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Study of heavy-flavor quarks produced in association with top-quark pairs at $\sqrt{s} = 7$ TeV using the ATLAS detector

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Using a sample of dilepton top-quark pair ($t\bar{t}$) candidate events, a study is performed of the production of top-quark pairs together with heavy-flavor (HF) quarks, the sum of $t\bar{t} + b + X$ and $t\bar{t} + c + X$, collectively referred to as $t\bar{t} + \text{HF}$. The data set used corresponds to an integrated luminosity of 4.7 fb^{-1} of proton-proton collisions at a center-of-mass energy of 7 TeV recorded by the ATLAS detector at the CERN Large Hadron Collider. The presence of additional HF (b or c) quarks in the $t\bar{t}$ sample is inferred by looking for events with at least three b -tagged jets, where two are attributed to the b quarks from the $t\bar{t}$ decays and the third to additional HF production. The dominant background to $t\bar{t} + \text{HF}$ in this sample is $t\bar{t} + \text{jet}$ events in which a light-flavor jet is misidentified as a heavy-flavor jet. To determine the heavy- and light-flavor content of the additional b -tagged jets, a fit to the vertex mass distribution of b -tagged jets in the sample is performed. The result of the fit shows that 79 ± 14 (stat) ± 22 (syst) of the 105 selected extra b -tagged jets originate from HF quarks, 3 standard deviations away from the hypothesis of zero $t\bar{t} + \text{HF}$ production. The result for extra HF production is quoted as a ratio (R_{HF}) of the cross section for $t\bar{t} + \text{HF}$ production to the cross section for $t\bar{t}$ production with at least one additional jet. Both cross sections are measured in a fiducial kinematic region within the ATLAS acceptance. R_{HF} is measured to be $[6.2 \pm 1.1$ (stat) ± 1.8 (syst)]% for jets with $p_T > 25$ GeV and $|\eta| < 2.5$, in agreement with the expectations from Monte Carlo generators.

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I. INTRODUCTION

In order to characterize the recently observed Higgs-like particle (H) [1,2], quantities such as the Yukawa coupling of the top quark and the Higgs boson need to be measured with precision. For a Standard Model (SM) Higgs boson with a mass of 125 GeV, the decay mode with the largest branching ratio is $H \rightarrow b\bar{b}$. Thus, the channel with the largest yields for studying $t\bar{t} + H$ production is $t\bar{t} + H$, $H \rightarrow b\bar{b}$. Production of top-quark pair ($t\bar{t}$) events featuring additional heavy-flavor (HF) b and c quarks, $t\bar{t} + b + X$ and $t\bar{t} + c + X$, referred to as $t\bar{t} + \text{HF}$, is the main irreducible background to $t\bar{t} + H$, $H \rightarrow b\bar{b}$. A study of $t\bar{t} + \text{HF}$ production is useful to constrain models of heavy-flavor quark production at the scale of the top-quark mass. This analysis is also of interest because of the many potential phenomena beyond the SM, such as composite Higgs models [3] and processes leading to final states with four top quarks [4–9], that could produce additional heavy-flavor quarks in the $t\bar{t}$ candidate sample.

This paper describes a study of $t\bar{t} + \text{HF}$ production. Within the SM, heavy-flavor quark pairs, $c\bar{c}$ and $b\bar{b}$, are

expected to be produced in association with $t\bar{t}$ mainly via gluon splitting from initial- and final-state radiation [10]. In addition, the heavy-flavor content of the proton could lead to $t\bar{t}$ final states with at least one additional HF quark, $t\bar{t} + c$ and $t\bar{t} + b$. The data analyzed correspond to an integrated luminosity of 4.7 fb^{-1} at a center-of-mass energy of $\sqrt{s} = 7$ TeV produced at the Large Hadron Collider (LHC) and recorded in 2011 with the ATLAS detector.

This analysis is performed on $t\bar{t}$ dilepton candidate events in which each top quark decays to a b quark and a W boson, which subsequently decays to a neutrino and an isolated, charged lepton. The dilepton signature is selected for this measurement because it is relatively background free and precludes an additional b -tagged jet from a hadronically decaying W boson, predominantly via $W \rightarrow s\bar{c}$. The $t\bar{t} + \text{HF}$ signal region is the subset of these events with three or more jets identified as containing HF quarks (b -tagged jets, or b tags). However, jets without HF quarks may also be b -tagged, so that care must be taken to properly identify the flavor composition of the b -tagged jets in the sample. Two b -tagged jets from each event are presumed to originate from the b quarks from top-quark decays, $t\bar{t} \rightarrow W^+ b W^- \bar{b}$. Therefore, all events in the signal region have at least one additional b tag either from a b - or c -quark jet, or from a light-quark or gluon jet that was misidentified. The latter two are referred to as light-flavor or LF jets.

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Because of limited data statistics and discrimination between b and c jets, the sum of b -quark and c -quark jet rates is measured. Information about the composition of $t\bar{t} + b + X$ and $t\bar{t} + c + X$ in $t\bar{t} + \text{HF}$ is nevertheless required for the total correction due to acceptance, which is different for b - and c -quark jets. The composition is estimated with Monte Carlo simulation.

From the measurement of the fraction of jets with heavy-flavor content, the cross section for $t\bar{t}$ production with at least one additional HF jet can be extracted. To reduce some systematic uncertainties, the result is quoted as a ratio, termed R_{HF} , of the cross section for $t\bar{t}$ production with at least one additional HF jet to the cross section for $t\bar{t}$ production with at least one additional jet ($t\bar{t} + j$), regardless of flavor. The measurement of $t\bar{t} + j$ production is performed in dilepton $t\bar{t}$ candidate events with at least three jets, at least two of which are b -tagged and assumed to come from top-quark decays.

The paper is organized as follows. The ATLAS detector is briefly described in Sec. II. The data and Monte Carlo samples used in the analysis are described in Sec. III, followed by a description of the event selection in Sec. IV. The definition of the fiducial phase space used in the measurement of R_{HF} , and the calculation of acceptances and efficiencies are presented in Sec. V. In Sec. VI, observed and expected numbers of events with ≥ 3 b -tagged jets are shown. Section VII describes a two-dimensional fit to the vertex mass and jet transverse momentum [11] distributions of b -tagged jets in these data events to extract the fraction of HF jets produced in association with $t\bar{t}$. A discussion of the systematic uncertainties of the measurement is presented in Sec. VIII. Section IX shows the result of the measurements, followed by conclusions in Sec. X.

II. THE ATLAS DETECTOR

A detailed description of the ATLAS detector can be found elsewhere [12]. The innermost part of the detector is a tracking system that is immersed in a 2 T axial magnetic field and that measures the momentum of charged particles. The inner detector comprises a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker, providing tracking capability within the pseudorapidity range $|\eta| < 2.5$ [11]. The tracking system is also used to identify the displaced secondary vertex that is formed by hadrons containing a b or c quark. Calorimeter systems, which measure the electron, photon, and hadron energies, reside outside the inner detector and cover the region $|\eta| < 4.9$. Outside the calorimeters there is a muon spectrometer that is used to identify and measure the momentum of muons in an azimuthal magnetic field in the region $|\eta| < 2.7$. To reduce the data rate, a three-level trigger system selects the potentially interesting events that are recorded for off-line analysis.

III. DATA AND MONTE CARLO SAMPLES

The total integrated luminosity for the analyzed data sample is 4.7 fb^{-1} at a center-of-mass energy of $\sqrt{s} = 7 \text{ TeV}$. During the 2011 data-taking period the instantaneous luminosity of the LHC increased, causing the average number of simultaneous inelastic pp interactions per beam crossing (pileup) at the beginning of a pp fill to increase from about 6 to 17. Multiple pp interactions can occur either in the same bunch crossing as the primary vertex (termed “in-time pileup”) or in an adjacent bunch crossing (termed “out-of-time pileup”). To account for these effects, all Monte Carlo simulated events are overlaid with additional inelastic events generated with the PYTHIA AMBT1 tune [13], and the distribution of the number of vertices in the simulation is reweighted to match the distribution of the number of additional interactions per bunch crossing measured in the data.

Monte Carlo simulation is used to study signal and background processes. Inclusive $t\bar{t}$ production and dedicated $t\bar{t} + \text{HF}$ samples are simulated using the multileg matrix-element generator ALPGEN v2.13 [14] with the CTEQ6L1 [15] parton distribution function (PDF) set. Parton showering and hadronization are performed by HERWIG v6.520 [16]. Effects due to the mass of the heavy-flavor quarks are included by default in ALPGEN. In these samples, additional jets (including heavy-flavor) can also be produced in the parton shower. The parton-jet matching scheme described in [14] is applied to avoid double counting of configurations generated by both the parton shower and the leading-order (LO) matrix-element (ME) calculation. In addition, overlap between $t\bar{t}$ events with HF quarks that originate from ME production and those that originate from the parton shower is removed. This heavy-flavor overlap removal is based on the ΔR_{qq} [17] between simulated HF quarks. Events generated by the ME calculation containing two HF quarks separated by $\Delta R_{qq} < 0.4$ are vetoed, as are events containing two HF quarks from the parton shower with $\Delta R_{qq} > 0.4$.

To study the effect of different fixed-order calculations and matching schemes, samples of top-quark pair events are also generated using POWHEG v1.01 [18] and showered with HERWIG. In this sample the $t\bar{t}$ process is described at next-to-leading order (NLO), while the extra jets are described at LO. For each sample showered with HERWIG, JIMMY v4.31 [19] and the AUET1 tune [20] are used to simulate the underlying event and to model various soft interactions. To assess the effect of different parton shower models, a sample is generated using ALPGEN v2.14 with the PYTHIA v6.425 [21] parton shower and hadronization, using the CTEQ5L PDF set [22]. The uncertainty associated with the CTEQ6L1 PDF set is evaluated with an envelope calculated using the uncertainty set from the NLO PDF MSTW2008nlo68cl [23], and an additional term to account for the difference between the central values of the LO and NLO calculations.

Initial- and final-state radiation (ISR/FSR) variations are studied using samples generated with ACERMC v2.0 [24] interfaced with PYTHIA v6.2. In these samples the parameters that control the amount of ISR/FSR are set to points consistent with the PERUGIA Hard/Soft tune [25] in a range constrained by current experimental data [26].

In all samples the top-quark mass is set to $m_t = 172.5$ GeV. The cross section for Standard Model $t\bar{t}$ production at this mass is calculated using the approximate next-to-next-to-leading-order QCD calculation described in [27].

Background samples from the production of W and Z bosons are generated using the CTEQ6L1 PDFs with ALPGEN, which is interfaced to HERWIG for parton showering and hadronization; the ALPGEN matrix elements include diagrams with up to five additional partons. Separate samples of $W + b\bar{b}$ and $Z + b\bar{b}$ events are generated. The overlap between jets from the parton shower and the matrix element in the n and $n + 1$ jet multiplicity samples is removed for the $W + \text{jets}$ and $Z + \text{jets}$ samples in the same manner as for the $t\bar{t}$ samples. Single top-quark production is modeled using ACERMC in the t channel and MC@NLO v3.41 [28] for the Wt and s channels. Diboson (WW , WZ , and ZZ) production is modeled using ALPGEN interfaced with HERWIG. Less than 0.5% of the expected yield in the $t\bar{t} + \text{HF}$ sample comes from the associated production of $t\bar{t} + W/Z$ and $t\bar{t} + H$, and these processes are thus neglected in this analysis.

The resulting generated samples are passed through a GEANT4 simulation [29] of the ATLAS detector [30]. Events are then reconstructed in the same manner as the data.

IV. EVENT SELECTION

Events for the analysis are selected by at least one of the high- p_T [11] single-electron or single-muon triggers, as described in Refs. [31,32]. The single-electron triggers are based on calorimeter energy deposits, shower shape, and matching track quality constraints, while the single-muon triggers are based on a reconstructed track in the muon spectrometer that matches a track found in the inner detector. To ensure a final trigger rate that is compatible with the ATLAS data acquisition system, a minimum p_T threshold for the electron and muon triggers is used. The p_T threshold for the muon trigger is 18 GeV. For the electron trigger, the threshold is 20 or 22 GeV, depending on the data-taking period due to varying LHC luminosity conditions.

The selected events are required to contain a reconstructed primary vertex with at least five associated tracks with $p_T > 0.4$ GeV. Event reconstruction makes use of electrons (e), muons (μ), jets, and missing transverse momentum (E_T). Electrons are reconstructed by matching energy deposits in the electromagnetic calorimeter with tracks in the inner detector and are required to have $p_T > 25$ GeV and $|\eta| < 2.47$, excluding the transition

region between the barrel and end cap calorimeters at $1.37 < |\eta| < 1.52$ [33]. Muons are reconstructed by matching tracks in the inner detector with tracks measured in the muon spectrometer and are required to have $p_T > 20$ GeV and $|\eta| < 2.5$.

Tight isolation cuts are applied to both the electron and muon candidates to reduce the number of identified leptons (e, μ) that come from nonprompt (non- W/Z) sources and from misidentified hadrons. For electrons, the E_T deposited in the calorimeter cells in a cone in η - ϕ space of radius $\Delta R = 0.2$ around the electron position is summed, and the E_T due to the electron is subtracted. The scalar sum of track transverse momenta in a cone of $\Delta R = 0.3$, excluding the electron, is also measured. Cuts parametrized by the electron η and E_T are made on these two isolation variables to ensure a constant efficiency over the entire (η, E_T) range. For muons, the corresponding calorimeter isolation energy in a cone of $\Delta R = 0.2$ is required to be less than 4 GeV, and the scalar sum of track transverse momenta in a cone of $\Delta R = 0.3$ is required to be less than 2.5 GeV after subtraction of the muon p_T .

Jets are reconstructed from clustered energy deposits in the calorimeters with the anti- k_t [34] algorithm with a radius parameter $R = 0.4$ [35]. Jets selected for the analysis are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. In order to reduce the background from jets originating from pileup interactions, the jet vertex fraction, defined as the sum of the p_T of tracks associated to the jet and originating from the primary vertex divided by the sum of the p_T from all tracks associated with the jet, is required to be greater than 0.75.

The transverse momentum of neutrinos produced in the top-quark decays, measured as E_T , is inferred by balancing the vector sum of all visible transverse momenta. Specifically, the E_T is constructed from the vector sum of all calorimeter cell energies contained in topological clusters [35] with $|\eta| < 4.9$, projected onto the transverse plane. Contributions to the E_T from the calorimeter cells associated with jets are taken at the corrected energy scale that is used for jets, while the contribution from cells associated with electrons is substituted by the calibrated transverse momentum of the electron. The contribution to the E_T from the p_T of muons passing the selection requirements is also included.

The b -tagging algorithm [36,37] employed for this analysis uses track impact parameters (the distance of closest approach of each track to the primary vertex) and the properties of any reconstructed secondary vertex associated to the jet as inputs to a neural network. The b -tagging efficiency was calibrated in a multijet data sample where at least one jet contains a muon [37]. The c -tagging efficiency was calibrated in a data sample with reconstructed D^* mesons [38]. For this analysis, b -tagged jets are required to satisfy a selection that is 75% efficient for b -quark jets, approximately 30% efficient for c -quark jets,

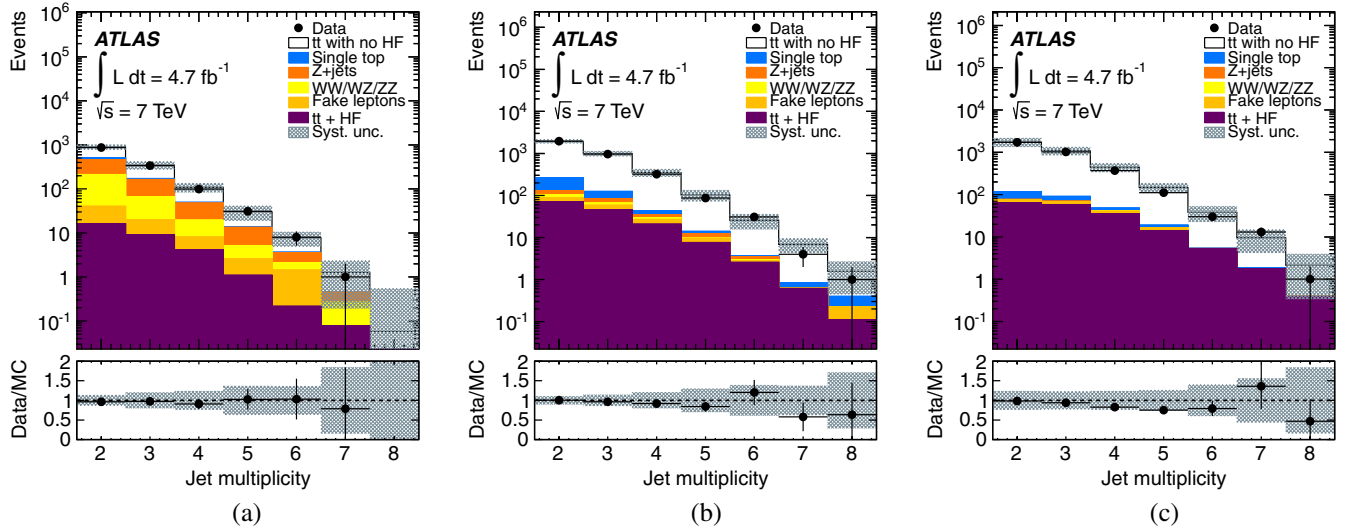


FIG. 1 (color online). Jet multiplicity distributions in dilepton $t\bar{t}$ candidate events with (a) zero b -tagged jets, (b) one b -tagged jet, or (c) two b -tagged jets for the sum of ee , $\mu\mu$ and $e\mu$ channels. The lower plots show the ratio between the data and the Monte Carlo predictions in each bin. Uncertainties are statistical and systematic. The last bin contains any overflow.

and rejects light-flavor jets by a factor of approximately 35 in simulated $t\bar{t}$ events. In this paper, a b tag (or a b -tagged jet) refers to any jet passing this selection, regardless of flavor. A b jet, by contrast, refers to a jet (which may or may not be b -tagged) which contains a b quark. Similarly, c jet and HF jet are statements of the flavor composition of the jet, not whether the jet is b -tagged. Three distinct subsets of the selected b -tagged jets with different b -jet purity are used in the measurement of $\sigma_{\text{fid}}(t\bar{t} + \text{HF})$, as described in Sec. VII.

Dilepton $t\bar{t}$ candidate events are selected by requiring exactly two opposite-sign leptons and at least two jets. To reduce the background from Z/γ^* processes, events with like-flavor leptons are required to have E_T above 60 GeV and a dilepton invariant mass satisfying $|m_{\ell^+\ell^-} - m_Z| > 10$ GeV. For events with one electron and one muon, the scalar sum of the lepton and jet transverse momenta is required to be above 130 GeV to reduce the backgrounds from $Z/\gamma^* \rightarrow \tau^+\tau^-$, as well as WW , WZ , and ZZ processes. This set of selection criteria is termed the “nominal” $t\bar{t}$ selection criteria. The measurement of $t\bar{t} + \text{HF}$ production is carried out in the subset of these events that contain three or more b -tagged jets, whereas the measurement of $t\bar{t}$ production with at least one additional jet is performed in the subset with at least three jets, at least two of which are b -tagged.

Using the nominal selection criteria described above, data and Monte Carlo events are compared in three control regions: dilepton $t\bar{t}$ candidate events with zero, one, or two b -tagged jets. Data-to-simulation normalization corrections are applied to Monte Carlo simulation samples when calculating acceptances to account for observed differences in predicted and observed trigger and lepton reconstruction efficiencies, jet flavor tagging efficiencies and mistag rates,

as well as jet and lepton energy scales and resolutions. In Fig. 1, the jet multiplicity distributions in the three regions are compared to Monte Carlo predictions. Agreement is observed within uncertainties.

V. DEFINITION OF THE FIDUCIAL PHASE SPACE AND CALCULATION OF CORRECTION FACTORS

To allow comparison of the analysis results to theoretical predictions, the measurement is made within a fiducial phase space. The fiducial volume is defined in Monte Carlo simulation by requiring two leptons (e , μ) from the $t \rightarrow Wb \rightarrow \ell\nu b$ decays (including electrons and muons coming from $\tau \rightarrow \ell\nu\nu_\tau$) with $p_T > 25(20)$ GeV for $e(\mu)$, and $|\eta| < 2.5$ as well as three or more jets with $p_T > 25$ GeV and $|\eta| < 2.5$.

In the simulation, jets are formed by considering all particles with a lifetime longer than 10 ps, excluding muons and neutrinos. Particles arising from pileup interactions are not considered. For the determination of the $t\bar{t} + \text{HF}$ fiducial cross section, $\sigma_{\text{fid}}(t\bar{t} + \text{HF})$, three or more jets are required to match a b or c quark, two of which must match a b quark from top-quark decay. All simulated b and c quarks that were generated with $p_T > 5$ GeV are considered for the matching and are required to satisfy $\Delta R(\text{quark}, \text{jet}) < 0.25$. Jets that match both a b and a c quark are considered as b jets. For the calculation of $\sigma_{\text{fid}}(t\bar{t} + j)$ three or more jets are required, two of which must contain a b quark from top-quark decay.

Each fiducial cross section is determined using measured quantities from the data, and a correction factor derived from the Monte Carlo simulation. The ratio of cross sections is defined as

$$R_{\text{HF}} = \frac{\sigma_{\text{fid}}(\bar{t}\bar{t} + \text{HF})}{\sigma_{\text{fid}}(\bar{t}\bar{t} + j)}.$$

The fiducial cross section for $\bar{t}\bar{t} + \text{HF}$ production is determined from

$$\sigma_{\text{fid}}(\bar{t}\bar{t} + \text{HF}) = \frac{N_{\text{HF}}}{\int \mathcal{L} dt \cdot \epsilon_{\text{HF}}}, \quad (1)$$

where N_{HF} is the number, after background subtraction, of b tags from HF jets observed in the data, in addition to the two b jets from top-quark decays. The integrated luminosity of the sample is denoted as $\int \mathcal{L} dt$, and ϵ_{HF} is a correction factor taken from Monte Carlo simulation that converts the number of observed b tags from additional HF jets to the number of events in the signal fiducial volume. This correction factor includes the acceptance within the fiducial region, the reconstruction efficiency, and a factor to account for the multiplicity of extra b -tagged HF jets per $\bar{t}\bar{t} + \text{HF}$ event in the signal region. This correction factor is different for $\bar{t}\bar{t} + b + X$ (ϵ_b) and $\bar{t}\bar{t} + c + X$ (ϵ_c), and thus ϵ_{HF} is determined as a weighted sum of these two contributions. The weight used to form the sum is the fraction of $\bar{t}\bar{t} + \text{HF}$ events in the fiducial volume which contain additional b jets as opposed to c jets. This fraction is termed $F_{b/\text{HF}}$. The total correction factor (ϵ_{HF}) is calculated as

$$\epsilon_{\text{HF}} = F_{b/\text{HF}} \cdot \epsilon_b + (1 - F_{b/\text{HF}}) \cdot \epsilon_c.$$

The denominator for R_{HF} , $\sigma_{\text{fid}}(\bar{t}\bar{t} + j)$, is computed using a similar prescription:

$$\sigma_{\text{fid}}(\bar{t}\bar{t} + j) = \frac{N_j}{\int \mathcal{L} dt \cdot \epsilon_j}, \quad (2)$$

where N_j is the yield of dilepton events in data with at least three jets, at least two of which are b -tagged, and ϵ_j is the $\bar{t}\bar{t} + j$ acceptance factor calculated from the Monte Carlo simulation. The acceptance calculation for each fiducial cross section assumes that all b -tagged jets are from real HF quarks. Events with b -tagged jets from LF quarks are treated as a background and subtracted when computing both N_{HF} and N_j .

The ALPGEN+HERWIG Monte Carlo sample predicts $\epsilon_b = 0.19$, $\epsilon_c = 0.06$, and $F_{b/\text{HF}} = 0.31$. The total correction factor is thus predicted to be $\epsilon_{\text{HF}} = 0.106 \pm 0.005$ (stat) for $\sigma_{\text{fid}}(\bar{t}\bar{t} + \text{HF})$. For $\sigma_{\text{fid}}(\bar{t}\bar{t} + j)$ the acceptance factor is calculated to be $\epsilon_j = 0.129 \pm 0.001$ (stat).

The prediction for R_{HF} from the ALPGEN+HERWIG Monte Carlo sample is 3.4%. The value obtained from the POWHEG v1.01 [18] generator showered with HERWIG [16] is $R_{\text{HF}} = 5.2\%$, with $F_{b/\text{HF}} = 0.34$. While this R_{HF} value is different to that from ALPGEN+HERWIG, the predicted $F_{b/\text{HF}}$ values are similar. Furthermore, a parton-level study using MADGRAPH5 v1.47 [39] gives $F_{b/\text{HF}} = 0.29$. The value of $F_{b/\text{HF}}$ is also stable when

different showering algorithms are used: the ALPGEN+PYTHIA Monte Carlo sample predicts a value of $F_{b/\text{HF}} = 0.32$, in good agreement with the prediction when HERWIG is used. Based on comparison of these predictions for $F_{b/\text{HF}}$, a symmetric 10% Monte Carlo systematic uncertainty is assigned, $F_{b/\text{HF}} = 0.31 \pm 0.03$.

VI. EXPECTED SIGNAL AND BACKGROUND YIELDS

Table I shows the number of events with ≥ 3 b -tagged jets expected in the Monte Carlo simulation from dilepton $\bar{t}\bar{t}$ production and from various background sources. At this point, no distinction is made between events with a true additional HF jet and those containing a mistagged LF jet. The number of observed events is also shown. While Monte Carlo simulation is used to estimate $\bar{t}\bar{t} + \text{HF}$ event rates and kinematic features, data-driven methods and Monte Carlo simulation are both used to estimate background processes, as detailed below.

Background processes containing real b jets and leptons, such as single top-quark, $Z/\gamma^* + \text{jets}$, and diboson (WW , WZ , and ZZ) production, are estimated using Monte Carlo simulation. Contributions from diboson production are found to be negligible.

A major source of background comes from $\bar{t}\bar{t}$ events in which one or more of the b -tagged jets is from a mistagged LF jet. This background is estimated using Monte Carlo simulation for the measurement of $\sigma_{\text{fid}}(\bar{t}\bar{t} + j)$. However, in the measurement of $\sigma_{\text{fid}}(\bar{t}\bar{t} + \text{HF})$, the final $\bar{t}\bar{t} + \text{LF}$ background is determined by a fit to the vertex mass distribution of b -tagged jets in data, as explained in Sec. VII.

Background from events in which at least one of the leptons is either nonprompt (originating from e.g. a photon conversion or b -quark decay) or is a misidentified hadron is estimated using data and Monte Carlo simulation. For instance, $W + \text{jets}$, multijet, and $\bar{t}\bar{t}$ events with one hadronically decaying W boson can contribute in this way. This contribution is determined by scaling the yield of events in the data with a pair of same-sign leptons by the ratio of opposite-sign to same-sign yields ($R_{\text{OS/SS}}$) obtained in Monte Carlo simulation. The opposite-sign to same-sign

TABLE I. Observed and expected number of events in the signal region (i.e. with ≥ 3 b -tagged jets). Uncertainties on individual components are statistical only. For the total expectation, systematic uncertainties are included.

| Process | Number of events |
|-------------------|--|
| $\bar{t}\bar{t}$ | 106.7 ± 3.4 |
| Single top | 2.2 ± 0.5 |
| $Z + \text{jets}$ | 0.2 ± 0.1 |
| Fake leptons | 0_{-0}^{+5} |
| Total expectation | $109_{-3}^{+6}(\text{stat}) \pm 35(\text{syst})$ |
| Data | 106 |

ratio is determined separately for the three dilepton channels and found to be $1.3 \pm 0.1(\text{stat})_{-1.3}^{+1.8}(\text{syst})$ for e^+e^- events, $1.2 \pm 0.1(\text{stat}) \pm 0.7(\text{syst})$ for $\mu^+\mu^-$ events, and $1.2 \pm 0.1(\text{stat}) \pm 0.5(\text{syst})$ for events with one electron and one muon. The systematic uncertainty takes into account the unknown relative mixture of fake-lepton sources (photon conversions, b - and c -hadron decays, or misidentified hadrons) in the $R_{\text{OS/SS}}$ calculation. As there are no same-sign events observed in the data, the central value of the prediction for this background is zero events. Therefore only upward fluctuations of this data count, and positive variations of $R_{\text{OS/SS}}$, are considered in the uncertainty calculation. This method for estimating the background due to events with fake leptons is validated in a control sample of dilepton events with less restrictive lepton identification requirements and no isolation criteria.

The dominant uncertainties on the total yield in Table I come from the jet energy scale, b -tagging efficiency, parton showering model, and initial- and final-state radiation.

VII. TEMPLATE FIT

For the measurement of $\sigma_{\text{fid}}(\bar{t}\bar{t} + \text{HF})$, the fraction of heavy-flavor jets produced in association with $\bar{t}\bar{t}$ is extracted by performing a binned maximum-likelihood fit on the displaced-vertex mass distribution using all b -tagged jets in the events with ≥ 3 b -tagged jets. Although the final result is for both flavors combined, the fit includes separate b - and c -quark components to improve the determination of the LF fraction. This displaced-vertex mass is constructed from the inner detector tracks associated with the secondary vertex using the multivariate algorithm described in Ref. [40]. While the presence of a displaced vertex is an indication that a jet contains a b quark, a jet can be b -tagged even without a secondary vertex by impact parameter information alone. In this case, the vertex mass is undefined. These jets are assigned a mass value of “ -1 GeV” and they are included in the fit to the displaced-vertex mass distribution. Keeping the events without a reconstructed vertex improves the discrimination between heavy-flavor and light-flavor jets.

While the vertex mass is a powerful discriminant, Monte Carlo studies indicate that the sensitivity to the fitted fraction of LF jets increases when the jet p_T is used as an additional discriminant. Considering only the statistical uncertainty, it is seen that a fit with both jet p_T and vertex mass is approximately half a standard deviation more sensitive than a fit with only the vertex mass. It was thus decided to define a two-dimensional probability density function, termed a “template,” for the fit using the vertex mass and jet p_T .

The fit is performed simultaneously in three *mutually exclusive* bins of b -jet purity, defined by different ranges of the b -tagging neural network output value. Certain values of the neural network output, termed “operating points,” are defined by the average b -jet selection efficiency resulting

TABLE II. Summary of the b -tagging efficiencies for b jets, c jets, and light-flavor jets for the three *mutually exclusive* b -tagging selections used in the vertex mass template fit.

| b purity | b -jet efficiency | c -jet efficiency | Light-flavor efficiency |
|------------|---------------------|---------------------|-------------------------|
| High | 60% | 17% | 0.43% |
| Medium | 10% | 7% | 1.00% |
| Low | 5% | 6% | 1.33% |
| Total | 75% | 30% | 2.76% |

from the applied selection. In this analysis, operating points of 60%, 70% and 75% efficiency are used to define the boundaries of the b -jet purity bins.

The first bin uses only the tightest calibrated operating point (60%), contains the highest-purity sample of b jets (referred to as “high purity”), and has a b -tagging efficiency of 60% for b jets. The second bin (referred to as “medium purity”) requires a b -tag selection between the tightest and second tightest (70%) operating points and contains a larger fraction of LF jets and c jets. The efficiency for this bin is 10% for b jets, i.e. the difference between the 70% and 60% operating points. The final bin (“low purity”) requires a b -tag selection between the second (70%) and third operating points (75%) and contains the largest fraction of LF jets. The efficiency for this bin is 5% for b jets. The b -tagging efficiencies for b jets, c jets, and light-flavor jets for each selection are given in Table II.

All three classes of b -tag purity are used in the analysis so that a jet is considered b -tagged if it satisfies any of these criteria. The discrimination power between LF and c jets is greatly improved by using three (as opposed to one) classes of b purity. The vertex mass distributions for all b -tagged jets in events passing the nominal $\bar{t}\bar{t}$ selection criteria are shown in Fig. 2 to confirm that (a) the data are well described by the Monte Carlo simulation (b) and the b -jet, c -jet and LF-jet fractions are different in the three purity selections. For the purpose of illustration, the normalization of the b -jet, c -jet, and LF-jet components is taken from Monte Carlo simulation.

The template fit has five components: b jets from top-quark decays, non- $\bar{t}\bar{t}$ background, extra b -tagged jets from b quarks, extra b -tagged jets from c quarks, and light-flavor b -tagged jets. The template for b jets from top-quark decays is obtained from the data in $\bar{t}\bar{t}$ dilepton events with exactly two b tags. Monte Carlo simulation indicates that 97% of b -tagged jets in $\bar{t}\bar{t}$ dilepton events with exactly two b tags come from the decay of the top quark. To account for this in the shape of the data template, a template for b tags not from the top-quark decays is derived from the $\bar{t}\bar{t}$ Monte Carlo simulation and subtracted with a 3% relative normalization from the data template. In the fit, the normalization for the template for b jets from the top-quark decays is fixed assuming it contributes two of the three or more b tags per observed event.

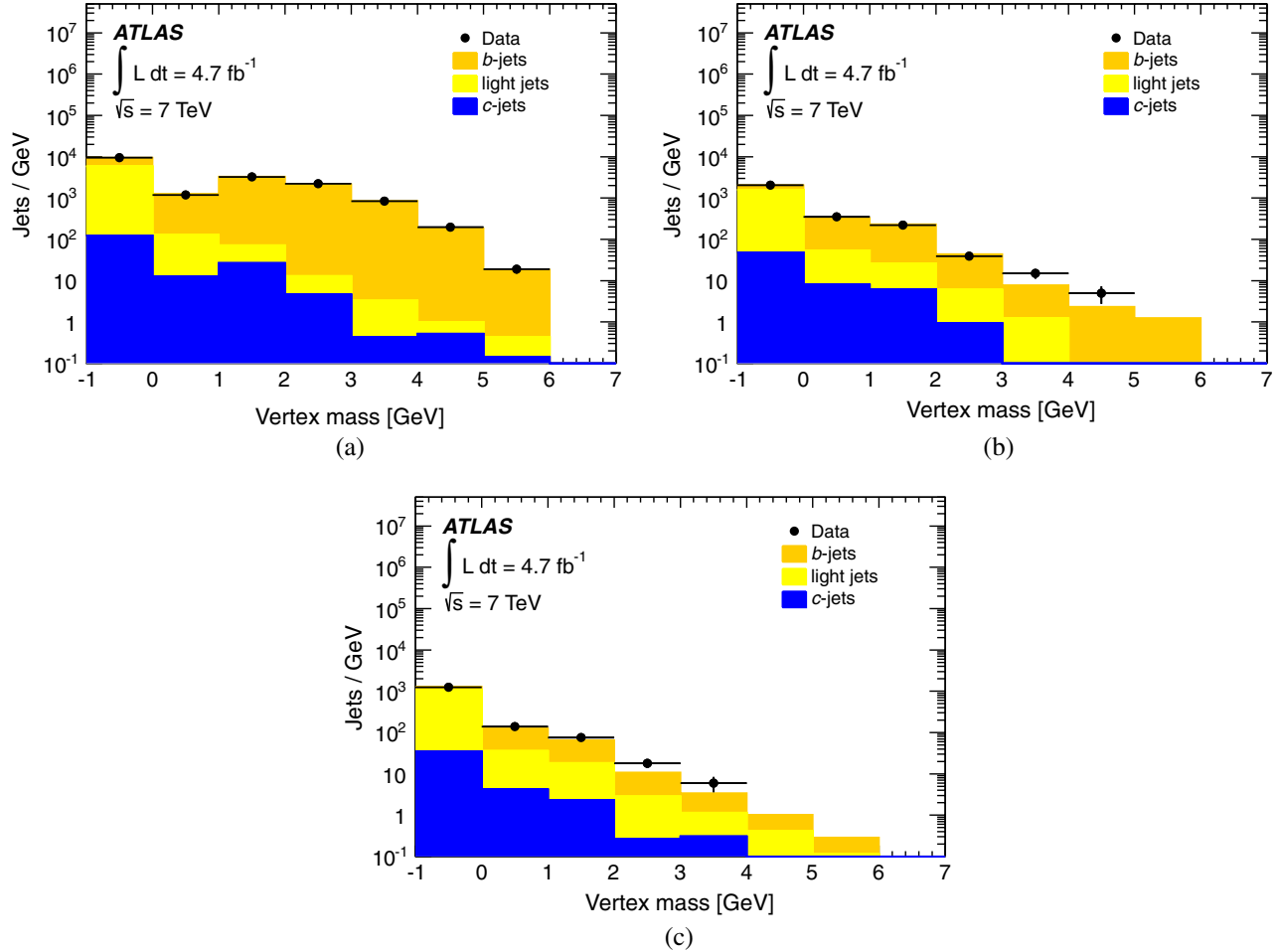


FIG. 2 (color online). (a) High-purity b -tagged jets, (b) medium-purity b -tagged jets, (c) low-purity b -tagged jets. Vertex mass distributions for all b -tagged jets in data events satisfying the nominal dilepton $t\bar{t}$ event selection, with no requirement on b -tagged jet multiplicity, compared to Monte Carlo predictions. By definition, jets with no reconstructed secondary decay vertex are assigned to the -1 GeV bin.

Background events from nondilepton $t\bar{t}$ processes are included using Monte Carlo simulation and enter the fit with a fixed normalization. Monte Carlo simulation is used to obtain templates for additional (non- $t \rightarrow Wb$) b jets, c jets, and LF jets.

In the fit to determine the number of b tags from HF jets in addition to the two b jets from top-quark decay, N_{HF} , separate templates for each category of jet in each of the three purity classes (high, medium, and low) are used. The b -tagging efficiencies (Table II) for each flavor of jet are used to relate the number of jets in each purity bin. After the application of all constraints, the fit has two floating parameters: the fraction of LF jets and the fraction of additional b jets. The fraction of additional c jets makes up the remainder.

Monte Carlo pseudoexperiments show that the fitting method is unbiased in both best-fit values and estimated uncertainties. The fit strategy (including estimates of statistical and systematic uncertainties) was verified using 10% of the full data sample as well as with Monte Carlo

pseudoexperiments before the fit was performed on the full data sample. These studies indicated that the fit could achieve only a 1σ separation of b vs c jets based on the expected statistical uncertainty alone. Inclusion of the systematic uncertainty would further reduce the sensitivity. However, the LF-jet fraction is expected to be measured with sufficient precision to give a statistically significant measurement of the total HF content, defined as the fraction of additional b -tagged jets not coming from LF jets. In the fit, the individual fractions are not constrained to be positive or below unity.

VIII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties may affect the shape of the vertex mass and p_T templates as well as the acceptance calculations. For the systematic uncertainties on the template shapes, the fit to the data is reevaluated using new templates, derived by varying the relevant parameters by their systematic uncertainties, and a new fit to the data is performed. Major uncertainties that affect the fit are the jet

energy scale and resolution, the tagging efficiencies for b , c and LF jets, the parton-shower and hadronization models, and the Monte Carlo event generators.

The template for b jets from top-quark decays is nominally taken from the data with exactly two b tags. To account for kinematic biases due to additional heavy-flavor jets in the event, a systematic uncertainty on the shape of this template is assessed using b jets from top-quark decays from Monte Carlo inclusive $t\bar{t}$ events with three or more b -tagged jets.

The vertex mass of additional b and c jets is sensitive to the number of HF quarks contained in a jet (for instance, for $b\bar{b}$ or $c\bar{c}$ produced via gluon splitting). The dominant uncertainty from this effect would manifest itself as a difference in the shape of the template for additional b jets. To assess this uncertainty, the template for additional b jets is replaced by the template for b jets from top-quark decays.

By default, the normalization of the template for b jets from top-quark decays is fixed to two per event. A systematic uncertainty on this normalization is assessed by using the predicted normalization from Monte Carlo simulation, which includes events with less than two b tags from top-quark decays, due to b -tagging inefficiency. The total uncertainty due to specific template shape variations is referred to as “additional fit uncertainties” for the rest of this paper.

Systematic uncertainties also affect the overall event reconstruction efficiency. Dominant sources of uncertainty for this category are the tagging efficiencies for b , c and LF jets, the jet energy scale and resolution, and the Monte Carlo event generator. Uncertainties on the lepton identification efficiency, E_T reconstruction, and fragmentation modeling are negligible. In general, systematic uncertainties are evaluated on the full data sample, with each uncertainty being taken as the difference between the nominal and the varied resulting values of R_{HF} .

An important uncertainty in this analysis comes from the flavor composition in the fiducial volume, namely in the value of $F_{b/\text{HF}}$, the fraction of $t\bar{t}$ + HF events in the fiducial volume which contain b jets, used to calculate the correction factor ε_{HF} . As described in Sec. V, an uncertainty of 10% on $F_{b/\text{HF}}$ is estimated using different Monte Carlo generators. While the template fit method described in Sec. VII can in principle evaluate $F_{b/\text{HF}}$ using the data, the present data sample does not allow a robust determination of this quantity.

IX. RESULTS

In the 106 events in the signal sample (with ≥ 3 b -tagged jets), there are 325 b -tagged jets. After subtracting the non- $t\bar{t}$ background component, and the contribution from the tagged jets from the $t \rightarrow Wb$ decay, the number of additional b tags is found to be 105. As described in Sec. VII, a template fit to all b -tagged jets is performed to determine the flavor composition of these additional b -tagged jets.

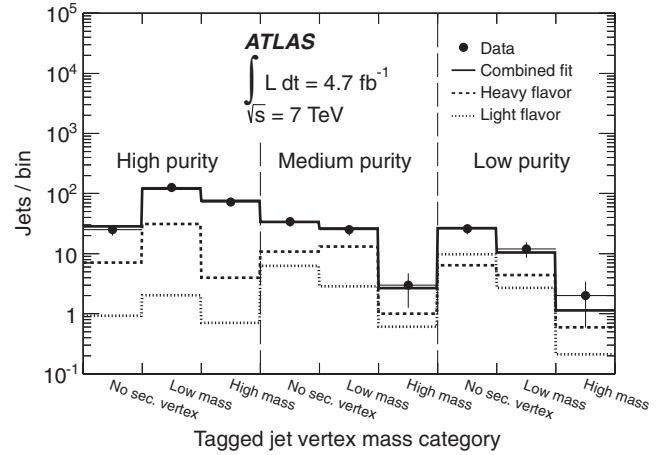


FIG. 3. The result of the template fit (solid line) to the vertex mass distribution in data (points). Data are divided into three groups depending on the purity of b jets passing each selection, as described in the text. The first three bins are the vertex mass distributions for the high-purity b tags, the middle three bins for the medium-purity b tags, and the last three bins for the low-purity b tags. Within each purity category, the first bin contains jets with no reconstructed secondary vertex. The middle bin contains jets with “low” mass: less than 2 GeV. The third bin contains jets with “high” mass: greater than 2 GeV. The best fit is shown as a sum (labeled as “combined fit,” which includes the b jets from top-quark decay) with separate contributions from additional b and c jets (labeled as “heavy flavor”), and LF jets (labeled as “light flavor”).

The result of the fit to all 325 b -tagged jets is shown in Fig. 3. The weighted sums of all fit templates are shown, with contributions for extra HF and mistagged LF jets shown separately. The fitted fractions of b tags from LF jets and b jets are given in Table III. Using these fractions,

TABLE III. Relative composition of b -tagged jets in the signal region, fitted in data and compared to the expectation from Monte Carlo (MC) simulation. The fraction of b jets from top-quark decays is fixed in the fit to two b tags in each event. The contributions from $t\bar{t}$ events with a fake lepton, or non- $t\bar{t}$ events are fixed in the fit (those are labeled as “ b jets from other sources” in the table). In data, the fractions of LF and additional b jets are determined by the fit. The fraction of the sum of b jets and c jets, labeled as “sum of HF jets,” is inferred from unitarity. All quoted errors are statistical.

| Type of b tag, fractions | Data fit | MC expectation |
|--------------------------------------|------------|----------------|
| Fit input assumptions | | |
| b jets from $t \rightarrow Wb$, % | 65 | ... |
| b jets from other sources, % | 2.5 | ... |
| Fit results | | |
| Additional LF jets, % | 8 ± 4 | 20 |
| Additional b jets, % | -2 ± 7 | 9 |
| Derived quantities | | |
| Sum of HF jets, % | 24 ± 4 | 12.5 |

TABLE IV. Summary of the relative systematic uncertainties (in percent) on the measurement of the ratio of fiducial cross sections, R_{HF} . Uncertainties are quoted separately for the number of HF jets measured in the fit (N_{HF}), the portion of the calculation affecting only the correction factors (ϵ_{HF}), and the full calculation. As the fit prefers 100% charm for additional heavy-flavor jets, it is sensitive to differences in the extra b -tagged jets from the c -quark template shape.

| Source | % (N_{HF}) | % (ϵ_{HF}) | % (full) |
|------------------------------------|-----------------------|------------------------------|----------|
| Lepton reconstruction | 0.1 | 0.2 | 0.2 |
| Jet reconstruction and calibration | 3.5 | 1.6 | 6.9 |
| E_T reconstruction | 0.5 | 0.6 | 0.9 |
| Fake-lepton estimate | 3.4 | 0.0 | 3.4 |
| Tagging efficiency for b jets | 1.1 | 2.4 | 3.1 |
| Tagging efficiency for c jets | 25.0 | 5.9 | 21.2 |
| Tagging efficiency for light jets | 8.4 | 0.2 | 8.4 |
| Fragmentation modeling | 6.5 | 15.7 | 10.2 |
| Generator variation | 0.7 | 1.0 | 1.8 |
| Initial- and final-state radiation | 0.1 | 1.7 | 1.9 |
| PDF uncertainties | 1.6 | 1.0 | 2.8 |
| Additional fit uncertainties | 6.6 | ... | 6.6 |
| Flavor composition | 0.0 | 6.0 | 6.0 |
| Total systematic | 29 | 18 | 28 |

$79 \pm 14(\text{stat}) \pm 22(\text{syst})$ of the 105 additional b tags are attributed to HF jets. A detailed breakdown of the systematic uncertainties on the total number of HF jets is shown in Table IV.

The uncertainty on the fitted fraction of light-flavor jets is significantly smaller than the uncertainty on the fitted fraction of additional b jets. This is understood as an effect of fitting in multiple b -purity bins: the low-purity bin is dominated by light-flavor jets and thus gives improved discrimination. The data resolve the total observed HF production rate with a significance of about 3σ .

Using Eq. (1), the number of HF jets observed in data, and the quoted correction factor ϵ_{HF} derived from the Monte Carlo simulation for $t\bar{t} + \text{HF}$ production as discussed in Sec. V, $\sigma_{\text{fid}}(t\bar{t} + \text{HF})$ is found to be $0.16 \pm 0.03(\text{stat})$ pb. This calculation assumes the value and uncertainty of $F_{b/\text{HF}}$ as determined from Monte Carlo simulation. ALPGEN interfaced with HERWIG predicts $\sigma_{\text{fid}}(t\bar{t} + \text{HF}) = 0.10$ pb.

In the data, 1656 $t\bar{t}$ dilepton candidate events are observed with at least three jets, at least two of which are b -tagged. The total background estimate, which is dominated by LF jets misidentified as b jets from top-quark decay, is found to be $112 \pm 4(\text{stat})$, leading to a background subtracted yield of $1544 \pm 41(\text{stat})$. Using Eq. (2), and the quoted acceptance factor for $t\bar{t} + j$ production, $\sigma_{\text{fid}}(t\bar{t} + j)$ is found to be $2.55 \pm 0.07(\text{stat})$ pb, compared to 2.83 pb predicted by ALPGEN and HERWIG. Taking into account the total uncertainty, it is found that $R_{\text{HF}} = [6.2 \pm 1.1(\text{stat}) \pm 1.8(\text{syst})]\%$. A full breakdown of the systematic uncertainties contributing to R_{HF} is given in Table IV.

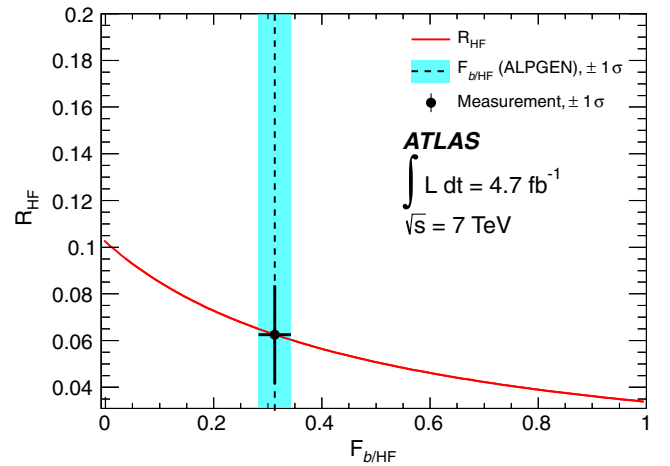


FIG. 4 (color online). Dependence of the data value for R_{HF} on the assumed value of $F_{b/\text{HF}}$. The value of $F_{b/\text{HF}}$ from Monte Carlo simulation, 0.31 ± 0.03 , is indicated by the vertical dashed line with its 1σ uncertainty band. For reference, the central value for the measurement of R_{HF} is indicated, along with an error bar corresponding to the 1σ total uncertainty.

The extracted value of $\sigma_{\text{fid}}(t\bar{t} + \text{HF})$ is very sensitive to the value of $F_{b/\text{HF}}$. As indicated in Sec. V, the efficiency for $t\bar{t} + b + X$ events is approximately a factor of 3 higher than the corresponding efficiency for $t\bar{t} + c + X$ events, implying a potential change in $\sigma_{\text{fid}}(t\bar{t} + \text{HF})$ by a factor of 3 if $F_{b/\text{HF}}$ is allowed to vary over the full range $[0, 1]$.

Ideally the fitted fraction of additional b jets, $F_{b/\text{HF}}$, would be extracted from data and used in the determination of R_{HF} . As stated previously, the limited resolving power of this data sample yields a determination of $F_{b/\text{HF}}$ that is consistent with the entire physical range of $[0, 1]$ at the one sigma level when statistical and systematic uncertainties are included. Figure 4 shows R_{HF} as a function of the assumed value of $F_{b/\text{HF}}$. The value obtained in Monte Carlo simulation, $F_{b/\text{HF}} = 0.31 \pm 0.03$, is also shown. Under the most extreme assumptions $F_{b/\text{HF}} = 0(1)$, the central value of R_{HF} is 10.3 (3.4)%. However, assuming the additional HF jets are either entirely c jets or entirely b jets is inconsistent with expectations from QCD and with the predictions of the Monte Carlo generators studied.

X. CONCLUSIONS

A 4.7 fb^{-1} sample of 7 TeV proton-proton collisions recorded by the ATLAS detector at the LHC was used to measure the ratio R_{HF} of the fiducial cross section for the production of $t\bar{t}$ events with at least one additional HF quark jet ($t\bar{t} + b + X$ or $t\bar{t} + c + X$) to that for the production of $t\bar{t}$ events with at least one additional jet, regardless of flavor, each with $p_T > 25$ GeV and $|\eta| < 2.5$. A fit to the vertex mass distribution for b -tagged jets in $t\bar{t}$ candidate events with three or more b -tagged jets is performed to determine the heavy- and light-flavor content of the additional b -tagged jets. The result of the fit shows

that $79 \pm 14(\text{stat}) \pm 22(\text{syst})$ of the 105 selected b -tagged jets originate from HF quarks, 3 standard deviations away from the hypothesis of zero $t\bar{t} + \text{HF}$ production. A value of $R_{\text{HF}} = [6.2 \pm 1.1(\text{stat}) \pm 1.8(\text{syst})]\%$ is extracted. This value of R_{HF} is consistent with the leading-order predictions of 3.4% obtained from the ALPGEN Monte Carlo generator interfaced with HERWIG and 5.2% from a calculation using POWHEG interfaced with HERWIG.

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