

# Search for a $W'$ Boson via the Decay Mode $W' \rightarrow \mu\nu_\mu$ in 1.8 TeV $p\bar{p}$ Collisions

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We report the results of a search for a  $W'$  boson produced in  $p\bar{p}$  collisions at a center-of-mass energy of 1.8 TeV using a  $107\text{ pb}^{-1}$  data sample recorded by the Collider Detector at Fermilab. We consider the decay channel  $W' \rightarrow \mu\nu_\mu$  and search for anomalous production of high transverse mass  $\mu\nu_\mu$  lepton pairs. We observe no excess of events above background and set limits on the rate of  $W'$  boson production and decay relative to standard model  $W$  boson production and decay using a fit of the transverse mass distribution observed. If we assume standard model strength couplings of the  $W'$  boson to quark and lepton pairs, we exclude a  $W'$  boson with invariant mass less than  $660\text{ GeV}/c^2$  at 95% confidence level.

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Three of the four known forces of nature, the strong, electromagnetic, and weak forces, are described by the standard model using a local gauge theory that accounts for each interaction using a vector boson force carrier [1]. The predictions of this model have been confirmed by the dis-

coveries of the  $W$  and  $Z^0$  bosons, the carriers of the weak force, and high precision measurements of their properties. The standard model is not a complete theory, however, as it fails to explain the number of lepton and quark generations, the rather large mass scale between the very lightest and

very heaviest of the fundamental fermions, and the number or structure of the gauge symmetries that exist in nature. It is still an open experimental question as to whether additional forces exist. Evidence for a new force could come from observation of the corresponding force carrier.

Previous searches have been conducted for possible new force carriers that couple to  $\mu$  final states in a manner similar to the vector bosons that mediate the weak force. These searches have yielded null results, and have set model-dependent limits on the rate at which such a particle is produced and its mass. The most sensitive searches have been performed at the Fermilab Tevatron Collider. A  $Z'$  boson with a mass  $< 690 \text{ GeV}/c^2$  has been excluded at 95% confidence level (C.L.) [2]. Searches considering the decay mode  $W' \rightarrow \mu\nu_\mu$  have excluded a  $W'$  boson with mass  $< 435 \text{ GeV}/c^2$  at 95% C.L. [3]. These mass limits all assume that the new vector boson's couplings to leptonic final states will be given by the standard model, which predicts that the total width of the boson increases linearly with  $M_{W'}$ , where  $M_{W'}$  is the mass of the boson. Indirect searches studying, for example, the Michel spectrum in  $\mu$  decay have resulted in more model-independent limits with less sensitivity [4]. Searches in other channels have also been used to place constraints on possible  $W'$  masses: The most stringent exclude a  $W'$  boson at 95% C.L. with a mass  $< 720 \text{ GeV}/c^2$  that decays via  $W' \rightarrow e\nu_e$  [5].

In this Letter, we present the results of a new search for a  $W'$  boson in the  $\mu\nu_\mu$  decay mode. We use a data sample of  $107 \text{ pb}^{-1}$  of  $1.8 \text{ TeV } p\bar{p}$  collisions recorded by the Collider Detector at Fermilab (CDF) detector during 1992–1995. This search is based on an analysis of high mass  $\mu\nu_\mu$  candidate final states, and is sensitive to a variety of new phenomena that would result in anomalous production of such high mass events. We use these data to set limits on the production cross section times branching fraction of the process

$$p\bar{p} \rightarrow W'X \rightarrow \mu\nu_\mu X, \quad (1)$$

normalizing the candidate event sample to the large observed  $W \rightarrow \mu\nu_\mu$  signal in the same event sample. This search assumes that the decay  $W' \rightarrow WZ^0$  is suppressed [6] and that  $M_\nu \ll M_{W'}$ , where  $M_\nu$  is the mass of the neutrino from a  $W'$  boson decay. We also assume that the daughter neutrino does not decay within the detector volume.

In this search, we select events that are consistent with the production of both the standard model  $W$  boson, followed by the decay  $W \rightarrow \mu\nu_\mu$ , and any heavier object that decays in the same manner. We place limits on the production and decay rate of such a massive object relative to the production and decay rate of the  $W$  boson. This approach avoids the need to make an absolute cross section measurement or upper limit, and avoids many of the uncertainties associated with such a technique. We subsequently use our relative production and decay rate upper limits to set lower limits on the mass of such a  $W'$  boson. However, these upper limits place constraints on any processes that

generate high mass  $\mu\nu_\mu$  pairs, and represent an increase of a factor of 20 in sensitivity from earlier searches in this channel. Additional details of this analysis are presented in Ref. [7].

The CDF detector is described in detail elsewhere [8]. The detector has a charged particle tracking system immersed in a 1.41 T solenoidal magnetic field, which is coaxial with the  $p\bar{p}$  beams. The tracking system consists of solid state tracking detectors and drift chambers that measure particle momentum with an accuracy of  $\sigma_{p_T}/p_T \sim 0.001 p_T$ , where  $p_T$  is the momentum of the charged particle measured in  $\text{GeV}/c$  transverse to the  $p\bar{p}$  beam line. The tracking system is surrounded by segmented electromagnetic and hadronic calorimeters that measure the flow of energy associated with particles that interact hadronically or electromagnetically out to a pseudorapidity  $|\eta|$  of 4.2 [9]. A set of charged particle detectors outside the calorimeter is used to identify muon candidates with  $|\eta| < 1.0$ .

Candidate events were identified in the CDF trigger system by the requirement of at least one muon candidate with  $p_T > 9$  or  $12 \text{ GeV}/c$ , depending on running conditions. The event sample was subsequently refined after full event reconstruction by requiring a well-identified muon candidate with momentum  $p_T > 20 \text{ GeV}/c$  and by requiring that the missing transverse energy in the event,  $\cancel{E}_T$ , be greater than  $20 \text{ GeV}$ .

Additional requirements were imposed to reject specific sources of backgrounds. Events consistent with arising from QCD dijet production, where one jet is misidentified as a muon candidate, were rejected by requiring that the muon candidate be isolated from energy flow in the event and that the energy deposited in the calorimeter by the muon candidate be consistent with that arising from a minimum ionizing particle. Events due to Drell-Yan production of dimuons (dominated by the decay  $Z^0 \rightarrow \mu^+\mu^-$ ) were rejected by vetoing events if a second isolated muon candidate with  $p_T > 15 \text{ GeV}/c$  was found in the event. Finally, events arising from cosmic rays were rejected by imposing tight requirements between the timing of the beam interaction and the muon candidate passing through the calorimeter, and by removing events that had evidence of a second charged particle observed within  $0.05 \text{ rad}$  of being back-to-back with the  $\mu$  candidate.

This selection resulted in a sample of 31 992 events. The distribution of the transverse mass

$$M_T \equiv \sqrt{2p_T\cancel{E}_T(1 - \cos\phi_{\mu\nu})}, \quad (2)$$

where  $\phi_{\mu\nu}$  is the azimuthal angle between the  $\mu$  candidate and the missing transverse energy vector, shows a clear Jacobian peak that is associated with the production and decay of the  $W$  boson. This distribution, illustrated in Fig. 1, also shows a smoothly falling distribution above the Jacobian peak with little obvious structure.

In order to understand the composition of this high transverse mass sample, we fit the  $M_T$  distribution between 40 and  $2000 \text{ GeV}/c^2$  using an unbinned maximum

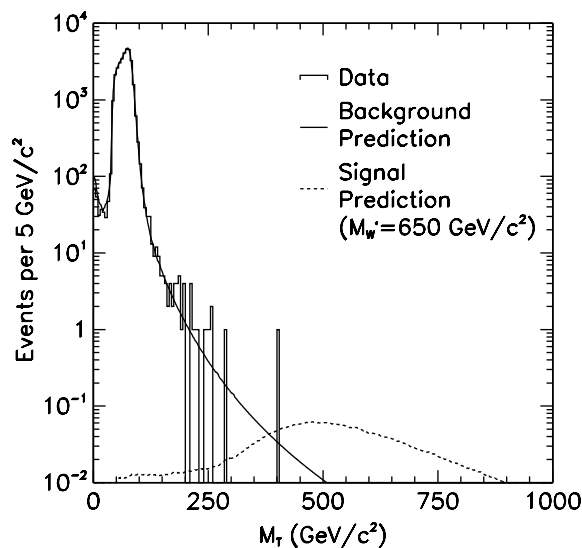


FIG. 1. The transverse mass spectrum of the  $\mu\nu_\mu$  candidate events. The background rate is predicted from the fit described in the text. The distribution expected from the production of a  $W'$  boson with a mass of  $650 \text{ GeV}/c^2$  is illustrated by the dashed distribution.

likelihood technique, which included contributions from a hypothetical  $W'$  boson decaying to the  $\mu\nu_\mu$  final state,  $W \rightarrow \mu\nu_\mu$  decay, and all other significant background sources. The largest background sources were the production and decay of the  $W$  and  $Z^0$  bosons into final states consisting of muons. These included the decay modes  $W \rightarrow \mu\nu_\mu$ ,  $W \rightarrow \tau\nu_\tau \rightarrow \mu\nu_\mu\nu_\tau$ ,  $Z^0 \rightarrow \tau^+\tau^- \rightarrow \mu X$ , and  $Z^0 \rightarrow \mu^+\mu^-$ . The other background sources were muons arising from top quark production and “fake” muons arising from QCD dijet production. The shape of the  $M_T$  distributions for the  $W'$  signal and the backgrounds from  $W$  and  $Z^0$  production were calculated using a Monte Carlo technique employing the PYTHIA program [10]. We used a next-to-leading order theoretical prediction for the  $p_T$  and  $\eta$  dependence of  $W'$  and  $W$  production [11]. Our model included a simulation of the CDF detector that was derived from studies of  $Z^0 \rightarrow \mu^+\mu^-$  candidate events.

Studies of specific data samples constrained the size and shape of the other possible background contributions. The relative size of the various  $W$  and  $Z^0$  boson decay modes and  $t\bar{t}$  production were determined using the measured production ratios and branching fractions to these final states

[12]. The size of the dijet background was determined by studying the characteristics of event samples enriched in this dijet contamination. The total number of events with  $M_T > 200 \text{ GeV}/c^2$  from standard model sources was estimated from the fit to the  $M_T$  distribution between 40 and  $2000 \text{ GeV}/c^2$  to be  $11.8 \pm 0.9$  events, with the largest contribution arising from off-mass-shell  $W$  boson production. This agrees with the observed yield of 14 events in this  $M_T$  region.

The results of the fit to the  $M_T$  data distribution assuming only contributions from  $W$  production and decay and the other known background sources are plotted in Fig. 1. The agreement between the data distribution and the fit prediction is good. A small excess of events with transverse masses around  $200 \text{ GeV}/c^2$  is not statistically significant. The contributions from the various background sources are listed in Table I.

Our Monte Carlo calculation together with the detector model was used to determine the ratio of acceptances for detection of  $W'$  and  $W$  bosons. This ratio rises as a function of  $M_{W'}$ , peaking at  $\sim 1.7$  for  $M_{W'} = 300 \text{ GeV}/c^2$ , and then falling to  $\sim 1.5$  for  $M_{W'} = 800 \text{ GeV}/c^2$ . The initial increase in acceptance is due to a heavier  $W'$  boson being produced more centrally. The subsequent decrease results from very high energy muon daughters depositing significant amounts of energy in the calorimeter.

We set upper limits on the relative contribution of a  $W'$  boson by fitting the data distribution to a combination of the background distributions described above and a  $W'$   $M_T$  distribution expected from the production and decay of a  $W'$  boson of a given mass. The results of the fit, expressed as the ratio of observed  $W'$  boson candidates to the number expected assuming standard model strength couplings, are shown in Table II. We then used the resulting likelihood function to set a 95% C.L. upper limit on this ratio, also shown in Table II. In setting these limits, we considered only the likelihood function in the “physical region” where this ratio was greater than or equal to zero. We note that these limits are insensitive to the assumed width of the  $W'$  boson, as the width of the expected signal distribution is dominated by detector resolution for  $W'$  masses greater than approximately  $300 \text{ GeV}/c^2$ .

The procedure used to calculate this upper limit incorporated various systematic uncertainties using the method given in [12]. The largest resulted from the choice of

TABLE I. The event yields for the background sources above and below  $M_T = 200 \text{ GeV}/c^2$ . Uncertainties are correlated.

Process	Fitted Event Yield	
	$(40 < M_T < 200 \text{ GeV}/c^2)$	$(M_T > 200 \text{ GeV}/c^2)$
$W \rightarrow \mu\nu_\mu$	$27925 \pm 209$	$8.99 \pm 0.81$
$W \rightarrow \tau\nu_\tau$	$687 \pm 27$	$0.04 \pm 0.01$
$Z/\gamma \rightarrow \mu\mu$	$2824 \pm 196$	$2.02 \pm 0.35$
$Z/\gamma \rightarrow \tau\tau$	$47 \pm 3$	$0.02 \pm 0.02$
$t\bar{t}$	$14_{-3}^{+4}$	$0.29_{-0.06}^{+0.07}$
QCD	$74 \pm 37$	$0.42_{-0.42}^{+0.43}$

TABLE II. The expected number of events from  $W'$  boson production,  $N_{\text{exp}}$ , assuming standard model strength couplings and normalized to the observed  $W$  boson yield. We also show the rate of  $W'$  boson production and decay relative to the rate predicted using standard model couplings, and the 95% C.L. upper limit on this relative rate as a function of  $M_{W'}$ . The uncertainties are statistical and do not include the systematic uncertainties. They are defined by requiring the log-likelihood to change by one-half unit and are not 68% C.L. intervals. The 95% C.L. upper limit includes both statistical and systematic uncertainties and have been determined as described in the text.

$M_{W'}$ (GeV/ $c^2$ )	$N_{\text{exp}}$ (events)	$\frac{\sigma \cdot \mathcal{B}(W' \rightarrow \mu \nu_\mu)}{\sigma \cdot \mathcal{B}(W' \rightarrow \mu \nu_\mu)_{\text{SM}}}$	
		Fit	Upper limit
200	$2330 \pm 100$	$0.009^{+0.004}_{-0.004}$	0.08
250	$984 \pm 45$	$0.011^{+0.007}_{-0.006}$	0.10
300	$456 \pm 26$	$0.006^{+0.011}_{-0.006}$	0.10
350	$224 \pm 13$	$0.000^{+0.014}_{-0.000}$	0.09
400	$115 \pm 8$	$0.000^{+0.018}_{-0.000}$	0.11
450	$60.2 \pm 3.5$	$0.000^{+0.026}_{-0.000}$	0.14
500	$32.5 \pm 2.4$	$0.000^{+0.039}_{-0.000}$	0.20
550	$17.2 \pm 1.4$	$0.000^{+0.058}_{-0.000}$	0.30
600	$9.69 \pm 0.84$	$0.000^{+0.096}_{-0.000}$	0.50
650	$5.37 \pm 0.50$	$0.000^{+0.159}_{-0.000}$	0.83
700	$3.01 \pm 0.31$	$0.000^{+0.273}_{-0.000}$	1.60
750	$1.72 \pm 0.21$	$0.000^{+0.495}_{-0.000}$	2.94

parton distribution function, which at the highest masses contributed  $\sim \pm 10\%$  uncertainty to the relative  $W$  and  $W'$  production cross section. We used the CTEQ4A1 parton distribution functions with a four-momentum transfer squared  $Q^2 = M_{W'}^2$  for our result [13] but employed several parton distribution functions to determine our sensitivity to this choice. Other systematic uncertainties included those arising from our knowledge of the track  $p_T$  resolution and the uncertainty in acceptance arising from variations in the  $W'$  boson  $p_T$  distribution. The total systematic uncertainty varied from 4% for  $M_{W'} = 200$  GeV/ $c^2$  to 12% for  $M_{W'} = 700$  GeV/ $c^2$ . These were incorporated into our upper limits using a procedure that convoluted the likelihood function determined by our fit to the  $M_T$  distribution with the probability distribution functions associated with each uncertainty. The results are dominated by the statistical uncertainties of the data sample. We also computed cross section upper limits by counting signal events above background in the high transverse mass region and obtained comparable results to the likelihood fit, though these depended on the region chosen for signal events.

We can convert the 95% C.L. upper limit on the relative cross sections and decay rates into a lower limit on the mass of the  $W'$  boson by excluding all masses where our 95% C.L. limit on the ratio of cross sections times branching fractions is less than unity. We determined the predicted cross sections using a parton-level matrix element calculation and the CTEQ4A1 parton distribution functions, taking into account the fact that a  $W'$  boson with a mass above approximately 180 GeV/ $c^2$  decays into three quark generations.

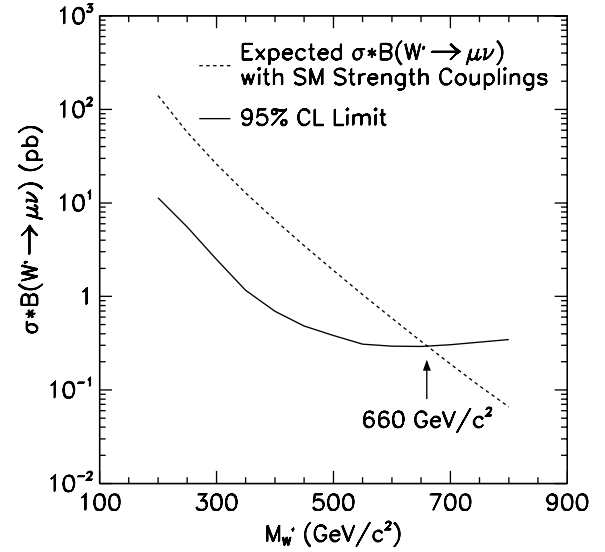


FIG. 2. The upper limits on the  $W'$  boson production cross section as a function of the  $W'$  boson mass.

The resulting upper limit on the  $W'$  boson cross section versus  $M_{W'}$  is shown in Fig. 2, where we have now normalized our upper limits on the production cross section ratios using the predicted  $W$  boson production cross section, which is consistent with measurements [14]. We compare this upper limit with the predictions for a  $W'$  boson with standard model strength couplings, also shown in the figure. This allows us to exclude a  $W'$  boson with mass between 200 and 660 GeV/ $c^2$ . Taking into account the previous searches in this channel, a  $W'$  boson with standard model strength couplings and mass below 660 GeV/ $c^2$  can be excluded. This corresponds to an increase in sensitivity of approximately a factor of 20 from the earlier studies of this final state.

In summary, we have performed a search for the production of a new heavy vector gauge boson in 1.8 TeV  $p\bar{p}$  collisions and decaying into the  $\mu\nu_\mu$  final state. We use a fit of the  $M_T$  distribution to exclude a  $W'$  boson with mass  $< 660$  GeV/ $c^2$  at 95% C.L., assuming standard model strength couplings. This limit is comparable to those set using the  $e\nu_e$  decay modes, and represents a significant improvement in sensitivity for  $W'$  boson searches using the muon decay mode.

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