FERMILAB-CONF-08-667-PPD

Electroweak Measurements (including Dibosons) at the Tevatron

A. W. Askew
Florida State University, Fermilab MS 352, P.O. Box 500, Batavia, Illinois USA

Abstract

The large amounts of data being integrated by the CDF and DØ experiments at the Fermilab Tevatron allow for large samples of vector bosons to be collected. As a result precise measurements of the properties of inclusive W and Z production can be made. At the same time studies of events with multiple vector bosons may be studied for insight into the structure of the Standard Model.

1 Introduction

The increasing integrated luminosity being delivered to the CDF and DØ experiments at the Fermilab Tevatron, allow for many different electroweak measurements to be made. The production properties of W and Z bosons give insight into the structure of the proton, and the behavior of the Standard Model. These measurements, by their very nature, require large inclusive samples of events, since they require differential (and in some cases, double differential) cross section measurements. On the other end of the spectrum, with more data, comes an opportunity to study very low cross section processes such as ZZ, which can give information as to the structure of the underlying gauge theory. The analyses presented here make use of 0.2-1.9 fb^{-1} of integrated luminosity.

2 Inclusive W measurements

The large cross section for W production at the Tevatron makes available large samples of W events, even after accounting for the branching fraction for decays to electron (and neutrino) and muon (and neutrino). Using these samples, precision measurements of the mass and width, as well as the production charge asymmetry may be made. Those summarized here are the W charge asymmetry as well as the W mass and width.

2.1 *W Charge Asymmetry*

On average, the u-quark carries more of the proton momentum than the d-quark. Thus in the production of W bosons, the W^+ tends to be produced with momentum along the proton direction, and likewise the W^- is produced along the direction of the anti-proton. This charge asymmetry can be observed in two ways: one can make a hypothesis as to the unknown p_Z of the neutrino from the W decay and solve for the W rapidity directly [1], or one may assume the V-A structure of the W decay is well known, and instead measure the rapidity of the charged lepton.

The CDF experiment chooses to do the former, and selects the best hypothesis for the neutrino p_Z based on the event kinematics. Using 1 fb^{-1} of data, CDF reconstructs the W rapidity in the electron channel (due to the large coverage of the calorimeter, which yields good acceptance for the leptons).

The DØ experiment does the latter, using the lepton charge asymmetry in the muon channel, due to the much smaller backgrounds and charge misidentification systematics in this channel. The measurement of the muon charge asymmetry uses 0.3 fb^{-1} of integrated luminosity [2].

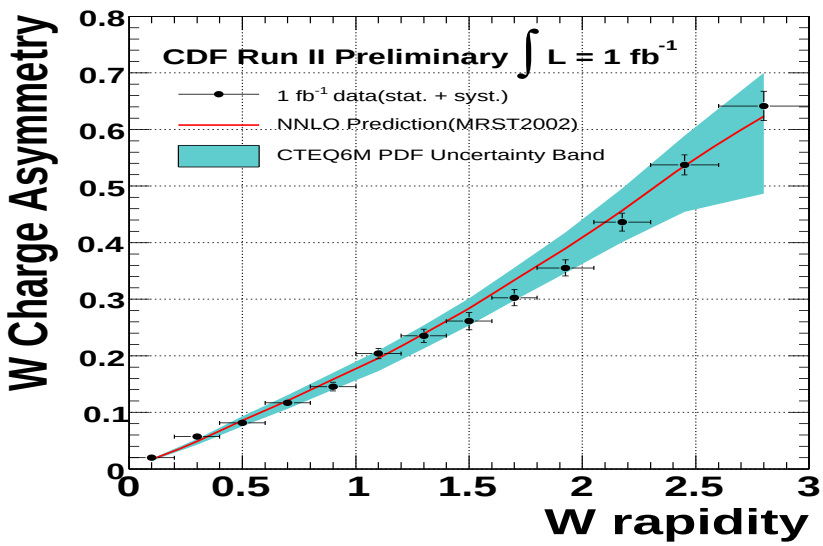

Figure 1: *CDF W charge asymmetry measurement (preliminary). The points correspond to the measured data, the red curve is the NNLO Monte Carlo prediction* [3] *(using MRST2002 parton distribution functions), and the blue band is the uncertainty from the CTEQ6M parton distribution functions.*

2.2 *W Mass and Width*

A full discussion of the measurement of the W mass and W width is beyond the scope of these proceedings. In short, by use of the kinematic quantities sensitive to these properties (the lepton p_T, the missing transverse energy, and the transverse mass), and a detailed and precise understanding of detector response, one may generate templates for different values of the mass and width, and find the values which are most representative of the data distributions (full discussions of these measurements are detailed in [4] and [5]) . The CDF experiment has measured the W mass with 200 pb^{-1}, and the W-width with 350 pb^{-1}. The W-mass is measured to be 80413 $\pm$ 34(stat.) $\pm$ 34(syst.) MeV/c^2. This is the single most precise measurement of this quantity, and improves the uncertainty on the world average by 15%. The W-Width is measured to be 2032 $\pm$ 73(stat.+syst.) MeV/c^2. This is the most precise single direct measurement of this quantity, and decreases the uncertainty on the world average

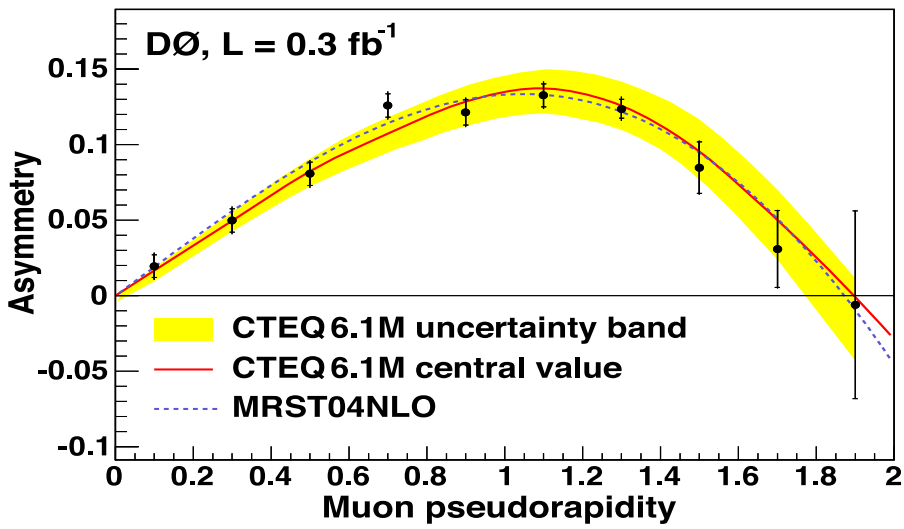

Figure 2: *DØ muon charge asymmetry measurement. The points correspond to the measured data, the red line is the RESBOS plus PHOTOS central value using CTEQ6.1M parton distribution functions, the blue dotted line is the RESBOS plus PHOTOS central value using MRST2004 parton distribution functions, and the yellow band represents the uncertainty from the CTEQ6.1M parton distribution functions.*

by 22%.

3 Inclusive Z measurements

Measurements of inclusive Z boson production can shed light on not only the parton distribution functions, but also the extent to which the merger of perturbation theory and soft gluon resummation provide a consistent description of the p_T distribution of the produced Z bosons. In addition, $Z \to \tau\tau$ events provide an important calibration for hadronic τ decays.

3.1 *$Z \to \tau\tau$ Cross Section*

The measurement of Z boson decays provide a standard candle not only for studying detector performance for the reconstruction of leptons, but also to ensure that the energy scale and resolution for these leptons is properly determined. For processes such as Z$\to \tau\tau$, it is vital to assess both performance

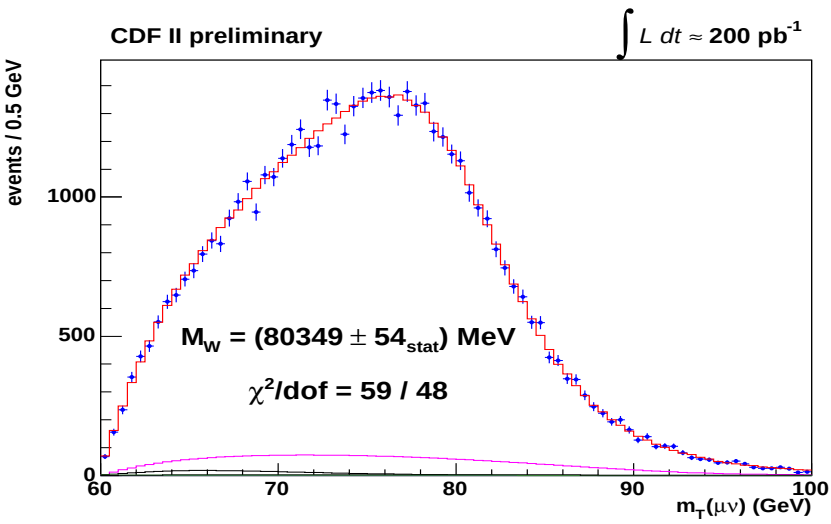

Figure 3: *Transverse mass of W→ $\mu\nu$ from CDF W-mass measurement. The blue points are the data with statistical uncertainties. The red curve is the combined W-mass Monte Carlo (for the measured value) combined with the estimated backgrounds (the pink and grey curves).*

(of both reconstruction and triggering) and resolution/scale for further analyses involving τ decays to hadrons (notably Higgs searches). Using 1 fb^{-1} of integrated luminosity, the DØ experiment measures the Z→ $\tau\tau$ cross section when one τ decays leptonically, and then other τ decays to hadrons. The cross section is measured to be $\sigma(p\overline{p} \rightarrow Z \rightarrow \tau\tau)$= 247 ± 8(stat.) ± 13(syst.) ± 15(lumi.) pb, in good agreement with the Standard Model value of $251^{+5}_{-11.8}$ pb.

3.2 *Z Rapidity Measurement*

At leading order, the Z rapidity is specified by the momentum fractions carried by the colliding partons. So natively, this is a distribution that is highly influenced by the parton distribution functions. At next-to-leading order, gluon radiation also makes changes to this distribution, making this measurement sensitive to the measurement of these effects as well.

CDF measures the differential cross section for Z→ *ee* events as a function of rapidity. While statistics limited, the measured distribution is in good agreement with the shape of the NLO MC theory distribution (normalized to

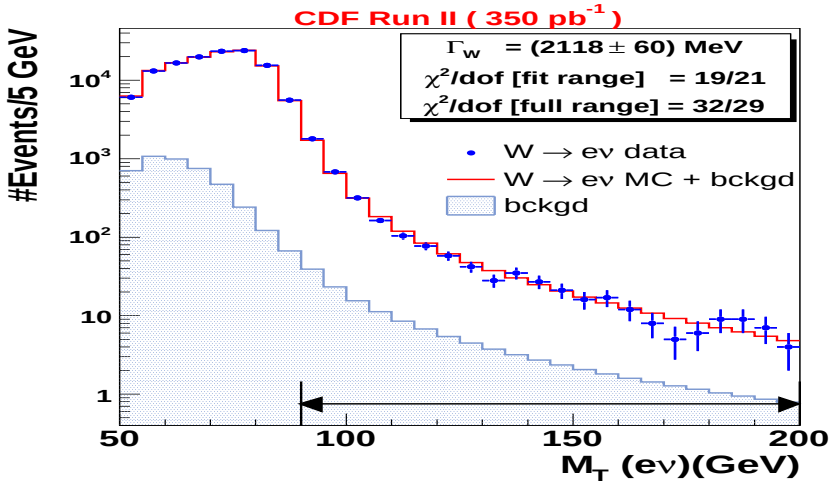

Figure 4: *Transverse mass of W→ eν from CDF W-width measurement. The blue points are the data with statistical uncertainties. The red curve is the combined W-width Monte Carlo (for the measured value) combined with the estimated background (the grey shaded histogram).*

the data cross section) using the CTEQ6.1M parton distribution functions.

3.3 *Z p_T Measurement*

At leading order, the produced Z boson p_T is zero. Thus measuring this distribution is a direct probe of NLO QCD, which has two distinct regimes. For large p_T, the theoretical calculation can be made in perturbation theory. For very small p_T one must invoke soft gluon resummation, which involves free parameters which must be measured from the data. One of these parameters, g_2, determines the position of the peak of the distribution in Z p_T (which is the same parameter which determines the peak position for W p_T, making this an important measurement for precision tests such as W-mass).

The DØ experiment measures the shape of the Z p_T distribution using approximately 1 fb^{-1} of integrated luminosity. Using the low p_T data, the value for g_2 is measured. The shape of the data at high p_T agrees well with the NNLO theory prediction from [7].

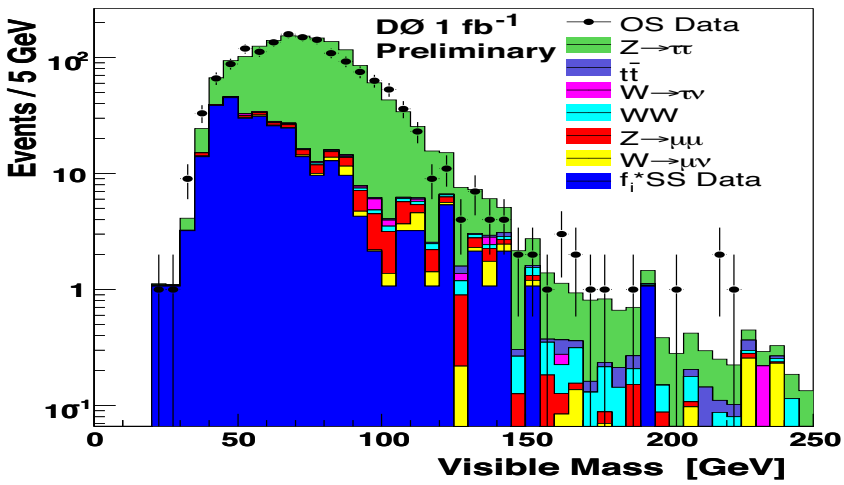

Figure 5: *Visible mass of Z→ ττ with subsequent decay of one τ → μ and one τ decaying hadronically, from DØ cross section measurement (preliminary). The points represent the data candidates with statistical uncertainties. The green shaded histogram is the sum of the Z→ ττ Monte Carlo combined with the estimated backgrounds (QCD multijet(dark blue), $t\bar{t}$ (blue-grey), W→ τν (pink), WW (light blue), Z→ μμ (red), and W→ μν (yellow).*

4 Diboson Measurements

At hadron colliders, in the same manner as on-shell W production, one may produce off-shell, high mass W propagators. As a consequence of this, there is the opportunity to study such final states as WZ, which in the case of the trilinear vector boson coupling is the result of a very off-shell W radiating a Z boson to become an on-shell W boson. In the case of these trilinear vertices, the Standard Model prediction is absolute (there is no tuning possible), the coupling of the W and Z must be as predicted, and as such any deviation is evidence for new physics. In the case of ZZ production, there is no trilinear boson diagram in the Standard Model, and thus if there is anomalous production of pairs of Z bosons, then this again is evidence for new physics.

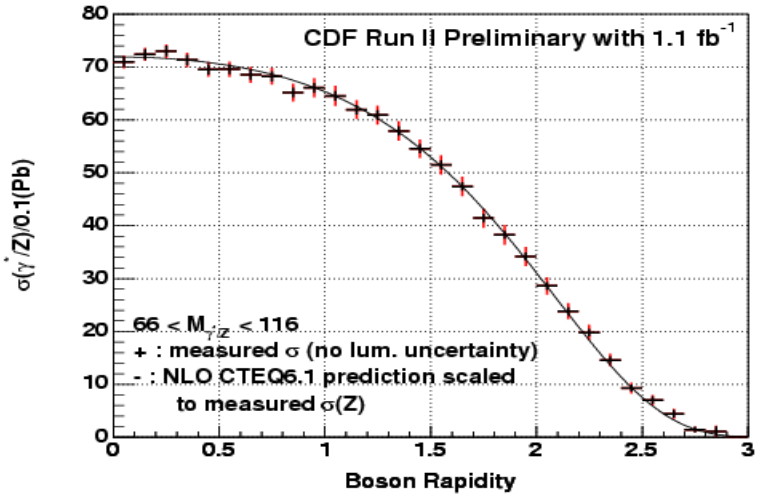

Figure 6: *CDF Z rapidity measurement. The measured differential cross section (without luminosity uncertainty) is shown as the points. The solid line is the NNLO prediction from* [6] *using CTEQ6.1M parton distribution functions, scaled to match the measured cross section.*

4.1 $WW/WZ \to \ell\nu jj$

At hadron colliders, in general, only leptonic decays of W and Z bosons are discenable from the large QCD dijet backgrounds. However, in the case of semileptonic decay of WW/WZ→ $\ell\nu$jj, the much larger branching fraction of W or Z to hadrons, produced in association with a well identified lepton and missing transverse energy, motivates an attempt to winnow out a signal. WW/WZ are combined together as the resolution on the jet transverse momentum (for both Tevatron experiments) is insufficient to separate the constituent W and Z decays to hadrons.

CDF attempts to find evidence for this diboson final state by first selecting a sample of W bosons produced in association with two or more jets. Then a neural network is used, trained on Monte Carlo, which exploits the kinematic correlations present in W and Z decays to jets, as opposed to the inclusive QCD background. Template shapes are verified in the di-jet mass bins which should have little signal contribution, and then bin by bin template fits are performed to extract the signal contribution in the range of 60-100 GeV. The number of signal extracted from these fits is 410 ± 212(stat.) ± 107(syst.) events. Since

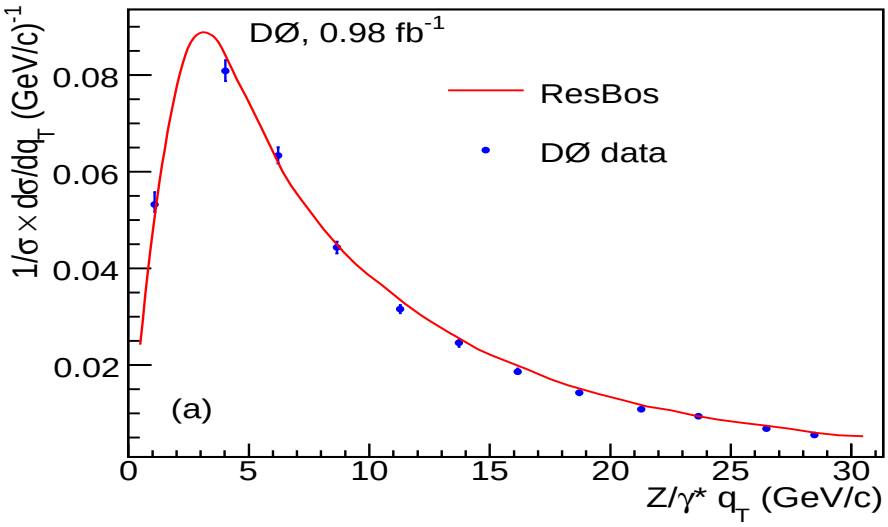

Figure 7: *DØ Z p_T spectrum: Low p_T region used for measurement of g_2 parameter. The points are the measured data, the red line is the RESBOS prediction.*

this is not sufficient to claim evidence, a limit of 2.88 pb is set on the cross section times branching fraction.

4.2 *WZ→ $\ell\ell\ell\nu$*

Unlike the semileptonic decay of WZ, the three charged lepton decay mode is one of the cleanest signals at a hadron collider. This comes at the cost of the branching fraction of both the W and the Z to leptons, specifically electrons and muons. Both CDF and DØ have significant samples of WZ→ $\ell\ell\ell\nu$, which then can be used to set limits on anomalous WWZ couplings, by use of the Z boson p_T spectrum.

The DØ experiment uses 1 fb^{-1} of data and finds 13 candidate events, with expected signal of 9.2±1.0 and expected background of 4.5±0.6. The measured cross section is $2.7^{+1.7}_{-1.3}$ pb [8]. The CDF experiment uses 1.9 fb^{-1} of data and finds 25 candidate events, with expected signal of 16.5±2.0 and expected background of 5.8±0.7. The measured cross section is $4.3^{+1.4}_{-1.0}$ pb.

When setting limits on anomalous WWZ couplings, both CDF and DØ use a form factor scale $\Lambda = 2$ TeV. The one-dimensional limits from CDF are: $-0.13 < \lambda_Z < 0.14$, $-0.15 < \Delta g_1^Z < 0.24$, and $-0.82 < \Delta\kappa_Z < 1.27$. The

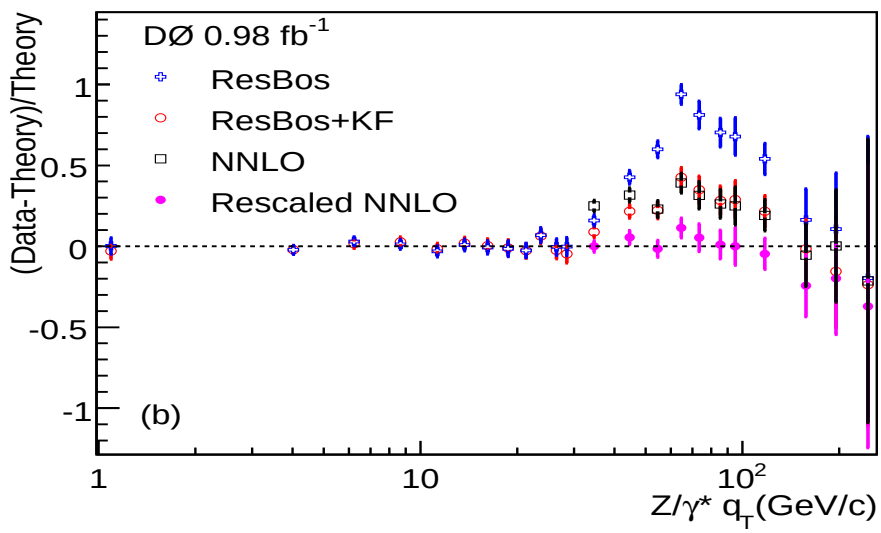

Figure 8: *DØ Z p_T spectrum, (Data- Theory)/Theory. The blue points use RESBOS as the theory. The red points use RESBOS as the theory, along with a k-factor to adjust to NNLO effects. The black points are the NNLO prediction from* [7], *and the pink points are the NNLO theory predition rescaled to the data normalization.*

DØ one-dimensional limits, which assume $\Delta g_1^Z = \Delta\kappa_Z$ (and are thus not directly comparable), are: $-0.17 < \lambda_Z < 0.21$, $-0.14 < \Delta g_1^Z < 0.34$, and $-0.12 < \Delta\kappa_Z < 0.29$.

4.3 *ZZ→ ℓℓℓℓ*

The smallest cross section times branching fraction diboson process at hadron colliders is that of ZZ→ $\ell\ell\ell\ell$. In no other analysis is the acceptance times efficiency of the detector tested as in this one. Both DØ and CDF have performed searches for this process. The DØ experiment finds one candidate using 1 fb^{-1} of integrated luminosity and sets a limit on the cross section of σ_{ZZ} <4.4 pb. Limits on anomalous neutral gauge couplings are also set (for the first time at a hadron collider) [9].

CDF finds three candidates with an estimated background of less than 0.1 event, and claims 4.2σ evidence for ZZ production in the four charged lepton channel [10]. Thus a cross section of $1.4^{+0.7}_{-0.6}$ pb is measured for this

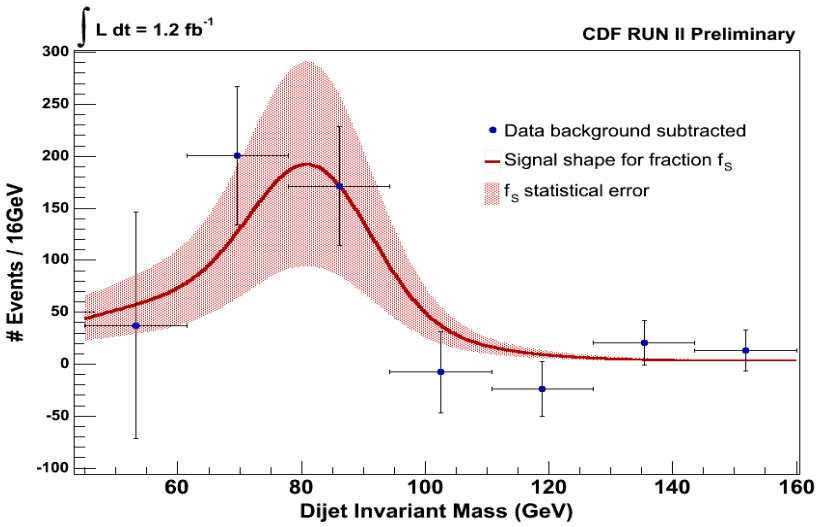

Figure 9: *CDF WW/WZ→ $\ell\nu jj$: Di-jet invariant mass after background subtraction. Each point is the result of a template fit to the neural network discriminant in the corresponding di-jet mass bins.*

process. It is worth noting that substantial improvement in the identification of leptons was found by using calorimeter clusters without tracks (in areas of lower tracking coverage) and isolated tracks without calorimetry (in areas of sparse calorimeter coverage) to build a more uniform lepton acceptance.

5 Summary

Both of the Tevatron experiments are taking full advantage of the integrated luminosity received in Run II. Precision measurements of W and Z boson properties are becoming available, as are measurements of the smallest diboson production cross sections yet observed. All measurements will improve in uncertainty with the addition of integrated luminosity being gained at the time of these proceedings.

References

1. A. Bodek *et al.*,"Direct measurement of W Production Charge Asymmetry at the Tevatron," arXiv:0711.2859 [hep-ph].

2. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **77**, 011106 (2008).

3. C. Anastasiou *et al.*, Phys. Rev. D **69** 094008 (2004).

4. T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **99**, 151801 (2007).

5. T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **100**, 071801 (2008).

6. C. Anastasiou *et al.*, Phys. Rev. D **69**, 094008 (2004).

7. K. Melnikov *et al.*, Phys. Rev. D **74**, 144017 (2006).

8. V. M. Abazov *et al.*, Phys. Rev. D **76** 111104(R) (2007).

9. V. M. Abazov *et al.* [D0 Collaboration], Accepted by PRL, arXiv:0712.0599 [hep-ex].

10. T. Aaltonen *et al.* [CDF Collaboration], Submitted to PRL, arXiv:0801.4806 [hep-ex].