Baryonic $Z'$ Explanation for the CDF $Wjj$ Excess

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The latest CDF anomaly, the excess of dijet events in the invariant-mass window 120 – 160 GeV in associated production with a $W$ boson, can be explained by a baryonic $Z'$ model in which the $Z'$ boson has negligible couplings to leptons. Although this $Z'$ model is hardly subject to the Drell-Yan constraint from Tevatron, it is constrained by the dijet data from UA2 ($\sqrt{s} = 630$ GeV), and the precision measurements at LEP through the mixing with the SM $Z$ boson. We show that under these constraints this model can still explain the excess in the $M_{jj} \sim 120 – 160$ GeV window, as well as the claimed cross section $\sigma(WZ') \sim 4$ pb. Implications at the Tevatron would be the associated production of $\gamma Z'$, $ZZ'$, and $Z'Z'$ with the $Z' \rightarrow jj$. We show that with tightened jet cuts and improved systematic uncertainties both $\gamma Z' \rightarrow \gamma jj$ and $ZZ' \rightarrow \ell^+\ell^- jj$ channels could be useful to probe this model at the Tevatron.

Introduction.— The year 2011 is perhaps the last year of running for the Tevatron, which is subject to a severe budget cut. Hopefully, the recent surprises$^{1,2}$ from the Tevatron can reverse its fate. The latest surprise is an excess in the invariant-mass window 120 – 160 GeV in the dijet system of the associated production of a $W$ boson with 2 jets$^2$. We shall denote it by $Wjj$ production. The excess in the window $M_{jj} \sim 120 – 160$ GeV appears to be a resonance, but the current resolution$^2$ cannot tell whether it is a narrow resonance. From the distribution we can naively see that the width of the resonance appears to be slightly wider than the SM $Z$ boson.

In this Letter, we propose a baryonic $Z'$ model to explain the anomaly. The reason for being baryonic is that even if this $Z'$ has a small leptonic branching ratio, even $O(1)\%$, it would suffer from strong constraints of the Tevatron $Z'$ search in the dilepton mode$^3$. The $Z'$ boson model was proposed by Barger, Cheung, and Langacker in 1996$^4$ in light of the $R_b/R_c$ crisis of the LEP precision measurements at that time$^5$: $R_b = \Gamma(Z \rightarrow bb)/\Gamma(Z \rightarrow \text{hadrons})$ deviated by 3.7$\sigma$ while $R_c$ deviated by $-2.4$ from the SM. Through some adjustment of the mixing angle and vector and axial-vector couplings the $R_b/R_c$ crisis can be solved (the most current data do not show any more of the problem$^6$). Such a $Z'$ interpretation at that time had suggested strong implications at the Tevatron$^4$ via s-channel $Z'$ production and the pair production processes ($WZ', \gamma Z'$) with $Z' \rightarrow jj$ (in particular $bb$), with invariant mass $M_{jj}$ peaked at $M_{Z'}$. The s-channel $Z'$ production is buried under the QCD background, but the associated production with a $W$ boson has a good chance to appear. The current CDF anomaly$^2$ may be of this origin.

Additional $Z'$ bosons can appear in many extensions of the SM with extra $U(1)'s$$^7$. The most famous example is $E_6$, in which there are a number of extra neutral gauge bosons. A baryonic $Z'$ can arise from a gauge symmetry generated by the baryon number $U(1)_B$ as an interesting possibility$^8$, since this avoids potential problems associated with the breaking of global baryon number by quantum gravity effects (e.g., an unacceptable proton decay rate in supersymmetric theories). Another possibility is kinetic mixing of the two $U(1)'s$$^9$ to suppress the leptonic couplings. Here we assume that the model can be embedded in an anomaly-free theory.

In this work, we use the baryonic $Z'$ model with $M_{Z'} \sim 145$ GeV to explain the excess of events in the invariant-mass window of $M_{jj} \sim 120 – 160$ GeV in $Wjj$ production. The $Z'$ boson has negligible couplings to leptons, and so is not affected by the dilepton $Z'$ constraints. However, it is constrained by the dijet searches at hadronic colliders. We found that all the dijet searches by CDF$^{10}$ focused on the mass region $M_{jj} > 200$ GeV, and so the $Z'$ with $M_{Z'} \sim 145$ GeV is not subject to these searches. On the other hand, some old data from UA2 ($\sqrt{s} = 630$ GeV)$^{11}$ had better measurements in $M_{jj} = 100 – 200$ GeV. We use the constraint on the coupling of the $Z'$ obtained in Ref.$^3$. Furthermore, the precision measurements at LEP also constrained the mixing with the SM $Z$ boson to be small $\lesssim 10^{-3}$. We show that under these constraints this model can still explain the excess in the $M_{jj} \sim 120 – 160$ GeV window, as well as the claimed cross section $\sigma(WZ') \sim 4$ pb. This is the main result of this work. Further implications at the Tevatron would be the associated production of $\gamma Z'$, $ZZ'$, and $Z'Z'$ with the $Z' \rightarrow jj$. We show that it is hard to see the excess in both $\gamma Z' \rightarrow \gamma jj$ and $ZZ' \rightarrow \ell^+\ell^- jj$ channels under the current level of systematic uncertainties and jet cuts. However, with tightened jet cuts and improved systematic uncertainties it could be promising to test the model in these two channels.

The interactions.— Following Ref.$^{12}$, the Lagrangian describing the neutral current gauge interactions of the standard electroweak $SU(2) \times U(1)$ and extra $U(1)'s$ is
given by
\[ -\mathcal{L}_{NC} = e J^\mu_{em} \alpha_\mu + \sum_{\alpha=1}^{n} g_\alpha J^\mu_\alpha Z^0_{\alpha} \] 
where \( Z^0_\alpha \) is the SM Z boson and \( Z^0_\alpha \) with \( \alpha \geq 2 \) are the extra Z bosons in the weak-eigenstate basis. For the present work we only consider one extra Z boson mixing with the SM Z boson. The coupling constant \( g_1 \) is the SM coupling \( g/\cos\theta_w \). For grand unified theories (GUT) \( g_2 \) is related to \( g_1 \) by
\[ \frac{g_2}{g_1} = \left( \frac{5}{3} x_w \lambda \right)^{1/2} \simeq 0.62 \lambda^{1/2}, \] 
where \( x_w = \sin^2 \theta_w \) and \( \theta_w \) is the weak mixing angle. The factor \( \lambda \) depends on the symmetry breaking pattern and the fermion sector of the theory, which is usually of order unity.

Since we only consider the mixing of \( Z^0_\alpha \) and \( Z^0_\alpha \) we can rewrite the Lagrangian with only the \( Z^0_1 \) and \( Z^0_2 \) interactions
\[ -\mathcal{L}_{Z^0_1 Z^0_2} = g_1 Z^0_{1\mu} \left[ \frac{1}{2} \sum_{i} \bar{\psi}_i \gamma^\mu (g^{i(1)}_1 - g^{i(1)}_2 \gamma_5) \psi_i \right] + g_2 Z^0_{2\mu} \left[ \frac{1}{2} \sum_{i} \bar{\psi}_i \gamma^\mu (g^{i(2)}_2 - g^{i(2)}_2 \gamma_5) \psi_i \right]. \]
where for both quarks and leptons \( g^{i(1)}_1 = T^i_{3L} - 2x_w Q_i \), \( g^{i(1)}_2 = T^i_{3L} \), and we consider the case in which \( Z^0_2 \) couples only to quarks,
\[ g^{i(2)}_2 = \epsilon_V, \quad g^{i(2)}_a = \epsilon_A, \quad g^{i(2)}_a = g^{i(2)}_a = 0. \] 
Here \( T^i_{3L} \) and \( Q_i \) are, respectively, the third component of the weak isospin and the electric charge of the fermion \( i \). The parameters \( \epsilon_V \) and \( \epsilon_A \) are the vector and axial-vector couplings of \( Z^0_2 \). Without loss of generality we choose \( \epsilon_V = \sin \gamma \) and \( \epsilon_A = \cos \gamma \) such that \( \epsilon_V^2 + \epsilon_A^2 \) is normalized to unity. The mixing of the weak eigenstates \( Z^0_1 \) and \( Z^0_2 \) to form mass eigenstates \( Z \) and \( Z' \) are parametrized by a mixing angle \( \theta \):
\[ \left( \begin{array}{c} Z \\ Z' \end{array} \right) = \left( \begin{array}{cc} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{array} \right) \left( \begin{array}{c} Z^0_1 \\ Z^0_2 \end{array} \right). \] 
The mass of \( Z \) is \( M_Z = 91.19 \) GeV.

After substituting the interactions of the mass eigenstates \( Z \) and \( Z' \) with fermions are
\[ -\mathcal{L}_{ZZ'} = \sum_{i} \frac{g_i}{2} \left[ Z_{\mu} \bar{\psi}_i \gamma^\mu (v^i_a - a^i_a \gamma_5) \psi_i \right] + Z'_{\mu} \bar{\psi}_i \gamma^\mu (v^i_n - a^i_n \gamma_5) \psi_i, \] 
where
\[ v^i_a = g^{i(1)}_a + \frac{g_2}{g_1} \theta g^{i(2)}_a, \quad a^i_a = g^{i(1)}_a + \frac{g_2}{g_1} \theta g^{i(2)}_a, \] 
\[ v^i_n = \frac{g_2}{g_1} g^{i(2)}_n - \theta g^{i(1)}_n, \quad a^i_n = \frac{g_2}{g_1} g^{i(2)}_n - \theta g^{i(1)}_n. \]
Here we have used the valid approximation \( \cos \theta \approx 1 \) and \( \sin \theta \approx \theta \). In the following, we ignore the mixing \( \theta = 0 \) such that the precision measurements for the SM Z boson are not affected, unless stated otherwise. We also take the democratic choice of equal couplings of \( Z' \) to up-type and down-type quarks. This is in accord with the CDF observation that there is no preference for \( b \) quarks in the dijet window \( M_{jj} = 120 - 160 \) GeV [2].

\[ \Gamma(Z' \rightarrow f \bar{f}) = \frac{G_F M_{Z'}^3}{6\pi \sqrt{2}} N_c C(M_{Z'}^2) M_{Z'} \sqrt{1 - 4x} \times \left[ v^2_1 (1 + 2x) + a^2_1 (1 - 4x) \right], \] 
where \( G_F \) is the Fermi coupling constant, \( C(M_{Z'}^2) = 1 + \alpha_s/\pi + 1.409(\alpha_s/\pi)^2 - 12.77(\alpha_s/\pi)^3 \), \( \alpha_s = \alpha_s(M_{Z'}) \) is the strong coupling at the scale \( M_{Z'} \), \( x = m_{Z'}/M_{Z'} \), and \( N_c = 3 \) or 1 if \( f \) is a quark or a lepton, respectively. The \( Z' \) width is proportional to \( \lambda \), which sets the strength of the \( Z' \) coupling. For \( \lambda = 1 \) the total \( Z' \) width is \( \Gamma_{Z'}/M_{Z'} = 0.022 \) for \( M_{Z'} < 2m_t \). The width would be increased somewhat if there are open channels for decay into the top quark, superpartners, and other exotic particles. Essentially, it is a narrow resonance.

The \( Z' \) boson can be directly produced at a hadron collider via the \( q \bar{q} \rightarrow Z' \) subprocess, for which the cross section in the narrow \( Z' \) width approximation is
\[ \sigma(q \bar{q} \rightarrow Z') = K \frac{2\pi G_F M_{Z'}^2}{3\sqrt{2}} \left[ (v^2_1 + a^2_1)^2 \right] (\delta(s) - M_{Z'}^2) \] 
The K-factor represents the enhancement from higher order QCD processes, estimated to be \( K = 1 + \alpha_s(M_{Z'}^2) \times \left( 1 + \frac{4}{3} \pi^2 \right) \approx 1.3 \). When the mixing is ignored, \( (v^2_1 + a^2_1)^2 = (0.62)^2 \lambda \) and the cross section is independent of the parameter \( \gamma \) as long as \( \epsilon_V^2 + \epsilon_A^2 = 1 \).

Note that all the current and previous dijet-mass searches at the Tevatron are limited to \( M_{jj} > 200 \) GeV, which are not applicable to the present \( Z' \) with \( M_{Z'} \approx 145 \) GeV. The relevant dijet data were from the UA2 Collaboration with collision energy at \( \sqrt{s} = 630 \) GeV. The UA2 Collaboration[11] has detected the W + Z signal in the dijet-mass region \( 48 < m(jj) < 138 \) GeV and has placed upper bounds on \( \sigma(B(Z' \rightarrow jj)) \) over the range \( 80 < m(jj) < 320 \) GeV. The analysis against the UA2 data was shown in Fig. 1 of Ref. [4]. We do not repeat the exercise here, but just use the result there. From Fig. 1 of Ref. [4] the allowed values are \( \lambda \lesssim 1 \) for \( M_{Z'} = 100 - 180 \) GeV, given the uncertainty in the K-factor in the theoretical cross section calculation and the difficulty in obtaining an experimental bound by subtraction of a smooth background. We shall consider \( \lambda \lesssim 1 \) in the following.

**Associated Production.** The associated production of \( Z' \) with a W boson goes through the t- and u-channel exchange of quarks while the s-channel exchange is
highly suppressed because of the negligible mixing angle between the SM Z boson and the $Z'$. Consequently, we expect similar or even larger cross sections for $M_{Z'} \sim M_Z$ than the SM $WZ$ production in which there is a delicate gauge cancellation among the $t$, $u$, and $s$-channel diagrams. The cross sections at the Tevatron energy $\sqrt{s} = 1.96$ TeV are shown for $\lambda = 1$ in Fig. 1. We have included a $K$-factor of $K = 1.3$ to approximate next-to-leading order QCD contributions. We can see that at $M_{Z'} = 140 - 150$ GeV the cross section is right at the order of 4 pb, which is required to explain the excess in the CDF $Wjj$ anomaly. The choice of vector and axial-vector couplings are

$$\epsilon_V = \epsilon_A = \frac{1}{\sqrt{2}},$$

which are the same for up- and down-type quarks.

The total width of the $Z'$ for $M_{Z'} = 145$ GeV is a mere 3 GeV. This is not in contrast with the width observed because the $M_{jj}$ distribution is dominated by the resolution. We are not going to fit our model to the $M_{jj}$ distribution (Fig. 1 of Ref. [2]), because it can always be done by adjusting the bin resolution and the peak normalization.

Since we have assumed here democratic couplings to all quarks, $Z'$ can decay into $b\bar{b}$ with a branching ratio $B(Z' \rightarrow b\bar{b}) = 0.2$. Therefore, $WZ'$ production can give rise to a $1\ell v b\bar{b}$ final state. Both CDF and DØ have dedicated searches for $1\ell v b\bar{b}$ final state for the Higgs boson. The preliminary 5.7 fb$^{-1}$ result of CDF [12] put 95% C.L. upper limits on the ratio $\sigma(WX) \times B(X \rightarrow b\bar{b})/\sigma(WH_{SM}) \times B(H_{SM} \rightarrow b\bar{b})$. For the particle with mass equal to 140, 145, and 150 GeV, the limits on the ratio are 15.8, 25.3, and 44.3, respectively. The $WZ'$ cross section here is about 4 pb for $M_{Z'} = 145$ GeV, and with a branching ratio $B(Z' \rightarrow b\bar{b}) = 0.2$ the $\sigma(WZ') \times B(Z' \rightarrow b\bar{b}) \approx 0.8$ pb. On the other hand, the SM $\sigma(WH) \times B(H \rightarrow b\bar{b}) \approx 21$ fb for $m_H = 145$ GeV. Thus, the largest allowed cross section for $\sigma(WZ') \times B(Z' \rightarrow b\bar{b}) \approx 0.53$ pb. Given the uncertainty in all these estimations, the current upper limit on $\sigma(WH) \times B(H \rightarrow b\bar{b})$ from the Tevatron begins to constrain the $Z'$ model. If we give up the simple assumption of democratic choice on $Z'$-$q\bar{q}$ couplings to all generations, we can easily lower the $Wb\bar{b}$ event rate. Also, note that the amount to be reduced is mere.

**Implications at the Tevatron.** As shown in Ref. [4] other associated production channels, $\gamma Z'$, $ZZ'$, and $Z'Z'$ are possibly observable, provided that the current excess is due to $WZ'$ production. We show the production cross sections for these channels in Fig. 2. We have imposed the following acceptance on the final state photon:

$$p_T(\gamma) > 50 \text{ GeV}, \quad |\eta(\gamma)| < 1.1.$$  

The irreducible backgrounds to the $(\gamma, W, Z)Z'$ signals with $Z' \rightarrow jj$ arise from the $(\gamma, W, Z)jj$ final states. An analysis with $jj = b\bar{b}$ had been performed in Ref. [4]. The $WZ'$ signal has the advantage that its significance in the presence of the corresponding background is better than the other channels. We expect that a similar advantage is enjoyed by the $WZ' \rightarrow Wjj$ mode.

It was mentioned in Refs. [2, 17] and in Ref. [18] that no significant excess is observed in $Zjj$ and $\gamma jj$ channel, respectively. We shall show that with current systematic uncertainties of level 10% [2, 17, 18] and a similar set of jet cuts, no significant excess can be observed in
both channels. With the jet cuts $E_{Tj} > 30$ GeV, $|\eta_j| < 2.4$, $p_{Tjj} > 40$ GeV, $120$ GeV $< M_{jj} < 160$ GeV and leptonic cuts $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.8$, the $\sigma_{\text{signal}} : \sigma_{\text{bkgd}} = 26$ fb : 171 fb for the $Zjj$ channel. It would give a significance of $S/(\sqrt{B} \pm 0.1B) \approx 1.4\sigma$ for $L = 4.3$ fb$^{-1}$, where the factor 0.1 is the systematic uncertainties. With the same set of jet cuts and photon cuts in Eq. (12) to the $\gamma jj$ channel, we obtain $\sigma_{\text{signal}} : \sigma_{\text{bkgd}} = 0.5 \text{ pb} : 9.9 \text{ pb}$, which gives a significance of $S/(\sqrt{B} \pm 0.1B) \approx 0.5\sigma$. Therefore, we cannot observe any significant excess in both channels, in accord with the claims in Refs. [2, 18].

Nevertheless, if we tighten the jet cuts the backgrounds will suffer more than the signals. With $E_{Tj} > 50$ GeV and $L = 10$ fb$^{-1}$, the significance can improve to $2.3\sigma$ and $1\sigma$ for $Zjj$ and $\gamma jj$ channel, respectively. If the systematic uncertainties can be reduced to an ideal level of $2\% - 3\%$ the significance can be further improved to $5\sigma$ and $4\sigma$, respectively. Details will be presented later [20].

Conclusions.—We have shown that a baryonic $Z'$ boson can explain the excess in the invariant-mass window $120 - 160$ GeV in the dijet system of $Wjj$ production. Such a $Z'$ boson with depleted leptonic couplings is not subject to the current dilepton limits on extra gauge bosons. Yet, the strongest constraint comes from the dijet search of the UA2 data, from which the size of coupling would be $\lambda \lesssim 1$. With $\lambda = 1$ we are able to explain the required cross section of 4 pb in the excess window. We have also shown that it is hard to see the excess in both $\gamma Z' \rightarrow \gamma jj$ and $ZZ' \rightarrow \ell^+\ell^-jj$ channels under the current systematic uncertainties and jet cuts. However, with tightened jet cuts and improved systematic uncertainties it could be promising to test the excess in these two channels.

Other comments and possibilities are given as follows:

(i) A more dedicated dijet analysis at the energy range $100 - 200$ GeV at the Tevatron could be another important test for this baryonic $Z'$ model.

(ii) A baryonic $W'$ boson is equally possible to explain the anomaly, although the size of coupling would be different. In addition, this $W'$ has an additional advantage since the constraint from the current upper limit on $\sigma(WH) \times B(H \rightarrow b\bar{b})$ at the Tevatron does not apply to $m_{W'} < m_t + m_b$. However, it would also be subject to the dijet constraint of UA2. Similarly, it would predict excess in $\gamma W'$ and $ZW'$ production.

(iii) Another interesting kinematics to look at is the angular distribution of the scattering angle $\theta_{sc}$. Similar to the SM $WZ$ production, the scattering angle of the $Z'$ would also be peaked at $|\cos \theta_{sc}| = 1$. On the other hand, a Higgs-like boson would have a flat distribution in $\cos \theta_{sc}$.

(iv) The prospects for detecting the $Z'$ would be best in the $Z' \rightarrow b\bar{b}$ final state, with $b$-tagging by vertex detector or semileptonic decays to reject backgrounds from light quarks and gluons in the $(\gamma, W, Z)jj$ final state.

(v) Dedicated searches on $t\bar{t}bb$ or $t\bar{t}b\bar{b}$ also provide useful tests for the model. As long as the new $Z'$ does not have suppressed couplings to $b\bar{b}$, such searches will begin to probe the useful range of the parameters.

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Note added.—A few papers [21] appeared one day after the appearance of Ref. [2]. We share similar ideas, though in a different framework. Also, there were some related works [22] before that.

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