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Could large *CP*-violation be detected at colliders?

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We argue that *CP*-violation effects below a few $\times 10^{-3}$ are probably undetectable at hadron and electron colliders Thus only operators whose contributions interfere with tree-level Standard Model amplitudes are detectable We list these operators for Standard Model external particles and some two- and three-body final state reactions that could show detectable effects. These could test electroweak baryogenesis scenarios.

1. Introduction

Our understanding of the baryon asymmetry of the universe is at an exciting stage of development. Ideas that show promise for explaining the baryon asymmetry at the electroweak scale are being studied [1]. So far, all such approaches require large *CP*-violation, i.e., *CP*-violating terms in the lagrangian with coefficients of the same order as the gauge couplings.

If such terms exist, their presence may be directly detectable in collisions at the electroweak scale. The purpose of this paper is to emphasize several processes that can be studied at present and future colliders to search for large *CP*-violating effects, with emphasis on FNAL. While the possibility of relating such effects to the origin of the baryon asymmetry is particularly exciting, motivation for the study of such processes is also provided by the simple observation that at the present time published limits do not exist for the size of most *CP*-violating processes at the 100 GeV scale. Thus heretofore undetected large ($\sim 50\%$) *CP*-violation could occur in some processes at high energy hadron colliders.

Existing electroweak baryogenesis scenarios often depend on *CP*-violating Higgs interactions such as $ih\bar{t}\gamma_5 t$. These are probably the most important vertices to study. Although the motivation for hypothesizing other vertices is less compelling, given the speculative nature of present electroweak baryogenesis scenarios we believe that a systematic study of all processes which could show a large *CP*-violation is appropriate.

We understand, of course, that none of the reactions we list will be easy to study, but we think it will eventually be possible to carry out such analyses. The implications of a positive result are large enough that the effort is justified.

We will parameterize general *CP*-violation in terms of *CP*-violating operators of dimension less than or equal to six. In this paper, we confine our attention to those operators that involve only the Standard Model (SM) fields; perhaps eventually operators involving, for example, superpartners can be studied.

CP-violation parameters at low energies such as ϵ, ϵ', and d_n [2] generally place only weak constraints on higher dimensional *CP*-violating operators because some of these operators contain derivative couplings that provide a factor of $\hat{s}$ that leads to suppression at low energies. At collider energies, however, these operators can be as large as the SM vertices. At the present time we have only made qualitative analyses of such constraints and checked that none of the processes we examine are excluded from occurring at significant levels; we will report a more careful and systematic analysis in the future.

2. *CP*-violation at colliders

A number of analyses of possible *CP*-violation effects at colliders have been published [3–7]. Some have emphasized the possible role of the top quark [6–12]. There is, however, a major constraint that we feel has not been considered sufficiently. For both theoretical and experimental reasons, we think that it is probably impossible to detect *CP*-violation effects of the order of 10^{-3} in collider experiments.

The first reason is that the detectors will not be *CP*-invariant. Systematic studies can be done to determine at what level asymmetries in electric or magnetic field lines, nonuniformity in acceptance efficiency, or spatial asymmetries in the detector could induce an apparent *CP*-asymmetry. Intuitively one might guess they could be of the order of 10^{-3}. To argue they were smaller than that level would require careful studies of SM processes that are not sensitive to *CP*-violation effects. In this experimental "proof", it will be necessary to get the errors on charge and parity dependent measurements of particular processes below 0.1%. This could be very difficult, since even the most abundant process that might allow such a measurement, probably single W production, will have statistical errors on any measurement even at the SSC that are of the order of 10^{-3}. Whether systematic errors can be reduced to that level is not known. Furthermore, all analysis cuts and whatever processes are used to calibrate the detector must be shown to be *CP*-invariant at the relevant level.

The second reason is that it will probably be very difficult to isolate and eliminate spurious *CP*-violating effects from the SM processes at the 10^{-3} level. Whenever one is studying *CP*-violation by actually studying "naive T"-violation and assuming *CPT*-invariance, one has to be sure that spurious "T"-violating effects such as final state interactions [9,11] are not present. For example, gluon exchange induces an apparent parity-violating transverse polarization of the order of (1–2)% in $t\bar{t}$ production [6]. This effect can be approximately calculated [6] and a correction made both theoretically and experimentally, but it will be difficult to eliminate a residual effect of the order of 0.2%. The process $u\bar{t}\to t\bar{b}$ provides another example. For this reaction, one can search for *CP*-violation by studying $u\bar{d}\to t\bar{b}$ and looking for "T"-violating observables formed from momenta and the top spin. Then final state QCD interactions and top width effects both induce such observables in the range (0.1–1)%. Yet another example is the Wjj channel, perhaps plus softer jets, that will be a background for $t\bar{t}$. Parton level processes in which quarks scatter by exchanging a gluon and one of the quarks radiates a W will interfere with processes in which the quarks scatter by exchanging a Z and one of the quarks or the Z radiates a W, generating an irreducible parity violating component in the background; this can easily look like a *CP*-violating effect of the order of 1% if it is not corrected for. Perhaps after a detailed simulation is studied it can be reduced by an appropriate choice of bins and cuts. The difficulty is that one must find all such effects and eliminate them before one could believe that there is a new source of *CP*-violation.

Furthermore, even when comparing *CP*-conjugate reaction corrections must be made for structure function differences and backgrounds. These effects are partly measurable and calculable in the SM, so they can be partly corrected for, but it would take a great deal of effort and confidence to believe in a new effect that was much below about a few tenths of a percent. In addition, any effects that depend on top spin may be affected by some hadronization of the top quark that polarizes or depolarizes the top quark spin.

We can categorize these arguments [#1] as follows. *CP*-violating effects could be searched for with three different approaches. First, one can compare explicitly *CP*-conjugate processes such as W^+ versus W^-, t versus $\bar{t}$. These are particularly sensitive to structure function effects. Second, one can look for triple scalar products with non-zero averages. These are particularly sensitive to backgrounds. In this case one should try to use integral techniques such as the method given in our numerical example of section 3.1 below. Third, perhaps the most hopeful approach is using inclusive integrated observables, as emphasized in ref. [7], where the number of positive and negative leptons from top decay is compared. Even here, to claim an effect at the 10^{-4} level it is necessary to prove that the detector is *CP*-invariant at the 3×10^{-5} level, and background effects such as the non-equality of $bW^+\to t$ and $\bar{b}W^-\to\bar{t}$ must be suppressed by at least two orders of magnitude. We emphasize that what can ultimately be achieved is up to the experimenters to decide, independent of theoret-

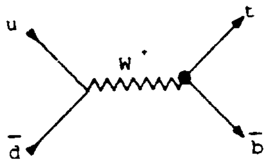
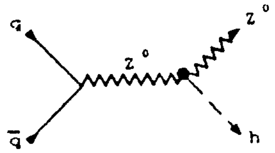
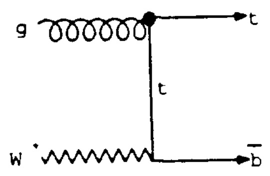
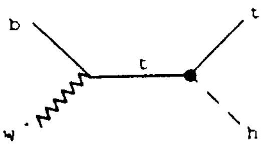
[#1] One of us appreciates a discussion on these questions with M Peskin ical arguments (but taking account of SM backgrounds). We urge that the sensitivity be pushed as far as possible.

Even if an observable that does not suffer from any of the above effects could be constructed, it cannot signal *CP*-violation on an event-by-event basis. Thus, in order to probe *CP*-violating effects that the 10^{-3} level, it would require at least 10^{6-7} events of some particular type. This is already at the limit of the capabilities of the SSC/LHC.

Because of these arguments we have become convinced that it is probably impossible to establish new *CP*-violating effects of the order of 10^{-3} colliders. That is not much of a constraint on FNAL searches, where most channels will have statistical limits of the same order or larger, but it may limit searches at SSC/LHC where statistical effects might approach the 10^{-3}–10^{-4} level. Even though inclusive integral searches such as that of ref. [7] may have a chance to get below the 10^{-3} sensitivity, we will proceed here on the assumption that 10^{-3} is the best that can be achieved since our own thinking leads us to that conclusion.

There is a qualitative difference in the physics one

Table 1
We list several two-body processes that can be tested at hadron colliders to detect large *CP*-violation. For each process we show one of several diagrams that contribute, where a solid circle stands for the *CP*-violating vertex; these interfere with the tree-level SM amplitudes of the same form. The next column gives typical *CP*-violating operators that contribute to the process, and the final column lists ways to observe the effect For $gt\bar{t}$ we exhibit an operator different from the usual magnetic moment one, the operator shown has an extra derivative and thus a stronger dependence on energy, so that at hadron colliders it may dominate In all cases, $\hat{\boldsymbol{\sigma}}_t$ is the top-quark spin, $\hat{\boldsymbol{z}}$ is one of the beam directions, $\boldsymbol{p}_t(\boldsymbol{p}_Z)$ is the momentum of the top-quark (Z), and $\boldsymbol{q}_+$ is the momentum of the positively charged decay product of the Z in $q\bar{q}\to Z^0h$ There are two possible choices for $\hat{\boldsymbol{z}}$, but the observables are independent of this choice. Finally, $N_+(N_-)$ refers to the number of positively charged decay products of either Z or top-quark emerging above (below) the x–z plane, where the coordinate system is defined so that $\hat{\boldsymbol{z}}$ is the beam momentum making an acute angle with $\boldsymbol{p}_t$, and $\boldsymbol{p}_t$ lies in the first quadrant of the x–z plane. $\hat{\boldsymbol{y}}=\hat{\boldsymbol{z}}\times\hat{\boldsymbol{x}}$ The coefficients Δ measure the strengths of the *CP*-violating operators Note that Δ_{Wt}, Δ_{zh}, and Δ_{gt} have dimensions of M^{-2}, while Δ_{ht} is dimensionless.

Reaction	Example	*CP*-violating operator	Observables
$u\bar{d}\to t\bar{b}$		$i\Delta_{WT} W^{+}_{\mu\nu}\bar{t}_L\gamma^\mu\partial^\nu b_L$	$\boldsymbol{p}_t\cdot\hat{\boldsymbol{z}}\,\hat{\boldsymbol{\sigma}}_t\cdot(\boldsymbol{p}_t\times\hat{\boldsymbol{z}})$, N_+-N_-
$q\bar{q}\to Z^0h$		$\Delta_{Zh}h\epsilon^{\mu\nu\sigma\eta}\tilde{Z}_{\mu\nu}Z_{\sigma\eta}$	$\boldsymbol{p}_Z\cdot\hat{\boldsymbol{z}}\,\boldsymbol{q}_+\cdot(\boldsymbol{p}_Z\times\hat{\boldsymbol{z}})$, N_+-N_-
$gW^+\to t\bar{b}$		$i\Delta_{gt}G^a_{\mu\nu}\bar{t}\gamma^\mu\lambda^a\partial^\nu t$	$\boldsymbol{p}_t\cdot\hat{\boldsymbol{z}}\,\hat{\boldsymbol{\sigma}}_t\cdot(\boldsymbol{p}_t\times\hat{\boldsymbol{z}})$, N_+-N_-
$bW^+\to th$		$i\Delta_{ht}h\bar{t}\gamma_5 t$	$\boldsymbol{p}_t\cdot\hat{\boldsymbol{z}}\,\hat{\boldsymbol{\sigma}}_t\cdot(\boldsymbol{p}_t\times\hat{\boldsymbol{z}})$, N_+-N_-

can study with 10^{-2} effects and with 10^{-3} effects. Since *CP*-violating effects always arise from interferences, and since all loops in the SM are already suppressed by factors of the order of 10^{-3}, if 10^{-3} is indeed a lower limit on what could be discovered, we conclude that *only new CP-violating effects that interfere with SM tree amplitudes could be detected at colliders.*

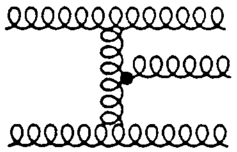
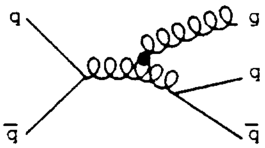
This observation allows one to enumerate systematically all processes in which new *CP*-violating effects coming from vertices with dimension $\leqslant 6$ and not otherwise excluded could be observed. We only need to consider processes that involve at least one top quark or boson–boson couplings (such as gauge self-couplings or Higgs–gauge boson couplings [13]) since the requirement of interference brings in a factor of the mass of any participating fermion. As a corollary, we find that even if there is a *CP*-violating effect in the process $p\bar{p}\to Zg$, it will be unobservable at collider experiments, contrary to a recent speculation [14]. This point will be elaborated elsewhere.

The processes that exhibit tree-level *CP*-violation are shown in tables 1, 2. Fortunately all interesting vertices in the SM are present, though very large luminosity would be required to study them all down to the 10^{-3} level. The two-body processes shown allow one to study all possible vertices of dimension $\leqslant 6$ that satisfy the following constraints: (i) in order to observe *CP*-violation either one must form a *T*-violating observable, which requires that at least one of the particles have spin since they are two-body, or observe charge conjugate particles which requires efficient observation of electric charges, (ii) only SM external particles, and (iii) an effect of order 10^{-3} or larger is possible taking into account constraints such as those of ref. [15] on the *ZWW* vertex. We assume here that $SU(2)\times U(1)$ invariance allows one to obtain $Zt\bar{t}$ vertices from $Wt\bar{b}$ ones, etc. Going to three-body processes one can add the three-gluon vertex. In the second column of table 1, we only show a typical hypothetical *CP*-violating diagram. These interfere with the *CP*-even contribution from the SM to yield tree-level *CP*-violation effects. Not all of the processes generated this way yield an observable in practice. In $gg\to g\to t\bar{t}$ with a *CP*-violating *ggg*-vertex, for example, the *CP*-violating effect vanishes upon averaging over initial gluon spins. In the third column we show *CP*-violating operators that correspond to the *CP*-odd diagrams. We have written them in a transparent form, but in actual calculations we use operators that are fully gauge-invariant [5,15,16]. Thus, ∂_ν really is the covariant derivative

$$D_\nu = \partial_\nu - \tfrac{1}{2} i g_2 W^a_\nu \tau^a - \tfrac{1}{2} i g_1 B_\nu - \tfrac{1}{2} i g_3 G^a_\nu \lambda^a ,$$

Table 2

We list some of the three-body processes that can be tested at FNAL to detect large *CP*-violation The entries are defined as in table 1. In all cases, the p_i (q_i) are the incoming (outgoing) momenta If the charges of parent partons of jets can be identified (see text for details), we use the sign of their charges as subscripts of the corresponding momenta. Hence $\boldsymbol{q}_0$ is the momentum of a gluon jet, $\boldsymbol{q}_+$ the momentum of a u, $\bar{d}$ or $\bar{s}$, etc For $gg\to ggg$, the observable $\mathcal{O}_g$, defined in section 3.4, is totally symmetric in the q_j and in the p_i. This observable can also be used for $qq\to qqg$. The simplest observable for $qq\to qqg$ is symmetric in the two momenta of the jets coming from the charged quark pairs. Hence, in practice, one only needs to isolate the neutral jet The vector $\hat{\boldsymbol{z}}$ is along one of the beam directions.

Reaction	Example	*CP*-violating operator	Observables
$gg\to ggg$		$\Delta_g f_{abc}\epsilon^{\nu\nu\sigma\eta} G^{a\rho}_{\mu} G^{b}_{\rho\nu} G^{c}_{\sigma\eta}$	$\mathcal{O}_g$
$qq\to gqq$		$\Delta_g f_{abc}\epsilon^{\mu\nu\sigma\eta} G^{a\rho}_{\mu} G^{b}_{\rho\nu} G^{c}_{\sigma\eta}$	$(\boldsymbol{q}_+ - \boldsymbol{q}_-)\cdot\hat{\boldsymbol{z}}\ (\boldsymbol{q}_+ \times \boldsymbol{q}_-)\cdot\hat{\boldsymbol{z}}$

which connects the $W\bar{t}b$ vertex to the $G\bar{t}t$ vertex, etc.

Since some of the CP-violating operators are dimension 6, they have an effective coefficient proportional to Λ^{-2}, where Λ is some mass scale characteristic of the new physics. Then the contribution to observables could have a factor of $\hat{s}/\Lambda^2$, and the effect will grow with energy. At e^+e^- colliders this will be a useful effect, but at hadron colliders the structure functions cut off such an enhancement.

3. Observables

In general, there are two ways to observe CP-violation in high energy processes [3–7]. One can compare CP-conjugate reactions, such as $bW^+\to th$ and $\bar{b}W^-\to\bar{t}h$ at the appropriate angles. Then it is necessary that electric charges and certain kinematic quantities be measured. In most cases that will eventually be possible (see section 3.4). Alternatively, assuming CPT-invariance, one can look for "T"-violating observables in a single process as long as we look for effects larger than the expected final state interaction (FSI). The sensitivity of this method can be sharpened somewhat by calculating the expected FSI.

In two-body reactions one needs a spin as well as momenta to form CP-violating observables. For top-quark production processes, the simplest "T"-violating observable is $\mathcal{O}_1=\hat{\boldsymbol{\sigma}}_t\cdot\hat{\boldsymbol{n}}$, where $\hat{\boldsymbol{n}}_t$ and $\hat{\boldsymbol{n}}$ are the top spin and the unit vector normal to the top production plane. The top spin can be analyzed unambiguously by letting the top decay into a b-quark and a W and measuring their momenta, or even from the charged lepton from the W decay [17]. For a top production process $ab\to tX$, the corresponding CP-violating observable is $\hat{\boldsymbol{\sigma}}_t\cdot(\boldsymbol{p}_t\times\boldsymbol{p}_a)+\hat{\boldsymbol{\sigma}}_{\bar{t}}\cdot(\boldsymbol{p}_{\bar{t}}\times\boldsymbol{p}_{\bar{a}})$. However, if the incoming a can be in either of the collider beams, then averaging over the two possible beam directions makes $\mathcal{O}_1$ identically zero. In this case, one has to look for a more complicated "T"-violating observable that does not vanish upon averaging over the two possible directions of the incoming a. Finally, one must verify explicitly that the observable thus constructed yields a non-vanishing expectation value. We have followed this procedure in this paper.

To convert observables containing the top spin into observables containing the momenta of the decay products of the top, replace $\hat{\sigma}^\mu$ in the observable defined in terms of the top spin by $q_w^\mu-q_b^\mu(q_w\cdot q_b)/M_w^2$. The momenta q_b and q_w are the momenta of the decay products of the top, $p_t=q_w+q_b$. Thus, $\hat{\boldsymbol{\sigma}}\cdot\hat{\boldsymbol{n}}=\hat{\boldsymbol{\sigma}}\cdot(\boldsymbol{p}_t\times\boldsymbol{p})$ is equivalent to $\boldsymbol{q}_w\cdot(\boldsymbol{q}_b\times\boldsymbol{p})$, where p is the momentum of one of the incoming particles.

Below we quote numbers for the maximum sensitivity achievable in measuring some of the coefficients Δ_i of tables 1, 2. These numbers are estimated with a Monte Carlo program by computing the cross section for each process for which the exhibited observable is positive and that for which it is negative. The cross sections are converted into a number of events (N^+ and N^-) by using an integrated luminosity of 30 000 pb^{-1} for the SSC, 170 000 pb^{-1} for the LHC, and 1000 pb^{-1} for FNAL; such luminosities are appropriate to learn what can ultimately be achieved. With CP-violating coefficients Δ_i set to zero it is checked that the difference $N^+-N^-\ll\sqrt{N^++N^-}$, i.e., the SM exhibits no CP-violation. The Δ_i is increased until $N^+-N^-\gtrsim 3.5\sqrt{N^++N^-}$, which is the minimal size at which an effect could be observable. Using $\sqrt{N}$ errors for Monte Carlo results is a little optimistic since statistical errors will be larger with cross sections that vary over the phase space, but since we are only estimating the sensitivity it is appropriate to use methods that can be simply understood and applied.

3.1 $bW^+\to th$

Once the top and a Higgs boson are discovered, one can imagine studying this important process. The Higgs boson will decay to $b\bar{b}$ with $M_{b\bar{b}}=M_h$, and M_h will be known. There will be an electroweak-QCD background with the same characteristics as signal events, but the background will not produce a CP-violating effect.

The simplest observable $\hat{\boldsymbol{\sigma}}_t\cdot(\boldsymbol{p}_b\times\boldsymbol{p}_t)$ works if we can identify event-by-event the direction of the incoming b-quark. This may be achievable in practice by exploiting the fact that the energy distribution of the incoming W in the proton beam is significantly lower than that of the incoming b-quark. Hence the direction of the center-of-mass momentum of the th system, which is along one of the beam directions, is highly correlated with the direction of the initial b-

quark momentum. Thus the appropriate observable in this case is $\boldsymbol{p}_h\cdot(\boldsymbol{p}_t\times\hat{\boldsymbol{\sigma}}_t)$.

If $\boldsymbol{p}_b$ is not identified event-by-event, the simplest observable is $\boldsymbol{p}_t\cdot\boldsymbol{z}\ \boldsymbol{z}\cdot(\boldsymbol{p}_t\times\hat{\boldsymbol{\sigma}}_t)$. Equivalently, in terms of the decay product momenta of the top-quark, the observable is $\boldsymbol{p}_t\cdot\boldsymbol{z}\ \boldsymbol{z}\cdot(\boldsymbol{q}_b\times\boldsymbol{q}_w)$ (see table 1). Since the charged lepton from t semileptonic decay goes preferentially in the direction of the top spin [17], one can replace $\hat{\boldsymbol{\sigma}}_t$ by $\boldsymbol{p}_{l^+}$ in any observable. For $\bar{t}$, $\hat{\boldsymbol{\sigma}}_{\bar{t}}$ should be replaced by $-\boldsymbol{p}_{l^-}$. With a parity-even phase space used in the analysis, the SM predicts vanishing expectation values for these observables.

Using the technique described above, we find that a value of Δ_{th} as small as $g_2/10$ ($g_2=0.65$) could conceivably be detected here. This amounts to saying that an interference term $\simeq 20\%(=2\times0.1)$ of the SM cross section could be seen. This takes into account some geometrical losses by requiring particles to have $|\eta|<5$, but no losses from branching ratios or triggering. More realism would presumably give the observable $\Delta_{th}\gtrsim g_2/2$ or $g_2/3$. Numerically, the SM cross section for the SSC is about 8.4 pb, and $N^+-N^-\simeq-20\pm500$, while with $\Delta_{th}=0.1$ one has $N^+-N^-=-2000\pm500$. For the LHC the cross section is about $\frac{1}{8}$ that of SSC, so with six times the integrated luminosity one does almost as well. For FNAL the SM cross section would produce about 30 events, so to see an effect one would need $\Delta_{th}\sim 20g_2$. These numbers imply that CP-violating vertices with strengths of the order of g_2 or somewhat less may eventually be directly detectable at hadron colliders. While one would prefer smaller numbers, these are large enough to overlap with the domain of interest for generating a baryon asymmetry if indeed a CP-violating contribution of the order of the SM one is needed.

3.2. $q\bar{q}\to Zh$

The situation here is similar to that of $bW^+\to th$. The h is only used to provide a direction, and is detected by selecting $b\bar{b}$ with $M_{b\bar{b}}=M_h$. Background from production of $Z+g(\to b\bar{b})$ will necessarily be present but will not produce a CP-violation effect. The analysis is similar to that for $bW^+\to th$, with the Z polarization vector replacing the top spin direction, and in practice the Z polarization is analyzed by its decay into l^+l^- or into $q\bar{q}$ [18].

A Monte Carlo study suggests that for both SSC and LHC a coefficient Δ_{Zh} of the order of $0.05\ g_2/M_Z$ or larger is observable ($\mathrm{BR}(Z\to l^+l^-)$ is included). Note that here the effective coupling has dimensions $(\text{mass})^{-1}$, and thus the effect is enhanced by $\sqrt{\hat{s}}/M_Z$ so that a somewhat smaller coefficient is observable than for the $t\bar{t}h$ vertex.

For $q\bar{q}\to Zh$ at FNAL, the initial q and $\bar{q}$ carry approximately equal fractions of the beam momentum so that it is necessary to use observables independent of the directions of the incoming momenta as written in table 1. At pp colliders the q will typically carry a larger fraction of momenta then the $\bar{q}$, thus there is a correlation between $\boldsymbol{p}_q$ and the direction of the motion of the center-of-mass of the Zh system. In this case, the simple observable $(\boldsymbol{p}_Z+\boldsymbol{p}_h)\cdot(\boldsymbol{\epsilon}_Z+\boldsymbol{p}_Z)$ can be used, with the momentum of one of the Z decay products replacing $\boldsymbol{\epsilon}_Z$ in practice.

3.3. $gW^+\to t\bar{b}$, $u\bar{d}\to t\bar{b}$, and $ud\to tb$

The situation here is analogous to th production. If an effect is ever found, it will be possible to untangle which process is involved by using the top production rate and the decay angular distribution information. The $\bar{b}$ (or b) provides a direction and possibly a way to discriminate between $t\bar{b}$, $\bar{t}b$, tb final states. The process $ud\to tb$ is doubly CKM suppressed.

3.4. $q\bar{q}\to gq\bar{q}$ and $gg\to ggg$

Construction of an observable for $g(p)g(\bar{p})\to g(q_1)g(q_2)g(q_3)$ is complicated by the fact that the simplest observables, such as the triple vector product, are antisymmetric in its momenta and the cross section is symmetric. For this process, any observable that depends on ordering of jets (according to their energies, etc.) will have exactly vanishing expectation value. This contrasts with the cases considered by Donoghue and Valencia [3]. By trial and error, one finds that the simplest observable that is symmetric in p and $\bar{p}$ and in q_1, q_2, and q_3 is

$$\mathcal{O}_g=\hat{\boldsymbol{z}}\cdot(\boldsymbol{q}_1\times\boldsymbol{q}_2)\times\hat{\boldsymbol{z}}\cdot(\boldsymbol{q}_1-\boldsymbol{q}_2)\ \hat{\boldsymbol{z}}\cdot(\boldsymbol{q}_1-\boldsymbol{q}_3)\ \hat{\boldsymbol{z}}\cdot(\boldsymbol{q}_2-\boldsymbol{q}_3)\,,$$

where $\hat{\boldsymbol{z}}$ is a unit vector along one of the beam directions.

The ALEPH group [19] has published results implying that the electric charge of energetic jets can be measured by performing an appropriately weighted sum over particles in the jet, using techniques based on earlier studies of the JADE [20] and MAC [21] groups. There appears to be no reason [#2] why these techniques could not be used at hadron colliders. Assuming they can be used, to study $q\bar{q}\to gq\bar{q}$ one should select events with three jets with one jet having positive electric charge, one negative, and one zero, summing over all quark types. This should ensure a sample mainly from $u\bar{u}\to gq\bar{q}$ and $d\bar{d}\to gq\bar{q}$, separating them from $u\bar{d}$ or uu initiated events. At SSC/LHC, the events to consider are $uu\to gqq$ and $dd\to gqq$, so that one would select events with two like-signs and one neutral jet. In this case the simplest observable is $(\boldsymbol{q}_1-\boldsymbol{q}_2)\cdot\hat{\boldsymbol{z}}(\boldsymbol{q}_1\times\boldsymbol{q}_2)\cdot\hat{\boldsymbol{z}}$, where q_1 and q_2 are the momenta of the jets from the $q\bar{q}$ pair and $\hat{z}$ is along one of the beam directions.

Gluons radiated off quarks will not induce any apparent large CP-violating effect, but will dilute any real effect, so they should be suppressed by cutting out events where the neutral jet is near the beam direction or either of the final quarks. Final state interactions will cause effects of the order of α_s/π, so only a signal larger than this could be trusted (see section 2). On the other hand, too large an effect here would induce a neutron electric dipole moment. We estimate that there is room between these constraints to look for an effect of the order of 0.1. Monte Carlo studies are considerably more difficult here than for two-body processes; we will provide numbers for these three-body processes at a later time.

4. Summary

As discussed in the introduction, there is good motivation to look for new, large CP-violation effects at the electroweak scale, because it is crucial to demonstrate experimentally that spurious CP-violation from detector and electroweak-QCD effects (examples are given in section 2) are absent at the level of any claimed effect. We have argued that CP-violating effects of the order of 10^{-3} are probably unobservable at colliders.

Given this conclusion, it is only possible to observe a new, CP-violating contribution that interferes with a SM tree level process; any SM loop correction is already too small to be observable at colliders. Then only a small number of such processes could be detected. We have listed most processes with external SM particles that could show such effects, and described how to analyze the data to search for them.

In the future we will report similar analyses for external supersymmetric partners and perhaps other non-SM particles. We hope that eventually either such large CP-violating effects can be detected, or that limits can be obtained that are relevant for understanding baryogenesis at the electroweak scale.

[#2] G.K appreciates discussions with A Blondel on these questions

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