PROCEEDINGS OF SCIENCE

Diboson Production at the Tevatron

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The measurement of diboson production in proton anti-proton collisions at a centre-of-mass energy of $\sqrt{s} = 1.96$ TeV at the Tevatron in Run II is presented in this report. Cross-section measurements and limits on cross sections for diboson production have been reported by the experiments CDF and DØ for the final states WW, WZ, ZZ, Wγ and Zγ. The results are also interpreted as searches for anomalous couplings which would lead to an increase of events with large transverse momenta of the gauge bosons. All measured cross sections are in good agreement with the theoretical predictions.
The Lagrangian in the Standard Model (SM) to describe the WWZ and WWγ vertices, including only the C and P conserving couplings, is given by:

$$\mathscr{L}_{WWV} \sim g_V^1 \left(W^{\dagger}_{\mu\nu} W^{\mu} V^{\nu} - W^{\dagger}_{\mu} V_{\nu} W^{\mu\nu} \right) + \kappa_V W^{\dagger}_{\mu} W_{\nu} V^{\mu\nu} + \frac{\lambda_V}{M_W^2} (W^{\dagger}_{\lambda\mu} W^{\mu}_{\nu} V^{\nu\lambda}),$$

where $V = Z$ or γ. Five of these couplings are CP conserving and their values in the SM are: $\lambda_Z = \lambda_\gamma = 0$, $\Delta\kappa_Z = \Delta\kappa_\gamma = 0 \quad (\Delta\kappa = \kappa - 1)$ and $\Delta g_Z^1 = 0 \quad (\Delta g_Z^1 = g_Z^1 - 1)$. Any deviation from the SM value is called anomalous coupling.
Vertices with three neutral gauge bosons, e.g. ZZγ, are forbidden in the SM. An observation of such would be a sign for physics beyond the SM. The non-SM couplings can be characterised by an effective Lagrangian with 8 form-factor coupling parameters called $h_1^V, h_2^V, h_3^V, h_4^V$ where V stands for γ or Z. The couplings h_1^V and h_2^V are CP violating while the other four couplings are CP conserving. In the SM all of these couplings are equal to zero.
When comparing the limits on anomalous couplings from the Tevatron with those from LEP, the limits from LEP are stronger in most cases. The limits on h_2^V and h_4^V from the Tevatron are better though.

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1. Introduction

Diboson production is an important test of the Standard Model (SM) as due to its non-abelian component self interactions of gauge bosons are possible. The measurement of total and differential cross sections in diboson final states is also sensitive to anomalous, i.e. not in the SM allowed, couplings. The existence of such couplings would in general lead to an excess of events with large transverse momenta of the gauge bosons.

Further, diboson final states are also possible final states from Higgs boson decays and have to be understood before any discovery of the Higgs boson could be claimed.

2. WW Production

WW production is observed in the dilepton final state where both W bosons decay leptonically. Only decays into first or second generation leptons are considered in the analyses. WW production has contributions from diagrams with triple gauge couplings WWZ and WWγ. The cross section for this process is predicted in next to leading order to be 12.4 ± 0.8 pb [1]. The results from CDF [2] and DØ [3] are shown in Figure 2. DØ observes in a data set with an integrated luminosity of 240 pb^{-1} 25 events with a background expectation of $8.1 \pm 0.85 \pm 0.5$(lum) events. This corresponds to a measured cross section of $\sigma = 13.8^{+4.3}_{-3.8}(\text{stat})^{+1.2}_{-0.9}(\text{syst}) \pm 0.9(\text{lum})$pb. The significance of this measurement is 5.2 σ.

CDF has also started an analysis with one W boson decaying hadronically but the statistical significance for the measurement of the cross section of this analysis due to the larger background contribution is less than that of the dilepton analyses. Final states from WZ production, where the Z boson decays hadronically, are also selected. Using this analysis, searches for anomalous couplings in WW and WZ production have been performed by analysing the transverse momentum spectrum of the W bosons, shown in Figure 1. From this, limits for the anomalous couplings of $-0.42 < \Delta\kappa < 0.58, \quad -0.32 < \lambda < 0.35$ at 95% CL. have been determined.

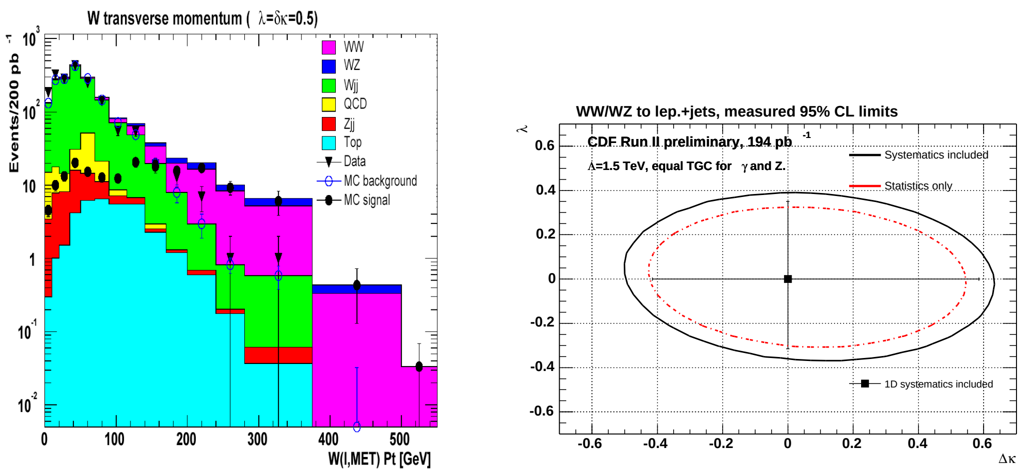

Figure 1: Left: Transverse momentum distribution of the W boson. A hypothetical signal for couplings of $\lambda = \Delta\kappa = 0.5$ is included. The data are the triangles. Right: 2D limit plot on the anomalous couplings.

3. WZ and ZZ Production

When investigating final states with one W and one Z boson only a single triple gauge coupling, WWZ, contributes. At the Tevatron this vertex is measured independently for the first time, as at LEP it was probed only in combination with the WW γ vertex. This process has a small cross section of 3.7 ± 0.1 pb and is observed in the trilepton final state $(eee, ee\mu, e\mu\mu, \mu\mu\mu)$, where both gauge bosons decay leptonically. The advantage of the pure leptonic final state is the very low expected background but the branching ratio of about 1.5% results also in a low signal rate. DØ observes in a data set with an integrated luminosity of about 300 pb^{-1} 3 events [4], requiring three leptons (e or μ) with $p_T > 15$ GeV and a missing energy greater than 20 GeV. The background expectation for this data set is 0.71 ± 0.08 events with the main background stemming from Z+jets events. The measured cross section is $4.5^{+3.8}_{-2.6}$ (stat + syst) pb. The probability of the background of 0.71 events to fluctuate to the three observed events is 3.5%. Limits on anomalous couplings are derived as no deviation from the SM is observed. The limits for the absolute values of $\lambda_Z, \Delta g_1^Z$ and $\Delta\kappa_Z$ are all around 0.5 at 95% CL for $\Lambda = 1.5$ TeV.

The process of ZZ production has an even smaller cross section than WZ production and has therefore not yet been observed at the Tevatron. CDF has an analysis [5] that measures the processes WZ and ZZ production in final states with two, three or four charged leptons. They observe 3 events with a background expectations of 1.0 ± 0.2 events for an integrated luminosity of 194 pb^{-1}. The upper limit on the cross section for WZ and ZZ production is 15.2 pb at 95% CL.

4. Wγ and Zγ Production

Wγ production can occur either by the radiation of a photon in the initial or final state or via a WWγ vertex. The cross section for this process depends on the cuts that are applied to the photon. CDF measures the cross section times branching ratio for the transverse energy of the photon of more than 7 GeV and the separation of the lepton and the photon of $\Delta R(\ell, \gamma) = \sqrt{(\eta_\ell - \eta_\gamma)^2 + (\phi_\ell - \phi_\gamma)^2} > 0.7$ to be $\sigma \times BR(W \to \ell\nu) = 18.1 \pm 3.1$ pb [6] which is in good agreement with the theoretical prediction at next to leading order of 19.3 ± 1.4 pb. The main background stems from jets that are misidentified as photons. This misidentification rate depends strongly on the jet momentum and is measured in data.

The spectrum of the transverse energy of the photon for similar cuts is measured by DØ. Only a single triple gauge coupling contributes to this final state and limits for the following couplings have been derived at 95% CL [7]: $-0.88 < \Delta\kappa_\gamma < 0.96, \quad -0.20 < \lambda_\gamma < 0.20$.

In the SM triple gauge couplings between neutral gauge bosons are forbidden. For the Zγ final state the photon can therefore only be emitted from a fermion in the initial or final state. This can be seen in Figure 2 where either the invariant mass of the two leptons from the Z boson decay or of the two leptons and the photon cluster at the Z boson mass. For low momenta of the photon the two masses are very similar, resulting in the diagonal line of events.

The Zγ final state is observed in the leptonic decay of the Z boson ($ee, \mu\mu$). Lower masses are cut away by requiring $m(\ell\ell) > 40(30)$ GeV by CDF (DØ). CDF observes 71 events in an integrated luminosity of about 200 pb^{-1} with only 4.9 background events. The measurement of $\sigma \times BR(Z \to \ell^+\ell^-) = 4.5 \pm 0.3$ pb [6] agrees well with the SM prediction of 4.6 ± 0.6 pb.

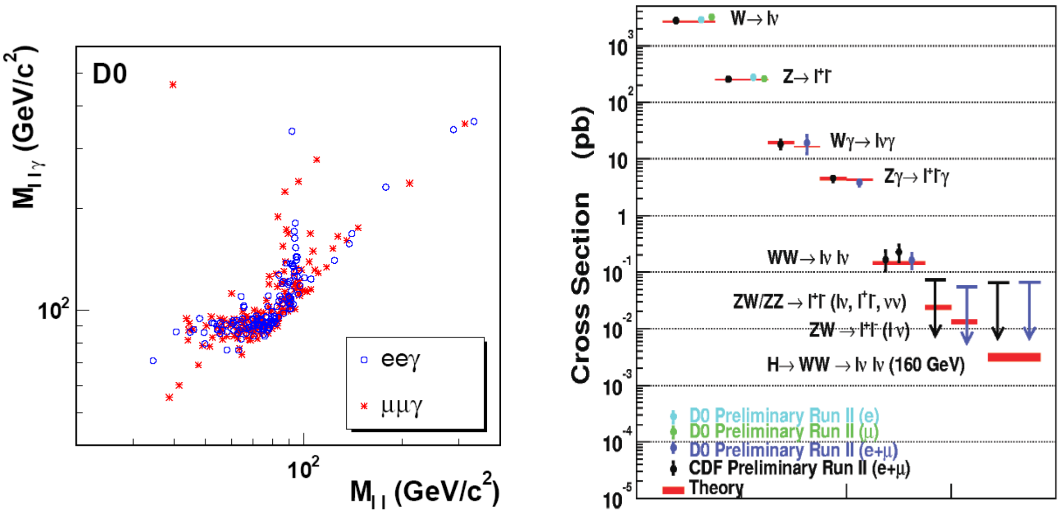

Figure 2: Left: Invariant mass of the two leptons and the photons vs that of the two leptons in $Z\gamma$ events. Right: Summary of all single and diboson production cross-section measurements (or upper limits on cross sections) and the theoretical predictions.

DØ interprets their measurement of the transverse energy spectrum of the photon for the existence of anomalous couplings. The limits found are very similar for the CP conserving and CP violating couplings [8]: $|h^V_{10,30}| < 0.23, \quad |h^V_{20,40}| < 0.019$. The limits on h^V_2 and h^V_4 are stronger than those from LEP [9].

5. Summary

Diboson production has been studied at the Tevatron in RunII by the CDF and DØ experiments. WW production has been established for the first time at a hadron collider. For WZ and ZZ production upper limits have been derived. As no deviations from the SM have been observed, limits on anomalous couplings are given.

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