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R.N. Cahn, S.D. Ellis and W.J. Stirling

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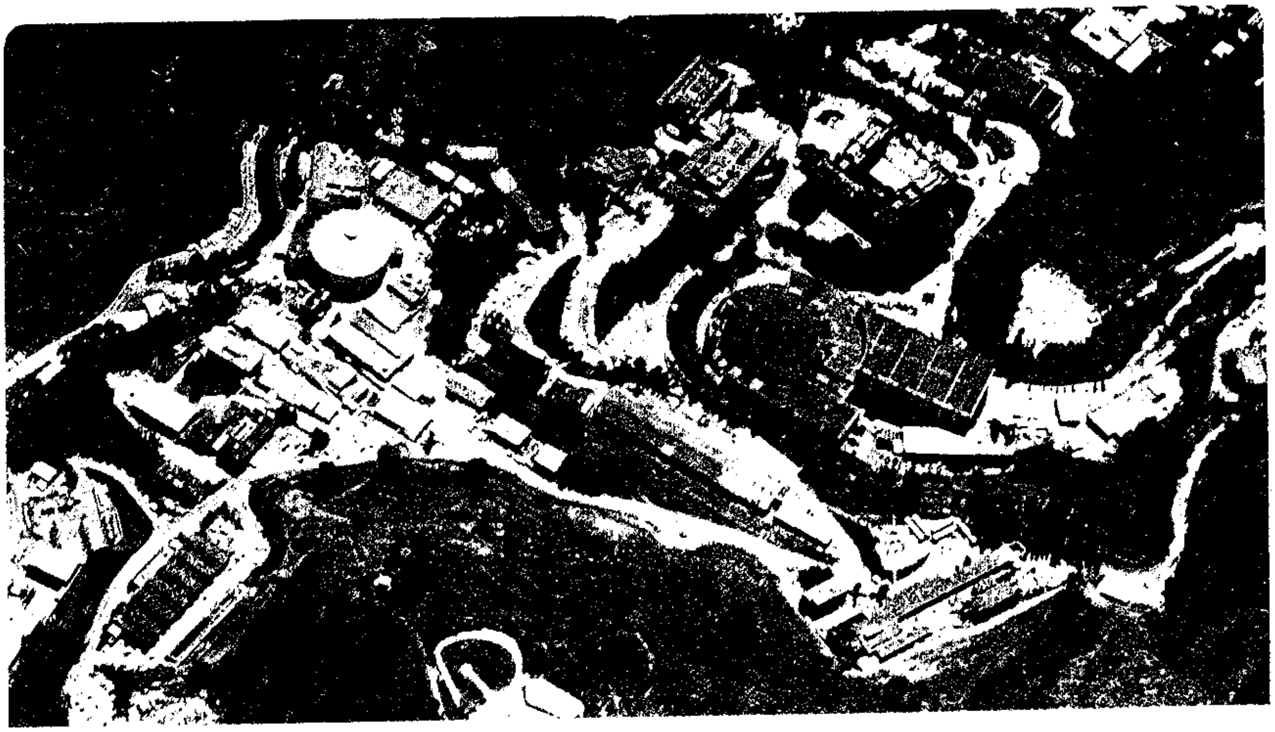

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Transverse Momentum Signatures for Heavy Higgs Bosons [*]

Robert N. Cahn
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Stephen D. Ellis
Physics Department
University of Washington
Seattle, WN 91895

Ronald Kleiss
CERN
CH 1211 Geneva 23
Switzerland

and

W. J. Stirling
Physics Department
University of Durham
Durham City DH1 3LE
U.K.

Abstract

Heavy Higgs bosons produced by WW fusion at the SSC will have transverse momentum of order M_W. The background due to $q\bar{q} \to ZZ$ will produce pairs with characteristically less transverse momentum. This provides a useful discriminator. It may be possible to tag the WW fusion events in a manner analogous to that used in two photon physics.

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The investigation of electroweak symmetry breaking is a primary goal of the proposed Superconducting Super Collider (SSC). A particularly severe challenge is the detection of the Higgs boson of the minimal standard model. For Higgs bosons with masses greater than twice the mass of the W or Z, the dominant decays of the Higgs boson are $H \to W^+W^-$ and $H \to ZZ$. There are two significant production mechanisms for such very massive Higgs bosons in the SSC energy range ($\sqrt{s} \approx 40$ TeV). The first is the gluon-fusion mechanism [1] in which two gluons couple to a heavy fermion loop. The Higgs boson is emitted from this loop. The second is the WW fusion mechanism in which incident quarks emit W's or Z's which collide to form the Higgs boson [2]. For $M_H > 300$ GeV, it is the latter mechanism that dominates [2,3]. The cross sections are in the picobarn range, giving some tens of thousands of Higgs bosons produced in a nominal SSC year (defined to have an integrated luminosity of 10^{40} cm^{-2}).

While the total number of Higgs bosons produced is thus expected to be large, kinematic cuts forced by detector considerations take their toll. More importantly, studies show [4,5] that the detection of two W's or Z's when only one decays leptonically is extremely difficult. These events are overwhelmed by the background from events containing a single real W or Z together with a pair of hadronic jets that together simulate a second W or Z . The conservative alternative is to require that both intermediate vector bosons decay leptonically. Clearly, the ZZ signature is far superior to that of the W's. We concentrate henceforth on the sequence $H \to ZZ \to (l^+l^-)(l^+l^-)$.

If it is assumed that both μ's and e's can be identified reliably and their momenta measured, this sequence has a branching ratio of nearly $(1/3) \times (0.06)^2 \approx 1.2 \times 10^{-3}$. Thus each picobarn of Higgs production cross section will produce 12 such events in a standard SSC year. While this is a small number, the signature is extremely clean. It is reasonable to assume that the primary background comes entirely from pairs of Z's that are not associated with the Higgs boson. The simplest process contributing is $q\bar{q} \to ZZ$.

This background can be separated from the signal in a variety of ways. The most obvious is that the background falls uniformly as a function of the invariant mass of the ZZ pair. If the Z's are required to have rapidities less than 1.5, the cross section is roughly $d\sigma/dM_{ZZ} = 0.3\exp(-M_{ZZ}/125\text{ GeV})$ pb/GeV [6]. A narrow signal could be isolated over this smooth background. In fact, the width of the Higgs increases rapidly with its mass: $\Gamma_H \approx 55\times(M_H/500\text{ GeV})^3$ GeV. Thus a Higgs boson with a mass of 200 GeV is quite narrow (about 2 GeV) while a 600 GeV Higgs would be very broad (about 100 GeV). Of course, the resolution of the detector would broaden a narrow resonance into one with a width of perhaps 10 GeV or so. A realistic assessment of the signal requires comparing the signal and background integrated over some appropriate interval. In this regard, it should be noted that the canonical reference, Eichten *et al.* [3] (EHLQ). compared the full signal to the background integrated only over a single width of the Higgs (or 10 GeV for a narrower Higgs). This produced an overly optimistic comparison. We have chosen always to integrate the signal and the background over two widths, or 20 GeV, whichever is greater. Compared to EHLQ, this means roughly that the background is twice as big, while the signal is only 70% as big. Unfortunately, this is a more realistic approach.

At very low Higgs mass, but still above the ZZ threshold, there is no problem in isolating the Higgs assuming, as always, the integrated luminosity and energy postulated for the SSC. A Higgs with mass 200 GeV is narrow and copiously produced. In addition to about 10 pb produced by the WW mechanism, there are about 20 pb produced through gluon fusion, both figures representing totals without kinematic cuts[7]. Together, they produce about 10 pb in the ZZ channel (which is roughly one third of the total Higgs rate). The background due to continuum ZZ production would be roughly 5 pb. This would give about 84 events of signal (using only the 70% within two widths) over 60 events of background and should present no problem.

Assuming that the mass of the t-quark is not much greater than 50 GeV and that there are no other heavy quarks yet to be discovered, the gluon fusion mechanism quickly becomes ineffective for producing the Higgs boson as its mass increases. For a mass of 300 GeV, the WW fusion mechanism is already slightly more productive. Of course, this latter mechanism also produces a cross section that falls with increasing Higgs mass. By 500 GeV, the cross section has fallen to about 3.3 pb, and by 1000 GeV it has fallen by another factor of three to 1.1 pb[7].

Despite this falling cross section, the background does not overwhelm the signal. This is so for two reasons. First, the background $d\sigma/dM$ falls roughly exponentially as noted above, so that even though this background must be integrated over an interval, Δ, increasing as M^3, the total background falls rapidly. Second, the background, while composed of the same final state particles, ZZ, differs from the signal in important ways.

The Higgs particle has spin zero, so the decay angular distribution of the Z's from it is necessarily isotropic. The Z's produced by $q\overline{q}$ annihilation tend to be forward and backward, once the invariant mass is large compared to $2M_Z$.[8] This can be exploited by requiring that the Z's observed have not too large center of mass rapidity. Indeed, this may be unavoidable unless the detector is specially designed to accept leptons in the very forward and backward directions. The effect of such a cut is displayed in Figs. 1 and 2. These show ZZ pair invariant masses for Higgs bosons with mass 400 and 600 GeV. The backgrounds are also shown. A cut of $|\eta| < 1.5$, where η is the Z rapidity, reduces the background by about five and the signal by about two. While the signal to background ratio seen in Figs. 1 and 2 is encouraging, the total number of events expected is small. For the 600 GeV case, after the rapidity cut, $|\eta| < 1.5$, there remains only 0.3 pb in the ZZ channel, corresponding to 10 or 11 events in the all charged lepton mode. For this reason, it is important to seek additional signatures, characteristics of the events arising from Higgs decay that can distinguish them from the background of continuum ZZ production.

In this paper we explore the utility of measuring the transverse momentum of the Higgs boson, that is, the vector sum of the transverse momenta of the Z's into which it decays. The background production of Z pairs from $q\overline{q}$ annihilation is expected to produce little transverse momentum for the pair. We shall estimate the transverse momentum distribution using perturbative

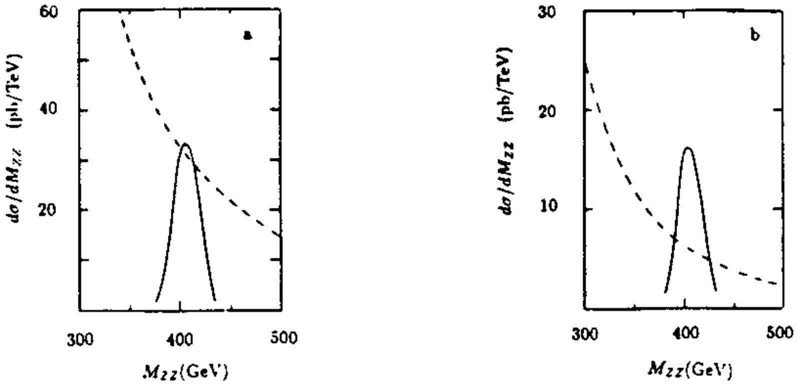

Figure 1: (a)The invariant mass distribution of Z pairs from Higgs decay (solid line) for $M_H = 400$ GeV and the continuum background, $q\bar{q} \rightarrow ZZ$. No cuts are made. (b) The same as (a) except that the outgoing Z's are required to have rapidity $|\eta| < 1.5$.

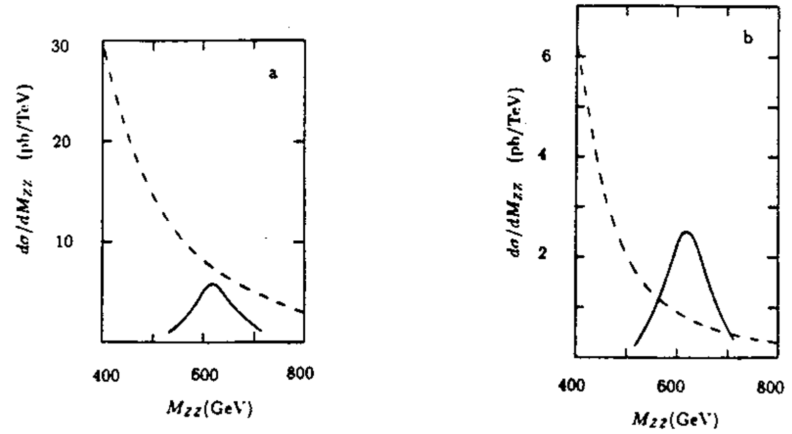

Figure 2: (a)The invariant mass distribution of Z pairs from Higgs decay (solid line) for $M_H = 600$ GeV and the continuum background, $q\bar{q} \rightarrow ZZ$. No cuts are made.(b) The same as (a) except that the outgoing Z's are required to have rapidity $|\eta| < 1.5$.

methods. For example, we calculate the process $q\bar{q} \rightarrow ZZg$. The Z pair recoils against the gluon and thus receives transverse momentum. In contrast, the WW fusion mechanism produces Higgs bosons with sizeable transverse momentum. This follows from the behavior of the propagator for the virtual W's (or Z's) producing the Higgs boson. The propagator is roughly $1/(P_\perp^2 + M_W^2)$ where $P_\perp$ is the transverse momentum of the W relative to the incident direction. Thus the transverse momenta of the virtual W's are of order M_W, and, consequently, so is the transverse momentum of the Higgs boson they form.

The transverse momentum of the Higgs boson is balanced by that of the jets formed by the quarks that emitted the virtual W's or Z's. These quarks are analogous to the e^+ and e^- that emit virtual photons in two-photon processes. This raises the possibility of using quark jets to tag WW or ZZ fusion events. Such triggering necessarily reduces the event rate and could be justified only if it permitted looser constraints on the final state identification. In particular, tagging might be a way to isolate events in which a Higgs boson was produced, decayed into ZZ and subsequently one of the Z's decayed hadronically. Our preliminary analysis of this possibility suggests that it warrants a more complete investigation.

To the extent to which the partons inside the proton have no transverse momentum, the continuum ZZ pairs produced by $q\bar{q} \rightarrow ZZ$ in lowest order have no transverse momentum. If gluons are emitted by the annihilating quarks, the produced ZZ pair will generally have transverse momentum. For small values of this transverse momentum, multiple gluon emission is important. For sufficiently large transverse momentum, it is the first order emission of a single hard gluon or quark that dominates. The important processes are then $q\bar{q} \rightarrow ZZg$, $qg \rightarrow ZZq$, and $\bar{q}g \rightarrow ZZ\bar{q}$.

When is the transverse momentum large enough so that the single emission picture can be trusted? The relevant scale for comparison is the Q^2 at which the incoming parton structure functions are evaluated. A crude measure of the contributions from multiple emission processes is offered by the double logarithmic terms characteristic of the Sudakov form factor. Such contributions are not important as long as $(\alpha_s/2\pi)\log^2(Q^2/P_\perp^2) << 1$. For the scales of interest here, this relation suggests that the single emission processes will provide an adequate estimate of the full cross section for $P_\perp > Q/10$. This certainly covers the domain we concerned with where $Q \simeq M_W$ and $P_\perp \simeq M_W$. A second constraint on the range of applicability of the single emission picture arises from insisting that the contribution to the total cross section from the production of a ZZ pair plus an extra gluon or quark integrated over $P_\perp$ in the range of applicability be only a small correction to the lowest order process $q\bar{q} \to ZZ$.

The calculation of the processes producing a ZZ pair and an additional quark or gluon is facilitated by the use of "spinor techniques" [12]. These are used in the Monte Carlo calculations discussed in a subsequent section. Alternatively, approximate calculations can be made by treating the QCD part of the process as nearly on-shell. Thus for $q\bar{q} \to ZZg$, we write

$$d\sigma_{q\bar{q}\to ZZg} = \frac{d^2P_\perp}{(2\pi)^3P_\perp^2}\frac{dy}{y}\left[1+(1-y)^2\right]4\pi\alpha_s(4/3)d\sigma_{q\bar{q}\to ZZ}. \qquad (.1)$$

We recognize the familiar Altarelli-Parisi splitting function for $q \to qg$. The factor $(4/3)$ comes from color considerations. The gluon carries a fraction y of the incident quark or anti-quark momentum. The result must be multiplied by 2 to account for emission of the gluon from both the quark and anti-quark. The analogous formula for $gq \to ZZq$ is

$$d\sigma_{gq\to ZZq} = \frac{d^2P_\perp}{(2\pi)^3P_\perp^2}\frac{dy}{y}\frac{y}{2}\left[y^2+(1-y)^2\right]4\pi\alpha_s d\sigma_{q\bar{q}\to ZZ}. \qquad (.2)$$

The quantity of interest is $d\sigma/dM_{ZZ}$ for transverse momentum of the ZZ pair restricted to some interval, say, $P_{\perp min} < P_\perp < P_{\perp max}$. Thus, for example, we have

$$\begin{aligned}\frac{d\sigma_{q\bar{q}\to ZZg}}{dM_{ZZ}^2} &= \int \frac{d^2P_\perp}{(2\pi)^3P_\perp^2}\frac{dy}{y}\left[1+(1-y)^2\right]4\pi\alpha_s(4/3)d\sigma_{q\bar{q}\to ZZ} \\ &\quad \times\delta(\hat{s}(1-y)-M_{ZZ}^2) \qquad (.3)\end{aligned}$$

where $\hat{s}$ is the c.m. energy squared for the $q\bar{q}$ system and y is the fraction of the initial q momentum given to the gluon. This and the analogous formulae for $qg \to ZZq$ may be compared to the full Monte Carlo simulation done with the complete matrix elements.

These analytic approximations are useful guides to the cross section, but inclusion of realistic cuts requires Monte Carlo techniques. Without too much additional effort, the full matrix elements can be used. The structure functions used were those of Eichten *et al.*[3].

For the Higgs production, both the $WW \to H$ and $ZZ \to H$ processes were included. The Higgs boson was treated as a Breit-Wigner resonance. The background processes $q\bar{q} \to ZZg$, $qg \to ZZq$, and $\bar{q}g \to ZZ\bar{q}$ were calculated using the spinor techniques and checked with the approximations (1) and (2). The results of the Monte Carlo simulations for $M_H = 400$ GeV and $M_H = 600$ GeV are shown in Figs. 3 and 4 and in Table 1 and Table 2.

The backgrounds calculated for $q\bar{q} \to ZZ$, $q\bar{q} \to ZZg$, $qg \to ZZq$, and $\bar{q}g \to ZZ\bar{q}$ are shown in Table 2. From the Tables and Figures it is clear that a $P_\perp$ cut, for example $P_\perp > 60$ GeV as indicated, provides an extra means of isolating the Higgs boson production.

It should be noted that the transverse momentum distribution of the Higgs can have important consequences for other signatures. In particular, the sequence $H \to WW, W \to l\nu, W \to l'\nu'$ will be more difficult to analyze because it is incorrect to assume that the transverse momenta of the W's add to zero.

A preliminary investigation [6] of the possibility of tagging Higgs production by the WW mechanism by observing the jets arising from the quarks that emitted the W's has given some hopeful results. If the quark jets are required to have transverse momentum greater than 60 GeV and longitudinal momentum greater than 500 GeV, and if the Z's are required to have rapidity less than 1.5, the cross section for the production of a 400 GeV Higgs with subsequent decay into ZZ is 0.07 pb. The cross section of a particular background, $q\bar{q} \to ZZgg$ passing the same cuts (with the gluons providing

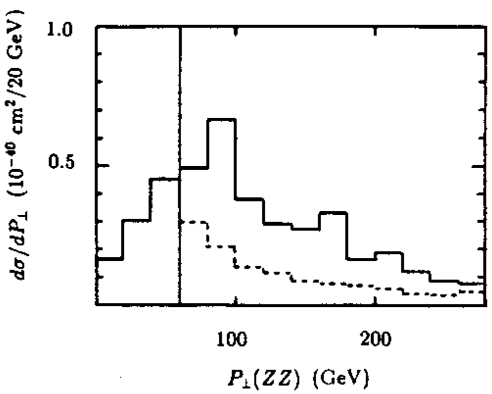

Figure 3: The transverse momentum distribution of Z pairs that decay into $(e^+e^-)(e^+e^-)$, from Higgs bosons of mass 400 GeV (solid line) and from background (dotted line).

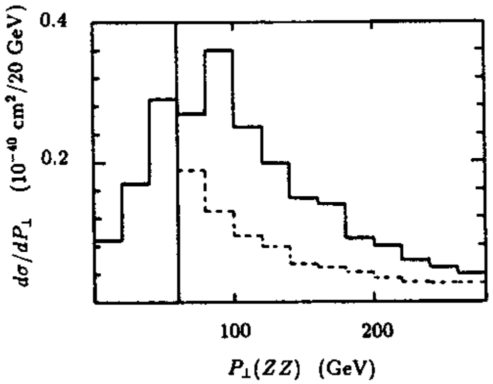

Figure 4: The transverse momentum distribution of Z pairs that decay into $(e^+e^-)(e^+e^-)$, from Higgs bosons of mass 600 GeV (solid line) and from background (dotted line).

the hadronic jets) is only 1.7×10^{-4} pb. The 700 real events of ZZ would provide about 63 events in the channel in which one Z decayed hadronically and the other into charged leptons. The serious background would come from processes like qg → Zqggg, where two hadronic jets simulated a hadronically decaying Z. From experience with backgrounds to ordinary ZZ production [4,5], we estimate that this false signal might be 100 times as large as the background with real ZZ pairs. This would give about 10 background events. Of course, this is a crude estimate and ignores several other possible background channels. Nevertheless, it does indicate that tagging of the WW mechanism may be feasible.

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	$M_H = 400$ GeV	$M_H = 600$ GeV
$\sigma(H \to ZZ)$	1.5	0.9
and within $\pm\Gamma$	1.0	0.6
and $\eta_Z < 1.5$	0.5	0.3
and $P_\perp$(Higgs)> 60 GeV	0.4	0.24

Table 1: Production of Higgs bosons that decay into ZZ in pp collisions at center of mass energy 40 GeV. All cross sections are in pb. Only production from the WW and ZZ fusion mechanisms is included. A pb corresponds to 10,000 events for an integrated luminosity of 10^{40} cm^{-2}, or to approximately 36 events if it is required that the Z's decay into e's or μ's.

	$M_H = 400$ GeV	$M_H = 600$ GeV
$\sigma(\mathrm{q\bar{q}} \to ZZ)$ within $\pm\Gamma$	1.5	1.5
and $\eta_Z < 1.5$	0.3	0.2
$\sigma(\mathrm{q\bar{q}} \to ZZ\mathrm{g})$ $\eta_Z < 1.5$, $P_\perp$(ZZ)> 60 GeV	0.05	0.07
$\sigma(\mathrm{gq}, \mathrm{\bar{q}} \to ZZ\mathrm{q}, \mathrm{\bar{q}})$ $\eta_Z < 1.5$, $P_\perp$(ZZ)> 60 GeV	0.08	0.06

Table 2: Continuum production of ZZ, the background for the detection of the Higgs boson. The cross sections are in pb. A pb corresponds to 10,000 events for an integrated luminosity of 10^{40} cm^{-2}, or to approximately 36 events if it is required that the Z's decay into e's or μ's.

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LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720