

Hadronic final states in high- p_T QCD at CDF

KEITH MATERA, ON BEHALF OF THE CDF COLLABORATION

University of Illinois at Urbana-Champaign

The heavy quark content associated with gauge boson production is of great interest to studies of QCD. These events probe the gluon and heavy-quark parton distribution functions of the proton, and also provide a measurement of the rate of final state gluon splitting to heavy flavor. In addition, gauge boson plus heavy quark events are representative of backgrounds to Higgs, single top, and supersymmetric particle searches. Recent work with the CDF II detector at the Fermilab Tevatron has measured the cross-section of several gauge boson plus heavy flavor production processes, including the first Tevatron observation of specific charm process $p\bar{p} \rightarrow W + c$. Results are found to be in agreement with NLO predictions that include an enhanced rate of $g \rightarrow c\bar{c}/b\bar{b}$ splitting. Lastly, a new analysis promises to probe a lower $p_T(c)$ region than has yet been explored, by fully reconstructing $D^* \rightarrow D^0(K\pi)\pi$ decays in the full CDF dataset (9.7 fb^{-1}).

1. Introduction

The study of gauge boson ($\gamma/W/Z$) plus heavy quark Q (b and c) production in hadronic collisions provides valuable information about the nature of QCD in accelerator events.

Measurements of these events are sensitive to the gluon and heavy-quark parton distribution functions of the proton. While convention assumes that charm and bottom quarks in the proton arise only from gluon splitting, there are other models that allow for intrinsic heavy quarks in the proton [1]. Measuring the cross-sections of $p\bar{p} \rightarrow \gamma/W/Z+b/c$ production tests these models, as well as measuring the rate of final-state gluon splitting to heavy quarks [2, 3]. Previous work has suggested that the rate of final-state gluon splitting to heavy quarks is roughly twice as large as that predicted by PYTHIA simulations [4–6].

Careful measurement of gauge boson plus heavy flavor cross-sections could also lead to a better understanding of other processes. The final state of $p\bar{p} \rightarrow \gamma/W/Z+b/c$ events are similar to the final states of neutral and charged Higgs boson production, single top production, and supersymmetric top quark production.

The CDF II detector at the Fermilab Tevatron [7] is well-suited to search for these events. The CDF II is a cylindrical detector with approximate azimuthal and forward-backward asymmetry. Three separate silicon microstrip detectors near the beampipe allow vertex reconstruction of prompt decays with a resolution of $30 \mu\text{m}$ in the transverse direction ($60 \mu\text{m}$ along the beamline). The central outer tracker (COT), an open-cell drift chamber, provides excellent track resolution from a radius of $40 - 137 \text{ cm}$. The COT and silicon detectors are immersed in a 1.4 T magnetic field parallel to the beamline, sourced by a solenoid outside of the COT. This field provides charge identification through track curvature. Electromagnetic calorimeters outside of the solenoid provide photon and electron identification, while hadronic calorimeters and muon chambers allow the identification of neutral hadrons and muons, respectively. A three-layer trigger system identifies events of interest, including those with secondary vertices (such as charm and bottom events), and those with high- p_T photon or lepton candidates (such as gauge-boson events).

In this paper, we first discuss recent CDF measurements of $\gamma + b/c$ cross-sections [8], and then move onto observations of $W/Z + b/c$ events [9, 10]. We conclude with a new approach at CDF for identifying $W/Z + c$ events [11].

2. Prompt photon + heavy flavor

We begin by discussing a recent CDF analysis of $\gamma + b/c$ cross-sections [8]. Direct photon production in association with heavy flavor is dominated by $gQ \rightarrow \gamma Q$ for $E_T^\gamma < 100 \text{ GeV}/c$. At higher E_T^γ , production is dominated by quark-antiquark annihilation $q\bar{q} \rightarrow \gamma g \rightarrow \gamma QQ$ [12].

To identify these events, a photon candidate must first be identified which satisfies $E_T^\gamma > 30 \text{ GeV}/c$ and $|\eta| < 1.04$. An artificial neural network, constructed from isolation variables and calorimeter- and strip-chambers-shape information, is used to reduce background among the candidates [13].

Once a photon candidate has been tagged, jets are reconstructed using the JETCLU algorithm with cone radius $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.4$. At least one jet with $E_T > 20 \text{ GeV}$ and $|\eta| < 1.5$ must be classified as a heavy-flavor jet using a secondary-vertex tagger [14], and this jet must be reconstructed in a volume outside of the $R = 0.4$ cone surrounding the photon candidate. If multiple jets pass these cuts, the jet with the highest E_T is selected for further analysis.

The invariant mass M_{SecVtx} of the system of charged particles originating at the secondary vertex is then calculated, assuming that all particles are pions. The M_{SecVtx} distribution is fit using templates for b -, c -, and light quark jets constructed with PYTHIA [15].

Results, reported as a differential cross-section, are compared to Monte

Carlo predictions (Figure 1). The NLO pQCD predictions agree with data for low E_T^γ , but do not well describe the data for $E_T^\gamma > 70$ GeV. This is true for both the charm- and bottom-jet cross-sections. This can be explained by noting that in this high- E_T^γ regime, the dominant production process is $q\bar{q} \rightarrow \gamma g \rightarrow \gamma Q\bar{Q}$, which is present only to leading order in NLO predictions.

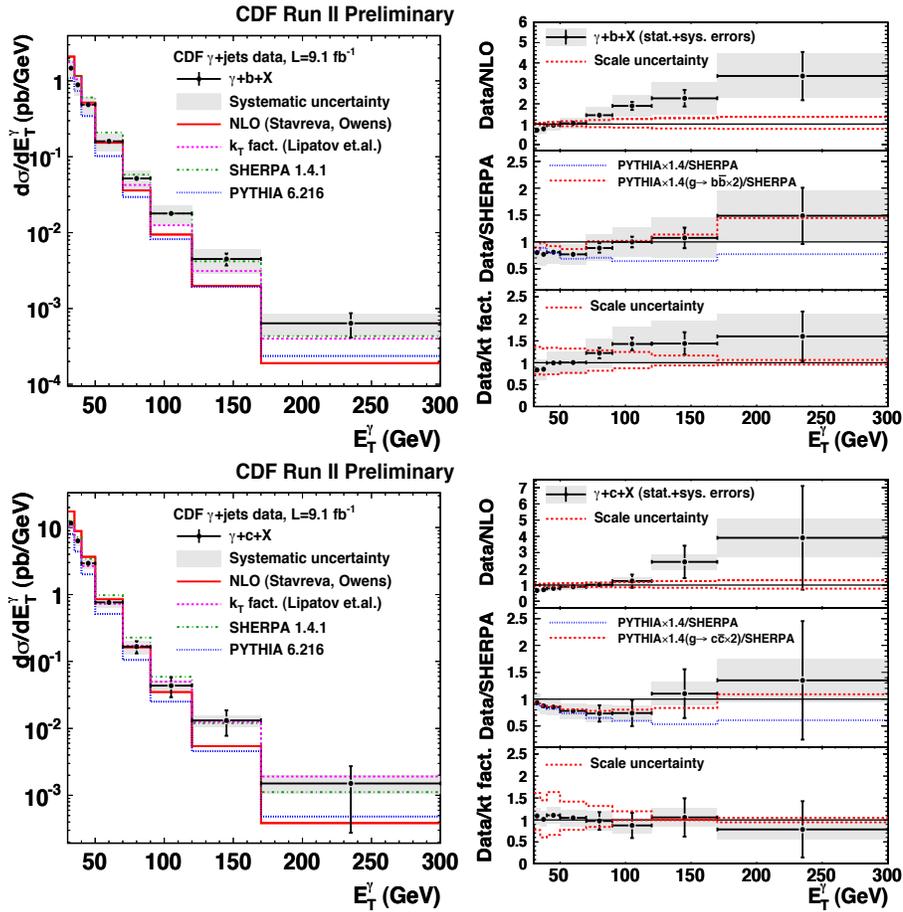


Fig. 1. Measured differential cross-sections compared with theoretical predictions. The left plots show absolute comparisons. The right plots show the ratios of data to theoretical predictions, with PYTHIA predictions scaled by 1.4. Scale uncertainties are shown for the NLO and k_T -factorization predictions.

The k_T -factorizations and SHERPA are in agreement with the measured cross-sections. PYTHIA can be made to agree well with data by doubling the rate for $g \rightarrow b\bar{b}/c\bar{c}$, and scaling the prediction by a factor of 1.4.

3. $W + c$ production

We now consider a recent CDF search [9] for the specific charm production process $p\bar{p} \rightarrow Wc$. To first order, this process proceeds as $gq \rightarrow Wc$, where q is a d , s , or b quark. In $p\bar{p}$ collisions, the larger d quark PDF is overridden by the small quark-mixing Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{cd}|$, such that about 80% of Wc production is due to strange-quark gluon fusion. Therefore, $p\bar{p} \rightarrow Wc$ production is sensitive to the s and g PDFs of the proton [2, 3], as well as CKM matrix element $|V_{cd}|$.

In this search [9], the W boson is identified through leptonic decay by looking for an electron (muon) with $E_T > 20$ GeV ($p_T > 20$ GeV/ c), in events with missing energy $\cancel{E}_T > 25$ GeV. The charm quark is identified by looking for semi-leptonic decays of the charm hadron: an electron or muon candidate within a jet ($E_T^{jet} > 20$ GeV and $|\eta^{jet}| < 2.0$). This is referred to as “soft lepton tagging” or “SLT $_\ell$ ” [16–19].

Charge conservation in the process $p\bar{p} \rightarrow W + c$ allows only final states in which the W and c are oppositely charged. As such, the final state must involve two oppositely-signed leptons. The $p\bar{p} \rightarrow W + c$ production cross-section is found as

$$\sigma_{Wc} = \frac{N_{\text{tot}}^{\text{OS-SS}} - N_{\text{bkg}}^{\text{OS-SS}}}{SA \int L dt} \quad (1)$$

where $N_{\text{tot}}^{\text{OS-SS}}$ ($N_{\text{bkg}}^{\text{OS-SS}}$) is the difference in the number of OS and SS events in data (background). A is the acceptance times efficiency for identifying Wc events, and $S = (N_{Wc}^{\text{OS}} - N_{Wc}^{\text{SS}})/(N_{Wc}^{\text{OS}} + N_{Wc}^{\text{SS}})$ accounts for the charge asymmetry of the real reconstructed Wc events. Both A and S are derived from a Monte Carlo simulation of Wc events and the CDF detector.

Accounting for background, the final result yields $\sigma_{WC} \times B(W \rightarrow \ell\nu) = 13.6 \pm 2.2(\text{stat})_{-1.9}^{+2.3}(\text{syst}) \pm 1.1(\text{lum})\text{pb} = 13.6_{-3.1}^{+3.4}\text{pb}$ for $p_{Tc} > 20$ GeV/ c , $|\eta_c| < 1.5$. This agrees with a NLO calculation over the same phase space of 11.4 ± 1.3 pb [9]. Figure 2 shows the measured SLT muon and electron p_T distribution spectra as measured in data.

4. $Z + b$ production

Another CDF search [10] measures the production cross section of b jets with a Z boson, using 9.1 fb^{-1} of data. An artificial neural network is used to improve lepton identification efficiency for leptonic decays $Z \rightarrow \mu\mu/ee$. Jets are identified using the MidPoint algorithm with a cone size of $R = 0.7$, and a merging/splitting fraction set to 0.75. Jets are required to have corrected $p_T \geq 20\text{GeV}/c$ and $|Y| \leq 1.5$. To be considered a b jet candidate,

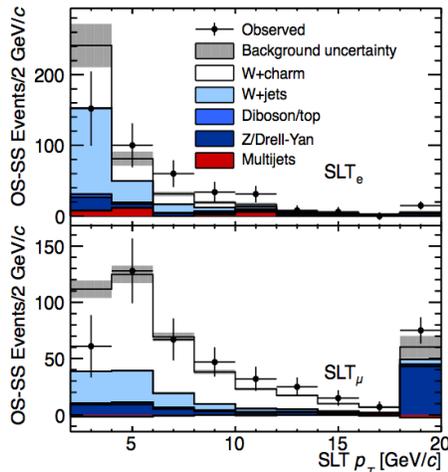


Fig. 2. The soft muon and soft electron p_T distributions. The Wc contribution shown is normalized to the measured cross section.

a jet must also have a reconstructed secondary vertex within a cone of 0.4 with respect to the jet axis.

As in [8], the fraction of jets that contain bottom hadron decays is found by fitting the M_{SecVtx} distribution of these reconstructed secondary vertices with b, c, and light flavor jets templates. The fraction of inclusive Z that are produced in association with a b jet is found to be $\sigma_{Z+bjet}/\sigma_Z = 0.261 \pm 0.023(\text{stat}) \pm 0.029(\text{syst})\%$. The fraction of Z + jet events with at least one bottom jet is found to be $\sigma_{Z+bjet}/\sigma_{Z+jet} = 2.08 \pm 0.18(\text{stat}) \pm 0.27(\text{syst})\%$. These measured cross-section ratios are found to be larger than those of the ALPGEN prediction by a factor of 1.6 [10], but are in agreement with MCFM within uncertainty (Table 1).

Table 1. Cross section ratios as calculated by MCFM. Within uncertainty, these results agree with measurements in data.

| | NLO $Q^2 = m_Z^2 + p_{T,Z}^2$ | NLO $Q^2 = \langle p_{T,jet}^2 \rangle$ |
|-------------------------------------|-------------------------------|---|
| $\frac{\sigma(Z+b)}{\sigma(Z)}$ | 2.3×10^{-3} | 2.9×10^{-3} |
| $\frac{\sigma(Z+b)}{\sigma(Z+jet)}$ | 1.8×10^{-3} | 2.2×10^{-3} |

The differential cross section measurements for Z +b jet production as a function of jet p_T is shown in Figure 3. These measurements have a large statistical uncertainty ($\sim 16\%$), but are in good agreement with NLO theory evaluated with MCFM predictions.

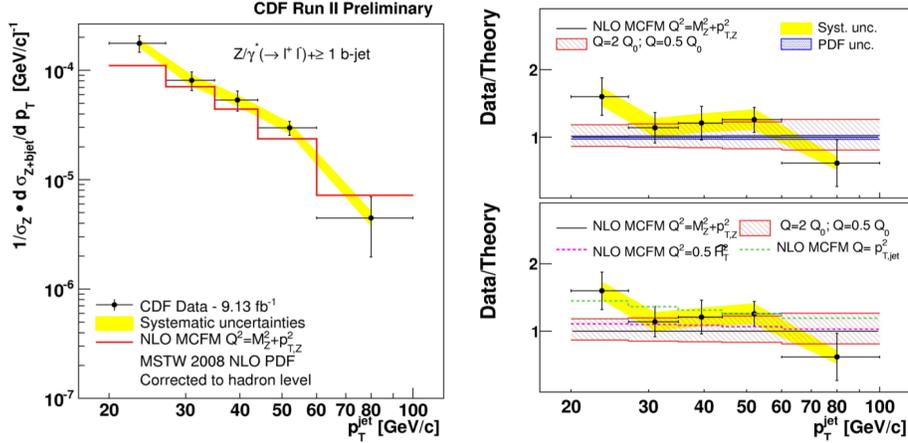


Fig. 3. The left panel displays the measured Z+b jet differential cross section with respect to the inclusive Z differential cross section, as a function of b jet p_T . The right panel shows the ratios of data to theoretical predictions at different renormalization and factorization scales.

5. A new approach to $W/Z + c$ at the Tevatron

Bottom and charm production in W/Z events at the Tevatron has, to date, been measured primarily by identifying heavy flavor in W/Z plus jet events. The standard procedure is to find candidate jets with a secondary vertex and $E_T^{jet} > 15$ or 20 GeV, and to fit the mass distribution of the secondary vertex M_{SecVtx} with b -, c -, and light-jet templates (as in [8, 10]).

A new CDF analysis [11] seeks instead to identify charm content in $W/Z+c$ events in which the charm quark hadronizes as $c \rightarrow D^*$ (2010). First, W/Z events are selected with standard cuts of event $\cancel{E}_T > 25$ (20) GeV and $E_T > 25$ GeV ($p_T > 20$ GeV) for electron (muon) objects with low relative isolation ($Iso_\ell < 0.1$). Vertex fitting is then used to reconstruct the decay $D^{*+} \rightarrow D^0 \pi^+$ with $D^0 \rightarrow K^- \pi^+$. After cuts on π track kinematics and the mass of the reconstructed D^0 vertex, the vertex mass difference $\Delta m = m(K\pi\pi) - m(K\pi)$ of remaining candidates is binned. The Δm values of real D^* will produce a signal peak above background near $\Delta m = 0.1455 \text{ GeV}/c$. This can be fit with a signal plus background hypothesis in order to count the number of $D^{*+} \rightarrow D^0 (\rightarrow K^- \pi^+) \pi^+$ events in the sample.

This is the first application at the Tevatron of this D^* tagging technique in a search for $W/Z + c$ events. This approach explores a kinematic regime with much lower average charm momentum (~ 10 GeV) [11] than the regime explored by jet-based studies: secondary-vertex tagging in jet events generally considers only events with $E_T^{b,cjet} > 15$ or 20 GeV.

Thus far, this search has identified both $W(\rightarrow \ell\nu) + D^*$ and $Z(\rightarrow \ell^+\ell^-) + D^*$ events in the full CDF high- p_T muon and electron datasets (9.7fb^{-1}) (Figure 4). As of the writing of this paper, the work is ongoing.

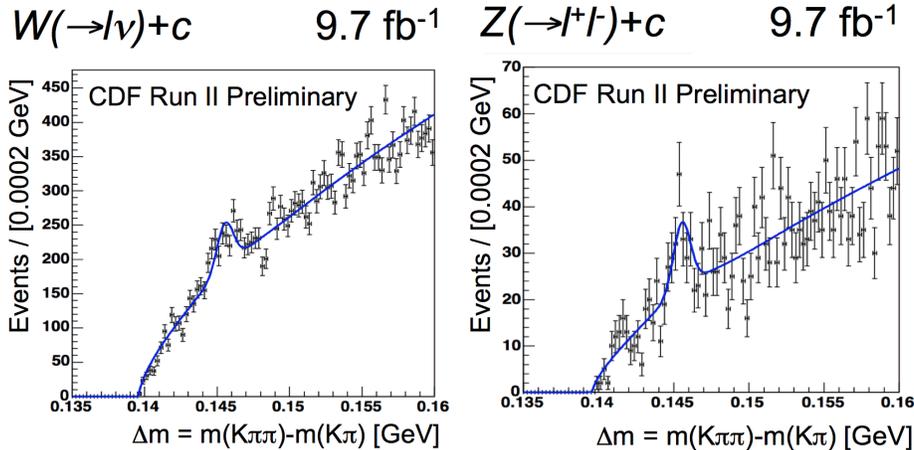


Fig. 4. Plots of discriminant $\Delta m = m(K\pi\pi) - m(K\pi)$ as used to identify $D^{*+} \rightarrow D^0(K^-\pi^+)\pi$ decays in W/Z events. Each plot is fit to a signal plus background hypothesis. Signal can be seen above background near $\Delta m = 0.1455$ GeV/ c .

6. Summary

This is an exciting time for electroweak gauge boson plus heavy flavor physics. Results continue to support charm and bottom event production that may be higher than NLO predictions, highlighting the importance of heavy flavor work in modeling data. In addition, CDF is now probing new kinematic regimes in W/Z plus heavy flavor studies by exploring low $p_T(D^*)$ produced in association with W/Z . Further extensions in complementary kinematic regions may soon be made with higher statistics at the Large Hadron Collider. This growing improvement to the state of $W/Z/\gamma$ plus heavy flavor knowledge will benefit future analyses by both furthering our understanding of heavy flavor production, and by serving as a model for background in increasingly-sensitive measurements of Higgs, single top and supersymmetric particle searches.

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