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Search for a Resonance Decaying into WZ Boson Pairs in $p\bar{p}$ Collisions

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We present the first search for an electrically charged resonance W' decaying to a WZ boson pair using 4.1 fb^{-1} of integrated luminosity collected with the D0 detector at the Fermilab Tevatron $p\bar{p}$ collider. The WZ pairs are reconstructed through their decays into three charged leptons ($\ell = e, \mu$). A total of 9 data events is observed in good agreement with the background prediction. We set 95% C.L. limits on the $W'WZ$ coupling and on the W' production cross section multiplied by the branching fractions. We also exclude W' masses between 188 and 520 GeV within a simple extension of the standard model and set the most restrictive limits to date on low-scale technicolor models.

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The standard model (SM) of particle physics is widely believed to be a low energy approximation of a more fundamental theory of elementary particles and their interactions. Many extensions of the SM, such as the sequential standard model (SSM) [1], extra dimensions [2], little Higgs [3], and technicolor [4] models, predict new heavy W' resonances decaying to a pair of electroweak W and Z bosons. Some models [2–4] also offer an alternative to the SM mechanism of electroweak symmetry breaking. Thus, the observation of resonant WZ boson production would not only manifest new physics beyond the SM, but also could yield an insight into the origin of mass.

This Letter describes the first search for a heavy charged boson, referred to as the W', decaying to W and Z bosons. The CDF and D0 collaborations have searched for a W' decaying to fermions [5–7]. Current limits exclude W' with masses $\lesssim$1 TeV at 95% C.L., assuming the SSM as benchmark and that the $W' \to WZ$ decay is fully suppressed. Thus, our search is complementary to the previous studies.

In technicolor, particles such as ρ_T and a_T have narrow widths and can decay to WZ bosons. The experimental signature of these particles is therefore similar to that of a W'. We will interpret the results of our search within the low-scale technicolor model (LSTC), where the masses of ρ_T and a_T are predicted to be below 500 GeV, well within the energy reach of the Tevatron. Since ρ_T and a_T have almost the same mass we refer to them collectively as ρ_T. The branching fraction for $\rho_T \to WZ$ depends strongly on the relative masses of the technipion, $M(\pi_T)$, and technirho, $M(\rho_T)$. The D0 collaboration searched previously for technicolor in the $W\pi_T \to W + \text{jets}$ final state [8], which is one of the major decay channels for light technipions. In this Letter we present a search in a previously unexplored region of LSTC phase space with $M(\pi_T) \lesssim M(\rho_T)$ where ρ_T decays predominantly to a WZ boson pair.

We perform the search using data collected with the D0 detector [9] at the Fermilab Tevatron $p\bar{p}$ collider at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. After applying data quality and trigger requirements, the integrated luminosity corresponds to 4.1 fb^{-1}.

The Monte Carlo (MC) samples for resonant WZ signal and SM backgrounds are generated using PYTHIA [10], with the exception of $Z + \text{jets}$ and $t\bar{t}$ processes that are generated using ALPGEN [11] interfaced with PYTHIA for showering and hadronization. All MC samples are passed through a full GEANT [12] simulation of the D0 detector. The MC data are corrected to describe the luminosity dependence of the trigger and reconstruction efficiencies in data and the contribution from multiple $p\bar{p}$ interactions. The MC sample for signal is produced assuming SSM W' production for masses starting at 180, 190, 200 GeV and then up to 1 TeV in steps of 50 GeV, using CTEQ6L1 [13] parton distribution functions (PDF). The interference between signal and the SM s channel WZ production [14] is negligible and is not taken into account. We generate technicolor WZ samples using typical parametrization of LSTC phenomenology implemented in PYTHIA [15] to estimate the leading order cross section, efficiency, and acceptance of the selection criteria of the $\rho_T \to WZ$ production. All MC samples are normalized to the integrated luminosity using next-to-leading order cross section calculations, with the exception of the W' signal cross section, which is known to next-to-next-to-leading order (NNLO) [16]. All MC samples are subject to the same event selection as applied to data.

In this search we select events where both the W and the Z bosons decay leptonically and consider only final states with electrons and muons. Candidate events with at least two final state electrons are selected using single-electron triggers, while those with at least two muons are selected using single-muon triggers resulting in efficiencies of 100% and 92%, respectively, for signal events. The events are required to have missing transverse energy $\not{E}_T >$ 30 GeV [17] (from the undetected neutrino) and at least three charged leptons with transverse momenta $p_T >$ 20 GeV satisfying the electron or muon identification criteria described below. An electron candidate is identified as a central track matched to an isolated cluster of energy in the calorimeter, with a shower shape consistent with that of an electron, in the pseudorapidity range $|\eta| < 1.1$ or $1.5 < |\eta| < 2.5$. A muon candidate is reconstructed from segments in the muon spectrometer matched to a central track, and is required to be within $|\eta| < 2$. The muon candidate must be isolated from other activity in the tracker and calorimeter.

The selection of WZ candidate events is done in two steps. We first require the presence of a candidate Z boson by selecting the electron pairs and muon pairs with opposite electric charges that have invariant mass nearest to the mass of the Z boson. The reconstructed mass of the Z boson candidate must be between 80 and 102 GeV for an electron pair and between 70 and 110 GeV for a muon pair. Then, we select the highest transverse momentum lepton among the remaining lepton candidates in the event as the lepton from the W boson decay. The W and Z bosons produced from heavy resonances can be highly boosted, resulting in a large spatial separation between leptons from the W and Z decays. To reduce background, we require the lepton from the W boson decay to be separated by $\Delta\mathcal{R} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 1.2$ from Z decay leptons.

Several background processes contribute to the trilepton + $\not{E}_T$ final state. The largest background having at least three genuine leptons in the final state is from SM WZ production, followed by the ZZ process, where one of the leptons from the Z boson is not reconstructed and gives rise to $\not{E}_T$. These are estimated from MC simulation. The instrumental background is due to misidentification of a lepton in processes such as $Z + \text{jets}$, $Z\gamma$, and $t\bar{t}$. Contribution from $t\bar{t}$ is estimated from MC simulation and found to be negligible. $Z + \text{jets}$ and $Z\gamma$ productions are the major instrumental backgrounds and they are estimated using data driven techniques described below.

Jets from $Z + \text{jets}$ production can be misidentified as either an electron or a muon from W boson decay. To estimate this contribution, we select a sample of Z boson decays with an additional *"false"* lepton candidate for each final state. For the $Z +$ electron final state the lepton candidate is required to have most of its energy deposited in the electromagnetic calorimeter and satisfy the electron isolation criteria, but at the same time a shower shape

TABLE I. Number of data events, expected number of signal events for a SSM W' mass of 500 GeV, and expected number of background events with statistical and systematic uncertainties.

Source	Total
W' (500 GeV)	4.4 ± 1.1
WZ	9.0 ± 1.5
ZZ	1.0 ± 0.2
Z + jets	0.2 ± 0.1
$Z\gamma$	0.1 ± 0.1
Total	10.2 ± 1.6
Observed	9

inconsistent with that of an electron. For the Z + muon final state, the lepton candidate is required to fail the isolation criteria used to select muons. These requirements ensure that the lepton is either a misidentified jet or a lepton from a semileptonic decay of a heavy-flavor quark. The contribution from the Z + jets background with misidentified leptons is estimated by scaling the number of events in this sample with a p_T-dependent ratio of misidentified leptons passing the two different sets of criteria measured in a multijet data sample depleted of true isolated leptons.

The channels with $W \to e\nu$ decays can be mimicked by the initial or final state radiation $Z\gamma$ processes where a photon is either incorrectly matched to a track, or converts, and one of the conversion electrons is selected as the candidate for W boson decay. To estimate the contribution from this background, we measure the rate at which a photon can be misidentified as an electron in $Z \to \mu\mu\gamma$ final states in data, as it offers a virtually background-free source of photons because of the $\mu\mu\gamma$ invariant mass constraint to the $M(Z)$. We choose the muon decay of the Z boson to avoid ambiguity in assigning the electromagnetic showers in the $ee\gamma$ final states. The $Z\gamma$ contribution is estimated by folding in the p_T-dependent photon to electron misidentification rate with the p_T distribution of γ in the $Z\gamma$ Monte Carlo simulation [18].

The selection criteria yield 9 events in data with an estimate of 10.2 ± 1.6 background events. The final numbers of observed candidates and expected signal and background events with total uncertainties are summarized in Table I. The expected and observed yields for the four independent samples used in this search are given in Table II. Several sources of systematic uncertainties are considered here. The major systematic uncertainty is associated with the modeling of the trigger, the lepton identification efficiency and the detector acceptance. It is estimated to be 15%. This uncertainty is taken as fully correlated between signal and background. We assign to the $Z\gamma$ background estimation a systematic uncertainty of 100% for any potential mismodeling of $\not{E}_T$. The dominant systematic uncertainty on Z + jets background is from the limited statistics of the Z + false lepton sample. We estimate this uncertainty to be 40%. Finally, the uncertainty on integrated luminosity is 6.1% [19], and the uncertainty on the theoretical NNLO production cross section of signal is 5%.

As the number of observed candidates is consistent with the background-only hypothesis, we set limits on W' production in a modified frequentist approach [20] that uses a log-likelihood ratio (LLR) test statistic [21]. It calculates the confidence levels for the signal + background, CL_{s+b}, and background-only hypothesis, CL_b, by integrating the LLR distributions obtained from simulated pseudoexperiments using Poisson statistics. Systematic uncertainties are treated as uncertainties on the expected number of signal and background events. This ensures that the uncertainties and their correlations are propagated to the outcome with proper weights. The 95% C.L. limit on the cross section is then defined as a cross section for which the ratio $CL_s = CL_{s+b}/CL_b$ is 0.05.

We use the WZ transverse mass to discriminate between the W' signal and the backgrounds in the limit setting procedure. It is calculated as

$$M_T = \sqrt{(E_T^Z + E_T^W)^2 - (p_x^Z + p_x^W)^2 - (p_y^Z + p_y^W)^2},$$

where E_T^Z and E_T^W are the scalar sums of the transverse momenta of the decay products of the Z and W candidates, respectively; while p_x^Z, p_x^W, p_y^Z, and p_y^W are obtained by summing the x and y components of momenta of the respective decay particles. In these sums, the transverse momentum of the neutrino arising from the W boson decay is inferred from the direction and magnitude of $\not{E}_T$. The distribution of the WZ transverse mass is given in Fig. 1 for data, backgrounds, and two signal hypotheses. We obtain a limit on the production cross section of W' multiplied by

TABLE II. Background estimation from the leading sources, the total background, expected signal, and observed events for each signature. The signal corresponds to a SSM W' with a mass of 500 GeV. The uncertainties reflect both the statistics of the MC and data samples and systematics.

Mode	WZ	ZZ	Z + jets	$Z\gamma$	Total	W'	Data
eee	1.4 ± 0.3	0.07 ± 0.02	0.02 ± 0.01	0.03 ± 0.03	1.52 ± 0.33	1.07 ± 0.28	3
$ee\mu$	2.0 ± 0.4	0.24 ± 0.06	0.07 ± 0.04	<0.01	2.31 ± 0.49	1.17 ± 0.31	2
$e\mu\mu$	2.0 ± 0.4	0.10 ± 0.03	0.04 ± 0.02	0.07 ± 0.07	2.21 ± 0.46	0.83 ± 0.22	2
$\mu\mu\mu$	3.6 ± 0.8	0.54 ± 0.12	0.05 ± 0.03	<0.01	4.19 ± 0.89	1.28 ± 0.34	2

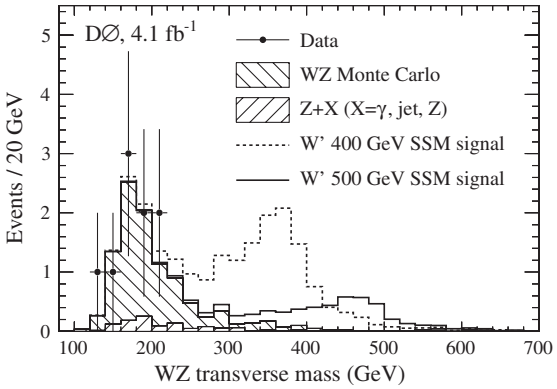

FIG. 1. Transverse mass distribution of the WZ system in data with the major SM backgrounds and two SSM W' mass hypotheses overlaid.

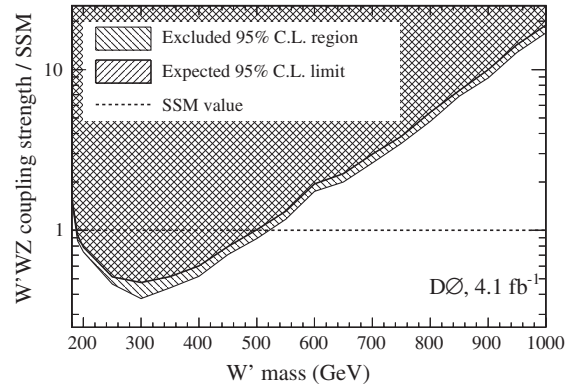

FIG. 3. Expected and excluded area of the $W'WZ$ coupling strength normalized to the SSM value as a function of the W' mass.

the branching ratio $B(W' \to WZ)$ as a function of the $M(W')$ as shown in Fig. 2. This is the first limit to date on resonant $W' \to WZ$ production. Assuming SSM production, we exclude a W' with mass $188 < M(W') < 520$ GeV at 95% C.L.. This result agrees with the expected sensitivity limit of $188 < M(W') < 497$ GeV.

We also study the sensitivity to other models that predict a W'-like resonance with width greater than in the SSM by varying the width of the W' resonance while keeping $\sigma(W') \times B(W' \to WZ)$ fixed to the SSM value. We find that the limits slightly degrade but stay within 1 standard deviation (s.d.) around the expected sensitivity limits for models with widths up to 25% of the resonance mass. Since the limits have a limited sensitivity to the width of the W', we can exclude more general models that predict W' bosons with arbitrary couplings to the W and Z bosons. We interpret the results in terms of the $W'WZ$ trilinear coupling normalized to the SSM value as function of the W' mass (see Fig. 3).

The limits on the resonant WZ production cross section $\sigma \times B(W' \to WZ)$ yield stringent constraints on the LSTC and exclude most of the allowed phase space where $\rho_T \to WZ$ decay is dominant. The excluded and expected limits at 95% C.L., as a function of the ρ_T and π_T masses, are shown in Fig. 4.

In summary, we have presented a search for hypothetical W' particles decaying to a pair of WZ bosons using leptonic W and Z decay modes in 4.1 fb^{-1} of Tevatron Run II data. We observe no evidence of resonant WZ production, and set limits on the production cross section $\sigma \times B(W' \to WZ)$. Within the SSM we exclude W' masses between 188 and 520 GeV at 95% C.L. This is the best limit to date on $W' \to WZ$ production and is complementary to previous searches [5–7] for W' decay to fermions. These limits are less stringent for the models that predict W' with width greater than that predicted by the SSM model, but stay within the 1 s.d. band around the expected SSM limits for widths below 25% of the W' mass. The original limits are also interpreted within the technicolor model. We exclude ρ_T with mass between 208 and 408 GeV at 95% C.L. for $M(\rho_T) < M(\pi_T) + M(W)$. These are the most stringent constraints on a typical LSTC phenomenology model [15] when the ρ_T decays predominantly to WZ boson pair.

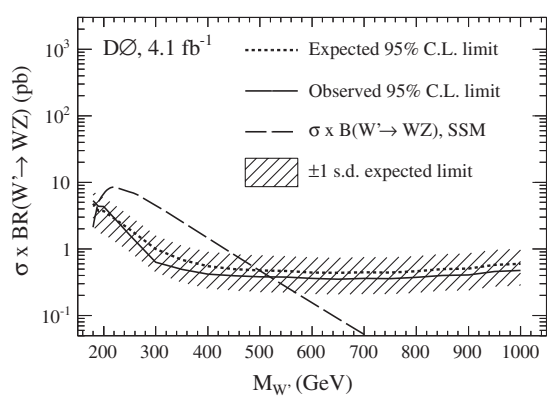

FIG. 2. Observed and expected 95% C.L. upper limits and ± 1 s.d. band around the expected limits on the cross section multiplied by $B(W' \to WZ)$ with the SSM prediction overlaid.

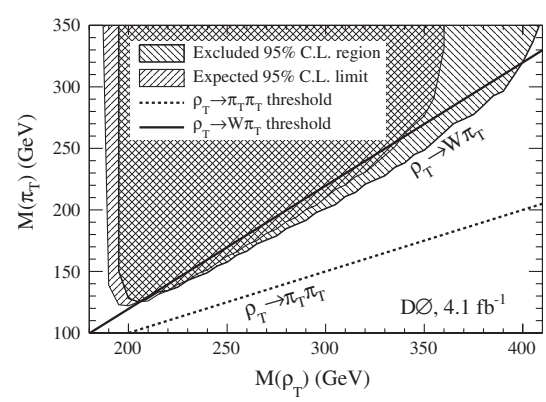

FIG. 4. Expected and excluded areas of the π_T *vs.* ρ_T masses are given with the thresholds of the $\rho_T \to W\pi_T$ and $\rho_T \to \pi_T\pi_T$ overlaid.

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