Slepton pair production in the POWHEG BOX

Barbara Jäger, Andreas von Manteuffel, Stephan Thier

PRISMA Cluster of Excellence, Institute of Physics (THEP), Johannes Gutenberg University, 55099 Mainz, Germany
E-mail: jaegerba@uni-mainz.de, manteuffel@uni-mainz.de, thiers@uni-mainz.de

Abstract: We present an implementation for slepton pair production at hadron colliders in the POWHEG BOX, a framework for combining next-to-leading order QCD calculations with parton-shower Monte-Carlo programs. Our code provides a SUSY Les Houches Accord interface for setting the supersymmetric input parameters. Decays of the sleptons and parton-shower effects are simulated with PYTHIA. Focussing on a representative point in the supersymmetric parameter space we show results for kinematic distributions that can be observed experimentally. While next-to-leading order QCD corrections are sizable for all distributions, the parton shower affects the color-neutral particles only marginally. Pronounced parton-shower effects are found for jet distributions.
1 Introduction

With the start-up of the CERN Large Hadron Collider (LHC) unprecedented opportunities have emerged for experimentally accessing the terascale. The capability of the LHC was impressively demonstrated by the recently announced discovery [1, 2] of a new particle compatible with the Higgs boson of the Standard Model. Yet, numerous extensions of the Standard Model are being discussed, some of the best-motivated ones being supersymmetric (SUSY) models that predict the existence of supersymmetric partners for all Standard Model particles.

Direct production of the scalar partners of the leptons proceeds via slepton pair production, if R-parity is conserved. Compared to the production of the color-charged squarks and gluinos, the production cross sections are smaller but also the signatures in the detector are cleaner (see, e.g., Ref. [3] for a recent review). Current searches at ATLAS [4] already supplement the LEP limits [5] by excluding masses of the left-handed sleptons up to 185 GeV for exclusive decays into a lepton and the lightest neutralino, depending on the neutralino mass. Precision measurements in the slepton sector would be possible at a future \(+e^-\) linear collider [6, 7] and to a less general extent also at a muon collider [9].

For slepton pair production at hadron colliders, the leading order (LO) [8, 10] and next-to-leading order (NLO) QCD [11] and SUSY-QCD [12] contributions are known for the total cross sections as well as for differential distributions. The latter have been implemented in the computer package PROSPINO [13], which is publicly available. Uncertainties inherent to the fixed-order parton-level calculations have been further reduced by taking resummation effects into account. In Refs. [14] and [15], transverse momentum and threshold resummation for slepton pair production at hadron colliders was considered, while Ref. [16] provided joint resummation predictions for this class of reactions. More recently, using methods of soft-collinear effective theory invariant-mass distributions and total cross sections have been presented at next-to-next-to-next-to-leading logarithmic accuracy [17].

Ideally, precise predictions for the production cross sections should be combined with realistic simulations of parton-shower effects, multi-parton interactions, and underlying event – effects that are omni-present at hadron colliders. Moreover, the complex decay patterns of the heavy SUSY particles should fully be taken into account and realistic analysis cuts should be applied. These requirements call for the use of multi-purpose Monte-Carlo generators such as HERWIG [18, 19] or PYTHIA [20], which are, however, mostly restricted to leading order matrix elements for hard scattering processes. A framework that allows to combine the merits of both, flexible parton-shower programs with precise NLO-QCD calculations, is the so-called POWHEG approach [21, 22]. The POWHEG BOX [23] is a public tool providing all general building blocks of this method, but requiring the user to individually implement process-specific pieces such as matrix elements for the hard scattering process at NLO-QCD accuracy. Several Standard-Model processes bearing similar kinematic features as slepton pair production are available in the POWHEG BOX [24, 25]. Selected SUSY processes have been studied in the POWHEG approach as well [26, 27].

In this article, we present an implementation of charged slepton pair production at hadron colliders in the POWHEG BOX and study the relevance of parton-shower effects for
representative distributions. The slepton decay implementation of PYTHIA is used to produce experimentally accessible final states. Firstly, we describe our calculation in Sec. 2. In Sec. 3, we provide representative phenomenological results for a specific parameter point of the minimal supersymmetric extension of the Standard Model (MSSM). Our conclusions are given in Sec. 4.

2 Framework of the calculation

The NLO-QCD and SUSY-QCD (SQCD) corrections to slepton pair production at hadron colliders are known for quite some time [11, 12] and publicly available, e.g. in the parton-level Monte Carlo program PROSPINO [13]. Nonetheless, we decided to re-calculate the full $\mathcal{O}(\alpha_s)$ corrections to this class of processes in the framework of the MSSM. In the following, we consider the production of a pair of charged sleptons and leave a discussion of final states involving sneutrinos for future work.

At LO, the production of charged slepton pairs at hadron colliders dominantly proceeds via the Drell-Yan type annihilation of a quark-antiquark pair into a virtual $Z$ boson or photon that in turn decays into a pair of heavy sfermions, c.f. Fig. 1 (a). The SQCD-NLO corrections to this reaction comprise virtual one-loop corrections and real-emission contributions with an extra parton in the final state. To the former only self-energy and vertex corrections contribute, since the sleptons do not carry color charge, see Fig. 1 (b). For the real-emission corrections we consider $q\bar{q}$ annihilation diagrams with a gluon being radiated off either of the incoming fermions, and crossing-related contributions where the gluon is promoted to the initial state while the final state features a quark or anti-quark in addition to the slepton pair, as shown in Fig. 1 (c).

We employ the on-shell scheme for the renormalization of the wave functions of the massless quarks, which requires the evaluation of additional self energy diagrams not depicted here. Other quantities such as the couplings receive no non-trivial contributions at the order of perturbation theory considered. We account for large universal corrections to the electromagnetic coupling due to light fermions by a running coupling. We input its value at the scale $m_Z$ and use the resummed one-loop contributions to evolve to the invariant mass of the slepton pair.

We generate the Feynman diagrams with QGRAF [28] and build the interference terms with in-house developed FORM [29, 30] scripts. The relative sign of interference produced by QGRAF cannot be used due to the presence of Majorana fermions; we generate this sign according to Ref. [31]. Contraction of Lorentz indices leaves us with scalar integrals which are reduced to master integrals with the program Reduze 2 [32, 33]. The resulting expressions are exported to Fortran77 files that make use of the QCDLoop library [34] for the numerical evaluation of the scalar master integrals. Conventional dimensional regularization is used to regularize both ultraviolet (UV) and infrared (IR) divergences. No supersymmetry-restoring counterterms are needed here [35]. The calculation employs $\gamma^5 = (i/4!)\epsilon_{\mu\nu\rho\sigma}\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma$ for the axial couplings [36, 37]. Additionally we performed an independent calculation utilizing the Mathematica package FeynArts [38] for amplitude generation, FormCalc [39, 40] for algebraic simplifications including tensor reductions, and
Feynman diagrams contributing to slepton pair production at hadron colliders: tree-level contribution (a), virtual NLO-QCD and SQCD corrections (b) and real-emission contributions (c) from different channels.

LoopTools [39, 41] for the numerical evaluation of the scalar integrals. This calculation uses the so-called naive anticommuting scheme [42] for $\gamma^5$. The results of these two calculations are in complete agreement with each other. In both approaches, we neglect masses of quarks and leptons for the first and second generations. Consequently, the scalar partners of these left and right-chiral fermions are treated as mass eigenstates. While partons of the third generation may safely be ignored in the initial state, mixing of staus is taken into account.

Having calculated the $\mathcal{O}(\alpha_s)$ corrections to the partonic scattering process has put us in a position to work out an implementation of slepton pair production in the POWHEG BOX. We merely have to provide the following ingredients:

- a list of all flavor structures for the LO and the real-emission contributions,
- a suitable parameterization of the Born phase space,
- the Born amplitudes squared for all partonic subprocesses,
- the color correlated and the spin correlated Born amplitudes,
- the finite part of the virtual QCD and SQCD corrections,
- the real-emission matrix elements squared for all partonic subprocesses.

Once these building blocks are implemented in the POWHEG BOX, the program itself performs the phase-space integration and convolution with the set of parton-distribution functions selected by the user. IR divergent configurations are taken care of internally by a subtraction procedure based on Ref. [43]. The POWHEG BOX also provides the means for checking that the real-emission contributions approach the respective counterterms for soft and collinear configurations. This constitutes a useful debugging tool as it tests the correct normalization of the real-emission amplitudes relative to the Born matrix elements that are used for the computation of the counterterms.
We have compared our total cross section with results obtained from PROSPINO 2.1 and found agreement both at LO and at NLO. In addition, we checked that our virtual Standard-Model-QCD and SUSY-QCD corrections as well as LO and NLO total cross sections are in agreement with [17].

In our implementation, spectrum dependent decays of the on-shell sleptons are incorporated via PYTHIA 6.4.25. For the input of fully general MSSM parameters, we employ the SUSY Les Houches Accord (SLHA) [44, 45] interface. The production part of our implementation utilizes the SLHALib 2 library [46] (SLHA 1 & SLHA 2), while the decay code of PYTHIA already features configuration via SLHA 1. In this way, the output of spectrum generators can be passed directly to our program in a well-defined and user-friendly way.

3 Phenomenological results and discussion

Our implementation of slepton pair production in the POWHEG BOX will be made publicly available at the homepage of the POWHEG BOX project, http://powhegbox.mib.infn.it. We encourage the phenomenologist to use this code with his or her own preferred settings for the SUSY spectrum, Standard-Model input parameters and experimental selection cuts. A documentation of the code including recommended values for technical parameters is provided together with the code. Here, we show representative results for a specific point in the SUSY parameter space.

We consider proton-proton collisions at the LHC with a center-of-mass energy of \( \sqrt{S} = 8 \text{ TeV} \). For the electroweak parameters we use input provided by the particle data group (PDG) [47]. We set the mass of the Z boson \( m_Z = 91.1876 \text{ GeV} \), the fine-structure constant \( \alpha = 1/137.036 \) and use a running electromagnetic coupling in the on-shell scheme with \( \alpha(m_Z) = 1/128.919 \). For the electroweak mixing angle we obtain \( \sin^2 \theta_W = 0.23103 \) from the PDG value for Fermi’s constant, \( m_Z \) and \( \alpha(m_Z) \) using the tree-level relation. The Z width is set to its PDG value but has no impact on the results discussed in the following.

For the masses of the sleptons and the lightest neutralino we set

\[
\begin{align*}
    m_{\tilde{\ell}^R} & = 180 \text{ GeV} \quad \text{for } \tilde{\ell}^R = \tilde{\ell}^R, \tilde{\mu}^R, \\
    m_{\tilde{\chi}_1^0} & = 80 \text{ GeV},
\end{align*}
\]

while for squarks and gluino we use \( m_{\tilde{q}_L} = m_{\tilde{q}_R} = 1500 \text{ GeV} \) for \( \tilde{q} = \tilde{u}, \tilde{d}, \tilde{c}, \tilde{s} \) and \( m_{\tilde{g}} = 2000 \text{ GeV} \). While SUSY particles of these masses are not excluded by collider data, from Ref. [4] one may expect such a slepton sector to be accessible by future slepton searches at the LHC experiments. The virtual SQCD corrections induced by the squarks and gluinos are included but found to be numerically irrelevant because of their large masses in this setup.

For the numerical analysis we restrict ourselves to the pair production of the SUSY partners of the right-handed leptons of the first and second generation, the R-selectrons and R-smuons. The sleptons are assumed to exclusively decay into a lepton and the lightest neutralino, where we employ PYTHIA 6.4.25 for the decay. Throughout, we switch off QED radiation, underlying event and hadronization effects in PYTHIA. Unless stated otherwise, factorization and renormalization scales are identified with the invariant mass of the
slepton pair. For the parton-distribution functions of the proton, we use the MSTW2008 parameterization \cite{48} as implemented in the LHADPDF library \cite{49}. The real-emission contributions of the NLO-QCD calculation as well as the parton shower can give rise to partons in the final state. These are recombined into jets according to the anti-$k_T$ algorithm \cite{50} as implemented in the FASTJET package \cite{51,52}, with $R = 0.4$ and $y_{\text{jet}} < 4.5$.

For the total cross section we find $\sigma = 5.93 \, \text{fb}$ at NLO-QCD. In order to illustrate the dependence of our results on unphysical scales, we evaluated the total cross sections for our default setup at LO and NLO-QCD, varying the factorization and renormalization scales in the range $\mu_0/2$ to $2\mu_0$, with $\mu_0 = 2m_{\tilde{l}_R}$. Note that the renormalization scale does not enter the LO results, since at tree-level slepton pair production is a purely electroweak process. While at LO we find a scale uncertainty of about 8%, the NLO results for different values of $\mu_0$ differ by only 4%.

In Figs. 2 (a) and (b) we present the invariant-mass distribution of the slepton pair and the transverse momentum of the negatively charged selectron, respectively, for our default setup at LO, NLO, and for POWHEG+PYTHIA (NLO+PS). The statistical errors on the distributions are at the order of 1% per bin or smaller and therefore not explicitly indicated in the histograms. As expected, relatively large positive NLO-QCD corrections are encountered for both observables, while the impact of the parton shower on the NLO result is marginal for these slepton distributions.

More pronounced parton-shower effects can be observed in distributions related to the hardest jet produced in association with the slepton pair. In the NLO-QCD calculation, a jet can only arise from the final-state parton of the real-emission contributions. In contrast, the parton shower can give rise to events with even more than one hard jet in the POWHEG+PYTHIA result. The transverse-momentum distribution of the hardest jet is shown in Fig. 3 (a) for the fixed-order and the POWHEG+PYTHIA calculation. While in the
Figure 3. Transverse momentum (a) and rapidity distribution (b) of the hardest jet for slepton pair production at the LHC with $\sqrt{S} = 8$ TeV. In (b) we additionally require $p_T^{jet} > 20$ GeV.

Figure 4. Transverse-momentum distribution of the negatively charged lepton (a) and $m_{T2}$ distribution (b) with POWHEG+PYTHIA within the cuts of Eq. (3.2) for slepton pair production at the LHC with $\sqrt{S} = 8$ TeV.

The fixed-order QCD prediction $d\sigma/dp_T^{jet}$ rises steadily towards very low transverse momenta, this rise is damped by the Sudakov factor in the POWHEG+PYTHIA result. In either case, the extra jet tends to be produced at central rapidities, as illustrated by Fig. 3 (b). There, we imposed an extra cut on the transverse momentum of the jet, $p_T^{jet} > 20$ GeV to avoid contributions from very soft partons produced by the parton shower.

An important feature of our code is the possibility to interface the calculation of the slepton pair production cross section with PYTHIA in such a way that decays of the sleptons can be simulated, and the user gets access on kinematic distributions of the decay products within selection cuts of his own choice. In Fig. 4 (a) we present predictions at the NLO+PS level for the transverse-momentum distribution of the hardest negatively charged lepton.
within our standard setup, and with additional cuts on the charged leptons, requiring them to be hard and centrally produced,

\[ p_T^\ell > 20 \text{ GeV} \quad \text{and} \quad |\eta^\ell| < 2.5. \quad (3.2) \]

Providing predictions in terms of final decay products, our code can be used directly also for more elaborate analysis techniques such as studies of the \( m_{T2} \) distribution defined in Ref. [53]. This is demonstrated in Fig. 4 (b), where we used the code of Ref. [54] for the calculation of \( m_{T2} \).

While these results are meant as an illustration of the capability of our code, we would like to stress that the user is free to add distributions, modify cuts, and set masses of the SUSY particles according to his needs in a straightforward manner.

## 4 Conclusions

In this work, we have presented an implementation of slepton pair production at hadron colliders in the POWHEG BOX, a framework that allows to combine NLO-QCD calculations with parton-shower Monte-Carlo programs. We have described how we calculated the QCD and SQCD corrections to the hard scattering process, and then explained the technical details of their implementation in a publicly available computer code. The program we developed contains an SLHA interface that allows the use of MSSM input parameters provided by stand-alone spectrum generators. When our program is run with PYTHIA, decays of the sleptons can be simulated by the Monte-Carlo generator.

We provided representative results for various kinematic distributions of the sleptons and their decay products for a specific point in the MSSM parameter space. Our analysis showed that NLO-QCD corrections modify tree-level predictions for slepton pair production processes significantly. Parton-shower effects can be pronounced for jet observables, while they are typically small for distributions related to the sleptons.

### Note added in proof

During the completion of this work, a similar study appeared [55], containing a simulation of slepton pair production at NLO-QCD in HERWIG++ [56]. Two separate implementations of this reaction in completely different program packages provide excellent means to check the independence of predictions from a specific tool. In this sense, it would be interesting to compare the results of the two implementations in the future.

### Acknowledgments

We are grateful to Alessandro Broggio for numerous helpful discussions and to Christian Speckner and Giulia Zanderighi for valuable comments. This work is supported in part by the Research Center Elementary Forces and Mathematical Foundations (EMG) of the Johannes-Gutenberg-Universität Mainz and by the German Research Foundation (DFG). S. T. is a recipient of a fellowship through the graduate school Symmetry Breaking (DFG/GRK 1581).
References

[1] G. Aad et al. [The ATLAS Collaboration], arXiv:1207.7214 [hep-ex].
[2] S. Chatrchyan et al. [The CMS Collaboration], arXiv:1207.7235 [hep-ex].
[3] M. Kramer et al., arXiv:1206.2892 [hep-ph].
[4] ATLAS collaboration, ATLAS-CONF-2012-076 (2012); http://cdsweb.cern.ch/record/1460273.
[5] LEP SUSY Working Group (ALEPH, DELPHI, L3, OPAL), Notes LEP SUSYWG/01-03.1 and 04-01; http://lepsusy.web.cern.ch/lepsusy/Welcome.html.
[6] H. -U. Martyn and G. A. Blair, in 2nd ECFA/DESY study (1998-2001) 743-747 [hep-ph/9910416].
[7] A. Freitas, A. von Manteuffel and P. M. Zerwas, Eur. Phys. J. C 34 (2004) 487 [hep-ph/0310182].
[8] F. del Aguila and L. Ametller, Phys. Lett. B 261 (1991) 326.
[9] A. Freitas, arXiv:1107.3853 [hep-ph].
[10] H. Baer, C. H. Chen, F. Paige and X. Tata, Phys. Rev. D 49 (1994) 3283 [hep-ph/9311248].
[11] H. Baer, B. W. Harris and M. H. Reno, Phys. Rev. D 57 (1998) 5871 [hep-ph/9712315].
[12] W. Beenakker, M. Klasen, M. Kramer, T. Plehn, M. Spira and P. M. Zerwas, Phys. Rev. Lett. 83 (1999) 3780 [Erratum-ibid. 100 (2008) 029901] [hep-ph/9906298].
[13] W. Beenakker, R. Hopker and M. Spira, hep-ph/9611232.
[14] G. Bozzi, B. Fuks and M. Klasen, Phys. Rev. D 74 (2006) 015001 [hep-ph/0603074].
[15] G. Bozzi, B. Fuks and M. Klasen, Nucl. Phys. B 777 (2007) 157 [hep-ph/0701202].
[16] G. Bozzi, B. Fuks and M. Klasen, Nucl. Phys. B 794 (2008) 46 [arXiv:0709.3057 [hep-ph]].
[17] A. Broggio, M. Neubert and L. Vernazza, JHEP 1205 (2012) 151 [arXiv:1111.6624 [hep-ph]].
[18] G. Marchesini et al., Comp. Phys. Commun. 67 (1992) 465.
[19] G. Corcella et al., JHEP 0101 (2001) 010. [hep-ph/0011363].
[20] T. Sjostrand, S. Mrenna, P. Z. Skands, JHEP 0605 (2006) 026. [hep-ph/0603175].
[21] P. Nason, JHEP 0411 (2004) 040. [hep-ph/0409146].
[22] S. Frixione, P. Nason, C. Oleari, JHEP 0711 (2007) 070. [arXiv:0709.2092 [hep-ph]].
[23] S. Alioli, P. Nason, C. Oleari, E. Re, JHEP 1006 (2010) 043. [arXiv:1002.2581 [hep-ph]].
[24] S. Alioli, P. Nason, C. Oleari and E. Re, JHEP 0807 (2008) 060 [arXiv:0805.4802 [hep-ph]].
[25] S. Frixione, P. Nason and G. Ridolfi, JHEP 0709 (2007) 126 [arXiv:0707.3088 [hep-ph]].
[26] E. Bagnaschi, G. Degrassi, P. Slavich and A. Vicini, JHEP 1202 (2012) 088 [arXiv:1111.2854 [hep-ph]].
[27] M. Klasen, K. Kovarik, P. Nason and C. Weydert, arXiv:1203.1341 [hep-ph].
[28] P. Nogueira, J. Comput. Phys. 105 (1993) 279.
[29] J. A. M. Vermaseren, math-ph/0010025.
[30] J. Kuipers, T. Ueda, J. A. M. Vermaseren and J. Vollinga, arXiv:1203.6543 [cs.SC].
[31] A. Denner, H. Eck, O. Hahn and J. Kublbeck, Nucl. Phys. B 387 (1992) 467.
[32] C. Studerus, Comput. Phys. Commun. 181 (2010) 1293 [arXiv:0912.2546 [physics.comp-ph]].
[33] A. von Manteuffel and C. Studerus, arXiv:1201.4330 [hep-ph].
[34] R. K. Ellis and G. Zanderighi, JHEP 0802 (2008) 002 [arXiv:0712.1851 [hep-ph]].
[35] W. Hollik and D. Stockinger, Eur. Phys. J. C 20 (2001) 105 [hep-ph/0103009].
[36] G. ’t Hooft and M. J. G. Veltman, Nucl. Phys. B 44 (1972) 189.
[37] S. A. Larin, Phys. Lett. B 303, 113 (1993) [hep-ph/9302240].
[38] T. Hahn, Comput. Phys. Commun. 140 (2001) 418 [hep-ph/0012260].
[39] T. Hahn and M. Perez-Victoria, Comput. Phys. Commun. 118 (1999) 153 [hep-ph/9807565].
[40] T. Hahn, Comput. Phys. Commun. 178 (2008) 217 [hep-ph/0611273].
[41] G. J. van Oldenborgh, Comput. Phys. Commun. 66 (1991) 1.
[42] M. S. Chanowitz, M. Furman and I. Hinchliffe, Nucl. Phys. B 159 (1979) 225.
[43] S. Frixione, Z. Kunszt, A. Signer, Nucl. Phys. B467 (1996) 399. [hep-ph/9512328].
[44] P. Z. Slands et al., JHEP 0407 (2004) 036 [hep-ph/0311123].
[45] B. C. Allanach et al., Comput. Phys. Commun. 180 (2009) 8 [arXiv:0801.0045 [hep-ph]].
[46] T. Hahn, Comput. Phys. Commun. 180 (2009) 1681 [hep-ph/0605049].
[47] J. Beringer et al. (Particle Data Group), Phys. Rev. D86 (2012) 010001.
[48] A. D. Martin, W. J. Stirling, R. S. Thorne, G. Watt, Eur. Phys. J. C63 (2009) 189-285. [arXiv:0901.0002 [hep-ph]].
[49] M. R. Whalley, D. Bourilkov, R. C. Group, hep-ph/0508110.
[50] M. Cacciari, G. P. Salam and G. Soyez, JHEP 0804 (2008) 063 [arXiv:0802.1189 [hep-ph]].
[51] M. Cacciari, G. P. Salam, Phys. Lett. B641 (2006) 57 [hep-ph/0512210].
[52] M. Cacciari, G. P. Salam and G. Soyez, arXiv:1111.6097 [hep-ph].
[53] C. G. Lester and D. J. Summers, Phys. Lett. B 463 (1999) 99 [hep-ph/9906349].
[54] H. -C. Cheng and Z. Han, JHEP 0812 (2008) 063 [arXiv:0810.5178 [hep-ph]].
[55] I. Fridman-Rojas and P. Richardson, arXiv:1208.0279 [hep-ph].
[56] M. Bahr et al., Eur. Phys. J. C 58 (2008) 639 [arXiv:0803.0883 [hep-ph]].