CP VIOLATION IN Wγ and Zγ PRODUCTION

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Abstract

We study the capability of a 2 TeV p̅p collider with an integrated luminosity of 10 fb⁻¹ to study CP violation in the processes p̅p → W±γ and p̅p → Zγ. We assume the existence of new CP violating interactions beyond the standard model which we describe with an effective Lagrangian. We find that the study of CP-odd observables would allow this machine to place bounds on CP violating anomalous couplings similar to the bounds that the same machine can place on CP conserving anomalous couplings. For example it could place the bound |κγ| < 0.1 at the 95% confidence level.

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1 Introduction

There has been a recent effort to investigate the physics potential of a high-luminosity upgrade of the Fermilab Tevatron collider [1]. One of the directions of this study is the possibility to probe new $\mathcal{CP}$ violating interactions in $W$ and $Z$ physics. We have previously studied the issue of searching for $\mathcal{CP}$ violation in $W$ and $W$ jet production [2]. In this paper we extend that study to the case of $W\gamma$ and $Z\gamma$ production.

The motivation for this study is, of course, that the origin of $\mathcal{CP}$ violation remains unexplained and the question should be pursued experimentally wherever possible. The reactions $p\bar{p} \rightarrow W^\pm\gamma$ or $Z\gamma$ have been studied at the Tevatron and will be studied in further detail at an upgraded machine where samples of a few thousand events are expected [1]. The kinematics of these reactions, unlike that of single $W^\pm$ or $Z$ production, allows triple-product $\mathcal{CP}$ violating correlations to exist.

It is known that the standard model and minimal extensions (for example multi-Higgs models) do not produce sizable $\mathcal{CP}$ violating effects in high-energy processes as the ones we discuss in this paper [3]. We will assume that there are new $\mathcal{CP}$ violating interactions at high energy [4] which manifest themselves at energy scales up to a few TeV as $\mathcal{CP}$ violating operators in an effective Lagrangian that involves only the fields present in the minimal standard model and respects its symmetries [1, 2, 3, 6, 7, 8, 9].

The $\mathcal{CP}$ violating operators that could lead to a $\mathcal{CP}$-odd observable in direct $W\gamma$ and $Z\gamma$ production would also contribute to low energy processes where there is no evidence for $\mathcal{CP}$ violation beyond that present in the CKM phase of the minimal standard model. However, as we argued in Ref. [2], there are several reasons why the higher energy processes would be more sensitive to certain types of interactions than the lower energy counterparts. Among them, that contributions from the new operators (associated with physics at some high energy scale $\Lambda$) to amplitudes at an energy scale $\mu$ are suppressed by powers of $(\mu/\Lambda)^2$. The effects of these operators in direct $W^\pm\gamma$ production are thus enhanced by at least a factor of $M_W^2/m_W^2 \approx 3.5 \times 10^5$ over their effects in, say, radiative pion decays [2]. It is true that there are stringent indirect bounds on some of the new operators from observables such as the electric dipole moment of the neutron [10]. However, these bounds depend on naturalness assumptions and are, therefore, complementary to the ones that can be placed in direct $W^\pm\gamma$ and $Z\gamma$ production.

For our study, we will use $\mathcal{CP}$ odd observables already described in the literature or very closely related ones [3, 4, 6, 11]. We present this analysis as a framework for experimental searches for $\mathcal{CP}$ violation. Having a specific parameterization of $\mathcal{CP}$ violating interactions it is possible to compare different observables and distributions, and in that way distinguish truly $\mathcal{CP}$ violating new physics from potential $\mathcal{CP}$ biases of the detectors.

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2 As it is necessary in order to explain the baryon asymmetry in the universe.
\[ p\bar{p} \rightarrow W^\pm \gamma \rightarrow \ell^\pm \nu \gamma \]

This reaction is similar to the process \( p\bar{p} \rightarrow W^\pm \text{jet} \) that we considered in Ref. [2]. In fact, the same operator that we considered in that case, Eq. 18 of Ref. [2], would generate \( \mathcal{CP} \)-odd asymmetries in this process as well. We will focus here on a different operator that generates \( \mathcal{CP} \)-odd asymmetries in this mode through a \( \mathcal{CP} \) violating \( WW\gamma \) coupling. The \( \mathcal{CP} \) violating \( WW\gamma \) couplings have been traditionally parameterized in terms of \( \tilde{\kappa} \) and \( \tilde{\lambda} \) following Ref. [12]. However, within an effective Lagrangian description of the symmetry breaking sector of the standard model, the coupling \( \tilde{\lambda} \) is suppressed with respect to \( \tilde{\kappa} \) by a factor \( \mu^2/\Lambda^2 \) for a process with a typical energy scale \( \mu \). We denote by \( \Lambda \) the scale of the new \( \mathcal{CP} \) violating interactions that give rise to \( \tilde{\kappa} \) and \( \tilde{\lambda} \). For this reason we concentrate on the coupling \( \tilde{\kappa} \) using the effective Lagrangian in a notation similar to that of Ref. [9]:

\[
\mathcal{L} = \frac{v^2}{\Lambda^2} \left( \frac{1}{4} \alpha_{13} g g' \epsilon_{\mu
u\rho\sigma} B_{\mu\nu} \text{Tr}(T W_{\rho\sigma}) + \frac{1}{8} \alpha_{14} g^2 \epsilon_{\mu
u\rho\sigma} \text{Tr}(T W_{\mu\nu}) \text{Tr}(T W_{\rho\sigma}) \right). \tag{1}
\]

This differs from Ref. [9] in that we have introduced a factor \( v^2/\Lambda^2 \) (\( v \approx 246 \text{ GeV} \)), for consistency with the power counting relevant for this type of new physics [13]. In terms of the conventional notation of Ref. [12] we have [9]:

\[
\tilde{\kappa}_\gamma = -\frac{e^2 v^2}{s_\theta^2 \Lambda^2} (\alpha_{13} + \alpha_{14}), \quad \tilde{\kappa}_Z = \frac{v^2}{\Lambda^2} \left( \frac{e^2}{e_\theta^2} \alpha_{13} - \frac{e^2}{s_\theta^2} \alpha_{14} \right), \tag{2}
\]

where \( e_\theta = \cos \theta_W \), \( s_\theta = \sin \theta_W \). The process \( p\bar{p} \rightarrow W^\pm \gamma \) is only sensitive to \( \tilde{\kappa}_\gamma \).

The new physics that generates these anomalous couplings will in general give rise to form factors in the \( WW\gamma \) vertex with imaginary (absorptive) parts that are typically of the same size as the real parts. These absorptive parts combine with the \( \mathcal{CP} \) violating couplings to generate additional \( \mathcal{CP} \) odd observables. To study these observables we will assume that there is such an absorptive phase in the \( WW\gamma \) vertex and parameterize it by \( \sin \delta(WW\gamma) \) which we assume to be a number of order one [9].

With all this in mind we proceed to compute the differential cross-section for the process \( \bar{u}(p_u)d(p_d) \rightarrow \ell^-(p_\ell)\nu(p_\nu)\gamma(p_\gamma) \). We find a \( \mathcal{CP} \) violating term linear in \( \tilde{\kappa}_\gamma \) that contains a triple product. After squaring the matrix element, averaging over initial quark color and spin, and summing over the final photon polarization, we find for this term:

\[
|M_{\mathcal{CP}}|^2 = \frac{4}{3} e^2 g^4 |V_{ud}|^2 \tilde{\kappa}_\gamma \frac{e(p_u,p_d,p_\ell,p_\gamma)}{(s - M_W^2)(m_\ell^2 - M_W^2)^2} \cdot \left[ \frac{2p_\ell \cdot p_u}{3(p_\gamma - p_u)^2} + \frac{p_\ell \cdot p_u + p_\nu \cdot p_d}{(s - M_W^2)} + \frac{p_\nu \cdot p_d}{3(p_\gamma - p_d)^2} \right], \tag{3}
\]

\[ ^3 \text{See Ref. [9] for a calculation of such an absorptive phase within a specific model for } \mathcal{CP} \text{ violation.} \]
where \( \hat{s} = (p_u + p_d)^2 \) and \( m_W^2 = (p_\ell + p_\nu)^2 \). We use the narrow width approximation and, therefore, neglect the contributions to \( pW \to \ell^- \nu \gamma \) from radiative \( W \) decays. To justify this approximation we restrict our study to the region of phase space where it works best, given by the cuts described in Ref. [14]. For our numerical results we use set B1 of the Morfin-Tung parton distribution functions [15] evaluated at a scale \( \mu^2 = M_W^2 + p_{T,\gamma}^2 \) and the following cuts: \( p_{T,\gamma} > 10 \text{ GeV}, p_{T,\ell} > 20 \text{ GeV}, p_T > 20 \text{ GeV}, |y_\gamma| < 2.4, |y_\ell| < 3.0, \Delta R(\ell_\gamma) > 0.7 \) and \( M_T(\ell_\gamma, p_T) > 90 \text{ GeV} \). The first and last two cuts, defined as in Ref. [14], suppress the radiative \( W \) decays. The other cuts are typical Tevatron acceptance cuts [1].

The correlation in Eq. 3 generates \( CP \)-odd and \( T \)-odd observables based on the following triple-product in the lab frame: \( \vec{p}_\gamma \cdot (\vec{p}_\ell \times \vec{p}_{\text{beam}}) \). We proceed as in Ref. [2] and construct the \( T \)-odd observable:

\[
A^\pm = \sigma^\pm[(\vec{p}_\gamma \times \vec{p}_{\text{beam}}) \cdot \vec{p}_\ell > 0] - \sigma^\pm[(\vec{p}_\gamma \times \vec{p}_{\text{beam}}) \cdot \vec{p}_\ell < 0] \tag{4}
\]

where \( A^\pm \) refers to the observable for \( W^\pm \) events (or \( \ell^\pm \nu \) events). Using Eq. 4 we construct the following \( CP \)-odd observables:

\[
R_1 \equiv \frac{A^+ - A^-}{\sigma^+ + \sigma^-} \\
R_2(y_0) \equiv \frac{\frac{dA^+}{dy} |_{y=y_0} - \frac{dA^-}{dy} |_{y=-y_0}}{\frac{dA^+}{dy} |_{y=y_0} + \frac{dA^-}{dy} |_{y=-y_0}}, \tag{5}
\]

where \( y \) can be the rapidity of the lepton or the photon (or the \( W \)). Similar observables can be constructed for other distributions [2] but we will not consider them in this paper.

When we allow for a non-zero absorptive phase, sin \( \delta(WW\gamma) \), there are additional \( CP \) violating terms in the differential cross-section. They generate a new set of \( (T\)-even) \( CP \)-odd asymmetries and following Ref. [2] we construct the following:

\[
\tilde{R}_1 \equiv \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \\
\tilde{R}_2(y_0) \equiv \frac{\frac{d\sigma^+}{dy} |_{y=y_0} - \frac{d\sigma^-}{dy} |_{y=-y_0}}{\frac{d\sigma^+}{dy} |_{y=y_0} + \frac{d\sigma^-}{dy} |_{y=-y_0}}, \tag{6}
\]

where \( \sigma^\pm \) refers to \( \sigma(p\overline{p} \to \ell^\pm \nu \gamma) \).

With the set of cuts discussed above, we find numerically that:

\[
\sigma^- \approx (245 - 36\tilde{\kappa}_\gamma \sin(\delta(WW\gamma))) \text{fb} \\
\sigma^+ \approx (245 + 36\tilde{\kappa}_\gamma \sin(\delta(WW\gamma))) \text{fb} \\
A^+ = -A^- \approx 119\tilde{\kappa}_\gamma \text{fb} \tag{7}
\]

and, therefore, \( R_1 \approx 0.49\tilde{\kappa}_\gamma \) and \( \tilde{R}_1 \approx 0.15\tilde{\kappa}_\gamma \sin(\delta(WW\gamma)) \). For an integrated luminosity of 10 fb\(^{-1}\) we thus expect some 2500 \( W^- \gamma \) events within the phase space region defined by our cuts and this translates into the 95% confidence level bound:

\[
|\tilde{\kappa}_\gamma| \leq 0.1 \tag{8}
\]
Taking $\Lambda \sim 1$ TeV, the bound Eq. 8 translates into $|\alpha_{13} + \alpha_{14}| \leq 4$. In a theory where there is no suppression of $\mathcal{CP}$ violating interactions with respect to $\mathcal{CP}$ conserving ones, these couplings could be of order one and thus this bound could be significant. However, it is more likely that these couplings are much smaller. For example, Ref. [9] finds in generic technicolor models, $\alpha_{13,14} \sim 10^{-4}$ ($\tilde{\kappa}_\gamma \sim 8 \times 10^{-6}$).

It is interesting to compare this bound with the corresponding bound that the same machine could place on similar, but $\mathcal{CP}$ conserving, anomalous couplings. For example it has been claimed that a 95% confidence level bound $|\kappa_\gamma| \leq 0.2$ can be achieved [10]. It is possible to place similar constraints on $\mathcal{CP}$ violating and $\mathcal{CP}$ conserving anomalous couplings. Traditional studies of anomalous couplings [1, 14] have not discussed the coupling $\tilde{\kappa}_\gamma$ because there is a very strong indirect limit coming from the electric dipole moment of the neutron $|\tilde{\kappa}_\gamma| \leq 2 \times 10^{-4}$ [10]. This is a very tight indirect bound, and it indicates that it is quite unlikely that a non-zero $\mathcal{CP}$-odd effect will be observed in $p\bar{p} \to W^{\pm}\gamma$. Nevertheless, in full generality, the electric dipole moment of the neutron and the $\mathcal{CP}$-odd observables that we study here, depend on different combinations of anomalous couplings and, therefore, complement each other. Because of this, and because the origin of $\mathcal{CP}$ violation is not understood, we would argue that an experimental search is necessary regardless of the merits of the limits that can be placed on couplings like $\tilde{\kappa}_\gamma$.

Obviously, any experimental search will have to be able to distinguish between truly $\mathcal{CP}$ violating effects and possible $\mathcal{CP}$ biases of the detector. An important tool for this goal is the simultaneous measurement and comparison of as many observables as possible. With this in mind, we present in Figure [1] the observable $R_2(y_e)$ as an example. The curve corresponds to $\tilde{\kappa}_\gamma = 1$, and scales linearly with $\tilde{\kappa}_\gamma$. This observable is zero for all values of $y_e$ if $\mathcal{CP}$ is conserved.

3 $p\bar{p} \to Z\gamma \to \ell^\pm \ell^\mp \gamma$

Unlike the reaction which we studied in the previous section, $p\bar{p} \to Z\gamma \to \ell^\pm \ell^\mp \gamma$ is self-conjugate under a $\mathcal{CP}$ transformation. This results in the need for different $\mathcal{CP}$-odd observables. Another difference between the two processes is that $p\bar{p} \to Z\gamma \to \ell^\pm \ell^\mp \gamma$ does not receive contributions from Eq. 1 because the next to leading order effective Lagrangian for the symmetry breaking sector of the standard model does not produce anomalous $ZZ\gamma$ or $Z\gamma\gamma$ couplings. To generate a non-zero effect in this process we will have to go beyond the next to leading order effective Lagrangian, and we thus expect that any effect in $p\bar{p} \to Z\gamma \to \ell^\pm \ell^\mp \gamma$ will be smaller than a corresponding effect in $p\bar{p} \to W^{\pm}\gamma \to \ell\nu\gamma$.

In Ref. [12] the anomalous $Z(q_1^\alpha)\gamma(q_2^\beta)V(P^\mu)$ vertices are parameterized in terms of several form factors, (where $V = Z, \gamma$). For example, there is a $\mathcal{CP}$ violating term

\footnote{Among other things this would be a theory with no custodial $SU(2)$ symmetry.}
The overall factor \( (P^2 - M^2)/M_Z^2 \) is required by electromagnetic gauge invariance for \( V = \gamma \) and by Bose symmetry for \( V = Z \) \([12]\). Because of this factor, the contributions from Eq. \( 9 \) to \( q \bar{q} \rightarrow Z \gamma \) are equivalent to those of local operators of the forms:

\[
\mathcal{O}_\gamma = \frac{1}{\Lambda^2} \frac{eg}{2c_\theta} Q_q \bar{q} \gamma^\mu q Z^\nu F_{\mu\nu},
\]

\[
\mathcal{O}_Z = \frac{1}{\Lambda^2} \frac{eg}{4c_\theta} \bar{q} \gamma^\mu [R_q(1 + \gamma_5) + L_q(1 - \gamma_5)] q Z^\nu F_{\mu\nu},
\]

where \( F_{\mu\nu} \) is the electromagnetic field strength tensor, \( L_q = \tau_3 - 2Q_q s_\theta^2 \) and \( R_q = -2Q_q s_\theta^2 \). We have changed the normalization scale from \( M_Z \) to \( \Lambda \), the scale of the new physics responsible for this operator. Since we want to insist on an effective Lagrangian that preserves the symmetries of the standard model we must convert these operators into fully \( SU(2)_L \times U(1)_Y \) gauge invariant versions. There are at least two ways to do this. One way would be to obtain the \( Z^\nu \) field from an \( SU(2) \) covariant derivative acting on the fermion field. There are several dimension 6 operators with the desired properties listed in Ref. \([9]\). One of them is:

\[
\mathcal{L} = i \frac{\bar{q} \gamma_\mu (\mathcal{O}_Q + \mathcal{O}_u + \mathcal{O}_d) + \text{h.c.}}{2\Lambda^2} + i \frac{\bar{q} \gamma_\mu [R_q(1 + \gamma_5) + L_q(1 - \gamma_5)] q \gamma^\nu q B_{\mu\nu}}{4c_\theta} + \text{h.c.}
\]
With this approach we have an operator that is suppressed by only two powers of the new physics scale. However, as one can see from Eq. 11, the fully gauge invariant version of the operator Eq. 10 also generates $\bar{q}qZ$ and $\bar{q}q\gamma$ vertices. When all of these new vertices are systematically taken into account, the interference between the lowest order standard model amplitude and the new $\mathcal{CP}$-violating amplitude for the process $\bar{q}q \rightarrow \ell^+\ell^-\gamma$ vanishes and one is left with no $\mathcal{CP}$-odd effects. This is a rather surprising result that we have checked for all the relevant operators in Ref. [5].

A second way to make Eq. 10 fully gauge invariant uses a non-linearly realized electroweak symmetry breaking sector. In this case we think of Eq. 10 as the unitary gauge version of fully gauge invariant operators that can be constructed as described in Refs. [8, 13]. This construction generates the $\mathcal{CP}$ odd observables which we discuss next. However, the counting rules appropriate for this construction [18], tell us that the operators are suppressed by four inverse powers of the symmetry breaking scale and any effects are, therefore, expected to be extremely small.

Taking the unitary gauge Lagrangian

$$\mathcal{L} = \frac{v^2}{\Lambda^4} \left( h_1^1 \mathcal{O}_\gamma + h_1^Z \mathcal{O}_Z \right)$$

we find for $\bar{q}q \rightarrow \ell^+\ell^-\gamma$ a term linear in $h_1^Y$ that contains a triple product:

$$|\mathcal{M}_{\mathcal{CP}}|^2 = \frac{1}{12} \frac{v^2 h_1^Y}{\Lambda^4} e^2 Q_q \left( \frac{1}{m_{\ell\ell}^2 - M_Z^2} \right)^2 \epsilon(p_q, p_{\bar{q}}, p^+, p^-) \cdot \left[ (L_\ell^2 + R_\ell^2) C_{V1} \left( \frac{p_q \cdot (p^- - p^+)}{2p_q \cdot p_{\gamma}} - \frac{p_{\bar{q}} \cdot (p^- - p^+)}{2p_{\bar{q}} \cdot p_{\gamma}} \right) \right]$$

where $C_{\gamma 1} = Q_q(L_q - R_q)$, $C_{Z1} = L_q^2 - R_q^2$, $C_{\gamma 2} = Q_q(L_q + R_q)$ and $C_{Z2} = L_q^2 + R_q^2$. We use the narrow-width approximation again and neglect the contributions from radiative $Z$ decays. As before, we restrict ourselves to the region of phase space where this approximation works best by imposing the cuts: $p_{T\gamma} > 10$ GeV, $p_{T\ell} > 20$ GeV, $|y_\gamma| < 2.4$, $|y_\ell| < 3.0$, $\Delta R(\ell\gamma) > 0.7$ and $M_{\ell^+\ell^-\gamma} > 100$ GeV. As in the case of $W^\pm\gamma$, the first and last two cuts, defined as in Ref. [14], suppress the radiative $Z$ decays and the remainder of the cuts are typical Tevatron acceptance cuts [1].

In this reaction there can also be an absorptive phase in the form-factor of Eq. 4. If we include this absorptive phase, $\sin \delta(qqZ\gamma)$, we find additional $\mathcal{CP}$ violating contributions to the differential cross-section. As in the case of $W^\pm\gamma$, these new contributions are too cumbersome to write out explicitly but we include them in our numerical work.

The reaction $p\bar{p} \rightarrow \ell^+\ell^-\gamma$ is self-conjugate under a $\mathcal{CP}$ transformation and this allows us to write fully integrated $\mathcal{CP}$ odd observables in the lab-frame such as:

$$A_T \equiv \int \text{sign}(\vec{p}_{\text{beam}} \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-})) d\sigma$$

5 Similar observations have been made before in the literature [17].
\[ A_E \equiv \int \text{sign}(E_{E^+} - E_{E^-})d\sigma \quad (14) \]

There will also be observables analogous to those in Eqs. 5, 6. As an illustration we present in Figure 2 the following observable:

\[
\Delta(y_0) \equiv \frac{\frac{d\sigma}{dy_{E^+}}|_{y_{E^+}=y_0}}{\frac{d\sigma}{dy_{E^-}}|_{y_{E^-}=-y_0}} - \frac{\frac{d\sigma}{dy_{E^-}}|_{y_{E^-}=-y_0}}{\frac{d\sigma}{dy_{E^+}}|_{y_{E^+}=y_0}}.
\]

(15)

Numerically we use \( \sin \delta(qqZ\gamma) = 1 \) and \( \Lambda = 1 \text{ TeV} \).

Figure 2: \( \Delta(y_0) \) for \( p\bar{p} \to \ell^+\ell^−\gamma \) at \( \sqrt{S} = 2 \text{ TeV} \). These curves are normalized to \( h_1^\gamma = 1 \) and scale linearly with \( h_1^\gamma \). We have used \( \Lambda = 1 \text{ TeV} \).

With the set of cuts that we are using we find numerically that:

\[
\begin{align*}
\sigma & \approx 348 \text{ fb} \\
A_T & \approx (5.6h_1^\gamma + 12h_1^Z) \times 10^{-3} \left(\frac{1 \text{ TeV}}{\Lambda}\right)^4 \text{ fb} \\
A_E & \approx (1.3h_1^\gamma + 0.54h_1^Z) \times 10^{-3} \left(\frac{1 \text{ TeV}}{\Lambda}\right)^4 \sin \delta(qqZ\gamma) \text{ fb}
\end{align*}
\]

(16)

For an integrated luminosity of \( 10 \text{ fb}^{-1} \) we thus expect about 3500 \( Z\gamma \) events within the phase space region defined by our cuts. This translates into 95\% confidence level bounds:

\[
|h_1^\gamma + 2h_1^Z| \leq 2700 \left(\frac{\Lambda}{1 \text{ TeV}}\right)^4 .
\]

(17)
4 Conclusions

We have constructed several $\mathcal{CP}$-odd asymmetries that can be used in the search for $\mathcal{CP}$ violation in $W^\pm \gamma$ and $Z \gamma$ events in $p\bar{p}$ colliders. We have estimated the contributions to these asymmetries from some simple $\mathcal{CP}$ violating effective operators that respect the symmetries of the Standard Model. We find that an upgraded Tevatron with $10 \, fb^{-1}$ at $\sqrt{S} = 2$ TeV can place limits of $|\alpha_{13} + \alpha_{14}| < 4(\Lambda/1 \, \text{TeV})^2$ and $|h_1^\gamma + 2h_1^Z| < 2700(\Lambda/1 \, \text{TeV})^4$. The first bound corresponds to $|\tilde{\kappa}_\gamma| < .1$, which is comparable to the bound obtainable for the $\mathcal{CP}$ conserving couplings in the next-to-leading effective Lagrangian.

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