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W/Z+JETS AND W/Z+HF PRODUCTION AT THE TEVATRON

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Measurements of $W/Z+$ jets and $W/Z+$ heavy flavor (hf) events play a key role in particle physics—from testing models of quantum chromodynamics, to describing background in Higgs, top, dark matter, and supersymmetric particle searches. Increasingly sensitive searches will require an increasingly precise understanding of these events. We present four recent results in this regime, produced by the CDF and D0 collaborations: the first observations of $Z+c$ jet and W/Z plus low-momentum (p_T<15 GeV) charm production at the Tevatron; a search for $\Upsilon+W/Z$ production; and an expanded, comprehensive set of general W+n jets measurements.

1 Introduction

Vector bosons produced in association with jets ($W/Z+$ jets) and heavy flavor ($W/Z+$ hf) are an omnipresent feature in particle physics analyses. $W/Z+$ jets/hf 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 addition, measurements of $W/Z+$ jets/hf events test current models of perturbative quantum chromodynamics (pQCD); in turn, these models often need to be fitted with data in order to provide accurate results. In these proceedings, we probe $W/Z+$ jets/hf events by discussing recent studies at the Fermilab Tevatron's D0 and CDF experiments, including measurements of $W+$ n jets [1], $\Upsilon+W/Z$ [2], $Z+c$ jet [3], and $W/Z+D^*$ production [4].

2 W+jets at D0

The production of $W+$ jets events probes the dynamics of quark and gluon behavior at high momentum transfers, providing an important test of perturbative QCD. A recent D0 analysis [1] extensively probes the production rates and kinematics of $W+n$ jet events in a 3.7 fb^{-1} data sample, and significantly expands upon the number of measured observables in this regime with respect to earlier analyses [1]. This new analysis selects a high-purity sample of $W(\rightarrow e\nu)+n$ jet events, and unfolds these measurements back to the particle level for comparisons with theory. Backgrounds from EWK, QCD multijet, and top production are modeled with Monte Carlo simulations, and are subtracted to produce the final distributions.

Over forty different cross-sections are measured [1], three samples of which are displayed in Fig. 1. Agreement with theoretical models varies by observable, *e.g.*, measurements of H_T (the sum of the transverse momentum of all event objects) agree best with NLO BlackHat; measurements of wide jet opening angles are better predicted by SHERPA or HEJ.

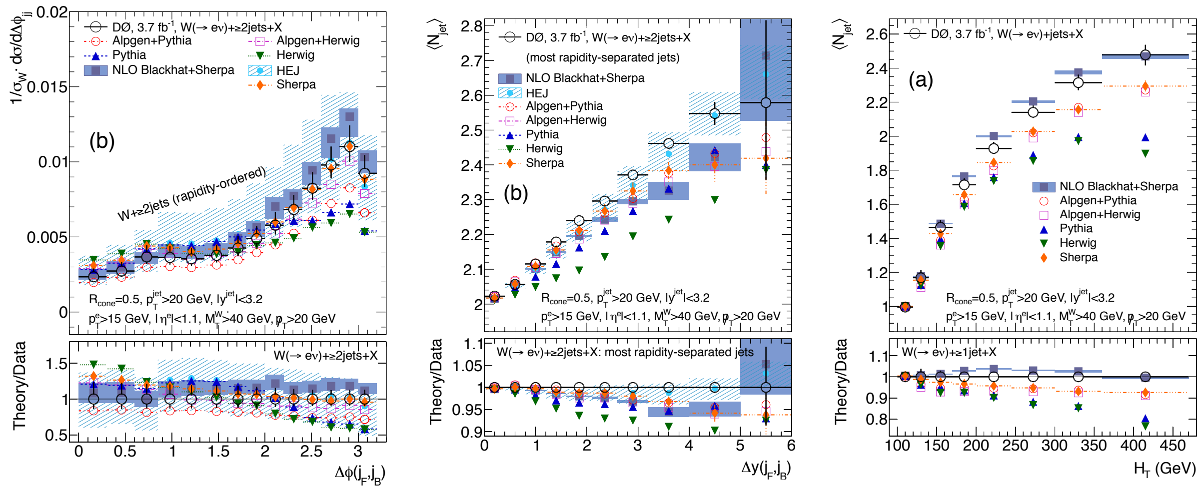

Figure 1 – Sample W+n jets differential cross-sections from D0. The model that provides the best agreement with data, varies by observable: H_T agrees best with NLO BlackHat; large opening angles, with sherpa or hej.

Table 1: CDF cross section limits at 95% CL. This analysis utilizes 9.4 fb^{-1} of CDF Run 2 data.

	$\Upsilon + W$	$\Upsilon + Z$
expected limit (pb)	5.5	13
observed limit (pb)	5.5	20
Run I observed limit (pb)	93	101

3 $W/Z + \Upsilon$ at CDF

The standard model cross-section for $p\bar{p} \to \Upsilon(1S) + W/Z$ production at $\sqrt{s} = 1.96$ TeV is predicted to be outside of the range of sensitivity of experiments at the Tevatron [5]. 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 [5].

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

One $\Upsilon + W(\to \ell\nu)$ candidate and one $\Upsilon + Z(\to \ell\ell)$ candidate are observed, over expected backgrounds of 1.2 ± 0.5 and 0.1 ± 0.1 events, respectively [2]. 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 [6].

4 $Z + c_{\,\text{jet}}$ at D0

A recent D0 analysis [3] provided the first observation of Z boson production in association with charmed jets ($p_T^{\text{jet}} > 20$ GeV, $|\eta^{\text{jet}}| < 2.5$). A unique discriminant was used to identify charmed jets: $D_{MJL} = 0.5 \times (M_{SV}/5\text{ GeV} - \ln(\text{JLIP})/20)$, where M_{SV} is the jet secondary vertex mass, and JLIP is the jet lifetime impact parameter [7]. D_{MJL} is binned for all events passing a multivariate heavy flavor cut that superedes the earlier neural network taggers used by D0 [8].

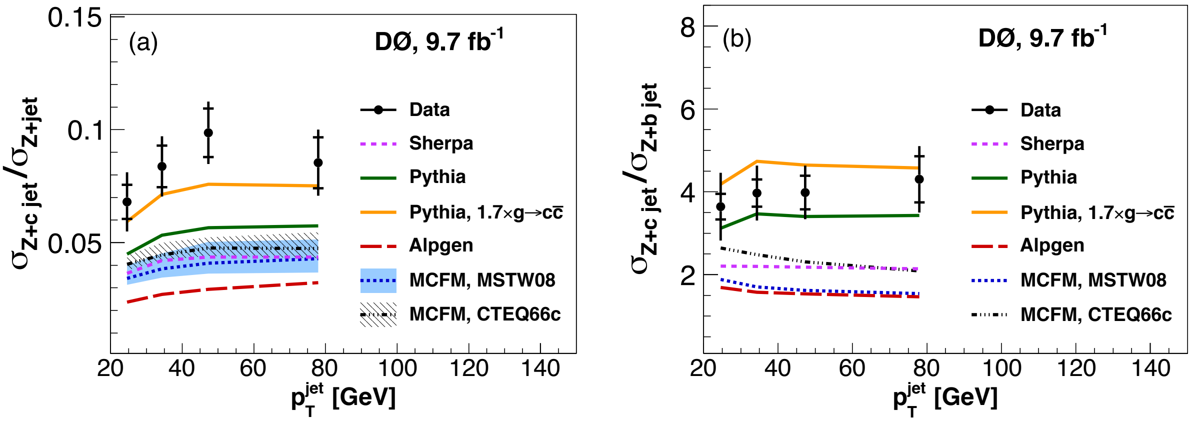

Figure 2 – D0 differential cross-sections measurements $\sigma_{Z+c\text{ jet}}/\sigma_{Z+\text{jet}}$ (left) and $\sigma_{Z+c\text{ jet}}/\sigma_{Z+b\text{ jet}}$ (right) as a function of p_T^{jet} ($p_T^{\text{jet}} > 20$ GeV, $|\eta^{\text{jet}}| < 2.5$). Best agreement is with PYTHIA with 1.7× enchanced $g \to c\bar{c}$ rate.

Table 2: The ratio of inclusive cross-sections $\sigma(W/Z + D^*)/\sigma(W/Z)$ for $p_T(D^*) > 3$ GeV, compared with the predictions of Pythia 6.2.16 using PDF set CTEQ5L. Results are shown as value ± stat ± syst.

Measured quantity for $p_T(D^*) > 3$ GeV	CDF Run II Data (%)	Pythia 6.2.16 CTEQ5L (%)
$\sigma(W_{e\nu} + D^*)/\sigma(W_{e\nu})$	$1.74 \pm 0.21 \pm 0.17$	1.77 ± 0.01
$\sigma(W_{\mu\nu} + D^*)/\sigma(W_{\mu\nu})$	$1.75 \pm 0.17 \pm 0.03$	1.77 ± 0.01
$\sigma(Z_{ee} + D^*)/\sigma(Z_{ee})$	$1.0 \pm 0.6 \pm 0.2$	1.36 ± 0.01
$\sigma(Z_{\mu\mu} + D^*)/\sigma(Z_{\mu\mu})$	$1.8 \pm 0.5 \pm 0.2$	1.36 ± 0.01

Charmed jets are then counted by fitting the D_{MJL} distribution to a sum of bottom, charm, and light jet templates.

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. 2). NLO predictions are found to underestimate the integrated results by a factor of 2.5: compare measured fractions $R_{c/\text{jet}}$ =0.0829±0.0052(stat)±0.0089(syst) and $R_{c/b}$ =4.00±0.21(stat)±0.58(syst), against MCFM predictions $R_{c/\text{jet}}$ =0.0425 and $R_{c/b}$ =2.23. PYTHIA predictions agree more closely with data. The best agreement is found for PYTHIA with the default $g \to c\bar{c}$ splitting rate enhanced by a factor of 1.7.

5 $W/Z + D^*$ at CDF

Finally, CDF has made the first observation of low-momentum (p_T<15 GeV) charm production in association with vector bosons [4] at the Tevatron. In contrast to a standard jets-based approach for identifying charm, this analysis fully reconstructs the charmed meson decay $D^*(2010) \to D^0$ ($\to$ K π) π_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 down to a momentum of $p_T(D^*) > 3$ GeV, 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 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 both for the inclusive sample (Table 2), and for differential rates as a function of $p_T(D^*)$ (Fig. 3). Tagged event rates as a function of the number of jets in $W + D^*$ events, are also found to agree with simulated PYTHIA events [4].

This full-reconstruction approach also enables the identification of particular production

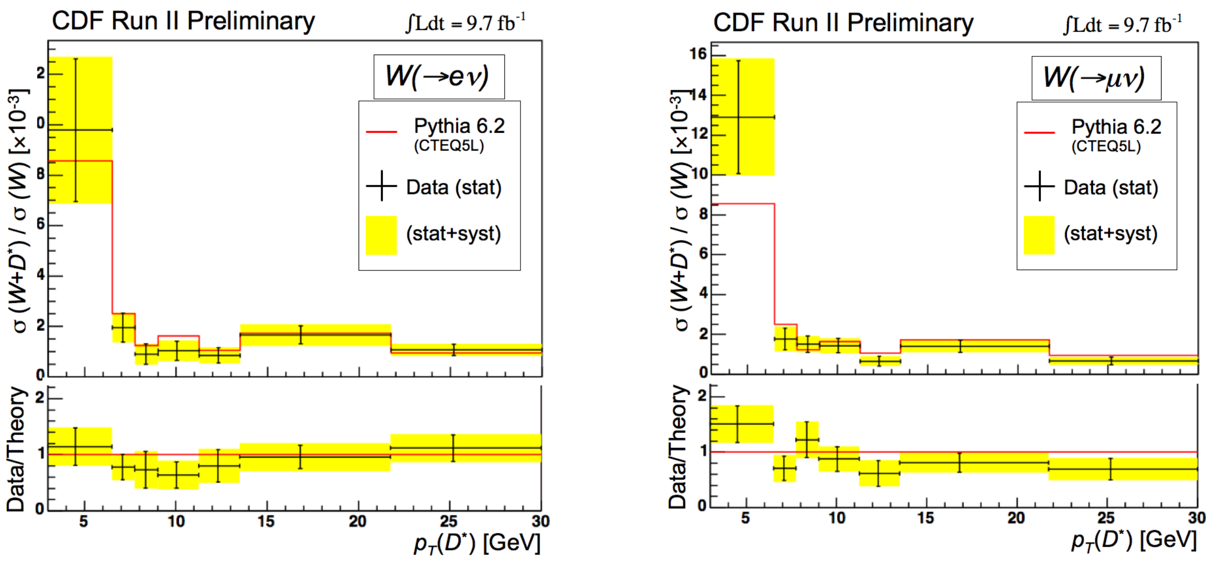

Figure 3 – Differential rates of cross-section ratio $\sigma(W + D^*)/\sigma(W)$ as a function of $p_T(D^*)$, as measured by CDF in the $W \to e\nu$ (left) and $W \to \mu\nu$ (right) decay channels. Measurements show good agreement with theory (PYTHIA 6.2 with CTEQ5L) in all bins.

processes that contribute to the signal. By exploiting sign correlations between the D^* and the W in $W + D^*$ events, and by training two-tiered neural networks to separate different 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(→ c$\bar{\text{c}}$) production; and $13 \pm 5\%$ W+g(→ b$\bar{\text{b}}$), B→ D*+X production.

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