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R. Mohapatra – University of Maryland
N. Okada – University of Maryland
H. Yu – University of Maryland

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Diquark Higgs bosons at the CERN LHC

R. N. Mohapatra,* Nobuchika Okada,† and Hai-Bo Yu‡

Department of Physics, University of Maryland, College Park, Maryland 20742, USA

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Existence of color sextet diquark Higgs fields with TeV masses will indicate a fundamentally different direction for unification than conventional grand unified theories. One class of models where they appear naturally is the supersymmetric $SU(2)_L \times SU(2)_R \times SU(4)_c$ model embedding the seesaw mechanism for neutrino mass with seesaw scale around 10^{11} GeV. The diquark Higgs fields in this model couple only to up-type quarks. We discuss phenomenological constraints on these fields and show that they could be detected at LHC via their decay to either tt or single top + jet. We also find that existing Tevatron data gives a lower bound on its mass somewhere in the 400–500 GeV, for reasonable values of its coupling.

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I. INTRODUCTION

The soon-to-start Large Hadron Collider (LHC) is expected to probe a new hitherto unexplored domain of particles and forces beyond the standard model in the near future. It cannot only clarify some of the mysteries of the standard model but also provide a glimpse of other new physics in the TeV energy range. The sense of expectation generated by this in the particle physics community has led to a burst of theoretical activity designed to explore a great many theoretical concepts such as extra dimensions, supersymmetry, new strong forces, new Higgs bosons, new quarks and leptons, etc. In this paper, we explore the possibility that LHC can throw light on a new kind of color sextet Higgs fields (denoted by $\Delta_{u^cu^c}$) with mass in the TeV range. Existence of such fields will indicate a fundamentally new direction for unification than the conventional grand unified theories. Our choice of this specific sextet field is motivated by a supersymmetric $SU(2)_L \times SU(2)_R \times SU(4)_c$ model that embeds the seesaw mechanism where $\Delta_{u^cu^c}$ fields indeed appear with mass in the TeV range even though the gauge symmetry breaking scale is around 10^{11} GeV due to the existence of accidental symmetries [1]. These models are interesting since they not only unify quarks and leptons but are also realistic extensions of MSSM that explain neutrino masses. The $\Delta_{u^cu^c}$ fields couple in this model exclusively to the right-handed up-type quarks of all generations and are connected to baryon number violating process neutron-anti-neutron oscillation [1]. Discovery of these particles would point towards quark-lepton unification at an intermediate scale rather than at the commonly assumed grand unification scale of 10^{16} GeV.

An interesting point about these particles is that they can be produced and detected at the LHC. Their couplings are however constrained by low energy observations. In this paper, we explore this topic and the main results of our investigation are (i) the present experimental information on $D^0 - \overline{D^0}$ mixing can be satisfied by setting to zero only the diagonal coupling of the $\Delta_{u^cu^c}$ to the charm quarks; (ii) the remaining coupling can be large enough so that the production rate in pp collision is significant and there are observable signals for the diquark Higgs field via its double top and single top plus jet production. Note also that a pp colliding machine such as LHC is more favorable for the production of these kinds of fields compared to a $p\overline{p}$ machine e.g. Tevatron; (iii) the $\Delta_{u^cu^c}$ coupling matrix to quarks can be a direct measure of the neutrino mass matrix if the neutrino masses have an inverted hierarchy within our scheme, providing a unique way to probe the lepton flavor structure using the LHC.

II. BRIEF OVERVIEW OF MODEL WITH NATURALLY LIGHT $\Delta_{u^cu^c}$

In order to theoretically motivate our study of color sextet Higgs fields, we discuss how these "light mass" particles can naturally arise in a class of supersymmetric seesaw models for neutrino masses. The seesaw mechanism extends the standard model with three right-handed neutrinos with large Majorana masses. The fact that the seesaw scale is much lower than the Planck scale suggests that there may be a symmetry protecting this scale. A natural symmetry is local $B - L$ symmetry whose breaking leads to the right-handed Majorana neutrino masses. A gauge theory that accommodates this scenario is the left-right symmetric model based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_c$. This model being quark-lepton symmetric easily lends itself to quark-lepton unification *à la* Pati-Salam into the gauge group $SU(2)_L \times SU(2)_R \times SU(4)_c$. It has already been shown [1] that, within a supersymmetric Pati-Salam scheme, if $SU(4)_c$ color is broken not by $SU(2)_{L,R}$ doublet fields but rather by triplets, then despite the high seesaw scale of around 10^{11} GeV or so, there are light (TeV mass) sextet diquarks of the type $\Delta_{u^cu^c}$.

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[*] rmohapat@physics.umd.edu

[†] On leave of absence from Theory Division, KEK, Tsukuba 305-0801, Japan.
okadan@post.kek.jp

[‡] hbyu@physics.umd.edu

To show this more explicitly, recall that the quarks and leptons in this model are unified and transform as ψ: $(\mathbf{2},\mathbf{1},\mathbf{4}) \oplus \psi^c$: $(\mathbf{1},\mathbf{2},\bar{\mathbf{4}})$ representations of $SU(2)_L \times SU(2)_R \times SU(4)_c$. For the Higgs sector, we choose ϕ_1: $(\mathbf{2},\mathbf{2},\mathbf{1})$ and ϕ_{15}: $(\mathbf{2},\mathbf{2},\mathbf{15})$ to give mass to the fermions and the Δ^c: $(\mathbf{1},\mathbf{3},\mathbf{10}) \oplus \bar{\Delta}^c$: $(\mathbf{1},\mathbf{3},\overline{\mathbf{10}})$ to break the $B-L$ symmetry and extra Higgs field Ω: $(\mathbf{1},\mathbf{3},\mathbf{1})$ to reduce the global symmetry of the model. The diquarks mentioned above are contained in the Δ^c: $(\mathbf{1},\mathbf{3},\mathbf{10})$ multiplet.

The most general renormalizable superpotential of this model $W = W_Y + W_H$ is

$$W_H = \lambda_1 S(\Delta^c\bar{\Delta}^c - M_\Delta^2) + \mu_i \mathrm{Tr}(\phi_i\phi_i) + \lambda_C \Delta^c\bar{\Delta}^c\Omega,$$
$$W_Y = h_1\psi\phi_1\psi^c + h_{15}\psi\phi_{15}\psi^c + f\psi^c\Delta^c\psi^c. \tag{1}$$

It has $U(10,c) \times SU(2)$ global symmetry. When the neutral component of $(\mathbf{1},\mathbf{3},\mathbf{10} + \overline{\mathbf{10}})$ picks up VEV, this symmetry breaks down to $U(9,c) \times U(1)$, leaving 21 complex massless scalar fields. Since the gauge symmetry also breaks down from $SU(2)_R \times SU(4)_c$ to $SU(3)_c \times U(1)_Y$, nine of these are absorbed leaving 12 complex massless states, which are the sextet $\Delta_{u^cu^c}$ plus its complex conjugate states from the $\overline{\mathbf{10}}$ representation above. Once supersymmetry breaking effects are included and higher dimensional terms $\lambda_A \frac{(\Delta^c\bar{\Delta}^c)^2}{M_{\mathrm{Pl}}} + \lambda_B \frac{(\Delta^c\Delta^c)(\bar{\Delta}^c\bar{\Delta}^c)}{M_{\mathrm{Pl}}} + \lambda_D \frac{\mathrm{Tr}(\phi_1\Delta^c\bar{\Delta}^c\phi_{15})}{M_{\mathrm{Pl}}}$, are included, these $\Delta_{u^cu^c}$ fields pick up mass (denoted by m_Δ) of order $\lambda_B \frac{v_{\mathrm{BL}}^2}{M_{\mathrm{Pl}}}$ which for $v_{\mathrm{BL}} \sim 10^{11}$ GeV is in the 100 GeV to TeV range naturally.

III. PHENOMENOLOGICAL CONSTRAINTS ON $\Delta_{u^cu^c}$ COUPLINGS TO QUARKS

The magnitudes of the couplings of diquark Higgs to up-type quarks are important for its LHC signal as well as other manifestations in the domain of rare processes. As is clear from Eq. (1), the sextet $\Delta_{u^cu^c}$ couplings to quarks, f_{ij}, are also directly related to the neutrino masses, which provides a way to probe neutrino masses from LHC observations. Because of the existence of other parameters, current neutrino observations do not precisely pin down the f_{ij}. There are however other constraints on them.

To study these constraints, we define the $\Delta_{u^cu^c}$ couplings (f_{ij}) in a basis where the up-type quarks are mass eigenstates. A major constraint on them comes from the $D^0 - \overline{D^0}$ mixing which is caused by the exchange of the $\Delta_{u^cu^c}$ field. Present observations [2] imply that the transition mass ΔM_D for $D^0 - \overline{D^0}$ to be $8.5 \times 10^{-15} \leq \Delta M_D \leq 1.9 \times 10^{-14}$ in GeV units. In our model, we can estimate this to be $\Delta M_D \simeq \frac{f_{11}f_{22}}{4m_\Delta^2} f_D^2 M_D$ which implies that $\frac{f_{11}f_{22}}{4m_\Delta^2} \leq 10^{-12}$ GeV^{-2}; for a TeV $\Delta_{u^cu^c}$ mass, which is in the range of our interest, this implies $f_{11}f_{22} \leq 4 \times 10^{-6}$. If we assume that $f_{11} \gg f_{22}$, then for $f_{11} \sim 0.1$ or so, f_{22} is close to zero, which we assume to be the case in our phenomenological analysis. The next constraint comes from nonstrange pion decays e.g. $D \to \pi\pi$ which are suppressed compared to the decays with strange final states. This bound however is weak. The present limits on such nonstrange final states are at the level of $B \leq 10^{-4}$ [3], which implies $f_{11}f_{12} \leq 4 \times 10^{-2}$ for $M_\Delta \sim$ few hundred to TeV range. This will be easily satisfied if $f_{11} \sim f_{12} \sim 0.2$.

IV. COLLIDER PHENOMENOLOGY

Because of the diquark Higgs coupling to a pair of up-type quarks, it can be produced at high energy hadron colliders such as Tevatron and LHC through the annihilation of a pair of up quarks. Clearly, a proton-proton collider leads to a higher production rate for $\bar{\Delta}_{u^cu^c}$ compared to the proton-antiproton colliding machine. As a signature of diquark productions at hadron colliders, we concentrate on its decay channel which includes at least one antitop quark (top quark for antidiquark Higgs case) in the final state. The top quark has large mass and decays electroweakly before hadronizing. Because of this characteristic feature distinguishable from other quarks, top quarks can be used as an ideal tool [4] to probe other new physics beyond the standard model [5].

Since the diquark couples with only up-type quarks, once it is produced, its decay give rise to production of double top quarks ($\bar{\Delta}_{u^cu^c} \to tt$) and a single top quark + jet ($\bar{\Delta}_{u^cu^c} \to tu$ or tc). These processes have no standard model counterpart, and the signature of diquark production would be cleanly distinguished from the standard model background. We leave detailed collider studies on signal event of diquark (antidiquark) Higgs production and the standard model background event for future works. Instead, as a conservative treatment, we calculate resonant production of diquark and antidiquark Higgs at Tevatron and LHC and compare it to $t\bar{t}$ production in the standard model. The reason is that, to observe resonant production of $\Delta_{u^cu^c}$ and measure its mass, it is necessary to reconstruct the invariant mass of the final state. In the double top quark production, if one uses the leptonic decay mode of a top quark, $t \to bW^+ \to b\ell^+\nu$, for the identification of top quark, with one missing neutrino and the hadronic decay mode for the other top quark to reconstruct the invariant mass [6], it becomes difficult to tell t from $\bar{t}$. However, note that, if one can use leptonic decay modes for both tops, one can distinguish tt from $t\bar{t}$ through charges of produced leptons.

First, we give basic formulas for our study on diquark Higgs production at hadron colliders. The fundamental processes in question are $uu \to \bar{\Delta}_{u^cu^c} \to tt, tu, tc$ ($\bar{u}\bar{u} \to \Delta_{u^cu^c} \to \bar{t}\bar{t}$, $\bar{u}\bar{t}$, $\bar{c}\bar{t}$ for antidiquark Higgs production). From Eq. (1), the cross section is found to be

$$\frac{d\sigma(tt)}{d\cos\theta} = \frac{|f_{11}|^2|f_{33}|^2}{16\pi\sqrt{\hat{s}}} \frac{(\hat{s} - 2m_t^2)\sqrt{\hat{s} - 4m_t^2}}{(\hat{s} - m_\Delta^2)^2 + m_\Delta^2\Gamma_{\text{tot}}^2} \tag{2}$$
$$\frac{d\sigma(ut, ct)}{d\cos\theta} = \frac{|f_{11}|^2|f_{13,23}|^2}{8\pi\hat{s}} \frac{(\hat{s} - m_t^2)^2}{(\hat{s} - m_\Delta^2)^2 + m_\Delta^2\Gamma_{\text{tot}}^2}.$$

Here, we have neglected all quark masses except for top quark mass (m_t), $\cos\theta$ is the scattering angle, and Γ_{tot} is the total decay width of diquark Higgs, which is the sum of each partial decay width, $\Gamma(\bar{\Delta}_{u^c u^c} \to uu, cc) = \frac{3}{16\pi}|f_{11,22}|^2 m_\Delta$ and similarly for $\Gamma(\bar{\Delta}_{u^c u^c} \to tt)$ and $\Gamma(\bar{\Delta}_{u^c u^c} \to uc)$. Note that the cross section is independent of the scattering angle because the diquark Higgs is a scalar.

With these cross sections at the parton level, we study the diquark production at Tevatron and LHC. At Tevatron, the total production cross section of an up-type quark pair ($u_i u_j$ where $u_{1,2,3} = u, c, t$) through diquark Higgs in the s-channel is given by

$$\sigma(p\bar{p} \to u_i u_j) = \int dx_1 \int dx_2 \int d\cos\theta f_u(x_1, Q^2) \times f_{\bar{u}}(x_2, Q^2) \frac{d\sigma(u_i u_j; \hat{s} = x_1 x_2 E_{\text{CM}}^2)}{d\cos\theta}, \tag{3}$$

where $f_u(x_1, Q^2)$ and $f_{\bar{u}}(x_2, Q^2)$ denote the parton distribution function, and E_{CM} is the collider energy (CM is center of mass). Note that one parton distribution function is for up quark and the other is for the sea up quark, since it comes from an antiproton (for a proton-antiproton system such as at Tevatron). This fact indicates that at Tevatron the production cross section of diquark Higgs is the same as the one of antidiquark Higgs, reflecting that the total baryon number of initial $p\bar{p}$ state is zero.

At LHC, the total production cross section of an up-type quark pair is given by replacing $f_{\bar{u}}$ into f_u in Eq. (3), since both parton distribution functions are for up quark in proton (both valence quarks), corresponding to a proton-proton system at LHC. The total production cross section of an up-type antiquark pair ($\bar{u}_i \bar{u}_j$) is obtained by replacing the parton distribution function into the one for antiquark. The initial pp state has a positive baryon number, so that the production cross section of diquark Higgs is much larger than the one of antidiquark Higgs. The dependence of the cross section on the final state invariant mass $M_{u_i u_j}$ is described as

$$\frac{d\sigma(pp \to u_i u_j)}{dM_{u_i u_j}} = \int d\cos\theta \int_{M_{u_i u_j}^2/E_{\text{CM}}^2}^1 dx_1 \frac{2M_{u_i u_j}}{x_1 E_{\text{CM}}^2} \times f_u(x_1, Q^2) f_u\left(\frac{M_{u_i u_j}^2}{x_1 E_{\text{CM}}^2}, Q^2\right) \frac{d\sigma(u_i u_j)}{d\cos\theta}. \tag{4}$$

The production cross section of the diquark Higgs and its branching ratio to final state up-type quarks depends on the coupling f_{ij}. This coupling is, in general, a free parameter in the model, and in our following analysis, we take an example for f_{ij},

$$f_{ij} = \begin{bmatrix} 0.3 & 0 & 0.3 \\ 0 & 0 & 0 \\ 0.3 & 0 & 0.3 \end{bmatrix}. \tag{5}$$

In this example, the phenomenological constraints on f_{ij} discussed in the previous section are satisfied with $f_{12} = f_{22} = 0$. This example gives rise to processes, $uu \to tt$, ut that we are interested in.

Let us first examine the lower bound on the diquark Higgs mass from Tevatron experiments. We refer to the current experimental data of the cross section of top quark pair production [7],

$$\sigma(t\bar{t}) = 7.3 \pm 0.5(\text{stat}) \pm 0.6(\text{syst}) \pm 0.4(\text{lum})\ \text{pb}, \tag{6}$$

and impose a constraint for the double top quark and a single top quark production cross section through diquark Higgs in the s-channel as

$$\sigma(p\bar{p} \to \Delta_{u^c u^c} \to tt, ut) \lesssim 1.5\ \text{pb}. \tag{7}$$

In our numerical analysis, we employ CTEQ5M [8] for the parton distribution functions with the factorization scale $Q = m_t = 172$ GeV. Figure 1 shows the total cross section of tt and tu productions as a function of the diquark Higgs mass, with $E_{\text{CM}} = 1.96$ TeV. The lower bound is found to be $m_\Delta \gtrsim 490$ GeV.

Next we investigate the diquark and antidiquark Higgs production at LHC with $E_{\text{CM}} = 14$ TeV. The differential cross sections for each process with $m_\Delta = 600$ GeV and 1 TeV are depicted in Fig. 2, together with the $t\bar{t}$ production cross section in the standard model. We can see that the peak cross sections for the tt and tu productions exceed the standard model cross section while the $\bar{t}\bar{t}$ and $\bar{t}\bar{u}$ cross sections are lower than it. This discrepancy between the

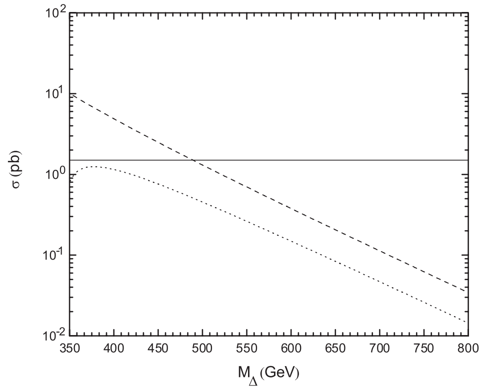

FIG. 1. The cross sections of tt (dotted line) and tj (dashed line) productions mediated by the diquark Higgs in s-channel at Tevatron with $E_{\text{CM}} = 1.96$ TeV.

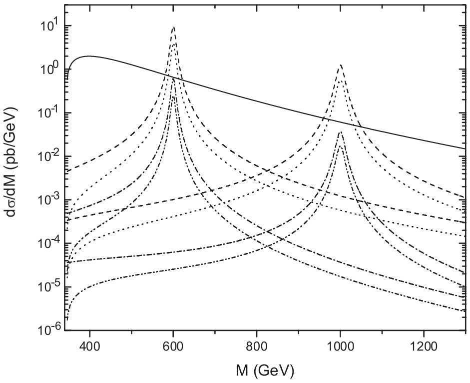

FIG. 2. The differential cross sections for tj (dashed line), tt (dotted line), $\bar{t}j$ (dash-dotted line), and $\bar{t}\,\bar{t}$ (dash-dot-dotted line) as a function of the invariant mass of final state M. The left peak corresponds to $m_\Delta = 600$ (GeV) and the right one to $m_\Delta = 1$ TeV. The solid line is the standard model $t\bar{t}$ background.

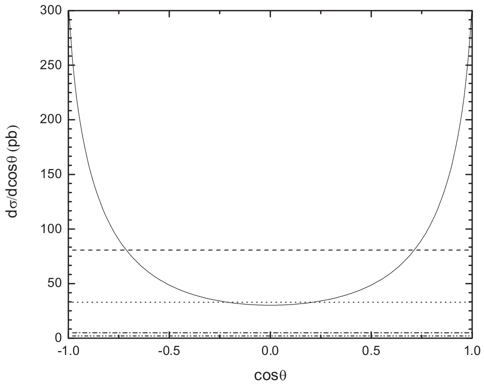

FIG. 3. Angular distribution of the cross section for $m_\Delta = 600$ GeV with $M_{\rm cut} = 550$ GeV, together with the $t\bar{t}$ production in the standard model. The same line convention as in the Fig. 2 has been used.

production cross sections of diquark and antidiquark Higgs at LHC is the direct evidence of the nonzero baryon number of diquark Higgs. The charge of the lepton from leptonic decay of top quark or antitop quark can distinguish top quark from antitop quark. Counting the number of top quark events and antitop quark events from their leptonic decay modes would reveal a nonzero baryon number of diquark Higgs.

The angular distribution of the final states carries the information of the spin of the intermediate states. As shown in Eq. (2), there is no angular dependence on the diquark Higgs production cross section, because the diquark Higgs is a scalar particle. On the other hand, the top quark pair production in the standard model is dominated by the gluon fusion process, and the differential cross section shows peaks in the forward and backward region. Therefore, the signal of the diquark Higgs production is enhanced at the region with a large scattering angle (in the center of mass frame of colliding partons). Imposing a lower cut on the invariant mass $M_{\rm cut}$, the angular dependence of the cross section is described as

$$\frac{d\sigma(pp \to u_i u_j)}{d\cos\theta} = \int_{M_{\rm cut}}^{E_{\rm CM}} dM_{u_i u_j} \frac{d^2\sigma(pp \to u_i u_j)}{dM_{u_i u_j} d\cos\theta} \quad (8)$$

with the cross section in Eq. (4). The results for $m_\Delta = 600$ GeV with $M_{\rm cut} = 550$ GeV are depicted in Fig. 3, together with the standard model result. Here the lower cut on the invariant mass close to the diquark Higgs mass dramatically reduces the standard model cross section compared to the diquark Higgs signal.

Clearly, the diquark couplings are related to neutrino masses, since once $B - L$ symmetry is broken by $\langle\Delta^c\rangle$, right-handed neutrinos acquire masses which via type I seesaw gives light neutrino masses. When we impose the left-right symmetry on this model, Δ^c is accompanied by $\bar{\Delta}$: $(\mathbf{3}, \mathbf{1}, \overline{\mathbf{10}})$, which adds a new term to the superpotential $f\psi\bar{\Delta}\psi$ with the same Yukawa coupling f_{ij}. Through this Yukawa coupling, the type II seesaw mechanism can generate Majorana masses for left-handed neutrinos in which case the light neutrino mass matrix becomes proportional to f_{ij} giving a direct relation between the collider physics involving diquark Higgs production and neutrino oscillation data. A sample f_{ij} that fits neutrino observations is given by

$$f_{ij} = \begin{bmatrix} 0.27 & -0.48 & -0.47 \\ -0.48 & 0 & -0.38 \\ -0.47 & -0.38 & 0.2 \end{bmatrix}.$$

Here the resultant light neutrino mass spectrum is the inverse hierarchical. The lower bound on the diquark Higgs mass from Tevatron data in this case is $m_\Delta \gtrsim 470$ GeV and the peak cross section of only the single top + jet production exceeds the $t\bar{t}$ production cross section of the standard model. The differential cross section of Eq. (8) is independent of the scattering angle, and we find $d\sigma/d\cos\theta = 60.6$ pb for the single top + jet production for $m_\Delta = 600$ GeV with $M_{\rm cut} = 550$ GeV.

Finally, we comment on spin polarization of the final state top (antitop) quark. Because of its large mass, the top quark decays before hadronizing and the information of the top quark spin polarization is directly transferred to its decay products and results in significant angular correlations between the top quark polarization axes and the direction of motion of the decay products [9]. Measuring the top spin polarization provides the information on the chirality nature of the top quark in its interaction vertex. It has been shown that measuring top spin correlations can increase the sensitivity to a new particle at Tevatron [10] and LHC [11]. In the diquark Higgs production, it is very interesting to measure the polarization of top (antitop) quark in the single top production. Only the right-handed top quark couples to the diquark Higgs and therefore the top quark produced from diquark Higgs decay is a right-handed state, while the top quark from the single top production through electroweak processes in the standard model is purely left handed.

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