Anomalous \( tqV \) couplings and FCNC top quark production\(^1\)

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Abstract

We discuss FCNC top quark production via anomalous \( tqV \) couplings at the Tevatron and HERA colliders. We calculate higher-order soft-gluon corrections to such processes and demonstrate the stabilization of the cross section when these corrections are included.

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1 Introduction

Flavor-changing neutral-current (FCNC) processes involving the top quark appear in several models of physics beyond the Standard Model. The effective Lagrangian involving anomalous $tqV$ couplings can be written as

$$\Delta L^{\text{eff}} = \frac{1}{\Lambda} \kappa_{tqV} e i \sigma_{\mu\nu} q F_{\mu\nu}^V + h.c.$$  

where $\kappa_{tqV}$ is the anomalous coupling, with $q$ denoting an up or charm quark and $V$ a photon or $Z$-boson with field tensor $F_{\mu\nu}^V$; $\sigma_{\mu\nu} = (i/2)(\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu)$ with $\gamma_\mu$ the Dirac matrices; and $\Lambda$ is an effective scale which we set equal to the top quark mass, $m$.

The present TeV energy scale colliders – Tevatron and HERA – can probe FCNC interactions in the top-quark sector and set limits on $\kappa_{tq\gamma}$ and $\kappa_{tqZ}$. However, there are large uncertainties in the lowest-order results from variation of the factorization/renormalization scales, $\mu$. Therefore the stabilization of the cross section for these FCNC processes is timely and important. We have calculated next-to-leading order (NLO) and next-to-next-to-leading order (NNLO) soft-gluon corrections for the following processes: $gu \to tZ$, $gu \to t\gamma$, and $uu \to tt$ at the Tevatron [1]; and $eu \to et$ at HERA [1,2]. As a result, we show that inclusion of QCD corrections significantly stabilizes the cross sections.

2 FCNC top quark cross sections

We define $s_4 = s + t + u - \sum m^2$, with $s, t, u$ standard kinematical invariants, and where the sum is over the masses squared of the particles in the scattering. At threshold $s_4 \to 0$. The soft-gluon corrections [3,4] are of the form $[(\ln^l(s_4/m^2))/s_4]_+$, where $l \leq 2n - 1$ for the order $\alpha_s^n$ corrections. These corrections are expected to dominate the cross section in the near-threshold region, which is relevant for the processes studied here. The leading logarithms (LL) are those with $l = 2n - 1$ while the next-to-leading logarithms (NLL) are those with $l = 2n - 2$. Here we calculate NLO and NNLO corrections in $\alpha_s$ at NLL accuracy, i.e. keeping LL and NLL at each order in $\alpha_s$. We denote them as NLO-NLL and NNLO-NLL, respectively, and calculate them using the master formulas in Ref. [5].

![Figure 1: Tree-level diagrams for $gu \to tZ$.](image1.png)

First we study the process $gu \to tZ$ in $p\bar{p}$ collisions at the Tevatron. In Fig. 1 we show the lowest-order Feynman diagrams.

In Fig. 2 we show plots versus top quark mass of the Born, NLO-NLL, and NNLO-NLL cross sections and of various $K$-factors, which are defined as ratios of cross sections at different orders. Note that $K$-factors are independent of the notation/specification for the anomalous couplings. We have set the scale $\mu$ equal to the top quark mass and set $\kappa_{tuZ} = 0.1$. 


In Fig. 3 we plot the scale dependence of the cross section for a top mass $m = 175$ GeV. It’s clear that the dependence of the cross section on scale is significantly decreased when we add the NLO-NLL and NNLO-NLL corrections. For $\mu = m = 175$ GeV, $\kappa_{tuZ} = 0.1$ and $\sqrt{S} = 1.96$ TeV we find $\sigma_{NNLO-NLL} = 87_{-3}^{+2}$ fb where the uncertainty comes from scale variation between $m/2$ and $2m$. We note that the cross section for the process

Figure 2: Cross sections (left) and K-factors (right) for $gu \rightarrow tZ$ at the Tevatron.

Figure 3: The scale dependence of the $gu \rightarrow tZ$ cross section at the Tevatron.
$g c \rightarrow t Z$, involving the charm quark, is negligible by comparison. We also note that the cross section for anti-top production, $g \bar{u} \rightarrow \bar{t} Z$, is the same as for top production.

The results for $g u \rightarrow t \gamma$ are qualitatively the same – we find again stabilization of the cross section versus scale variation, as well as a similar cross section level ($\sigma_{NNLO-NLL}^{g u \rightarrow t \gamma} = 95^{+17}_{-11} \text{ fb}$ for $\mu = m = 175$ GeV and $\kappa_{tu \gamma} = 0.1$). In the case of the process $u u \rightarrow t t$ the cross section is also stabilized; however, this process is qualitatively different: it has a significantly lower cross section ($\sigma_{NLO-NLL}^{u u \rightarrow t t} = 1.74^{+0.00}_{-0.02} \text{ fb}$ for $\mu = m = 175$ GeV and $\kappa_{t u Z} = \kappa_{t u \gamma} = 0.1$) but a much cleaner signature [1].

Figure 4: Tree-level diagrams for $eu \rightarrow et$.

Next we study the process $eu \rightarrow et$ in $ep$ collisions at HERA [6, 7, 8]. In Fig. 4 we show the lowest-order Feynman diagrams. In Fig. 5 we show plots of the Born, NLO-NLL, and NNLO-NLL cross sections versus top mass, and of contour levels in the $\kappa_{tu \gamma}, \kappa_{t u Z}$ plane. We have set $\mu = m$. It is evident that HERA is much more sensitive to the $\kappa_{tu \gamma}$ coupling than to $\kappa_{t u Z}$. The NNLO-NLL cross section at HERA for $\mu = m = 175$ GeV, $\kappa_{tu \gamma} = \kappa_{t u Z} = 0.1$ and $\sqrt{S} = 318$ GeV is $\sigma_{NNLO-NLL}^{eu \rightarrow et} = 0.64^{+0.05}_{-0.04} \text{ pb}$, where again the uncertainty comes from scale variation between $m/2$ and $2m$. We note that almost all of the cross section comes from the $\kappa_{\gamma}$ coupling. We also note that contributions from charm

![Figure 5: Cross sections (left) and HERA reach (right) for the process $eu \rightarrow et$.](image-url)
are negligible. In the case of $e\bar{t}$ production, involving the anti-top, the cross section is quite small $\sigma_{NLO-NLL}^{e\bar{t}} = 0.0079 \text{ pb}$, and thus assymetrical to $e\bar{t}$ production.

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