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Search for the fourth standard model family

M. Sahin*
TOBB University of Economics and Technology, Physics Division, Ankara, Turkey

S. Sultansoy†
TOBB University of Economics and Technology, Physics Division, Ankara, Turkey and Institute of Physics, National Academy of Sciences, Baku, Azerbaijan

S. Turkoz‡
Ankara University, Department of Physics, Ankara, Turkey
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Existence of the fourth family follows from the basics of the standard model (SM) and the actual mass spectrum of the third family fermions. We discuss possible manifestations of the fourth SM family at existing and future colliders. The LHC and Tevatron potentials to discover the fourth SM family have been compared. The scenario with dominance of the anomalous decay modes of the fourth-family quarks has been considered in detail.

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I. INTRODUCTION

Even though the standard model with three fermion families (SM3) accounts for almost all of the large amount of the particle physics phenomena [1], there are a number of fundamental problems which cannot be addressed in the framework of the SM3: quark-lepton symmetry, fermion's mass and mixing pattern, family replication and the number of families, L-R symmetry breaking, electroweak scale, etc. In addition, SM3 contains an unacceptably large number of arbitrary free parameters put by hand: 19 if the neutrinos are massless, 26 if neutrinos are Dirac particles and more than 30 if neutrinos are Majorana particles. Flavor democracy hypothesis (FDH), which is quite natural in respect to the SM basics, provides a partial solution to the above-mentioned problems, namely, sheds light on fermion's mass and mixing pattern, implies the number of SM families to be four, and reduces the number of free parameters [2–4] (see also reviews [5–10] and references therein).

Historical analogy.—Let us emphasize the analogy of today's SM fermions and parameters inflation with chemical elements inflation in 19th century and hadron inflation in 1950–1960. Both cases have been clarified through four stages: systematics, predictions confirmed, clarifying experiments, and new basic physics level (see Table I). We have added the last row to the table in order to reflect the present situation in particle physics.

Let us remind that flavor physics met a lot of surprises. The first example was discovery of the μ meson (we were looking for the π- meson predicted by Yukawa but discovered the ''heavy electron''). The next example was represented by strange particles (later we understood that they contain strange quarks). The story was followed by the τ lepton, and c and b quarks discovered in the 1970's. Actually, the c quark was foreseen by the Glashow-Iliopoulos-Maiani mechanism and quark-lepton symmetry and its mass was estimated in the few GeV region, whereas the discovery of the τ lepton and the b quark was completely surprising for physicists. According to the standard model, they are the members of the third fermion family, which was completed by the discovery of the t quark in 1995 at Tevatron. Actually, we need at least three fermion families in order to handle CP violation within the SM [11]. CP violation is necessary for the explanation of baryon asymmetry of the universe (BAU). Unfortunately, SM with three fermion families does not provide actual magnitude for BAU. Fortunately, the fourth SM family could provide an additional factor of order of 10^{10} and, therefore, solves the problem [12].

The status of the fourth SM family (SM4) was clearly emphasized at a dedicated international workshop held at CERN in September 2008. The outcome of the workshop was published in a paper titled ''Four statements about the fourth generation'' [13]. These statements are:

(1) The fourth generation is not excluded by electroweak (EW) precision data.
(2) SM4 addresses some of the currently open questions.
(3) SM4 can accommodate emerging possible hints of new physics.
(4) LHC has the potential to discover or fully exclude SM4.

In our opinion the last statement is the most important one, because indirect manifestations could have many different explanations, the existence of the fourth SM family will be proved with the direct discovery of its

*m.sahin@etu.edu.tr
†ssultansoy@etu.edu.tr
‡turkoz@science.ankara.edu.tr

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TABLE I. Historical analogy.

Inflation	Systematic	Confirmed predictions	Clarifying experiments	Fundamentals
Chemical elements	Mendeleyev periodic table	New elements	Rutherford	p, n, e
Hadrons	Eightfold way	New hadrons	SLAC DIS	Quarks
SM fermions	Flavor democracy	Fourth family?	LHC?	Preons?

quarks and leptons. Current experimental bounds on the masses of the fourth SM family fermions are as follows [1,14]: $m_{u_4} > 256$ GeV, $m_{d_4} > 338$ GeV, $m_{l_4} > 100.8$ GeV, $m_{\nu_4} > 90.3$ GeV (Dirac type), $m_{\nu_4}(\text{light}) > 80.5$ GeV (Majorana type).

By this time almost all papers on the SM4 searches consider only SM decay modes. However, it is possible that anomalous decay modes could be dominant, if some criteria is met [15]. In this case, the search strategy should be changed drastically and current low limits from Tevatron experiments are not valid. It should be noted that here we keep in mind beyond the SM4 anomalous interactions. The possible dominance of flavor-changing neutral-current decay modes of d_4 quark within the SM through loop diagrams, proposed in Refs. [16–21], is excluded due to the largeness of d_4 mass.

The scope of the paper is the following: in Sec. II we give a brief review of the flavor democracy hypothesis and discuss possible manifestations of the fourth SM family at existing and future colliders. Then, we concentrate on the scenario with dominance of the anomalous decay modes of the fourth-family quarks. The criteria for this dominance are considered in Sec. III. In Sec. IV we consider pair production at the Tevatron and LHC with subsequent anomalous decays. Section V is devoted to investigation of anomalous resonant production of the fourth-family quarks with subsequent anomalous decays. Finally, in Sec. VI we present concluding remarks and recommendations.

II. WHY THE FOUR SM FAMILIES?

First of all, the number of fermion families is not fixed by the SM. But the asymptotic freedom restricts this number from above, namely, $N \leq 8$. Then, the number of SM families with "massless" neutrinos (which means $m_\nu < m_Z/2$) is determined to be equal to 3 by the LEP1 data. Therefore, the number of families could be any number between 3 and 8, inclusively. Most of the free parameters (put by hand) in the SM come from the Yukawa interactions between the SM fermions and the Higgs doublet, which provides fermion masses and mixings through spontaneous symmetry breaking (SSB). It should be noted that, before the SSB, fermions with the same quantum numbers are indistinguishable. Naturally, all Yukawa coupling constants for indistinguishable fermions should be the same. This is the first assumption of the flavor democracy hypothesis. If there is only one Higgs doublet all fundamental fermions (up- and down-type quarks, charged leptons, and neutrinos) should have the same Yukawa coupling constants, since all fermions interact with the same Higgs field. This is the second assumption of the FDH. After the SSB these assumptions in the case of N SM families result with $N-1$ fermion families to be massless and the Nth family to be heavy and degenerate. By taking into consideration masses of the third SM family, the FDH implies at least the existence of the fourth SM family [2–4]. In this case, the masses of the first three family fermions come from the slight violation of the full democracy [22–24].

There are two arguments against the existence of the fifth SM family [7,9,10]. The first one is the large value of the t-quark mass: in the case of five SM families the FDH gives $m_t \ll m_4 \ll m_5$, but it contradicts to partial-wave unitarity constraint $m_Q \leq 700\ \text{GeV} \approx 4m_t$ (we do not consider the possible situation in which perturbation theory does not hold for the fifth family). The second argument is the neutrino counting at the LEP1: data gives three massless nonsterile neutrinos, whereas in the case of the five SM families the FDH predicts this number to be four. The second argument is not as strict as the first one if m_{ν_4} is close to the experimental lower bound $\sim$100 GeV.

The main reason why the HEP community has objected against the fourth SM family so far comes from the incorrect interpretation of the electroweak precision data. This interpretation since the 1990's has been included into PDG reports published biannually in leading HEP journals. It should be noted that recent opinion [25] of the writers of the corresponding part of PDG reports is not as strict as it was. Actually in a number of papers published during the past decade [26–38] it has been shown that the precision data and the SM4 are not mutually exclusive. It is interesting that the updated precision data is shifted into the direction of SM4 predictions. For the investigation of the compatibility of the precision data with the fourth SM family and other physics beyond the SM3, a new code named OPUCEM [38,39] has been developed very recently. Using this code we determined the validity of SM4 with a given set of parameters, namely, $m_{u_4} = 410$ GeV, $m_{d_4} = 390$ GeV, $s_{34} = 0.01$ (Cabibbo-Kobayashi-Maskawa (CKM) mixing between fourth and third SM family quarks), $m_{\nu_4}(l) = 105$ GeV for light Majorana neutrino, $m_{l_4} = 450$ GeV, $m_H = 290$ GeV,

TABLE II. S, T and R parameters for there SM4 points and SM3.

SM4 points	1	2	3	SM3
m_{u_4}, GeV	410	440	440	
m_{d_4}, GeV	390	390	390	
m_{l_4}, GeV	450	390	390	
m_{ν_4} (L), GeV	105	91	95	
m_{ν_4} (H), GeV	2300	2900	2900	
m_H, GeV	290	250	115	115
s_{34}	0.01	0.02	0.02	
R	0.97	0.56	0.036	1.7
S	0.17	0.15	0.09	0
T	0.19	0.16	0.12	0

and $m_{\nu_4}(h) = 2300$ GeV for heavy Majorana neutrino. This set is favored by FDH if the common Yukawa coupling for all SM4 fermions is equal to the $SU_W(2)$ gauge constant g_W ($m_H = 290$ GeV corresponds to quartic coupling of the Higgs field equal to g_W). The result is $R = 0.97$ which is 2 times better than the SM3 value $R = 1.7$ (here $R = \Delta\chi^2$ denotes the "distance" from the central values of S and T parameters, for details see [38,39]).

Actually, there is an infinite number of SM4 points (analog of the well-known SUGRA points) which are in better agreement with precision EW data than the SM3. In Table II we present three of them. In Fig. 1 we present these points in the S-T plane together with SM3 predictions. It is seen that SM4 points are closer to central values of S and T parameters.

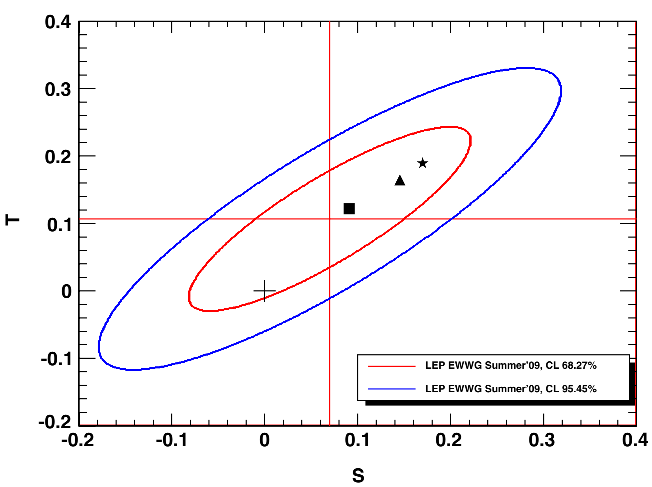

FIG. 1 (color online). SM3 and three SM4 points in the S-T plane. The 1 and 2σ error ellipses represent the 2009 results of the $U = 0$ fit from LEP EWWG. The cross corresponds to SM3 with $m_H = 115$ GeV; the star, the triangle, and the square correspond to SM4 points 1, 2, and 3 from Table II, respectively. This figure is obtained by using OPUCEM] software.

A. Indirect manifestations

The existence of the fourth SM family could lead to a number of different manifestations [12,13,40–46], such as essential contribution to the baryon asymmetry of the Universe (SM3 case does not provide enough amount of CP violation), explanation for a 2.5σ deviation from SM3 predictions on B-meson decays observed by Tevatron and B factories, etc. It should be noted that these are not a validation, but just an indication of the fourth SM family, since there are a lot of models (including SUSY) which potentially could lead to the same manifestations. However, the essential enhancement (from 9 times at $m_H \approx 150$ GeV to 4 times $m_H \approx 500$ GeV) of Higgs boson production via gluon-gluon fusion at hadron colliders [47–55] could not be provided by other models. This enhancement could give to Tevatron an opportunity to discover the Higgs boson before the LHC [53,55]. Very recent combined results of the CDF (with 4.8 fb^{-1}) and D0 (with 5.4 fb^{-1}) searches for a standard model Higgs boson in the process $gg \to H \to W^+W^-$ exclude the 131 GeV $< m_H <$ 204 GeV region in the SM4 case [56]. This excluded region will be essentially enlarged with the accumulated luminosity, or the Higgs boson will be observed at Tevatron if it has appropriate mass. Moreover, simultaneous discovery of both the Higgs boson and the fourth-family neutrino is probable at the early stages of LHC operation or at the Tevatron [57–59].

B. Direct manifestations

Obviously, the discovery of the fourth SM family may be only provided by their production and observation at high energy colliders. The fourth-family quarks will be copiously produced in pairs at the LHC [5,48,60] when the designed center of mass energy and luminosity values are achieved. However, Tevatron still has a chance to observe u_4 before the LHC if u_4 mass is less than 425 GeV (current low limit is 340 GeV from CDF with 4.6 fb^{-1}). If the fourth-family quarks mix dominantly with the first two families, u_4 and d_4 quarks will give the same signature and the observation limit will be extended to 450 GeV.

In Table III we present the center of mass energies and luminosity values of existing and planned TeV scale colliders (see [6,8,61,62] and references therein). Observational possibilities for fourth SM family fermions at these colliders are presented in Tables IV and V. The direct production of the fourth SM family quarks and leptons at TeV scale colliders, namely, Tevatron, LHC, QCD Explorer, Linac-LHC Energy Frontier, ILC, CLIC, and muon collider, have been considered in a number of papers [63–94] (this list includes publications appearing during the past decade, see also fourth-family web pages [95,96]). Tables VI and VII give the classification of these papers according to colliders and processes considered.

TABLE III. Parameters of existing and planned TeV scale colliders.

Colliders	Beams	$\sqrt{s}$, TeV	L, 10^{32} cm^{-2} s^{-1}	$L_{\text{int}}(2012)$, fb^{-1}
Tevatron	$p\bar{p}$	1.96	3.5	12
LHC 1	pp	7	$0.01 \to 1$	1
LHC 2	pp	10	10	
LHC 3	pp	14	100	
QCD-E 1	ep, γp	1.4	30	
QCD-E 2	ep, γp	1.98	10	
Linac-LHC EF	ep, γp	3.74	3	
ILC 1	e^-e^+, γe, $\gamma\gamma$	0.5	100	
ILC 2	e^-e^+, γe, $\gamma\gamma$	0.8	100	
CLIC 1	e^-e^+, γe, $\gamma\gamma$	0.5	100	
CLIC 2	e^-e^+, γe, $\gamma\gamma$	1	100	
CLIC 3	e^-e^+, γe, $\gamma\gamma$	3	100	
Muon collider	$\mu\mu$	4	100	

TABLE IV. Production of the fourth SM family fermions at existing and planned high energy colliders. Abbreviations are: P (pair production), AP (associate pair production), S (single production through CKM mixings), A (production through anomalous interactions), KA (kinematically allowed), Res (resonant production), G (good), VG (very good). V_{4i} denotes corresponding CKM matrix elements, Λ denotes scale of anomalous interactions.

Colliders	Tevatron	LHC	ILC/CLIC		
Beams	$p\bar{p}$	pp	e^+e^-	γe	$\gamma\gamma$
$q_4(P)$	if KA	VG	if KA, VG		if KA
$\bar{u}_4d_4(AP)$	?	?			
$q_4(S)$	large V_{4i}	mid V_{4i}			
$q_4(S, A)$	low Λ, Res	mid Λ, Res	low Λ		low Λ
$l_4(P)$	?	?	if KA, VG		if KA, G
$\nu_4(P)$	?	G	if KA, VG		
$l_4\nu_4(AP)$	?	G			
$l_4(S, A)$	?	?	low Λ	mid Λ, Res	low Λ
$\nu_4(S, A)$	?	?	low Λ		
Scalar quarkonia		?			if KA, G
Vector quarkonia		?	if KA, G		
Hadrons		?	if KA, G		if KA

TABLE V. Notations as in Table IV.

	Linac-LHC				
Colliders	QCD explorer		Energy frontier		Muon collider
Beams	ep	γp	ep	γp	$\mu\mu$
$q_4(P)$	if KA	if KA	G	VG	VG
$q_4(AP)$					
$q_4(S)$	large V_{4i}		mid V_{4i}		
$q_4(S, A)$	low Λ	mid Λ, Res	mid Λ	mid Λ, Res	low Λ
$l_4(P)$					VG
$\nu_4(P)$					VG
$l_4\nu_4(AP)$					
$l_4(S, A)$	low Λ		mid Λ		low Λ
$\nu_4(S, A)$	low Λ		mid Λ		low Λ
Scalar Quarkonia					
Vector Quarkonia					VG
Hadrons					VG

TABLE VI. The papers considered production of the fourth SM family fermions at existing and planned high energy colliders.

Colliders	Tevatron	LHC	ILC/CLIC		
Beams	$p\bar{p}$	pp	ee	γe	$\gamma\gamma$
u_4 (P), SM decays	[78,86]	[48,60,76,77,80,81,83]	[66,73]		[66,73]
u_4 (P), anomalous decays					
d_4 (P), SM decays	[86]	[48,77,80,81,83,94]	[66,73]		[66,73]
d_4 (P), anomalous decays	[15,63,78]				
q_4 (AP)					
q_4 (S)		[82]			
q_4 (S, A), SM decays	[69,71]	[85,91]	[70]		
q_4 (S, A), anomalous decays	[68,69,71,72]	[85,97,98]	[70,97,98]		
l_4 (P)			[66,73]		[66,73]
ν_4 (P)	[93]	[57,58,93]	[66,73,74]		
$l_4\nu_4$ (AP)		[89]			
l_4 (S, A)		[84]		[87]	
ν_4 (S, A)					
Scalar quarkonia		[48,67]			[66,73]
Vector quarkonia			[65,66,73]		
Hadrons			[65]		

TABLE VII. The papers considered production of the fourth SM family fermions at existing and planned high energy colliders (continued).

Colliders	Linac LHC QCD explorer		Linac LHC Energy frontier		Muon collider
Beams	ep	γp	ep	γp	$\mu\mu$
u_4 (P), SM decays					[64]
u_4 (P), anomalous decays					
d_4 (P), SM decays					[64]
d_4 (P), anomalous decays					
q_4 (AP)					
q_4 (S)	[90,92]				
q_4 (S, A), SM decays					
q_4 (S, A), anomalous decays	[88,97,98]				
l_4 (P)					[64]
ν_4 (P)					[64]
$l_4\nu_4$ (AP)					
l_4 (S, A)	[75]		[75]		
ν_4 (S, A)	[79]		[79]		
Scalar Quarkonia					
Vector Quarkonia					[64,65]
Hadrons					[65]

III. ANOMALOUS DECAY MODES

The effective Lagrangian for anomalous magnetic type interactions of the fourth-family quarks is given as [71,99,100]

$$L = \sum_{q_i} \frac{\kappa_\gamma^{q_i}}{\Lambda} e_q g_e \bar{q}_4 \sigma_{\mu\nu} q_i F^{\mu\nu} + \sum_{q_i} \frac{\kappa_Z^{q_i}}{2\Lambda} g_Z \bar{q}_4 \sigma_{\mu\nu} q_i Z^{\mu\nu} + \sum_{q_i} \frac{\kappa_g^{q_i}}{\Lambda} g_s \bar{q}_4 \sigma_{\mu\nu} T^a q_i G_a^{\mu\nu} + \text{H.c.}, \quad (1)$$

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. $g_Z = g_e/\cos\theta_W \sin\theta_W$, where θ_W is the Weinberg angle. κ_γ, κ_Z, and κ_g are the strength of anomalous couplings with photon, Z boson and gluon, respectively. Λ is the cutoff scale for new physics. This type of gauge and Lorentz invariant effective Lagrangian has been proposed in the framework of composite models for interactions of excited fermions with ordinary fermions and gauge bosons [99,100]. For numerical calculations we implement the Lagrangian (1), as well as the fourth-family SM Lagrangian into the CALCHEP package [101].

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:

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

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

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

where $s_Z = (2 - x_Z^4 - x_Z^2 - 4x_q^2 - x_q^2 x_Z^2 - 6x_q x_Z^2 + 2x_q^4)$, $s_1 = (1 + x_Z^4 + x_q^2 - 2x_Z^2 - 2x_q^2 - 2x_Z^2 x_q^2)$, and $x_Z = (m_Z/m_{u_4})$,

$$\Gamma(u_4 \to gq) = \frac{2\alpha_s m_{u_4}^3}{3}\left(\frac{\kappa_g^q}{\Lambda}\right)^2 s_2, \tag{4}$$

where $s_2 = (1 - 3x_q^2 + 3x_q^4 - x_q^6)$,

$$\Gamma(u_4 \to \gamma q) = \frac{\alpha_e m_{u_4}^3 Q_q^2}{2}\left(\frac{\kappa_\gamma^q}{\Lambda}\right)^2 s_2. \tag{5}$$

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

$$\Gamma(d_4 \to W^-q) = \frac{|V_{qd_4}|^2 \alpha_e m_{d_4}^3}{16 M_W^2 \sin^2\theta_W} \chi_W \sqrt{\chi_0}, \tag{6}$$

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

$$\Gamma(d_4 \to Zq) = \frac{\alpha_e m_{d_4}^3}{16\cos^2\theta_W \sin^2\theta_W}\left(\frac{\kappa_Z^q}{\Lambda}\right)^2 \chi_Z\sqrt{\chi_1}, \tag{7}$$

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

$$\Gamma(d_4 \to gq) = \frac{2\alpha_s m_{d_4}^3}{3}\left(\frac{\kappa_g^q}{\Lambda}\right)^2 \chi_2, \tag{8}$$

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

$$\Gamma(d_4 \to \gamma q) = \frac{\alpha_e m_{d_4}^3 Q_q^2}{2}\left(\frac{\kappa_\gamma^q}{\Lambda}\right)^2 \chi_2. \tag{9}$$

One can wonder what is the criteria for the dominance of anomalous decay modes over SM ones. It is seen from Eqs. (6)–(9) that the anomalous decay modes of the fourth SM family quarks are dominant, i.e. $\Gamma(d_4 \to gq) + \Gamma(d_4 \to Zq) + \Gamma(d_4 \to \gamma q) > \Gamma(d_4 \to W^-q)$, if the relation $(\kappa/\Lambda) \gtrsim 1.2(V_{ud_4}^2 + V_{cd_4}^2 + V_{td_4}^2)^{1/2}$ TeV^{-1} is satisfied (hereafter $\kappa_Z^q = \kappa_g^q = \kappa_\gamma^q = \kappa$ is assumed). The experimental upper bounds for the fourth-family quark CKM matrix elements are $|V_{u_4d}| \le 0.063$, $|V_{u_4s}| \le 0.46$, $|V_{u_4b}| \le 0.47$, $|V_{ud_4}| \le 0.044$, $|V_{cd_4}| \le 0.46$, $|V_{td_4}| \le 0.47$ [80]. On the other hand, the predicted values of these matrix elements are expected to be rather small in the framework of flavor democracy hypothesis. For example, the mass matrix parametrization proposed in [24], which gives correct predictions for CKM and Maki-Nakagawa-Sakata mixing matrix elements through use of SM fermion mass values as input, predicts $|V_{u_4d}| = 0.0005$, $|V_{u_4s}| = 0.0011$, $|V_{u_4b}| = 0.0014$, $|V_{ud_4}| = 0.0002$, $|V_{cd_4}| = 0.0012$, and $|V_{td_4}| = 0.0014$. In this case, the anomalous decay modes are dominant, if $(\kappa/\Lambda) > 0.0022$ TeV^{-1}. The latter corresponds to upper limit 500 TeV for new physics scale Λ, assuming $\kappa = O(1)$.

In Figs. 2–5, we plotted branching ratios of u_4 quark as a function of V_{u_4b} for different values of κ/Λ. Branching

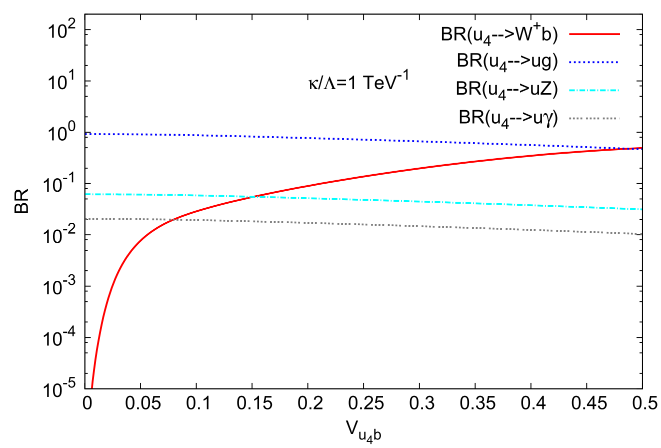

FIG. 2 (color online). Branching ratio of u_4 versus V_{u_4b} for $(\kappa/\Lambda) = 1$ TeV^{-1}.

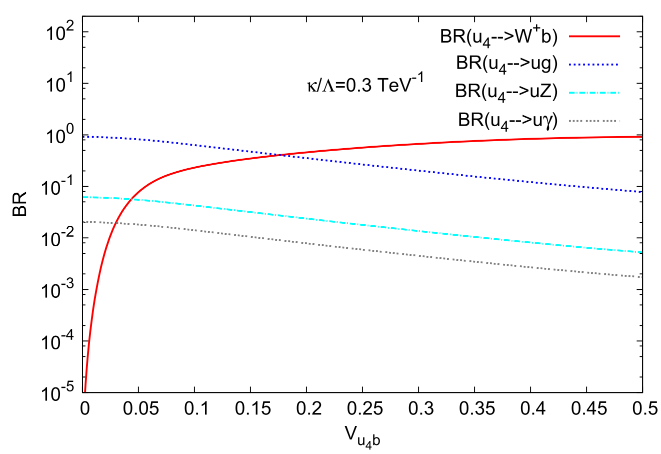

FIG. 3 (color online). Branching ratio of u_4 versus V_{u_4b} for $(\kappa/\Lambda) = 0.3$ TeV^{-1}.

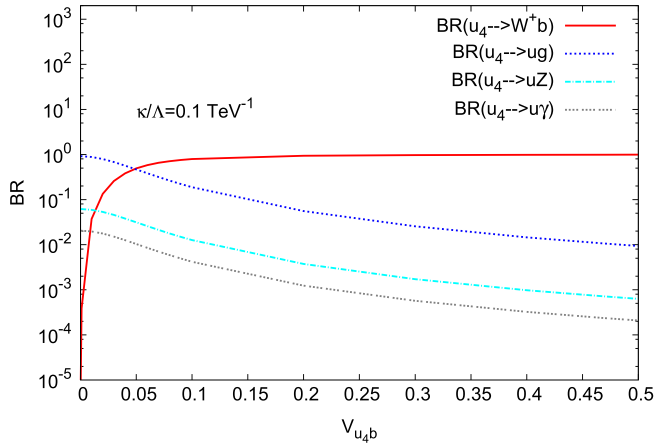

FIG. 4 (color online). Branching ratio of u_4 versus $V_{u_4 b}$ for $(\kappa/\Lambda) = 0.1\ \mathrm{TeV}^{-1}$.

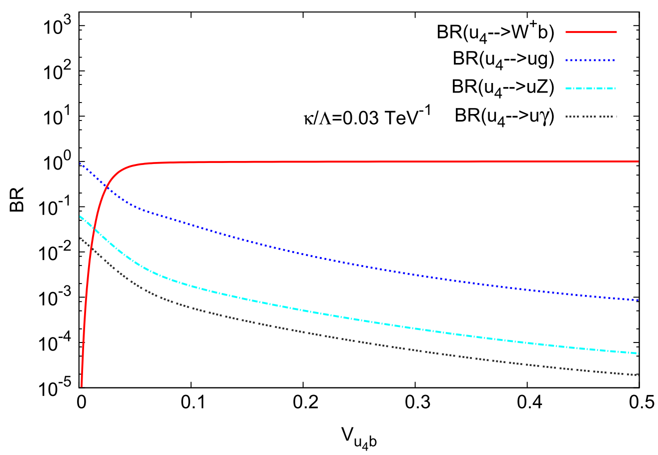

FIG. 5 (color online). Branching ratio of u_4 versus $V_{u_4 b}$ for $(\kappa/\Lambda) = 0.03\ \mathrm{TeV}^{-1}$.

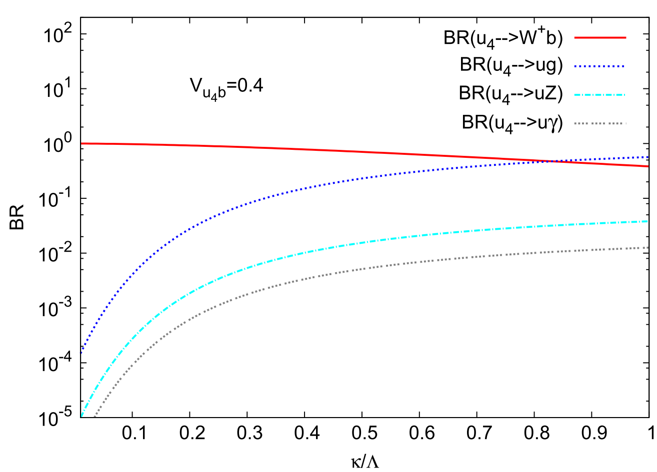

FIG. 6 (color online). Branching ratio of u_4 versus (κ/Λ) for $V_{u_4 b} = 0.4$.

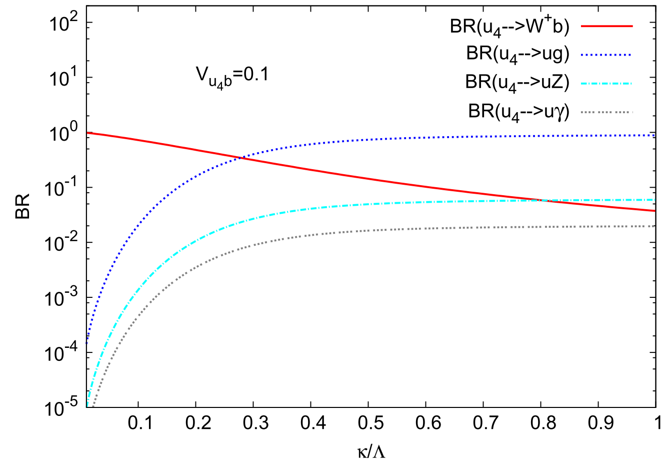

FIG. 7 (color online). Branching ratio of u_4 versus (κ/Λ) for $V_{u_4 b} = 0.1$.

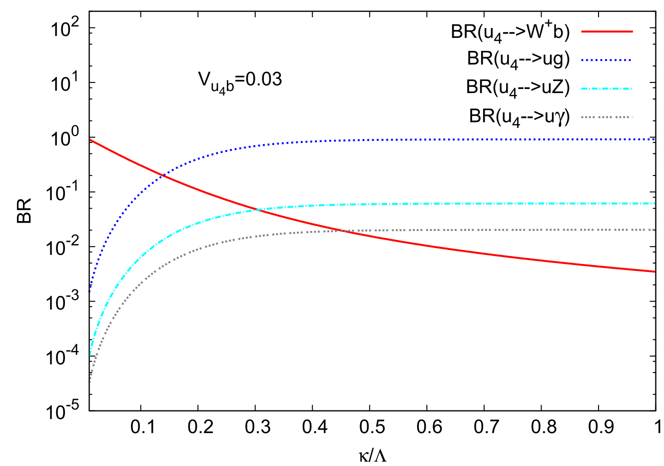

FIG. 8 (color online). Branching ratio of u_4 versus (κ/Λ) for $V_{u_4 b} = 0.03$.

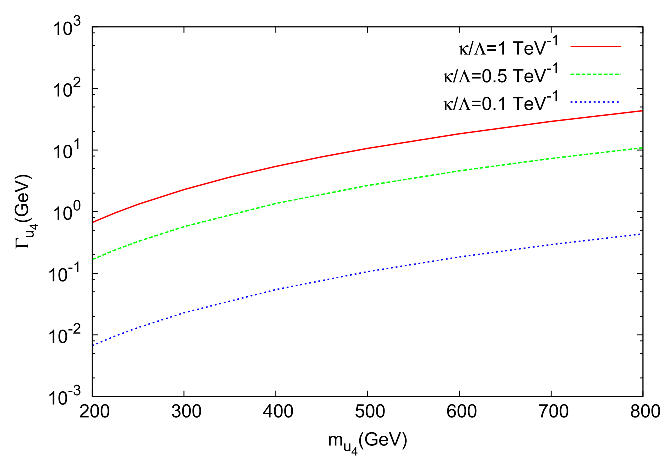

FIG. 9 (color online). Anomalous decay width of u_4 versus m_{u_4}.

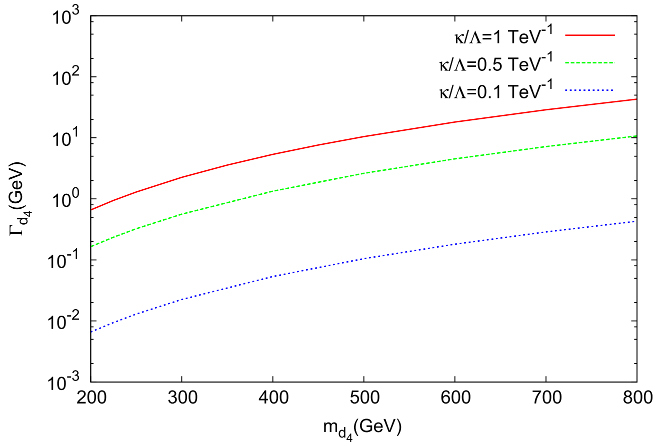

FIG. 10 (color online). Anomalous decay width of d_4 versus m_{d_4}.

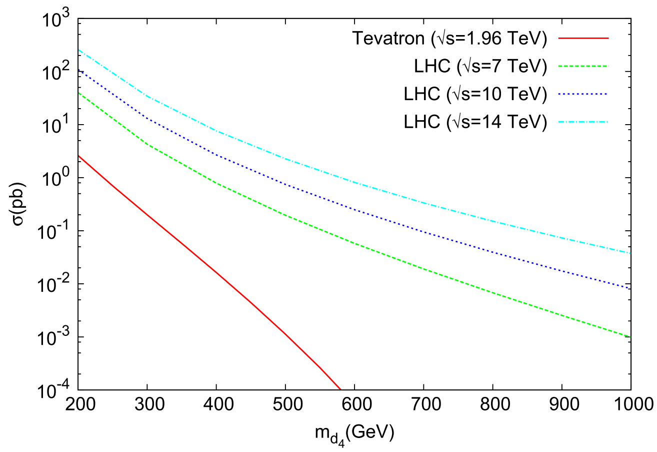

FIG. 11 (color online). The pair production cross section of $d_4\bar{d}_4$ versus m_{d_4} at the Tevatron and LHC.

ratios of u_4 quarks as a function of κ/Λ for different values of $V_{u_4 b}$ are shown Figs. 6–8. It is seen that the assumption of the dominance of anomalous decay modes is quite realistic, especially for small CKM mixing parameters. Total decay widths of u_4 and d_4 quarks depending on their masses were plotted in Figs. 9 and 10, respectively.

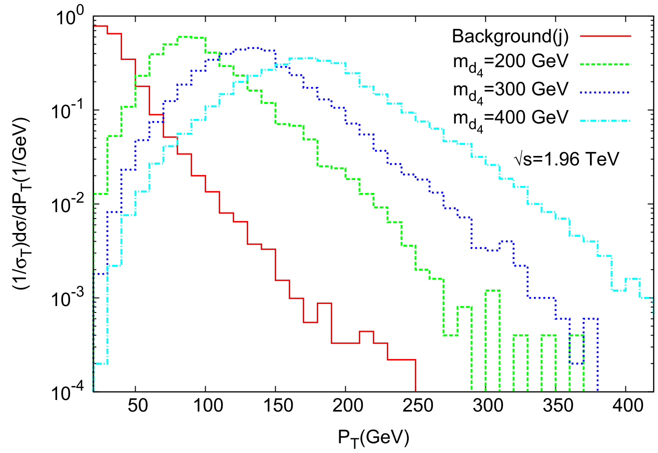

FIG. 12 (color online). Normalized p_T distributions of partons for signal and background for pair d_4 production at the Tevatron.

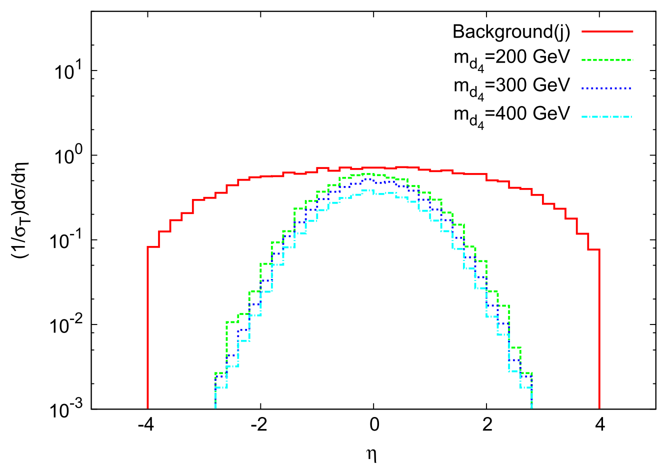

FIG. 13 (color online). Normalized η distributions of partons for signal and background for pair d_4 production at the Tevatron.

IV. PAIR d_4 PRODUCTION AT TEVATRON AND LHC WITH SUBSEQUENT ANOMALOUS DECAYS

In this section, we study pair production of d_4 quarks at the Tevatron and LHC. For the numerical calculations we

TABLE VIII. Signal and background cross-section values for various cuts at Tevatron [15]. All cuts include $p_T > 50$ GeV, $|\eta| < 2$, $|M_{\rm inv}(\gamma j) - M_{d_4}| < 20$ GeV, and $|M_{\rm inv}(jj) - M_{d_4}| < 20$ GeV.

M_{d_4}	200 GeV		300 GeV		400 GeV	
Cuts	σ_S, fb	σ_B, fb	σ_S, fb	σ_B, fb	σ_S, fb	σ_B, fb
$p_T > 20$ GeV	39.2	5.4×10^5	2.92	5.4×10^5	0.23	5.4×10^5
$p_T > 50$ GeV	24.5	2.7×10^3	2.40	2.7×10^3	0.21	2.7×10^3
All cuts	21.8	3.63	2.27	0.091	0.20	0.006

implement an anomalous interaction Lagrangian of the fourth-family quarks into the CALCHEP package program [101] and we used CTEQ6L [102] parton distribution functions with factorization scale $Q^2 = m_{d_4}^2$. The pair production cross sections of $d_4\bar{d}_4$ at the Tevatron and LHC are plotted in Fig. 11. It is seen that, i.e., for $m_{d_4} = 300$ GeV pair production cross section at LHC with $\sqrt{s} = 7$ TeV is 20 times larger than at Tevatron. This ratio can be used to compare Tevatron and LHC capacities. Namely, for $m_{d_4} = 300$ GeV LHC needs 20 times less luminosity than the Tevatron.

The pair production of fourth SM family quarks at hadron colliders have been analyzed in a number of papers (see corresponding rows in Table VI) assuming SM decays. For this reason below we consider the process $p\bar{p}(p) \to d_4\bar{d}_4X \to gd\gamma\bar{d}X$ in order to compare the Tevatron and LHC search potential in the case where anomalous decays are dominant. This process will be seen in the detector as $\gamma + 3j$ events, for background calculations we use the MADGRAPH package [103].

A. Signal and background analysis at the Tevatron

Normalized transverse momentum (p_T) and pseudorapidity (η) distributions of final state partons (quarks, photon, and gluon) for signal and background processes are shown in Figs. 12 and 13, respectively. It is seen that the $p_T > 50$ GeV cut essentially reduces background, whereas the signal is almost unaffected. In addition to $p_T > 50$ GeV, we have used the CDF cut value $|\eta| < 2$ for pseudorapidity, as well as invariant mass within ± 20 GeV around d_4 mass. In Table VIII we present the values of the signal and background cross sections for different cuts.

Statistical significance has been calculated by using the following formula [104]:

$$S = \sqrt{2\left[(s+b)\ln\left(1+\frac{s}{b}\right) - s\right]}, \tag{10}$$

where s and b represent the numbers of signal and background events, respectively.

In Fig. 14 we plot the necessary luminosity for 2σ exclusion, 3σ observation, and 5σ discovery limits depending on d_4 mass. Reachable masses for the d_4 quark

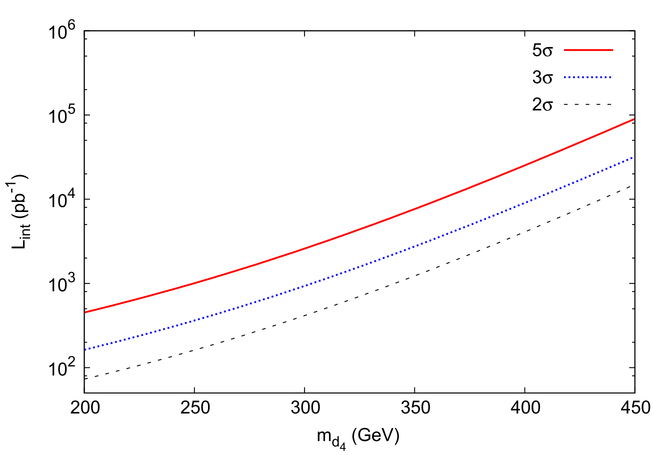

FIG. 14 (color online). The necessary integrated luminosity for exclusion, observation, and discovery of d_4 quark at the Tevatron [15].

TABLE IX. Reachable m_{d_4} mass values for discovery, observation, and exclusion at the Tevatron [15].

$L_{\rm int}$, fb^{-1}	5	10	20
2σ exclusion	390 GeV	430 GeV	460 GeV
3σ observation	370 GeV	410 GeV	440 GeV
5σ discovery	340 GeV	360 GeV	390 GeV

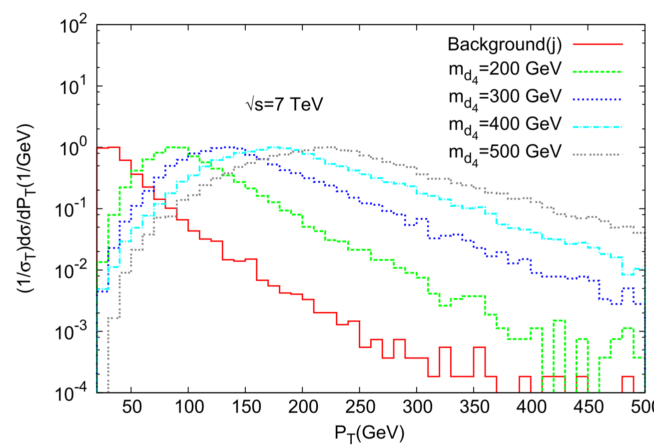

FIG. 15 (color online). Normalized p_T distributions of partons for the signal and background for pair d_4 production at the LHC.

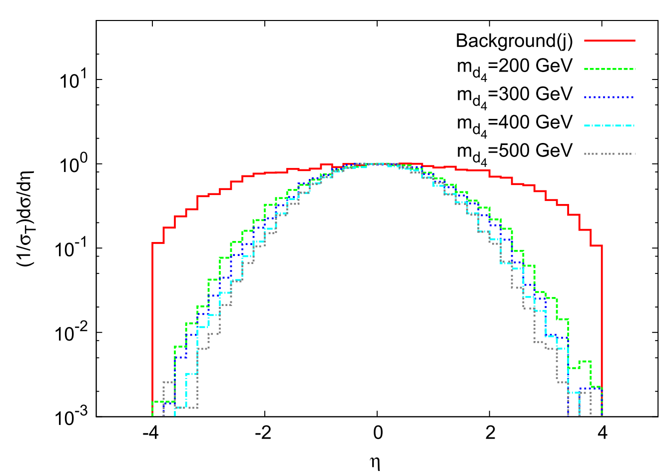

FIG. 16 (color online). Normalized η distributions of partons for the signal and background for pair d_4 production at the LHC.

TABLE X. Signal and background cross-section values for various cuts at the LHC. All cuts include $p_T > 50$ GeV, $|\eta| < 2.5$, $|M_{\rm inv}(\gamma j) - M_{d_4}| < 20$ GeV, and $|M_{\rm inv}(jj) - M_{d_4}| < 20$ GeV.

M_{d_4}	200 GeV		300 GeV		400 GeV		500 GeV	
Cuts	σ_S, fb	σ_B, fb	σ_S, fb	σ_B, fb	σ_S, fb	σ_B, fb	σ_S, fb	σ_B, fb
$p_T > 20$ GeV	3.77×10^3	7.44×10^6	394	7.44×10^6	71.1	7.44×10^6	19.2	7.44×10^6
$p_T > 50$ GeV	2.14×10^3	1.12×10^5	319	1.12×10^5	63.7	1.12×10^5	17.9	1.12×10^5
all cuts	315	13.62	46.94	1.03	9.3	0.59	2.4	0.037

at different values of the Tevatron integrated luminosity are presented in Table IX.

B. Signal and background analysis at the LHC

Normalized transverse momentum (p_T) and pseudorapidity (η) distributions of final state partons (quarks, photon, and gluon) for signal and background processes are shown in Figs. 15 and 16, respectively. It is seen that the $p_T > 50$ GeV cut essentially reduces background, whereas the signal is almost unaffected. In addition to $p_T > 50$ GeV, we have used ATLAS cut value $|\eta| < 2.5$ for pseudorapidity, as well as invariant mass within ± 20 GeV around d_4 mass. In Table X we present the values of the signal and background cross sections for different cuts.

In Fig. 17 we plot the necessary luminosity for 2σ exclusion, 3σ observation, and 5σ discovery limits depending on d_4 mass. Reachable masses for the d_4 quark at different values of the Tevatron integrated luminosity are presented is Table XI.

Comparing Tables IX and XI one can conclude that LHC with $\sqrt{s} = 7$ TeV and integrated luminosity $L_{\rm int} = 300$ pb^{-1} surpasses the Tevatron with $L_{\rm int} = 10$ fb^{-1}.

TABLE XI. Reachable m_{d_4} mass values for discovery, observation, and exclusion at the LHC.

$L_{\rm int}$, pb^{-1}	100	300	1000
2σ exclusion	420 GeV	510 GeV	640 GeV
3σ observation	370 GeV	430 GeV	550 GeV
5σ discovery	310 GeV	360 GeV	460 GeV

V. ANOMALOUS RESONANT u_4 PRODUCTION AT TEVATRON AND LHC WITH SUBSEQUENT ANOMALOUS DECAY

Total cross sections for the anomalous resonant production of the u_4 quark at the Tevatron and LHC are shown in Fig. 18. It is seen that for $m_{d_4} = 300$ GeV the cross section at the LHC with $\sqrt{s} = 7$ TeV is 40 times larger than the cross section at the Tevatron.

A. Signal and background analysis at the Tevatron

The $p\bar{p} \rightarrow u_4 X \rightarrow \gamma u X$ process is considered as a signature of anomalous resonant production of the fourth SM family up-type quark. The SM background for this process is $p\bar{p} \rightarrow \gamma j X$, where $j = u, \bar{u}, d, \bar{d}, c, \bar{c}, s, \bar{s}, b, \bar{b}, g$. In order to determine appropriate kinematical cuts, p_T and η

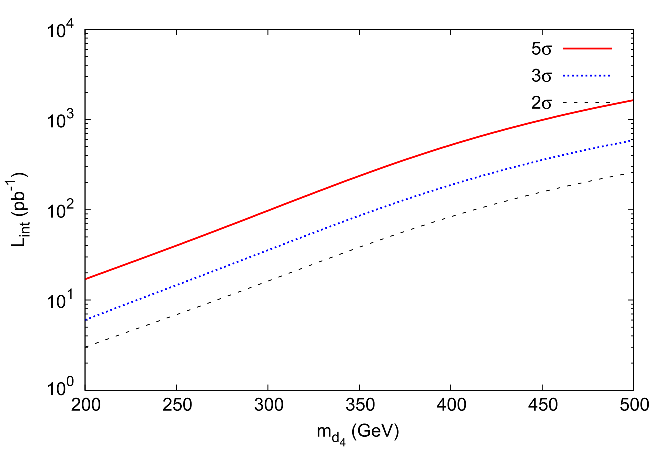

FIG. 17 (color online). The necessary integrated luminosity for exclusion, observation, and discovery of d_4 quark at the LHC.

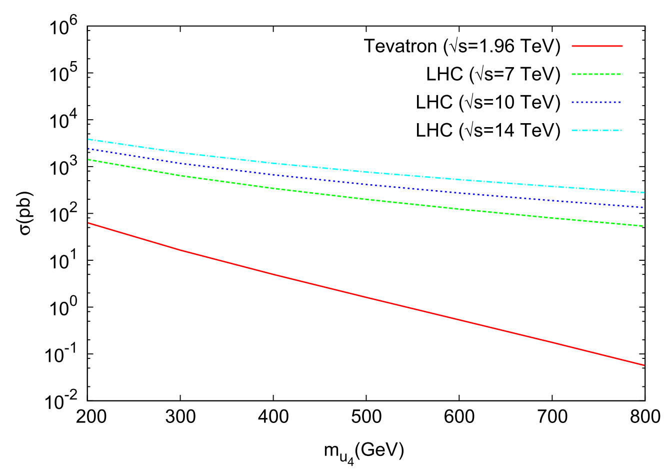

FIG. 18 (color online). The anomalous resonant production cross sections of u_4 at Tevatron and LHC.

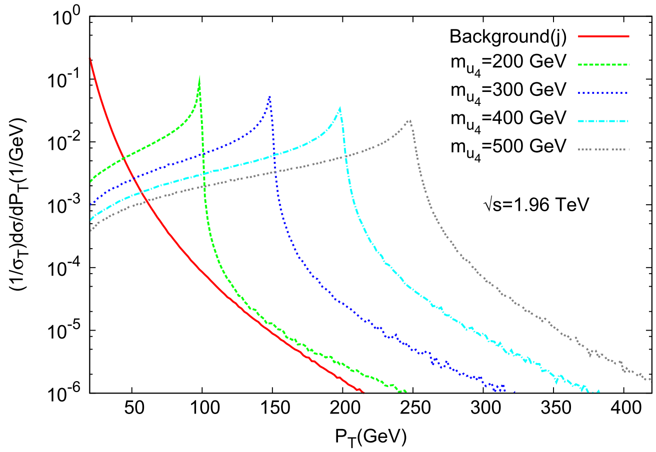

FIG. 19 (color online). Normalized p_T distributions of partons for the signal and background for anomalous resonant u_4 production at the Tevatron.

TABLE XII. Reachable m_{u_4} mass values for discovery, observation, and exclusion at the Tevatron.

L_{int}, fb^{-1}	5	10	20
2σ exclusion	480 GeV	560 GeV	630 GeV
3σ observation	400 GeV	470 GeV	540 GeV
5σ discovery	270 GeV	360 GeV	440 GeV

distributions for signal and background processes are given in Figs. 19 and 20, respectively.

In order to extract the u_4 signal and to suppress the background, the following cuts are applied: $p_T > 75$ GeV and $|\eta| < 2$ for all final state partons and photon, as well as invariant mass within ± 20 GeV around the u_4 mass. For the signal calculations $\kappa/\Lambda = 0.1$ TeV^{-1} have been used.

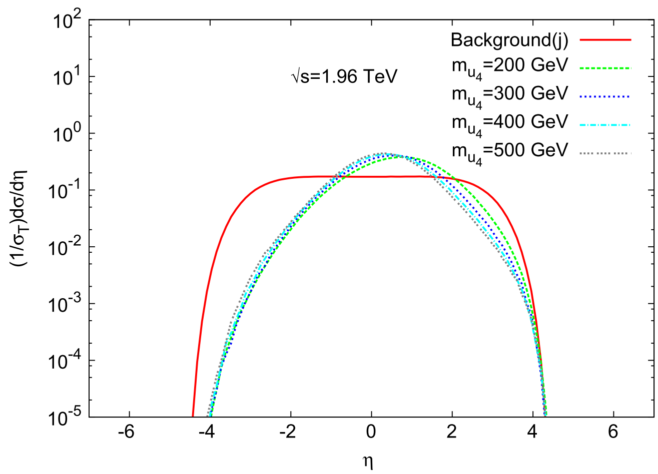

FIG. 20 (color online). Normalized η distributions of partons for the signal and background for anomalous resonant u_4 production at the Tevatron.

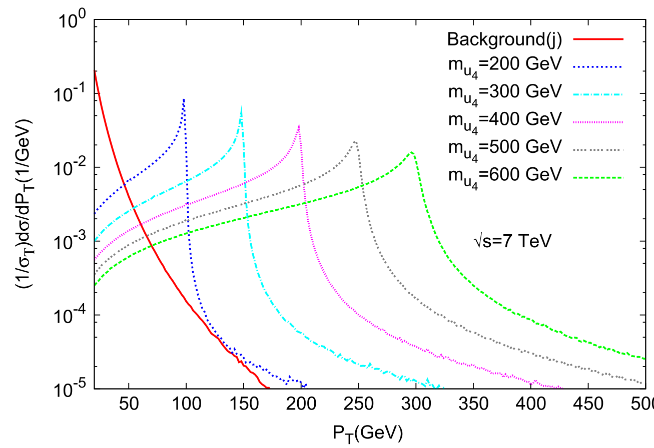

FIG. 22 (color online). Normalized p_T distributions of partons for the signal and background for anomalous resonant u_4 production at the LHC.

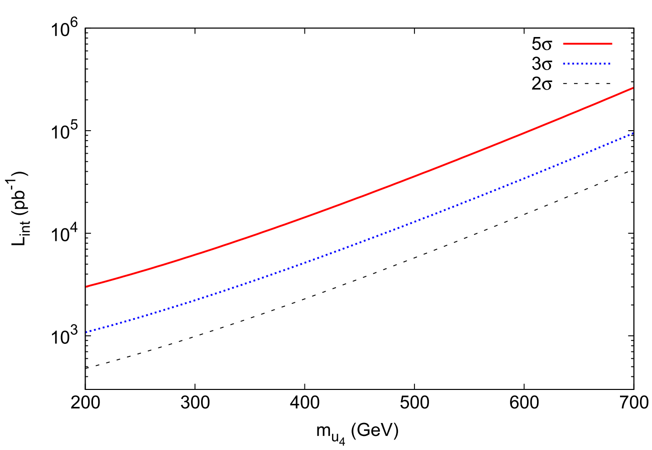

FIG. 21 (color online). The necessary integrated luminosity for exclusion, observation, and discovery of u_4 quark at the Tevatron.

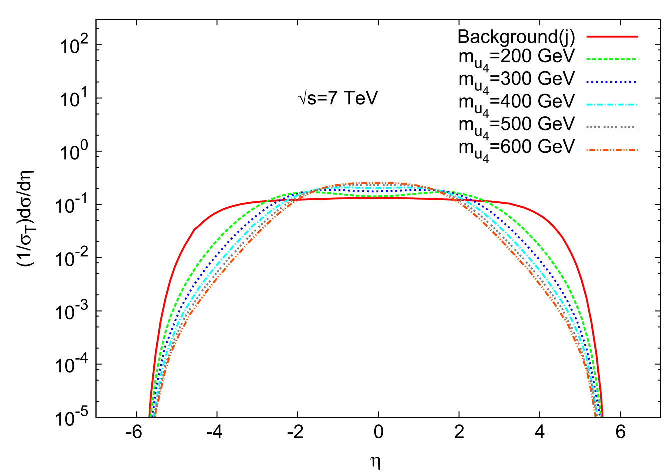

FIG. 23 (color online). Normalized η distributions of partons for the signal and background for anomalous resonant u_4 production at the LHC.

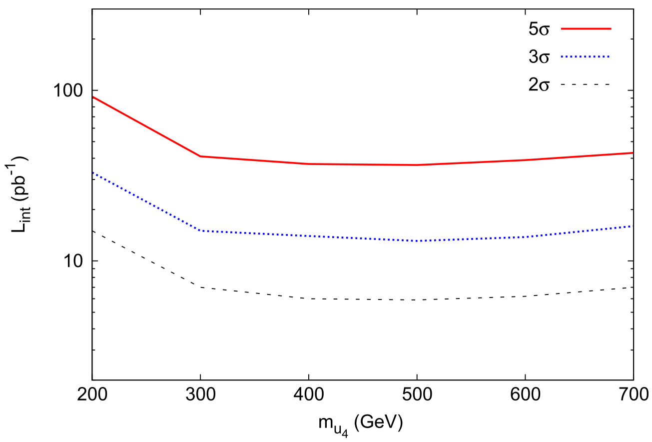

FIG. 24 (color online). The necessary integrated luminosity for exclusion, observation, and discovery of u_4 quark at the LHC.

In Fig. 21 we plot the necessary luminosity for 2σ exclusion, 3σ observation, and 5σ discovery limits depending on u_4 mass. Reachable masses for the u_4 quark at different values of the Tevatron integrated luminosity are presented in Table XII.

B. Signal and background analysis at the LHC

In order to determine appropriate kinematical cuts, p_T and η distributions for signal and background processes are given in Figs. 22 and 23, respectively.

In order to extract the u_4 signal and to suppress the background, the following cuts are applied: $p_T > 75$ GeV and $|\eta| < 2.5$ for all final state partons and photon, as well as invariant mass within ± 20 GeV around the u_4 mass. For the signal calculations $\kappa/\Lambda = 0.1$ TeV^{-1} have been used.

In Fig. 24 we plot the necessary luminosity for 2σ exclusion, 3σ observation, and 5σ discovery limits depending on u_4 mass.

Comparing Figs. 21 and 24, it is obvious that LHC with $\sqrt{s} = 7$ TeV and integrated luminosity $L_{\text{int}} = 50$ pb^{-1} surpasses the Tevatron with $L_{\text{int}} = 10$ fb^{-1}.

VI. CONCLUSION

It is seen that there is a tough competition between Tevatron and LHC in a search for the fourth SM family quarks. We have shown that in case the anomalous decay modes are dominant:

(a) for pair production, LHC with $\sqrt{s} = 7$ TeV and $L_{\text{int}} = 300$ pb^{-1} surpasses Tevatron with $L_{\text{int}} = 10$ fb^{-1},

(b) for anomalous resonant production, LHC with $L_{\text{int}} = 100$ pb^{-1} covers the whole mass range if $\kappa/\Lambda = 0.1$ TeV^{-1}.

ACKNOWLEDGMENTS

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