Vector Boson + Heavy Flavor Jets Production at the Tevatron

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Recent measurements on the vector boson plus heavy-flavor jets production by the CDF and D0 experiments are presented in comparisons with recent theoretical predictions. Good understanding of such processes is important to improve our understanding of QCD and also to enhance the potential to search for yet-to-be-discovered new physics phenomena which lead to similar final states.

1. Introduction

Events containing vector bosons and heavy-flavor jets constitute valuable data samples for a variety of physics analyses at both CDF and D0 experiments at the Fermilab Tevatron $p\bar{p}$ collider. For example, an event sample containing a $W/Z$ boson and $b$-jet(s) is a golden sample for the Higgs search at low masses, studies of top quark production and properties, and also searches for the beyond-the-standard-model phenomena. Thus, the measurements of cross sections for QCD production of vector boson + heavy-flavor jets are important not only to enhance our understanding of QCD but also to better understand the backgrounds to other important physics studies. Presented below are recent measurements by the CDF and D0 experiments on these processes.

2. W+b-Jets Production

CDF has made a measurement of the $W+b$-jets cross section \cite{1} using 1.9 fb$^{-1}$ of $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV. The event sample used in this measurement is selected from the high $p_T$ electron and muon samples by requiring a reconstructed isolated electron with $E_T > 20$ GeV or muon with $p_T > 20$ GeV/c, missing transverse energy ($E_T$) > 25 GeV, and one or two jets with $E_T > 20$ GeV and $|\eta| < 2$.

$b$-jets are “tagged” by the presence of a displaced secondary vertex within the jet arising from the decay of the long-lived $B$ hadron. The $b$-tagged jet sample includes background contributions from charm and light-flavor (LF) jets. The fraction of $b$-jets in the $b$-tagged sample is estimated by performing a fit to the invariant mass of all charged tracks associated with the secondary vertex as shown in Fig. 1; on average, $b$-jets have a larger mass than $c$-jets and LF jets due to the hierarchy of $B$, $D$ and LF hadron masses.

There are non-negligible contributions to $W+b$-jet candidates from processes other than QCD $W+b$ production. The largest background contribution comes from QCD multijet production in which there is no real $W$, but a combination of jets faking leptons, mismeasured jet energy, or semileptonic $b$-decay make the events pass through all the event selections. The other major background sources are $t\bar{t}$ production and single top quark production. The QCD multijet production contribution is estimated using data, and the other background contributions are estimated from MC predictions.

The cross section for $b$-jets with $E_T > 20$ GeV and $|\eta| < 2$ from QCD $W+b$ production is measured to be $\sigma(Wb) \times BR(W \rightarrow l^\pm \nu) = 2.74 \pm 0.27$(stat) $\pm 0.42$(syst) pb which is higher than the Alpgen prediction of 0.78 pb by
4. Photon+Heavy-Flavor Jet Production

In the standard model (SM), $\gamma + b/c$ events are produced predominantly produced via the compton scattering $Q + g \rightarrow Q + \gamma$ (where $Q = b/c$) at low $p_T$, and the contribution of the annihilation process $q\bar{q} \rightarrow Q\bar{Q}\gamma$ increases with increasing $p_T$. The cross section is sensitive to the $b$-quark density in the proton as in the case of the $Z + b$-jet production.

| CDF Data | Pythia | Alpgen | MCFM NLO | MCFM NLO+UE +Hadronization |
|----------|--------|--------|----------|---------------------------|
| $\sigma(Z + b$-jet) | 0.86 ± 0.14 ± 0.12 pb | – | – | 0.51 pb |
| $\sigma(Z + b$-jet)/$\sigma(Z)$ | 0.336 ± 0.053 ± 0.041% | 0.35% | 0.21% | 0.21% |
| $\sigma(Z + b$-jet)/$\sigma(Z + \gamma)$ | 2.11 ± 0.33 ± 0.34 % | 2.18% | 1.45% | 1.88% |

$\sim 3.5$. This large disagreement is somewhat unexpected and indicates a need for an improved theoretical prediction for this process.

3. Z+b-Jets Production

The $Z + b$-jets production has been studied by both D0 [2] and CDF [3]. The dominant production diagrams contributing to the $Z + b$-jets final state are (a) $bg \rightarrow Zb$ ($\sim 65\%$) and (b) $q\bar{q} \rightarrow Zb\bar{b}$ ($\sim 35\%$) in next-to-leading order (NLO) pQCD predictions. The cross section is sensitive to the $b$-quark density in the proton, and thus the cross section measurement provides important information for the $b$-quark density which is so far indirectly extracted from gluon density. A good understanding of the $b$ density is essential to accurately predict the production of particles that couple strongly to $b$-quarks including supersymmetric Higgs bosons and single top production. $Z + b$-jets production is also a major background in searches for the Higgs production in the $ZH \rightarrow Zbb$ channel.

CDF has recently updated the measurement on $Z + b$-jet production using 2.0 fb$^{-1}$ of data. The measurement was made using jets with $E_T > 20$ GeV and $|\eta| < 1.5$ tagged as $b$-jets by the secondary vertex algorithm in $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ events and the results are summarized in Table. The high statistics in the data used in the recent analysis also allowed the first measurement of differential distributions, which are shown in Fig. together with several theoretical predictions. The data are in general agreement with the data, but differences at the level of up to 2σ are observed. Both Alpgen and MCFM NLO predictions lie somewhat below the data at low jet $E_T$ ($Z p_T$), but agree better with data at higher jet $E_T$ ($Z p_T$). Pythia is in good agreement with data at low jet $E_T$, but less so at higher jet $E_T$. Large variations in theoretical predictions are not well understood and need to be resolved.

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production. The good understanding of these processes is also important as the QCD production of $\gamma + b/c$ is a significant background in new physics searches, including searches for the techniomega production ($\omega_{TC} \to \gamma\pi_{TC} \to \gamma b\bar{b}$), some SUSY scenarios, and excited b-quark production.

The $\gamma + b$-jet cross section was measured by CDF [4] and D0 reported improved measurements on $\gamma + b/c$-jet recently [5] based on the 1 fb$^{-1}$ of data. The measurement is made in the kinematic region of $30 < p_T^\gamma < 150$ GeV/c, $|y^\gamma| < 1$, $p_T^{jet} > 15$ GeV/c, and $|y^{jet}| < 0.8$ for events with $y^\gamma y^{jet} > 0$ (region 1) and $y^\gamma y^{jet} < 0$ (region 2), separately. These two rapidity combinations helps to differentiate the parton $x$ regions contributing to the two regions. The regions 1 and 2 are sensitive to $0.01 < x_1 < 0.03$, $0.03 < x_2 < 0.09$, and $0.02 < x_1, x_2 < 0.06$, respectively.

Photon candidates are selected using a neural network (NN) approach [6]. The photon purity is higher than 50% in all kinematic regions and improves with increasing $p_T^\gamma$. The heavy-flavor jet tagging is also performed using a NN which exploits the longer lifetime of $B/D$ hadrons compared to the lighter ones. The inputs to the neural network include the number of secondary vertices, secondary vertex mass, a weighted combinations of the track’s impact parameter significances and the probability that a jet originates from the primary vertex (JLIP probability). Among the tagged jets, the fraction of $b$, $c$, and light-flavor jets is determined based on a template fit to the JLIP probability distribution.

The measured differential cross sections for the $\gamma + b/c$-jet production are compared to their theoretical predictions from NLO pQCD as functions of $p_T^\gamma$ in Fig. 3. For $\gamma + b$, data and theoretical predictions are in good agreement over the full kinematic region explored. For $\gamma + c$, a reasonable agreement is observed only at $p_T^\gamma < 50$ GeV/c, and the deviation increases with increasing $p_T^\gamma$ in both regions 1 and 2. The deviation may be attributed to a possible non-negligible intrinsic charm content in the proton and/or the inaccurate description of $g \to c\bar{c}$ fragmentation.

5. W+Single Charm Production

$W + c$ events are produced by $gs \to Wc$ ($\sim 90\%$) and $gd \to Wc$ ($\sim 10\%$) in the SM. Thus, the production cross section is sensitive to the $s$-quark PDFs in the proton at a scale on the order of the $W$ mass, and it is also sensitive to the element of the CKM matrix $V_{cs}$. Also, $Wc$ is an important component of the $W+1$ and 2 jet samples, that are used in searches for e.g. a single top, the Higgs boson, and a supersymmetric top, and the searches will benefit from good understanding of QCD $Wc$ production.

Both CDF [2] and D0 [3] studied W+single $c$ production recently. In both measurements, $W \to l\nu$ events are selected by requiring a high $p_T$ isolated electron or muon with large $E_T$. Charm jets are identified from their semileptonic decay by looking for a muon within the jet; this charm jet identification algorithm is referred to as the
soft lepton tagging (SLT) algorithm. W + c events are identified by utilizing the charge correlation between a lepton from W decay (W lepton) and SLT muon, i.e., the difference between events in which the W lepton and SLT muon have opposite charge (OS) and events in which they have same charge (SS). The Wc production mainly leads to OS events; however most of background processes such as the Wc¯ production give OS and SS events almost equally. Therefore, events from Wc production can be extracted from the excess of OS-SS events.

Figure[2](top) shows the number of OS-SS events as a function of SLT muon pT measured by CDF, with an excess which is consistent with the presence of the Wc production. After taking into account the OS-SS events from backgrounds, such as W+light-flavor jets, Drell-Yan, and QCD multijet production, the cross section of the Wc production for pT > 20 GeV/c and |η| < 1.5 is measured to be σ(Wc) × BR(W → lν) = 9.8 ± 3.2 pb which is in good agreement with the NLO pQCD prediction of 11.0±1.4 pb.

D0 measured the cross section ratio σ(W + c)/σ(W + jets), since in the ratio many systematic uncertainties cancel. The measurement was made as a function of jet pT as shown in Fig. 4(bottom). The cross section ratio integrated over pT > 20 GeV/c and |η| < 2.5 is measured to be 0.074 ± 0.019(stat)+0.012−0.014 which is somewhat higher but consistent with the Alpgen prediction of 0.044 ± 0.003.

6. Summary

Final states containing a vector boson and heavy-flavor jets appear in many interesting physics processes. The good understanding of QCD production of such final states is critical for physics analyses at the Tevatron and also at the upcoming LHC, and both CDF and D0 Collaborations have made extensive studies on these processes. It was found that W + c and γ + b measurements are well described by the state-of-the-art recent theoretical calculations; however, the measurements on the W/Z + b-jets and γ + c-jet indicate a need of an improved understanding of these processes. The measurements with improved precision from the Tevatron experiments would be the keys for deeper understanding of these processes and benefit for future physics analyses at the Tevatron and also at the LHC.

References

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