First Measurement of the b-jet Cross Section in Events with a W Boson in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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The cross section for jets from b quarks produced with a W boson has been measured in $p\overline{p}$ collision data from 1.9 fb^{-1} of integrated luminosity recorded by the CDF II detector at the Tevatron. The $W + b$-jets process poses a significant background in measurements of top quark production and prominent searches for the Higgs boson. We measure a b-jet cross section of $2.74 \pm 0.27(\text{stat.}) \pm 0.42(\text{syst.})$ pb in association with a single flavor of leptonic W boson decay over a limited kinematic phase space. This measured result cannot be accommodated in several available theoretical predictions.

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The measurement of associated production of a W boson and one or more jets from b quarks, herein referred to as $W + b$-jet production, provides an important test of quantum chromodynamics (QCD). The understanding of this process and its description by current theoretical calculations are important since it is the largest background to the search for the standard model Higgs boson via WH production with decay $H \to b\bar{b}$ [1, 2], to measurements of top quark properties via single [3, 4] and pair production [5–7] with decay $t \to Wb$, and to some searches for physics beyond the standard model [8].

Theoretical predictions for vector boson production with associated b jets have a large uncertainty. Summed fixed-order QCD calculations for $W{+}b\bar{b}{+}N$-jets production are available for up to $N{=}4$ additional light flavor jets and take into account b-quark mass effects [9]. The next-to-leading order (NLO) calculations for $W + b$-jets production in the 1-jet and 2-jet multiplicities show an enhancement over LO up to a factor of two for certain diagrams [10–12]. In order to minimize the impact of the $W + b$-jets theoretical uncertainty in top quark property measurements and searches for WH production, the theoretical prediction for the cross section of $W + b$-jets production is not used in the evaluation of background estimates. Instead, the prediction from theory for the ratio of the event yields from $W + b$ jets and W + inclusive jets, corrected to match what is measured in data control samples, is scaled to the observed cross section of W+jets in data. The systematic uncertainty on the $W + b$-jets yield, driven by imprecise knowledge in the fraction of jets from b production, is approximately 30-40% [1–7]. These uncertainties are very large compared to the small expected cross sections of the processes mentioned above. We therefore wish to directly measure the $W + b$-jet cross-section with sufficient precision to improve those background estimations. In addition, such a measurement will provide an important constraint on the theoretical predictions. Finally this measurement is a complement to other Tevatron measurements of vector boson plus heavy flavor jet production[13–16].

In this Letter, we describe a measurement of the b-jet cross section in events with a W boson in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV from a data sample corresponding to an integrated luminosity $\mathcal{L}$=1.9 fb^{-1} acquired by the Collider Detector at Fermilab (CDF II)[5]. We select events that are consistent with the electronic or muonic decay of a W boson and contain one or two jets. Among the jets in these selected events, we seek those that originate from b-quark production. Hadrons that contain a b quark have a relatively long lifetime of ∼1.6 ps, and a large mass of ∼5.3 GeV/c^2 [17]. We exploit the B hadron's long lifetime by examining the charged particles within each jet and attempting to reconstruct a common origin for their trajectories that is well-displaced from the primary $p\bar{p}$ interaction location. The distance between the primary and secondary vertices corresponds to the trajectory through which the relativistically boosted B hadron traveled during its lifetime. The technique is commonly known as vertex b-tagging.

The n_{tag} tagged jets in the selected sample are not purely from b jets. Charm hadrons and certain light flavor hadrons have an appreciable lifetime, and hence jets containing these hadrons can be tagged despite not originating from b-quark production. Also, the finite resolution of the CDF tracking system can allow for spurious displaced vertices. In order to reduce contamination from charm and light flavor/gluon jets, the requirements on the quality of the secondary decay vertex have been optimized for this measurement. Further, we exploit the B hadron's large mass by examining the invariant mass of the charged particles forming the secondary decay vertex (vertex mass, M_{vert}). Vertex mass is correlated with the mass of the parent hadron and partially discriminates between the possible jet flavors to yield the b-jet fraction, f^b. The number of b jets from other processes, $n^{b\text{ jets}}_{\text{bkg}}$, is estimated for top quark pair, single top quark, diboson, and multijet production. The acceptance $\mathcal{A}^{b\text{ jets}}_{W+b}$ is defined with respect to the restricted region of phase space defined below. The b-jet identification efficiency, ϵ^b_{tag}, and the event trigger efficiencies, ϵ, are calibrated with data. The cross section for b jets times the branching fraction for one flavor of $W \to \ell\nu$ decay is defined as

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$$\sigma_{b\ \mathrm{jets}} \times \mathcal{B}(W \to \ell\nu) \;=\; \frac{n_{\mathrm{tag}} \cdot f^{b} - n_{\mathrm{bkg}}^{b\ \mathrm{jets}}}{\sum\limits_{i=e,\mu} (\mathcal{L} \cdot \mathcal{A}_{W+b}^{b\ \mathrm{jets}} \cdot \epsilon_{\mathrm{tag}}^{b} \cdot \epsilon)_i} \quad (1)$$

where the sum is over the electron and muon channels.

It is important to note that we quote our result as a jet-level cross section in order to avoid a model-dependent correction on the number of b jets per event that would be required to convert our result into an event-level cross section. Further the result is defined in a restricted region of phase space for the kinematics and multiplicity of the outgoing particles in order to make comparisons with theoretical predictions that minimize extrapolation outside the experimentally accessible region. We define this restricted region of phase space as coincident with our analysis selection criteria, namely to events that contain one or two hadron-level jets with $E_{\mathrm{T}}>$ 20 GeV and $|\eta| < 2.0$, an electron or muon with $p_{\mathrm{T}}>$ 20 GeV/c and $|\eta| < 1.1$, and a neutrino with $p_{\mathrm{T}}>$ 25 GeV/c [18]. We compute the theoretical predictions with these requirements imposed as well.

The data used in this measurement come from the general purpose CDF II detector [19] operating at Fermilab's Tevatron collider. Detailed descriptions of the various subdetectors new for Run II can be found elsewhere [20–24]. The data are collected with a charged lepton trigger that requires an electron (muon) candidate with $|\eta| < 1.0$ (1.1) and $E_{\mathrm{T}}>$ 18 GeV ($p_{\mathrm{T}}>$ 18 GeV/c). The identified charged lepton and the large missing transverse energy, $\not\!\!E_{\mathrm{T}}$, from the undetected neutrino provide background suppression compared to hadronic W decays. In offline event selection we require a single reconstructed electron (muon) with $E_{\mathrm{T}}>$ 20 GeV ($p_{\mathrm{T}}>$ 20 GeV/c) that is well-isolated from other activity in the calorimeter, and $\not\!\!E_{\mathrm{T}}>$ 25 GeV. A cone-algorithm-based jet reconstruction with cone size $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ is used; jet reconstruction and calibration are described elsewhere [25]. We require exactly one or two jets with $E_{\mathrm{T}}>$ 20 GeV and $|\eta| < 2.0$. Events consistent with cosmic rays, $Z \to \ell^+\ell^-$, photon conversions, and multi-jet QCD production are rejected [26]. In data from 1.9 fb^{-1} of integrated luminosity, there are 175,712 events satisfying the W selection and jet requirements.

The b-tagging criteria have been designed for this measurement to obtain a significantly higher purity for b jets and thus reduce the overall systematic uncertainty from the model of the vertex mass distribution. With respect to the default CDF vertex b-tagging [5], this optimized algorithm reduces the rate for false positives of jets from light quark flavors (u, d, s) and gluons by a factor of 10 and charm by a factor of 4 at the expense of a 50% reduction in efficiency for b jets. To be considered for b-tagging, charged particle tracks within the jet cone are required to have $p_{\mathrm{T}}>$ 0.5 GeV/c, and impact parameter significance $\frac{d_0}{\delta_{d_0}} > 3.5$, where the impact parameter d_0 is the distance of closest approach of the particle track to the location of the primary $p\overline{p}$ interaction in the transverse plane with respect to the beam axis, and δ_{d_0} is its uncertainty. Particles must also have an impact parameter less than 0.15 cm, originate from within 2 cm of the primary $p\overline{p}$ interaction location in the z coordinate [18], and have at least a minimum number of hits from the silicon tracking detectors. These requirements reduce contamination from interactions with detector material, multiple $p\overline{p}$ interactions, and misreconstruction, respectively. A common decay vertex is sought among subsets of these selected particles, and if one is found that contains three or more particles, then the decay length in the transverse plane, L_{2D}, is calculated as the projection along the jet axis of the displacement of the secondary vertex with respect to the primary $p\overline{p}$ interaction location. The vertex is required to have decay length significance $\frac{L_{2D}}{\delta_{L_{2D}}} > 7.5$, and pseudo-c$\tau \equiv \frac{L_{2D} \cdot M_{\mathrm{vert}} \cdot c}{p_{\mathrm{T,vert}}} < 1.0$ cm, where the invariant mass M_{vert} and transverse momentum $p_{\mathrm{T,vert}}$ of the vertex are calculated from the constituent particles. Note that the mass of each particle is set to the charged pion mass. Any vertices consistent with K_S^0 and Λ decay, and nuclear interactions in the detector material are rejected. The sign of the vertex tag is determined by the position of the vertex with respect to the jet direction; those on the same (opposite) hemisphere as the jet direction are called positively (negatively) tagged.

Among the events satisfying our event selection, $n_{\mathrm{tag}} =$ 943 jets are found to be positively tagged. The flavor composition of the positively tagged sample is determined through a maximum likelihood fit of the distribution of the vertex mass in the data. Simulated distributions for b and charm jets are formed from standard model processes that are major contributors to the selected event sample. Sources of b jets include W+b jets, which is simulated by the Monte Carlo event generator ALPGEN version 2.1.0 [27] with CTEQ5L parton densities [28] and PYTHIA version 6.325 for hadronization [29]; $t\bar{t}$ and diboson production are simulated with PYTHIA version 6.216, and single top quark production by MADEVENT version 4.2.11 [30]. The yields of tagged jets from these processes are determined from the simulated samples scaled to the latest theoretical cross sections [31–33] with the event selection requirements applied.

We check the simulation model of b jets against an independent data sample from double-tagged dijet events collected with a single $p_{\mathrm{T}}>$ 9 GeV/c muon trigger. One jet is required to contain the muon, presumably from semileptonic B hadron decay. The other tagged jet in these events is a sample whose b-jet purity is estimated to be above 99%. This sample is used to validate the model of the b-jet vertex mass; the agreement between simulation and data is shown in Fig. 1. We use the difference between simulation and data to estimate the systematic uncertainty from the b-jet model.

Vertex tags of jets from charm hadrons are primarily due to W+c-jets production, which is simulated with ALPGEN. Positive vertex tags of light flavor jets are modeled with a simulation of inclusive jet production from PYTHIA. We use negatively tagged jets in the data as an alternative model for light flavor. This second light flavor model is used in the vertex mass fit to assess the impact of light flavor model choice on the result.

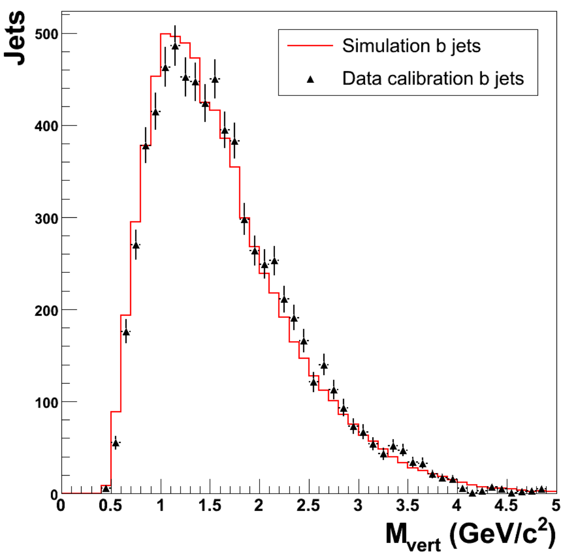

FIG. 1: Comparison of the vertex mass distributions of tagged b jets from a simulated sample and from data.

The maximum likelihood fit of the vertex mass data distribution, shown in Fig. 2, is used to extract two parameters: the fraction of jets from bottom hadrons f^b, and the fraction of jets from charmed hadrons f^c, where the fraction of jets from light flavors is $f^{\mathrm{LF}} \equiv 1 - f^b - f^c$. The best fit is $f^b = 0.71 \pm 0.05(\mathrm{stat.})$ corresponding to $670 \pm 44(\mathrm{stat.})$ tagged jets from bottom hadrons. From simulated experiments with flavor compositions similar to the data, we confirmed that our vertex mass fit procedure returns results consistent with the assumed background content. These simulated experiments indicated that the systematic uncertainties on the model of the b, charm, and light flavor vertex mass distributions manifest themselves as relative systematic uncertainties of 0.08, 0.01 and 0.03, respectively, on the fitted b-jet fraction.

This yield of b jets includes our signal but also contains a contribution from other processes with jets from b-quark production. We use simulated samples and the theoretical predictions for production rates of $t\bar{t}$ [31], single top quark [32], and diboson processes (WZ, WW, and ZZ) [33] in order to estimate a contribution of 152 ± 21 b jets from these processes. This includes a small contribution of 7.3 ± 0.8 jets from W+b-jets production with $W \to \tau\nu$, which is treated as a background. Sources of

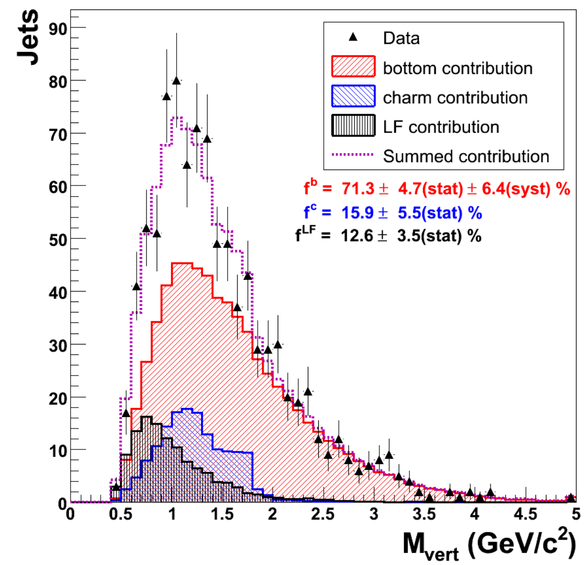

FIG. 2: Maximum likelihood fit of the vertex mass for tagged jets in the selected data sample.

systematic uncertainty in the background yield of tagged b jets include the uncertainty in the b-jet tagging efficiency in the data (a relative 6% uncertainty on all tagged b-jet yields), the uncertainty on the top quark and diboson predicted cross sections (a relative uncertainty of 10% on $t\bar{t}$ and diboson, and 30% on single top yields, which translate to an overall 2% uncertainty on $\sigma_{b\text{ jets}} \times \mathcal{B}$) and the uncertainty in the accumulated CDF luminosity (a relative 6% on all yields).

We estimate a contribution of 25 ± 8 b-jets from QCD multijet production, where mismeasured jets pass the lepton identification requirements and result in sufficient $\not\!\!E_{\mathrm{T}}$. As this background is difficult to model with simulation, a complementary data sample was collected with the same high p_{T} electron trigger, but where the electron candidate failed at least two of the identification criteria [34]. This provides both a model of the $\not\!\!E_{\mathrm{T}}$ distribution, which is used to estimate the rate of QCD multijet background above our selection [34], and a vertex mass distribution, which is used to determine the fraction of tagged jets from bottom hadrons. The model for tagged jets from multijet production is statistics limited; we recover statistics by relaxing the $\not\!\!E_{\mathrm{T}}$ requirement and perform the vertex mass distribution fit for $\not\!\!E_{\mathrm{T}} > 15$ and 20 GeV as well as the default $\not\!\!E_{\mathrm{T}} > 25$ GeV and use all three results to determine the fitted b fraction from multijet production. The uncertainties on the QCD multijet tagged b-jet background come from the modeling of the $\not\!\!E_{\mathrm{T}}$ distribution for the overall multijet normalization (a relative 30% uncertainty, which translates to a 1% uncertainty on $\sigma_{b\text{ jets}} \times \mathcal{B}$), and the spread in the fitted b fraction from vertex mass distribution fits from the different $\not\!\!E_{\mathrm{T}}$ thresholds (a relative 25% uncertainty, which translates to a 1% uncertainty on $\sigma_{b\text{ jets}} \times \mathcal{B}$).

After subtracting the background of $n_{\rm bkg}^{b\ {\rm jets}} = 177 \pm 22$, we have a yield of 493 ± 48(stat.) tagged b jets from W+b production. We define the acceptance, $\mathcal{A}_{W+b}^{b\ {\rm jets}}$, of our selection with respect to a restricted region of kinematic phase space, as defined earlier. The phase space restrictions are applied to the outgoing leptonic W daughters and jets in the simulated W+b production ALPGEN events. Hadron-level jets are defined by SpartyJet [35] as a collection of simulated final state particles that have been clustered using the same cone algorithm as in the jet reconstruction. A hadron-level jet is said to be b-matched if it has $\Delta R < 0.4$ with respect to a b quark in the simulated event. The matching considers b-quark candidates after showering but before hadronization. The denominator of the acceptance is the number of b-matched hadron-level jets in simulated $W + b$-jet events that pass the phase space requirements as given earlier; the numerator is the number of b-matched reconstructed jets in simulated $W + b$-jet events that pass the phase space requirements and, in addition, the event selection described above through the jet multiplicity requirement. The weighted average acceptance over the electron and muon channels is found to be 0.68 ± 0.03, where the sources that dominate the systematic uncertainty are the jet energy calibration (3%), the factorization and renormalization scale (3%), and the dependence of event kinematics on the parton distribution functions (2%).

For clarity, we separate the b-tag efficiency and several data-based corrections from the acceptance. The b-tag efficiency is the ratio of the number of b-tagged reconstructed b-matched jets to the number of reconstructed b-matched jets in the simulated $W + b$-jet events that have passed the event selection and phase space requirements: $\epsilon_{\rm tag}^{b,{\rm sim}} = 0.177 \pm 0.001$(stat.). This value needs to be corrected by a factor of 0.88 ± 0.01(stat.) ± 0.05(syst.), which quantifies the discrepancy in tag efficiency between simulation and data [36]. The corrected b-tag efficiency is then $\epsilon_{\rm tag}^{b} = 0.156 \pm 0.009$. The final correction factor ϵ is the average over all triggers of the product of the following three terms determined from data: the fraction of events that happen in the luminous region well-contained by the CDF detector, with primary $p\overline{p}$ interaction within 60 cm of the center of the detector along the beam line, 0.963 ± 0.003; the efficiency of the trigger, 0.943 ± 0.004; and the correction factor for charged lepton identification efficiency, 0.969 ± 0.004.

Having obtained all of the information needed as input to Eq. 1, we measure the b-jet cross section to be $\sigma_{b\ {\rm jets}} \times \mathcal{B}(W \to \ell\nu) = 2.74 \pm 0.27$(stat.) ± 0.42(syst.) pb with a W boson decaying to a single leptonic flavor within the restricted kinematic phase space defined earlier. The overall relative uncertainty on the measurement is 18%. This uncertainty is dominated by the uncertainty in the b-jet vertex mass model (a relative 8% on $\sigma_{b\ {\rm jets}} \times \mathcal{B}$), the tag efficiency (6%), and the luminosity (6%). The results in the electron and muon channels were examined independently as a cross check and are consistent.

Finally, we have determined the theoretical prediction of $\sigma_{b\ {\rm jets}} \times \mathcal{B}$, using our kinematic definition above, at leading order from PYTHIA and at summed fixed-order from ALPGEN. The PYTHIA prediction is 1.10 pb and the ALPGEN prediction is 0.78 pb, assuming a Q^2 scale of $M_W^2 + p_{{\rm T},W}^2$; these predictions are factors of 2.5-3.5 lower than our result. These are important comparisons given the wide use of these programs in the generation of simulated physics events at the Tevatron and LHC experiments. A NLO calculation of $\sigma_{b\ {\rm jets}} \times \mathcal{B}$ has recently been completed [37]; their prediction of 1.22 ± 0.14(syst.) pb is also low with respect to the measured value. Further study is underway to examine the differential cross section as a function of jet kinematics and compare to LO, summed fixed-order and NLO predictions.

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