First observation of top quark production in the forward region

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Abstract: Top quark production in the forward region in proton-proton collisions is observed for the first time. The $W + b$ final state with $W \rightarrow \mu \nu$ is reconstructed using muons with a transverse momentum, $p_T$, larger than 25 GeV in the pseudorapidity range $2.0 < \eta < 4.5$. The $b$ jets are required to have $50 < p_T < 100$ GeV and $2.2 < \eta < 4.2$, while the transverse component of the sum of the muon and $b$-jet momenta must satisfy $p_T > 20$ GeV. The results are based on data corresponding to integrated luminosities of 1.0 and 2.0 fb$^{-1}$ collected at center-of-mass energies of 7 and 8 TeV by LHCb. The inclusive top quark production cross-sections in the fiducial region are $\sigma$(top)$[7\text{TeV}] = 239 \pm 53\text{(stat)} \pm 33\text{(syst)} \pm 24\text{(theory)} \text{ fb}$ and $\sigma$(top)$[8\text{TeV}] = 289 \pm 43\text{(stat)} \pm 40\text{(syst)} \pm 29\text{(theory)} \text{ fb}$. These results, along with the observed differential yields and charge asymmetries, are in agreement with next-to-leading order Standard Model predictions.

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First Observation of Top Quark Production in the Forward Region

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Top quark production in the forward region of proton-proton collisions is observed for the first time. The $W + b$ final state with $W \rightarrow \mu \nu$ is reconstructed using muons with a transverse momentum, $p_T$, larger than 25 GeV in the pseudorapidity range $2.0 < \eta < 4.5$. The $b$ jets are required to have $50 < p_T < 100$ GeV and $2.2 < \eta < 4.2$, while the transverse component of the sum of the muon and $b$-jet momenta must satisfy $p_T > 20$ GeV. The results are based on data corresponding to integrated luminosities of 1.0 and 2.0 fb$^{-1}$ collected at center-of-mass energies of 7 and 8 TeV by LHCb. The inclusive top quark production cross sections in the fiducial region are $\sigma$(top)[7 TeV] = 239 ± 53(stat) ± 33(syst) ± 24(theory) fb, $\sigma$(top)[8 TeV] = 289 ± 43(stat) ± 40(syst) ± 29(theory) fb. These results, along with the observed differential yields and charge asymmetries, are in agreement with next-to-leading order standard model predictions.

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The production of top quarks ($t$) from proton-proton ($pp$) collisions in the forward region is of considerable experimental and theoretical interest. In the standard model (SM), four processes make significant contributions to top quark production: $t\bar{t}$ pair production, single-top production via processes mediated by a $W$ boson in the $t$ channel ($qb \rightarrow q't$) or in the $s$ channel ($q\bar{q}' \rightarrow t\bar{b}$), and single top produced in association with a $W$ boson ($q\bar{b} \rightarrow tW$). The initial-state $b$ quarks arise from gluon splitting to $bb$ pairs or from the intrinsic $b$ quark content in the proton. Top quarks decay almost entirely via $t \rightarrow Wb$. The SM predicts that about 75% of $t \rightarrow Wb$ decays in the forward region are due to $t\bar{t}$ pair production. The remaining 25% are mostly due to $t$-channel single-top production, with $s$-channel and associated single-top production making percent-level contributions.

The enhancement at forward rapidities of $t\bar{t}$ production via $q\bar{q}$ and $gg$ scattering, relative to $gg$ fusion, can result in larger charge asymmetries, which may be sensitive to physics beyond the SM [1,2]. Forward $t\bar{t}$ events can be used to constrain the gluon parton distribution function (PDF) at a large momentum fraction, resulting in reduced theoretical uncertainty for many SM predictions [3]. Furthermore, both single-top and $t\bar{t}$ cross-section measurements in the forward region will provide important experimental tests of differential next-to-next-to-leading order theoretical calculations as they become available [4].

This Letter reports the first observation of top quark production in the forward region. The data used correspond to integrated luminosities of 1.0 and 2.0 fb$^{-1}$ collected at center-of-mass energies of $\sqrt{s} = 7$ and 8 TeV in $pp$ collisions with the LHCb detector. The $W$ bosons are reconstructed using the $W \rightarrow \mu \nu$ decay with muons having a transverse momentum, $p_T$, larger than 25 GeV ($c = 1$ throughout this Letter) in the pseudorapidity range, $2.0 < \eta < 4.5$. The analysis is performed using jets clustered with the anti-$k_T$ algorithm [5] using a distance parameter $R = 0.5$. The jets are required to have $50 < p_T < 100$ GeV and $2.2 < \eta < 4.2$. The muon and jet ($j$) must be separated by $\Delta R(\mu, j) > 0.5$, with $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$. Here $\Delta \eta(\Delta \phi)$ is the difference in pseudorapidity (azimuthal angle) between the muon and jet momenta. The transverse component of the sum of the muon and jet momenta must satisfy $p_T(\mu + j) = \sqrt{\vec{p}(\mu) + \vec{p}(j)} > 20$ GeV.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < |\eta| < 5$, designed for the study of particles containing $b$ or $c$ quarks. It is described in detail in Refs. [6,7]. The trigger [8] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. This analysis requires at least one muon candidate that satisfies the trigger requirement of $p_T > 10$ GeV. Global event cuts (GECs), which prevent high-occupancy events from dominating the processing time of the software trigger, have an efficiency of about 90% for $W + j$ and top quark events.

Simulated $pp$ collisions are generated using Pythia [9] with an LHCb configuration [10]. Decays of hadronic particles are described by EvtGen [11] in which final-state radiation is generated using Photos [12]. The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [13] as described in Ref. [14]. Further theory calculations are performed at

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next-to-leading order (NLO) with the MCFM package [15] and the CT10 PDF set [16], and are cross-checked using POWHEGBOX [17] with hadronization simulated by pythia. The theoretical uncertainty on the cross-section predictions is a combination of PDF, scale, and strong-coupling ($\alpha_s$) uncertainties. The PDF and scale uncertainties are evaluated following Refs. [16] and [18], respectively. The $\alpha_s$ uncertainty is evaluated as the envelope obtained using $\alpha_s(M_Z) \in [0.117, 0.118, 0.119]$ in the theory calculations.

The event selection is the same as that in Ref. [19] but a reduced fiducial region is used to enhance the top quark contribution relative to direct $W+b$ production. The signature for $W+jet$ events is an isolated high-$p_T$ muon and a well-separated jet originating from the same $pp$ interaction. Signal events are selected by requiring a high-$p_T$ muon candidate and at least one jet with $\Delta R(\mu, j) > 0.5$. For each event, the highest-$p_T$ muon candidate that satisfies the trigger requirements is selected, along with the highest-$p_T$ jet from the same $pp$ collision. The primary background to top quark production is direct $W+b$ production; however, $Z+b$ events, with one muon undetected in the decay $Z \rightarrow \mu\mu$, and di-$b$-jet events also contribute to the $b+\mu$-jet final state.

The anti-$k_T$ clustering algorithm is used as implemented in FastJet [20]. Information from all the detector subsystems is used to create charged and neutral particle inputs to the jet-clustering algorithm using a particle flow approach [21]. The reconstructed jets must fall within the pseudorapidity range $2.2 < \eta(j) < 4.2$. The reduced $\eta(j)$ acceptance ensures nearly uniform jet-reconstruction and heavy-flavor tagging efficiencies. The momentum of a reconstructed jet is corrected to obtain an unbiased estimate of the true jet momentum. The correction factor, typically between 0.9 and 1.1, is determined from simulation and depends on the jet $p_T$ and $\eta$, the fraction of the jet $p_T$ measured with the tracking system, and the number of $pp$ interactions in the event.

The high-$p_T$ muon candidate is not removed from the anti-$k_T$ inputs and so is clustered into a jet. This jet, referred to as the muon jet and denoted as $j_{\mu}$, is used to discriminate between $W+jet$ and dijet events [19]. No correction is applied to the momentum of the muon jet. The requirement $p_T(j_{\mu}) > 20$ GeV is made to suppress dijet backgrounds, which are well balanced in $p_T$, unlike $W+jet$ events, where there is undetected energy from the neutrino. Events with a second, oppositely charged, high-$p_T$ muon candidate from the same $pp$ collision are vetoed. However, when the dimuon invariant mass is in the range $60 < M(\mu^+\mu^-) < 120$ GeV, such events are selected as $Z(\mu\mu) + jet$ candidates, which are used to determine the $Z+jet$ background.

The jets are identified (tagged) as originating from the hadronization of a $b$ or $c$ quark by the presence of a secondary vertex (SV) with $\Delta R < 0.5$ between the jet axis and the SV direction of flight, defined by the vector from the $pp$ interaction point to the SV position. Two boosted decision trees (BDTs) [22,23], trained on the characteristics of the SV and the jet, are used to separate heavy-flavor jets from light-parton jets, and to separate $b$ jets from $c$ jets. The two-dimensional distribution of the BDT responses observed in data is fitted to obtain the SV-tagged $b$, $c$, and light-parton jet yields. The SV-tagger algorithm is described in Ref. [24], where the heavy-flavor tagging efficiencies and light-parton mistag probabilities are measured in data. The data samples used in Ref. [24] are too small to validate the performance of the SV-tagger algorithm in the $p_T(j) > 100$ GeV region. Furthermore, the mistag probability of light-parton jets increases with jet $p_T$. Therefore, only jets with $p_T < 100$ GeV are considered in the fiducial region, which, according to simulation, retains about 80% of all top quark events.

Inclusive $W+jet$ production, i.e., where no SV-tag requirement is made on the jet, is only contaminated at the percent level by processes other than direct $W+jet$ production. Therefore, $W+jet$ production is used to validate both the theory predictions and the modeling of the detector response. Furthermore, the SM prediction for $\sigma(Wb)/\sigma(Wj)$ has a smaller relative uncertainty than $\sigma(Wb)$ alone, since the theory uncertainties partially cancel in the ratio. The analysis strategy is to first measure the $W+jet$ yields, and then to obtain predictions for the yields of direct $W+b$ production using the prediction for $\sigma(Wb)/\sigma(Wj)$. To an excellent approximation, many experimental effects, e.g., the muon reconstruction efficiency, are expected to be the same for both samples and do not need to be considered in the direct $W+b$ yield prediction.

The $W+jet$ yield is determined by performing a fit to the $p_T(\mu)/p_T(j_{\mu})$ distribution with templates, histograms obtained from data, as described in Ref. [19]. The $Z+jet$ contribution is fixed from the fully reconstructed $Z(\mu\mu) + jet$ yield, where the probability for one of the muons to escape detection is obtained using simulation. The contributions of $b$, $c$, and light-parton jets are each free to vary...
in the fit. Figure 1 shows the fit for all candidates in the data sample. Such a fit is performed for each muon charge separately in bins of $p_T(\mu+j)$; the differential $W$ + jet yield and charge asymmetry, defined as $[\sigma(W^+ j) - \sigma(W^- j)]/\sigma(W^0 j)$, are given in Fig. 2.

To compare the data to theory predictions, the detector response must be taken into account. All significant aspects of the detector response are determined using data-driven techniques. The muon trigger, reconstruction, and selection efficiencies are determined using $Z \to \mu\mu$ events [21,25]. The GEC efficiency is obtained following Ref. [21]: an alternative dimuon trigger requirement, which requires a looser GEC, is used to determine the fraction of events that are rejected. Contamination from $W \to \tau \to \mu$ decays is studied with a data sample enriched in $W$ + jet events. The resolution and scale for each jet $p_T$ bin are varied in simulation to find the best description of the data and to construct a detector response matrix. Figure 2 shows that the SM predictions, obtained with all detector response effects applied, agree with the inclusive $W$ + jet data.

The yields of $W + c$ and $W + b$, which includes $t \to Wb$ decays, are determined using the subset of candidates with a SV-tagged jet and binned according to $p_T(\mu)/p_T(j_\mu)$. In each $p_T(\mu)/p_T(j_\mu)$ bin, the two-dimensional SV-tagger BDT-response distributions are fitted to determine the yields of $c$-tagged and $b$-tagged jets, which are used to form the $p_T(\mu)/p_T(j_\mu)$ distributions for candidates with $c$-tagged and $b$-tagged jets. These $p_T(\mu)/p_T(j_\mu)$ distributions are fitted to determine the SV-tagged $W + c$ and $W + b$ yields.

A fit to the $p_T(\mu)/p_T(j_\mu)$ distribution built from the $c$-tagged jets from the full data sample is provided as Supplemental Material to this Letter [27]. Figure 3 shows that the $W + c$ yield versus $p_T(\mu + c)$ agrees with the SM prediction. Since the $W + c$ final state does not have any significant contributions from diboson or top quark production in the SM, this comparison validates the analysis procedures.

Figure 4 shows a fit to the $p_T(\mu)/p_T(j_\mu)$ distribution built from the $b$-tagged jets from the full data sample. For $p_T(\mu)/p_T(j_\mu) > 0.9$ the data are dominantly from $W$ decays. Figure 5 shows the yield and charge asymmetry distributions obtained as a function of $p_T(\mu + b)$. The direct $W + b$ prediction is determined by scaling the inclusive $W$ + jet distribution observed in data by the SM prediction for $\sigma(Wb)/\sigma(Wj)$ and by the $b$-tagging efficiency measured in data [24]. As can be seen, the data cannot be described by the expected direct $W + b$ contribution alone. The observed yield is about 3 times larger than the SM prediction without a top quark contribution.

FIG. 2 (color online). Results for the inclusive $W + j$ yield (left) and charge asymmetry (right) versus $p_T(\mu + j)$ compared to SM predictions at NLO obtained using MCFM. The data error bars are smaller than the marker size; the SM uncertainties are highly correlated across $p_T(\mu + j)$ bins.

FIG. 3 (color online). Results for $W + c$ compared to SM predictions at NLO obtained using MCFM.
directly. This validates the direct production, of agreement with SM predictions, which include top quark is measured in the larger fiducial region to be direct contribution is expected to be about half as large as that of predicted using Wilks theorem [28] is 5.4σ, confirming the observation of top quark production in the forward region. The yield and charge asymmetry distributions versus $p_T(\mu + b)$ observed at $\sqrt{s} = 7$ and 8 TeV are each consistent with the SM predictions. The excess of the observed yield relative to the direct $W + b$ prediction at each $\sqrt{s}$ is attributed to top quark production, and used to
measure the cross sections. Some additional systematic uncertainties that apply to the cross-section measurements do not factor into the significance determination. Only the luminosity uncertainty depends on $\sqrt{s}$: 2% at 7 TeV and 1% at 8 TeV.

### Table I. Relative systematic uncertainties.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
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</thead>
<tbody>
<tr>
<td>GEC</td>
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<td>$p_T(\mu)/p_T(j_\mu)$ templates</td>
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</tr>
<tr>
<td>Jet reconstruction</td>
<td>2%</td>
</tr>
<tr>
<td>SV-tag BDT templates</td>
<td>5%</td>
</tr>
<tr>
<td>$b$-tag efficiency</td>
<td>10%</td>
</tr>
<tr>
<td>Trigger and $\mu$ selection</td>
<td>2% $^a$</td>
</tr>
<tr>
<td>Jet energy</td>
<td>5% $^a$</td>
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</tr>
<tr>
<td>Luminosity</td>
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</tr>
<tr>
<td>Theory</td>
<td>10%</td>
</tr>
</tbody>
</table>

$^a$An uncertainty that only applies to the cross-section measurement and not the significance determination. Only the luminosity uncertainty depends on $\sqrt{s}$: 2% at 7 TeV and 1% at 8 TeV.


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