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W/Z properties and V+jets at the Tevatron

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Abstract. We present a summary of recent measurements of W and Z properties and W/Z production in association with jets in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with the CDF and DØ detectors. Latest measurements of Z/γ^* transverse momentum and are presented along with new measurements of the angular distributions of final state electrons from Drell Yan events as a way to probe Z boson production mechanisms. The mass dependence of the forward-backward asymmetry in $p\bar{p} \to Z/\gamma^* \to e^+e^-$ interactions is measured, the effective weak mixing angle extracted, and the most precise direct measurement of the vector and axial-vector couplings of u and d quarks to the Z boson presented. New measurements of jets produced in association with Z and W bosons for inclusive, beauty and charm jets are also discussed.

1 Introduction

Precision Tevatron measurements of W and Z boson properties and W/Z boson production in association with jets continue to provide rich legacy for the understanding of Standard Model processes, both for future precision measurements that are subject to these processes as significant backgrounds and for searches of physics beyond the Standard Model that have the same final state signatures.

This contribution presents the latest measurements of W and Z bosons produced inclusively and in association with jets, representing world-leading precision measurements of electroweak parameters and tests of perturbative QCD (pQCD) theory across a wide kinematic range, for high jet multiplicities and in events with heavy-flavour jet components.

2 Z/γ^* transverse momentum

Recent measurement of the Z/γ^* transverse momentum [1] made extensive comparison of corrected data against theoretical predictions that had varied success in describing the data. The measurement was dominated at low p_T by uncertainties arising from corrections for experimental resolution and efficiency that limited the precision of studies in this region. A new observable, ϕ^*_η (see Ref.[2] for definition), highly correlated with transverse momentum, was proposed to allow high precision study of this low p_T region due to its dependence only on the lepton directions that are experimentally measured with much higher precision than lepton momenta.

Using 7.3 fb^{-1} of integrated luminosity, the normalised differential production cross section of $Z/\gamma^* \to \ell^+\ell^-$ as a function of ϕ^*_η was measured [2] by DØ. Figure 1 shows a comparison of the corrected data compared to Monte Carlo (MC) predictions from ResBos. While the general shape of the distribution is reproduced, the precision of the data reveal some some areas of significant discrepancy in modelling. The width of the ϕ^*_η distribution becomes narrower with increasing rapidity faster in data than predicted by ResBos and in particular the small-x broadening model is seen to have poor agreement with the data.

3 Z/γ^* angular distributions

CDF measured [3] the angular distributions of final state electrons from $p\bar{p} \to Z/\gamma^* \to e^+e^-$ interactions in the Collins-Soper frame for the invariant mass interval $66 < M_{e+e-} < 116$ GeV using 2.1 fb^{-1} of integrated luminosity in order to extract measurement of the angular coefficients A_i as a function of the Z transverse momentum.

From pQCD, the Lam-Tung relation suggests that A_0 and A_2 have a specific dependence on p_T (dependent on the contribution from quark-antiquark annihilation and Compton scattering processes) but should be equal to each other up to corrections of order α_s^2.

A strong p_T dependence was observed with $A_{0,2}$. The results were compared to a variety of Monte Carlo predictions and are used to assess the relative contributions of Compton and annihilation processes to Z/γ^* production, highlighting that at low p_T production dominantly occurs via annihilation processes, with Compton scattering playing an increasingly large role at higher p_T. The average $A_0 - A_2$ value across the p_T range studied was 0.02 ± 0.02. As the Lam-Tung relation is only valid for spin-1 gluons, this result confirms the vector nature of the gluon. By contrast to $A_{0,2}$, A_3 and A_4 are expected (and confirmed by data) to have a value independent of p_T, and from A_4 a (theory-dependent) determination of the weak mixing angle is extracted to be $\sin^2\theta_W = 0.2329 \pm 0.0012$.

4 Z/γ^* forward-backward asymmetry

The presence of both vector and axial vector couplings in $Z/\gamma^* \to \ell^+\ell^-$ production gives rise to an asymmetry in the polar angle θ^* of the negatively-charged lepton relative to the incoming quark direction in the Z/γ^* rest frame,

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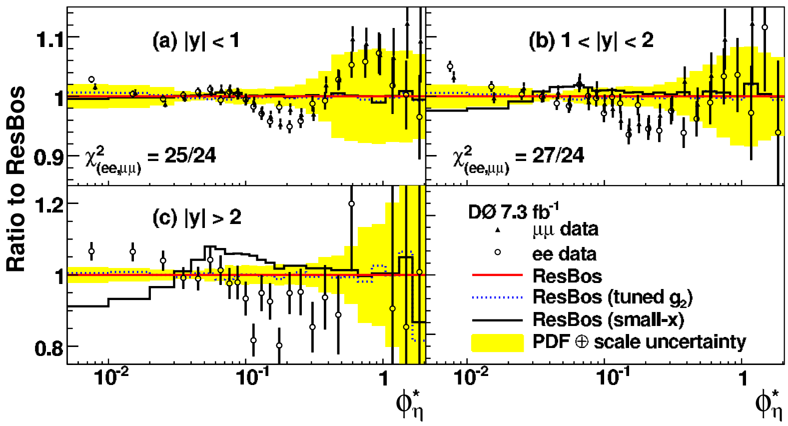

Fig. 1. Ratio of the corrected distributions of $(1/\sigma) \times (d\sigma/d\phi^*_\eta)$ to ResBos for three rapidity intervals. For the first two rapidity intervals, both dielectron and dimuon data are presented. Comparison is also made to a variety of ResBos models. Differences between data and predictions are observed, and in particular ResBos with small-x broadening is disfavoured.

with events having this lepton $\cos\theta^* > 0$ being classified as 'forward' and those with $\cos\theta^* < 0$ being classified as 'backward'. The mass dependence of this forward-backward charge asymmetry A_{FB} was studied [4] by DØ using $p\bar{p} \rightarrow Z/\gamma^* \rightarrow e^+e^-$ data corresponding to an integrated luminosity of 5.0 fb^{-1}. Any deviation from predictions at high mass could be due to the presence of new physics effects. No such discrepancy was observed. The unfolded asymmetry measurement as a function of dilepton invariant mass is shown in Figure 2.

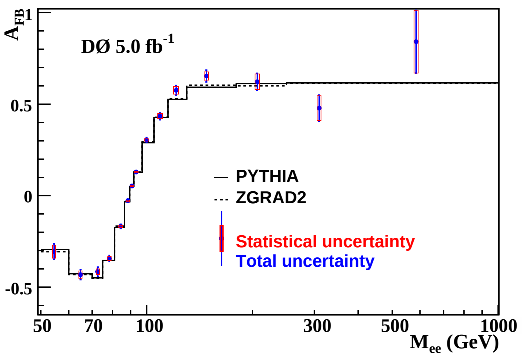

Fig. 2. Unfolded forward-backward asymmetry measurement (points) compared with predictions from PYTHIA (solid line) and ZGRAD2 (dashed line). No significant departure from expectation is observed across the range $50 < M_{e+e-} < 1000$ GeV studied.

In the vicinity of the Z pole, A_{FB} is sensitive to the charged lepton effective mixing angle. This angle is extracted from the detector-level data before corrections by comparing the measured background-subtracted distribution with templates simulated with PYTHIA and ZGRAD2 using a variety of $\sin^2\theta^\ell_{\text{eff}}$ inputs. This allows for a precise measurement of the mixing angle without introducing systematic uncertainties in the unfolding process. Using events in the range $70 < M_{e+e-} < 130$ GeV a measurement of $\sin^2\theta^\ell_{\text{eff}} = 0.2304 \pm 0.0008$ (stat.) ± 0.0006 (syst.) is extracted. By comparing the unfolded A_{FB} spectrum with templates generated using ResBos for a variety of Z-light quark couplings the individual measured quark couplings can be determined. For this measurement, the mixing angle is fixed to the global fit value of 0.23153. The results are summarised in Figure 3 for a two and four-dimensional fit procedure. These coupling extractions are the most precise direct measurements to-date.

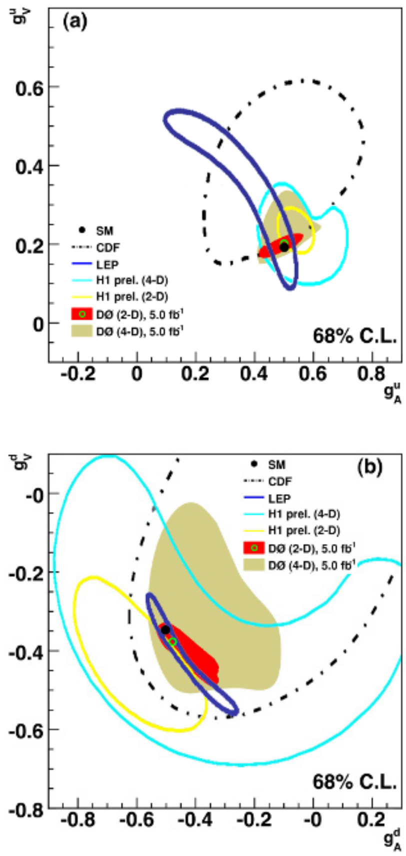

Fig. 3. The 68% C.L. contours of the measured vector and axial-vector couplings of the (a) up-quark and (b) down-quark to the Z boson compared with prior measurements. The DØ data contours are presented for both a two-dimensional fit, fixing the u (d) couplings to the Standard Model values while fitting the d (u) couplings, and a simultaneous four-dimensional fit.

5 W+jets production measurements

The production of a W boson in association with jets was recently studied [5] by the DØ Collaboration with 4.2 fb^{-1} of data. Measurements of the inclusive $W + n$-jet production cross sections and $R = \sigma_n/\sigma_{n-1}$ ($n = 0-4$) were produced and differential cross sections as a function of the n^{th} jet p_T were unfolded (shown in Figure 4 as the ratio of theory over data). These measurements were compared to NLO pQCD calculations (LO for 4-jet). Reasonable agreement was seen between between unfolded data and theoretical predictions, although some tension was observed in the scaling behaviour between the two and three jet cross sections in particular.

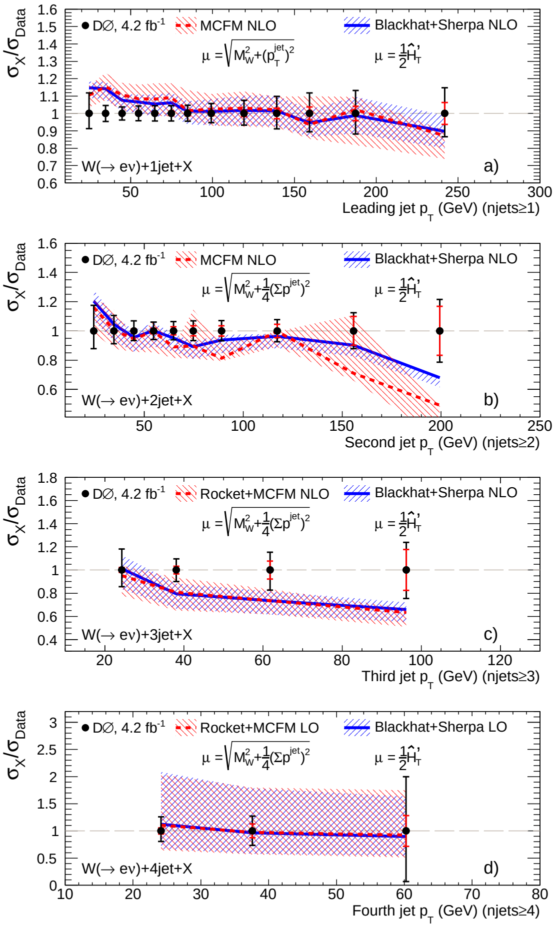

Fig. 4. The ratio of pQCD predictions to the measured differential cross sections for the n^{th} jet p_T ($n = 1-4$). The corrected data and theory predictions are normalised by the measured inclusive W boson cross section and the predicted inclusive W boson cross sections, respectively. The inner (red) bars represent the statistical uncertainties of the measurement, while the outer (black) bars represent the statistical and systematic uncertainties added in quadrature. The shaded areas indicate theoretical uncertainties due to variations of the factorisation/renormalisation scales.

The CDF Collaboration has measured the production of W bosons in association with b-jets [6] with 1.9 fb^{-1} of data and determined the cross section times branching fraction of $W+b$-jets to be 2.74 ± 0.27 (stat.)±0.42 (syst.) pb in significant disagreement with the prediction from MCFM of 1.22 ± 0.14 pb.

This discrepancy is only apparent in b-jets however, as production of W bosons in association with charm jets was recently studied [7] by CDF on 4.3 fb^{-1} of data and the cross section times branching fraction measured to be $13.3^{+3.3}_{-2.9}$ (stat. + syst.) pb in comparison to NLO predictions of 11.3 ± 2.2 pb.

6 Z+jets production measurements

CDF have recently released detailed inclusive and differential measurements [8] of the kinematics of Z bosons and jets in Z+jet associated production, for up to three jets. Figure 5 shows the inclusive cross sections for $Z + (n)$jets for $n = 1-4$ along with comparisons to LO/NLO pQCD predictions for a variety of scale choices and parton density functions (pdfs), as well as comparison to the matrix element-parton shower matched ALPGEN+PYTHIA MC predictions.

Detailed corrected data comparisons to NLO pQCD predictions have been made differentially to a range of kinematic variables [8], including the inclusive and n^{th} jet p_T in $Z+(n = 1-3)$-jet events, inclusive jet rapidities, H_T^{jet}, M_{jj}, M_{Zjj}, ΔR_{jj}, $\Delta\phi_{jj}$, and dijet p_T.

Broadly NLO predictions are found to describe the data well, although several areas are observed where descriptions could be improved. The BLACKHAT pQCD prediction differs from MCFM in the choice of scale and some improvement with the BLACKHAT scale choice is observed in the description of the high p_T tail of jet p_T in Z+1jet events. ALPGEN gives a good general agreement within the uncertainties. The use of a new α_s-consistent tuning of ALPGEN+PYTHIA, Perugia 2011, leads to improved agreement. Uncertainties on parton density functions are quite small with respect to the scale uncertainty and in general the measurement cannot be used to distinguish between different pdfs.

The production of Z bosons has also been studied in association with b-jets, as for the W, both by the DØ Collaboration on 4.2 fb^{-1} of data, and the CDF Collaboration with 7.86 fb^{-1} The DØ analysis performed measurement [9] of the $(Z + b)/(Z$+jet) production cross-section ratio, combining not just the secondary vertex invariant mass, but additional discriminating information such as B-lifetime and decay length significance as inputs to a neural network in order to build discriminant template shapes for light, charm and beauty jets. These templates were then fit to the data to extract the $(Z + b)/(Z$+jet) fraction 1.92 ± 0.22 (stat.) $\pm$ 0.15 (syst.)%, the most precise measurement of this quantity to-date.

The new CDF analysis [10] performs a similar discriminant template fit to the data (shown in Figure 6) to extract both the $(Z + b)/(Z$+jet) fraction: 2.24 ± 0.23 (stat.) ±0.32 (syst.)% (in a different phase-space to the DØ analysis), and also the $(Z + b)/Z$ ratio: 0.293 ± 0.030 (stat.) ±0.036 (syst.)%, both in good agreement with MCFM NLO predictions of $1.8 - 2.2$% and $0.23 - 0.28$% respectively (range of predictions from different scale choices for the MCFM prediction).

The large dataset analysed has also allowed for measurement of the $(Z + b)/Z$ ratio to be conducted in bins of jet p_T and rapidity for the first time. Doing so leads to a normalised differential production cross-section mea-

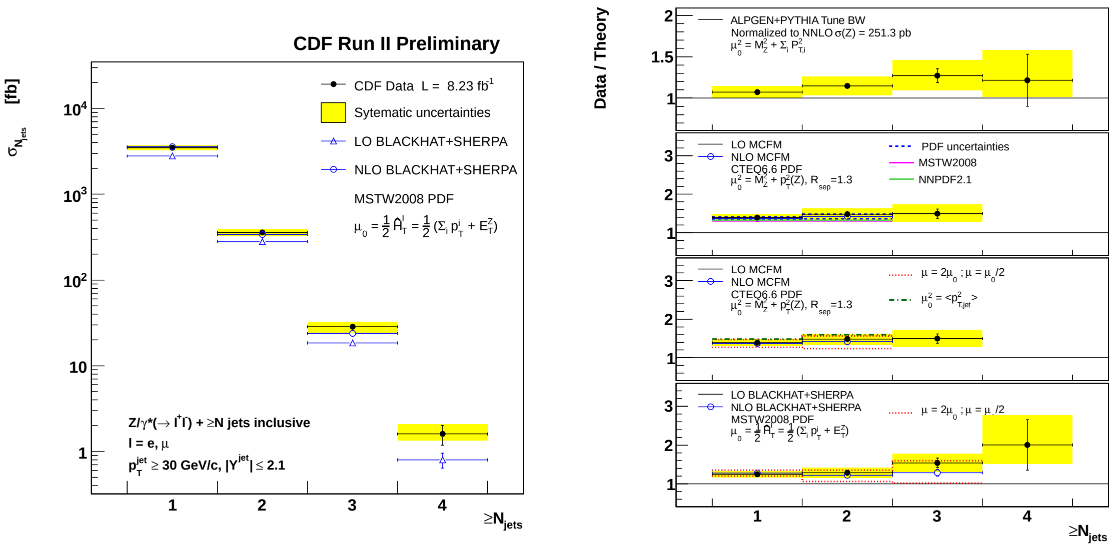

Fig. 5. Measurement of the inclusive production cross sections of $Z + (n)$jets for $n = 1 - 4$. Comparison is made to LO/NLO pQCD predictions from Blackhat+Sherpa and also presented as a ratio of data/theory in comparison with Alpgen+Pythia predictions and LO/NLO pQCD predictions from mcfm for a variety of choices of scale and parton density functions.

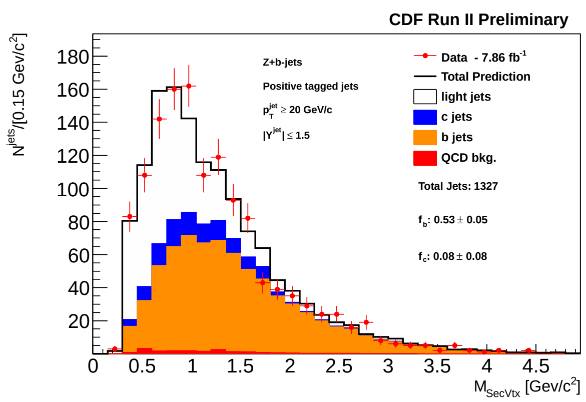

Fig. 6. Secondary vertex invariant mass distribution for $Z \to \ell^+\ell^-$ events, used to determine the $Z + b$-jet fractions from data. Fitted Alpgen-derived templates for the light, charm and beauty jet contributions to the data are also displayed.

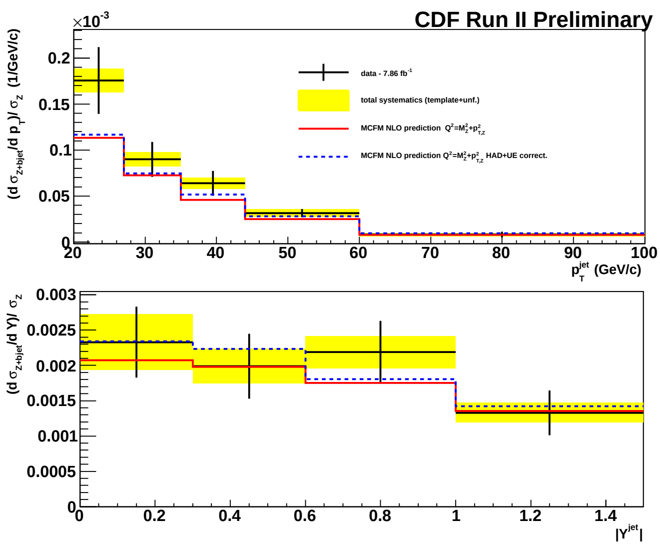

Fig. 7. Normalised differential cross section of $Z+b$-jet events as function of jet transverse momentum (top) and as function of jet rapidity (bottom). Comparison is made to MCFM NLO predictions with and without non-perturbative corrections applied.

surement for $Z + b$-jets as a function of the leading b-jet p_T and rapidity, as shown in Figure 7. This measurement is statistically limited, with statistical uncertainties of around 20%. Comparison is made to NLO MCFM predictions, with and without corrections to the theory for non-perturbative hadronisation and underlying event effects. The data show good agreement with the theory predictions, albeit with large uncertainties on the measurement.

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