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

Jason Kumar\textsuperscript{a} and Arvind Rajaraman\textsuperscript{a} and James D. Wells\textsuperscript{c,}\textsuperscript{†}

\textsuperscript{a} Physics Department, University of California, Irvine, CA 92697
\textsuperscript{b} CERN, Theory Division (PH-TH), CH-1211 Geneva 23, Switzerland
\textsuperscript{c} Michigan Center for Theoretical Physics (MCTP), Ann Arbor, MI 48109

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.

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 which 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 CKM phase – is not sufficient to generate the known baryon asymmetry, and so some other source is needed.

In many models, large 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. 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 a specific operator which contributes to the WWZ vertex, and show that collider searches can improve current bounds on this operator by well over an order of magnitude.

**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]

\[ i\mathcal{L}_{\text{eff}} = g_{WZW} \left[ g_1^Z Z^\mu (W_{\mu}^- W^{\tau +} - W_{\mu}^+ W^{\tau -}) + \kappa_Z W_{\mu}^+ W_{\nu}^- Z^{\mu\nu} + \frac{\lambda_2}{M_W^2} Z_{\mu\nu} W_{\nu}^+ W_{\mu}^- + ig_5^Z \epsilon_{\mu\nu\rho\sigma} ((\partial^\alpha W_{\nu}^-) W_{\mu}^{\tau +} - W_{\mu}^- \partial^\alpha W_{\mu}^{\tau +}) Z^{\alpha\rho\sigma} + \frac{\lambda_5}{2M_W^2} W_{\mu}^- W_{\nu}^+ (\partial^\alpha Z^{\mu\nu} + \partial^\nu Z^{\mu\nu}) + \frac{\tilde{\lambda}_Z}{2M_W^2} W_{\mu}^- W_{\nu}^+ \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_2}{2M_W^2} W_{\mu}^- W_{\mu}^+ \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} \right] \]

(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, $g_1^Z = 1$, and all the other terms are zero.

In this Lagrangian, $g_1^Z, \kappa_Z, \lambda_Z, g_5^Z$ 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 $\sim 0.1$. The DELPHI Collaboration [5] used the process $e^+e^- \to W^+W^- \to l\nu q\bar{q}(l = e/\mu)$ to obtain the measurements

\[ g_5^Z = -0.39^{+0.10}_{-0.20} \] (2)
\[ \kappa_Z = -0.09^{+0.08}_{-0.05} \] (3)
\[ \lambda_Z = -0.08 \pm 0.07 \] (4)

LEP and Tevatron sensitivities to the related coefficient $\lambda_2$ are only at $\lambda_2 \leq 0.3$ [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

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*Electronic address: kumarj@uci.edu
†Electronic address: arajaram@uci.edu
‡Electronic address: jwells@umich.edu
element and $\delta M$ 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 CKM 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 $\epsilon_{\mu
u\rho\sigma}$ 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 $t \rightarrow -t$). Indeed explicit computations using the effective Lagrangian show that all terms proportional to the epsilon tensor in the interference term are proportional to CP-violating coefficients. Note that $g_{\epsilon}^{Z}$ is the coefficient of a parity-violating, CP-conserving operator which also is proportional to the $\epsilon$ 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 $\delta \sigma \propto \epsilon_{\mu
u\rho\sigma}$. Experimental signals of these terms can be used to probe the couplings $g_{\epsilon}^{Z}, \tilde{k}_Z, \tilde{\lambda}_Z$. In this note, we shall discuss the experimental sensitivities on $\tilde{\lambda}_Z$, leaving the more exhaustive analysis for future work.

**Signals of CP-violation**

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

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

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

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

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

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

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 $2 \rightarrow 2$ 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 $2 \rightarrow 2$ process, while the $\epsilon$ contribution will be non-zero only if contracted into 4 independent momenta. For example, one cannot detect an asymmetry in the spin-averaged process $q\bar{q} \rightarrow WZ$.

To obtain an asymmetry, one must keep track of the polarization of the outgoing gauge bosons. There is a 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 $W \rightarrow l\nu, Z \rightarrow ll$ 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 $p_{\nu}$ 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 $Z \rightarrow l^+l^-$ decay product leptons. Then we will have new terms in the cross-section proportional to

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

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 non-zero result, we must weight the events by an asymmetric observable, for instance, the sign of a triple-product. We further observe that $p_q$ and $p_{\bar{q}}$ have non-zero components only along the time and beam axes. This implies that the outgoing lepton and $Z$ contraction into the $\epsilon$ 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

$$\Xi^\pm(k_Z,p_t) \equiv sgn(k_Z^2)sgn(p_t \times k_Z)^{\pm}$$

(10)
as a substitute for the more direct, but unmeasurable full triple product. Although this substitution is imperfect, it should provide for a non-vanishing 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

$$\Delta\sigma = \int d\sigma(pp \rightarrow W^* \rightarrow WZ) \Xi^\pm(k_Z,p_t)$$

(11)

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

**Event rates**

Considerable effort has been expended in determining the ability of the LHC to probe corrections to the $WWZ$ vertex, particularly through the $pp \rightarrow WZ \rightarrow lll\nu$ 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:

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

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

These events will be distributed symmetrically. We therefore expect to have $\sim 1250$ events with one particular sign of the $\Xi^\pm(k_Z,p_t)$, and $\sim 1250$ 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 $\sim 250$ asymmetric events with $30 \text{ fb}^{-1}$, and by extrapolation, $\sim 460$ asymmetric events with $100 \text{ fb}^{-1}$ of data.

![FIG. 1: Plot of $\Delta\sigma$ asymmetry cross-section as a function of $\lambda_Z$. Lines (a), (b) and (c) correspond respectively to $\Delta\sigma$ in 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 5$\sigma$ and 95% confidence reach, respectively.](image)

Note that the number of asymmetric events required is still only $\sim 10\%$ 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.

**Results**

We can now calculate the reach of the LHC for the vertex [8]. We compute the linear interference term in the $pp \rightarrow W^* \rightarrow WZ$ cross-section by computing the Feynman diagrams associated with $q\bar{q}' \rightarrow WZ$. 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 $\Xi^\pm(k_Z,p_t)$. We calculate the cross-section for the asymmetric observable at the LHC to be

$$\Delta\sigma \simeq \lambda_Z \times (3 \times 10^3 \text{ fb}).$$

(12)

As shown above, we need $\sim 460$ asymmetric events for a 5$\sigma$ detection of this operator with $100 \text{ fb}^{-1}$ of data. We conclude that LHC should be sensitive to the $\lambda_Z$ operator coefficient at the level of

$$\lambda_Z \lesssim 0.002$$

(13)

with $100 \text{ fb}^{-1}$ of data. This is almost two orders of magnitude better than the results of the LEP2 experimental measurements.
The level of sensitivity is similar to the sensitivity that EDM experiments have to $\lambda_\gamma$ and $\tilde{\kappa}\gamma$ [11, 12, 13], the coefficients of related CP-violating operators. The sensitivity limits there are approximately $|\tilde{\kappa}| < 5.2 \times 10^{-5}$ and $|\lambda_\gamma| < 0.019$ [14]. Although $\lambda_\gamma$ 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 better that of EDMs.

**Additional Applications**

In this letter we have illustrated the general features of an interference analysis which is very sensitive to CP-violating physics. The interference analysis we presented of an interference analysis which is very sensitive to CP-violating physics. The interference analysis we presented of an interference analysis which is very sensitive to CP-violating physics. One can furthermore study a variety of similar CP-violating operators at the LHC, such as $\lambda_\gamma$. Due to the comparable efficiency in detecting the $\gamma$ as opposed to the $Z$, one expects that the sensitivity to this operator at hadron colliders is similar to the sensitivity to $\lambda_\gamma$. 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 as opposed to the $Z$, one expects that the sensitivity to this operator at hadron colliders is similar to the sensitivity to $\lambda_\gamma$. However, one would have to consider the background in detail in order to assess the detection possibilities.

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

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