The Fourth Generation t'-prime in Extensions of the Standard Model

Erin De Pree
Department of Physics, St. Mary's College of Maryland, St. Mary's City, MD 20686, USA

Gardner Marshall and Marc Sher
Particle Theory Group, Department of Physics, College of William and Mary, Williamsburg, VA 23187, USA

We study the effects of a fourth generation t' quark in various extensions of the standard model. In the Randall-Sundrum model, the decay t' → tZ has a large branching ratio that could be detected at the Large Hadron Collider (LHC). We also look at the two-Higgs doublet models I, II and III, and note that, in the latter, the branching ratio of t' → tφ, where φ is a Higgs scalar or pseudoscalar, is huge and we discuss detection at the LHC.

I. INTRODUCTION

Interest in a sequential fourth generation has waxed and waned over the years [1, 2]. Shortly after the discovery of the third generation, a fourth generation was an obvious extension. However, interest in a fourth generation dropped substantially after measurement of the number of light neutrinos at the Z pole showed that only three light neutrinos could exist. The discovery of neutrino oscillations suggested the possibility of a mass scale beyond the standard model, and models with a fourth generation containing a sufficiently massive neutrino became acceptable. In the early part of this decade, it was thought [3] that electroweak precision measurements ruled out a fourth generation quark in various extensions of the standard model. In this model, the portion of the Lagrangian responsible for SM flavor violation is given by [11]

\[ f^{(0)}(c_f, z) = \left[ \frac{k(1 - 2c_f)(kz)^{(1 - 2c_f)}}{e^{\beta(1 - 2c_f)} - 1} \right]^{1/2}, \]

where \( \beta = kR \pi \approx 37 \), \( 1/k \lesssim z \leq e^{\beta/k} \) and \( c_f \) is the 5-D mass parameter describing the location of the fermion in the bulk. For \( c_f < 1/2 \) (\( c_f > 1/2 \)) the fermion lives near the TeV (Planck) brane since its resulting Yukawa coupling with the Higgs field becomes large (small). Since the Kaluza-Klein (KK) modes lie near the TeV brane, the heavier fermions have larger couplings to KK bosons. As noted by Agashe et al. [10, 11], there is mixing between the Z-boson and the KK-Z boson, resulting in a shift of the fermionic couplings to the Z.

In this model, the portion of the Lagrangian responsible for SM flavor violation is given by [11]

\[ \mathcal{L}^Z \sim g_z \beta \Delta Z \mu \sum_f \bar{\psi}_f^{(0)} \gamma_\mu \frac{1}{f_f}(v_f - a_f \gamma_5) \psi_f^{(0)}, \]

where \( g_z = \frac{2}{\pi \cos \theta_W} \) and \( \Delta = \left( \frac{M_Z}{M_{KK}} \right)^2 \). The vector and axial vector coefficients depend on the fermion \( \psi_f \) and are given by \( v_f = T_3^f - Q_3^f \sin^2 \theta_W \), and \( a_f = T_3^f \). The constants \( f_f \) are given in terms of equation [1] by \( \sqrt{2k/f_f} = f^{(0)}(c_f, e^\beta/k) \). Lastly, \( \psi_f^{(0)} \) is the zero-mode of the 4-D fermion field in the basis of diagonal 5-D bulk masses. However, this basis is not the same as the basis in which the 4-D mass terms are diagonal. This gives rise to flavor violating terms in the 4-D basis, which have larger couplings for heavier fermions.

Using this formalism, Agashe et al. [10] point out that with three generations, the branching ratio for

II. RANDALL-SUNDRUM MODEL

The Randall-Sundrum model (RS1) [3] is a popular solution to the hierarchy problem, where the warped geometry of an additional dimension is responsible for generating TeV scale physics from a more fundamental Planck scale. In the original RS1 model, the standard model (SM) fields were confined to the TeV brane, but it was quickly noted that they could be placed in the bulk without problems [7, 8, 9]. This led to a natural resolution of the flavor hierarchy problem.

In the basis of diagonal bulk masses, the normalized wavefunction of zero-mode fermions is given by [7, 8, 9]

\[ f^{(0)}(c_f, z) = \left[ \frac{k(1 - 2c_f)(kz)^{(1 - 2c_f)}}{e^{\beta(1 - 2c_f)} - 1} \right]^{1/2}, \]

where \( \beta = kR \pi \approx 37 \), \( 1/k \lesssim z \leq e^{\beta/k} \) and \( c_f \) is the 5-D mass parameter describing the location of the fermion in the bulk. For \( c_f < 1/2 \) (\( c_f > 1/2 \)) the fermion lives near the TeV (Planck) brane since its resulting Yukawa coupling with the Higgs field becomes large (small). Since the Kaluza-Klein (KK) modes lie near the TeV brane, the heavier fermions have larger couplings to KK bosons. As noted by Agashe et al. [10, 11], there is mixing between the Z-boson and the KK-Z boson, resulting in a shift of the fermionic couplings to the Z.
t → cZ is of $\mathcal{O}(10^{-5})$ for a KK-Z mass of 3 TeV. This is a significant increase from the SM value. In the case of a fourth generation however, there are no electroweak precision constraints and so very large flavor changing neutral currents (FCNC) are allowed. In particular, one expects to observe $t' → tZ$ at a large rate. Due to the fact that the $t'$ and the $b'$ have nearly degenerate masses, the decay of the $t'$ is dominated by $t' → Wb$ unless the mixing angle is very small. Thus the decay rate for $t' → Wb$ is proportional to $|V_{tb}|^2 \sim |(U_f)_{34}|^2$, where $(U_f)$ is the mixing matrix that arises when expanding out the 4-D fermion fields from equation (2) in the basis of diagonal 4-D mass terms. Thus the $|V_{tb}|^2$ factor in $\Gamma(t' → Wb)$ conveniently cancels the $|(U_f)_{34}|^2$ factor in $\Gamma(t' → tZ)$ when calculating the branching ratio $BR(t' → tZ)$.

The decay rate and branching ratio for $t' → tZ$ depend on the four 5-D mass parameters for the left and right handed $t$ and $t'$. Two of these can be eliminated in favor of the $t$ and $t'$ masses. Using the central value of $c_{tL}$ given by Agashe [11], the number of free parameters is reduced to the $t'$ mass and the fermion mass parameter $c_{tL}$, which describes the location of the $t'$ in the bulk.

The results for the branching ratio are given in Figure 1 for $t'$ masses of 400 and 500 GeV. As one varies the third generation mass parameter $c_{tL}$ parameter (discussed in the previous paragraph) over a reasonable range, this result changes by less than a factor of two. We find a branching ratio of $\mathcal{O}(10^{-3} - 10^{-2})$.

ATLAS [12] has claimed that a bound of $10^{-5}$ can be reached in 100 fb$^{-1}$ for $t → cZ$. Since the Z energy in the $t' → tZ$ decay is similar to that in $t → cZ$, one can get a rough estimate of the sensitivity by simply scaling this by the production cross section. This gives a sensitivity of $10^{-3}$ for $t' → tZ$. One can probably do substantially better if one includes the fact that the $t$ in the decay can be detected, which will help eliminate backgrounds. It is clear that this places the decay within reach of the LHC, although a more precise analysis would be welcome.

How does this branching ratio compare with other models? The most comprehensive study considering FCNC in the fourth generation Standard Model is the work of Arhrib and Hou [13]. They considered loop induced FCNC decays of fourth generation quarks, plus effects of fourth generation quarks on FCNC decays of third generation quarks. They found that the decay $t' → tZ$ can occur in the standard model with a branching ratio of $\mathcal{O}(10^{-5} - 10^{-4})$ and suggest that this may be measurable at the LHC. In the Randall-Sundrum case, the branching ratio will be larger by approximately a factor of 100. What about flavor models? We know of no such models for four generations. One of us (MS) is studying such a model, but the rate will be similar to that of Arhrib and Hou (additionally, flavor models do not typically give large rates for $t → cZ$). It is also likely that other models will have a rate for $t' → t\gamma$ or $t' → tg$ which is comparable to $t' → tZ$, unlike the Randall-Sundrum case.

III. TWO HIGGS DOUBLET MODELS

Among the most popular extensions of the Standard Model are two Higgs doublet models [14]. The most common is called Model II. In the two Higgs doublet model II, due to a discrete symmetry, the down-type quarks and leptons couple to one complex doublet $\phi_1$ while the up-type quarks and neutrinos couple to the other $\phi_2$. The ratio of vacuum expectation values (vev) is a free parameter defined by $\tan(\beta) = v_2/v_1$. By requiring that the theory be perturbative we obtain a bound on the possible values of $\tan(\beta)$. The Yukawa couplings of fourth generation quarks are given by $g_{t'}/\sqrt{2} = m_{t'}/v_2$ and $g_{b'}/\sqrt{2} = m_{b'}/v_1$, where $v^2 = v_1^2 + v_2^2 = (246\text{GeV})^2$. If we approximate $m_{t'} \sim m_{b'} \equiv M \gtrsim 280 \text{ GeV}$ and relate $v_1$ and $v_2$ to the Standard Model Higgs vev $v$ in terms of $\tan(\beta)$, then the theory will remain perturbative, $g_{t'}^2 < 4\pi$ and $g_{b'}^2 < 4\pi$, only if

\[ \frac{1}{\sqrt{2\pi(v/M)^2 - 1}} < \tan(\beta) < \sqrt{2\pi(v/M)^2 - 1}. \]  

Thus for Model II with $M \gtrsim 280 \text{ GeV}$ we find $1/2 < \tan(\beta) < 2$. In Model I the $\phi_1$ field does not couple to fermions, which eliminates the upper bound, the lower bound however remains unchanged.

Issues of perturbation theory and vacuum stability pose a challenge to four-generation models. As noted most recently by Kribs [5], in the Standard Model the large Yukawa couplings will cause the scalar self-coupling to either go negative (leading to vacuum instability) or reach a Landau pole well before the GUT scale. The Yukawa coupling itself can also reach a Landau pole at relatively low scales. Although methods can be found to extend the reach of perturbation

![Branching Ratio for $t' → tZ$](image-url)
theory [15], they do involve addition of new physics just above the TeV scale. In the two Higgs doublet models, the situation is much more complicated since there are many scalar self-couplings, many other vacua (such as charge-breaking vacua) and many other opportunities for instabilities. Our approach here is to assume that the two Higgs doublet model is an effective theory below the TeV scale, and will presume that physics above that scale will not substantially affect our results.

Since the charged Higgs $H^\pm$ is a possible decay product of the $t'$ through the decay $t' \to H b$, and this decay will be very difficult to observe, there will be a slight suppression in the branching ratio $BR(t' \to W b)$, which is shown in Figure 2 as a function of the charged Higgs mass.

A much more interesting situation arises in Model III. In Model III, there is no discrete symmetry prohibiting tree level flavor changing neutral currents. Initially this appears to be very problematic. However, if one goes to a basis in which one of the scalar fields gets a vacuum expectation value and the other does not, then the couplings of the latter, $\phi$, will be, in general, flavor changing. By analyzing various mass matrix textures, Cheng and Sher [16] argued that fine-tuning can be avoided if the flavor changing neutral couplings $\xi_{ij} f_i^T f_j \phi$ are given by

$$\xi_{ij} = \lambda_{ij} \frac{m_i m_j}{v/\sqrt{2}}$$

and the couplings $\lambda_{ij}$ are of $O(1)$. In other words, the flavor changing Yukawa couplings are the geometric mean of the two Yukawa couplings of the fermions involved. Model III is defined as the two Higgs doublet model with Yukawa couplings given by the above expression. Recent studies [17] of heavy quark mixing and decays have begun exploring interesting regions of parameters space (which depends on the $\lambda_{ij}$ and the relevant Higgs masses). Note that in this model, the flavor changing couplings of the light quarks are very small, and the constraints from kaon physics are not as severe. Only a few studies of Model III have been done [18, 19, 20] involving fourth generation fields.

In this Model, one would expect an enormous flavor changing coupling between the $t'$, the $t$ and the $\phi$. The coupling, in fact, would be substantially larger than the top quark Yukawa coupling. If kinematically accessible, then one would expect $t' \to t \phi$ to overwhelmingly dominate $t'$ decays. Here, $\phi$ can be the combination of neutral scalars that is orthogonal to the state that gets a vev, or it can be the pseudoscalar. In either event, this decay will dominate.

The cross section for producing a 400 GeV $t'$ is 15 picobarns [21]. Virtually all of these $t'$s will decay into $t \phi$, leading to a dramatic $t \bar{t} \phi \phi$ signature. If $\phi$ is a pseudoscalar or a neutral scalar lighter than about 140 GeV, then it will decay into $b \bar{b}$, leading to a $b \bar{b}$, $2W$ final state. The biggest Standard Model background to these events would come from double pair production of $ttbb$. The cross section for this background [22] is approximately 2 picobarns, and it gives a $4b, 2W$ final state. If one only looks at events with three or more tagged $b$'s and one or more leptons, and assumes a $b$-tag efficiency of 40%, then the signal will pass the cut 20% of the time, and the background will pass the cut 8% of the time, leading to a signal of 3150 fb and a background of only 160 fb. Thus, it appears that the signal will easily be detectable, possibly in an early run at the LHC.

If $\phi$ is a neutral scalar heavier than 140 GeV, then it will decay into $WW$ leading to a $2b, 6W$ final state. Here, if one looks at events with three or more leptons and one or more tagged $b$'s, then 12% of the decays will pass the cuts, leading to an event rate of 1.8 picobarns. We know of no standard model background that comes close to this signal. This signal would also be easily detectable at the LHC.

IV. CONCLUSIONS

There continues to be interest in the phenomenology of a sequential fourth generation. Yet almost all discussion have been in the context of the Standard Model. In this paper, we have explored the phenomenology of the fourth generation, focusing on the $t'$ quark, in extensions of the Standard Model. In the Randall-Sundrum model, the decay $t' \to tZ$ can occur at a rate approaching one percent, which should be detectable at the LHC. In two-Higgs doublet model, one gets a suppression of the branching ratio $t' \to W b$ in Models I and II, but in Model III the decay of $t' \to t \phi$, where $\phi$ is a scalar or pseudoscalar, dominates the decay, leading to spectacular $t \bar{t} \phi \phi$ signatures at very large rates, which could be detected during the early months of running at the LHC.
Acknowledgments

We are grateful to Chris Carone, Graham Kribs and Xerxes Tata for useful discussions. This work was supported by the National Science Foundation grant NSF-PHY-0757481.

[1] For a review and an extensive set of references of work before 2000, see P. H. Frampton, P. Q. Hung and M. Sher, Phys. Rept. 330, 263 (2000) [arXiv:hep-ph/9903387].

[2] For a review and extensive set of references of work after 2000, see B. Holdom, W. S. Hou, T. Hurth, M. L. Mangano, S. Sultansoy and G. Unel, arXiv:0904.4698 [hep-ph].

[3] C. Amsler et al. [Particle Data Group], Phys. Lett. B 667, 1 (2008).

[4] M. Maltoni, V. A. Novikov, L. B. Okun, A. N. Rozanov and M. I. Vysotsky, Phys. Lett. B 476, 107 (2000) [arXiv:hep-ph/9911335]; H. J. He, N. Polonsky and S. f. Su, Phys. Rev. D 64, 053004 (2001) [arXiv:hep-ph/0102144]; B. Holdom, Phys. Rev. D 54, 721 (1996) [arXiv:hep-ph/9602248].

[5] G. D. Kribs, T. Plehn, M. Spannowsky and T. M. P. Tait, Phys. Rev. D 76, 075016 (2007) [arXiv:0706.3718 [hep-ph]].

[6] L. Randall and R. Sundrum, Phys. Rev. Lett. 83, 3370 (1999) [arXiv:hep-ph/9905221].

[7] T. Gherghetta and A. Pomarol, Nucl. Phys. B 586, 141 (2000) [arXiv:hep-ph/0003129].

[8] S. J. Huber, Nucl. Phys. B 666, 269 (2003) [arXiv:hep-ph/0303183].

[9] S. J. Huber and Q. Shafi, Phys. Lett. B 498, 256 (2001) [arXiv:hep-ph/0010195].

[10] K. Agashe, G. Perez and A. Soni, Phys. Rev. D 75, 015002 (2007) [arXiv:hep-ph/0606293].

[11] K. Agashe, G. Perez and A. Soni, Phys. Rev. D 71, 016002 (2005) [arXiv:hep-ph/0408134].

[12] J. Carvalho et al. [ATLAS Collaboration], Eur. Phys. J. C 52, 999 (2007) [arXiv:0712.1127 [hep-ex]].

[13] A. Arhrib and W.-S. Hou, JHEP 0607, 009 (2006) [arXiv:hep-ph/0602035].

[14] J. F. Gunion, H. E. Haber, G. L. Kane and S. Dawson, “The Higgs Hunter’s Guide”, Westview Press (2000).

[15] Z. Murdock, S. Nandi and Z. Tavartkiladze, Phys. Lett. B 668, 303 (2008) [arXiv:0806.2064 [hep-ph]].

[16] T. P. Cheng and M. Sher, Phys. Rev. D 35, 3484 (1987).

[17] A comprehensive list of Model III studies can be found in the citations to Ref. [16]. The most recent works include J. L. Diaz-Cruz, J. Hernandez-Sanchez, S. Moretti, R. Noriega-Papaqui and A. Rosado, Phys. Rev. D 79, 055025 (2009) [arXiv:0902.4490 [hep-ph]]; J. P. Idarraga, R. Martinez, J. A. Rodriguez and N. Poveda, Braz. J. Phys. 38, 531 (2008); F. Mahmoudi and O. Stal, arXiv:0907.1791 [hep-ph].

[18] M. Sher, Phys. Rev. D 61, 057303 (2000) [arXiv:hep-ph/9908238].

[19] A. Arhrib and W. S. Hou, Phys. Rev. D 64, 073016 (2001) [arXiv:hep-ph/0012027].

[20] W. S. Hou, F. F. Lee and C. Y. Ma, Phys. Rev. D 79, 073002 (2009) [arXiv:0812.0064 [hep-ph]].

[21] R. Bonciani, S. Catani, M. L. Mangano and P. Nason, Nucl. Phys. B 529, 424 (1998) [Erratum-ibid. B 803, 234 (2008)] [arXiv:hep-ph/9801375].

[22] A. Breidenstein, A. Denner, S. Dittmaier and S. Pozzorini, arXiv:0905.0110 [hep-ph].