Precision predictions for direct gaugino and slepton production at the LHC

B. Fuks
CERN, PH-TH, CH-1211 Geneva 23, Switzerland;
Institut Pluridisciplinaire Hubert Curien/Département Recherches Subatomiques, Université de Strasbourg/CNRS-IN2P3, 23 Rue du Loess, F-67037 Strasbourg, France

M. Klasen, D.R. Lamprea, M. Rothering
Institut für Theoretische Physik, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Straße 9, D-48149 Münster, Germany

Abstract

The search for electroweak superpartners has recently moved to the centre of interest at the LHC. We provide the currently most precise theoretical predictions for these particles, use them to assess the precision of parton shower simulations, and reanalyse public experimental results assuming more general decompositions of gauginos and sleptons.

Keywords:
Supersymmetry, QCD, LHC

1. Introduction

For many theoretical and phenomenological reasons, supersymmetry (SUSY) remains one of the best motivated extensions of the Standard Model (SM) of particle physics. The strongly interacting superpartners in the Minimal SUSY SM (MSSM), the first- and second-generation squarks and gluinos, are largely restricted after the first LHC run at 7 and 8 TeV centre-of-mass energy to be heavier than 1 TeV. However, this is not the case for stops, which play a central role in explaining the relatively large mass of the SM-like Higgs boson, and the electroweakly interacting sleptons and gauginos, which provide natural candidates for the dark matter in the universe. The search for these particles has therefore recently moved to the centre of interest at the LHC.

LHC analyses on SUSY particle searches rely heavily on precision calculations of SM backgrounds and SUSY signals. At next-to-leading order (NLO) of QCD, SUSY production cross sections have been calculated more than a decade ago [1, 2, 3, 4, 5, 6, 7]. More recently, resummation methods have been applied at next-to-leading logarithmic (NLL) accuracy [8]. Here, we present our NLO+NLL calculations for direct gaugino [9, 10, 11, 12] and slepton [13, 14, 15, 16] production near threshold and close to vanishing transverse momentum ($p_T$), use them to assess the precision of parton shower simulations, and reanalyse public experimental results assuming more general decompositions of gauginos and sleptons.

2. Resummation

The hadronic cross section for the production of SUSY particles at the LHC

$$\sigma_{pp} = f_{a/p}(x_a, \mu_f) \otimes f_{b/p}(x_b, \mu_f) \otimes \sum_{n=0}^{\infty} \alpha_s^n(\mu_r) \sigma_{ab}^{(n)}(\mu_r, \mu_f)$$

is obtained by a convolution of the parton densities (PDFs) $f(x, \mu_f)$, that depend on the partonic momentum fraction $x$ and the factorisation scale $\mu_f$, with the partonic cross section $\sigma_{ab}$, that can be expanded in powers of the strong coupling constant $\alpha_s(\mu_r)$ running with the renormalisation scale $\mu_r$. 
Near production threshold, where the ratio of the squared invariant mass $M^2$ of the produced particle pair over the partonic centre-of-mass energy $s$, $z = M^2/s$, approaches unity, the cross section exhibits logarithmic enhancements,

$$\sigma^{(n)}(z) = \sum_{m=0}^{2n-1} c^{(m)} \left[ \frac{\ln^m(1-z)}{(1-z)} \right].$$

(2)

After applying a Mellin transform, e.g.

$$\left[ \frac{\ln^m(1-z)}{(1-z)} \right] \rightarrow \ln^{m+1}(N),$$

(3)

these logarithmically enhanced terms, coming from soft gluon radiation, can be resummed to all orders,

$$\sigma^{(n)}(N) = H_{qg} \cdot \exp\left(\tilde{c}^{(1)} \ln(N) + \tilde{c}^{(2)} + \ldots\right),$$

(4)

where $H$ represents the hard, non-singular part and $\tilde{c}^{(i)}$ are universal coefficients. Since also the dominant collinear $1/N_C$ terms ($N_C$ being the number of colours in QCD) are universal, they can also be exponentiated in a so-called “collinear improved” resummation calculation [17].

A second critical region is encountered when the transverse momentum of the produced particle pair tends to zero, $p_T \to 0$. There, the cross section behaves as

$$\sigma^{(n)}(p_T) = \sum_{m=0}^{2n-1} c^{(m)} \left[ \frac{1}{p_T^2} \ln^m\left(\frac{M^2}{p_T^2}\right) \right].$$

(5)

After applying a Fourier transform,

$$\left[ \frac{1}{p_T^2} \ln^m\left(\frac{M^2}{p_T^2}\right) \right] \rightarrow \ln^{m+1}\left(\frac{M^2 b_0^2}{b_0^2} + 1\right)$$

(6)

with $b_0 = 2e^{-\gamma_E}$, the logarithms can again be resummed to all orders,

$$\sigma^{(n)}(N) = H_{qg} \cdot \exp\left(\tilde{c}^{(1)} \ln(b) + \tilde{c}^{(2)} + \ldots\right).$$

(7)

Since the threshold and transverse-momentum logarithms are of the same kinematic origin, i.e. soft gluon radiation, they can also be resummed jointly in $(N, b)$ space.

To achieve the best possible accuracy over the full kinematic ranges, the fixed-order and resummed results are added. However, since the logarithmically enhanced terms are present in both parts, this overlap must be subtracted to avoid double counting,

$$\sigma_{ab} = \sigma_{ab}^{\text{ LO}} + \sigma_{ab}^{\text{ res}} - \sigma_{ab}^{\text{ exp}}.$$

(8)

| $(m_{1/2}, m_0)$ | $m_h$ | $\langle m_{h} \rangle$ | $\text{BR}(\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 h)$ |
|----------------|-------|------------------|------------------|
| (600, 400)    | 1370  | 1275             | 92%              |

Table 1: Our constrained MSSM benchmark point with $\tan\beta = 10$ and $A_0 = 0$ GeV. All mass are in units of GeV, and the gluino and average squark masses are rounded to 5 GeV accuracy.

Distributions in the measured quantities $M$ and $p_T$ are then obtained by applying an inverse Mellin transform

$$M^2 \frac{d\sigma_{AB}(\tau)}{dM^2} = \frac{1}{2\pi i} \int_{C_N} dN r^{-N} M^2 \frac{d\sigma_{AB}(N)}{dM^2}$$

(9)

with the so-called minimal prescription, where an integration contour $C_N$ is defined by $N = C + ze^{i\phi}$ and $\tau \in [0; \infty]$, and an inverse Fourier transform

$$\frac{d\sigma}{dp_T^2} = \frac{M^2}{s} \int_0^\infty \frac{db}{2} J_0(b p_T) \, d\sigma(b)$$

(10)

with a deformed contour $b = (\cos \phi + i \sin \phi) t$ and $t \in [0; \infty]$ for a proper treatment of all encountered poles in the complex plane.

3. Gauginos

Using the resummation formalisms described briefly above, we demonstrate the impact of our precision predictions for gaugino pair production at the LHC with a centre-of-mass energy of $\sqrt{s} = 8$ TeV at the constrained MSSM benchmark point defined in Tab. $1_t$. It features sufficiently high squark and gluino masses, that are not yet excluded, and an interestingly large branching fraction of the second lightest neutralino into the lightest neutralino and the SM-like Higgs boson. The neutralino/chargegaino masses are 250 GeV for $\tilde{\chi}_1^0$, 472 GeV for $\tilde{\chi}_2^0/\tilde{\chi}_1^0$, and 766 for $\tilde{\chi}_3^0/\tilde{\chi}_2^0$, and the corresponding total cross sections are shown in Tab. $2_t$. As one can see, they are often increased, in particular from LO to NLO and, as one approaches the production threshold, also from NLO to NLL, and the scale uncertainty is always considerably stabilised.

It is interesting to compare the NLL threshold resummed results with a Monte Carlo prediction at LO using the multi-parton generator MadGraph [18] and the PYTHIA [19] parton shower. As one can see in Fig. 1, the NLL+NLO invariant mass distribution (red, thick full) agrees in general very well with the Monte Carlo results obtained after matching matrix elements containing no (green, dotted), one (blue, dashed), and up to two (red, dot-dashed) additional jets to parton showering. As the NLO+NLL calculation does not contain more
4. Sleptons

The production of slepton ($\tilde{\ell}$) pairs has so far been analysed by the LHC experiments ATLAS and CMS using simplified models. In particular, they assume a flavour-conserving decay into a SM lepton $l$ and the lightest SUSY particle (LSP, $\chi_1^0$), while all other SUSY particles, in particular the squarks and gluinos, are assumed to be heavy and to decouple. The experimental signature is then a pair of same-flavour leptons and missing transverse energy ($E_T$).

In our (re-)analysis [21], we take into account different slepton flavors (also $\tilde{\tau}$), both left- and right-handed sleptons (incl. mixing for staus) [22], and a different gaugino or higgsino nature of lightest neutralino [23]. The stau mass eigenstates are in particular obtained through

$$\begin{pmatrix} \tilde{\tau}_1 \\ \tilde{\tau}_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_{\tilde{\tau}} & \sin \theta_{\tilde{\tau}} \\ -\sin \theta_{\tilde{\tau}} & \cos \theta_{\tilde{\tau}} \end{pmatrix} \begin{pmatrix} \tilde{\tau}_L \\ \tilde{\tau}_R \end{pmatrix}.$$  

Their couplings to $Z$ bosons and neutralinos are given by

$$C_Z^{\tau} = \left[ -\frac{1}{2} + \frac{\tilde{\tau}_w^2}{\tilde{\tau}_w^2} \cos^2 \theta_{\tilde{\tau}} + \frac{\tilde{\tau}_w^2}{\tilde{\tau}_w^2} \sin^2 \theta_{\tilde{\tau}} \right]$$

$$C_{\tau N}^{(\tau L)} = \sqrt{2} \tilde{\tau}_w s_{\tilde{\tau}} N_{\tilde{\tau}}^1 \cos \theta_{\tilde{\tau}} - 2 c_{\tilde{\tau}} w s_{\tilde{\tau}} N_{\tilde{\tau}}^2 y_{\tilde{\tau}} \sin \theta_{\tilde{\tau}}$$

$$C_{\tau N}^{(\tau R)} = -2 \sqrt{2} \tilde{\tau}_w s_{\tilde{\tau}} N_{\tilde{\tau}} \sin \theta_{\tilde{\tau}} - 2 c_{\tilde{\tau}} w s_{\tilde{\tau}} N_{\tilde{\tau}}^2 y_{\tilde{\tau}} \cos \theta_{\tilde{\tau}}$$

where $y_{\tilde{\tau}}$ denotes the tau lepton Yukawa coupling, which in the case of third-generation (s)leptons cannot be neglected. The four neutralino mixing parameters are constrained by a unitarity relation,

$$|N_1|^2 + |N_2|^2 + |N_3|^2 + |N_4|^2 = 1.$$
Figure 3: Total cross sections for stau pair production at the LHC, running at centre-of-mass energies of 8 TeV. We present predictions as functions of the stau mass and the stau mixing angle after matching the NLO results with threshold resummation at the NLL accuracy.

Figure 4: 95% confidence exclusion limit for left-handed selectron pair production, given in the \((M_{\tilde{e}_L}, M_{\tilde{\chi}_0^1})\) mass plane of a simplified model for different choices of the neutralino nature taken as bino (top) and wino (bottom). We present the visible cross section after applying the ATLAS selection strategy. The limits are extracted for 4.7 fb\(^{-1}\) of LHC collisions at a centre-of-mass energy of 7 TeV.

Figure 4: 95% confidence exclusion limit for left-handed selectron pair production, given in the \((M_{\tilde{e}_L}, M_{\tilde{\chi}_0^1})\) mass plane of a simplified model for different choices of the neutralino nature taken as bino (top) and wino (bottom). We present the visible cross section after applying the ATLAS selection strategy. The limits are extracted for 4.7 fb\(^{-1}\) of LHC collisions at a centre-of-mass energy of 7 TeV.

5. Conclusion

The most precise electroweak SUSY particle production cross sections at NLO+NLL are by now routinely taken into account by the LHC experiments ATLAS and CMS for gaugino/higgsino and slepton searches, in particular when deriving exclusion limits. The corresponding computer code RESUMMINO has been made public and is available for use in experimental analyses and
Figure 5: 95% confidence exclusion limit for left-handed (top) and right-handed (bottom) smuon pair production, given in the $(M_1, M_{\tilde{l}_R})$ mass plane of a simplified model for mixed bino-wino neutralino nature. We present the visible cross section after applying the ATLAS selection strategy. The limits are extracted for 4.7 fb$^{-1}$ of LHC collisions at a centre-of-mass energy of 7 TeV.

References

[1] W. Beenakker, R. Hopker, M. Spira and P. M. Zerwas, Nucl. Phys. B 492 (1997) 51 [hep-ph/9610490].
[2] W. Beenakker, M. Kramer, T. Plehn, M. Spira and P. M. Zerwas, Nucl. Phys. B 515 (1998) 3 [hep-ph/9710451].
[3] E. L. Berger, M. Klasen and T. M. P. Tait, Phys. Rev. D 59 (1999) 074024 [hep-ph/9807230].
[4] 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].
[5] E. L. Berger, M. Klasen and T. M. P. Tait, Phys. Lett. B 459 (1999) 165 [hep-ph/9902350].
[6] E. L. Berger, M. Klasen and T. M. P. Tait, Phys. Rev. D 62 (2000) 095014 [hep-ph/0005196] and Phys. Rev. D 67 (2003) 099901 [hep-ph/0212306].
[7] M. Spira, hep-ph/0211145.
[8] M. Kramer, A. Kulesza, R. van der Leeuw, M. Mangano, S. Padhi, T. Plehn and X. Portell, arXiv:1206.2892 [hep-ph] and references therein.
[9] J. Debove, B. Fuks and M. Klasen, Phys. Lett. B 688 (2010) 208 [arXiv:0907.1105 [hep-ph]].
[10] J. Debove, B. Fuks and M. Klasen, Nucl. Phys. B 842 (2011) 51 [arXiv:1005.2909 [hep-ph]].
[11] J. Debove, B. Fuks and M. Klasen, Nucl. Phys. B 849 (2011) 64 [arXiv:1102.4422 [hep-ph]].
[12] B. Fuks, M. Klasen, D. R. Lamprea and M. Rothering, JHEP 1210 (2012) 081 [arXiv:1207.2159 [hep-ph]].
[13] G. Bozzi, B. Fuks and M. Klasen, Phys. Rev. D 74 (2006) 015001 [hep-ph/0603074].
[14] G. Bozzi, B. Fuks and M. Klasen, Nucl. Phys. B 777 (2007) 157 [hep-ph/0701202].
[15] G. Bozzi, B. Fuks and M. Klasen, Nucl. Phys. B 794 (2008) 46 [arXiv:0709.3057 [hep-ph]].
[16] B. Fuks, M. Klasen, D. R. Lamprea and M. Rothering, JHEP 1401 (2014) 168 [arXiv:1310.2621, arXiv:1310.2621 [hep-ph]].
[17] M. Kramer, E. Laenen and M. Spira, Nucl. Phys. B 511 (1998) 523 [hep-ph/9611272].
[18] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, JHEP 1106 (2011) 128 [arXiv:1106.0522 [hep-ph]].
[19] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP 0605 (2006) 026 [hep-ph/0603175].
[20] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A. D. Polosa, JHEP 0307 (2003) 001 [hep-ph/0206293].
[21] E. Conte, B. Fuks and G. Serret, Comput. Phys. Commun. 184 (2013) 222 [arXiv:1206.1599 [hep-ph]].
[22] G. Bozzi, B. Fuks and M. Klasen, Phys. Lett. B 609 (2005) 339 [hep-ph/0411318].
[23] J. Debove, B. Fuks and M. Klasen, Phys. Rev. D 78 (2008) 074020 [arXiv:0804.0423 [hep-ph]].
[24] G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 718 (2013) 879 [arXiv:1208.2884 [hep-ex]].
[25] B. Fuks, M. Klasen, D. R. Lamprea and M. Rothering, Eur. Phys. J. C 73 (2013) 2480 [arXiv:1304.0790 [hep-ph]].
[26] B. Fuks, M. Klasen, F. Ledroit, Q. Li and J. Morel, Nucl. Phys. B 797 (2008) 322 [arXiv:0711.0749 [hep-ph]].