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Probing *CP*-violation at colliders through interference effects in diboson production and decay

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We define a *CP*-asymmetric observable that is sensitive to *CP*-violating interactions in the gauge-boson sector. We illustrate the utility of this observable by studying how well the LHC can measure the coefficient of a particular dimension-six *WWZ* operator. We find that sensitivity at the 10^{-3} level is possible at the LHC with 100 fb^{-1} of integrated luminosity, which would greatly exceed the sensitivity achieved at LEP, and would rival or may even better the indirect sensitivities inferred from related operators constrained by electric dipole moment experiments.

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I. PROBING *CP*-VIOLATION

One of the most well-motivated possibilities for new physics is *CP* violation. Many new experimental probes of *CP* violation have been studied, both at accelerators and at other experiments. There are several reasons for this. Firstly, *CP* violation has been observed in kaon decays, and there is great interest in determining all possible theoretical sources of new physics that could contribute, as well as possible new experimental signatures of *CP* violation. Secondly, *CP* violation is required for baryogenesis. The known source of *CP* violation in the standard model (SM)—the Cabibbo-Kobayashi-Maskawa phase—is not sufficient to generate the known baryon asymmetry, and so some other source is needed.

In general, *CP* violation can be induced in the gauge-boson sector. For instance, an exotic fermion coupled to the electroweak bosons can induce *CP*-violating couplings. The large number of fermions that can arise in intersecting brane models of string theory could thus be a source of large *CP* violation in the gauge-boson sector. Absent an argument based on symmetry (or a fixed choice of new physics model), there is no reason for those gauge-boson sector couplings to be suppressed by any factors except the scale of new physics. It is therefore of great interest to look for the effects of such new physics (related triple gauge-boson coupling signatures from string theory have been discussed in [1]).

In this paper, we discuss the possibility of probing *CP* violation in the gauge-boson sector at colliders, and in particular, at the Large Hadron Collider (LHC). We introduce observables that are directly sensitive to *CP* violation, and argue that they can be utilized to probe *CP*-violating couplings at a wide variety of accelerator experiments, and for a large class of new physics models. We apply this to the specific operator that contributes to the triple-gauge-boson (WWZ) vertex, and show that collider searches can improve current bounds on this operator by well over an order of magnitude.

II. *CP* VIOLATION IN THE WWZ TRIPLE GAUGE COUPLINGS

We begin by considering new physics that modifies the WWZ vertex. The WWZ vertex can, up to general dimension six operators, be parameterized in terms of the effective Lagrangian [2]

$$\begin{aligned} i\mathcal{L}_{\text{eff}} = g_{WWZ}[&g_1^Z Z^\mu (W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}) + \kappa_Z W^+_\mu W^-_\nu Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2} Z^{\mu\nu} W_\nu^{+\rho} W^-_{\rho\mu} + i g_5^Z \epsilon_{\mu\nu\rho\sigma}((\partial^\rho W^{-\mu})W^{+\nu} \\ &- W^{-\mu}\partial^\rho W^{+\nu})Z^\sigma + i g_4^Z W^-_\mu W^+_\nu (\partial^\mu Z^\nu + \partial^\nu Z^\mu) + \frac{\tilde{\kappa}_Z}{2} W^-_\mu W^+_\nu \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_Z}{2M_W^2} W^-_{\rho\mu} W_\nu^{+\mu} \epsilon^{\nu\rho\alpha\beta} Z_{\alpha\beta}], \end{aligned} \tag{1}$$

where $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$, $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$. In the SM, $g_1^Z = \kappa_Z = 1$, and all the other terms are zero.

In this Lagrangian, g_1^Z, κ_Z, λ_Z, g_5^Z are *CP* conserving, and the other terms are *CP* violating. The *CP*-conserving operators have been studied in great detail [3], and the bounds on these parameters have been analyzed (see e.g., LEP studies in [4]). The *CP*-violating operators have also been studied at colliders [5,6], but the bounds are only at best ∼0.1. The DELPHI Collaboration [6] used the process $e^+e^- \to W^+W^- \to l\nu q\bar{q}(l = e/\mu)$ to obtain the measurements

$$g_4^Z = -0.39^{+0.19}_{-0.20}, \tag{2}$$

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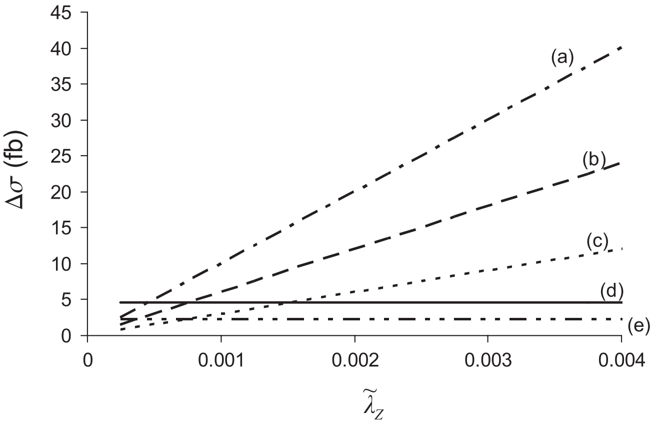

FIG. 1. Plot of $\Delta\sigma$ asymmetry cross section as a function of $\tilde{\lambda}_Z$. Lines (a), (b), and (c) correspond, respectively, to $\Delta\sigma$ in the cases where no kinematics cuts are imposed, kinematic cuts on the Z decay products are imposed, and the full kinematic cuts are imposed. Lines (d) and (e) correspond to the required $\Delta\sigma$ for 5σ and 95% confidence reach, respectively.

$$\tilde{\kappa}_Z = -0.09^{+0.08}_{-0.05}, \tag{3}$$

$$\tilde{\lambda}_Z = -0.08 \pm 0.07 \tag{4}$$

LEP and Tevatron sensitivities to the related coefficient $\tilde{\lambda}_\gamma$ are only at $\tilde{\lambda}_\gamma \leq 0.3$ [7,8].

We will now consider the sensitivity to the LHC to these coefficients. We consider a scattering process with matrix element $\mathcal{M}_0 + \delta\mathcal{M}$, where $\mathcal{M}_0$ is the SM matrix element and $\delta\mathcal{M}$ is the contribution arising from new physics. The leading change in the cross section due to new physics is then the interference term

$$\delta\sigma \propto \Re(\mathcal{M}_0 \delta\mathcal{M}^*). \tag{5}$$

We now wish to look for CP-violating physics in the interference effects. We assume that the SM matrix element is CP conserving; this will be the case in any process for which fewer than three generations participate. Even more generally, the only source of SM CP violation is the small contribution from the Cabibbo-Kobayashi-Maskawa phase, and we assume new physics to carry the larger contribution. This assumption is especially warranted if we envision the new CP violation as accounting for the baryon asymmetry.

To look for the effects of new physics, we note that a term in the cross section proportional to $\epsilon_{\mu\nu\rho\sigma}$ is always a signal of CP-violating physics. One way to see this is that such a term is odd under naive time reversal (the flip $t \to -t$). This suggests that it will probe a CP-violating term. Indeed, explicit computations using the effective Lagrangian (1) show that all terms proportional to the epsilon tensor in the interference term are proportional to CP-violating coefficients. Note that g_5^Z is the coefficient of a parity-violating, CP-conserving operator, which also is proportional to the ϵ tensor. But because this term comes with an imaginary coefficient, it will cancel out of the interference cross section.

We will therefore focus on terms in the cross section proportional to $\delta\sigma \propto \epsilon_{\mu\nu\rho\sigma}$. Experimental signals of these terms can be used to probe the couplings g_4^Z, $\tilde{\kappa}_Z$, $\tilde{\lambda}_Z$. In this note, we shall discuss the experimental sensitivities on $\tilde{\lambda}_Z$, leaving the more exhaustive analysis for future work.

III. SIGNALS OF *CP* VIOLATION

One can write the first-order shift in the differential cross section for the process $q\bar{q} \to W^* \to WZ \to l\nu Z$ as

$$d\sigma = \frac{1}{12}\frac{1}{2E_q 2E_{\bar{q}}|v_q - v_{\bar{q}}|}\left(\prod_{f=l,\nu,Z}\frac{d^3p_f}{(2\pi)^3}\frac{1}{2E_f}\right) \times (2\pi)^4 \delta^4\left(P + \sum p\right) \times \Re(2\mathcal{M}_0 \delta\mathcal{M}^*). \tag{6}$$

The SM matrix element $\mathcal{M}_0$ is given by W,Z production via t- and u-channel exchange of a quark, and by s-channel production of an off-shell W^* boson decaying to W, Z via the SM WWZ vertex

$$\Gamma_{\mu\nu\rho} = ie\cot\theta_W(k_{1\mu}g_{\nu\rho} - k_{1\rho}g_{\nu\mu} - k_{2\mu}g_{\nu\rho} + k_{2\nu}g_{\rho\mu} + k_{Z\rho}g_{\mu\nu} - k_{Z\nu}g_{\mu\rho}). \tag{7}$$

Here, $k_{1,2}$ are the momenta of the W's, and k_Z is the momentum of the Z.

If $\tilde{\lambda}_Z$ is nonzero, the WWZ vertex is shifted by a term of the form

$$\delta\Gamma_{\mu\nu\rho} = e\cot\theta_W \frac{\imath\tilde{\lambda}_Z}{M_W^2}(k_{2\nu}\epsilon_{\mu\rho\sigma\tau}k_2^\sigma k_1^\tau + k_{1\rho}\epsilon_{\mu\nu\sigma\tau}k_2^\sigma k_1^\tau - k_1 \cdot k_2 \epsilon_{\mu\nu\sigma\tau}k_2^\sigma k_1^\tau). \tag{8}$$

This vertex will lead to a potentially observable correction to the cross section for WZ production at the LHC.

The immediate difficulty is that a spin-averaged $2 \to 2$ scattering process cannot yield a term in the cross section proportional to the epsilon tensor. This is because there are only 3 independent momenta in a $2 \to 2$ process, while the ϵ contribution will be nonzero only if contracted into 4 independent momenta. For example, one cannot detect an asymmetry in the spin-averaged process $q\bar{q} \to WZ$.

To obtain an asymmetry, one must keep track of the polarization of the outgoing gauge bosons. There is vast literature on measuring W and Z polarizations, via asymmetries in their decays to leptons or jets. A complete analysis using these polarizations is left for future work. For this analysis, we shall instead focus on a particular decay channel $W \to l\nu$, $Z \to ll$, which has a clean trilepton signal. This will enable us to use the background analysis of [9].

Specifically, we denote by p_q and $p_{\bar{q}}$ the momenta of the incoming quark and antiquark, respectively, and by p_l and

p_ν the momenta of the lepton and neutrino arising from the decay of the outgoing W. We treat the Z as an outgoing particle with momentum k_Z, since it can be reconstructed easily using the $Z \to l^+ l^-$ decay product leptons. Then, we will have new terms in the cross section proportional to

$$\epsilon_{\mu\nu\rho\sigma}(p_q + p_{\bar{q}})^\mu (p_q - p_{\bar{q}})^\nu p_l^\rho k_Z^\sigma. \tag{9}$$

As explained above, such a term is a direct probe of *CP* violation.

For the form of $d\sigma$ given above, the integrated change in the cross section will vanish. To obtain a nonzero result, we must weight the events by an asymmetric observable, which is itself parity asymmetric, for instance, the sign of a triple product. We further observe that p_q and $p_{\bar{q}}$ have nonzero components only along the time and beam axes. This implies that the outgoing lepton and Z contraction into the ϵ is proportional to $k_Z^T \times p_l^T$. Hence, for our asymmetric observable, we should weight events by the sign of the cross product $p_q \cdot (k_Z \times p_l)$.

But we cannot measure the momentum of the quark, and there is a 4-fold ambiguity in its reconstruction. We will instead use the momentum of the Z along the beam axis as a proxy for the quark momentum. Since the quark typically has a larger momentum fraction than the antiquark, the Z boson will typically move in the same direction along the beam axis as the quark. Through numerical simulations we find that this correlation is $\gtrsim 70\%$, so the *CP* asymmetry will not be degraded significantly by choosing the Z momentum as the proxy for the quark momentum.

We will therefore weight events by

$$\Xi^z_\pm(k_Z, p_l) \equiv \mathrm{sgn}(k_Z^z)\mathrm{sgn}(p_l \times k_Z)^z \tag{10}$$

as a substitute for the more direct, but unmeasurable full triple product. Although this substitution is imperfect, it should provide for a nonvanishing weighted cross section and a striking test of *CP* violation if it is present. The resulting asymmetric observable is then obtained by integrating the sign-weighted differential cross section

$$\Delta\sigma = \int d\sigma(pp \to W^* \to WZ)\Xi^z_\pm(k_Z, p_l). \tag{11}$$

Experimentally, this observable is measured by counting trilepton events weighted by a sign determined from the observed momenta.

IV. EVENT RATES

Considerable effort has been expended in determining the ability of the LHC to probe corrections to the WWZ vertex, particularly through the $pp \to WZ \to lll\nu$ channel. We can therefore make use of the cuts and backgrounds determined for previous WWZ analyses.

We will here follow the analysis presented in [9]. The following cuts were used in this analysis:

(i) Three isolated electrons or muons with $|\eta| < 2.5$ and $|P_T| > 25$ GeV.
(ii) Two leptons are of like flavor and opposite sign, and reconstruct to an on-shell Z within 10 GeV.
(iii) Missing $P_T > 25$ GeV
(iv) No other charged leptons with $|\eta| < 2.5$, $|P_T| > 25$ GeV
(v) There exists a solution for neutrino momentum that reconstructs to an on-shell W.

Subject to these cuts, the number of events with 30fb^{-1} of integrated luminosity was found to be ~2500, including both tree-level WWZ processes and other SM contributions [9].

These events will be distributed symmetrically. We therefore expect to have ~1250 events with one particular sign of the $\Xi^z_\pm(k_Z, p_l)$, and ~1250 events with the opposite sign. The net expected value of the observable $\Delta\sigma$ is thus zero. However, due to the statistical uncertainties, the observable will have a variance of $\sqrt{2500} \sim 50$. To have a signal-to-background ratio of 5, we need ~250 asymmetric events with 30 fb^{-1}, and by extrapolation, ~460 asymmetric events with 100 fb^{-1} of data.

Note that the number of asymmetric events required is still only ~10% of the number of tree-level events. This is consistent with a small linear asymmetric correction, where the quadratic piece can be ignored when computing the statistical significance of the $\Delta\sigma$ asymmetry signal.

V. RESULTS

We can now calculate the reach of the LHC for the vertex (8). We compute the linear interference term in the $pp \to W^* \to WZ$ cross section by computing the Feynman diagrams associated with $q\bar{q}' \to WZ$. There are four such diagrams, three of which are SM diagrams (s-channel W^* exchange, and t and u-channel quark exchange diagrams), and one is the *CP*-violating interaction diagram (s-channel W^* exchange with *CP*-violating WWZ interaction). We then generate a large number of events using PYTHIA 6.401 [10], modified to include the *CP*-violating interaction and the weighted signs $\Xi^z_\pm(k_Z, p_l)$. We calculate the cross section for the asymmetric observable at the LHC to be

$$\Delta\sigma \simeq \tilde{\lambda}_Z \times (3 \times 10^3 \text{ fb}). \tag{12}$$

It may seem surprising that such a large cross section is generated by the addition of a dimension 6 operator (suppressed by M_W^2). But the extra derivatives in the operator allow a dependence on the external momenta, which can enhance the signal. The momentum structure that dominates the asymmetric signal scales as $(p_q - p_{\bar{q}}) \cdot (p_l - p_{\bar{\nu}})/M_W^2$, which can be large at LHC energies.

As shown above, we need ~460 asymmetric events for a 5σ detection of this operator with 100 fb^{-1} of data. Using the results shown in Fig. 1, we conclude that LHC should be sensitive to the $\tilde{\lambda}_Z$ operator coefficient at the level of

$$\tilde{\lambda}_Z \lesssim 0.002 \tag{13}$$

with 100 fb^{-1} of data. This is almost 2 orders of magnitude better than the results of the LEP2 experimental measurements.

This asymmetric observable can also receive contributions from CP-conserving terms (both from new physics and the SM) with absorptive phases. The SM contribution is in principle computable (as are the new physics contributions, given the observation of the relevant new particles at the LHC). But these absorptive phases are typically dealt with by considering an observable that is defined as the difference between two charge conjugate observables; the absorptive phases then cancel. One can consider the above asymmetric observable defined separately for outgoing $l^+l^+l^-$ and $l^+l^-l^-$ states, and take the difference after normalizing each by the total cross section to W^+Z and W^-Z, respectively (to account for the fact that the initial pp state is not CP-symmetric). Of the WZ events we generated, a W^+ was in the outgoing state ~70% of the time. Thus, this method for accounting for absorptive phases should only reduce sensitivity by $\mathcal{O}(1)$ factors. A more complete analysis of these absorptive effects is possible, but beyond the scope of this paper.

The level of sensitivity is similar to the sensitivity that electric dipole moment experiments have to $\tilde{\lambda}_\gamma$ and $\tilde{\kappa}_\gamma$ [11–13], the coefficients of related CP-violating operators. The sensitivity limits there are approximately $|\tilde{\kappa}_\gamma| < 5.2 \times 10^{-5}$ and $|\tilde{\lambda}_\gamma| < 0.019$ [13]. Although $\tilde{\lambda}_Z$ is the coefficient of a different operator, it is often thought that limits on any CP-violating operator apply to the rest of the operators, since they are presumably related by the underlying theory. We have no strong opinion on this connection, but merely note here that under this philosophy the LHC sensitivity rivals or may be better that of electric dipole moments.

VI. ADDITIONAL APPLICATIONS

In this paper, we have illustrated the general features of an interference analysis that is very sensitive to CP-violating physics. The interference analysis we presented can be applied to a wide variety of processes at different experiments. For example, CP-violating corrections to the WWZ vertex can also be studied at the Tevatron [14], through the process $p\bar{p} \rightarrow W^* \rightarrow WZ \rightarrow lll\nu$. Although the number of events in the sample is currently low—approximately 13 candidate events in 1 fb^{-1} at D0 [15]—some useful bounds may be obtainable if the luminosity increases substantially and the CDF and D0 experiments are combined.

Similarly, one can probe CP violation in the WWZ vertex at linear colliders [16] via the process $e^+e^- \rightarrow Z^* \rightarrow W^+W^- \rightarrow l\nu l\nu$. Note that the natural channel for observing this effect operates when running well above the Z-boson pole. As such, this type of analysis could provide a very sharp tool at the ILC.

One can furthermore study a variety of similar CP-violating operators at the LHC, such as $\tilde{\lambda}_\gamma$. Because of the comparable efficiency in detecting the γ as opposed to the Z, one expects that the sensitivity to this operator at hadron colliders is similar to the sensitivity to $\tilde{\lambda}_Z$. However, one would have to consider the background in detail in order to assess the detection possibilities.

Lastly, one can certainly probe CP violation beyond the WWZ and $WW\gamma$ vertices using this type of interference effect. For example, CP violation in the Higgs sector can manifest itself in $H^* \rightarrow ZZ$ decays after applying a similar analysis.

These channels are currently under study, and we hope to report on them soon.

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