

## Electroweak Physics at the Tevatron

P. CATASTINI<sup>(1)</sup>, ON BEHALF OF THE CDF AND D0 COLLABORATIONS

<sup>(1)</sup> *Fermilab, Batavia, IL, USA*

**Summary.** — We discuss recent results in the Electroweak sector at the Tevatron. We will focus on latest results in the measurement of diboson production cross sections and limits on anomalous triple gauge coupling. At first, we will consider purely leptonic decays. Then, we will describe the recent observations of diboson processes with jets in the final state.

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### 1. – Introduction

The study of diboson production represents a relevant portion of the current Electroweak Physics program at the Tevatron. Dibosons are of great interest because they provide unique opportunities to test the Standard Model at the TeV scale and they are a relevant probe to new physics through deviations of Triple Gauge Couplings (TGCs) from Standard Model (SM) predictions. Moreover, each combination of associated production of  $W$  and  $Z$  boson decaying in any final state has a counterpart search channel for the Higgs boson at the Tevatron. Worth mentioning:  $WW + WZ \rightarrow l\nu + jj$  that shares the same topology of  $WH \rightarrow l\nu + b\bar{b}$ , the golden process for low mass Higgs searches;  $WW \rightarrow l\nu + l\nu$  that is the dominant background for  $H \rightarrow WW$ , the golden process for high mass Higgs searches.

As a consequence, establishing diboson production, at first in their leptonic decays and more recently with jets in the final state, represented an important milestone for the development and the assesment of techniques used in Higgs boson searches at the Tevatron. In this paper we examine diboson production in 1.96 TeV  $p\bar{p}$  collision using the CDF and D0 detectors, compare this production to Standard Model predictions, and set limits on the strength of some anomalous couplings. Signals of the  $WW$ ,  $WZ$ ,  $ZZ$  are searched through their leptonic and semi-leptonic final states.

### 2. – $WW \rightarrow l\nu + l\nu$

The process  $WW \rightarrow l\nu + l\nu$  is interesting for several reasons. Among them, we might mention the measurement of  $WW$  cross section to test the SM prediction and the search

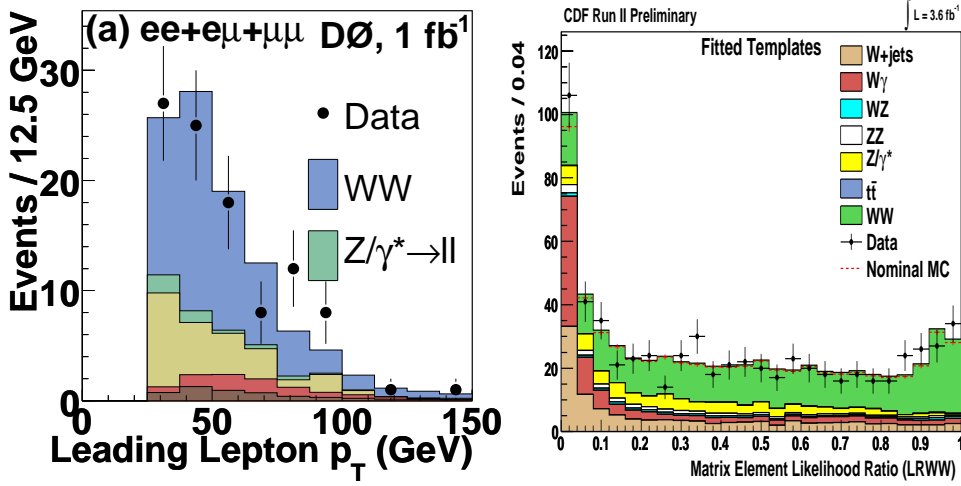


Fig. 1. – (left) Leading lepton  $p_T$  distribution in  $WW \rightarrow l^+l^-\nu\bar{\nu}$  candidate events at D0. (right) Likelihood ratio used to extract the  $WW \rightarrow l^+l^-\nu\bar{\nu}$  signal at CDF.

for anomalous trilinear gauge couplings. In addition, it represents the main background of the process  $H \rightarrow WW$ , the golden process for high mass Higgs boson searches at the Tevatron.

D0, using a data sample of  $1 \text{ fb}^{-1}$ , studied the process  $WW \rightarrow l^+l^-\nu\bar{\nu}$  and measured the  $WW$  cross section to be  $\sigma(p\bar{p} \rightarrow WW) = 11.5 \pm 2.1(\text{stat} + \text{syst}) \pm 0.7(\text{lumi})$  pb, in agreement with the SM expectation of  $12.0 \pm 0.7$  pb. In addition, D0 imposed also limits on TGC [1]

CDF measured the  $WW$  production cross section in the two charged lepton ( $e$  or  $\mu$ ) and two neutrino final state using an integrated luminosity of  $3.6 \text{ fb}^{-1}$  [2]. The  $WW$  signal is separated from backgrounds using matrix element based likelihood ratios. The  $WW$  cross section is extracted using a binned maximum likelihood method which best fits  $LR_{WW}$  signal and background shapes to data (see fig. 1, right). The measured  $WW$  cross section is  $12.1 \pm 0.9(\text{stat.})^{+1.6}_{-1.4}(\text{syst.})$  pb. It is in good agreement with the Standard Model prediction and it represents the most precise measurement up to date. An updated version of this analysis sets limits on aTGC [3].

### 3. – $ZZ$

The SM prediction for the total  $ZZ$  production cross section in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.9 \text{ TeV}$  is  $\sigma(ZZ) = 1.4 \pm 0.1$  pb. Therefore,  $ZZ$  has the smallest SM diboson production cross section. The requirement of leptonic  $Z$  boson decays provides a clear signature with extremely low background; on the other hand, it reduces the  $ZZ$  observable cross section, making its measurement rather challenging.

Using  $1.7 \text{ fb}^{-1}$  of data, D0 observed, for the first time at a hadron collider,  $ZZ \rightarrow l^+l^-l'^+l'^-$  ( $l, l' = e$  or  $\mu$ ) production with a significance of 5.3 standard deviations, Fig.2 (left). D0 also combined this channel with  $ZZ \rightarrow l^+l^-\nu\bar{\nu}$ , yielding a significance of 5.7 standard deviations and measured  $\sigma(ZZ) = 1.60 \pm 0.63(\text{stat})^{+0.16}_{-0.17}(\text{syst})$  pb [4].

Recently, CDF re-observed  $ZZ \rightarrow l^+l^-l'^+l'^-$  with a significance of 5.7 standard devia-

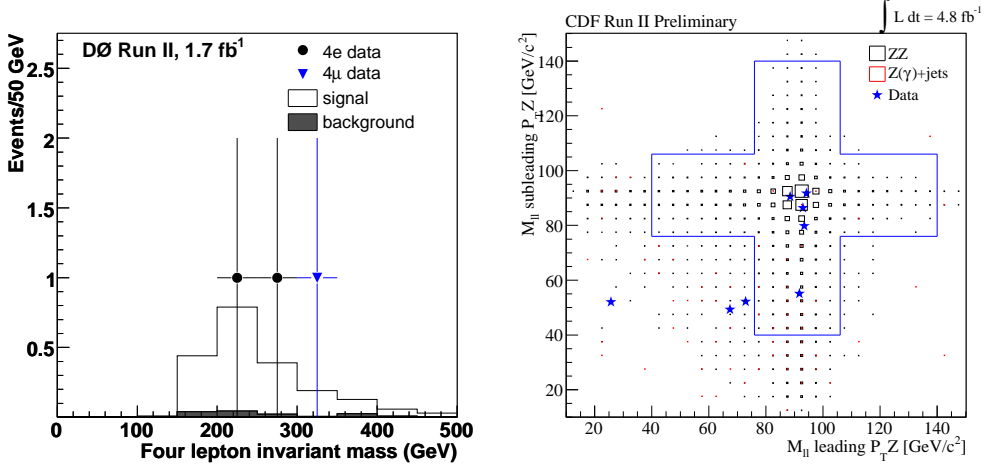


Fig. 2. – (left) Four lepton invariant mass distribution at D0. (right)  $M_{jj}$  of the leading  $P_T$  Z candidate versus the subleading one at CDF.

tions, using  $4.8 \text{ fb}^{-1}$  of data, Fig.2 (right). CDF measured  $\sigma(ZZ) = 1.56^{+0.80}_{-0.63}(\text{stat}) \pm 0.25(\text{syst}) \text{ pb}$ , [5]. D0 and CDF measurements are in agreement with the SM prediction.

#### 4. – Combined limits on anomalous trilinear gauge couplings

D0 combined different diboson production and decay channels to set limits on  $WW\gamma$  and  $WWZ$  trilinear gauge couplings [6]. Four channels were considered:  $WW + WZ \rightarrow l\nu + jj$ ,  $WW \rightarrow l^+l^-\nu\bar{\nu}$ ,  $WZ \rightarrow l\nu + l^+l^-$  and  $W\gamma \rightarrow l\nu\gamma$ .

The corresponding results, shown in Fig.3, set the most stringent limits to date on  $W$  magnetic dipole  $\mu_W$  and quadrupole  $q_W$ .

#### 5. – $VV \rightarrow \cancel{E}_T + jj$

The  $VV$  ( $VV = WW, WZ, ZZ$ ) production and decay into hadronic final states are topologically similar to the  $VH$  production and decay which is the most promising Higgs discovery channel at low Higgs mass. Also, study of the diboson production is sensitive to extra gauge couplings not present in the Standard Model.

CDF observed diboson production with jets in the final states for the first time at a hadron collider using a sample of events with large  $\cancel{E}_T$  ( $> 60 \text{ GeV}$ ) and two jets with  $E_T$  above  $25 \text{ GeV}$  [7]. Due to limited energy resolution it is impossible to distinguish between  $WW$ ,  $WZ$  and  $ZZ$  events so what CDF measured was a sum of these processes. No requirement on the number of leptons in the event was applied, therefore the analysis was also sensitive to lepton decays of the gauge bosons. The multijet QCD contribution, which is large in this channel, is heavily suppressed through novel algorithms related to  $\cancel{E}_T$  significance. Diboson signal was extracted from the background using the invariant mass distribution of the two selected jets (Fig. 4). The extraction of the signal did not use the theoretical calculation of the  $V$ +jets integral cross section and its invariant mass shape was cross checked with  $\gamma$ +jets events from the data, hence considerably reducing the systematic uncertainty on the shape of this main background. The final dijet mass

Results respecting $SU(2)_L \otimes U(1)_Y$ symmetry			
Parameter	Minimum	68% C.L.	95% C.L.
$\Delta\kappa_\gamma$	0.07	$[-0.13, 0.23]$	$[-0.29, 0.38]$
$\Delta g_1^Z$	0.05	$[-0.01, 0.11]$	$[-0.07, 0.16]$
$\lambda$	0.00	$[-0.04, 0.05]$	$[-0.08, 0.08]$
$\mu_W$	2.02	$[1.93, 2.10]$	$[1.86, 2.16]$
$q_W$	-1.00	$[-1.09, -0.91]$	$[-1.16, -0.84]$
Results for equal-couplings			
Parameter	Minimum	68% C.L.	95% C.L.
$\Delta\kappa$	0.03	$[-0.04, 0.11]$	$[-0.11, 0.18]$
$\lambda$	0.00	$[-0.05, 0.05]$	$[-0.08, 0.08]$
$\mu_W$	2.02	$[1.94, 2.09]$	$[1.88, 2.15]$
$q_W$	-1.02	$[-1.09, -0.94]$	$[-1.16, -0.87]$

Fig. 3. – Combined D0 limits on TGC.

fit was an unbinned extended maximum likelihood with Jet Energy Scale, and the slope and the normalization of the multijet background treated as nuisance parameters and allowed to float in the fit within their predetermined uncertainties. The EWK background and diboson signal normalization are also freely floating in the fit with no constraints. Using a sample of  $3.5 \text{ fb}^{-1}$  of data, CDF observed  $1516 \pm 239(\text{stat.}) \pm 144(\text{syst.})$  diboson events with a significance of  $5.3\sigma$ . The corresponding cross section was measured to be  $\sigma(p\bar{p} \rightarrow VV + X) = 18.0 \pm 2.8(\text{stat.}) \pm 2.4(\text{syst.}) \pm 1.1(\text{lum.}) \text{ pb}$ , in good agreement with the Standard Model predictions.

## 6. – $WV \rightarrow l \cancel{E}_T + jj$

D0 and CDF utilize similar selections to reconstruct  $WV \rightarrow l \cancel{E}_T + jj$  with  $V = W, Z$ . At first we look for an energetic lepton, electron or muon; we then require large  $\cancel{E}_T$  and at least two additional jets in the event. Moreover, both CDF and D0 further select events with higher transverse mass of the lepton- $\cancel{E}_T$  system. The main background for the process  $WV \rightarrow l \cancel{E}_T + jj$  is  $W + jets$  with much less, but not negligible, contributions from  $t\bar{t}$ , single  $t$ ,  $Z + jets$  and multijet QCD background.

D0 reported the first evidence of  $WW + WZ$  production in lepton+jets final states with a statistical significance of  $4.4 \sigma$  using  $1.1 \text{ fb}^{-1}$  of data, [8]. Diboson signal was separated from backgrounds using a multivariate classifier to combine information from several kinematic variables. A Random Forest (RF) classifier was built using thirteen kinematic variables characterized by separation between signal and at least one of the backgrounds. The signal cross section is determined by a fit to the RF distribution by varying the diboson and the dominant background W+jet templates. Other background contributions are normalized to the SM predictions. D0 measured  $\sigma(WW + WZ) = 20.2 \pm 2.5(\text{stat}) \pm 3.6(\text{syst}) \pm 1.2(\text{lumi}) \text{ pb}$  from the fit to the RF distribution, Fig.5 (left). A consistent result was found by performing a fit to the dijet invariant mass distribution as a cross check, Fig.5 (right).

CDF observed  $WW/WZ \rightarrow l + \nu jj$  production and decay. Two different approaches were

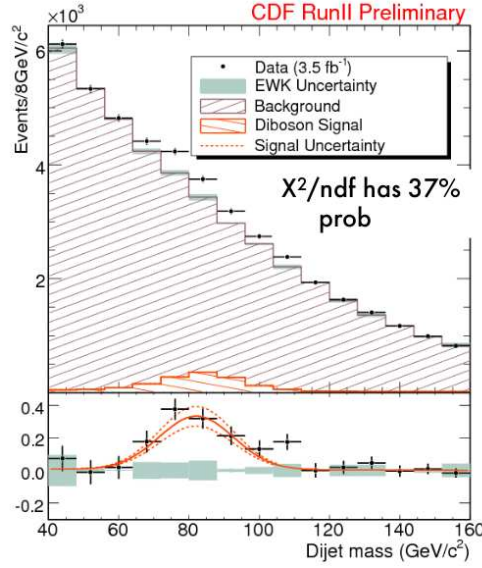


Fig. 4. –  $VV \rightarrow \ell\ell_T + \text{jets}$  search fit result at CDF.

used: the first looks for a bump in the dijet mass distribution ( $M_{jj}$ ), while the second uses Matrix Element computation (ME) to exploit additional kinematic information. In  $3.9 \text{ fb}^{-1}$ , the  $M_{jj}$  method result had a significance of  $4.6 \sigma$ , while the ME approach resulted in the first  $WW/WZ \rightarrow \ell\nu jj$  observation, with a significance of  $5.4 \sigma$ .

Both CDF analysis have been recently updated using additional data. The  $M_{jj}$  method now uses a data sample corresponding to approximately  $4.3 \text{ fb}^{-1}$  of integrated luminosity to reconstruct  $WW/WZ$  events [10]. The diboson signal is extracted from the background using a  $\chi^2$  fit of the invariant mass distribution of the two leading jet separately for the electron and muon samples. This simple method allows to search for a signal peak over a smooth background. The fit (Fig. 6 right) estimates  $1582 \pm 275(\text{stat.}) \pm 107(\text{syst.})$   $WW + WZ \rightarrow \ell\nu jj$  events, corresponding to a statistical significance of  $5.2\sigma$  ( $5.1\sigma$  expected) and measured  $\sigma(WW + WZ) = 18.1 \pm 3.3(\text{stat.}) \pm 2.5(\text{syst.})$ .

The ME approach uses  $4.6 \text{ fb}^{-1}$  and takes advantage of a multivariate technique to exploit all the information in the event [11]. Event probability densities are calculated under the signal and background hypotheses using a set of measured variables of each event (the 4-vectors of the lepton and the two jets). The probability is constructed by integrating over the parton-level differential cross-section, which includes the matrix element for the process, the parton distribution functions, and the detector resolutions. These probabilities are used to construct a discriminant variable for each event, referred to as the Event Probability Discriminant, or EPD. To quantify the  $WW+WZ$  content in the data, a binned maximum likelihood fit to the data was performed (Fig. 6 left) by fitting a linear combination of signal and background shapes of the event probability discriminant. CDF, using the ME method, measured  $\sigma(WW + WZ) = 16.5_{-3.0}^{+3.3}(\text{stat} + \text{syst}) \text{ pb}$ , with a significance of  $5.4\sigma$ . The results from the two approaches at CDF are in agreement with each other and with the Standard Model prediction.

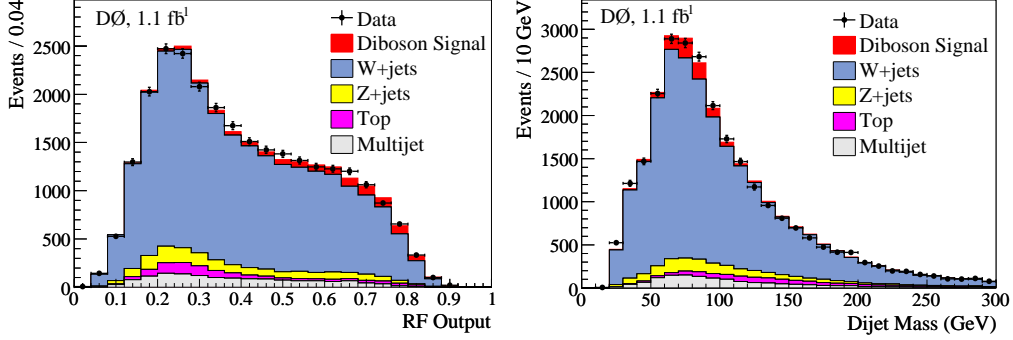


Fig. 5. –  $WV \rightarrow l \cancel{E}_T + jj$ : (left) Random Forest discriminant fit at D0. (right) dijet mass fit at D0.

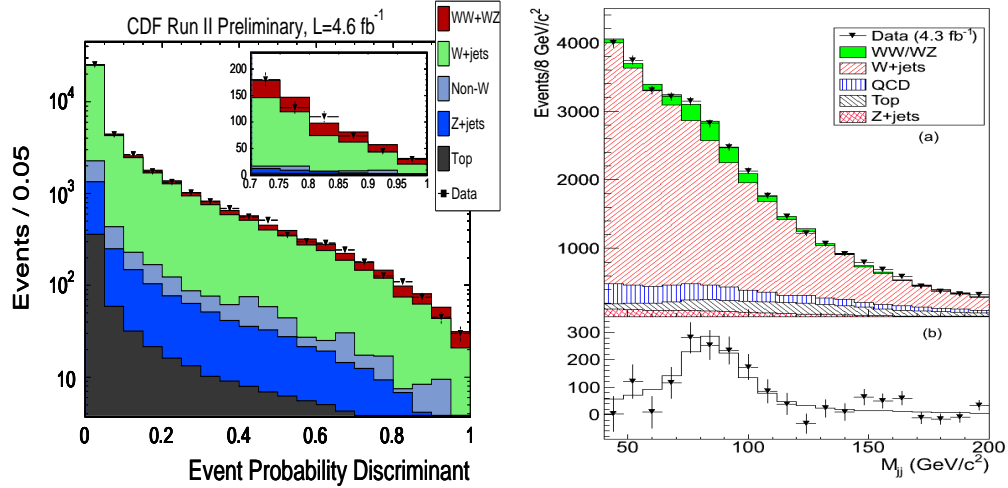


Fig. 6. –  $WV \rightarrow l \cancel{E}_T + jj$ : (left) EPD discriminant fit at CDF (right) dijet mass fit at CDF

## 7. – Conclusions

The Electroweak Physics program at the Tevatron is producing exciting results in the diboson sector. Both CDF and D0 have well established final states with leptons and jets. These processes represent important tests of the Standard Model by measuring the production cross sections and setting limits on TGC. Moreover, dibosons represent an important milestone for the development of techniques used in low mass and high mass Higgs boson searches.

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