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Vector boson + heavy flavor production at the Tevatron

K. Matera, on behalf of the CDF and D0 Collaborations

Department of Physics, University of Illinois at Urbana-Champaign
Urbana, IL, USA

Abstract

Studies of the associated production of heavy-flavor bottom and charm quarks with vector bosons (W, Z, and γ) provide important tests of perturbative quantum chromodynamics calculations. These studies also improve constraints on parton distribution functions, and improve our understanding of major backgrounds in Higgs studies and searches for new phenomena. In these proceedings, we present several measurements of vector boson plus heavy-flavor quark production at Tevatron experiments CDF and D0, including measurements of cross-sections for $Z + c/b$ jets, $\gamma + b$ jet, $\Upsilon + W/Z$, and $W/Z + D^*$ production processes. These results include the first measurements of $Z + c$ production at the Tevatron, as well as the lowest-momentum measurements of charmed meson production in association with W and Z bosons at the Tevatron.

Keywords: vector boson, heavy flavor, Tevatron, CDF, D0

1. Introduction

Vector bosons (V) produced in association with heavy flavor (h.f.) bottom and charm quarks are an omnipresent feature in particle physics analyses. $V + c$ production processes are sensitive to the strange quark content of the proton, while measurements of V produced in association with $g \to b\bar{b}/c\bar{c}$ provide useful tests of perturbative quantum chromodynamics (pQCD). In addition, V + h.f. events have a detector signature consisting of high-p_T leptons and/or missing energy, plus one or more particle jets; this is a signature that is shared by many searches for standard model (top, Higgs) and beyond the standard model (dark matter, supersymmetry) processes. In these proceedings, we discuss V + h.f. events in the context of recent studies at the Fermilab Tevatron's D0 and CDF experiments, including measurements of $Z+c/b$ jets [1, 2], $\gamma+b$ jet [3], $\Upsilon+W/Z$ [4], and $W/Z + D^*$ production [5].

2. $Z + b/c_{\text{jet}}$ at D0

A recent D0 analysis [1] provides the first observation of Z boson production in association with charmed jets ($p_T^{\text{jet}} > 20$ GeV/c, $|\eta^{\text{jet}}| < 2.5$). A unique discriminant is used to identify charmed jets: $D_{MJL} = 0.5\times(M_{SV}/5\ \text{GeV}/c^2 - \ln(\text{JLIP})/20)$, where M_{SV} is the jet secondary vertex mass, and JLIP is the jet lifetime impact parameter [2]. D_{MJL} is binned for all events passing a multivariate heavy flavor cut that supersedes earlier neural network taggers used by D0 [6]. Charmed jets are counted by first fitting the D_{MJL} distribution to a sum of bottom, charm, and light jet templates. This direct approach yields a large uncertainty on the charmed-jet fraction, due to similarities between charm and light jets; this is reduced by imposing a more stringent multivariate heavy flavor cut, after which the small remaining light jet contribution—as estimated with data-corrected simulation—is removed. The remaining component is then fit to a bottom jet plus charm jet hypothesis.

Quantities $R_{c/\text{jet}} \equiv \sigma_{Z+c\,\text{jet}}/\sigma_{Z+\text{jet}}$ and $R_{c/b} \equiv \sigma_{Z+c\,\text{jet}}/\sigma_{Z+b\,\text{jet}}$ are measured as a function of p_T^{jet} and p_T^{Z} (Fig. 1). NLO predictions are found to underestimate the integrated results by a factor of 2.5: compare measured fractions $R_{c/\text{jet}} = 0.0829 \pm 0.0052$ (stat) ± 0.0089 (syst) and $R_{c/b} = 4.00 \pm 0.21$(stat) ± 0.58 (syst), against MCFM predictions $R_{c/\text{jet}} = 0.0425$ and $R_{c/b} = 2.23$.

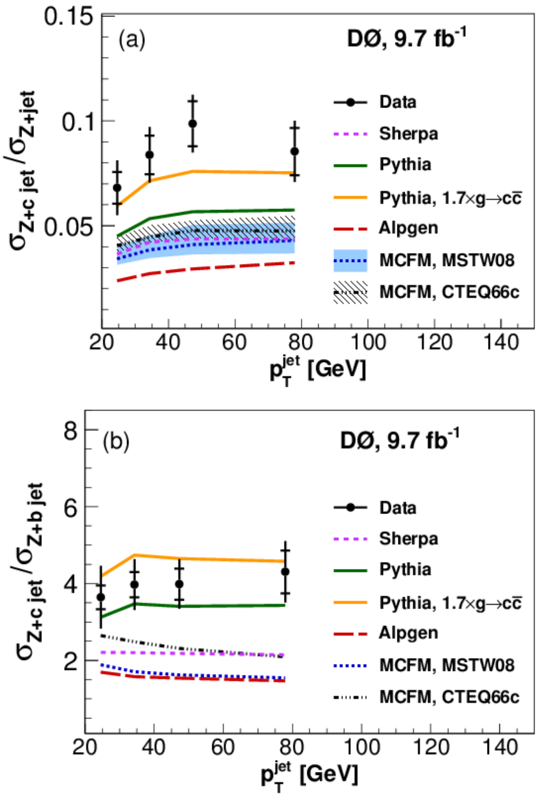

Figure 1: D0 differential cross-sections measurements $\sigma_{Z+c\text{ jet}}/\sigma_{Z+\text{jet}}$ (top) and $\sigma_{Z+c\text{ jet}}/\sigma_{Z+b\text{ jet}}$ (bottom) as a function of p_T^{jet} ($p_T^{\text{jet}} > 20$ GeV/c, $|\eta^{\text{jet}}| < 2.5$). Flavor fractions are determined for the highest p_T jet in each Z event, employing a fit to binned quantity D_{MJL} for all events passing a multivariate heavy flavor cut. Best agreement is with PYTHIA with 1.7× enchanced $g \to c\bar{c}$ rate.

The best agreement is found for PYTHIA predictions with the default $g \to c\bar{c}$ splitting rate enhanced by a factor of 1.7.

This work extends earlier studies of Z boson production in association with bottom jets ($p_T^{\text{jet}} > 20$ GeV/c, $|\eta^{\text{jet}}| < 2.5$): in this work, a b-tagging algorithm [6] is used to select a sample of Z+jets events that is enriched in heavy flavor jets. As in the Z+charm jet study, discriminant D_{MJL} is binned for all events passing a multivariate heavy flavor cut [6], and then is fit to a combination of bottom, charm, and light jet templates. Quantity $R_{b/\text{jet}} \equiv \sigma_{Z+b\text{ jet}}/\sigma_{Z+\text{jet}}$ is reported as a function of p_T^{jet}, p_T^{Z}, η^{jet}, and $\Delta\phi_{Z\text{jet}}$ (with the latter pictured in Fig. 1). NLO predictions are found to agree with the integrated results: compare measured fraction $R_{b/\text{jet}}$ =0.0196±0.0012(stat)±0.0013(syst) to NLO prediction $R_{b/\text{jet}}$ =0.0206.

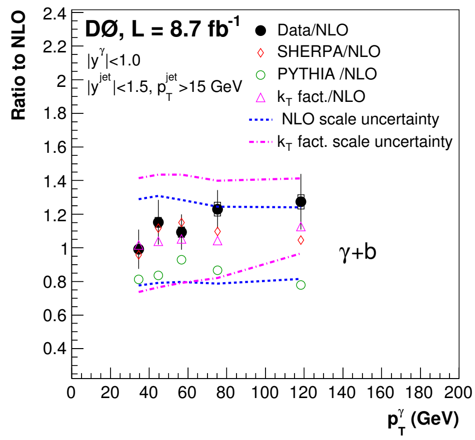

Figure 2: Ratio of data to NLO predictions of differential cross-sections measurements $\sigma_{\gamma+b\text{-jet}}/\sigma_{\gamma+\text{jet}}$ (top) , as a function of p_T^{γ} ($30 < p_T(\gamma) < 200$ GeV/c, $|y(\gamma)| < 1.0$). NLO predictions provide good agreement, though PYTHIA generally underestimates the predicted rates of b-jet production.

3. $\gamma + b_{\text{ jet}}$ at D0

A D0 study of photons produced in association with bottom jets extends D0's b-jet tagging work in a new direction [3]. Because photons do not interact through the strong force, high-energy photons provide a clean probe of the hard-scattering dynamics that underlie hard parton-parton scattering. Prompt photons produced in association with bottom jets therefore provide an important test of pQCD predictions over a wide range of parton momentum fractions, as well as better illuminating the proton's bottom quark and gluon parton density functions (PDFs). At low and moderate photon momenta p_T^{γ}, γ+b-jet events are produced dominantly through Compton process $gb \to \gamma b$; at high momentum, through quark-antiquark annihilation $q\bar{q} \to \gamma g \to \gamma b\bar{b}$.

Photons are selected with triggers on the D0 detector's electromagnetic calorimeter hits, including loose shower shape requirements. For photon events satisfying $|y^{\gamma}| < 1.0$, $30 < p_T^{\gamma} < 200$ GeV/c, the $n = 1, 2$ jets with highest p_T^{jet} satisfying $p_T^{\text{jet}} > 15$ GeV and $|y^{\text{jet}}| < 1.5$ are selected. The fraction of these jets that are bottom jets is determined following the D_{MJL}-binning procedure used in aforementioned $Z + c$ jet study [1, 2] : discriminant D_{MJL} is binned for the highest-p_T jet(s) in all passing events; the expected light jet contribution is removed; and the resulting distribution is fit to a sum of b-jet and c-jet templates.

The $\gamma + b$-jet production cross-section $\mathrm{d}\sigma/\mathrm{d}p_T^{\gamma}$ is measured differentially as a function of p_T^{γ} for $\gamma + n\,b$-jet

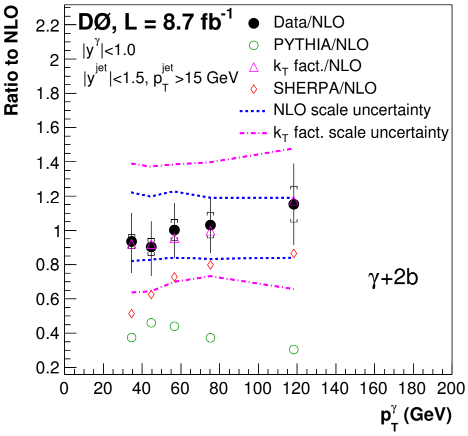

Figure 3: Ratio of D0 measurements in data to NLO predictions of differential cross-sections measurements $\sigma_{\gamma+2b\text{-jet}}/\sigma_{\gamma+\text{jet}}$ (bottom) as a function of p_T^{γ} ($30 < p_T(\gamma) < 200$ GeV/c, $|y(\gamma)| < 1.0$). NLO predictions provide good agreement, though PYTHIA generally underestimates the predicted rates of b-jet production.

events, with $n = 1, 2$. Measurements are compared to NLO QCD calculations using the CTEQ6.6M PDFs and predictions from SHERPA, PYTHIA and k_T factorization. NLO predictions provide good agreement with data, with the best predictions generally provided by SHERPA and k_T factorization (Figs. 2, 3).

4. W/Z + Υ at CDF

The standard model cross-section for $p\bar{p} \rightarrow \Upsilon(1S) + W/Z$ production at $\sqrt{s} = 1.96$ TeV is predicted to be outside of the range of sensitivity of experiments at the Tevatron [7]. Calculations of this cross-section are very sensitive to non-relativistic QCD models, especially to the long distance matrix elements (LDME) which determine the probability that a $b\bar{b}$ pair will form a bound state. The measured cross-section is also sensitive to some supersymmetry (SUSY) models, which predict charged (neutral) Higgs boson decays into a $\Upsilon + W(Z)$ final state [7].

Events are selected by first requiring two low-energy muons ($1.5 \leq p_T \leq 15$ GeV$/c$) with an invariant mass in the $\Upsilon(1S)$ mass region ($9.25 < M_{\mu\mu} < 9.65$ GeV$/c^2$). Then, a search is performed for an additional high-energy electron (muon) with E_T (p_T) $>$ 20 GeV$/c$, which is paired with missing energy $\not{E}_T >$ 20 GeV$/c^2$ (for a W candidate), or with another high-energy lepton with opposites charge and E_T (p_T) $>$ 15 GeV$/c^2$ (for a Z candidate). The main backgrounds to this selection are real W/Z plus fake Υ, and real Υ plus fake W/Z.

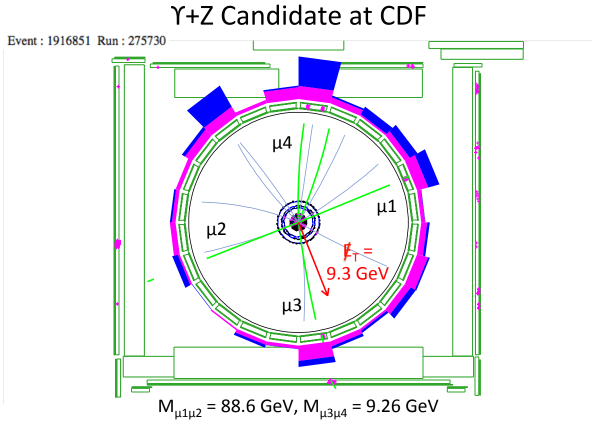

Figure 4: Event display of the observed $\Upsilon + Z$ candidate, showing the muon candidates identified from the Υ and Z decays

One $\Upsilon + W(\rightarrow \ell\nu)$ candidate and one $\Upsilon + Z(\rightarrow \ell\ell)$ candidate are observed, over expected backgrounds of 1.2 ± 0.5 and 0.1 ± 0.1 events, respectively [4]. With no clear evidence for $\Upsilon + W/Z$ signal, a 95% confidence level upper limit is set on production cross sections for $\Upsilon + W$ and $\Upsilon + Z$ (Table 1). These results improve significantly upon previous CDF Run I measurements [8].

	$\Upsilon + W$	$\Upsilon + Z$
expected limit (pb)	5.6	13 3
observed limit (pb)	5.6	21
Run I observed limit (pb)	93	101

Table 1: Cross section limits at 95% CL. This analysis utilizes 9.4 fb^{-1} of CDF Run 2 data, and provides substantial improvement with respect to earlier measurements (shown).

5. W/Z + D^* at CDF

Finally, CDF has made the first observation of low-momentum (p_T<15 GeV/c) charm production in association with vector bosons [5] at the Tevatron. In contrast to a standard jets-based approach for identifying charm, this analysis fully reconstructs the charmed meson decay $D^*(2010) \rightarrow D^0 (\rightarrow K\pi)\,\pi_s$, at the track level. Signal is identified by binning the reconstructed vertex mass difference $\Delta m \equiv m(K\pi\pi_s) - m(K\pi)$, and then performing a double-gaussian signal plus power-law background fit. A neural network is used to reduce combinatoric background.

This technique identifies $W/Z + D^*$ events in the W/Z leptonic decay channels down to a momentum of

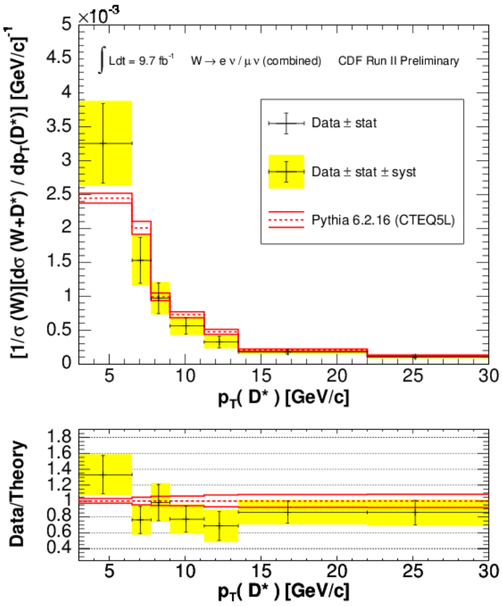

Figure 5: Differential rates of cross-section ratio $\sigma(W + D^*)/\sigma(W)$ as a function of $p_T(D^*)$, as measured by CDF in the $W \to e\nu/\mu\nu$ (combined) decay channels. Measurements show good agreement with theory, within uncertainty.

$p_T(D^*) > 3$ GeV/c, making this the lowest p_T measurement of charm produced in association with vector boson events at the Tevatron (compare $p_T(c\text{ jet}) > 15$ or 20 GeV/c for a typical jet-based analysis [9, 10]). The measured production rates $\sigma(W/Z + D^*)/\sigma(W/Z)$ are found to agree with PYTHIA: for the inclusive sample $p_T(D^*) >$ 3 GeV/c, compare measured ratios $\sigma(W + D^*)/\sigma(W) =$ 1.75 ± 0.13 (stat) $\pm$ 0.09 (syst) and $\sigma(Z + D^*)/\sigma(Z) =$ 1.5 ± 0.4 (stat) ± 0.2 (syst) to MC predictions 1.77 ± 0.07 and 1.36 ± 0.05, respectively. Differential rates as a function of $p_T(D^*)$ are found to agree equally well with Monte Carlo predictions, within uncertainty (Fig. 5).

This full-reconstruction approach also enables the identification of particular production processes that contribute to the $W + D^*$ signal. By exploiting sign correlations between the W and D^*, and by training two-tiered neural networks to separate different production processes, it is determined that the $W + D^*$ signal events consist of: $14 \pm 6\%$ $s(d)$+g→W+c production; $73 \pm 8\%$ W+$g(\to c\bar{c})$ production; and $13 \pm 5\%$ W+$g(\to b\bar{b})$, $B\to$ D^*+X production.

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