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Electroweak Physics at the Tevatron

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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.

PACS 14.70.Fm – W bosons.
PACS 14.80.Bn – Standard-model Higgs bosons.

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: $WW + WZ \to l\nu + jj$ that shares the same topology of $WH \to l\nu + b\bar{b}$, the golden process for low mass Higgs searches; $WW \to l\nu + l\nu$ that is the dominant background for $H \to WW$, 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 assessement 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.

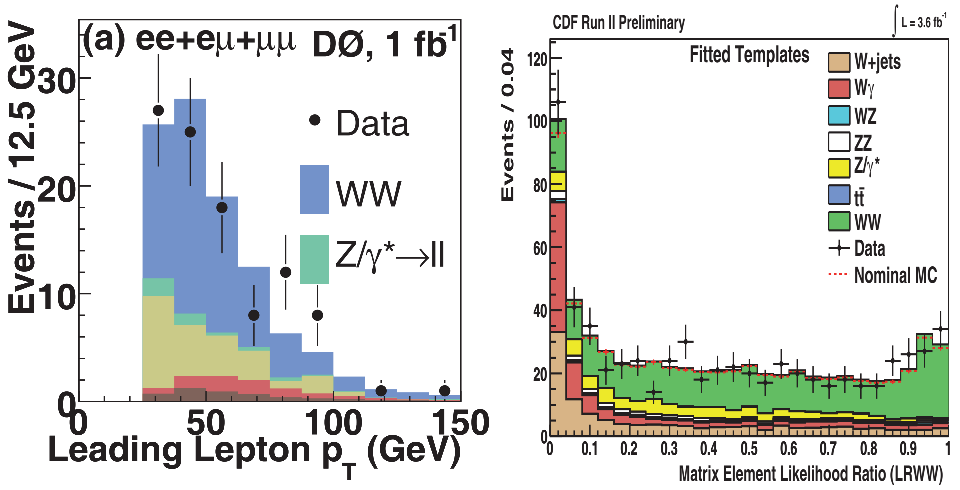

Fig. 1. – (Left) Leading lepton P_T distribution in $WW \to l^+l^-\nu\bar{\nu}$ candidate events at D0. (Right) Likelihood ratio used to extract the $WW \to l^+l^-\nu\bar{\nu}$ signal at CDF.

2. – $WW \to l\nu + l\nu$

The process $WW \to l\nu + l\nu$ is interesting for several reasons. Among them, we might mention the measurement of WW cross section to test the SM prediction and the search for anomalous trilinear gauge couplings. In addition, it represents the main background of the process $H \to WW$, the golden process for high mass Higgs boson searches at the Tevatron.

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

CDF measured the WW production cross section in the two charged lepton (e or μ) 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 $12.1 \pm 0.9(\text{stat})^{+1.6}_{-1.4}(\text{syst})\,\text{pb}$. 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 TGC [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 $\sigma(ZZ) = 1.4 \pm 0.1\,\text{pb}$. 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, $ZZ \to$

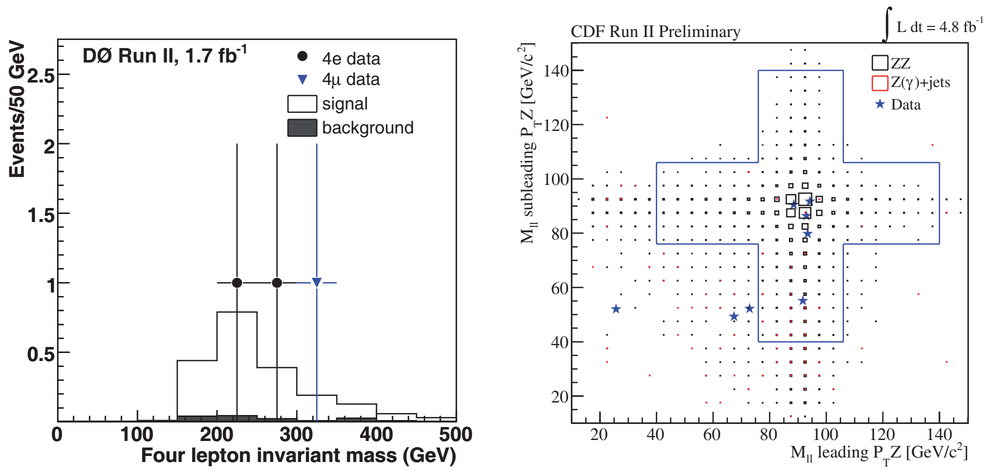

Fig. 2. – (Left) Four-lepton invariant mass distribution at D0. (Right) M_{jj} of the leading P_T Z candidate *vs.* the subleading one at CDF.

$l^+l^-l'^+l'^-$ (l, $l' = e$ or μ) production with a significance of 5.3 standard deviations, fig. 2 (left). D0 also combined this channel with $ZZ \to l^+l^-\nu\bar{\nu}$, 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 $ZZ \to l^+l^-l'^+l'^-$ with a significance of 5.7 standard deviations, using $4.8\,\text{fb}^{-1}$ of data, fig. 2 (right). CDF measured $\sigma(ZZ) = 1.56^{+0.80}_{-0.63}(\text{stat}) \pm 0.25(\text{syst})$ 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: $WW + WZ \to l\nu + jj$, $WW \to l^+l^-\nu\bar{\nu}$, $WZ \to l\nu + l^+l^-$ and $W\gamma \to l\nu\gamma$.

The corresponding results, shown in fig. 3, set the most stringent limts to date on W magnetic dipole μ_W and quadrupole q_W.

5. – $VV \to \not{E}_T + jj$

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 $\not{E}_T$ ($> 60\,\text{GeV}$) and two jets with E_T above 25 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 $\not{E}_T$ significance. Diboson signal was extracted from the background using the invariant

Results respecting $SU(2)_L \otimes U(1)_Y$ symmetry			
Parameter	Minimum	68% C.L.	95% C.L.
$\Delta\kappa_\gamma$	0.07	$[-0.13, 0.23]$	$[-0.29, 0.38]$
Δg_1^Z	0.05	$[-0.01, 0.11]$	$[-0.07, 0.16]$
λ	0.00	$[-0.04, 0.05]$	$[-0.08, 0.08]$
μ_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	$[-0.04, 0.11]$	$[-0.11, 0.18]$
λ	0.00	$[-0.05, 0.05]$	$[-0.08, 0.08]$
μ_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.

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 γ+jets events from the data, hence considerably reducing the systematic uncertainty on the shape of this main background. The final dijet mass 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

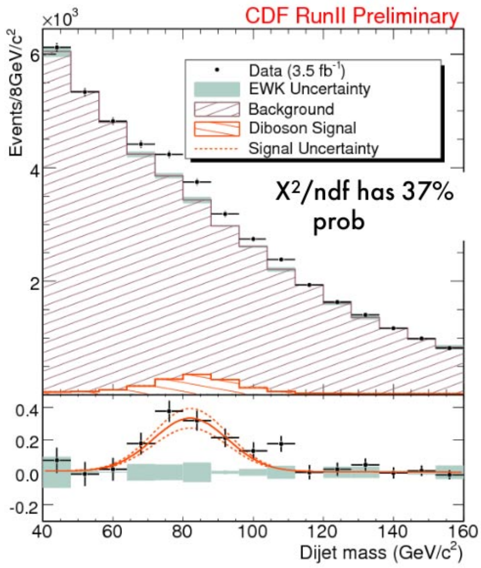

Fig. 4. – $VV \rightarrow \not{E}_T$+jets search fit result at CDF.

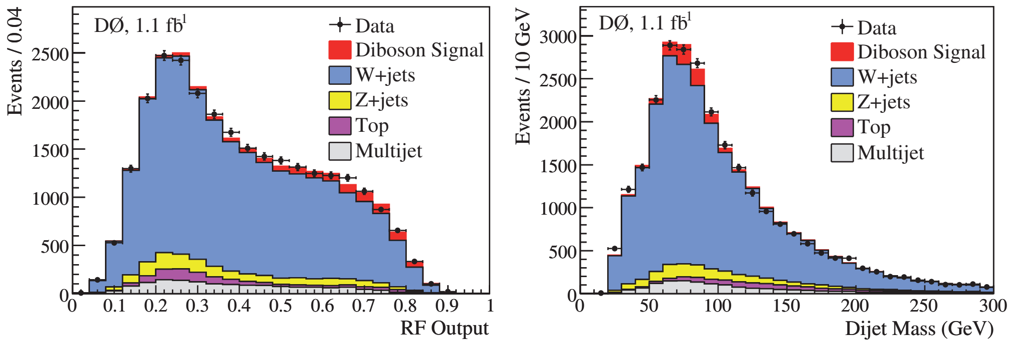

Fig. 5. – $WV \to l\,\not\!\!E_T + jj$: (left) Random Forest discriminant fit at D0. (right) dijet mass fit at D0.

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 5.3σ. The corresponding cross section was measured to be $\sigma(p\bar{p} \to VV + X) = 18.0 \pm 2.8(\text{stat}) \pm 2.4(\text{syst}) \pm 1.1(\text{lum})\,\text{pb}$, in good agreement with the Standard Model predictions.

6. – $WV \to l\,\not\!\!E_T + jj$

D0 and CDF utilize similar selections to reconstruct $WV \to l\,\not\!\!E_T + jj$ with $V = W, Z$. At first we look for an energetic lepton, electron or muon; we then require large $\not\!\!E_T$ and at least two additional jets in the event. Moreover, both CDF and D0 further select events with higher transverse mass of the lepton-$\not\!\!E_T$ system. The main background for the process $WV \to l\,\not\!\!E_T + jj$ 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 σ 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 $\sigma(WW + WZ) = 20.2 \pm 2.5(\text{stat}) \pm 3.6(\text{syst}) \pm 1.2(\text{lum})\,\text{pb}$ 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 $WW/WZ \to l + \nu jj$ production and decay [9]. Two different approaches were 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 σ, while the ME approach resulted in the first $WW/WZ \to l\nu jj$ observation, with a significance of 5.4 σ.

Both CDF analyses 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

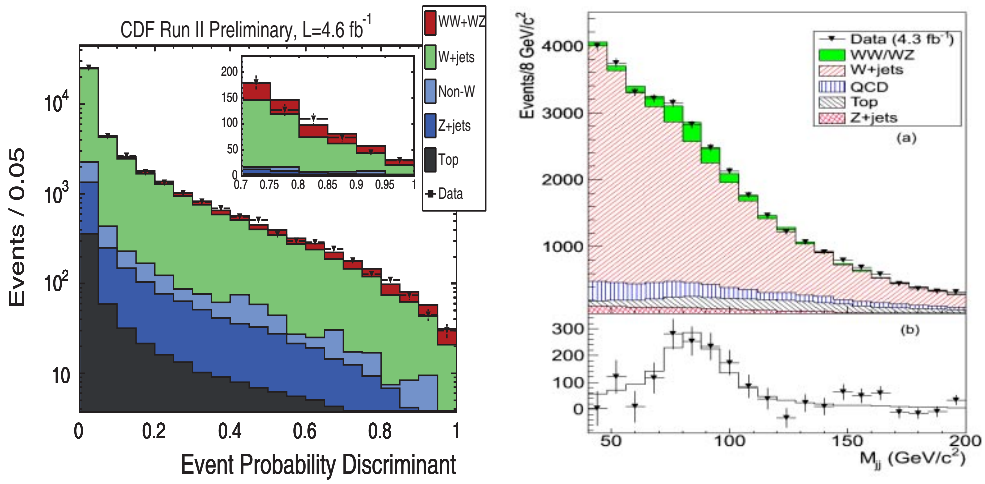

Fig. 6. – $WV \to l\,\not\!\!E_T + jj$: (left) EPD discriminant fit at CDF, (right) dijet mass fit at CDF.

the background using a χ^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 $1582 \pm 275(\text{stat}) \pm 107(\text{syst})$ $WW + WZ \to \ell\nu jj$ events, corresponding to a statistical significance of 5.2σ (5.1σ 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 $\sigma(WW + WZ) = 16.5^{+3.3}_{-3.0}(\text{stat} + \text{syst})$ pb, with a significance of 5.4σ. The results from the two approaches at CDF are in agreement with each other and with the Standard Model prediction.

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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