Dibosons at the Tevatron

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Recent developments in the study diboson production at the Tevatron are reviewed. These include indications at the $2.6\sigma$ level for a radiation amplitude zero in the $W\gamma$ process at DØ and a $4.4\sigma$ signal for $ZZ$ production in hadron collisions from CDF.

1 Introduction

The process of the simultaneous production of two electroweak bosons is one of the few tree-level processes that is sensitive to the couplings between gauge bosons. These couplings are a direct consequence of the non-abelian group structure of the standard model (SM). At the Tevatron, a broad program of measuring cross-sections and kinematic distributions is aimed testing whether these processes are consistent with the SM predictions and searching for evidence of non-standard model contributions. The $WW$ and $ZZ$ final states are also of interest as potential Higgs search channels.

The leading-order Feynman diagrams for diboson production are shown in Figure 1. The $t$-channel shown in Figure 1(a) is effectively two copies of single boson production and involves only the fermion to boson couplings. The $s$-channel shown in Figure 1(b) involves the triple gauge couplings. In the standard model, only the $WW\gamma$ and $WWZ$ vertices are non-zero; the $Z\gamma\gamma$, $ZZ\gamma$, and $ZZZ$ vertices do not exist.

The CDF and DØ have studied the $W\gamma$, $Z\gamma$, $WZ$, and $ZZ$ final states in 1-2 $fb^{-1}$ of $pp$ collisions at 1.96 TeV produced by the Tevatron. A summary of the predicted and observed cross-sections is shown in Figure 1(c). Shown for comparison are the single boson production cross-sections which present a significant experimental challenge because they are three to four orders of magnitude larger than the diboson cross-sections.
2 Radiation Amplitude Zero

In the $W\gamma$ process, the two Feynman diagrams shown in Figure 1 interfere destructively. This interference is complete when the angle of the $W^\pm$ relative to the incoming quark in the $W\gamma$ rest-frame is $\pm \frac{\pi}{3}$, causing the leading-order differential cross-section to completely disappear in what is known as the radiation amplitude zero (RAZ). Although long predicted, it is difficult to observe because the missing neutrino information when $W$ is reconstructed in the $l\nu$ final state. There is however an approximate zero in the quantity $Q_l \times (\eta_\gamma - \eta_l)$ where $Q_l$ is the lepton charge, and $\eta_\gamma$ and $\eta_l$ are the pseudo-rapidities of the photon and lepton respectively. The observation of the zero would be a demonstration of the presence of the $WW\gamma$ vertex contribution to the $W\gamma$ process.

Using 0.7 fb$^{-1}$ of $pp$ collisions, DØ has reconstructed a sample of $W\gamma \rightarrow l\nu\gamma$ events where $l$ is either $e$ or $\mu$. The $Q_l \times (\eta_\gamma - \eta_l)$ distribution of these events, after subtracting the estimated background, is shown in Figure 2(a). In order to quantify the significance of the dip, a minimal unimodal hypothesis (MUH) is constructed by choosing a set of $WW\gamma$ couplings such that there is no dip in the distribution (shown in Figure 2(b)). They then find that it is ruled out at the 2.6$\sigma$ level.
Deviations of the boson to boson couplings from the SM are referred to as anomalous triple gauge couplings (aTGCs) and are parameterized by adding terms to the SM Lagrangian; for example for the $W W \gamma$ vertex:

$$\mathcal{L}_{aTGC}/g_{WW\gamma} = \Delta \kappa_{\gamma} W^\ast_{\mu} W^\mu + \lambda_{\gamma} M_W W^\ast_{\mu} W^\mu F_{\mu\nu} + \lambda_{\gamma} M_W W^\ast_{\mu} W^\mu F_{\mu\nu}$$  \hspace{1cm} (1)

where the form-factors $\lambda_{\gamma}$ and $\Delta \kappa_{\gamma}$ are zero in the SM. In addition to differences in the integrated cross-sections, anomalous TGCs typically give rise to significant enhancements at large diboson invariant mass $\hat{s}$. In fact aTGCs can cause unitarity violations at large $\hat{s}$, so the form-factors must be constructed so as to turn off as $\hat{s}$ gets large; e.g. $\lambda_{\gamma}(\hat{s}) = \lambda_{\gamma}/(1 + (\hat{s}/\Lambda)^2)^2$ where $\Lambda$ is typically 1.5 to 2.0 TeV. This also means that these form-factors are intrinsically energy dependent and Tevatron limits should be considered as complementary to the LEP limits which are at $\hat{s} \approx 2M_W$. CDF and DØ have recently updated limits on aTGCs using the $\gamma E_T$ distributions for $W \gamma$ (DØ 3) and $Z\gamma$ (CDF 4 and DØ 5), the $Z$ boson $p_T$ for $W Z$ (CDF 4 and DØ 6), and the cross-section alone for $ZZ$ (DØ 7). Sample distributions used in setting aTGC limits are shown in Figure 3.

3 Triple Gauge Couplings

The $ZZ$ final state is the only SM diboson state not yet conclusively observed in hadron collisions (not including those involving the Higgs) and is unique in providing access to the $ZZZ$ coupling. DØ has searched in the four charged-lepton $llll$ channel finding 1 candidate event in 1.0 fb$^{-1}$ of data with an expected signal yield of 1.71 ± 0.15 events and background of 0.13 ± 0.03 events. Based of this search an upper limit of $\sigma(ZZ) < 4.4$ pb is set to be compared to an NLO prediction of 4.4 pb.

CDF finds a 4.4$\sigma$ signal for $ZZ$ production using 1.9 fb$^{-1}$ of data by combining the $llll$ (4.2$\sigma$) and $ll\nu\nu$ (1.2$\sigma$) channels. The $llll$ channel is subdivided into two categories based on whether the candidate contains an electron that occurs outside the acceptance of the tracking system and therefore has a significantly large background rate. Three $llll$ candidate events are found with the predicted signal and background yields shown in Table II. In the $ll\nu\nu$ channel, a matrix-element (ME) based probability calculation is used to separate the $ZZ$ signal from the much larger $WW$ background. The likelihood ratio from the ME calculation is shown in Figure 4 along with the four lepton invariant mass distribution from the $llll$ channel. The measured...
Table 1: Expected and observed number of $ZZ \rightarrow llll$ candidate events. The first uncertainty is statistical and the second one is systematic.

| Category | Candidates without a trackless electron | Candidates with a trackless electron |
|----------|----------------------------------------|--------------------------------------|
| $ZZ$     | $1.990 \pm 0.013 \pm 0.210$            | $0.278 \pm 0.005 \pm 0.029$          |
| $Z + \text{jets}$ | $0.014^{+0.010}_{-0.007} \pm 0.003$ | $0.082^{+0.089}_{-0.066} \pm 0.016$ |
| Total    | $2.004^{+0.016}_{-0.015} \pm 0.210$   | $0.360^{+0.089}_{-0.066} \pm 0.033$ |
| Observed | $2$                                    | $1$                                  |

Cross-section $\sigma(p\bar{p} \rightarrow ZZ) = 1.4^{+0.7}_{-0.6}$ (stat.+syst.) pb is consistent with the standard model expectation.

5 Summary

The increased luminosity at the Tevatron has allowed for substantial progress in diboson physics and marks entry into a new sensitivity regime where electroweak bosons are now being pair produced in significant numbers. Recent accomplishments include $2.6\sigma$ signal for the RAZ in $W\gamma$, a $4.4\sigma$ signal for $ZZ$ production, and limits on anomalous couplings that continue to improve.

References

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