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Sensitivity to New Physics in the W + jet-jet Decay Channel at the Tevatron

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ABSTRACT

Anomalous production of W + jet-jet events is possible at the Tevatron in many theories of new physics such as technicolor and extended gauge models. We outline methods for searching for new heavy particles, X, via the decay $X \to Wjj$ with and without jet b-tagging. We estimate the sensitivity to $W' \to WZ$, $Z' \to WW$ and $\rho_{\rm T} \to Wjj$ for Run II (2 fb^{-1}) and TeV33 (30 fb^{-1}) and discuss some of the challenging experimental problems associated with searching for technicolor signatures.

I. INTRODUCTION

W', Z' and technicolor models [1, 2] have long been known to predict new heavy particles which in turn decay into the W+jet-jet final state at the Tevatron [3]. The W' search in the Run 1 data is complete, so we use it to outline the search methods and, using some simple assumptions, we extrapolate the sensitivity to 30 fb^{-1} of data. For those cases which have final state b-quarks, we discuss possibilities using b-tagging. Finally, we discuss some of the challenging problems associated with searching for technicolor signatures.

II. THEORY

A. Heavy Vector Bosons W' and Z'

In the simplest W' model, known as the reference model [1], the W' is a heavier version of the ordinary W and is assumed to have the same vertex couplings ($Wq\bar{q}$, $Wl\nu$ and WWZ) as the ordinary W in the Standard Model (SM). Also all fermions, specifically neutrinos, are the same as their SM counterparts. The dominant features of this model are the high production cross sections and the increase in $\Gamma(W' \to WZ)$ as $\mathrm{M}^5_{W'}$ which gives rise to a large branching fraction into WZ. However, at large masses ($\mathrm{M}_{W'} \approx$425 GeV) the resonance width becomes so wide ($\Gamma \approx \frac{M_{W'}}{2}$) that perturbation theory breaks down[4] and the model is no longer applicable. This model has already been excluded in the Run 1 data [5].

In extended gauge models[1], proposed to restore left-right symmetry to the weak force, the effective $W'WZ$ vertex becomes parameterized in terms of a mixing angle ξ which is estimated to be $\xi = C(\frac{M_W}{M_{W'}})^2$ where C is a constant of order 1[6]. In this case the width only increases linearly with $\mathrm{M}_{W'}$. In this note all results assume C=1. Similar arguments hold for the production and decay of $Z' \to WW \to e\nu jj$. In the mass region above 200 GeV, as shown in [1], $\sigma \cdot Br(Z' \to e\nu jj) \approx \sigma \cdot Br(W' \to e\nu jj)$.

B. Technicolor

We assume a simple toy model of color singlet technicolor[2], which has a technirho ($\rho_{\rm T}$) which decays into a pair of technipions ($\Pi_{\rm T}$). In this model, there is an isotriplet of mass-eigenstate technipions $\pi^\pm_{\rm T}$ and $\pi^0_{\rm T}$ which mix with $W^\pm_{\rm L}$ and $Z^0_{\rm L}$ via $|\Pi_{\rm T}>= \sin\chi|W_{\rm L}> + \cos\chi|\pi_{\rm T}>$, where χ is a mixing angle. Thus, depending on the masses and the value of the mixing angle, the following decay modes are allowed:

- Charged decays
  $\rho^+_{\rm T} \to W^+Z^0 \leftarrow$
  $\rho^+_{\rm T} \to W^+\pi^0_{\rm T} \leftarrow$
  $\rho^+_{\rm T} \to Z^0\pi^+_{\rm T}$
  $\rho^+_{\rm T} \to \pi^0_{\rm T}\pi^+_{\rm T}$
- Neutral decays
  $\rho^0_{\rm T} \to W^+W^- \leftarrow$
  $\rho^0_{\rm T} \to W^+\pi^-_{\rm T} \leftarrow$
  $\rho^0_{\rm T} \to W^-\pi^+_{\rm T} \leftarrow$
  $\rho^0_{\rm T} \to \pi^+_{\rm T}\pi^-_{\rm T}$

where the arrows indicate the channels which have possible Wjj final states.

Technipion decays are Higgs-like, i.e, the dominant decay is expected to be into heavy fermion pairs:

- $\pi^0_{\rm T} \to b\bar{b}$ if $\mathrm{M}_{\pi_{\rm T}} < 2m_t$
- $\pi^0_{\rm T} \to t\bar{t}$ if $\mathrm{M}_{\pi_{\rm T}} > 2m_t$
- $\pi^+_{\rm T} \to c\bar{b}, c\bar{s}$ or $\tau\nu$ if $\mathrm{M}_{\pi_{\rm T}} < m_t + m_b$
- $\pi^+_{\rm T} \to t\bar{b}$ if $\mathrm{M}_{\pi_{\rm T}} > m_t + m_b$

These processes can be broken down into three final state jj cases: 2 b-quarks, 1 b-quark and 0 b-quarks. However, the cross sections and branching ratios are HIGHLY dependent on the masses of the $\rho_{\rm T}$ and the $\pi_{\rm T}$ as well as the mixing angle between the vector bosons and the mass-eigenstate $\pi_{\rm T}$'s.

There are many challenges associated with looking for technicolor signatures. There are (at least) three unknown parameters in the theory; M_ρ, M_π, and χ, which make it unclear where it is we should look. However, many of the final state signatures are similar and can be searched for simultaneously. Another problem with multiple similar signatures is that for some combination of the parameters, many of the final states would look similar and perhaps even completely wash out a signal. For example, if M_ρ = 400 GeV, M_π = 110 GeV, and the mixing angle is such that $\sigma \cdot Br(\rho \to WW) \approx \sigma \cdot Br(\rho \to WZ) \approx \sigma \cdot Br(\rho \to W\pi)$ we could have three resonances so close that we might misinterpret the events as a continuum and part of a small normalization problem.

III. WHAT'S BEEN DONE SO FAR: THE SEARCH FOR $W' \to WZ$

The Run 1 $W' \to WZ$ search is complete[5], so we use it to outline the general W + jet-jet search, and making some simple assumptions, extrapolate the sensitivity to 30 fb^{-1} of data.

We highlight the main features of the methods used in the $W' \to WZ$ search and point out the primary limitations to using this as an example for technicolor:

- The search identifies the W via the decay channel $W \to e\nu$;
- The search identifies the Z via the decay[7] channel $Z \to jj$
- It uses high kinematic thresholds to reduce the W+Jets backgrounds
- The limits already set assume that the new production would show up as ONE bump in the jet-jet mass spectrum (coming from a Z boson and centered at 90 GeV) vs. W+jet-jet mass[8] spectrum (coming from a new particle and centered at its mass)
- When the total widths are well defined and small, the limits used in the extended gauge model are applicable
- The method was designed for good acceptance for the total event mass in the region around 500 GeV. It is not clear that this is the optimal method for lower mass configurations
- The method is very general and can be used to search for any high-mass jet-jet vs. W+jet-jet mass spectral anomaly (i.e, from any new particle or particles X, Y, which might decay via $X \to WY \to Wjj$)
- The region 'outside the peak' is used to normalize the W+Jets cross section
- Using these cuts, roughly 20% of the events are from backgrounds other than SM W+Jets

We summarize the cuts here:

- electron $E_T \geq 30$ GeV, $|\eta| < 1.0$
- $\not{E}_T \geq 30$ GeV (neutrino)
- At least two high energy jets. (1 Jet with $E_T \geq 50$ GeV, a second Jet with $E_T \geq 20$ GeV. Both with $|\eta| < 2.0$)

IV. RESULTS

A. Looking at the data in Run 1

Figure 1 shows the W+jet-jet mass spectra for the data and background from Run 1. We note that the number of W+jets events is normalized to the number of data events minus the other backgrounds. The data are well modeled by the background Monte Carlos. If there were new particle production (W', Z' or ρ_T) with a large enough cross section, it would show up as a bump in this distribution.

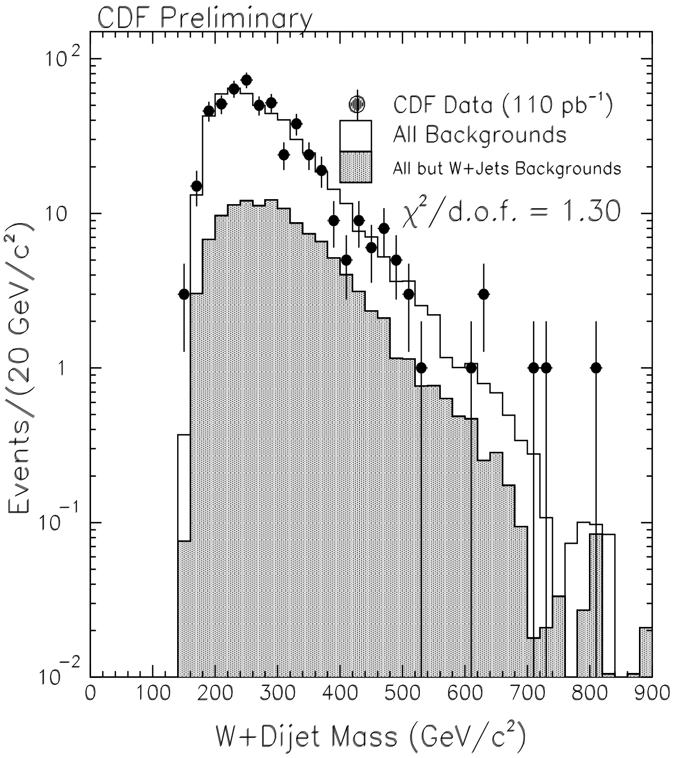

Figure 1: W+jet-jet mass spectrum for the data along with the background predictions. The background spectrum is normalized to the same number of events in the data as in the backgrounds. There is no evidence for W' or any new particle produced in association with a W. The χ^2/d.o.f. = 1.30. We expect 4.2 events above $M_{W+jj} > 600$ GeV; we observe 7.

B. Results from the $W' \to WZ$ Search

The acceptance rises from 6% at $M_{W'}$ = 200 GeV/c^2 to 35% at $M_{W'}$ = 600 GeV/c^2, and the 95% CL exclusion limits in the mass vs. ξ plane are shown in Figure 2. Since we have excluded the reference model, we concentrate on the sensitivity to the extended gauge model with $\xi = (\frac{M_W}{M_{W'}})^2$. For simplicity, because this is a background limited exclusion, we have made the reasonable assumption that the cross section limits scale as the inverse of the square root of the luminosity.

Similar arguments hold for the production and decay of $Z' \rightarrow WW \rightarrow e\nu jj$. Since the W and the Z have similar masses we expect that the limits are virtually identical to those of the W', i.e, we assume $\sigma_{95\%\mathrm{CL}} \cdot Br(Z' \rightarrow e\nu jj) = \sigma_{95\%\mathrm{CL}} \cdot Br(W' \rightarrow e\nu jj)$. These results are shown in Figure 3.

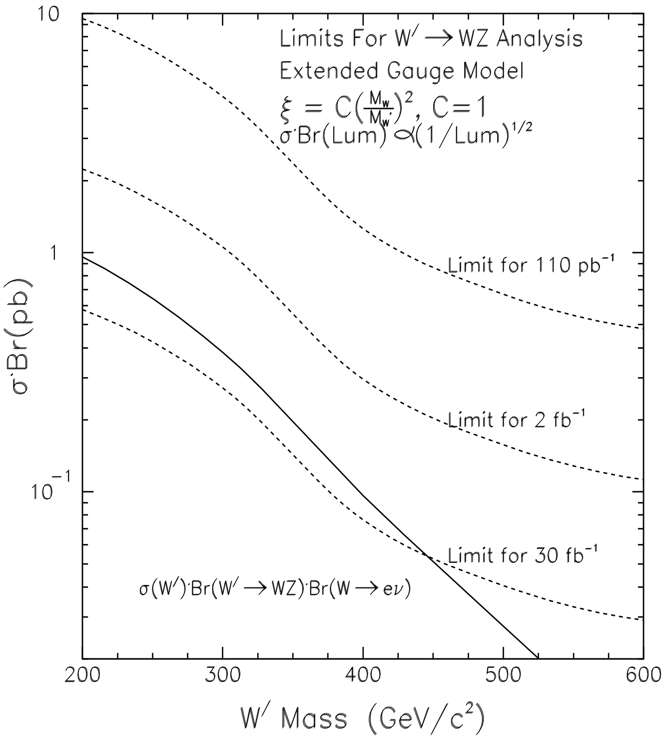

Figure 2: 95% CL upper limit of $\sigma \cdot Br(W' \rightarrow WZ) \cdot Br(W \rightarrow e\nu)$ vs. $M_{W'}$ for the extended gauge model with $\xi = (\frac{M_W}{M_{W'}})^2$. The solid line is the theoretically expected $\sigma \cdot Br$. The dashed lines show predicted limits for 110 pb^{-1}, 2 fb^{-1} and 30 fb^{-1} respectively. Note that we have assumed that the limits simply scale as the inverse of the square root of the luminosity.

C. Extrapolating Results to the $\rho_{\mathrm{T}} \rightarrow WX \rightarrow e\nu jj$ Search

As previously mentioned, the masses as well as the branching ratios to the various decay modes are highly model dependent. For simplicity, we assume that the limits for $\rho_{\mathrm{T}} \rightarrow WX \rightarrow e\nu jj$ are identical to that for the W' case and that they scale as the inverse of the square root of the luminosity. For the theoretical predictions we assume that the branching ratio $\rho_{\mathrm{T}} \rightarrow WX \rightarrow Wjj = 100\%$, and that the mass of the intermediate particle, X, is near that of the Z. These results are shown in Figure 4.

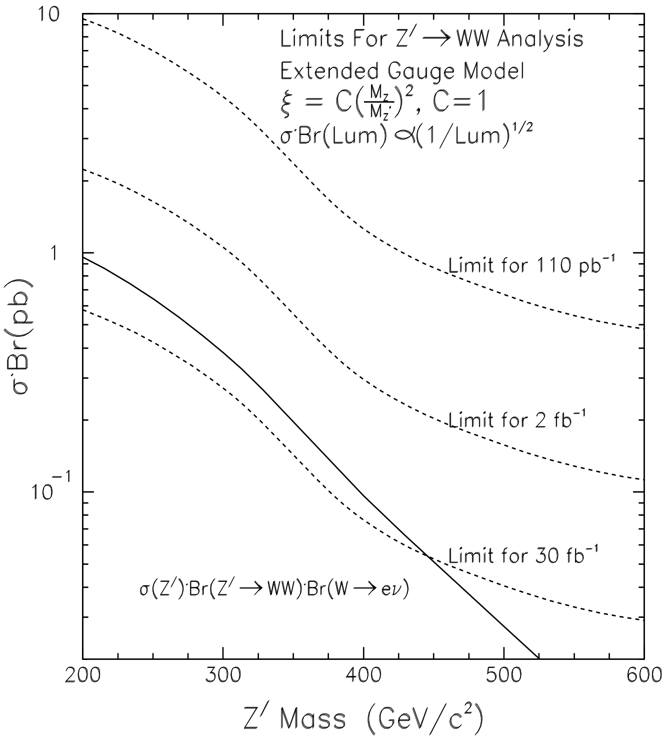

Figure 3: 95% CL upper limit of $\sigma \cdot Br(Z' \rightarrow WW) \cdot Br(W \rightarrow e\nu)$ vs. $M_{Z'}$ for the extended gauge model with $\xi = (\frac{M_Z}{M_{Z'}})^2$. The solid line is the theoretically expected $\sigma \cdot Br$. The dashed lines show predicted limits for 110 pb^{-1}, 2 fb^{-1} and 30 fb^{-1} respectively. We have assumed $\sigma_{95\%\mathrm{CL}} \cdot Br(Z' \rightarrow e\nu jj) = \sigma_{95\%\mathrm{CL}} \cdot Br(W' \rightarrow e\nu jj)$ and that the limits simply scale as the inverse of the square root of the luminosity.

V. WHEN THERE ARE FINAL STATE B-QUARKS

A. Overview

The ρ_{T} often decays to π_{T} which in turn can decay to b-quarks. The $e\nu bj$ and $e\nu bb$ final states are very different from the generic $e\nu jj$ final states as they have the additional final state b-quark which can be tagged. Since there could be either one or two final state b's we use an event selection similar to that of the CDF top analysis [9]. This selection criteria has a number of advantages and disadvantages:

- Advantages

  Less background;

  We can an lower kinematic thresholds to get more acceptance;

  Cleaner signal

- Disadvantages

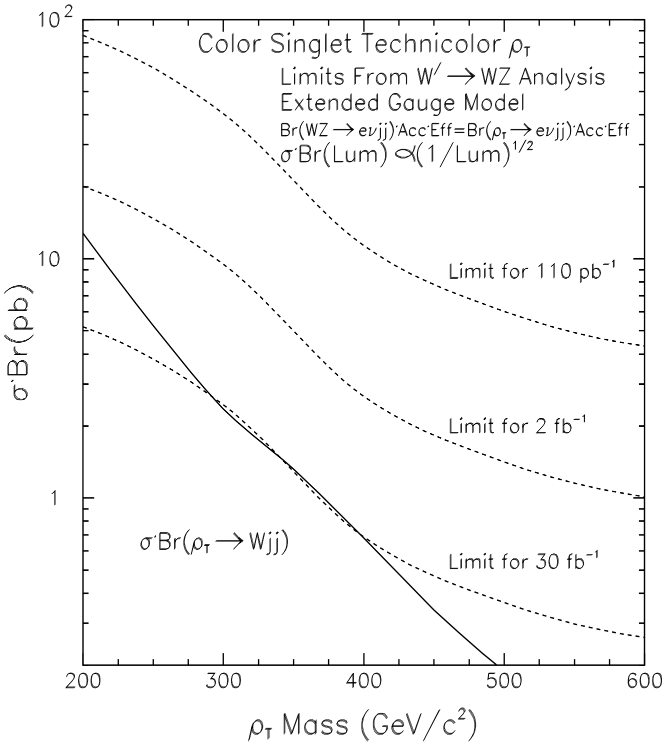

Figure 4: 95% CL upper limit of $\sigma \cdot Br(\rho_{\rm T} \to Wjj)$ vs. $M_{\rho_{\rm T}}$. The solid line is the theoretically expected $\sigma \cdot Br$ for the color singlet case and assume $\rho_{\rm T} \to WX \to Wjj$ = 100%. The dashed lines show predicted limits for 110 pb^{-1}, 2 fb^{-1} and 30 fb^{-1} respectively. Note that we have assumed that the limits simply scale as the inverse of the square root of the luminosity

Smaller Branching Ratio into final state b-quarks.

Smaller Efficiency·Acceptance

Looser Kinematic thresholds require tighter lepton identification cuts.

We use the following cuts:

- Central, isolated electron or muon ($|\eta| < 1.0$)
- Tight electron and Muon identification cuts [9]
- Lepton $E_{\rm T} > 20$ GeV
- $\not{E}_{\rm T} > 20$ GeV
- One or more b-tagged jet

B. Limit Estimates

We expect roughly 50 events passing the above cuts for Run 1, and the efficiency $\times$ Acceptance for these cuts is $\approx 0.5\%$ for $\pi_{\rm T} \to b\bar{b}$ with $M_{\pi_{\rm T}} = 100$ GeV and $M_{\rho_{\rm T}} = 200$ GeV. To set limits we use:

$$\sigma = \frac{N_{\rm Events}}{\rm Lum \cdot Acc \cdot \epsilon}$$

Two methods are used to estimate the limits:

- Assume all are 'signal' to set limits (Conservative):
  95% CL Upper Event Limit = 64 events
  $\to \sigma \cdot Br(\rho_{\rm T} \to l\nu bb) = 120$ pb.

- Assume all are 'background' to set limits:
  95% CL Upper Event Limit = 14 events
  $\to \sigma \cdot Br(\rho_{\rm T} \to l\nu bb) = 30$ pb.

Scaling by the square root of the luminosity we find limits of 2 pb with 30 fb^{-1}. However, we could probably do better with fits and smarter cuts.

VI. CONCLUSIONS

We have outlined methods for searching for new heavy particles, X, via the decay $X \to Wjj$ and presented a summary of the sensitivity to new physics for luminosities up to 30 fb^{-1} for heavy vector bosons (W' and Z') and for color singlet technicolor. Since some cases have final state b-quarks, we presented some preliminary methods and results using b-tagging. In addition we have highlighted some of the problems associated with searching for technicolor signatures. The bottom line is that the W+jet-jet channel is a good place to look for new physics. In fact there are so many things which could show up that we wouldn't even know what we had if we did find something. If there is nothing to be found we will have sensitivity to these processes at the 300 - 500 GeV level with 30 fb^{-1} of data.

VII. ACKNOWLEDGMENTS

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VIII. REFERENCES

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[3] We note that these methods are applicable for searches such as $W' \to tb, W' \to WH, H \to WW$ and associated Higgs (WH) production.

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[7] Note that we are not requiring the jets to be hadronic decays from quarks. Specifically, $Z^0 \rightarrow e^+e^-$ and $Z^0 \rightarrow \tau^+\tau^-$ decays are included in this search by virtue of the fact that we are simply searching for two energy clusters in the detector.

[8] The jet-jet and W+jet-jet invariant masses are created using the electron, $\not{E}_{\mathrm{T}}$, and the two jets with the highest $\mathrm{E_T}$ in the events with $|\eta| < 2.0$. We define the jet-jet mass to be $m = \sqrt{(E_1 + E_2)^2 - (\vec{P}_1 + \vec{P}_2)^2}$. The jet-jet mass resolution is roughly 10%. To reconstruct the W+jet-jet mass we need the longitudinal component of the neutrino momentum (P_{z}^{ν}) since it cannot be measured, as particles exiting the detector with large $|\eta|$ can carry large high longitudinal momenta. If we assume the mass of the electron-neutrino system to be equal to W boson mass[10] (taken to be 80 GeV/c^2) then P_{z}^{ν} is restricted to two possible values. When the transverse mass is greater than 80 GeV/c^2, the two an P_{z}^{ν} solutions have imaginary components. In such events the constraint is made to the value of the transverse mass instead of to 80 GeV/c^2 which gives two identical solutions. Once we have the neutrino solution(s), we find the invariant mass of the W+jet-jet system by using the two jets. We choose the solution with the lower invariant mass since studies have shown that it does a better job of giving back the correct W' mass and width. We also use the same procedure on the data as for the background and the signal Monte Carlo samples to reduce any other systematic problems introduced by this method.

[9] F. Abe et al., Phys. Rev. D 50, 2966 (1994)

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