

Supersymmetric particle production at hadron colliders

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The theoretical status of MSSM particle production at the hadron colliders Tevatron and LHC is reviewed, including next-to-leading order supersymmetric QCD corrections. The higher-order corrections significantly reduce the theoretical uncertainty and lead to a rise of the lower bounds on supersymmetric particle masses, as demonstrated for the case of top-squark and gaugino pair production at the Tevatron.

1. Introduction

The search for supersymmetric particles ranks among the most important experimental endeavours at existing and future hadron colliders. At the upgraded $p\bar{p}$ collider Tevatron, chargino and neutralino searches, as well as squark and gluino searches, will cover a wide range of the MSSM parameter space [1]. Squarks and gluinos up to masses $\lesssim 2.5$ TeV can be discovered at the pp collider LHC [2], so that the entire canonical parameter space of strongly interacting particles in low-energy SUSY will be explored eventually.

The cross sections for the production of SUSY particles in hadron collisions have been calculated at the Born level already quite some time ago [3].¹ Only recently have the theoretical predictions been improved by calculations of the next-to-leading order SUSY-QCD corrections for the production of

- squarks, gluinos $p\bar{p}/pp \rightarrow q\bar{q}, \tilde{g}\tilde{g}, \tilde{q}\tilde{q}$ [5]
- top-squark pairs $p\bar{p}/pp \rightarrow t\bar{t}$ [6]
- gaugino pairs $p\bar{p}/pp \rightarrow \tilde{\chi}\tilde{\chi}$ [7–9]
- slepton pairs $p\bar{p}/pp \rightarrow \tilde{l}\tilde{l}$ [10]

The higher-order corrections in general increase the production cross section compared to the predictions at the Born level and thereby improve experimental mass bounds and exclusion limits.

¹The MSSM Higgs sector will not be discussed here, see e.g. Refs.[4] for recent reviews.

Moreover, by reducing the dependence of the cross section on spurious parameters, *i.e.* the renormalization and factorization scales, the cross sections in NLO are under much better theoretical control than the leading-order estimates.

In the simplest realization of supersymmetric grand unified theories, the lightest supersymmetric particles are in general the non-coloured gauginos, with masses in the range 50 to 200 GeV for the lightest of these states. Within the strongly interacting SUSY sector, the top-squark (stop) eigenstate \tilde{t}_1 is expected to be the lightest particle [11]. Stop and gaugino pair production are therefore among the most promising reactions for supersymmetric particle searches at the Tevatron and will be focussed upon in the following.

2. Top-squark production

At hadron colliders, the lowest order QCD processes for the production of \tilde{t}_1 pairs are quark-antiquark annihilation and gluon-gluon fusion

$$q\bar{q} \rightarrow \tilde{t}_1\tilde{t}_1 \quad \text{and} \quad gg \rightarrow \tilde{t}_1\tilde{t}_1 \quad (1)$$

as shown in Fig. 1. The hadronic $p\bar{p}/pp$ cross sections are obtained by folding the partonic cross sections with the $q\bar{q}$ and gg luminosities. At the Tevatron the dominant mechanism for large stop masses $m_{\tilde{t}_1} \gtrsim 100$ GeV is the valence $q\bar{q}$ annihilation. The fraction of $q\bar{q}$ initiated events rises from 50 to 80%, if the \tilde{t}_1 mass is increased from 100 to 200 GeV. At the LHC the gluon-fusion mecha-

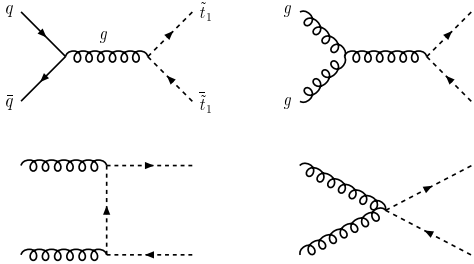


Figure 1. *Generic leading-order Feynman diagrams for the production of stop pairs in quark-antiquark annihilation and gluon fusion.*

nism plays a more prominent role. For a \tilde{t}_1 mass below 200 GeV, more than 90% of the events are generated by gg fusion.

The lowest order cross section depends strongly on the renormalization and factorization scales. As a result, the theoretical predictions are uncertain within factors of two. Including the SUSY-QCD corrections [6,9], this scale dependence is reduced significantly, as shown in Fig. 2. At the same time the cross section is considerably enhanced at the central scale ($\mu = m_{\tilde{t}_1}$).

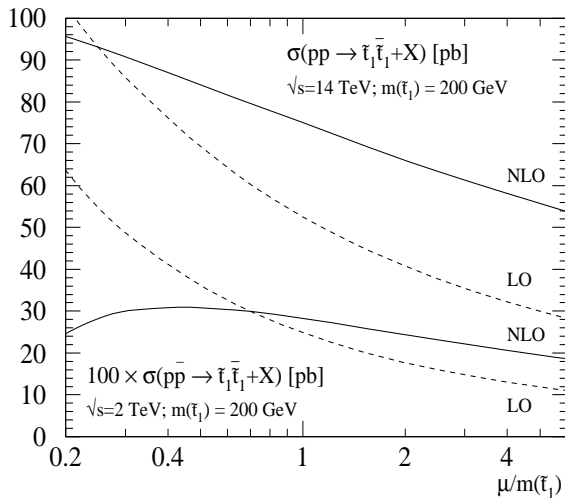


Figure 2. *The renormalization/factorization-scale dependence of the total cross section for \tilde{t}_1 -pair production at the Tevatron and the LHC.*

The magnitude of the SUSY-QCD corrections is illustrated by the K factors in Fig. 3 for \tilde{t}_1 -pair production at the Tevatron and the LHC. The K factor is defined as $K = \sigma_{NLO}/\sigma_{LO}$, with all quantities calculated consistently in lowest and in next-to-leading order. In the mass range considered, the SUSY-QCD corrections are positive and reach a level of 30 to 50% if the gg initial state dominates. If, in contrast, the $q\bar{q}$ initial state dominates, the corrections are small. The relatively large mass dependence of the K factor for $\tilde{t}_1\tilde{t}_1$ production at the Tevatron can therefore be attributed to the fact that the gg initial state is important for small $m_{\tilde{t}_1}$, whereas the $q\bar{q}$ initial state dominates for large $m_{\tilde{t}_1}$.

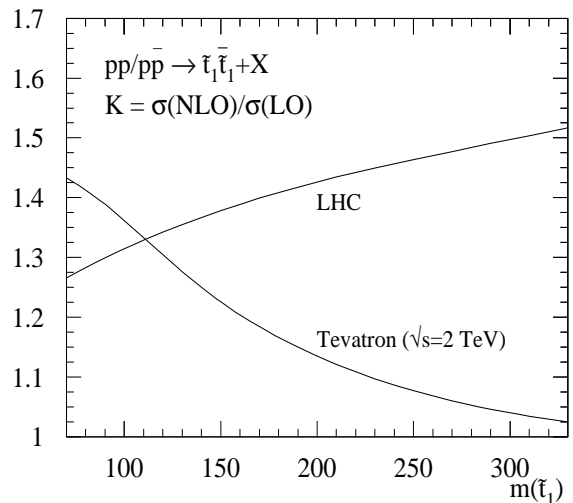


Figure 3. *K -factors for \tilde{t}_1 -pair production at the Tevatron and the LHC as a function of the stop mass. The renormalization and factorization scale is fixed at the central value $\mu = m_{\tilde{t}_1}$.*

The cross section for \tilde{t}_1 -pair production depends essentially only on the stop mass $m_{\tilde{t}_1}$. The dependence of the cross section on the other SUSY parameters, *i.e.* the gluino mass, the masses of the other squarks and the mixing angle, which enter at next-to-leading order, is very weak. The squark and gluino contributions in virtual loops are essentially decoupled for canonical SUSY masses and the general behaviour of the higher-order corrections is determined by ordinary QCD gluon radiation. Bounds on the $\tilde{t}_1\tilde{t}_1$

production cross section can therefore easily be translated into lower bounds on the lightest stop mass without reference to other supersymmetric parameters. On the other hand, if stop particles were to be discovered, the cross section can be exploited directly to determine the stop mass $m_{\tilde{t}_1}$. The impact of the SUSY-QCD corrections on the experimental mass bounds for \tilde{t}_1 will be discussed in Sec. 4.

3. Gaugino production

In many supersymmetric models, the light neutralinos and charginos are significantly lighter than squarks or gluinos, and may therefore be the only supersymmetric particles directly accessible at the Tevatron. Because of the low SM background, the production of $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ followed by the decays $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 l^+ l^-$ and $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 l^\pm \nu$ is one of the gold-plated trilepton SUSY signatures at colliders.

Neutralinos and charginos can be produced at hadron colliders in quark-antiquark annihilation via s -channel gauge boson (γ, Z, W) production and (t, u)-channel squark exchange, e.g.

$$u\bar{d} \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^+ \quad \text{and} \quad d\bar{u} \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^- \quad (2)$$

as shown in Fig. 4. The production cross sections

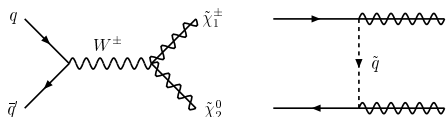


Figure 4. *Generic leading-order Feynman diagrams for the production of $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ pairs in quark-antiquark annihilation and t -channel squark exchange.*

are not simple functions of the chargino and neutralino masses but depend strongly on the mixing (i.e. on the gaugino and Higgsino compositions) and the squark masses. In the following, for illustration the supersymmetric parameters have been fixed within the minimal supergravity model [12] taking the GUT scale parameters at $m_{1/2} = 150$ GeV, $m_0 = 100$ GeV, $A_0 = 300$ GeV, $\tan\beta = 4$, and $\mu > 0$. The particle masses

in this scenario are given by $m_{\tilde{\chi}_2^0} = 103$ GeV, $m_{\tilde{\chi}_1^\pm} = 100$ GeV, $m_{\tilde{g}} = 402$ GeV, $m_{\tilde{q}} = 352$ GeV and $\tilde{t}_1 = 197$ GeV.

The hadronic gaugino-pair production cross section depends on the factorization scale via the parton densities. This scale dependence is reduced when the SUSY-QCD corrections [7–9] are included. The renormalization scale dependence introduced by the $\mathcal{O}(\alpha_s)$ corrections is weak and the overall theoretical uncertainty due to scale variation is small at the NLO level, see Fig. 5.

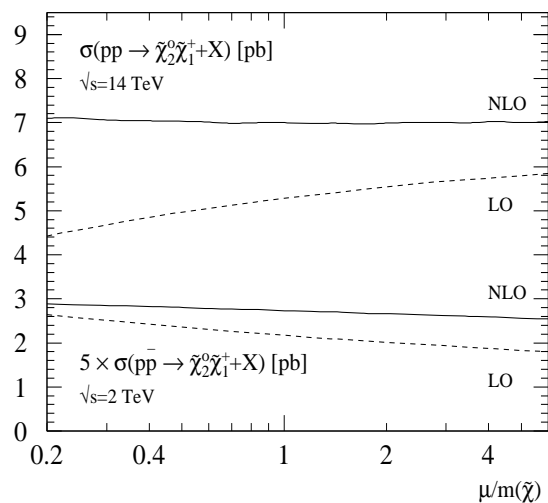


Figure 5. *The renormalization/factorization-scale dependence of the total cross section for $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ production at the Tevatron and the LHC. $m_{\tilde{\chi}}$ denotes the average mass of the produced particles.*

The SUSY-QCD corrections significantly enhance the cross section for the production of gaugino pairs at the Tevatron and the LHC, as illustrated by the K factors in Fig. 6. For the $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ cross at the Tevatron, the higher-order corrections reach a level of $\sim 30\%$ for small $m_{1/2}$ (and, accordingly, small gaugino masses) and decrease with increasing $m_{1/2}$. At the LHC the corresponding K factors are larger and range between 1.25 and 1.35. A detailed analysis of all relevant gaugino pair production cross sections at the Tevatron and the LHC will be given in Ref. [7].

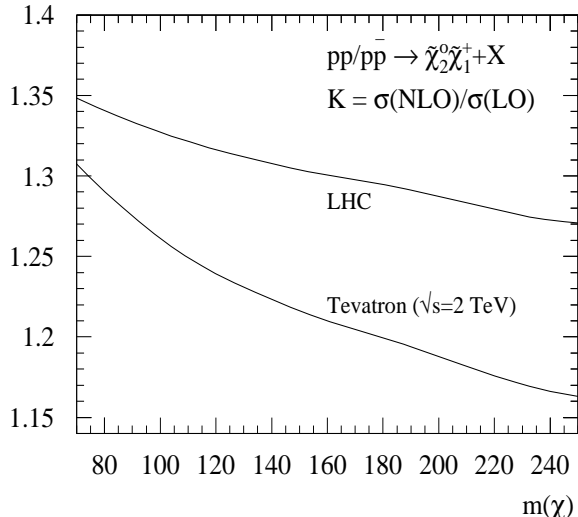


Figure 6. K -factors for $\tilde{\chi}_2^0 \tilde{\chi}_1^+$ production at the Tevatron and the LHC as a function of the gaugino mass $m_{\tilde{\chi}}$ (the masses of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$ differ only marginally in the SUGRA inspired scenario adopted here). The cross sections are varied with $m_{1/2}$. The renormalization and factorization scale is fixed at the average final state particle mass $\mu = m_{\tilde{\chi}}$.

4. Experimental searches and mass bounds

SUSY particle searches have been performed by the CDF and D0 collaborations at the Fermilab Tevatron. No signal has been found in the analysed data samples, resulting in upper cross section limits [13]. Comparing the experimental limits with the theoretical cross section prediction one can exclude parts of the SUSY parameter space or place lower bounds on the sparticle masses. The impact of the higher-order QCD corrections on the interpretation of the experimental cross section limits is exemplified in Fig. 7 for stop searches in like-sign dielectron plus multi-jet events [14] which can arise in R -parity violating neutralino decays $p\bar{p} \rightarrow \tilde{t}_1 \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 \bar{c}\tilde{\chi}_1^0 \rightarrow e^{\pm}e^{\pm} + \geq 2j$. The SUSY-QCD corrections increase the lower mass bound by ~ 10 GeV and, in particular, they reduce the theoretical uncertainty by a factor ~ 4 . Qualitatively similar conclusions hold for \tilde{t}_1 searches in R -parity conserving decay modes [15].

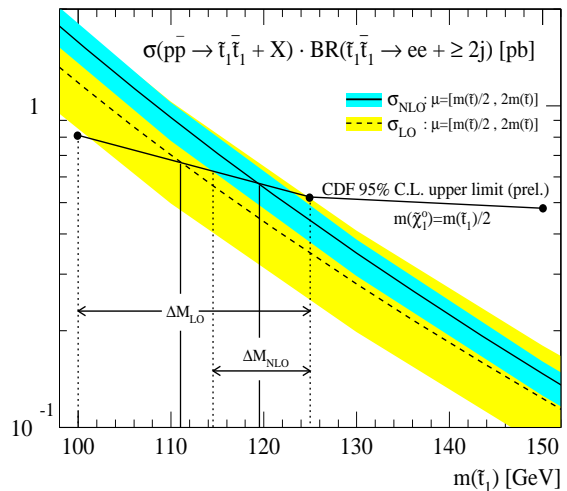


Figure 7. The 95% confidence level cross section times branching ratio upper limit for $\tilde{t}_1 \tilde{t}_1$ production at the Tevatron [14] compared to the LO and NLO theoretical prediction as a function of the stop mass $m_{\tilde{t}_1}$. The theoretical curves are multiplied by a branching ratio of $1/8$. The LO and NLO bands show the renormalization and factorization scale dependence of the cross section prediction.

5. Summary

The next-to-leading order SUSY-QCD corrections for the production of top-squark and gaugino pairs at the hadron colliders Tevatron and LHC have been discussed. By reducing the scale dependence of the cross section considerably, the quality of the theoretical predictions is substantially improved compared with the lowest-order calculations. A collection of relevant MSSM particle production cross sections at the upgraded Tevatron and the LHC is shown in Fig. 8, including next-to-leading order SUSY-QCD corrections.

The improved cross section predictions play a crucial role in the experimental analyses. They either serve to extract the exclusion regions in the SUSY parameter space from the data, or, in the case of discovery, they can be exploited to determine the masses of the sparticles.

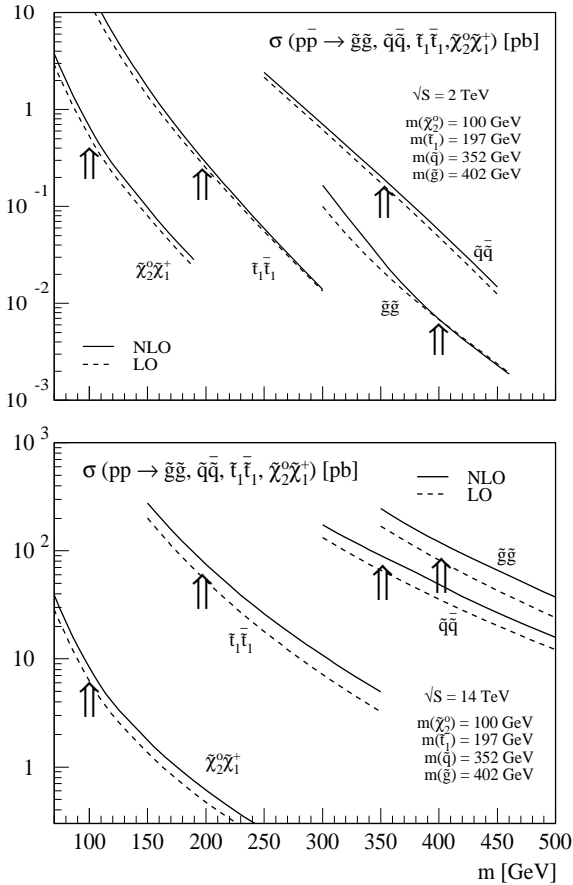


Figure 8. *The total cross section for pair production of squarks, gluinos, stops and gauginos as a function of the mass of the produced particles. The arrows denote the mass spectrum of the SUGRA inspired scenario described in the text. The cross sections are shown for the upgraded Tevatron and the LHC.*

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