Search for the fourth family up quarks at CERN LHC

E. Arık,[1] S. Atağ,[2] Z. Z. Aydin,[3] A. Çelikel,[3] Z. Çiçek,[1] A. K. Çiftçi,[2] A. Mailov,[1,4] S. Sultansoy,[3,4] and G. Ünel[1]
[1]*Physics Department, Faculty of Arts and Sciences, Boğaziçi University, Istanbul, Turkey*
[2]*Physics Department, Faculty of Sciences, Ankara University, 06100, Tandoğan-Ankara, Turkey*
[3]*Department of Engineering Physics, Faculty of Sciences, Ankara University, 06100, Tandoğan-Ankara, Turkey*
[4]*Institute of Physics, Academy of Sciences, Baku, Azerbaijan*

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Pair production of the fourth standard model (SM) family up quarks at the CERN Large Hadron Collider (LHC) has been investigated. It is shown that the LHC will provide clarifying information on the existence of the fourth SM family. [S0556-2821(98)01419-2]

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I. INTRODUCTION

The discovery of the top quark in Fermilab experiments Collider Detector at Fermilab (CDF) [1] and D0 [2] was beautiful confirmation of predictions of the standard model (SM). But, certain unexplained questions still remain: the number of families, mass and mass hierarchies for quarks and leptons, flavor mixing, etc. Several attempts to explain all these questions have been made using different extensions of the SM (see, for example [3–5] and references therein). However, some of the above mentioned questions might have an answer within the SM. For example, the democratic mass matrix (DMM) approach [6] has been developed to solve the problem of masses and mixings of fundamental fermions. Since some difficulties arise in the case of three families, the extension of this DMM approach to include a fourth family into the SM was considered by Ref. [7], where a parametrization of the mass matrix was proposed and quark and leptonic Cabibbo-Kobayashi-Maskawa (CKM) matrices were calculated, the results being in good agreement with experimental data. The predicted masses of the fourth family fermions are close to each other within an accuracy of the order of a few GeV and lie between 300 and 700 GeV.

Experimental searches for heavy fourth family quarks and leptons at e^+e^- and $p\overline{p}$ colliders yield limits $m_{\ell_4}, m_{\nu_4} \geqslant 45$ GeV and $m_{q_4} > 100$ GeV [8]. It seems that the best place to search for the fourth family leptons will be the future linear e^+e^- colliders whereas the fourth family quarks will be copiously produced at future hadron machines [9].

II. THE FOURTH SM FAMILY QUARKS

The fourth family fermion masses, in the case of full democracy, are given by $m_{q_4} = 4a\eta$ [7], where $\eta \simeq 249$ GeV is the vacuum expectation value of the Higgs field, and the first three families of fermions remain massless. If a is taken as the weak coupling constant g_w, then one gets $m_{q_4} = 8m_w \simeq 640$ GeV, for $a = e = \sqrt{4\pi\alpha_{em}}$, one has $m_{q_4} = 320$ GeV. After violating democracy, the first three families of fermions acquire masses and the CKM matrix becomes nontrivial. Using the mass values of the observed quarks as input parameters, one obtains the fourth family quark masses and the CKM matrix. For the case where $a = g_w$, the predicted masses of the fourth family quarks are $m_{u_4} = 638.6$ GeV, $m_{d_4} = 639.7$ GeV, and the corresponding CKM matrix is

$$O_{CKM} = \begin{pmatrix} 0.9755 & -0.2198 & 0.0021 & 0.0001 \\ 0.2196 & 0.9749 & 0.0334 & 0.0001 \\ -0.0094 & -0.0321 & 0.9994 & -0.0017 \\ -0.0001 & -0.0001 & 0.0017 & 1.0000 \end{pmatrix}. \quad (1)$$

For the case where $a = e$, one gets $m_{u_4} = 318.6$ GeV, $m_{d_4} = 319.7$ GeV, and

$$O_{CKM} = \begin{pmatrix} 0.9755 & -0.2199 & 0.0021 & 0.0001 \\ 0.2197 & 0.9749 & 0.0334 & 0.0002 \\ -0.0094 & -0.0321 & 0.9994 & -0.0057 \\ -0.0002 & -0.0003 & 0.0057 & 1.0000 \end{pmatrix}. \quad (2)$$

The dominant decay mode of new up quark will be $u_4 \rightarrow b + W^+$. Using appropriate values from Eq. (1) and Eq. (2), one gets 0.993 and 0.998 for the branching ratios, respectively.

The fourth family up-quarks will be pairly produced at the CERN Large Hadron Collider (LHC) in the process:

$$pp \rightarrow \overline{u}_4 u_4 X \rightarrow W^- \overline{b} W^+ b + X. \quad (3)$$

The $b, \overline{b}$ quarks can be identified in the detector as b-jets (so called b-tagging), the hadronic decay modes of the W will be observed as two jets and its leptonic decay modes will be observed as a charged lepton+unbalanced transverse momentum, $\not{p}_t$. Excluding the final states containing τ leptons, the expected event topologies for process (3) are

$$\overline{u}_4 u_4 \rightarrow \begin{cases} e^- e^+ (e^-\mu^+, \mu^- e^+, \mu^-\mu^+) + 2b_{jet} + \not{p}_t & 4.9\%, \\ e^- (\mu^-, e^+, \mu^+) + 2b_{jet} + 2j + \not{p}_t & 29.6\%, \\ 2b_{jet} + 4j & 44.4\%. \end{cases}$$

The six-jet mode is not suitable for detection of the fourth family quarks due to the large QCD background [10].

III. THE EVENT GENERATION

We have studied the pair-production of the fourth family up-quarks at the future Large Hadron Collider (pp, $\sqrt{s}$

$=14$ TeV) with integrated luminosity $\int L dt=10^5$ pb^{-1}. The events were simulated at the particle-level using the Monte Carlo programs PYTHIA 5.7 [11] to generate hard processes and JETSET 7.4 [12] for parton showering, fragmentation, and decay of particles. At the parton-level, the following settings were used in PYTHIA: initial and final state QCD and QED radiations were enabled; processes such as multiple interactions, pileup, beam remnant treatment of the events were switched off. For the fourth family quarks, we assumed that they have no time to fragment and initially they decay into a light one with subsequent fragmentation of the light quark.

For realistic simulation results which take the detector effects into consideration, we used a fast simulation program ATLFAST [13] written for the ATLAS detector. ATLFAST performs the following tasks: jet reconstruction in the hadronic and electromagnetic calorimeters; selection of isolated leptons and photons; missing transverse momentum reconstruction; parametrization of the detector response. The jet reconstruction is based on depositing the energy of undecayed particles into idealized segmented calorimeter which covers the full azimuthal angle around the beam axis and pseudorapidity interval $|\eta|\leqslant 5$. The cells of size $\Delta\eta\times\Delta\Phi=0.1\times 0.1$ and $\Delta\eta\times\Delta\Phi=0.2\times 0.2$ are chosen for barrel $(|\eta|\leqslant 2.5)$ and forward regions $(3\leqslant|\eta|\leqslant 5)$, respectively. Particle energies are smeared with energy resolution of the calorimeter, namely $\sigma_h=(0.5\times\sqrt{E})\oplus 0.03$ GeV for hadrons and $\sigma_{e/\gamma}=(0.1\times\sqrt{E})\oplus 0.03$ GeV for electrons and photons. In each cell, the particle energies are summed. Starting from highest transverse energy $E_\perp$, the transverse energy of nearest cells within a cone of size $\Delta R=\sqrt{\Delta\eta^2+\Delta\phi^2}\leqslant 0.4$ are added. If this sum is greater than a threshold of 15 GeV, then all particles within this cone are identified as forming a jet.

The reconstructed b-jets are accepted if they satisfy the following cuts: (a) a b-jet pseudorapidity cut of $|\eta_{b_{jet}}|\leqslant 2.5$; (b) transverse momentum of b-quark after final state radiation $p_t\geqslant 5$ GeV; (c) distance between b-quark and b-jet axis $\Delta R\leqslant 0.2$. The pattern of the signal process dictates the tagging of two b-jets in the event. For the ATLAS detector, the expected b-tagging efficiency is about 60%. In addition, c-quark jets will be mistagged as b-jets with probability of about 10% and mistagging of light-quark jets as b-jets is about 1%. We randomly tagged all jets accordingly.

Events with an isolated lepton are selected using the cuts:

(a) maximum transverse energy deposition in cells in a cone $\Delta R\leqslant 0.2$ around the lepton of $E_T\leqslant 10$ GeV,

(b) distance from any jet $\Delta R\geqslant 0.4$,

(c) transverse momentum of lepton $p_t\geqslant 5$ GeV,

(d) pseudorapidity of lepton $|\eta_{lepton}|\leqslant 2.5$,

(e) missing transverse momentum $\not{p}_t/\geqslant 20$ GeV.

The lepton isolation efficiency of ATLFAST is about 95%, whereas the jet reconstruction efficiency is about 80%.

The effect of the solenoidal 2T magnetic field is also simulated assuming a shift in ϕ position of charged particles due to their deflection.

IV. SIGNAL AND BACKGROUND PROCESSES

In our analysis, we have considered the signal process (3) with one W decaying leptonically and the other one producing a pair of hadronic jets, namely $u_4\overline{u_4}\to l^{\pm}+2j+2b_{jet}+\not{p}_t$. W-boson produced by a heavy quark will be recoiling against the b-jet and the lepton from W-decay will be clearly separated (i.e., isolated) from any jet. Hence, isolated lepton trigger will yield a high rejection efficiency for background processes.

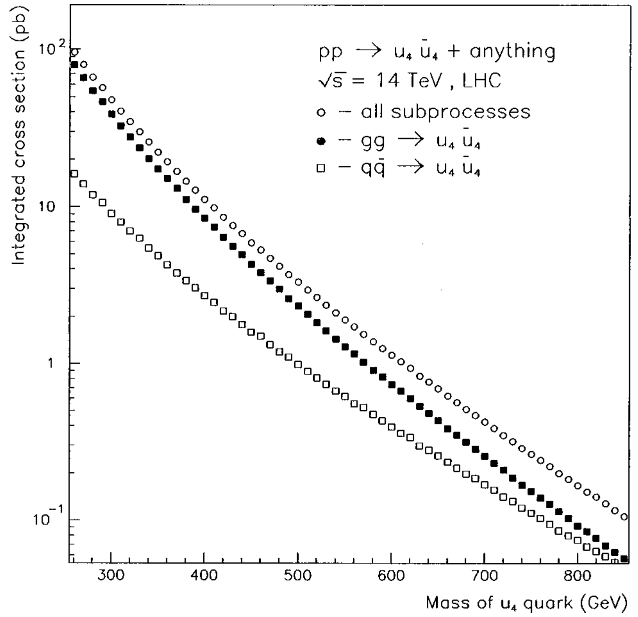

FIG. 1. Integrated cross sections of heavy u_4-quark production for the LHC.

The dominant production subprocesses for heavy quarks are the lowest-order QCD gluon-gluon (gg) and quark-antiquark $(q\overline{q})$ fusion mechanisms producing $Q\overline{Q}$ pairs, where Q denotes a heavy quark (e.g., u_4). Total cross section for the production of heavy quarks in the lowest order is well known [14]. Calculations including next-to-leading order contributions $O(\alpha_s^3)$ are performed in Ref. [15]. The simulated integrated cross section obtained for the process (3) as a function of mass M_{u_4} at the LHC is presented in Fig. 1. In the same figure, the contributions of gg and $q\overline{q}$ fusion subprocesses are also shown. It can be seen that the main contribution to the production cross section arises from gg fusion subprocess at the LHC.

The major backgrounds to the signal process (3) are the following.

(a) $pp\to t\overline{t}\to l\nu+2b_{jet}+2j$. This background is irreducible because it has the same real particles in final state and therefore is most dangerous. The expected total cross section of $t\overline{t}$ production at the LHC energy is quite large $(\sigma\cdot B\simeq 0.767$ nb$)$, but using the appropriate kinematic cuts and isolation criteria, it is possible to reduce this background to an acceptable level. For example, the authors in [16] proposed a set of cuts which eliminates $t\overline{t}$ background from the fourth family signal. This interesting result might be taken into consideration for future analyses at the LHC, when $t\overline{t}$ production is a background to new physics.

(b) $pp\to W^{\pm}+4\ jets\to l\nu+4\ jets$. This reducible

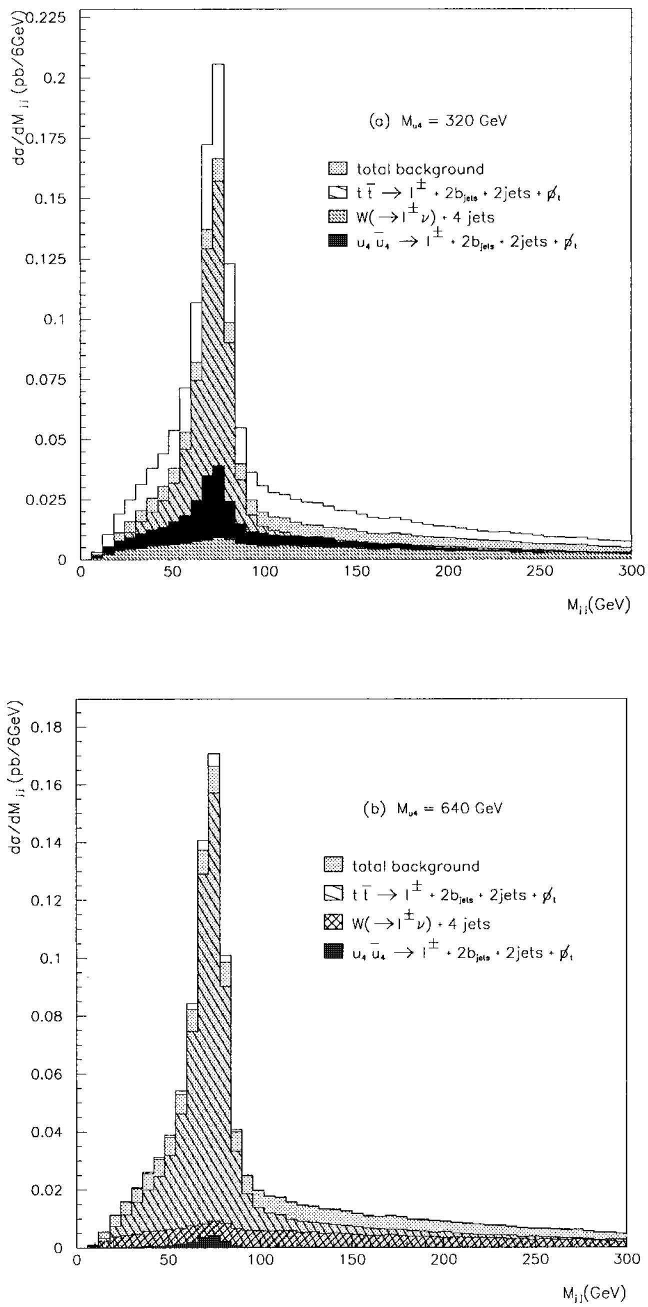

FIG. 2. The invariant mass distributions M_{jj} for masses of u_4 quark 320 GeV and 640 GeV.

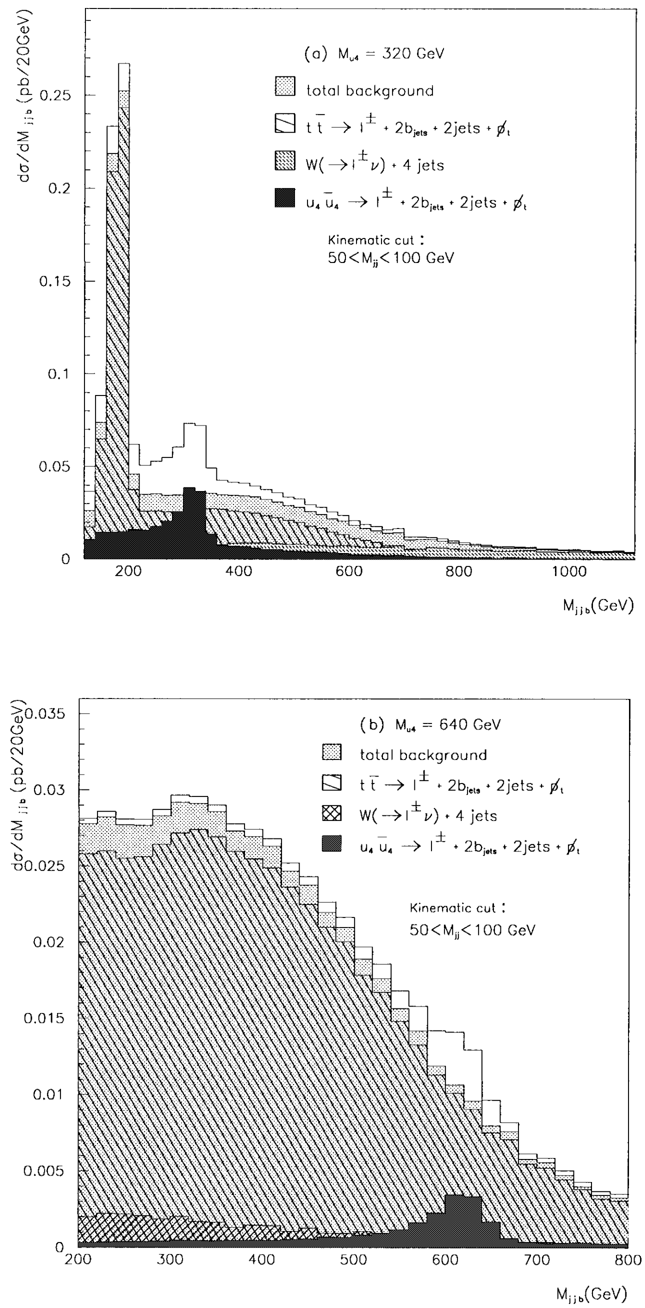

FIG. 3. The invariant mass distributions M_{jjb} for masses of u_4 quark 320 and 640 GeV with kinematic cut $50 \leqslant M_{jj} \leqslant 100$ GeV.

QCD process has a single lepton and also has large cross section, but produced jets have lower p_t than those from $u_4 \to Wb$ with subsequent decay of $W \to 2j$. Also this background rarely contains two b-jets. Hence the $W+4$ jets background can be considerably reduced using kinematic cuts and b-tagging. The cross section $\sigma \cdot B \simeq 8$ pb was calculated after the selection of two tagged b-jets.

(c) $pp \to WW+2$ *jets*. The other source of background, where the light-quark jets fake b-jets and one of the W's fakes lepton signal. The expected total cross section of W^+W^- pair production at the LHC is about 72 pb, but simultaneous tagging of two b-jets will reduce it significantly $(\sigma \cdot B \simeq 0.43\text{ pb})$. Hence the contribution from double-W production in the region of the invariant mass spectrum 200 GeV$\leqslant M_{jjb} \leqslant$1000 GeV is quite small.

(d) $pp \to ZZ+2j$. In this process one Z^0 fakes two b-jets signal and second Z^0 will fake a single isolated lepton, if the second lepton from the decay $Z^0 \to l^+l^-$ is undetected. Our analysis shows that the contribution of such a process is negligible $(\simeq 0.04\text{ pb})$.

Comparing the transverse momentum distributions for b-jets and leptons for different backgrounds and signal process, one can see that b-jets and isolated leptons from the fourth family quark decays have higher transverse momentum than those from $W+jets$ background. Hence, in addition to ATLFAST selection criteria, we have applied the cuts

$p_t \geqslant 250$ GeV for b-jets, $p_t \geqslant 50$ GeV for leptons.

The reconstruction of jets from hadronic decay of W has been performed using jet cone algorithm mentioned above. In Figs. 2(a) and 2(b) the reconstructed invariant mass distributions of two jets for u_4 masses at 320 and 640 GeV are shown together with the backgrounds. The signal and $t\bar{t}$ background processes have clear peaks near the mass of W-boson. A systematic shift, of $\simeq 8$ GeV in peak position for reconstructed M_{jj} is observed due to final-state radiation and effect of magnetic field which cause degradation of the mass spectrum. A large combinatorial background from additional jets contributes to the events outside the W mass peak. A jet-jet mass cut $M_{jj} = m_W \pm 25$ GeV is also used to enhance the u_4 quark signal relative to background.

Figures 3(a) and 3(b) show the reconstructed invariant mass distributions of jjb system for background and signal processes with dijet mass in the interval $50 \leqslant M_{jj} \leqslant 100$ GeV. In all figures clear excesses around the u_4 quark masses are observed and statistical significances of the signals above background are quite large. Now we can conclude that at the LHC, it is possible to distinguish the u_4 signal from main backgrounds such as $t\bar{t}$ and $W+$jets processes.

In Table I we present the expected rates for the pair production of u_4 quarks with masses 320 and 640 GeV at the LHC for an integrated luminosity 10^5 pb^{-1} together with the contributions from different backgrounds. The statistical significances (signal to background ratio $S/\sqrt{B}$) are also presented in the same table. In the last column of Table I, we present the results for $m_{u_4} = 780$ GeV which we quote as the discovery limit corresponding to $S/\sqrt{B} = 5$. Note that partial wave unitarity at high energies restricts the mass values of the fourth family fermions to be less than 1 TeV [17].

TABLE I. Expected rates of the fourth family up-quarks for an integrated luminosity 10^5 pb^{-1} at the LHC.

Fourth family quark mass	320 GeV	640 GeV	780 GeV
$t\bar{t}$	19320	8930	4851
$W+4$ jets	760	327	224
$WW+2$ jets	113	48	27
$ZZ+2$ jets	17	6	2
Background	20210	9311	5104
Signal	10600	1591	382
$\frac{S}{\sqrt{B}}$	74.5	16.6	5.3

V. SUMMARY

We have shown that the fourth SM family up-quark with predicted mass in the range of 300–700 GeV will clearly manifest itself at the LHC. Finally, the LHC will answer the question is there a fourth generation with u_4 mass below 780 GeV.

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