A model independent study of non-Standard Model CP-violating processes is presented with emphasis on the observability of the effects.
1. Introduction

The origin of CP violation is one of the important unanswered questions in particle physics despite the enormous attention the subject has received\textsuperscript{1).} The question which I will address in this lecture is what kind of CP violating effects can we expect from non-Standard Model physics, what type of new physics can generate such effects, and whether they can be observed at present and near-future colliders.

There have been many studies of CP violation for specific models\textsuperscript{2).} There have also been some attempts to obtain model-independent statements concerning CP violation\textsuperscript{3).} The formalism which I will use is based on a gauge-invariant effective Lagrangian approach\textsuperscript{4)} which provides not only a consistent framework for this study but also provides estimates of the magnitude of the effects under consideration.

2. Effective Lagrangians

Consider a theory containing a set of light fields $\phi$ and a set of heavy fields $\Phi$ described by the action $S[\phi; \Phi]$. Suppose also that we cannot directly observe the heavy physics which becomes manifest at a scale $\Lambda$. In this case heavy physics can be observed using only virtual heavy effects which are described by the effective action $S_{\text{eff}}$ defined by $\exp(iS_{\text{eff}}[\phi]) = \int[d\Phi]e^{iS}$. Expanding $S_{\text{eff}}$ in powers of $1/\Lambda^4$, $S_{\text{eff}} = \int L_{\text{eff}}$ defines the effective Lagrangian

$$L_{\text{eff}} = \sum_n \alpha_n \Lambda^n O_n. \quad (2.1)$$

in terms of a series of local operators $O_n$. If all terms of dimension $\leq 4$ have a local symmetry then either that symmetry is preserved by all the operators, or else the renormalization group will generate terms of dimension $\leq 4$ which break this symmetry\textsuperscript{5).} If we assume that the terms in $L_{\text{eff}}$ of dimension $\leq 4$ correspond to the Standard Model, it follows that we must assume that all $O_n$ are $SU(3) \times SU(2) \times U(1)$ invariant.\textsuperscript{*} To complete this parameterization one requires the list of light fields; and currently we have two possibilities depending on the presence or absence of light scalars. In this talk I will assume that the light spectrum coincides with the one in the Standard Model(including a Higgs doublet)\textsuperscript{6).} \textsuperscript{†}

Any kind of new physics can be parameterized by the $\alpha_n$ which summarize all the virtual heavy-physics effects. Any experiment which do not probe the new physics directly can glean information about the new interactions only by measuring these coefficients.

It is, of course, possible to assume that the effective operators of dimension $> 4$ satisfy a larger local symmetry than the one of the Standard Model\textsuperscript{7),} it is also possible to consider more complicates light scalar sectors\textsuperscript{8).} I will not consider these cases for simplicity.

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\textsuperscript{*} Similar statements do not apply to global symmetries.

\textsuperscript{†} If there are no light scalar excitations a chiral Lagrangian description of the theory is appropriate\textsuperscript{1).}
3. Phenomenological estimates

The coefficients $\alpha_n$ can be constrained by requiring consistency of the theory\(^9\). For the case under consideration (where there are light scalars), I will assume that the underlying theory is weakly coupled\(^10\). Then the relevant property of a given operator is whether it can be generated at tree level by the heavy physics\(^11\): all tree-level-generated operators have coefficients equal to some product of the coupling constants, loop-generated operators have additional suppression factors\(^\ddagger\) $\sim 1/(4\pi)^2$. I will also assume that gauge fields are universally coupled. These considerations lead to the estimates presented in figure 1; such estimates are also verified in explicit calculations. With this estimates $\Lambda$ is identified as a physical mass scale (eg. the mass of a heavy particle).

Using the above estimates one can determine whether a given experimental bound does constrain a theory or not. For example consider the $WW\gamma$ interaction\(^12\) (in unitary gauge),

$$L_{WWV} = \frac{ie\lambda}{M_W^2} W_{\alpha \mu} W_{\nu \mu}^\dagger F^{\lambda \nu}, \quad W_{\mu \nu}^{\pm} = \partial_\mu W_\nu^\pm - \partial_\nu W_\mu^\pm$$

where $W^\pm$ denote the $W$-boson fields, and $F$ the usual photon field strength which is generated by the operator $O_W = \epsilon_{IJK} W_I^\mu W_J^\nu W_K^\lambda$, so that

$$\lambda_V = \frac{3gv^2}{2\Lambda^2} \alpha_W$$

where $v$ denotes the Standard Model vacuum expectation value, $g$ the $SU(2)_L$ gauge coupling constant and $\alpha_W$ the coefficient of $O_W$ in the effective Lagrangian. Since $O_W$ is only generated via loops\(^11\) in the underlying theory we expect $\alpha_W \sim g^3/(16\pi^2)$. A given bound on $\lambda$ can now be translated into a constraint on $\Lambda$, for example

$$|\lambda_V| < 0.1 \Rightarrow \Lambda > \text{few} \times 10 \text{ GeV},$$

so that one cannot claim consider this a high precision measurement\(^13\)

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\(\ddagger\) When there are many ($\sim 150$) loop graphs which add coherently to cancel this loop suppression factor the low energy spectrum is also modified since the theory becomes strongly coupled: the one loop and the tree level graphs are of the same order. See \(^10\) for more details.
Within specific models it is possible to find $\alpha_n$ enhanced or suppressions (perhaps due to unknown symmetries) with respect to the above estimates. Still one cannot assume with impunity for $\alpha_n$ are enhanced by many orders of magnitude: such enormous discrepancies would have observable consequences in other processes and would have been detected. Note that the same statement can be made about the gluon operator studied in $^4$.

4. CP violating operators

I will now consider the operators which do not respect CP for the case where the underlying theory is weakly coupled and decoupling. The light excitations will be again those of the Standard Model with one scalar doublet. In this case all operators of dimension $\leq 6$ are known $^6$. From the above arguments I only need those operators that can be generated by tree-level graphs $^\S$.

The number of operators is surprisingly small, they fall into three categories:

$$\begin{align*}
&\left(\bar{\psi}_L^{(1)} \psi_R^{(2)}\right) \left(\bar{\psi}_{L,R}^{(3)} \psi_{R,L}^{(4)}\right) - \text{H.c.} : \text{Type I} \\
&\left(\bar{\psi}_L^{(1)} \psi_R^{(2)} \phi\right) \left(\phi \phi\right) - \text{H.c.} : \text{Type II} \\
&\left(\phi^T \epsilon D_\mu \phi\right) \left(\bar{\psi}_{L,R}^{(1)} \gamma^\mu \psi_{L,R}^{(2)}\right) - \text{H.c.} : \text{Type III}
\end{align*}$$

(4.1)

where $\psi_L$ denote left-handed fermion doublets, $\psi_R$ right-handed fermion singlets, $\phi$ represents the scalar doublet, $D_\mu$ the covariant derivative and $\epsilon = i\sigma_2$ is the $2 \times 2$ antisymmetric matrix of unit determinant. In (4.1) the fields are restricted by the condition that the total hypercharge should be zero in order to preserve gauge invariance.

The various types of heavy physics responsible for the operators of types I, II and III are given in figure 2 above (since all heavy physics effects vanish as $\Lambda \to \infty$ this type of new physics is labeled “decoupling” $^{15}$). Such operators appear in the effective Lagrangian with

$^\S$ I will also use the equations of motion to eliminate operators that are indistinguishable at the level of the $S$ matrix $^{14}$
unknown coefficients (bounded by the requirement that they are $\lesssim 1$). There are, however, some experimental bounds on the $\alpha_n$.

**Operators of type I.** When the operators involve first generation fermions only $\Lambda \gtrsim 10$ TeV ($\alpha \sim 1$) from $\pi, K \to e\nu^{16}$ and from the electron and neutron dipole moments$^{17}$. When the operators involve second and third generation fermions the bounds are weak ($\Lambda \gtrsim 10$ GeV). These operators also contribute at one loop to the $\theta$ parameter. If we require the theory to be natural$^{18}$ (at least where $\theta$ is concerned) then $\Lambda \gg 10$ TeV.

**Operators of type II.** For first generation fermions $\Lambda \gtrsim \text{few} \times 100$ GeV ($\alpha \sim 1$) from the electric and magnetic dipole moments of the leptons and neutron, using a Higgs mass$^{14}$ $\sim 100$ GeV. When these operators involve the second and third generation fermions the bounds are very weak. These operators also modify to the $\theta$ parameter at tree-level for natural$^{18}$ theories $\Lambda > 10^4$ TeV.

**Operators of type III.** When involving first-generation fermions only bounds can be obtained using the $W$ lifetime and branching ratios, the $K_L - K_S$ mass difference$^{19}$ which leads to $\Lambda \gtrsim 500$ GeV; a bound using the neutron edm$^{20}$ is polluted by the presence of unknown angles. When these operators involve the second and third generation fermions the bounds are very weak. These are the least constrained operators, processes affected by these operators may then be particularly sensitive to heavy CP violating effects. This type of operators are generated only by a heavy fermion isodoublet of non-zero hypercharge. It is interesting to note that this type of heavy fermions would suppress the $Z \to b\bar{b}$ branching ratio.

5. Conclusion

For the case of decoupling heavy physics the best windows into new types of CP violation is through those observables sensitive to three types of operators: 4-fermion operators, operators modifying the fermion-Higgs couplings and operators modifying the $Wtb$ and $WtbH$ couplings. If the underlying theory is also assumed to satisfy the usual naturality criteria$^{18}$ then only the operators modifying the $W$ couplings could be generated by physics light enough to be of interest in near-future collider experiments.

Having a CP violating terms in the Lagrangian is, unfortunately, not enough. In order to probe the CP violating effects one must construct observables containing the corresponding coefficients. Such observables are either proportional to the interference of some CP-even phase with the CP violating phase$^{21}$, or are obtained by averaging a CP-violating quantity$^{22}$. In both cases the effects are considerably suppressed

Thus, even when $\Lambda$ is sufficiently small for the effects of the heavy physics to be observable at a given collider, the CP-violating effects would be very hard to observe: the CP violating couplings (for the case of the fermion-$W$ interactions) are $\sim g(v/\Lambda)^2$; if we take the LEP bounds of $\Lambda \gtrsim 2$ TeV$^{23}$ this is reduced to $\lesssim g/64$.

$^{14}$ These bounds are generated by loop graphs involving these operators and therefore depend on the Higgs mass.

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I would like to conclude by noting that a similar investigation can be done in the case where there are no light scalars by using a chiral effective Lagrangian. Finally one might wonder what would happen if the underlying theory is both decoupling and strongly coupled. In this case (which I completely ignored) it is difficult to maintain the Higgs mass significantly below the cutoff requiring fine-tuning. The alternative is to modify the low-energy spectrum. I will consider all these possibilities in a forthcoming publication.

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heavy scalar

\[ \tau, \mu \rightarrow s, c, b, t \]

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4 quarks \( \neq u, d \)

from

heavy scalar
light quarks or leptons

from

heavy fermion

heavy scalar
The graph has no CP-violating piece from

\[ u,c,t \quad \rightarrow \quad H \quad \rightarrow \quad W \]

\[ d,s,b \quad \rightarrow \quad H \quad \rightarrow \quad W \]

from

heavy fermion

The graph has no CP-violating piece
heavy fermion