Revisiting the QCD Corrections to the R-Parity Violating Processes $p\bar{p}/pp \rightarrow e\mu + X$

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Abstract

We present the theoretical predictions up to QCD next-to-leading order for the cross section of high-mass electron-muon pair production at the Tevatron and at the Large Hadron Collider (LHC), considering only the dominant contributions from the third-generation sneutrino. The dependence of the renormalization and factorization scales on the total cross section, and the effects on the $K$-factor due to the uncertainty of parton distribution function (PDF) are carefully investigated. By considering soft-gluon resummation effects to all orders in $\alpha_s$ of leading logarithm, we present the transverse momentum distributions of the final $e\mu$ pair.

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Observation of electron-muon resonance high invariant mass ($Q$) at hadron colliders could provide evidence of R-parity violating (RPV) interactions. The $e\mu$ pair productions at hadron colliders induced by RPV interactions at the leading order were investigated in Ref. [1]. In Ref. [2, 3, 4] the QCD next-to-leading order (NLO) corrections to resonant sneutrino production at hadron colliders were studied, while the QCD corrections to $R$-violating process $p\bar{p}/pp \rightarrow q\bar{q}, gg \rightarrow e\mu + X$ involving three generations of sneutrinos and squarks was discussed in Ref. [5]. Since there are increasing interests in searching for high-mass $e\mu$ resonance at hadron colliders [6], we revisit this topic to provide thorough theoretical prediction as a reference for experimental analysis. In this Letter only resonance contributions from the third-generation sneutrino are involved in high-mass $e\mu$ search under the single dominance assumption, [7] and the contributions from squark-exchanging diagrams are neglected by applying a high threshold cut ($Q_0$) on $e\mu$ invariant mass. [1, 5] The tree-level and the one-loop QCD NLO diagrams for sneutrino $e\mu$ resonance subprocess considering in our calculation are depicted in Figs. 1 and 2 respectively.

Figure 1: Tree-level Feynman diagrams for subprocess $d\bar{d} \rightarrow e\mu$.

We adopt the dimensional regularization (DR) method and the modified minimal subtraction ($\overline{\text{MS}}$) scheme. After renormalization procedure, the virtual correction part of the cross section is UV-finite. The IR divergences from the one-loop diagrams will be cancelled by adding the soft real gluon/light-quark emission corrections by using the two cutoff phase space slicing method (TCPSS). [8] The remaining collinear divergences can be absorbed into the parton distribution functions (PDF).

We use the CTEQ6L parton distribution functions for the tree-level cross sections and CTEQ6.1M for the QCD NLO corrected ones. [9, 10] During the numerical calculation, we
Figure 2: Fig.2. QCD one-loop diagrams (1)-(4) for subprocess $d\bar{d} \rightarrow e\mu$. QCD one-loop diagrams (a)-(j) for $gg \rightarrow e\mu$, where the superscripts $s, t (= 1, 2)$ represent two physical scalar quarks and the subscript $j (= 1, 2, 3)$ is for three generations.

also investigate the uncertainty induced by the factorization scale $\mu_f$ and the CTEQ6 PDF. We take 40 sets of CTEQ61.xx PDF’s [10] (set number goes form 201 to 240) to estimate the uncertainty induced by the PDF. Actually, in the precise calculation of the distributions of the transverse momentum($q_T$) for the $e\mu$ pair, the quantitative comparison of $q_T$ and $Q$ is very crucial. When the $q_T$ value is comparable with $Q$ or larger, fixed order perturbation theory gives sufficiently accurate results. However, when $q_T \ll Q$, large logarithmic terms, such as $[\alpha_s \ln (q_T/Q)]^n$, arise at fixed order perturbation calculations and need to be resummed. Therefore, we adopt the standard procedure [11] to resummate the multiple soft gluon effects on $q_T$ distribution.

The R-violating lagrangian relevant to present discussion is expressed as [12]

$$L_{R} = \frac{1}{2} \lambda_{ijk} \cdot (\bar{\nu}_{Li} e_{Lj} e_{Lk} \bar{e}_{Lj} + e_{Li} \bar{\nu}_{Lj} \bar{e}_{Rk} + \nu_{Li} e_{Lj} \bar{e}_{Rk} - e_{Li} \bar{\nu}_{Lj} \bar{e}_{Rk}) +$$

$$\lambda'_{ijk} \cdot (\bar{\nu}_{Li} d_{Lj} d_{Rk} - e_{Li} \bar{\nu}_{Lj} \bar{d}_{Rk} + \nu_{Li} d_{Lj} \bar{d}_{Rk} - e_{Li} \bar{\nu}_{Lj} \bar{d}_{Rk}) +$$

$$h.c.$$  \hspace{1cm} (0.1)$$

where $i, j, k = 1, 2, 3$ are generation indices, the superscript $c$ refers to charge conjugation, $\lambda$ and $\lambda'$ are dimensionless R-violating Yukawa couplings, and $\lambda$ behaves as $\lambda_{ijk} = -\lambda_{jik}$.
In the numerical calculations, we take the RPV parameters $\lambda$ and $\lambda'$ to be real for simplicity with the values as: $\lambda_{312} = 0.062$, $\lambda_{321} = 0.070$, $\lambda'_{311} = 0.11$, which are under the experimental constraints presented in Ref.[7]. We set the factorization and the renormalization scales being equal and $\mu_f = \mu_r = m_{\tilde{\nu}}$. The invariant mass cut of the $e\mu$ pair is set to be $Q_0 = 50$ GeV. We apply the naive fixed-width scheme in the sneutrino propagator to avoid the possible resonant singularities (here we fix $\Gamma_{\tilde{\nu}} = 10$ GeV as demonstration). In principle, the value choice of the width of sneutrino has an influence on the cross section, but does not affect the $K$-factor. Since the sneutrino is non-colored supersymmetry particle, there is no problem with double counting in the QCD NLO calculation of the $d\bar{d} \rightarrow e\mu$ cross section. The gluino and squark masses are taken as $m_{\tilde{g}} = m_{\tilde{q}} = 1$ TeV, in order to decouple the interactions involving gluino and squarks and neglect the contributions of squark-exchange diagrams. We have verified that the total cross section involving the QCD NLO corrections is independent of the cutoffs $\delta_s$ and $\delta_c$ in adopting the TCPSS method. In the following calculation, we fix the soft cutoff as $\delta_s = 10^{-3}$ and collinear cutoff as $\delta_c = \delta_s/50$. The calculations are carried out at the Tevatron and the CERN LHC with $p\bar{p}$ colliding energy $\sqrt{s} = 1.96$ TeV and $pp$ colliding energy $\sqrt{s} = 14$ TeV, respectively. Since the $\overline{MS}$ scheme violates supersymmetry, the $q\bar{q}g$ Yukawa coupling constant $\hat{g}_s$ takes a finite shift at one-loop order as [13]: 

$$
\hat{g}_s = g_s \left[1 + \frac{6}{8\pi^2} \left(\frac{4}{3}N_c - C_F\right)\right], \text{ with } N_c = 3 \text{ and } C_F = 4/3.
$$

We shall take this coupling strength shift between $\hat{g}_s$ and $g_s$ into account in our calculation.

In Fig.3(a) we depict the curves of the tree-level and QCD NLO corrected cross sections ($\sigma^0$ and $\sigma^{QCD}$) of the processes $p\bar{p}/pp \rightarrow e^+\mu^- + X$ versus the sneutrino mass $m_{\tilde{\nu}}$ at the Tevatron and the LHC. Their corresponding $K$-factors ($K \equiv \frac{\sigma^{QCD}}{\sigma^0}$) as a function of $m_{\tilde{\nu}}$ are depicted in Fig.3(b). We can see that both the $K$-factor curves for the Tevatron and the LHC colliders in Fig.3(b) show the difference between the curve tendencies of $K$-factors for processes $pp(\bar{p}p) \rightarrow e\mu + X$ and $p\bar{p}(pp) \rightarrow \tilde{\nu} + X$. For the later process, both the calculations in Ref.[2] and our cross-check for confidence show that the $K$-factor curve for the Tevatron always goes down when $m_{\tilde{\nu}}$ varies from 200 GeV to 1 TeV, while the $K$-factor curve for the LHC goes up with the increment of $m_{\tilde{\nu}}$ from 100 GeV to 600 GeV. It manifests that the QCD NLO corrections...
to high-mass $e\mu$ resonance production at both the Tevatron and the LHC cannot be adopted directly from those for the single $\tilde{\nu}$ production process as presented in Refs.\cite{2,4}. We can read out from Fig.3(b) that the $K$-factors vary in the ranges of $[1.182, 1.643]$ at the Tevatron and $[1.335, 1.614]$ at the LHC.

Figure 3: The tree-level and total QCD NLO corrected cross sections of the processes $pp/pp \rightarrow e\mu + X$ at the Tevatron and the LHC as a function of the sneutrino mass $m_{\tilde{\nu}}$ are shown in Figure 3(a). Figure 3(b) shows the corresponding relations between the $K$-factors and the sneutrino mass $m_{\tilde{\nu}}$.

Figures 4(a) and 4(b) demonstrate the dependence of $K$-factor on the factorization scale $\mu_f/m_{\tilde{\nu}}$, when the sneutrino mass is set to be $m_{\tilde{\nu}} = 100, 250, 500$ GeV. From the two figures we can estimate the uncertainty of the QCD NLO correction induced by scale parameter $\mu_f$. In Fig.4(a), we can read out that in the scale $\mu/m_{\tilde{\nu}}$ region of $[0.5, 2]$ the $K$-factors at the Tevatron vary in the ranges of $[1.639, 1.645], [1.446, 1.498]$ and $[1.251, 1.328]$ corresponding to $m_{\tilde{\nu}} = 100, 250$ and 500 GeV respectively. Figure 4(b) shows that the $K$-factors at the LHC are in the ranges of $[1.567, 1.668], [1.396, 1.434]$ and $[1.362, 1.375]$ in the scale region of $\mu/m_{\tilde{\nu}} \in [0.5, 2]$ for $m_{\tilde{\nu}} = 100, 250$ and 500 GeV separately. From Figs.4(a) and 4(b) we can see the relative errors of $K$-factor induced by the factorization scale $\mu_f$ for $m_{\tilde{\nu}} = 100$ GeV, 250 GeV, 500 GeV in the scale region $\mu_f/m_{\tilde{\nu}} \in [0.5, 2]$ are $0.17\% (3.1\%), 1.8\% (1.3\%)$ and $3.0\% (0.46\%)$ at the Tevatron(LHC), respectively.

We investigate the uncertainty range due to the different CTEQ sets. In Table 1 we list the $K$-factor values obtained by using different CTEQ61.xx PDF sets, where the $K$-factor
obtained from the best fit CTEQ6.1M PDF is taken as the central value at sneutrino mass. From the data in Table 1 we find that the deviations of $K$-factor from the central value at the Tevatron are in the ranges of $[-0.053, 0.046]$, $[-0.055, 0.060]$, $[-0.073, 0.110]$ and the average values of absolute deviations are 0.014, 0.025, 0.042 for $m_{\tilde{\nu}} = 100, 250, 500$ GeV, respectively. The deviations of $K$-factor from the central value at the LHC are in the ranges of $[-0.057, 0.036]$, $[-0.044, 0.027]$, $[-0.057, 0.025]$, and the average values of absolute deviations are 0.018, 0.016, 0.019 for $m_{\tilde{\nu}} = 100, 250, 500$ GeV respectively. The relative errors of $K$-factor due to the PDF (defined as $\delta \equiv \frac{K_{\text{max}} - K_{\text{min}}}{K_{\text{central}}}$) for $m_{\tilde{\nu}} = 100$ GeV, 250 GeV, 500 GeV, are $6.0\%(5.8\%)$, $7.8\%(5.0\%)$ and $14.2\%(5.9\%)$ at the Tevatron (LHC), separately.

Considering soft-gluon resummation effects to all the orders in $\alpha_s$ of leading logarithm, we present the distributions of the differential cross sections ($d\sigma^{QCD}/dq_T$ and $d\sigma^{\text{resum}}/dp_T$) for the processes $p\bar{p}/pp \to e^+\mu^- + X$ versus the transverse momentum $q_T$ with $m_{\tilde{\nu}} = 250$ GeV and 500 GeV in Figs.5(a) and 5(b), where $q_T$ is defined as $q_T^2 = (\vec{p}_{cT} + \vec{p}_{\mu T})^2$. Figure 5(a) is for the process $p\bar{p} \to e\mu + X$ at the Tevatron and Figure 5(b) is for the process $pp \to e\mu + X$ at the LHC.

In summary, our numerical results demonstrate that the QCD corrections to single sneutrino production cannot directly be applied to the study of high-mass RPV $e\mu$ pair production. The $K$-factors of the processes $p\bar{p}/pp \to e\mu + X$ vary in the ranges of $[1.182, 1.643]$ and

Figure 4: Dependence of $K$-factor on the factorization scale $\mu_f/m_{\tilde{\nu}}$. (a) at the Tevatron, (b) at the LHC.
| CTEQ6 | $m_\nu = 100$ GeV | $m_\nu = 250$ GeV | $m_\nu = 500$ GeV |
|-------|-----------------|-----------------|-----------------|
|       | $K_{\text{Tevatron}}$ | $K_{\text{LHC}}$ | $K_{\text{Tevatron}}$ | $K_{\text{LHC}}$ | $K_{\text{Tevatron}}$ | $K_{\text{LHC}}$ |
| 6.1M  | 1.643           | 1.614           | 1.471           | 1.418           | 1.290           | 1.379           |
| 201   | 1.610           | 1.576           | 1.458           | 1.379           | 1.285           | 1.335           |
| 202   | 1.672           | 1.631           | 1.492           | 1.432           | 1.293           | 1.386           |
| 203   | 1.643           | 1.582           | 1.505           | 1.397           | 1.339           | 1.356           |
| 204   | 1.638           | 1.629           | 1.444           | 1.419           | 1.239           | 1.366           |
| 205   | 1.632           | 1.607           | 1.505           | 1.400           | 1.373           | 1.349           |
| 206   | 1.648           | 1.601           | 1.448           | 1.411           | 1.217           | 1.374           |
| 207   | 1.590           | 1.591           | 1.416           | 1.376           | 1.233           | 1.320           |
| 208   | 1.689           | 1.616           | 1.531           | 1.432           | 1.345           | 1.403           |
| 209   | 1.625           | 1.565           | 1.454           | 1.381           | 1.268           | 1.348           |
| 210   | 1.657           | 1.651           | 1.499           | 1.433           | 1.313           | 1.375           |
| 211   | 1.640           | 1.620           | 1.479           | 1.411           | 1.306           | 1.358           |
| 212   | 1.644           | 1.591           | 1.473           | 1.403           | 1.275           | 1.359           |
| 213   | 1.645           | 1.608           | 1.480           | 1.410           | 1.304           | 1.366           |
| 214   | 1.639           | 1.601           | 1.473           | 1.403           | 1.275           | 1.355           |
| 215   | 1.638           | 1.596           | 1.468           | 1.396           | 1.227           | 1.353           |
| 216   | 1.634           | 1.602           | 1.479           | 1.407           | 1.351           | 1.367           |
| 217   | 1.642           | 1.604           | 1.473           | 1.414           | 1.357           | 1.377           |
| 218   | 1.629           | 1.596           | 1.474           | 1.391           | 1.233           | 1.336           |
| 219   | 1.684           | 1.635           | 1.502           | 1.444           | 1.320           | 1.400           |
| 220   | 1.601           | 1.577           | 1.451           | 1.373           | 1.268           | 1.324           |
| 221   | 1.634           | 1.618           | 1.482           | 1.416           | 1.292           | 1.362           |
| 222   | 1.638           | 1.601           | 1.478           | 1.396           | 1.308           | 1.351           |
| 223   | 1.666           | 1.623           | 1.495           | 1.427           | 1.319           | 1.384           |
| 224   | 1.655           | 1.620           | 1.485           | 1.420           | 1.280           | 1.375           |
| 225   | 1.668           | 1.619           | 1.511           | 1.425           | 1.338           | 1.390           |
| 226   | 1.651           | 1.620           | 1.479           | 1.421           | 1.285           | 1.370           |
| 227   | 1.634           | 1.592           | 1.512           | 1.400           | 1.378           | 1.366           |
| 228   | 1.645           | 1.590           | 1.527           | 1.393           | 1.392           | 1.351           |
| 229   | 1.643           | 1.618           | 1.485           | 1.413           | 1.324           | 1.362           |
| 230   | 1.630           | 1.557           | 1.496           | 1.380           | 1.306           | 1.350           |
| 231   | 1.646           | 1.583           | 1.488           | 1.397           | 1.296           | 1.360           |
| 232   | 1.652           | 1.620           | 1.485           | 1.423           | 1.298           | 1.374           |
| 233   | 1.665           | 1.627           | 1.492           | 1.431           | 1.298           | 1.380           |
| 234   | 1.666           | 1.627           | 1.490           | 1.430           | 1.294           | 1.388           |
| 235   | 1.648           | 1.595           | 1.526           | 1.403           | 1.396           | 1.363           |
| 236   | 1.639           | 1.588           | 1.529           | 1.399           | 1.401           | 1.354           |
| 237   | 1.637           | 1.586           | 1.526           | 1.398           | 1.400           | 1.359           |
| 238   | 1.647           | 1.595           | 1.529           | 1.399           | 1.395           | 1.360           |
| 239   | 1.655           | 1.606           | 1.504           | 1.409           | 1.339           | 1.372           |
| 240   | 1.656           | 1.603           | 1.513           | 1.406           | 1.351           | 1.366           |

Table 1: Full set of $K$-factor predictions for the CTEQ family of PDFs for $m_\nu = 100$, 250, 500 GeV at the Tevatron and the LHC.
Figure 5: Distributions of the transverse momentum of final $e\mu$-pair $q_T$, which is defined as $q_T^2 = (\vec{p}_{eT} + \vec{p}_{\mu T})^2$. (a) for the Tevatron, and (b) for the LHC.

[1.335, 1.614] at the Tevatron and the LHC separately, and the relative errors of $K$-factor are found to be less than 3%(3.1%) due to $\mu_f$, and 14.2%(5.9%) due to PDF at the Tevatron(LHC) respectively in our investigating parameter space. We also present the distributions of the transverse momentum of final $e\mu$-pair by resummating the logarithmically-enhanced terms for soft gluon as a reference for future experimental analysis.

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