USING GLUON FUSION TO PROBE CP VIOLATION IN THE HIGGS SECTOR

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ABSTRACT

A technique for directly probing CP violation in the Higgs sector of a multi-doublet model using gluon-gluon collisions at the SSC is reviewed.

1. Introduction

Understanding the Higgs sector is one of the fundamental missions of future high energy colliders such as the SSC and LHC. In particular, it will be important to know if CP violation is present in the Higgs sector. Generally, either spontaneous or explicit CP violation can be present if the Higgs sector consists of more than the single doublet field of the Standard Model (SM). (For a review of this and other issues summarized below, see Ref. [1], and references therein.) The presence of significant CP violation would provide strong constraints on possible models. For instance, although CP violation is certainly possible in a general two-Higgs-doublet model (2HDM), it does not arise (either explicitly or spontaneously) in the highly restricted version of the 2HDM that emerges in the Minimal Supersymmetric Model (MSSM). Nor does CP violation occur spontaneously in the simplest extension of the MSSM containing one additional singlet Higgs field and only trilinear terms in the superpotential. In addition, in general supersymmetric models a large CP-violating phase associated with the vacuum expectation value of a Higgs field will give rise to large imaginary terms in the mass matrices for the neutralino-gaugino fermions and the squarks. The resulting imaginary parts of the propagators for the mass eigenstates would be CP-violating and result in contributions to neutron and electron electric dipole moments (EDM's) that would exceed current experimental limits. Overall, observation of large CP violation in the Higgs sector would be very difficult to reconcile with a supersymmetric theoretical structure. Thus, it will be of great interest to determine the CP nature of any Higgs boson that is found.

Although there are a variety of experimental observables that are indirectly sensitive to CP violation in the Higgs sector (such as EDM’s, top quark production and decay distributions, etc.), CP-violating contributions typically first appear at one-loop, or are otherwise suppressed, and will be very difficult to detect in a realistic experimental environment. In addition, if CP violation in this class of observables is detected, it could easily arise from sources other than the Higgs sector. Consequently, direct probes of CP violation in the Higgs sector are sorely needed. Here we describe a production rate asymmetry that directly probes...
the CP nature of any (observed) Higgs boson that is produced via gluon-gluon fusion at the SSC/LHC. (The proposed asymmetry is closely analogous to that developed previously for collisions of polarized back scattered laser beams at a future linear e+ e− collider.) The primary experimental requirement is the ability to polarize the colliding protons. The difference between Higgs boson production rates for colliding beams of different polarizations can be quite large in a general 2HDM. Asymmetries larger than 10% are quite typical. The reason that such large asymmetries can be achieved is easily explained. First, we note that in the neutral Higgs sector a CP-violating phase for one of the neutral field vacuum expectation values leads to mass matrix mixing between the CP-even scalar fields and the CP-odd scalar fields. Since the gg coupling to CP-even scalars is not very different in magnitude from that to CP-odd scalars (both arising at one loop, see below) there is clear opportunity for large interference effects when the Higgs mass eigenstate (φ) contains substantial components of both types. Of course, event rates in channels where φ can be detected are not guaranteed to be large, and the observability of the predicted maximal asymmetry must be carefully evaluated.

2. Gluon Fusion

The basic production mechanism in question is gluon fusion through a triangle diagram. In gluon fusion, any colored particle which acquires its mass via the Higgs mechanism can appear in the loop. In particular, a heavy quark does not decouple when its mass is much greater than the Higgs boson mass. Thus, in the SM the top quark typically dominates. Additional arbitrarily heavy quarks would each contribute coherently to the loop sum, implying that models with additional heavy families would yield far larger rates than obtained in the SM. Of course, other types of colored particles appearing in extended models can also contribute. In the computations quoted here, we consider the model in which the only extension of the SM occurs in the Higgs sector, but clearly the rates and consequent detectability of CP-violating asymmetries could be very much larger in theories containing many heavy fermions.

At hadron colliders, the gluons within the hadrons provide a large effective gluon-gluon collision luminosity. The procedure for computing the gg → Higgs cross section in leading order is well-known. Our computations will employ the leading order formalism, but it should be noted that radiative corrections to this procedure have been computed, and for a typical value of α_s result in an enhancement factor of about 1.7. In this sense, our results will be conservative.

Crucial to our discussion is the degree of polarization that can be achieved for gluons at the SSC. The amount of gluon polarization in a positively-polarized proton beam, defined by the structure function difference Δg(x) = g_+(x) − g_−(x), is not currently known with any certainty. (Here, the ± subscripts indicate gluons with ± helicity, and g(x) = g_+(x) + g_−(x) is the unpolarized gluon distribution function.) Many models used to describe the EMC data require a significant amount of the proton’s spin to be carried by the gluons. A value for Δg = \int Δg(x) dx of Δg ∼ 3 is not atypical. In the results to be quoted, we shall employ the form: Δg(x) = g(x) (x > x_c), Δg(x) = x x_c g(x) (x < x_c), where x_c ∼ 0.2 yields a value of Δg ∼ 3.5 over the Higgs mass range (which determines the momentum transfer scale at which g(x) is evaluated) that we consider. (Strictly speaking, Δg(x) should be chosen to be of this form at some given \Q_0 and then evolved to obtain the form at other \Q values — we ignore this subtlety here.) Although this form maximizes Δg(x) at large x, the x values most important for Higgs production are substantially below 0.2.
3. Asymmetry and Results

The asymmetry we compute is simply $A \equiv [\sigma_+ - \sigma_-]/[\sigma_+ + \sigma_-]$, where $\sigma_\pm$ is the cross section for Higgs production in collisions of an unpolarized proton with a proton of helicity $\pm$, respectively. $\sigma_+ - \sigma_-$ is proportional to the integral over $x_1$ and $x_2$ (with $x_1 x_2 = m'^2/\sqrt{s}$) of $g(x_1)\Delta g(x_2) \left[|M_{++}|^2 - |M_{--}|^2\right]$, while $\sigma_+ + \sigma_-$ is determined by the integral of $g(x_1)g(x_2) \left[|M_{++}|^2 + |M_{--}|^2\right]$. (We have assumed that it is proton 2 that is polarized.) Now, $|M_{++}|^2 - |M_{--}|^2$ vanishes for a CP eigenstate, but can be quite large in a general 2HDM; the difference is proportional to $\text{Im} \left(e^o\ast\right)$, where $e$ ($o$) represents the $gg$ coupling to the CP-even (-odd) component of $\phi$.

To obtain a numerical indication of the observability of $A$, we have proceeded as follows. First, we maximize $(\sigma_+ - \sigma_-)/\sqrt{\sigma_+ + \sigma_-}$ (which determines the statistical significance of our observation) by choosing an optimum value for $x_{\text{cut}}^F$ such that only $x_2 - x_1 > x_{\text{cut}}^F$ is included in our integrals; such a cut pushes the integrals into the region where $\Delta g(x_2)/g(x_2)$ is less suppressed — $x_{\text{cut}}^F$ near 0.05 typically yields optimal results. Second, we assume that $\phi$ can only be detected in the $\phi \rightarrow ZZ \rightarrow l^+l^-X$ modes. Third, we have searched (at fixed $\tan\beta = v_2/v_1$) for the parameters of the most general CP-violating 2HDM that yield the largest achievable statistical significance, $N_{SD}^{max}$, for measuring $A$ in the $ZZ \rightarrow l^+l^-X$ mode — the need for keeping a large rate in the $ZZ$ mode competes with the requirement of keeping $\text{Im} \left(e^o\ast\right)$ large.

Figure 1: Maximal statistical significance achieved for asymmetry signal as a function of $m_\phi$ at the SSC with $L = 10 \text{ fb}^{-1}$. The branching ratio for $\phi \rightarrow ZZ \rightarrow l^+l^-X$ is included.
The results for $N_{SD}^{max}$ at the SSC with integrated luminosity of 10 fb$^{-1}$ appear in Fig. 1, for $\tan \beta = 2$ and 10, and $m_t = 150$ GeV. Detection of this asymmetry is clearly not out of the question. Indeed, the Higgs sector parameters required to achieve the illustrated $N_{SD}^{max}$ are not at all fine tuned. Large ranges of parameter space yield values very nearly as big. It should be noted that for the parameter choices which yield these maximal results, the production rate for $\phi$ at $\tan \beta = 2$ is quite similar to that for production of a SM Higgs boson of the same mass, once $m_\phi > 2m_t$, and that the branching ratio for $\phi \to ZZ, WW$ decays is close to the SM value. Thus, without this asymmetry measurement, distinguishing between a $\phi$ which is a CP mixture and the SM Higgs boson could be difficult. At $\tan \beta = 10$, the $\phi$ production rate becomes increasingly suppressed relative to the SM value at larger $m_\phi$, and would alone indicate a non-SM scenario.

Our ability to detect $A$ may be either better or worse than that illustrated in Fig. 1. If only partial polarization for the proton beam can be achieved $N_{SD}^{max}$ would worsen. Limited acceptance for the final states of interest would also cause $N_{SD}^{max}$ to decrease by a factor of $\sqrt{\epsilon}$, where $\epsilon$ is the acceptance efficiency. If additional decay modes could be employed (e.g. $WW$ decay channels with one $W$ decaying leptonically) or if enhanced luminosity can be used, $N_{SD}^{max}$ could be improved. Of course, if only the $ZZ \to ll^+ll^-$ channel can be employed then the statistical significance is decreased (by a factor of roughly 5.5); a higher luminosity would definitely be required to detect the asymmetry. However, we are optimistic that once a Higgs boson is found and its mass known, techniques for employing more than just the gold-plated 4$l$ mode will be found.

4. Conclusion

The ability to polarize one of the proton beams at the SSC will provide a unique opportunity for determining the CP nature of any observed neutral Higgs boson. Indeed, if the Higgs boson has both significant CP-even and CP-odd components, then a large asymmetry between production rates for positively versus negatively polarized protons will arise. If measurable CP violation is found in the Higgs sector many otherwise very attractive models will be eliminated, including the Standard Model and most supersymmetric models. This should provide a rather strong motivation for expending the relatively modest monetary amounts needed to achieve polarized SSC beams.

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