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Publication Date

1986



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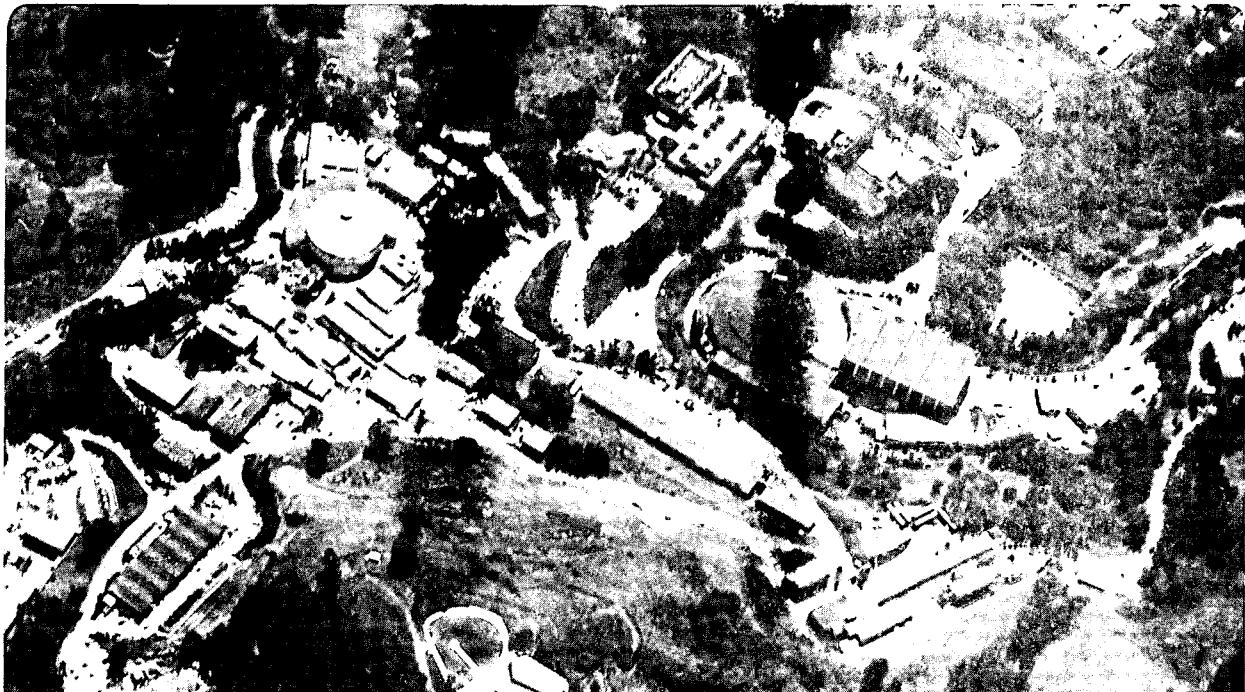
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January 1986

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Detecting Higgs Boson Decays into Z Pairs *

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Abstract

A Higgs boson in the mass range 400 - 1000 GeV would be observable at the SSC through its decay into two Z's, one of which decays into e^+e^- or $\mu^+\mu^-$ and the other into $\nu\bar{\nu}$. A comparison with the background from continuum Z pairs shows that the signal would be apparent in the transverse mass spectrum. The increase in statistics provided by these decays substantially extends the reach of the SSC for discovering the Higgs boson.

A central motivation for the proposed Superconducting Super Collider (SSC) is to investigate the mechanism responsible for breaking the $SU(2)_L \times U(1)$ gauge symmetry of the electroweak interactions. In the context of the standard model this means discovering the Higgs boson. More generally, it could mean finding a new sector of strongly interacting particles at the TeV scale or higher [1]. For either the standard model with $M_H > 2M_Z$ or a TeV scale new particle sector, the crucial experimental measurements are the inclusive yields of WW and ZZ pairs.

The predicted cross sections for Higgs boson production are in the few picobarn range. For the standard SSC year ($\int \mathcal{L} dt = 10^{40} \text{ cm}^{-2}$, $\sqrt{s} = 40 \text{ TeV}$) this gives tens of thousands of events. It will, however, be a formidable task to identify many of these events. In the standard model, about three-fourths of the W's and Z's decay to $q\bar{q}$, a two jet signature with an enormous QCD background. Even for the Higgs decays in which one W decays leptonically and the other hadronically, the QCD background (W + 2 jets) is at least fifty times greater than the signal [2,3]. There remains some possibility that a judicious choice of cuts will be able to isolate a useful signal in this channel [4].

At the other extreme we may consider the cleanest, most reconstructable decay modes

$$H \rightarrow ZZ \rightarrow (l^+l^-)(l^+l^-) \quad (1)$$

where l is e or μ . However, process (1) occurs with such a small branching ratio, $BR \approx (1/3) \cdot (0.06)^2 \approx 1.2 \cdot 10^{-3}$ that the predicted event rates are uncomfortably small, even for the postulated SSC parameters. The problem is most severe for large values of the Higgs mass: at 1 TeV fewer than ten events of process (1) are

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under contract DE-AC03-76SF00098.

predicted for the detectable signal, and these will be spread over hundreds of GeV in ZZ invariant mass.

We are therefore led to consider another purely leptonic process

$$H \rightarrow ZZ \rightarrow (l^+l^-)(\nu\bar{\nu}) \quad (2)$$

that occurs at six times the rate of process (1). The potential usefulness of this channel was first discussed by Gaillard and one of us but has not been examined previously in any detail [1]. While process (2) may at first seem an unlikely channel since the second Z is not detected, further reflection reveals that the signature for process (2), a Z with large transverse momentum opposite a missing transverse momentum of approximately the same size, has little background in the standard model. Moreover, little information is lost in (2) relative to (1) if the Higgs mass is large. This is not really a surprising conclusion given the success at the Sp \bar{p} S collider where the W boson was discovered and its mass measured to $\approx 5\%$ accuracy using ≈ 150 events in the analogous channels, $W \rightarrow (e\nu), (\mu\nu)$.

In this paper we will examine process (2) for four values of the Higgs boson mass, $M_H = 400, 600, 800, 1000$ GeV. We find that a measurement of the transverse mass

$$M_T = 2\sqrt{p_\perp^2 + M_Z^2} \quad (3)$$

where p_\perp is the transverse momentum of the observed Z , is sufficient to reveal the Higgs signal above the background from $q\bar{q} \rightarrow ZZ$ for $M_H = 400$ to 1000 GeV. This signature is most powerful for large Higgs mass, and thus extends the range of potential Higgs mass that can be explored with the proposed SSC.

In a future paper [5] we will consider other possible backgrounds, such as $q\bar{q} \rightarrow ZW \rightarrow (l^+l^-)(l'\nu)$ where the charged lepton $l' = e, \mu, \tau$ escapes detection. Another background that may require detector simulation to address properly arises from Z + jets, where enough of the jets escape detection to leave large missing p_\perp . In future work we shall also consider whether the $q\bar{q} \rightarrow ZZ$ and $q\bar{q} \rightarrow ZW$ backgrounds can be further reduced by taking advantage of the distinction between the longitudinally polarized Z 's produced in Higgs decay and the transversely polarized Z 's produced in $q\bar{q}$ annihilation [6]. We shall also consider signals to be expected if there is a strongly interacting new particle sector above 1 TeV, using the low energy theorems that apply in such circumstances [1].

There are two primary mechanisms for Higgs boson production in high energy

hadronic collisions. In the first, two gluons produce a virtual heavy quark - anti-quark pair that annihilate into a Higgs boson [7]. In the second, incoming quarks (or anti-quarks) emit virtual W 's or Z 's which collide to form the Higgs boson [8,1,9,10,11]. The latter process dominates if the mass of the Higgs boson exceeds 300 GeV, provided the heaviest quark has a mass no greater than 40 GeV or so. We shall consider exclusively the WW fusion process since our concern is primarily with very heavy Higgs bosons. A good approximation to the cross section for $q_1q_2 \rightarrow q'_1q'_2H$ is given by

$$\sigma = \frac{1}{16\pi^2} \left(\frac{\alpha}{x_W}\right)^3 s M_W^2 \int \frac{dx_1 dx_2 d^2p_{\perp 1} d^2p_{\perp 2}}{(p_{\perp 1}^2/x_1 + M_W^2)^2 (p_{\perp 2}^2/x_2 + M_W^2)^2} \times \delta(s(1-x_1)(1-x_2) - M_H^2) \quad (4)$$

This gives a total cross section of

$$\sigma = \frac{1}{16M_W^2} \left(\frac{\alpha}{x_W}\right)^3 \left[(1 + M_H^2/s) \ln(s/M_H^2) - 2 + 2M_H^2/s \right] \quad (5)$$

the standard result [1,9,10]. These approximations are not entirely adequate for our purposes. In the Monte Carlo calculations described below we have used the complete matrix elements without approximation.

It is possible to deduce from Eq. (4) an important consequence: the Higgs boson is produced with a transverse momentum typically of order M_W [12]. As a result, the Jacobian peak in M_T is smeared substantially. Of course, the peak is also spread out by the finite width of the Higgs boson itself. This width grows nearly as M_H^2 and is close to 500 GeV for $M_H = 1000$ TeV. For such a large mass, the effect of the transverse momentum of the Higgs boson is not important. However, for $M_H = 400$ GeV the width is only 25 GeV so the width of the peak in the variable M_T is dominated by the effect of the transverse momentum of the Higgs boson. If we had instead used the effective- W approximation [1,9,10], the 400 GeV Higgs would, incorrectly, have appeared to give a narrow (≈ 50 GeV) structure in M_T .

The dominant background is the production of Z pairs through $q\bar{q}$ annihilation. The fundamental cross section has been calculated by Brown and Mikaelian [13]. For $q\bar{q}$ subenergies not much greater than $2M_Z$, the produced Z 's are isotropic in the subprocess center of mass. However, for high subprocess energies, the Z 's tend to be produced along the beam direction. As a result, it is useful to make a

	$M_T > 400$	$M_T > 500$	$M_T > 700$	$M_T > 900$
$M_H = 400$	71/112	26/53	4/17	1/7
$M_H = 600$	107/112	86/53	26/17	8/7
$M_H = 800$	76/112	72/53	54/17	30/7
$M_H = 1000$	61/112	59/53	53/17	43/7

Table 1: Signal from Higgs bosons over background from $q\bar{q}$ annihilation. The observed channel is ZZ with one Z decaying to e or μ pair and the other to neutrinos. The visible Z has rapidity less than 1.5. The masses are in GeV and the events are for a standard SSC year.

cut in rapidity for the observed Z . Here we consider just the dominant $q\bar{q} \rightarrow ZZ$ background. Other, smaller, backgrounds will be considered in a future work [5].

Figure 1 shows the Monte Carlo results for pp collisions with $\sqrt{s} = 40$ TeV. The final state includes a Z pair. The cross section is given as a function of the transverse mass, Eq. (3), derived from the one observed Z . The background falls steeply with increasing transverse mass. The signals for $M_H = 600, 800,$ and 1000 GeV are shown. Figure 2 differs in that a rapidity cut, $\eta < 1.5$, is made on the observed Z . It is clear that the rapidity cut improves the signal to noise and that the variable M_T is most useful in discriminating between signal and background for very heavy Higgs bosons. In addition, the rapidity cut insures that the bulk of the charged leptons will have rapidities less than 2.5 and will be observable in a central detector.

The actual event rates can be determined by noting that the branching ratio for a Z pair into the observed final state is about $3.6 \cdot 10^{-3}$. The numbers of events expected in appropriate ranges in M_T are displayed in Table 1.

Some caution is appropriate in interpreting the ratios of signal to noise given in the Table. Since the sum of the signal plus noise will not show a peak, the subtraction of the background will require care. In principle, the background is calculable. In practice there are uncertainties both in structure functions and in QCD corrections for the processes involved. These uncertainties can, however, be reduced once data are available. At low values of M_T the data will be copious. In this region it will be possible to check the normalization and shape of the predicted

distribution against the measured distribution and tune the calculation accordingly. In addition, other processes involving some of the same structure functions can be measured in the same kinematic domain. [14]. This will provide a further control on the background calculations. A reliability of at least 20 % seems likely given the extensive data the SSC would provide. It is clear from the Table that the signals would be apparent even with 50% uncertainties in the background.

The Table shows that a 1 TeV Higgs is within the reach of the SSC. The statistically strong signal in the channel $(Z \rightarrow l^+l^-)(Z \rightarrow \nu\bar{\nu})$ would be supplemented by a few unequivocal $(Z \rightarrow l^+l^-)(Z \rightarrow l^+l^-)$ events confirming the source of the larger signal. It is also clear that an order of magnitude reduction in the luminosity from the design value would result in the inability to observe very massive Higgs bosons. A similar conclusion applies to the beam energy: reducing the center of mass energy from 40 to 20 TeV would reduce the 43 events with $M_T > 900$ GeV for the $M_H = 1000$ GeV example to just 7 events.

The search for the conventional Higgs boson is a particularly severe test of the capabilities of the SSC. The unfavorable branching ratios reduce a large initial sample of events to rather few. Using the neutrino decay mode of the Z substantially increases the range of Higgs mass the SSC can explore. The technique appears to be the best way, as well, to explore the strongly interacting Higgs sector alternative since it is most effective for high ZZ invariant mass.

We thank I. Hinchliffe for valuable suggestions and S. D. Ellis, R. Kleiss, and W. J. Stirling for the use of their Monte Carlo simulation programs. This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under contract DE-AC03-76SF00098.

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Figure Captions

- 1 The transverse mass distribution of the $q\bar{q}$ annihilation background and the Higgs signal for $pp \rightarrow ZZ X$ for $\sqrt{s} = 40$ TeV. The transverse mass is defined in terms of the transverse momentum of one of the Z's. The signals shown correspond to $M_H = 600, 800, 1000$ GeV. The dashed curve corresponds to the background. No rapidity cut is applied.
- 2 The transverse mass distribution of the background and signal for $pp \rightarrow ZZ X$ for $\sqrt{s} = 40$ TeV. The transverse mass is defined in terms of the transverse momentum of the observed Z. The signals shown correspond to $M_H = 600, 800, 1000$ GeV. The dashed curve corresponds to the background. The observed Z has a rapidity with magnitude less than 1.5.

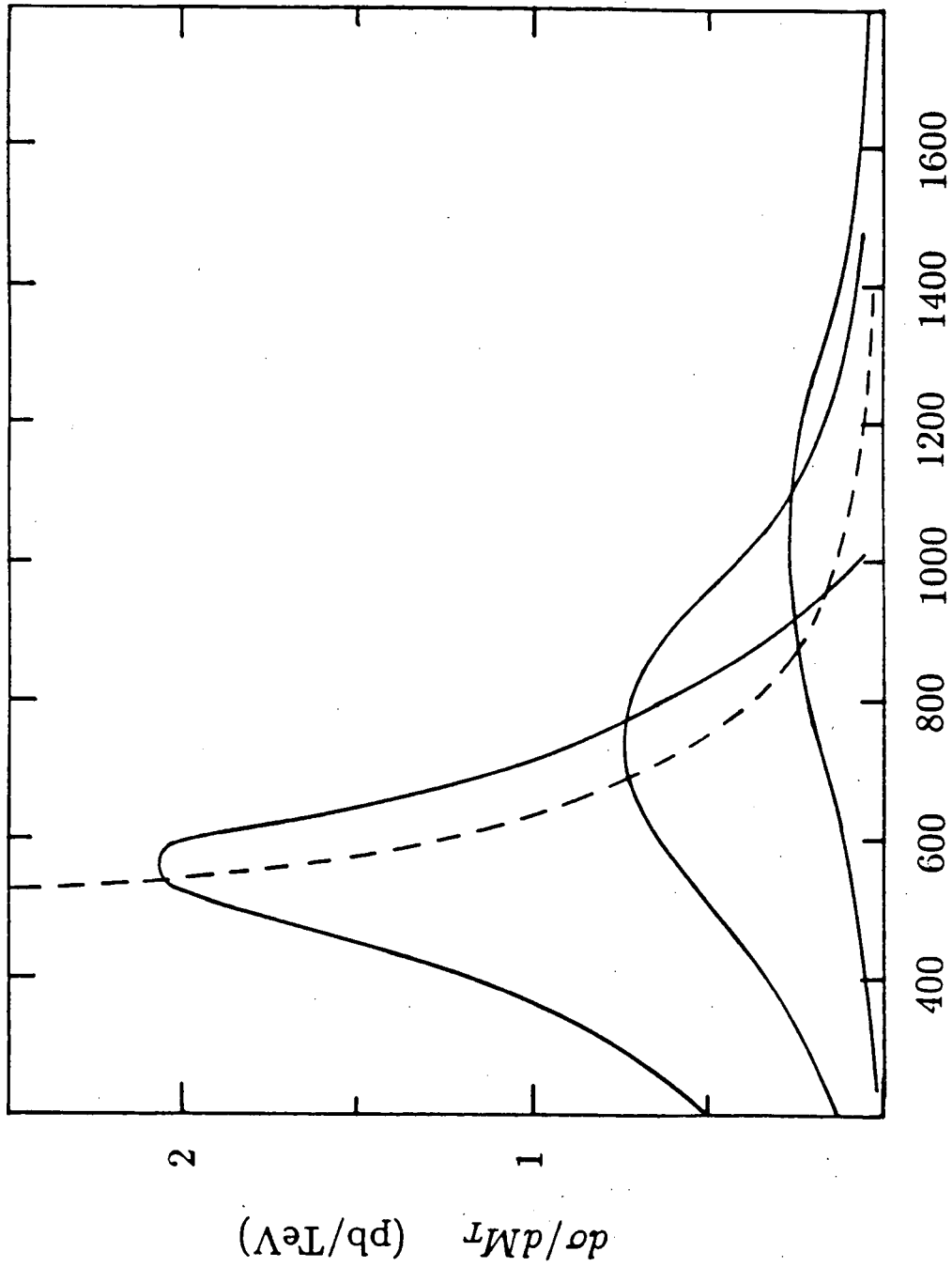


Fig. 1

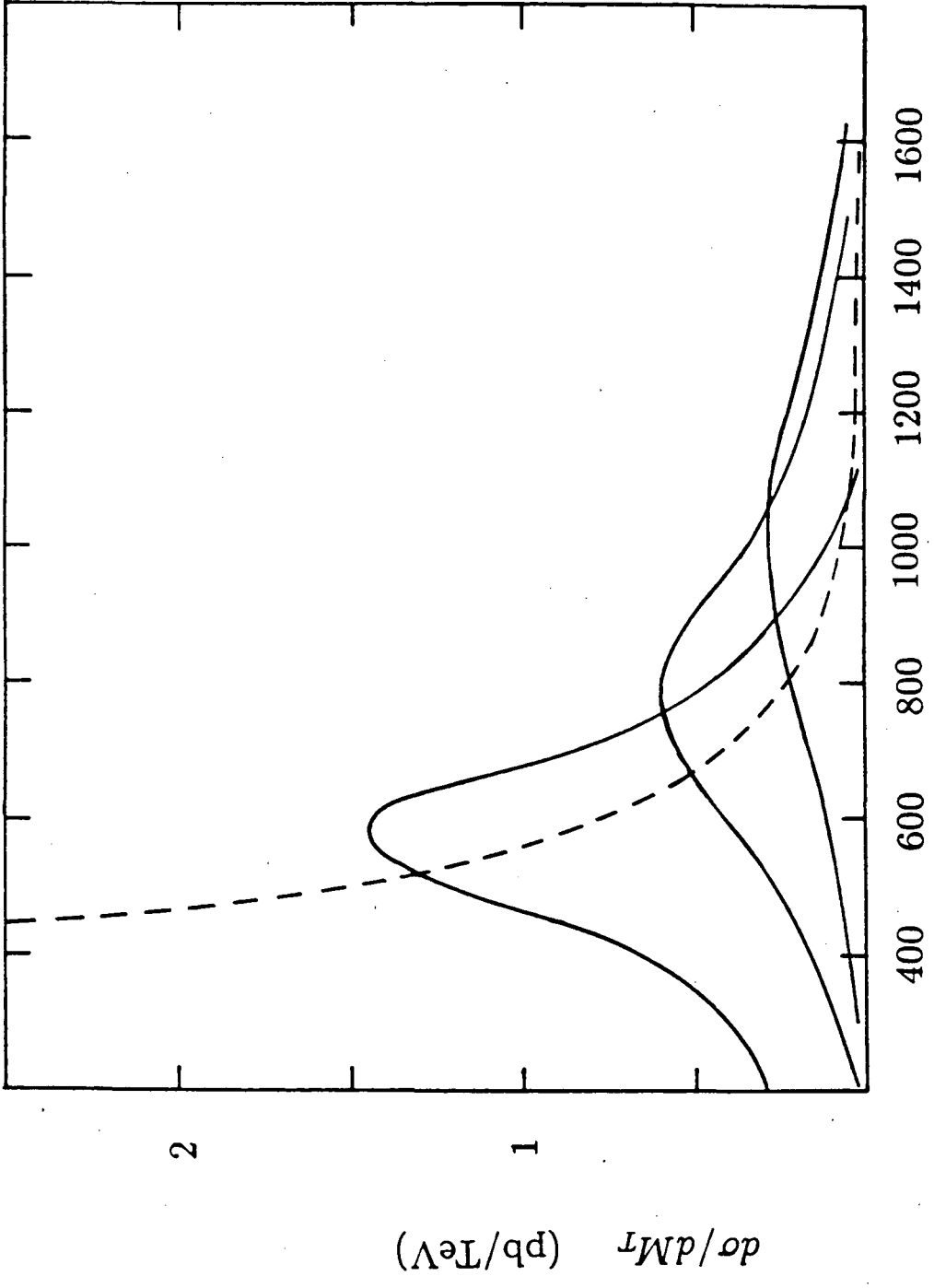


Fig. 2

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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