PROCEEDINGS OF SCIENCE

$W/Z/\gamma+$ *jets* and $W/Z/\gamma+$ *heavy flavor* at the Tevatron

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We present a variety of measurements of differential cross sections of $W/Z/\gamma+$ *jets* and $W/Z/\gamma+$ *heavy flavor* processes from the DØ and CDF experiments. The measurements are compared to theoretical predictions from next-to-leading order (NLO) perturbative QCD calculations where available, and to several Monte Carlo model predictions. Kinematic regions where theoretical predictions cannot reproduce the data measurements are identified and discussed.

XXth Hadron Collider Physics Symposium
November 16 – 20, 2009
Evian, France

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PoS(HCP2009)010

1. Introduction

Measurements of $W/Z/\gamma+$ *jets* and $W/Z/\gamma+$ *heavy flavor* processes are valuable for two principle reasons. Boson production provides a hard scale, which, along with associated jet production, is an ideal environment to test perturbative QCD (pQCD). The photon, or leptonic decay of the W or Z boson, provides a clean signal for reconstruction of the events, and small background contamination. The test of pQCD is made by comparing the measurements to NLO pQCD predictions. $W/Z/\gamma+$ *jets* and $W/Z/\gamma+$ *heavy flavor* also make up a major background of many new physics searches at both the Tevatron and LHC. Therefore, these data measurements unfolded to the particle level are useful for tuning LO simulation programs which are heavily relied upon to model background processes. There are several programs on the market that can simulate hadronic interactions at next-to-leading order (NLO) accuracy, but the processes included in these programs are limited. Matrix element plus parton shower (MEPS) programs simulate a more comprehensive set of processes, typically at leading-log (LL) or leading order (LO), and rely on models to simulate emissions and fragmentation associated with higher order processes.

The Tevatron measurements presented here are compared to predictions by NLO pQCD as implemented in MCFM [1] or JetPhox [6], MEPS programs ALPGEN [2] and SHERPA [3], and PS programs HERWIG [4] and PYTHIA [5]. The measurements have either been published [7] [8] [9] [10] [11] [12] [14] [15] or have been submitted for publication [13] at the time these proceedings were written. ALPGEN employs the MLM algorithm to ensure jets originating from the matrix element and the parton shower are not double counted. SHERPA is a CKKW-inspired model which uses a reweighting of the matrix elements to achieve the same appropriate jet configurations. A detailed description of these programs can be found in [16].

2. Results

A selection of particle level differential cross sections as functions of a variety of variables are shown in Figures 1-5 and 7-8 for $W/Z/\gamma+$ *jets* and $W/Z/\gamma+$ *heavy flavor* processes. Comparisons are made to NLO pQCD predictions, which are corrected for non-perturbative effects. The NLO pQCD predictions generally describe the data measurements well. However, some of these measurements identify particular kinematic regions where the NLO calculation begins to diverge from the data. The description of the data by the LO MC models is mixed. All LO MC models suffer from large scale uncertainties which impair their ability to make precise predictions. Figure 6 shows a measurement of the mass of jets produced in associated with a W boson, and an extraction of the bottom, charm and light quark jet fractions by the CDF experiment. Assuming standard model cross sections for top and diboson processes, the b jet production cross section for events with a leptonically decaying W boson is measured to be 2.74 +- 0.27 (stat) +- 0.42(syst) pb. This cross section corresponds to a value more than twice as large as predictions from NLO calculations and LO MC models. Additional discrepancies with NLO calculations are seen at low E_T^{jet} in the Z+b jet measurement from CDF, and in certain kinematic regions of the $\gamma+$jet and $\gamma+$heavy flavor jet measurements from DØ .

3. Conclusions

Several differential cross sections of $W/Z/\gamma+$ *jets* and $W/Z/\gamma+$ *heavy flavor* events measured with the CDF and DØ detectors have been presented. The data are generally consistent with predictions from NLO pQCD, although some LO programs can reproduce the shape of the data better than NLO, due either to their inclusion of higher parton multiplicity matrix elements than can be currently included in a fixed order pQCD calculation, or an optimized tune of the Monte Carlo. These data should be useful for continued tuning of these and other Monte Carlo programs. Kinematic regimes which are not described well by theoretical predictions in final states involving a W, Z or γ + light or heavy flavor jets have been identified. Because these final states make up significant backgrounds to new physics searches, understanding and resolving these discrepancies are of utmost importance.

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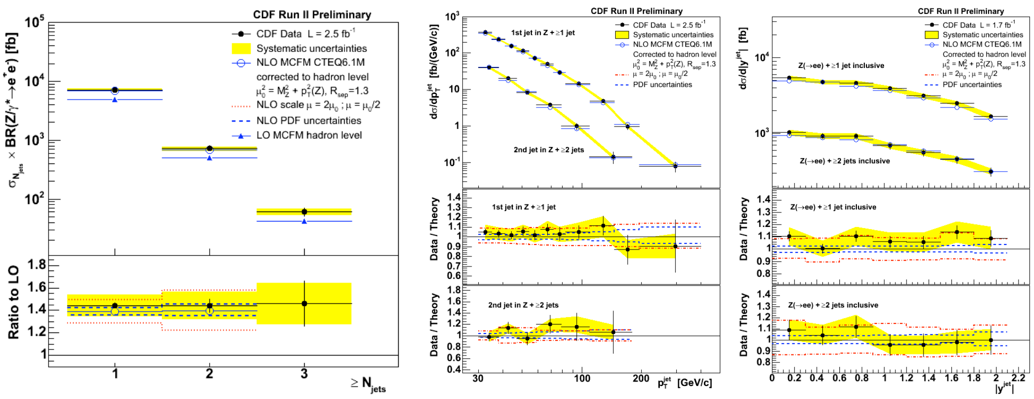

Figure 1: Measured differential cross sections of Z/γ^* + jet + X events with the CDF experiment. The left plot shows the inclusive jet multiplicity cross sections compared with NLO and LO predictions from MCFM. The jet multiplicities are well described by the NLO calculation, whereas the LO calculation indicates a 40% discrepancy in all bins. The inclusive jet cross sections measured as a function of p_T^{jet} and $|y^{jet}|$ are shown in the middle and right plots. The shape of these cross sections are well described by the NLO theory.

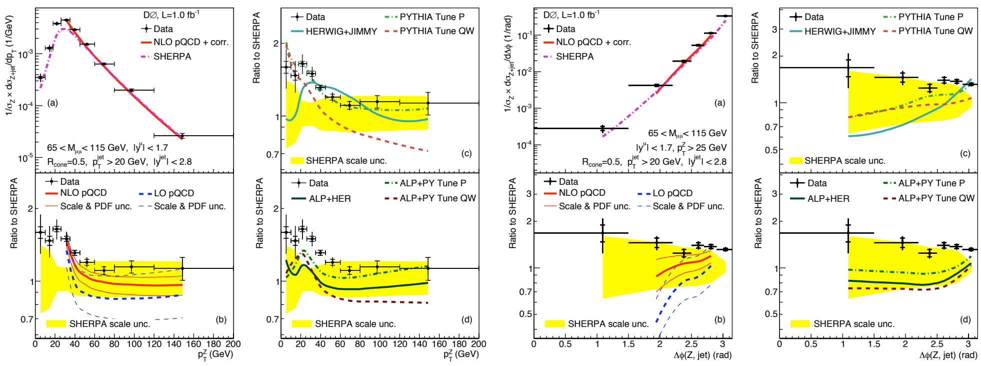

Figure 2: Measured differential cross sections in bins of Z/γ^* + jet + X events with the DØ experiment. Cross sections are measured as a function of p_T^Z and $\Delta\phi(Z, jet)$. The measurements are compared to NLO pQCD predictions and LO MC predictions from SHERPA, PYTHIA, ALPGEN and HERWIG, for certain tune choices. The ratio of data and other predictions to SHERPA are shown in the lower panel of each plot. The yellow band indicates the magnitude of the uncertainty of SHERPA due to the choice of renormalization and factorization scales. The NLO predictions at low p_T^Z are not included in order to avoid the region where non-perturbative effects become large. The data are generally well-described by the NLO prediction within the theoretical and experimental uncertainties. The LO MC programs produce a wide variety of predictions; the p_T^Z distribution is best described by PYTHIA Tune P, whereas the $\Delta\phi(Z, jet)$ shape is best described by SHERPA.

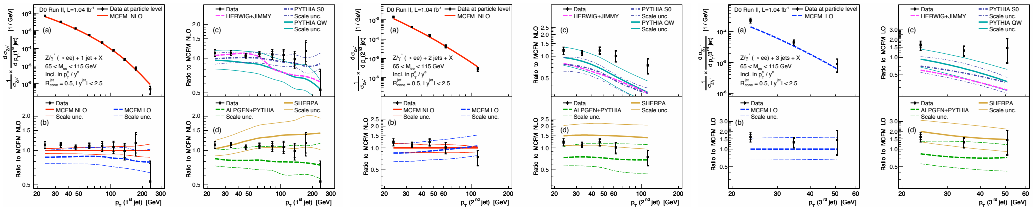

Figure 3: Measured differential cross section of Z/γ^* + (n) jet + X events, where n = 1, 2 or 3 in bins of n^{th} jet p_T with the DØ experiment. The measurements are compared to NLO pQCD predictions with MCFM and LO MC predictions from SHERPA, ALPGEN, PYTHIA and HERWIG, for certain tune choices. The NLO predictions describe the data very well. The predictions based on matrix element + parton shower programs generally describe the data better than simple parton shower Monte Carlos.

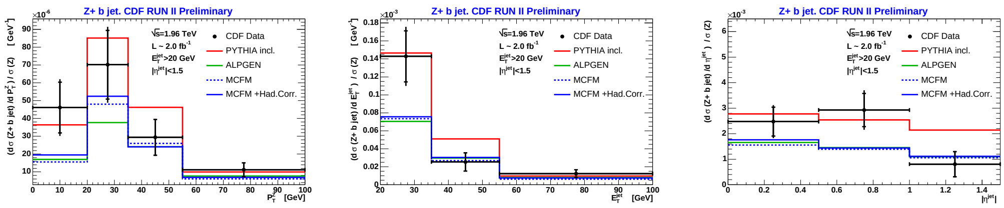

Figure 4: Measured differential cross sections of Z/γ^* + b jet + X events in bins of p_T^Z , E_T^{jet} and $|\eta^{jet}|$ with the CDF experiment. The data are compared with NLO and LO theoretical predictions. The NLO prediction underestimates the data at low E_T^{jet} , where PYTHIA gives a better description. None of the theoretical prediction can describe the data across all variables consistently.

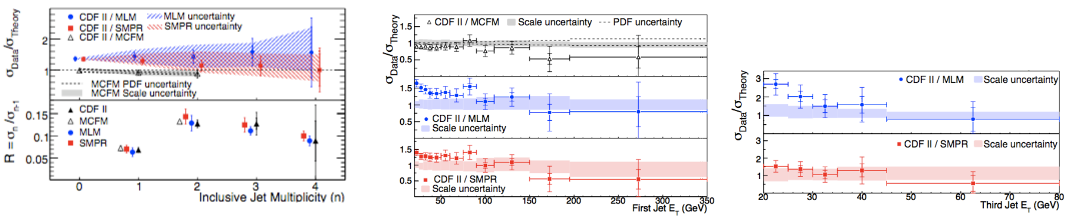

Figure 5: Measured cross sections of W + (n) jet + X events where n = 1,2,3 or 4. The data are displayed as ratios with theoretical predictions from MCFM (a NLO pQCD calculation), MLM (a matrix element + parton shower program comparable to ALPGEN) and SMPR (a matrix element + parton shower program comparable to SHERPA). The MCFM prediction does the best job of describing the inclusive jet multiplicity. Differential cross sections as a function of the leading and third leading jets (ordered in E_T are shown. MCFM can describe the data across the entire spectrum, whereas MLM diverge from the data at low E_T. The SMPR prediction gives an adequate description of the data.

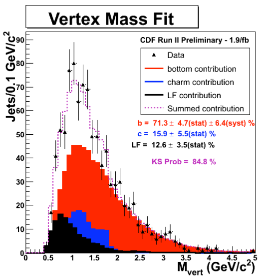

Figure 6: The measured b and c and light quark fractions of W + jet events, extracted from a fit of the mass of the jet vertex, by the CDF experiment.

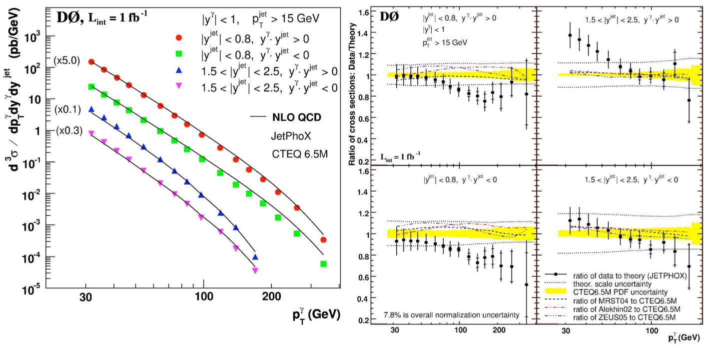

Figure 7: Measured triple differential cross sections of $\gamma +$ jet + X events in bins of p_T^{gamma} , y^γ and y^{jet} with the DØ experiment. The data are compared to NLO predictions calculated by JetPhoX, using CTEQ 6.5M PDFs. Although the NLO calculation generally describes the data very well, the ratios of data to theory reveal certain regions in which the NLO calculation breaks down.

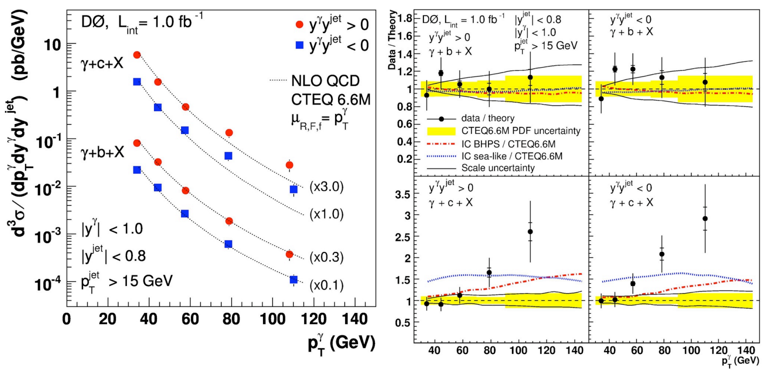

Figure 8: Measured triple differential cross sections of γ + b jet + X and γ + c jet + X events in bins of p_T^{gamma} , y^γ and y^{jet} with the DØ experiment. The data are compared to NLO predictions [17] using CTEQ 6.6M PDFs. Although the NLO calculation generally describes the data very well, the ratios of data to theory reveals the calculation has difficulty describing the high p_T^{gamma} region for $\gamma +$ c jet + X events.