

Gluon Fusion: A Probe of Higgs Sector CP Violation

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We demonstrate that CP violation in the Higgs sector, e.g., of a multidoublet model, can be directly probed using gluon-gluon collisions at the Superconducting Super Collider.

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Understanding the Higgs sector is one of the fundamental missions of future high energy colliders such as the Superconducting Super Collider (SSC) and CERN Large Hadron Collider (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.) However, important classes of models with extended Higgs sectors either do not allow for Higgs sector CP violation or are inconsistent with current experiment if significant CP violation in the Higgs sector is present. Among such models, supersymmetric theories are the most important example. There, a phase for a Higgs field vacuum expectation value in excess of about 10^{-2} would imply imaginary components for slepton, squark, chargino, and neutralino propagators that would result in electric dipole moments of the electron and neutron in excess of experimental limits. Thus, once a Higgs boson is discovered, it will be crucial to determine whether or not it is a pure CP eigenstate.

Although there are a variety of experimental observables that are indirectly sensitive to CP violation in the Higgs sector (such as electric dipole moments, top quark production, and decay distributions, etc.), CP -violating contributions typically first appear at one-loop order, 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. In this Letter, we shall show that the CP nature of a neutral Higgs boson (ϕ) is directly probed by the difference between its production rates through gluon-gluon fusion processes for colliding proton beams of opposite polarizations. (The proposed asymmetry is closely analogous to that developed previously for collisions of polarized backscattered laser beams at a future linear e^+e^- collider [2].) We compute the magnitude of the asymmetry that can be expected at the SSC in the context of a general two-Higgs-doublet model (2HDM) for a variety of models of the polarized gluon distribution func-

tion $\Delta g(x)$. For all but extremely conservative $\Delta g(x)$ choices, large asymmetries are possible since the gg coupling to the CP -even and CP -odd components of the ϕ are generically comparable (both arising at one loop). Indeed, we find that asymmetries larger than 10% are quite typical; these would be observable in the $\phi \rightarrow ZZ \rightarrow l^+l^-X$ final state after 1–3 years of running. In the computations quoted here, we consider the situation in which the only extension of the SM occurs in the Higgs sector— ϕ production rates and asymmetries are generally larger in theories containing additional heavy colored fermions.

The procedure for computing the $gg \rightarrow \phi$ cross section in leading order is well known [1]. 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 [3]. 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 $\Delta g(x) = g_+(x) - g_-(x)$, is not currently known with any certainty. [Here, the \pm subscripts indicate gluons with \pm helicity, and $g(x) = g_+(x) + g_-(x)$ is the unpolarized gluon distribution function.] The relative behavior of $\Delta g(x)$ compared to $g(x)$ is theoretically constrained in the $x \rightarrow 1$ and $x \rightarrow 0$ limits: $\Delta g(x)/g(x) \rightarrow 1$ for $x \rightarrow 1$ and $\Delta g(x)/g(x) \propto x$ for $x \rightarrow 0$. Simple models which satisfy these constraints suggest [4] that a significant amount of the proton's spin could be carried by the gluons. The European Muon Collaboration (EMC) [5] data on the polarized structure function $g_1^p(x)$ is also most easily interpreted if this is the case [6].

We shall employ a variety of models that have appeared in the literature. In one extreme, also considered in Ref. [7], we assume that $\Delta g(x) = 0$ at all x when $Q^2 = 10 \text{ GeV}^2$. Q^2 evolution will retain $\Delta g \equiv \int_0^1 \Delta g(x) dx = 0$ (i.e., gluons never carry any portion of the proton's spin), but $\Delta g(x)$ will develop substantial oscillations at the large Q values of interest for Higgs production. Another extreme is to assume that none of the proton's

spin can be carried by strange quarks. This is the second case considered in Ref. [7], and leads to large $\Delta g, \Delta g \sim 4.5$ at $Q^2 = 10 \text{ GeV}^2$. Aside from numerical differences, this is also the choice considered in Ref. [6]. We shall label this as case (2). We employ the detailed $\Delta g(x)$ form given in Ref. [7]. We also compute results for an intermediate choice, case (3), of $\Delta g \sim 2$ (at $Q^2 = 10 \text{ GeV}^2$) considered in Ref. [7], using their parametrization for $\Delta g(x)$. Two additional $\Delta g(x)$ parametrizations have also been employed. These are the Berger-Qiu parametrization [8] $\Delta g(x) = g(x)$ ($x > x_c$), $\Delta g(x) = (x/x_c)g(x)$ ($x < x_c$), where $x_c \sim 0.2$ yields a value of $\Delta g \sim 2.5$ at $Q^2 = 10 \text{ GeV}^2$, case (4); and the rather modest $\Delta g(x)$ proposal of Ref. [9], with $\Delta g \sim 0.2$ at $Q^2 = 10 \text{ GeV}^2$, case (5). Quark distributions can be chosen, in association with all the $\Delta g(x)$ forms adopted in the above five cases, that reproduce the normal deep inelastic data and the polarized proton EMC data. In obtaining results for Higgs production, we have computed the evolved $\Delta g(x)$ starting with the $Q^2 = 10 \text{ GeV}^2$ inputs specified in cases (1)–(5), using standard polarized structure function evolution [10].

The asymmetry we compute is simply $A \equiv [\sigma_+ - \sigma_-] / [\sigma_+ + \sigma_-]$, where σ_{\pm} is the cross section for Higgs boson 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 $x_1 x_2 = m_\phi^2/s$) of $g(x_1)\Delta g(x_2)[|\mathcal{M}_{++}|^2 - |\mathcal{M}_{--}|^2]$, while $\sigma_+ + \sigma_-$ is determined by the integral of $g(x_1)g(x_2)[|\mathcal{M}_{++}|^2 + |\mathcal{M}_{--}|^2]$. (We have assumed that it is proton 2 that is polarized. Distribution functions will be evaluated at $Q = m_\phi$.) Now, $|\mathcal{M}_{++}|^2 - |\mathcal{M}_{--}|^2$ vanishes for a CP eigenstate, but can be quite large in a general 2HDM. We find $|\mathcal{M}_{++}|^2 - |\mathcal{M}_{--}|^2 \propto -4\text{Im}(\mathcal{E}\mathcal{O}^*)$ and $|\mathcal{M}_{++}|^2 + |\mathcal{M}_{--}|^2 \propto 2(|\mathcal{E}|^2 + |\mathcal{O}|^2)$, where $\mathcal{E}(\mathcal{O})$ represents the gg coupling to the CP -even (-odd) component of ϕ . These depend upon the reduced CP -even (scalar, s) and CP -odd (pseudoscalar, p) couplings given by $s_{i\bar{i}} = u_2/\sin\beta$, $p_{i\bar{i}} = -u_3 \cot\beta$, $s_{b\bar{b}} = u_1/\cos\beta$, and $p_{b\bar{b}} = -u_3 \tan\beta$ (reduced couplings are defined relative to SM-like couplings). Here, the u_i specify the eigenstate ϕ in the Φ_i basis of Ref. [11] (see Ref. [12] for more details). In a 2HDM, $\sum_i u_i^2 = 1$, but they are otherwise unconstrained. Results for the SM Higgs boson correspond to taking $u_1 = \cos\beta$, $u_2 = \sin\beta$, and $u_3 = 0$. More generally, for a CP -even eigenstate we would have $u_3 = 0$, while for a CP -odd eigenstate $|u_3| = 1$. We note that the widths for the ϕ to decay to $b\bar{b}$ and $t\bar{t}$ are determined using these reduced couplings by appropriately weighting the results for CP -even and CP -odd scalars as given in Appendix B of Ref. [1]. ZZ and W^+W^- widths are obtained using the reduced scalar coupling $s_{W^+W^-,ZZ} = u_2 \sin\beta + u_1 \cos\beta$.

To obtain a numerical indication of the observability of A , we have proceeded as follows. We assume that ϕ can be best detected in the $\phi \rightarrow ZZ \rightarrow l^+l^-X$ modes (where $l = e, \mu$ and we include all possible $X = l^+l^-, \tau\bar{\tau}$,

$q\bar{q}, \nu\bar{\nu}$ —so that the net branching ratio for $ZZ \rightarrow l^+l^-X$ is ~ 0.134). We compute the statistical significance of the asymmetry signal as $N_{SD} \equiv (N_+ - N_-) / \sqrt{N_+ + N_-}$, where N_+ (N_-) is the number of events predicted for positive (negative) proton polarization in the $ZZ \rightarrow l^+l^-X$ mode. Since $\Delta g(x) \rightarrow g(x)$ at large x , we impose a cut on the Higgs boson events designed to enhance the importance of large x_2 in the convolution integrals contributing to the numerator and denominator of the asymmetry A . The appropriate cut takes the form $x_1^{\text{cut}} = x_1 - x_2 < x_2^{\text{cut}}$. For each value of m_ϕ and each $\Delta g(x)$ case we search for the choice of x_2^{cut} which optimizes N_{SD} ; this optimal x_2^{cut} is independent of the Higgs sector CP violation parameters. Finally, we search (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} . Of course, it will be noted that our estimate for N_{SD} does not include the ZZ continuum background, other ϕ production mechanisms, the amount of polarization that can be actually achieved at the SSC, nor other possible channels in which the ϕ could be detected. We shall comment on these and other issues shortly.

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 $m_t = 150 \text{ GeV}$. Detection of this asymmetry is clearly not out of the question. The reason that significant N_{SD} values can be achieved becomes clear from the plot of the corresponding values of A , Fig. 2. Quite large A values are achieved in the more favorable $\Delta g(x)$ models (2) and (4). It should be noted that the Higgs sector parameters required to achieve the illustrated N_{SD}^{max} results are not at all fine tuned. Large ranges of parameter space yield values very nearly as big. The large dif-

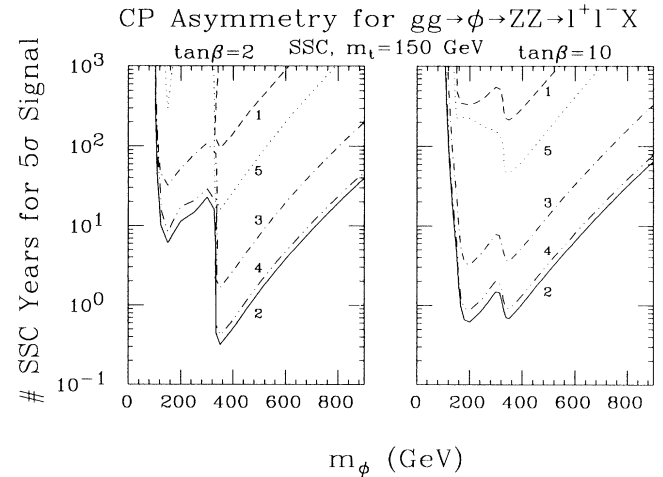


FIG. 1. Maximal statistical significance, N_{SD}^{max} , achieved for the asymmetry signal in the $\phi \rightarrow ZZ \rightarrow l^+l^-X$ channel as a function of m_ϕ at the SSC with $L = 10 \text{ fb}^{-1}$. The curves for different $\Delta g(x)$ choices are labeled by the case numbers, 1–5.

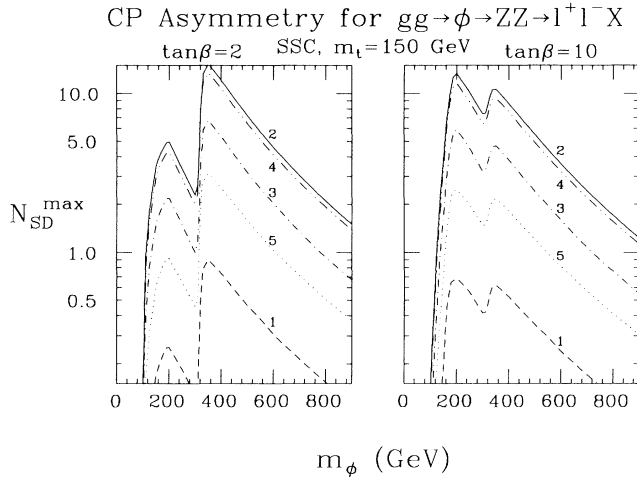


FIG. 2. Fractional asymmetry A for which N_{SD} is maximal, as a function of m_ϕ at the SSC with $L=10 \text{ fb}^{-1}$. The curves for different $\Delta g(x)$ choice are labeled by the case numbers, 1-5.

ference between the N_{SD}^{\max} results in cases (1) and (5), illustrated in Fig. 1, despite the close similarity in the A values, Fig. 2, is due to the much smaller event rates for case (1) compared to other cases, including (5). This difference arises because of the strong x_F^{cut} needed to probe only one sign of the oscillating $\Delta g(x)$ of case (1) (thereby allowing for significant A).

It is amusing to note that, without a determination of A , the ϕ is not necessarily so easily distinguished from a SM Higgs boson (ϕ^0) of the same mass. For instance, for the parameter choices which yield N_{SD}^{\max} , both the ϕ and ϕ^0 total production rates and the $\phi \rightarrow ZZ$ and $\phi^0 \rightarrow ZZ$ branching ratios are similar. Of course, the total width of the ϕ is generally somewhat smaller than that of the ϕ^0 since the dominant W^+W^- and ZZ widths are suppressed. However, the resolution needed to distinguish the ϕ from the ϕ^0 is unlikely to be adequate for $m_\phi \lesssim 400$ GeV.

Our ability to detect A may be either better or worse than that illustrated in Fig. 1. If only partial polarization, P , for the proton beam can be achieved $N_{SD}^{\max} \rightarrow PN_{SD}^{\max}$. Expectations [13] are that P of about 0.7 can be achieved at the SSC with the introduction of appropriate Siberian Snakes, etc., into the injector and main rings of the SSC. Limited acceptance efficiency, ϵ , for the final states of interest yields $N_{SD}^{\max} \rightarrow \sqrt{\epsilon}N_{SD}^{\max}$.

As noted earlier, in computing N_{SD}^{\max} in the ZZ channel, we have not accounted for the ZZ continuum background. If this background is large, it would significantly dilute A since it would yield an additional contribution to the $N_+ + N_-$ denominator of A , and negligible contribution to the $N_+ - N_-$ numerator. Since the ϕ is distinctly narrower than the SM ϕ^0 , this contamination is not so large as one might guess. Below we shall compute the effect of the $ZZ \rightarrow l^+ l^- X$ continuum background upon

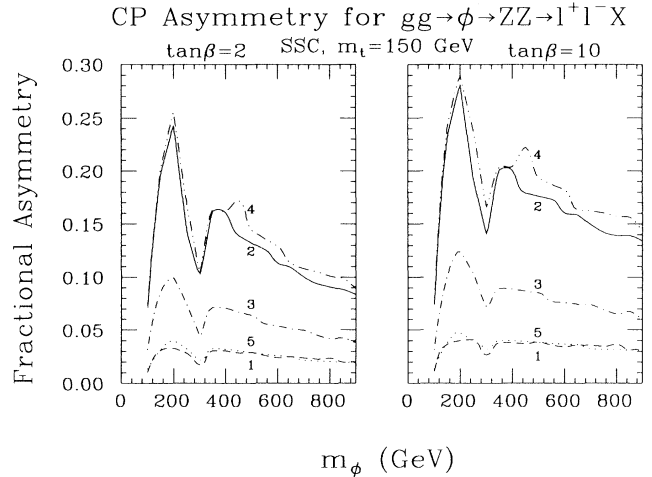


FIG. 3. We plot the number of 10 fb^{-1} SSC years required to detect A at the $N_{SD}^{\max}=5$ sigma level. The different curves are for the five different $\Delta g(x)$ cases. Fractional polarization of $P=0.7$ is employed. The $ZZ \rightarrow l^+ l^- X$ continuum background has been included after imposing an approximate acceptance cut on both it and the Higgs boson signal characterized by $z_0=0.7$ (see text).

the observability of A .

Similarly, WW fusion production of the ϕ would not contribute significantly to $N_+ - N_-$, but would add to $N_+ + N_-$. We have estimated its effects and found them to be insignificant (at $m_t=150$ GeV) for Higgs boson masses below 800 GeV. For m_ϕ between 800 GeV and 1 TeV, N_{SD}^{\max} is reduced by at most 15% due to dilution from WW fusion. For this high mass region, it might prove beneficial to veto against the energetic spectator jets at high rapidity associated with the WW fusion mechanism. Such vetoing can be done with little effect upon the gg fusion events of interest.

In summary, we should combine a polarization fraction of $P \sim 0.7$, a reasonable acceptance efficiency, and some ZZ continuum dilution in estimating realistically achievable N_{SD}^{\max} values. We have done this numerically as follows. We have computed the ZZ continuum and the $\phi \rightarrow ZZ$ rates by imposing an angular cut on the outgoing Z 's in the ZZ center of mass. We require $|z| < z_0 = 0.7$ (where z is the cosine of the angle of one of the Z 's with respect to the beam direction); this corresponds to an acceptance of $\epsilon = 0.7$. For such a cut, most $ZZ \rightarrow l^+ l^- X$ events will fall within the usable portion of a typical detector. The ZZ continuum is integrated over a mass range given by $\Delta m_{ZZ} = \max\{1.5\Gamma_7(\phi), 10 \text{ GeV}\}$. For the most part, the result is that the N_{SD}^{\max} values plotted in Fig. 1 should perhaps be multiplied by about 0.5 for a conservative estimate of the achievable statistical significance for an observation of A in the $ZZ \rightarrow l^+ l^- X$ channel. In Fig. 3 we display the number of SSC 10 fb^{-1} years required to achieve $N_{SD}^{\max}=5$ for $z_0=0.7$ and $P=0.7$. This plot makes it clear that there is a reason-

able chance of observing or placing a meaningful bound on A , if $\Delta g(x)$ is cooperative, in 1–10 SSC years, at least for Higgs boson masses above about $2m_Z$ and below about 500–700 GeV. Results for the LHC are similar. For measuring A , a 100 fb^{-1} LHC year is just slightly better than a 10 fb^{-1} SSC year. Of course, it should be kept in mind that determination of A is certainly a second generation experiment, and it is quite likely that the SSC could achieve 100 fb^{-1} per year by the time this experiment is performed.

It is important to reemphasize the uncertainties associated with $\Delta g(x)$. It is clear that if $\Delta g(x)$ is typified by our cases (2) or (4), then detection of A could prove to be relatively straightforward. Given the theoretical constraints on the $x \rightarrow 0$ and $x \rightarrow 1$ limits of $\Delta g(x)$, and the models that have been constructed which incorporate these constraints, we do not regard such favorable forms of $\Delta g(x)$ as particularly unlikely. Certainly, cases (1) and (5) seem to be somewhat extreme in their conservatism. In our opinion, case (3) could be employed as a reasonable lower bound for use in planning. Were this close to the true $\Delta g(x)$, then observing or bounding A would generally require running the SSC at enhanced luminosity of order 100 fb^{-1} per year.

Finally, it should not be forgotten that all our predictions are based upon the assumption that the heaviest colored fermion that acquires its mass via the Higgs mechanism is the top quark. For $m_\phi > 2m_t$, the addition of a new generation of quarks yields a large increase in the observability of A (not to mention the observability of the ϕ in the first place). For $\Delta g(x)$ case (3), at most 3 SSC years would be required to measure A in the $2m_t < m_\phi \lesssim 1 \text{ TeV}$ range.

In conclusion, we emphasize that the ability to polarize one of the proton beams at the SSC or LHC 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 a reasonable amount of the proton polarization is transmitted to the gluon distributions. If measur-

able CP violation is found in the Higgs sector many otherwise very attractive models will be eliminated, including the standard model and most supersymmetric models. In fact, we have noted that measurement of the polarization asymmetry might be the only tool that will clearly distinguish a Higgs boson that is a mixed CP eigenstate from the SM Higgs boson (or a Higgs boson with SM-like couplings). This should provide a rather strong motivation for expending the relatively modest monetary amounts needed to achieve polarized SSC or LHC beams.

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- [1] J. F. Gunion, H. E. Haber, G. Kane, and S. Dawson, *The Higgs Hunter's Guide*, Frontiers in Physics Lecture Note Series Vol. 80 (Addison-Wesley, Redwood City, CA, 1990).
 - [2] B. Grzadkowski and J. F. Gunion, Phys. Lett. B **294**, 361 (1992).
 - [3] S. Dawson, Nucl. Phys. **B359**, 283 (1991); A. Djouadi, M. Spira, and P. Zerwas, Phys. Lett. B **264**, 440 (1991).
 - [4] See, for example, S. Brodsky and I. A. Schmidt, Phys. Lett. B **234**, 144 (1990).
 - [5] European Muon Collaboration, J. Ashman *et al.*, Nucl. Phys. **B328**, 1 (1989).
 - [6] See, for example, G. Ross, in *Proceedings of the XIVth International Symposium on Lepton and Photon Interactions, Stanford, California, 1989*, edited by M. Riordan (World Scientific, Singapore, 1990).
 - [7] H.-Y. Cheng and C. F. Wai, Phys. Rev. D **46**, 125 (1992).
 - [8] E. L. Berger and J. Qiu, Phys. Rev. D **40**, 778 (1989).
 - [9] C. Bourrely, J. Soffer, F. M. Renard, and P. Taxil, Phys. Rep. **177**, 319 (1989).
 - [10] The program employed is that developed by W.-K. Tung.
 - [11] S. Weinberg, Phys. Rev. D **42**, 860 (1990).
 - [12] B. Grzadkowski and J. F. Gunion, Phys. Lett. B **287**, 237 (1992).
 - [13] S. Y. Lee (private communication).