Diboson Physics at the Tevatron

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We present an overview of the recent results on the production of massive boson pairs in p-pbar collisions at a center-of-mass energy of 1.96 TeV, studied by the CDF and D0 experiments at the Tevatron. The measurements performed are a precise test of the Standard Model and crucial backgrounds for several different searches for new physics. In particular the good knowledge of the diboson production in decay modes involving heavy quarks improved the CDF and D0 sensitivity in Higgs boson searches. The results presented in this paper, which in some cases refer to the full Tevatron data sample, represent part of the Tevatron legacy.

1 Introduction

The precise measurement of the production of pairs of gauge bosons is a fundamental test of the Standard Model (SM) predictions in the electroweak sector and a way to search for evidence of new physics at a given energy scale. Contributions from new physics can modify the expected production rates and the observed process topology, through deviations of the trilinear gauge couplings (TGCs)[1], indicating possible exotic contributions. Measuring increasingly small cross sections is also a milestone in the exploration path: as diboson production is a major background to Higgs searches, it is important to understand it properly. After the end of the Tevatron operation, the complete collected dataset can be exploited to achieve the maximum precision measurements.

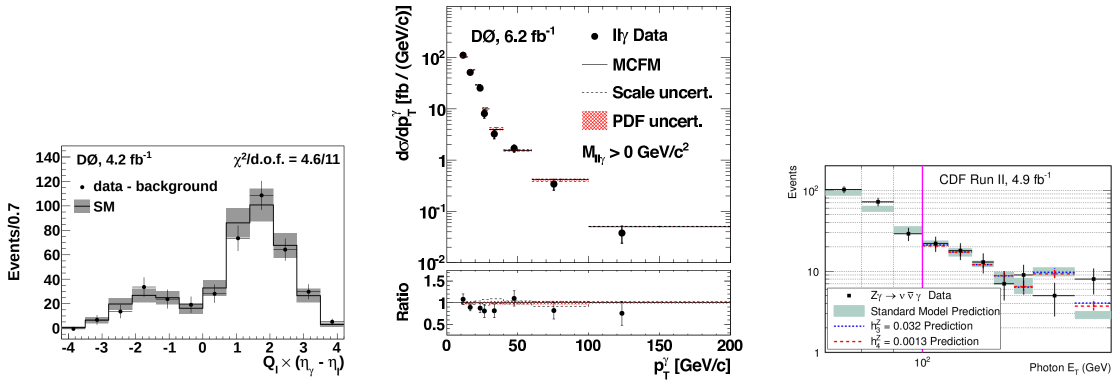
2 $W\gamma$ and $Z\gamma$

The production of $\mathbf{W}\gamma$ in hadronic collisions presents a peculiar interference between tree level diagrams at specific angles between the incoming q and the W boson in the $W\gamma$ rest-frame[a]. This structure can be experimentally observed as a dip in the charge-signed lepton-photon rapidity difference around -1/3. This is sensitive to contribution from additional diagrams due to physics beyond the SM (BSM) that can modify the observed topology. The analysis carried out by D0 exploits 4.2 fb^{-1} of data[2] and selects events based on the presence of an isolated lepton (e, μ), missing transverse energy, and a photon identified using a neural network (NN). Background contributions to this signature are at the level of 20-25%, dominated by W+jets production, which is estimated from data. Figure 1(a) shows the distribution of the signed rapidity difference for the data compared with the expectation from the simulation. The cross section times $BR(W \to \ell\nu)$ is measured in a subsample of events that have $E_T(\gamma)$ >15 GeV

[a] The production has amplitude zero in the SM around $\cos\theta$ = -1/3.

and $\Delta R(\ell\gamma)$ >0.7 and is found to be 7.6±0.4(stat.)±0.6(syst.) pb, in good agreement with the SM expectation of 7.6 ± 0.2 pb[3]. The contribution from anomalous TGC would modify the photon energy spectrum, increasing the high-E_T photon production. A binned likelihood fit to the $E_T(\gamma)$ distribution is used to extract limits on the $WW\gamma$ couplings. Assuming new physics contribution at the scale $\Lambda = 2$ TeV 95% C.L. limits on Δk_γ and λ_γ are set: $|\Delta k_\gamma| < 0.4$ and $-0.08 < \lambda_\gamma < 0.07$.

D0 exploits 6.2 fb^{-1} of data to measure **Z**γ production in the $\ell\ell\gamma$ final state[4], selecting events with two leptons (ℓ=e,μ) with an invariant mass greater than 60 GeV, and an isolated photon ($\Delta R_{\ell\gamma}$ >0.7). The observed yields in this selected sample give a measured cross section $\sigma(Z\gamma \to \ell\ell\gamma)$=1.09±0.04(stat.)±0.06(syst.) pb in agreement with the NLO SM predictions obtained using the MCFM generator[3]. From the photon p_T distribution (Figure 1(b) shows the differential cross section $d\sigma/dp_T$) for events with $p_T(\gamma)$ >30 GeV 95% C.L. limits are set on neutral $ZZ\gamma$ and $Z\gamma\gamma$ TGCs, combined with previous results in $\ell\ell\gamma$[4] and $\nu\nu\gamma$[5] decay modes. The limits for Λ=1.5 TeV are $|h_3^Z|$ <0.026, $|h_4^Z|$ <0.0013, $|h_3^\gamma|$ <0.027, $|h_4^\gamma|$ <0.0014. CDF considered $\ell\ell\gamma$ and $\nu\nu\gamma$ decay modes in a sample of 5 fb^{-1} of data[6] to set limits on anomalous TGC from the $E_T(\gamma)$ >50 GeV and $E_T(\gamma)$ >100 GeV photon spectrum in the two decay channel respectively (see Figure 1(c)): -0.020< $|h_3^Z|$ <0.021, $|h_4^Z|$ <0.0009, -0.022< $|h_3^\gamma|$ <0.020, $|h_4^\gamma|$ <0.0008.



(a) (b) (c)

Figure 1: (a)The charge-signed photon-lepton rapidity difference distribution for $W\gamma$ events selected by D0. (b) Differential cross section $d\sigma/dp_T^\gamma$ distribution for $Z\gamma$ events selected by D0. (c) $E_T(\gamma)$ distribution for $Z\gamma \to \nu\nu\gamma$ events selected by CDF, exploited for the TGC limit calculation.

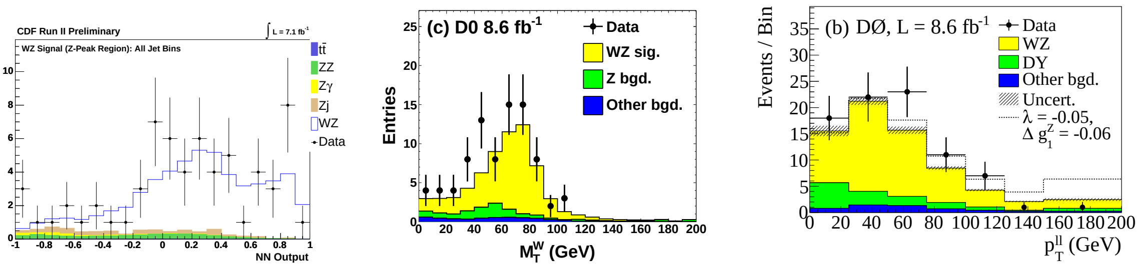
3 Heavy dibosons

3.1 $WZ \to \ell\nu\ell'\ell'$

The reconstruction of **WZ** production in its leptonic decay is based on the identification of three isolated high-momentum leptons (ℓ=e,μ), and a significant amount of missing transverse energy $\not{E}_T$ ($\not{E}_T$ ≥25 GeV). These requirements select a clean WZ sample reducing the background contribution below 10%. The CDF and D0 collaborations carried out a measurement of the WZ production cross section using 7.1 fb^{-1}[7] and 8.6 fb^{-1}[8] of integrated luminosity respectively. CDF exploits an artificial neural network (NN) to separate signal from background and measures the cross section from a fit to the NN output distribution, shown in Figure 2(a). The fit gives a cross section of $3.9^{+0.6}_{-0.5}$(stat.)$^{+0.6}_{-0.4}$(syst.) pb, in agreement with the SM expectation σ_{WZ}= 3.46±0.21 pb[3]. D0 measures a cross section of 4.50±0.61(stat.)$^{+0.16}_{-0.25}$(syst.) pb[b] from a fit to the W boson transverse mass distribution, $m_T(W)$, shown in Figure 2(b). Both CDF and D0 extracted 95%

[b]This cross section is calculated in the kinematic region of events with $m_{\ell\ell} \in$[60,120] GeV/c^2, to be comared with σ_{WZ}^{NLO}=3.21±0.19 pb.

C.L. limits on anomalous TGC from a fit to the $p_T(\ell\ell)$ distribution (see Figure 2(c)), since a deviation of the couplings with respect to the SM predictions would result in a harder Z boson p_T spectrum. For a new physics contribution at Λ=2 TeV CDF obtains the limits -0.09< λ_Z <0.11, -0.08< Δg_1^Z <0.20, -0.39< Δk_Z <0.90, while D0 sets -0.077< λ_Z <0.089, -0.055< Δg_1^Z <0.117. D0 combined the analysis in this final state with the aforementioned $W\gamma$ analysis and previous measurements of $WW \to \ell\nu\ell'\nu$ done using 1.0 fb^{-1} and of $WW + WZ \to \ell\nu jj$ using a total of 5.4 fb^{-1} to set the most stringent limits on neutral TGC parameters at hadron colliders [9].

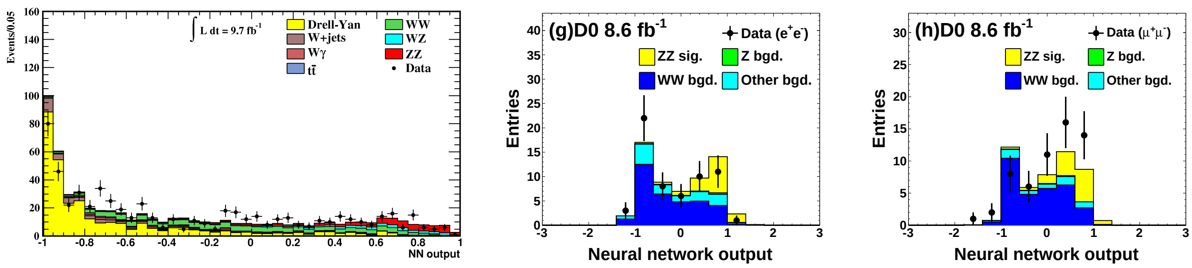


(a) (b) (c)

Figure 2: (a)The NN output distribution for $WZ \to \ell\nu\ell'\ell'$ events selected by CDF. (b)The W transverse mass distribution for $WZ \to \ell\nu\ell'\ell'$ events selected by D0. (c) The $p_T(\ell\ell)$ distribution exploited by D0 to set limits on neutral TGCs.

3.2 $ZZ \to \ell\ell\ell'\ell'$, $ZZ \to \ell\ell\nu\nu$

CDF considered the full collected dataset, corresponding to 9.7 fb^{-1}, to obtain the best measurement to date of the ZZ production cross section exploiting the two leptonic decay modes $\ell\ell\ell'\ell'$ and $\ell\ell\nu\nu$. The reconstruction of four isolated leptons (ℓ=e,μ) provides a really clean ZZ sample in the former decay mode, while additional requirements on the two dilepton invariant masses reduce the background below 1%, mainly due to jets misidentified as leptons. $ZZ \to \ell\ell\nu\nu$ reconstruction is based on the presence of two leptons and a significant amount of $\not{E}_T$, aligned in the opposite direction with respect to the $Z \to \ell\ell$. An artificial NN is then exploited to further separate the signal from the dominant background due to Z+jets production, and the NN output distribution of it is used to measure the production cross section. The combination of the measurements in the two leptonic decay modes gives as a result $\sigma(ZZ)$= $1.38^{+0.28}_{-0.27}$ pb, in good agreement with the theoretical prediction of 1.4±0.1 pb[3]. D0 carried out similar measurements using 6.4 fb^{-1} and 8.6 fb^{-1} of data in the $\ell\ell\ell'\ell'$ and $\ell\ell\nu\nu$ decay respectively[10]. The combination of the analysis in the two final states gives a measured cross section of $1.44^{+0.31}_{-0.28}$(stat.)$^{+0.17}_{-0.19}$(syst.) pb. D0 is currently updating the ZZ analyses to the full dataset; the combination with CDF result will be the most precise measurement at the Tevatron for this process.

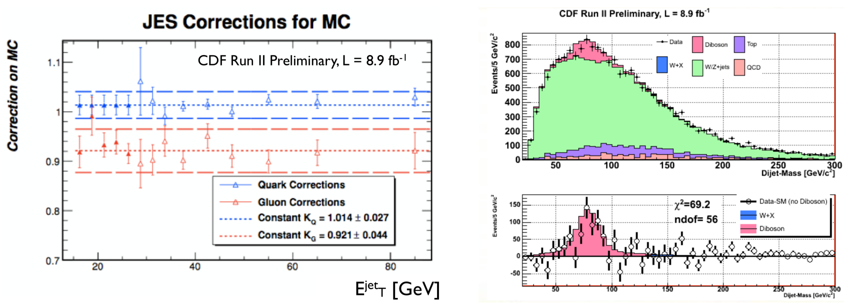


(a) (b) (c)

Figure 3: (a)The NN output distribution for $ZZ \to \ell\ell\nu\nu$ events selected by CDF. (b-c) The NN output distribution for $ZZ \to ee\nu\nu$(b) and $ZZ \to \mu\mu\nu\nu$(c) events selected by D0.

3.3 $WW/WZ \to \ell\nu jj$

The semileptonic decay of dibosons is more challenging at hadron colliders since a small signal has to be extracted from background dominated sample, mostly composed by W/Z+jets production and QCD processes. The reconstruction of **WW** and **WZ** in events with one lepton (ℓ=e,μ), significant $\not\!\!E_{\rm T}$ and at least two hadronic jets is important to validate the searches for the Higgs boson production in similar final states. Once reconstructed the W boson from its $\ell\nu$ decay, interesting properties of the investigated signal can be obtained from the di-jet invariant mass distribution m_{jj}. After the observation of this process by CDF[11,12] and D0[14] exploiting part of the collected dataset, CDF reported on a larger data sample an excess in the data with respect to SM expectation[15] that D0 did not confirmed. A lot of effort has been done to understand this behaviour and improve the modeling of hadronic jets in the detector applying specific corrections for quark and gluon jets (see Figure 4). As a result of these tuning studies CDF obtained a good agreement between data and SM only expectations, as sown in Figure 4 for the di-jet invariant mass distribution for $\ell\nu jj$ events selected[13].



(a) (b)

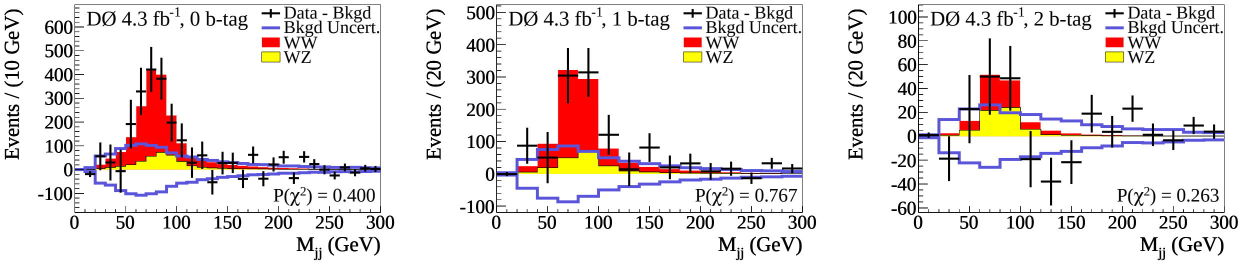
Figure 4: (a) Jet Energy Scale correction applied to quark/gluon-like jets in MC simulations, as a function of the jet E_T. (b) The m_{jj} distribution for $\ell\nu jj$ events collected by CDF, compared to signal and background expectations.

The D0 collaboration considered the same processes and separated the collected data in different subsample according to the tagged-flavor[c] of the jets reconstructed in the final state. In the sub-samples of events with zero, one, or two b-tagged jets the WW/WZ ratio is different and the two processes are expected to appear as two slightly displaced peaks in the m_{jj} spectrum, centered at m_W and m_Z respectively. To separate the signal from the large W+jets background contamination D0 uses a Random Forest (RF) classifier, including the number of b-tagged jets as input information. Combining the m_{jj} distribution in the three subchannels shown in Figure 5 D0 measures in a sample of 4.3 fb^{-1} of data a cross section $\sigma(WW+WZ)$= $1.96^{+0.32}_{-0.30}$ pb, assuming the ratio WW/WZ fixed to the SM prediction. The simultaneous fit of the cross section of the two processes gives as a result $\sigma(WW)$= $15.9^{+3.7}_{-3.2}$ pb and $\sigma(WZ)$= $3.3^{+4.1}_{-3.3}$ pb, where the correlation between the two components is shown in the contour plot in Figure 6(a).

3.4 $WZ/ZZ \to \ell\nu$+heavy flavor

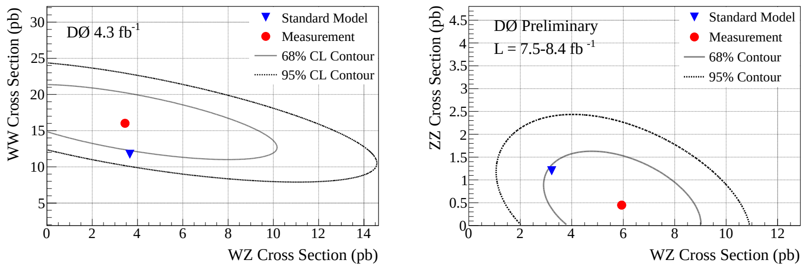
The $\mathbf{WZ+ZZ}$ production in final states including heavy flavor jets is the measurement that completes the knowledge of heavy diboson production at the Tevatron. A pair of b-jets from the Z decay can be combined with different decay modes of the second vector boson, leading to $\nu\nu b\bar{b}$, $\ell\nu b\bar{b}$, $\ell\ell b\bar{b}$ final states. These signatures are very similar to those exploited in the search for a low-mass Higgs boson at the Tevatron ($WH \to \ell\nu b\bar{b}$, $ZH \to \ell\ell b\bar{b}$, and $ZH \to$

[c] As it's usually done in similar multipurpose experiments, *tagging* algorithms are used to identify jets from b-quarks looking for clusters of tracks pointing to a secondary vertex displaced from the collision one.



(a) (b) (c)

Figure 5: Background subtracted di-jet invariant mass distribution for $\ell\nu jj$ events with (a) no tagged, (b) one tagged, (c) two tagged jets, collected by CDF, compared to diboson signal expectation.



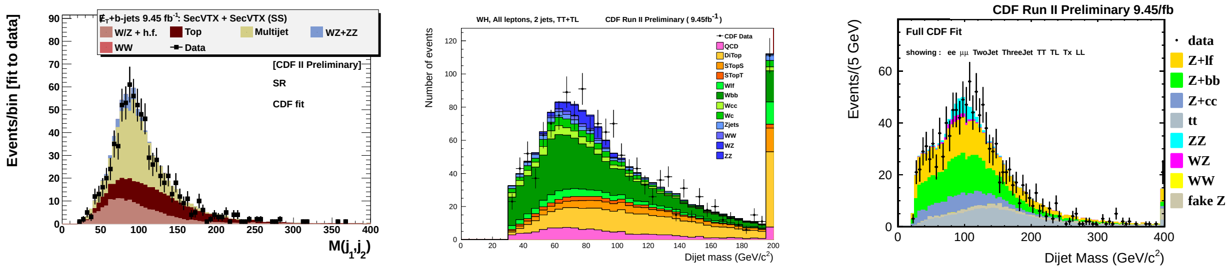
(a) (b)

Figure 6: (a)Result of the simultaneous fit of WW and WZ cross section made by D0 exploiting different tag sub-channels in $\ell\nu jj$ sample. (b)Result of the simultaneous fit of WZ and ZZ cross section made by D0 combining different semileptonic decays of VZ.

$\nu\nu b\bar{b}$), hence the diboson measurements would be a validation of the searches carried out at CDF and D0 in these channels. The different analyses aiming to search for the Higgs boson have been re-optimized for the diboson cross section measurement, adapting the multivariate discriminants for the isolation of WZ and ZZ signals. CDF combined the data from the full collected dataset for the three aforementioned final states (see Figure 7), and for each one considered sub-channels corresponding to events with one or two tagged jets. The fit to the final discriminant gives as a result $\sigma(WZ+ZZ)= 4.08^{+1.38}_{-1.26}$ pb, that has a large uncertainty but is compatible with the SM expectation $\sigma(WZ+ZZ)= 4.4\pm0.3$ pb[3]. A similar combination of the tagged final states has been done by D0[16] (see Figure 8(a-b)) exploiting samples of data ranging from 7.5 fb^{-1} to 8.4 fb^{-1}. The combined fit to the final discriminant distributions gives $\sigma(WZ+ZZ)= 5.0\pm1.0(\text{stat.})^{+1.3}_{-1.2}(\text{syst.})$ pb assuming the SM prediction for the ratio WZ/ZZ. The simultaneous fit to the two processes cross sections gives $\sigma(WZ)= 5.9\pm1.4(\text{stat.})\pm0.7(\text{syst.})$ pb and $\sigma(ZZ)= 0.45\pm0.61(\text{stat.})\pm1.2(\text{syst.})$ pb, with the correlation between the two highlighted in Figure 6(b). All CDF and D0 subchannels were used as input into a single final discriminant, shown in Figure 8(c); the fitted cross section is $\sigma(WZ+ZZ)= 4.47\pm0.64(\text{stat.})\pm0.72(\text{syst.})$ pb, and the diboson signal is observed with 4.6 σ significance[17].

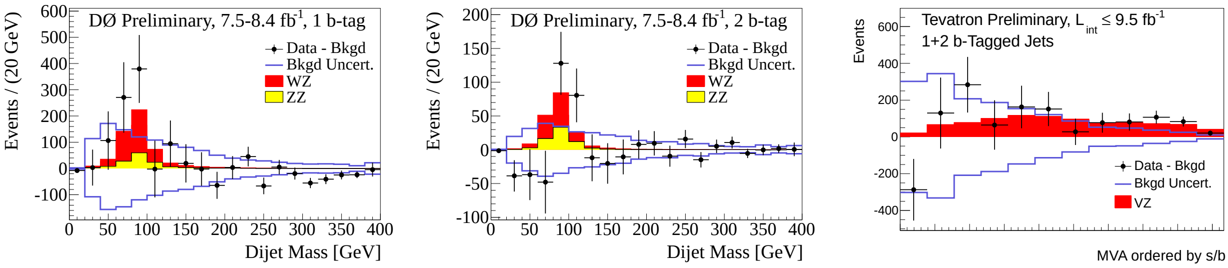
4 Conclusions

The CDF and D0 collaborations presented their recent results on the study of diboson production at the Tevatron. The production of gauge boson pairs has been measured in different final state, involving both leptonic and hadronic decays of the bosons. The measured cross sections have been found in agreement with the SM expectation within the statistical and systematic uncertainties, and tight constraints have been set on the TGC parameters. The evidence of heavy diboson production in final states containing heavy flavor jets is a validation of the several low-



(a) (b) (c)

Figure 7: Di-jet invariant mass distribution for events collected by CDF in the (a)$\nu\nu b\bar{b}$, (b)$\ell\nu b\bar{b}$, (a)$\ell\ell b\bar{b}$ final state, compared to the signal and background expectations.



(a) (b) (c)

Figure 8: (a-b)Background subtracted di-jet invariant mass distribution for (a) single-tag and (b) double-tag events collected by D0 combining all the considered final states. (c)Final discriminant distribution exploited for the Tevatron combined measurement of WZ/ZZ cross section in semileptonic final states containing b-jets.

mass Higgs boson searches carried out by CDF and D0. These results join the set of the other precise measurements preformed at the Tevatron that probed the consistency of the Standard Model so far.

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