FERMILAB-CONF-11-227-E-PPD MAN/HEP/2011/07

Single W and Z boson production properties and asymmetries

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Recent analyses of single W and Z boson production properties and asymmetries from the CDF and DØ experiments at the Fermilab Tevatron are reported. For W boson production, measurements of the production and lepton charge asymmetries are presented. For Z/γ^* production, the following measurements are presented: $d\sigma/dy$, $(1/\sigma)(d\sigma/dp_T)$, $(1/\sigma)(d\sigma/d\phi^*_\eta)$, lepton angular coefficients, and A_{FB} with extraction of $\sin^2\theta_W$ and the light quark couplings to the Z. Most of these measurements are in good agreement with QCD predictions.

1 Introduction

Production of electroweak vector bosons at hadron colliders provides a rich testing ground for predictions of the Standard Model. The production cross sections and distributions are sensitive to higher order QCD corrections, and to the parton distribution functions (PDFs). Leptonic (involving electrons and muons rather than taus) final states are experimentally convenient, due to the relatively low background rates and straightforward triggering on single (or pairs of) high transverse momentum, p_T, leptons.

2 *W* boson charge asymmetry

The production of W bosons at the Tevatron is mostly via the annihilation of valence light quarks; for example the annihilation of a u from a proton with a $\bar{d}$ from an antiproton to produce a W^+. It is well known that $u(\bar{u})$ quarks tend to carry a larger fraction (x) of the $p(\bar{p})$ momentum than $d(\bar{d})$ quarks. For the process $p\bar{p} \to W$, this implies a preferred boost of W^+s along the *proton* direction, and along the *antiproton* direction for W^-s. The W boson production asymmetry is defined as

$$A(y_W) = \frac{N^+(y_W) - N^-(y_W)}{N^+(y_W) + N^-(y_W)}$$

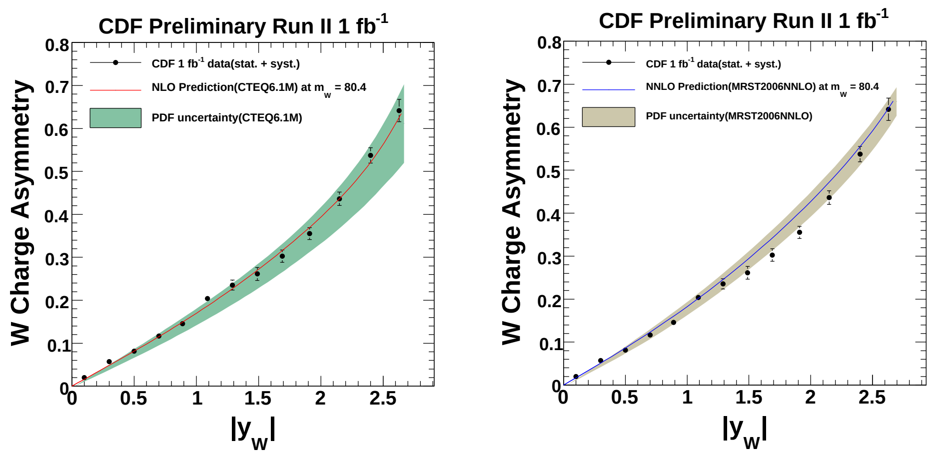

Figure 1: Comparison of the measured W boson charge asymmetry from CDF with (left) a NLO QCD prediction with CTEQ 6.6 PDFs, and (right) a NNLO QCD prediction with MRST2008 PDFs.

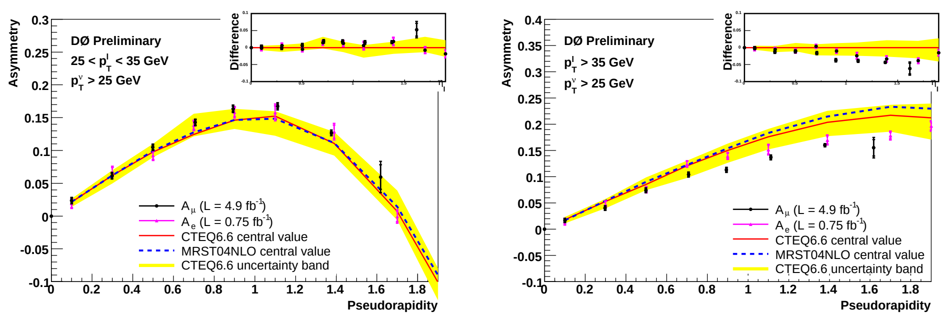

Figure 2: Comparison of the measured muon charge asymmetry from DØ with NLO QCD predictions for (left) $20 > p_T > 35$ GeV, and (right) $p_T > 35$ GeV.

where y_W is the boson rapidity, and is primarily sensitive to the slope of the ratio of u and d quark PDFs as a function of x. Unfortunately, y_W is unobservable due to the unknown momentum of the neutrino along the beam direction. A novel solution suggested by Bodek *et al* [1] involves constraining the invariant mass of the charged lepton and neutrino to the known W boson mass, leaving two solutions for y_W. Each of these is assigned a weight assuming the known $V-A$ structure of the weak decay vertex. This method was employed in a measurement by CDF in the $W \to e\nu_e$ channel using 1 fb^{-1} of data [2]. Figure 2 shows that the measured $A(y_W)$ agrees well with QCD predictions at both NLO and NNLO accuracies.

An alternative approach is to measure the asymmetry as a function of the *observable* lepton pseudorapidity, η_l. Unfortunately, the lepton charge asymmetry, $A(\eta_l)$, is less sensitive to the production asymmetry and thus also the PDFs. The $V-A$ structure of the decay vertex implies that the charged lepton tends to head backwards in the W boson rest frame, i.e. cancelling the production asymmetry; particularly at low lepton p_T and/or large lepton η. Nevertheless, the two approaches provide complementary information. The DØ Collaboration recently measured $A(\eta_l)$ using 4.9 fb^{-1} of data in the $W \to \mu\nu_\mu$ channel [3], and compared to NLO QCD predictions as shown in figure 2. The measurement is performed in two bins of muon p_T which partially disentangles the production and decay asymmetries. Interestingly, this measurement does not agree so well with the QCD predictions, particularly at larger muon p_T and pseudorapidity.

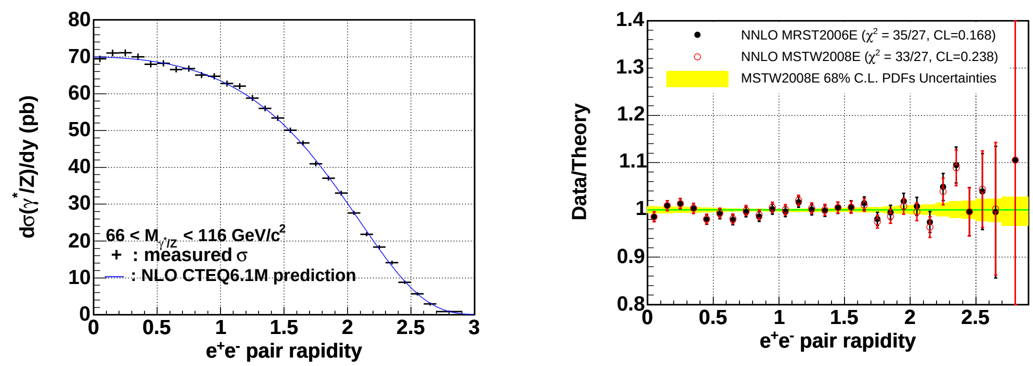

Figure 3: Left: measured $d\sigma/dy$ from CDF compared to a NLO QCD prediction. Right: ratio of the data to NNLO QCD predictions, where the yellow band represents the uncertainty on the prediction due to the PDFs.

3 Z/γ^* rapidity distribution

The rapidity, y, of the dilepton system in Z/γ^* decays is directly related to the x of the two partons: $x_{1,2} = (M_{ll}/\sqrt{s})e^{\pm y}$, where M_{ll} is the dilepton invariant mass, and $\sqrt{s}$ is the centre of mass energy of the collider. Events with large rapidity correspond to the annihilation of a low-x parton and a high-x parton. Thus, a measurement of $d\sigma/dy$ provides additional information on the PDFs that is complementary to the W charge asymmetry. CDF has measured $d\sigma/dy$ in the e^+e^- decay channel using 1 fb^{-1} of data [4]. Figure 3 shows that the data are in good agreement with NLO/NNLO QCD predictions, over the full range of probed rapidities. The Z/γ^* production cross section is measured as 257 ± 16 pb, also in agreement with NLO/NNLO QCD predictions.

4 Z/γ^* transverse momentum distribution

At lowest order in Z/γ^* production, the dilepton system has zero momentum transverse to the beam direction, p_T. Higher order QCD corrections include radiation of gluons from the one or both of the annihilating quarks. Alternatively, one or both of the annihilating quarks can result from a gluon splitting into a pair of quarks. In addition, the partons may carry some intrinsic transverse momentum within the colliding hadrons. A good understanding of these effects is paramount for many physics analyses at hadron colliders; for example the W boson mass measurement, which relies on a precise prediction of the lepton kinematics for different mass hypotheses.

The DØ Collaboration has recently measured the shape of the p_T distribution in the $\mu^+\mu^-$ final state using 1.0 fb^{-1} of data [5]. For $p_T > 10$ GeV, NLO QCD is able to describe the data reasonably well, whilst resummation is needed at lower p_T, as implemented at approximate leading-log (LL) in various Monte Carlo event generators, and at next-to-LL in the ResBos program [6]. Compared to the data, ResBos underestimates the cross section for larger p_T ($p_T >$ 50 GeV), and varying levels of agreement are observed for the different event generators.

This and other recent measurements of the Z/γ^* p_T distribution have been dominated by uncertainties in correcting for detector resolution and efficiency. An alternative approach is to measure the distribution of a variable that is less sensitive to these effects, such as a_T [7], or more recently ϕ^* [8] defined as $\phi^*_\eta = \tan([(\pi - \Delta\phi)/2]\sin\theta^*$, where $\Delta\phi$ is the azimuthal opening angle between the two leptons, and $\cos\theta^* = \tanh[(\eta^{(-)} - \eta^{(+)})/2]$, with $\eta^{(-)}$ being the pseudorapidity of the negatively charged lepton. The variable ϕ^*_η is sensitive to the same physics as the p_T, but is determined exclusively from lepton angles resulting in far better experimental resolution. Furthermore, ϕ^*_η is less correlated than the p_T, with efficiencies of typical Z/γ^* event selection

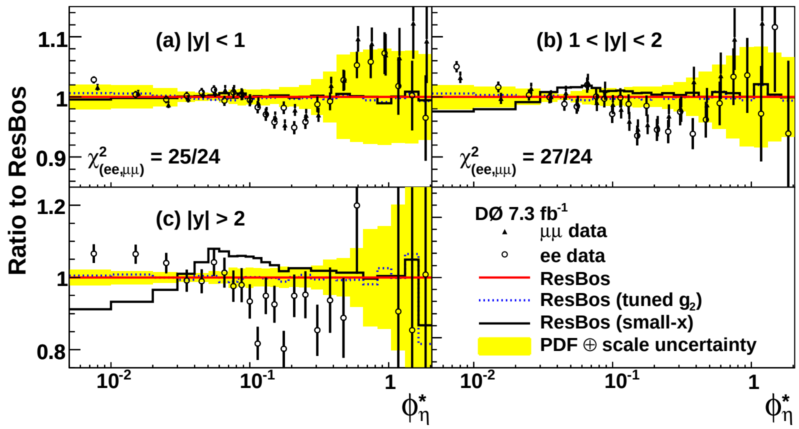

Figure 4: Ratio of measured $(1/\sigma)(d\sigma/d\phi^*_\eta)$, and alternative ResBos predictions, to the nominal ResBos prediction. The yellow band around the ResBos prediction represents the uncertainty due to renormalisation and factorisation scale variation added in quadrature with PDF parameter variations.

requirements; e.g. on lepton isolation.

The DØ Collaboration recently measured $(1/\sigma)$ $(d\sigma/d\phi^*_\eta)$ using 7.3 fb^{-1} of data, in the e^+e^- and $\mu^+\mu^-$ decay channels, and in three bins of dilepton rapidity [9]. The measured distributions are compared to predictions from the ResBos program in figure 4, with a modest level of agreement.

ResBos includes a non-perturbative form factor which has been tuned to simultaneously describe low-Q^2 Drell-Yan data, and Tevatron Run I Z/γ^* data [10]. Floating the g_2 parameter, which controls the width of the form factor, does not substantially improve the agreement, as represented by the blue line in figure 4. Recently, the x-dependence of the non perturbative form factor has received some attention, and an additional "small-x broadening" was suggested to describe SIDIS data from HERA [11], which would have significant effects at the LHC [12]. The $|y| > 2$ data clearly disfavour the small-x modification, which is represented by the black line in figure 4.

5 Z/γ^* lepton angular distributions and forward-backward asymmetry

The angular distributions of the leptons from Z/γ^* decays are often considered in the Collins-Soper frame [13], and are predicted by perturbative QCD [14] to take the following form:

$$\begin{aligned}
\frac{d\sigma}{d\cos\theta d\phi} &\propto (1+\cos^2\theta) \\
&+ \tfrac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi \\
&+ \tfrac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi \\
&+ A_4\cos\theta + A_5\sin^2\theta\sin 2\phi \\
&+ A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi
\end{aligned}$$

where θ and ϕ are the polar and azimuthal angles respectively [13]. The coefficients, A_i, are dependent on the kinematics of the dilepton system; in particular the p_T. The A_5, A_6, A_7 parameters are calculated to be negligible [14]. The $A_4(\cos\theta)$ term generates an asymmetry in the $\cos\theta$ distribution, and is due to the different couplings of the Z boson to left- and right-handed fermions, whose relative strength is determined by the value of $\sin^2\theta_W$.

The forward-backward asymmetry is defined as $A_{FB} = (\sigma_F - \sigma_B)/(\sigma_F + \sigma_B)$, where σ_F and σ_B are the cross sections for forward ($\theta > 0$) and backward ($\theta < 0$) events respectively. Interference between the Z and the γ^* diagrams leads to an enhanced asymmetry for masses away from the Z pole. At higher invariant masses, A_{FB} is sensitive to the presence of additional

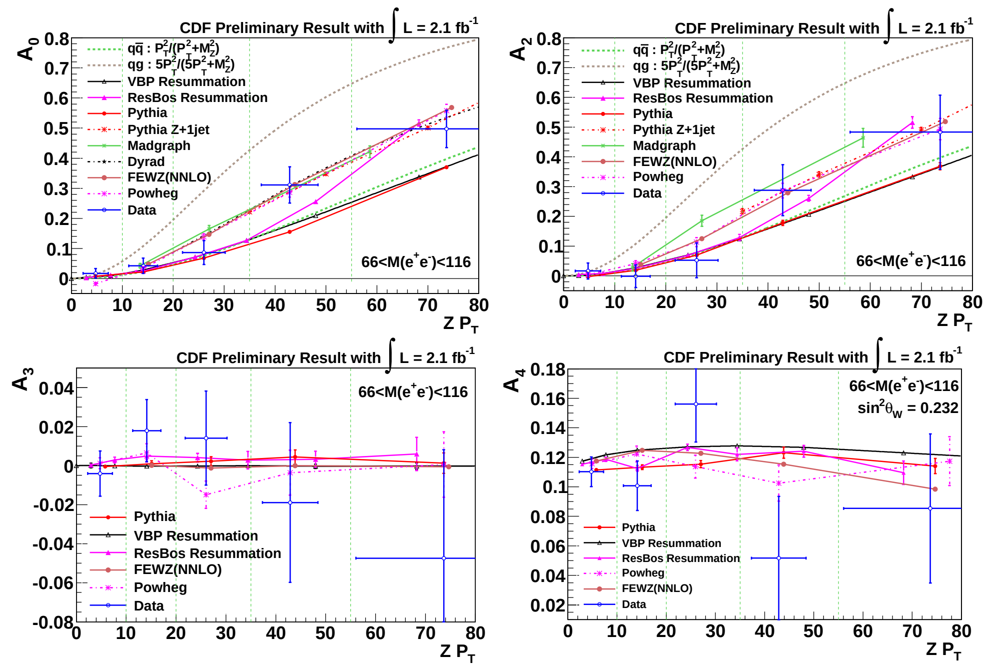

Figure 5: Measured angular coefficients as a function of dilepton p_T, compared to various QCD predictions.

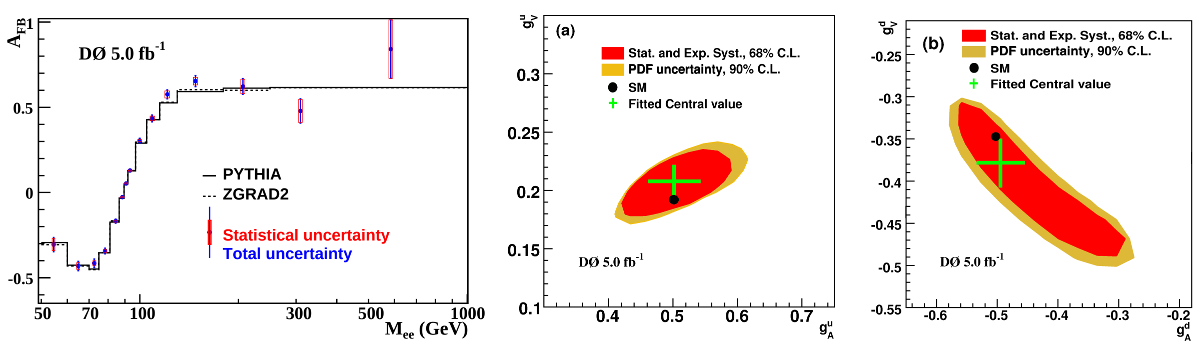

Figure 6: Left: measured A_{FB} compared to Standard Model predictions. Middle and right: measured u and d quark couplings to the Z.

gauge bosons. A_{FB} is sensitive to the couplings of the light quarks to the Z, which are relatively poorly constrained by measurements at LEP.

The CDF collaboration have measured A_0, A_2, A_3 and A_4 as a function of the dilepton p_T, using 2.1 fb^{-1} of data in the e^+e^- decay channel [15]. The data are compared to various QCD predictions in figure 5. The A_4 parameter (multiplying the $\cos\theta$ term) is directly related to the A_{FB}, and thus also the value of $\sin^2\theta_W$. The A_4 measurement is translated into a measurement of $\sin^2\theta_W = 0.2329 \pm 0.0008^{+0.001}_{-0.0009}$, where the first uncertainty is experimental and the second is theoretical.

The DØ Collaboration has recently measured A_{FB} as a function of the dilepton invariant mass, using 6.1 fb^{-1} of data, in the e^+e^- channel [16]. Figure 6 shows that the measurement is in reasonable agreement with Standard Model predictions. In addition, the couplings of the u and d quarks to the Z are extracted as shown in figure 6. A value of $\sin^2\theta_W$ is extracted as 0.2309 $\pm$ 0.001, in good agreement with the world average.

6 Conclusions

Recent analyses of single W and Z boson production properties and asymmetries from the CDF and DØ experiments at the Fermilab Tevatron are presented. A measurement of the W boson production asymmetry in $W \rightarrow e\nu_e$ events from CDF is in good agreement with QCD predictions. Conversely, a measurement of the muon charge asymmetry in $W \rightarrow \mu\nu_\mu$ events from DØ is in modest agreement with QCD predictions. The Z/γ^* production cross section, and rapidity distribution is measured in the e^+e^- decay channel by CDF, and agrees well with QCD predictions. The shape of the Z/γ^* transverse momentum distribution is measured using 1 fb^{-1} of data in the $\mu^+\mu^-$ decay channel by DØ, in reasonable agreement with various QCD predictions. The ϕ^*_η variable was recently proposed as an alternative variable for studying the transverse momentum. A measurement of the shape of the ϕ^*_η distribution from DØ using 7.3 fb^{-1} of data, in the e^+e^- and $\mu^+\mu^-$ decay channels is in modest agreement with a state-of-the-art QCD prediction. Four coefficients describing the angular distributions of the decay leptons from Z/γ^* decays are studied in the e^+e^- channel by CDF using 2.1 fb^{-1} of data. DØ measures A_{FB} as a function of the dilepton invariant mass, using 5 fb$^-1$ of data in the e^+e^- decay channel, in agreement with a QCD prediction. This measurement is used to extract $\sin^2\theta_W = 0.2309 \pm 0.001$, and the most precise determination of the Z boson couplings to u and d quarks.

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