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Search for $W$ bosons decaying to an electron and a neutrino with the D0 detector


FERMILAB-PUB-07/499-E

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This Letter describes the search for a new heavy charged gauge boson $W'$ decaying into an electron and a neutrino. The data were collected with the D0 detector at the Fermilab Tevatron $p\bar{p}$ Collider at $\sqrt{s} = 1.96$ TeV, and correspond to an integrated luminosity of about 1 fb$^{-1}$. Lacking any significant excess in the data in comparison with known processes, an upper limit is set on $\sigma_{W'} \times B(W' \rightarrow e\nu)$.
and a $W'$ boson with mass below 1.00 TeV can be excluded at the 95% C.L., assuming standard-model-like couplings to fermions. This result significantly improves upon previous limits, and is the most stringent to date.

PACS numbers: 12.60.Cn, 13.85.Rm, 14.70.Pw

The standard model (SM) describes the fundamental fermions and their interactions via gauge bosons at a high level of accuracy, but it is not considered to be a complete theory. Additional gauge bosons are introduced in e.g. left-right-symmetric models (broken $SU(2)_L \times SU(2)_R$) or in grand unified theories which may also involve supersymmetry (e.g. $E_6$) [1]. Assuming the most general case, a new gauge group can comprise a new mixing angle $\xi$, new couplings to the fermions $g'$ and a new CKM matrix $U'$. In some models the $W'$ boson ($W'^+ or W'^-$) is right-handed, and decays therefore into a right-handed neutrino and a charged lepton. However, such a neutrino has not yet been observed. The mass limits on the $W'$ boson will in general depend on $\xi$, $g'$, $U'$, and the masses of possible additional neutrinos.

In this Letter we make the assumption that there is no mixing, $g'$ is equal to the SM coupling, $U'$ is equal to the SM CKM matrix, and that the decay channel $W' \rightarrow WZ$ is suppressed. Furthermore, the width $\Gamma_{W'}$ of the $W'$ boson is assumed to scale with its mass $m_{W'}$,

$$\Gamma_{W'} = \frac{4}{3} \frac{m_{W'}}{m_W} \cdot \Gamma_W. \quad (1)$$

The factor of 4/3 is applied in order to account for the decay into the third quark family (e.g. $W' \rightarrow t\bar{b}$) which is possible for $m_{W'}$ above the kinematic threshold for this process. In case of the existence of additional generations of fermions, it is assumed that they are too heavy to be produced by a $W'$ decay. This generic model has been introduced by Altarelli et al. [2]. It corresponds to the manifest left-right-symmetric model [3] with light right-handed neutrinos if the $W'$ boson is right-handed. In this report, the general approach [2] is considered, where the additional gauge boson $W'$ can be right- or left-handed.

The $W'$ boson has been searched for previously by the D0 [4, 5, 6] and the CDF experiments [7, 8, 9] in various final states. The most restrictive limit so far is $m_{W'} > 800$ GeV at the 95% C.L. [3] reported by D0 ($W' \rightarrow q\bar{q}'$, Run I).

Data collected with the D0 detector [10] at the Fermilab Tevatron $p\bar{p}$ Collider at a center-of-mass energy of 1.96 TeV are analyzed for the production of $W'$ bosons and the subsequent decay into an electron and a neutrino. The neutrino can not be detected, but it gives rise to missing transverse energy ($E_T$) in the detector. The dataset corresponds to an integrated luminosity [11] of $0.99 \pm 0.06$ fb$^{-1}$, and was collected between 2002 and 2006 during Run II of the Tevatron.

The D0 detector has a central-tracking system, consisting of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet, with designs optimized for tracking and vertexing at $|\eta| < 3$ and $|\eta| < 2.5$, respectively, where $\eta = -\ln \tan \frac{\theta}{2}$ is the pseudorapidity and $\theta$ the polar angle w.r.t. the z-axis (proton-beam direction). A liquid-argon and uranium calorimeter has a central section (CC) covering pseudorapidities $|\eta|$ up to $\approx 1.1$, and two end calorimeters (EC) that extend coverage to $|\eta| \approx 4.2$, each housed in separate cryostats. An outer muon system, at $|\eta| < 2$, consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T iron toroids, followed by two similar layers after the toroids. Luminosity is measured using plastic scintillator arrays placed in front of the EC cryostats.

Different SM processes contribute to the electron and $E_T$ final state: inclusive production of $W$ or $Z$ bosons, dibosons ($WW, WZ, ZZ$) or $t\bar{t}$ pairs where at least one boson or one top quark decays into electrons directly or via tau decays. In these processes the missing energy is due to the neutrino. There are also two sources of misidentification background that can contribute to the electron and $E_T$ final state: QCD multijet background with one jet misidentified as an electron and energy mismeasurement which can cause large $E_T$ either along or in the opposite direction of the electron, and $Z \rightarrow ee$ events where one electron is lost (e.g. entering non-instrumented sections of the calorimeter) or misreconstructed. The latter case can lead to large $E_T$.

The $W'$ signal and SM processes (including $Z \rightarrow ee$) have been simulated with the PYTHIA 6.323 [12] Monte Carlo program using the CTEQ6L1 [13] parton distribution functions (PDFs), except for the QCD multijet background, which is estimated from data. The generated events are passed through a detailed detector simulation based on GEANT [14], and combined with randomly triggered events from data to simulate the effects of pile-up and multiple interactions. Higher order corrections to the PYTHIA leading order cross sections ($K$ factors) have been applied. The next-to-next-to-leading order (NNLO) $K$ factors and errors due to PDF uncertainties for the signal, the $W$ and the $Z$ samples are extracted from Ref. [15]: the NNLO (NLO) cross section for $t\bar{t}$ (di-boson) production is taken from Ref. [16] (17).

The signal cross section falls steeply with increasing mass of the $W'$ boson. In addition, for very large masses the on-mass-shell production of $W'$ bosons is heavily suppressed due to the smallness of the PDFs at large $x$. As shown in Fig. [14] the Jacobian distribution no longer exhibits a pronounced peak. The transverse mass $m_{T}$ is calculated from the transverse energy of the electron, $E_T$. [4]
the missing transverse energy, $E_T$, and the azimuth angle difference between the electron and $E_T$ via

$$m_T = \sqrt{2E_T^\text{el}E_T(1 - \cos \Delta \phi(\text{electron}, E_T))}. \quad (2)$$

Events triggered by a set of inclusive single electron triggers are considered. Electrons with $E_T^\text{el} > 30$ GeV passing the offline identification criteria are selected. Monte Carlo studies have shown that the majority ($\approx 80\%$) of the electrons stemming from the $W'$ decays are emitted into the central detector region. Since the forward detector region exhibits a small signal-to-background ratio, only electrons reconstructed in the CC region exhibit a small signal-to-background ratio. Electrons reconstructed in the CC region are emitted into the central detector region. Since $94 \%$ of the electrons stemming from the $W'$ boson production and decay in the $e\nu$ mode using the $W'$ peak region (60 GeV < $m_T$ < 140 GeV, as shown in Fig. 2(a)) because many efficiency and acceptance errors largely cancel in this ratio. We use the theoretical prediction for the $W'$ boson production cross section $\sigma_W \times B(W \rightarrow e\nu) = 2583^{+94}_{-84}$ pb from Ref. [13].

Jets may be present in conjunction with a $W'$ boson due to higher order QCD contributions. Since PYTHIA does not properly describe the transverse momentum distribution of the $W'$ boson in such processes, this spectrum is separately reweighted in events with one, two and three jets in order to match the distributions observed in the data. This correction affects $10\%$ of the $W'$ Monte Carlo events. The sample defined by the selection cuts mentioned above contains 452,984 data events compared to 454,000 events expected from SM processes and instrumental backgrounds after applying all corrections.

Two kinds of systematic uncertainties contribute in this analysis. The uncertainties of the normalization in the $W$ peak region (4%), the cross sections of the SM processes (4-10%), the electron reconstruction efficiency corrections (2%) and the scale factor for the QCD multijet sample (7%) affect only the global normalization. Uncertainties on the PDFs, electron energy scale and resolution, jet energy scale, decay width $\Gamma_W$ of the $W'$ boson, and the reweighting of the transverse momentum of the $W$ boson lead to changes of the shape of the distributions.

In order to study the effect of the electron energy scale and resolution, the electron energies have been varied within the known uncertainties. The variations of scale and resolution are performed independently. The $E_T$ is recalculated after varying the electron energy. The overall uncertainty on the event numbers is large for the
uncertainty is below 1%. The overall uncertainty varies between 3% (m_{W'} = 500 \text{ GeV}) and 8% (m_{W'} = 1200 \text{ GeV}). For the W sample an uncertainty of 3% is derived. The width of the W boson is known to about 2% \cite{20}. This can cause a shift (∼4%) of the tail of the transverse mass distribution of the W boson. Finally, the jet energy scale has been varied, and the E_T recalculated. The resulting uncertainty is below 1%.

The tail of the spectrum (m_T > 140 \text{ GeV}) is now considered to search for W' \rightarrow e\nu. A good agreement between data and background prediction can be observed as shown in Fig. 2b, c. In Table I the breakdown of the individual contributions of the various background processes is given, including expected numbers of signal events. Since we do not observe any significant excess in the data, an upper limit is set on the production cross section times branching fraction σ_{W'} × B(W' → e\nu).

The limit is derived using a binned likelihood for the whole transverse mass spectrum with 140 \text{ GeV} < m_T < 1000 \text{ GeV}. The individual shape-changing systematic uncertainties (up and down variation) enter the limit calculation via individual histograms; bin correlations are taken into account.

A Bayesian approach \cite{21} is used to calculate upper limits on the cross section for different resonance masses. A Poisson distribution is assumed for the number of expected events in each bin of the transverse mass distribution, as well as flat prior probabilities for the signal cross sections. The prior for the combined signal acceptance and background yields is a multivariate Gaussian with uncertainties and correlations described by the corresponding covariance matrix.

The observed and expected 95% C.L. limits on the production cross section times branching fraction σ_{W'} × B(W' → e\nu) are shown in Fig. 3. The lower bound of the theoretical cross section is used to obtain the mass limit. Hence, an additional heavy charged gauge boson with mass below 1.00 \text{ TeV} is excluded at the 95% C.L.

In summary, a search for a new heavy charged gauge boson W' decaying to an electron and a neutrino has been performed using 1 fb^{-1} of data collected with the D0 detector in Run II. We do not observe an excess in the data, and set upper limits on the cross section times branching fraction, which are of the order of 10 – 40 fb.

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|}
\hline
\textbf{Process} & \textbf{Events} & \textbf{stat} & \textbf{sys} \\
\hline
\textbf{Data} & 967 & & & \\
\textbf{Sum of backgrounds} & 959 & 21 & 90 \\
W → e\nu & 875 & 20 & 90 \\
QCD multijet (from data) & 27 & 2 & 2 \\
other & 57 & 3 & 4 \\
W' → e\nu & & & \\
m_{W'} = 500 \text{ GeV} & 1169 & 24 & 86 \\
m_{W'} = 600 \text{ GeV} & 393 & 8 & 32 \\
m_{W'} = 700 \text{ GeV} & 147 & 3 & 13 \\
m_{W'} = 800 \text{ GeV} & 51 & 1.1 & 5.4 \\
m_{W'} = 900 \text{ GeV} & 19 & 0.4 & 2.4 \\
m_{W'} = 1000 \text{ GeV} & 7.4 & 0.2 & 1.1 \\
m_{W'} = 1100 \text{ GeV} & 3.4 & 0.1 & 0.5 \\
m_{W'} = 1200 \text{ GeV} & 1.7 & 0.1 & 0.2 \\
\hline
\end{tabular}
\caption{Event numbers in the data compared to the background prediction after applying the cut on the transverse mass m_T > 140 \text{ GeV}. For the signal and background processes statistical and systematic uncertainties are given.}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Comparison between data and background prediction: (a) Distribution of the transverse mass m_T; (b) distribution of the electron transverse energy E_T in events with m_T > 140 \text{ GeV}; (c) distribution of the ratio of electron transverse energy and E_T in events with m_T > 140 \text{ GeV}. The signal is shown for two different masses of the W' boson.}
\end{figure}
for $W'$ boson masses of 500 GeV < $m_{W'}$ < 1200 GeV. Further, a lower limit on the mass of the $W'$ boson is derived, assuming that the new gauge boson as introduced in [2] has the same couplings to fermions as the SM $W$ boson. We exclude a $W'$ boson with $m_{W'}$ < 1.00 TeV at the 95% C.L. This result represents the most stringent limit on the mass of a charged heavy gauge boson beyond the standard model to date.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CAPES, CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); Science and Technology Facilities Council (United Kingdom); MSMT and GACR (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); CAS and CNSF (China); Alexander von Humboldt Foundation; and the Marie Curie Program.

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[a] Visitor from Augustana College, Sioux Falls, SD, USA.

[18] The azimuth angle $\phi$ is defined in the plane perpendicular to the beams, with $\phi = \pi/2$ pointing up.