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Squark Production and Decay at NLO matched with Parton Showers

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The production of squarks is among the main search channels for SUSY at the LHC. For the interpretation of experimental data precise theoretical predictions are crucial. The work presented here contributes to this effort by providing fully differential calculations of the NLO SUSY-QCD corrections to the on-shell production of squarks supplemented by the decay into the lightest neutralino and a quark in the MSSM. In contrast to previous calculations no assumptions regarding the squark masses are made and the different subchannels are treated independently. For realistic predictions a combination of these fixed-order NLO calculations and parton showers is mandatory. To this end, the processes have been implemented in the POWHEG-BOX framework and interfaced with different parton shower programs. We study the impact of the NLO corrections on the individual subchannels and differential K-factors and investigate the parton shower effects.

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1. Introduction

The direct search for supersymmetric (SUSY) particles is a major task at the LHC. The main production channels for SUSY particles are the ones where colored sparticles, squarks ($\tilde{q}$) and gluinos ($\tilde{g}$), are produced: $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{q}^*$, $\tilde{q}\tilde{g}$ and $\tilde{g}\tilde{g}$.
The leading order (LO) SUSY-QCD cross sections have been calculated in the 80's [1]. The calculation of the next-to-leading order (NLO) corrections to these processes have been completed about 10 years later [2] and made publicly available in the program package PROSPINO [3]. However, in these calculations the mass spectrum has been assumed to be degenerate. Although a lot of effort has been put in the last years in calculations without any assumptions on the mass spectrum and in taking into account beyond NLO effects, all publicly available predictions that are used by the experiments are based on the first SUSY-QCD NLO corrections which today are available via PROSPINO2. Additionally, in the current version of this program the individual subchannels of each production process are not treated independently: The K-factor in all subchannels is assumed to be constant. The differential distributions in transverse momentum and rapidity presented in the old works showed only modest shape distortions due to the NLO corrections. Since that time it has been assumed that differential K-factors are flat.
The fully differential recalculation of squark pair production for squarks of the first two generations presented here has been done without any assumptions on the mass spectrum and with all subchannels treated individually [4]. Additionally, we have recalculated the decay of each squark into a quark and the lightest neutralino fully differentially at NLO and combined this decay with our production process [5]. However, for realistic predictions a combination of these results with parton shower programs is mandatory. To this end we have matched our NLO calculations with different shower algorithms via the POWHEG-BOX [6]. After a short discussion of the crucial points of the NLO calculation, the combination of the production and decay at NLO and the matching to parton showers, phenomenologically relevant results will be presented. These will be supplemented by new results obtained from an analogous calculation for squark antisquark production [5, 7]. The implementation of both squark production processes and their decays is publicly available in the version 2 of the POWHEG-BOX and can be obtained from the repository as explained at the webpage `http://powhegbox.mib.infn.it/`.

2. Elements of the NLO Calculation

At LO the pair production of squarks of the first two generations is realized via two quarks in the initial state. At NLO contributions from virtual and real corrections have to be taken into account. The divergences are regularized in the dimensional regularization scheme. For the mass and field renormalization we work in the on-shell scheme. In case of the strong coupling constant we work in the $\overline{MS}$-scheme and decouple the heavy particles from the running of α_s. The matrix elements of the real corrections can be classified in two topologies: qq initiated processes with an additional gluon and qg initiated processes with an additional antiquark. To cancel the infrared (IR) divergences between the virtual and real corrections in a fully differential way we apply the Catani-Seymour subtraction formalism [8].
Some of the gluon-initiated real contributions allow for the production of on-shell intermediate

gluinos if one or both of the final state squarks are lighter than the gluino. These parts are considered contributions from LO $\tilde{q}\tilde{g}$ production with the subsequent decay of the gluino into a $\tilde{q}$ and a q. When considering all SUSY-QCD pair production channels, especially $\tilde{q}\tilde{g}$ production, and their decays, these channels would be double counted and need to be subtracted. This subtraction has been performed with a new approach, which guarantees a gauge-invariant removal of the resonant contributions by a local counterterm. Details on the method can be found in [4].

Certainly, an investigation of the process at production level with unstable particles in the final state is only a first step towards a realistic analysis of the effects of NLO corrections. In order to obtain more realistic predictions we have added the decay into a quark and the lightest neutralino, $\tilde{q} \to q + \tilde{\chi}_1^0$. In the combination of the results for the production and decay we take into account only those contributions to the process $pp \to 2q + 2\tilde{\chi}_1^0$ that can lead to two on-shell intermediate squarks. In the narrow-width approximation, which is valid here since the widths of the squarks fulfill $\Gamma_{\tilde{q}_i}/m_{\tilde{q}_i} \ll 1$, the total cross section then factorizes into the production cross section times the branching ratios of both decays. In order to not only combine the LO decays but also the decays at NLO with the production process at NLO, the NLO quantities for the production cross section and partial and total decay widths have to be inserted. However, this leads to an expression which includes beyond NLO contributions. The results presented here have been evaluated according to a Taylor expansion of the whole expression up to NLO, i.e. Eq. (3.72) in [7].

Although the NLO SUSY-QCD corrections to the decay have been known for several years [9], this original work provides only the results for the partial widths but not the fully differential matrix element. For this reason the calculation of the decay at NLO has been repeated [5].

To obtain realistic predictions for measurements at the LHC a combination of the fixed NLO results with the all-order effects of parton shower programs is mandatory. This combination is non-trivial, as the double counting of contributions present in both parts has to be avoided. The POWHEG method is one option to perform this matching consistently. The basic idea behind this method consists in generating the hardest emission first, maintaining full NLO accuracy and adding subsequent radiation with a p_T-vetoed shower program. The main steps of the method are process-independent and have been automated in the POWHEG-BOX framework. Since the POWHEG-BOX allows the user to produce as a by-product arbitrary differential distributions at LO and NLO, this implementation serves as an independent check of our NLO calculation. We performed this comparison and found agreement for all considered observables.

3. Phenomenological results

The results are obtained for the sample CMSSM-point 10.3.6*, described in detail in [4]. The masses of the squarks of the first two generations are about 1.8 TeV, the gluino has a mass of about 1.6 TeV. The renormalization and factorization scales have been set to a common value, $\mu_R = \mu_F = \overline{m}_{\tilde{q}}$, the average of all squark masses of the first two generations. The charge conjugated processes are included for every subchannel. We use CTEQ6L1 PDFs for LO results and the CT10NLO PDF set for NLO results. For the strong coupling α_s the 1-loop (2-loop) RGEs are used for the LO (NLO) results. The up to three partons present in results including the decays of the produced squarks are clustered into jets using the anti-k_T algorithm implemented in FASTJET 3.0.3 [10] with $R = 0.4$. The jets are required to fulfill only minimal cuts on transverse momentum and

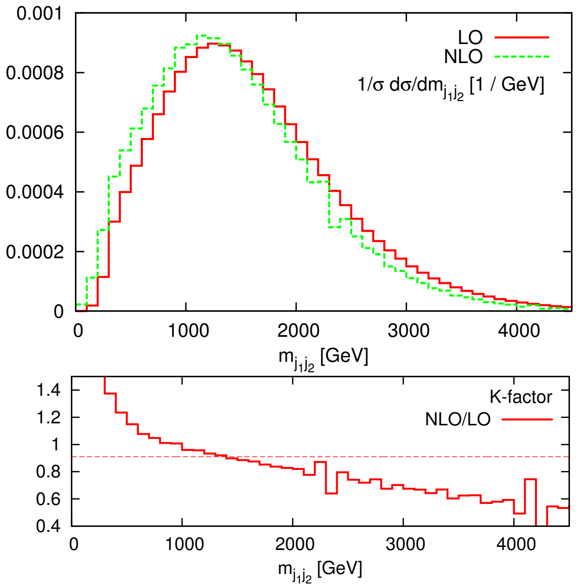

Figure 1: Upper panel: Invariant mass distribution of the two hardest jets in squark pair production combined with subsequent decays $\tilde{q} \to q + \tilde{\chi}_1^0$ at LO and NLO. Lower panel: The differential K-factor (full) and K-factor from the total cross section (dashed).

pseudorapidity:

$$p_T^j > 20 \text{ GeV}, \qquad |\eta^j| < 2.8 \,.$$

As a first step our results for the total cross sections can be compared to results obtained by PROSPINO2. Since this program package is designed for degenerate squark masses only, a comparison is most sensible when all squark masses are set to a common value: $m_{\tilde{q}} = 1800$ GeV. Additionally, PROSPINO2 uses the CTEQ6M set for NLO cross sections. With this input LO and NLO cross sections for a center-of-mass energy of $\sqrt{s} = 8$ TeV have been produced. We find perfect agreement with the numbers obtained by PROSPINO2 in all subchannels at LO as well as in the total NLO cross section and therefore in the total K-factor, i.e. the ratio between the NLO and LO cross sections. However, this is not the case for the NLO cross sections of the individual subchannels. In PROSPINO2 these are obtained by scaling the LO cross section with the K-factor of the total cross section - therefore assuming it to be constant in the various subchannels. The K-factors in the scenario analyzed here vary in a range of $\mathscr{O}(10\%)$, revealing that the assumption made by PROSPINO2 is not entirely satisfactory. An independent treatment of the subchannels is mandatory as squarks of different chiralities have different branching ratios and kinematic distributions.

Based on the first NLO calculations [2] where the analyzed differential distributions showed only modest shape distortions due to the NLO corrections it was assumed that differential K-factors are flat, i.e. NLO distributions are obtained by scaling the LO distributions with the K-factor of the total cross section. As an example that this approximation is not always justified the invariant mass distribution of the two hardest jets at LO and NLO and the differential K-factor are shown in Fig. 1 for a center-of-mass energy of $\sqrt{s} = 14$ TeV. The differential K-factor shown in the lower panel varies in a range of $\pm 40\%$ and scaling the LO distribution with the constant K-factor of the total cross section, displayed by the dashed line in the lower panel, would overestimate the tail and underestimate the threshold region of the NLO distribution. A similar strong phase space dependence of the differential K-factors in some observables can already be observed on production level. These findings are in agreement with an earlier work [11] where NLO corrections to produc-

$\tilde{q}\tilde{q}$	PYTHIA	HERWIG++
Full NLO	0.883 fb	0.895 fb
ATLAS	0.855 fb	0.858 fb

$\tilde{q}\tilde{q}^*$	PYTHIA	HERWIG++
Full NLO	0.0797 fb	0.0807 fb
ATLAS	0.0664 fb	0.0667 fb

Table 1: Total event rates for squark pair production (left) and squark antisquark production (right) with subsequent decays $\tilde{q} \to q + \tilde{\chi}_1^0$ after event selection cuts from [14]. Numbers obtained with the full NLO calculation (upper rows) and the approximate method used by ATLAS (lower rows).

tion and decay of squarks have been analyzed, too.

In the last step towards a realistic simulation the NLO calculation is combined with parton shower programs. The generated event samples from the POWHEG-BOX are showered with two Monte Carlo event generators, PYTHIA 6 [12] and HERWIG++ [13]. Summarizing our observations in distributions for variables depending solely on the two hardest jets, we can conclude that the predictions of the different parton showers agree within about 10%. Comparing the results of the parton showers to a pure NLO simulation, the effects of the parton showers are at most 10-20%, except for the threshold region where only very few events occur. Larger deviations between the different parton showers emerge in the predictions for the third jet, which is formally described only at LO in our hard process.

The matching of production and decay to parton showers allows for a comparison of results for total event rates to those used by the ATLAS group as theoretical predictions for their analyzes. To this end the generated event samples for squark pair production and squark antisquark production are processed using the event selection cuts of the signal region A-loose from the SUSY search in two-jet events [14]. The numbers obtained with our full simulation including shower effects using the showers of PYTHIA 6 and HERWIG++ are listed each in the first row of Table 1 for squark pair production (left) and squark antisquark production (right), respectively. In the analysis performed in [14] the theoretical predictions for the event rates are obtained by scaling the LO production processes, evaluated with the LO PDF set CTEQ6L1, with a global K-factor calculated by PROSPINO2. Higher-order effects in the decays are included by multiplying the subchannels with the NLO branching ratios calculated with SDECAY [15]. The decays and the showering are performed by PYTHIA 6 and HERWIG++. We mimic this approximate method and obtain the results shown in the lower row of Table 1. Comparing our full simulation of NLO effects in production and decay with the approximate method shows that the discrepancy in case of squark pair production in Table 1 is almost negligible, whereas the rates for squark antisquark production differ by 20%.

4. Conclusion

A recalculation of squark pair (and squark antisquark) production at NLO without any assumptions on the mass spectrum combined with NLO results for the subsequent decays into quarks and neutralinos has been presented. Additionally, the combined result has been matched to parton showers via the POWHEG-BOX. It was found that in the analyzed scenario it is essential to treat the contributing subchannels independently and that differential K-factors can not be assumed to be flat. Of course, an analysis for a randomly chosen phase space point does not allow for a conclusive statement on the validity of the approximations made so far. Since the effects actually can be

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large, the full NLO calculation for production and decay matched consistently with parton showers is however necessary to achieve as precise predictions for shapes of distributions and total rates as possible. The implementation of this matched NLO calculation is publicly available and can be downloaded from the POWHEG-BOX website `http://powhegbox.mib.infn.it/`.

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