$\mathscr{O}(\alpha_s^2)$ QCD corrections to the resonant sneutrino / slepton production at LHC

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We present a complete next to next to leading order QCD corrections to the resonant production of sneutrino and charged slepton at the Tevatron and the Large Hadron Collider within the context of R-parity violating supersymmetric model. We have demonstrated the role of NNLO QCD corrections in reducing uncertainties resulting from renormalisation and factorisation scales and thereby making our predictions reliable.

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1. Introduction

In supersymmetry[1], *R*-parity violation is one of the possible scenario in beyond standard model physics. With many interest, we consider only on the λ'_{ijk} couplings which arises in lepton number violating term in *R*-parity violation superpotential given below

$$\mathcal{W} = \mu_i L_i H_2 + \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c \,, \tag{1.1}$$

where L_i and Q_i are the $SU(2)$-doublet lepton and quark superfields, E_i^c, U_i^c, D_i^c the singlet super-fields and H_i the Higgs superfields. The subscripts i, j, k are generational indices. Note that λ_{ijk} is antisymmetric under the interchange of the first two indices and λ''_{ijk} is antisymmetric under the interchange of the last two. The first three terms in eqn.(1.1) violate lepton number (*L*) and the last term violates baryon number (*B*) conservation.

Recently ATLAS group have been studied resonant production of heavy neutral scalar like sneutrino and subsequent decay to $e\mu$ final state. In their analysis, they put the bounds on sneutrino masses (see Ref.[2]) on the basis of leading order (LO) result. In tevatron, both CDF[3] and D0[4] collaboration analyse their data (Run-I as well as Run-II data) using our first results[5] on the next to leading order (NLO) QCD corrections to sneutrino and charged slepton productions at hadron colliders. In their analysis to set bound on these R-parity violating couplings, cross section for SM background processes namely Drell-Yan production of pair of leptons (say $l^+l^-, l^\pm \nu$) (see first two papers of [16]) was considered at the next to next to leading order (NNLO) level while for the R-parity violating effects only NLO corrected cross section was used. It was found that the NLO QCD effects were quite large $\sim 10\% - 40\%$ at both Tevatron as well as LHC Therefore, it is desirable to compute the cross sections for the resonant sneutrino and/or charged slepton productions at NNLO in QCD. These results will quantitatively improve the analysis based on high statistics data available in the ongoing and future experiments. From the theoretical point of view, higher order radiative corrections provide a test of the convergence of the perturbation theory and hence the reliable comparison of data with the theory predictions is possible. The fixed order perturbative results most often suffer from large uncertainties due to the presence of renormalisation and factorisation scales. They get reduced as we include more and more terms in the perturbative expansion thanks to renormalisation group invariance. In this article we have systematically included its scale dependence through the renormalisation group equations and we discussed the impact of it in the next sections.

2. Brief discussion of NNLO calculations

In this section, we describe very briefly, the computation of second order (α_s^2) QCD radiative corrections to resonant production, in hadron colliders, of a sneutrino/charged slepton. We present our results in such a way that they can be used for any scalar-pseudoscalar production which is the main goal of this work. The inclusive hadronic cross section for the reaction

$$H_1(P_1) + H_2(P_2) \rightarrow \phi(p_\phi) + X \,, \tag{2.1}$$

is given by

$$\sigma_{\text{tot}}^\phi = \frac{\pi \lambda'^2(\mu_R^2)}{12 S} \sum_{a,b=q,\bar{q},g} \int_\tau^1 \frac{dx_1}{x_1} \int_{\tau/x_1}^1 \frac{dx_2}{x_2} f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \Delta_{ab} \left(\frac{\tau}{x_1 x_2}, m_\phi^2, \mu_F^2, \mu_R^2 \right)$$

$$\text{with} \quad \tau = \frac{m_\phi^2}{S} \quad , \quad S = (P_1 + P_2)^2 \quad , \quad p_\phi^2 = m_\phi^2, \tag{2.2}$$

where H_1 and H_2 denote the incoming hadrons and X represents an inclusive hadronic state. The parton densities denoted by $f_c(x_i, \mu_F^2)$ ($c = q, \bar{q}, g$) depend on the scaling variables x_i ($i = 1, 2$) through $p_i = x_i P_i$ and the mass factorization scale μ_F. Here p_i ($i = 1, 2$) are the momenta of incoming partons namely quarks, antiquarks and gluons. The coupling constant λ' gets renormalised at the renormalisation scale μ_R due to ultraviolet singularities present in the theory. The factorisation scale is introduced on the right hand side of the above equation to separate long distant dynamics from the perturbatively calculable short distant partonic coefficient functions Δ_{ab}. Δ_{ab} depends on both μ_R and μ_F in such a way that the entire scale dependence goes away to all orders in perturbation theory when convoluted with appropriate parton densities. This is due to the fact that the observable on the left hand side of the above equation is renormalisation group (RG) invariant with respect to both the scales. This implies

$$\mu^2 \frac{d\sigma_{\text{tot}}^\phi}{d\mu^2} = 0, \qquad \mu = \mu_F, \mu_R, \tag{2.3}$$

$$\mu_R^2 \frac{d}{d\mu_R^2} \left[\lambda'^2(\mu_R^2) \Delta_{ab} \left(x, m_\phi^2, \mu_F^2, \mu_R^2 \right) \right] = 0. \tag{2.4}$$

The partonic coefficient functions that appear in eqn.(2.2) are computable in perturbative QCD in terms of strong coupling constant g_s. The ultraviolet singularities present in the theory are regularised in dimensional regularisation and are removed in $\overline{MS}$ scheme, introducing the renormalisation scale μ_R at every order in perturbative expansion. In addition, the Yukawa coupling λ' also gets renormalised due to strong interaction dynamics. Hence, for our computation, we require only two renormalisation constants to obtain UV finite partonic coefficient functions, Δ_{ab}. These constants are denoted by $Z(\mu_R)$ and $Z_{\lambda'}(\mu_R)$, where the former renormalises the strong coupling constant g_s and the later Yukawa coupling λ' and both the couplings $a_s(= g_s/(4\pi))$ (and λ') evolve with scale to NNLO through renormalisation group equations:

$$\mu_R^2 \frac{d}{d\mu_R^2} \ln a_s(\mu_R^2) = -\sum_{i=1}^\infty a_s^i(\mu_R^2) \, \beta_{i-1},$$
$$\mu_R^2 \frac{d}{d\mu_R^2} \ln \lambda'(\mu_R^2) = -\sum_{i=1}^\infty a_s^i(\mu_R^2) \, \gamma_{i-1}. \tag{2.5}$$

where coefficients β_i for $i = 0, ..., 3$ can be found in [6] for $SU(N)$ QCD. The anomalous dimensions γ_i for $i = 0, ..., 3$ can be obtained from the quark mass anomalous dimensions given in [7]. The perturbatively calculable Δ_{ab} can be expanded in powers of strong coupling constant $a_s(\mu_R^2)$ as

$$\Delta_{ab} \left(x, m_\phi^2, \mu_F^2, \mu_R^2 \right) = \sum_{i=0}^\infty a_s^i(\mu_R^2) \Delta_{ab}^{(i)} \left(x, m_\phi^2, \mu_F^2, \mu_R^2 \right).$$

Δ_{ab} gets contributions from various partonic reactions.

    The calculation of various contributions from the partonic reactions involves careful handling of divergences that result from one[8] and two loop[9] integrations in the virtual processes and

two and three body phase space integrations in the real emission processes. The loop integrals often give ultraviolet, soft and collinear divergences. But the phase space integrals give only soft and collinear singularities. Soft divergences arise when the momenta of the gluons become zero while the collinear diverges arise due to the presence of massless partons. We have regulated all the integrals in dimensional regularisation with space time dimension $n = 4 + \varepsilon$. The singularities manifest themselves as poles in ε.

We have reduced all the one loop tensorial integrals to scalar integrals using the method of Passarino-Veltman [10] in $4 + \varepsilon$ dimensions and evaluated resultant scalar integrals exactly. The 2-loop form factor, $\mathscr{F}_\phi(m_\phi^2, \mu^2)$, is calculated using the dispersion technique [11]. Two and three body phase space integrals are done by choosing appropriate Lorentz frames[12]. Since we integrate over the total phase space the integrals are Lorentz invariant and therefore frame independent. Several routines are made using the algebraic manipulation program FORM[13] in order to perform tensorial reduction of one loop integrals and two and three body phase space integrals.

The UV singularities go away after performing renormalisation through the constants Z and $Z_{\lambda'}$. The soft singularities cancel among virtual and real emission processes[14] at every order in perturbation theory. The remaining collinear singularities are renormalised systematically using mass factorisation[15]. For more details on the computation of NNLO QCD corrections to process of the kind considered here can be found in [16, 17]. The full analytical results for NNLO calculation for sneutrino and/or charge slepton can be found out in our original paper[17].

3. Results and Discussion

We considered only the contributions from the first generation of quarks. Since at hadron colliders, the resonant production is through the interaction term $\lambda'_{ijk} L_i Q_j D_k^c$ in the Lagrangian (see eq.(1.1)), for $j, k = 2, 3$, the production rate will be suppressed due to the low flux of the sea quarks. To obtain the production cross section to a particular order, one has to convolute the partonic coefficient functions Δ_{ab} with the corresponding parton densities f_a, both to the same order. Further the coupling constants $a_s(\mu_R)$ and $\lambda'(\mu_R)$ should also be evaluated using the corresponding RGEs (eqn.(2.5)) computed to the same order (more details see Ref[7, 18]). We have used the latest MSTW parton densities [19] in our numerical code and the corresponding values of $\alpha_s(M_Z)$ for LO, NLO and NNLO provided with the sets. Since we are considering one λ'_{i11} non-zero, the LO and NLO cross sections get contributions only from $d\bar{d}$, dg and $\bar{d}g$ initiated subprocesses and no other quark (antiquark) flavors contribute to this order. At NNLO level, the incoming quarks other than d type quarks can also contribute. The total sneutrino production cross section as function of its mass is plotted in fig. 1 for LHC (left panel) and Run II of Tevatron (right panel) energies. We have set the renormalisation scale to be the mass of the sneutrino, $\mu_R = m_{\tilde{v}}$. The pair of lines corresponds to the two extreme choices of factorisation scale: $\mu_F = 10\, m_{\tilde{v}}$ (upper) and $\mu_F = m_{\tilde{v}}/10$ (lower). The plots clearly demonstrate that the NNLO contributions reduce the factorisation scale dependence improving the theoretical predictions for sneutrino production cross section.

The cross section falls off with the sneutrino mass due to the availability of phase space with respect to the mass, the choice of $\mu_R = m_{\tilde{v}}$ and the parton densities. The latter effect, understandably, is more pronounced at the Tevatron than at the LHC.
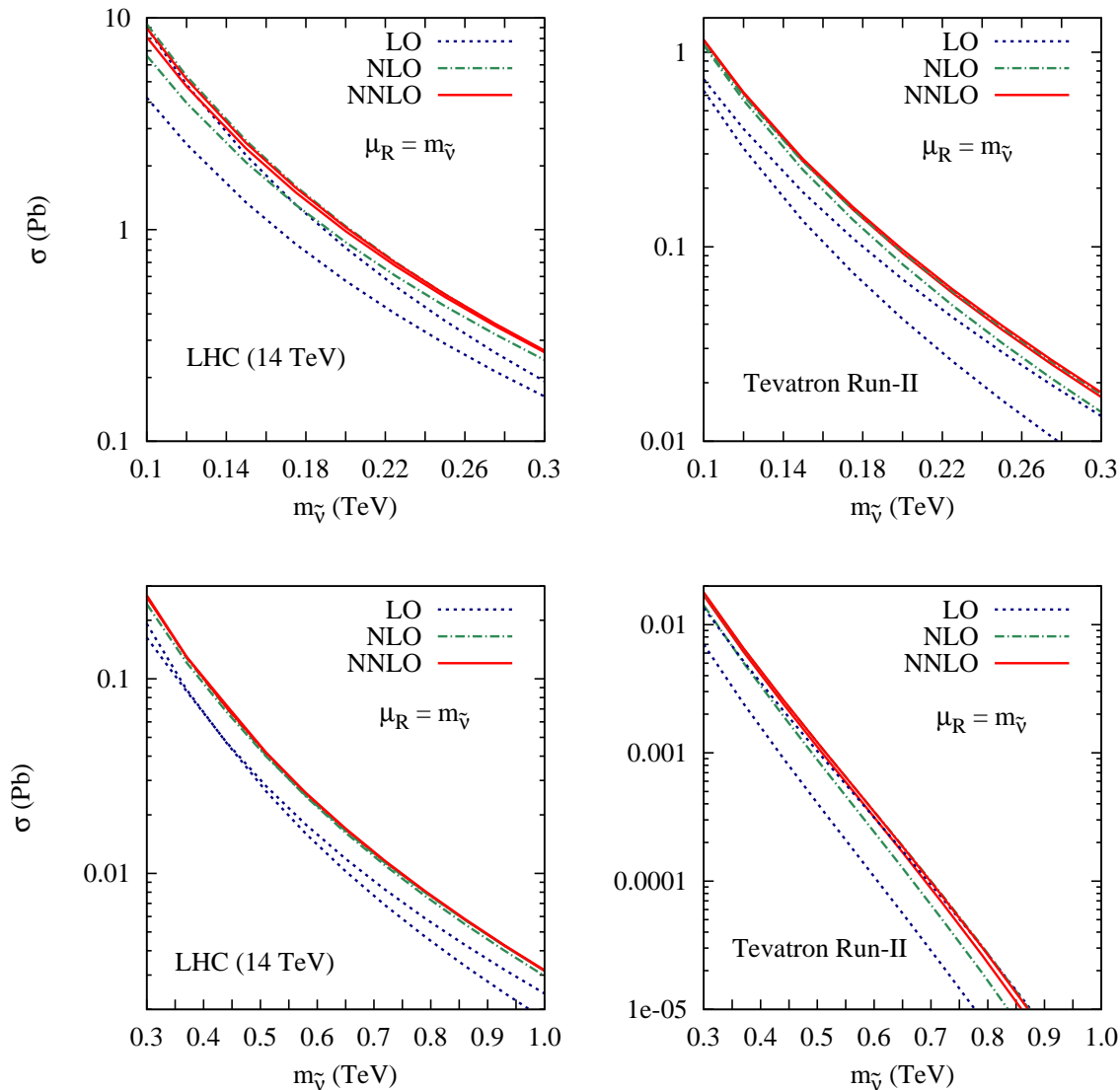
Figure 1: *Total cross-section for the $\tilde{\nu}$ production as a function of $m_{\tilde{\nu}}$. For smaller values of sneutrino mass the upper (lower) set of lines correspond to the factorisation scale $\mu_F = 10m_{\tilde{\nu}}(0.1m_{\tilde{\nu}})$. For larger values of sneutrino mass the lines cross each other.*

In order to estimate the magnitude of the QCD corrections at NLO and NNLO, we define the K-factors as follows:

$$K^{(1)} = \sigma^{\phi}_{tot,\text{NLO}}/\sigma^{\phi}_{tot,\text{LO}}, \qquad K^{(2)} = \sigma^{\phi}_{tot,\text{NNLO}}/\sigma^{\phi}_{tot,\text{LO}}.$$

In fig.2, we have plotted both $K^{(i)}$ ($i = 1,2$) as a function of sneutrino mass. We have chosen $\mu_F = \mu_R = m_{\tilde{\nu}}$ for this study. At the LHC, The $K^{(1)}$ varies between 1.23 to 1.46 and $K^{(2)}$ between 1.27 to 1.52 in the mass range $100\ GeV \leq m_{\nu} \leq 1\ TeV$. At the Tevatron, we find that $K^{(1)}$ varies between 1.55 to 1.53 and $K^{(2)}$ between 1.65 to 1.85 for the same mass range. Note that numbers for $K^{(1)}$ differ from those given in our earlier work [5] due to the running of λ' in the present analysis. The present analysis using running λ' is the correct way to reduce renormalisation scale dependence in the cross section. We also observe that K factor is much bigger at the Tevatron
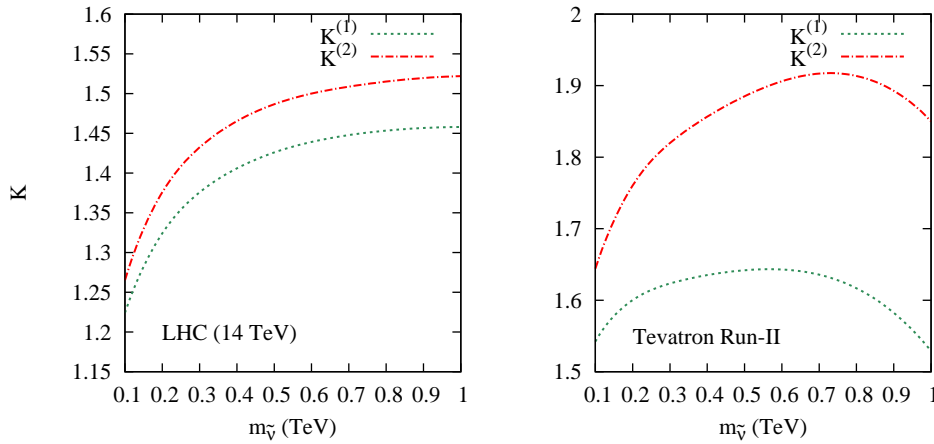
Figure 2: *NLO K-factor $K^{(1)}$ and NNLO K-factor $K^{(2)}$ are plotted for sneutrino production at the LHC (left panel) and the Tevatron Run-II (right panel) as a function of its mass.*

compared to that of at the LHC. The reason behind this is attributed to the different behavior of parton densities at the Tevatron and the LHC. Note that parton densities rise steeply as $x \to 0$ and fall off very fast as $x \to 1$, which means the dominant contribution to the production results from the phase space region where $x \sim \tau(= m_{\tilde{v}}^2/S)$ becomes small. τ at Tevatron ($0.05 \lesssim \tau \lesssim 0.5$) is larger compared to that at LHC ($0.007 \lesssim \tau \lesssim 0.07$) (see also fig.2). Because of this, at Tevatron the valence quark initiated processes dominate while gluon and sea quark initiated processes dominate at the LHC. As the mass of the sneutrino increases, that is x approaches to unity, the K-factor at Tevatron naturally falls off. At LHC, in the higher mass region (~ 1 TeV), valence quark densities start to dominate and hence it stays almost flat compared to Tevatron. We now turn to study the impact of the factorisation scale (μ_F) and the renormalisation scale (μ_R) on the production cross section. The factorisation scale dependence for both LHC (left panel) and Tevatron (right panel) are shown in upper panels of fig. 3, for $m_{\tilde{v}} = 300$ *GeV* (LHC), $m_{\tilde{v}} = 120$ *GeV* (Tevatron). We have chosen $\mu_R = m_{\tilde{v}}$ for both the LHC and the Tevatron. The factorisation scale is varied between $\mu_F = 0.1\, m_{\tilde{v}}$ and $\mu_F = 10\, m_{\tilde{v}}$. We find that the factorisation scale dependence decreases in going from LO to NLO to NNLO as expected.

The dependence of the renormalisation scale dependence on the total cross sections for the resonant production of sneutrino at the LHC and the Tevatron is shown in the lower panels of fig. 3. Note that the LO is already μ_R dependent due to the coupling $\lambda'(\mu_R)$. We have performed this analysis for sneutrino mass $m_{\tilde{v}} = 300$ *GeV* (LHC), $m_{\tilde{v}} = 120$ *GeV* (Tevatron). We have set the factorisation scale $\mu_F = m_{\tilde{v}}$ and the renormalisation scale is varied in the range $0.1 \leq \mu_R/m_{\tilde{v}} \leq 10$. We find significant reduction in the μ_R scale dependence when higher order QCD corrections are included. It is clear from both the panels of fig. 3 that our present NNLO result makes the predictions almost independent of both factorisation and renormalisation scales.

We could not discuss or show the results of charged slepton due to page limitation. We request reader to follow the Ref.[17].
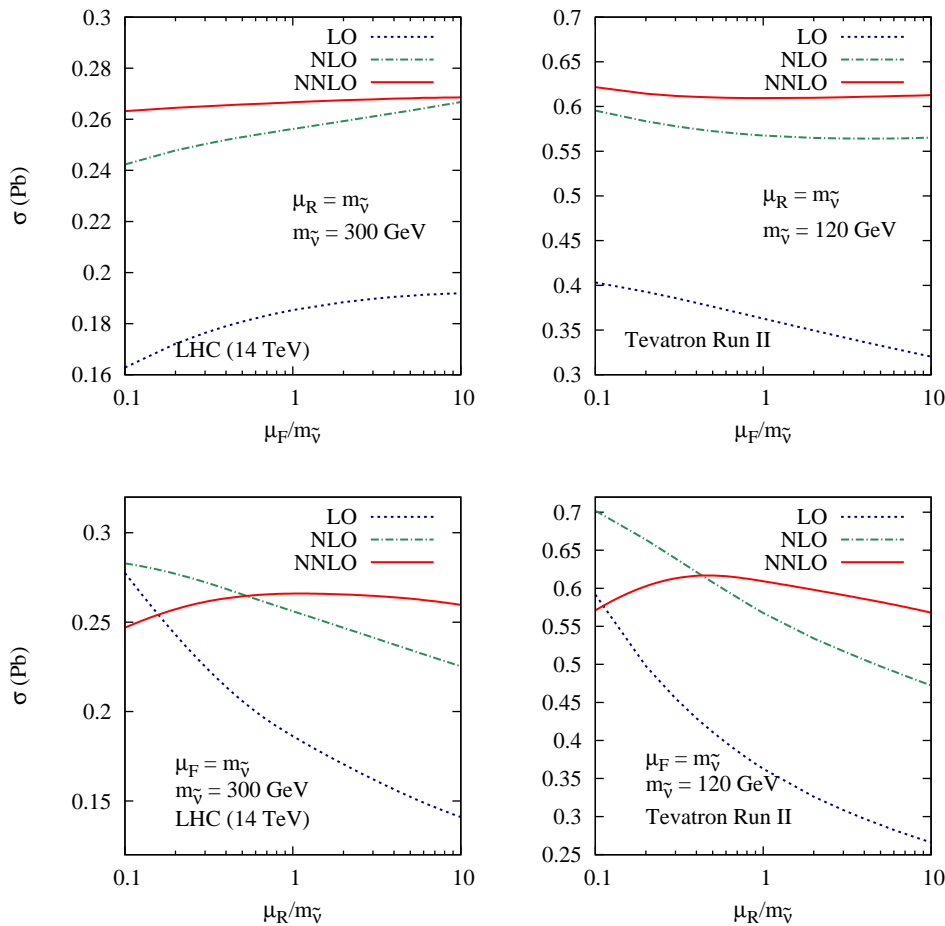
Figure 3: *In the upper panel, sneutrino production cross sections are plotted against the factorisation scale μ_F with a fixed renormalisation scale $\mu_R = m_{\tilde{\nu}}$ for both LHC and Tevatron energies. In the lower panel, they are plotted against the renormalisation scale μ_R with a fixed factorisation scale $\mu_F = m_{\tilde{\nu}}$ for both LHC and Tevatron energies. The mass of the sneutrino is taken to be 300 GeV (120 GeV) at LHC (Tevatron).*

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