Correlation between decay planes in Higgs-boson decays into a W pair (into a Z pair)

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For a conventional Higgs boson the decay correlation function for the azimuthal angle between the two W decay planes is $F(\phi)=1+\alpha\cos\phi+\beta\cos2\phi$, where $\alpha=(3\pi/8)^2\gamma/(1+\gamma^2/2)$, $\beta=\frac{1}{4}1/(1+\gamma^2/2)$, with $\gamma=(M_H^2-2m_W^2)/2m_W^2$. While β is negligible, there will be a decay correlation from α if M_H is not too large ($\alpha\geq\frac{1}{4}$ if $M_H\leq400$ GeV). By $\alpha\neq0$, the standard $g_{\mu\nu}$ coupling is distinguished from the complete decoupling of a Higgs boson from transverse W bosons. For a technipion $\alpha=0$, but uniquely $\beta=-\frac{1}{4}$. For the Z pair decay mode, α contains an extra factor of $2r/(1+r^2)$ from each $Z\to\bar{f}f$, where r is the ratio of the axial-vector- to the vector-coupling coefficients. This suppresses α since $2r/(1+r^2)\simeq1/\sqrt{2}$ for $\bar{d}d$, $\simeq-\frac{1}{3}$ for $\bar{u}u$, and $\simeq\frac{1}{4}$ for $\mu^+\mu^-$,

The most controversial and poorly tested component of the standard electroweak theory remains the Higgs sector. Recently, the impetus from potential Superconducting Super Collider (SSC) experiments has initiated studies[1–5] of the size of the signal-to-background ratio for the decay of a conventional Higgs boson through a standard $g_{\mu\nu}$ coupling into a W pair and into a Z pair. Both because of the fundamental uncertainties surrounding the Higgs sector and because of the magnitude of SSC experiments, it is very important to be able to decisively pin down the form of the Higgs-boson coupling through carefully planned experiments. These uncertainties about the Higgs-boson coupling are clearly relevant to decisions about how various empirical cuts can enhance the discovery of a Higgs-boson signal and exclude spurious background effects. Here we discuss the effects of various choices for the Higgs-boson coupling on the general decay correlation function[6,7] $I(\theta_1,\theta_2,\phi)$ for a Higgs-boson decay[8] into a W^+W^- pair and into a ZZ pair.

By Lorentz invariance and CP invariance, measurement of $I(\theta_1,\theta_2,\phi)$ will provide full information on the magnitude of the two CP-even helicity decay amplitudes and their relative phase.[9] The azimuthal angle ϕ is the angle between the $W^+\to\bar{b}t$, $e^+\nu_e,\ldots$ and the $W^-\to b\bar{t}$, $e^-\bar{\nu}_e,\ldots$ decay planes, measured between the $\bar{b}$ or e^+ half of the W^+ decay plane and the b or e^- half of the W^- plane. The polar angle θ_1 (θ_2) for the $\bar{b}$ or e^+ momentum (the b or e^- momentum) is the usual helicity angle defined in the W^+ rest frame (W^- rest frame).

W^+W^- DECAY MODE

(i) By integration over the entire θ_1,θ_2 acceptance, the decay correlation function for the azimuthal angle between the two W-pair decay planes is

$$F(\phi)=1+\alpha\cos\phi+\beta\cos2\phi \ . \tag{1}$$

From the most general Lorentz-invariant, CP-conserving coupling

$$g\epsilon_\mu^{+*}(P)\epsilon_\nu^{-*}(K)(m_W^2g^{\mu\nu}-\lambda e^{i\delta}K^\mu P^\nu) \tag{2}$$

with g, λ, and δ real, we find

$$\beta=\mathcal{R}\mathcal{U}\frac{2}{2+\gamma^2-2\lambda\gamma(\gamma^2-1)\cos\delta+\lambda^2(\gamma^2-1)^2} \tag{3}$$

and

$$\left[\frac{8}{3\pi}\right]^2\alpha=-\mathcal{T}\mathcal{W}\frac{2[\gamma-\lambda(\gamma^2-1)\cos\delta]}{2+\gamma^2-2\lambda\gamma(\gamma^2-1)\cos\delta+\lambda^2(\gamma^2-1)^2} , \tag{4}$$

where

$$\gamma=(M_H^2-2m_W^2)/2m_W^2 \tag{5}$$

is the relativistic γ for a boost between the two vector-boson rest frames. Neglecting final-fermion masses, the W^+ (W^-) decay density matrix parameters[7]

$$\mathcal{R}=-\tfrac{1}{2} \quad (\mathcal{U}=-\tfrac{1}{2}) \tag{6}$$

and

$$\mathcal{T}=-1 \quad (\mathcal{W}=+1) \ . \tag{7}$$

In the standard SU(2)×U(1) electroweak gauge theory with a complex Higgs doublet, after spontaneous symmetry breaking the physical Higgs scalar has a pure $g_{\mu\nu}$-type coupling. Figures 1 and 2, respectively, show the corresponding variations of β and α with increasing M_H. While β is negligible for a standard $g_{\mu\nu}$ coupling, there will be a decay correlation from α if M_H is not too large ($\alpha\geq\frac{1}{4}$ if $M_H\leq400$ GeV). Also by

$$\alpha\neq0 \ , \tag{8}$$

the standard $g_{\mu\nu}$ coupling is distinguished from the complete decoupling of a Higgs boson from transverse W bosons. Also shown are the results for a manifestly gauge-invariant coupling

$$H(\partial_\mu W_\nu^+-\partial_\nu W_\mu^+)(\partial^\mu W^{-\nu}-\partial^\nu W^{-\mu}) \tag{9}$$

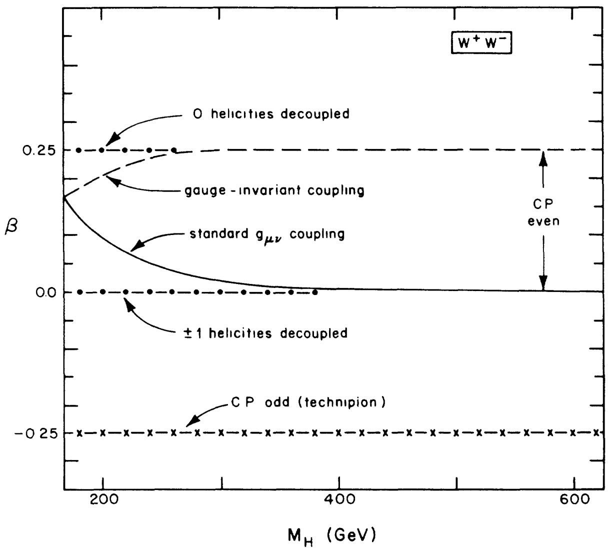

FIG. 1. Variation of the β parameter with increasing Higgs-boson mass M_H for the W^+W^- mode. β is the coefficient of $\cos 2\phi$ in the azimuthal distribution $F(\phi)$ with ϕ is the angle between the two W decay planes.

which almost saturates the bound for β (the magnitude of α is always bounded by the value for β, see Ref. 8). The upper bound for β, i.e., $\beta = 0.25$, corresponds to an interaction which completely decouples zero-helicity states of the W bosons.

(ii) By separate integrations over the four θ_1, θ_2 quadrants,

$$F_{11,22}(\phi) = \gamma_S \left[1 + \frac{\alpha_S}{\gamma_S}\cos\phi \pm \frac{\alpha_{XS}}{\gamma_S}\sin\phi + \frac{\beta}{\gamma_S}\cos 2\phi \right] \tag{10}$$

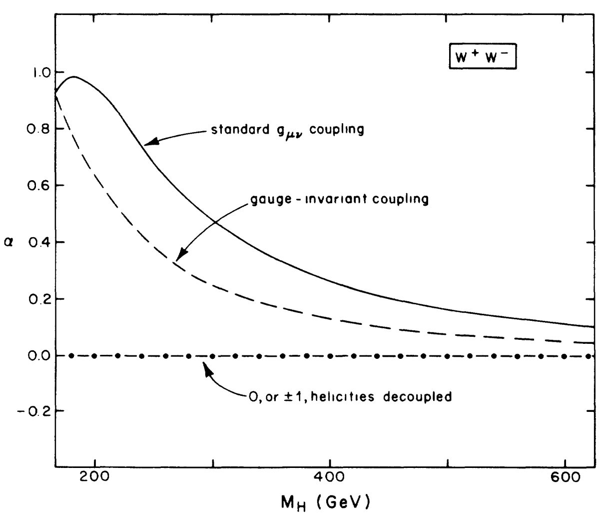

FIG. 2. Variation of the α parameter with increasing Higgs mass M_H for the W^+W^- mode. α is the coefficient of $\cos\phi$ in the azimuthal distribution $F(\phi)$.

for $0 \le \theta_{1,2} \le \pi/2$ and for $\pi/2 \le \theta_{1,2} \le \pi$, respectively,

$$F_{12,21}(\phi) = \gamma_D \left[1 + \frac{\alpha_D}{\gamma_D}\cos\phi \pm \frac{\alpha_{XD}}{\gamma_D}\sin\phi + \frac{\beta}{\gamma_D}\cos 2\phi \right] \tag{11}$$

for $0 \le \theta_1 \le \pi/2$, $\pi/2 \le \theta_2 \le \pi$, and for $0 \le \theta_2 \le \pi/2$, $\pi/2 \le \theta_1 \le \pi$, respectively. The normalizations[10] are such that

$$F(\phi) = \tfrac{1}{4}(F_{11} + F_{22} + F_{12} + F_{21}) \ .$$

We argue in the next paragraph that, assuming time-reversal invariance and a weak decay, the only nonzero new parameters in Eqs. (10) and (11), versus $F(\phi)$, are α_S and α_D, and that they provide information equivalent to α. With these assumptions, α and β are related by

$$\left[\frac{8}{3\pi} \right]^2 \alpha = 4\sqrt{2\beta(1/4 - \beta)} \ . \tag{12}$$

Figures 3 and 4 show[10] how α_s/γ_S and α_D/γ_D vary with increasing M_H.

For the general case, from Eq. (2) we obtain

$$\alpha_{S,D} = \alpha \pm \alpha_0 \ , \tag{13}$$

$$\alpha_{XS,XD} = \frac{3\pi}{8}(\alpha^{(6)} \pm \alpha^{(8)}) \ , \tag{14}$$

where

$$\alpha^{(6)} = \mathcal{RW} \frac{2\lambda(\gamma^2 - 1)\sin\delta}{2 + \gamma^2 - 2\lambda\gamma(\gamma^2 - 1)\cos\delta + \lambda^2(\gamma^2 - 1)^2} \ . \tag{15}$$

To obtain $\alpha^{(8)}$ in Eq. (15) replace $\mathcal{RW}$ by $\mathcal{TU}$. To obtain α_0 in Eq. (4) write only α_0 on the left-hand side and replace $\mathcal{TW}$ by $\mathcal{RU}$ on the right-hand side. Therefore, α_S and α_D are proportional to α and do not provide new information; however, a fit of the full $I(\theta_1, \theta_2, \phi)$ might provide a more significant determination of α. Second, $\alpha^{(6)}$ and $\alpha^{(8)}$ are also proportional to each other and to $\sin\delta$. By S-matrix unitarity, for weak decays where final-state interactions can be neglected, the transition matrix must be Hermitian, so T invariance then forces $\delta = 0$.

(iii) The full $I(\theta_1, \theta_2, \phi)$ sequential decay correlation function, assuming Lorentz invariance and CP invariance, provides no further information than that provided by separate integrations over the four θ_1, θ_2 quadrants. It is of the form

$$I(\theta_1, \theta_2, \phi) = C(\theta_1, \theta_2) + A(\theta_1, \theta_2)\cos\phi + A_X(\theta_1, \theta_2)\sin\phi + B(\theta_1, \theta_2)\cos 2\phi \ , \tag{16}$$

where β determines $B(\theta_1, \theta_2)$ and $C(\theta_1, \theta_2)$, α determines $A(\theta_1, \theta_2)$, and $\alpha^{(6)}$ determines $A_X(\theta_1, \theta_2)$. Furthermore, assuming also a weak decay and time-reversal invariance, $I(\theta_1, \theta_2, \phi)$ is completely determined by the parameter α, or equivalently β, which can be determined by measurement of $F(\phi)$. [These facts are easily seen from Eqs. (1)–(6), and Table VI of Ref. 8.]

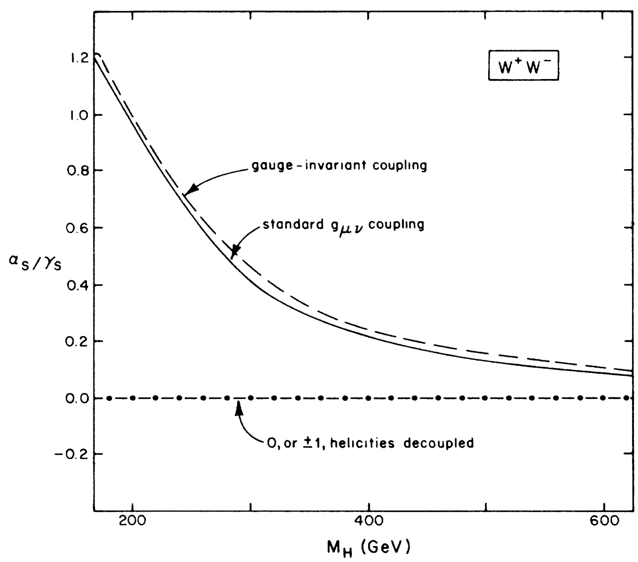

FIG. 3. Variation of the α_S/γ_S parameter with increasing M_H for the W^+W^- mode. This parameter is the coefficient of $\cos\phi$ in the θ_1,θ_2 quadrant distributions $F_{11}(\phi)$ and $F_{22}(\phi)$.

For large M_H the standard $g_{\mu\nu}$ coupling and an interaction which decouples the transverse-helicity states of the W bosons cannot be distinguished; the associated distribution is

$$I(\theta_1,\theta_2,\phi)\sim\sin^2\theta_1\sin^2\theta_2 \ . \tag{17}$$

Similarly, for large M_H the gauge-invariant coupling of Eq. (9) and an interaction which decouples the zero-helicity states of the W bosons cannot be distinguished; the associated distribution is

$$I(\theta_1,\theta_2,\phi)\sim C(\theta_1,\theta_2)+B(\theta_1,\theta_2)\cos 2\phi \ , \tag{18}$$

where

$$B(\theta_1,\theta_2)=\sin^2\theta_1\sin^2\theta_2 \ ,$$

$$C(\theta_1,\theta_2)=\sin^2\theta_1\sin^2\theta_2+4\cos^2\theta_1\cos^2\theta_2+2\sin^2\theta_1\cos^2\theta_2 +2\cos^2\theta_1\sin^2\theta_2-4\cos\theta_1\cos\theta_2 \ .$$

Z^0-Z^0 DECAY MODE

(i) The $F(\phi)$ distribution is as in Eq. (1) with β and α given by Eqs. (3) and (4). Again, neglecting final fermion masses, the $Z^0\to\mu^+\mu^-$, $\bar{q}q$ decay density parameters are $\mathcal{R}=-\frac{1}{2}$ and $\mathcal{T}=-2r/(1+r^2)$ where r is the ratio of the axial-vector- to the vector-coupling coefficients so $\mathcal{T}\simeq-0.706$ for $\bar{d}d$, 0.337 for $\bar{u}u$, and -0.237 for $\mu^+\mu^-$. Accordingly, in comparison with the W^+W^- mode, the α parameter is suppressed. For the Z^0Z^0 mode Fig. 5 shows the variation of β with increasing M_H, and Fig. 6 shows the variation of α *when both Z^0 decay into $\bar{d}d$. The smaller α's* for the other Z^0 decay modes can be read off by using the obvious scale factors.

(ii) If the Higgs-boson mass M_H is not too large, instead of $F(\phi)$, it appears better to use $F_{11}(\phi)$ and $F_{22}(\phi)$ or the full $I(\theta_1,\theta_2,\phi)$ to determine α since, see Fig. 7, $\alpha_S/\gamma_S\geq\frac{1}{4}$ for $M_H\leq372$ GeV. The behavior of α_D/γ_D is shown in Fig. 8.

Assuming time-reversal invariance and weak decay, α and β are related by

$$\left[\frac{8}{3\pi}\right]^2\alpha=-4\mathcal{T}\mathcal{W}\sqrt{2\beta(1/4-\beta)} \ . \tag{19}$$

(iii) The preceding discussion about $I(\theta_1,\theta_2,\phi)$ for the W^+W^- decay mode also applies to the Z^0Z^0 decay mode except $C(\theta_1,\theta_2)$ Eq. (18) is replaced by

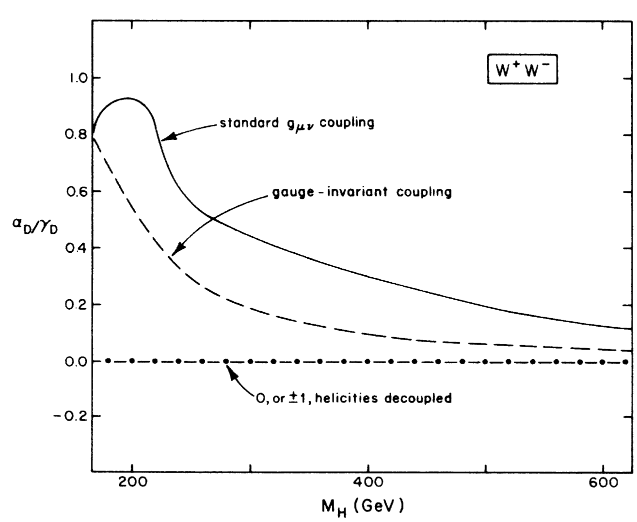

FIG. 4. Variation of the α_D/γ_D parameter with increasing M_H for the W^+W^- mode. This parameter is the coefficient of $\cos\phi$ in the θ_1,θ_2 quadrant distributions $F_{12}(\phi)$ and $F_{21}(\phi)$.

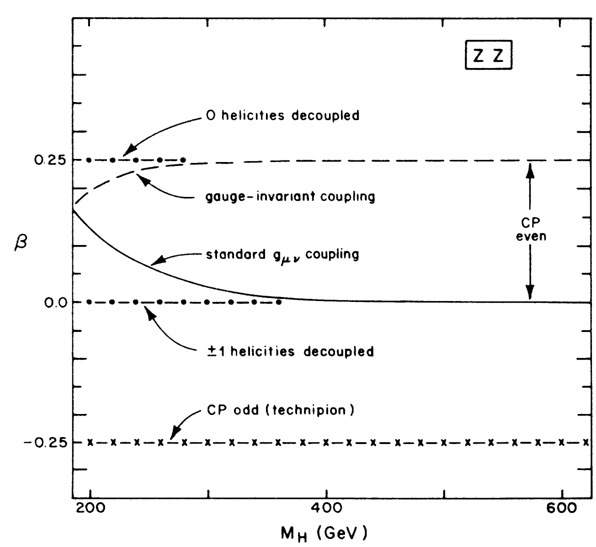

FIG. 5. Variation of the β parameter with M_H for the Z^0Z^0 mode.

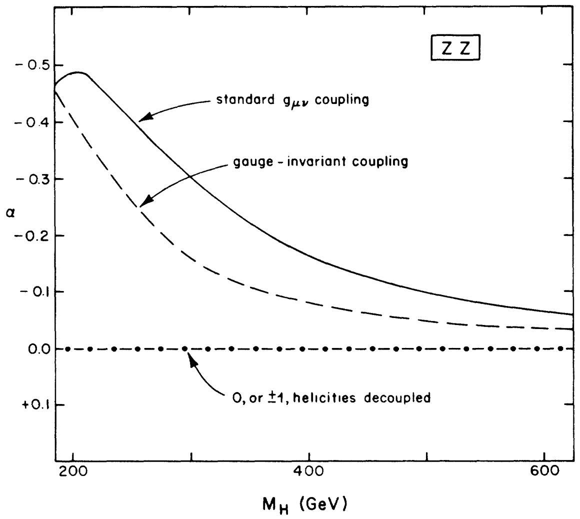

FIG. 6. Variation of the α parameter with M_H for the Z^0Z^0 mode when both Z^0's decay into $\bar{d}d$. Other Z^0 decays give α scaled downward (see text).

$$C(\theta_1,\theta_2)=\sin^2\theta_1\sin^2\theta_2+4\cos^2\theta_1\cos^2\theta_2+2\sin^2\theta_1\cos^2\theta_2+2\cos^2\theta_1\sin^2\theta_2+4\left[\frac{2r}{1+r^2}\right]^2\cos\theta_1\cos\theta_2\ . \tag{20}$$

CLOSING REMARKS

In closing we emphasize that this treatment assumes *CP* invariance. However, it was previously shown[11] that there are many signatures and consistency checks from the full $I(\theta_1,\theta_2,\phi)$ for a violation of *CP* invariance in a W^+W^- or Z^0Z^0 decay channel. If *CP* invariance is not assumed, there are three independent amplitudes, and except for the unobservable overall phase, measurement of $I(\theta_1,\theta_2,\phi)$ will in principle determine them completely. If *CP* invariance is not assumed, but instead Hermiticity and *T* invariance of the transition matrix are assumed, measurement of $I(\theta_1,\theta_2,\phi)$ will determine the three independent real parameters.

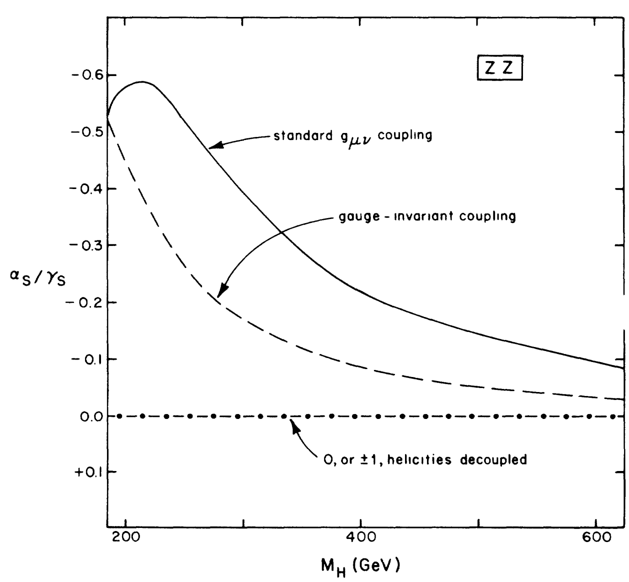

FIG. 7. Variation of the α_S/γ_S parameter with M_H for the Z^0Z^0 mode when both Z^0's decay in $\bar{d}d$.

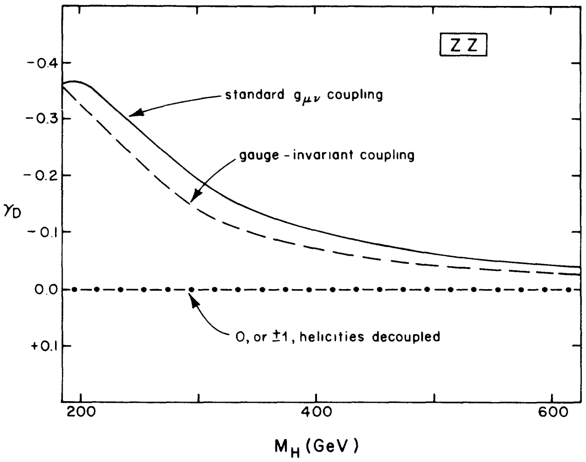

FIG. 8. Variation of the α_D/γ_D parameter with M_H for the Z^0Z^0 mode when both Z^0's decay in $\bar{d}d$.

Finally, we explain why α appears here in $F(\phi)$ but not for the sequential decay $X\to V_1V_2$ with, for example, $\phi\to K^+K^-$, $\omega\to\pi^+\pi^-\pi^0$, or J/ψ or $\Upsilon\to\mu^+\mu^-$: Vector-meson "probes" are of course especially useful since polarization information is carried forward and displayed kinematically upon the vector meson's decay into a two-body, or into a three-body, channel. *Z^0 and $W^\pm$ decays violate P and C separately so their decay density matrices[7] involve r, the ratio of the axial-vector- to the vector-coupling coefficient, and therefore their decay distributions provide more information about the first decay $X\to V_1V_2$.* This effect is largest for $W^\pm$ decays and next largest for $Z^0\to\bar{q}q$ where $Q^{EM}=-\frac{1}{3}$ versus $\bar{q}q$ with $Q^{EM}=\frac{2}{3}$ or $\mu^+\mu^-$. It is also larger when final-fermion masses are smaller versus the magnitude of the decay momentum.

ACKNOWLEDGMENTS

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APPENDIX: SEPARATION OF THE SIGNALS FROM THE EXPECTED BACKGROUNDS

The text shows that at the SSC there will be signals independent of the production mechanism which could be used to decisively pin down the form of a low-mass Higgs coupling, $M_H \lesssim 400$ GeV, through carefully planned experiments. Here we make some remarks about some of the issues involved in the separation of these signals from the expected backgrounds.[12–14]

An important point is that in using $W^\pm$ or Z polarizations to apply cuts on Higgs events produced by high-energy pp collisions to extract the Higgs signal from the expected backgrounds, *measurement of the* β *decay correlation parameter in* $I(\theta_1,\theta_2,\phi)$ *is dependent on whether or not all* W *or* Z *polarizations are included in the signal.* Therefore, for a low- or high-mass Higgs boson (see Figs. 1 and 5), separation of a CP-odd Higgs boson, i.e., a technipion, from a CP-even Higgs boson is affected by any detector and/or data analysis bias to W or Z polarizations. *Also measurement of the* α *decay correlation parameter requires that any cuts on the raw data not affect the ratio of transverse to longitudinal* W*'s, or* Z*'s, present in the signal.* In other words, the text of this paper shows that a correlation measurement of the ratio of transverse to longitudinal W's, or Z's, in a Higgs-boson-like signal can distinguish the standard model Higgs boson from other spin-zero, CP-even or -odd mesons.

Next for clarity in our remarks we refer to the process

$$H^0 \rightarrow WW \rightarrow e\nu_e + q\bar{q}$$

which has been analyzed quite extensively in the 1986 Snowmass Summer Study.[14] An important point is that since α is the coefficient of $\cos\phi$ in the decay correlation function for the azimuthal angle between the two W decay planes

$$F(\phi) = 1 + \alpha\cos\phi + \beta\cos^2\phi$$

it is necessary to measure (i) the sign of the charge of isolated leptons, so in $W \rightarrow e\nu$, $\mu\nu$ it is known with good confidence what the charge of the lepton is, and to measure (ii) the sign of the charge of the q (or $\bar{q}$) jet from the other $W \rightarrow q\bar{q}$. *Note that measurement of* β *does not require tagging of lepton or quark charges.* For (ii) the best procedure may be to trigger on the semileptonic decay of t-quark jets in conjunction with B mesons, i.e., to use $W^+ \rightarrow t\bar{b}$ and $W^- \rightarrow b\bar{t}$, and thereby also use the sign of isolated leptons from the top quark's semileptonic decay.

At present the top-quark mass is thought to lie between about 50 GeV and about 185 GeV assuming three generations of quark-lepton families. Simulations of top-quark jets with top-quark masses of about 40 GeV have shown that there are no major differences in jet samples from a top quark and from an off-mass-shell light quark so measurement of the jet mass for $m_t \approx 40$ GeV is not helpful. Simulations for higher m_t need to be carried out. To make use of $W \rightarrow t\bar{b}$, of course m_t must be less than about 70 GeV. Unfortunately, for a low-mass Higgs boson ($M_H \lesssim 400$ GeV) the best procedures for identification and treatment of production mechanisms and major backgrounds may be sensitive to what is the value of the top-quark mass. (Forward t tagging[13] would only affect the production mechanism and so would not affect α or β of the signal.) Once the major background(s) are identified with good confidence, the β and α dependence of these backgrounds needs to be studied in the context of detector simulations to see what is the overlap(s) with the signal—that is, for example, with the ranges of α and β in the figures in this paper.

In the 1986 Snowmass Summer Study, the two major backgrounds to $pp \rightarrow H^0 \rightarrow e\nu q\bar{q}$ for 300-GeV Higgs-boson masses which were quite extensively studied with respect to the signal/background ratio under various cuts and detector properties were the "W+jet background" where the jet appears to be a W decaying hadronically and the W decays in a leptonic mode, and the "QCD background $pp \rightarrow qq$ or gg or qg" where one of the final particles emits a W.

To date, the $H^0 \rightarrow ZZ$ modes which have been rather extensively studied in which the H^0 *might* be detected over competing gackgrounds, all involve at least one $Z^0 \rightarrow l^+l^-$ so the $2r/(1+r^2) \approx \frac{1}{4}$ suppression factor means α is more difficult to measure via such modes. Nevertheless, β can be measured if the two Z decay planes are determined independent of assumptions as to Z polarizations. Assuming a WW fusion production of the standard $g_{\mu\nu}$ coupled Higgs boson, in Ref. 15 for Higgs-boson masses of 500 and 1000 GeV, there are plots of the behavior of α and β versus the Z^0 pair invariant mass and versus the cosine of the angle between the two Z^0's in the Z^0 center of mass. The usage of the variation of the longitudinal-polarization fraction as a method of Higgs-boson identification has been studied in Refs. 3, 15, and 16.

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[9] See Appendix of Ref. 8.

[10] The notation in this paper follows Ref. 8 except herein we let $\alpha \equiv (3\pi/8)^2\alpha^{(3)}$, $\beta = \beta_0$, and choose the constant terms in $F(\phi)$, and in $F_{11}(\phi) \cdots$ at large M_H, to be one. The normalizations $\gamma_{S,D} = 1 \pm \frac{1}{4}\gamma^{(11)}$ with $\gamma^{(11)} = 9\beta\mathcal{T}\mathcal{W}/4\mathcal{R}\mathcal{U}$ rapidly and monotonically approach one as M_H increases; for a W pair, or a Z pair, $\gamma_{S,D}$ are within 4% of one for $M_H \geq 300$ GeV. At threshold $\gamma_S = 0.625$ (1.19) and $\gamma_D = 1.375$ (0.813) for a W pair (Z pair). For the Z^0Z^0 mode, the angle ϕ is measured between the two antifermion directions (θ_1 and θ_2 label the

antifermion momenta) so $\mathcal{W}=\mathcal{T}$.

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