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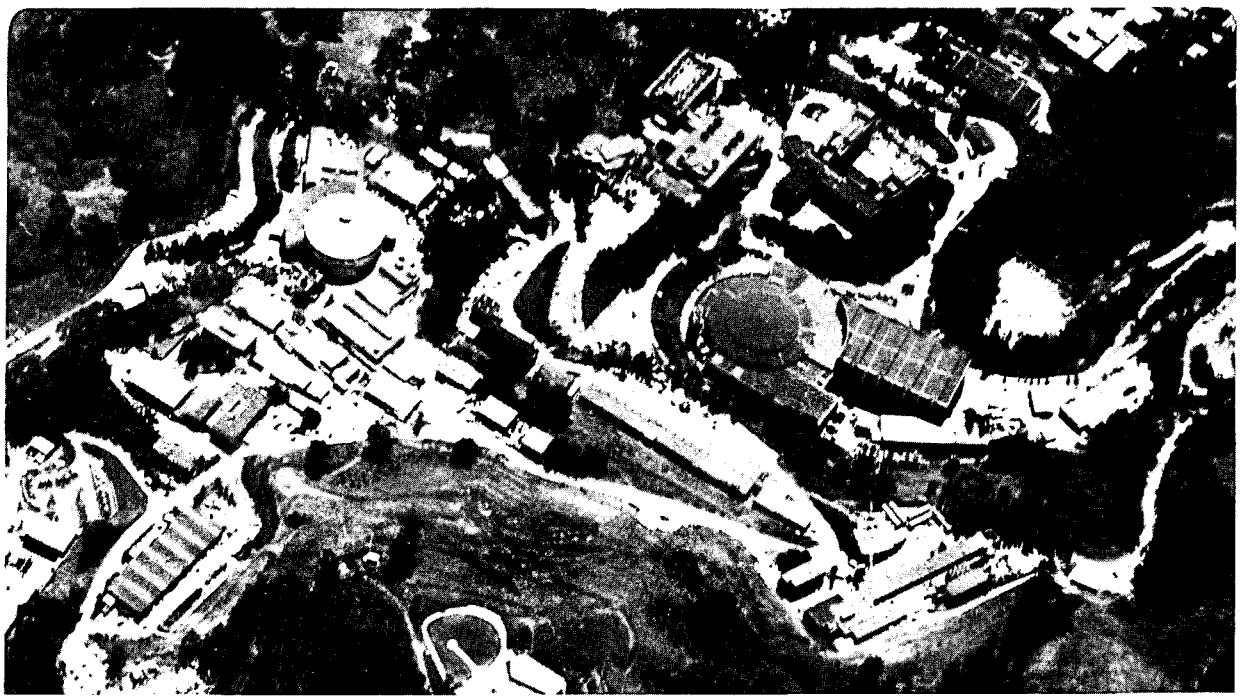

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Effect of Lepton Energy Resolution on Higgs Searches at the SSC.*

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Presented at the 1988 DPF Summer study on High Energy Physics in the 1990's, Snowmass Colorado, June 27 - July 15 1988.

Abstract

We discuss the effects of realistic detector resolutions on the processes $H \to ZZ \to e^+e^-e^+e^-$ and $H \to ZZ \to e^+e^-\mu^+\mu^-$ at the SSC. The background from $Zt\bar{t}$ where the $t\bar{t}$ system produces two isolated leptons in its decays is discussed.

In this paper, we analyse the effects of detector resolution on attempts to extract the signal for a Higgs decaying via two Z's into four charged leptons, either electrons or muons at the SSC. Previous studies[1] of this decay mode have shown that the background to it arises from the production of two Z bosons via quark-antiquark[2] or gluon-gluon annihilation.[3] These studies have demonstrated that, given a good determination of the Z pair invariant mass, a convincing signal can be extracted and that Higgs bosons of mass in the range $2M_Z$ to 800 GeV can be found in a canonical SSC year which corresponds to an integrated luminosity of $10^{40} cm^{-2}$. Here we shall investigate in detail what is meant by "a good determination" of the Z momenta and will indicate the effects of expected lepton momentum resolution. We will only consider Higgs bosons of mass 400 GeV. The reader is assumed to be familiar with the basics of Higgs boson production and detection at the SSC. (These issues are reviewed in Ref. 1.)

Higgs bosons are produced at the SSC via gluon-gluon[4] and WW fusion[5]. The rate from the former process depends on the top quark mass. We will assume 40 GeV in our discussion unless otherwise stated. The rate for production of Higgs bosons with masses in the region 300-800 GeV increases as the top quark mass rises above this value. A Higgs boson in this mass range decays to ZZ with a branching ratio of approximately 1/3. The Z bosons can be reconstructed via their decays to $\mu^+\mu^-$ or e^+e^-. The only important source of background Z pairs arises from the processes $q\bar{q} \to ZZ$ and $gg \to ZZ$ (the former dominates in the case of interest[3]). Figure 1 shows the distribution in ZZ invariant mass arising from the production of a 400 GeV Higgs boson. The final state leptons are required to have rapidity $|y| < 2.5$ and are assumed to have their momenta measured with no error. The background shown includes only the process $q\bar{q} \to ZZ$ and we have used the scale $Q = M_{ZZ}$, the invariant mass of the Z pair, in evaluating the structure functions needed in estimating its rate. For a discussion of the scale dependence and the effect of the $gg \to ZZ$ process, see reference 1; a more reasonable scale choice tends to decrease the rate from $q\bar{q} \to ZZ$ by about 30-40%.

It can be seen from Figure 1 that a clear signal is visible as a peak above the background. We will investigate what happens to this peak as the momentum resolution on the leptons is degraded.

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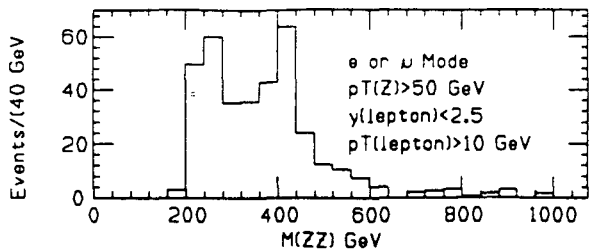

Figure 1. Histogram showing the invariant mass distribution of a pair of Z bosons. The events, which were generated with the PYTHIA event generator, correspond to an integrated luminosity of $10^{40} cm^{-2}$. The Z pairs arise from the production of a Higgs boson of mass 400 GeV and the process $q\bar{q} \rightarrow ZZ$. The Z's are reconstructed in the decay modes $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$; all of the leptons All of the leptons are required to satisfy $|y| < 2.5$, $p_t > 10$ GeV. In addition the reconstructed Z's must have $P_t > 50$ GeV.

In the case of electron momentum determination, it is reasonable to expect[6] that one will have an error $\Delta E/E \sim 15\%/\sqrt{E} + 1\%$, where E is expressed in GeV. In the case of muons the resolution is expected to be much worse, $\Delta E/E \sim 10 - 20\%$ if only the muon toroids are used[7]. The muon resolution could be improved by including information on the muon track from close to the interaction point. We show in Figure 2 the effect of resolution on the dilepton invariant mass. This Figure show clearly that the reconstructed Z no longer has a well defined mass when the resolution is poor. This gives rise to the first source of difficulty. If there is a source of dilepton pairs of invariant mass close to that of the Z, some of these pairs will have to be included in the background. These "fake Z's" will then increase the background shown in Figure 1. In the case of the final state with only e^+e^- pairs, the spread of the reconstructed Z mass shown in Figure 2 is small, and this extra background will be irrelevant. The resolution in the $\mu^+\mu^-$ mass may be poor and this extra background must be considered.

Where does the extra background come from? The leptons from the decay of a Z will be isolated and will have large invariant mass. The largest source of leptons at SSC will be from the production and decay of charm, bottom and top quarks since these quarks are produced by strong interaction processes. Of these, the leptons arising from top decay will be more isolated than those from charm and bottom. Consider the final state $Z + Q\bar{Q} + X$ which can arise from the partonic initial states *gluon + gluon* and *quark + antiquark*. We estimated these rates by using the known matrix elements[8] for $gg \rightarrow Zq\bar{q}$ and $q'\bar{q}' \rightarrow Zq\bar{q}$, where q and q are massless quarks, together with the correct phase space for massive final state particles. The same approximation applied to the process $gg \rightarrow Q\bar{Q}$ is accurate to 30%.

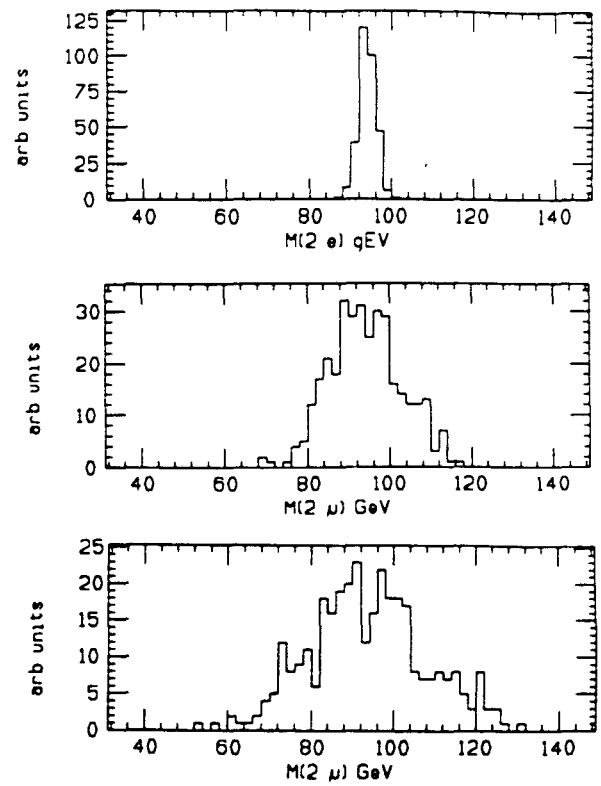

Figure 2 Histogram showing the effect of lepton energy resolution on the reconstructed Z mass. Figures (a), (b) and (c) have $\Delta E/E = .15\sqrt{E} + 0.01$, $\Delta P/P = 0.1$ and $\Delta P/P = 0.2$ respectively.

In Table 1, we show the rates from this process. In obtaining the values in this Table, we have required that the Z have transverse momentum greater than 100 GeV. Table 2 shows the rates from $Z + t\bar{t}$ where we have required additionally that there be a lepton pair

arising from the $t\bar{t}$ system with invariant mass between 40 and 130 GeV and transverse momentum larger than 100 GeV. The number of similar events from the background process $q\bar{q} \to ZZ$ is also shown for comparison. Notice that the number of events from the $ZQ\bar{Q}$ final state is smaller than that from ZZ. This indicates that this additional source of background which will be present in the $e^+e^-\mu^+\mu^-$ mode is not large. The invariant mass distribution of the $Z + fake\ Z$ system from $ZQ\bar{Q}$ is shown in Figure 3. It has no peaks and contributes a smooth background which falls rapidly with increasing M_{ZZ}. Figure 4 shows the transverse momentum distribution of the real and fake Z's. The real Z was required to have $p_t > 50GeV$. This Figure shows that a cut requiring the fake Z also to have $p_t > 50$ GeV, is very powerful in reducing the background rate (approximately 70% of the events fail this cut). The reduction in the number of signal events due to this cut is approximately 30%. Table 2 shows the effects of various cuts on the processes $H \to ZZ$, $q\bar{q} \to ZZ$ and the $Zt\bar{t}$ final state giving rise to Z and "fake" Z. This Table shows that the extra background is not a problem.

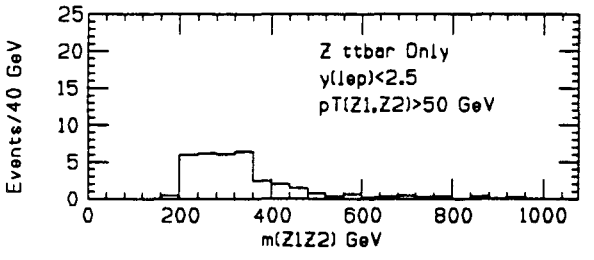

Figure 3. Histogram showing the invariant mass distribution of a Z and " fake" Z. The latter arises as a lepton pair from the final state $Z+t+\bar{t}$; the lepton pair arising from the $t\bar{t}$ is required to have invariant mass between $M_Z - 50$ and $M_Z + 50$ GeV. The events, which were generated with the partonic generator discussed in the text, correspond to an integrated luminosity of $10^{40} cm^{-2}$. All of the leptons All of the leptons are required to satisfy $|y| < 2.5$, $p_t > 10$ GeV. In addition the reconstructed Z's must have $P_t > 50$ GeV.

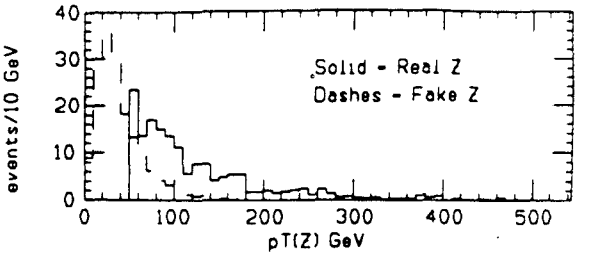

Figure 4. Transverse momentum distribution of the real and "fake" $Z's$ arising from the process $pp \to Zt\bar{t} \to 4l + X$. The physical is required to have $p_t > 50$ GeV, and the "fake" Z is defined to be a lepton pair with invariant mass between 40 and 130 GeV. All of the leptons are required to satisfy $|y| < 2.5$. $p_t > 10$ GeV.

Process	PYTHIA	ISAJET	PARTON (I.H.)
$gq, q\bar{q} \to Z + q, g$ $p_{t_Z} > 100$ GeV	2.9 nb	3.5 nb	2.5nb
$q\bar{q} \to Z + g$ $p_{t_Z} > 100$ GeV	210 pb	295 pb	not run
$gg, q\bar{q} \to Zc\bar{c}$ ($q\bar{q}$ only)	n.a. 15.7 pb	n.a. 13.0 pb	205 pb 9 pb
$gg, q\bar{q} \to Zb\bar{b}$ ($q\bar{q}$ only)	n.a. 9.2 pb	n.a. 14.2 pb	204 pb not run
$gg, q\bar{q} \to Zt\bar{t}$ ($m_{top} = 100$ GeV) ($q\bar{q}$ only)	n.a. 0	n.a. < .7 pb	8.2 pb not run
$gg, q\bar{q} \to Zt\bar{t}$ ($m_{top} = 40$ GeV) ($q\bar{q}$ only)	n.a. 0	n.a. 1.8 pb	40 pb 1.8 pb
$gg, q\bar{q} \to Zt\bar{t}$ ($m_{top} = 5$ GeV) ($q\bar{q}$ only)	n.a. 0	n.a. 13.6 pb	156 pb 6.6 pb

Table 1. Cross sections for various processes as given by PYTHIA[9], ISAJET[10], and the parton calculation outlined in this paper. The Z is required to have $p_t > 100$ GeV. n.a. means not available.

Process (4lepton mode)	NoCuts	$p_{t_0} = 50$ GeV $\Delta = 50$ GeV	$p_{t_0} = 50$ GeV $\Delta = 10$ GeV
$H \to ZZ$	140	90	90
$q\bar{q} \to ZZ$	1500	280	280
$Zt\bar{t}$	large	43	14

Table 2. The number of lepton pair events from various sources for an integrated luminosity of 10^{40} cm^{-2}. The leptons are required to have $|y| < 2.5$. The pairs of leptons are each required to from a "Z", i.e. are required to have invariant mass between $M_Z \pm \Delta$ and the Z's are required to have $p_t > p_{t_0}$.

Isolation cuts on the leptons are not required to reduce this background to an irrelevant level. However such cuts may be required to eliminate the other leptonic backgrounds. For example, cuts requiring that the leptons be isolated from hadronic jets will be particularly effective in reducing the background due to charm and bottom decays. We have not included the fake Z's from the production of charm and bottom followed by their leptonic decay. Such leptons are softer than those from top and are not isolated.

For comparison purposes we have also indicated in Table 1 the event rates arising from the $Z + jet$ processes that are produced by the ISAJET[10] and PYTHIA[9] event generators. These generators produce first produce the final state $Z + parton$, where the parton can either be a quark or a gluon. The parton then showers and the $Q\overline{Q}$ pair can be produced as a component of this shower. An approximation to the $Z + Q\overline{Q}$ rate is then obtained. Unfortunately the approximation is not good as can be seen from the Table. The difficulty is as follows. There is no partonic process of the form $gluon + gluon \to Z + parton$, hence the event generators are not including any approximation to $gluon + gluon \to Z + Q + \overline{Q}$.* The process $q\bar{q} \to Zg$ followed by the "decay" $g \to Q\overline{Q}$ is present and, as Table 1 shows, provides a good approximation to the $q\bar{q} \to ZQ\overline{Q}$ process. However the gg initiated process is dominant.

Since the event generators do not accurately reproduce the rates for $ZQ\overline{Q}$ final states they cannot be used in a background study. Nevertheless it is clear from our partonic analysis, that bad resolution in the $\mu\mu$ system does not seriously increase the background in the mode $H \to ZZ \to \mu^+\mu^-e^+e^-$.

In the case of the $\mu^+\mu^-\mu^+\mu^-$ final state, there is another additional source of potential background, namely the $Q\overline{Q}\ Q\overline{Q}$, where all of the quarks decay semileptonically and two fake Z's are produced. We have not attempted to estimate this background here.

The second difficulty caused by poor resolution is that the peak in the reconstructed Z pair is smeared out. This effect is shown in Figure 5. It is clear from this Figure that in the 4μ with 20% resolution, the peak has disappeared. However at 10% a peak is still clearly visible. In the $2e2\mu$ final state the signal is still observable. We have tried using the Z mass as a constraint in the reconstruction; the effect of this is shown in Figure 6. By comparison with Figure 5, it can be seen that the improvement is not significant.

In conclusion, we have investigated the effect of detector resolution on the four lepton decay mode of the Higgs boson at the SSC. The bad resolution characteristic of a muon system with resolution of order 20% does not cause an appreciable increase in background due to "fake" Z's in the $4e$ or $2e2\mu$ channels. However it does degrade the resolution in the Z pair invariant mass to such an extent that the peak due to Higgs boson of mass 400 GeV is no longer visible in the 4μ channel and the $2e2\mu$ channel is compromised. A resolution of order 10% or better is required if the peak is to survive. We have only considered backgrounds due to real leptons. It is possible that in a more realistic detector simulation, backgrounds due to misidentified particles or other detector related sources could be significant.

*In principle, the process can be approximated from $gg \to Q\overline{Q}$ if the Z is then radiated off an outgoing quark line. This is not likely to be an efficient way of simulating the rate.

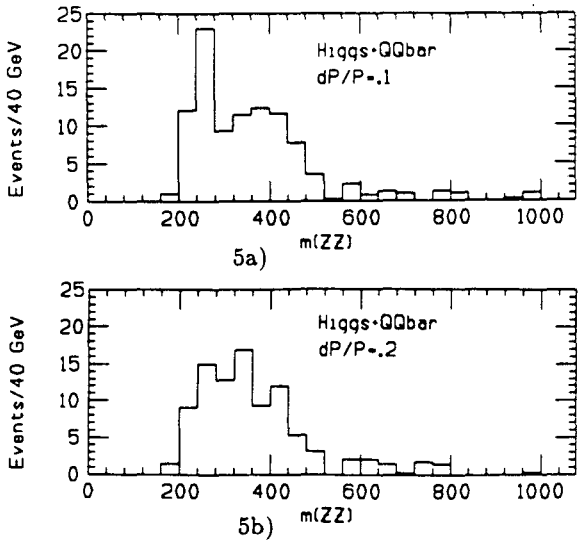

Figure 5. The reconstructed invariant mass distribution for Z pairs from the final states $ZZ \to \mu^+\mu^-\mu^+\mu^-$ The cuts are the same as in Figure 1 In 5a) we have taken $\Delta P/P = 0.1$ for muons and in 5b) $\Delta P/P = 0.2$

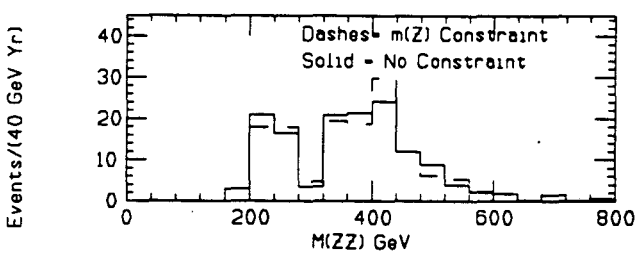

Figure 6. As Figure 5 except for the final state $ZZ \to e^+e^-\mu^+\mu^-$. We have taken $\Delta E/E = .15\sqrt{E} + 0.01$, for electrons and $\Delta P/P = 0.1$ for muons. The dashed histogram shows the effect on resolution if the Z mass is used as a constraint in the fit.

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