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Search for charge-asymmetric production of W′ bosons in $\mathrm{t\bar{t}}+$ jet events from pp collisions at $\sqrt{s}=7$ TeV

The CMS Collaboration*

Abstract

A search is presented for charge-asymmetric production of a W′ boson that has been proposed to accommodate the forward-backward asymmetry observed in the production of top-antitop quark pairs at the Tevatron. The new heavy W′ boson would be produced in association with a top quark and would decay into top and down quarks. The data correspond to an integrated luminosity of 5.0 fb^{-1} in pp collisions at a center-of-mass energy of 7 TeV, recorded by the CMS detector at the LHC. No significant excess above the standard model expectations is observed, and, from a combination of the electron-plus-jets and muon-plus-jets channels, a 95% confidence level lower limit of 840 GeV/c^2 is set on the W′ boson mass for a W′ boson model with values for coupling constants to top and down quarks $g_L=0$ and $g_R=2$. In addition, a kinematic reconstruction of the W′ resonance mass using the inherent charge asymmetry of this model finds no indication of the presence of W′ events in the data.

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1 Introduction

Many extensions to the standard model (SM) involve enhanced gauge symmetries that give rise to additional gauge bosons. Within these extensions, one of the additional bosons could be the W' boson, a proposed heavy partner to the W boson. There are many scenarios with a W' boson: a left-right symmetric model [1], a model based upon a new SU(2) sector [1], a technicolor model [2], and a W' as the lowest Kaluza–Klein mode of the W boson [3].

A W' boson with a coupling to top (t) and down (d) quarks has been proposed [4] to explain the anomalous forward-backward asymmetry in $t\bar{t}$ events reported at the Tevatron [5–7]. The observed effect, which is particularly significant for large values of the $t\bar{t}$ mass, could be explained by the production of a W' boson with a mass in the range of 200–600 GeV/c^2 [4]. A search for a W' decaying to top and light quarks was conducted by the CDF experiment [8]. With a predicted cross section around 20 pb at 7 TeV and an assumed 100% branching fraction into t and d quarks, as illustrated in Fig. 1, the W' boson is potentially observable with the data already collected by the Compact Muon Solenoid (CMS) collaboration at the Large Hadron Collider (LHC).

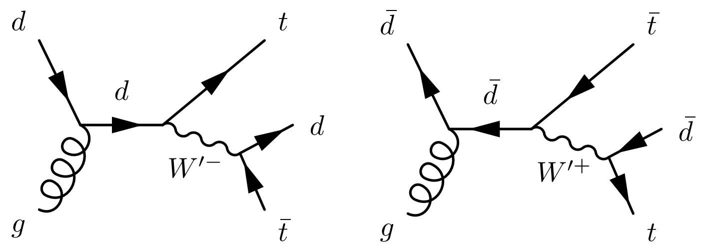

Figure 1: Feynman diagrams for s-channel production of (left) W'^- and (right) W'^+. Diagrams for t-channel production can be found in Ref. [9].

Because the LHC collides protons with protons, rather than with antiprotons, the valence d quarks have a much larger fraction of beam particle momentum than $\bar{d}$ quarks, which come from the proton "sea". The result is that, at leading order (LO), the W'^- (W'^+) contributes about 85% (15%) of the total W' production cross section, for W' masses in the range from 400–1200 GeV/c^2 [9]. This feature can be used to aid in the identification of the W', as explained in Section 6.

The LO processes shown in Fig. 1 result in a final state of $t\bar{t}$ plus a d quark or antiquark. This final state can be classified according to how the W bosons from the top quarks decay: all hadronic (both W bosons decaying hadronically), partially leptonic (one decaying hadronically, the other leptonically), or fully leptonic (both decaying leptonically). We focus on the partially leptonic mode because it has a larger branching fraction than the fully leptonic mode and a cleaner signature than the all-hadronic mode. The event selection for this analysis requires one electron or muon accompanied by several jets and an imbalance in transverse momentum. The main background originates from SM $t\bar{t}$ production with initial- or final-state radiation. We conduct a search for the W' signal by comparing the number of observed events in data with the total expected from SM sources. In addition, we utilize a kinematic reconstruction of the W' resonance mass and the inherent charge asymmetry of this model to perform an independent test for the presence of W' events in the data.

2 The CMS Detector and Data Samples

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker resides within the field volume, surrounded by a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the flux-return yoke of the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis along the counterclockwise beam direction. The polar angle, θ, is measured from the positive z axis and the azimuthal angle, ϕ, is measured in the x-y plane. The pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$. A more detailed description of the detector can be found in Ref. [10].

The data sample corresponds to an integrated luminosity of $5.0 \pm 0.1\,\text{fb}^{-1}$ in pp collisions at a center-of-mass energy $\sqrt{s} = 7\,\text{TeV}$, collected by the CMS detector at the LHC. We perform our search in both the electron-plus-jets (e+jets) and muon-plus-jets (μ+jets) channels. For the e+jets channel, about $0.2\,\text{fb}^{-1}$ of data were initially collected by requiring one electron with transverse momentum (p_T) greater than $27\,\text{GeV}/c$. For the next $1\,\text{fb}^{-1}$ of data, the p_T threshold had to be raised to $32\,\text{GeV}/c$. During the course of data taking, the maximum instantaneous luminosity increased by an order of magnitude, reaching up to $4 \times 10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$, thereby requiring changes in the trigger configurations. For the remaining $3.8\,\text{fb}^{-1}$ of data, it was necessary to include several jets in the electron trigger, resulting in an electron p_T threshold of $25\,\text{GeV}/c$ plus three jets with $p_\text{T} > 30\,\text{GeV}/c$. For the μ+jets channel, $2.2\,\text{fb}^{-1}$ of data were initially collected by requiring a single muon with $p_\text{T} > 30\,\text{GeV}/c$, with this threshold later raised to $40\,\text{GeV}/c$ for the last $2.8\,\text{fb}^{-1}$ of data.

The data are compared with simulations of SM background contributions from leptonically enriched multijets, single top quark, $\text{t}\bar{\text{t}}$, W, and Z production, with all sources including additional jets. The $\text{t}\bar{\text{t}}$ background is dominant, and is simulated with up to three additional partons by the MADGRAPH 4.4.12 [11] event generator interfaced with the PYTHIA 6.4.22 [12] parton shower simulator. In the matching procedure for this parton showering [13], the k_T matrix element uses a matching scale of $30\,\text{GeV}/c$, according to the MLM scheme [14]. The W and Z background processes are produced with the MADGRAPH event generator. The W' signal samples are produced with MADGRAPH for masses $M_{\text{W}'}$ = 400, 600, 800, 900, 1000, and $1200\,\text{GeV}/c^2$ with values of the W' coupling constants to top and down quarks $g_L = 0$ and $g_R = 2$ [9]. Additional W' benchmark points are produced for masses $M_{\text{W}'}$ = 600 and $800\,\text{GeV}/c^2$ with $g_L = 0$ and $g_R = \sqrt{2}$. Compared to Ref. [8], the definition of g_R used here gives values smaller by a factor of $1/\sqrt{2}$. Single top quark production is simulated with the POWHEG [15] event generator and includes s- and t-channel production, along with tW associated production. The multijet background contribution is simulated using a combination of two sets of samples, one generated with MADGRAPH and the other with PYTHIA. The CTEQ6L1 parton distribution function (PDF) set [16], which are LO PDFs, is used for generating all simulated events. The events for all samples are passed through a GEANT4-based simulation [17] of the CMS detector and reconstructed with the same program used to reconstruct data.

3 Event Selection and Reconstruction

The particle-flow (PF) algorithm [18] is used to reconstruct and identify each particle based upon an optimized combination of information from all the sub-detectors. The particles are classified as charged hadrons, neutral hadrons, photons, muons, or electrons.

Charged leptons originating from W boson decays are expected to be isolated from other particles in the event. A variable to quantify this lepton isolation, I, is defined as a sum of momenta, divided by the lepton p_{T}, where the sum is of the transverse momenta of charged hadrons, neutral hadrons, and photons in a cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ around the lepton direction, excluding the contribution from the lepton itself. Muons are reconstructed using information from the silicon tracker and the muon chambers. Muon candidates are required to be isolated, with $I < 0.125$, and to have $p_{\mathrm{T}} > 42\,\mathrm{GeV}/c$ and $|\eta| < 2.1$. Electrons are reconstructed using associated clusters of energy deposits in the ECAL that are then combined with tracks from the inner tracker [19]. The electron candidate is required to be isolated, with $I < 0.1$, and to have $p_{\mathrm{T}} > 45\,\mathrm{GeV}/c$ and $|\eta| < 2.5$. The p_{T} thresholds for the leptons are chosen so as to ensure a p_{T}-independent trigger efficiency, whose value is about 98%, for selected events. Electrons in the η range around the interface between the ECAL endcap and ECAL barrel ($1.444 < |\eta| < 1.566$) are excluded from the selection. From the high-quality vertices that are close to the beam spot, the vertex with the highest sum of p_{T}^2 of its constituent tracks is chosen as the primary vertex. To ensure the reconstructed muon or electron track is consistent with originating from the primary vertex, we require the longitudinal distance between the track and vertex to be less than 1 cm, and the point of closest approach to the primary vertex in the transverse direction to be less than 0.02 cm, as suggested by Ref. [20]. Selected events must contain exactly one electron or muon meeting the above requirements, and events are rejected if they have any additional muons with $p_{\mathrm{T}} > 10\,\mathrm{GeV}/c$, $|\eta| < 2.5$, and $I < 0.2$ or electrons with $p_{\mathrm{T}} > 20\,\mathrm{GeV}/c$, $|\eta| < 2.5$, and $I < 0.2$. To remove electrons resulting from photon conversions, we eliminate those events with a single electron candidate that has no hits in the innermost pixel layer or that is accompanied by a nearby track.

Jets are reconstructed from PF constituents with the FASTJET package [21], using the anti-k_{T} [22] clustering algorithm with a distance parameter 0.5 and a jet clustering recombination scheme that merges particles by summing their four-vectors [23]. Only charged PF jets that are consistent with originating from the primary vertex are considered. Correction factors [24] are applied to the jet energy to account for non-linearities in detector response.

Selected events must have at least five jets with a minimum p_{T} of $35\,\mathrm{GeV}/c$ and $|\eta| < 2.4$. The highest-p_{T} jet is required to have $p_{\mathrm{T}} > 180\,\mathrm{GeV}/c$, and the second-highest-p_{T} jet must have $p_{\mathrm{T}} > 90\,\mathrm{GeV}/c$. The requirement for the highest-p_{T} jet is intended, in part, to select for the d-quark jet coming from the W$'$ decay. We also require $H_{\mathrm{T}} > 700\,\mathrm{GeV}/c$, where H_{T} is the scalar sum of all jet p_{T}, the lepton p_{T}, and a quantity called $E_{\mathrm{T}}^{\mathrm{miss}}$, which is the absolute value of the vector sum of the transverse momenta of all particles found by the PF algorithm, with the particles being treated as massless. These H_{T} and jet p_{T}values are determined from optimizing the selection to suppress SM backgrounds while enhancing the signal significance, which is taken to be the expected number of signal events for a benchmark point with a W$'$ mass of $600\,\mathrm{GeV}/c^2$ divided by the square root of the number of expected background events. This benchmark corresponds to the highest mass point that is able to account well for the forward-backward asymmetry in $\mathrm{t\bar{t}}$ events observed at the Tevatron [4]. We further require that at least one jet is identified as originating from a b quark. Jets from b quarks are identified by an algorithm [25] that reconstructs a displaced secondary vertex with high efficiency by combining two or more tracks and then assigns a likelihood of b-quark origin based upon the three-dimensional decay length of the vertex.

The leptonic decay of the W boson arising from a top quark produces a neutrino, which escapes the detector without interacting. The $E_{\mathrm{T}}^{\mathrm{miss}}$ provides a measure of this missing energy, so we require $E_{\mathrm{T}}^{\mathrm{miss}} > 20\,\mathrm{GeV}$.

The estimated background contribution from SM processes is obtained from simulation. After all selection requirements are applied, $\mathrm{t\bar{t}}$ decays matching the signal topology are the dominant background source, with W+jets events also contributing, but at a much smaller level.

Simulated events are corrected to account for effects of the trigger selection and differences between data and simulation in lepton and b-quark jet identification efficiency. The correction factors for leptons are obtained using a high-purity data sample of $\mathrm{Z} \to \ell^+\ell^-$ decays, where ℓ is an electron or muon. To account for the difference between data and simulation in the performance of the b-tagging algorithm, we follow the method described in Ref. [26], which entails adding or removing a b tag on each jet in simulated events, based upon p_{T}- and η-dependent correction factors [26].

Table 1 provides the cross sections used for each of the SM backgrounds, which, multiplied by the integrated luminosity of $5.0\,\mathrm{fb}^{-1}$ and selection efficiencies, give the expected number of background events. For $\mathrm{t\bar{t}}$, we use the measured cross section from Ref. [27]. The single top quark next-to-next-to-leading-order (NNLO) cross section is obtained from Refs. [28–30]. The W+jets and Z+jets cross sections are computed to NNLO using the Fully Exclusive W, Z Production (FEWZ) pQCD generator [31]. Finally, the cross section for multijets is obtained, at LO, from PYTHIA [12].

The uncertainties quoted in Table 1 reflect statistical and systematic sources, which are elaborated in Section 4. Although large, the estimated background is comparable to the predicted signal for a W' with a mass of $600\,\mathrm{GeV}/c^2$ and with $g_L = 0$ and $g_R = 2$ [9, 32], given in the next-to-last row in Table 1. The numbers of observed events in data in the e+jets and μ+jets channels are presented in the last row in Table 1. For W' signal events, the total selection efficiency is roughly 2%, while for the main background, $\mathrm{t\bar{t}}$, it is roughly 0.2%.

Table 1: Number of events in the e+jets and μ+jets channels, for simulated background, a possible W' signal with a $600\,\mathrm{GeV}/c^2$ mass, and data, corresponding to $5.0\,\mathrm{fb}^{-1}$ integrated luminosity. The uncertainties include both statistical and systematic contributions from all sources discussed in Section 4.

Sample	Cross section [pb]	Number of events e+jets	μ+jets
$\mathrm{t\bar{t}}$	154 ± 17 [27]	734 ± 204	888 ± 276
Single top quark	85	32 ± 16	40 ± 20
W+jets	31314	64 ± 32	49 ± 25
Z+jets	3048	8 ± 4	12 ± 6
Multijets	6.7×10^6	5 ± 5	-
Total background		843 ± 209	989 ± 279
Signal ($M_{\mathrm{W}'} = 600\,\mathrm{GeV}/c^2, g_L = 0, g_R = 2$)	18.2	723 ± 140	858 ± 120
Data		726	904

4 Systematic Uncertainties

The following sources of systematic uncertainty are evaluated for their effect on simulated signal and background yields: jet energy corrections, b-tagging corrections, lepton charge misidentification, lepton trigger and identification efficiencies, and the integrated luminosity measurement. In addition, the parameters used in generating simulated events have associated systematic uncertainties, as does the procedure to make the distribution of additional interaction vertices from pileup match simulation to data.

Uncertainties from corrections on the jet energy scale are taken into account by shifting the energy of each jet by ± 1 standard deviation [24]. The $E_{\mathrm{T}}^{\mathrm{miss}}$ is corrected simultaneously since it is almost fully correlated with the jet energies. The effect on yields is about 10% for both signal and background. Similarly, with simulated events, varying the b-tagging corrections by their estimated uncertainty leads to a 2% change in the event yields.

A wrong charge assignment for a reconstructed lepton could also cause its momentum determination to be incorrect. As a check of the significance of this effect, study of the charge-misidentification rate with a sample of simulated $\mathrm{t\bar{t}}$ events shows the effect to be negligible. To match the trigger and lepton identification efficiencies in simulated samples and data, correction factors are applied. The uncertainty on these corrections is approximately 2% of event yields in signal and background.

The uncertainty in the luminosity determination is 2.2% [33] and affects the overall scaling of signal and background samples.

The uncertainty in the choice of PDFs used for generating simulated events is evaluated following the PDF4LHC recommendation [34]. We calculate an uncertainty of around 13% in the number of expected events, for both signal and $\mathrm{t\bar{t}}$ background. We also evaluate the uncertainty associated with the choice of renormalization and factorization scales and the initial- and final-state radiation used in simulation. Varying the q^2 scale by a factor of 4 or 0.25 results in a 7% change in the estimated signal yield. For $\mathrm{t\bar{t}}$, the yield changes by about 20%. This systematic uncertainty is the dominant one for the background prediction, and it reflects uncertainties in modeling events with five or more jets, as our selection requires.

All simulated background samples are scaled using their corresponding cross sections. For $\mathrm{t\bar{t}}$ we use the CMS measured value of $154 \pm 17\,\mathrm{pb}$ [27]. We conservatively treat the systematic uncertainty on the $\mathrm{t\bar{t}}$ cross section as uncorrelated with the systematic uncertainties on the $\mathrm{t\bar{t}}$ acceptance because the cross-section measurement employs techniques and simulated samples significantly different from those we use. The other backgrounds are small, and their uncertainties do not make a significant contribution to the total background uncertainty, so conservative estimates of their uncertainties are used. A 50% uncertainty in the event yield is assumed for the electroweak backgrounds (W, Z) as well as for single top quark production, and a 100% uncertainty is assigned to the multijet background [27].

Simulated samples are produced with a generic distribution describing additional interactions in the same bunch crossing at high instantaneous luminosities (event pileup). A reweighting procedure is applied to match the pileup conditions in the data. The uncertainty in the reweighting procedure has an effect of about 1% on the event yields for both simulated signal and background.

5 Limits on W′ Production

We perform a counting experiment where the number of observed events (N_{obs}) is compared with the number of expected events from background (N_{exp}). From Table 1, we have $N_{\mathrm{obs}} = 726$ and $N_{\mathrm{exp}} = 843 \pm 209$ for the e+jets channel, and $N_{\mathrm{obs}} = 904$ and $N_{\mathrm{exp}} = 989 \pm 279$ for the μ+jets channel. We observe no significant excess above the SM background expectation in the two channels.

From a comparison of the observed and estimated numbers of events, we calculate an upper limit on the cross section of W′ production as a function of mass. A 95% confidence level (CL) upper limit is calculated using the CL_S technique [35, 36]. Any theoretical uncertainty in the LO W′ cross section is not included. Systematic uncertainties in the luminosity, jet energy scale, b-tagging efficiency, pileup, and lepton ID efficiency are taken to be 100% correlated between signal and background. Systematic uncertainties due to PDFs and factorization scales are taken to be uncorrelated for signal and the leading $t\bar{t}$ background. All systematic uncertainties are assumed to follow log-normal distributions.

The 95% CL upper limit on the number of selected signal events is 581 for the combination of the e+jets and μ+jets channels with W′ coupling constant values $g_L = 0$ and $g_R = 2$. Figure 2 shows the corresponding 95% CL upper limit on the W′ production. For this W′ model, we exclude W′ masses below 840 GeV/c^2.

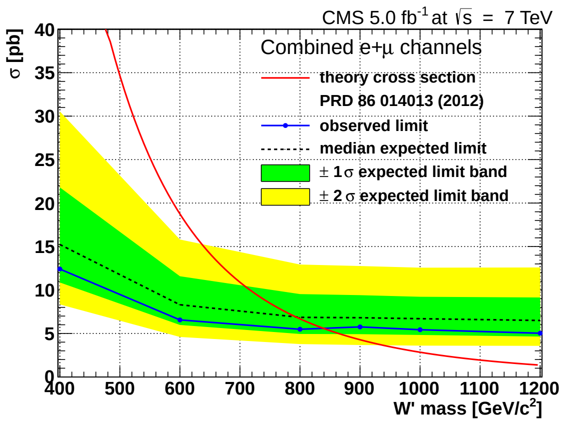

Figure 2: The 95% CL expected and observed limits on LO W′ production for $g_L = 0$ and $g_R = 2$ as a function of the W′ boson mass for e+jets and μ+jets channels combined.

To provide comparison between two important theoretical benchmark points of the W′ model, we also calculate limits on the cross section for W′ masses of 600 and 800 GeV/c^2 and g_R values of 2 and $\sqrt{2}$, as shown in Table 2.

Table 2: W′ cross-section limits for $g_R = 2$ and $\sqrt{2}$ (with $g_L = 0$) for the combined e+jets and μ+jets channels. The W′ model includes both s- and t-channel production. Thus, the acceptance changes with the coupling, and the cross section does not simply scale with the coupling.

W′ mass	600 GeV/c^2		800 GeV/c^2	
Coupling g_R	2	$\sqrt{2}$	2	$\sqrt{2}$
Cross section [pb]	18.2	6.3	6.5	2.1
Acceptance (comb.)	1.8%	2.2%	2.1%	2.8%
Expected limit [pb]	8.3	6.3	6.9	5.3
Observed limit [pb]	6.6	5.0	5.5	4.3

6 Search for W′ Asymmetry

As an independent cross check, we attempt the reconstruction of the W′ mass and derive an asymmetry to check whether there is any indication of signal in the data, as suggested by

Ref. [9]. We exploit the charge asymmetry in W' production, a key feature of this theoretical model.

To reconstruct the W', we first reconstruct two top quarks. Three jets in the event are used to reconstruct one top quark, with the jets being considered to match the decay chain $t \to W + b$, $W \to j + j$, where j is a jet resulting from the hadronic decay of the W boson. Out of the many three-jet combinations possible in each event, we choose the one in which a pair of jets gives an invariant mass closest to the W boson mass [37] and the three jets give an invariant mass closest to the top quark mass [37]. From the lepton, one jet, and E_T^{miss}, we reconstruct the second top quark, following the decay chain $t \to W + b$, $W \to \ell + \nu$. Again, out of the several combinations with the jets in each event, we choose the one giving an invariant mass closest to the top quark mass. Though the event selection requires at least one b-tagged jet, b tagging is not considered when choosing the jets used for top reconstruction. Next, the highest-p_T, non-b-tagged jet not used in the top reconstruction is labeled as the candidate d-quark jet.

Each of the two top candidates are combined in turn with the d-quark jet so that two W' candidates are reconstructed for each selected event. The charge of the W' candidate that has the lepton in its decay chain is determined by the charge of the lepton, while the other W' candidate has the opposite charge. In a true W' event, only the W' candidate that matches the true W' charge could possibly be correctly reconstructed, and thus, because of the charge asymmetry in W' production, the W'^- candidate is more likely to be correctly reconstructed than the W'^+ candidate. Figure 3 shows the invariant mass distributions for both W' candidates reconstructed from every selected event in data and the simulated background. Included with both distributions is the expected signal for a W' boson with a mass of 600 GeV/c^2. The invariant mass distribution for the W'^- candidates shows a high peak around the W' mass, while the distribution for the W'^+ candidates has a lower, more rounded peak. The simulated W' events provide this shape difference, since, for these events, W'^- candidates cluster more around the W' mass while W'^+ candidates, likely to be mis-reconstructed, create a broader distribution. A window of 200 GeV/c^2 width around the W' mass contains, for W' signal with a mass of 600 GeV/c^2, about 42% of W'^- candidates compared with only about 34% of W'^+ candidates. The background components of both distributions look identical since the additional jet originates from initial- or final-state radiation and there is no preference in combining it with either top candidate. The data distributions agree within the uncertainties with the background model.

To illustrate the asymmetry of the W' model, we calculate the difference in yields for the W'^- and W'^+ invariant mass distributions. The result is shown in Fig. 4. The data are represented by black points, and blue X's show the expected difference for a combination of background and a simulated W' signal at a mass of 600 GeV/c^2. The shaded blue band represents the statistical uncertainty for the combined signal and background. The predicted signature of W' events, as seen in Fig. 4 is a bump at the W' mass and a dip at higher mass, due to the fact that the W'^- mass distribution is more tightly concentrated within a narrow peak compared with the broader distribution seen for W'^+. In contrast, the data are statistically consistent with a flat distribution.

7 Summary

A search has been performed by the CMS collaboration for a W' boson via the process $d + g \to t + W'$, $W' \to \bar{t} + d$. This model represents one possible explanation for the $t\bar{t}$ forward-backward asymmetry seen at the Tevatron. The data showed no significant deviation from the standard model prediction. A counting experiment set a 95% CL limit on the W' production cross section as a function of mass. This W' model with $g_L = 0$ and $g_R = 2$ has been

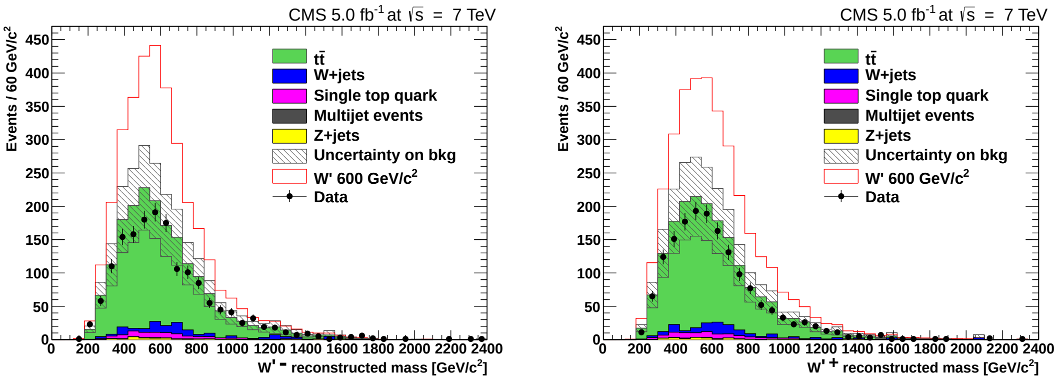

Figure 3: Invariant mass distributions for (left) $W^{\prime -}$ candidates and (right) $W^{\prime +}$ candidates. The figures show a comparison between the background prediction, with candidates reconstructed from simulated signal events stacked on top, and data. Uncertainty bands represent statistical and systematic uncertainties on the background prediction.

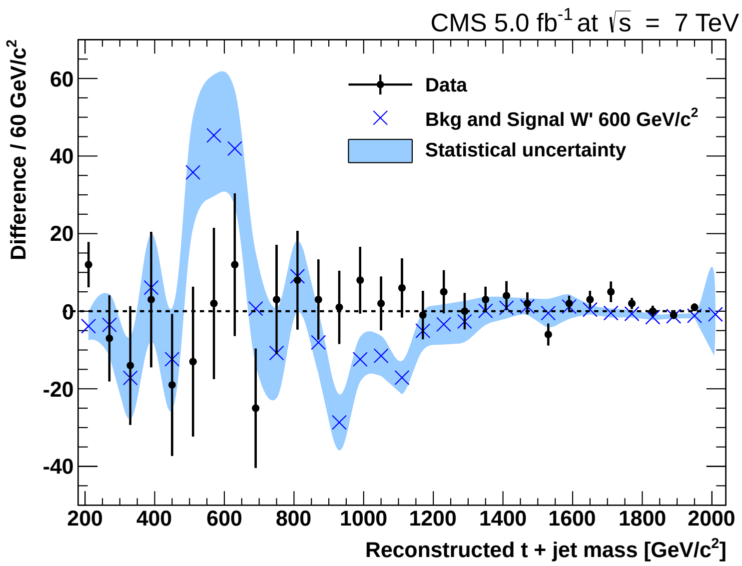

Figure 4: Difference in yields for $W^{\prime -}$ and $W^{\prime +}$ candidate invariant mass distributions. Data are compared with the combination of background and a simulated $W^{\prime}$ signal with a mass of $600\,\mathrm{GeV}/c^2$ and $g_L = 0$ and $g_R = 2$. The shaded blue band indicates the statistical uncertainty of the signal and background combination.

excluded below a mass of 840 GeV/c^2 in the combined e+jets and μ+jets channels. In addition, no statistically significant indication of the predicted W' mass distribution asymmetry has been observed in the data.

During the final stages of publication of this work, a related article has appeared [38], suggesting that interference effects were not properly taken into account in the theoretical model used in our analysis, with a possible result being the alteration of the limits we quote. The interference effects discussed in Ref. [38] arise mainly in diagrams with t-channel W' exchange, but these effects do not contribute significantly in the region of phase space chosen by our full selection.

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