Colored scalars and the CDF W+dijet excess

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ABSTRACT: The recent data on W+dijet excess reported by CDF may be interpreted as the associated production of a W and a new particle of mass about $150\,\mathrm{GeV}$ which subsequently decays into two hadron jets. We study the possibility of explaining the W+dijet excess by colored scalar bosons. There are several colored scalars which can have tree level renormalizable Yukawa couplings with two quarks, $(\mathbf{8}, \mathbf{2}, 1/2)$, $(\bar{\mathbf{6}}(\mathbf{3}), \mathbf{3}(\mathbf{1}), -1/3)$, $(\bar{\mathbf{6}}(\mathbf{3}), \mathbf{1}, -4/3(2/3))$. If one of these scalars has a mass about $150\,\mathrm{GeV}$, being colored it can naturally explain why the excess only shows up in the form of two hadron jets. Although the required production cross section and mass put constraints on model parameters and rule out some possible scenarios when confronted with other existing data, in particular FCNC data, we find that there are strong constraints on the Yukawa couplings of these scalars. Without forcing the couplings to be some special texture forms most of the scalars, except the $(\mathbf{3}, \mathbf{3}, -1/3)$, are in trouble with FCNC data. We also study some features for search of these new particles at the RHIC and the LHC and find that related information can help further to distinguish different models.

KEYWORDS: Beyond Standard Model, Hadronic Colliders

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Contents

1 Introduction

The CDF collaboration has reported an excess in the production of two jets in association with a W boson production [1] from data collected at the Tevatron with a center-of-mass energy of $1.96\,\mathrm{TeV}$ and an integrated luminosity of $4.3\,\mathrm{fb}^{-1}$. The W boson is identified through a charged lepton (electron or muon) with large transverse momentum. The invariant mass of the dijet system is found to be in the range of 120-160 GeV. The W+dijet production has a few pb cross-section which is much larger than standard model (SM) expectation. The dijet system may be interpreted as an unidentified resonance with mass around 150 GeV which predominantly decays into two hadron jets. This leads to the speculation that a beyond SM new particle has been found. At present the deviation from the SM expectation is only at 3.2σ level. The excess needs to be further confirmed. On the theoretical side, our understanding of the parton distributions and related matter still have room for improvement to make sure that the excess represents genuine new physics beyond the SM [2–4]. Nevertheless studies of new particle explanation has attracted much attention.

Several hypothetic particles beyond SM have been proposed to explain the CDF W+dijet excess, such as leptophobic Z' model [5–19], technicolor [20], colored vector, scalar [21–23], quasi-inert Higgs bosons [24–27] and the other possibilities [28–33]. Common to all of these models is that the new particle must decay predominantly into hadrons (dijet). We note that a class of particles which can naturally have this property. These are those scalars which are colored and couple to quarks directly. In order for these scalars to be considered as a possible candidate, it must satisfy constraints obtained from existing

experimental data. Colored particles which couple to two quarks have been searched for at the Tevatron and the LHC. If the couplings to quarks/gluon are the same as the QCD coupling, the color triplet diquark with a mass in the range $290 < m < 630\,\text{GeV}$ is excluded at the Tevatron [34], and the mass intervals, $500 < m < 580\,\text{GeV}$, $0.97 < m < 1.08\,\text{TeV}$ and $1.45 < m < 1.6\,\text{TeV}$ are excluded at the LHC [35, 36] whereas the LHC data is limited for $m_{jj} > 200\,\text{GeV}$. The color sextet diquarks with electric charge, $\pm 2/3$, $\pm 1/3$, $\pm 4/3$, are excluded for their masses less than 1.8, 1.9, 2.7 TeV, respectively [37]. The color octet vectors/scalars which interact with quarks/gluon by QCD coupling are excluded for $m < 1.6\,\text{TeV}$ [37]. If their couplings to quarks/gluon are smaller than the QCD coupling the constraints are weaker.

Some aspects of colored scalars relevant to the CDF W+dijet data have been considered recently [21–23]. In this work we carry out a systematic study to investigate the possibility of colored scalar bosons η as the new particle explaining the CDF excess through $W\eta$ production followed by η decays into two hadron jets.

At the tree level, there are several new scalar bosons which can have renormalizable couplings to two quarks (or a quark and an anti-quark). A complete list of beyond SM scalars which can couple to SM fermions at the tree level [38] and some of the phenomenology have been studied before [38, 39]. The required production cross section and the mass from W+dijets excess put constraints on model parameters. Some possible scenarios are ruled out when confronted with other existing data, such as data from flavor changing neutral current (FCNC) processes. We find that without forcing of the Yukawa couplings to be some special forms most of the scalars, except the $(\mathbf{3}, \mathbf{3}, -1/3)$, are in trouble with FCNC data. We, however, do find that some other cases can be made consistent with all data by tuning their couplings providing a possible explanation for the W+dijet excess from CDF. Justification of such choices may have a realization in a flavor model, which is beyond the scope of the present work of phenomenology. These colored scalars also have interesting signatures at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) which can be used to further distinguish different models.

The paper is organized as follows. In section 2, we study possible colored-scalars which can couple to two quark (or a quark and a anti-quark), and determine their Yukawa couplings by requiring that the colored scalar with a mass of 150 GeV to explain the CDF W+dijet excess data. In section 3, we study the constraints from FCNC data on colored scalar couplings. In section 4, we give some implications for the RHIC and the LHC. Finally, we summarize our results in section 5.

2   Colored scalars and the CDF W+dijet excess

Scalar bosons which have color and have renormalizable Yukawa couplings to two quarks or a pair of a quark and an anti-quark can be easily determined by studying bi-products of two quarks [38]. The quarks transform under the SM $\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$ as: $q_L^i = (u_L^i, d_L^i)^T : (\mathbf{3}, \mathbf{2}, 1/6)$ the following bi-products, $u_R^i : (\mathbf{3}, \mathbf{1}, 2/3)$ and $d_R^i : (\mathbf{3}, \mathbf{1}, -1/3)$. Here i and j are generation indices. With these quantum numbers, we can have the
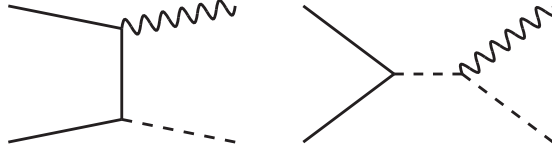
Figure 1. Feynman diagrams for the t-channel and s-channel process in $W + \eta$ production. Solid, wavy and dashed line represents quark or anti-quark, $W^{\pm}$ and η, respectively.

following quark bi-products

$$
\begin{aligned}
\overline{u_R^i} q_L^j &: (\mathbf{1} + \mathbf{8}, \mathbf{2}, -1/2) , & \overline{d_R^i} q_L^j &: (\mathbf{1} + \mathbf{8}, \mathbf{2}, 1/2) , \\
\overline{q_L^{ic}} q_L^j &: (\bar{\mathbf{3}} + \mathbf{6}, \mathbf{1} + \mathbf{3}, 1/3) , & \overline{u_R^{ic}} u_R^j &: (\bar{\mathbf{3}} + \mathbf{6}, \mathbf{1}, 4/3) , \\
\overline{u_R^{ic}} d_R^j &: (\bar{\mathbf{3}} + \mathbf{6}, \mathbf{1}, 1/3) , & \overline{d_R^{ic}} d_R^j &: (\bar{\mathbf{3}} + \mathbf{6}, \mathbf{1}, -2/3) ,
\end{aligned}
\tag{2.1}
$$

where the superscript "c" indicates charge conjugation.

For those scalars which only couple to right-handed quarks, the contribution to W associated production will be small because they do not directly couple to W boson. To have large W associated production for the CDF excess, we therefore consider the following colored scalars which can couple to left-handed quarks

$$
\begin{aligned}
\eta_8 &= \sqrt{2} T^a \eta_8^a : (\mathbf{8}, \mathbf{2}, 1/2), \\
\eta_{(6,3)} &= K_{\alpha\beta}^a \eta_{(6,3)}^a : (\bar{\mathbf{6}}, \mathbf{3}, -1/3), & \eta_{(6,1)} &= K_{\alpha\beta}^a \eta_{(6,1)}^a : (\bar{\mathbf{6}}, \mathbf{1}, -1/3), \\
\eta_{(3,3)} &= \eta_{(3,3)}^\alpha : (\mathbf{3}, \mathbf{3}, -1/3), & \eta_{(3,1)} &= \eta_{(3,1)}^\alpha : (\mathbf{3}, \mathbf{1}, -1/3),
\end{aligned}
\tag{2.2}
$$

where α is a color index, T^a is the $SU(3)_C$ generator normalized as $\text{Tr}\,(T^a T^b) = \delta^{ab}/2$, and K^a ($a = 1, \ldots, 6$) is a generator of the symmetric tensor ($K_{11}^1 = K_{22}^2 = K_{33}^3 = 1$, $K_{12}^4 = K_{21}^4 = K_{13}^5 = K_{31}^5 = K_{23}^6 = K_{32}^6 = 1/\sqrt{2}$). The color component fields, η_8^a, $\eta_{(6,3)}^a$ and $\eta_{(6,1)}^a$, are defined by having the kinetic energy term normalized properly.

We denote the component fields of $SU(2)_L$ as follows:

$$
\eta_8^A = \begin{pmatrix} \eta_8^0 \\ \eta_8^- \end{pmatrix}, \; \eta_{(6,3)B}^A = \begin{pmatrix} \eta_{(6,3)}^{-1/3}/\sqrt{2} & \eta_{(6,3)}^{2/3} \\ \eta_{(6,3)}^{-4/3} & -\eta_{(6,3)}^{-1/3}/\sqrt{2} \end{pmatrix}, \; \eta_{(3,3)B}^A = \begin{pmatrix} \eta_{(3,3)}^{-1/3}/\sqrt{2} & \eta_{(3,3)}^{2/3} \\ \eta_{(3,3)}^{-4/3} & -\eta_{(3,3)}^{-1/3}/\sqrt{2} \end{pmatrix},
\tag{2.3}
$$

where A, B are the $SU(2)_L$ indices. For neutral η^0, the physics component can be separated according to their parity property with $\eta^R = \sqrt{2}\,\text{Re}\,(\eta^0)$ and $\eta^I = \sqrt{2}\,\text{Im}\,(\eta^0)$.

For $W\eta$ production by $p\bar{p}$ collision, the leading contributions are from the t-channel and s-channel tree diagrams as shown in figure 1. For η_8, $\eta_{(6,3)}$ and $\eta_{(3,3)}$ the s-channel production can exist in addition to the diagram of t-channel quark exchange. One needs to know how the colored scalars couple to quarks and the W boson. We list the Yukawa couplings in the quark mass eigenstate basis in the following,

$$
\begin{aligned}
-L_\eta = \; & \overline{U_R} Y_{8u} \eta_{8\,A}^a T^a Q_L^A + \overline{Q_{LA}} Y_{8d} \eta_8^{aA} T^a D_R \\
& + \frac{1}{2} \overline{Q_{LA}^c} Y_{(6,3)} \eta_{(6,3)B}^{aA} K^a Q_L^B + \frac{1}{2} \overline{Q_{LA}^c} Y_{(6,1)} \eta_{(6,1)}^a K^a Q_L^A \\
& + \frac{1}{2} \overline{Q_{LA}^{c\,\alpha}} Y_{(3,3)} \eta_{(3,3)B}^{\beta A} Q_L^{\gamma B} \epsilon_{\alpha\beta\gamma} + \frac{1}{2} \overline{Q_{LA}^{c\,\alpha}} Y_{(3,1)} \eta_{(3,1)}^\beta Q_L^{\gamma A} \epsilon_{\alpha\beta\gamma} + h.c.
\end{aligned}
\tag{2.4}
$$

where $\eta_A = (i\sigma_2)_{AB}\eta^B$. The flavor space is described as $U_R = (u_R^i)^T$, $D_R = (d_R^i)^T$ and $Q_L = (q_L^i)^T = (u_L^i, V_{ij}d_L^j)^T$, where V is a CKM quark mixing matrix, and Y_I^{ij} ($I = 8q$, (6,3), (6,1), (3,3), (3,1)) are the coupling matrix in flavor space. $Y_{(6,3)}^{ij}$ and $Y_{(3,1)}^{ij}$ are symmetric, and, $Y_{(6,1)}^{ij}$ and $Y_{(3,3)}^{ij}$ are anti-symmetric, under the exchange of flavor indices i and j. The diquark couplings are

$$
\begin{aligned}
-L_{\eta_{\text{tri}}} &= \frac{1}{2}\overline{Q_L^c}Y_{\text{tri}}\eta_{\text{tri}}Q_L + h.c. \\
&= \frac{1}{2}\overline{U_L^c}Y_{\text{tri}}\eta_{\text{tri}}^{-4/3}U_L - \frac{1}{\sqrt{2}}\overline{U_L^c}Y_{\text{tri}}V\eta_{\text{tri}}^{-1/3}D_L + \frac{1}{2}\overline{D_L^c}V^TY_{\text{tri}}V\eta_{\text{tri}}^{2/3}D_L + h.c.,\quad (2.5)
\end{aligned}
$$

$$
-L_{\eta_{\text{s}}} = \frac{1}{2}\overline{Q_L^c}Y_{\text{s}}\eta_{\text{s}}Q_L + h.c. = \overline{U_L^c}Y_{\text{s}}V\eta_{\text{s}}^{-1/3}D_L + h.c.,
$$

where η_{tri}^Q is $SU(2)_L$ triplet, and η_{s}^Q is $SU(2)_L$ singlet.

The electroweak gauge interactions are given by

$$
L_W = i\overline{Q_L}\gamma_\mu\mathcal{D}^\mu Q_L + i\overline{U_R}\gamma_\mu\mathcal{D}^\mu U_R + i\overline{D_R}\gamma_\mu\mathcal{D}^\mu D_R + (\mathcal{D}^\mu\eta_I)^\dagger(\mathcal{D}_\mu\eta_I),\qquad (2.6)
$$

where $\mathcal{D}_\mu$ is the covariant derivative. The electroweak gauge interactions of the colored scalars are obtained from the following:

$$
\begin{aligned}
(\mathcal{D}^\mu\eta_8)^\dagger(\mathcal{D}_\mu\eta_8) &= \left|\left(i\partial_\mu + \left(\frac{1}{2} - s_W^2\right)g_Z Z_\mu + eA_\mu\right)\eta_8^+ + \frac{1}{\sqrt{2}}gW_\mu^+\eta_8^0\right|^2 \\
&\quad + \left|\left(i\partial_\mu - \frac{1}{2}g_Z Z_\mu\right)\eta^0 + \frac{1}{\sqrt{2}}gW_\mu^+\eta^-\right|^2,
\end{aligned}
$$

$$
\begin{aligned}
(\mathcal{D}^\mu\eta_{\text{tri}})^\dagger(\mathcal{D}_\mu\eta_{\text{tri}}) &= \left|\left(i\partial_\mu + \left(1 - \frac{2}{3}s_W^2\right)g_Z Z_\mu + \frac{2}{3}eA_\mu\right)\eta_{\text{tri}}^{2/3} + gW_\mu^+\eta_{\text{tri}}^{-1/3}\right|^2 \\
&\quad + \left|\left(i\partial_\mu + \frac{1}{3}s_W^2 g_Z Z_\mu - \frac{1}{3}eA_\mu\right)\eta_{\text{tri}}^{-1/3} + gW_\mu^-\eta_{\text{tri}}^{2/3} + gW_\mu^+\eta_{\text{tri}}^{-4/3}\right|^2 \\
&\quad + \left|\left(i\partial_\mu\left(-1 + \frac{4}{3}s_W^2\right)g_Z Z_\mu - \frac{4}{3}eA_\mu\right)\eta_{\text{tri}}^{-4/3} + gW_\mu^-\eta_{\text{tri}}^{-1/3}\right|^2,\quad (2.7)
\end{aligned}
$$

$$
(\mathcal{D}^\mu\eta_{\text{s}})^\dagger(\mathcal{D}_\mu\eta_{\text{s}}) = \left|\left(i\partial_\mu + \frac{1}{3}s_W^2 g_Z Z_\mu - \frac{1}{3}eA_\mu\right)\eta_{\text{s}}^{-1/3}\right|^2,
$$

where s_W is the sine of the Weinberg angle θ_W, and $g_Z = e/s_W c_W$. In the above color indices are suppressed and interaction with gluons are omitted.

For η_8 color-octet and $\eta_{(6,3)}$, $\eta_{(3,1)}$ diquarks, the dominant contributions to the $W\eta$ production are from η couplings to the first generation, Y_I^{11}. For $\eta_{(6,1)}$, $\eta_{(3,3)}$ diquarks, on the other hand, because the Yukawa coupling matrix is anti-symmetric in generation space, the dominant contribution would come from Y_I^{12} term (which includes u and d quark coupling suppressed by Cabibbo mixing).

In general different component in η can have different masses. In order to avoid the contribution to ρ parameter, we assume that all the components have the same masses for simplicity.

Since interactions and the masses of the colored scalars are fixed, the only unknowns parameters, the Yukawa couplings, can be determined by requiring the colored scalars to
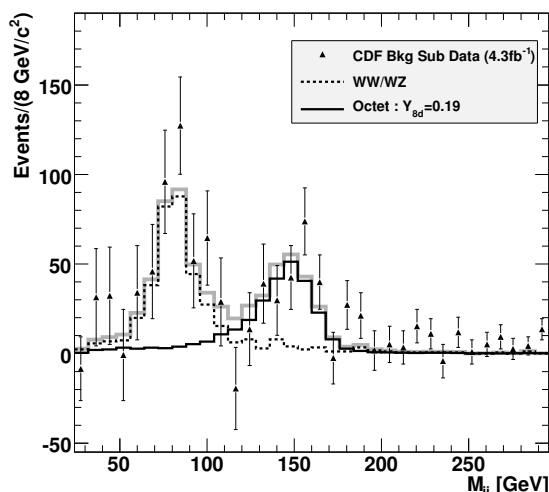
Figure 2. Dijet invariant-mass distribution in W+dijets events at the Tevatron. CDF data taken from ref. [1] is shown with our MC simulation results for the color-octet scalar model with $Y_{8d} = 0.19$ (solid) and the standard-model $WW + WZ$ contribution (dashed).

explain the CDF W+dijet data. We consider the different type of colored scalars separately. For the fit, we use `MadGraph/MadEvent` [40, 41] and `Pythia` [42] for the particle-level event-generation, and `PGS` for the fast detector simulation. Jets are defined in cone algorithm with $R = 0.4$. We apply the same kinematical cuts as those denoted in ref. [1]. The reconstructed jet momenta are rescaled so that the dijet invariant-mass has correct peak at the resonance masses. The simulation result for the case of color-octet scalars η_8 with Y_{8d} coupling is shown in figure 2. Inclusive $W + \eta$ production cross-section at the Tevatron is estimated to be 2 pb (without multiplying K-factor). For other cases, we obtained similar distribution. We list the central values of Yukawa couplings for each case in the following,

$$
\begin{aligned}
Y_{8u}^{11} &= 0.13 \,, & Y_{8d}^{11} &= 0.19 \,, \\
Y_{(6,3)}^{11} &= 0.32 \,, & Y_{(3,1)}^{11} &= 0.5 \,, \\
Y_{(6,1)}^{12} &= 1.0 \,, & Y_{(3,3)}^{12} &= 0.62 \,.
\end{aligned}
\tag{2.8}
$$

We see that the Yukawa couplings are of order $\mathcal{O}(10^{-1})$ for color-octet scalars, but close to $\mathcal{O}(1)$ for diquark scalars. The sizeable Yukawa couplings for the diquark scalars come from the fact that the Tevatron is a $p\bar{p}$ collider therefore the production of diquark must pick up one sea-quark whose distribution function is suppressed. The large values for $Y_{(6,1)}^{12}$ and $Y_{(3,3)}^{12}$ couplings are required since the production cross-section is suppressed due to the Cabibbo mixing suppressed couplings to u and d quarks and the suppressed s or c-quark parton distribution inside a proton. The difference between them is mainly due to being a triplet or a singlet under $SU(2)_L$.

Two comments are in order about the sizeable colored scalar Yukawa couplings which may cause problems in decay widths and constraints from direct resonant search for these scalers, at experiments such as at the UA2 [43]. First, the decay widths of these scalars are less than $1\,\text{GeV}$ for color-octet cases, and a few to several GeV for diquark scalars,

where the flavour structure of the Yukawa couplings of the scalars to quarks is assumed to those determined in the next section. These decay widths are small enough to regard the width of the observed dijet resonance as the consequence of the resolution of the jet momentum measurements. Second, inclusive production of the scalars which couple to quarks are constrained by the two-jet invariant mass spectrum measurement in the UA2 experiment [43]. For $m_{jj} \simeq 150\,\text{GeV}$, the cross-section times the branching ratio to two jets is excluded for $\sigma \cdot \mathcal{B} \gtrsim 80$ pb. The couplings in eq. (8) provide values for $\sigma \cdot \mathcal{B}$ in pb as

$$\eta_8 : 41 \text{ (for } Y_{8u}^{11}), \quad 34 \text{ (for } Y_{8d}^{11}), \quad \eta_{(6,3)} : 14, \quad \eta_{(6,1)} : 78, \quad \eta_{(3,1)} : 29, \quad \eta_{(3,3)} : 33 . \quad (2.9)$$

From the above values we see that the couplings in eq. (8) cannot be excluded by the UA2 measurement. The cross section for $\eta_{(6,1)}$ is on the border of the constraint.

We can estimate the Z+dijet production cross-section at the Tevatron. For the couplings in eq. (2.8), the $Z + \eta$ production cross-sections are estimated to be

$$\eta_8 : 0.16 \ (Y_{8u}^{11}), \quad 0.25 \ (Y_{8d}^{11}), \quad \eta_{(6,3)} : 0.14, \quad \eta_{(6,1)} : 0.69, \quad \eta_{(3,1)} : 0.67, \quad \eta_{(3,3)} : 0.38 \text{ [pb]}. \quad (2.10)$$

The largest $\sigma(Z\eta)$ is about 0.7 pb, which is 23% of $\sigma(ZZ+ZW)$ within the SM estimation in leading-order. This fraction is similar to $\sigma(W\eta)/\sigma(WW + WZ) \sim (2 \text{ to } 4)/18$. Therefore, although there have been no statistically significant signal on the diboson production in $\ell^- \ell^+ jj$ mode at the Tevatron yet, $Z + \eta$ production should be more carefully studied.

3 FCNC constraints on colored scalars

From the previous section we see that the Yukawa couplings of these colored scalars to the first and second generations are much larger than that of the usual Higgs in order to explain the CDF W+dijets excess. Therefore we need to check whether such large Yukawa couplings are consistent with data. We now study constraints from new FCNC interactions by colored scalars which may induce sizeable meson-antimeson mixing. We consider each case separately in the following.
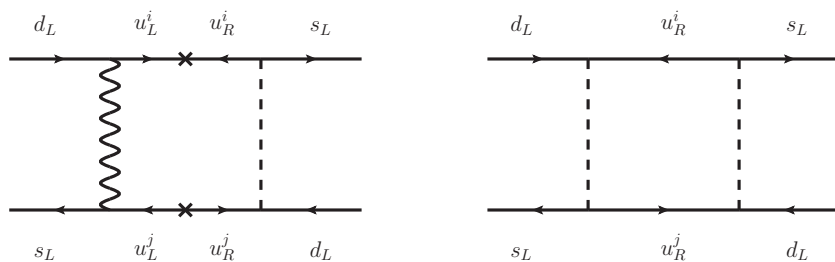
3.1 Octet-doublet scalar

Some phenomenological studies of the octet-doublet scalar can be found in [38, 39, 44, 45]. Here we study the constraints from the mixing of mesons for large Yukawa coupling to the first generation of quarks.

For η_8 couples with U_R and Q_L, we have

$$\overline{U_R} Y_{8u} \eta_{8A} Q_L^A = \bar{U}_R Y_{8u} \eta_8^0 U_L - \bar{U}_R Y_{8u} V \eta_8^+ D_L. \quad (3.1)$$

If Y_{8u} is not diagonal, exchange of η_8^0 will induce large FCNC effects at tree level, such as D^0-$\bar{D}^0$ mixing, making the model inconsistent. Even if Y_{8u} is diagonal, exchange of η_8^+ at loop level can also induce FCNC interaction which may result in too large K^0-$\bar{K}^0$ and $B_{d,s}^0$-$\bar{B}_{d,s}^0$ mixings. To minimize possible FCNC interaction, we will work with a special case where $Y_{8u} = y_{8u} I$ (where I is a unit matrix) for illustration ($Y_{8u}^{ij} = y_{8u} \delta^{ij}$).

Figure 3. Box diagrams for the K^0-$\bar{K}^0$ mixing induced by Y_{8u} coupling. Dashed line represents the octet-doublet scalar propagation.

In the case where only Y_{8u} coupling is turned on ($Y_{8d} = 0$), the K^0-$\bar{K}^0$ mixing operator $(\overline{d_L}\gamma_\mu s_L)(\overline{d_L}\gamma^\mu s_L)$ is induced by W-η and η-η box diagrams shown in figure 3.

In order to show the η contribution, we define the following quantities:

$$
\begin{aligned}
E_1 &= \sum_{i,j} \lambda_i^s \lambda_j^s z_W \sqrt{z_i z_j}\, G(z_i, z_j, z_W), \\
E_2 &= \sum_{i,j} \lambda_i^s \lambda_j^s z_W F(z_i, z_j, z_W), \\
E_3 &= \sum_{i,j} \lambda_i^s \lambda_j^s \sqrt{z_i z_j}\, F(z_i, z_j, z_W), \\
E_4 &= \sum_{i,j} \lambda_i^s \lambda_j^s z_i z_j\, G(z_i, z_j, z_W), \\
E_5 &= \sum_{i,j} \lambda_i^s \lambda_j^s z_W F(z_i, z_j, 1),
\end{aligned}
\tag{3.2}
$$

where $z_i = m_{u_i}^2/m_\eta^2$, $z_W = M_W^2/m_\eta^2$ (m_η is the mass of η boson), and $\lambda_i^s = V_{id}^* V_{is}$. The loop functions F and G are given by

$$
\begin{aligned}
F(x,y,z) &= \frac{x^2 \log(x)}{(1-x)(x-y)(x-z)} + \frac{y^2 \log(y)}{(1-y)(y-x)(y-z)} + \frac{z^2 \log(z)}{(1-z)(z-y)(z-x)}, \\
G(x,y,z) &= \frac{x \log(x)}{(1-x)(x-y)(x-z)} + \frac{y \log(y)}{(1-y)(y-x)(y-z)} + \frac{z \log(z)}{(1-z)(z-y)(z-x)}.
\end{aligned}
\tag{3.3}
$$

We obtain the η contribution of K^0-$\bar{K}^0$ mixing amplitude as

$$
M_{12}^K(\eta) = \frac{f_K^2 m_K \hat{B}_1}{48\pi^2 M_W^2} \left(\frac{1}{3} \frac{y_{8u}^2 g_2^2}{2} \left(-E_1 + \frac{1}{8} E_3 \right) + \frac{11}{18} \frac{y_{8u}^4}{8} E_5 \right),
\tag{3.4}
$$

where f_K is a kaon decay constant, m_K is a kaon mass, and $\hat{B}_1$ is a bag parameter from the matrix element of the $(\overline{d_L}\gamma_\mu s_L)(\overline{d_L}\gamma^\mu s_L)$ operator between K mesons [46]. Here the E_1 and E_3 terms are from the W-η box diagram while the E_5 term is from the η-η box diagram.

The kaon mass difference is obtained by $\Delta m_K = 2|M_{12}^K(\text{full})|$. Inserting the value Y_{8u}^{11} given in eq. (2.8) (under the current assumption, $y_{8u} = Y_{8u}^{11}$), we find that the E_1 term

gives dominant contribution, which corresponds to the W-η box diagram with charm quark mass insertions. The short distance SM contribution has uncertainty which mainly comes from the charm mass and QCD correction. For the K^0-$\bar{K}^0$ system, the short distance SM contribution with the next-to-leading order QCD correction can fill roughly 80% of the experimental result, $\Delta M_K = 3.483 \times 10^{-15}$ GeV [47]. Though the long distance contribution is hard to be estimated, the total mixing amplitude in SM can be consistent with the experiment. We exhibit the ratio of the leading order η contribution and the short distance SM contribution, which is free from the hadronic uncertainty,

$$\frac{M_{12}^K(\eta)}{M_{12}^K(\text{SM})} \simeq 0.12 \times \left(\frac{y_{8u}}{0.13}\right)^2 \left(\frac{150\,\text{GeV}}{m_\eta}\right)^4. \tag{3.5}$$

Here we see that the contributions from the octet scalar is at 12% of the short distance SM contribution of the mixing amplitude for the value $Y_{8u}^{11} \simeq 0.13$ suggested by the W+dijet excess, and therefore, consistent with the experimental result of kaon mass difference. The imaginary part of the mixing amplitude gives indirect CP violation in K^0-$\bar{K}^0$ mixing. We find that Im $M_{12}^K(\eta)/$Im $M_{12}^K(\text{SM})$ is less than 2%, and thus it is consistent with experiments. The mixing amplitudes of $B_{s,d}^0$-$\bar{B}_{s,d}^0$ are obtained just by replacing λ_i^s, f_K, m_K and $\hat{B}_1$ properly, and they are found to be at the level of less than 1% of the standard model prediction as well as the experimental result.

When η_8 couples to D_R and Q_L, we have

$$\overline{Q_{LA}} Y_{8d} \eta_8^A D_R = \overline{U_L} Y_{8d} \eta_8^+ D_R + \overline{D_L} V^\dagger Y_{8d} \eta_8^0 D_R. \tag{3.6}$$

In this case, to avoid large tree level FCNC, one is forced to have $V^\dagger Y_{8d}$ to be diagonal. Also similar to the previous case to avoid potential large one loop FCNC, we make our illustration, of the form $(Q \to Q' = V^\dagger Q)$

$$\overline{Q'_{LA}} Y_{8d} \eta_8^A D_R = \overline{U_L} V Y_{8d} \eta_8^+ D_R + \overline{D_L} Y_{8d} \eta_8^0 D_R, \tag{3.7}$$

with $Y_{8d} = y_{8d} I$. In this case, the η contribution is

$$M_{12}^K(\eta) = \frac{f_K^2 m_K}{48\pi^2 M_W^2} \left(\frac{-\hat{B}_4 + \hat{B}_5}{8} \left(\frac{m_K}{m_s + m_d} \right)^2 \frac{y_{8d}^2 g_2^2}{2} \left(-E_2 + \frac{1}{2} E_4 \right) + \frac{11}{18} \hat{B}_1 \frac{y_{8d}^4}{8} E_5 \right), \tag{3.8}$$

where $\hat{B}_4$ and $\hat{B}_5$ operators are the bag parameters from the matrix elements of the operators, $(\overline{d_R} s_L)(\overline{d_L} s_R)$ and $(\overline{d_R}^\alpha s_{\beta L})(\overline{d_L}^\beta s_{\alpha R})$ between K mesons, respectively [48, 49]. The contribution is small ($O(1)$% of the experimental value) for the value for the Yukawa coupling chosen from W+dijet excess. The situation is the same for the B^0-$\bar{B}^0$ mixing amplitude.

The D^0-$\bar{D}^0$ mixing amplitude is obtained by exchanging $y_{8u} \leftrightarrow y_{8d}$, and replacing $m_{u_i} \to m_{d_i}$ and $\lambda_i^s \to V_{ui} V_{ci}^*$ in the expressions of K^0-$\bar{K}^0$ mixing. The mixing amplitude of D^0-$\bar{D}^0$ induced by the $Y_{8u} = y_{8u} I$ coupling is found to be very small at the level of less than 10^{-3} compared to the short distance SM contribution. On the other hand, D^0-$\bar{D}^0$ mixing amplitude induced by the $Y_{8d} = y_{8d} I$ coupling receives a large W-η box

contribution (corresponding to the E_1 term), which is comparable to the short distance SM one. However, the short distance SM contribution of D^0-$\bar{D}^0$ mixing is tiny compared to the experimental result,

$$\frac{2|M_{12}^D(\eta)|}{\Delta m_D^{\mathrm{exp}}} \simeq 5.5 \times 10^{-4} \left(\frac{y_{8d}}{0.19}\right)^2 \left(\frac{150\,\mathrm{GeV}}{m_\eta}\right)^4. \tag{3.9}$$

It is expected that long distance contribution in the SM can produce the experimental value. For our purpose, it is therefore safe to say that Y_{8d} coupling required by the CDF W+dijet data can satisfy constraints from D^0-$\bar{D}^0$ mixing data

Note that the octet-doublet scalar with the form $Y_{8d}^{ij} = y_{8d}\delta^{ij}$ can decay into $b\bar{b}$, giving 20% of b-jet pair fraction in $W + \eta$ events.

One can also try to keep both Y_{8u} and Y_{8d} simultaneously non-zero. But there is a large contribution to $b_L \to s_R\gamma$ ($b_R \to s_L\gamma$) amplitude proportional to $Y_{8u}^{33}Y_{8d}^{22}V_{ts}$ ($Y_{8u}^{33}Y_{8d}^{33}V_{ts}$). This combination must be small resulting in one of the $|Y_{8u,8d}^{11}|$ to be much smaller than the other. This virtually goes back to the previous two cases studied.

One may be able to forbid one of the $Y^{8u,8d}$ couplings by some discrete Z_2 symmetry, such as $\eta_8 \; to - \eta_8$ and $U_R \to -U_R$ and $D_R \to D_R$ to eliminate Y^{8d}. But to have Y^{8u} proportional to unit chosen earlier, this raises a question how natural the choice is. While this may be achievable by some flavor symmetry to enforce the special texture form, such endeavor is beyond scope of this work and we will confine ourselves to phenomenological study only. We conclude that the cases with η_8 couples to either U_R only or D_R only is a phenomenologically viable model.

3.2 Color sextet and triplet diquarks

Now let us study if the color sextet or triplet diquarks are allowed. Some phenomenological studies of the color sextet and triplet scalars can be found in [38, 39, 50–58].

3.2.1 The $(\mathbf{6}, \mathbf{3}, 1/3)$ scalar

The sextet diquark $\eta_{(6,3)}$ with Yukawa couplings required to explain CDF W+dijet excess will lead to too large mixing in D^0-$\bar{D}^0$ and K^0-$\bar{K}^0$ in contradiction with data. From eq. (2.5) one can see that exchange of $\eta_{(6,3)}^{-4/3}$ at tree level can generate a mixing amplitude for D^0-$\bar{D}^0$ if $Y_{(6,3)}^{11}Y_{(6,3)}^{22} \neq 0$. The constraint is estimated as $Y_{(6,3)}^{11}Y_{(6,3)}^{22} \lesssim 10^{-7}(m_\eta^2/(150\,\mathrm{GeV}))^2$. Tree level mixing for $K^0 - \bar{K}^0$ is also generated by $\eta_{(6,3)}^{2/3}$ exchange. These mixing contributions can be eliminated by letting $Y_{(6,3)}^{22} = (V^T Y_{(6,3)} V)_{22} = 0$ by choosing $Y_{(6,3)}^{12} = Y_{(6,3)}^{11} \tan\theta_C/2$, where θ_C is a Cabibbo mixing angle. However, under the exact cancellation of the tree level contributions, the loop level contributions are too large. One then has to arrange cancellation between the tree and one loop contributions. This may represents a problem of fine tuning. Although this appears quite unnatural and harder to realize for building a model compared to the octet case, from purely phenomenological point of view it is not ruled out yet.

The other diquarks $\eta_{(6,1),(3,3),(3,1)}$ do not induce the tree-level meson-antimeson mixing, but can be generated at the 1-loop level through the box diagram.

3.2.2 The $(\mathbf{6}, \mathbf{1}, 1/3)$ scalar

Because the diquark $\eta_{(6,1)}$ is an $\mathrm{SU}(2)_L$ singlet and $Y_{(6,1)}^{ij}$ is anti-symmetric. The CDF W+dijet excess requires a large value of $Y_{(6,1)}^{12}$. For illustration, let us consider a simple case with $Y_{(6,1)}^{12} \neq 0$ and $Y_{(6,1)}^{23} = Y_{(6,1)}^{13} = 0$ in the $Q' = (V^\dagger U_L, D_L)$ basis:

$$-L = \frac{1}{2}\overline{Q_L'^c}Y_{(6,1)}\eta_{(6,1)}^a K^a Q_L' = Y_{(6,1)}^{12}(V_{i1}^*\overline{u_L^{i\,c}}\eta_{(6,1)}^a K^a s_L - V_{i2}^*\overline{u_L^{i\,c}}\eta_{(6,1)}^a K^a d_L). \quad (3.10)$$

The contribution to K^0-$\bar{K}^0$ mixing amplitude from $\eta_{(6,1)}$ is

$$M_{12}^K(\eta) = \frac{f_K^2 m_K}{48\pi^2 M_W^2}\left(\frac{(Y_{(6,1)}^{12})^2 g_2^2}{4}\hat{B}_1\left(-E_2 + \frac{1}{2}E_4\right) + \frac{15\hat{B}_4 + \hat{B}_5}{16}\left(\frac{m_K}{m_s + m_d}\right)^2\frac{(Y_{(6,1)}^{12})^4}{8}E_5\right). \quad (3.11)$$

For $Y_{(6,1)}^{12} = 1$ and $m_\eta = 150\,\mathrm{GeV}$ as required by the CDF W+dijet data, it gives twice that of the short distance SM contribution constructively, due to the enhancement factor $(m_K/(m_s + m_d))^2$. The coupling $Y_{(6,3)}^{12}$ can also cause an excess of strangeless charm decay, such as $D \to \pi\pi$. The interaction generates a strangeless charm decay operator,

$$-\frac{(Y_{(6,1)}^{12})^2 V_{cd}V_{ud}^*}{4m_\eta^2}\left[(\overline{u_L}^\alpha\gamma_\mu c_{\alpha L})(\overline{d_L}^\beta\gamma^\mu d_{\beta L}) + (\overline{u_L}^\alpha\gamma_\mu c_{\beta L})(\overline{d_L}^\beta\gamma^\mu d_{\alpha L})\right], \quad (3.12)$$

where we use

$$(K^a)_{\alpha\beta}(K^a)^{\delta\gamma} = \frac{1}{2}(\delta_\alpha^\gamma\delta_\beta^\delta + \delta_\alpha^\delta\delta_\beta^\gamma). \quad (3.13)$$

The contribution interfere with the standard model amplitude at 40% (including the color suppressed process) for $Y_{(6,3)}^{12} = 1$ and $m_\eta = 150\,\mathrm{GeV}$, which contradict with the experimental result of the branching ratio [47]: $\mathrm{Br}(D^+ \to \pi^+\pi^0) = (1.24 \pm 0.07) \times 10^{-3}$. We conclude that $\eta_{(6,1)}$ is problematic to explain the CDF W+dijets excess, though the quantities can be adjusted by choosing the possible couplings to right-handed quarks.

3.2.3 The $(\mathbf{3}, \mathbf{3}, -1/3)$ scalar

In the case of $\eta_{(3,3)}$, a similar analysis as in the previous section can be done by supposing $Y_{(3,3)}^{12} \neq 0$ and $Y_{(3,3)}^{23} = Y_{(3,3)}^{13} = 0$ in the $Q' = (V^\dagger U_L, D_L)$ basis. In this case, W-η box diagram for the K^0-$\bar{K}^0$ mixing vanishes due to the color anti-symetricity,

$$\epsilon_{\alpha\beta\gamma}\epsilon^{\rho\eta\gamma} = \delta_\alpha^\rho\delta_\beta^\eta - \delta_\alpha^\eta\delta_\beta^\rho, \quad (3.14)$$

and only η-η box diagram contributes. As a result we have:

$$M_{12}^K(\eta) = \frac{f_K^2 m_K}{48\pi^2 M_W^2}\left(+\frac{3\hat{B}_4 + \hat{B}_5}{4}\left(\frac{m_K}{m_s + m_d}\right)^2\frac{(Y_{(3,3)}^{12})^4}{32}E_5\right). \quad (3.15)$$

For $Y_{(3,3)}^{12} = 0.62$ and $m_\eta = 150\,\mathrm{GeV}$ which is chosen from the W+dijet excess, the box contribution is the same size of the short distance SM contribution. The coupling can also contribute to the strangeless charm decay width about 20%. While those quantities may be allowed within hadronic uncertainty, they nevertheless push this scenario to the allowed boundary.

	$(\mathbf{8}, \mathbf{2}, 1/2)$ with Y_{8u}	$(\mathbf{8}, \mathbf{2}, 1/2)$ with Y_{8d}	$(\mathbf{6}, \mathbf{3}, 1/3)$	$(\mathbf{6}, \mathbf{1}, 1/3)$	$(\mathbf{3}, \mathbf{1}, -1/3)$	$(\mathbf{3}, \mathbf{3}, -1/3)$
Flavor index	Arbitrary	Arbitrary	Symmetric	Anti-symmetric	Symmetric	Anti-symettric
CDF W+dijet	$Y_{8u}^{ij} = 0.13\delta^{ij}$	$Y_{8d}^{ij} = 0.19\delta^{ij}$	$Y^{11} = 0.32$	$Y^{12} = 1$	$Y^{11} = 0.5$	$Y^{12} = 0.62$
FCNC	OK	OK	Fine tuning	Problematic	OK	Boundary

Table 1. List of eligibility from the FCNC constraints of the couplings to explain the CDF W+dijets.

3.2.4 The $(\mathbf{3}, \mathbf{1}, -1/3)$ scalar

In the case of $\eta_{(3,1)}$ diquark, the diquark coupling is a symmetric matrix,

$$\frac{1}{2}\overline{Q_L^c}Y_{(3,1)}\eta_{(3,1)}Q_L = \overline{U_L^c}Y_{(3,1)}V\eta_{(3,1)}D_L. \tag{3.16}$$

The W-η box contribution also vanishes due to the color anti-symmetricity. The contribution to K^0-$\bar{K}^0$ mixing amplitude is

$$M_{12}^K(\eta) = \frac{f_K^2 m_K}{48\pi^2 m_\eta^2}\left(+\frac{3\hat{B}_4 + \hat{B}_5}{4}\left(\frac{m_K}{m_s + m_d}\right)^2 \frac{X_{ij}}{8}F(z_i, z_j, 1)\right), \tag{3.17}$$

where

$$X_{ij} = (Y_{(3,1)}V)_{i1}^*(Y_{(3,1)}V)_{i2}(Y_{(3,1)}V)_{j1}^*(Y_{(3,1)}V)_{j2}. \tag{3.18}$$

If we take $Y_{(3,1)} = y_{(3,1)}I$, $y_{(3,1)} = 0.5$ and $m_\eta = 150\,\text{GeV}$, the η contribution is twice as much as the short distance SM contribution. However, $Y_{(3,1)}$ is a symmetric matrix, and thus, one can choose $(Y_{(3,1)}V)_{12}$ and $(Y_{(3,1)}V)_{21}$ to be zero to eliminate the flavor changing process. (Under the choice, $(Y_{(3,1)}V)_{22} \simeq -(Y_{(3,1)}V)_{11}$.) Therefore, the mixing amplitudes can be consistent with experiments. There is no contribution to strangeless charm decay in this choice.

We note that the color triplet bosons, $\eta_{(3,1)}$ and $\eta_{(3,3)}$, can also have a leptoquark coupling $\overline{q_L^c}\ell\eta^*$ in general, and it causes a severe problem of inducing too rapid nucleon decays. One can avoid the rapid proton decays by introducing a symmetry [57–60], allowing a milder baryon number violating process, such as neutron-antineutron oscillations which can be tested at near future experiments [61].

We summarize the results in table 1 for the Yukawa couplings of the colored scalars and FCNC constraints. We conclude that there are scenarios which are consistent with FCNC data. Other ways of distinguishing these scenarios should be studied. In the next section, we will study possible signatures at the RICH and LHC.

4 Production of colored scalar at the RHIC and the LHC

In this section, we study some implications for the colored scalars which explain the CDF dijet excess at the RHIC and the LHC.

	$(\mathbf{8},\mathbf{2},1/2)$ with Y_{8u}	$(\mathbf{8},\mathbf{2},1/2)$ with Y_{8d}	$(\mathbf{6},\mathbf{3},1/3)$	$(\mathbf{6},\mathbf{1},1/3)$	$(\mathbf{3},\mathbf{1},-1/3)$	$(\mathbf{3},\mathbf{3},-1/3)$
RHIC inclusive [pb]	2.8	4.0	70	85	194	28
LHC $W+\eta$ [pb]	8.8	15	75	70	42	50
LHC $Z+\eta$ [pb]	0.8	1.5	3.0	23	13	8.6
Couple to $u_R d_R$	Forbidden	Forbidden	Forbidden	Allowed	Allowed	Forbidden

Table 2. List of the inclusive production cross sections at the RHIC and the W/Z boson associate production at the LHC. At the RHIC, the diquark couplings to right-handed quarks can be also tested.

Because the color sextet and triplet scalars can couple to di-quarks, pp colliders are suitable to search them from the resonance signal. Since the mass of the scalar is not large, the pp collider with low center of mass energy has an advantage to avoid huge QCD backgrounds, such as at the RHIC.

In hadroproduction of single heavy particle with the mass m, the mean value of the energy fraction of partons inside proton is $\langle x \rangle \sim \sqrt{\tau}$ where $\tau \equiv m^2/s$. For the production of η with $m_\eta = 150\,\text{GeV}$ at the RHIC with $\sqrt{s} = 500\,\text{GeV}$, one has $\langle x \rangle \sim 0.3$, thus we expect valence-valence quarks contribution brings large cross-section.

The diquark resonance signal can be observed as an excess in the inclusive dijet events around $m_{jj} \sim m_\eta$. We estimate the single diquark resonant production cross-section at the RHIC. The obtained cross-sections are listed in table 2. The diquark-type scalars has a large cross-section of several tens to hundreds pb. On the other hand, for the color-octet scalar case, the cross-section is only a few pb.

The main background comes from QCD processes which have broad dijet invariant-mass distributions. However, jets from the QCD processes have relatively large pseudo-rapidity and small transverse momentum distributions, selection cuts of, for example, $|\eta_j| < 0.5$ and $p_{T,j} > 50\,\text{GeV}$ can enhance the signal to background ratio.

For the $\eta_{(3,1)}$ case, it can give an excess to the dijet invariant-mass distribution by roughly $S/N \sim 1/5$. In figure 4, we plot the dijet invariant-mass distribution at the RHIC with $\sqrt{s} = 500\,\text{GeV}$, after selecting the two-jet events with the above pseudo-rapidity and transverse-momentum cuts for the jets. The QCD background is estimated by QCD $2\to2$ processes without K-factor correction. The number of the event is adjusted to the integrated luminosity of $L = 10\,\text{pb}^{-1}$, which is already collected in 2009. Since the accessible integrated luminosity at the RHIC is an order of hundreds pb^{-1}, it should be possible to distinguish the excess from the backgrounds even if one includes theoretical and experimental uncertainties.

The triplet diquark $\eta_{(3,1)}$ can couple with right-handed quarks by Yukawa-type interaction,

$$-L = \overline{U_R^c}^\alpha Y_r \eta_{(3,1)}^\beta D_R^\gamma \epsilon_{\alpha\beta\gamma} + h.c. \tag{4.1}$$

The coupling Y_r is generally independent from the couplings to the left-handed quarks.
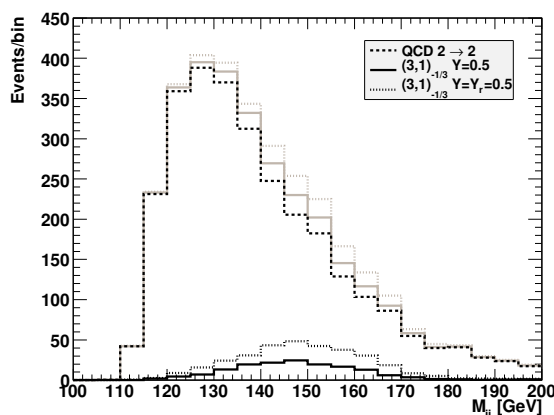
Figure 4. Dijet invariant-mass distribution at the RHIC, for the exactly two-jet events with $|\eta_j| < 0.5$ and $p_{T,j} > 50\,\text{GeV}$. $L = 10\,\text{pb}^{-1}$ of the integrated luminosity is assumed. Background event (dashed) is estimated by the $2{\to}2$ QCD processes without K-factor correction. Signal events in $\eta_{(3,1)}$ case are estimated without couplings to right-handed quarks (solid), and with couplings to right-handed quarks with $Y_r = 0.5$ (dotted).

Although the $W + \eta$ production cross-section is unchanged by the right-handed quark coupling, the single η production cross-section can be increased. In figure 4, we also show how the cross-section would change by introducing the coupling to right-handed quarks for $\eta_{(3,1)}$ case. Assuming the same size coupling $Y_r^{11} = Y_{(3,1)}^{11} = 0.5$ to the first generation quarks, $q_R q_R$ scatterings give the same size cross-section as the $q_L q_L$ scatterings, as easily expected.

Couplings to right-handed quarks are also possible for $(\mathbf{6}, \mathbf{1}, 1/3)$ case, but forbidden in color-octet, $(\mathbf{6}, \mathbf{3}, 1/3)$ and $(\mathbf{3}, \mathbf{3}, -1/3)$ cases. Note that $W + \eta$ production cross-section has no dependence on the couplings to the right-handed quarks, but $Z + \eta$ production cross-section has small dependence on the couplings to the right-handed quarks, because $Z q_R q_R$ couplings are smaller than the $Z q_L q_L$ couplings.

At the RHIC, using the polarization of the proton beam [62], it is possible to test the chiral structure of the diquark couplings to quarks. The partonic spin asymmetry, defined as

$$\hat{a} = \frac{\hat{\sigma}_{LL} - \hat{\sigma}_{RR}}{\hat{\sigma}_{LL} + \hat{\sigma}_{RR}}, \tag{4.2}$$

where the subscripts describe the parton's helicity (chirality), is found to be $\hat{a} = ((Y_{(3,1)}^{11})^2 - (Y_r^{11})^2)/((Y_{(3,1)}^{11})^2 + (Y_r^{11})^2)$ for the case we consider. Thus, it can probe the ratio of the left-handed coupling $Y_{(3,1)}^{11}$ which is fixed by the CDF W+dijet excess, and the right-handed coupling Y_r which is unknown yet. Using the knowledge of the polarized parton distribution functions of quarks in valence distribution regions, it is possible to extract the partonic spin asymmetry from the hadronic observables. However, the detailed study is beyond the scope of this paper.

At the LHC, $W+\eta$ or $Z+\eta$ process followed by $\eta \to jj$ decay can be the signal again. The production cross-sections at the LHC with $\sqrt{s} = 7\,\text{TeV}$ are also listed in table 2. The

expected major backgrounds are similar to those at the Tevatron; W/Z+jets, $t\bar{t}$ and single-top production. Detailed studies for the signal-to-background analysis at the LHC can be found in refs. [63–65], for example. The $W+\eta$ or $Z+\eta$ processes have large cross-sections as can be seen from table 2, especially for the diquark-type models. Following the study in ref. [65], by taking into account the QCD W+jets background, the $\ell\nu jj$ signal in the $\eta_{(3,1)}$ case can be seen with the signal-to-background ratio of ~ 0.12 for the events with $120 < M_{jj} < 160$ [GeV]. Assuming the total detection efficiency to be ~ 0.05, an expected integrated luminosity for the 5σ discovery is ~ 0.5 [fb^{-1}] in this case. For the color-octet scalar cases, the signal-to-background ratio is estimated to be ~ 0.03, therefore a better understanding of the background events is needed to find the signal.

5 Summary

We have studied the possibility of explaining the CDF W+dijet excess by introducing colored scalar η bosons. Being colored scalars, through coupling to two quarks, they naturally decay into dijet which provides one of the key feature of the W+dijet excess. There are several colored scalars, $(\mathbf{8}, \mathbf{2}, 1/2)$, $(\bar{\mathbf{6}}(\mathbf{3}), \mathbf{3}(\mathbf{1}), -1/3)$, $(\bar{\mathbf{6}}(\mathbf{3}), \mathbf{1}, -4/3(2/3))$, which can have tree level renormalizable Yukawa couplings with two quarks. Not all of them can successfully explain the W+dijet excess. Because the W+dijet excess requires a sizable coupling to the first generation of quarks compared to the Higgs couplings to them, the sizable couplings must also be consistent with other existing experimental data. We have analyzed FCNC constraints from meson-antimeson data. We find that without forcing of the Yukawa couplings to be some special texture forms most of the scalars, except the $(\mathbf{3}, \mathbf{3}, -1/3)$, are in trouble with FCNC data. We, however, find that the $(\mathbf{8}, \mathbf{2}, 1/2)$, $(\mathbf{6}, \mathbf{3}, 1/3)$ and $(\mathbf{3}, \mathbf{1}, -1/3)$ can be made consistent with all data.

While we confined our study to phenomenological implications of these colored particle, we note that a concrete realization of their coupling is harder to achieve. Even one finds a flavor symmetry to forbid certain entries of the Yukawa matrices, for example the off-diagonal entries of Y_{8u} for the octet, it is often the case that they are induced at loop level. In this sense, all the scenarios discussed here are to be considered as fine-tuned until a concrete realization is achieved.

The candidate of the color triplet scalar is an $\mathrm{SU}(2)_L$ singlet, and it also produces Z+dijet excess at about $1/4$ of the $ZZ + ZW$ process, which is not observed as a bump around $150\,\mathrm{GeV}$ yet. We also studied some predictions for the diquark signal at pp colliders, the RHIC and the LHC. If the CDF excess is the diquark origin, it may be confirmed at the early LHC study. The RHIC experiment can help to distinguish the diquarks.

Note added. After finishing this work, the CDF reported an updated analysis [66] using data collected through to November 2010 corresponding to an integrated luminosity of $7.3\,\mathrm{fb}^{-1}$. Their results are consistent with their early analysis [1] and increased the significance to 4.1σ. Recently D0 collaboration also reported their results of an analysis [67] with

an integrated luminosity of $4.3\,\text{fb}^{-1}$. They did not find similar W+diget excess. Although D0 was also looking at similar excess, the methodology differs in some way which may be potentially important cause for differences. We are not in a position to decide which one may be correct which has to be settled among the experimental groups. We think that a study of implications of the CDF results is still worthy. Our results are not altered by the new CDF data.

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