Next-to-leading Order Calculation
of Associated Production of Gauginos and Gluinos

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Results are presented of a next-to-leading order calculation in perturbative QCD of the production of charginos and neutralinos in association with gluinos at hadron colliders. Predictions for total and differential cross sections are shown at the energies of the Fermilab Tevatron and CERN Large Hadron Collider for a typical supergravity model of the sparticle mass spectrum and for a light gluino model.

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1 Introduction

The mass spectrum in typical supergravity and gauge-mediated models of supersymmetry (SUSY) breaking favors much lighter masses for gauginos than for squarks. Because the masses are smaller, there is greater phase space at the Tevatron and greater partonic luminosities for gaugino pair production, and for associated production of gauginos and gluinos, than for squark pair production. Another point in favor of associated production is the relative simplicity of the final state. For example, the lowest lying neutralino is the (stable) lightest supersymmetric particle (LSP) in supergravity (SUGRA) models, manifest only as missing energy in the events, and it is the second lightest in gauge-mediated models. The charginos and higher mass neutralinos may decay leptonically leaving a lepton signature plus missing transverse energy; relatively clean events ensue. Furthermore, associated production may be the best channel for measurement of the gluino mass.

The search for direct experimental evidence of supersymmetry at colliders requires a good understanding of theoretical predictions of the total and differential cross sections for production of the superparticles. In the case of hadron colliders, where collisions of strongly interacting hadrons are studied, the large strong coupling strength ($\alpha_s$) leads to potentially large contributions beyond the leading order (LO) in a perturbation series expansion of the cross section. To have accurate theoretical estimates of production rates, it is necessary to include corrections at next-to-leading order (NLO) or beyond. In this contribution, we summarize our recent calculations at next-to-leading order in perturbative quantum chromodynamics (QCD) of the total and differential cross sections for associated production of gauginos and gluinos at hadron colliders$^{1,2}$. Associated production offers a chance to study the parameters of the soft SUSY-breaking Lagrangian. Rates are controlled by the magnitudes and phases of the gaugino ($\tilde{\chi}$) and gluino ($\tilde{g}$) masses and by mixing in the squark and gaugino sectors. Our analysis is general in that it is not tied to a particular SUSY breaking model. We can provide cross sections for arbitrary gluino and gaugino masses.

2 NLO SUSY-QCD Formalism

Associated production of a gluino and a gaugino proceeds in leading order (LO) through a quark-antiquark initial state and the exchange of an intermediate squark in the $t$-channel or $u$-channel$^3$. At NLO, loop corrections must be included. In addition, there are 2 to 3 parton processes initiated either by quark-antiquark scattering, with a gluon radiated into the final state, $q + \overline{q} \rightarrow g + \tilde{g} + \tilde{\chi}$, or by quark-gluon scattering with a light quark radiated into the final state, $q + g \rightarrow q + \tilde{g} + \tilde{\chi}$. For the quark-antiquark initial state, the loop diagrams involve the exchange of intermediate
Figure 1: Predicted total hadronic cross sections at Run II of the Tevatron and at the LHC for all six $\tilde{g}\tilde{\chi}$ channels in a typical SUGRA model as functions of the gluino mass.
Standard Model or SUSY particles in self-energy, vertex, or box diagrams. Ultraviolet and infrared divergences appear at the upper and lower boundaries of integration over unobserved loop momenta. They are regulated dimensionally and removed through renormalization or cancellation with corresponding divergences in the 2 to 3 parton (real emission) diagrams that have an additional gluon radiated into the final state. In addition to soft divergences, real emission contributions have collinear divergences that are factored into the NLO parton densities.

The set of Feynman diagrams with light quark emission includes diagrams in which an intermediate squark splits into a quark and either a gluino or gaugino. After all initial state collinear singularities are removed by mass factorization, the matrix elements may still contain integrable singularities if the mass of the squark is larger than the mass of the gluino or gaugino. In these cases, the intermediate squark state can be on its mass-shell. These singularities represent the LO production of a squark and a gluino or gaugino, followed by the LO decay of the squark. They may be regulated if one includes the full Breit-Wigner form for the squark propagator including a finite squark width. There is a further subtlety associated with the requirement that we not double-count the region of phase space in which the squark is on-shell. The kinematic configuration with an on-shell squark is included in the LO production of a squark and a gluino or a squark and a gaugino, and it should not be considered as a genuine higher order correction to the production of gluinos with gauginos. To avoid double counting, we thus subtract the on-shell squark contribution. It can be subtracted leaving a genuine NLO contribution in the limit of small squark width.

The full treatment of the NLO analysis is presented in our long paper.[2]

3 Tevatron and LHC Cross Sections

To obtain numerical predictions for hadronic cross sections, we choose an illustrative SUGRA model with parameters $m_0 = 100$ GeV, $A_0 = 300$ GeV, tan $\beta = 4$, and sign $\mu = +$. Because the gluino, gaugino, and squark masses all increase with parameter $m_{1/2}$ (but are insensitive to $m_0$), we vary $m_{1/2}$ between 100 and 400 GeV. The resulting masses for $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$ vary between 31...162, 63...317, 211...665, and 241...679 GeV; $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$ are almost degenerate in mass with $\tilde{\chi}_2^0$. The mass $m_{\tilde{\chi}_3^0} < 0$ inside a polarization sum. Our approach is general, and results can be obtained for any set of gaugino and gluino masses. For our second model, we select one[4] with an intermediate-mass gluino as the lightest SUSY particle (LSP), fixing $m_\tilde{g} = 30$ GeV, and $m_\tilde{q} = 450$ GeV. We choose a weak sector identical to the SUGRA case. In our paper[2], we also quote results for anomaly mediated, gauge mediated, and gaugino mediated models.

We convolve LO and NLO partonic cross sections with CTEQ5 parton densities in LO and NLO (\text{MS}) along with 1- and 2-loop expressions for $\alpha_s$, the corresponding values of $\Lambda$, and five active quark flavors.
For the SUGRA case, we present total hadronic cross sections in Fig. 1 as functions of the gluino mass. The common renormalization and factorization scale $\mu$ is set equal to the average particle mass $m$. The light gaugino channels should be observable at both colliders. At the Tevatron, for $2 \text{ fb}^{-1}$ of integrated luminosity, 10 or more events could be produced in each of the lighter gaugino channels if $m_{\tilde{g}} < 450 \text{ GeV}$. The heavier Higgsino channels are suppressed by about one order of magnitude and might be observable only at the LHC. As a rough estimate of uncertainty associated with the choice of parton densities, we note that the NLO cross section for $\tilde{\chi}_2^0$ production is lower by 12% at the Tevatron with the CTEQ5 set than for the CTEQ4 set, and 4% lower at the LHC. The impact of the NLO corrections can be seen more readily in the ratio of NLO to LO cross sections computed at a renormalization scale set equal to the average mass of the final state particles. The NLO effects are moderate ($O (10\%)$) at the Tevatron, while at the LHC the NLO contributions can increase the cross sections by as much as a factor of two. The second initial-state channel, initiated by gluon quark scattering, plays a significant role at the energy of the LHC.

For the case of a gluino with mass 30 GeV, the total hadronic cross sections are shown in Fig. 2 as functions of $m_{1/2}$. At the Tevatron, for $2 \text{ fb}^{-1}$ of integrated luminosity, 100 or more events could be produced in each of the lighter gaugino channels if $m_{1/2} < 400 \text{ GeV}$. In this case, NLO enhancement factors lie in the ranges 1.3 to 1.4 at the Tevatron and 2 to 4 at the LHC.

An important measure of the theoretical reliability is the variation of the hadronic cross section with the renormalization and factorization scales. At LO, these scales enter only in the strong coupling constant and the parton densities, while at NLO they appear also explicitly in the hard cross section. The scale dependence is reduced considerably after NLO effects are included, as shown in Fig. 3. The Tevatron (LHC) cross sections vary by $\pm 23(12)\%$ at LO, but only by $\pm 8(4.5)\%$ in NLO when the scale is varied by a factor of two around the central scale.

For experimental searches, distributions in transverse momentum are important since cuts on $p_T$ help to enhance the signal. In our long paper\cite{2}, we show that NLO contributions can have a large impact on $p_T$ spectra at the LHC, owing to contributions from the $gq$ initial state. At the Tevatron the NLO $p_T$-distribution is shifted moderately to lower $p_T$ with respect to the LO expectation. Examples for the $\tilde{g}\tilde{\chi}_1^\pm$ channel are shown in Fig. 4. The shapes of the rapidity distributions of the gauginos are not altered appreciably by NLO contributions.

4 Summary

In our long paper we report a complete next-to-leading order analysis of the associated production of gauginos and gluinos at hadron colliders. If supersymmetry exists at the electroweak scale, the cross section for this process is expected to be observable
at the Fermilab Tevatron and/or the CERN LHC. It is enhanced by the large color charge of the gluino and the relatively small mass of the light gauginos in many SUSY models. Associated production offers a chance to study in detail the parameters of the soft SUSY-breaking Lagrangian. The rates are proportional to the phases of the gaugino and gluino masses, and to the mixings in the squark and chargino/neutralino sectors. In combination with other channels, associated production could allow one to measure some or all of these quantities.

The physical gluino and gaugino masses that we use, as well as the gaugino mixing matrices, are based on four popular SUSY breaking models plus a fifth scenario in which the gluino mass is relatively light. Because the LO cross sections in gauge-mediated, gaugino-mediated, and anomaly-mediated supersymmetry breaking models are not too dissimilar from those of the SUGRA case at Tevatron energies, we focus our NLO work on the SUGRA model and on a model in which a light gluino, with mass \( \tilde{m}_g = 30 \text{ GeV} \), is the lightest supersymmetric particle (LSP).

In the SUGRA model, the largest cross sections at the Fermilab Tevatron energy are those for neutralino \( \tilde{\chi}_2^0 \), enhanced by its \( \tilde{W}_3 \)-like coupling with respect to the \( \tilde{B} \)-like \( \tilde{\chi}_1^0 \), and the chargino \( \tilde{\chi}_1^\pm \), about equal in mass with the \( \tilde{\chi}_2^0 \). The NLO corrections to associated production are generally positive, but they can be modest in size, ranging in the SUGRA model from a few percent at the energy of the Tevatron to 100% at the energy of the LHC, depending on the sparticle masses. In the light-gluino case, NLO contributions increase the cross section by factors of 1.3 to 1.4 at the energy of the Tevatron and by factors of 2 to 3.5 at the energy of the LHC. The large enhancements owe their origins to the important role of the \( gq \) channel that enters first at NLO.

Owing to the NLO enhancements, collider searches for signatures of associated production will generally discover or exclude sparticles with masses larger than one would estimate based on LO production rates alone. More significant from the viewpoint of reliability, the renormalization and factorization scale dependence of the cross sections is reduced by a factor of more than two when NLO contributions are included.

At Run II of the Fermilab Tevatron, for an integrated luminosity of 2 fb\(^{-1} \), we expect that 10 or more events could be produced in each of the lighter gaugino channels of the SUGRA model, \( \tilde{g}\tilde{\chi}_1^0, \tilde{g}\tilde{\chi}_2^0, \) and \( \tilde{g}\tilde{\chi}_1^\pm \), provided that the gluino mass \( \tilde{m}_g \) is less than 450 GeV. The cross sections for the three heavier gaugino channels, \( \tilde{g}\tilde{\chi}_3^0, \tilde{g}\tilde{\chi}_4^0, \) and \( \tilde{g}\tilde{\chi}_2^\pm \), are smaller by an order of magnitude or more than those of the lighter gaugino channels. In the light gluino LSP model, more than 100 events could be produced in the three lighter gaugino channels provided that the common GUT-scale fermion mass \( m_{1/2} \) is less than 400 GeV, and as many as 10 events in the three heavier gaugino channels as long as \( m_{1/2} \) is less than 200 GeV. At the higher energy and luminosity of the LHC, at least a few events should be produced in every channel in the SUGRA model and many more in the light gluino model.

The relatively large cross sections suggest that associated production is a good
channel for discovery of a light gluino at the Tevatron, for closing the window on this possibility, and/or for setting limits on light gaugino masses. The usual searches for a light gluino LSP are based on the assumption that gluinos are produced in pairs. In this situation, the dominant background is QCD production of hadronic jets. Hard cuts on transverse momentum must be made to reduce this background to tolerable levels. The cuts, in turn, mitigate against gluinos of modest mass. By contrast, if light gluinos are produced in association with gauginos, one can search for light gluino monojets accompanied by leptons and/or missing transverse energy from gaugino decays.

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Figure 2: Predicted total hadronic cross sections at Run II of the Tevatron and at the LHC for all six $\tilde{g}\tilde{\chi}$ channels in our model with a gluino of mass 30 GeV, as functions of the parameter $m_{1/2}$. 
Figure 3: Dependence of the predicted NLO and LO total cross sections at the Tevatron and at the LHC on the renormalization and factorization scale. We show the case of $\tilde{g}\tilde{\chi}_2^0$ production in the SUGRA model, with $m_{\tilde{g}} = 410$ GeV and $m_{\tilde{\chi}_2^0} = 104$ GeV.
Figure 4: Differential cross section in transverse momentum $d\sigma/dp_T$ for the production of $\tilde{\chi}_1^\pm$ with mass 101 GeV in association with a $\tilde{g}$ of mass 410 GeV at the Tevatron and at the LHC.