pi) = \frac{G_F^2}{6912\pi^5 \tilde{m}_-^3 f_\pi^2} \int_{9m_\pi^2}^{(\Delta m_{\tilde{\chi}_1})^2} dq^2 \lambda^{1/2}(\tilde{m}_-, \tilde{m}_0^2, q^2) |\text{BW}_a(q^2)|^2 g(q^2) \\ \times \left\{ [(O_{11}^L)^2 + (O_{11}^R)^2] \left[ \tilde{m}_-^2 + \tilde{m}_0^2 - 2q^2 + \frac{(\tilde{m}_-^2 - \tilde{m}_0^2)^2}{q^2} \right] - 12O_{11}^L O_{11}^R \tilde{m}_- \tilde{m}_0 \right\}. \quad (\text{A2c})$$

Here,  $\vec{k}_\pi = \lambda^{1/2}(\tilde{m}_-, \tilde{m}_0^2, m_\pi^2)/(2\tilde{m}_-)$  in Eq. (A2a) is the pion's 3-momentum in the chargino rest frame, and  $f_\pi \approx 93$  MeV is the pion decay constant. The form factor  $F(q^2)$  appearing in Eq. (A2b) has been defined in Eqs. (A3) and (A4) of Appendix A. Explicit expressions for the Breit-Wigner propagator  $\text{BW}_a$  of the  $a_2$  meson, the exchange of which is assumed to dominate  $3\pi$  production, as well as for the three-pion phase space factor  $g(q^2)$  can be found in Eqs. (3.16)–(3.18) of Ref. [2]. We have used the propagator without ‘‘dispersive correction.’’ This underestimates the partial width for  $\tau^- \rightarrow 3\pi \nu_\tau$  decays by about 35%; in our numerical results, we have therefore multiplied the right-hand side of Eq. (A2c) by 1.35. Nevertheless the branching ratio for these modes never exceeds  $\sim 18\%$ ; note that Eq. (A2c) includes both  $\pi^- \pi^0 \pi^0$  and  $\pi^- \pi^- \pi^+$  modes, which occur with equal frequency.

The new results for the lifetime  $\tau$  and for the branching ratios of the  $\tilde{\chi}_1^-$  are shown in Fig. 1, which is the replacement for Fig. 6 (as well as for Fig. 2 of Ref. [1]). The main modifications of our previous results are due to the greatly increased partial width of the single pion  $\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 \pi^-$  mode

(which now swamps the  $\tilde{\chi}_1^0 \pi^- \pi^0$  two-pion mode). Figure 1(b) shows that the  $\tilde{\chi}_1^0 \pi^-$  mode dominates  $\tilde{\chi}_1^-$  decays for  $m_\pi \leq m_{\tilde{\chi}_1} \leq 1$  GeV. As shown in Fig. 1(a), this leads to a rapid drop of the lifetime of the  $\tilde{\chi}_1^-$  once this mode opens up. The implications for observing chargino pair production at an  $e^+ e^-$  collider are the following.

(a) For  $\Delta m_{\tilde{\chi}_1} \equiv m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} < m_\pi$  our previous results are unchanged. The produced charginos travel distances of order a meter or more and appear as heavily ionizing tracks in the vertex detector and the main detector, thereby making  $e^+ e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$  production background-free and observable for  $m_{\tilde{\chi}_1^\pm}$  up to near  $\sqrt{s}/2$ .

(b) For  $m_\pi < \Delta m_{\tilde{\chi}_1} < 1$  GeV,  $c\tau$  is smaller than in our original calculation. One must consider this range in some detail. We give a discussion<sup>1</sup> appropriate to a silicon vertex

<sup>1</sup>We were greatly aided in putting this discussion together by several conversations with H. Frisch from the CDF Collaboration.

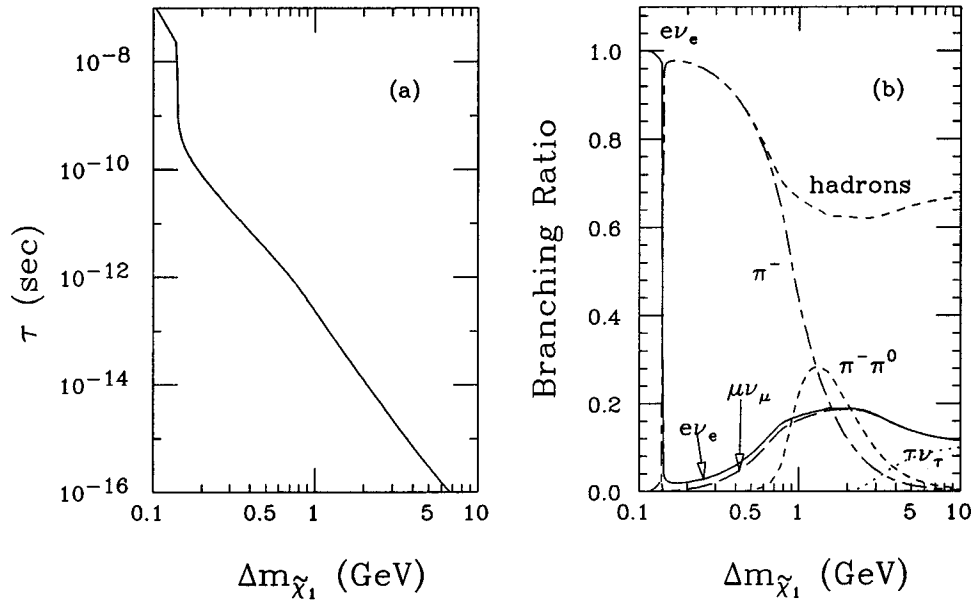
Large  $|\mu|$  Limiting Case

FIG. 1. In (a), we show the lifetime of  $\tilde{\chi}_1^-$  for the case  $M_1 \approx M_2 \ll |\mu|$ .  $\Delta m_{\tilde{\chi}_1}$  is the chargino-neutralino mass difference. In (b), we give the corresponding branching ratios of  $\tilde{\chi}_1^-$ . For  $\Delta m_{\tilde{\chi}_1} \leq 1.5$  GeV, the branching ratio for “hadronic” decays is computed as the sum of the branching ratios for 1, 2, and 3 pion final states, while for larger mass splittings the parton model result has been used.

detector of the type planned by CDF for run II.<sup>2</sup> This detector will have layers at  $r \sim 11, 8.5, 7, 4.5, 3,$  and  $1.6$  cm (this latter being the L00 layer) [5]. For  $m_\pi < \Delta m_{\tilde{\chi}_1} < 160$  MeV,  $c\tau > 7$  cm, implying that a  $\tilde{\chi}_1^-$  or  $\tilde{\chi}_1^+$  produced with low rapidity will typically pass through 4 or more layers of the vertex detector before decaying (for  $\langle \beta \rangle \geq 0.7$ ). This is probably sufficient to recognize the  $\tilde{\chi}_1^\pm$  track as being clearly heavily ionizing. For  $160 \text{ MeV} < \Delta m_{\tilde{\chi}_1} < 190$  MeV,  $7 \text{ cm} > c\tau > 3$  cm and the  $\tilde{\chi}_1^\pm$  will typically pass through at least two layers. Even though these layers would register passage of a heavily-ionizing object, this alone might not be enough to clearly identify an unusual event. However, the  $\tilde{\chi}_1^\pm$  track will end (which possibly helps to distinguish it from longer tracks, etc., that happen to have large deposits in the inner few layers) and emit a single charged pion. The single pion will typically have transverse momentum of order its momentum,  $p_\pi \sim \sqrt{\Delta m_{\tilde{\chi}_1}^2 - m_\pi^2}$ , in the  $\tilde{\chi}_1^\pm$  rest frame. For 160

MeV  $< \Delta m_{\tilde{\chi}_1} < 190$  MeV,  $p_\pi \sim 77 - 130$  MeV. The corresponding impact parameter resolution (taking  $p_\pi^T \sim p_\pi$ ),  $b_{\text{res}} \sim 300 - 700 \mu\text{m}$  (these are the  $1\sigma$  values from Fig. 2.2 of [5] when L00 is included), is much smaller than the actual impact parameter ( $\sim c\tau > 3$  cm). Perhaps the combination of a track that produces large deposits in a few layers and then ends with the emission of such a pion will be sufficient to pick out this type of event when combined with an appropriate trigger. For  $\Delta m_{\tilde{\chi}_1} > 230$  MeV,  $c\tau < 1.6$  cm and the  $\tilde{\chi}_1^\pm$  will not even pass through the innermost layer unless it has a very large  $\beta$ . However,  $p_\pi > 180$  MeV and the impact parameter resolution for the single emitted pion moves into the  $< 150 \mu\text{m}$  range. For example, if  $\Delta m_{\tilde{\chi}_1} = 240, 300, 500, 1000$  MeV,  $c\tau \sim 1.2, 0.37, 0.09, 0.007$  cm while  $p_\pi \sim 195, 265, 480, 990$  MeV yields  $1\sigma$  impact parameter resolutions of  $\sim 120, 90, 50, 25 \mu\text{m}$ . For  $\Delta m_{\tilde{\chi}_1} < 1$  GeV, we have  $c\tau/b_{\text{res}} > 3$ . We think it is possible that an event defined by an appropriate trigger and the presence of one or more high- $b$  charged pions would be quite distinctive. It seems probable that directly triggering on  $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$  production using just these vertex detector tracks would be highly problematical. However, for  $m_\pi < \Delta m_{\tilde{\chi}_1} < 1$  GeV,  $e^+e^- \rightarrow \gamma \tilde{\chi}_1^+ \tilde{\chi}_1^-$  would produce an event with an energetic photon and substantial missing energy in association with either heavily-ionizing vertex detector tracks or charged pions with clearly nonzero impact parameter. We are hopeful that such events would prove to be essentially background free. As long as efficiencies for singling out such events are not very small (a detailed study is required), rates at the NLC would be adequate for discovery for  $m_{\tilde{\chi}_1^\pm}$  up to near  $\sqrt{s}/2$ . In fact,

<sup>2</sup>The vertex detector for the Next Linear Collider (NLC) could be built with similar characteristics. For example, Ref. [3] discusses a 3–5 layer charge-coupled device vertex detector beginning no further out than 2 cm. Calculated backgrounds at 2 cm are described as “sufficiently low for efficient vertexing,” but do depend upon details of the interaction region design. Apparently [4], a layer close to  $r=1$  cm is being studied. The SLD vertex detector has an innermost layer at  $r=2.5$  cm. However, the innermost layers of the vertex detectors at LEP are at 6.3 cm. Thus, the LEP detectors have less ability to see direct evidence for a short heavily-ionizing track for the  $c\tau$  range being considered. But their impact parameter resolution for single tracks is still very good.

$\gamma\tilde{\chi}_1^+\tilde{\chi}_1^-$  events with nonzero impact parameter tracks will be present even for  $\Delta m_{\tilde{\chi}_1}$  somewhat larger than 1 GeV, coming from  $\tilde{\chi}_1^\pm$  decays on the large  $c\tau$  tail of the decay distribution. Although the probability for this declines with increasing  $\Delta m_{\tilde{\chi}_1}$ , significant discovery reach (although presumably not all the way up to  $\sqrt{s}/2$ ) will result. Indeed, at the CERN  $e^+e^-$  collider LEP2, DELPHI [6] is able to exclude  $m_{\tilde{\chi}_1^\pm} < 60$  GeV (the result for large sneutrino mass) for  $\Delta m_{\tilde{\chi}_1}$  as large as 3 GeV, based on a search for  $\gamma\tilde{\chi}_1^+\tilde{\chi}_1^-$  events with one or more soft tracks even before requiring high impact parameter.

(c) For  $\Delta m_{\tilde{\chi}_1}$  above 1 GeV, there is little change relative to our previous results. The  $\tilde{\chi}_1^\pm \rightarrow l\nu\tilde{\chi}_1^0$  branching ratio is typically  $>10\%$  for  $l=e$  or  $\mu$ , with the remainder of the  $\tilde{\chi}_1^\pm$  decays being into soft multiple pion states or jets, and  $c\tau$  is such that the  $\tilde{\chi}_1^\pm$  decay would be fairly prompt. It is then possible that there is an interval of  $\Delta m_{\tilde{\chi}_1}$  in which the  $\tilde{\chi}_1^\pm$  decay is too prompt for high-impact-parameter tracks to be seen, and yet  $\Delta m_{\tilde{\chi}_1}$  is so small that the decay produces (hadrons or  $l\nu$ ) produced along with the  $\tilde{\chi}_1^0$  would be too soft to be distinctively visible in the main part of the detector. If such an interval exists, one will have to detect  $e^+e^- \rightarrow \gamma\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \gamma + \mathbf{E}_T$  as an excess relative to the large  $e^+e^- \rightarrow \gamma Z^* \rightarrow \gamma\nu\bar{\nu}$  background. The resulting limits on the  $m_{\tilde{\chi}_1^\pm}$  values for which the  $\gamma\tilde{\chi}_1^+\tilde{\chi}_1^-$  signal can be detected are those given in the original version of the paper: LEP2 would not be able to improve the LEP1  $Z$ -pole limits on  $m_{\tilde{\chi}_1^\pm}$  ( $m_{\tilde{\chi}_1^\pm} < 45$  GeV) but the NLC (with  $L=50$  fb $^{-1}$ ) could probe up to  $m_{\tilde{\chi}_1^\pm} \sim 200$  GeV. A detailed simulation is required to determine exactly how large  $\Delta m_{\tilde{\chi}_1}$  needs to be in order for the soft  $l$ 's or hadrons to be sufficiently energetic to be detected and direct  $\tilde{\chi}_1^+\tilde{\chi}_1^-$  production events identified. In particular, the boost from the  $\tilde{\chi}_1^\pm$  rest frame is determined by both the machine energy and the chargino mass in question. The strength of the magnetic field is also important. Studies by the DELPHI group at LEP [6] have shown that for  $\Delta m_{\tilde{\chi}_1} > 3$  GeV they can pick out the soft leptons with sufficient efficiency to exclude  $m_{\tilde{\chi}_1^\pm} < 90$  GeV. Combined with the DELPHI result under (b), we see that, for the DELPHI detector, there is no interval in  $\Delta m_{\tilde{\chi}_1}$  for which it is both impossible to see the soft  $l$ 's or hadrons in  $\tilde{\chi}_1^+\tilde{\chi}_1^-$  events and also impossible to detect high-impact-parameter single pion tracks from delayed  $\tilde{\chi}_1^\pm$  decays in  $\gamma\tilde{\chi}_1^+\tilde{\chi}_1^-$  events. Hopefully, the NLC detectors will also have no interval in  $\Delta m_{\tilde{\chi}_1}$  where the only signal is  $\gamma + \mathbf{E}_T$ .

We now give a corresponding summary for a hadron collider.

(a) Long-lived heavily ionizing tracks from  $\tilde{\chi}_1^\pm$ 's produced in SUSY pair production events will only be present for  $\Delta m_{\tilde{\chi}_1} < m_\pi$ . For such  $\Delta m_{\tilde{\chi}_1}$  values, events containing a  $\tilde{\chi}_1^\pm$  will be essentially background free, and high SUSY mass scales can be probed using (for example)  $\tilde{g}\tilde{g}$  events in which  $\tilde{g} \rightarrow q'\bar{q}\tilde{\chi}_1^\pm$ . (Note that if the momentum of the long-lived  $\tilde{\chi}_1^\pm$  is correctly measured, such events could be reconstructed in such a way that there is no missing energy associated with the  $\tilde{\chi}_1^\pm$  decay.)

(b) For  $m_\pi < \Delta m_{\tilde{\chi}_1} \leq 1$  GeV or so, the background to jets + missing energy events in which gluinos (and squarks) decay to one or more  $\tilde{\chi}_1^\pm$  might be largely eliminated assuming that the short heavily-ionizing tracks or the pions with nonzero impact parameter coming from the  $\tilde{\chi}_1^\pm$ 's can be detected in the vertex detector. The backgrounds that remain after the usual jet and missing energy cuts and that are due to multiple scattering in the silicon (causing low- $b$  pions to apparently have larger  $b$ ), charged kaon (delayed) decays, and the like, would have to be carefully studied before a definitive conclusion can be reached. However, as stated in the original paper, the standard tri-lepton signal from  $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$  production (that arises when  $\tilde{\chi}_1^\pm \rightarrow l^\pm\nu\tilde{\chi}_1^0$  and  $\tilde{\chi}_2^0 \rightarrow l^+l^-\tilde{\chi}_1^0$ ) and the like-sign di-lepton signal for  $\tilde{g}\tilde{g}$  production (arising when both  $\tilde{g}$ 's decay via  $\tilde{g} \rightarrow q'\bar{q}\tilde{\chi}_1^\pm$  followed by  $\tilde{\chi}_1^\pm \rightarrow l^+\nu\tilde{\chi}_1^0$ , or the charge conjugate) will both be essentially unobservable because of the softness of the  $l$ 's produced in  $\tilde{\chi}_1^\pm \rightarrow l\nu\tilde{\chi}_1^0$  decays.<sup>3</sup>

(c) If there is an interval of  $\Delta m_{\tilde{\chi}_1}$  such that the  $\tilde{\chi}_1^\pm$  decay is effectively prompt but  $\Delta m_{\tilde{\chi}_1}$  is still too small for the  $\tilde{\chi}_1^\pm$  decay products to be clearly separable (using the main tracker and calorimeters of the detector) from soft debris produced during a typical collision, the associated discussion of the original paper remains unchanged. The only mode yielding a viable signal for  $\tilde{g}\tilde{g}$  production (for example) would be jets + missing energy, and for parameters such that  $m_{\tilde{g}}$  is near  $m_{\tilde{\chi}_1^\pm}$  the discovery reach at the Tevatron is substantially reduced compared to mSUGRA boundary conditions. A very careful study by the experimental groups will be required to determine whether or not such an interval in  $\Delta m_{\tilde{\chi}_1}$  exists.

We thank James Wells for bringing the problem in our original calculation to our attention.

<sup>3</sup>Also, for a B-inolike  $\tilde{\chi}_2^0$ , the production rate for  $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$  is suppressed.

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