An Explanation of the CDF Dijet Anomaly within a $U(1)_X$ Stueckelberg Extension

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We discuss the recent excess seen by the CDF Collaboration [1] has reported an excess of events in the invariant mass distribution of jet pairs produced in association with a $W$ boson in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. In this note we analyze this anomaly in the framework of a Stueckelberg $U(1)_X$ extension of the Standard Model [2-4]. The mechanism to explain the anomaly that we propose is different from those discussed in the literature [5-10]. Further, we consider the associated $Zjj$ and $\gamma jj$ production, which is addressed only in [7, 8]. Additionally, for this framework we study the production of $Wjj$, $Zjj$ and $\gamma jj$ at the Large Hadron Collider at $\sqrt{s} = 7$ TeV (LHC7).

We begin by extending the Standard Model by the following additional piece in the Lagrangian

$$\mathcal{L}_1 = - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + g_X X_{\mu} J_{\mu}^X - \frac{1}{2} \left( \partial_{\mu} \sigma + M_1 X_{\mu} + M_2 B_{\mu} \right)^2 . \tag{1}$$

where $B_{\mu}$ ($X_{\mu}$) is the gauge boson associated with the gauge group $U(1)_{Y}$ ($U(1)_X$), where $Y$ refers to the hypercharge. The Lagrangian of Eq.(1) is invariant under hypercharge $U(1)_Y$ transformations $\delta Y = \partial_{\mu} \lambda_Y$, $\delta Y X_{\mu} = 0$ and $\delta Y = -M_2 X_Y$, and under the $U(1)_X$ transformations $\delta X_{\mu} = \partial_{\mu} X_Y$, $\delta X_B = 0$ and $\delta X = -M_1 X_X$. Thus there are three neutral gauge bosons in the extended Lagrangian, $\mathcal{L} = \mathcal{L}_SM + \mathcal{L}_1$, which are $X_{\mu}$, $B_{\mu}$ and $A_{\mu}^3$, where $A_{\mu}^3$ is the third component of the SU(2)$_L$ gauge multiplet $A_{\mu}^a$ ($a = 1, 2, 3$).

We will focus on the neutral current interaction which arises from the couplings of $A_{\mu}^3$, $B_{\mu}$ and $X_{\mu}$.

$$\mathcal{L}_{NC} = g_2 A_{\mu}^3 J_{\mu}^{3}\mu + g_B B_{\mu} J_{\mu}^{B} + g_X X_{\mu} J_{\mu}^{X} , \tag{2}$$

where $J_{\mu}^{3\mu}$ is the third component of SU(2)$_L$ current, $J_{\mu}^{B}$ is the hypercharge current and $J_{\mu}^{X}$ is a vector current to which the $U(1)_X$ gauge field $X_{\mu}$ couples. After spontaneous breaking of the electroweak symmetry one will have, along with Eq.(1), a $3 \times 3$ mass matrix which mixes the three neutral gauge fields $A_{\mu}^a$, $B_{\mu}$, $X_{\mu}$. The diagonalization of this mass matrix leads to a massless neutral state (the photon), and two massive neutral bosons (the $Z$ boson and the new $Z'$ boson). Transforming to the mass diagonal basis, the couplings of the $Z$ and $Z'$ arising from $J_{\mu}^{3\mu}$ and $J_{\mu}^{B}$ are given by the following

$$\mathcal{L}_2 = \frac{g_2}{\cos \theta} \left[ Z_{\mu} \left( \cos \psi \right) \left( \sin^2 \theta \right) Q J_{\mu}^{B} - J_{\mu}^{3\mu} \right] - \tan \phi \sin \psi \sin \theta \left( Q J_{\mu}^{B} - J_{\mu}^{3\mu} \right) + Z_{\mu} \left( \sin^2 \theta \right) Q J_{\mu}^{B} - J_{\mu}^{3\mu} \right] \right) . \tag{3}$$

Additionally one has the following set of couplings for $Z$ and $Z'$ from $J_{\mu}^{X}$$

$$\mathcal{L}_2' = g_X \left( \cos \psi \cos \phi - \sin \theta \sin \phi \sin \psi \right) Z_{\mu} J_{\mu}^X + g_X \left( \sin \psi \cos \phi - \sin \theta \sin \phi \cos \psi \right) Z_{\mu} J_{\mu}^X . \tag{4}$$

In the above the angles $\phi$ and $\psi$ are given by

$$\tan \phi = \frac{M_2}{M_1} , \tag{5}$$

$$\tan \psi = \frac{\tan \theta \tan \phi M_2^2}{\cos \theta \left( M_2^2 - M_1^2 \left( 1 + \tan^2 \theta \right) \right)} , \tag{6}$$

where $\tan \theta = \tan \theta_W \cos \phi$. In addition to the above there is also a triple gauge boson vertex with the $Z'W W$ couplings given by

$$\mathcal{L}_{Z'W W} = i g_2 R_{31} \left[ W_{\mu}^{+} W^{-\mu} Z'^{\nu} + W_{\mu}^{-} W^{+\mu} Z'^{\nu} + W^{+\nu} W^{-\nu} Z'^{\mu} \right] . \tag{7}$$

We next consider a specific model for $J_{\mu}^{X}$ so that $J_{\mu}^{X} = \sum_{a} \bar{q}_{a} \gamma^{\mu} q$. Now from the electroweak data the ratio $M_2/M_1$ is known to be typically small, i.e., $M_2/M_1 \ll 1$. For small $M_2/M_1$, both $\tan \phi$ and $\tan \psi$ are small, i.e., $\tan \phi, \tan \psi \ll 1$. Thus the couplings of the $Z'$ to fermions given by Eq.(3) would be typically much smaller compared to the couplings of $Z'$ given by Eq.(4). Further, for the same reason $R_{31} \ll 1$, and

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thus the $Z'WW$ vertex of Eq. (6) is significantly suppressed. The implication of the above is the following: for the amplitude $q_1 \bar{q}_2 \to WZ'$, the s-channel pole contribution via $q_1 \bar{q}_2 \to W \to WZ'$ will be suppressed compared to the t-channel production of $WZ'$. Thus we focus on the $WZ'$ production via the t-channel exchange, which is illustrated in Fig. 1. Since by assumption $X_\mu$ couples only to quarks, and since $Z'$ is dominantly $X_\mu$ in the limit $M_{X}/M_{1} \ll 1$, the decays of $Z'$ are dominantly to quarks and the leptonic final states, $W\ell^{+}\ell^{-}$, are suppressed. Thus in this case $WZ'$ production will result in $Wjj$, i.e. a $W$ boson plus dijets.

The signal of a baryonic vector boson is constrained by the dijet search at colliders. The current Tevatron data constrains the $Z'$ boson with Standard Model couplings within the mass range $\in (320, 740)$ GeV [11]. Below 200 GeV, however, the UA2 experiment [12] gives a better constraint than what the Tevatron data gives (see e.g. [9, 7]). For a $Z'$ boson with $\sim 144$ GeV mass, the UA2 bound on the $Z'$ coupling to quarks is estimated in Ref. 1 of [9]. Their results are consistent with our analysis given below.

As discussed after Eq. (7), we assume that the $Z'$ couples mostly to quarks and we will assume a $Z'$ mass of 144 GeV and a coupling of $g_X = 0.35$. For simulations we use MadGraph 4.4 [13], PYTHIA [14] and PGS 4 [15] and we consider the $Wjj$, $Zjj$ and $\gamma jj$ production channels where the dijets arise from the Standard Model (SM) or from the decay of the $Z'$. All processes are simulated at $\sqrt{s} = 1.96$ TeV for a $pp$ collider, at $\sqrt{s} = 7$ TeV for a $pp$ collider (LHC7) and the $Z' \to jj$ production is simulated at UA2 ($p\bar{p}$ collider with $\sqrt{s} = 630$ GeV) to verify that this model was not already excluded [12]. At the Tevatron and LHC7, we do not consider the single production of $Z'$, i.e. $pp \to Z' \to jj$ or $pp \to Z' \to jj$, since this would be a relatively hard signal to find compared to the standard model, namely due to QCD.

The contribution of this $Z'$ model to the $Wjj$ (pre-cut) cross section is 3.62 pb, which is in agreement with the CDF reported value [1] and the number of events (after cuts) are in good agreement with the CDF reported values [1] as shown in Table II. The effective cross section of $Wjj$, $Zjj$ and $\gamma jj$ after trigger and cut efficiencies are taken into account at the Tevatron and LHC7 are shown in Table II and Table III. Below we discuss our selection cuts on various final states in details.

In Ref. 1 of [12], the UA2 Collaboration puts a 90% CL upper limit on the dijet production rate of an extra vector boson. For our $Z'$ model we calculate the cross section (taking into account the cut and the trigger efficiencies reported in Ref. 1 of [12]) to be $2.32 \times 10^{2}$ pb. As pointed out in [9], the analysis of UA2 was done using comparatively primitive Monte Carlo, detector simulations and jet algorithms. For these reasons we assume, as in [9], that the UA2 bound is an order of magnitude limit.

The particle identification criteria used for the Tevatron are as follows: a lepton (electron or muon) candidate must have $p_T > 20$ GeV and $|\eta| < 1.0$. Jets candidates have $p_T > 30$ GeV, $|\eta| < 2.4$ and are removed if the jet is within $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.52$ of a lepton. Following the framework of [7], for the $\gamma jj$ search we use the criteria that the selected photon must have $p_T > 50$ GeV and $|\eta| < 1.1$, which is a higher momentum cut than the one used in [8]. Similar identification criteria are used for the LHC7 analysis.

For the $Wjj$ analysis we follow the cuts used in [1] where events are selected to have one identified lepton, two identified jets and missing transverse energy. In addition to this, we check to make sure the event does not have a second lepton (with $p_T > 10$ GeV) and that the dilepton invariant mass is not in the $Z$ range. Further selection includes events with two identified jets, missing transverse energy which exceeds 25 GeV. Additionally we require the spacing between the missing transverse energy exceeds 30 GeV, and that the transverse mass between the lepton and the two jets exceeds 30 GeV. The two jets must have $|\Delta \eta| < 2.4$ and the momentum of the dijet system must exceed 40 GeV. In addition events are required to have the spacing between the missing transverse energy and the leading jet to be separated by at least $|\Delta \phi| = 0.4$. After applying these cuts we calculate that our model produces $104 \pm 10$ electron events and $124 \pm 11$ muon events which are roughly within $1\sigma$ of the values CDF reported [1]. Table I shows how our model compares to the CDF values.

Now for the $Zjj$ analysis, we select events with two
identified leptons with the dilepton invariant mass in the range of 76 GeV to 106 GeV, i.e. the Z range. Further events are required to have two identified jets with the same jet event selection as the Wjj case including the dijet system momentum and Δη. After taking into account the trigger and cut efficiencies, the cross section of the signal is 3.8 fb compared to 213.5 fb for the SM background, which at the Tevatron with 4.3 fb⁻¹ of integrated luminosity would not produce a visible excess. Additionally, if one also requires the dijet invariant mass to be in the 120 GeV to 160 GeV range the effective cross section of the signal becomes 0.8 fb. 

Additionally, events are selected for the γjj analysis that have no identified leptons, one identified photon, dijet invariant mass in the range of 120 GeV to 160 GeV and two identified jets with the same jet event selection as the Wjj case. The cross section for the signal after trigger and cut efficiencies is 72.1 fb and for the SM background we get 3.0 × 10³ fb, which at the Tevatron with 4.3 fb⁻¹ of integrated luminosity would not produce a visible excess.

**Effective Dijet Cross Sections at the Tevatron**

|        | SM (fb) | Z' (fb) |
|--------|---------|---------|
| Wjj    | 3.2 × 10⁴ | 53.1    |
| Zjj    | 213.5   | 3.8     |
| γjj    | 3.0 × 10³ | 72.1    |

TABLE II: Exhibition of the effective cross sections at the Tevatron for Wjj, Zjj and γjj using the Z' model (as well as the cuts) discussed in the text. Before cuts the Z' contribution to the Wjj cross section is 3.62 pb and is in agreement with the CDF reported value. As shown in Table I the number of events for this Z' model agrees within 1σ to the CDF reported value.

We discuss now the implications of the model at LHC7 using the same trigger and cut efficiencies as stated above. For the Wjj production channel we find that the signal cross section is 160.5 fb compared to the SM cross section of 3.4 × 10⁴ fb. After applying the Zjj analysis we find that the effective cross section for the signal is 9.3 fb and the SM background is 2.4 × 10⁴ fb. If we further require that the dijet invariant mass be in the 120 GeV to 160 GeV range we get the effective cross section of the signal to be 1.5 fb. Additionally, for the γjj channel we find the effective cross section to be 115.5 fb for the signal and 6.2 × 10³ fb for the SM background which gives a 5σ excess with 12.3 fb⁻¹ of integrated luminosity. For this part of the analysis we have used S/√B = 5, where S is the number of signal events and B is the number of background events; however with a better statistical procedure and/or better set of cuts a possible discovery could occur at a lower luminosity.

**Effective Dijet Cross Sections at LHC7**

|        | SM (fb) | Z' (fb) |
|--------|---------|---------|
| Wjj    | 3.4 × 10⁵ | 160.5   |
| Zjj    | 2.4 × 10⁵ | 9.3     |
| γjj    | 6.2 × 10³ | 115.5   |

TABLE III: Display of the effective cross sections at the LHC with √s = 7 TeV for Wjj, Zjj and γjj using the Z' model and cuts discussed in the text.

In the above analysis we have ignored the corrections arising from finite but small ϵ = M_Z/M_1. Inclusion of this term would make only a small correction relative to the contribution arising from J_μ in the hadronic channels and thus all our conclusions above remain unchanged. The decay width of such a Z' into quarks is given by

\[ \Gamma (Z' \rightarrow q\bar{q}) = \frac{N_c N_f g_{Z'}^2}{12\pi} M_{Z'} \left(1 + \frac{\alpha_s}{\pi}\right), \]  

where N_c = 3 is the number of colors and N_f is the number of flavors (N_f = 5 for M_p = 144 GeV) which gives \( \Gamma (Z' \rightarrow q\bar{q}) \approx 7.3 \text{ GeV} \). If we turn on the mixings between B_µ and X_µ then such mixing is constrained by the precision electroweak data. We have analyzed the constraints on ϵ from the electroweak data and find that these constraints are much less stringent than in the analysis of [2] since here X_µ couples only to quarks. Our analysis shows that for the present model ϵ < 0.11 compared to the more stringent constraint of ϵ < 0.05 in the works of [2]. Now a small M_2/M_1 would produce a small production cross section for leptons via the Drell-Yan process p\bar{p} → Z' → ℓ⁺ℓ⁻. A Stueckelberg Z' in the dileptonic channel has been probed by the DØ experiment at the Tevatron which puts limits on ϵ for various Z' masses. Thus the experiment puts a constraint on ϵ so that ϵ < 0.02 for M_Z' = 200 GeV. We estimate that for Z' mass of 150 GeV, the limit on ϵ from the DØ experiments would be smaller than 0.02. Thus the Tevatron gives a more stringent limit on ϵ than the precision electroweak analysis.
In conclusion, we have analyzed in this work the $Wjj$ anomaly reported by the CDF experiment at the Tevatron. We show that the dijet anomaly can arise from a $U(1)_X$ Stueckelberg extension of the Standard Model where the $U(1)_X$ couples only with the quarks. An extra $U(1)$ gauge field coupling to quarks only was also considered in [7-10]. However, unlike the analysis of [7] our couplings are purely vector and we work within the Stueckelberg mechanism where no Higgs is required for the $Z'$ mass growth. Our framework is also different from of [10]. We have also analyzed the $Zjj$ and $\gamma jj$ production and find that they are consistent with current data as well as the results reported in [11-13].

We further extend our results to show expected effective cross sections at the LHC assuming the same event selection and identification criteria as at the Tevatron. Thus the $U(1)_X$ Stueckelberg extension of the Standard Model appears a valid explanation of the $Wjj$ anomaly if such an anomaly is indeed confirmed by DØ, the LHC and through the TeraGrid under grant numbers TG-DMR080036 and TG-PHY100036.

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