CDF/PUB/ELECTROWEAK/PUBLIC/7082

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Electroweak Physics at the Tevatron

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On Behalf of the CDF and DØ Experiments

Abstract — The CDF and DØ experiments at the Tevatron have used $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV to perform electroweak physics measurements. A program of *precision* electroweak tests of SM already started. Measurements performed are: *W* and *Z* bosons production cross section using different leptonic final states, dielectron Forward-Backward Asymmetry A_{FB} and di-boson cross section production. We also report the prospects for the W mass measurements.

FERMILAB-CONF-04-120-E NOVEMBER 2004

Introduction

The Collider Detector at Fermilab (CDF) and the DØ detectors are general purpose experiments located at the Tevatron collider, [1)]. $p\bar{p}$ collisions at the Tevatron reach an energy in the center of mass of $\sqrt{s} = 1.96$ TeV. We are reporting here electroweak physics measurements performed using physics-quality data of RunII.

We will start reviewing *W* and *Z* cross section measurements, then we will concentrate on precision electroweak measurements. We will conclude giving some perspectives for the RunII mass measurement.

1 *W* and *Z* Cross Sections

W and *Z* bosons are produced by $q\bar{q}$ annihilation. Due to the large QCD background, decay channels of bosons involving quarks are difficult to identify; therefore *W* and *Z* bosons are identified through their leptonic decays.

1.1 Measuring *W* Cross Section

The signature for a leptonic *W* boson decay is a high momentum isolated lepton with missing transverse energy accounting for the undetected neutrino.

At CDF, $W \to e\nu$ candidates are collected with a trigger selecting high-E_T central electron candidates; after requiring one tight electron with $E_T > 25$ GeV matched to a track with $P_T > 10$ GeV/c and missing transverse energy $\not\!\!E_T > 25$ GeV, 38628 events are left in data. The transverse mass distribution of the candidate events is reported in Fig.1(*Left*). Background from QCD dijets is estimated from data assuming that its distribution is flat with respect to the missing transverse energy. Background contamination from other electroweak processes like $W \to \mu\nu$, $Z \to ee$ and $W \to \tau\nu$ is estimated from MC events after a detailed simulation through our detector.

$W \to \mu\nu$ candidates are collected by a high-P_T muon trigger. After requiring an isolated muon with $P_T > 20$ GeV/c and $\not\!\!E_T > 20$ GeV, 21599 *W* candidates remain. The main background contamination comes from $Z \to \mu\mu$, $W \to \tau\nu$, cosmic rays and dijet QCD events. The transverse mass distribution of the candidate events is shown in Fig.1(*Right*).

With the upgrades of the CDF forward calorimeters (pseudorapidity region coverage is $1.1 < |\eta| < 3.6$)[3] and the silicon tracking detectors ([2]) it has been possibile to identify a clean sample of $W \to e\nu$ candidate events

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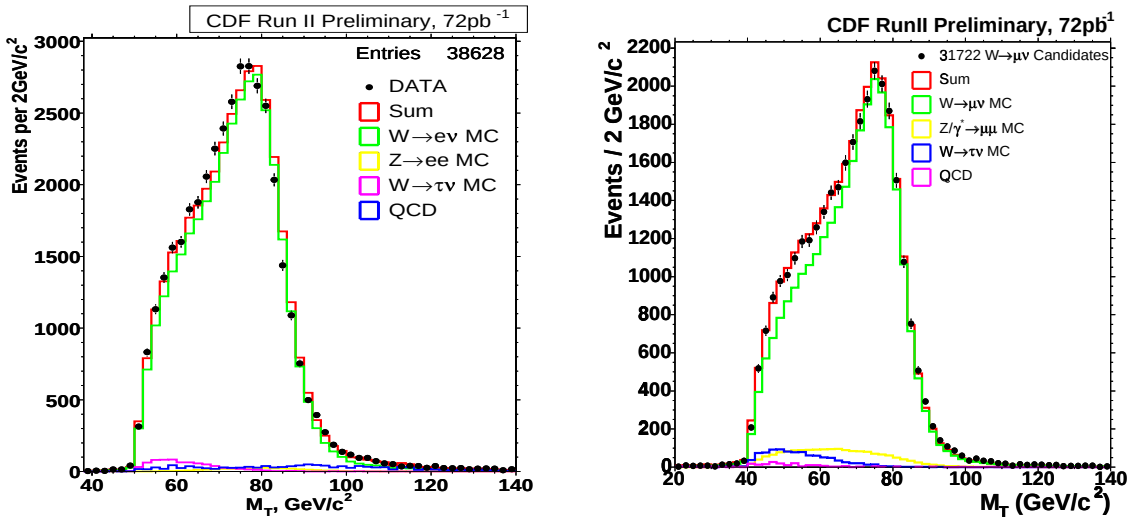

Figure 1: *Left:* Transverse mass distribution for $W \rightarrow e\nu$ candidates with electron $|\eta| < 1.1$. *Right* Transverse mass distribution for $W \rightarrow \mu\nu$ candidates ($|\eta| < 1.0$).

with electron pseudorapidity in the range $1.1 < |\eta| < 2.8$. $W \rightarrow e\nu$ events are identified requiring at trigger level $E_T \geq 20$GeV and $\not{E}_T \geq 20$ GeV. Then, after applying calorimetric isolation cuts, a track is matched to the electromagnetic calorimetric cluster requiring that the distance between the shower position and the track extrapolation is within 3 cm. The transverse mass of $W \rightarrow e\nu$ candidates is shown in Fig.2.

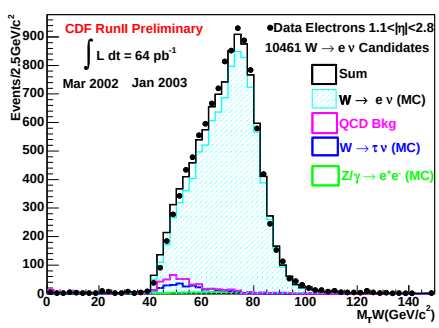

Figure 2: Transverse Mass distribution of $W \rightarrow e\nu$ with electrons detected by forward calorimeters($1.1 \leq |\eta| \leq 2.8$)

Specific triggers for selecting a sample enriched with τ events decaying into hadrons have been designed for RunII [5]. They are based on the possibility to use tracking information at trigger levels in RunII: in particular the tracking processor at Level-1 (L1) and the refined tracking information available at Level-2 (L2). Events with $\not{E}_T > 25$ GeV and with the topology of the τ decaying hadronically are selected at trigger level. $W \rightarrow e\nu$ events are explicitly removed. In Fig.3(*left*), the track multiplicity for $W \rightarrow \tau\nu$ events is shown. 2345 events pass the selection with an estimated background mainly from QCD of 612 ± 61 events.

At DØ $W \rightarrow e\nu$ candidates are selected requiring an isolated electron with $P_T \geq 25$ GeV/c with $|\eta| < 1.1$ and $\not{E}_T \geq 25$ GeV. The transverse mass is shown in Fig.4(*left*). $W \rightarrow \mu\nu$ events are selected requiring a muon with $P_T \geq 25$ GeV/c and $|\eta| \leq 1.6$ and with $\not{E}_T \geq 25$ GeV. The transverse mass distribution is shown in Fig.4(*right*).

The number of *W* bosons candidates found in the different decay channels by DØ and CDF together with the measured cross section are shown in Table.1. The measured values are in agreement with the predicted theoretical values[1] (NNLO) of 2.731 ± 0.002 nb.

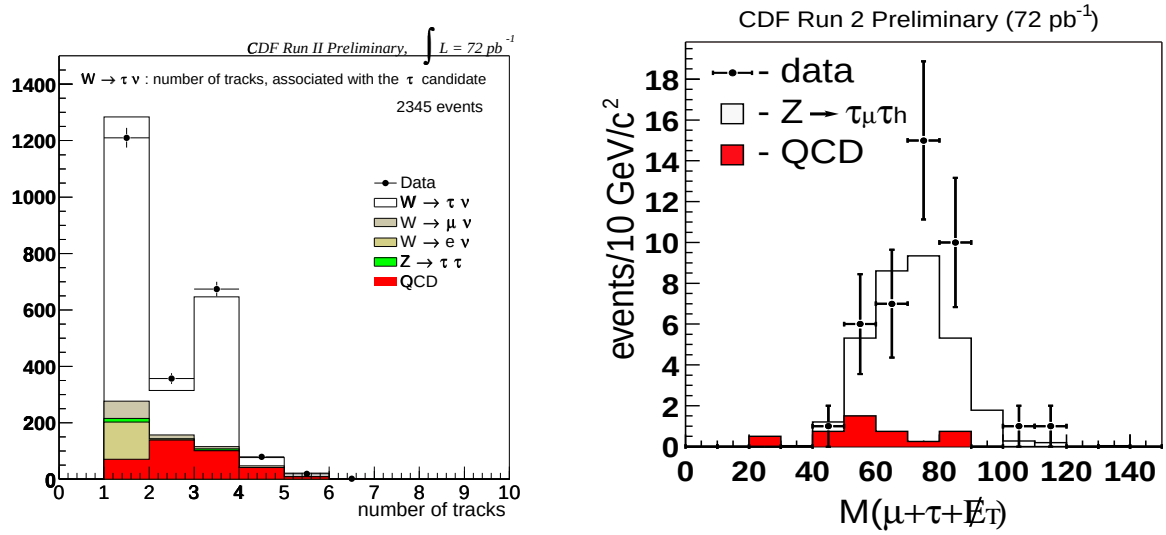

Figure 3: *Left:* Charged Track multiplicity distribution for $W \to \tau\nu$ candidates. *Right* Invariant mass of $(\tau + \mu + \not{E}_T)$ for $Z \to \tau\tau$ candidates: $\tau_{\rm had}$ track multiplicity is 1 or 3 and $\tau_{\rm had}$ and μ candidates have opposite charge.

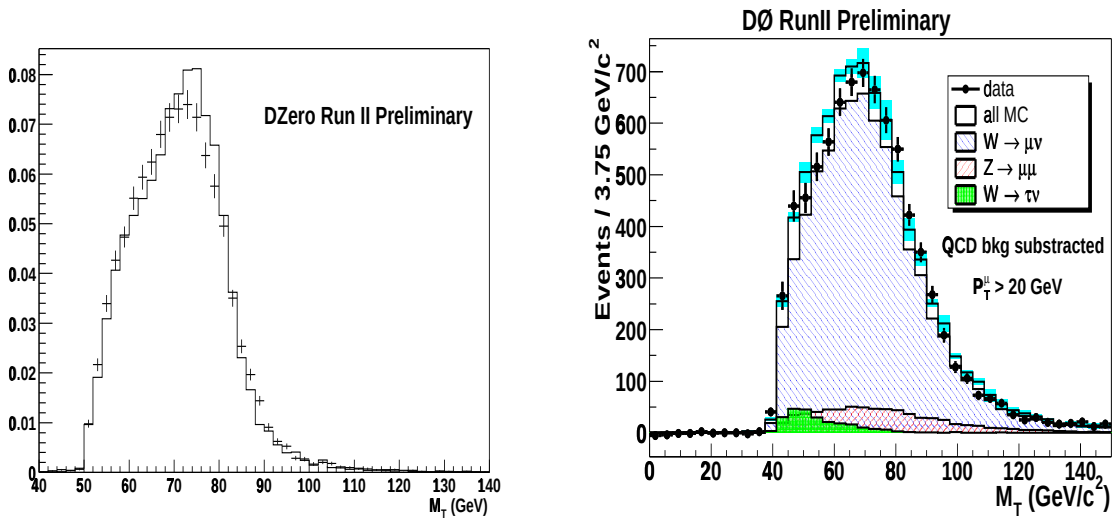

Figure 4: *Left:* Transverse mass distribution for $W \to e\nu$ events collected by DØ ($\int \mathcal{L}dt = 41.6pb^{-1}$).*Right:* Transverse mass distribution for $W \to \mu\nu$ events collected by DØ ($\int \mathcal{L}dt = 17.3pb^{-1}$).

Table 1: *W* boson yield in the different leptonic decay channels with the measured $\sigma \times BR(W \to \ell\nu)$. Quoted uncertainties are respectively for statistics, systematics and luminosity.

Channel	Events	Bkg. (%)	$\sigma \times BR(W \to \ell\nu)$ (nb)	$\int \mathcal{L}dt(\mathrm{pb}^{-1})$	
$e\nu_e(\lvert\eta\rvert < 1)$	38625	6	$2.78 \pm 0.01 \pm 0.06 \pm 0.17$	72	
$e\nu_e(1.1\lvert\eta\rvert < 2.8)$	10461	6	$2.87 \pm 0.03 \pm 0.18 \pm 0.17$	64	
$\mu\nu_\mu$	21599	11	$2.78 \pm 0.02 \pm 0.06 \pm 0.17$	72	CDF
$\tau\nu_\tau$	2345	26	$2.62 \pm 0.07 \pm 0.21 \pm 0.16$	72	
$e\nu_e$, $\mu\nu_\mu$	combined		$2.777 \pm 0.010 \pm 0.052 \pm 0.167$	72	
$e\nu_e$	27370	n.p.	$2.84 \pm 0.02 \pm 0.13 \pm 0.28$	42	DØ
$\mu\nu_\mu$	8305	12	$3.23 \pm 0.13 \pm 0.10 \pm 0.32$	17	

1.2 Measuring *Z* Cross Section

The signature of $Z/\gamma^\star \to \ell\ell$ events are two high-P_T isolated leptons. At CDF for the dielectron channel, $Z/\gamma^\star \to ee$ events are selected requiring at least two central high-P_T isolated electrons with opposite charge (CC events) or at least one central high-P_T isolated electron and one high-E_T electromagnetic cluster in the plug calorimeters ($1.1 < |\eta| < 2.8$) without a track matching requirement (CP events). The invariant mass is required to be between 66 and 116 GeV/c^2. The number of candidates events is 4242 with an estimated background contamination of 10 ± 5 events. The invariant mass of the dielectron pair is reported in Fig.5 *left*.

$Z/\gamma^\star \to \mu\mu$ candidates are selected requiring one isolated central muon with $P_T > 20$ GeV/c and a second isolated high-P_T track passing minimum ionizing energy requirements.

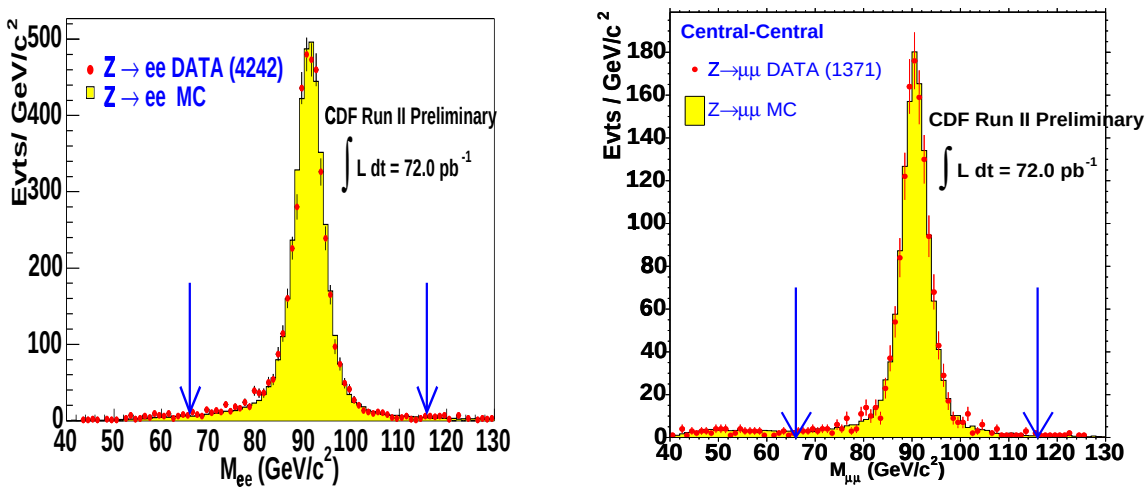

Figure 5: *Left:* Dielectron invariant mass for $Z \to ee$ events collected by the CDF experiment. *Right:* Dimuon invariant mass for $Z \to \mu\mu$ events collected by the CDF experiment.

$Z \to \tau^+\tau^-$ candidates are selected requiring one τ identified from its electronic decay and the other one from its hadronic decay. To increase the purity we require $M_T(e, \not{E}_T) \leq 25$ GeV/c^2 and $P_T(e, \not{E}_T) \geq 25$ GeV/c. The invariant mass is shown in Fig.6.

Similarly, DØ selects $Z \to ee$ and $Z \to \mu\mu$ candidates. The invariant mass distributions are shown respectively in Fig.7 (*left* and *right*).

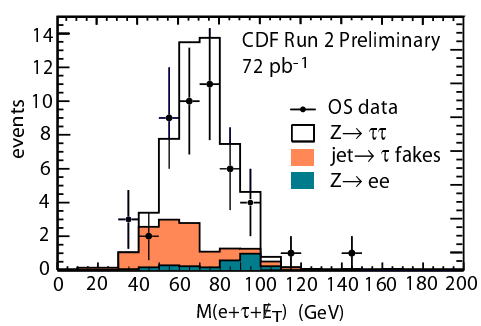

Figure 6: Invariant Mass distribution of $Z \to \tau\tau$ candidates.

$Z/\gamma^\star \to \ell\ell$ candidates yield in the different decay channels and the measured production cross section times branching fraction are shown in Table 2. They are in agreement with the predicted *Z* boson production (NNLO) 250.5 ± 3.8 pb [1] . The measured values of $\sigma \times BR(Z \to \ell\ell)$ and $\sigma \times BR(W \to \ell\nu_\ell)$ are shown in Fig.8 with the values measured by previous experiments at different values of the $p\bar{p}$ center of mass energies.

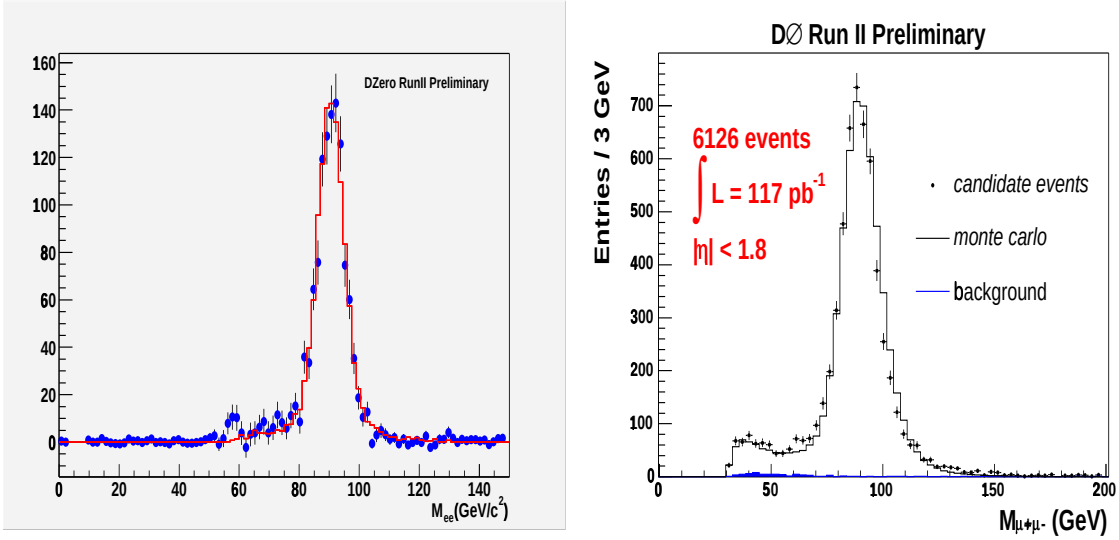

Figure 7: *Left:* Invariant mass distribution for $Z \to ee$ events collected by DØ .*Right:* Invariant mass distribution for $Z \to \mu\nu$ events collected by DØ .

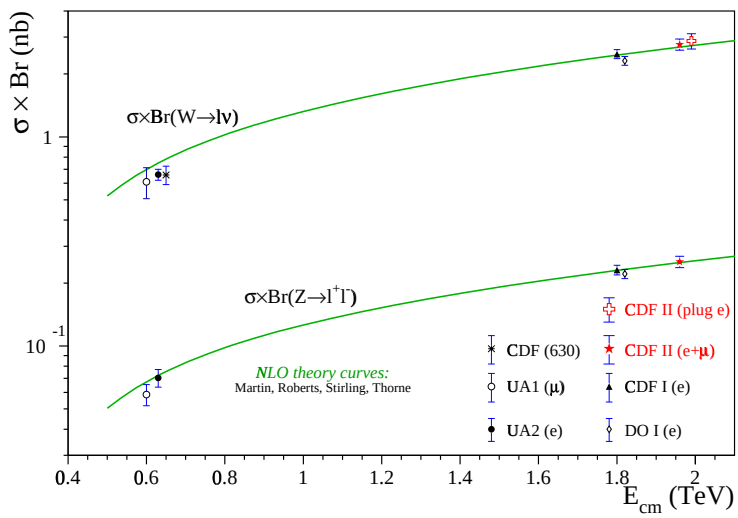

Figure 8: Measured values of $\sigma(p\bar{p} \to W/Z) \times BF(\ell\nu/\ell\ell)$ measured at the $p\bar{p}$ colliders as a function of $\sqrt{s}$. Most recent Tevatron RunII results are included.

Table 2: Z boson yield in the different leptonic decay channels with the measured $\sigma \times BR(Z \to \ell\ell)$. Quoted uncertainties are respectively for statistics, systematics and luminosity.

Channel	Events	Bkg. (%)	$\sigma \times BR(Z \to \ell^+\ell^-)$ (nb)	$\int \mathcal{L}dt(\mathrm{pb}^{-1})$	
e^+e^-	4242	0.6	$255 \pm 4 \pm 5 \pm 15$	72	
$\mu^+\mu^-$	1372	0.9	$249 \pm 9^{+7}_{-6} \pm 15$	72	
e^+e^-, $\mu^+\mu^-$	combined		$254.3 \pm 3.3 \pm 4.3 \pm 15.2$	72	
e^+e^-	1139	2.3	$275 \pm 9 \pm 9 \pm 28$	42	CDF
$\mu^+\mu^-$	6126	1.1	$262 \pm 5 \pm 9 \pm 26$	117	DØ

1.3 Indirect measurement of W width

After evaluating the ratio $R = \sigma \times BF(W \to \ell\nu_\ell)/\sigma \times BF(Z \to \ell\ell)$ it is possibile to measure indirectly the W total width. In fact:

$$\begin{aligned} R &= \frac{\sigma \times BF(W \to \ell\nu_\ell)}{\sigma \times BF(Z \to \ell\ell)} \\ &= \frac{\sigma(p\bar{p} \to W)}{\sigma(p\bar{p} \to Z)} \times \frac{\Gamma(Z)}{\Gamma(Z \to \ell\ell)} \times \frac{\Gamma(W \to \ell\nu_\ell)}{\Gamma(W)}; \end{aligned}$$

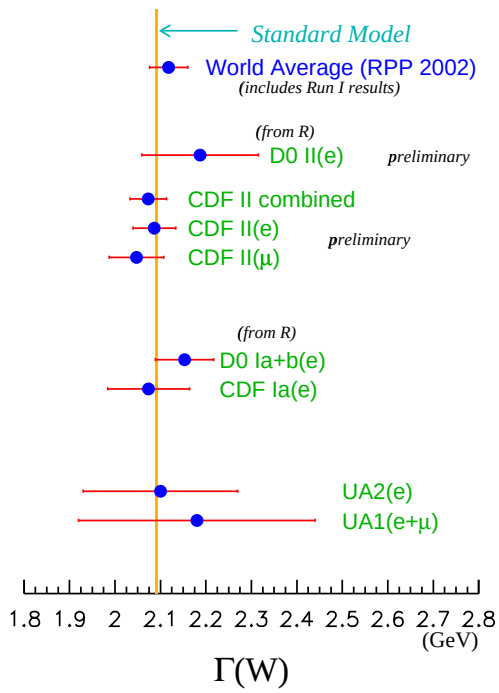

Figure 9: Indirect measurement of W boson width. Both CDF and DØ preliminary RunII results are shown.

The ratios $\sigma(p\bar{p} \to W)/\sigma(p\bar{p} \to Z)$ and the partial leptonic *W* boson width $\Gamma(W \to \ell\nu_\ell)$ are respectively taken from theoretical calculation[6] and [7]; the ratio $\Gamma(Z)/\Gamma(Z \to \ell\ell)$ comes from the LEP experiments[7]. The measured values from both CDF and DØ experiments are shown in Fig.9 together with previous results and Standard Model predictions. As mentioned in Sec.3 the direct $\Gamma(W)$ measurement will be performed together with the *W* boson mass measurement.

1.4 Checking Lepton Universality

Using double ratios like U_μ and U_τ respectively:

$$\begin{aligned} U_{\mu(\tau)} &= \frac{R_{\mu(\tau)}}{R_e} \\ &= \frac{\sigma \times BF(W \to \mu\nu_\mu(W \to \tau\nu_\tau))/\sigma \times BF(Z \to \mu\mu(Z \to \tau\tau))}{\sigma \times BF(W \to e\nu_e)/\sigma \times BF(Z \to ee)} \\ &= \frac{\Gamma(W \to \mu\nu_\mu(W \to \tau\nu_\tau))}{W \to e\nu_e} \\ &= \frac{g^2_{W\mu(W\tau)}}{g^2_{We}} \end{aligned}$$

it is possible to check lepton universality. CDF measures $g_\mu/g_e = 1.011 \pm 0.018$. g_τ/ge together with other measurements, world average, SM expectations is shown in Fig.10.

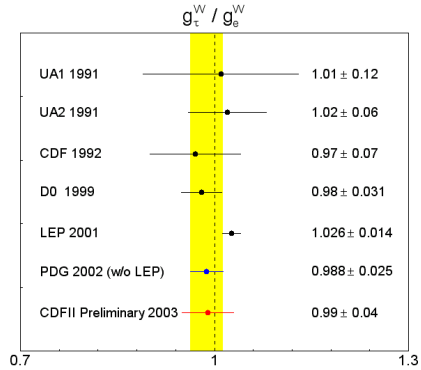

Figure 10: Lepton universality g_τ/g_e ratio measured by CDF with SM expectations and several other measurements.

2 Precision Electroweak Measurements

2.1 Dielectron Forward Backward Asymmetry

With dielectron pairs created by Drell-Yan process it is possible to measure the Forward Backward asymmetry (A_{FB}). A_{FB} is a probe of the strength of the vector and axial-vector couplings. What is unique at the Tevatron experiments is the possibility to probe A_{FB} not only at the Z-pole but up to a range of M_{ee} of 600 GeV/c^2 as shown in Fig.11.

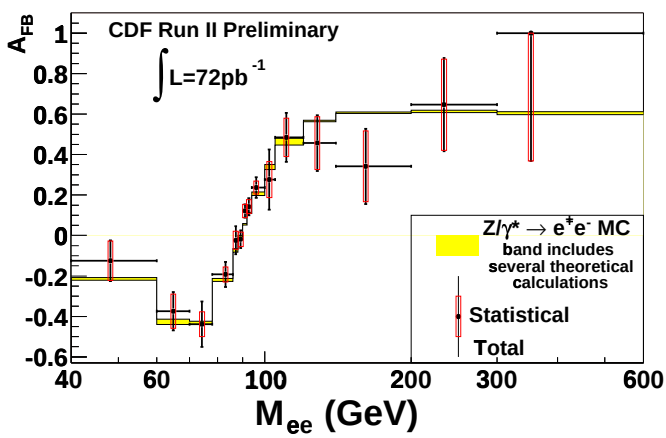

Figure 11: Forward Backward asymmetry for dielectron pairs compared with theoretical predictions.

2.2 W/Z + γ production

Electroweak interaction allow bosons to self-interact due to the non-abelian structure of the gauge symmetry through the triple gauge couplings. Direct production of $W\gamma$ and $Z\gamma$ is searched. These processes probe anomalous couplings increasing therefore the sensitivity to physics beyond the Standard Model. $W\gamma$ and $Z\gamma$ events are searched starting from the samples described in previous section (electron and muon channel). The presence of anomalous gauge coupling would modify the photon E_T spectrum boosting it at higher E_T[4]. At CDF, a high energy photon with $E_T > 7$ GeV is required with $\Delta R_{(\gamma,\ell)} \geq 0.7$. The E_T distribution for the photon in $W\gamma$ candidates is shown in Fig.12 The *cluster transverse mass* distribution for $W\gamma$ candidates , defined as the invariant mass of the three body system (lepton, neutrino and photon) reaches a minimum with respect of the longitudinal component of the neutrino momentum, is shown in Fig:12[2)]. The photon E_T distribution and the three-body invariant mass for $Z\gamma$ events is shown in Fig.13.

The DØ experiment performed a measurement of $W\gamma$ production cross section. The E_T distribution for the

[2)] The cluster transvere mass is defined as $M^2_{CT}(l\gamma, \not{E}_T) = [(M^2_{l\gamma} + |P_{T\gamma} + P_{T,l}|^2)^{1/2} + \not{E}_T]^2 - |P_{T\gamma} + P_{Tl} + \not{E}_T|^2$

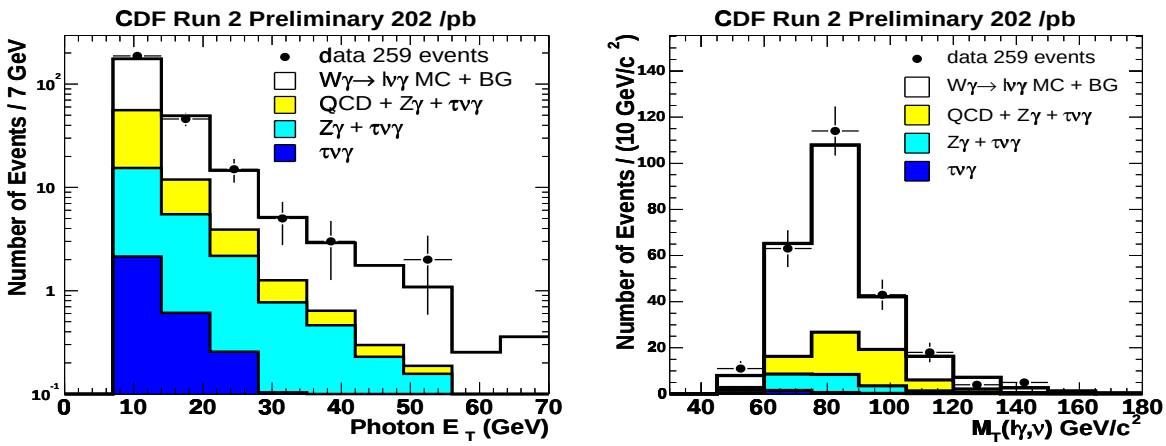

Figure 12: *Left:*Photon E_T distribution of the $W-\gamma$ events on a logarithmic scale for the data, MC signal and background processes contamination. *Right:* Cluster Transverse Mass for $W-\gamma$ candidates with MC signal and background contributions.

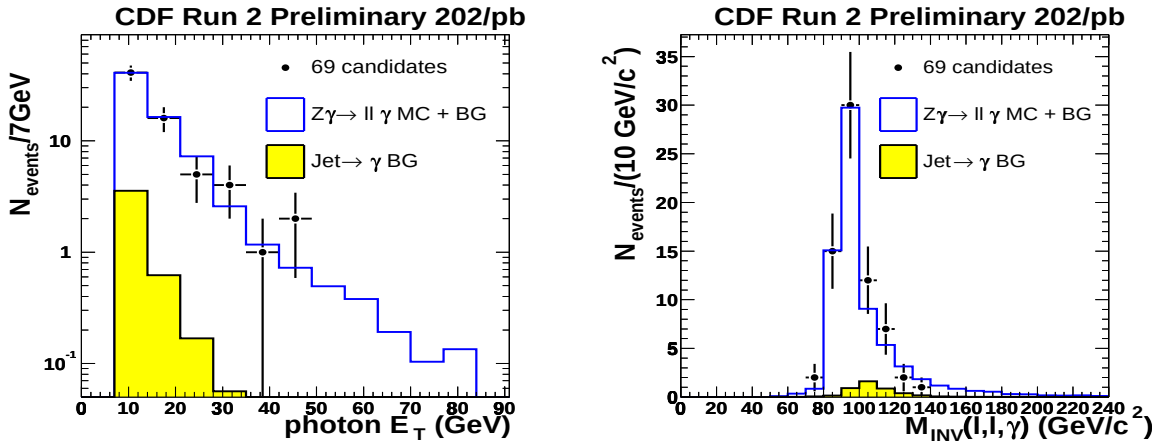

Figure 13: *Left:*Photon E_T distribution of the $Z-\gamma$ events on a logarithmic scale for the data, MC signal and background processes contamination. *Right:* Cluster Transverse Mass for $Z-\gamma$ candidates with MC signal and background contributions.

Table 3: $W\gamma$ direct production yield in the e and μ decay channel. Quoted uncertainties are respectively for statistics, systematics and luminosity.

Channel	Events	Bkg.	$\sigma \times BR(W\gamma \to \ell\nu\gamma)$ (pb)	$\int \mathcal{L}dt \mathrm{pb}^{-1}$	
e	131	$34.03 \pm 0.26 \pm 8.47$	$21.9 \pm 2.6 \pm 2.2 \pm 1.3$	202	
μ	128	$41.12 \pm 0.39 \pm 6.52$	$20.0 \pm 2.9 \pm 1.8 \pm 1.2$	202	CDF
combined				$19.3 \pm 4.2 \pm 5.2 \pm 1.2$	
e	146	87.1 ± 7.5	$17.8 \pm 3.6 \pm 5.3 \pm 1.1$	162	DØ
μ	77	37 ± 10	$22.0 \pm 4.2 \pm 7.3 \pm 1.4$	82	

Table 4: Direct $Z\gamma$ production yield in the e and μ. Quoted uncertainties are respectively for statistics, systematics and luminosity.

Channel	Events	Signal	Signal+Bkg (%)	$\int \mathcal{L}dt$	$\sigma \times BR(Z\gamma \to \ell^-\ell^+\gamma)$ (pb)
e CC	23	19.95 ± 1.11	21.61 ± 1.20	201.8	$5.8 \pm 1.2 \pm 0.3 \pm 0.3$
e CP	11	$11.97 \pm 0.83 \pm 1.87$	13.10 ± 0.91	167.8	$4.5 \pm 1.3 \pm 0.4 \pm 0.3$
μ	35	33.84 ± 1.84	35.74 ± 1.92	191.6	$5.3 \pm 0.9 \pm 0.3 \pm 0.3$
combined	69				$5.3 \pm 0.6 \pm 0.3 \pm 0.3$

photon and the cluster transverse mass distributions are shown in Fig.14.

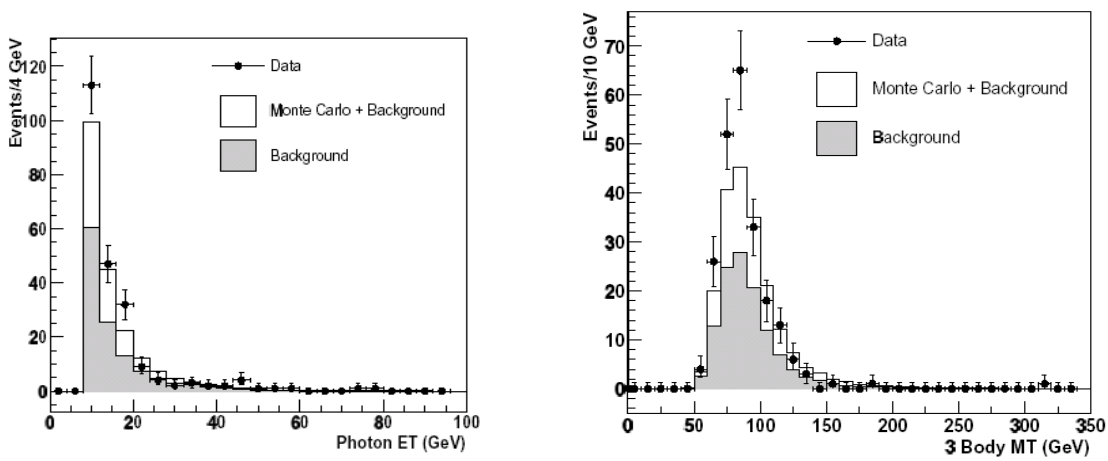

Figure 14: *Left:*Photon E_T distribution of the $W-\gamma$ events on a for data, MC signal and background processes contamination. *Right:* Cluster Transverse Mass for $W-\gamma$ candidates with MC signal and background contributions.

The number of $W\gamma$ and $Z\gamma$ candidate events are reported respectively in Tab.3 and Tab.4. The predicted production cross sections are respectively 18.7 ± 1.3 pb and 5.4 ± 0.4 pb.

2.3 WW diboson production

CDF has measured also the WW diboson production in the dilepton channel in two complementary ways. One analysis (*dilepton*) has been optimized to high purity selecting events with two isolated leptons, large missing energy and no jets. The second approach (*lepton+track*) applies looser selection cuts on the second lepton increasing the acceptance for the signal and of the background. The numbers of observed and expected events, the S/B ratio and the measured cross section are shown in Tab:5. In Fig.15(left), the distribution of *di-lepton* events in the $\Delta\phi$ between the transverse missing energy and the closest lepton is shown for candidates and expected signal(MC). In Fig.15 (right), the dilepton invariant mass of the *lepton+track* candidates is shown, together with the various background contributions.

Table 5: *W W* candidate yield and measured cross section measured by CDF with $202pb^{-1}$ of data. Predicted SM cross section is reported.

Method	Exp. Events	Observed	S/B	$\sigma(p\bar{p} \to WW)$ (pb)
di-lepton	$16.1 \pm 1.6\text{stat} + \text{syst}$	17	2.3	$14.3^{+5.5}_{-4.9}\text{stat} \pm 1.6\text{syst} \pm 0.9\text{lum}$
lepton+track	$31.5 \pm 1.0\text{stat}$	39	1.1	$19.4 \pm 5.1\text{stat} \pm 3.5\text{syst} \pm 1.2\text{lum}$
Theory				12.5 ± 0.8

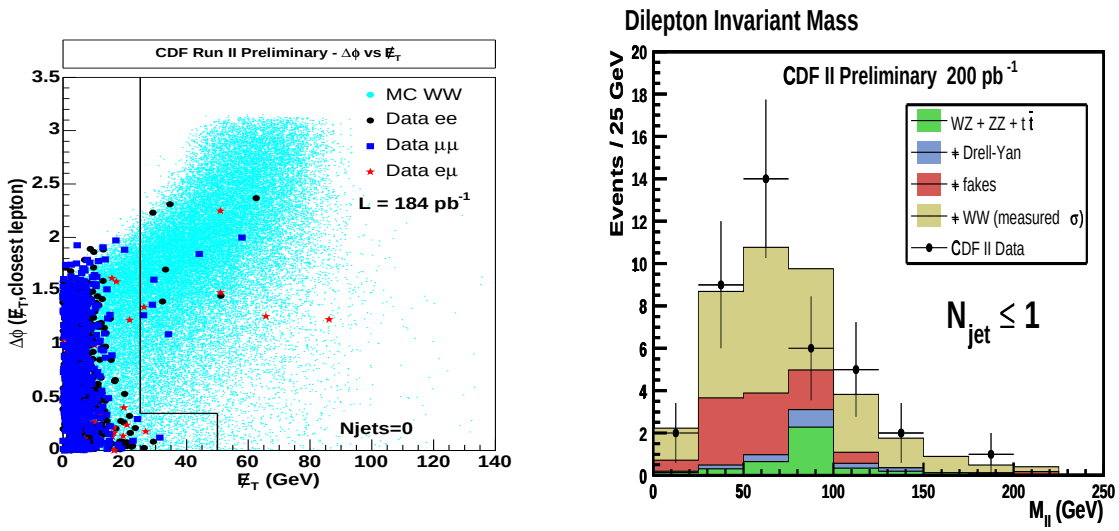

Figure 15: *Left:* WW candidate events (*dilepton* analysis) distribution in the $\Delta\phi(\not{E}_T, \ell)$. *Right:* WW candidate events (*lepton+track* analysis) dilepton invaraint mass distribution with background contribution.

3 Towards a W mass measurement

The W boson mass is a fundamental paremeter for the Standard Model. Combining it with the *top* mass will result in a larger constraint on the Standard Model Higgs mass. The CDF and DØ RunI Tevatron combined measurement was $M_W = 80.456 \pm 0.059$ GeV/c^2. The goal of this first phase of RunII is to reach an uncertainty of about 40 MeV/c^2. To reach that goal an excellent knowledge of the detector is required. CDF method for measuring the W mass consists in using different Monte Carlo at different W mass values (called signal templates) together with expected background distributions to fit the candidates transverse mass distributions. The principal systematics are coming from the lepton momentum scale and missing transverse energy resolution. In Fig.16 (*left*) the dimuon invariant mass distribution for $Z \to \mu\mu$ canddidates events is compared with Monte Carlo generated with RESBOS[8]. Together with the lepton energy scale extracted with the dimuon invariant mass from $J/\psi \to \mu\mu$ candidates it will be possible to check the linearity with energy of the lepton momentum scale. In Fig.16 (*Right*), the W transverse mass distribution for the $W \to \mu\nu$ candidate events is shown for the data collected for the 200 pb^{-1}. CDF expects to give for summer 2004 a preliminary measurement of both W boson mass and its width $\Gamma(W)$.

Conclusions

Electroweak measurements have been performed using *physics quality* data collected by the CDF and DØ experiment. *W* and *Z* production cross section values, dielectron forward backward asymmetry and diboson production have been established showing a substantial agreement with Standard Model predictions. For this latter electroweak measurement, the integrated luminosity of data analyzed amounts approximately to twice the one that was collected in RunI allowing a smaller statistical uncertainty. We are expecting significant improvement also reducing the systematic uncertainties increasing the control samples. Both CDF and DØ experiments are quickly stepping towards precision electroweak measurements.

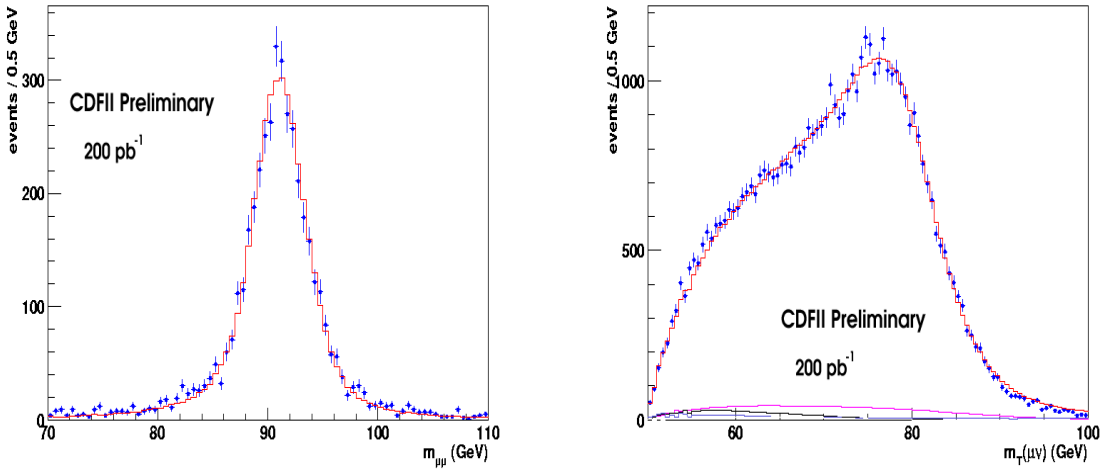

Figure 16: *Left:* $Z \to \mu\mu$ dimuon invariant mass for data compared to MonteCarlo ($t\bar{t}$ Resbos). *Right:* $W \to \mu\nu$ transverse mass for candidate candidate events.

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