QCD corrections to the R-parity violating processes

\[ p\bar{p}/pp \rightarrow e\mu + X \] at hadron colliders

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Abstract

We present the QCD corrections to the processes \( p\bar{p}/pp \rightarrow e\mu + X \) at the Tevatron and the CERN large hadron collider (LHC). The numerical results show that variation of K factor is in the range between 1.28(1.32) and 1.79(1.58) at the Tevatron (LHC). We find that the QCD correction part from the one-loop gluon-gluon fusion subprocess is remarkable at the LHC and should be taken into account.

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In the R-parity violating minimal supersymmetric standard model, the most general representations of superpotential can be written as

\[ W_{R^p} = \frac{1}{2} \epsilon_{ab} \lambda_{ijk} \hat{L}_i^a \hat{L}_j^b \hat{E}_k + \epsilon_{ab} \lambda'_{ijk} \hat{L}_i^a \hat{Q}_j^b \hat{D}_k + \frac{1}{2} \epsilon_{\alpha\beta\gamma} \lambda''_{ijk} \hat{U}_i^\alpha \hat{D}_j^\beta \hat{D}_k^\gamma + \epsilon_{ab} \delta_i^a \hat{L}_i \hat{H}_2 \]  

(0.1)

where \( i, j, k = 1, 2, 3 \) are generation indices; \( a, b = 1, 2 \) are SU(2) isospin indices and \( \alpha, \beta, \gamma \) are SU(3) color indices. \( \lambda, \lambda', \lambda'' \) are dimensionless R-violating Yukawa couplings behaving as \( \lambda_{ijk} = -\lambda_{jik} \) and \( \lambda''_{ijk} = -\lambda''_{jik} \). In above superpotential, the trilinear terms only violate either L- or B-symmetry respectively, and the terms which may produce both L- and B-violation simultaneously, are absent so that a stable proton is ensured.

An observation of electron-muon pair events with high invariant mass at hadron colliders would provide evidence of R-parity violating (RPV) interactions. The electron-muon pair productions at hadron colliders induced by RPV interactions at the leading order were investigated in Ref.\[1\]. In this report, we present the QCD corrections to the RPV processes \( pp \rightarrow e\mu + X \) at hadron colliders including the contributions of the NLO QCD and gluon-gluon fusion subprocess. We adopt the dimensional regularization (DR) method in \( D = 4 - 2\epsilon \) dimensions to isolate the ultraviolet (UV), infrared (IR) (soft and collinear) singularities. In order to remove the UV divergences, we employ the modified minimal subtraction (\( \overline{\text{MS}} \)) scheme to renormalize and eliminate UV divergences. After renormalization procedure, the virtual correction part of the cross section is UV-finite. The IR divergences from the one-loop diagrams involving gluon will be cancelled by adding the soft real gluon emission corrections by using the two cutoff phase space slicing method (TCPSS)\[2\]. The remaining collinear divergences can be absorbed into the parton distribution functions.

Although the contribution of the \( e\mu \) production via gluon-gluon fusion at the lowest order is an one-loop subprocess and this contribution part to the process \( pp \rightarrow e\mu + X \) is at \( \mathcal{O}(\alpha_s^2) \) order, which is higher than that of the NLO QCD correction to the process \( pp \rightarrow q\bar{q} \rightarrow e\mu + X \), it is possible that the production rate of the \( pp \rightarrow gg \rightarrow e\mu + X \) could be non-negligible in contrast with the NLO QCD correction to the process via \( q\bar{q} \) annihilation, due to large gluon luminosity in TeV-scale proton-proton (anti-proton) collisions. In this
report we present also the contribution part via gluon-gluon fusions.

In the numerical calculations of the QCD corrected cross sections at the Tevatron and the LHC, we take the RPV parameters $\lambda$ and $\lambda'$ to be real for simplicity with the values as

$$
\begin{align*}
\lambda_{112} &= \lambda_{221} = 0, & \lambda_{212} &= \lambda_{121} = 0.049, & \lambda_{312} &= 0.062, & \lambda_{321} &= 0.070, \\
\lambda'_{111} &= 5.2 \times 10^{-4}, & \lambda'_{112} &= \lambda'_{113} = 0.021, \\
\lambda'_{121} &= 0.043, & \lambda'_{131} &= 0.019, & \lambda'_{211} &= \lambda'_{212} = \lambda'_{213} = 0.059, \\
\lambda'_{221} &= \lambda'_{231} = 0.18, & \lambda'_{311} &= 0.11,
\end{align*}
$$

(0.2)

where the values of $\lambda$ and $\lambda'$ are under the experimental constraints presented in Ref. [3]. We use the CTEQ6L parton distribution function for the tree-level cross sections and CTEQ6M for one-loop QCD corrected cross section results [4]. The factorization and the renormalization scales are set to be equal and taken as $\mu_f = \mu_r = m_{\tilde{\nu}}$. We applied the naive fixed-width scheme and fix the decay width of the sneutrino propagator being $\Gamma = 10$ GeV, to avoid the possible resonant singularities. Since the sneutrinos are non-colored supersymmetric particles, there is no problem with gauge invariance or double counting of higher-order effects in calculating the cross sections of $q\bar{q} \rightarrow e\mu$ involving the NLO QCD corrections. The gluino and squark masses are set to be $m_{\tilde{g}} = 916.1$ GeV and $m_{\tilde{q}} = 200(900)$ GeV, and $2 \times 2$ mixing matrices $R^u$ and $R^d$ are taken to be unit for simplification. By using the TCPSS method, we take the soft cutoff $\delta_s = 10^{-2}$ and collinear cutoff $\delta_c = \delta_s/50$. The calculations are carried out at the Tevatron with $p\bar{p}$ colliding energy $\sqrt{s} = 1.96$ TeV, and at the LHC with $pp$ colliding energy $\sqrt{s} = 14$ TeV. Since the $\overline{MS}$ scheme violates supersymmetry, the $q\bar{q}g$ Yukawa coupling $\hat{g}_s$ takes a finite shift at one-loop order as shown in Eq. (0.3) [5]:

$$
\hat{g}_s = g_s \left[ 1 + \frac{\alpha_s}{8\pi} \left( \frac{4}{3} N_c - C_F \right) \right],
$$

(0.3)

with $N_c = 3$ and $C_F = 4/3$. In our numerical calculation we take this coupling strength shift between $\hat{g}_s$ and $g_s$ into account.

In Fig.1(a) and (b) we depict the curves of the tree-level and QCD corrected cross sections($\sigma^0$ and $\sigma^{QCD}$) of the processes $p\bar{p}/pp \rightarrow e^+\mu^- + X$ involving NLO QCD and gluon-
gluon fusion subprocess corrections versus the sneutrino mass \( m_{\tilde{\nu}} \) with squark mass being 200 GeV and 900 GeV at the Tevatron and the LHC, respectively. Their corresponding K factors \( K \equiv \frac{\sigma_{QCD}}{\sigma_0} \) as the functions of \( m_{\tilde{\nu}} \) are depicted in Fig.1(c) and (d), separately. We can see the cross section curves in Fig.1(a,b) decrease rapidly with the increment of \( m_{\tilde{\nu}} \), and the QCD corrected cross sections for a sneutrino with several hundred GeV mass are changed slightly when the \( m_{\tilde{q}} \) value runs from 200 GeV to 900 GeV, due to the decrease of contribution from the squark exchanging ones. We can read out from Fig.1(c-d) that the K factors vary in the ranges of \([1.28, 1.79]\) at the Tevatron and \([1.32, 1.58]\) at the LHC. For a 100 GeV sneutrino and 900 GeV squarks, the K factors reach 1.79 and 1.58 at the Tevatron and the LHC, respectively.

In Table 1 we list the tree-level cross sections of the processes \( pp/\bar{p}p \rightarrow e^+\mu^- + X \), their K factors and the contributing parts from gluon-gluon fusion mechanism in conditions of taking different mass values of sneutrino and squark at the Tevatron and the LHC, with positron transverse momentum \( p_T \) \( > p_T^{cut} = 20 \) GeV at the Tevatron and \( p_T \) \( > p_T^{cut} = 25 \) GeV at the LHC. We can read from Table 1 that the relative corrections from the gluon-gluon fusion subprocess at the Tavatron is less than 1% and can be negligible, but at the LHC the relative corrections from the gluon-gluon fusion subprocess can reach 6% when \( m_{\tilde{\nu}} \) has the value of 200 GeV due to large gluon luminosity at the LHC. We can see that in evaluating the QCD corrections to the processes \( pp/\bar{p}p \rightarrow e^+\mu^- + X \) at the LHC, it is reasonable to take the contribution from the gluon-gluon fusion subprocess into account.
Figure 1: The tree-level and total QCD corrected cross sections ($\sigma^0$ and $\sigma^{QCD}$) of the processes $p\bar{p}/pp \rightarrow e^+\mu^- + X$ involving NLO QCD and gluon-gluon fusion subprocess corrections at the Tevatron and the LHC as the functions of the sneutrino mass $m_{\tilde{\nu}}$ with different squark masses are shown in Fig.7(a) and (b), respectively. Fig.7(c-d) show the corresponding relations between the K factors of the processes and the sneutrino mass $m_{\tilde{\nu}}$. (c) at the Tevatron, (d) at the LHC.
Table 1: The tree-level cross sections of the processes \( p\bar{p}/pp \rightarrow e^+\mu^- + X \) (in fb), the K factor and the relative correction from the gluon-gluon fusion subprocess with different mass values (GeV) of the sneutrino and the squark at the Tevatron and the LHC, in conditions of positron transverse momentum \( p_T > p_{T \text{cut}} = 20 \text{ GeV} \) for the Tevatron and \( p_T > p_{T \text{cut}} = 25 \text{ GeV} \) for the LHC.

| \( m_{\tilde{\nu}} \) | \( m_{\tilde{q}} \) | \( \sigma^0_{\text{Tevatron}} \) | \( K_{\text{Tevatron}} \) | \( \sigma^{gg}_{\text{Tevatron}}/\sigma^0_{\text{Tevatron}} \) | \( \sigma^0_{\text{LHC}} \) | \( K_{\text{LHC}} \) | \( \sigma^{gg}_{\text{LHC}}/\sigma^0_{\text{LHC}} \) |
|---|---|---|---|---|---|---|---|
| 200 | 200 | 39.83 | 1.5737 | 0.00487 | 467.5 | 1.525 | 0.0598 |
| 500 | 200 | 1.925 | 1.4312 | 0.00741 | 61.25 | 1.477 | 0.0107 |
| 900 | 200 | 0.2436 | 1.6671 | 0.00229 | 15.13 | 1.520 | 0.0144 |
| 200 | 900 | 39.60 | 1.6421 | 0.00488 | 61.25 | 1.477 | 0.0107 |
| 500 | 900 | 1.708 | 1.3954 | 0.000461 | 58.60 | 1.489 | 0.00707 |
| 900 | 900 | 0.03171 | 1.2778 | 0.00195 | 12.37 | 1.433 | 0.00154 |

Table 1: The tree-level cross sections of the processes \( p\bar{p}/pp \rightarrow e^+\mu^- + X \) (in fb), the K factor and the relative correction from the gluon-gluon fusion subprocess with different mass values (GeV) of the sneutrino and the squark at the Tevatron and the LHC, in conditions of positron transverse momentum \( p_T > p_{T \text{cut}} = 20 \text{ GeV} \) for the Tevatron and \( p_T > p_{T \text{cut}} = 25 \text{ GeV} \) for the LHC.

In summary, we studied the QCD corrections to the lepton flavor violating processes \( p\bar{p}/pp \rightarrow e\mu + X \) at the Tevatron and the LHC including the one-loop QCD corrections to \( q\bar{q} \rightarrow e\mu \) subprocess and the one-loop subprocess \( gg \rightarrow e\mu \). In our investigating parameter space the K factors vary in the ranges of \([1.28, 1.79]\) at the Tevatron and \([1.32, 1.58]\) at the
LHC. For a 100 GeV sneutrino and 900 GeV squarks, the K factors reach 1.79 and 1.58 at the Tevatron and the LHC, respectively. We find that the contribution to the total QCD correction from the one-loop gluon-gluon fusion subprocess is remarkable at the LHC, and its relative correction can reach 6% at the LHC when $m_{\tilde{\nu}} = m_{\tilde{q}} = 200$ GeV.

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