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SUSY Production Cross Sections

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Abstract

We summarize the status of next-to-leading order perturbative quantum chromodynamics (pQCD) calculations of the cross sections for the production of squarks, gluinos, neutralinos, charginos, and sleptons as a function of the produced sparticle masses in proton-antiproton collisions at the hadronic center-of-mass energy 2 TeV.

I. PERTURBATIVE QCD RESULTS

The possibility of supersymmetry (SUSY) at the electroweak scale and the ongoing search for the Standard Model (SM) Higgs boson constitute two major related aspects of the motivation for the Tevatron upgrade currently under construction at Fermilab. The increase in the center-of-mass energy to 2 TeV and the luminosity to an expected 2 fb^{-1}, together with detector improvements, should permit discovery or exclusion of supersymmetric partners of the standard model particles up to much higher masses than at present [1].

Estimates of the production cross sections for pairs of supersymmetric particles may be computed analytically from fixed-order quantum chromodynamics (QCD) perturbation theory. Calculations that include contributions through next-to-leading order (NLO) in QCD have been performed for the production of squarks and gluinos [2], top squark pairs [3], slepton pairs [4], gaugino pairs [5], and the associated production of gauginos and gluinos [6]. The cross sections can be calculated as functions of the sparticle masses and mixing parameters.

In a recent paper [7], Berger, Klasen, and Tait provide numerical predictions at next-to-leading order for the production of squark-antisquark, squark-squark, gluino-gluino, squark-gluino, and top squark - antitop squark pairs in proton-antiproton collisions at the hadronic center-of-mass energy 2 TeV. These calculations are based on the analysis of Refs. [2,3], and the CTEQ4M parametrization [8] of parton densities. The hard scale dependence of the cross section at leading order (LO) in perturbative QCD is reduced at NLO but not absent. An estimate of the theoretical uncertainty at NLO is approximately ± 15 % about a central value. The central value is obtained with the hard scale chosen to be equal to the average of the masses of the produced sparticles, and the band of uncertainty is determined from a variation of the hard scale from half to twice this average mass. The next-to-leading order contributions increase the production cross sections by 50 % and more from their LO values. For example, in the case of squark-antisquark production the next-to-leading order cross section lies above the leading order cross section by 59 %. This increase translates into a shift in the lower limit of the produced squark mass of 19 GeV. The cross sections for squark-antisquark production, gluino pair production, and the associated production of squarks and gluinos of equal mass are of similar magnitude, whereas the squark pair production and top squark-antitop squark production cross sections are smaller by about an order of magnitude [2,3].

The cross sections reported in Ref. [7] are for inclusive yields, integrated over all transverse momenta and rapidities. In the search for supersymmetric states, a selection on transverse momentum will normally be applied in order to improve the signal to background conditions. The theoretical analysis can also be done with similar selections. A tabulation of cross sections for various squark and gluino masses is available upon request from the authors of Ref. [7].

Next-to-leading order calculations of the production of neutralino pairs, chargino pairs, and neutralino-chargino pairs are reported to be on the way to completion [5], but final numerical predictions are not yet available for general use.

The strongly interacting squarks and gluinos may also be produced singly in association with charginos and neutralinos. Leading-order production cross sections for the associated production of a chargino plus a squark or gluino and of a neutralino plus a squark or gluino are published [9], and a next-to-leading order calculation of associated production of a gaugino plus a gluino is now available [6].

Berger, Klasen, and Tait [6] compute total cross sections for all the gaugino-gluino production reactions $\tilde{g}\tilde{\chi}^0_{(1-4)}$ and $\tilde{g}\tilde{\chi}^\pm_{(1-2)}$ in next-to-leading order SUSY-QCD. For numerical results, they select an illustrative mSUGRA scheme in which the GUT scale common scalar mass $m_0 = 100$ GeV, the common gaugino mass $m_{1/2} = 150$ GeV, the trilinear coupling $A_0 = 300$ GeV, $\tan(\beta) = 4$ and $\mathrm{sgn}(\mu) = +$. (The sign convention for A_0 is opposite to that in the ISASUGRA code). They convolute the NLO hard partonic cross sections with the CTEQ4M parametrization [8] of parton densities, and present physical cross sections as a function of the $\tilde{g}$ mass or of the average mass $m = (m_{\tilde{\chi}} + m_{\tilde{g}})/2$. For $p\bar{p}$ collisions at $\sqrt{S} = 2$ TeV the cross sections at $m_{\tilde{g}} = 300$ GeV range from $\mathcal{O}(1\mathrm{pb})$ for the $\tilde{\chi}^0_2$ and the $\tilde{\chi}^\pm_1$ to $\mathcal{O}(10^{-3}\mathrm{pb})$ for the $\tilde{\chi}^0_3$. The $\tilde{g}\tilde{\chi}^0_{(1,2)}$ and $\tilde{g}\tilde{\chi}^\pm_1$ cross sections are of hadronic size despite the fact that the overall coupling strength is $\mathcal{O}(\alpha_{EW}\alpha_s)$ not $\mathcal{O}(\alpha_s^2)$. The masses of the $\tilde{\chi}^0_{(1,2)}$ and $\tilde{g}\tilde{\chi}^\pm_1$ are significantly smaller in a typical mSUGRA scenario than those of the squarks and gluinos. The phase space and the parton luminosity are therefore greater for associated production of a gluino and a gaugino than for a pair of squarks or gluinos, and the smaller coupling strength is compensated. The next-to-leading-order cross sections are enhanced by typically 10% to 25% relative to the leading order values. The theoretical uncertainty resulting from variations of the factorization/renormalization scale is approximately ±10% at NLO for the $\tilde{\chi}^0_2$ and the $\tilde{\chi}^\pm_1$, a factor of 2 smaller than the LO variation. Shown in Fig. 1

are the predicted cross sections as a function of the average mass.

Baer, Harris, and Reno [4] compute total cross sections for all the slepton pair production reactions $\tilde{e}_L\tilde{\nu}_L$, $\tilde{e}_L\bar{\tilde{e}}_L$, $\tilde{e}_R\bar{\tilde{e}}_R$ and $\tilde{\nu}_L\bar{\tilde{\nu}}_L$ in next-to-leading order QCD. The analytic calculations are very similar to the QCD corrections to the Standard Model massive lepton-pair production (Drell-Yan) process. Numerical results are based on the CTEQ4M parametrization [8] of parton densities. For $p\bar{p}$ collisions at $\sqrt{S} = 2$ TeV, the cross sections range from $\mathcal{O}(1\text{pb})$ at $m_{\text{slepton}} = 50$ GeV to $\mathcal{O}(10^{-3}\text{pb})$ at $m_{\text{slepton}} = 200$ GeV. The next-to-leading-order cross sections are enhanced by typically 35% to 40% relative to the leading order values. The theoretical uncertainty resulting from variations in the hard scattering scale and parton distribution functions is approximately $\pm 15\%$. In the mSUGRA model, slepton pair production is most important for small values of the parameter m_0. The next-to-leading order enhancements of slepton pair cross sections at Tevatron energies can push predictions for leptonic SUSY signals to higher values than typically quoted in the literature in these regions of model parameter space.

For current expectations of the hierarchy of masses and cross sections, consult Ref. [1].

II. MONTE CARLO METHODS

Experimental searches for supersymmetry rely heavily on Monte Carlo simulations of cross sections and event topologies. Two Monte Carlo generators in common use for hadron-hadron collisions include SUSY processes; they are ISAJET [10] and SPYTHIA [11,12]. Both the Monte Carlo approach and the fixed order pQCD approach have different advantages and limitations. Next-to-leading order perturbative calculations depend on very few parameters, e.g., the renormalization and factorization scales, and the dependence of the production cross sections on these parameters is reduced significantly in NLO with respect to LO. Therefore, the normalization of the cross section can be calculated quite reliably if one includes the NLO contributions. On the other hand, the existing next-to-leading order calculations provide predictions only for fully inclusive quantities, e.g., a differential cross section for production of a squark or a gluino, after integration over all other particles and variables in the final state. In addition, they do not include sparticle decays. This approach does not allow for event shape studies nor for experimental selections on missing energy or other variables associated with the produced sparticles or their decay products that are crucial if one wants to enhance the SUSY signal in the face of substantial backgrounds from Standard Model processes.

The natural strength of Monte Carlo simulations consists in the fact that they generate event configurations that resemble those observed in experimental detectors. Through their parton showers, these generators include, in the collinear approximation, contributions from all orders of perturbation theory. In addition, they incorporate phenomenological hadronization models, a simulation of particle decays, the possibility to implement experimental cuts, and event analysis tools. However, the hard-scattering matrix elements in these generators are accurate only to leading order in QCD, and, owing to the rather complex nature of infra-red singularity cancellation in higher orders of perturbation theory, it remains a difficult challenge to incorporate the full structure of NLO contributions successfully in Monte Carlo simulations. The limitation to leading-order hard-scattering matrix elements leads to large uncertainties in the normalization of the cross section. The parton shower and hadronization models rely on tunable parameters, another source of uncertainties.

In Ref. [7] a method is suggested to improve the accuracy of the normalization of cross sections computed through Monte Carlo simulations. In this approach, the renormalization and factorization (hard) scale in the Monte Carlo LO calculation is chosen in such a way that the normalization of the Monte Carlo LO calculation agrees with that of the NLO perturbative calculation. The scale choice depends on which partonic subprocess one is considering and on the kinematics. This choice of the hard scale will affect both the hard matrix element *and* the initial-state and final-state parton shower radiation. On the other hand, an alternative rescaling of the cross section by an overall K-factor will have no bearing on the parton shower radiation. A reduction in the hard scale leads generally to less evolution and less QCD radiation, and vice-versa, in the initial- and final-state showering. A change of the hard scale will be reflected in the normalization of the cross section as well as in the event shape. Investigations are underway to determine how significant the changes are in computed final state momentum distributions.

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FIGURES

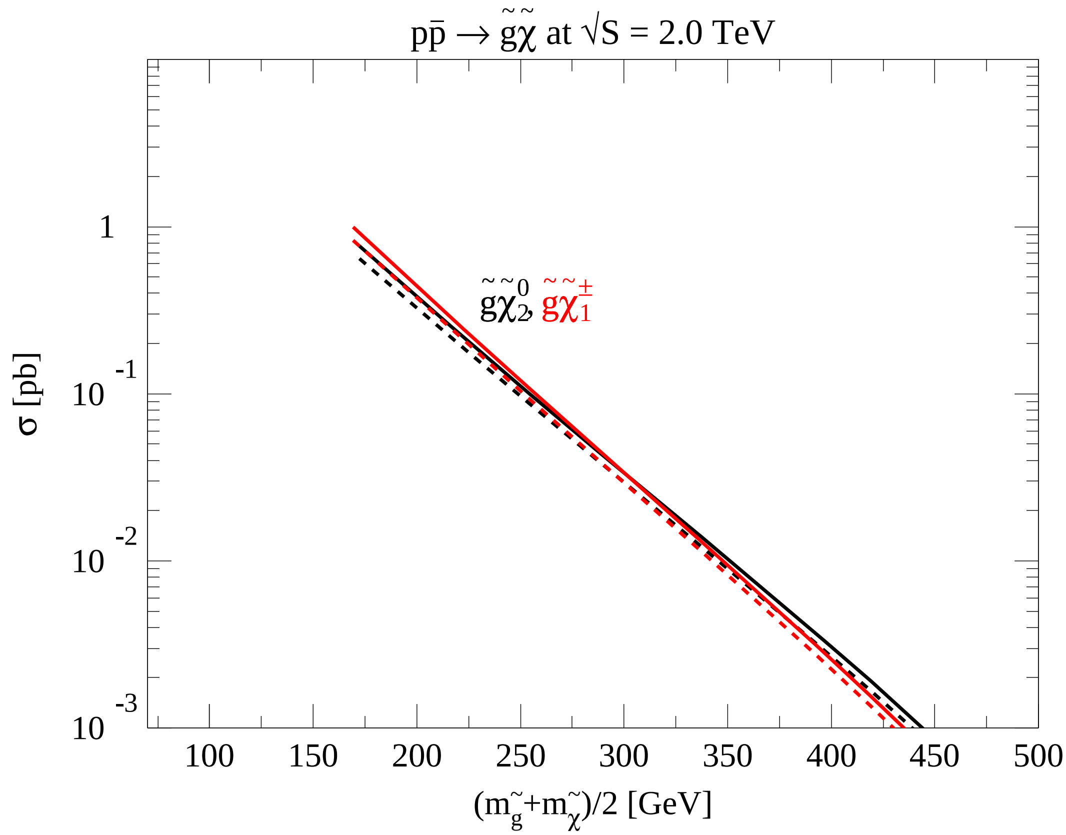

FIG. 1. Total hadronic cross sections for the associated production of gluinos and gauginos at Run II of the Tevatron from Ref.[6]. NLO results are shown as solid curves, and LO results as dashed curves. The chargino cross sections are summed over positive and negative chargino states.