We present an analysis of $ZZ$ production at the upgraded Fermilab Tevatron for general $ZZZ$ and $ZZ\gamma$ couplings. Achievable limits on these couplings are shown to be a significant improvement over the limits currently obtained by LEP II.

1. Introduction

The Standard Model (SM) of electroweak interactions makes precise predictions for the couplings between gauge bosons due to the non-abelian gauge symmetry of $SU(2)_L \otimes U(1)_Y$. These self-interactions are described by the triple gauge boson (trilinear) $WWV$, $Z\gamma V$, and $ZZV (V = \gamma, Z)$ couplings and the quartic couplings. Vector boson pair production provides a sensitive ground for direct tests of the trilinear couplings. Deviations of the couplings from the expected values would indicate the presence of new physics beyond the SM.

To date the SM has passed this rigorous test with no observed deviations from the SM values. The $WWV$ and $Z\gamma V$ couplings have been measured with an accuracy of $O(10\%)$ at LEP2 and the Tevatron. The $ZZV$ couplings, on the other hand, are only loosely constrained at the moment through $ZZ$ production at LEP2. Due to low event rates after branching ratios, or large backgrounds, $ZZ$ production was not observed by the Tevatron experiments in Run I. In Run II of the Tevatron which will begin in 2001, an integrated luminosity of $2 - 15 \text{ fb}^{-1}$ is envisioned, and a sufficient number of $ZZ$ events should be available to commence a detailed investigation of the $ZZV$ couplings. In the following we summarize the results of a recent detailed study of the capabilities of future Tevatron experiments to test the $ZZV$ vertices via $ZZ$ production.

2. $ZZZ$ and $ZZ\gamma$ Anomalous Couplings

Two $ZZZ$ couplings, and two $ZZ\gamma$ couplings, are allowed by electromagnetic gauge invariance and Lorentz invariance for on-shell $Z$ bosons. In the massless fermion
limit, the most general form of the $Z^\alpha(q_1) Z^\beta(q_2) V^\mu(P)$ ($V = Z, \gamma$) vertex function may be written as
\[ g_{ZZV} \Gamma_{ZZV}^{\alpha\beta\mu} = e \frac{P^2 - M_Z^2}{M_Z^2} \left[ i f_4^V (P^\alpha g_{\mu\beta} + P^\beta g_{\mu\alpha}) + i f_5^V \epsilon^{\mu\alpha\beta\rho} (q_1 - q_2)_\rho \right], \tag{1} \]
where $M_Z$ is the Z-boson mass and $e$ is the proton charge. The overall factor $(P^2 - M_Z^2)$ in Eq. (1) is a consequence of Bose symmetry for $ZZZ$ couplings, while it is due to electromagnetic gauge invariance for the $ZZ\gamma$ couplings. All couplings are $C$ odd; $CP$ invariance forbids $f_4^V$ and parity conservation requires that $f_5^V$ vanishes. In the SM, at tree level, $f_4^V = f_5^V = 0$.

$S$-matrix unitarity restricts the $ZZV$ couplings uniquely to their SM values at asymptotically high energies. This requires that the couplings $f_4^V$ possess a momentum dependence which ensures that the $f_4^V(\hat{s})$ vanish for $\hat{s} \to \infty$. In order to avoid unphysical results that would violate unitarity, the $\hat{s}$ dependence thus has to be taken into account. To parameterize the $\hat{s}$ dependence of the form factor, we use a generalized dipole form factor, $f_4^V(\hat{s}) = f_4^V(0)/(1 + \hat{s}/\Lambda_{FF}^2)^n$, $(i = 4, 5)$, where $\Lambda_{FF}$ is the form factor scale which is related to the scale of the new physics which is generating the anomalous $ZZV$ couplings. The values of the form factors at low energy, $f_4^V(0)$, and the power of the form factor, $n$, are constrained by partial wave unitarity of the inelastic $ZZ$ production amplitude in fermion antifermion annihilation at arbitrary center-of-mass energies.

3. Signatures of Anomalous $ZZV$ Couplings

Our analysis examines the observable final state signatures, $ZZ \to \ell^+\ell^-\ell^+\ell^-$, $\ell^+\ell^-\nu\bar{\nu}$, $\ell^+\ell^-jj$ ($\ell$, $\ell_1, \ell_2 = e, \mu$) and $\bar{\nu}\nu jj$. The total cross section for $pp \to ZZ$ at $\sqrt{s} = 2$ TeV, including NLO QCD corrections is approximately 1.5 pb. For an integrated luminosity of 2 fb$^{-1}$ one thus expects a few $ZZ \to \ell^+\ell^-\ell^+\ell^-$, $\ell^+\ell^-\nu\bar{\nu}$, $\ell^+\ell^-jj$ and $ZZ \to \bar{\nu}\nu jj$. These channels, however, suffer from non-trivial background contributions.

The effects of anomalous $ZZV$ couplings are enhanced at large energies. A typical signal of nonstandard $ZZZ$ and $ZZ\gamma$ couplings thus will be a broad increase in the $ZZ$ invariant mass distribution, the $Z$ transverse momentum distribution and the $p_T$ distribution of the $Z$ decay leptons.

The number of $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ signal events is about a factor 6 larger than the number of $ZZ \to 4$ leptons events. The two most important backgrounds to $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ production are $t\bar{t} \to W^+W^-bb$ and $W^+W^- \to \ell^+\ell^-\nu\bar{\nu}$ production. A jet veto almost completely eliminates the $t\bar{t}$ background. The $W^+W^-$ background exceeds the $ZZ$ signal cross section for $p_T(e^+e^-) < 80$ GeV. The $p_T(e^+e^-)$ distribution of the $W^+W^-$ background, however, drops much faster than that of the $ZZ$ signal, and, thus, will only marginally affect the sensitivity to $ZZV$ couplings.

The decay modes where one of the two $Z$ bosons decays hadronically have much larger branching fractions than the $ZZ \to 4$ leptons and the $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ chan-
nels, but also much higher backgrounds. The main background sources are QCD $Z + 2 \text{jet}$ ("$Zjj$" ) production and $WZ$ production with $W \rightarrow jj$. In both cases the $jj$ invariant mass is constrained to be near the $Z$ pole. Other potentially dangerous background sources are $t\bar{t}$ and $Wjj$ production. The $Wjj$ background contributes only to the $\bar{\nu}\nu jj$ final state. For $ZZ \rightarrow \ell^+\ell^−jj$, the $t\bar{t} \rightarrow \ell^+\nu\ell^−\bar{\nu}bb$ background can be reduced by requiring that the missing transverse momentum is $p_T < 20 \text{ GeV}$.

For $ZZ \rightarrow \ell^+\ell^−\bar{\nu}\nu$, suppression of the $t\bar{t} \rightarrow \ell^+\nu\ell^−\bar{\nu}bb$ and $W(\rightarrow \ell\nu)jj$ backgrounds is possible by requiring that there are no central high-$p_T$ charged leptons present in the event. The $Zjj$ background is found to be, by far, the largest background. Its size is uniformly about one order of magnitude larger than the SM $ZZ$ signal. It will therefore be very difficult to observe $ZZ$ production in the semi-hadronic channels, if the SM prediction is correct. However, for sufficiently large anomalous $ZZV$ couplings, the $ZZ$ cross section exceeds the background at large transverse momenta. The semi-hadronic channels therefore may still be useful in obtaining limits on the $ZZV$ couplings at the Tevatron.

4. Sensitivity Limits

In order to derive sensitivity limits for anomalous $ZZV$ couplings which one can hope to achieve in Run II, we use the $p_T(\ell^+\ell^−)$ distribution for $ZZ \rightarrow 4$ leptons, $ZZ \rightarrow \ell^+\ell^-\bar{\nu}\nu$ and $ZZ \rightarrow \ell^+\ell^−jj$. For the $ZZ \rightarrow \bar{\nu}\nu jj$ channel we use the $p_T(jj)$ distribution. Other distributions, such as the $ZZ$ invariant mass distribution (useful only for $ZZ \rightarrow 4$ leptons), or the maximum or minimum transverse momenta of the charged leptons or jets, yield similar results. In deriving our sensitivity limits, we combine channels with electrons and muons in the final state. We calculate 95% confidence level (CL) limits performing a $\chi^2$ test, allowing for a normalization uncertainty of 30% of the SM cross section. The most stringent bounds at Tevatron energies are obtained from $ZZ \rightarrow \ell^+\ell^-\bar{\nu}\nu$ and $ZZ \rightarrow \bar{\nu}\nu jj$. For $\int \mathcal{L} dt = 2 \text{ fb}^{-1}$, $n = 3$ and $\Lambda_{FF} = 750 \text{ GeV}$ one finds:

$$|f^Z_{40}| < 0.159 < f^Z_{50} < 0.162$$

(2)

$$|f^\gamma_{40}| < 0.163 < f^\gamma_{50} < 0.170.$$  

(3)

These bounds improve the present limits from LEP II by a factor 3 to 6. The limits from the $ZZ \rightarrow \ell^+\ell^- jj$ and $ZZ \rightarrow 4$ leptons channels are about a factor 1.5 and 2 weaker than those from $ZZ \rightarrow \ell^+\ell^-\bar{\nu}\nu$ and $ZZ \rightarrow \bar{\nu}\nu jj$. Bounds roughly scale with $(\int \mathcal{L} dt)^{1/4}$. At the LHC one will be able to probe $ZZV$ couplings of $\mathcal{O}(10^{-3})$ in magnitude.

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