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Jet Analysis in Higgs Search*

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Abstract

In high energy e^+e^- annihilations, events with jets dominate. Since heavy quark jets often contain undetectable neutrinos, methods of jet analysis are needed to study such events. A simple procedure is presented here and illustrated by applying to the search for the neutral Higgs boson H^0 produced at LEP at the center-of-mass energy of 200 GeV.

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1. Introduction

Experimental high energy physics is entering an exciting era: within the next one or two years, both SLC and LEP are expected to become operational. In these experiments, the final states are most conveniently described in terms of jets and isolated leptons. Roughly speaking, jets are taking the place of hadrons. Just as there are different kinds of hadrons, there are also different kinds of jets: various kinds of quark jets [1] and gluon jets [2].

The data analysis for events involving jets is, however, quite different from that for events involving hadrons not forming jets. In this paper, we initiate the study of some of the problems of jet analysis by considering two examples of Higgs search at center-of-mass energy of 200 GeV at LEP. This basic idea is to make use of all the information about the process under consideration. Although this idea is self-evident, its implementation is by no means simple, and will be illustrated by these two examples. These basic ideas and procedures are of course applicable to other situations. They are especially relevant at LEP and SLC because, in spite of the high event rate, the interesting events are expected to be rather few in number.

In Section 2 and Section 3, we consider respectively the Higgs search through the processes

$$e^+e^- \rightarrow H^0 Z^0$$

$$(1)$$

and

[illegible]

The necessary Monte Carlo calculations are carried out using a realistic detector simulation and apply a pattern recognition and track reconstruction program. At the center-of-mass energy of 200 GeV, there are large background from W^+W^- and Z^0Z^0 pair productions and QCD processes. Therefore a number of event selection criteria, i.e. cuts, are necessary to reduce the backgrounds. In order to avoid obscuring the main points, these cuts are not described here. The Monte Carlo calculations, the appropriate cuts, and more detailed results are described in a separate report [3].

2. Higgs Search with $Z^0 \rightarrow \nu\bar{\nu}$

The most straightforward way of analyzing process (1) is to plot the invariant mass of the two observed jets. The invariant mass distribution from the Monte Carlo simulation for a Higgs of 60 GeV is shown in Fig. 1. The invariant mass is calculated from the detected particles using the ALEPH detector [4] at LEP as an example. As seen from this figure, the invariant mass distribution has a sharp edge near M_{H^0} and a falling distribution for decreasing invariant mass. This is due to the fact that there are undetected particles in the decay $H^0 \rightarrow b\bar{b}$ (neutrinos, neutrons, K^0 and particles escaping the detector). Since it is difficult to determine the mass of the Higgs from such a peak, it is natural to ask how the quality of this peak can be improved. Specifically, it is desirable to get a peak which is more symmetrical and centers at the correct Higgs mass. To obtain such an improvement, it is useful to note that, in obtaining Fig. 1, we have not made use of the information that the invariant mass of the two unobserved neutrinos is that of Z^0 .

This information can be readily incorporated as follows. Let $\vec{P}_i$ and E_i be the momentum and energy of the detected particles respectively. Let $\vec{P}_{obs}$ be the total momentum of the observed particles and E_{obs} be the total energy of the observed particles.

Then

$$\begin{aligned}\vec{P}_{obs} &= \sum_i \vec{P}_i \\ E_{obs} &= \sum_i E_i\end{aligned}$$

Let $\vec{P}_{H^0}$ and E_{H^0} be the momentum and energy of the Higgs particle and assume

$$\begin{aligned}\vec{P}_{H^0} &= \alpha \vec{P}_{obs} \\ E_{H^0} &= \alpha E_{obs}\end{aligned}\tag{3}$$

where α is a constant to be determined by the constraint equation:

$$\begin{aligned}(E_{cm} - E_{H^0})^2 - (\vec{P}_{H^0})^2 &= M_{Z^0}^2 \\ \text{or} \quad (E_{cm} - \alpha E_{obs})^2 - (\alpha \vec{P}_{obs})^2 &= M_{Z^0}^2\end{aligned}$$

Solving for α , we have

$$\alpha = \frac{E_{cm}E_{obs} \pm \sqrt{E_{cm}^2 E_{obs}^2 - (E_{obs}^2 - \vec{P}_{obs}^2)(E_{cm}^2 - M_{Z^0}^2)}}{E_{obs}^2 - \vec{P}_{obs}^2}$$

If the plus (+) sign is used, then it can be verified easily that $E_{cm} - \alpha E_{obs}$, the energy of the Z^0 , is negative. Thus we must use the lower negative (−) sign, and

$$\begin{aligned}M_{H^0} &= \sqrt{E_{H^0}^2 - \vec{P}_{H^0}^2} \\ &= \frac{E_{cm}E_{obs} - \sqrt{E_{cm}^2 E_{obs}^2 - (E_{obs}^2 - \vec{P}_{obs}^2)(E_{cm}^2 - M_{Z^0}^2)}}{\sqrt{E_{obs}^2 - \vec{P}_{obs}^2}}\end{aligned}\tag{4}$$

Fig. 2 shows the invariant mass distribution calculated with equation (4). This distribution centers at the M_{H^0} of 60 GeV with a FWHM of about 5 GeV.

Note that the application of equation (4) demonstrates the power of a e^+e^- colliding beam machine. The knowledge of the total center-of-mass energy and total momentum responsible for the reaction enables us to reconstruct the process without measurements of all the particles.

The final invariant mass distribution for integrated luminosity of 500pb^{-1} are shown in Fig. 3(a), (b) and (c) for $M_{H^0} = 40, 60$ and 80 GeV respectively with cuts applied to reduce the backgrounds from W^+W^- , Z^0Z^0 and QCD processes as given in Ref. [3].

3. Higgs Search with $Z^0 \rightarrow q\bar{q}$

In this case, the most straightforward procedure is to use the four-jet analysis of Wu [5]. Apply four-jet analysis to each event, take the observed particles of each jet and calculate the velocity $\vec{\beta}_j$ of each jet:

$$\vec{\beta}_j = \frac{\vec{P}_{j\text{ obs}}}{E_{j\text{ obs}}}$$

where $\vec{P}_{j\text{ obs}} =$ the total observed momentum of jet j

$E_{j\text{ obs}} =$ the total observed energy of jet j

Let E_1, E_2, E_3 and E_4 be the energies of the four jets, then it follows from energy and momentum conservation that

$$\begin{aligned} E_1 + E_2 + E_3 + E_4 &= E_{cm} \\ \vec{\beta}_1 E_1 + \vec{\beta}_2 E_2 + \vec{\beta}_3 E_3 + \vec{\beta}_4 E_4 &= 0 \end{aligned} \tag{5}$$

Given the values of $\vec{\beta}_j$, we can solve for E_1, E_2, E_3 and E_4 , the newly reconstructed energies of the four jets. The backgrounds from $e^+e^- \rightarrow W^+W^-$ and Z^0Z^0 are unfortunately very large. In order to reduce these backgrounds, we make use of the fact that, for $e^+e^- \rightarrow H^0Z^0$, the invariant mass of one pair of jets is that of Z^0 , while, for $e^+e^- \rightarrow W^+W^-$ or Z^0Z^0 , the invariant masses of the pairs of jets are the same. Therefore we apply a new fitting procedure with the following two hypotheses:

(A) A fit procedure with $e^+e^- \rightarrow W^+W^-$, Z^0Z^0 hypotheses.

In the above reconstruction method, we use an additional constraint to equation (5) that the jet-jet invariant masses of two pairs of jets are equal i.e. in the three possible pairing: $M_{12} = M_{34}$ or $M_{13} = M_{24}$ or $M_{23} = M_{14}$. We allow the four

jet energies E_1, E_2, E_3 and E_4 to vary as before and also allow the directions of each jet to vary. We choose the one pairing among the three possible ones with the best fit. Fig. 4 shows the jet-jet invariant mass distribution after the application of this fit procedure from $e^+e^- \rightarrow W^+W^-, Z^0Z^0$ events simulated using the ALEPH detector. The FWHM of the $W^\pm$ and Z^0 is a few GeV.

(B) A fit procedure with $e^+e^- \rightarrow H^0Z^0$ hypothesis.

In this case, we use instead an additional constraint to equation (5) that the jet-jet invariant mass of one of the two pairs should be M_{Z^0} i.e. in the 6 possible pairings: M_{12} or M_{13} or M_{14} or M_{23} or M_{24} or M_{34} is equal to M_{Z^0} . Choose the pairing that gives the best fit. Fig. 5 shows that jet-jet invariant mass distribution after the application of this fit procedure from $e^+e^- \rightarrow H^0Z^0$ events simulated in the ALEPH detector for $M_{H^0} = 40$ GeV.

By removing events that give a good fit under (A) and keeping those that give a good fit under (B), and by using suitable cuts [3] to remove the QCD backgrounds, the final results are given in Fig. 6 for Higgs mass at 40 and 60 GeV. In this jet-jet invariant mass distribution the H^0 mass peak stands out clearly above the W^+W^- , Z^0Z^0 and QCD background. These figures are normalized to $500pb^{-1}$ integrated luminosity.

4. Discussions and Conclusions

So far as the search for the Higgs boson H^0 is concerned, the conclusion is that, at center-of-mass energy of 200 GeV and with an integrated luminosity of $500pb^{-1}$, significant signals are certainly observable up to $M_H = 80$ GeV from process (1) and up to $M_H = 70$ GeV from process (2). [It is assumed that H^0 does not decay into $t\bar{t}$. If it does, the search is expected to be easier.]

A comparison of Fig. 1 and Fig. 2 shows the power of using a simple scaling factor α as shown in eq. (3). In the future, as we learn more about the structure of jets, better methods of correcting for the lost particles will undoubtedly be found. For example,

since the presence of a lepton in a jet indicates an unobserved neutrino, a different α may be appropriate.

As already mentioned, the underlying idea of the method of analysis is to make use of all the available information about the process under consideration. For process (1), we make use of the fact that H^0 recoils against Z^0 , whose mass is known. For process (2), backgrounds from W^+W^- and Z^0Z^0 pair production are suppressed by the special fits (A) and (B) described in Section 3. Such an idea has wide applications. For example, at LEP1 and SLC if $Z^0 \rightarrow t\bar{t}$ does occur, and both t and $\bar{t}$ decay into three jets, a six-jet analysis can be devised to determine t mass by incorporating the equality of the t and $\bar{t}$ masses.

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Figure Captions

- Fig. 1 Invariant mass distribution from the process $e^+e^- \rightarrow H^0 Z^0$ ($H^0 \rightarrow b\bar{b}$ jets; $Z^0 \rightarrow \nu\bar{\nu}$) for $M_{H^0} = 60$ GeV.
- Fig. 2 Invariant mass distribution calculated with equation (4) (see text) from the process $e^+e^- \rightarrow H^0 Z^0$ ($H^0 \rightarrow b\bar{b}$ jets; $Z^0 \rightarrow \nu\bar{\nu}$) for $M_{H^0} = 60$ GeV.
- Fig. 3 Invariant mass distribution after final analysis for the process $e^+e^- \rightarrow H^0 Z^0$ ($H^0 \rightarrow b\bar{b}$ jets; $Z^0 \rightarrow \nu\bar{\nu}$) for (a) $M_{H^0} = 40$ GeV (b) $M_{H^0} = 60$ GeV and (c) $M_{H^0} = 80$ GeV. The shaded area are background due to QCD, W^+W^- and $Z^0 Z^0$ production. The distribution is normalized to 500pb^{-1} and $E_{cm} = 200$ GeV.
- Fig. 4 The jet-jet invariant mass distribution from the process $e^+e^- \rightarrow W^+W^-$ and $Z^0 Z^0$ after application of fit procedure (A) (see Text).
- Fig. 5 The jet-jet invariant mass distribution from the process $e^+e^- \rightarrow H^0 Z^0$ ($H^0 \rightarrow b\bar{b}$ jets and $Z^0 \rightarrow q\bar{q}$ jets) after fit procedure (B) (See Text)
- Fig. 6 The jet-jet invariant mass distribution after final analysis from the process $e^+e^- \rightarrow H^0 Z^0$ ($H^0 \rightarrow b\bar{b}$ jets and $Z^0 \rightarrow q\bar{q}$ jets) for (a) $M_{H^0} = 40$ GeV, (b) $M_{H^0} = 60$ GeV. The shaded areas are background due to QCD, W^+W^- and $Z^0 Z^0$ production. The distribution is normalized to 500pb^{-1} and $E_{cm} = 200$ GeV.

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Fig. 3

Fig. 3 Invariant mass distribution after final analysis for the process $e^+e^- \rightarrow H^0 Z^0$ ($H^0 \rightarrow b\bar{b}$ jets; $Z^0 \rightarrow \nu\bar{\nu}$) for (a) $M_{H^0} = 40$ GeV (b) $M_{H^0} = 60$ GeV and (c) $M_{H^0} = 80$ GeV. The shaded area are background due to QCD, W^+W^- and $Z^0 Z^0$ production. The distribution is normalized to 500pb^{-1} and $E_{cm} = 200$ GeV.

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Fig. 6 The jet-jet invariant mass distribution after final analysis from the process $e^+e^- \rightarrow H^0 Z^0$ ($H^0 \rightarrow b\bar{b}$ jets and $Z^0 \rightarrow q\bar{q}$ jets) for (a) $M_{H^0} = 40 \text{ GeV}$, (b) $M_{H^0} = 60 \text{ GeV}$. The shaded areas are background due to QCD, W^+W^- and $Z^0 Z^0$ production. The distribution is normalized to 500pb^{-1} and $E_{cm} = 200 \text{ GeV}$.