Polarization and Resummation in Slepton Production at Hadron Colliders

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In R-parity conserving supersymmetric (SUSY) models, sleptons are produced in pairs at hadron colliders through neutral and charged electroweak currents. We demonstrate that the polarization of the initial hadron beams allows for a direct extraction of the slepton mixing angle and thus for a determination of the underlying SUSY-breaking mechanism. We also perform a first precision calculation of the transverse-momentum ($q_T$) spectrum of the slepton pairs by resumming soft multiple-gluon emission at next-to-leading logarithmic order. The results show a relevant contribution of resummation both in the small and intermediate $q_T$-regions, which strongly influences the extraction of the missing transverse-momentum signal and the subsequent slepton mass-determination, and little dependence on unphysical scales and non-perturbative contributions.

1. Introduction

The Minimal Supersymmetric Standard Model (MSSM) 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, leads to gauge coupling unification in a straightforward way, and includes the lightest supersymmetric particle as a dark matter candidate. 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) and also at next-to-leading order (NLO) of perturbative QCD.

2. LO cross section with polarization

Despite the first successful runs of the RHIC collider in the polarized $pp$ mode (and due to its limited energy range of $\sqrt{s} \leq 500$ GeV), polarized SUSY production cross sections have received much less attention. Only the pioneering LO calculations for massless squark and gluino production have recently been confirmed, extended to the massive case, and applied to current hadron colliders.

Due to their purely electroweak couplings, sleptons are among the lightest SUSY particles in many SUSY-breaking scenarios. 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.

The neutral current cross section for the production of non-mixing slepton pairs in collisions of quarks with definite helicities has been calcu-
lated in \[17\]. In general SUSY-breaking models, where the sfermion interaction eigenstates are not identical to the respective mass eigenstates, the left- and right-handed coupling strengths must be multiplied by $S_j S_i^* (i, j = L, R)$, respectively, where the unitary matrix $S$ diagonalizes the sfermion mass matrix, $S M S^\dagger = \text{diag}(m_1^2, m_2^2)$. These slepton mixing effects have recently been included in the polarized hadroproduction cross section \[18\].

One can then calculate the longitudinal double-spin asymmetry, however with the result that

$$A_{LL} = \frac{d\Delta \hat{\sigma}_{LL}}{d\hat{\sigma}} = -1$$

is totally independent of all SUSY-breaking parameters. It is thus far more interesting to calculate the single-spin asymmetry $A_L = d\Delta \hat{\sigma}_L/d\hat{\sigma}$ from the polarized differential cross section

$$d\Delta \hat{\sigma}_L = \frac{d\hat{\sigma}_{1,1} + d\hat{\sigma}_{1,-1} - d\hat{\sigma}_{-1,1} - d\hat{\sigma}_{-1,-1}}{4}, \tag{2}$$

i.e. for the case of only one polarized hadron beam. Not only does the neutral current cross section remain sensitive to the SUSY-breaking parameters, but even more the squared photon contribution, which is insensitive to these parameters, is eliminated. Finally, this scenario may also be easier to implement experimentally, e.g. at the Tevatron, since protons are much more easily polarized than antiprotons \[19\].

For the only existing polarized hadron collider RHIC, which will be operating at a center-of-mass energy of $\sqrt{s} = 500$ GeV in the near future, and in the GMSB model with a light tau slepton, we show the single-spin asymmetry in Fig. 2 as a function of the cosine of the stau mixing angle. The asymmetry is quite large and depends strongly on the stau mixing angle. However, very large values of $\cos \theta_\tau$ and stau masses below 52 GeV may already be excluded by LEP \[20\], while small values of $\cos \theta_\tau$ may be unaccessible at RHIC due to its limited luminosity, which is not expected to exceed 1 fb$^{-1}$. Polarization of the proton beam will also not be perfect, and the calculated asymmetries should be multiplied by the degree of beam polarization $P_L \simeq 0.7$. The uncertainty introduced by the polarized parton densities increases considerably to the left of the plot, where the stau mass $41 \text{ GeV} \leq m_\tau \leq 156 \text{ GeV}$ and the associated values of the parton momentum fractions $x_{a,b} \simeq 2m_\tau/\sqrt{s}$ become large.

The SM background cross section can be reduced by imposing an invariant mass cut on the observed lepton pair, e.g. of 2-52 GeV. While the cross section of 0.13 pb is then still two orders of magnitude larger than the SUSY signal cross section of 1 fb, the SM asymmetry of -0.04 for standard polarized parton densities or -0.10 for the valence-type polarized parton densities can clearly be distinguished from the SUSY signal due to its different sign.

3. Total cross section at NLO

The QCD corrections to the total slepton-pair production cross section in quark-antiquark annihilation are completely equivalent to those encountered in the Drell-Yan process and have been calculated (for the unpolarized case) in Ref. \[11\].
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Figure 2. Ratios of the total NLO SUSY-QCD cross sections to the corresponding LO cross sections for slepton-pair production at the LHC (full) and Tevatron (dashed) as a function of the squark mass \(m_{\tilde{q}}\) for a gluino mass of 200 GeV and slepton masses of \(\tilde{e}/\tilde{\nu} = 120/150/135\) GeV.

\[ \mathcal{O}(\alpha_s), \] also the SUSY-QCD corrections must be added, which affect the \(q\bar{q}V\) vertices [12]. Since heavy-mass SUSY particles (squarks and gluinos) are involved in the loops, the genuine SUSY corrections are expected to be considerably smaller than the standard QCD corrections.

This is indeed borne out by detailed calculations, an example of which is presented in Fig. 2. The SUSY-QCD \(K\)-factors differ little from the QCD \(K\)-factors, which are approached in the asymptotic limit of large \(q/\bar{q}\) masses at the right-hand \(y\)-axis of the figure. The QCD corrections to the production of \(\mu\) and \(\tau\) pairs follow the same pattern for equivalent invariant masses of the pairs.

4. Transverse-momentum distribution at NLL

Since in hadronic collisions the longitudinal momentum balance is unknown, a precise knowledge of the transverse-momentum \((q_T)\) balance is of vital importance for the discovery of SUSY particles. In the case of sleptons, the Cambridge (s)transverse mass \(m_{T2}\) proves to be particularly useful for the reconstruction of their masses [21] and determination of their spin [22], the two key features that distinguish them from SM leptons produced mainly in \(WW\) or \(t\bar{t}\) decays [23,24]. Furthermore, both detector kinematic 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 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 logarithms, \(\ln(M^2/q_T^2)\). As a consequence, results based on fixed-order calculations diverge as \(q_T \to 0\), 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 [26]. 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.

We have recently implemented the formalism proposed in [25] and computed 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 \(q_T\) [27]. In this computation, we use the MRST (2004) NLO set of parton distribution functions [27] 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 the double-differential cross section \(d\sigma/dM^2 dq_T^2\) with respect to \(M^2\), taking as lower limit the energy threshold for \(\tilde{\tau} \tilde{\nu}_L \tilde{\tau} \tilde{\nu}_L\) production and as upper limit the hadronic en-


\[ \Delta = \frac{d\sigma^{\text{res.+NP}}(\mu = M) - d\sigma^{\text{res.}}(\mu = M)}{d\sigma^{\text{res.}}(\mu = M)} \]  \hspace{1cm} (3)

The parameter \( \Delta \) gives thus an estimate of the contributions from different NP parameterizations (LY-G [29], BLNY [30], KN [31]) that we included in the resummed formula.

We can see that the LO result diverges to \(+\infty\), as expected, for both processes as \( q_T \to 0 \), and that 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 \( q_T = 50 \) 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 \( \mathcal{O}(\alpha_s) \) [12].

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 is always less than 5% for the NLL+LO curve. Fi-
nally, non-perturbative contributions are under good control. Their effect is always less than 5% for \( q_T > 5 \text{ GeV} \) and thus considerably smaller than resummation effects.

5. Conclusions

The recent luminosity upgrade of the Tevatron and the imminent start-up of the LHC put the discovery of SUSY particles with masses up to the TeV-scale within reach. Since this discovery depends critically on the missing transverse-energy signal, a precise knowledge not only of the total cross section, but also of the \( q_T \)-spectrum is mandatory. We have performed a first step in this direction by resumming multiple soft-gluon emission for slepton-pair production at next-to-leading logarithmic order and matching it to the fixed-order calculation. We demonstrated that the total cross section at NLO is reproduced very well. (S)transverse mass measurements will then lead to precise slepton mass and spin determinations, while polarization of the initial hadron beams may allow for an extraction of the slepton mixing angle and the underlying SUSY-breaking parameters.

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