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Measurement of $\Gamma_{b\bar{b}}/\Gamma_{had}$ from hadronic decays of the Z

The L3 Collaboration

Abstract

We report a measurement of $R_b = \Gamma_{b\bar{b}}/\Gamma_{had}$ from $Z \to q\bar{q}$ events at LEP. $Z \to b\bar{b}$ events are identified using a multidimensional analysis based on a neural network approach. We obtain 60% sample purity with an efficiency of 35%. Our measured value of R_b is $0.222 \pm 0.003 \pm 0.007$.

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1 Introduction

The measurement of the partial decay width of Z into $\mathrm{b\bar{b}}$, $\Gamma_{\mathrm{b\bar{b}}}$, at LEP, provides an important test of the validity of the Standard Model (SM) [1] and allows a precise determination of the neutral current couplings to b quarks. With high statistics and precision, the measurement is sensitive to deviations from the one loop prediction of the SM and may give hints of new physics.

For $\Gamma_{\mathrm{b\bar{b}}}$, radiative corrections are two-fold, the oblique correction to the gauge boson propagator, $\Delta\rho$, and the one loop correction to the $\mathrm{Zb\bar{b}}$ vertex coming from virtual t–W exchange. These corrections are sensitive to the top quark mass and are less sensitive to the Higgs mass. The oblique correction affects all the partial decay widths of Z into fermions while the vertex correction is specific to decays into $\mathrm{b\bar{b}}$. The ratio

$$R_{\mathrm{b}} = \Gamma_{\mathrm{b\bar{b}}}/\Gamma_{\mathrm{had}} \tag{1}$$

has a contribution from the vertex correction $\mathrm{Zb\bar{b}}$ and is free from $\Delta\rho$ as well as from QCD and Higgs mass effects. It can give a clean constraint on the top mass within the SM [2] provided it is known to better than one percent.

In this paper we present a measurement of R_{b} from hadronic decays of the Z collected with the L3 detector. The selection of $\mathrm{b\bar{b}}$ events and their discrimination from other hadronic events is performed using a multidimensional analysis based on a neural network approach. In contrast to our previous measurement [3], we use the entire hadronic sample without requiring a semileptonic decay and so are not limited by the knowledge of the semileptonic branching ratio.

The neural network method has proven to be very effective for event classification in a complex pattern environment [4, 5] and is being increasingly used in high energy physics [6, 7].

2 The L3 Detector

The L3 detector covers 99% of 4π. The detector consists of a central tracking chamber, a high resolution electromagnetic calorimeter composed of BGO crystals, a ring of scintillation counters, a uranium and brass hadron calorimeter with proportional wire chamber readout, and a precise muon spectrometer. These detectors are installed in a 12 m diameter magnet which provides a uniform field of 0.5 T along the beam direction. A detailed description of each detector subsystem, and its performance, is given in reference 8.

The fine segmentation of the electromagnetic and the hadron calorimeter allows us to measure the direction of jets with an angular resolution of 2.5°, and to measure the total energy of hadronic events from Z decay with a resolution of 10.2%. For the present analysis, we use the data collected in the polar angular ranges of $5° < \theta < 175°$ for the hadron calorimeter and $11° < \theta < 169°$ for the electromagnetic calorimeter.

3 Hadron Event Selection

Events of the type $\mathrm{e^+e^-} \rightarrow$ hadrons are selected by requiring:

- $0.45 < E_{\mathrm{vis}}/\sqrt{s} < 1.4$;
- $|E_{||}|/E_{\mathrm{vis}} < 0.5$;

- $E_\perp / E_{\rm vis} < 0.5$;
- $N_{\rm cluster} > 18$;
- at least two jets with $E_{\rm jet} > 10$ GeV and a minimum of four clusters in each jet.

$E_{\rm vis}$ is the total visible energy in the detector. $|E_{||}|$ and $E_\perp$ are the parallel and transverse energy imbalances. $N_{\rm cluster}$ is the number of clusters with energy greater than 100 MeV. The cluster and jet reconstruction proceeds using a two step pattern recognition algorithm [9] which groups adjacent energy depositions in the electromagnetic and the hadron calorimeters into clusters and then collects these clusters into jets. Typically each cluster represents a single particle (hadron, electron, photon). The direction of the cluster is defined by the energy weighted vector sum of all the hits that belong to it. The purpose of the above criteria is to keep only $\rm Z \rightarrow q\bar{q}$ events and reject all $\rm e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$, and two-photon hadron production to better than 0.1%.

For the present analysis we select 238,000 $\rm Z \rightarrow q\bar{q}$ events collected with the L3 detector during 1991 LEP running on the Z peak.

We use a sample of Monte Carlo events based on JETSET7.3 [10] with parton shower fragmentation. The response of the detector is simulated using the L3 simulation program [11]. The simulated events are then reconstructed by the same reconstruction program as that used for the data.

4 Identification of $\rm b\bar{b}$ Events

Because the b quark is heavy, $\rm b\bar{b}$ events can be distinguished from events containing lighter quarks. A standard method is to use the high momentum leptons coming from the semileptonic decays of b quarks. We present here a different method which relies on the general properties of the $\rm b\bar{b}$ events, rather than exclusively on their semileptonic decays.

In the hadronization of a b quark, very little energy is radiated in the form of gluons. Thus, the resulting b hadron carries off a large fraction of the beam energy, typically 70%. It then decays into several particles in a weak decay process. In contrast, most of the energy from a light quark is radiated out in the form of gluons leading to a broad energy spectrum of particles. Thus, the energy gaps between the leading particles are larger for light quark jets. Also the leading light hadron being stable can still be fairly energetic. So, by comparing the energies of the leading particles, as well as the differences in energies of particles within a jet, one can distinguish between b quark and lighter quark jets. In addition, the mass of the b quark affects the jet characteristics. Jets from b quarks are typically broader than light quark jets. The jet boost ($\gamma\beta = p/m$) is also smaller for b quark jets.

None of the above properties alone is sufficient to select a sample of $\rm b\bar{b}$ events with high purity and good efficiency. However, when used in a multidimensional analysis which exploits the correlations between them, a high selection efficiency with good sample purity can be achieved.

We consider five variables, described below, for each of the two most energetic jets of the event. The information used is based only on the calorimetric clusters. All clusters with energy exceeding 100 MeV within 30° of the jet axis are used and the jet energy, invariant mass and the jet direction are redefined on the basis of these clusters. The discriminating features of the variables are checked using data. For this purpose we use $\rm b\bar{b}$ events tagged by high $p_t(> 1$ GeV) muons, where p_t is the momentum of the muon transverse to the jet axis. To avoid biases, we use the jet opposite the muon-tagged jet for studying the variables.

The variables that we use are:

1. The $\gamma\beta$ of the jet using the jet energy and the invariant mass determined by the clusters, where the clusters are assumed to be massless. In figure 1a we show the $\gamma\beta$ distribution

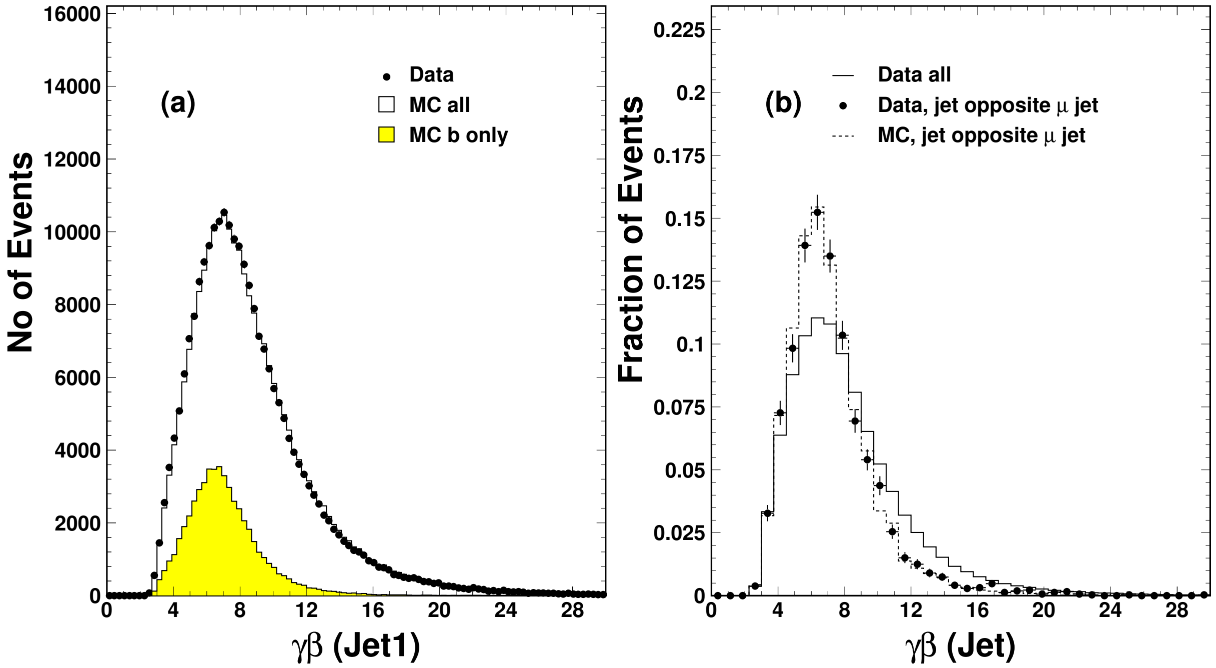

Figure 1: The distribution of $\gamma\beta$ for (a) the most energetic jet compared to the Monte Carlo, and for (b) the muon tagged sample compared to all data.

   for the most energetic jet for the data compared to the Monte Carlo. In figure 1b the distribution for all data is compared with that for jets opposite to a muon-tagged jet. Both the data and the Monte Carlo show that b jets tend to have smaller $\gamma\beta$ value than light quark jets.

2. The energy of the most energetic cluster which tends to be lower for $b\bar{b}$ events than for light quark events.

3. The directed sphericity of the jet defined as

$$S_{\mathrm{dir}} = \frac{\sum p_\perp^2}{\sum p^2},$$

   where the momenta are in the jet rest frame, and the transverse direction is with respect to the jet direction. Figure 2(a) shows the distribution for all data compared to the muon-tagged events.

4. The $\gamma\beta$ of the set of the four leading clusters in the jet.

5. The energy gap between the first and the fourth most energetic clusters, E_{gap}, scaled by the jet energy. In figure 2(b) we plot this distribution for all jets compared to the muon-tagged sample.

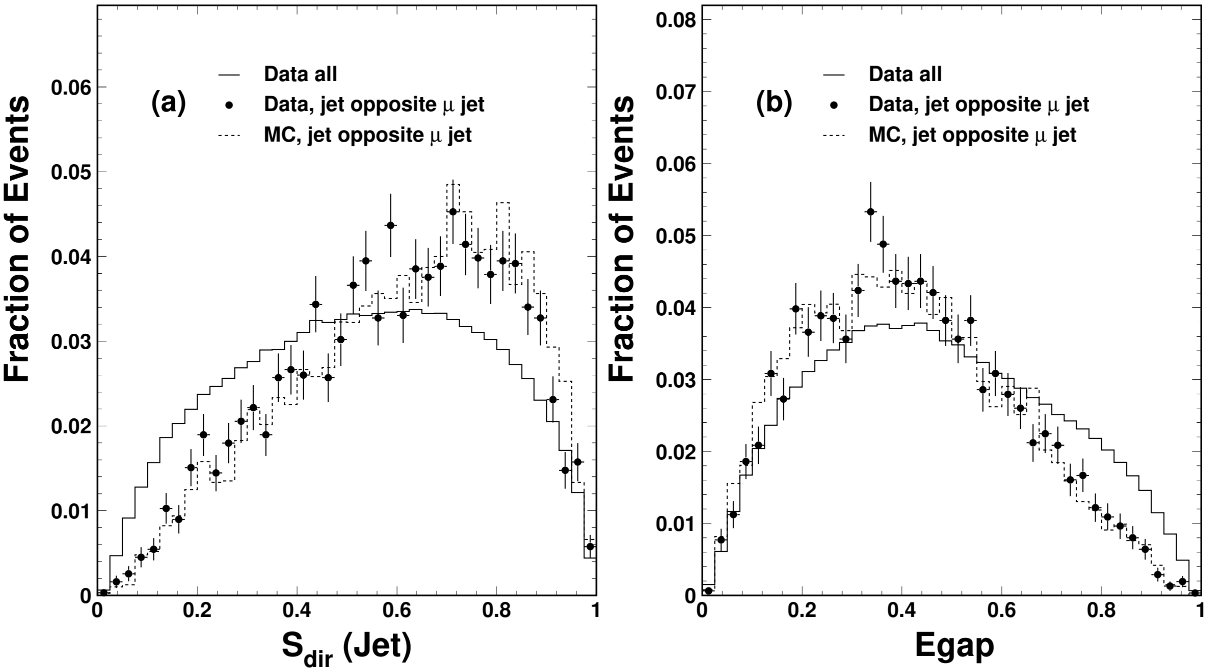

Figure 2: (a) The directed sphericity distribution for all jets compared to the muon-tagged sample and (b) the energy gap between the most energetic and fourth most energetic clusters for all jets compared to the the muon-tagged sample.

In addition we use the global variable $E_{\rm left}$ defined as the fraction of visible energy outside the two most energetic jets:

$$E_{\rm left} = \frac{E_{\rm vis} - (E_{\rm jet1} + E_{\rm jet2})}{E_{\rm vis}}$$

where $E_{\rm jet1}$ and $E_{\rm jet2}$ are the energies of the two jets. Although the distribution of $E_{\rm left}$ for b and non-b events is similar, the correlation between it and other variables is useful in a multidimensional analysis.

Altogether, 11 variables are used per event.

Figures 1 and 2 show that the Monte Carlo describes the data well. Before performing the multidimensional analysis of these quantities, we have also checked that their correlations with each other are in good agreement. In figure 3 we show, as an example, the correlation between $\gamma\beta$ for the most energetic jet and all other quantities, and between the energy gap of the second jet and the other quantities. One can also see that variables within the same jet have stronger correlations compared to those in different jets.

5 The Multidimensional Analysis

Multidimensional analysis for event classification exploits the correlations between the various quantities that characterize the events. For every event the characterizing quantities can be considered as a vector $\boldsymbol{x}(x_1, x_2, ...x_N)$. In our particular case, the vector $\boldsymbol{x}$ has the 11 quantities described above as components. We then determine the classifier function $F_c(\boldsymbol{x}, \boldsymbol{w})$ to separate b quark events from non-b quark events. The vector $\boldsymbol{w}$ is a vector of weights adjusted to

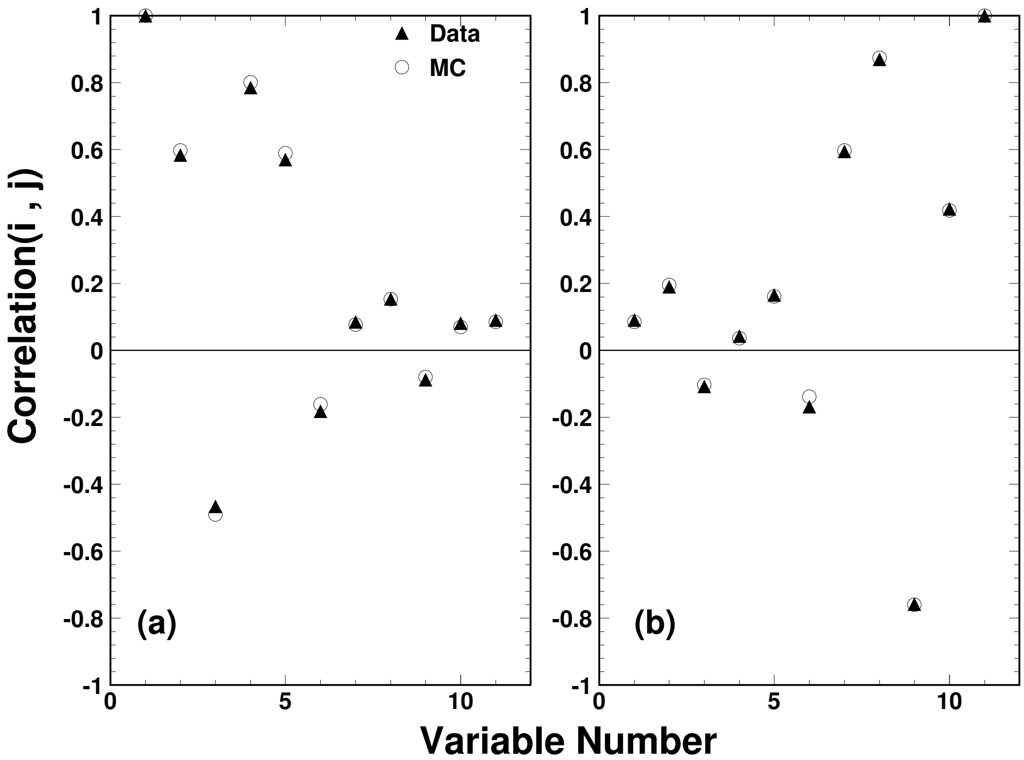

Figure 3: The correlation coefficient (a) between $\gamma\beta$ of the most energetic jet and all other quantities and (b) between the energy gap of the second jet and all other quantities. The quantites are labelled 1-5 for the most energetic jet, 7-11 for the second most energetic jet, and 6 for the global event quantity, $E_{\rm left}$.

minimize the classification error

$$\int \mid F_c(\boldsymbol{x},\boldsymbol{w}) - F_{\rm known}(\boldsymbol{x}) \mid^2 \rho(\boldsymbol{x}) d\boldsymbol{x},$$

where $\rho(\boldsymbol{x})$ is the density function of the events and $F_{\rm known}$ the classifier function known from Monte Carlo. The determination of the weight vector ("training") is performed using Monte Carlo events. The probability distribution of the classifier $F_c(\boldsymbol{x},\boldsymbol{w})$ for Monte Carlo events is expected to agree with the data provided that $\rho_{MC}(\boldsymbol{x}) = \rho_{data}(\boldsymbol{x})$.

In a conventional neural network [4, 5], the classifier function is derived from successive layers of neurons. Each neuron gets as input a linear sum of the quantities of the previous layer and provides as output a non-linear transformation of the linear sum. In the less conventional approach that we follow [5], the input variables are first expanded using orthonormal functions. A simple summation of the transformed variables is used in only one non-linear transformation. This eliminates the intermediate stages and reduces the number of weights.

Each input quantity, x_k is first scaled to be in the range $(-1, 1)$. It is then expanded using the functional transform $f(x_k)$ given by

$$f(x_k) = w_{1k} x_k + \sum_{j=1}^{n} \left(w_{2kj} \sin(j\pi x_k) + w_{3kj} \cos(j\pi x_k) \right) \tag{2}$$

For our purposes, we have determined that $n = 4$ is an optimal choice for the performance of the network. The transformed input quantities are then summed to form:

$$X = \sum_{k=1}^{11} f(x_k) + w_0. \tag{3}$$

The classifier function used is

$$F_c(X) = \frac{1}{1 + e^{-X}} \equiv F_c(\boldsymbol{x}, \boldsymbol{w}) \tag{4}$$

We determine the weights $\boldsymbol{w}$ with a sample of 150,000 Monte Carlo events to minimize

$$\left[F_c(\boldsymbol{x}, \boldsymbol{w}) - F_{\text{known}}\right]^2 \tag{5}$$

where F_{known} is chosen to be 0.025 for non-b and 0.975 for b events. The discriminating power of the classifier function is then tested using an independent sample of 200,000 Monte Carlo events.

The network classifier response for the Monte Carlo test sample is shown in figure 4(a). The

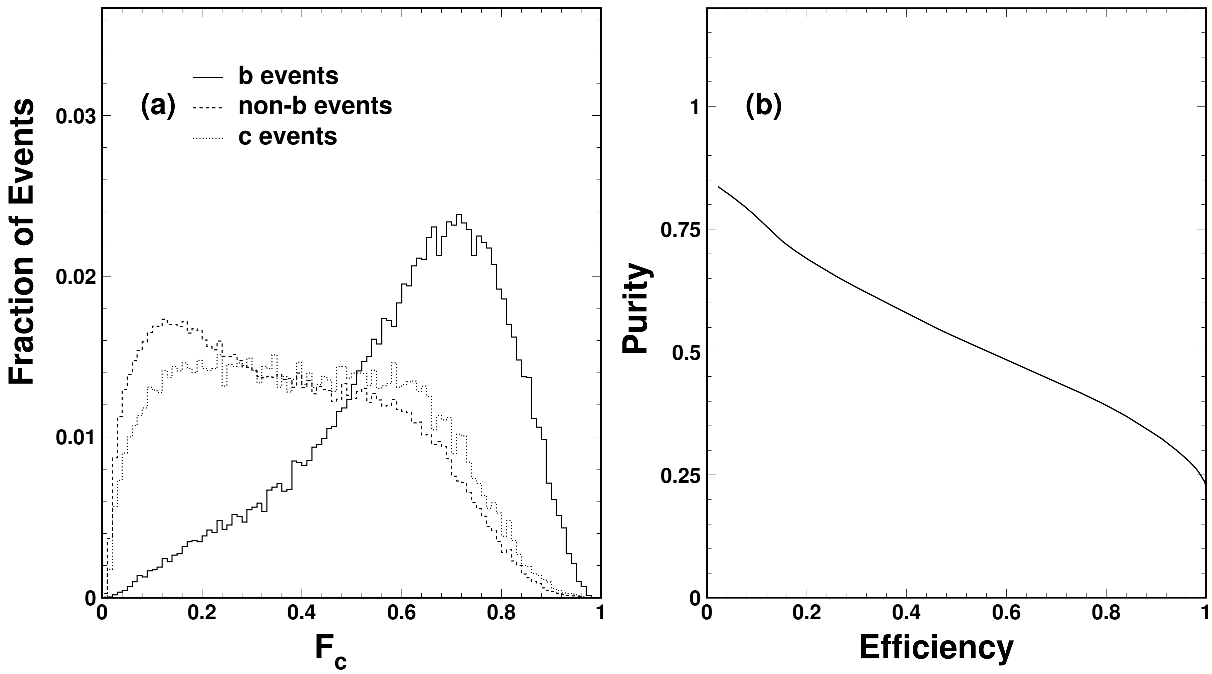

Figure 4: (a) The network response for b events and non-b events separately. (b) Purity and efficiency of the classifier function for b events.

b events dominate at larger values of F_c and the non-b at smaller values. Figure 4(b) shows the b sample purity as a function of the tagging efficiency. As an example of the performance of the network, we achieve 35% efficiency for 60% purity. For high purities the efficiency is approximately a factor two better than those in similar studies [7].

In order to test the network reliability and to make sure that the correlations among the different variables both in the Monte Carlo and the data are well understood, the response of the network which has been trained using Monte Carlo $q\bar{q}$ events is compared for those events that have a high $p_t (> 1$ GeV) muon (figure 5). The whole event is used but no information from

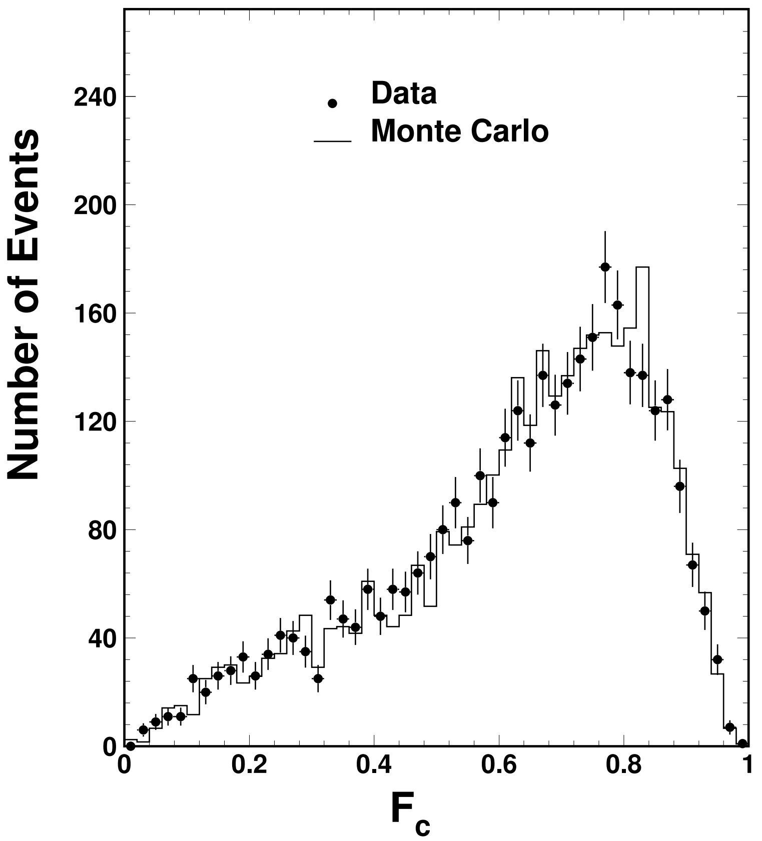

Figure 5: The network response for events tagged by a high p_t muon for the data compared to the Monte Carlo.

the muons themselves is used in the network. These events are approximately 80% $b\bar{b}$ [12]. The Monte Carlo reproduces well the data. This indicates that the correlations among the different variables used are well simulated in the Monte Carlo and it does represent the data in detail. An important point to note is that the high p_t muon events are distributed in the entire range of F_c in much the same way as all other b events indicating that the high purity sample of b events from the network are not just from the semileptonic decays of b hadrons. Thus the uncertainty in the semileptonic branching ratio of b quark has an insignificant effect on the network results.

6 Determination of $\Gamma_{b\bar{b}}/\Gamma_{had}$

To determine $R_b = \Gamma_{b\bar{b}}/\Gamma_{had}$, we perform a fit to the data distribution of F_c by varying the b and non-b contribution from the Monte Carlo. In figure 6 we compare the data with the fitted distribution and also plot the b and non-b contributions. We determine $\Gamma_{b\bar{b}}/\Gamma_{had} = 0.222 \pm 0.003$. The error includes the statistical error due to the Monte Carlo test sample. We obtain similar results using a simpler procedure of applying a cut on the value of the classifier depending upon the desired sample purity and the tagging efficiency.

As we use Monte Carlo events to describe the data and estimate the different acceptances, there are several parameters that affect the event description. Details of the various parameters

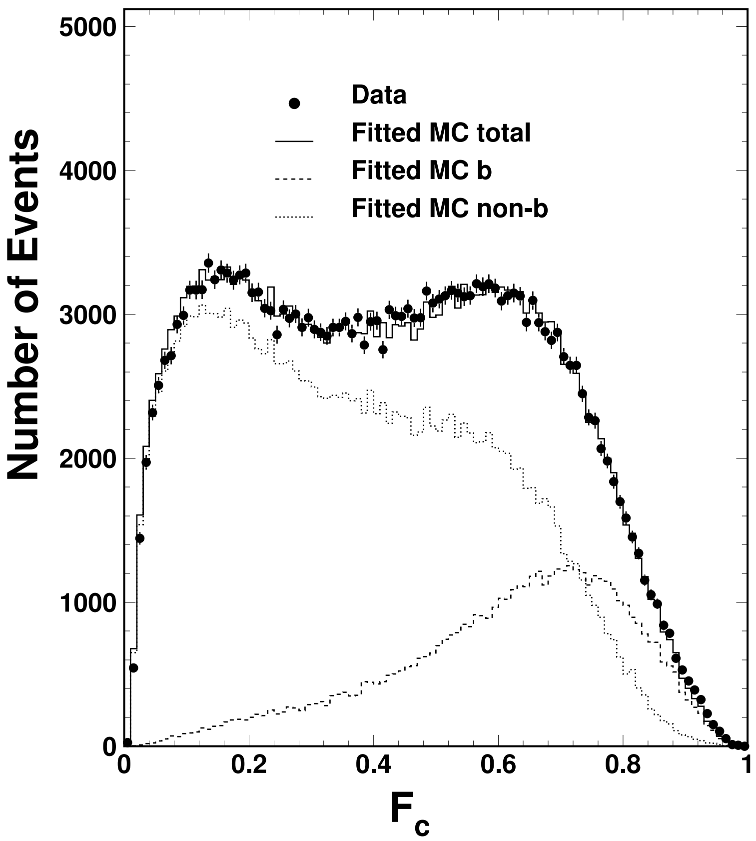

Figure 6: Fit of the network response to the data. Also shown is the response for b and non b events separately.

used in the Monte Carlo and the different fragmentation schemes is given in reference 13. For the light u, d, and s quarks the Lund symmetric fragmentation function is used while for b and c quarks the Peterson fragmentation function [14] is used. For estimating the systematic error each parameter is varied by its error [13] and a new test sample is generated. Comparing the sample purity and tagging efficiency of the new test sample with the standard test sample the change in $R_{\rm b}$ is estimated. For this purpose fast simulations using approximate detector resolutions have been made. The changes in $R_{\rm b}$ for different parameters are given in table 1. In addition to the QCD parameters we have changed the semileptonic branching ratio of b hadrons and varied the detector response. Adding all the systematic errors in quadrature, we arrive at the total systematic error on $R_{\rm b}$ of 0.007.

7 Conclusions

We have identified $\mathrm{b\bar{b}}$ events in Z hadronic decays using a multidimensional analysis with several variables which characterize the event topology. A neural network based on functional expansion provides a very good separation between b and non-b events. We achieve high sample purity of $\mathrm{b\bar{b}}$ events with good tagging efficiency: for 60% sample purity we obtain 35% efficiency. From a fit to the full range of the classifier function, we determine:

$$R_{\rm b} = 0.222 \pm 0.003 \pm 0.007.$$

Source of systematic error	Variation	ΔR_{b}
$\mathrm{b} \rightarrow \ell\nu\mathrm{X}$ branching ratio	0.02	0.0010
b quark fragmentation parameter ϵ_{b}	0.004	0.0031
c quark fragmentation parameter ϵ_{c}	0.02	0.0018
Λ_{LL} (GeV) the shower scale parameter	0.03	0.0037
b (GeV^{-2}) parameter in Lund Sym. Fragmentation	0.08	0.0024
σ_{q} (GeV), Gaussian p_t width of hadrons	0.03	0.0022
Mass of the b quark (GeV)	0.5	0.0006
$\Gamma_{\mathrm{c\bar{c}}}$ (MeV)	15	0.0011
Change in energy resolution of the calorimeter $\Delta\sigma(E)$	10%	0.0020
Total uncertainty from all sources		0.007

Table 1: Summary of the systematic errors due to various sources.

This result is a significant improvement of our previous measurement [3], $R_{\mathrm{b}} = 0.218 \pm 0.004 \pm 0.012$, using only the semileptonic decays, and is in good agreement with the Standard Model value $R_{\mathrm{b}} = 0.216$ computed with a top mass of 150GeV.

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