Resonant production of fourth chiral family up-quark at the LHC via anomalous interactions have been analyzed. It is shown that search for resonances in $W^+b$ final states could lead to discovery of the fourth chiral family and simultaneously determine scale of the new physics, presumably related to the quark and lepton compositeness. Obtained results emphasize an importance of $W$-leading jet invariant mass analysis in search for $W^+\text{jets}$ final states at the LHC, both with and without $b$-tagging.
I. INTRODUCTION

It is known that the Standard Model does not fix the number of fermion families. This number should be less than 9 in order to preserve asymptotic freedom and more than 2 in order to provide CP violation. According to the LEP data on Z decays, number of chiral families with light neutrinos ($M_\nu \ll M_Z$) is equal to 3, whereas extra families with heavy neutrinos are not forbidden. The fourth chiral family was widely discussed thirty years ago (see, for example [1][2]). However, the topic was pushed off the agenda due to the misinterpretation of the LEP data.

Twenty years later 3 workshops on the fourth SM family [3–5] were held (for summary of the first and third workshops see [6] and [7], respectively). Main motivation was Flavor Democracy [8–10] which naturally provides heavy fourth family fermions including neutrino (consequences of Flavor Democracy Hypothesis for different models, including MSSM and $E_6$, have been considered in [11][12]). In addition, fourth family gives opportunity to explain baryon asymmetry of Universe, it can accommodate emerging possible hints of new physics in rare decays of heavy mesons etc (see [5] and references therein). Phenomenological papers on direct production (including anomalous resonant production) of the SM4 fermions at different colliders are reviewed in [13] (see tables VI and VII in [13]).

This activity has almost ended due to misinterpretation of the LHC data on the Higgs decays. It should be emphasized that these data exclude the minimal SM4 with one Higgs doublet, whereas non-minimal SM4 with extended Higgs sector are still allowed [14][15]. On the other hand, partial wave unitarity puts an upper limit around 700 GeV on the masses of fourth SM family quarks [16], which is almost excluded by the recent ATLAS and CMS data on search for pair production. For example, ATLAS $\sqrt{s} = 8$ TeV data with 20.3 fb$^{-1}$ integrated luminosity excludes new chiral quarks with mass below 690 GeV at 95% confidence level assuming BR($Q \to Wq$) = 1 [17].

Even if SM4 may be excluded by the LHC soon, this is not the case for the general chiral fourth family (C4F). Therefore, ATLAS and CMS should continue a search for C4F up to kinematical limits. Concerning pair production, rescaling of the ATLAS lower bound using collider reach framework [18] shows that LHC with $\sqrt{s} = 13$ TeV will give opportunity to cover $M_{u_4}$ up to 0.94, 1.25, 1.50, and 2.13 TeV with integrated luminosities 20, 100, 300 and 3000 fb$^{-1}$, respectively.

This study is motivated by a recent paper [19], which shows that in order to interpret 125 GeV scalar boson as dilaton the mass of the fourth family quarks should exceed 2-2.5 TeV; therefore fourth family quarks cannot be observed at the LHC via pair production. For this reason, we consider possible resonant production of C4F through their anomalous interactions with light quarks. In Section II standard and anomalous decays of the C4F quarks are considered. Resonant production of fourth chiral family quarks is analyzed in Section III. Finally, conclusions and recommendations are given in Section IV.

II. STANDARD AND ANOMALOUS DECAYS OF THE C4F QUARKS

The effective Lagrangian for anomalous magnetic type interactions of the fourth family quarks is given as [20][22]:

$$
L = \sum_{q_i} \frac{\kappa^q_i}{\Lambda} e_q g \bar{q}_i \sigma_{\mu\nu} q_i F^{\mu\nu} + \sum_{q_i} \frac{\kappa^Z_i}{2\Lambda} g_Z \bar{q}_i \sigma_{\mu\nu} q_i Z^{\mu\nu} + \sum_{q_i} \frac{\kappa^g_i}{\Lambda} g_s \bar{q}_i \sigma_{\mu\nu} T^a q_i G^{\mu\nu}_a + H.c.
$$

(1)

where $F^{\mu\nu}$, $Z^{\mu\nu}$, and $G^{\mu\nu}$ are the field strength tensors of the gauge bosons, $\sigma_{\mu\nu}$ is the antisymmetric tensor, $T^a$ are Gell-Mann matrices, $e_q$ is electric charge of quark, $g_e$, $g_Z$ and $g_s$ are electromagnetic, neutral weak, and strong coupling constants, respectively. $g_Z = g_e/cos\theta_W$, where $\theta_W$ is the Weinberg angle, $\kappa_e$, $\kappa_Z$, and $\kappa_g$ are the strength of anomalous couplings with photon, Z boson and gluon, respectively. $\Lambda$ is the cutoff scale for new physics. For numerical calculations, we implement Lagrangian (1) into CalcHEP package [23].

The partial decay widths of $u_4$ for SM ($u_4 \to W^+q$, where $q = d, s, b$) and anomalous ($u_4 \to \gamma q$, $u_4 \to Zq$, $u_4 \to gq$, where $q = u, c, t$) modes are given below [19]:

$$
\Gamma(u_4 \to W^+q) = \frac{|V_{u_4q}|^2 \alpha_e m_{u_4}^3}{16m_W^2 sin^2\theta_W} s_W \sqrt{s_0},
$$

(2)

where $s_W = (1 + x_q^2 + x_q^2 x_W^2 - 2 x_q^2 - 2 x_W^2 + x_W^4)$, $s_0 = (1 + x_q^4 + x_q^2 - 2 x_q^2 W - 2 x_q^2 - 2 x_q^2 x_W^2)$, $x_q = (m_q/m_{u_4})$, and $x_W = (m_W/m_{u_4})$,

$$
\Gamma(u_4 \to Zq) = \frac{\alpha_e m_{u_4}^3}{16cos^2\theta_W sin^2\theta_W} \left( \frac{\kappa_Z}{\Lambda} \right)^2 \frac{s_Z}{s_1},
$$

(3)
where \( \zeta_Z = (2 - x_Z^4 + x_Z^2 - 4x_Z^2 - x_Z^2x_Z^2 - 6x_Zx_Z^2 + 2x_Z^4), \) \( \zeta_1 = (1 + x_Z^4 + x_Z^2 - 2x_Z^2 - 2x_Z^2x_Z^2) \), and \( x_Z = (m_Z/m_{u_4}), \)

\[
\Gamma(u_4 \rightarrow gg) = \frac{2\alpha_s m_{u_4}^3}{3} \left( \frac{\kappa_2^2}{\Lambda} \right)^2 \zeta_2, \tag{4}
\]

where \( \zeta_2 = (1 - 3x_q^2 + 3x_q^4 - x_q^6), \)

\[
\Gamma(u_4 \rightarrow \gamma q) = \frac{\alpha_\gamma m_{u_4}^3 Q_q^2}{2} \left( \frac{\kappa_2^2}{\Lambda} \right)^2 \zeta_2, \tag{5}
\]

The partial decay widths of \( d_4 \) for SM \( (d_4 \rightarrow W^{-} q, \) where \( q = u, c, t) \) and anomalous \( (d_4 \rightarrow \gamma q, d_4 \rightarrow Zq, d_4 \rightarrow gg, \) where \( q = d, s, b) \) modes are given below:

\[
\Gamma(d_4 \rightarrow W^{-} q) = \frac{|V_{qd_4}|^2\alpha_\gamma m_{d_4}^3}{16m_W^3 \sin^2\theta_W} \chi_W \sqrt{x_0}, \tag{6}
\]

where \( \chi_W = (1 + y_d^4 + y_q^2y_W - 2x_d^2 - 2y_d^2 + y_W^2), \chi_0 = (1 + y_d^4 + y_q^4 - 2y_d^2 - 2y_q^2 - 2y_W^2, x_W), y_q = (m_q/m_{d_4}), \) and \( y_W = (m_W/m_{d_4}), \)

\[
\Gamma(d_4 \rightarrow Zq) = \frac{\alpha_\gamma m_{d_4}^3}{16\cos^2\theta_W \sin^2\theta_W} \chi_Z \sqrt{x_1}, \tag{7}
\]

where \( \chi_Z = (2 - y_Z^4 + y_Z^2 - 4y_Z^2 - y_Z^2y_Z - 6y_Zy_Z^2 + 2y_Z^4), \chi_1 = (1 + y_Z^4 + y_Z^2 - 2y_Z^2 - 2y_Z^2y_Z), \) and \( y_Z = (m_Z/m_{d_4}), \)

\[
\Gamma(d_4 \rightarrow gg) = \frac{2\alpha_s m_{d_4}^3}{3} \left( \frac{\kappa_2^2}{\Lambda} \right)^2 \chi_2, \tag{8}
\]

where \( \chi_2 = (1 - 3y_q^2 + 3y_q^4 - y_q^6), \)

\[
\Gamma(d_4 \rightarrow \gamma q) = \frac{\alpha_\gamma m_{d_4}^3 Q_q^2}{2} \left( \frac{\kappa_2^2}{\Lambda} \right)^2 \chi_2. \tag{9}
\]

Hereafter, we assume the dominance of CKM mixings between the fourth and third families for standard decays and dominance of anomalous interactions between fourth and first families. Partial decay widths of \( u_4 \) to \( W^+ b \) (assuming \( V_{u_4b} = 0.1) \) and \( u g \) (assuming \( \kappa = 1 \) and \( \Lambda = 100 \text{ TeV} \)) channels are presented in Figures 1 and 2, respectively. Branching ratios for \( u_4 \rightarrow W^+ b \) are presented in Figures 3 and 4. It is seen that this decay channel is dominant in large intervals of \( \Lambda \) and \( V_{u_4b}. \)

![Figure 1](image-url)  
Figure 1. \( \Gamma(u_4 \rightarrow W^+ b) \) with \( V_{u_4b} = 0.1. \)
III. RESONANT PRODUCTION OF $u_4$ QUARKS AT THE LHC

Anomalous resonant production of $u_4$ quarks with dominant $u_4 \rightarrow W^+b$ decays could provide unique opportunity for the discovery of the fourth chiral family at the LHC because this signature can not be imitated by other BSM particles. Corresponding Feynman diagram is given in Figure 5. In Figure 6 we present dependence of resonance $u_4$
production cross section at the LHC with $\sqrt{s} = 13$ TeV for different values of $\Lambda$. For numerical calculations, CalcHEP with CTEQ6L pdf has been used [24].

Following study is performed for leptonic decay of W boson, namely $W^+ \rightarrow e^+\nu_e$. In order to determine discovery cuts, $p_T$ distributions of b-quarks, positrons and neutrinos (missing transverse momentum) for signal and background processes have been analyzed. It was seen that $p_T^b > 200$ GeV and $p_T^{e+}, p_T^{\mu\mu} > 100$ GeV drastically reduce background whereas signal is almost unchanged. In addition we choose $0.9M_{u_4} < M_{inv} < 1.1M_{u_4}$ for invariant mass window. Statistical significance is determined as:

$$SS = \sqrt{2[(S + B) \ln(1 + (S/B)) - S]}$$

where $S$ and $B$ are number of events of signal and background, respectively. With these cuts, for $\Lambda = 100$ TeV we obtain discovery limits on the mass of $u_4$ as 3.5, 4.3 and 5.9 TeV for $L_{int} = 100, 300$ and 3000 $fb^{-1}$, respectively. Discovery of $u_4$ at the LHC via the channel under the consideration will simultaneously determine $\Lambda$ scale. Achievable $\Lambda$ values for different $M_{u_4}$ and $L_{int}$ are presented in Table I.

Table I. Achievable $\Lambda$ values for different $M_{u_4}$ and $L_{int}$.

| $M_{u_4}$, TeV | $L_{int}$, $fb^{-1}$ | $\Lambda$, TeV ($SS = 3$) | $\Lambda$, TeV ($SS = 5$) |
|---------------|---------------------|--------------------------|--------------------------|
| 1             | 3000                | 680                      | 540                      |
|               | 300                 | 390                      | 292                      |
|               | 100                 | 286                      | 220                      |
| 2             | 3000                | 510                      | 395                      |
|               | 300                 | 285                      | 219                      |
|               | 100                 | 218                      | 163                      |
| 3             | 3000                | 420                      | 324                      |
|               | 300                 | 234                      | 175                      |
|               | 100                 | 171                      | 127                      |
| 4             | 3000                | 285                      | 218                      |
|               | 300                 | 151                      | 109                      |
|               | 100                 | 109                      | 76                       |
| 5             | 3000                | 208                      | 167                      |
|               | 300                 | 103                      | 70                       |
|               | 100                 | 68                       | 38                       |
| 5.5           | 3000                | 168                      | 122                      |
|               | 300                 | 78                       | 46                       |
|               | 100                 | 45                       | -                        |
| 6             | 3000                | 137                      | 96                       |
|               | 300                 | 11                       | 22                       |
|               | 100                 | -                        | -                        |
It is seen that search for resonance in $W^+b$ final state at the LHC could lead to discovery of the fourth chiral family and simultaneously determine scale of the new physics, presumably related to the quark and lepton compositeness. In this paper only special case, namely $ug \rightarrow u_4 \rightarrow W^+b$ has been analyzed ($W^-j$ final states are suppressed since they are originated from sea $\bar{u}$ quarks). In the same manner $d_4$ quarks can also be produced with cross section approximately half of $u_4$. In this case $d_4$ has following decay chain: $d_4 \rightarrow W^-t \rightarrow W^-W^+b$.

If CKM mixings with the second (first) family are dominant, in spite of dominance of CKM mixings with the third family considered in this study, main decay modes will be $u_4 \rightarrow W^+s(W^+d)$ and $d_4 \rightarrow W^-c(W^-u)$. In this case both $W^+j$ and $W^-j$ final states are expected with the ratio of 2:1.

Fourth family quarks may also be produced via anomalous couplings with second and third family quarks. In this case production cross sections are suppressed since initial states includes sea quarks. Anomalous coupling with second family quarks results in the processes $sg \rightarrow d_4 \rightarrow W^-b$, $sg \rightarrow d_4 \rightarrow W^+\bar{b}$, $cg \rightarrow u_4 \rightarrow W^+b$, $cg \rightarrow \bar{u}_4 \rightarrow W^-\bar{b}$ (if CKM mixings with first two families are dominant b-jets are replaced by lighter quark-jets). Anomalous coupling with third family quarks contributes to the production of chiral fourth family down quarks via $bg \rightarrow d_4 \rightarrow W^-b$, $\bar{b}g \rightarrow d_4 \rightarrow W^+\bar{b}$.

Finally, it is possible that anomalous decay modes of fourth family quarks may be dominant. Unfortunately, in this case, identification of fourth family quarks will be problematic since, for example, excited quarks ($q^*$) has similar signatures.

In conclusion, results of this study emphasize an importance of W-leading jet invariant mass analysis in search for $W^+j$ final states at the LHC, both with and without b-tagging.

ACKNOWLEDGMENTS

Authors are grateful to Y. C. Acar, M. Sahin and G. Unel for useful discussions. This work is partially supported by TÜBİTAK under the grant no 114F337.

[1] Proceedings of the First International Symposium on the fourth family of quarks and leptons, 26-28 February 1987, Santa Monica, CA, published in Annals of the New York Academy of Sciences, 518 (1987), edited by D. Cline and A. Soni.
[2] Proceedings of the Second International Symposium on the fourth family of quarks and leptons, 23-25 February 1989, Santa Monica, CA, published in Annals of the New York Academy of Sciences, 578 (1989), edited by D. Cline and A. Soni.
[3] Beyond the 3SM generation at the LHC era Workshop, 4-5 September 2008, CERN, Geneva, Switzerland.
http://indico.cern.ch/event/33289
[4] Second Workshop on Beyond 3 Generation Standard Model New Fermions at the Crossroads of Tevatron and LHC, 14-16 January 2010 Taipei, Taiwan. [http://indico.cern.ch/event/68036]

[5] Third Workshop on Beyond 3 Generation Standard Model Under the light of the initial LHC results, 23-25 October 2011, Istanbul, Turkey. [https://indico.cern.ch/event/150154]

[6] B. Holdom et al., “Four statements about the fourth generation”, PMC Physics A 2009, 3:4; [arXiv:0904.4698 [hep-ph]].

[7] S. A. Cetin et al., “Status of the Fourth Generation: A Brief Summary of B3SM-III Workshop in Four Parts”, [arXiv:1112.2907]

[8] H. Fritzsch, “Light neutrinos, nonuniversality of the leptonic weak interaction and a fourth massive generation”, Phys. Lett. B 289.1-2 (1992) 92-96.

[9] A. Datta, “Flavour democracy calls for the fourth generation”, Pramana 40.6 (1993): L503-L509.

[10] A. Celikel, A. K. Ciftci, and S. Sultansoy, “A search for the fourth SM family”, Phys. Lett. B 342.1 (1995) 257-261.

[11] S. Sultansoy, “Why the four SM families”, [arXiv:hep-ph/0004271]

[12] S. Sultansoy, “Flavor democracy in particle physics”, AIP Conf. Proc. 899 (2007) 49; [arXiv:hep-ph/0610279]

[13] M. Sahin, S. Sultansoy, and S. Turkoz, “Search for the fourth standard model family”, Phys. Rev. D 83 (2011) 054022; [arXiv:1009.5405v2].

[14] S. Bar-Shalom, M. Geller, S. Nandi and A. Soni, “Two Higgs doublets, a 4th generation and a 125 GeV Higgs: a review”, Adv. High Energy Phys. (2013) 672972; [arXiv:1208.3195 [hep-ph]]

[15] S. Banerjee, M. Frank, S. K. Rai, “Higgs data confronts sequential fourth generation fermions in the Higgs triplet model”, Phys.Rev. D89 (2014) no.7, 075005.

[16] M. S. Chanowitz, M. A. Furman and I. Hinchliffe, “Weak interactions of ultra heavy fermions (II)”, Nucl. Phys. B153 (1979) 402.

[17] G. Aad et al., “Search for pair production of a new heavy quark that decays into a W boson and a light quark in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, Phys. Rev. D 92.11 (2015) 112007.

[18] G. Salam and A. Weiler, “The Collider Reach project”, [http://collider-reach.web.cern.ch/collider-reach]

[19] W.-S. Hou, “Connecting Electroweak Symmetry Breaking and Flavor: A Light Dilaton D and a Sequential Heavy Quark Doublet Q”, [arXiv:1606.03752] (2016).

[20] E. Arik, O. Cakir, and S. Sultansoy, “A search for the fourth SM family quarks at the Tevatron”, Eur. Phys. J. C 39, 499 (2005).

[21] G. Cabibbo, L. Maiani, and Y. Srivastava, “Anomalous Z decays: excited leptons?”, Phys. Lett. B 139, 459 (1984).

[22] K. Hagiwara, S. Komamiya, and D. Zeppenfeld, “Excited lepton production at LEP and HERA”, Z. Phys. C 29, 115 (1985).

[23] A. Belyaev, N. Christensen, A. Pukhov, “CalcHEP 3.4 for collider physics within and beyond the Standard Model”, Comput. Phys. Commun. 184 (2013)1279-1769; [arXiv:1207.6082]

[24] D. Stump et al., “Inclusive jet production, parton distributions and the search for new physics”, JHEP 0310 (2003) 046.