Fermi National Accelerator Laboratory

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# Search for $W' \rightarrow e\nu$ in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1800 GeV

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Glasgow Abstract
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# Search for $W' \to e\nu$ in $p\,\overline{p}$ Collisions at $\sqrt{s} = 1800$ $GeV$

CDF Collaboration[1]

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**Abstract**

We have searched for new, heavy charged gauge bosons, $W'$. The signature searched for is $W' \to e\nu$, where it is assumed that the neutrino in this decay is stable and non-interacting, thus leaving a momentum imbalance in our detector. We have examined the highest transverse mass electron + missing momentum events from $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ $TeV$ for new Jacobian peaks above the $W$ mass. The data used in the search represent 19.7 $pb^{-1}$ collected by CDF at the Fermilab Tevatron Collider. We establish limits on the $W'$ cross section times branching ratio; assuming standard couplings of the $W'$ to fermions, we establish the limit $M_{W'} > 634$ $GeV/c^2$ (95% C.L.).

The unified electroweak theory of Weinberg,[2] Salam,[3] and Glashow[4] has met with outstanding success with the discoveries[5,6] of the $W^{\pm}$ and $Z^0$ bosons at the CERN Sp$\overline{p}$S Collider. This paper presents a search for new, heavy charged gauge bosons, $W'$, in 19.7 $pb^{-1}$ of $p\overline{p}$ collisions from the 1992-1993 Run 1A of the Collider Detector at Fermilab. The properties of the $W'$ depend greatly upon the model used to introduce it. In its simplest form,[7] the $W'$ appears as a heavier version of the left-handed $W$. In this case, the primary decay of the $W'$ for very large masses is $W' \to WZ$. Several models[8,9,10] have also proposed the existence of a $W'$ in the context of restoring left-right symmetry to the weak force at some mass scale $\Lambda_{LR} \approx M_{W'}$. The coupling of the $W'$ to fermions and to left-handed bosons in these extended gauge models is less certain. It is has been argued,[11] for example, that the decay $W' \to WZ$ is

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suppressed because the coupling at the $W'WZ^0$ vertex is multiplied by a left-right mixing angle $\xi \sim \left(\frac{M_W}{M_{W'}}\right)^2$. The nature of the right-handed fermions, furthermore, is unknown. One may expect, for example, that the right-handed $W'$ decays to right-handed $e_R\nu_R$ pairs, but if neutrinos are not Dirac particles, the properties of the $\nu_L$ , namely that it is stable, massless, and non-interacting, may not apply to the $\nu_R$. In some models of extended gauge theories,[12] for example, the $\nu_R$ is too heavy for the process $W'\to e_R\nu_R$. to occur.

The coupling of the $W'$ to right-handed quarks is also *a priori* not known. The restrictions of Lorentz-invariance and renormalizability restrict[13] the $W'$-fermion coupling to be of the form $\frac{ig}{2\sqrt{2}}\overline{\psi}_i(a + b\gamma_5)\gamma_\mu W'^\mu \psi_j U_{ij}$, where $a$ and $b$ are constants and $U_{ij}$ is the CKM matrix element connecting fermions $i$ and $j$. $SU(2)_L$ gauge-invariance in the Standard Model leads to the $V$-$A$ character of the weak interaction with $a = 1$, $b = -1$. No such constraints exist for the right-handed CKM matrix in the context of extended gauge models which introduce a $W'$. With this coupling the partial width to fermions is

$$\Gamma(W'\to f_i f_j) = \frac{a^2 + b^2}{2}\frac{N_c\ G_F\ M_W^2\ M_{W'}}{6\sqrt{2}\pi}\,|U_{ij}|^2,$$

where $N_c$ is the color factor of three for quarks and is 1.0 for leptons. We define the parameter $\lambda^2 \equiv (a^2 + b^2)/2$ which is equal to one in, among other cases, the Standard Model. This is 1.0 in models in which the left- and right-handed gauge sectors couple to matter with equal strengths, known as manifest left-right symmetry ($U_R = U_L$). The case $\lambda^2 = 1$ is referred to as "standard strength couplings."

Many searches have been conducted for the $W'$.[14] Most pertain to the extended gauge models, and hence exploit the differences between the $V$-$A$ nature of the known electroweak interaction and the predicted $V$+$A$ nature of the right-handed sector. Table 1 summarizes the previous experimental limits. For very light neutrino masses, the most stringent limits are astrophysical or cosmological: for $m_\nu < 1\ MeV$ arguments of big bang nucleosynthesis[15] imply $M_{W'} \sim 1\ TeV$, and the energetics of Supernova 1987A imply[16]

$M_{W'} > 720\ GeV$ - $16\ TeV$, depending upon assumptions regarding the right-handed CKM matrix. Limits on $W'$ are also derived[17,18] using the limits on deviations of the muon decay parameters from the $V$-$A$ predictions. Here the limits require the neutrino that couples to the $W'$ to be light enough ($m_\nu < m_\mu$) so as not to cause a suppression of the right-handed decay. The measured difference $\Delta m_K$ between the $K_L$ and $K_S$, constrains the right-handed sector, since it is altered[19] if a right-handed current can contribute to the box diagram connecting the $K^0\overline{K}^0$ system. A light $W'$ could also affect the semileptonic branching ratio of $b \to X\ell\nu$. If the neutrino that couples to the $W'$ is a heavy ($m_\nu > m_b$) Dirac neutrino, then the right-handed charged current cannot contribute to $b$ semileptonic decays, but could contribute to non-leptonic $b$ decays. Thus, the branchiing ration adds constraints[20] to new charged currents with heavy neutrinos. $B_d$-$\overline{B}_d$ mixing strongly constrains[21] the right-handed current, but only in some models for the form of the $U_R$ matrix. The process of neutrinoless atomic double beta decay[22] imposes limits on the $W'$ for the case of heavy Majorana neutrinos. Finally, direct searches for $W'$ by the UA1,[23] UA2,[24] and CDF[25] Collaborationsin $p\overline{p}$ collisions at $\sqrt{s} = 0.6$ and $1.8\ TeV$ through the decay $W' \to \ell\nu$ have placed limits of $M_{W'} > 512\ GeV/c^2$ for the case of "standard strength couplings" ($U_R = U_L$).

We search for the $W'$ in $p\overline{p}$ collisions through the decay $W' \to e\nu$ . This search for new bosons $W'$ is specific to neither right- or left-handed bosons, but in the case of the $W_R'$ it is assumed that the $\nu_R$ is non-interacting and stable. It is not assumed that the $\nu_R$ is massless, only that it is much lighter than the $W'$ ($(m_\nu / M_{W'})^2 << 1$). We search for new Jacobian peaks in the transverse mass spectrum of electron + $\not{E}_T$ data. Doing so, we either measure or set a limit on the cross section times branching ratio into $e\nu$ of the $W'$: $\sigma \cdot B(p\overline{p} \to W' \to e\nu)$. To place a limit on the $W'$ mass requires an assumption regarding the right-handed couplings (the parameter $\lambda^2$ ).

To select candidate events, we require an electron in the central, barrel region of the detector ($|\eta_{(e)}| < 1.05$) with an $E_T$, as measured in the calorimeter, to be $E_T > 30\ GeV$ and the $P_T$, as measured in the central tracking chamber (CTC) to be $P_T > 13\ GeV/c$.[26] In addition we require the electron track to be isolated in the CTC, requiring $Iso(trk) < 5\ GeV/c$, where $Iso(trk)$ is defined as the scalar sum of the $P_T$ of all CTC tracks within a cone of $\Delta R = 0.25$

in $\eta$-$\phi$ space,[27] where $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$. The ratio of energy in the hadron and electromagnetic calorimeter towers of the electron cluster is required to satisfy Had/EM $< 0.055 + 0.045 \times \left(\frac{E}{100}\right)$ A transverse momentum imbalance is required to signal the presence of the non-interacting neutrino. We require $\not{E}_T > 30$ *GeV*, where the missing transverse momentum, or "$\not{E}_T$" is defined as the vector sum of the $E_T$ in all towers in the calorimeter with $|\eta| < 3.6$ and $E_T > 100$ *MeV*. Finally, the primary vertex of the event is required to be $|Z_{vertex}| < 60$ cm and total accidental energy out of time (measured by TDC's in the Hadron calorimeters) is required to be $E_T$ (out-of-time) $< 100$ *GeV*. There are 10845 events passing these cuts. From a study of electrons from $Z^0 \rightarrow e^+e^-$ decays, the efficiency of the isolation, Had/EM, out of time energy, and vertex cuts is found to be 94.3 ± 0.6 %. The Had/EM efficiency, furthermore, agrees well with the efficiency found from an electron testbeam which extended as far as electron energies of 175 *GeV*. A Monte Carlo simulation of the detector shows no degradation in electron identification efficiency up to ≈ 400 *GeV*.

Several other processes can mimic the *W* signal. $Z^0 \rightarrow e^+e^-$ decays, where one electron is detected and the other is lost because is falls into an uninstrumented region of the detector, can produce the signal of an electron and $\not{E}_T$. In some cases a second, isolated stiff track in the CTC or an electromagnetic cluster may be observed. Similarly, *QCD* dijets, where one jet passes our electron selection criteria and the other is mismeasured or falls into an uninstrumented region of the calorimeter to produce $\not{E}_T$, can mimic the $W'$ signal. It is similarly possible to remove these events by searching for clusters of tracks in the CTC which point at calorimeter cracks and at the $\not{E}_T$ vector. A total of 93 events with second isolated, stiff tracks or second electromagnetic clusters are removed from the $W'$ sample as $Z^0$ candidates and 226 events with clusters of tracks are removed as dijet candidates, leaving 10526 events. We estimate the efficiency of the $Z^0$ removal cuts for real *W* events to be 99.9 ± 0.1 % and the dijet removal cuts are estimated to be 99.5 ± 0.2 % efficient for real *W* events.

The backgrounds remaining in the $W'$ sample are *QCD* dijets, $Z^0 \rightarrow e^+e^-$ decays, and the process $W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$. We estimate the number of $Z^0 \rightarrow e^+e^-$ and

$W \to \tau\nu$ decays contaminating the $W'$ sample using the ISAJET Monte Carlo[28] and a detector simulation. We normalize to the results using measured[29] cross sections $\sigma \cdot B(p\overline{p} \to Z^0 \to e^+e^-)$ and $\sigma \cdot B(p\overline{p} \to W \to e\nu)$ and the measured branching ratio $BR(\tau \to e\nu\nu)$. ISAJET predicts well the number of $Z^0 \to e^+e^-$ decays in which the second electron could be observed using the second track in the CTC even when no calorimeter cluster is found. We find that the number of $Z^0$ events remaining in the $W'$ sample is 50 $\pm$ 15 events and the background from $W \to \tau\nu$ is 150 $\pm$ 45 events. We find a total of 0.01 $Z^0$ and $W \to \tau\nu$ events are expected above $M_T > 200\ GeV/c^2$.

The magnitude and shape of the $QCD$ dijet background is estimated from a study of a control sample in the data of "electrons" in which the "electron" has $Iso(trk) > 6\ GeV/c$ and $E_T > 30\ GeV$, and in which $\not{E}_T > 30\ GeV$. These events are presumably mismeasured dijets. We study the efficiency of our dijet removal algorithm on this sample and normalize to the number of events in the $W'$ sample removed using this algorithm. We estimate that the number of dijets left in the sample is 241 $\pm$ 40 events. We expect 2.2 events from dijets with $M_T > 200\ GeV/c^2$. Figure 1 shows the transverse mass distribution of the $W$ candidates and the expected contribution of the backgrounds.

The acceptance, $A_W$, is defined as the efficiency for $W$ (or $W'$ ) events to pass the kinematic cuts on the electron and neutrino and for the electron to be in the geometric acceptance of the detector. The acceptance is determined using a Monte Carlo which generates zeroth order diagrams of $W$ production, $q\overline{q} \to W$ and decays the $W$ into electron and neutrino pairs. The effects of higher order diagrams for $W$ production are mimicked by giving the bosons $P_T$ according to a previous measurement[30] of the $P_T^W$ spectrum. A detector model is used to smear the leptons. We use the MRSD-' structure functions.[31] Systematic uncertainties in the acceptance calculation come from the uncertainty in the $P_T^W$ distribution (0.6%), the detector model (1.3%), the choice of parton distribution functions (1.7%) input to the generator, and the effect of higher-order diagrams (0.8%) not properly accounted for by our lowest order Monte Carlo with $P_T^W$ added.[32] The total uncertainty in $A_W$ is found to be 3%. The acceptance for $M_{W'} = 80\ GeV/c^2$ is found to be $A_W = 0.2169 \pm 0.0064$.

The same Monte Carlo is used to model the $W'$ acceptance. In the Monte Carlo, the $W'$ decay width is taken to have the form $\Gamma(W') = (M_{W'}/M_W)\Gamma_0(W)$, where $\Gamma_0(W) = 2.07$ for $M_{W'} \lesssim 180\ GeV/c^2$ and $\Gamma_0(W) = 2.76$ for $M_{W'} \gtrsim 180\ GeV/c^2$, corresponding to the case where the decay $W' \to t\bar{b}$ is closed or open.[33] For the case where $W' \to t\bar{b}$ is open the leptonic branching ratio is taken to be 1/(12.3); otherwise it is taken to be 1/(9.2).[34] Table 2 lists the expected signal from a $W'$ of various masses in $\int \mathcal{L} dt = 19.7\ pb^{-1}$ of data. The $W'$ acceptance increases with $M_{W'}$ because the charged lepton is more likely to fall within the central barrel region for very heavy $W'$.

To determine a limit on the $W'$ cross section times branching ratio a binned log likelihood fit to the transverse mass spectrum in Figure 1 is performed in which the fraction of the data that is from $W'$ decays is determined. The expected entries, $\mu_i$, in the $i^{th}$ bin is calculated as the sum of non-$W$ background, $W$ decays, and $W'$ decays: $\mu_i \equiv Bck_i + (N_{cand} - \alpha)W_i + \alpha W_i'$, where $N_{cand}$ is the number of $W$ or $W'$ candidates. The parameter $\alpha$ is required to be non-negative ($0.0 \leq \alpha$ ), as prescribed by the Particle Data Group.[35] The case $\alpha = 0$ corresponds to no $W'$ events being present in our data.

For each $W'$ mass, the likelihood function is computed as a function of $\alpha$ and the associated probability function is obtained from the likelihood.[36] The probability function $P_0(\alpha)$ is the probability of obtaining the value $\alpha$ as determined from the likelihood. The systematic uncertainties described above are used to "smear" the probability distribution $P_0(\alpha)$. The probability distribution is convoluted with a gaussian, $G(\alpha;\Delta\alpha)$, where $\Delta\alpha$ is the size of the uncertainty in $\alpha$ from the systematic effects described above. The 95% C.L. upper limit on the $W'$ content in the data is obtained from the point $\alpha$ where $\int_0^{\alpha} P(\alpha')d\alpha' = 0.95$. For very high $W'$ masses, where there are no events in the data, the fit returns a maximum possible of 3 events, as expected from Poisson statistics.

The 95% upper limit on the $W'$ cross section times branching ratio is obtained using the 95% C.L. for $\alpha$, the acceptance for this $W'$ mass, the efficiency of the electron identification, and the acceptance:

$$\sigma \cdot B\,(95\%\ \mathrm{C.L.}) = \frac{\alpha^{(95\%)}}{A_W \varepsilon_W \int \mathcal{L}\, dt}$$

where $\alpha^{(95\%)}$ is determined from the fit, $\int \mathcal{L}\, dt = 19.7 \pm 0.6\ pb^{-1}$ is the integrated luminosity, and the acceptance $A_W$ and efficiency $\varepsilon_W$ come from Table 2. The 95% C.L. limit on the cross section times branching ratio as a function of the $W'$ mass is shown in Figure 2. For the case of standard couplings to fermions, we establish the limit $M_{W'} > 634\ GeV/c^2$ (95% C.L.).

In conclusion, we have conducted a search for new right-handed charged gauge bosons $W'$ in 19.7 $pb^{-1}$ of $p\overline{p}$ collisions at $\sqrt{s} = 1800\ GeV$. Assuming that the $W'$ has standard couplings to fermions, and assuming the right handed neutrino is non-interacting and stable, the 95% C.L. limit $M_{W'} > 634\ GeV/c^2$ is obtained by looking for new Jacobian peaks beyond the $W$ mass. This search is an extension of a previous search conducted by CDF using both electrons and muons in which the limit $M_{W'} > 512\ GeV/c^2$ was established.

| Experimental data - (Assumptions made regarding $\nu$ ) | Limit on $M_{W'}$, Weak Assumptions on $U_R$ $(GeV/c^2)$ | Limit on $M_{W'}$, Assuming $U_R = U_L$ $(GeV/c^2)$ |
|---|---|---|
| Nucleosynthesis ($m_\nu < 1$ $MeV$) | $O(1$ $TeV)$ | |
| SN 1987A ($m_\nu < 10$ $MeV$) | 720 | 16.2 $TeV$ |
| $\Delta m_K$, $B_d$-$\overline{B}_d$, $\mu$ decay ($m_\nu < m_\mu$) | 500 - 560 | 1.3 $TeV$ |
| $\Delta m_K$, $B_d$-$\overline{B}_d$, $b$ decay [a)] ($m_\nu > m_b$) | 450 - 740 | 1.4 $TeV$ |
| $\Delta m_K$, $B_d$-$\overline{B}_d$, $b$, $\beta\beta_{0\nu}$ [b)] ($m_\nu > m_b$) | 450 - 800 | 1.4 $TeV$ |
| $p\overline{p}$ Colliders ($m_\nu < M_W$) | 360 - 512 (old)<br>**450 - 634 (THIS RESULT)** | 512 (old)<br>**634 (THIS RESULT)** |

a) Dirac neutrino only  b) Majorana neutrino only

Table 1: After Langacker,[14] the current experimental limits on the $W'$ mass. The results of $p\overline{p}$ colliders are direct searches, whereas the other results are indirect limits.

| $M_{W'}$ $(GeV/c^2)$ | Expected $\sigma \cdot B\,(pb)$[a] | $A_{W'} \cdot \varepsilon$ (%) | $N_{exp}$[b] | 95% C.L. for $\sigma \cdot B\,(pb)$ |
|---|---|---|---|---|
| 80 | 2237 | 20.3 ± 0.6 | 8939 ± 395 | < 202 |
| 85 | 1487 | 23.5 ± 0.7 | 6874 ± 304 | < 168 |
| 90 | 1257 | 26.5 ± 0.8 | 6613 ± 289 | < 64 |
| 100 | 918 | 31.3 ± 1.0 | 5647 ± 249 | < 3.6 |
| 125 | 464 | 39.1 ± 1.2 | 3564 ± 157 | < 1.3 |
| 150 | 259 | 43.5 ± 1.4 | 2218 ± 98 | < 0.98 |
| 175 | 156 | 46.1 ± 1.5 | 1413 ± 62 | < 0.79 |
| 200 | 98.1 | 47.9 ± 1.5 | 924 ± 41 | < 0.68 |
| 250 | 43.2 | 50.0 ± 1.6 | 425 ± 19 | < 0.61 |
| 300 | 20.8 | 51.0 ± 1.6 | 209 ± 9 | < 0.48 |
| 350 | 10.6 | 51.7 ± 1.7 | 108 ± 5 | < 0.40 |
| 400 | 5.59 | 52.2 ± 1.7 | 57.4 ± 2.5 | < 0.35 |
| 450 | 3.02 | 52.4 ± 1.7 | 31.1 ± 1.4 | < 0.33 |
| 500 | 1.64 | 52.8 ± 1.7 | 17.1 ± 0.8 | < 0.31 |
| 550 | 0.820 | 52.8 ± 1.7 | 8.50 ± 0.38 | < 0.29 |
| 600 | 0.428 | 52.9 ± 1.7 | 4.45 ± 0.20 | < 0.29 |
| 650 | 0.223 | 53.0 ± 1.7 | 2.32 ± 0.10 | < 0.29 |
| 700 | 0.116 | 53.0 ± 1.7 | 1.00 ± 0.04 | < 0.29 |
| 750 | 0.061 | 53.0 ± 1.7 | 0.63 ± 0.03 | < 0.29 |

[a] Assuming "standard strength" coupling.
[b] Expected number of events in 19.7 $pb^{-1}$.

Table 2: Cross section times branching ratio into $e\nu$ of $W'$ and the $W'$ detector acceptance for several $W'$ masses. The branching ratio assumes the same coupling of the $W'$ to fermions as is observed for the $W$. The detector acceptance and identification efficiency do not depend upon the assumption of the couplings. Also shown in this table is the expected number of events in $\int \mathcal{L} dt = 19.7 \pm 0.6\ pb^{-1}$ of data: $N_{exp} = \sigma \cdot B \times (A \cdot \varepsilon) \times \int \mathcal{L} dt$. The cross sections and the $W'$ acceptances in Table 2 are calculated with the Monte Carlo, and the total detection efficiency $\varepsilon = 0.937 \pm 0.010$ is measured from the data. In the final column is shown the 95% C.L. limit on the cross section times branching ratio obtained from the data (see text).

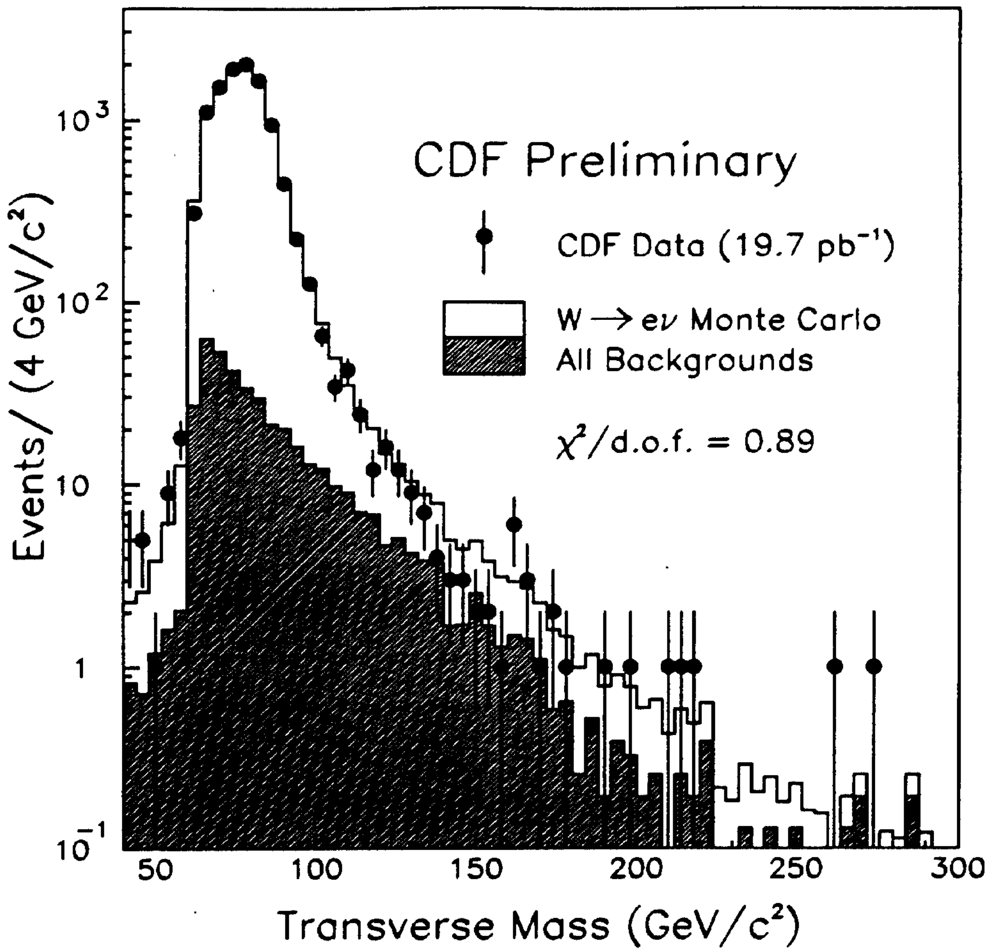


Figure 1: Transverse mass spectrum of the $W$ candidates, along with the expected contributions from non-$W$ backgrounds and from $W \to e\nu$ events. The $W \to e\nu$ curve is calculated with the Monte Carlo used to calculate the $W$ and $W'$ acceptances. No overflows are present. A signal from a $W'$ would show up as a second Jacobian peak at $M_T = M_{W'}$.

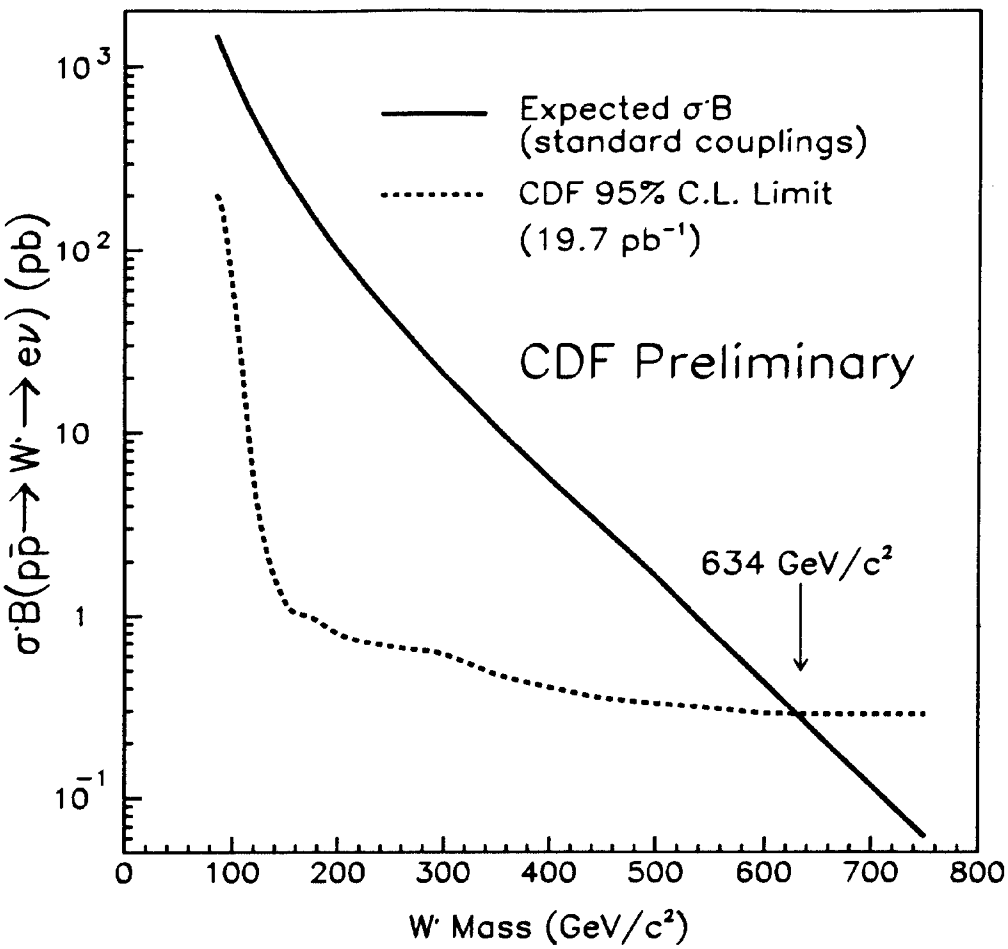


Figure 2: CDF 95% C.L. limit on $\sigma \cdot B(p\bar{p} \to W' \to e\nu)$ *vs.* the $W'$ mass. Also shown is the expected $\sigma \cdot B$, assuming standard couplings. The point $M_{W'} = 634\ GeV/c^2$ is our limit, assuming standard couplings.

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