Z^{′} model for the CDF dijet anomaly

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A Z' Model for the CDF Dijet Anomaly

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Abstract

We adopt a bottom-up approach to constructing a new physics model to explain the CDF excess seen in dijets with an associated lepton and missing transverse energy. We find that the 145 GeV broad feature seen by CDF in the dijet invariant mass distribution can be explained by a Z' boson with a mass of 145 GeV that couples only to first generation quarks. After dijet resonance constraints are considered, a sizeable region of the parameter space favored by the CDF anomaly remains viable.

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I. INTRODUCTION

Recently, using 4.3 fb^{-1}, the CDF collaboration reported a 3.3 sigma excess over Standard Model (SM) background in dijet events with an associated lepton (electron or muon) and missing energy [1]. This excess is present in the dijet invariant mass range of 120–160 GeV, and a Gaussian fit to the background-subtracted histogram in this mass range gives a Gaussian peak at 144 ± 5 GeV. While this anomaly is interesting in its own right, a confirmation by the D0 collaboration or the persistence of this anomaly as the Tevatron accumulates its final dataset would provide theorists with a robust signal of new physics (NP) beyond the SM. The gradual accumulation of such anomalies in collider data from the Tevatron and the LHC will serve as the bedrock for extending physics beyond the SM. While many of the NP models in the past few decades have been constructed from top-down approach, in this instance, we can adopt a bottom-up experimentally driven construction of a NP model.

From a bottom-up approach, we look for minimal extensions to the SM in terms of both new field content and new symmetries. While this approach will not in general lead to the construction of a full model, the resulting data-driven minimal model can readily be embedded as a feature of complete, top-down new physics constructions. This embedding is key to identifying future searches and cross channels that will validate or disprove the proposed full model.

In this paper, we consider possible new physics explanations for the CDF excess in dijet events with an electron or muon and missing energy. In Sec. II, we discuss our bottom-up approach to construct the simplest possible NP model that can give rise to the observed excess, which we find to be a Z' model with a Z' mass of about 150 GeV. In Sec. III, we briefly discuss the collider constraints on Z' masses and couplings and conclude that flavor-universal Z' models that could explain the CDF anomaly are excluded. We therefore discard flavor-universality and consider the Z'_{ud} model, a Z' that couples equally to and only to the first generation quarks, which we present in Sec. IV. We conclude in Sec. V with a summary and a brief discussion of possible cross-channels to check at the Tevatron or the LHC.

II. APPROACH

New physics parameter space is large, and many different models can be made to fit the excess. In our bottom-up approach, we seek minimal extensions of the SM, keeping in mind both theoretical and experimental constraints on such extensions.

The CDF event selection calls for events with one electron (muon) with $E_T(p_T) > 20$ GeV and no other leptons with $p_T > 10$ GeV; in addition, a Z mass window (from $76 - -106$ GeV) cut on dilepton candidate events is imposed. The event selection also requires strictly two jets, reconstructed using a fixed-cone algorithm with $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$, each with $E_T > 30$ GeV and $|\eta| < 2.4$: the dijet system must have $p_T \geq 40$ GeV. In addition, events are required to have missing transverse energy (MET) $\not{E}_T > 25$ GeV. The transverse mass of the single hard lepton and the MET is required to be compatible with a W-candidate, $m_T^W = \sqrt{2p_T^\ell \not{E}_T(1 - \cos(\Delta\phi_{\ell\nu}))} \geq 30$ GeV. Additional details regarding jet energy corrections and isolation requirements are given in [1] (cf. Table 4.2 and Section 8.1 of the Cavaliere thesis).

The event excess is present in both electrons and muons. For electrons, the excess number of events is 156 ± 42, and for muons, the excess is 97 ± 38. Naively summing the systematic errors in quadrature, we find the total excess is 256 ± 56.6 events. The new physics contribution thus needs to give an excess in the dijet, single hard lepton, and MET final state with an effective cross section (new physics cross section $\times$ acceptance) of about 60 fb for the Tevatron collider. If we presume the lepton arises from a W boson, the required effective cross section for NP production including a hard W boson is about 270 fb, and if we estimate the acceptance factor for our signal to be about 10%, then we are looking for a total signal cross section of about 2.7 pb. For comparison, the measured WW/WZ cross section is 18.1 ± 3.3 (stat.) $\pm$ 2.5 (syst.) pb, consistent with the SM prediction of 15.9 ± 0.9 pb [1]. Thus, we aim to develop a minimal new physics model that has approximately an $\mathcal{O}(1 \text{ pb})$ production cross section, including W emission.

There are two main issues from a bottom-up perspective. First, considering the excess in the dijet invariant mass distribution from 120–160 GeV, we can interpret it as a colored resonance, an uncolored resonance, or a kinematic feature from a cascade decay. Second, concerning the presence of the hard lepton, we can consider, in turn, scenarios that are lepton number violating, lepton number conserving but flavor violating, or lepton number and flavor conserving with the separate possibility of kinematic suppression of additional leptons. Separately, the observed MET could arise from SM neutrinos, or it could arise from a NP source of missing energy: in the first case, we could again consider possible NP scenarios of lepton flavor and/or number violation, but this is redundant and unnecessary given the hard lepton. We will first discuss the dijet invariant mass excess as a possible kinematic feature from a cascade decay chain.

A. Cascade decay chain explanation for the m_{jj} excess

Invariant mass distributions from cascade decay chains can appear to have broad resonance features when the underlying particle masses are tuned appropriately and the correct particle combinations are isolated [2, 3]. A simple example of such a cascade decay chain is when a massive color octet decays via a on- or off-shell massive color triplet to a color singlet that subsequently escapes the detector: in supersymmetry (SUSY), this is the familiar gluino cascade decay, $\tilde{g} \to q\tilde{q} \to qq\tilde{\chi}_1^0$, which can have a large rate if the $m_{\tilde{\chi}_1^0} < m_{\tilde{g}}$. For example, if $m_{\tilde{g}} = 420$ GeV, $m_{\tilde{q}} = 380$ GeV, and $m_{\tilde{\chi}} = 150$ GeV, the exact dijet invariant mass edge would be 164 GeV and the dijet invariant mass distribution would exhibit the usual triangular shape, assuming the emitted quarks are massless. Since the quarks shower and hadronize, however, we expect the triangular feature to be smoothed out and the distribution to have a tail from jet-parton momenta mismatch as well as pollution by wrong dijet combinations.

There are several difficulties with making such a possibility work. First, generating a lepton together with this dijet invariant mass feature requires additional ingredients. If we assume the lepton arose from the same decay chain, we can consider an illustrative SUSY example:

$$\tilde{g} \to q\tilde{q} \to qq\tilde{\chi}_1^\pm \to qq\ell^\pm\tilde{\nu} \ . \tag{1}$$

In this SUSY example, we would need to have large R-parity violation in order to singly produce the $\tilde{g}$, but we would also need to minimize R-parity violation in order to force the prescribed decay chain. If we retain R-parity and still assume the $\tilde{\nu}$ is the lightest supersymmetric particle (LSP), we can assume the gluino is either produced in pairs or in association with a squark. In either case, the searches for SUSY in final states of one lepton, jets, and MET [4] or opposite-sign dilepton events, jets, and MET [5] have put strict constraints on gluinos and squarks with masses below about 500 GeV (and even up to 700 GeV).

If we make $\tilde{\chi}_1^0$ the LSP, then the lepton could minimally arise from the leptonic decay of a W boson: such a W could be produced from a heavy squark to light squark decay or in a chargino to neutralino decay (or vice-versa). An example SUSY process for the CDF excess in this case is

$$\tilde{q}\tilde{g} \to (q_1 \tilde{\chi}_1^{\pm})(q_2 \tilde{q}) \to (q_1 W \tilde{\chi}_1^0)(q_2 q_3 \tilde{\chi}_1^0) \ , \tag{2}$$

where the $W \to \ell\nu$, q_1 is soft, and q_2 and q_3 are hard jets that give the invariant mass excess. Here, in contrast with the above gluino decay in Eq. (1), the necessary addition of a weak gauge coupling is a model-independent penalty in order to incorporate the W in a cascade decay chain, and the $\approx 22\%$ leptonic branching ratio of the W boson is an additional penalty. An alternative to Eq. (2) is if a slepton were part of the cascade process, but such decay chains typically give rise to large multilepton signals, which are disfavored from [4] and [5]. Moreover, cascade processes such as Eq. (2) can be easily checked in the jets+MET cross-channel, and recent results [6–8] on these final states indicate that such spectra would need fine-tuning in order to evade constraints. Other choices for the stable LSP besides a neutralino or sneutrino are ruled out or disfavored from the recent searches for long-lived massive charged particles [9–11].

To summarize, a SUSY decay chain explanation for the dijet excess suffers from two competing considerations. In order to have an appreciable SUSY colored cross section at the Tevatron, we must make the gluinos and squarks relatively light. Yet, the requirement to have a lepton emitted in a cascade requires a slepton, a sneutrino, or a W insertion, making the resulting effective cross section for a 2 jets + lepton + MET final state disfavored given ATLAS and CMS searches. Since there is a great deal of freedom in arranging the SUSY spectrum, however, we do not rule out a SUSY explanation for the CDF anomaly but instead leave such a construction for future work.

We can also consider a non-SUSY decay chain explanation. The simplest would be a non-SUSY version of Eq. (1), which minimally requires the introduction of a new heavy color octet X and triplet Q,

$$X \to qQ \to qqW \to qq\ell\nu \ . \tag{3}$$

We note that other color representations for the initial particle are also obviously possible:

the only assumption is that the W at the end of the decay arises from a weak coupling vertex involving a SM quark and some new physics particle, which must necessarily be in the triplet representation of $SU(3)$. For example, the new Q can be considered as a fourth generation quark, though no such assumption is truly motivated from the bottom-up approach. We note that although this decay chain readily produces all of the final state particles of the CDF anomaly, the decay chain arises from a resonance, and so must couple directly to quarks and/or gluons. This implies the constraints and phenomenology are similar to the dijet resonance considerations, and so we will incorporate this discussion with the next subsection.

B. Resonance decaying to two jets

A more straightforward bottom-up construction is to hypothesize the two jets arise from a resonance, not a cascade decay chain. Given the lack of b-tagging information about the jets, we note the resonance, if colored, could be one of many different color representations under $SU(3)$. In addition, the emission of the hard lepton and the MET requirement allows one of several possibilities: NP could be lepton number violating (LNV), lepton flavor violationg (LFV), or lepton number and flavor conserving. Because the MET requirement is small, we can naturally associate the MET to be a neutrino emission and confine our discussion to NP scenarios that conserve lepton number and lepton flavor. We leave the possible construction of a viable LNV or LFV model for future work. Therefore, we consider a new physics resonance that decays to two jets where the decay chain includes a W boson, or the resonance is produced in association with a W boson. The Tevatron production cross section then necessarily includes weak coupling and the W leptonic branching fraction penalty: to avoid this, we could instead consider a W' boson that decays favorably to leptons. Recent constraints on a new W' boson with leptonic couplings, however, completely exclude any such W' boson with a mass below about 1.5 TeV [12–16].

The main difficulty with the resonance + SM W model is that, by construction, the new resonance can always be produced in an s-channel process without an associated W boson and hence is subject to direct searches for dijet resonances. Correspondingly, the dijet resonance cannot be strongly coupled (the dijet search constraints are discussed in Sec. III), but even so, we are left with many possibilities for the couplings and character of the new resonance. The resonance can be colored or uncolored, can couple exclusively to gluons, quarks, or both, and can conserve or violate quark flavor. We will not consider a resonance coupling exclusively to gluons, because we require the resonance to be produced in association with a W boson. Similarly, we will not consider a fractionally-charged resonance with a gluon-(anti-)quark coupling because the coupling would be non-diagonal if the resonance were in the same $SU(3)$ representation as the (anti-) quark, and for higher $SU(3)$ representations, the gluon-quark resonance would require a careful consideration of constraints to ensure it remains viable. We reserve a study of phenomenology and constraints of this interesting quark–gluon resonance model for future work.

If the resonance has quark-(anti-)quark couplings, we could expect the dominant process for associated W boson production to come from the 2–2 t-channel scattering process

$$qq \to W X_{qq} \to (\ell\nu)(qq) \ , \tag{4}$$

where the t-channel exchanged $SU(3)$ fundamental could also be a fourth generation quark. We see that this process is reminiscent of Eq. (3): in fact these production processes can be considered as differing cases of the same underlying new physics model that introduces a new $SU(3)$ octet X_{qq} and a new $SU(3)$ triplet Q. We remark that if the t-channel exchange particle is a SM quark, then the only two free parameters are the resonance-quark-quark coupling and the width of the resonance, since the mass of the resonance is fixed from the Gaussian fit to the dijet excess performed by CDF. On one hand, these two free parameters are constrained by direct dijet searches, and on the other hand, these are the only parameters available to ensure the cross section for resonance + W production matches the observed number of events at CDF. If the t-channel also included a fourth generation quark, however, then we have additional freedom to modify separately the direct dijet cross section and the resonance + W production cross section.

Alternatively, for the resonance with quark-(anti-)quark couplings, the dominant process for W emission could be from s-channel production, as in

$$qq \to W' \to W Z' \to (\ell\nu)(qq) \ . \tag{5}$$

Here, we have changed the resonance notation to the traditional Z' to emphasize that it is a color singlet. Again, the advantage of this s-channel construction is there are separate couplings that control the CDF event excess and the direct dijet production of Z': this model freedom can clearly be used to evade constraints from direct searches while also ensuring the correct production cross section for the excess. A similar process to Eq. (5) would be production of a techni-rho decaying to a techni-pion: $qq \to \rho_{TC} \to W\pi_{TC} \to (\ell\nu)(qq)$.

The s-channel explanation is disfavored, however, from both the CDF data (cf. Fig. 9.13 of [1]) and the bounds on new dijet resonances (discussed in detail in Sec. III). In the CDF analysis, they do not find a resonance feature in the $jj\ell\nu$ invariant mass; instead, the total invariant mass is consistent with the background hypothesis. We note that we can avoid generating a feature in $m_{jj\ell\nu}$ by postulating additional decay products that are invisible, soft, or otherwise missed by the detector. Such constructions and their corresponding experimental constraints are very model dependent, however, so following our bottom-up approach, we consider t-channel production of a Z' resonance + SM W boson with only SM quarks exchanged. We will find that we can successfully fit the CDF dijet excess with such a Z' model.

In summary, from a bottom-up perspective, we discussed the possibility of a dijet cascade decay invariant mass feature and a dijet resonance. We also considered the origin of the observed lepton: if the lepton comes from a W boson, then the full cross section would require a weak coupling and pay a price in the W leptonic branching ratio. On the other hand, if the lepton is from a cascade decay, then model-dependent tuning is needed to ensure a large branching fraction for a single lepton. Given these considerations, we find the simplest new physics model for explaining the CDF anomaly is a Z' dijet resonance produced in association with a W that decays leptonically, as shown in Fig. 1.

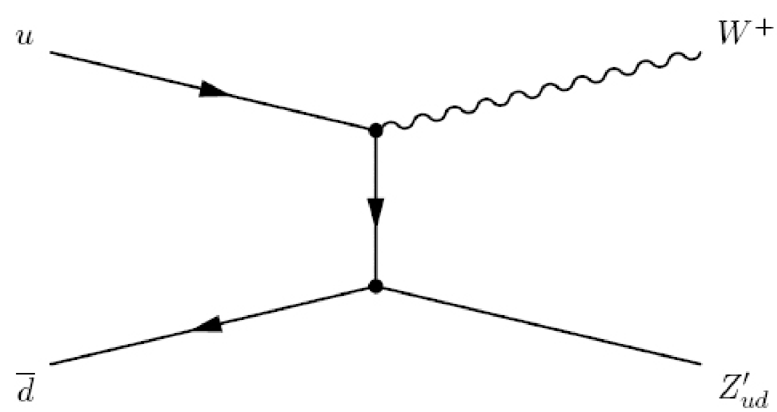

FIG. 1. $W^+Z'_{ud}$ associated production with a t-channel SM d quark.

III. BOUNDS ON A NEW Z' BOSON

From our bottom-up approach, the simplest model to explain the CDF anomaly is a Z' dijet resonance produced in association with a leptonically decaying W boson. Constraints on such a light Z', however, are very stringent.

For instance, a Z' boson with SM Z couplings to leptons is ruled out below a mass of 1071 GeV [17]. From a bottom-up approach, however, we do not require the Z' to couple to leptons, and hence we can postulate that the Z' is leptophobic, *i.e.* only couples to quarks. Even so, searches for dijet resonances place strong constraints on this type of Z' boson. The most recent results from ATLAS [18] and CMS [19], however, look for dijet invariant masses above 200 GeV and 220 GeV, respectively, in order to avoid, presumably, the QCD background contamination in the low dijet mass region. These hard cuts will clearly discard our light Z' events. Similarly, CDF and D0 searches applicable to leptophobic Z' bosons have dijet mass thresholds of at least 180 GeV [20–24] or look for $t\bar{t}$ resonances [25]. All of these constraints apply to Z' masses outside our range of interest, given the Gaussian fit of CDF's dijet excess has a mean 144 GeV.

We find the relevant experimental constraint on dijet resonances in this mass range comes from the UA2 collaboration [26]. In this analysis, they assumed a Z' with exactly SM couplings and a width that scaled with the mass ratio of the Z' to the Z. In addition, the cross section was also corrected with a K-factor of about 1.30 [27], based on the K-factor calculated for SM Drell-Yan Z production. Their results concluded that a SM-like Z' is excluded at 150 GeV.

Although our naive leptophobic Z' model with SM Z couplings to quarks is ruled out from UA2 data, we can choose to abandon flavor universality. In this case, we expect the UA2 bound implies our Z' coupling needs to be about $1/\sqrt{2}$ weaker than the SM Z coupling to quarks. If we retain flavor universality, we can satisfy the UA2 constraint and produce the desired CDF excess with a $g_{\text{universal}} = 0.20 - 0.25$, but we would also need to consider constraints from Higgs searches in the $\ell\nu bb$ final state [28]. We will therefore consider a Z' that only couples to up and down quarks with equal couplings, avoiding flavor constraints. This is our minimal model motivated from a bottom-up approach to the CDF dijet, lepton, and MET events excess. Taking into account the Z' mass will be fixed by the CDF dijet Gaussian fit, this model has two free parameters: g_{ud} and the Z'_{ud} width.

IV. THE Z'_{ud} MODEL AND SIMULATION

Faced with the severe constraint from UA2 on light Z' bosons in the 150 GeV mass range, we construct the Z'_{ud} model with the Lagrangian

$$\mathcal{L} \supset -g_{ud} Z'_{ud\mu} \overline{u} \gamma^{\mu} u - g_{ud} Z'_{ud\mu} \overline{d} \gamma^{\mu} d \ , \tag{6}$$

where Z'_{ud} is a new $U(1)'$ gauge boson, and g_{ud} is the new coupling, same for both up and down quarks. The Z'_{ud} is a singlet under the Standard Model gauge group and we turn off its mixing with the SM Z boson. (For a recent review on Z' models and phenomenology, see [29] by P. Langacker.)

For our purposes, we can consider the Z'_{ud} as a particular leptophobic Z' model based on gauging the SM baryon number symmetry. While additional field content is needed to cancel anomalies, such a full model description would follow the earlier work along the lines of [30–32].

We simulate the Z'_{ud} production for masses between 125 GeV to 175 GeV, couplings g_{ud} at leading order (LO) from 0.20 to 0.40, and a Z'_{ud} width of 8 GeV or 12 GeV, using MadGraph 5 v.0.5.1 [33] and MadEvent v.4.4.56 [34–36] interfaced with Pythia 6.4.20 [37] and PGS 4 [38]. For testing the match to the CDF excess, we generate Tevatron $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV, $p\overline{p} \to W^{\pm} Z'_{ud}$, use the Pythia interface to decay, shower, and hadronize, and then perform rough clustering and detector simulation using PGS. We apply identical cuts as the CDF analysis [1]. At each point of mass, coupling, and width, we count the number of events within the signal region of 120 GeV $< m_{jj} <$ 160 GeV. Based on this event count and the Gaussian fit performed by CDF, we find the best fit point is at about a Z' mass of 144 GeV and a coupling $g_{ud} \sim 0.33$, irrespective of the Z' width, see Fig. 2 and Fig. 3.

We also need to calculate the UA2 constraint [26] for this g_{ud} coupling v. Z'_{ud} mass plane. To do so, we simulate each model point for S$p\overline{p}$S collisions of $p\overline{p}$ at $\sqrt{s} = 630$ GeV to get a (LO) Z'_{ud} s-channel production cross section estimate. We also calculate the Z' cross section limit from Fig. 5 of [26]. Based on the g^4_{ud} scaling of the cross section, we can get a (LO) constraint on the g_{ud} coupling allowed by the UA2 search. Our results are displayed in Fig. 2 for a Z'_{ud} with an 8 GeV width and Fig. 3 for a 12 GeV width. We used BRIDGE v.2.21 [39] to calculate the Z' width for each point to ensure the partial width of $Z' \to u\overline{u}, d\overline{d}$ stayed

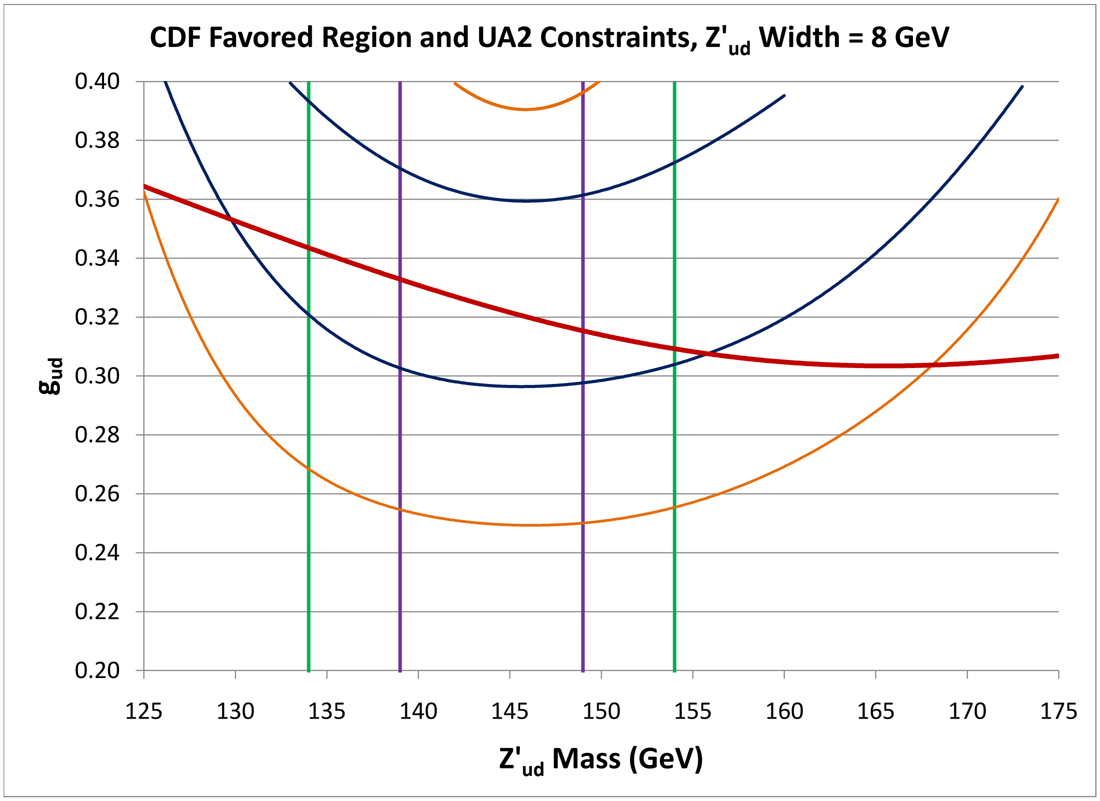

FIG. 2. (color online). The blue (orange) curves are the 1 (2) σ bounds on g_{ud} coupling for given Z' mass and obtained from matching the observed number of excess events seen at CDF (see text). The purple (green) vertical lines indicate the 1 (2) σ limits of the Z' mass from the Gaussian fit of m_{jj} performed by CDF. The red curve indicates the extracted limit (at LO) on the coupling g_{ud} from the UA2 search for SM-like Z's decaying to two jets [26] (see text). The Z' width is fixed to be 8 GeV for entire mass range.

below 8 GeV. As a point of comparison, for a Z' mass of 145 GeV, $g_{ud} = 0.35$, the calculated Z' width to quarks is 2.824 GeV. Additional invisible decay modes would need to added in a full model to account for the remaining Z' width.

Our results demonstrate that the CDF anomaly can be favorably fit with a Z'_{ud} of mass between about 140 GeV and 150 GeV and a coupling of $0.30 \lesssim g_{ud} \lesssim 0.36$. For a Z'_{ud} width of 8 GeV, however, slightly more than half of this favored region is excluded by UA2. If we

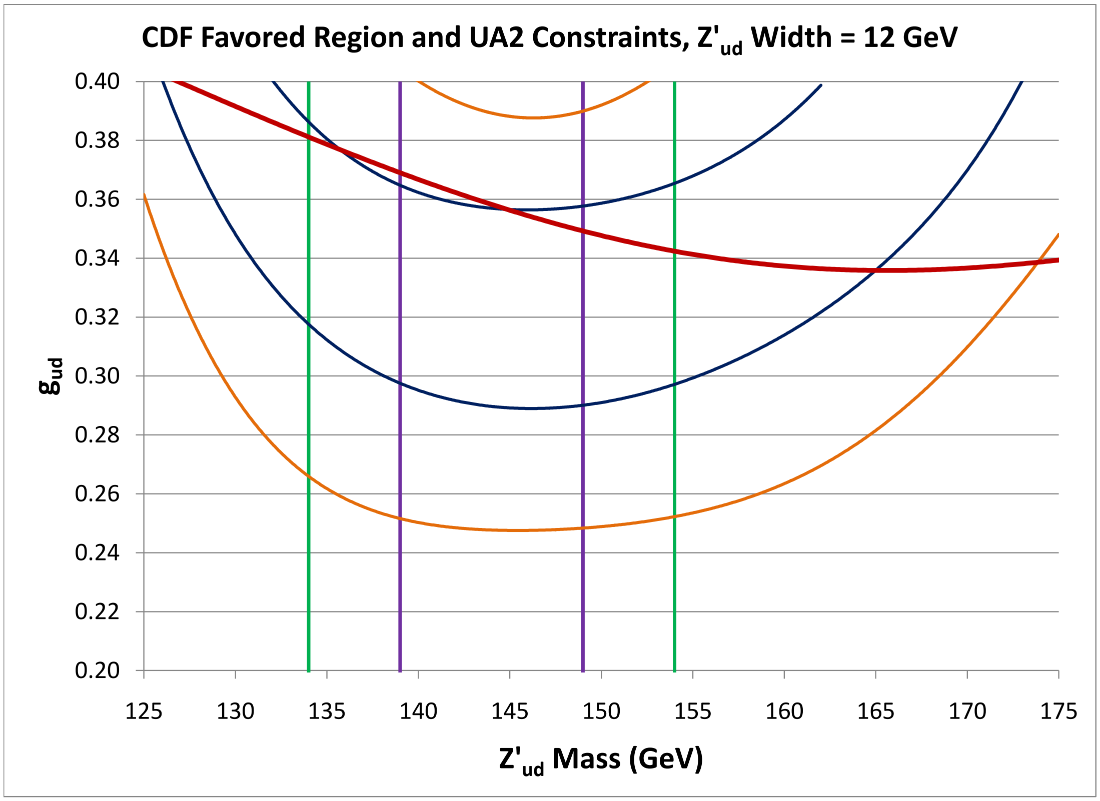

FIG. 3. (color online). Same as Fig. 2, except for a Z' with a width of 12 GeV.

increase the Z'_{ud} width to 12 GeV, though, the UA2 constraint eliminates only a small part of this favored region.

We note that we did not include K-factors for the Tevatron and UA2 production cross sections used in Fig. 2 and Fig. 3, while the UA2 collaboration did include NLO K-factors in their SM-like Z' exclusion limit contour. Clearly, a full calculation of the NLO K-factors for Z'_{ud} s-channel and $W^{\pm}Z'_{ud}$ associated production is beyond the scope of this work. We naively expect, however, the NLO K-factor for s-channel Z'_{ud} production to be about 1.30, given the work of [27], which should rescale the UA2 exclusion curve down by about 6.5%. In this case, even if no K-factor enhancement to $W^{\pm}Z'_{ud}$ production at Tevatron is assumed, our conclusions remain the same and much of our favored region is left intact.

V. CONCLUSIONS AND FUTURE SEARCHES

We have performed a bottom-up analysis of the excess events in the dijet, lepton, MET final state seen by CDF. After discussing possible new physics constructions that could explain the excess, we found a minimal model that satisfied all present collider constraints and had a minimal number of free parameters. The Z'_{ud} model introduces a new Z' gauge boson that only couples to first generation quarks. We calculated the exclusion curves for this model for two different Z'_{ud} widths and found that a significant portion of the CDF favored region was not excluded from the UA2 dijet constraint.

It remains to identify possible cross-channels for checking the validity of this model. While the CDF author acknowledges the entire anomaly may be an underestimated background (see Chapter 9 of the Cavaliere thesis [1]), a search in the same exclusive dijets, lepton, MET channel by D0 would certainly corroborate or refute the excess. A dijet signal from Drell-Yan production of the Z'_{ud} boson may be lost in the QCD background at Tevatron and the LHC, but a signal may be recoverable if the backgrounds are very well understood. Separately, because the lepton here arises from associated W production, a smaller penalty in cross section would be achieved by looking for a photon + dijet signal [1]. At the LHC, since exclusive dijet searches are expected to be difficult because of the QCD background, one possible search channel is in the exclusive four jets final state. Using MadEvent 4.4.56, we estimate the LO cross section for di-Z'_{ud} production at the 7 TeV LHC with $g_{ud} = 0.30$ and a width of 12 GeV is 1.51 pb, which could be testable with an integrated luminosity of $\mathcal{O}(1\text{ fb}^{-1})$. Since we have an estimate for the Z'_{ud} mass, the QCD background can readily be subtracted out from a sideband subtraction method, and wrong combinatorics can be removed from a mass window cut and a dijet p_T requirement [1, 3]. Additional search channels may also be available, but their presence would be motivated from the particular full model completion of the Z'_{ud} minimal model presented here. In a future work, we will consider possible full model completions and differentiate their phenomenology.

Recent work that also discussed light dijet resonances include [40–42]. In particular, we note a very similar model was considered in [42].

[1] We thank Tao Han for bringing up this point.

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[1] T. Aaltonen *et al.* [CDF Collaboration], [arXiv:1104.0699 [hep-ex]].
A preliminary study of CDF data was presented in
V. Cavaliere, FERMILAB-THESIS-2010-51, see http://inspirebeta.net/search?ln=en&p=fermilab-thesis-2010-51&f=&action_search=Search.
See also http://www-cdf.fnal.gov/physics/ewk/2010/WW_WZ/index.html and an earlier related work, T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. **D82**, 112001 (2010). [arXiv:1008.4404 [hep-ex]].

[2] B. C. Allanach, C. G. Lester, M. A. Parker, B. R. Webber, JHEP **0009**, 004 (2000). [hep-ph/0007009].

[3] A. Rajaraman, F. Yu, [arXiv:1009.2751 [hep-ph]].

[4] G. Aad *et al.* [Atlas Collaboration], [arXiv:1102.2357 [hep-ex]].

[5] S. Chatrchyan *et al.* [CMS Collaboration], [arXiv:1103.1348 [hep-ex]].

[6] D. S. M. Alves, E. Izaguirre, J. G. Wacker, [arXiv:1008.0407 [hep-ph]].

[7] V. Khachatryan *et al.* [CMS Collaboration], Phys. Lett. **B698**, 196-218 (2011). [arXiv:1101.1628 [hep-ex]].

[8] J. B. G. da Costa *et al.* [Atlas Collaboration], arXiv:1102.5290 [hep-ex].

[9] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **102**, 161802 (2009). [arXiv:0809.4472 [hep-ex]].

[10] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **103**, 021802 (2009). [arXiv:0902.1266 [hep-ex]].

[11] G. Aad *et al.* [ATLAS Collaboration], [arXiv:1102.0459 [hep-ex]].

[12] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **100**, 031804 (2008) [arXiv:0710.2966 [hep-ex]].

[13] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. **D83**, 031102 (2011). [arXiv:1012.5145 [hep-ex]].

[14] V. Khachatryan *et al.* [CMS Collaboration], Phys. Lett. B **698**, 21 (2011) [arXiv:1012.5945 [hep-ex]].

[15] S. Chatrchyan *et al.* [CMS Collaboration], [arXiv:1103.0030 [hep-ex]].

[16] G. Aad *et al.* [ATLAS Collaboration], arXiv:1103.1391 [hep-ex].

[17] T. Aaltonen *et al.* [The CDF Collaboration], [arXiv:1101.4578 [hep-ex]].

[18] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. Lett. **105**, 161801 (2010). [arXiv:1008.2461 [hep-ex]].

[19] V. Khachatryan *et al.* [CMS Collaboration], Phys. Rev. Lett. **105**, 211801 (2010). [arXiv:1010.0203 [hep-ex]].

[20] F. Abe *et al.* [CDF Collaboration], Phys. Rev. Lett. **74**, 3538-3543 (1995). [hep-ex/9501001].

[21] F. Abe *et al.* [CDF Collaboration], Phys. Rev. **D55**, 5263-5268 (1997). [hep-ex/9702004].

[22] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. **D69**, 111101 (2004). [hep-ex/0308033].

[23] A. S. Melnitchouk [CDF and D0 Collaboration], [arXiv:0810.3338 [hep-ex]].

[24] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. **D79**, 112002 (2009). [arXiv:0812.4036 [hep-ex]].

[25] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **100**, 231801 (2008). [arXiv:0709.0705 [hep-ex]].

[26] J. Alitti *et al.* [UA2 Collaboration], Nucl. Phys. **B400**, 3-24 (1993).

[27] R. Hamberg, W. L. van Neerven, T. Matsuura, Nucl. Phys. **B359**, 343-405 (1991).

[28] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. **D80**, 012002 (2009). [arXiv:0905.3155 [hep-ex]].

[29] P. Langacker, Rev. Mod. Phys. **81**, 1199-1228 (2009). [arXiv:0801.1345 [hep-ph]].

[30] R. Foot, G. C. Joshi, H. Lew, Phys. Rev. **D40**, 2487-2489 (1989).

[31] M. S. Carena, A. Daleo, B. A. Dobrescu, T. M. P. Tait, Phys. Rev. **D70**, 093009 (2004). [hep-ph/0408098].

[32] P. Fileviez Perez, M. B. Wise, Phys. Rev. **D82**, 011901 (2010). [arXiv:1002.1754 [hep-ph]].

[33] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer, https://launchpad.net/ madgraph5

[34] J. Alwall *et al.*, JHEP **0709**, 028 (2007) [arXiv:0706.2334 [hep-ph]].

[35] J. Alwall, P. Artoisenet, S. de Visscher, C. Duhr, R. Frederix, M. Herquet and O. Mattelaer, AIP Conf. Proc. **1078**, 84 (2009) [arXiv:0809.2410 [hep-ph]].

[36] F. Maltoni and T. Stelzer, JHEP **0302**, 027 (2003) [arXiv:hep-ph/0208156].

[37] T. Sjostrand, S. Mrenna, P. Z. Skands, JHEP **0605**, 026 (2006). [hep-ph/0603175].

[38] J. Conway, R. Culbertson, R. Demina, B. Kilminster, M. Kruse, S. Mrenna, J. Nielsen, M. Roco, http://www.physics.ucdavis.edu/ conway/research/software/pgs/pgs4-general.htm

[39] P. Meade and M. Reece, arXiv:hep-ph/0703031.

[40] Y. Bai and B. A. Dobrescu, arXiv:1012.5814 [hep-ph].

[41] M. S. Chanowitz, [arXiv:1102.3672 [hep-ph]].

[42] M. R. Buckley, D. Hooper, J. Kopp, E. Neil, [arXiv:1103.6035 [hep-ph]].