ASSOCIATED PRODUCTION OF DIFFERENT FLAVOR HEAVY QUARKS THROUGH W' BOSONS AT THE LHC

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Associated production of different flavor heavy quarks can provide a probe for W' bosons at the LHC. We study $pp \to t'\bar{b}'X$ process with the subsequent decays $t' \to W^+b$ and $\bar{b}' \to W^-W^+\bar{b}$, and compare the results with the $t\bar{b}$ final state. The effects of the W' boson to the different flavor pair production cross section are shown to be important in some parameter region for the heavy quark masses of 600 and 700 GeV. We present accessible mass limits for the W' boson at the LHC with $\sqrt{s} = 14$ TeV.

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1. Introduction

Discovery of new particles plays an important role for a clear evidence of the new physics at the Large Hadron Collider (LHC). The existence of additional charged massive bosons is predicted by various extensions of the

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Standard Model (SM). Such models candidates are the left–right symmetric [1–3], extra dimensional [4, 5], little Higgs [6–8] and models with extended gauge symmetry [9–13].

A reference model given in Ref. [14] can be used to confirm the results from experiments for searching new heavy bosons. The recent experimental results have reported the exclusion limit for the mass of the extra charged gauge boson (W') through leptonic decay channel below 2.5 TeV with an integrated luminosity of 4.7 fb^{-1} from ATLAS [15] and 5.0 fb^{-1} from CMS [16] Collaborations at the center of mass energy of 7 TeV.

The recent searches by the ATLAS Collaboration in the lepton+jet final state, under the assumption of BR($t' \to Wb$) = 1 based on 4.7 fb^{-1} of data at $\sqrt{s} = 7$ TeV excluded the existence of a fourth generation up-type quark t' with a mass lower than 656 GeV [17]. A search for the same sign dilepton signature by the ATLAS Collaboration in 4.7 fb^{-1} of data sets lower limit on $m_{b'} > 670$ GeV [18]. The CMS Collaboration using 5 fb^{-1} of data in the same final state set lower limit of $m_{t'} > 570$ GeV [19]. A search for fourth generation down type heavy quarks in the same sign dilepton or three lepton events by the CMS Collaboration sets a lower mass limit at 611 GeV with 4.9 fb^{-1} of data [20].

There are also constraints on the fourth generation quarks from Higgs searches at the Tevatron [21] and the LHC [22, 23]. The fourth generation fermions affect the phenomenology of the Higgs, leading to the changes in decays $\Gamma(H \to VV)$. The constraints of the fourth generation model can be relaxed when there is an extended Higgs sector, such as two Higgs doublet model [24], with an extra SU(2) symmetry.

In this study, we calculate cross section of associated production of different flavor heavy quarks (t', b') with the effects of W' boson at the LHC with $\sqrt{s} = 14$ TeV. We also calculate cross section of relevant background processes. We study accessible mass limits for the W' boson for different heavy quark masses of 600 and 700 GeV at the LHC. The result of this study can also be interpreted generically in the framework of heavy quark models in which BR($Q \to Wq$) becomes smaller than unity.

2. The model

The general interaction Lagrangian for W' and W bosons with the SM quarks and fourth generation quarks (t' and b') is given by

$$\mathcal{L} = -\frac{g}{\sqrt{2}} \sum_{\substack{i=u,c,t,t' \\ j=d,s,b,b' \\ i\neq j}} \left[V'_{ij} \bar{q}_i \gamma^\mu \left(f_{\mathrm{L}} P_{\mathrm{L}} + f_{\mathrm{R}} P_{\mathrm{R}} \right) q_j \; W'^{+}_{\mu} + V_{ij} \bar{q}_i \gamma^\mu P_L q_j \; W^{+}_{\mu} \right] + \mathrm{h.c.}\,, \tag{1}$$

where $g = e/\sin\theta_W$ is the electroweak coupling constant, $P_{\mathrm{L,R}}$ are the usual chirality projection operators and V_{ij} is the element of the extended CKM mixing matrix (CKM4) and V'_{ij} includes new mixing with the W' boson. W'^{+}_{μ} and W^{+}_{μ} are the vector field of W' and W bosons, respectively. f_{L} and f_{R} are the couplings of quarks with the W' boson corresponding to a new SU(2) symmetry [25]. The triple gauge interaction of the W' and SM gauge bosons is included in the benchmark model as given by Ref. [14].

A fit for the fourth generation quark mixing matrix elements (CKM4) are given as $|V_{t'd}| = 0.0058(0.0056)$, $|V_{t's}| = 0.0343(0.0309)$, $|V_{t'b}| = 0.1155$ (0.1185), $|V_{ub'}| = 0.0140(0.0130)$, $|V_{cb'}| = 0.0339(0.0309)$, $|V_{tb'}| = 0.1149$ (0.1179), $|V_{t'b'}| = 0.9926(0.9924)$ for $m_{t'} = 600(700)$ GeV [26]. In this study, we take $f_{\mathrm{R}} = 0$ and $f_{\mathrm{L}}V'_{ij}$ to be the same as CKM4 elements, and we assume the mass constraint $|m_{b'} - m_{t'}| \simeq 55$ GeV. For a simulation framework, the interactions of four generations quarks with W and W' bosons are implemented into computer package CompHEP [27].

TABLE I

The cross sections (σ_1 and σ_2) of the signal process $pp \to t'\bar{b}'X$ for t' mass 600 GeV and 700 GeV as well as SS values at $\sqrt{s} = 14$ TeV with $L = 10^5\,\mathrm{pb}^{-1}$. Here, $SS_{ij} = S_i/\sqrt{B_j}$, $i, j = 1, 2$ are the signal significances for the corresponding signal and background events. B_1 and B_2 denotes number of backgrounds events for $W^-W^+W^+Z$ and $W^-W^+W^+H$, respectively.

$m_{W'}$ [GeV]	$\sigma_1 \times 10^{-2}$ [pb]	$\sigma_2 \times 10^{-2}$ [pb]	SS_{11}	SS_{12}	SS_{21}	SS_{22}
2000	16.10	14.00	136.2	417.3	122.3	374.5
2200	10.40	9.40	88.2	270.2	82.0	251.3
2400	6.78	6.22	57.3	175.5	54.3	166.4
2600	4.50	4.11	37.9	116.4	35.9	109.8
2800	2.96	2.72	24.9	76.6	23.7	72.7
3000	2.01	1.81	16.9	52.0	15.8	48.5
3200	1.40	1.22	11.8	36.2	10.7	32.7
3400	1.01	0.84	8.6	26.2	7.4	22.5
3600	0.76	0.59	6.5	19.8	5.2	15.9
3800	0.61	0.43	5.1	15.7	3.8	11.6
4000	0.51	0.33	4.3	13.2	2.9	8.9

3. Analysis and results

The total decay widths of W' boson depending on its mass for the mass values of t' quark (600 and 700 GeV) are shown in Fig. 1. As can be seen from this figure, the decay widths are slightly different from each other. The estimated branching ratios of W' boson to the pair of heavy quarks

are the following: $\mathrm{BR}(W' \to t\bar{b}) \simeq 19\%$ and $\mathrm{BR}(W' \to t'\bar{b}') \simeq 16\%$. The $W' \to WZ$ mode becomes $\simeq 1\%$ for vertex parametrization $\xi = M_W^2/M_{W'}^2$. These branching ratios do not change significantly in the considered mass range of W' boson.

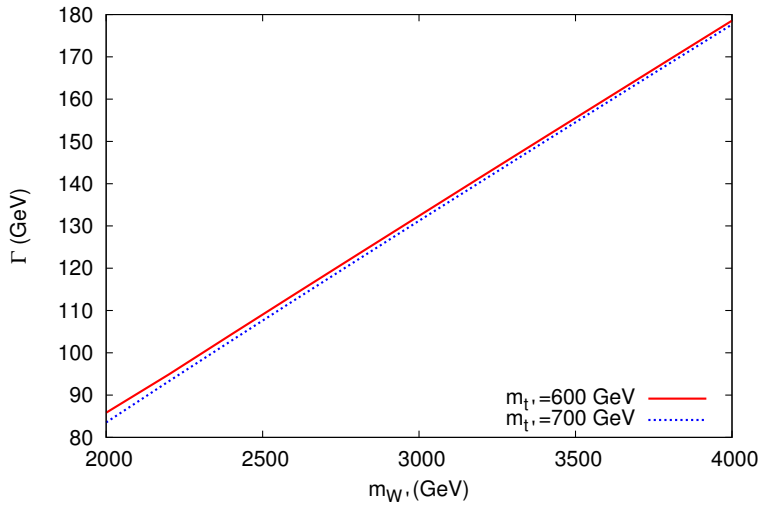

Fig. 1. Decay widths of W' boson depending on its mass for $\mathrm{m}_{t'} = 600\,\mathrm{GeV}$ (solid line) and 700 GeV (dotted line).

First, we consider signal process $pp \to (W', W) \to t\bar{b}X$ at the LHC. The cross section for the process is approximately 5.1 pb by using parton distribution functions library CTEQ6M [28] with $Q^2 = M_{W'}^2$. Figure 2 shows the total cross sections of $pp \to (W', W) \to t\bar{b}X$ (solid line) depending on the mass of the W' bosons at the collision center of mass energy of 14 TeV. From this figure it is seen that the cross section slightly changes with the mass of W'-boson in the range 2000–4000 GeV. For the cross section estimate, we assume the efficiency for b-tagging to be $\varepsilon = 0.5$ and we take the integrated luminosity $L = 10^5\,\mathrm{pb}^{-1}$ at the center of mass energy $\sqrt{s} = 14\,\mathrm{TeV}$. In this case, the background process $pp \to W^+ b\bar{b}X$ is calculated as 1.88×10^2 pb. We calculate the statistical significance $SS = S/\sqrt{B}$, as 27.4–27.9 depending on the mass $\mathrm{M}_{W'}$, where S and B denotes number of events of signal and background, respectively. The cross section of the process $pp \to (W, W') \to t\bar{b}X$ slightly changes with the mass of W'-boson.

Second, we consider signal process $pp \to (W', W) \to t'\bar{b}'$ at the LHC ($\sqrt{s} = 14\,\mathrm{TeV}$) with subsequent decays $t' \to W^+ b$, $\bar{b}' \to W^+ \bar{t}$ and $\bar{t} \to W^- \bar{b}$. The cross section depending on the W' mass is given in Fig. 2 taking $m_{t'} = 600\,\mathrm{GeV}$ (dashed line) and 700 GeV (dotted line). We take into account the primary SM background processes having the same final state

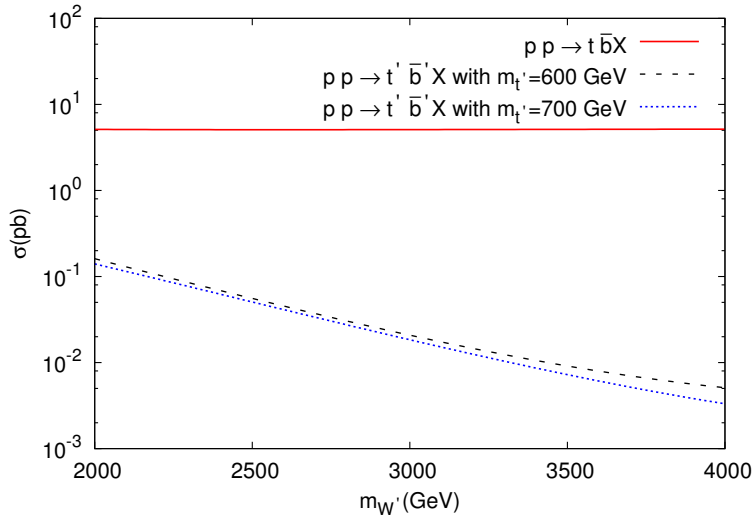

Fig. 2. The total cross section of $pp \to t'\bar{b}'X$ for $\mathrm{m}_{t'} = 600\,\mathrm{GeV}$ (dashed line) and 700 GeV (dotted line), and $pp \to t\bar{b}X$ (solid line) as function of $M_{W'}$ at the LHC with $\sqrt{s} = 14\,\mathrm{TeV}$.

with the signal process. In this case, we have two main background processes as $pp \to W^+W^+W^-Z$ (B_1) and $pp \to W^+W^+W^-H$ (B_2). We calculate the cross sections of these backgrounds as $\sigma_{B_1} = 3.58 \times 10^{-4}\,\mathrm{pb}$ and $\sigma_{B_2} = 4.44 \times 10^{-5}\,\mathrm{pb}$. In Table I, we present total cross sections of the signal processes, (σ_1) for $m_{t'} = 600\,\mathrm{GeV}$, (σ_2) for $m_{t'} = 700\,\mathrm{GeV}$, statistical significance for W' mass range 2000–4000 GeV at the center of mass energy $\sqrt{s} = 14\,\mathrm{TeV}$ and integrated luminosity $L = 10^5\,\mathrm{pb}^{-1}$. When calculating the number of signal and background events we take into account all W bosons decay leptonically in the final state, Z boson and Higgs boson decay to $b\bar{b}$. In the final state including b quarks, we take the b-tagging efficiency as $\epsilon = 0.5$.

4. Conclusion

We investigate the mass reach for W' boson decaying to different flavor heavy quarks with mass above the current mass bound at the LHC. With an integrated luminosity of 10^5 pb^{-1} and $\sqrt{s} = 14\,\mathrm{TeV}$ the W' mass exclusion below 4000 GeV is possible for the heavy quarks with mass 600–700 GeV. We find that $W' \to t\bar{b}$ and $W' \to t'\bar{b}'$ channels can be used to analyze new charged vector boson with the exploration of the parameter space of new charged current models.

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