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Study of the dijet mass spectrum in pp $\rightarrow$ W + jets events at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Abstract

A study is presented of the invariant mass spectrum of the two jets with highest transverse momentum in pp $\rightarrow$ W+2-jet and W+3-jet events. The data sample corresponds to an integrated luminosity of 5.0 fb^{-1} collected with the CMS detector at $\sqrt{s} = 7$ TeV. No evidence is found for the anomalous structure reported by the CDF Collaboration, and an upper limit of 5.0 pb is established at 95% confidence level on the production cross section for a generic Gaussian signal with mass near 150 GeV. Two theoretical models that predict a dijet resonance near 150 GeV are excluded.

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The CDF Collaboration reported evidence for an excess near 150 GeV in the invariant mass (m_{jj}) spectrum of the two leading transverse-momentum (p_{T}) jets produced in $\mathrm{p\overline{p}} \rightarrow \mathrm{W}$+2-jet events [1]. The D0 Collaboration carried out a similar analysis but did not confirm the result [2]. This letter details the search for a similar excess in the m_{jj} spectrum using $5.0\,\mathrm{fb}^{-1}$ of data collected from pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ with the Compact Muon Solenoid (CMS) detector at the CERN Large Hadron Collider (LHC) during 2010 and 2011.

Events are selected with one well-identified and isolated lepton (muon or electron), large missing transverse energy $\not\!\!E_{\mathrm{T}}$, and exactly two or exactly three high-p_{T} jets. The selection criteria are similar to those used at the Tevatron [1, 2], but modified to adapt to the higher background rates and different experimental conditions at the LHC. We also place more stringent requirements on the jet kinematics, as suggested in Ref. [3], to enhance any signal compared to the irreducible W plus jets background. We investigate three representative models, a technicolor π_{T} from the decay of a technicolor ρ_{T} [4], a leptophobic Z' decaying to two jets [5], and the standard model (SM) Higgs boson produced in association with a W boson (referred to as WH production) and decaying to a pair of jets. The WH production cross section at the LHC is negligible compared to contributions from other SM processes, which overwhelm any contribution to this analysis from $\mathrm{WH} \rightarrow \ell\nu jj$ decays for $m_{\mathrm{H}} \approx 125\,\mathrm{GeV}$ [6, 7].

The CMS coordinate system has its origin at the center of the detector, with the z axis pointing along the direction of the counterclockwise proton beam. The azimuthal angle is denoted as ϕ, the polar angle as θ, and the pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$. The central feature of the CMS detector is a superconducting solenoid, of 6 m internal diameter, that produces an axial magnetic field of 3.8 T. Located within the field volume is the silicon pixel and strip tracker extending up to $|\eta| = 2.5$, as well as a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadronic calorimeter (HCAL), both extending up to $|\eta| = 3$. Outside the field volume in the forward region ($3 < |\eta| < 5$) is an iron/quartz-fiber hadronic calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke outside the solenoid, in the pseudorapidity range $|\eta| < 2.4$. A detailed description of the CMS experiment can be found in Ref. [8].

The data were collected with a suite of single-lepton triggers, mostly with a p_{T} threshold of 24 GeV for muons and 25–32 GeV for electrons. The trigger efficiency for the selected muons (electrons) is about 94% (90%). Jets and $\not\!\!E_{\mathrm{T}}$ [9, 10] are reconstructed with the particle-flow algorithm [11], which combines information from several subdetectors. Jets are formed with the anti-k_{T} clustering algorithm [12] with a distance parameter of 0.5. We require $|\eta_{\mathrm{jet}}| < 2.4$ to ensure that they lie within the tracker acceptance, and a minimum jet p_{T} of 30 GeV. Jets are required to satisfy identification criteria that eliminate jet candidates originating from noisy channels in the hadron calorimeter [13]. Jet energy corrections [14] are applied to account for the jet energy response as a function of η and p_{T}, and to correct for additional proton-proton interactions occurring within the same bunch crossing [15, 16]. Charged-particle tracks not originating at the primary vertex are not considered for jet clustering. The jet p_{T} resolution varies from 15% at $p_{\mathrm{T}} = 40\,\mathrm{GeV}$ to 6% at $p_{\mathrm{T}} = 400\,\mathrm{GeV}$ [14]. The mass resolution σ_{jj} for a jet pair is 10% of m_{jj} for masses around 150 GeV.

Muon candidates are reconstructed in the region $|\eta| < 2.1$ by combining information from the silicon tracker and the muon detectors by means of a global fit. Electron candidates are identified within $|\eta| < 1.44$ and $1.57 < |\eta| < 2.5$ as clustered energy deposits in the electromagnetic calorimeter that are matched to tracks. Muon and electron candidates need to fulfill quality criteria established for the measurement of the inclusive W and Z cross sections [10]. In addition, all leptons must be well-separated from hadronic activity in the event. Jets within an η-ϕ cone of radius 0.3 around a lepton candidate are removed.

Leptons from candidate $\mathrm{W} \to \ell\nu$ decays must satisfy a single-lepton trigger and identification and isolation requirements. The muon (electron) transverse momentum must exceed 25 (35) GeV, and $E\!\!\!/_{\mathrm{T}}$ must be greater than 25 (30) GeV in the muon (electron) analysis. The transverse mass M_{T} of each W candidate must be greater than 50 GeV, where

$$M_{\mathrm{T}} \equiv \sqrt{2 p_{\mathrm{T}}^{\ell} E\!\!\!/_{\mathrm{T}} \left[1 - \cos(\phi_{\ell} - \phi_{E\!\!\!/_{\mathrm{T}}})\right]}$$

and ϕ_{ℓ} and $\phi_{E\!\!\!/_{\mathrm{T}}}$ are the azimuthal angles of the lepton and $E\!\!\!/_{\mathrm{T}}$, respectively. Events with more than one identified lepton are vetoed.

We retain events with exactly two or exactly three jets satisfying $p_{\mathrm{T}} > 30\,\mathrm{GeV}$. The leading jet is required to have $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ and point more than 0.4 rad in azimuth from the direction of the $E\!\!\!/_{\mathrm{T}}$. We further require $\|\vec{p}_{\mathrm{T}}^{\,j_1} + \vec{p}_{\mathrm{T}}^{\,j_2}\| > 45\,\mathrm{GeV}$ and $|\Delta\eta(j_1, j_2)| < 1.2$, where the jets are numbered in order of decreasing p_{T}. The selected jets and the lepton from the W decay are required to originate from the same primary vertex. The requirement $0.3 < p_{\mathrm{T}}^{j_2}/m_{jj} < 0.7$ is imposed to take advantage of the separation between resonant dijet and nonresonant W plus jets production observed in simulation studies.

The selected sample is dominated by events containing a W with two or more jets. Smaller contributions come from top-pair and single-top decays, Drell–Yan events with two or more jets, multijet production, and WW and WZ diboson production where one W decays into leptons and the other W or Z decays into quarks.

The shapes of the m_{jj} distributions for background processes are modeled using samples of simulated events. The MADGRAPH5 1.3.30 [17] event generator produces parton-level events with a W boson and up to four partons on the basis of matrix-element (ME) calculations. The ME–parton shower matching scale μ is taken to be 20 GeV [18], and the factorization and renormalization scales are set to $q^2 = M_{\mathrm{W}}^2 + p_{\mathrm{T,W}}^2$. Four alternative samples of W events are generated with the scales increased and reduced by a factor of two with respect to those of the reference sample. Samples of $\mathrm{t\bar{t}}$ and Drell–Yan events are also generated with MADGRAPH. Single-top production is modeled with POWHEG 1.0 [19]. Multijet and diboson samples (WW, WZ, ZZ) are generated with PYTHIA 6.422 [20]. PYTHIA provides the parton shower simulation in all cases, with parameters of the underlying event set to the Z2 tune [21]. The set of parton distribution functions used is CTEQ6LL [22]. Simulated signal samples for the technicolor and WH models are generated with PYTHIA, while the leptophobic Z' is generated with MADGRAPH. A GEANT4-based simulation [23] of the CMS detector is used in the production of all Monte Carlo (MC) samples. Multiple proton-proton interactions within a bunch crossing are taken into account, and the triggers are emulated. All simulated events are reconstructed and analyzed with the same software as data.

We determine the contributions of the known SM processes to the observed m_{jj} spectrum by means of an extended unbinned maximum-likelihood fit in the range between 40 GeV and 400 GeV. The fit is performed separately in four event categories, $\{\mu, \mathrm{e}\} \times \{\text{2-jet}, \text{3-jet}\}$, because the background compositions differ. The m_{jj} signal region, 123 to 186 GeV, corresponding to $\pm 2\sigma_{jj}$, is excluded from this fit in order to arrive at an unbiased estimate of a possible resonant enhancement in this region.

Table 1 lists the SM processes included in the fit. The W plus jets normalization parameter is a free fit parameter because it is by far the dominant background. The normalizations of the other background components are allowed to vary within Gaussian constraints around their

Table 1: Treatment of background m_{jj} shapes and normalizations in a fit to the data. The background normalizations are constrained within the fit to Gaussian distributions with the listed central values and widths.

Process	Shape	Constraint on normalization
W plus jets	MC/data	Unconstrained
Diboson (WW+WZ)	MC	61.2 pb ±10% (NLO) [24]
$\mathrm{t\bar{t}}$	MC	163 pb ±7% (NLO) [25]
Single-top	MC	84.9 pb ±5% (NNLL) [26–28]
Drell–Yan plus jets	MC	3.05 nb ±4.3% (NNLO) [29]
Multijet (QCD)	data	$\not\!\!E_\mathrm{T}$ fit (described in text)

central values. The central values for all processes except multijet are obtained from next-to-leading-order (NLO) or next-to-NLO (NNLO) calculations, and the constraints reflect the theoretical uncertainties. The m_{jj} distribution shapes are obtained from simulation. Multijet events contribute when jets are misidentified as isolated leptons. The central value of the multijet normalization is obtained from a separate fit to the $\not\!\!E_\mathrm{T}$ distribution [10], and the constraint is determined by the corresponding fit uncertainty. The shape of the m_{jj} distribution for multijet events is derived from data events with lepton candidates that fail the isolation requirements.

The m_{jj} spectrum of the dominant W plus jets component is not well described by the default CMS MADGRAPH sample. No significant improvement is observed with the alternative W plus jets samples. We employ a combination of three shapes to describe this component in the fitting function:

$$F_{\mathrm{W+jets}} = \alpha\, \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q'^2) + \beta\, \mathcal{F}_{\mathrm{W+jets}}(\mu'^2, q_0^2) + (1-\alpha-\beta)\, \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q_0^2)\,,$$

where $\mathcal{F}_{\mathrm{W+jets}}$ denotes the m_{jj} shape from simulation. The parameters μ_0 (μ') and q_0 (q') correspond to the default (alternative) values of μ and q, respectively, while fractional contributions α and β are free to vary between 0 and 1. We take $\mu' = 2\mu_0$ or $0.5\mu_0$ ($q' = 2q_0$ or $0.5q_0$), depending on which alternative sample provides a better fit to data. Furthermore, we verify via pseudo-experiment simulations that the function in the above equation has sufficient freedom to describe the W plus jets shape in the signal region.

Figure 1(a) shows the observed m_{jj} distribution for all four event categories combined, together with the fitted projections of the contributions of various SM processes. Figure 1(b) shows the same distribution after subtraction of all SM contributions from data except electroweak diboson WW/WZ events. No peak is visible in the spectrum except that near 80 GeV due to diboson events. Figure 1(c) shows the normalized residuals. Table 2 presents the yields of various SM components obtained from the fit. The sum of all the contributions is compared to the number of observed events. All numbers except those in the last two rows are for the m_{jj} range of 40 to 400 GeV. The last two rows compare the observed and predicted contributions in the m_{jj} range of 123 to 186 GeV. The data agree with the SM expectations, and we find no significant excess in the signal region. We observe a sizable deficit in the muon 2-jet data with respect to the prediction from our model. We do not observe similar deviations in the other three categories, suggesting it is a fluctuation and not a systematic bias.

We validate the fit procedure by performing pseudo-experiments. In each experiment, we generate the m_{jj} pseudo-data of the SM processes, taking into account the correlation among the yields, and then fit each pseudo-data sample. The results indicate that the bias on the total

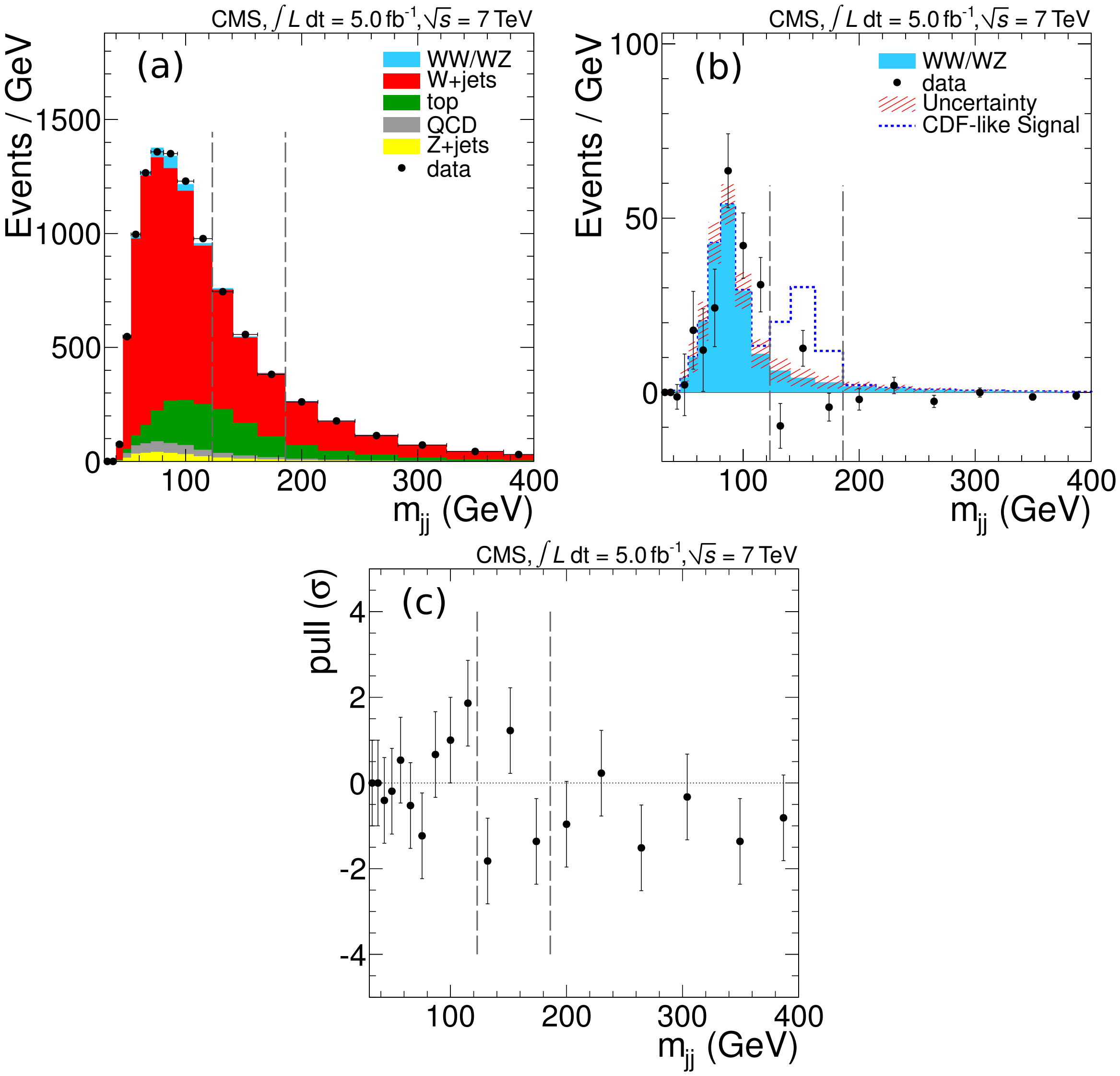

Figure 1: (a) Distribution of the invariant mass spectrum of the leading two jets observed in data. Overlaid are the fit projections of the various components. The region between the vertical dashed lines is excluded from the fit. Depicted is the number of events per GeV. (b) The same distribution after subtraction of all SM components except the electroweak processes WW/WZ. Error bars correspond to the statistical uncertainties. The hatched band represents the systematic uncertainty on the sum of the SM components. (c) The normalized residual, $(\text{data} - \text{fit})/(\text{fit uncertainty})$.

Table 2: Event yields determined from maximum-likelihood fits to the data. The total fit yields are corrected for bias. The total fit uncertainties include the corrections derived from the fit validation described in the text and the effect of correlations among the individual contributions.

	muons		electrons	
Process	2-jet	3-jet	2-jet	3-jet
W plus jets	58919 ± 530	13069 ± 366	29787 ± 1153	8397 ± 292
Dibosons	1236 ± 114	333 ± 32	685 ± 65	184 ± 18
$\mathrm{t\bar{t}}$	4570 ± 307	9049 ± 382	2556 ± 174	4265 ± 253
Single-top	1765 ± 87	1001 ± 50	916 ± 46	521 ± 26
Drell–Yan plus jets	1837 ± 79	561 ± 24	1061 ± 46	364 ± 16
Multijet (QCD)	29 ± 284	0 ± 90	3944 ± 1133	324 ± 160
Fit χ^2 probability	0.454	0.729	0.969	0.991
Total from fit	68294 ± 307	24013 ± 193	38949 ± 228	14055 ± 143
Data	67900	24046	38973	14145
In the signal region $123 < m_{jj} < 186\,\mathrm{GeV}$ (excluded from the fit)				
Total predicted	14511 ± 125	7739 ± 95	7944 ± 92	4347 ± 70
Data	14050	7751	8023	4438

yield is below 0.2% and that the fit underestimates the total yield uncertainty by about 30%. These effects are corrected for in the final result. Uncertainties in the jet energy are estimated using a sample of W bosons decaying hadronically in a pure sample of semileptonic $\mathrm{t\bar{t}}$ events. The mean and resolution of the reconstructed dijet mass distribution in data agree within 0.6% with the expectation from simulation. A small difference in $\not\!\!E_{\mathrm{T}}$ resolution [9] between data and simulation affects the signal acceptance for the new physics models under consideration at the 0.5% level. Further systematic uncertainties are due to the uncertainty of the trigger efficiency estimates (1%) and the estimate of lepton reconstruction and selection efficiency (2%) [10]. The uncertainty on the integrated luminosity is 2.2% [30].

We scrutinize the dijet mass spectrum near 150 GeV, searching for a technicolor, leptophobic Z', or WH resonant enhancement. We also use a generic signal model obtained by convolving a delta function centered at $m_{jj} = 150\,\mathrm{GeV}$ with a Gaussian function having width equal to σ_{jj}. The expected number of signal events at the LHC for a given cross section at the Tevatron can be estimated by considering the ratio of the predicted cross sections for our reference process, WH production with $M_{\mathrm{H}} = 150\,\mathrm{GeV}$. This process is dominated by quark-antiquark ($\mathrm{q\bar{q}}$) annihilation. As $\mathrm{q\bar{q}}$ processes have the smallest increase in parton luminosity from the Tevatron to the LHC, this choice provides a conservative limit. We therefore assume

$$\sigma_{\mathrm{LHC}}^{\text{dijet resonance}} = \sigma_{\mathrm{Tevatron}}^{\text{dijet resonance}} \frac{\sigma_{\mathrm{LHC}}^{\mathrm{WH}}}{\sigma_{\mathrm{Tevatron}}^{\mathrm{WH}}},$$

where $\sigma_{\mathrm{LHC}}^{\mathrm{WH}} = 300.1\,\mathrm{fb}$ [31] and $\sigma_{\mathrm{Tevatron}}^{\mathrm{WH}} = 71.8\,\mathrm{fb}$ [32]. A generic Gaussian signal normalized to $\sigma_{\mathrm{Tevatron}} = 4\,\mathrm{pb}$ corresponds to $\sigma_{\mathrm{LHC}} = 16.7\,\mathrm{pb}$. The values of $\sigma_{\mathrm{LHC}} \times \mathcal{B}(X \to jj)$ and $\varepsilon\mathcal{A}$ for the models considered are given in Table 3.

Since we observe no resonant enhancement, we proceed to set exclusion limits using a modified frequentist $\mathrm{CL_S}$ method [33, 34] with profile likelihood as the test statistic. Inputs to the limit-setting procedure are the m_{jj} distribution obtained by combining the SM components from the fit, the observed distribution in data, and the expectation from the dijet resonance model under consideration. Figure 2(a) shows the observed and expected $\mathrm{CL_S}$ values versus cross section

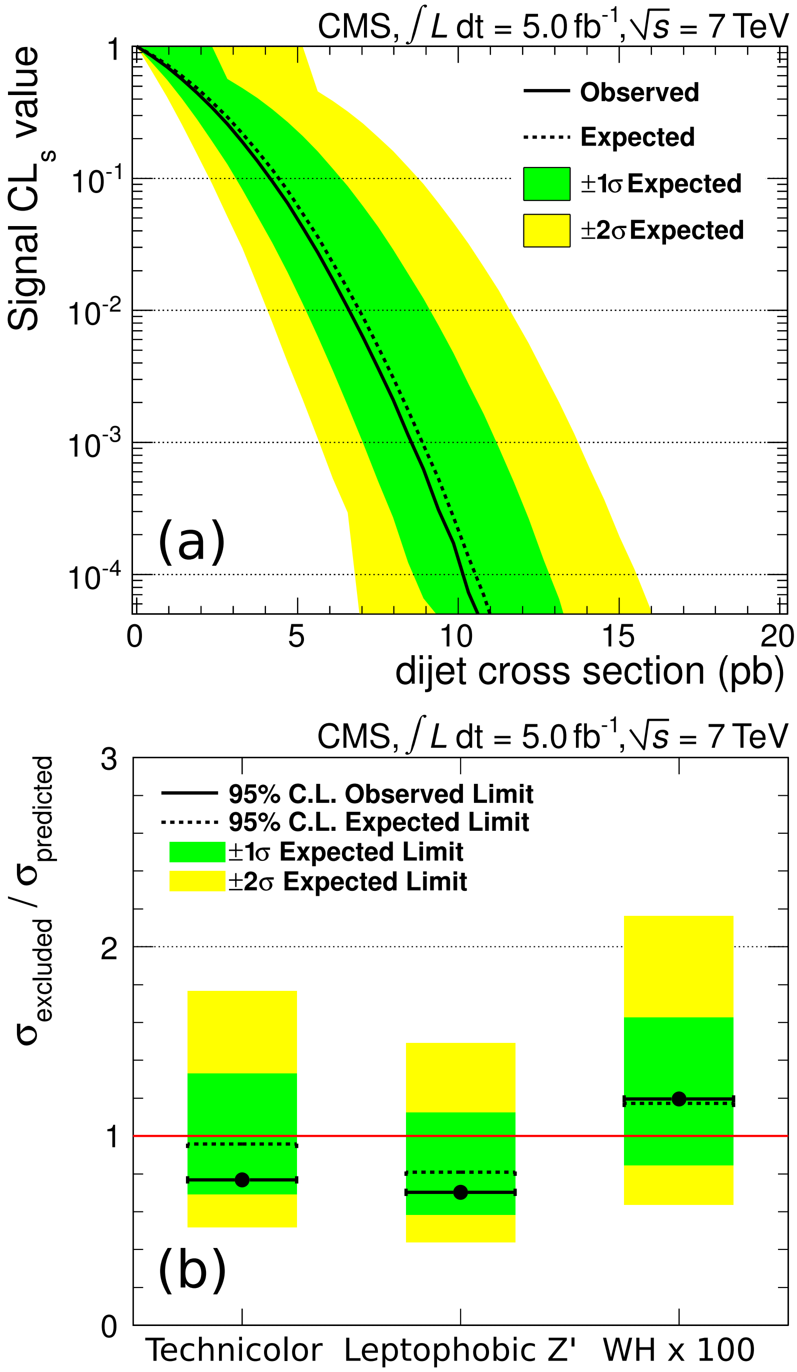

Figure 2: (a) The observed and expected values of the $\mathrm{CL_S}$ statistic for a generic Gaussian signal hypothesis with $M = 150\,\mathrm{GeV}$ and $\sigma = 15\,\mathrm{GeV}$, as a function of the dijet signal cross section. (b) Observed and expected 95% CL upper limits, with one- and two-sigma error bands, on the cross section divided by the expected values for various signal models. The limits are calculated using the $\mathrm{CL_S}$ method. A value of the excluded cross section over the predicted cross section of less than one indicates that the model is excluded at 95% CL. Table 3 lists the cross sections for these models.

Table 3: The PYTHIA cross sections at 7 TeV times branching fraction to jets ($\sigma \times \mathcal{B}$) and overall efficiency times acceptance ($\varepsilon\mathcal{A}$) for various signal models. The relative uncertainties in ε measurements are 1–2%.

		$\varepsilon\mathcal{A}$			
		muons		electrons	
Signal model	$\sigma \times \mathcal{B}$ (pb)	2-jet	3-jet	2-jet	3-jet
Technicolor [4]	7.4	0.065	0.020	0.039	0.011
Z′ [5]	8.1	0.070	0.023	0.042	0.014
WH [20]	0.059	0.060	0.019	0.038	0.013

for a generic Gaussian signal, after combining the results of all four event categories. We set a 95% confidence level (CL) upper limit of 5.0 pb and a 99.9% CL upper limit of 8.5 pb on the dijet production cross section for a generic resonance with WH-like $\varepsilon\mathcal{A}$.

Figure 2(b) compares the 95% CL upper limits with the expected cross sections for technicolor, leptophobic Z′, and WH ($M_{\mathrm{H}} = 150\,\mathrm{GeV}$) signals. The technicolor and Z′ models are excluded. Because we have minimal sensitivity to WH, we compare the limit in Fig. 2(b) to 100 times the SM cross section as an illustration.

In summary, we have studied the invariant mass spectrum of the two jets with highest transverse momentum in pp → W+2-jet and W+3-jet events, with the W decaying leptonically to a muon or electron. The analyzed data sample corresponds to an integrated luminosity of $5.0\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7\,\mathrm{TeV}$. We find no evidence for a resonant enhancement near a dijet mass of 150 GeV, as reported by the CDF Collaboration, and set upper limits on the dijet production cross section of 5.0 pb at 95% CL and 8.5 pb at 99.9% CL. Two theoretical models, leptophobic Z′ and technicolor, which predict the presence of a resonant enhancement near 150 GeV, are excluded.

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