The CDF dijet excess and

$Z'_c$ coupled to the second generation quarks

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Abstract

Recently the CDF collaboration has reported the excess in the dijet invariant-mass distribution of the $Wjj$ events, corresponding to a significance of 3.2 standard deviations. Considering the lack of similar excesses in the $\gamma jj$ and $Zjj$ events yet, we propose a new $Z'_c$ model: $Z'_c$ couples only to the second generation quarks. Single production of $Z'_c$ as well as associated production with $W, \gamma, Z$ are mainly from the sea quarks. Only $WZ'_c$ production has additional contribution from one valence quark and one sea quark, which is allowed by CKM mixing. We found that if the new gauge coupling is large enough, marginally permitted by perturbativity, this new model can explain the observed CDF $Wjj$ anomaly as well as the lack of $\gamma jj$ and $Zjj$ anomalies. Vanishing coupling of $Z'_c$-$b$-$\bar{b}$ protects this model from the constraint of $p\bar{p} \to WH \to \ell\nu b\bar{b}$.

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Recently the CDF collaboration has reported the excess in the dijet invariant-mass distribution associated with a \(W\) boson, using 4.3 \(fb^{-1}\) data at the Tevatron [1]. Such a disagreement with the standard model (SM) prediction to the 3.2 \(\sigma\) significance can be accommodated by adding a resonant excess in the 120 – 160 GeV mass region, which suggests a possibility of a new particle beyond the SM. According to the CDF fit result, the Gaussian peak of the resonance is around 145 GeV. The number of excess events are 156 ± 42 for the electron and 97 ± 38 for the muon, where the leptons come from \(W\) decays. With the number of observed excess, the production cross section multiplied by the particle branching ratio into dijets is estimated to be of the order of 4 pb. A few new physics models beyond the SM have been suggested to explain this CDF \(Wjj\) anomaly, including leptophobic \(Z'\) boson [2–5], supersymmetry with R-parity violation [6], technicolor [7], color octet boson [8], a flavor symmetry [9] and nucleon intrinsic quark [10]. Among these, models with leptophobic \(Z'\) boson [2–5] are the most explored in a short time period. There are some claims that this anomaly can be explained within the SM [11].

In order to probe the nature of the new physics, we have to consider more phenomenological hints in addition to the CDF \(Wjj\) anomaly. First, it is not likely that the resonant excess is due to the Higgs boson production in and beyond the SM. The estimated \(\sigma \times Br(jj)\) of the excess is much larger than that of the \(WH\) production of 12 fb in the SM for \(m_H = 150\) GeV. Moreover the CDF searches for \(\ell \nu b\bar{b}\) final states have found no significant excess in this mass region. Second, the light \(Z'\) model is to be leptophobic. The LEP and Tevatron dilepton searches provided a very strong constraint on the \(Z'\) boson mass. Third, the single production of this leptophobic \(Z'\) is constrained to some extent, which is subject to the two jet searches at the Tevatron [13] and UA2 experiment at \(Sp\bar{p}S\) [14]. In the mass region of \(m_{Z'} < 200\) GeV, the Tevatron two jet searches are not relevant because of overwhelming QCD background. The UA2 constraints are most important. To evade the UA2 constraints, couplings of \(Z'\) should be \(g_{uuZ'} < 0.4\) and \(g_{ddZ'} < 0.4\) for \(m_{Z'} \sim 150\) GeV [3].

The final hint comes from other associated productions of \(Zjj\) and \(\gamma jj\). Most leptophobic \(Z'\) models assume the universal couplings with all generation quarks. Similar excesses in the dijet invariant-mass (\(M_{jj}\)) distribution of the \(Zjj\) and \(\gamma jj\) events are expected as in the \(Wjj\) channel. Due to the smallness of couplings, \(Zjj\) and \(\gamma jj\) production cross sections are smaller than that of \(Wjj\). Moreover small leptonic branching ratio of \(Z\) boson suppresses the signal more as we identify the \(Z\) boson by leptonic decays: it is not promising to find the
excess at the $ZZ' \rightarrow Zjj$ channel. Instead the $\gamma Z' \rightarrow \gamma jj$ signal at the Tevatron should be observed if the $Wjj$ anomaly is explained solely by the universal leptophobic $Z'$ model [2]. At present, however, no significant indication of new physics has been found in $\gamma jj$ channel using 4.8 fb$^{-1}$ data of CDF at the Tevatron [15]. It might be a shortcoming of the universal leptophobic $Z'$ explanation for the CDF excess.

Summarizing the phenomenological signatures, we need a new resonance to explain the following features: (i) the excess of $Wjj$ events in the dijet invariant-mass range of 120 – 160 GeV; (ii) suppressed single production of the new resonance; (iii) very suppressed decays into leptons; (iv) no significant excess in the $\ell\nu b\bar{b}$ mode at the Tevatron; (v) not statistically significant excess of $\gamma jj$ events.

It is very likely that this CDF $Wjj$ anomaly is closely related with the SM $W$ boson. We notice that the SM $W$ is the only gauge boson which mediates flavor-changing current at tree level. Based on these observations, we propose a rather bold new physics model of $Z'$: the $Z'$ couples only to the second generation quarks. We denote this by $Z'_{cs}$ for the discrimination from the usual leptophobic $Z'$ with universal couplings to all generation quarks. This $Z'_{cs}$ model definitely introduces new flavor violation. Recently the possibility of new flavor violation was shown in the CDF observation of a large forward-backward asymmetry in $t\bar{t}$ production $A^t_{FB}$ [16] as well as the D0 measurement of the like-sign dimuon charge asymmetry [17]. B physics also constrains quite significantly a flavor symmetric model which can explain the CDF $Wjj$ anomaly as well as $A^t_{FB}$ [18]. One of the model classes to explain this new flavor violation is to introduce the flavor violating couplings of the SM quarks to new gauge bosons [19].

Phenomenological consequences of our model are as follows. First the $s$-channel single production of $Z'_{cs}$ at $p\bar{p}$ collisions is only through sea quarks, which is suppressed by small
We have assumed that $Z'_{cs}$ has the couplings only to the left-handed second generation quarks. This left-handed coupling maximizes the $WZ'_{cs}$ production while minimizing the $\gamma Z'_{cs}$ production \[12].

The cross section is given by

$$\sigma(p\bar{p} \to W^\pm Z'_{cs}) = \int dx_a dx_b f_{q/p}(x_a) f_{q'/\bar{p}}(x_b) \sum_{q,q'} \hat{\sigma}(qq' \to W^\pm Z'_{cs}),$$

(2)

where the parton level cross section for $W^+ Z'_{cs}$ production is

$$\sum_{q,q'} \hat{\sigma}(qq' \to W^+ Z'_{cs}) = \hat{\sigma}(u\bar{s} \to W^+ Z'_{cs}) + \hat{\sigma}(d\bar{c} \to W^+ Z'_{cs}) + \hat{\sigma}(c\bar{s} \to W^+ Z'_{cs}).$$

(3)
FIG. 3. As functions of the new resonance mass, the ratios of $\sigma(p\bar{p} \to \gamma Z')/\sigma(p\bar{p} \to WZ')$ and $\sigma(p\bar{p} \to Z'Z)/\sigma(p\bar{p} \to WZ')$ in our $Z'_{cs}$ model and in the universally baryonic $Z'$ model [2], at the Tevatron ($\sqrt{s} = 1.96$ TeV). On the final state photon, we have imposed the acceptance of $p_T^\gamma > 50$ GeV and $|\eta^\gamma| < 1.1$.

Similar processes can be written for $W^-Z'_{cs}$ production. The production channels of $u\bar{s}$ and $\bar{d}c$, as illustrated in Fig. 1, is mediated by one Feynman diagram. It has the suppressstion of the quark mixing $|V_{us}|^2$ and the PDF of one sea quark. Flavor-conserving channel of $c\bar{s}$ as in Fig. 2 has no quark mixing suppression, but additional sea quark PDF suppression.

In the Tevatron $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, we have

$$\sigma(p\bar{p} \to W^\pm Z'_{cs}) \simeq K \left(g_{cs}\right)^2 \times 0.3 \text{ pb}, \text{ for } M_{Z'_{cs}} = 145 \text{ GeV}. \quad (4)$$

Note that $\text{Br}(Z'_{cs} \to jj) = 100$% in this model. We have used the PDF of MRST [21]. With the $K$-factor of $K = 1.34$ [22], the observed $WZ'$ cross section of about 4 pb is explained by $g_{cs} \approx 3.2$. This value of $g_{cs}$ marginally satisfies the perturbativity condition of $g_{cs}^2 < 4\pi$. This large gauge coupling is attributed to small PDF of a sea quark as well as the small quark mixing angle.

Despite unpleasant largeness of the new gauge coupling $g_{cs}$, our model has attractive features of suppressed $\gamma jj$ and $\ell \nu b\bar{b}$ signatures at the Tevatron. In Fig. 3 we compare the ratios of $\sigma(p\bar{p} \to \gamma Z')/\sigma(p\bar{p} \to WZ')$ and $\sigma(p\bar{p} \to Z'Z)/\sigma(p\bar{p} \to WZ')$ in our $Z'_{cs}$ model and in the universally baryonic $Z'$ model [2]. (Note that $\sigma(WZ'_{(cs)})$ is fixed to be $\sim 4$ pb.)
For the photon acceptance we set \( p_T^\gamma > 50 \) GeV and \(|\eta^\gamma| < 1.1\). As shown in Fig. 3, \( ZZ' \) production cross sections with respect to the \( WZ' \) production are almost the same in the universally baryonic \( Z' \) model and our \( Z'_{cs} \) model. The \( ZZ' \rightarrow Zjj \) signal is a less sensitive probe because of small leptonic branching ratios of \( Z \). Instead \( \gamma Z' \) production in our model is about half of that in the universal \( Z' \) model.

These behaviors are understood as follows. In the universal \( Z' \) model, the main production channels of \( \gamma Z'_{cs} \) are through the valence quarks of \( u\bar{u} \) and \( d\bar{d} \). In a proton, the valence component of up quark with electric charge \(+2/3\) is twice of that of down quark with electric charge \(-1/3\), while the sea component of the \( c \) quark is almost the same as that of the \( s \) quark: the photon production from the valence quarks has larger coupling strength than that from the sea quarks. On the contrary, the \( Z \) coupling to the left-handed quarks, which is relevant in the associated production with the left-handed \( Z'_{cs} \) couplings in Eq. (1), has similar magnitudes for the up-type and down-type quarks.

Considering the lack of statistically significant excess of \( \gamma jj \) yet, the reduced \( \gamma Z'_{cs} \) production in our model compared to the universal \( Z' \) model can be one attractive merit. Nevertheless the reduction of \( \gamma Z'_{cs} \) is not that large: large enough luminosity at the Tevatron will probe this \( \gamma jj \) excess in the very near future. At the LHC energy, the sea quark contributions are larger. We expect that this \( \gamma jj \) process is more sensitive probe at the LHC.

In order to explain the recent CDF excess of the \( Wjj \) events in the dijet invariant-mass distribution as well as the (possible) lack of the excesses in the \( \gamma jj \) and \( Zjj \) events, we proposed a new \( Z'_{cs} \) model where the new gauge boson couples only to the second generation quarks. The CKM quark mixing allows more associated production with a \( W \) boson, while suppressing the single production of \( Z'_{cs} \), and the associated production of \( \gamma Z'_{cs} \) and \( ZZ'_{cs} \). If the new gauge coupling is large enough, marginally permitted in a perturbative theory, this new model can explain the observed CDF \( Wjj \) anomaly. Vanishing coupling \( Z'_{cs} \) with the \( b \) quarks protects this model from the constraint of the CDF and D0 searches for \( WH \rightarrow \ell\nu b\bar{b} \).

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