A Search for Vector Diquarks at the CERN LHC

E. Arik[a], O. Çakır[b], S. A. Çetin[a] and S. Sultansoy[c,d]

[a] *Bogazici University, Faculty of Sciences, Department of Physics, 80815, Bebek, Istanbul, Turkey*

[b] *Ankara University, Faculty of Sciences, Department of Physics, 06100 Tandogan, Ankara, Turkey*

[c] *Gazi University, Faculty of Arts and Sciences, Department of Physics, 06500, Teknikokullar, Ankara, Turkey*

[d] *Azerbaijan Academy of Sciences, Institute of Physics, H. Cavid av., 33, Baku, Azerbaijan*

Resonant production of the first generation vector diquarks at the CERN Large Hadron Collider (LHC) have been investigated. It is shown that the LHC will be able to discover vector diquarks with masses up to 9 (8) TeV if coupling $\alpha_D \simeq \alpha_s(\alpha_{em})$.

I. INTRODUCTION

The existence of at least three fermion families naturally leads to the hypothesis that they are made up of more fundamental constituents frequently called preons [1]. Today, the compositeness should be considered as a candidate for beyond the standard model (BSM) physics on the same footing as SUSY. Moreover, some assumptions made in order to get rid of huge number of free parameters in three family MSSM have natural explanation (see [2] and references therein) in the framework of preonic models. These models predict a rich spectrum of new particles with unusual quantum numbers at high energies such as excited quarks and leptons, diquarks, dileptons, leptoquarks, leptogluons, sextet quarks, octet bosons etc. In preonic models, diquarks are as natural as leptoquarks [3]. They are colored objects having integer-spin and baryon number $|B| = 2/3$. Diquarks are also predicted in the framework of superstring-inspired E_6 models [4].

Recent collider limits on the diquark masses come from Tevatron data which exclude the region $290 < M < 420$ GeV (for E_6 diquarks) [5]. Diquark production at e^+e^- colliders, ep colliders and $p\bar{p}$ colliders have been analyzed in [6], [7] and [8], respectively. Recently, the resonance production of scalar diquarks at CERN LHC has been studied in [9].

In this work, the sensitivity of LHC to composite vector diquark production is estimated. In section II, interaction lagrangian and quantum numbers of diquarks are discussed. Decay width and production cross section of a vector diquark at the CERN LHC are considered in section III. Then, in section IV, vector diquark signal and corresponding backgrounds are analyzed. Finally, in section V we give some conclusions and remarks.

II. INTERACTION LAGRANGIAN AND CLASSIFICATION

A model independent, most general, effective $SU(3)_C \times SU(2)_W \times U(1)_Y$ invariant lagrangian for diquarks has the form [9]:

$$L = g_{1L}\bar{q}^c_L i\tau_2 q_L D^c_1 + g_{1R}\bar{u}^c_R d_R D^c_1 + \tilde{g}_{1R}\bar{d}^c_R d_R \tilde{D}^c_1 + \tilde{g}'_{1R}\bar{u}^c_R u_R \tilde{D}'^c_1 + g_{3L}\bar{q}^c_L i\tau_2 \vec{\tau} q_L . \vec{D}^c_3$$

$$+ g_2 D^{cT}_{2\mu}\bar{d}^c_R i\tau_2\gamma^\mu q_L + \tilde{g}_2 \tilde{D}^{cT}_{2\mu}\bar{u}^c_R i\tau_2\gamma^\mu q_L + h.c. \quad (1)$$

where $q_L = (u_L, d_L)$ and $q^c = C\bar{q}^T$ ($\bar{q}^c = -q^T C^{-1}$). For the sake of simplicity, color and generation indices are ommitted. Scalar diquarks D_1, $\tilde{D}_1$, $\tilde{D}'_1$ are $SU(2)_W$ singlets and $\vec{D}_3$ is $SU(2)_W$ triplet. Vector diquarks D_2 and $\tilde{D}_2$ are $SU(2)_W$ doublets. Diquarks may transform as anti-triplet or sextet under $SU(3)_C$. At this stage, we assume each SM generation has its own diquarks and couplings in order to avoid restrictions imposed by Δm_K etc.

Lagrangian (1) can be rewritten in the following more transparent form:

$$L = L_S + L_V \tag{2}$$

$$L_S = \left[g_{1L}\left(\bar{u}^c P_L d - \bar{d}^c P_L u\right) + g_{1R}\bar{u}^c P_R d\right] D_1 + \tilde{g}_{1R}\bar{d}^c P_R d\tilde{D}_1 + \tilde{g}'_{1R}\bar{u}^c P_R u\tilde{D}'_1 + \sqrt{2}g_{3L}\bar{u}^c P_L u D_3^+ - \sqrt{2}g_{3L}\bar{d}^c P_L d D_3^- - g_{3L}\left(\bar{u}^c P_L d + \bar{d}^c P_L u\right) D_3^0 + h.c. \tag{3}$$

$$L_V = g_2\bar{d}^c\gamma^\mu P_L d D^1_{2\mu} - g_2\bar{d}^c\gamma^\mu P_L u D^2_{2\mu} + \tilde{g}_2\bar{u}^c\gamma^\mu P_L d\tilde{D}^1_{2\mu} - \tilde{g}_2\bar{u}^c\gamma^\mu P_L u\tilde{D}^2_{2\mu} + h.c. \tag{4}$$

where $P_L = (1-\gamma_5)/2$ and $P_R = (1+\gamma_5)/2$. A general classification of the first generation, color $\bar{\mathbf{3}}$ diquarks is shown in Table I.

III. DECAY WIDTH AND PRODUCTION CROSS SECTION

For the present analysis, we will take into account the color $\bar{\mathbf{3}}$ vector diquark D_2 which couples to ud-pair as described by the effective lagrangian (4). The decay width Γ_D, derived from the same lagrangian, is

$$\Gamma_D = C_F\frac{g_2^2 M_D}{24\pi} \tag{5}$$

where C_F is the color factor for triplet representation and M_D is the mass of vector diquark. We will use the definition $g_2^2 = 4\pi\alpha_D$ for numerical calculations:

$$\Gamma_D = C_F\frac{\alpha_D M_D}{6} \simeq 17\,GeV(\frac{C_F M_D}{1\,TeV}) \quad \text{for} \;\; \alpha_D = 0.1 \simeq \alpha_s \tag{6}$$

$$\simeq 1.3\,GeV(\frac{C_F M_D}{1\,TeV}) \quad \text{for} \;\; \alpha_D \simeq \alpha_{em} \quad . \tag{7}$$

In the narrow width approximation ($\Gamma/M < 0.1$), the cross section of the s-channel diquark resonance production can be obtained as

$$\sigma(pp \to D_2 X) = \sum_{ab}\frac{C_F^2\alpha_D\pi^2}{s}\int_{M_D^2/s}^1\frac{dx}{x}f_a(x,\hat{s})f_b(\frac{M_D^2}{sx},\hat{s}) \tag{8}$$

where $\hat{s} = x_a x_b s$, f_a and f_b are quark distribution functions of each proton. In Fig. 1, using the CTEQ5L quark distribution functions [10], the cross section versus diquark mass is plotted for coupling $\alpha_D = \alpha_s$ and $\alpha_D = \alpha_{em}$ at the LHC energy ($\sqrt{s} = 14$ TeV).

IV. SIGNAL AND BACKGROUND

D_2-type diquark resonance in s-channel will be formed via the subprocess $u + d \to D_2 \to u + d$. Therefore, the signal will contain two hard jets in the final state. Considering only the interference with the t-channel gluon exchange, the following differential cross section is obtained:

$$\frac{d\hat{\sigma}}{d\hat{t}}(q_i q_j \to q_i q_j) = C_F^2\pi[\frac{\alpha_D^2(\hat{s}+\hat{t})^2}{\hat{s}^2[(\hat{s}-M_D^2)^2 + M_D^2\Gamma_D^2]} + \frac{2\alpha_s^2}{\hat{s}^2}\frac{(2\hat{s}^2+\hat{t}^2+2\hat{s}\hat{t})}{\hat{t}^2} - \frac{2\alpha_D\alpha_s}{\hat{t}}\frac{(\hat{s}+\hat{t})^2(\hat{s}-M_D^2)}{\hat{s}^2[(\hat{s}-M_D^2)^2+M_D^2\Gamma_D^2]}] \quad . \tag{9}$$

At the LHC, QCD processes contributing to two jet final states and their integrated cross sections are given in Table II. The values in Table II have been generated by PYTHIA 6.1 [11] at parton level with various p_T cuts.

The cross section as a function of the dijet invariant mass M_{jj} with the rapidity cut $|y_{1,2}| \le Y$, where y_1 and y_2 are rapidities of the massless final quarks, is given by

$$\frac{d\sigma}{dM_{jj}} = \frac{M_{jj}^3}{2s}\int_{-Y}^{Y} dy_2 \int_{y_1^{\min}}^{y_1^{\max}} dy_1 \; \frac{1}{\cosh^2 y^\star} \tag{10}$$
$$\times[f_{u/A}(x_u,Q^2) f_{d/B}(x_d,Q^2)\frac{d\hat{\sigma}}{d\hat{t}}(\hat{s},\hat{t},\hat{u})$$
$$+ f_{d/A}(x_d,Q^2) f_{u/B}(x_u,Q^2)\frac{d\hat{\sigma}}{d\hat{t}}(\hat{s},\hat{u},\hat{t})]$$

with

$$y^\star = (y_1 - y_2)/2, \qquad y^b = (y_1 + y_2)/2$$
$$x_u = \sqrt{\tau} e^{y^b}, \qquad x_d = \sqrt{\tau} e^{-y^b}$$
$$\hat{s} = x_u x_d s, \qquad \hat{t} = -x_u p_T \sqrt{s} e^{-y_1}, \qquad \hat{u} = -x_d p_T \sqrt{s} e^{y_1}$$
$$y_1^{\min} = \max(-Y, \log\tau - y_2), \qquad y_1^{\max} = \min(Y, -\log\tau - y_2), \qquad \tau = M_{jj}^2/s \quad .$$

Fig. 2 shows jet-jet invariant mass distribution for the process $pp \to D_2 \to jjX$ together with the estimation of the QCD background at the LHC. For comparison, signal peaks for vector diquark masses $M_D = 2, 4, 6, 8$ TeV and $\alpha_D = 0.1$ are superimposed on the background distribution.

We have estimated signal and background events for an integrated LHC luminosity of 10^5 pb^{-1} taking into account, as an example, the energy resolution of ATLAS hadronic calorimeter [12]:

$$\frac{\delta E}{E} = \frac{50\%}{\sqrt{E}} + 3\% \tag{11}$$

for jets with $|y| < 3$. The mass resolution can be expressed as [9]

$$\frac{\Delta M_{jj}}{M_{jj}} \approx \frac{\delta E}{\sqrt{2}E} \quad . \tag{12}$$

We have chosen $2\Delta M_{jj}$ as the mass window centered at M_{jj} for signal and background estimations.

Number of signal (S), background (B) events and the corresponding significances for $\alpha_D = 0.1$ are tabulated in Table III. Evidently, tighter cut on the rapidity y improves the significance considerably. In Table IV, we present the achievable mass limits for different values of α_D. As discovery criteria, we adopt $S/\sqrt{B} \geq 5$ and $S \geq 25$.

V. CONCLUSIONS

The example of D_2 shows that the resonance production of vector diquarks at the LHC has large cross section. With reasonable cuts, it may be possible to cover the region up to 9 TeV. The LHC potential for the discovery of D_2 is clearly demonstrated in Fig. 3 where minimum integrated luminosities, needed to satisfy the adopted criteria, are plotted as a function of M_D for various α_D values.

VI. REFERENCES

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TABLE I. Quantum numbers of the first generation, color $\bar{3}$ diquarks described by the effective lagrangian given in the text according to $SU(3)_C \times SU(2)_W \times U(1)_Y$ invariance. $Q_{em} = I_3 + Y/2$

Scalar Diquarks	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	Q	Couplings
D_1	$3^\star$	1	2/3	1/3	$u_L d_L(g_{1L})$, $u_R d_R(g_{1R})$
$\tilde{D}_1$	$3^\star$	1	-4/3	4/3	$d_R d_R(\tilde{g}_{1R})$
$\tilde{D}_1'$	$3^\star$	1	8/3	-2/3	$u_R u_R(\tilde{g}_{1R}')$
D_3	$3^\star$	3	2/3	$\begin{pmatrix} 4/3 \\ 1/3 \\ -2/3 \end{pmatrix}$	$\begin{pmatrix} u_L u_L(\sqrt{2}g_{3L}) \\ u_L d_L(-g_{3L}) \\ d_L d_L(-\sqrt{2}g_{3L}) \end{pmatrix}$
Vector Diquarks					
$D_{2\mu}$	$3^\star$	2	-1/3	$\begin{pmatrix} 4/3 \\ 1/3 \end{pmatrix}$	$\begin{pmatrix} d_R d_L(g_2) \\ d_R u_L(-g_2) \end{pmatrix}$
$\tilde{D}_{2\mu}$	$3^\star$	2	5/3	$\begin{pmatrix} 4/3 \\ 1/3 \end{pmatrix}$	$\begin{pmatrix} u_R d_L(\tilde{g}_2) \\ u_R u_L(-\tilde{g}_2) \end{pmatrix}$

TABLE II. Cross sections (pb) for QCD backgrounds contributing to j-j final states at parton level generated by PYTHIA 6.1 with various cuts.

Process	$p_T > 100$ GeV	$p_T > 500$ GeV	$p_T > 1000$ GeV	$p_T > 1500$ GeV	$p_T > 2000$ GeV
$gg \to gg$	6.3×10^{5}	2.0×10^{2}	2.3×10^{0}	8.6×10^{-2}	5.7×10^{-3}
$q_i g \to q_i g$	6.4×10^{5}	4.8×10^{2}	1.0×10^{1}	6.4×10^{-1}	5.7×10^{-2}
$q_i q_j \to q_i q_j$	1.0×10^{5}	1.8×10^{2}	6.7×10^{0}	6.3×10^{-1}	8.8×10^{-2}
$gg \to q_k \bar{q}_k$	2.4×10^{4}	9.8×10^{0}	1.0×10^{-1}	4.9×10^{-3}	2.9×10^{-4}
$q_i \bar{q}_i \to q_k \bar{q}_k$	1.6×10^{3}	2.8×10^{0}	1.3×10^{-1}	9.0×10^{-3}	1.1×10^{-3}
$q_i \bar{q}_i \to gg$	1.5×10^{3}	2.5×10^{0}	6.7×10^{-2}	8.1×10^{-3}	8.5×10^{-4}
Total	1.4×10^{6}	8.8×10^{2}	1.9×10^{1}	1.4×10^{0}	1.5×10^{-1}

TABLE III. Observability of the vector diquark D_2 with $\alpha_D = 0.1$ at LHC for $L_{int} = 10^5 \text{pb}^{-1}$.

M_D (TeV)	1	2	3	4	5	6	7	8	9
$\|y\| < 2$									
S	7.7×10^{7}	6.6×10^{6}	1.1×10^{6}	2.4×10^{5}	5.0×10^{4}	9.9×10^{3}	1.7×10^{3}	2.5×10^{2}	2.7×10^{1}
B	2.8×10^{8}	5.6×10^{6}	4.2×10^{5}	5.4×10^{4}	8.4×10^{3}	1.4×10^{3}	2.2×10^{2}	3.0×10^{1}	3.1×10^{0}
$S/\sqrt{B}$	4585	2787	1768	1027	545	266	118	46	16
$\|y\| < 1$									
S	2.6×10^{7}	2.8×10^{6}	5.8×10^{5}	1.3×10^{5}	2.9×10^{4}	6.1×10^{3}	1.1×10^{3}	1.6×10^{2}	1.8×10^{1}
B	2.5×10^{7}	5.2×10^{5}	4.0×10^{4}	5.0×10^{3}	7.9×10^{2}	1.3×10^{2}	2.1×10^{1}	2.8×10^{0}	3.0×10^{-1}
$S/\sqrt{B}$	5213	3946	2889	1842	1044	534	245	99	34

TABLE IV. Achievable diquark mass limits for different diquark-quark-quark couplings in the framework of discovery criteria given in the text. The rapidity cut $|y| < 2$ is applied.

α_D	M_D(TeV)	S	B	$S/\sqrt{B}$
0.1	9	27	3.1	16.0
0.01	8	25	30	4.6
0.001	5	500	8400	5.4
0.0005	4	1200	540006	5.1

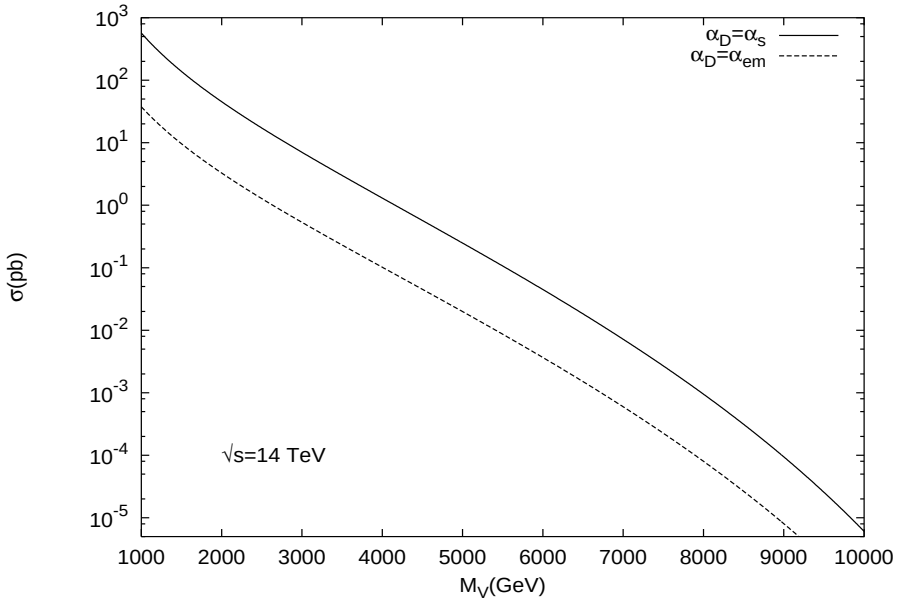

FIG. 1. Integrated cross section versus diquark mass for coupling strength $\alpha_D = \alpha_s$ and $\alpha_D = \alpha_{em}$.

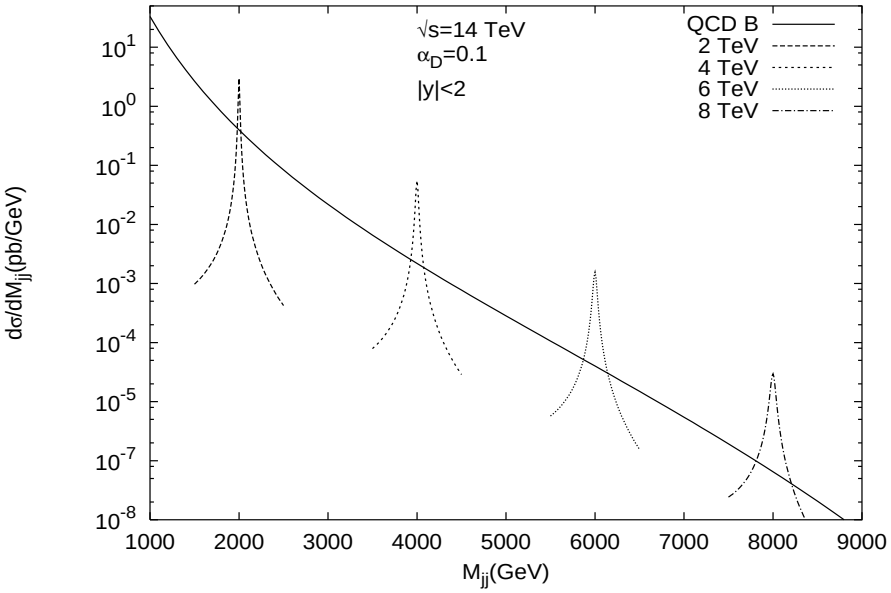

FIG. 2. Dijet invariant mass distribution for $M_D = 2, 4, 6, 8$ TeV superimposed over the QCD background.

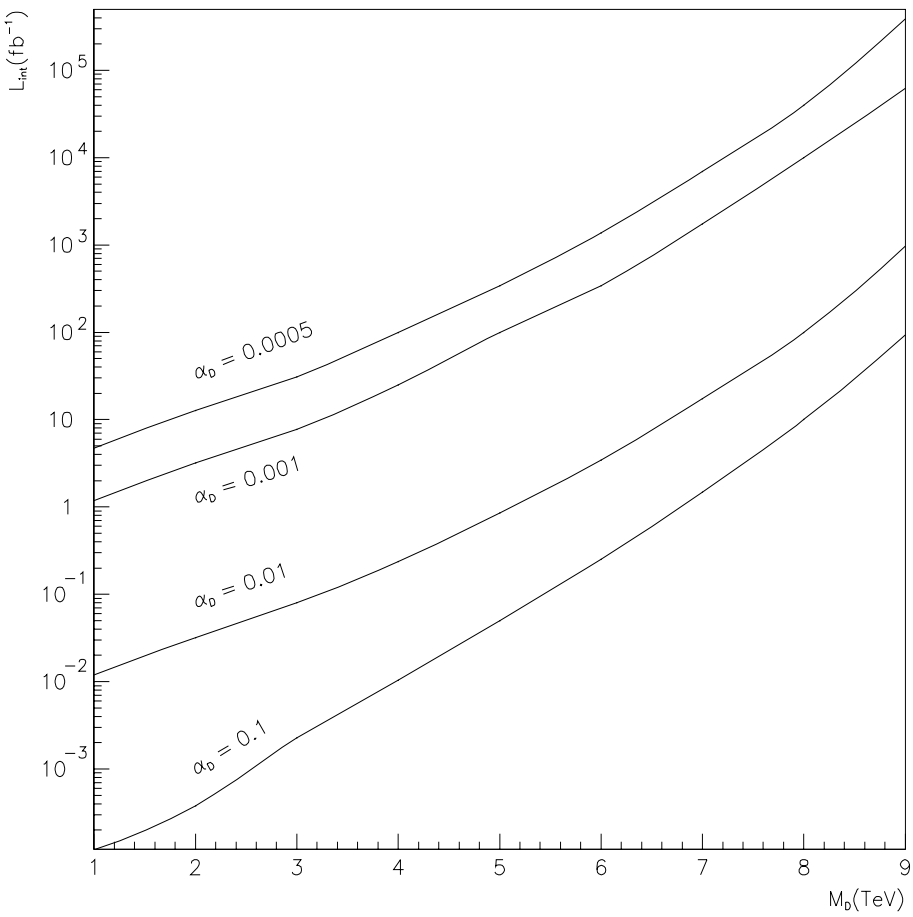

FIG. 3. The minimum integrated luminosities, needed to satisfy the adopted discovery criteria, as a function of M_D for various α_D values.