Production of Charginos, Neutralinos, and Sleptons at Hadron Colliders

W. Beenakker,[1] M. Klasen,[2] M. Krämer,[3] T. Plehn,[4] M. Spira,[5] and P. M. Zerwas[6]
[1]*Department of Physics, University of Durham, Durham DH1 3LE, United Kingdom*
[2]*Argonne National Laboratory, Argonne, Illinois 60439*
[3]*Theoretical Physics Division, CERN, CH-1211 Geneva 23, Switzerland*
[4]*Department of Physics, University of Wisconsin, Madison, Wisconsin 53706*
[5]*II. Institut für Theoretische Physik, Universität Hamburg, D-22603 Hamburg, Germany*
[6]*Deutsches Elektronen–Synchrotron DESY, D-22603 Hamburg, Germany*
(Received 14 June 1999)

We analyze the production of charginos, neutralinos, and sleptons at the hadron colliders Tevatron and LHC in the direct channels $p\overline{p}/pp \to \tilde{\chi}_i\tilde{\chi}_j + X$ and $\tilde{\ell}\bar{\tilde{\ell}}' + X$. The cross sections for these reactions are given in next-to-leading order supersymmetric QCD. By including the higher-order corrections, the predictions become theoretically stable, being nearly independent of the factorization and renormalization scales. Since the corrections increase the cross sections, the discovery range for these particles is extended in the refined analysis.

PACS numbers: 14.80.Ly, 12.38.Bx, 12.60.Jv, 13.85.Qk

Noncolored supersymmetric particles, i.e., charginos, neutralinos, and sleptons, can be searched for at the hadron colliders Tevatron and Cern Large Hadron Collider (LHC) in cascade decays of squarks/gluinos and in the direct production channels [1]

$$p\overline{p}/pp \to \tilde{\chi}_i\tilde{\chi}_j + X \quad \text{and} \quad p\overline{p}/pp \to \tilde{\ell}\overline{\tilde{\ell}}' + X \,. \tag{1}$$

In the minimal supersymmetric extension of the standard model (MSSM) the two charginos $\tilde{\chi}^{\pm}_{1,2}$ are mixtures of charged winos and higgsinos, while the four neutralinos $\tilde{\chi}^0_1, \ldots, \tilde{\chi}^0_4$ are mixtures of the neutral wino, the bino, and the two neutral higgsinos [2]. The scalar partners of the chiral lepton states are denoted by $\tilde{\ell}, \tilde{\ell}' = \tilde{\ell}^-_{L,R}, \tilde{\nu}_L$.

In order to exploit the full potential of these colliders, a proper understanding of the hadroproduction mechanisms of supersymmetric particles is mandatory. On the theoretical side this demands the control of higher-order SUSY-QCD corrections. They reduce the (artificial) dependence of the cross sections on the renormalization and factorization scales in leading order and refine the numerical accuracy of the theoretical predictions. This program has been carried out for the colored gluinos and squarks [3,4], including a special analysis for top squarks [5]. The associated production of gluinos with charginos/neutralinos has been addressed recently [6]. QCD corrections to the Drell-Yan production of slepton pairs have been analyzed in Ref. [7]. In this Letter, we present the complete SUSY-QCD analyses for the production of all possible pairs of noncolored supersymmetric particles.

1. In many models, the noncolored charginos, neutralinos, and sleptons belong to the class of the lightest supersymmetric particles. The low masses (partly) counterbalance the small cross sections for direct production. Moreover, the classical reaction $p\overline{p}/pp \to \tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$ with subsequent decays $\tilde{\chi}^{\pm}_1 \to \tilde{\chi}^0_1\ell^{\pm}\overset{(-)}{\nu_\ell}$ and $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\ell^+\ell^-$ leads to gold-plated $\ell^{\pm}\ell^+\ell^-$ trilepton signatures [8]. Such trilepton signatures have been exploited in several CDF and D0 analyses at the Tevatron [9], leading to bounds in the MSSM parameter space that are similar to those from LEP2. Increasing energies and luminosities will significantly extend the range of sensitivity in the near future; see, e.g., Refs. [10,11].

The basic diagrams for the production of pairs of charginos and neutralinos are depicted in Fig. 1(a) at the parton level. The vector bosons ($V = \gamma/Z/W$) in the s-channel couple to the gaugino and higgsino components of the charginos and neutralinos, whereas the u/t-channel squark diagrams, in the limit where the light-quark masses are neglected, involve only gaugino components. The mixing matrices $U[\tilde{\chi}^-], V[\tilde{\chi}^+]$, and $N[\tilde{\chi}^0]$ are defined such that the chargino and neutralino masses are real and positive [2,12]. After Fierz transformations of the squark-exchange amplitudes, the transition matrix element can be expressed in terms of four bilinear charges $Q_{\alpha\beta}$ [13], coefficients of the associated quark and gaugino currents carrying chiralities $\alpha, \beta = L, R$. For example, the partonic process $q\bar{q}' \to \tilde{\chi}^+_i\tilde{\chi}^0_j$, upon

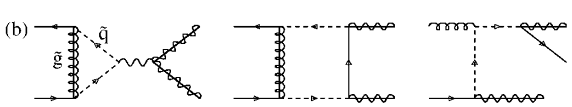

FIG. 1. Basic diagrams for the production of chargino/neutralino pairs at hadron colliders in quark-antiquark collisions; (b) generic diagrams of SUSY-QCD corrections, comprising vertices, box diagrams, and diagrams for three-parton final states.

0031-9007/99/83(19)/3780(4)$15.00 © 1999 The American Physical Society

neglecting generational mixing in the quark and squark sectors, is described by the bilinear charges:

$$
\begin{aligned}
Q_{LL} &= \frac{1}{\sqrt{2}s_W^2}\left[\frac{N_{j2}^*V_{i1} - N_{j4}^*V_{i2}/\sqrt{2}}{s - M_W^2} + \frac{V_{i1}}{c_W}\frac{N_{j1}^*(e_{\tilde{q}} - I_{3\tilde{q}})s_W + N_{j2}^*I_{3\tilde{q}}c_W}{u - m_{\tilde{q}}^2}\right] \\
Q_{LR} &= \frac{1}{\sqrt{2}s_W^2}\left[\frac{N_{j2}U_{i1}^* + N_{j3}U_{i2}^*/\sqrt{2}}{s - M_W^2} + \frac{U_{i1}^*}{c_W}\frac{N_{j1}^*(e_{\tilde{q}'} - I_{3\tilde{q}'})s_W + N_{j2}I_{3\tilde{q}'}c_W}{t - m_{\tilde{q}'}^2}\right] \\
Q_{RL} &= Q_{RR} = 0\,,
\end{aligned}
\tag{2}
$$

with $s = (p_q + p_{\overline{q}'})^2$, $t = (p_q - p_{\tilde{\chi}_i})^2$, and $u = (p_q - p_{\tilde{\chi}_j})^2$. The electric charges and third isospin components of the exchanged squarks are denoted by $e_{\tilde{q}}$ and $I_{3\tilde{q}}$, respectively. Furthermore, we define the cosine c_W and the sine s_W of the weak mixing angle by $s_W^2 = 1 - M_W^2/M_Z^2$. The generic form of the leading-order partonic cross section after spin and color averaging reads

$$
\begin{aligned}
\frac{d\hat{\sigma}}{dt}[q\overline{q}^{(\prime)} \to \tilde{\chi}_i\tilde{\chi}_j] = \frac{\pi\alpha^2}{3s^2}[(|Q_{LL}|^2 + |Q_{RR}|^2)u_iu_j + (|Q_{LR}|^2 + |Q_{RL}|^2)t_it_j \\
+ 2\,\mathrm{Re}(Q_{LL}^*Q_{LR} + Q_{RR}^*Q_{RL})m_{\tilde{\chi}_i}m_{\tilde{\chi}_j}s]\,,
\end{aligned}
\tag{3}
$$

with the abbreviations $t_{i,j} = t - m_{\tilde{\chi}_{i,j}}^2$ and $u_{i,j} = u - m_{\tilde{\chi}_{i,j}}^2$.

SUSY-QCD corrections involve quark/gluon and squark/gluino diagrams. Leaving aside the standard QCD diagrams, generic SUSY-QCD diagrams for qqV and $q\tilde{q}\tilde{\chi}$ vertex corrections, box diagrams, and diagrams of three-parton final states are shown in Fig. 1(b). The virtual corrections have been evaluated in the $\overline{\mathrm{MS}}$ renormalization scheme, with the $\tilde{q}$ and $\tilde{g}$ masses defined on-shell. The artificial breaking of supersymmetry by the mismatch of 2 gaugino and $(D - 2)$ transverse vector degrees of freedom in $D \neq 4$ dimensions is compensated by finite counterterms [4,14]. In this way, the supersymmetry can be restored by modifying the bare Yukawa $q\tilde{q}\tilde{\chi}$ coupling $\hat{g}$ with respect to the associated gauge coupling g: $\hat{g} = g[1 - \alpha_s/(6\pi)]$. The infrared and collinear singularities of the three-parton cross sections are extracted by applying the dipole subtraction method [15]. The virtual and real corrections are different for the s-channel and t/u-channel exchange mechanisms of the gauge bosons and squarks. This affects strongly any destructive interference effects that may be present between leading-order diagrams and may thus give rise to large K factors.

The inelastic Compton process in Fig. 1(b) evolves through a squark state, which can decay as an on-shell state into $q\tilde{\chi}$ if $m_{\tilde{q}} > m_{\tilde{\chi}}$. To avoid double counting, this resonance contribution is removed from the continuum $p\overline{p}/pp \to \tilde{\chi}\tilde{\chi}$ ensemble; it is counted naturally in the mixed $\tilde{q}\tilde{\chi}$ ensemble. The separation is technically defined by subtracting the resonance part $\sigma^{\mathrm{Res}} = \hat{\sigma}[qg \to \tilde{q}\tilde{\chi}]\,\mathrm{BR}[\tilde{q} \to \tilde{\chi}q]$ in the narrow-width approximation for the squark state [4].

The QCD corrections to the cross sections will be illustrated in the mSUGRA [2] scenario for the specific CP-conserving point [$m_{1/2} = 150$ GeV, $m_0 = 100$ GeV, $A_0 = 300$ GeV, $\mu > 0$, $\tan\beta = 4$]. The parameters $m_{1/2}$ and m_0 are the universal gaugino and scalar masses at the GUT scale, and A_0 is the universal trilinear coupling in the superpotential. From these five parameters, all the masses and couplings are determined by the evolution from the GUT scale down to the low electroweak scale [16], leading for the mSUGRA point defined above to the masses: $\tilde{\chi}_1^{\pm}/\tilde{\chi}_1^0/\tilde{\chi}_2^0 = 101/56/104$ GeV, $\tilde{q}/\tilde{g} = 359/406$ GeV, and $\mu/M_1/M_2 = 278/62/123$ GeV. In this specific example the light charginos and neutralinos are gauginolike. Chargino/neutralino masses are varied by varying $m_{1/2}$ while leaving the other parameters unchanged.

The theoretical improvement of the predictions for the chargino/neutralino cross sections is apparent from Fig. 2. The dependence on the factorization/renormalization scale Q, identified for the sake of simplicity, is clearly reduced in next-to-leading order QCD with respect to the factorization-scale dependence in leading order. (Only for channels with large destructive interferences between different exchange amplitudes is the Q dependence not reduced in NLO. However, in these cases the cross sections are very small and the

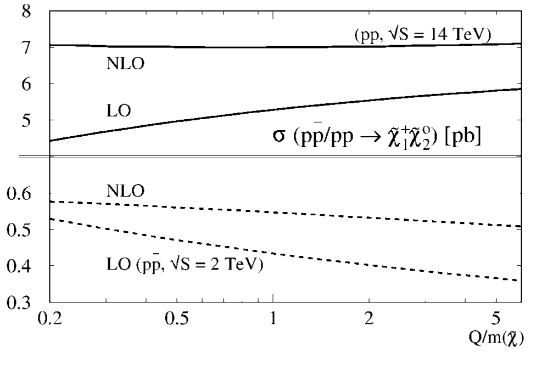

FIG. 2. Dependence of the cross sections for the production of $\tilde{\chi}_1^+\tilde{\chi}_2^0$ pairs on the factorization/renormalization scale Q in leading order and next-to-leading order SUSY QCD for the mSUGRA point defined in the text. The scale Q is given in units of the average of the $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0$ masses $m(\tilde{\chi})$.

channels cannot be explored experimentally.) The cross sections for $p\overline{p}/pp \to \tilde{\chi}_1^+\tilde{\chi}_2^0$ are nearly independent of Q. The improvement is most effective for the LHC, since the primary subprocesses in this case involve sea quarks in addition to valence quarks. The K factors of this process, Fig. 3(a), range from 1.15 to 1.30 at the Tevatron and from 1.25 to 1.35 at the LHC, the scale Q being fixed to the average final-state mass. For general chargino/neutralino final states the K factors extend up to 1.35 and 1.45 at the Tevatron and the LHC, respectively.

The size of the relevant cross sections for chargino/neutralino pair production at the Tevatron and the LHC is shown in Fig. 3(b). The cross sections for other pairs not shown explicitly in the figures are too small to be accessible experimentally. The whole set of cross sections can be obtained in Fortran code on request; they will be included in PROSPINO, which can be accessed at the address http://www.desy.de/~spira The next-to-leading order QCD corrections increase the cross sections for the production of chargino/neutralino pairs. The shift in the average of chargino and neutralino masses that can be probed at the Tevatron and the LHC is about 15 and 30 GeV, respectively. This corresponds to a significant improvement, by about 10%, of the discovery limits. Since the chargino/neutralino processes have a color flow similar to Drell-Yan processes, additional effects from higher-order soft-gluon radiation are expected to be small [18].

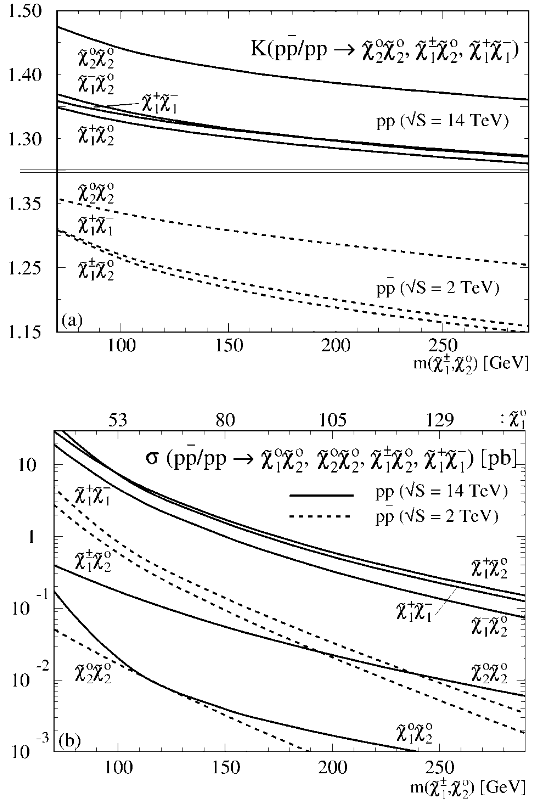

FIG. 3. (a) K factors for hadroproduction of chargino/neutralino pairs in NLO SUSY QCD, and (b) the NLO cross sections at Tevatron and LHC. The parameters are derived from the mSUGRA point defined in the text, but varying the gaugino mass $m_{1/2}$; the factorization/renormalization scale is taken at the average chargino/neutralino mass. The mass at the lower x axis is identified with the chargino/neutralino mass or the heavier of the chargino/neutralino masses in the pairs. [The $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^0$ masses nearly coincide.] Parton densities: CTEQ4L/M [17].

2. Pairs of sleptons, $\tilde{e}_L^+\tilde{e}_L^-$, $\tilde{e}_R^+\tilde{e}_R^-$, $\tilde{\nu}_L\overline{\tilde{\nu}}_L$ and $\tilde{e}_L^\pm \overset{(-)}{\tilde{\nu}}_L$ are generated in $q\overline{q}^{(\prime)}$ annihilation by s-channel vector-boson exchanges. The QCD corrections to these Drell-Yan processes have been calculated earlier in Ref. [7]. In this Letter we add the contributions of virtual squarks and gluinos, completing the analysis consistently to $\mathcal{O}(\alpha_s)$. SUSY-QCD corrections affect the qqV vertices, in analogy to the first column of diagrams in Figs. 1(a) and 1(b). Since heavy-mass SUSY particles are involved in the loops, the genuine SUSY corrections are expected to be considerably smaller than the standard QCD corrections. This is indeed borne out by detailed calculations, an example of which is presented in Fig. 4(a). The SUSY-QCD K factors differ little from the QCD K factors, which are approached in the asymptotic limit of large

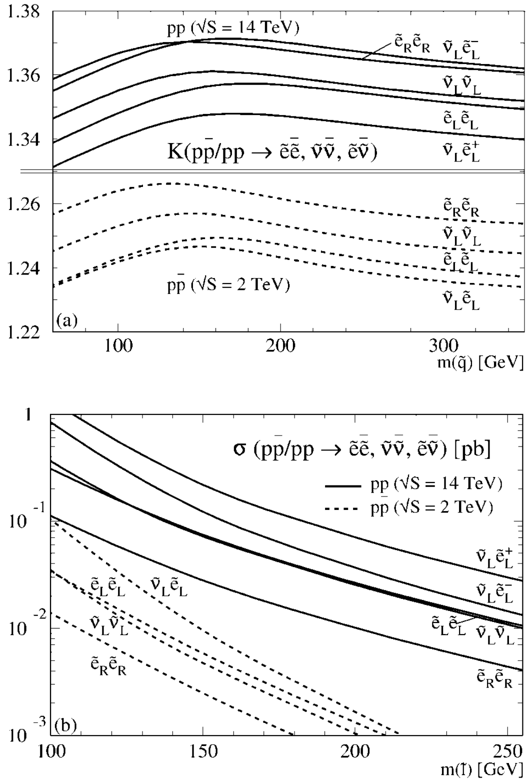

FIG. 4. (a) K factors for hadroproduction of slepton pairs in NLO SUSY QCD as a function of the squark mass $m_{\tilde{q}}$ for a gluino mass of 200 GeV and for slepton masses $\tilde{e}_R/\tilde{e}_L/\tilde{\nu}_L =$ 120/150/135 GeV. (b) The NLO cross sections at Tevatron and LHC as a function of the slepton masses [$\tilde{e}$ mass in mixed pairs] for squark/gluino masses fixed at 200 GeV. In both figures, the factorization/renormalization scale is taken at the average slepton mass. Parton densities: CTEQ4L/M [17].

$\tilde{q}/\tilde{g}$ masses at the right-hand y axis of the figure. A set of typical cross sections for the Tevatron and the LHC is presented in Fig. 4(b). The cross sections are shown as a function of the slepton masses for fixed squark/gluino masses. The QCD corrections to the production of $\tilde{\mu}$ and $\tilde{\tau}$ pairs follow the same pattern for equivalent invariant masses of the pairs.

In summary, we have determined the SUSY-QCD corrections to the cross sections for the production of chargino/neutralino and slepton pairs at the hadron colliders Tevatron and LHC consistently to $\mathcal{O}(\alpha_s)$. As a result of these refinements, the theoretical predictions are remarkably stable, being nearly independent of the renormalization/factorization scales. The SUSY-QCD corrections are positive, increasing the mass range of charginos, neutralinos, and sleptons that can be covered at these colliders by as much as 10%. This will significantly extend the area in the supersymmetric parameter space that can be probed at the Tevatron and LHC beyond the range already accessible at LEP.

We are grateful to our experimental CDF and D0 colleagues for helpful discussions on the experimental chargino/neutralino search programs during the recent Tevatron Run II Workshop at FNAL. Special thanks go to T. Kamon for a very valuable communication in this context. W. B. was supported by PPARC. M. Klasen was supported by DOE Grant No. W-31-109-ENG-38. M. Krämer was supported in part by the EU FF Programme under Contract No. FMRX-CT98-0194 (DG 12-MIHT). T. P. was supported in part by DOE Grant No. DE-FG02-95ER-40896 and in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

---

[1] V. Barger, R. W. Robinett, W. Y. Keung, and R. J. N. Phillips, Phys. Lett. **131B**, 372 (1983); S. Dawson, E. Eichten, and C. Quigg, Phys. Rev. D **31**, 1581 (1985).

[2] For reviews, see H. P. Nilles, Phys. Rep. **110**, 1 (1984); H. E. Haber and G. L. Kane, Phys. Rep. **117**, 75 (1985).

[3] W. Beenakker, R. Höpker, M. Spira, and P. M. Zerwas, Phys. Rev. Lett. **74**, 2905 (1995); Z. Phys. C **69**, 163 (1995).

[4] W. Beenakker, R. Höpker, M. Spira, and P. M. Zerwas, Nucl. Phys. **B492**, 51 (1997).

[5] W. Beenakker, M. Krämer, T. Plehn, M. Spira, and P. M. Zerwas, Nucl. Phys. **B515**, 3 (1998).

[6] M. Krämer, in *Proceedings of the Conference on Higgs and SuperSymmetry: Search & Discovery, Gainesville, Florida, 1999* (http://www.phys.ufl.edu/~rfield/higgs_susy.html); E. L. Berger, M. Klasen, and T. Tait, ANL-HEP-PR-99-03, hep-ph/9902350; W. Beenakker, M. Krämer, T. Plehn, M. Spira, and P. M. Zerwas (to be published).

[7] H. Baer, B. W. Harris, and M. Hall Reno, Phys. Rev. D **57**, 5871 (1998).

[8] H. Baer, K. Hagiwara, and X. Tata, Phys. Rev. D **35**, 1598 (1987); P. Nath and R. Arnowitt, Mod. Phys. Lett. **A2**, 331 (1987).

[9] D0 Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **76**, 2228 (1996); CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **80**, 5275 (1998).

[10] M. Carena, R. L. Culbertson, S. Eno, H. J. Frisch, and S. Mrenna, in “Perspectives on Supersymmetry,” edited by G. L. Kane, hep-ex/9802006; V. Barger and C. Kao, FERMILAB-PUB-98/342-T, hep-ph/9811489; K. T. Matchev and D. M. Pierce, FERMILAB-PUB-99/078-T, hep-ph/9904282; H. Baer, M. Drees, F. Paige, P. Quintana, and X. Xerxes, FSU-HEP-990509, hep-ph/9906233.

[11] I. Hinchliffe *et al.*, Phys. Rev. D **55**, 5520 (1997); CMS Collaboration, S. Abdullin *et al.*, CMS-NOTE-1998-006, hep-ph/9806366.

[12] J. F. Gunion and H. E. Haber, Nucl. Phys. **B272**, 1 (1986); **B402**, 567(E) (1993).

[13] S. Y. Choi, A. Djouadi, H. Dreiner, J. Kalinowski, and P. M. Zerwas, Eur. Phys. J. **C7**, 123 (1999); S. Y. Choi, A. Djouadi, H. S. Song, and P. M. Zerwas, Eur. Phys. J. **C8**, 669 (1999).

[14] S. P. Martin and M. T. Vaughn, Phys. Lett. B **318**, 331 (1993); W. Hollik, E. Kraus, and D. Stöckinger, hep-ph/9907393 [Eur. Phys. J. (to be published)].

[15] S. Catani and M. H. Seymour, Nucl. Phys. **B485**, 291 (1997); **B510**, 503(E) (1997).

[16] M. Drees and S. P. Martin, MADPH-95-879, hep-ph/9504324.

[17] H. L. Lai, J. Huston, S. Kuhlmann, F. Olness, J. Owens, D. Soper, W. K. Tung, and H. Weerts, Phys. Rev. D **55**, 1280 (1997).

[18] G. Sterman, Nucl. Phys. **B281**, 310 (1987); S. Catani and L. Trentadue, Nucl. Phys. **B327**, 323 (1989); S. Catani, M. L. Mangano, P. Nason, and L. Trentadue, Nucl. Phys. **B478**, 273 (1996).