PROCEEDINGS OF SCIENCE

Soft gluon resummation for associated squark-gaugino production at the LHC

Alexander Puck Neuwirth[a,*]

[a] *Institut für Theoretische Physik, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Straße 9, 48149 Münster, Germany*

E-mail: alexander.neuwirth@wwu.de

Due to the greater precision expected from LHC Run 3, similarly accurate theoretical predictions are essential. With increasing supersymmetry mass limits, predictions can be improved by including next-to-leading logarithms. We investigate the impact of threshold resummation on associated squark-electroweakino production at the LHC and find a slightly increased total cross section. In addition, the uncertainty of the factorisation and renormalisation scale is significantly reduced to the same order of magnitude as the PDF uncertainty.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

*Speaker

PoS(ICHEP2022)134

1. Introduction

In the upcoming LHC Run 3, extensions to the Standard Model (SM) such as Supersymmetry (SUSY) will be further explored. The Minimal Supersymmetric Standard Model (MSSM) can answer some open questions in the SM by providing a Dark Matter candidate, predicting the unification of strong and electroweak forces at large scales, and protecting the mass of the Higgs boson from radiative corrections. The associated production of a squark or gluino with an electroweakino becomes important, as light SUSY particles are ruled out by searches at the LHC, and squarks and gluinos turn out to be too heavy to be produced in pairs. The semi-strong production of a strongly interacting superpartner and an electroweak superpartner provide cross sections of intermediate size and a larger available phase space, since a typically lighter electroweakino is present in the final state. These processes have already been studied at LO [1, 2], NLO [3–6] and NLO+PS [7]. Current mass limits also imply that the kinematic configuration in each SUSY production process approaches the production threshold. This leads to large threshold logarithms that ruin the convergence of the perturbation series, so that they have to be resummed. Soft-gluon resummation takes these logarithms into account to reduce theoretical uncertainties, which can otherwise become quite large. Accurate predictions of strong [8–12] and electroweak [13–17] SUSY processes beyond NLO through resummation have been achieved over the past decade.

We briefly outline the threshold resummation formalism that can be used for such precision calculations in section 2 and illustrate its main effects on the associated squark-electroweakino production in section 3. We summarize our work in section 4.

2. Soft gluon resummation

Large logarithms can remain close to the threshold region after the soft and collinear divergences between the real and virtual corrections have been cancelled due to the different phase spaces [18, 19]. Since these logarithms spoil the convergence of fixed-order calculations, soft gluon emissions must be included up to all orders. To achieve this, the calculation must factorize both dynamically, by using eikonal Feynman rules, and kinematically, by transforming into Mellin space. Then, the large logarithms depend on the Mellin variable N and the hadronic differential cross section $\mathrm{d}\sigma_{AB}/\mathrm{d}M^2$ in the conjugate N-space depends on the invariant mass M, parton densities $f_{i/h}$ and partonic cross section σ_{ab} [20],

$$M^2\frac{\mathrm{d}\sigma_{AB}}{\mathrm{d}M^2}(N-1) = \sum_{a,b} f_{a/A}(N,\mu_F^2)\, f_{b/B}(N,\mu_F^2)\, \sigma_{ab}(N,M^2,\mu_F^2,\mu_R^2)\,. \tag{1}$$

Soft and collinear gluon radiation is included in the Sudakov form factors G. In particular, for squark-electroweakino production $G^{(2)}_{ab\to ij}$ contains the process-dependent modified soft anomalous dimension closely related to the topologically similar production of tW [21]. Next, the partonic cross section, which depends on both the factorisation scale μ_F and the renormalisation scale μ_R, is expressed in an exponential form scaled by the hard function $\mathcal{H}$,

$$\sigma^{\mathrm{Res.}}_{ab\to ij}(N,M^2,\mu^2_{F,R}) = \mathcal{H}_{ab\to ij}(M^2,\mu^2_{F,R})\ \exp\Big[\underbrace{LG^{(1)}_{ab}(N)}_{\mathrm{LL}} + \underbrace{G^{(2)}_{ab\to ij}(N,M^2,\mu^2_{F,R})}_{\mathrm{NLL}} + \dots\Big] \tag{2}$$

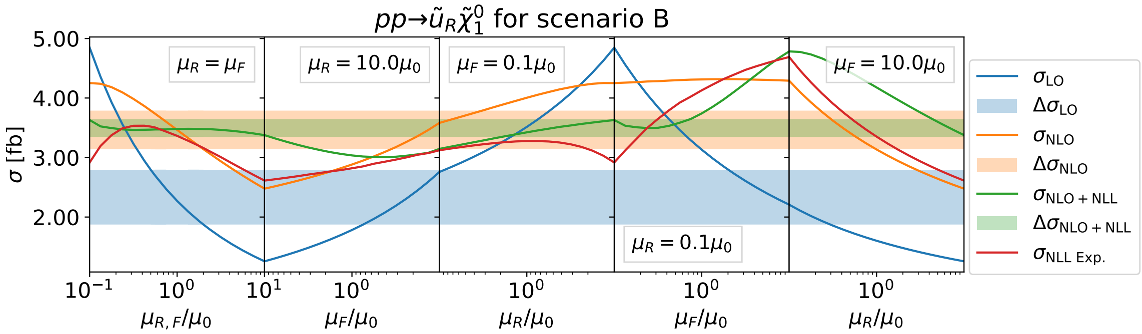


Figure 1: Profile of the renormalisation and factorisation scale dependence of the total cross section in the process $pp \to \tilde{u}_R\tilde{\chi}_1^0$ at $\sqrt{S} = 13$ TeV. The plots cover $\mu_{F,R} \in (0.1 - 10)\mu_0$ (reversed in panels 2 and 3) with the central scale $\mu_0 = (m_{\tilde{q}} + m_{\tilde{\chi}})/2$. The bands show the scale uncertainties from the seven-point method.

truncated to the next-to-leading logarithmic order (NLL). Because squark-electroweakino production includes only one colour basis tensor, the irreducible colour representation index can be neglected [22]. To consistently include these logarithms, we subtract the resummed cross section $\sigma^{\text{Res.}}$ expanded to $O(\alpha_s^2)$,

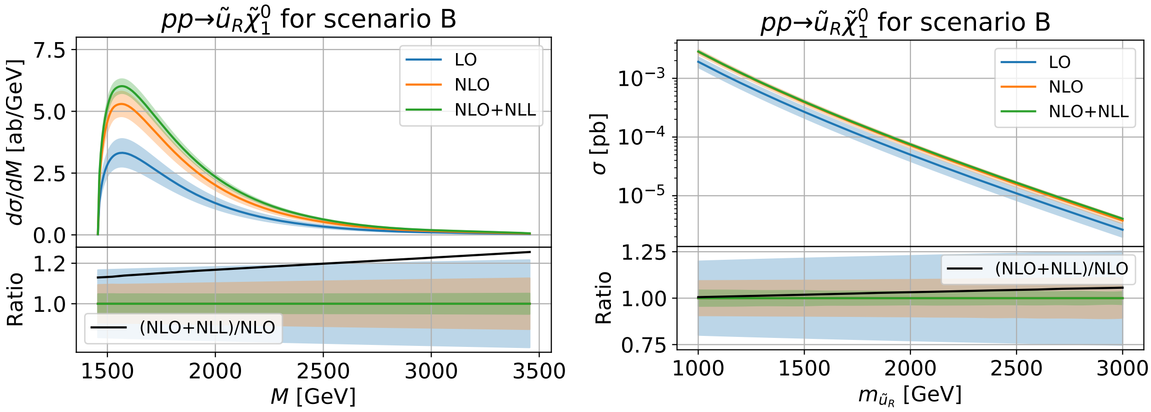
$$\sigma_{ab} = \sigma_{ab}^{\text{NLO}} + \sigma_{ab}^{\text{Res.}} - \sigma_{ab}^{\text{Exp.}} . \tag{3}$$

The double counting of $O(\alpha_s^2)$ contributions, which are already entirely included in the complete next-to-leading order calculation σ^{NLO} is thus eliminated. Due to singularities in the N-space cross section a distorted integration contour according to the principal value procedure and minimal prescription is required in order to return from Mellin space by an inverse transformation [23, 24].

3. Squark-electroweakino production at NLO+NLL accuracy

Fig. 1 focuses on the scale dependence of the total cross section for a pMSSM-11 scenario using $m_{\tilde{q}} = 1$ TeV, $m_{\tilde{\chi}_1^0} = 0.5$ TeV and $m_{\tilde{g}} = 3$ TeV [25]. The uncertainty bands are determined by the seven-point method, whereby the factorisation and renormalisation scales are varied independently by factors of 2 around the central scale $\mu_0 = (m_{\tilde{q}} + m_{\tilde{\chi}})/2$, excluding relative factors of 4, which translates to $1/2 \le \mu_R/\mu_F \le 2$. At large scales, the logarithms become dominant and the expansion $\sigma^{\text{Exp.}}$ approaches the NLO σ^{NLO}. We observe that the resummation reduces the scale uncertainty significantly, and only increases the cross section at the central scale for heavier superpartners (cf. Fig. 2). In several scenarios we have observed that the relative scale uncertainty decreases from about 20 % at LO to 10 % at NLO and finally to below 5 % at NLO+NLL.

The invariant mass distribution is shown on the left in Fig. 2. We approach the threshold region $M^2/s \to 1$ as the invariant mass M increases, and the NLL corrections contribute significantly more to the differential cross section. This behaviour is captured by the NLL+NLO/NLO K-factors shown in the lower panels of the figure. The lower panels also display the relative seven-point scale uncertainty, with the scale varying around a central scale choice of $\mu_0 = M$. The second figure shows the total cross section at $\mu_0 = (m_{\tilde{q}} + m_{\tilde{\chi}})/2$. While the central cross section increases by 50 % from LO to NLO, the additional increase from NLL resummation reaches only about 6 % in the mass ranges observable to the LHC in the near future. As expected, the production of right-handed squarks is slightly suppressed compared to the left-handed squarks [25].



(a) Invariant mass distribution.

(b) Total cross section by the squark mass $m_{\tilde{u}_R}$.

Figure 2: For the process $pp \to \tilde{u}_R\tilde{\chi}_1^0$ at $\sqrt{S} = 13$ TeV we show the mass dependence of the cross section. The lower panels show relative scale uncertainties and (NLO+NLL)/NLO K-factors.

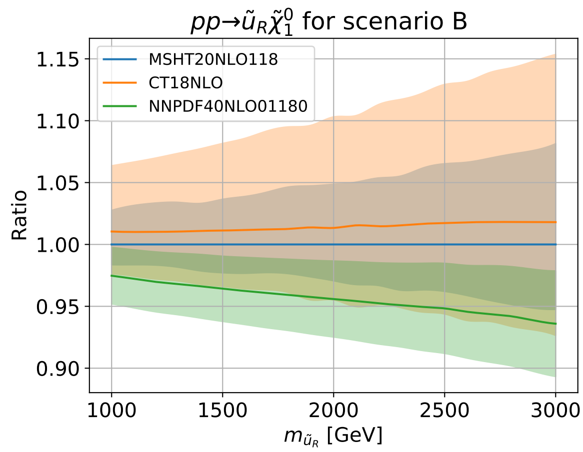


Figure 3: Relative PDF uncertainties at 90 % confidence level for the total cross sections of the process $pp \to \tilde{u}_R\tilde{\chi}_1^0$ at $\sqrt{S} = 13$ TeV and NLO+NLL.

Fig. 3 shows the uncertainties of the parton distribution functions MSHT20, CT18 and NNPDF40. Although the uncertainty for 1 TeV squarks is around 5 %, it increases up to 10 % to 15 % for squark masses of 3 TeV. The central cross section values obtained with the MSHT20 and CT18 sets agree consistently. The NNPDF40 predictions are a few percent lower, but still agree fairly well within their uncertainty intervals.

4. Summary

We have presented a threshold resummation calculation with NLO+NLL precision for the associated production of a squark and an electroweakino at the LHC. We have consistently combined the resummation of large logarithms that appear close to threshold with NLO results by matching fixed order and resummed predictions. The NLL resummation increased the NLO cross sections for central scales by up to 6 % and reduced the scale uncertainty below ±5 %. The uncertainty of the parton distribution functions is of the same order of magnitude, but becomes dominant for very massive final states. Our calculation adds squark-electroweakino production to existing slepton pair, electroweakino pair and electroweakino-gluino production in the public code RESUMMINO (resummino.hepforge.org).

References

[1] V.D. Barger, R.W. Robinett, W.-Y. Keung and R.J.N. Phillips, *Production of Gauge Fermions at Colliders*, *Phys. Lett. B* **131** (1983) 372.

[2] S. Dawson, E. Eichten and C. Quigg, *Search for Supersymmetric Particles in Hadron - Hadron Collisions*, *Phys. Rev. D* **31** (1985) 1581.

[3] E.L. Berger, M. Klasen and T.M.P. Tait, *Next-to-leading order SUSY QCD predictions for associated production of gauginos and gluinos*, *Phys. Rev. D* **62** (2000) 095014 [hep-ph/0212306].

[4] M. Spira, *Higgs and SUSY particle production at hadron colliders*, in *10th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY02)*, pp. 217–226, 11, 2002 [hep-ph/0211145].

[5] T. Binoth, D. Goncalves Netto, D. Lopez-Val, K. Mawatari, T. Plehn and I. Wigmore, *Automized Squark-Neutralino Production to Next-to-Leading Order*, *Phys. Rev. D* **84** (2011) 075005 [1108.1250].

[6] S. Frixione, B. Fuks, V. Hirschi, K. Mawatari, H.-S. Shao, P.A. Sunder et al., *Automated simulations beyond the Standard Model: supersymmetry*, *JHEP* **12** (2019) 008 [1907.04898].

[7] J. Baglio, G. Coniglio, B. Jager and M. Spira, *Next-to-leading-order QCD corrections and parton-shower effects for weakino+squark production at the LHC*, *JHEP* **12** (2021) 020 [2110.04211].

[8] A. Kulesza and L. Motyka, *Threshold resummation for squark-antisquark and gluino-pair production at the LHC*, *Phys. Rev. Lett.* **102** (2009) 111802 [0807.2405].

[9] W. Beenakker, S. Brensing, M. Kramer, A. Kulesza, E. Laenen and I. Niessen, *Soft-gluon resummation for squark and gluino hadroproduction*, *JHEP* **12** (2009) 041 [0909.4418].

[10] W. Beenakker, S. Brensing, M. Kramer, A. Kulesza, E. Laenen and I. Niessen, *NNLL resummation for squark-antisquark pair production at the LHC*, *JHEP* **01** (2012) 076 [1110.2446].

[11] W. Beenakker, C. Borschensky, M. Krämer, A. Kulesza, E. Laenen, V. Theeuwes et al., *NNLL resummation for squark and gluino production at the LHC*, *JHEP* **12** (2014) 023 [1404.3134].

[12] W. Beenakker, C. Borschensky, R. Heger, M. Krämer, A. Kulesza and E. Laenen, *NNLL resummation for stop pair-production at the LHC*, *JHEP* **05** (2016) 153 [1601.02954].

[13] G. Bozzi, B. Fuks and M. Klasen, *Threshold Resummation for Slepton-Pair Production at Hadron Colliders*, *Nucl. Phys. B* **777** (2007) 157 [hep-ph/0701202].

[14] J. Debove, B. Fuks and M. Klasen, *Threshold resummation for gaugino pair production at hadron colliders*, *Nucl. Phys. B* **842** (2011) 51 [1005.2909].

[15] B. Fuks, M. Klasen, D.R. Lamprea and M. Rothering, *Precision predictions for electroweak superpartner production at hadron colliders with Resummino*, *Eur. Phys. J. C* **73** (2013) 2480 [1304.0790].

[16] B. Fuks, M. Klasen and M. Rothering, *Soft gluon resummation for associated gluino-gaugino production at the LHC*, *JHEP* **07** (2016) 053 [1604.01023].

[17] J. Fiaschi, M. Klasen and M. Sunder, *Slepton pair production with aNNLO+NNLL precision*, *JHEP* **04** (2020) 049 [1911.02419].

[18] T. Kinoshita, *Mass singularities of Feynman amplitudes*, *J. Math. Phys.* **3** (1962) 650.

[19] T.D. Lee and M. Nauenberg, *Degenerate Systems and Mass Singularities*, *Phys. Rev.* **133** (1964) B1549.

[20] J.C. Collins, D.E. Soper and G.F. Sterman, *Factorization of Hard Processes in QCD*, *Adv. Ser. Direct. High Energy Phys.* **5** (1989) 1 [hep-ph/0409313].

[21] N. Kidonakis, *Single top production at the Tevatron: Threshold resummation and finite-order soft gluon corrections*, *Phys. Rev. D* **74** (2006) 114012 [hep-ph/0609287].

[22] W. Beenakker, T. Janssen, S. Lepoeter, M. Krämer, A. Kulesza, E. Laenen et al., *Towards NNLL resummation: hard matching coefficients for squark and gluino hadroproduction*, *JHEP* **10** (2013) 120 [1304.6354].

[23] H. Contopanagos and G.F. Sterman, *Principal value resummation*, *Nucl. Phys. B* **419** (1994) 77 [hep-ph/9310313].

[24] S. Catani, M.L. Mangano, P. Nason and L. Trentadue, *The Resummation of soft gluons in hadronic collisions*, *Nucl. Phys. B* **478** (1996) 273 [hep-ph/9604351].

[25] J. Fiaschi, B. Fuks, M. Klasen and A. Neuwirth, *Soft gluon resummation for associated squark-electroweakino production at the LHC*, *JHEP* **06** (2022) 130 [2202.13416].