$\not{C}$P in Colliders

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In this talk we discuss the level at which collider experiments can search for new CP violating interactions. We concentrate in a scenario in which there are no new particles with masses below the top-quark mass and where the effects of the new interactions show up as modified couplings of the W and Z.

1 Introduction

The motivation to search for CP violation in all possible experiments is clear: we still do not understand its origin. Although a phase in the CKM matrix is sufficient to accommodate the CP violation seen in kaon decays there are hints that it may not be sufficient to explain the observed baryon asymmetry in the universe (see McKellar's talk).

In general the CP violation in the standard model does not generate observable asymmetries in high energy experiments. This is due to the smallness of the CP violating invariant $|J| \leq \lambda^6 A^2 \eta \sim 7 \times 10^{-5}$ and to the fact that CP violation in the standard model vanishes if any pair of quarks with the same charge is degenerate. This results in high energy observables being suppressed by factors of small fermion masses (such as $m_s - m_d$) divided by a typical energy scale for the observable.

Simple and popular extensions of the standard model contain new sources of CP violation in the couplings of scalars to fermions. This type of model is also unobservable in high energy experiments because the induced observables are suppressed by powers of light fermion masses divided by typical energy scales. The only exception is for observables in top-quark physics where the relevant fermion mass, $m_t \sim 175$ GeV, is large. The case of CP violation in top-quark physics is the subject of Eilam's talk.

Without an obvious model to generate observable effects in collider experiments, we turn to an effective Lagrangian description of the possible, new, CP violating interactions. These are built as higher dimension operators that involve only the standard model fields [1,2,3].

The question that we will address is whether collider experiments can probe these CP violating operators significantly. This corresponds to the relevant phenomenology for experiments at energies around one TeV. We ignore the question of the origin of these operators with the philosophy that this will become relevant when something is actually observed.

2 $\not{C}$P in Gauge Boson Self-Couplings

In this section we assume that the new CP violating interactions are related to the physics responsible for the breaking of electroweak symmetry and manifest themselves as $\not{C}$P gauge boson self-couplings. The leading order effective Lagrangian that describes the electroweak symmetry breaking sector is

$$\begin{aligned}\mathcal{L} = & \frac{v^2}{4}\mathrm{Tr}D_\mu U D^\mu U^\dagger - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu} \\ & + \frac{v^2}{8}(\Delta\rho)_{\mathrm{NEW}}\left(\mathrm{Tr}TV_\mu\right)^2 \end{aligned} \tag{1}$$

The first term in Eq. 1 contains masses for the W and Z that satisfy the relation $M_W = M_Z\cos\theta_W$. The last term, on the other hand, gives contributions to the W and Z masses that do not satisfy this relation. This term causes the ρ parameter to deviate from one and the subscript "NEW" indicates that we only include deviations that are due to new physics and not to electroweak corrections. In order to have a term like this in the Lagrangian, one has to violate the so called "custodial" symmetry. The notation used in Eq. 1 is standard (see for example Ref. [3]). The one thing to remember is that the object T is what signals that a term breaks the custodial symmetry.

The effects that discriminate between different possibilities for electroweak symmetry breaking start to show up in the next to leading order effective Lagrangian. The terms that violate CP in the notation of Ref[3] are:

$$\begin{aligned}\mathcal{L}_{\not{C}\not{P}} = & 2g\alpha_{12}\mathrm{Tr}TV_\mu\mathrm{Tr}V_\nu W^{\mu\nu} + \frac{gg'}{4}\alpha_{13}\epsilon^{\mu\nu\rho\sigma}B_{\mu\nu}\mathrm{Tr}TW_{\rho\sigma} \\ & + \frac{g^2}{8}\alpha_{14}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}TW_{\mu\nu}\mathrm{Tr}TW_{\rho\sigma}\end{aligned} \tag{2}$$

The thing to notice is that **all** the CP violating terms in the effective Lagrangian also violate custodial symmetry (this can be seen from the explicit factors of T that are necessary to construct these terms).

The effective Lagrangian formalism is the only rigorous way to define these terms and to calculate with them. For historical reasons, the literature has adopted the notation:

$$\tilde{\kappa}_Z = e^2\left(\frac{\alpha_{13}}{\cos^2\theta_W} - \frac{\alpha_{14}}{\sin^2\theta_W}\right)$$

$$\tilde{\kappa}_\gamma = -\frac{e^2}{\sin^2\theta_W}(\alpha_{13}+\alpha_{14})$$
$$g_Z^4 = -\frac{e^2}{\cos^2\theta_W \sin^2\theta_W}\alpha_{12} \tag{3}$$

In the notation of Eq. 2 it is straightforward to estimate the size of the $\not{C}$P couplings:

- The operators occur at next to leading order, so the size of the couplings includes a factor v^2/Λ^2 where Λ is a scale that characterizes the new physics that breaks electroweak symmetry. For the effective Lagrangian formalism to make sense, this scale should be of order a few TeV.
- Since all the $\not{C}$P operators violate custodial symmetry the couplings will naturally include a factor of $(\Delta\rho)_{\mathrm{NEW}} \leq 0.002$. The number is the upper limit listed in the 1996 Particle Data Book.
- In most models of CP violation, the couplings of the CP violating effective operators are also suppressed by small dimensionless parameters such as mixing angles.

The implication is that the $\not{C}$P couplings are at most of order

$$\alpha_{12,13,14} \sim \frac{v^2}{\Lambda^2}(\Delta\rho)_{\mathrm{NEW}} \sim 10^{-4} \tag{4}$$

In most models they will actually be smaller due to small dimensionless mixing angles. They can only be larger if one believes that the ρ parameter is approximately one accidentally.

2.1 Upgraded Tevatron

Here we study the bounds that could be placed on the $\not{C}$P couplings of Eq. 2 with a 2 TeV $p\bar{p}$ collider with $10fb^{-1}$. In this case one can look for the $WW\gamma$ coupling in the process $p\bar{p} \rightarrow W^\pm\gamma \rightarrow \ell^\pm\nu\gamma$ (there are not enough WW pairs to study that channel meaningfully).

In this reaction it is simple to consider an observable that does not require an absorptive phase. If we define

$$A^\pm = \sigma^\pm((\vec{p}_\gamma \times \vec{p}_{beam})\cdot\vec{p}_\ell > 0) - \sigma^\pm((\vec{p}_\gamma \times \vec{p}_{beam})\cdot\vec{p}_\ell < 0) \tag{5}$$

then CP predicts that $A^+ = A^-$. In order to distinguish true CP violation from possible experimental biases it is always useful to consider differential distributions and not only fully integrated observables. For this purpose it is useful to recall that for the variables commonly used to describe these reactions, a CP transformation implies that

$$y_{\ell^\pm} \leftrightarrow -y_{\ell^\mp}\,, \quad P_{T\ell^\pm} \leftrightarrow P_{T\ell^\mp} \tag{6}$$

Possible CP-odd observables are then:

$$\begin{aligned} R_1 &= \frac{A^+ - A^-}{\sigma^+ + \sigma^-} \\ R_2(y_0) &= \frac{dA^+/dy|_{y=y_0} - dA^-/dy|_{y=-y_0}}{d\sigma^+/dy|_{y=y_0} + d\sigma^-/dy|_{y=-y_0}} \end{aligned} \tag{7}$$

For the second type of observable one could use the rapidity of the lepton, the photon or the W. One can also construct analogous observables using the transverse momentum instead of the rapidity.

A first estimate for the size of these observables is obtained ignoring the radiative W decays. This can be done if we implement kinematic cuts that minimize their impact [4]. We find that in the kinematic region defined by the cuts there are about 2500 $W\gamma$ events and that $R_1 \approx .49\tilde{\kappa}_\gamma$. With these numbers one could place a 95% confidence level bound [5]

$$|\tilde{\kappa}_\gamma| \leq 0.1 \quad \text{or} \quad |\alpha_{13} + \alpha_{14}| \leq 0.24 \tag{8}$$

It is useful to recall that our dimensional analysis estimate indicated that $\alpha_{13,14}$ was at most of order 10^{-4}. There are explicit models, such as the one of Appelquist and Wu [3] that saturate this dimensional analysis bound. There are also indirect bounds on these couplings from low energy physics. The most stringent low energy bound comes from the electric dipole moment of the neutron as analyzed by Marciano [6] $\tilde{\kappa}_\gamma \leq 2\times 10^{-4}$. However, strictly speaking, the electric dipole moment of the neutron and the high energy observables are sensitive to different combinations of couplings. We should also recall that the same machine is expected to place bounds on analogous, but CP conserving, couplings of the same order, for example $|\kappa_\gamma| \leq 0.2$ is expected [7].

As a theoretical curiosity we can also mention the case of $p\bar{p} \rightarrow Z\gamma \rightarrow \ell^\pm\ell^\mp\gamma$. One gets contributions from local operators of the form:

$$\begin{aligned} \mathcal{O}_\gamma &= \frac{1}{\Lambda^2}\frac{eg}{2c_\theta} Q_q \bar{q}\gamma^\mu q Z^\nu F_{\mu\nu} \\ \mathcal{O}_Z &= \frac{1}{\Lambda^2}\frac{eg}{4c_\theta} \bar{q}\gamma^\mu [R_q(1+\gamma_5) + L_q(1-\gamma_5)] q Z^\nu F_{\mu\nu}, \end{aligned} \tag{9}$$

where $F_{\mu\nu}$ is the electromagnetic field strength tensor, $L_q = \tau_3 - 2Q_q s_\theta^2$ and $R_q = -2Q_q s_\theta^2$. If we 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. In the linear realization of electroweak symmetry breaking this is done by obtaining the Z^ν 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. [1]. One of them is:

$$\begin{aligned}\mathcal{L} &= i\frac{\tilde{\alpha}}{2\Lambda^2}\left(\mathcal{O}_{qB} + \mathcal{O}_{uB} + \mathcal{O}_{dB}\right) + \text{ h.c.} \\ &= i\frac{\tilde{\alpha}}{\Lambda^2}\bar{q}\gamma_\mu\left(\partial_\nu + ieQ_q A_\nu + \frac{ig}{4c_\theta}[L_q(1-\gamma_5) + R_q(1+\gamma_5)]Z_\nu\right)qB^{\mu\nu} \quad (10)\end{aligned}$$

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.10, the fully gauge invariant version of the operator 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 CP-violating amplitude vanishes and one is left with no CP-odd effects. This is a rather surprising result that we have checked for all the relevant operators in Ref. [1].[a]

A second way to make Eq. 9 fully gauge invariant uses a non-linearly realized electroweak symmetry breaking sector. In this case we think of Eq. 9 as the unitary gauge version of fully gauge invariant operators. However, the counting rules appropriate for this construction 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. This translates into 95% confidence level bounds:

$$|h_1^\gamma + 2h_1^Z| \leq 2700\left(\frac{\Lambda}{1 \text{ TeV}}\right)^4. \quad (11)$$

2.2 500 GeV e^+e^- Linear Collider

The standard set of parameters quoted for a possible next linear collider is a center of mass energy of 500 GeV and an integrated luminosity of $50 fb^{-1}$. In this machine one would look for the CP violating $WW\gamma$ and WWZ couplings through the reaction $e^+e^- \to W^+W^-$. To estimate the bounds that can be placed, we begin by discussing observables without absorptive phases. For example we can bound these couplings from their quadratic effects in the

[a] Similar observations have been made before in the literature[8].

cross-section for production of W pairs. Including acceptance cuts and reconstruction efficiency it turns out that the best bounds can be placed from a χ^2 analysis of the differential distribution $d\sigma/d\cos\theta$ with five bins. The 95% confidence level bounds obtained this way are [9]

$$|\tilde{\kappa}_\gamma| \leq 0.1, \quad |\tilde{\kappa}_Z| \leq 0.1 \quad |g_Z^4| \leq 0.1 \tag{12}$$

These numbers are quite similar to the one we obtained from our study of the upgraded Tevatron. The main difference seems to be that this reaction is sensitive to all three CP violating couplings whereas the one considered for the upgraded Tevatron is only sensitive to one of them. Interestingly, one finds that the same process can bound the CP conserving couplings κ_γ, κ_Z and g_Z^1 at a comparable level. This happens even though the CP conserving couplings contribute linearly to the differential cross-section and indicates that the process is not very sensitive to these couplings.

Looking at a specific decay channel of the W one can place similar bounds. The advantage is that it is possible to construct CP-odd observables that receive contributions linear in the couplings and that can distinguish between CP conserving and violating new physics. An example of such an observable is constructed in terms of the variable

$$p_{\mu\times\mu} = \frac{4}{s}(\vec{p}_{\mu^+} \times \vec{p}_{\mu^-}) \cdot \vec{p}_{beam} \tag{13}$$

An antisymmetric component in the distribution with respect to this variable would signal CP violation. This can be extracted, for example, defining the observable

$$A = \int \frac{d\sigma}{dp_{\mu\times\mu}} sgn(p_{\mu\times\mu}) dp_{\mu\times\mu} \tag{14}$$

A measurement of this asymmetry at the level of two standard deviations in the cross-section would place the bound

$$|\tilde{\kappa}_Z + 0.7\tilde{\kappa}_\gamma| \leq 0.2 \tag{15}$$

and a much weaker bound for g_Z^4. In conclusion, a 500 GeV e^+e^- collider would place bounds very similar to those of an upgraded Tevatron although it would probe more of the couplings directly.

3 New Couplings to Fermions

We can also discuss the possibility of new CP violating interactions generating CP violating couplings of the standard model fermions to the gauge bosons. In this case we distinguish between the case of light fermions and the top-quark.

3.1 Light Fermions

For the case of light fermions we consider the udW and $e\nu W$ vertices plus the QED and QCD corrections to them. A first thought is that these vertices have already been probed in low energy experiments, for example, in pion decay. However, there are several factors that indicate that high energy experiments are actually more sensitive to CP violating new couplings:

- If the new physics enters at a scale Λ, an observable in an experiment at an energy scale E is proportional to $(E^2/\Lambda^2)^n$ where n is a positive power and the case $n = 1$ corresponds to the lowest dimension operators representing the effects of the new physics in the effective Lagrangian. This tells us that observables in W scale physics are enhanced with respect to observables in pion decays by at least a factor of $m_W^2/m_\pi^2 \sim 3.5 \times 10^5$.

- To construct a CP-odd observable one needs either an absorptive phase or more than three independent four-vectors to construct a T-odd correlation. For example, in the $W \to e\nu$ decay, an absorptive phase due to electroweak re-scattering introduces a suppression of $\Gamma_W/M_W \sim 3\%$. In the decay $\pi \to e\nu$ an electroweak re-scattering phase is suppressed by $G_F m_\pi^2 \sim 10^{-8}$ instead.

- For T-odd correlations one can obtain an additional independent four-vector at the W mass scale from gluon radiation, for example. This introduces a suppression factor of α_S. In the pion decays one needs either a radiative pion decay with a measurement of the photon polarization or a four body pion decay. The former is suppressed by a factor of 1000 with respect to the two-body pion decay, and the photon polarization is very difficult to measure. The four-body decay is nine orders of magnitude smaller than the two body decay.

The upgraded Tevatron discussed earlier would produce a sample of 10^6 to 10^7 W bosons. The first test of new CP violating couplings is thus to compare the cross-sections for $W^\pm$ production:

$$\tilde{R}_1 = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \tag{16}$$

Similarly one can construct differential distribution asymmetries with respect to the rapidity or transverse momentum[10].

All of these observables require an absorptive phase. The easiest way to parameterize it in the effective Lagrangian formalism is to consider new four-fermion operators with CP violating couplings. These four fermion operators then contribute a CP violating phase and an absorptive phase simultaneously to the Wff'vertex at one loop. For technical reasons discussed in Ref. [11], a four fermion operator with $ude\nu$ fields does not contribute to a CP asymmetry in $p\bar{p} \rightarrow W^{\pm} \rightarrow e^{\pm}\nu$. Instead we use

$$\mathcal{L} = \frac{4\pi}{\Lambda^2} e^{i\phi} \bar{c}_L \gamma_\mu s_L \bar{\ell}_L \gamma^\mu \nu_L + \text{ h. c.} \tag{17}$$

The Dirac structure of the interaction has been chosen to maximize its interference with the standard model, the coupling has the natural size given by dimensional analysis for a strongly interacting theory and the phase ϕ, if present, is responsible for the violation of CP symmetry. With this interaction it is straightforward to compute in the narrow width approximation[10]

$$\tilde{R}_1 = \tilde{R}_2(y_0) = -\frac{1}{3}\frac{M_W^2}{\Lambda^2}\sin\phi \tag{18}$$

This implies that with 10^6 reconstructed W events one would be probing a scale of up to 1 TeV for the new CP violating interactions.

We can once again use naturalness arguments to get a feeling for the significance of this potential bound. If the new theory responsible for CP violation at the high energy scale is flavor independent, there will be other four-quark operators with couplings of the same order. One of them will contribute to $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and produce a lower bound on the scale of new physics of $\Lambda > 70$ TeV. Before dismissing the importance of looking for CP violation in W production it is convenient to remember that it is quite likely that the new interaction will not be flavor independent.

Before ending this section we can ask whether it is possible to construct T-odd correlations that do not need an absorptive phase by considering $W^{\pm}+$ jet production. This is discussed in Ref. [10] in detail but the main result is that it is not possible to generate CP-odd asymmetries in this process with the lowest dimension operators. One needs to go to operators that are suppressed by at least four powers of the scale of new physics and hence the sensitivity of this process to new CP violating operators is much lower. As a figure of merit we find that at least 10^6 reconstructed W plus one jet events are needed to start probing the 1 TeV scale.

3.2 Heavy Fermions

As we mentioned in the introduction, we will not discuss the couplings of the top-quark to gauge bosons in any detail because this is the subject of Eilam's talk. Nevertheless we want to point out a special case of a Wtb interaction:

$$\mathcal{L} = \frac{2}{\sqrt{2}} V_{tb} \left[(1 + \kappa_L e^{i\phi_L}) \bar{t}_L \gamma^\mu b_L + \kappa_R e^{i\phi_R} \bar{t}_R \gamma^\mu b_R \right] W_\mu^+ + \text{ h.c.} \tag{19}$$

This is a new type of interaction that would be very hard to probe in high energy colliders. This is the case because the top-quark couples so dominantly to bottom that the production and decay vertices would be conjugates of each other removing any CP violating phase. Nevertheless, as shown in Ref. [12], this vertex contributes to CP asymmetries that can be measured in B-factories. The estimate is that by looking at the standard asymmetries one could place bounds

$$\begin{aligned} \kappa_L \sin \phi_L &\leq 0.03 \\ \kappa_R \sin \phi_R &\leq 0.001 \end{aligned} \tag{20}$$

The first number is better than the best bounds that one can expect from future colliders for the CP conserving part of this coupling $\kappa_L \leq 0.2$. The second bound also compares well with the current bound on the magnitude of κ_R (less than a few percent) from $b \to s\gamma$. It is also stringent enough to actually constrain existing models of CP violation like the one discussed by Appelquist and Wu [3]. Notice that this effect is equivalent to that of gluon operators such as those discussed by Kagan [13].

4 Summary and Conclusion

We have surveyed several observables at high energy colliders to estimate the level at which they will be able to probe new CP violating interactions. In general we find that both an upgraded Tevatron and an e^+e^- linear collider can probe CP violating anomalous couplings at about the same level at which they can probe CP conserving couplings. This is at least a couple of orders of magnitude above the expectations from dimensional analysis. From this we conclude that it is possible that these experiments will reveal new CP violating interactions, but that it is not likely.

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