Measurements of Vector Bosons Produced in Association with Jets

Ben Cooper
on behalf of the CDF and D0 Collaborations

Queen Mary University of London - Department of Physics
London - UK

The latest D0 and CDF measurements of the $W + \text{jets}$ and $Z/\gamma^* + \text{jets}$ processes are described, along with a discussion of the comparisons that have been made to LO and NLO perturbative QCD predictions.

1 Introduction

The direct production of $W^{\pm}/Z$ bosons in association with jets is a process of crucial importance at hadron collider experiments. The presence of a vector boson in the hard scatter means that these interactions occur at a scale that should make perturbative QCD applicable, and thus it is an excellent channel to test such predictions. Furthermore, many of the potential discovery channels for the Higgs boson and beyond standard model processes share a final state signature with the $W^{\pm}/Z + \text{jets}$ process. It is thus vital for the success of existing and future hadron collider experiments that this process is understood, and recently there has been a huge amount of work put into the modelling of this process, with the appearance of many new Monte Carlo generators that are already widely used at both the Tevatron and LHC. In Sections 2 and 3 the latest $W + \text{jets}$ and $Z/\gamma^* + \text{jets}$ measurements from the Tevatron are presented, and in Section 4 we discuss the results and implications of some of the theory comparisons that have thus far been made.

2 $Z/\gamma^* + \text{jets}$ Measurements

Both the CDF and D0 collaborations have produced Z/γ^*+jets measurements in the $Z/\gamma^* \rightarrow e^+e^-$ channel [1, 2], using 1.7fb^{-1} and 400pb^{-1} of Tevatron Run II data respectively. D0 has measured the ratio of $Z/\gamma^* \rightarrow e^+e^- + \geq n$ jets production cross sections to the total inclusive $Z/\gamma^* \rightarrow e^+e^-$ cross section for $n = 1-4$ and jet $P_T > 20$ GeV. CDF has measured the inclusive $Z/\gamma^* \rightarrow e^+e^- + \geq n$ jets differential cross section as a function of jet P_T for $n = 1, 2$ and $P_T > 30$ GeV. In both measurements, $Z/\gamma^* \rightarrow e^+e^-$ events are selected by requiring two electrons with $P_T > 25$ GeV that together form an invariant mass compatible with a Z resonance. In the D0 analysis only electrons within the central region of the calorimeter were used, whereas CDF used one central electron and allowed the second one to be either in the central or forward region of the calorimeter.

Both analyses use “tag and probe” methods to extract from the data efficiencies for electron identification, and both correct for the acceptance of the kinematic and geometrical selection criteria by using simulated signal Monte Carlo samples. In the CDF analysis, the measured cross section is defined for a limited kinematic range of the $Z/\gamma^* \rightarrow e^+e^-$ decay products (corresponding to the event selection criteria), and the acceptance factor is defined accordingly. In this way, the sensitivity of the measurement to the theoretical modelling of the signal is reduced.

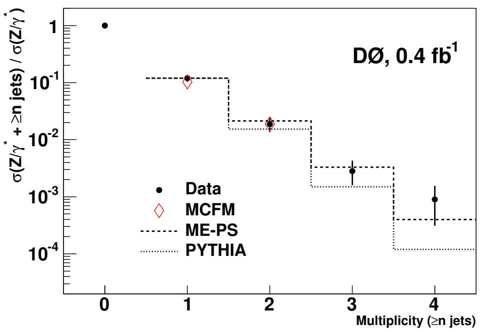

Figure 1: The D0 measured $Z/\gamma^* \rightarrow e^+e^- + \geq n$ jets$/Z/\gamma^* \rightarrow e^+e^-$ cross section ratios for $n = 1-4$ compared to three different predictions: MCFM NLO, a ME-PS matched prediction and PYTHIA.

The dominant sources of background to the $Z/\gamma^* +$ jets process are those arising from QCD multijet events and $W +$ jets events. In the CDF analysis a data-driven method is used to estimate both these sources by extracting from data the probability for an additional jet to fake the second leg of a Z boson decay in events with one electron in the final state. In the D0 analysis the QCD background is extracted from an analysis of the sidebands of the Z peak, and the $W +$jets background is taken from simulated Monte Carlo. In the D0 case the total background is found to be 3-5%, whereas in the CDF analysis it is at the level of 12-17%.

In the D0 measurement, jets were clustered using a cone algorithm [3] with cone radius $R = 0.5$, requiring jet $P_T > 20$ GeV and $|\eta| < 2.5$. In the CDF measurement, jets were clustered using a seeded midpoint cone algorithm with cone radius $R = 0.7$, requiring jet $P_T > 30$ GeV and $|y| < 2.1$. In both analyses data-driven methods were used to correct the transverse momentum of the jets to account for multiple $p\overline{p}$ interactions and the response of the calorimeter. In addition, jet reconstruction and identification efficiencies as well as the impact of the finite jet energy resolution of the detector are accounted for in the cross sections using simulated Monte Carlo samples that have been tuned on data.

In both CDF and D0 analyses the dominant source of systematic uncertainty is that arising from the determination of the calorimeter jet energy scale. In the CDF measurement the total systematic is $\sim 10\%$ (15%) at low (high) jet P_T. In the D0 measurement the total systematic is similar for $n \geq 1, 2$ but reaches $\sim 50\%$ for $n \geq 4$.

3 $W +$ jets Measurements

The CDF collaboration has recently published a $W +$ jets measurement [4] in the $W^\pm \rightarrow e^\pm\nu$ channel using 320pb^{-1} of Tevatron Run II data, measuring the differential $W \rightarrow e\nu + \geq n$ jets cross section as a function of the nth highest E_T jet above 20 GeV, for $n = 1-4$. In this analysis $W \rightarrow e^\pm\nu +$ jets events were selected by requiring exactly one central electron with $P_T > 20$ GeV along with missing transverse energy $\not{E}_T > 30$ GeV. It was also required that the reconstructed W transverse mass satisfies $M_T^W > 20\ GeV/c^2$, a cut which reduces background at little expense to the signal. As in the CDF $Z/\gamma^* +$ jets analysis, the cross section is defined for a limited kinematic range of the W decay products equal to this event selection criteria, and the acceptance and efficiencies are computed from simulated signal Monte Carlo samples accordingly.

Jets in the $W^\pm \rightarrow e^\pm\nu$ event sample were clustered using the JETCLU [5] cone algorithm with cone size 0.4, requiring jet $E_T > 20$ GeV and $|\eta| < 2.0$. The energy of each jet is corrected for multiple interactions and the calorimeter response. In addition, once the jet spectra had been corrected for backgrounds, simulated Monte Carlo signal samples were used to correct the jet spectra to account for the jet reconstruction efficiency and finite calorimeter energy resolution.

The dominant sources of background to the $W+$ jets process arise from from QCD multijet and $t\bar{t}$ production. In this analysis, the multijet background was estimated by using an alternative "antielectron" selection criteria to select from the data an event sample that could be used to reliably model the QCD background in the required jet kinematic distributions. The background from $t\bar{t}$, as well as the less important $W \to \tau\nu$, $Z/\gamma^* \to e^+e^-$, WW and $W\gamma$ processes, was modelled using simulated Monte Carlo samples. The total background fraction increases with increasing jet multiplicity and transverse energy, around 10% at low E_T, but reaching 90% at the highest measured E_T in the four jet sample.

At low jet E_T the dominant systematic on the measured cross sections is that arising from the jet energy scale determination, at the level of 5-10%. However, at higher jet E_T the uncertainty on the background determination is dominant, up to 80% in the highest jet E_T bins.

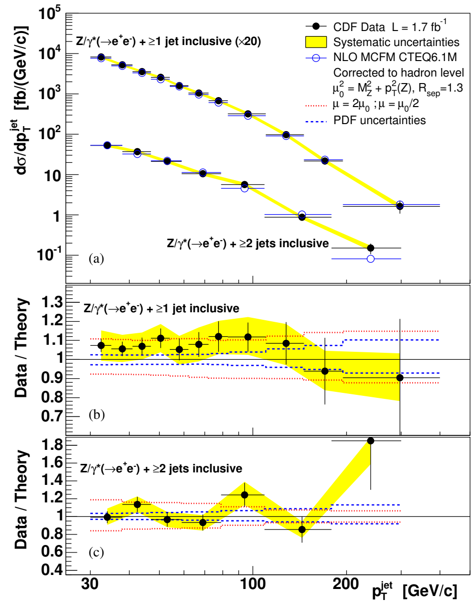

Figure 2: The CDF measured inclusive $Z/\gamma^* \to e^+e^- + \geq n$ jets differential cross sections as a function of jet P_T for events with $n \geq 1, 2$, compared to NLO MCFM predictions that have been corrected to the hadron level.

4 Theoretical Comparisons

Figures 1,2 and 3 show the results of the measurements described above compared to various next-to-leading order (NLO) and leading order (LO) perturbative QCD predictions. All three measurements make comparisons to MCFM [6] NLO predictions with up to 2 partons in the final state. These calculations are made at the parton level, and as such do not include the effects of hadronization or the underlying event which will be present in the data. However, the CDF Z measurement uses a PYTHIA TUNE-A [7, 8] Monte Carlo sample to derive for each jet P_T bin a parton-to-hadron correction factor that is applied to the MCFM predictions to approximately account for these non-perturbative contributions. In Figure 2 the CDF inclusive $Z/\gamma^* \to e^+e^- + \geq n$ jets differential cross sections as a function of jet P_T are compared with the corrected MCFM predictions, and good agreement is observed between the data and the prediction both in terms of overall rates and in the reproduction of the spectra shape. However, in Figures 1 and 3 one can see that the MCFM prediction still well reproduces the data even in the absence of such corrections. In the CDF $W+$ jets analysis it was observed that, for this particular jet definition, the effects of hadronization and the underlying event cancel each other out at the 5-10% level [4].

In Figure 1 comparisons of the D0 $Z/\gamma^* +$ jets data are made to a LO matrix element parton shower matched prediction [9] (ME-PS) based on a modified CKKW scheme [10, 11], and to PYTHIA. These predictions have been normalised to the measured $Z/\gamma^* + \geq 1$ jet cross section ratio. One can see that the ME-PS matched predictions better reproduce the rate of additional jets due to the inclusion of tree-level processes of up to three partons.

In Figure 3 comparisons of the CDF $W+$ jets data are made to two different ME-PS matched predictions; MADGRAPH [12] + PYTHIA predictions using a modified CKKW scheme [11] (SMPR), and ALPGEN[13] + HERWIG [14] predictions using the MLM scheme [15] (MLM). These predictions are not normalised to the data, and the limitations of LO calculations in reproducing absolute rates is clear. However, the SMPR prediction in particular well reproduces the shape of the measured spectra. The discrepancies observed at low jet E_T in the comparison to MLM are possibly due to the absence of a Tevatron Run II tuned underlying event model in this prediction.

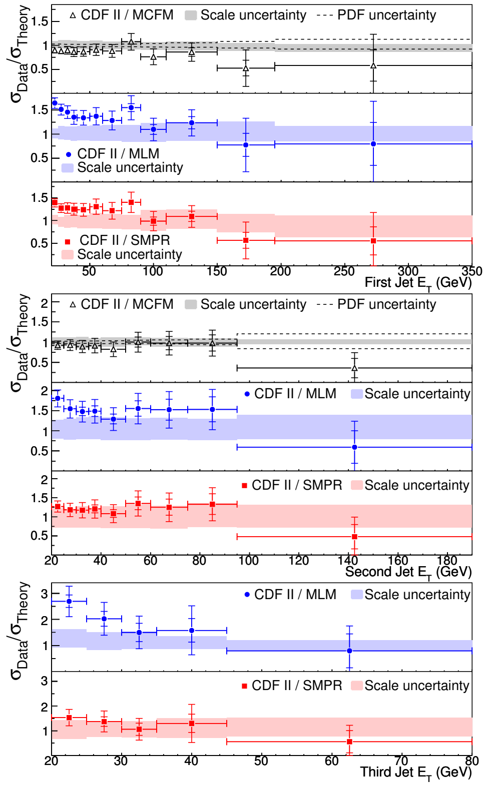

Figure 3: The CDF measured $W \rightarrow e\nu + \geq n$ jets differential cross section for $n = 1-3$ compared to MCFM NLO and ME-PS matched predictions.

5 Summary

The recent CDF and D0 measurements of the $W^{\pm}/Z+$jets process open the door for a thorough exploration into the ability of the latest theoretical predictions to model this important process. The comparisons to theory that have been made thus far indicate that important and impressive progress has been made with the latest Monte Carlo generators.

References

[1] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **100**, 102001 (2008).

[2] V. M. Abazov *et al.* (D0 Collaboration), Phys. Lett. B **658**, 112 (2008).

[3] C. G. Blazey *et al.*, in Proceedings of the Workshop "QCD and Weak Boson Physics in Run II", p. 47, Fermilab-Pub-00/297 (2000).

[4] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **77**, 011108 (2008).

[5] F. Abe *et al.* (CDF Collaboration), Phys. Rev. D **45**, 1448 (1992).

[6] J. Campbell and R. K. Ellis, Phys. Rev. D **65**, 113007 (2002).

[7] T. Sjostrand, S. Mrenna, and P. Skands, J. High Energy Phys. **0605**, 026 (2006).

[8] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **70**, 072002 (2004).

[9] J. Alwall *et al.*, Eur. Phys. J. C **53**, 473 (2008).

[10] S. Catani *et al.*, J. High Energy Phys. **0111**, 063 (2001); F. Krauss, J. High Energy Phys. **0208**, 015 (2002).

[11] S. Mrenna and P. Richardson, J. High Energy Phys. **0405**, 040 (2004).

[12] F. Maltoni and T. Stelzer, J. High Energy Phys. **0302**, 027 (2003).

[13] M. L. Mangano *et al.*, J. High Energy Phys. **0307**, 001 (2003).

[14] G. Corcella *et al.*, J. High Energy Phys. **0101**, 010 (2001).

[15] M. L. Mangano *et al.*, J. High Energy Phys. **0701**, 013 (2007).