Single Production of Fourth Family Quarks at LHeC

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The Large Hadron Collider (LHC) has started to scan a new range of energy, and mass to solve the well known unanswered questions in particle physics; especially concerned, two of them are the flavor problem and the electroweak symmetry breaking. Furthermore, one of the questions left open by the standard model (SM) is the replication of fermion generations. The SM does not provide a mathematical tool to predict the number of fermion families. One of the main aims of the present high energy collider experiments is to determine the number of fermion families. The possibility of existence of an extra fermion family is under discussion [1, 2] at hadron colliders, recently in the context of the LHC experiments. The LHeC would also be expected to have sensitivity to the new quarks and leptons. The discovery of fourth family fermions that have sequential couplings could play an important role to understand the flavor structure of the SM. The constraints on the fourth family depend not only on the masses of the new quarks but also on the mass of charged lepton and neutrino as well as the mass of the Higgs boson [2, 3].

Recently, the Collider Detector at Fermilab (CDF) has already constrained the masses of fourth family quarks: $m_Q > 335$ GeV at 95% CL. [4], and $m_{t'} > 338$ GeV at 95% CL. [5] complementing the previous limits [6]. However, there seems to be some parameter space (mass, mixing) left for the fourth family quarks which could be investigated in the future experiments.

Here, we investigate the discovery potential of the LHeC for the single production of fourth family $t'$ and $b'$ quarks via the process $e^+p \rightarrow t'\bar{\nu}_e X$ and $e^-p \rightarrow b'\nu_e X$ [7]. We calculate the cross sections of signal and corresponding backgrounds. The decay widths and branching ratios of the fourth family $t'$ and $b'$ quarks are calculated in the mass range 300-800 GeV. For the numerical calculations, we have implemented the new interaction vertices into the CompHEP [8] package and used the parton distribution function (PDF) CTEQ6M [9].

The simplest extension of the SM is to add a sequential fourth family fermions. Here, the left-handed components transform as a doublet of $SU(2)_L$ and right-handed components as singlets. The fourth family $Q' (= t', b')$ quark interacts with the quarks $q_i$ via the exchange of SM gauge bosons ($\gamma, g, Z^0, W^\pm$). The interaction lagrangian is given by

$$L = -g_Q Q'Q'^\dagger \gamma^\mu Q' A_\mu - g_s Q'Q'^\dagger \gamma^\mu Q' G_\mu^a - \frac{g}{2\cos\theta_W} Q'Q'^\dagger (g_V - g_A \gamma^5) Q'Z^0_\mu - \frac{g}{2\sqrt{2}} V_{Q'q} Q'^\dagger \gamma^\mu (1 - \gamma^5) q_i W^-_{\mu i} + h.c. \quad (1.1)$$

where $g_e$, $g$ are electro-weak coupling constants, and $g_s$ is the strong coupling constant. The vector fields $A_\mu$, $G_\mu$, $Z^0_\mu$ and $W^+_\mu$ denote photon, gluon, $Z^0$-boson and $W^+$-boson, respectively. $Q_{Q'}$ is the electric charge of fourth family $Q'$ quark; $T^a$ are the Gell-Mann matrices. The vector and axial-vector type couplings $g_V$ and $g_A$ of neutral weak current are defined as in the SM. Finally, the $V_{Q'q}$ denotes the elements of extended 4 × 4 CKM mixing matrix which are constrained by flavor physics. Here, we calculate the decay width and branchings in the case of a new parametrization which is well motivated in a recent study [10]: $|V_{t'd}| = 0.0044$, $|V_{t'b}| = 0.114$, $|V_{t'b'}| = 0.22$, $|V_{u'b'}| = 0.028$, $|V_{cb'}| = 0.116$, $|V_{ud'}| = 0.15$, $|V_{ub'}| = 0.99$, and here we assume a mass splitting of $|m_{t'} - m_{b'}| \approx 50$ GeV. However, other parametrizations are
Table 1.1: The total decay widths and the branching ratios of $t'$ and $b'$ quarks depending on their masses.

| Mass (GeV) | $\Gamma_{t'}$ (GeV) | $W^+b$(%) | $W^+s$(%) | $W^+d$(%) | $\Gamma_{b'}$ (GeV) | $W^-c$(%) | $W^-t$(%) | $W^-u$(%) |
|-----------|---------------------|-----------|-----------|-----------|---------------------|-----------|-----------|-----------|
| 300       | 0.54                | 79        | 21        | 0.03      | 0.18                | 66        | 30        | 3.9       |
| 400       | 1.29                | 79        | 21        | 0.03      | 0.55                | 52        | 45        | 3.0       |
| 500       | 2.53                | 79        | 21        | 0.03      | 1.22                | 46        | 52        | 2.7       |
| 600       | 4.38                | 79        | 21        | 0.03      | 2.25                | 43        | 55        | 2.5       |
| 700       | 6.96                | 79        | 21        | 0.03      | 3.72                | 41        | 57        | 2.4       |
| 800       | 10.39               | 79        | 21        | 0.03      | 5.70                | 40        | 58        | 2.3       |

Figure 1.1: The diagrams (a-b) for the single production of $t'(\bar{t}')$ quarks, and diagrams (c-d) for $b'(\bar{b}')$ at $ep$ collision.

commonly used in the recent studies [11, 7].

The relevant diagrams for the single production of $t'(\bar{t}')$ and $b'(\bar{b}')$ quarks are shown in Fig. 1.1. The total decay widths and the branching ratios of $t'$ and $b'$ quarks within the SM framework are presented in Table 1.1. The $b'$ quark decays to $W^-c$ dominantly in the mass range of 300-450 GeV, while the $W^-t$ channel becomes more pronounced for the high mass region (450-800 GeV). For the given parametrization, the $t'$ branchings remain practically unchanged with the highest branching 79% of $t' \rightarrow W^+b$ in the considered mass range. In Fig. 1.2, we show the cross sections for the single production of the fourth generation $t'$ and $b'$ quarks depending on their masses at the LHeC with $\sqrt{s} = 1.4$ TeV. As it can be seen from Fig. 1.2, the $t'$ and $\bar{t}'$ single production cross sections are the same due to small mixing between the fourth family and first family quarks. However, the cross sections for $b'$ and $\bar{b}'$ productions differ by about a factor 2-10 depending on the mass in the range 300-800 GeV. The cross-sections for the single production of $t'$ and $\bar{t}'$ (or $b'$ and $\bar{b}'$) can be added to enrich the statistics for the analysis.

The kinematical distributions of the final state $c$-quark (for single $b'$ production) or $b$-quark (for single $t'$ production) for the signal and background can be used for the effective cut analysis [7], here we apply $p_T^b > 50$ GeV. The signal and background show different rapidity distributions for the final state detectable particles. We infer from the results that the missing transverse momentum cut $p_T^{miss} > 20$ GeV is required for the analysis. The charm (bottom) quark hadronizes immediately after it is produced. A charmed (bottom) jet has a secondary vertex mass around 1 GeV (4 GeV). Here, we assume one can have success for tagging the charm (bottom) hadrons.

For the analysis we use invariant mass of the $W$-boson and heavy quark jet system ($b$-jet or $c$-jet) in the final state. Taking into account $W^+b_{jet}$ (for $t'$ signal), and $W^-c_{jet}$ (for $b'$ signal), we calculate the number of events in the invariant mass interval around the $m_{Q'}$, namely $|m_{Q'} - m_{Wq}| < 10-20$ GeV according to the mass and the decay width of $Q'(\equiv t', b')$ to obtain
Figure 1.2: The total cross section for the $t'(\bar{t}')$ (solid line), the $b'$ and $\bar{b}'$ (dashed and dotted lines) at $\sqrt{s} = 1.4$ TeV.
Table 1.2: The statistical significance (SS) values calculated for the single production $t'(or \bar{t}')$ at the LHeC with $\sqrt{s} = 1.4$ TeV and $L_{\text{int}} = 10$ fb$^{-1}$.

| $m_{t'}$ (GeV) | $\sigma_S$ (fb) | $\sigma_B$ (fb) | SS  |
|---------------|----------------|----------------|-----|
| 300           | $2.88 \times 10^3$ | $8.14 \times 10^{-1}$ | 30.5 |
| 400           | $9.92 \times 10^0$  | $2.27 \times 10^{-1}$ | 18.5 |
| 500           | $3.14 \times 10^0$  | $6.84 \times 10^{-2}$ | 10.5 |
| 600           | $1.00 \times 10^0$  | $4.35 \times 10^{-2}$ | 5.3  |
| 700           | $2.78 \times 10^{-1}$ | $1.31 \times 10^{-2}$ | 2.7  |
| 800           | $6.72 \times 10^{-2}$ | $3.65 \times 10^{-3}$ | 1.3  |

Table 1.3: The statistical significance (SS) values calculated for the single production $b'(or \bar{b}')$ at the LHeC with $\sqrt{s} = 1.4$ TeV and $L_{\text{int}} = 10$ fb$^{-1}$.

| $m_{b'}$ (GeV) | $\sigma_S$ (fb) | $\sigma_B$ (fb) | SS  |
|---------------|----------------|----------------|-----|
| 300           | $2.08 \times 10^3(8.63 \times 10^0)$ | $1.09 \times 10^0(1.09 \times 10^0)$ | 16.4(8.7) |
| 400           | $8.17 \times 10^0(2.36 \times 10^0)$ | $3.45 \times 10^{-1}(3.52 \times 10^{-1})$ | 10.7(4.4) |
| 500           | $3.34 \times 10^0(6.83 \times 10^{-1})$ | $1.13 \times 10^{-1}(1.14 \times 10^{-1})$ | 7.1(2.3) |
| 600           | $1.43 \times 10^0(2.09 \times 10^{-1})$ | $7.55 \times 10^{-2}(7.51 \times 10^{-2})$ | 4.3(1.0) |
| 700           | $5.71 \times 10^{-1}(5.98 \times 10^{-2})$ | $2.43 \times 10^{-2}(2.39 \times 10^{-2})$ | 2.8(0.5) |
| 800           | $1.94 \times 10^{-1}(1.58 \times 10^{-2})$ | $7.08 \times 10^{-3}(7.00 \times 10^{-3})$ | 1.7(0.3) |

The visible signal over the background. In this case, a significant reduction on the background can be obtained. In the following equation, $\sigma_S$ and $\sigma_B$ denote signal and background cross sections, respectively, in the selected mass bins. Assuming the Poisson statistics, the estimations for the statistical significance (SS) of signal is obtained by assuming an integrated luminosity of $L_{\text{int}} = 10$ fb$^{-1}$/year

$$SS = \sqrt{2L_{\text{int}}c[(\sigma_S + \sigma_B)\ln(1 + \sigma_S/\sigma_B) - \sigma_S].}$$ (1.2)

The number of events for the signal (S) and background (B) processes are calculated as $N_{S,B} = \sigma_{S,B} \epsilon_c L_{\text{int}}$. In Table 1.3, the results for the signal significances of the $t', b'$ quarks are shown for $L_{\text{int}} = 10$ fb$^{-1}$. Here, we assume the $c$-tagging efficiency as $\epsilon_c = 30\%$ and $b$-tagging efficiency as $\epsilon_b = 60\%$. The single production of $t'$ and $b'$ quarks can be observed at the LHeC in the mass range of 300-700 GeV provided the current bounds on the mixings with the other families are present. For the smaller values (half values of the current parametrization) of the $V_{q'b'}$ and $V_{t'q}$ mixings we obtain a $1\sigma$ significance for the $t'(b')$ signal at $m_{b'} = 400$ GeV.

The LHC can discover the fourth family quarks in pairs and measure their masses with a good accuracy. Here, we have explored the potential of the LHeC for searching for the $t'$ and $b'$ single production in the allowed parameter space. If the fourth family quarks have large mixing with the other families of the SM, it can be produced singly at the LHeC with large numbers. From the single production, a unique measurement can be performed for the family mixings with the four families.
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