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Chargino mass determination at a muon collider

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We analyze the prospects at a muon collider for measuring chargino masses in the $\mu^+\mu^-\to\tilde{\chi}^+\tilde{\chi}^-$ process in the threshold region. We find that for a gaugino-like chargino of mass 100–200 GeV, a measurement better than 50–300 MeV should be possible with 50 fb^{-1} integrated luminosity. The accuracy obtained here is better than with other techniques or at other facilities. The muon sneutrino mass, which enters through the $\tilde{\nu}_\mu$ exchange diagram, can also be simultaneously measured to a few GeV if it is not too heavy.
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I. INTRODUCTION

Particle masses can be measured to high precisions through threshold production cross sections at lepton colliders. This has been demonstrated at the CERN e^+e^- collider LEP II in W pair production at $\sqrt{s}=161$ GeV, just above $2M_W$. We have recently shown that future high-luminosity e^+e^- and $\mu^+\mu^-$ colliders can measure the W boson, top quark and Higgs boson masses at high precisions in the processes $l^+l^-\to W^+W^-, t\bar{t}, ZH$ [1,2]. Initial state radiation from muons is reduced compared to electrons, and muon colliders have negligible beamstrahlung which increasingly becomes a problem at linear electron colliders as the energy increases. Muon colliders thus could be very useful in precision measurements of particle masses, widths, and couplings [3–7].

In this Rapid Communication we study the achievable accuracy in measuring the mass of the lighter chargino in the minimal supersymmetric standard model (MSSM) via the cross section via

$$\mu^+\mu^-\to\chi^+\chi^- \tag{1}$$

near the threshold. We focus our attention on a chargino state that is dominantly gaugino for simplicity, since the threshold cross-section then depends mainly on just two parameters, the chargino mass ($m_{\tilde{\chi}^+}$) and the sneutrino mass ($m_{\tilde{\nu}}$). The minimal supergravity (MSUGRA) model predicts a lightest chargino that is gaugino-like. Our analysis is somewhat more general than MSUGRA in that we allow $m_{\tilde{\nu}}$ as a free parameter, rather than have it constrained by universal mass scale inputs at the grand unified scale. Our parameter choices permit us to make direct comparisons with previous e^+e^- studies.

The measurement of the chargino mass via the threshold cross section has been considered previously for e^+e^- machines in Refs. [8,9]. The narrower energy spread and the negligible beamstrahlung a muon collider offer a distinct advantage over most electron-positron designs. We assume in this Rapid Communication that the muon collider has a relatively modest (rms) beam energy spread of $R=0.1\%$. We consider a measurement with high integrated luminosity (50 fb^{-1}), carefully taking into account beam smearing effects and optimization of cuts to eliminate the background in the threshold region.

A precision measurement of the chargino mass is a highly desirable goal to test patterns of supersymmetry breaking. For example the relationship between the lightest neutralino and the lighter chargino masses can be used to test the existence of a universal soft supersymmetry- (SUSY)-breaking parameter. Renormalization group evolution (RGE) from the grand unification scale leads to the approximate prediction $m_{\tilde{\chi}^\pm}\simeq m_{\tilde{\chi}_2^0}\simeq 2m_{\tilde{\chi}_1^0}$ [10]. The predictions for chargino pair production have recently been investigated beyond the tree-level [11]. A precision measurement of the cross section can test radiative corrections coming from heavy squarks, since the corrections depend on $\log(M_{\tilde{Q}}/m_{\tilde{l}})$.

The cross section of the chargino pair production depends not only on $m_{\tilde{\chi}^\pm}$ but also on the mass of the muon sneutrino ($m_{\tilde{\nu}}$) which enters through a t-channel diagram. As we show in Sec. II, a simultaneous measurement of both $m_{\tilde{\chi}^\pm}$ and $m_{\tilde{\nu}}$ is possible if the chargino is gaugino-like. In Sec. III, we compare our results with that achievable at an e^+e^- linear collider and with the kinematical end-point technique. We also comment on the benefits of polarized muon beams in studying the chargino mass and properties.

II. ACHIEVABLE ACCURACY IN $m_{\tilde{\chi}^\pm}$

At the present we do not know the supersymmetry breaking parameters that determine the masses and couplings of the supersymmetric particles. Presumably the CERN Large Hadron Collider (LHC) will have been operating for several years before a muon collider is functioning, and will be able to measure parameters well enough to tell us whether the

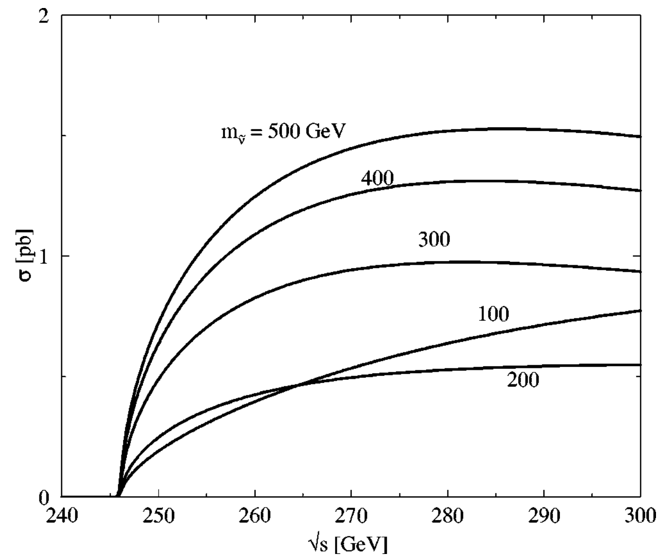

FIG. 1. The cross section for $\mu^+\mu^-\to\tilde{\chi}^+\tilde{\chi}^-$ in the threshold region for various sneutrino masses, with the parameters in Eq. (3). The sneutrino mass dependence arises from a *t*-channel contribution which interferes destructively with the *s*-channel diagrams. The muon collider is assumed to have a beam energy spread of $R=0.1\%$, and initial state radiation is included.

lightest charginos and neutralinos are gaugino-dominated, Higgsino-dominated, or in a more complicated mixed state. If the lighter chargino is gaugino-dominated as expected on theoretical grounds [12,13], then changing the parameters of the chargino mass matrix essentially changes the mass but does not significantly change its couplings. The chargino mass matrix is

$$M_C=\begin{pmatrix} M_2 & \sqrt{2}M_W\sin\beta \\ \sqrt{2}M_W\cos\beta & -\mu \end{pmatrix}, \tag{2}$$

and in supergravity models the diagonal terms are expected to be larger than the off-diagonal ones. As a typical illustration, we choose the representative MSSM parameters

$$M_2=120\ \text{GeV},\quad \mu=400\ \text{GeV},\quad \tan\beta=4, \tag{3}$$

where M_2 is the gaugino mass parameter, μ the Higgs mixing and $\tan\beta=v_2/v_1$ the ratio of the vacuum expectation values (VEVs) of the two Higgs doublets in the MSSM. The choice of Eq. (3) is motivated by the ''gaugino point'' of Ref. [14], so that the lighter chargino is gaugino-like ($M_2<|\mu|$). This choice corresponds to $m_{\tilde{\chi}^\pm}=123$ GeV.

For the chargino pair production under discussion, the cross section is insensitive to $\tan\beta$ and μ if $\mu\gtrsim 300$ GeV. However, the sneutrino contribution in the *t*-channel interferes destructively with the *s*-channel graphs. Therefore one can envision a measurement of the cross section that essentially depends on just two parameters, $m_{\tilde{\chi}^\pm}$ and $m_{\tilde{\nu}}$. Figure 1 illustrates the total cross sections versus the center-of-mass energy near threshold for various values of sneutrino mass, with other parameters as in Eq. (3). The rapid rise of the cross section near threshold is due to the *S*-wave pair production of spin-1/2 particles with small decay widths. The cross section is typically of order 1 pb. Thus a large signal sample of order 5×10^4 chargino events would be obtained with the assumed collider luminosity.

A simultaneous measurement of the chargino and sneutrino masses requires a sampling of the cross section of at least two points. As in other threshold measurements, the statistical precision on the chargino mass is maximized at c.m. energy $\sqrt{s}$ just above $2m_{\tilde{\chi}^\pm}$. However as is evident from Fig. 1, a change in the cross section at $\sqrt{s}=2m_{\tilde{\chi}^\pm}+1$ GeV can also be due to a variation in the sneutrino mass, so a second measurement of the cross section must be made at a higher $\sqrt{s}$ where the dependence of the cross section on the chargino mass and the slepton mass is different. It turns out to be advantageous for the chargino mass measurement to choose this higher energy measurement at a $\sqrt{s}$ point where the chargino cross section is not flat. The precision that can be obtained in the chargino mass depends substantially on the chargino mass itself since the cross-section decreases with an increasing $m_{\tilde{\chi}^\pm}$. The heavier the chargino is, the less accurate the measurement for a given luminosity. A rough determination of the chargino mass to about 1 GeV is necessary prior to the measurement of the threshold cross section. With 50 fb^{-1} of luminosity devoted to the standard above-threshold study, this should be easily achievable [14], and the scan points discussed above can be set.

The chargino decay mode is $\tilde{\chi}^\pm\to\tilde{\chi}^0 f\overline{f'}$, resulting in a large amount of missing energy due to $\tilde{\chi}^0$ in the final state, which is stable in the MSSM and thus escapes the detector. If $m_{\tilde{\chi}^\pm}-m_{\tilde{\chi}^0}>M_W$ then real *W* contributions (two-body decay) dominate and the $\chi^+\chi^-$ final state is comprised of 49% purely hadronic events, 42% mixed hadronic-leptonic events, and 9% purely leptonic events (these ratios are determined by the *W* branching fractions). The above estimate of the branching fractions is a very good approximation as long as the sleptons and squarks are sufficiently heavy ($m_{\tilde{l}},m_{\tilde{q}}\gtrsim 300$ GeV), whether or not the bosons from the decays are on-shell. We do not limit our study in this Rapid Communication to the chargino decays to on-shell *W*, and we use PYTHIA to determine the branching fractions. In the event that sleptons and squarks should be lighter than this, they may also be pair produced and there would be additional knowledge about the chargino decays that could be exploited in a similar analysis. To effectively suppress the backgrounds, we concentrate on the pure hadronic channel. The width of the chargino, typically less than a few MeV, has a negligible impact on the threshold cross section even for the two-body decay case, provided that the lighter chargino is gaugino-dominated. Based on the cross sections given in Fig. 1 and including the decay branching ratios and signal efficiencies, the signal rate at $\sqrt{s}=2m_{\tilde{\chi}^\pm}+1$ GeV would be about 20 fb for most values of the sneutrino mass. With 50 fb^{-1} integrated luminosity, the cross section could be measured to a statistical accuracy of about 3%. Thus an understanding of the background to at least this level is necessary.

There are several backgrounds to the chargino pair signal, by far the largest being $\mu^+\mu^-\to W^+W^-$. The backgrounds have been studied in Refs. [15,16], and signal efficiencies

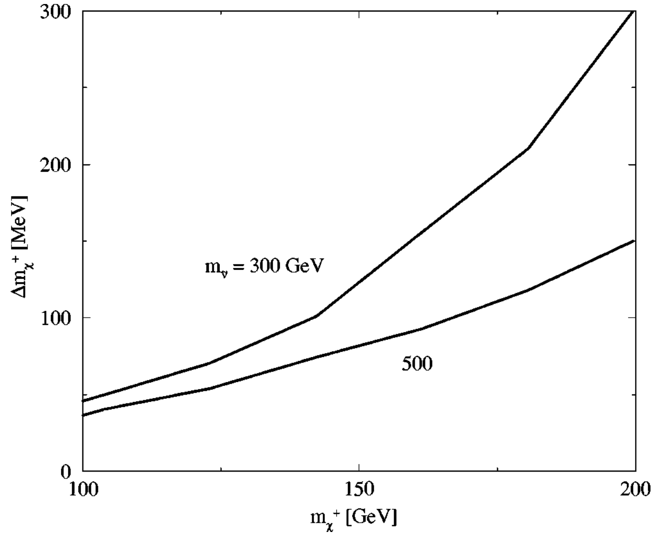

FIG. 2. The 1σ precision obtainable in the chargino mass taking $m_{\tilde{\nu}}=300$ and 500 GeV assuming 50 fb^{-1} integrated luminosity. The precision on $m_{\tilde{\chi}^\pm}$ is better for *larger* sneutrino mass (see Fig. 1).

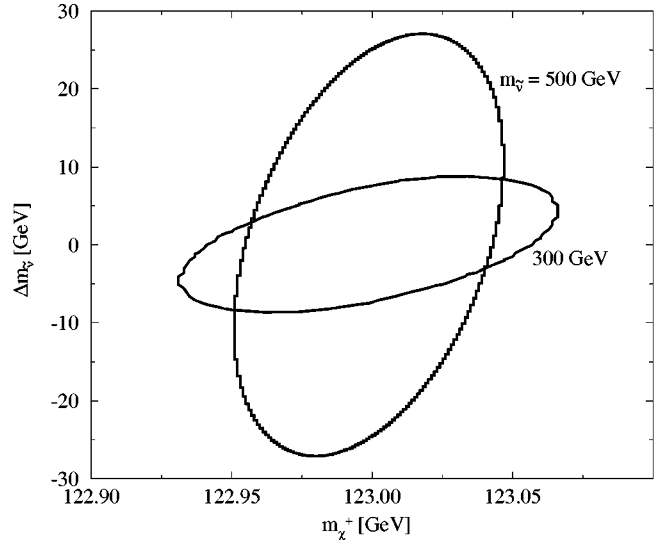

FIG. 3. The $\Delta\chi^2=1$ contours in the chargino mass-sneutrino mass plane, taking the parameters in Eq. (3) and $m_{\tilde{\nu}}=300$ and 500 GeV. The curves assume 25 fb^{-1} of integrated luminosity is devoted to $\sqrt{s}=2m_{\tilde{\chi}^\pm}+1$ GeV, and 25 fb^{-1} is applied at $\sqrt{s}=2m_{\tilde{\chi}^\pm}+20$ GeV.

were obtained for the various final states when the center-of-mass energy is $\sqrt{s}=500$ GeV. The dominant W^+W^- background can be effectively eliminated by angular cuts because the W's are produced in the very-forward direction. However, if the energy is reduced for running in the chargino threshold region, then the effectiveness of the angular cuts would be reduced since the background events become more spherical. Therefore we reinvestigate the acceptance criteria near the threshold.

Based on the characteristic kinematics of the signal, we impose the following cuts to remove the backgrounds, mainly from $W^+W^-\to 4$ jets:

A cut on missing mass, roughly $2M_{\tilde{\chi}_0}<M(\text{miss})<2M_{\tilde{\chi}_0}+20$ GeV.

Require $\cos(\theta_{\text{W-miss}})>-0.8$ where $\cos(\theta_{\text{W-miss}})$ is the minimum cosine of the angle between the reconstructed faster W^*[1] and the missing momentum.

Require the reconstructed W^* to be in the central region: $|\cos(\theta_W)|<0.7$.

These cuts greatly reduce the WW background to a negligible level. The overall signal efficiency with these cuts is about 10% for the fully hadronic decays. If we know, *a priori*, that $m_{\chi^\pm}-m_{\chi^0}<M_W$, then we can further reject the W^+W^- background by demanding the reconstructed W^* from the di-jet to have $m_{jj}<M_W$.

For the case where the W^* coming from the chargino decay is virtual, the identification of the jets is a relevant concern. A clustering algorithm such as the Durham jet algorithm takes clusters that satisfy some minimum distance measure and merges the clusters into one. For the Durham algorithm the measure is defined as

$$y_{ij}=\frac{2\min(E_i^2,E_j^2)(1-\cos\theta_{ij})}{E_{vis}^2}, \tag{4}$$

for clusters with energy E_i and E_j. By choosing a sufficiently large cutoff for y_{ij} one can force the event in two jets and thereby obtain an efficient reconstruction of virtual W bosons in both the signal and the background [17].

Figure 2 shows the expected precision of $m_{\tilde{\chi}^\pm}$ from fully hadronic decays with 50 fb^{-1} integrated luminosity and a sneutrino mass of 300 and 500 GeV. For a lighter sneutrino, for which the destructive interference between the s-channel and t-channel graphs is more severe, the precision of $m_{\tilde{\chi}^\pm}$ is less. In the range of $m_{\tilde{\chi}^\pm}=100$–200 GeV, a measurement better than 50–300 MeV is possible, much below the 1% level. The precision decreases with increasing chargino mass since the production cross section decreases.

The result of a fit to the chargino event rate is shown in Fig. 3, taking the parameters in Eq. (3) and assuming an integrated luminosity of 50 fb^{-1}. The cross section is measured just above the threshold $\sqrt{s}=2m_{\tilde{\chi}^\pm}+1$ GeV, and at a point well above the threshold, $\sqrt{s}=2m_{\tilde{\chi}^\pm}+20$ GeV (with 25 fb^{-1} at each measurement). The chargino mass determination is better for higher sneutrino mass. The cross section is more sensitive to $m_{\tilde{\nu}}$ when it is lighter, resulting in a better measurement of the sneutrino mass. The sneutrino mass can be measured to about 6 GeV accuracy for $m_{\tilde{\nu}}=300$ GeV and to about 20 GeV accuracy for $m_{\tilde{\nu}}=500$ GeV. This provides an indirect method of measuring the sneutrino mass [14], which would be especially valuable when the threshold for sneutrino pair production is not open.

[1]Here W^* generically denotes a W boson of on- or off-mass shell. For a signal with off-mass shell W from the chargino decay, the WW background, is even less severe.

III. DISCUSSIONS

Comparing our results with similar studies for e^+e^- colliders, we find that the beam energy spread can cause a significant reduction in the precision of the threshold measurement. The most recent Cornell TeV Energy Superconducting Linear Collider (TESLA) design envisions an electron beam energy spread of $R=0.2\%$ [18] while the Next Linear e^+e^- Collider (NLC) design anticipates a beam energy spread of $R=1.0\%$. The NLC will be able to achieve precisions which are from 15% to 90% worse (for $m_{\tilde{\chi}^\pm}$ from 100 GeV to 200 GeV) than for the muon collider considered here, while the TESLA design should achieve precisions less than 10% worse than the muon collider. A high energy e^+e^- collider in a very large hadron collider (VLHC) tunnel would have a beam spread of $\sigma_E=0.26$ GeV [19] and would obtain results with a precision comparable to those considered here.

The mass of the chargino can also be measured by finding the endpoint in the spectrum (or by fitting to the full spectrum) of the chargino decay products [9,15,20–22]. The endpoint is determined strictly by the kinematics of the decay $\tilde{\chi}^\pm \to \tilde{\chi}^0 f \overline{f'}$, so it is sensitive to both the chargino and neutralino masses. However the expected precision of the end point method with 50 fb^{-1} of integrated luminosity is 1% or larger [15], larger than the precision obtained from measuring the threshold cross section. For the threshold measurement, the cross section for chargino pair production is independent of the final state decays, and only the branching fractions and detector efficiencies for the various final states impact this measurement. This approach is complementary to using kinematic end-points of chargino decays to determine the chargino mass. Our considerations are based on a large μ-value, $|\mu|>7M_2$, as usually found in MSUGRA and gauge-mediated symmetry breaking models. In this case the $\chi_2^0\chi_2^0$ cross section is negligible compared to the $\chi_1^+\chi_1^-$ cross section for $m_{\tilde{\mu}} \gtrsim 300$ GeV. χ_1^+ is Higgsino-like and the cross sections become sensitive to the value of $|\mu|$. Secondly, $\chi_2^0\chi_2^0$ production may have a comparable cross section to $\chi^+\chi^-$ and the final-state kinematics need to be taken into account to separate the $\chi_1^+\chi_1^-$ and $\chi_2^0\chi_2^0$ contributions.

We have assumed here that the chargino is lighter than the muon sneutrino, as is normally the case in MSUGRA models [12,13]. If that is not so, the chargino has a new decay mode: $\tilde{\chi}^\pm \to l^\pm \tilde{\nu}$. The signal efficiency of the cuts against background would need to be reconsidered if this mode is kinematically allowed.

It is expected that the both beams of a muon collider can be partially polarized, although with some loss of luminosity for high polarization [7]. Polarization could prove a useful tool for studying the chargino pair production. When the chargino is gaugino-dominated, it couples to the left-handed μ^- because it is then dominantly the partner to the W. Should the chargino be Higgsino-dominated, one would want to employ right-handed μ^- polarization since the W^+W^- background would then be largely reduced. In addition, the t-channel sneutrino exchange contribution can be turned off by operating with a right-handed polarized μ^- beam.

For the gaugino-dominated chargino considered here, both the signal and background are approximately proportional to $(1-P)^2$ where $P\equiv P_{\mu^-}=-P_{\mu^+}$ is the polarization of the two muon beams ($P=-1$ for a pure left-handed μ^- or a right-handed μ^+). The background (W pairs) and the t-channel sneutrino signal contribution couple to the left-handed μ^- (and right-handed μ^+) beam. In the limit of $SU(2)\times U(1)$ symmetry, the $U(1)$ gauge boson couples only to the Higgsino component of the lighter chargino [14,23]. So the s-channel graph also couples predominantly to the left-handed μ^- when the lighter chargino is gaugino-like as considered here. Thus for 100% polarized μ^+ and μ^- beams the mass determination would improve by a factor of 2 assuming the same integrated luminosity.

We have assumed in this study that the chargino cross section is theoretically known, apart from the contribution from the t-channel diagram from a sneutrino of unknown mass, which may require that one-loop corrections be taken into account. One can relax this assumption and allow the cross section normalization to be another free parameter. Then at least three measurements for the cross section would be required to extract the two masses ($m_{\tilde{\chi}^\pm}, m_{\tilde{\nu}}$) and the cross section normalization. This would test the theoretical prediction for radiative corrections from which the mass scale of squarks might be inferred [11]. On the other hand, if the sneutrino is discovered independently and its mass reasonably well measured, one could carry out the two-point measurement, as presented this Rapid Communication, to determine $m_{\tilde{\chi}^\pm}$ and the cross section normalization.

IV. CONCLUSIONS

We studied the pair production of a gaugino-like chargino at a muon collider. A measurement of the lighter chargino mass to better than 50–300 MeV is possible for $m_{\tilde{\chi}^\pm} =100$–200 GeV by measuring the pair production cross section near the threshold at a muon collider with 50 fb^{-1} luminosity. We demonstrated that for gaugino-like charginos this is superior to the kinematical end-point method and to results obtainable with the same integrated luminosity at other colliders. Only modest beam energy resolution ($R \sim 0.1\%$) is needed for the threshold measurements. The muon sneutrino mass can also be simultaneously measured to a few GeV if it is not too heavy.

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