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Hidden Extra $U(1)$ at the Electroweak/TeV Scale

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Abstract

We propose a simple extension of the Standard Model (SM) by adding an extra $U(1)$ symmetry which is hidden from the SM sector. Such a hidden $U(1)$ has not been considered before, and its existence at the TeV scale can be explored at the LHC. This hidden $U(1)$ does not couple directly to the SM particles, and couples only to new $SU(2)_L$ singlet exotic quarks and singlet Higgs bosons, and is broken at the TeV scale. The dominant signals at the high energy hadron colliders are multi lepton and multi b-jet final states with or without missing energy. We calculate the signal rates as well as the corresponding Standard Model background for these final states. A very distinctive signal is 6 high p_T b-jets in the final state with no missing energy. For a wide range of the exotic quarks masses the signals are observable above the background at the LHC.

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1 Introduction

The Standard Model (SM) is now well established as the effective theory of the quarks, leptons and the gauge bosons below the TeV scale. However, it is almost universally believed that the SM is not the final theory. Many extensions of the SM have been proposed to solve some of the shortcomings of the SM. Grand unified theories have been proposed to unify the three gauge couplings into one. Supersymmetric extensions have been proposed to solve the gauge hierarchy problem. A singlet Higgs boson, with a Z_2 symmetry has been added to the SM which can serve as a plausible candidate for dark matter [1]. One or more extra space-like compact dimensions has been added to the usual four dimensions to incorporate TeV scale as the fundamental scale of gravity [2], or to unify the gauge and Higgs bosons, and as well as the fermions, and understand the Yukawa interactions as part of the gauge interactions [3]. Most of these extensions involve new gauge interactions, commonly an extra $U(1)$, as well as new particles beyond the SM.

Many kinds of extra $U(1)$ gauge symmetries have been considered. These include the left-right symmetric model [4], $SO(10)$ or E_6 GUTs, superstring E_6 models [5], topflavor models [6], and string-inspired supersymmetric models.[7] In most of these models, the SM fermions and the Electroweak (EW) Higgs boson carry non-trivial charges under the $U(1)$. Other variations of the extra $U(1)$ symmetry, such as a hadro-phobic $U(1)$, lepto-phobic $U(1)$, and an extra $U(1)$ which couples only to the third family of fermions have been considered [5].

Hidden sectors of matter are ubiquitous among models due to the need to break supersymmetry, as well as the common addition of particle dark matter which cannot be charged under the Standard Model gauge groups unless it is very heavy.[8] An extra $U(1)$ can be a natural way to link the "dark" sector with the Standard Model.

In this work, we consider an extra $U(1)$ symmetry [9] in which the SM particles (the SM fermions, gauge bosons and the EW doublet Higgs bosons) are neutral. We call this a hidden extra $U(1)$ [9]. Only new exotic quarks, and the EW singlet Higgs bosons couple to this extra $U(1)$ gauge boson. These exotic quarks and the EW singlet Higgs bosons act as messenger particles between the hidden $U(1)$ sector and the SM sector. This extra $U(1)$ symmetry is broken at the EW scale by the vacuum expectation value (VEV) of the EW

singlet Higgs boson. Thus this extra gauge boson, the exotic quarks, and the singlet Higgs boson all acquire masses at the EW scale, and can be searched for at high energy colliders, such as the Tevatron and the LHC. The dominant signals of our scenario at the hadron colliders are multi-b and multi-lepton final states, with little or no missing energy.

2 The Hidden $U(1)$ Model

Our gauge symmetry is the usual Standard Model $SU(3)_C \times SU(2)_L \times U(1)_Y$ supplemented by an extra $U(1)$ symmetry, which we call $U(1)'$. We introduce two exotic quarks D_L and D_R which are color triplets and singlets under the $SU(2)_L$ gauge symmetry, but charged under the $U(1)_Y$. We denote the gauge boson for the $U(1)'$ by Z'. We also introduce a complex Higgs field S which is a color and EW singlet, and has a charge q' under the $U(1)'$. This singlet Higgs field has a VEV v_S at the TeV or EW scale, and breaks the $U(1)'$ symmetry.

The Lagrangian for the gauge part of the interaction for the exotic D quark is given by the usual gauge interaction under the $SU(3)_C$ symmetry with the gauge coupling g_3. The EW and $U(1)'$ interactions of the matter fields with the gauge bosons can be obtained from the Lagrangian:

$$\mathcal{L} = \overline{q}^i_L i\not{\mathcal{D}}_2 q^i_L + \overline{\ell_L}^i i\not{\mathcal{D}}_2 \ell^i_L + \overline{u}^i_R i\not{\mathcal{D}}_1 u^i_R + \overline{d}^i_R i\not{\mathcal{D}}_1 d^i_R + \overline{e}^i_R i\not{\mathcal{D}}_1 e^i_R + \overline{D} i\not{\mathcal{D}}'_1 D \tag{1}$$

where q_L, ℓ_L are the $SU(2)_L$ quark and lepton doublets while u_R, d_R, e_R, and D are the $SU(2)_L$ up-, down-quark, lepton and exotic quark singlets, respectively. The different covariant derivatives are defined as

$$\begin{aligned} \mathcal{D}_{2\mu} &= \partial_\mu - i\frac{g_2}{2}\tau \cdot W_\mu - i\frac{g'}{2} Y B_\mu, \\ \mathcal{D}_{1\mu} &= \partial_\mu - i\frac{g'}{2} Y B_\mu, \\ \mathcal{D}'_{1\mu} &= \partial_\mu - i\frac{g'}{2} Y B_\mu - i g_{z'} Y_{z'} Z'_\mu, \end{aligned} \tag{2}$$

where τ's are the Pauli matrices; Y, $Y_{z'}$ are the charges of the matter fields under the $U(1)_Y$ and the new gauge group $U(1)'$ respectively; while Z' represents the new gauge boson.

The Higgs potential, with the usual doublet Higgs H and the EW singlet Higgs S, is

$$V(H,S) = -\mu_H^2 (H^\dagger H) - \mu_S^2 (S^\dagger S) + \lambda_H (H^\dagger H)^2 + \lambda_{HS} (H^\dagger H)(S^\dagger S) + \lambda_S (S^\dagger S)^2. \tag{3}$$

We can also write a mass term for the vector-like quark,

$$\mathcal{L}_{\text{mass}} = M_D \overline{D}_L D_R. \tag{4}$$

Note that the new exotic vector-like quark D is like a new flavor, and it has color, hypercharge, and an extra $U(1)'$ interaction, but no $SU(2)_L$ interaction. Since this new D quark is vector-like with respect to both $U(1)$ as well as $U(1)'$, the model is anomaly free. Without any other interaction, the D quark will be stable. As none of the SM particles are charged under the new $U(1)'$ symmetry, the new symmetry will remain hidden from the SM, provided the gauge-kinetic-mixing terms are strongly suppressed. However, its gauge quantum numbers allow flavor changing Yukawa interactions with the bottom, strange, and down quarks via the singlet Higgs boson S.

$$\mathcal{L}_{\text{Extra Yukawa}} = Y_{Db} \overline{D}_L b_R S + Y_{Ds} \overline{D}_L s_R S + Y_{Dd} \overline{D}_L d_R S + h.c. \tag{5}$$

Note that in order the above Lagrangian to be hypercharge singlet, the hypercharge of both D_L and D_R must be equal to that of b_R. This also requires that the $U(1)'$ charge ($Y_{z'}$) for the exotic quark D must satisfy $Y_{z'} = q'$. Such a term in the Lagrangian leads to mixing between the down-type quarks with the new exotic vector-like quark D, giving rise to EW decay modes for the heavy quark.

We assume that the parameters in the Higgs potential are such that H has VEV at the electroweak (EW) and S has a VEV around the TeV scale. Then, in the unitary gauge, we can write the H and S fields as

$$H(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_H + H_0(x) \end{pmatrix}, \qquad S(x) = \frac{1}{\sqrt{2}}(v_S + S_0(x)), \tag{6}$$

where v_H is the VEV of the doublet Higgs, and v_S is the singlet VEV. From the minimization of the Higgs potential, we obtain,

$$v_H^2 = \frac{\mu_H^2 - \frac{\lambda_{HS}}{2\lambda_S}\mu_S^2}{\lambda_H - \frac{\lambda_{HS}^2}{4\lambda_S}}, \qquad v_S^2 = \frac{\mu_S^2 - \frac{\lambda_{HS}}{2\lambda_H}\mu_H^2}{\lambda_S - \frac{\lambda_{HS}^2}{4\lambda_H}}. \tag{7}$$

The scalar mass-squared matrix in the (H_0, S_0) basis is given by

$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda_H\, v_H^2 & \lambda_{HS}\, v_H\, v_S \\ \lambda_{HS}\, v_H\, v_S & 2\lambda_S\, v_S^2 \end{pmatrix}. \tag{8}$$

The masses of the two mass eigenstate Higgs scalars ϕ_H and ϕ_S as well as their mixing angle β, in terms of the fundamental parameters of the Lagrangian, can be obtained from the above mass matrix. In particular, the mixing angle β is given by

$$\tan 2\beta = \frac{\lambda_{HS} v_H v_S}{\lambda_S v_S^2 - \lambda_H v_H^2} \quad . \tag{9}$$

In addition to the usual gauge interaction for the H_0 and S_0, the interaction among the Higgs from the potential $V(H_0, S_0)$ after symmetry breaking is given by

$$\begin{aligned} V(H_0, S_0) = \lambda_H v_H {H_0}^3 + \frac{\lambda_{HS} v_S}{2} \left({H_0}^2 S_0 + H_0 {S_0}^2 \right) + \lambda_S v_S {S_0}^3 \\ + \frac{\lambda_H}{4} {H_0}^4 + \frac{\lambda_{HS}}{4} {H_0}^2 {S_0}^2 + \frac{\lambda_S}{4} {S_0}^4. \end{aligned} \tag{10}$$

The interaction among the Higgs mass eigenstates ϕ_H and ϕ_S can be obtained by using

$$H_0 = \phi_H \cos\beta + \phi_S \sin\beta, \qquad S_0 = -\phi_H \sin\beta + \phi_S \cos\beta. \tag{11}$$

To explore the phenomenological implications of the model, we need to consider the various mixings which lead to the effective interaction of these exotic particles to SM particles and are responsible for their decays. We have already considered the mixing in the scalar sector of the model which has interesting consequences for Higgs searches at colliders such as LHC [10]. We also find that by allowing the Yukawa interactions given in Eq. 5, there will be mixing between the down-type quarks with the new exotic quark D once the scalar S gets a VEV. The mixing between the down-type quarks with the exotic D quark gives rise to EW decay modes for the heavy quark. The heavy Z' also has additional interactions which lead to interesting decay modes.

For simplicity, we assume that only Y_{Db} is non-zero in Eq. 5 while the other Yukawa coefficients are negligibly small. This would imply that the exotic quark mixes only with the bottom quark, thus indirectly affecting the top-bottom vertex (V_{tb} in the CKM matrix) as well as inducing a coupling between the exotic D quark with the top quark. The mixing can be parametrized in terms of two mixing angles θ_L and θ_R which represent the mixing angles of the b_L and b_R with D_L and D_R respectively. Expressing the gauge eigenstates for the mixing quarks as b^0 and D^0, the mass matrix in the (b^0, D^0) basis is given by

$$\mathcal{M} = \begin{pmatrix} y_b\, v_H/\sqrt{2} & 0 \\ Y_{Db}\, v_S/\sqrt{2} & M_D \end{pmatrix}. \tag{12}$$

This matrix can be diagonalized with a bi-unitary transformation $\mathcal{M}_{\rm diag} = \mathcal{R}_L \mathcal{M} \mathcal{R}_R^\dagger$, where $\mathcal{R}_L$ and $\mathcal{R}_R$ are unitary matrices which rotate the left-chiral and right-chiral gauge eigenstates to the mass eigenstates respectively. The interaction of the physical mass eigenstates (b, D) can then be obtained by writing the gauge basis states as

$$b_i^0 = b_i \cos\theta_i + D_i \sin\theta_i, \qquad D_i^0 = -b_i \sin\theta_i + D_i \cos\theta_i. \tag{13}$$

The rotation matrices $\mathcal{R}_i$ are given by

$$\mathcal{R}_i = \begin{pmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{pmatrix}, \quad \text{where } i = L, R. \tag{14}$$

The corresponding mixing angles for the left- and right-handed fields follow from diagonalizing the matrices $\mathcal{M}\mathcal{M}^\dagger$ and $\mathcal{M}^\dagger\mathcal{M}$ respectively and are given by

$$\tan 2\theta_L = \frac{-2\, Y_{Db}\, y_b\, v_S\, v_H}{2M_D^2 + Y_{Db}^2 v_S^2 - y_b^2 v_H^2}, \qquad \tan 2\theta_R = \frac{-2\sqrt{2}\, Y_{Db}\, v_S\, M_D}{2M_D^2 - Y_{Db}^2 v_S^2 - y_b^2 v_H^2}. \tag{15}$$

3 Phenomenological Implications

In hadronic colliders such as the LHC and Tevatron, the dominant signals arise from the pair productions of the exotic colored quarks, D and $\overline{D}$, and their subsequent decays (because D has hypercharge, the LEP2 bound of $\sim$ 100 GeV on its mass applies [11]). The other important production process is the pair productions of the exotic quark in association with the new $U(1)'$ gauge boson, $D\overline{D}Z'$. It turns out that this is the only way the new gauge boson Z' can be produced on-shell at LHC because of its very suppressed or vanishing couplings to the SM particles in this model. In the following subsections we discuss the signals from the $D\overline{D}$ production. We also discuss the couplings of the extra gauge boson Z' with the SM particles.

3.1 Signals from $D\overline{D}$ Productions

The heavy exotic quarks being colored particles will be produced copiously at the LHC through strong interactions. The major contribution, as in the case of top quarks, would

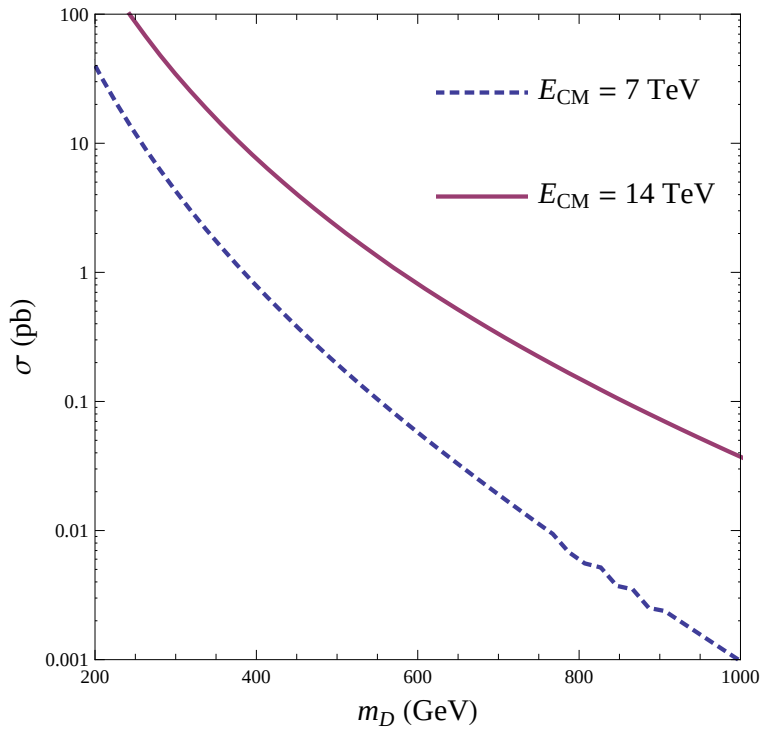


Figure 1: *Pair production cross section for the exotic quarks at LHC as a function of its mass (m_D). We use the CTEQ6L1 parton distribution functions (PDF) [12] for the protons. We have set the scale $Q^2 = m_D^2$.*

come from the gluon induced subprocess ($\sim 80\%$). In Fig. 1 we plot the pair production cross section for the process

$$pp \longrightarrow D\overline{D} \tag{16}$$

at LHC for two different center-of-mass energies (7 TeV and 14 TeV). The figure clearly shows that one can have quite large production cross section for such an exotic quark at the LHC and its signals should be observable through its decay products. We have implemented the model into CalcHEP [13] to calculate the production cross sections as well as the two-body decays of the new particles in the model.

The heavy quark in the gauge eigenbasis couples directly to the Z' gauge boson through the $U(1)'$ charge, with the gauge coupling strength $g_{z'}$. However, its decay is more dependent on the mixing parameters resulting from its mixing with the b quark, leading to a much richer

phenomenology. The heavy exotic itself is a mixed mass eigenstate and we list its couplings to the other particles of the model in Table 1.

The two body decay width for D of mass m_D, in its rest frame can be written down as

$$\Gamma(D \to X_2 X_3) = \frac{1}{16\pi m_D} \lambda^{1/2} \left(1, \frac{m_{X_2}^2}{m_D^2}, \frac{m_{X_3}^2}{m_D^2}\right) \quad \overline{|\mathcal{M}|^2} \tag{17}$$

where the function $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2(xy + yz + zx)$. Using the effective couplings given in Table 1, one can write down the explicit decay amplitudes for the exotic quarks decaying into vector (V) and scalar (Φ) modes.

$$\begin{aligned} \overline{|\mathcal{M}|^2}(D \to fV) &= K^2 \left[3\left(m_D^2 + m_f^2 - 2m_V^2 + \frac{(m_D^2 - m_f^2)^2}{m_V^2}\right)(c_V^2 + c_A^2) \right. \\ &\qquad \left. -18 m_D m_f (c_V^2 - c_A^2)\right] \\ \overline{|\mathcal{M}|^2}(D \to f\Phi) &= K^2 \left[3\left(m_D^2 + m_f^2 - m_\Phi^2\right)(c_S^2 + c_P^2) + 6 m_D m_f (c_S^2 - c_P^2)\right] \end{aligned} \tag{18}$$

We can now estimate the decay probabilities of the heavy exotic D quark. To highlight distinct scenarios, we choose two different sets of input values for the free parameters as representative points in the model listed in Table 2. Note that the input parameters for the model also affect some EW observables, e.g. the Z boson decay width or the mass limits for Higgs boson and other heavy exotics that appear in our model. We have checked that the input parameters given in Table 2 are allowed and do not contradict any existing experimental bounds [11]. In Fig. 2 we present the decay branching ratios (BR) of the heavy quark D as a function of its mass (m_D) for the representative points I & II given in Table 2. The curves in Fig. 2(a) represent Point-I from Table 2. When D is lighter than $m_t + M_W$ then it always decays to $Z\,b$ through mixing if its coupling to the lighter Higgs boson is very suppressed. This would happen when the lighter scalar state is dominantly an $SU(2)$ doublet. The $t\,W^-$ mode starts picking up and becomes comparable to the $Z\,b$ mode for heavier D. $t\,W^-$ is a common decay mode in 4th-generation models and theories with top or bottom partners as studied in Ref.[14] and results in multi-lepton signals.

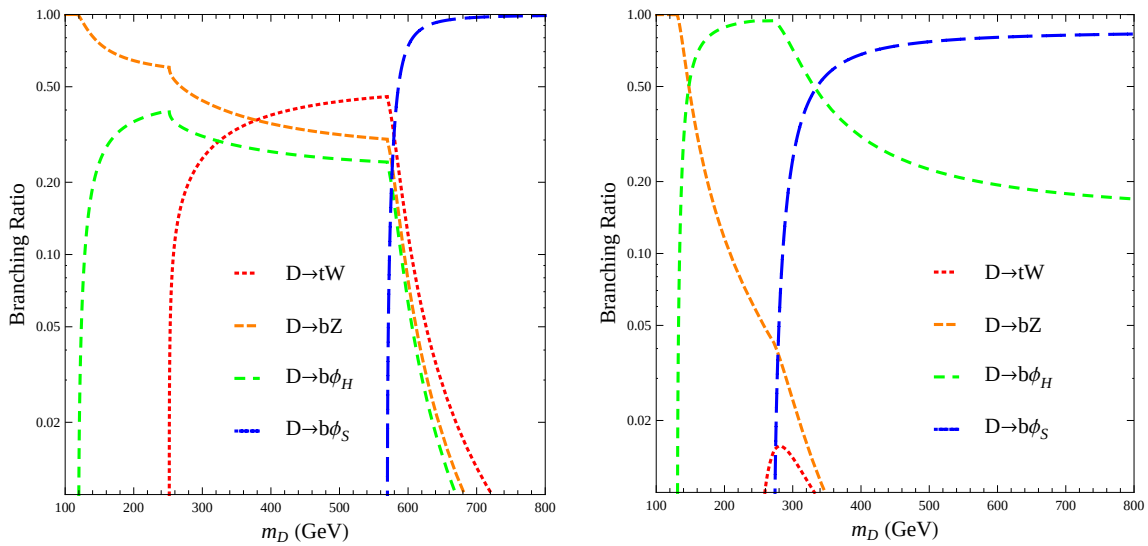
The curves in Fig. 2(b) represent Point-II, where the choice of parameters give a very suppressed mixing angle θ_L. The couplings of $Z\,b$ and $t\,W$ to the exotic quark are proportional to $\sin\theta_L$ and hence also get suppressed. As soon as the scalar modes become kinematically accessible, they completely dominate the decay properties of the exotic quark.

	K	c_V	c_A
$\overline{b}bZ_\mu$	$\frac{e}{12\sin 2\theta_W}$	$4\cos 2\theta_W + 3\cos 2\theta_L - 1$	$3(1+\cos 2\theta_L)$
$\overline{D}DZ_\mu$	$\frac{e}{12\sin 2\theta_W}$	$4\cos 2\theta_W - 3\cos 2\theta_L - 1$	$3(1-\cos 2\theta_L)$
$\overline{b}DZ_\mu$	$\frac{-e}{4}\frac{\sin 2\theta_L}{\sin 2\theta_W}$	1	1
$\overline{b}bZ'_\mu$	$\frac{g_{z'}Y_{z'}}{4}$	$\cos 2\theta_L + \cos 2\theta_R - 2$	$\cos 2\theta_L - \cos 2\theta_R$
$\overline{D}DZ'_\mu$	$\frac{-g_{z'}Y_{z'}}{4}$	$\cos 2\theta_L + \cos 2\theta_R + 2$	$\cos 2\theta_L - \cos 2\theta_R$
$\overline{b}DZ'_\mu$	$\frac{-g_{z'}Y_{z'}}{4}$	$\sin 2\theta_L + \sin 2\theta_R$	$\sin 2\theta_L - \sin 2\theta_R$
$\overline{t}b\ W^+_\mu$	$\frac{-e\cos\theta_L}{2\sqrt{2}\sin\theta_W}$	1	1
$\overline{t}D\ W^+_\mu$	$\frac{e\sin\theta_L}{2\sqrt{2}\sin\theta_W}$	1	1
	K	c_S	c_P
$\overline{b}b\phi_H$	$\frac{\cos\theta_R}{\sqrt{2}}$	$y_b\cos\beta\cos\theta_L + y_{Db}\sin\beta\sin\theta_L$	0
$\overline{D}D\phi_H$	$\frac{\sin\theta_R}{\sqrt{2}}$	$y_b\cos\beta\sin\theta_L - y_{Db}\sin\beta\cos\theta_L$	0
$\overline{b}b\phi_S$	$\frac{-\cos\theta_R}{\sqrt{2}}$	$y_b\sin\beta\cos\theta_L - y_{Db}\cos\beta\sin\theta_L$	0
$\overline{D}D\phi_S$	$\frac{-\sin\theta_R}{\sqrt{2}}$	$y_b\sin\beta\sin\theta_L + y_{Db}\cos\beta\cos\theta_L$	0
$\overline{b}D\phi_H$	$\frac{1}{2\sqrt{2}}$	$y_{Db}\sin\beta\cos(\theta_L+\theta_R)$ $- y_b\cos\beta\sin(\theta_L+\theta_R)$	$y_{Db}\sin\beta\cos(\theta_L-\theta_R)$ $- y_b\cos\beta\sin(\theta_L-\theta_R)$
$\overline{b}D\phi_S$	$\frac{1}{2\sqrt{2}}$	$y_{Db}\cos\beta\cos(\theta_L+\theta_R)$ $+ y_b\sin\beta\sin(\theta_L+\theta_R)$	$y_{Db}\cos\beta\cos(\theta_L-\theta_R)$ $+ y_b\sin\beta\sin(\theta_L-\theta_R)$

Table 1: *The effective coupling of the exotic D quark with the other particles in the model. The electromagnetic coupling with photon and the strong coupling with gluon is the same as any down-type quarks in the SM. Couplings are of the form $K\gamma^\mu(c_V - c_A\gamma^5)$ and $K(c_S - c_P\gamma^5)$. Note that we have put $V_{tb} = 1$.*

Parameters	**I**	**II**
$(\lambda_H, \lambda_S, \lambda_{HS})$	$(0.11, 0.16, 0.005)$	$(0.2, 0.05, 0.1)$
v_S	1000 GeV	800 GeV
Y_{Db}	0.15	0.05
m_{ϕ_H}	115 GeV	127 GeV
m_{ϕ_S}	566 GeV	268 GeV
$m_{Z'}$	1000 GeV	800 GeV

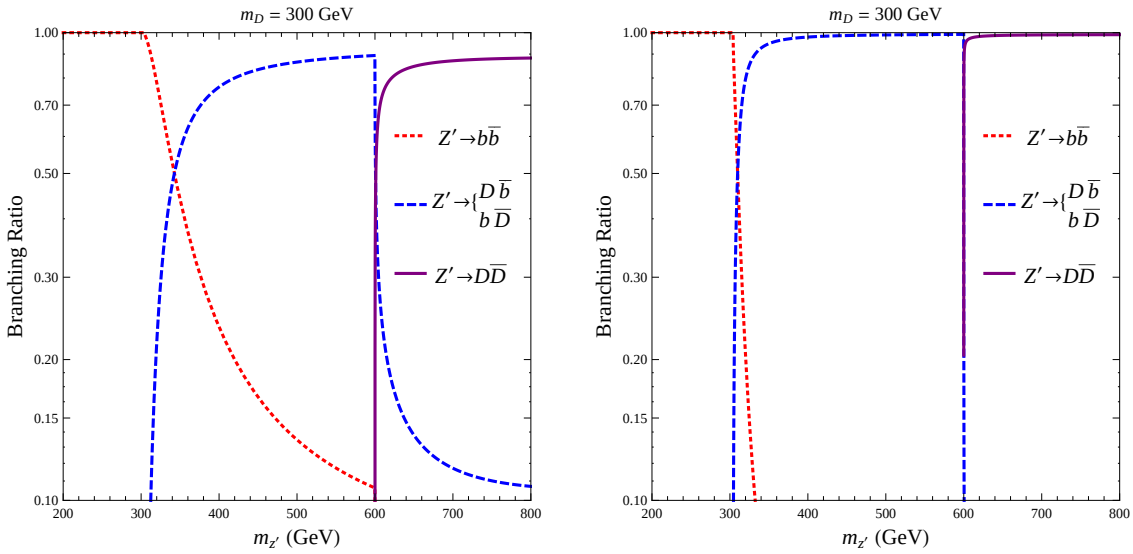
Table 2: *Representative points in the model parameter space and the relevant mass spectrum used in the analysis.*



(a) Parameter Set I **(b) Parameter Set II**

Figure 2: *Illustrating the decay probabilities of the D quark as a function of its mass m_D.*

We find if the Z' boson is light, then as soon as the $D \to Z'b$ mode opens up, the remaining modes drop out very quickly for Point-I while for Point-II it becomes comparable to the scalar mode for very large mass m_D. It is worth pointing out here that the dominant decay mode for the Z' when $m_{Z'} < m_D$ is to $b\bar{b}$ with 100% branching probability. However



(a) Parameter Set I **(b) Parameter Set II**

Figure 3: *Illustrating the decay probabilities of the Z' as a function of its mass $m_{Z'}$.*

for Z' heavier than D the dominant decay of Z' is to $D\bar{b}$ and $\bar{D}b$ as shown in Fig. 3; and as soon as $m_{Z'} > 2\ m_D$ it decays dominantly to $\bar{D}D$ with maximum probability. We should also point out that the Z' phenomenology in our model is quite different from other models with $U(1)$ extension of the SM. As there exists no coupling between any SM fermion pair

Decays	Branching Ratios		Decays	Branching Ratios	
	I	II		I	II
$\phi_H \to b\bar{b}$	0.672	0.510	$\phi_S \to \phi_H\phi_H$	0.25	0.27
$\phi_H \to c\bar{c}$	0.031	0.024	$\phi_S \to W^+W^-$	0.42	0.51
$\phi_H \to \tau^+\tau^-$	0.093	0.072	$\phi_S \to ZZ$	0.20	0.22
$\phi_H \to gg$	0.104	0.096	$\phi_S \to t\bar{t}$	0.13	–
$\phi_H \to WW^*$	0.088	0.266			

Table 3: *Branching Ratios for various Higgs decay modes for parameter sets I and II.*

(other than b quark) or with the EW gauge bosons (no kinetic mixing), it is not possible to produce this particle directly through exchange of SM particles at LEP or Tevatron and so the strong constraints that exist on the mass of similar Z' exotics through the effective four-fermion operators [15] do not apply in our case and neither do the search limits from the Tevatron experiments [16]. Thus the Z' in our model can be light but remain invisible in the existing experimental data. We will however not discuss the Z' signals any further and only focus on the signals arising from the production of the exotic D quarks in the model. To understand the full decay chain of the D quark to final state particles we also list the decay probabilities of the scalars ϕ_H and ϕ_S in Table 3 for the two representative points I & II.

Thus the above decay patterns suggest that one can have the following interesting final states from the decay of the exotic quarks

$$pp \to D\overline{D} \to \begin{cases} (Zb)(Z\bar{b}) & \Longrightarrow b\bar{b} + 2Z \\ (tW^-)(\bar{t}W^+) & \Longrightarrow t\bar{t} + W^+W^- \\ (tW^-)(Z\bar{b}) & \Longrightarrow t\bar{b} + ZW^- \\ (\phi_H b)(\phi_H \bar{b}) & \Longrightarrow b\bar{b} + 2\phi_H \quad \to b\bar{b} + 2(W^+W^-) \\ (\phi_H b)(\phi_H \bar{b}) & \Longrightarrow b\bar{b} + 2\phi_H \quad \to 3(b\bar{b}) \\ (\phi_S b)(\phi_S \bar{b}) & \Longrightarrow b\bar{b} + 2\phi_S \quad \to 3(b\bar{b}) \\ (\phi_H b)(\phi_S \bar{b}) & \Longrightarrow b\bar{b} + \phi_H\phi_S \quad \to b\bar{b} + 3\phi_H \quad \to 4(b\bar{b}) \\ (\phi_S b)(\phi_S \bar{b}) & \Longrightarrow b\bar{b} + 2\phi_S \quad \to b\bar{b} + 4\phi_H \quad \to 5(b\bar{b}) \end{cases} \tag{19}$$

where the first four suggest multi-lepton and multi-jet final states with two or more b-jets, while the remaining give more exotic signatures like N b-jet final states where N can be as large as 10. Note that the above decays only illustrate some of the possible decay chains and we have not listed other possible combinations of the D decays which can also lead to similar final states.

In Table 4 we list the probabilities for the decay modes for a few specific values of the D quark mass. We also show the corresponding cross sections for the pair production of these exotics at LHC for the center of mass energies of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 14$ TeV. The decays

m_D	$\sigma(D\bar{D})$(pb)		Branching Ratios							
			$D \to tW$		$D \to bZ$		$D \to b\phi_H$		$D \to b\phi_S$	
	7 TeV	14 TeV	I	II	I	II	I	II	I	II
250	12.15	87.760	0	0	0.603	0.055	0.397	0.945	0	0
300	4.265	34.368	0.251	0.014	0.438	0.024	0.311	0.715	0	0.247
400	0.791	7.692	0.381	0.005	0.351	0.005	0.268	0.308	0	0.681
500	0.194	2.270	0.434	0.003	0.316	0.002	0.250	0.225	0	0.770
600	0.059	0.820	0.121	0.002	0.078	0.001	0.063	0.194	0.738	0.803

Table 4: *Cross sections and branching probabilities for specific mass values of D quark for the representative points I and II.*

suggest a large multiplicity of b quarks in the final state. It turns out that six-b final states for the signal is very promising. However, there exists no estimate for this final state in the literature, arising from the SM. We present below a leading-order (LO) estimate of the cross section for the six-b SM background from QCD for LHC energies.

3.2 Calculation of Six-b Final States from QCD

The six-b final state is interesting, independent of our particular model. The presence of six b jets allow the jets to be tagged. All other 6-jet final states involve mixtures of light quarks and gluons, and one cannot separate light jets from gluon jets. Therefore the six-b final state itself presents an interesting test of QCD. Furthermore by computing the full Matrix Element, we can test the validity of the differential cross section by looking at differential observables. While we only use the six-b cross section as a background to our signal, this is the first time such a six-b cross section in QCD has been estimated, and this also is an important result of this paper.

Any six-final state process is a challenge to compute. The phase space is 20 dimensional, there are thousands of diagrams, and thousands of distinct color configurations. While six-

jet final states are produced every day by Monte Carlo generators such as PYTHIA [17] and HERWIG [18], the mechanism they use creates additional jets from an initial $2 \to 2$ or $2 \to 3$ process via a showering procedure that resums leading logarithms, splitting an extra gluon from the hard final state partons.

As is well known, the showering procedure cannot produce the correct correlations among 3 or more hard jets, nor can it compute the total cross section for 3 or more hard jets. It assumes that each parton is independent of all the others. For a single radiation it is strictly correct in the limit that the extra radiation is soft and/or collinear with the inital parton. However for multiple radiations it ignores the QCD connection among the radiations, assuming that each radiation factorizes from the others. There is also quantum mechanical interference in different radiations which result in the same final state that is ignored.

This means that one should not examine in detail observables such as the angles between jets, invariant masses of jet pairs, or the thrust, when one hard jet came from the showering procedure. This showering technique is however extremely useful as long as one is not sensitive to the details of correlations in the differential cross section, as this method is computationally simpler than a full Matrix Element calculation.

Therefore to have an accurate Monte Carlo with six jets in the final state, one must compute the full Matrix Element, which automatically includes all color flows and interference. This is accurate to approximately the 10% level, at which point NLO loop corrections become important. Note that due to the b quark mass, there is no soft radiation which benefits significantly from the usual Sudakov logarithm resummation. The b mass acts as a regulator, relegating this cross section strictly into the "hard" regime, in which the Matrix Element is valid. Even if all six b's are at rest, the energy in the final state is 30 GeV, and any virtual gluon must have a virtuality $q^2 \sim 10$ GeV.

For this calculation we have chosen the tool MadEvent, which is an event generator built upon the Matrix Element generator MadGraph [19]. We have modified these tools to be able to cope with thousands of diagrams and thousands of color configurations. Computing 5 and 6 final state QCD processes has a number of challenges, all of which are technical rather than physics-based. MadEvent is in principle capable of computing any process with any

number of final state particles, however several internal restrictions caused previous versions to fail on processes such as 6 b's. Although the program is equipped to handle the large color configurations, some input/output statements restrict this computation to a smaller number of color flow configurations which makes it incapable of calculating the six b final states at a hadron machine like the LHC. These have been repaired to calculate the six b cross section in the SM from QCD at the LHC.

3.3 Signal and Background Analysis

A simple minded estimate of the cross section using $\sigma \times BR$ shows that the final states which would be of interest at the LHC would involve at least 2 b-jets in the final state. Besides the two hard b-jets, one expects charged leptons in the final state coming from the decays of the weak gauge bosons. It is also worth noting that when the D quark decays to the Higgs bosons, one would get a large multiplicity of b-jets in the final states as the Higgs with $M_{\phi_H} < 2M_W$ dominantly decays to b-jets. To select our events for the final states given in Table 5, we have imposed the following kinematic cuts:

- All the b-jets must have a $p_T^b > 20$ GeV and lie within the rapidity gap of $|\eta^b| < 3.0$.
- All charged leptons ($\ell = e, \mu$) must have a $p_T^\ell > 20$ GeV and lie within the rapidity gap of $|\eta^\ell| < 2.5$.
- The final states also must satisfy $\Delta R_{bb} > 0.7$, $\Delta R_{b\ell} > 0.4$, and $\Delta R_{\ell\ell} > 0.2$ where $\Delta R_{ij} = \sqrt{(\Delta\eta_{ij})^2 + (\Delta\phi_{ij})^2}$.
- All b-jet pairs must have a minimum invariant mass $M_{bb} > 10$ GeV.

In Table 5 we present the cross-sections for the signal for two different mass values of the exotic D quark after passing through the above mentioned kinematic cuts. As expected, the favored final states are dependent on the high b-jet multiplicity. At the hadron collider such as LHC, one favors final states with leptons. However b-jets can also be triggered upon and identified and thus can prove to be useful in isolating new physics signals such as ours which involve at least two or more b-jets. Looking at Table 5 we find that we get a good

	$m_D = 300$ GeV				$m_D = 500$ GeV			
Final	$\sqrt{s} = 7$ TeV		$\sqrt{s} = 14$ TeV		$\sqrt{s} = 7$ TeV		$\sqrt{s} = 14$ TeV	
States	I	II	I	II	I	II	I	II
$6b + X$	181.92	718.79	1394.32	5521.23	4.94	10.79	531.10	115.02
$nb + \ell + X$ $(n \geq 2)$	452.50	188.22	3559.94	1465.42	32.17	27.88	43.37	313.96
$2b + 2\ell + X$	146.53	14.95	1127.15	117.08	8.71	6.61	11.77	75.56
$4b + 2\ell + X$	51.07	24.36	384.24	183.73	1.85	2.06	20.33	22.20

Table 5: *Illustrating the final state cross sections after the decay of D quarks. All cross sections are in units of femtobarn (fb).*

signal rate for the inclusive $6b + X$ final state. The SM background for multi-b final state is quite large [20]. However no estimate of a $6b$ final state exists in the literature, which we find relevant for our signal. We have used the *Madgraph+MadEvent* package to estimate the leading order partonic cross section for the $6b$ final state at LHC. With the above mentioned kinematic cuts, we find that for LHC energy of $\sqrt{s} = 14$ TeV, the SM background for $6b$ final state is ~ 70 fb and falls to less than 10 fb for the $\sqrt{s} = 7$ TeV option. This implies that the signal in our model is much larger than the SM background even for larger mass values of the exotic D quark. The other signals which are worth looking for in this model is one or two charged leptons with varying b-jet multiplicities. We have listed the interesting ones in Table 5. The final state with $2\ell + 4b + X$ also stands out against the SM background, where one gets the SM cross sections to be quite small as it is already α_{EW}/α_s suppressed compared to the $6b$ cross section. The SM background is much larger for the final states $\ell + nb + X$ where $n = 2$ and $2\ell + 2b + X$, where the significant SM background results from the $t\bar{t}$ production. For the final states $\ell + nb + X$ one can get rid of the huge $t\bar{t}$ background by demanding $n \geq 3$. This helps in improving the significance of the signal, even though we also lose a large fraction of the signal events in the process. For the other final state, we find that at leading order, at LHC with pp collision energy of $\sqrt{s} = 7$ TeV, the $2\ell + 2b + X$

SM background is ~ 3.3 pb. As the leading two b-jets in our signal come from the decays of the heavy exotic D quark, we put a stronger p_T cut of 100 GeV. This reduces the signal by two-thirds. However the SM background is reduced by more than an order of magnitude, and becomes ~ 232 fb for $\sqrt{s} = 7$ TeV collisions while it is ~ 1.63 pb for $\sqrt{s} = 14$ TeV which does look promising for the signal with large enough luminosities at the LHC. We must point out that we have not incorporated any efficiency factors for our final state particles. Most notably, all numerical estimates involving b-jets for signal as well as the SM background will have to be scaled with the b-tagging efficiency of around 50-60% expected at the LHC [21].

4 Summary and Conclusions

In this work, we have proposed a new extension of the SM, by introducing a hidden $U(1)'$ symmetry. The difference with the previously studied $U(1)'$'s is that all the SM particles are singlets under our proposed new $U(1)'$, and hence hidden. Such a symmetry may be present at the TeV scale, and may manifest at the LHC giving new signals observable at the LHC. The model incorporates a new EW singlet Higgs, as well as new vector-like charge $-1/3$ quarks. We have studied the pair productions of these new quarks and their subsequent decays. The dominant final states include multiple b jets with high p_T, or b jets plus charged leptons with high p_T and missing energy, and stands out beyond the SM background. The most distinctive final state signal is the $6b$ quark with high p_T and no missing energy. A lot of effort have been put in both for the ATLAS and CMS detectors to improve the b-tagging efficiency. So the calculation for this $6b$ final state is also of great importance in the SM, and has not yet been calculated. We have calculated this $6b$ signal in our model, and have also estimated the SM expectation using MadGraph and MadEvent. We found that the signal in our model stands well above that expected from the SM.

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