Transverse-Momentum Resummation for Slepton-Pair Production at the LHC

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We perform a first precision calculation of the transverse-momentum ($q_T$) distribution of slepton pair and slepton-sneutrino associated production at the CERN Large Hadron Collider (LHC). We implement soft-gluon resummation at the next-to-leading logarithmic (NLL) level and consistently match the obtained result to the pure fixed-order perturbative result at leading order (LO) in the QCD coupling constant, i.e. $O(\alpha_s)$. We give numerical predictions for $\tilde{\tau}_1\tilde{\tau}_1^*$ and $\tilde{\tau}_1\tilde{\nu}_\tau^* + \tilde{\tau}_1\tilde{\nu}_\tau$ production, also implementing recent parameterizations of non-perturbative effects. The results show a relevant contribution of resummation both in the small and intermediate $q_T$-regions and little dependence on unphysical scales and non-perturbative contributions.

INTRODUCTION

The Minimal Supersymmetric Standard Model (MSSM) [1, 2] is one of the most promising extensions of the Standard Model (SM) of particle physics. It postulates a symmetry between fermionic and bosonic degrees of freedom in nature and predicts the existence of a fermionic (bosonic) supersymmetric (SUSY) partner for each bosonic (fermionic) SM particle. It provides a qualitative understanding of various phenomena in particle physics, as it stabilizes the gap between the Planck and the electroweak scale [3], leads to gauge coupling unification in a straightforward way [4], and includes the lightest supersymmetric particle as a dark matter candidate [5]. Therefore the search for supersymmetric particles is one of the main topics in the experimental program of present (Fermilab Tevatron) and future (CERN LHC) hadron colliders.

SUSY must be broken at low energy, since spin partners of the SM particles have not yet been observed. As a consequence, the squarks, sleptons, charginos, neutralinos and gluino of the MSSM must be massive in comparison to their SM counterparts. The LHC will perform a conclusive search covering a wide range of masses up to the TeV scale. Total production cross sections for SUSY particles at hadron colliders have been extensively studied in the past at leading order (LO) [6–8] and also at next-to-leading order (NLO) of perturbative QCD [9–15].

We focus our attention on slepton pair (slepton-sneutrino associated) production at the LHC through the neutral (charged) current Drell-Yan (DY) type processes

$$q\bar{q} \rightarrow \gamma, Z^0 \rightarrow \tilde{l}\tilde{l}^*, \quad q\bar{q}' \rightarrow W^+ \rightarrow l\tilde{\nu}_l^*, l'^*\tilde{\nu}_{l'}.$$  

Due to their purely electroweak couplings, sleptons are among the lightest SUSY particles in many SUSY-breaking scenarios [16]. Sleptons and sneutrinos often decay directly into the stable lightest SUSY particle (lightest neutralino in mSUGRA models or gravitino in GMSB models) plus the corresponding SM partner (lepton or neutrino). As a result, the slepton signal at hadron colliders will consist in a highly energetic lepton pair, which will be easily detectable, and associated missing energy.

In this Letter, we study the transverse-momentum ($q_T$) distribution of the slepton pair. Since in hadronic collisions the longitudinal momentum balance is unknown, a precise knowledge of the $q_T$-balance is of vital importance for the discovery of SUSY particles. In the case of sleptons, the Cambridge (s)transverse mass $m_T$ proves to be particularly useful for the reconstruction of their masses [17] and determination of their spin [18], the two key features that distinguish them from SM leptons produced mainly in WW or $t\bar{t}$ decays [19, 20]. Furthermore, both detector kinematical acceptance and efficiency depend, of course, on $q_T$.

When studying the $q_T$-distribution of a slepton pair produced with invariant mass $M$ in a hadronic collision, it is appropriate to separate the large-$q_T$ and small-$q_T$ regions. In the large-$q_T$ region ($q_T \geq M$) the use of fixed-order perturbation theory is fully justified, since the perturbative series is controlled by a small expansion parameter, $\alpha_s(M^2)$. The QCD [14] and full SUSY-QCD [15] corrections for slepton pair production are known to increase the hadronic cross sections by about 25% at the Tevatron and 35% at the LHC, thus extending their discovery reaches by several tens of GeV. Recently the LO calculation for slepton pair production has been extended to include mixing between left- and right-handed sfermions and longitudinal beam polarization [21].

The bulk of the events will be produced in the small-$q_T$ region, where the coefficients of the perturbative expansion in $\alpha_s(M^2)$ are enhanced by powers of large logarithmic terms, $\ln(M^2/q_T^2)$. As a consequence, results based on fixed-order calculations diverge as $q_T \rightarrow 0$, and the convergence of the perturbative series is spoiled. These logarithms are due to multiple soft-gluon emission from the initial state and have to be systematically resummed to all orders in $\alpha_s$ in order to obtain reliable perturbative predictions. The method to perform all-order soft-gluon resummation at small $q_T$ is well known [22–32]. The resummation of leading logs was first performed in [22].
It was shown in [23] that the resummation procedure is most naturally performed using the impact-parameter \((b)\) formalism, where \(b\) is the variable conjugate to \(q_T\) through a Fourier transformation, to allow the kinematics of multiple gluon emission to factorize. In the special case of DY lepton pair or electroweak boson production, \(b\)-space resummation was performed at next-to-leading level in [25], an all-order resummation formalism was developed in [29], and the next-to-next-to-leading order terms have been calculated in [30].

At intermediate \(q_T\) the resummed result has to be consistently matched with fixed-order perturbation theory in order to obtain predictions with uniform theoretical accuracy over the entire range of transverse momenta.

In this work we implement the formalism proposed in [31, 32] and compute the \(q_T\)-distribution of a slepton pair produced at the LHC by combining NLL resummation at small \(q_T\) and LO \(\mathcal{O}(\alpha_s)\) perturbation theory at large \(q_T\).

\section*{\(q_T\)-Resummation at the NLL Level}

The partonic cross section for DY slepton pair production can be written as

\[
\frac{d\hat{\sigma}_{ab}}{dM^2 dq_T^2} = \frac{d\hat{\sigma}_{ab}^{(\text{res.})}}{dM^2 dq_T^2} + \frac{d\hat{\sigma}_{ab}^{(\text{fin.})}}{dM^2 dq_T^2},
\]

where \(a, b\) label the partons which take part in the hard process. The resummed contribution can be written as

\[
\frac{d\hat{\sigma}_{ab}^{(\text{res.})}}{dM^2 dq_T^2}(q_T, M, \hat{s}; \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2) = \frac{M^2}{\hat{s}} \int_0^\infty db b J_0(bq_T) \mathcal{W}_{ab}(b, M, \hat{s}; \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2),
\]

where \(J_0(x)\) is the 0-th order Bessel function, \(\mu_R\) (\(\mu_F\)) is the renormalization (factorization) scale, and \(\hat{s}\) is the partonic center-of-mass (CM) energy.

The perturbative function \(\mathcal{W}\) embodies the all-order dependence on the large logarithms \(\ln(M^2/b^2)\). They correspond, in the conjugate space, to the previously mentioned terms, \(\ln(M^2/q_0^2)\), that spoil the convergence of the perturbative series at small \(q_T\) (large \(b\)). Performing a Mellin transformation with respect to the variable \(z = M^2/\hat{s}\) at fixed \(M\), we can define the \(N\)-moments \(\mathcal{W}_N\) of \(\mathcal{W}\) and express them in an exponential form

\[
\mathcal{W}_N(b, M; \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2) = \mathcal{H}_N(M, \alpha_s(\mu_R^2); M^2/\mu_R^2, M^2/\mu_F^2, M^2/Q^2) \times \exp\{g_N(\alpha_s(\mu_R^2), L; M^2/\mu_R^2, M^2/Q^2)\},
\]

where constant \(i.e., \) finite as \(q_T \to 0\) and logarithmically divergent terms are factorized into the functions \(\mathcal{H}_N\) and \(g_N\), respectively. This factorization implies some degree of arbitrariness, and the scale \(Q\) is introduced to parameterize this uncertainty. As in the case of \(\mu_R\) and \(\mu_F\), one should set \(Q = M\) and estimate the uncertainty from uncalculated subleading logarithmic corrections by varying \(Q\) around this central value.

The function \(\mathcal{H}_N\) does not depend on the impact parameter \(b\) and, therefore, it contains all the perturbative terms that behave as constants in the limit \(b \to \infty\). In addition it contains the whole process dependence as well as factorization scale and scheme dependence. Its expansion in powers of \(\alpha_s\) gives

\[
\mathcal{H}_N(M, \alpha_s; M^2/\mu_R^2, M^2/\mu_F^2, M^2/Q^2) = \sigma^{(0)}(\alpha_s, M) \left[ 1 + \frac{\alpha_s}{\pi} \mathcal{H}_N^{(1)}(M^2/\mu_R^2, M^2/\mu_F^2, M^2/Q^2) + \left(\frac{\alpha_s}{\pi}\right)^2 \mathcal{H}_N^{(2)}(M^2/\mu_R^2, M^2/\mu_F^2, M^2/Q^2) + \ldots \right],
\]

where \(\sigma^{(0)}\) is the lowest-order partonic cross section for the hard-scattering process. The coefficient \(\mathcal{H}_N^{(1)}\) splits into a process-independent flavor off-diagonal contribution and a process-dependent [33, 34] flavor diagonal contribution. The general expression for \(\mathcal{H}_N^{(1)}\), needed to perform a NLL analysis, can be found in [32]. The second order coefficient \(\mathcal{H}_N^{(2)}\) has not yet been computed.

The exponent \(g_N\) includes all the terms that are logarithmically divergent when \(b \to \infty\) \((q_T \to 0)\) \(i.e.,\) proportional to \(L = \ln(M^2/b^2)\), where \(b_0 = 2e^{-\gamma_E}\) and \(\gamma_E\) is the Euler number). However these terms become large both for small and large \(b\)-values, introducing unjustified large contributions also at large \(q_T\). It is useful to introduce a modified expression of the expansion parameter,

\[
\tilde{L} \equiv \ln\left(\frac{Q^2 b^2}{b_0^2} + 1\right).
\]
The second term \( (d\sigma^{(6n.)}_{ab})/dM^{2}dq_{T}^{2} ) \) in Eq. (2) is free of divergent contributions and can be computed by fixed-order truncation of the perturbative series. In order to be consistently matched with the resummed contribution at intermediate \( q_{T} \) \( (q_{T} \simeq M) \), this term should be evaluated starting from the usual perturbative truncation of the partonic cross section and subtracting from it the expansion of the resummed part at the same perturbative order. This matching procedure between small- and large- \( q_{T} \) regions prevents double-counting (or neglecting) of perturbative contributions and guarantees a uniform theoretical accuracy over the entire transverse-momentum spectrum. Since the fixed-order cross section for slepton production at non-vanishing transverse-momentum is known at LO (slepton pair + one parton) \( [14, 15] \), we can only consistently perform a NLL+LO matching.

The above formalism refers to a purely perturbative framework. Nonetheless it is known \( [27] \) that the transverse-momentum distribution is affected by non-perturbative (NP) effects which become important in the large- \( b \) region. In the case of electroweak boson production, these contributions are usually parameterized by multiplying the function \( W \) in Eq. (3) by a NP form factor \( F^{NP}(b) \) \( [35–39] \), whose coefficients are obtained through global fits to DY data. We include in our analysis three different parameterizations of NP effects corresponding to three different choices of the form factor: the Ladinsky-Yuan (LY-G) \( [36] \), Brock-Landry-Nadolsky-Yuan (BLNY) \( [38] \), and the recent Konychev-Nadolsky (KN) \( [39] \) form factor.

**SLEPTON PAIR PRODUCTION AT THE LHC**

In this Section we present quantitative results for the \( q_{T} \)-spectrum of slepton pair (slepton-sneutrino associated) production at NLL+LO accuracy at the LHC collider. We focus our study on the lightest slepton mass eigenstate \( \tilde{\tau}_{1} \) and thus we consider the processes

\[
\begin{align*}
q\bar{q} & \rightarrow \gamma, Z^{0} \rightarrow \tilde{\tau}_{1}\tilde{\tau}_{1}^{*}, \\
q\bar{q}' & \rightarrow W^{\pm} \rightarrow \tilde{\tau}_{1}\tilde{\nu}_{\tau}^{*}, \tilde{\tau}_{1}^{*}\tilde{\nu}_{\tau}.
\end{align*}
\]

We use the MRST (2004) NLO set of parton distribution functions \( [40] \) and \( \alpha_{s} \) evaluated at two-loop accuracy. We fix the resummation scale \( Q \) equal to the invariant mass \( M \) of the slepton (slepton-sneutrino) pair and we allow \( \mu = \mu_{F} = \mu_{R} \) to vary between \( M/2 \) and \( 2M \) to estimate the perturbative uncertainty. We also integrate Eq. (2) with respect to \( M^{2} \), taking as lower limit the energy threshold for \( \tilde{\tau}_{1}\tilde{\tau}_{1}^{*}(\tilde{\tau}_{1}\tilde{\nu}_{\tau}) \) production and as upper limit the hadronic energy \( (\sqrt{S}=14 \text{ TeV} \text{ at the LHC}) \).

In the case of \( \tilde{\tau}_{1}\tilde{\tau}_{1}^{*} \) production (neutral current process, see Fig. 1), we choose the SPS7 mSUGRA benchmark point \( [16] \) which gives, after the renormalization group (RG) evolution of the SUSY-breaking parameters performed by the SUSPECT computer program \( [41] \), a light \( \tilde{\tau}_{1} \) of mass \( m_{\tilde{\tau}_{1}} = 114 \text{ GeV} \).

In the case of \( \tilde{\tau}_{1}\tilde{\nu}_{\tau}^{*} + \tilde{\tau}_{1}^{*}\tilde{\nu}_{\tau} \) production (charged current process, see Fig. 2), we use instead the SPS1 mSUGRA benchmark point which gives a light \( \tilde{\tau}_{1} \) of mass \( m_{\tilde{\tau}_{1}} = 136 \text{ GeV} \) as well as a light \( \tilde{\nu}_{\tau} \) of mass \( m_{\tilde{\nu}_{\tau}} = 196 \text{ GeV} \).

In both cases we plot the LO result (dashed line), the expansion of the resummation formula at LO (dotted line), the total NLL+LO matched result (solid line), the uncertainty band from scale variation, and the quantity

\[
\Delta = \frac{d\sigma^{\text{res.}+\text{NP}}(\mu=M) - d\sigma^{\text{res.}}(\mu=M)}{d\sigma^{\text{res.}}(\mu=M)}.
\]

The parameter \( \Delta \) gives thus an estimate of the contributions from the different NP parametrizations (LY-G, BLNY, KN) that we included in the resummed formula.

We can see that the LO result diverges to \( +\infty \), as expected, for both processes as \( q_{T} \rightarrow 0 \), and the asymptotic expansion of the resummation formula at LO is in very good agreement with LO both at small and intermediate values of \( q_{T} \). The effect of resummation is clearly visible at small and intermediate values of \( q_{T} \). The resummation-improved result being nearly 39% (36%) higher at \( q_{T} = 50 \text{ GeV} \) than the pure fixed order result in the neutral (charged) current case. When integrated over \( q_{T} \), the former leads to a total cross section of 66.8 fb (12.9 fb) in good agreement (within 3.5%) with the QCD-corrected total cross section at \( \mathcal{O}(\alpha_{s}) \) \( [15] \).

The scale dependence is clearly improved in both cases with respect to the pure fixed-order calculations. In the small and intermediate \( q_{T} \)-region (up to 100 GeV) the effect of scale variation is 10% for the LO result, while it
numerical results show the importance of resummed slepton-sneutrino associated production at the LHC. The resummation has been performed by applying the spectrum for SUSY particle production at hadron colliders, thus considerably smaller than resummation effects.

is always less than 5\% for the NLL+LO curve. Finally, non-perturbative contributions are under good control. Their effect is always less than 5\% for $q_T > 5$ GeV and thus considerably smaller than resummation effects.

CONCLUSIONS

In this Letter, a first precision calculation of the $q_T$-spectrum for SUSY particle production at hadron colliders has been performed by applying the $q_T$-resummation formalism at the NLL+LO level to slepton pair and slepton-sneutrino associated production at the LHC. The numerical results show the importance of resummed contributions at small and intermediate values of $q_T$, both enhancing the pure fixed-order result and reducing the scale uncertainty.

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