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Search for a W' Boson Decaying to a Top and Bottom Quark Pair in 1.8 TeV $p\bar{p}$ Collisions

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Abstract

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 106 pb^{-1} data sample recorded by the Collider Detector at Fermilab. We observe no significant excess of events above background for a W' boson decaying to a top and bottom quark pair, with the top quark subsequently decaying into a semileptonic final state. These data allow us to set limits on the rate of W' boson production and decay. In a model where this boson would mediate interactions involving a massive right-handed neutrino (ν_R) and has Standard Model strength couplings, we exclude a W' boson with mass between 225 and 536 GeV/c^2 at 95% confidence level for $M_{W'} \gg M_{\nu_R}$ and between 225 and 566 GeV/c^2 at 95% confidence level for $M_{W'} < M_{\nu_R}$.

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The search for additional forces in nature have focused on identifying particle physics phenomena not predicted by the strong, electromagnetic and weak forces. These are described by the Standard Model using a local gauge theory that accounts for each interaction using a vector boson force carrier [1]. Evidence for a new force could come from observation of the corresponding force carrier. There are a number of extensions to the Standard Model that predict the existence of a new charged vector boson, generically known as a W' boson. The most common extensions are left-right symmetric [2], in that they presume that the W' boson mediates right-handed interactions, in the same way that the Standard Model W boson mediates only left-handed interactions.

Previous searches for new charged vector bosons with couplings to quarks and leptons have been reported. These searches have set model dependent limits on the new boson mass as well as limits on cross section times branching ratio. A comprehensive set of searches has been performed at the Fermilab Tevatron Collider. Searches using the decay mode $W' \to e\nu_e$ exclude a W' boson with mass < 754 GeV/c^2 at 95% CL [3,4], while similar searches considering the decay mode $W' \to \mu\nu_\mu$ have excluded a W' boson with mass < 660 GeV/c^2 at 95% CL [5]. The most stringent single limit comes from a search combining both of these leptonic channels and excludes a W' boson with mass < 786 GeV/c^2 at 95% CL [3]. These mass limits all assume that the new vector boson's couplings to leptonic final states will be given by the Standard Model, with the additional assumption that the mass of the neutrino produced in the leptonic decay of the W' is much less than the mass of the W' boson itself. With these assumptions, the predicted total width of the boson increases linearly with $M_{W'}$, where $M_{W'}$ is the mass of the boson. A search that avoids any assumptions regarding the neutrino mass has involved the decay mode $W' \to q\bar{q}'$ where the quarks are observed as high-energy jets, but is background-limited and only excludes W' bosons with $300 < M_{W'} < 420$ GeV/c^2 at 95% CL [6]. Indirect searches studying, for example, the Michel spectrum in μ decay have resulted in more model-independent limits with less sensitivity [7].

In this letter, we present the results of a new search for a W' boson decaying to a top quark-bottom quark pair, *i.e.* $W' \to t\bar{b}$. Although this search is only sensitive to W' bosons with mass above the $t\bar{b}$ kinematic threshold of approximately 200 GeV/c^2, it is relatively free of background compared to the $W' \to q\bar{q}'$ decay mode because of the signature from the top quark decay $t \to Wb$. Furthermore, the interpretation of the data is less sensitive to assumptions regarding the right-handed neutrino sector, since we avoid having to make assumptions regarding the nature of the right-handed neutrino or the leptonic couplings of the W' boson [8]. We use a data sample of 106 ± 4 pb^{-1} of 1.8 TeV $p\bar{p}$ collisions recorded by the Collider Detector at Fermilab (CDF) detector during 1992-95.

The CDF detector is described in detail elsewhere [9]. The detector has a charged particle tracking system immersed in a 1.4 T solenoidal magnetic field, which is coaxial with the $p\bar{p}$ beams. The tracking system consists of silicon strip detectors and drift chambers that measure particle momentum with an accuracy of $\sigma_{p_T}/p_T = \sqrt{(0.0009 p_T)^2 + (0.0066)^2}$, where p_T is the momentum of the charged particle measured in GeV/c transverse to the $p\bar{p}$ beamline. The tracking system is surrounded by segmented electromagnetic and hadronic calorimeters measuring the flow of energy associated with particles that interact hadronically or electromagnetically out to $|\eta|$ of 4.2 [10]. Electron candidates with $|\eta| < 1.0$ are identified using the pattern of energy distribution in the electromagnetic and hadronic calorimeters and the presence of a charged track consistent with the calorimeter information. A set of charged particle detectors outside the calorimeter is used to identify muon candidates with $|\eta| < 1.0$.

Because of the good background rejection of the electron and muon identification systems in the CDF detector, we choose to search for those events that are consistent with $W' \to t\bar{b}$ with the top quark decaying to final states including either $e\nu_e b$ or $\mu\nu_\mu b$. The primary selection criteria is identical to an earlier study searching for single top quark production [11]. Candidate events are identified in the CDF trigger system by the requirement of at least one electron or muon candidate with $p_T > 18$ GeV/c. The event sample is subsequently refined after full event reconstruction by requiring a well-identified electron or muon candidate with $p_T > 20$ GeV/c and by requiring that the missing transverse energy in the event, $\not{E}_T$, be greater than 20 GeV. We reject events that are identified as dilepton candidates arising from top quark pair production ($t\bar{t}$) [12], and reject other dilepton candidates as described in Ref. [11]. For example, candidate events with two well-identified electron or muon candidates consistent with coming from top quark decay were rejected. To select events with at least two bottom quark candidates, we require either two or three jets with transverse energy $E_T > 15$ GeV and $|\eta| < 2.0$, where the jets are defined using a fixed-cone clustering algorithm employing a cone-size of $R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$. The jet transverse energies are subsequently corrected with an algorithm that accounts for the effects of jet fragmentation, calorimeter non-uniformities and energy flow from the rest of the event [13]. We require that at least one of the jets be identified as a b quark candidate using displaced secondary vertex information from the silicon vertex detector [14]. This selection results in 57 candidate events.

We use a PYTHIA Monte Carlo calculation [15] and a CDF detector simulation to determine the expected number of candidate events we would observe in this data sample as a function of W' boson mass. We require the W' boson to have a right-handed coupling to the $t\bar{b}$ final state, we set the top quark mass to 175 GeV/c^2 and we assume that the top quark always decays to a Wb final state. We expect negligible signal yield differences between right-handed and left-handed couplings. We use the MRS(G) parton distribution functions [16] to model the momentum distribution of the initial state partons. We use a next-to-leading-order calculation to estimate the production cross section, as the next-to-leading order contributions are substantial [17]; the increase in cross section over the leading-order prediction ranges from a factor of 1.50 at $M_{W'} = 225$ GeV/c^2 to 1.26 at $M_{W'} = 600$ GeV/c^2. The efficiency times acceptance in both the electron and muon channels for our event selection is approximately 9% for $M_{W'} = 225$ GeV/c^2, increases to 12% for $M_{W'} = 300$ GeV/c^2 and is approximately constant for masses up to 600 GeV/c^2. The corresponding efficiency times acceptance for the τ lepton channel, where this lepton decays to an energetic muon or electron, is approximately a factor of six to ten smaller. We will not attempt to interpret our data for masses $M_{W'} < 225$ GeV/c^2 as the cross section calculation and the acceptance calculation become increasingly uncertain as one nears the kinematic threshold for the decay $W' \to t\bar{b}$. The production cross section times branching ratio and the expected number of signal events as a function of $M_{W'}$ are shown in Table I. Over a wide-range of W' boson masses, we would expect to see significant numbers of events contributing to our candidate sample.

We identified three sources that comprise the dominant background contributions to this search: the pair production of top quarks ($t\bar{t}$), single top quark production and the associated QCD production of W bosons with one or more heavy quarks ($Wb\bar{b}$ and Wc where c is the charm quark). We have investigated other possible background sources and find them to be individually insignificant. We estimate the background contribution from $t\bar{t}$ production by employing a PYTHIA Monte Carlo calculation of this process and a detector simulation. Using the predicted $t\bar{t}$ production cross section of 5.1 ± 0.9 pb [18], we estimate the $t\bar{t}$ background to be 15.0 ± 4.0 observed events. We use the same methods as in our measurement of single top quark production search [11] to estimate the single top quark contribution to our candidate sample to be 3.9 ± 0.9 observed events. The largest single background contribution comes from the associated QCD production of W bosons with heavy quarks. We employ the technique described in an earlier report [14] to estimate these, taking into account the different event selection requirements, and find a total expected background contribution of 15.6 ± 3.0 events. Other sources of background, including events not containing a heavy quark jet, dilepton final states and events with misidentified lepton candidates are predicted to give rise to 13.6 ± 2.9 events. We thus expect 48 ± 6 candidate events from background processes. This is in reasonable agreement with the 57 candidate events observed, and we conclude we have no significant evidence for W' boson production.

To set a limit on the W' mass, we employ the invariant mass distribution of the $Wb\bar{b}$ final state as that provides more information about possible W' production than the number of candidate events alone. We reconstruct the momentum of the neutrino along the beam axis (p_z) by constraining the invariant mass of the lepton-neutrino pair to equal the W boson mass of 80.22 GeV/c^2 [19], which results in a quadratic constraint on p_z. This generally provides two solutions, and we select the solution with the smaller value of $|p_z|$ as that is more likely correct given the central nature of the production mechanism of this very heavy state. If the solution has an imaginary component, we use only the real component. The resulting $Wb\bar{b}$ mass distribution for our 57 candidate event sample is shown in Fig. 1 and is compared with the expected mass distribution for a W' boson with $M_{W'} = 500$ GeV/c^2 . We also show the mass distribution expected from the sum of the background processes.

To estimate the size of the potential signal contribution, we perform an unbinned maximum likelihood fit to both the number of observed events and the observed mass distribution, allowing for both a signal and background contribution for different values of $M_{W'}$ ranging from 225 to 600 GeV/c^2. We use a fitting technique that is identical to that employed in the recent search for single top quark production [11], where we model the expected mass distribution as a sum of a signal component with size $\beta_{W'}$, and three background components with sizes $\beta_{t\bar{t}}$, β_{st} and β_{nt} for the backgrounds from top quark pair production, single top quark production, and sources not containing a top quark, respectively. These parameters are normalized so that they equal unity when the fit results in the number of observed events equal to the number of predicted events from each individual source. With this choice of normalization, we can interpret

$$\beta_{W'} = \frac{\sigma \cdot \mathcal{B}(W' \to t\bar{b})}{\sigma \cdot \mathcal{B}(W' \to t\bar{b})_{SM}}, \tag{1}$$

where the denominator is the expected production cross section times branching fraction for the W' boson assuming Standard Model couplings. Since the latter depends on the nature of the right-handed neutrino, we express our results using the two scenarios described earlier. We include in the likelihood Gaussian constraints on the expected number of events from the three background sources. The results of the fit are presented in Table II. An example of the dependence of the likelihood on $\beta_{W'}$ is shown in Fig. 2 for the case $M_{W'} = 550$ GeV/c^2 and $M_{W'} < M_{\nu_R}$.

We set Bayesian 95% CL upper limits on the relative contribution of a W' boson by constructing a posterior distribution $f(\beta_{W'})$ for each fixed value of $M_{W'}$. First we maximize the likelihood function for fixed values of $\beta_{W'}$ and multiply the resulting function by a flat prior distribution for $\beta_{W'}$. We then convolute $f(\beta_{W'})$ with two Gaussian prior distributions to take into account the systematic uncertainties that affect the number of expected background or signal events and the shape of the resulting invariant mass distribution. The largest systematic uncertainties arise from our uncertainty in the efficiency for b quark tagging (11%), our understanding of the lepton selection efficiency (10%) and on the parton distribution functions (between 4 and 11%). We are also sensitive to the value of the top quark mass near kinematic threshold; its current uncertainty of ± 5 GeV/c^2 [20] results in a systematic uncertainty on the acceptance and cross section of 15% at $M_{W'} = 225$ GeV/c^2, 8% at $M_{W'} = 250$ GeV/c^2, and $\leq 4\%$ for higher masses. The systematic uncertainties from all effects total approximately 20% for W' boson masses ranging from $M_{W'} = 225$ GeV/c^2 to 600 GeV/c^2. To set a 95% CL upper limit on $\beta_{W'}$, we integrate the posterior distribution $f(\beta_{W'})$. A frequentist calculation of this limit yields consistent results.

The results of the fit and this limit-setting procedure are summarized in Table II and plotted in Fig. 3. We find that we can exclude a W' boson at 95% CL with masses $225 < M_{W'} < 536$ GeV/c^2 for $M_{W'} \gg M_{\nu_R}$ and $225 < M_{W'} < 566$ GeV/c^2 assuming $M_{W'} < M_{\nu_R}$.

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 $t\bar{b}$ final state. We see no evidence for a signal above the expected background contributions. We use a fit of the final state invariant mass distribution to exclude a W' boson with $225 < M_{W'} < 536$ GeV/c^2 for $M_{W'} \gg M_{\nu_R}$ and $225 < M_{W'} < 566$ GeV/c^2 for $M_{W'} < M_{\nu_R}$. This is the first study made of this production process, and we expect that it will continue to be an effective search signature for higher mass W' bosons that might be produced at future higher energy and higher luminosity colliders.

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[10] We use a coordinate system where θ is the polar angle to the proton beam, ϕ is the azimuthal angle about this beam axis, and η is the pseudorapidity defined as $-\ln\tan(\theta/2)$. Missing transverse energy, $\not\!\!E_T$, is defined as the magnitude of $-\sum_i E_T^i \hat{n}_i$, where $\hat{n}_i$ is a unit vector in the azimuthal plane that points from the beamline to the ith calorimeter tower.

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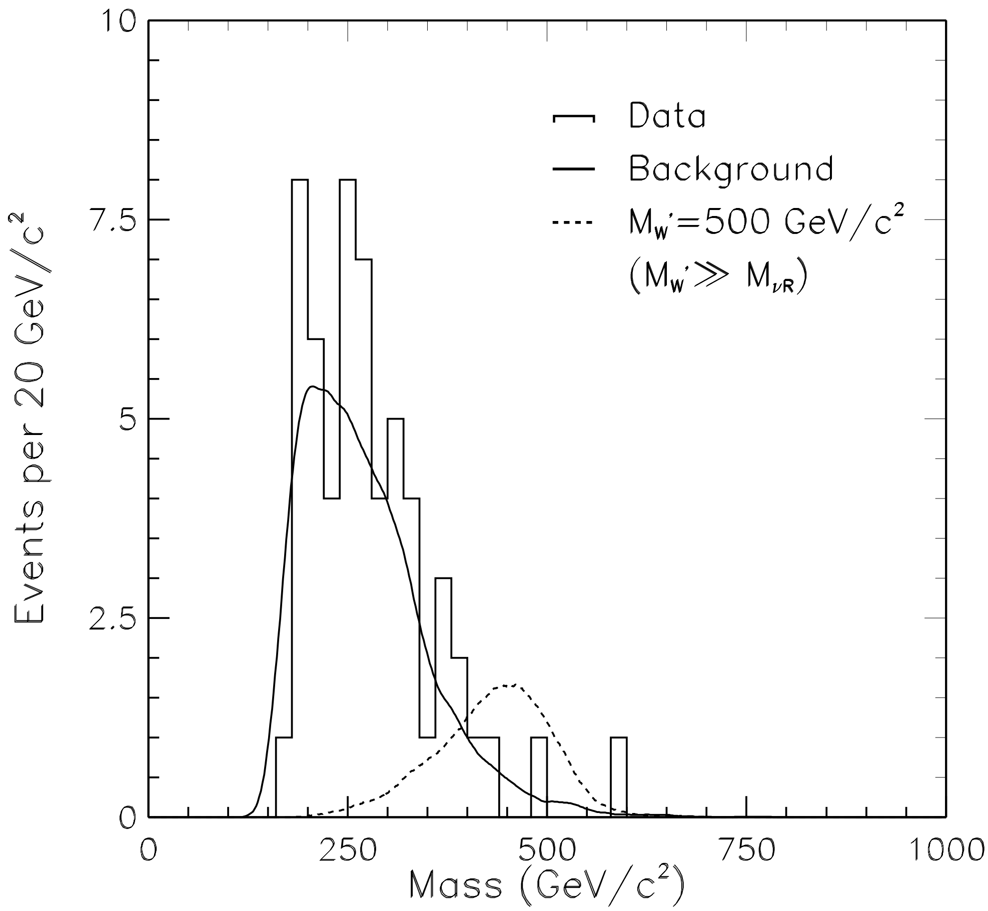

FIG. 1. The $Wb\bar{b}$ mass spectrum of the candidate events after constraining the lepton-neutrino invariant mass to the W boson mass. The distribution expected from the production of a W' boson with a mass of 500 GeV/c^2 is illustrated by the dashed curve. The distribution expected from the background processes is shown by the solid curve, which is normalized to the expected total background rate.

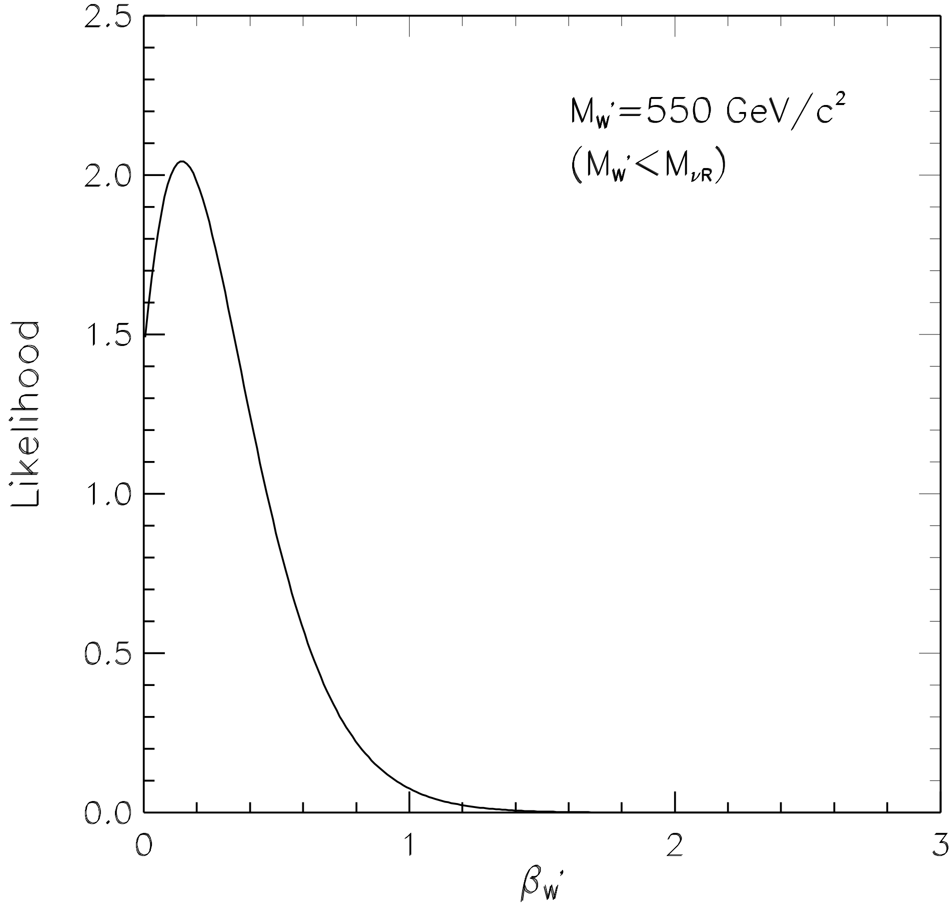

FIG. 2. The dependence of the likelihood on $\beta_{W'}$ with the assumption of $M_{W'} = 550$ GeV/c^2 and $M_{W'} < M_{\nu_R}$. The likelihood plots with other assumptions are similar.

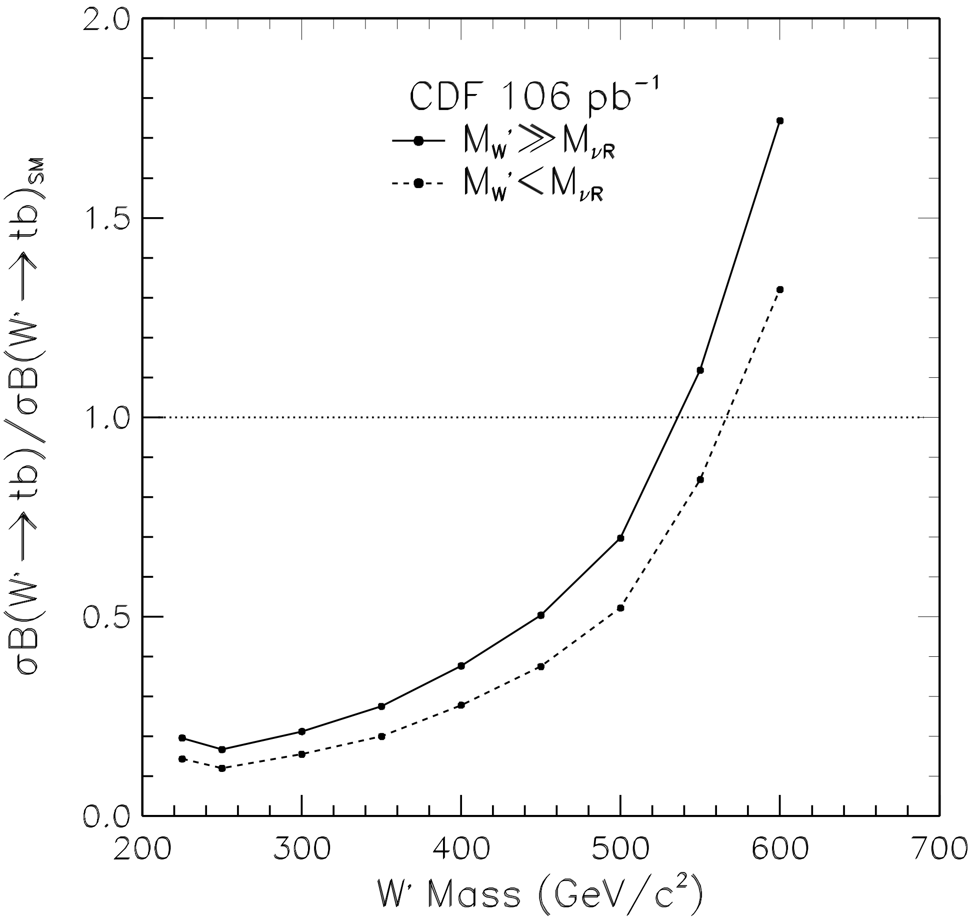

FIG. 3. The upper limits on the W' boson production cross section as a function of the W' boson mass. Limits are shown for the case $M_{W'} \gg M_{\nu_R}$ (solid) and $M_{W'} < M_{\nu_R}$ (dashed). The intercepts at $\frac{\sigma\mathcal{B}(W'\to tb)}{\sigma\mathcal{B}(W'\to tb)_{SM}} = 1$ correspond to the 95% CL limits on the W' boson mass with Standard Model strength couplings.

TABLES

$M_{W'}$	$M_{W'} \gg M_{\nu_R}$		$M_{W'} < M_{\nu_R}$	
(GeV/c^2)	$\sigma \cdot \mathcal{B}(W' \to t\bar{b})$ (pb)	Events	$\sigma \cdot \mathcal{B}(W' \to t\bar{b})$ (pb)	Events
225	53.4	116	77.2	168
300	37.4	115	52.1	161
400	13.3	43	18.0	58
500	4.38	14	5.87	19
600	1.43	4.5	1.89	5.9

TABLE I. The production cross section times branching fraction and the number of expected events for different W' masses and different assumptions regarding the right-handed neutrino sector.

$M_{W'}$	$M_{W'} \gg M_{\nu_R}$		$M_{W'} < M_{\nu_R}$	
(GeV/c^2)	Fit	Upper Limit	Fit	Upper Limit
225	$0.04^{+0.07}_{-0.04}$	0.20	$0.03^{+0.05}_{-0.03}$	0.14
300	$0.07^{+0.07}_{-0.06}$	0.21	$0.05^{+0.05}_{-0.04}$	0.15
400	$0.09^{+0.13}_{-0.09}$	0.38	$0.06^{+0.09}_{-0.06}$	0.27
500	$0.06^{+0.25}_{-0.06}$	0.70	$0.05^{+0.18}_{-0.05}$	0.53
600	$0.31^{+0.51}_{-0.29}$	1.74	$0.23^{+0.38}_{-0.22}$	1.32

TABLE II. The fit results for the number of events arising from W' production, normalized to the expected number of events for a given W' mass, and the Bayesian 95% CL upper limit on this fraction for the two different assumptions on the mass of the right-handed neutrino.