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Published in:
Physics Letters B

DOI:
10.1016/0370-2693(90)91666-Y

MEASUREMENT OF $Z^0 \to b\bar{b}$ DECAY PROPERTIES

L3 Collaboration

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Received 20 February 1990

We have measured the properties of $Z^0 \to b\bar{b}$ decays using a sample of 944 inclusive muon events, corresponding to 18000 hadron events obtained with the L3 detector at LEP. We measured the partial decay width of the Z^0 into $b\bar{b}$, $\Gamma_{b\bar{b}} = 353 \pm 48$ MeV, and we determined the vector coupling of the Z^0 to the b quark; $g_V^2(b) = 0.095 \pm 0.047$. We measured the forward–backward charge asymmetry in $e^+e^- \to b\bar{b}$ events at $\sqrt{s} \approx M_Z$, and obtained $A_{b\bar{b}} = 13.3 \pm 9.9\%$.

1. Introduction

Measurements of decays of the Z^0 boson into $b\bar{b}$ pairs may be used to precisely determine the weak neutral couplings of heavy quarks, and to test the universality of the quark couplings. In the standard model [1] the partial width in $Z^0 \to q\bar{q}$ depends on the weak isospin of the quark: the partial width is expected to be larger for down-type quarks than for up-type quarks. Precise determinations of the partial decay width for $Z^0 \to b\bar{b}$ ($\Gamma_{b\bar{b}}$) and of the forward–backward asymmetry ($A_{b\bar{b}}$), with high statistics at LEP, may therefore be used to perform stringent tests of the standard model and to accurately measure $\sin^2\Theta_w$ [2].

[1] Supported by the German Bundesministerium für Forschung und Technologie.

In previous measurements with the L3 detector at LEP [3,4], we have determined the total width of the Z^0 boson Γ_Z, and the partial widths into charged leptons ($\Gamma_{\ell\ell}$), hadrons ($\Gamma_{hadrons}$) and neutrinos ($\Gamma_{invisible}$). In this paper we present our determinations of $\Gamma_{b\bar{b}}$ and $A_{b\bar{b}}$.

Our measurements are based on a study of inclusive muons in the reaction $e^+e^- \to \mu + $hadrons. The data were taken at ten center of mass energies covering the range of the Z^0 peak: 88.28 GeV $\leqslant \sqrt{s} \leqslant$ 95.04 GeV. Inclusive muons have been used in previous measurements of heavy quark properties, at lower energies or with lower statistics [5]. The clean identification and measurement of muons in the L3 detector allows us to select inclusive muons events from the reaction $e^+e^- \to b\bar{b}$, where the muon has a large transverse momentum with respect to the nearest jet, with little background from $c\bar{c}$ or light $q\bar{q}$ production.

2. The L3 detector

The L3 detector covers 99% of 4π. The detector consists of a central vertex 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 very accurate muon chamber system. These detectors are installed in a 12 m diameter magnet which provides a uniform field of 0.5 T along the beam direction. The luminosity, which is measured using small angle Bhabha events in two calorimeters situated on either side of the interaction point, has been determined with a total systematic uncertainty of 1.7% [3]. The detector is described in detail in ref. [6].

The fine segmentation of the BGO detector and the hadron calorimeter allows us to measure the axis of jets with an angular resolution of 2.5°, and to measure the total energy of hadronic events from Z^0 decay with a resolution of 12%. The muon detector consists of three layers of precise drift chambers, which measure a muon's trajectory 56 times in the bending plane, and 8 times in the non-bending direction.

Fig. 1 illustrates that the L3 detector is well suited for the study of inclusive muon events. The muon is observed in the vertex chamber, as well as in the hadron calorimeter, as a well defined track. It deposits energy corresponding to a minimum ionizing particle in the electromagnetic and hadronic calorimeters. A clearly isolated muon track is measured in the muon chambers.

Backgrounds from π and K decay in flight are suppressed because of the short decay path (a transverse distance of 52 cm) from the interaction point to the front face of the BGO crystals. Background from noninteracting hadrons and secondary hadrons produced in showers (punch through) is suppressed, because a pion has to penetrate an average of 6.5 nuclear absorption lengths to reach the muon chambers. The inclusive muon signal is then further separated from the residual lower-momentum punch through and decay backgrounds be measuring the momentum after the hadron absorbers.

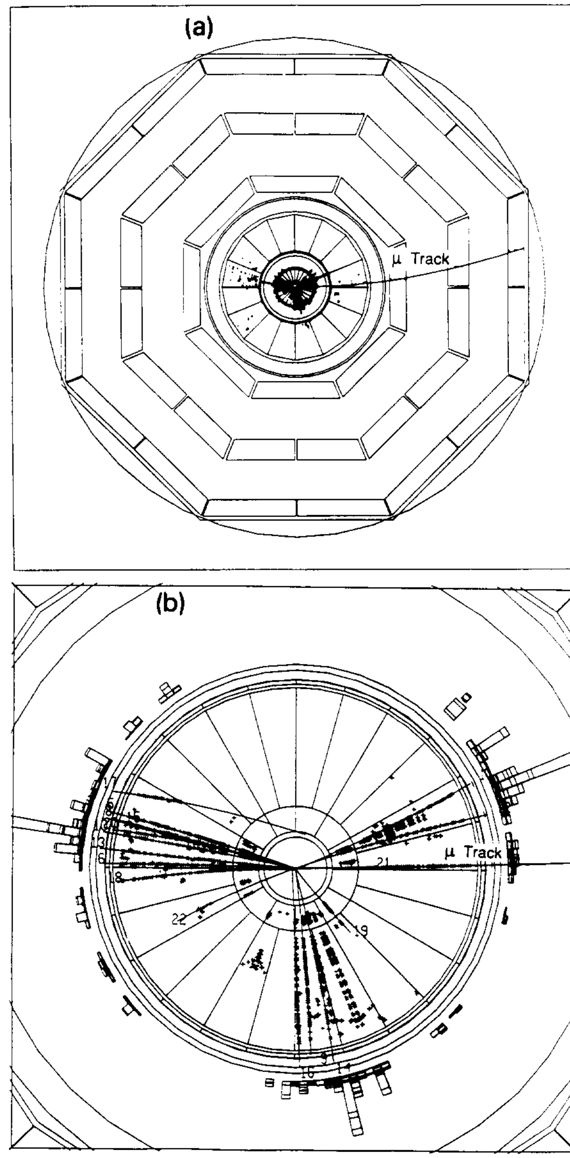

Fig. 1. Example of a hadronic event with a high $p_\perp$ inclusive muon (labeled "μ track"). (a) shows the display of the event in the L3 detector. (b) shows a close-up view in the vertex chamber.

3. Selection of inclusive muon events

Inclusive muon events from the reaction $Z^0 \rightarrow \mu + \text{hadrons}$ were triggered by either one of two independent triggers. The primary trigger required a total energy of 15 GeV in the BGO and hadron calorimeters. The second trigger, which allowed us to check our trigger efficiency, was a muon trigger which required two of sixteen scintillation counter ϕ sectors in coincidence with a track in the muon chambers. The combined trigger efficiency for hadronic events with muons was greater then 99.9%.

The data sample used in this analysis corresponds to a total integrated luminosity of 924 nb^{-1}, and 18000 hadron events.

The inclusive muon events were selected using the criteria:

(1) $E_{vis} > 40$ GeV,

(2) $|E_{\parallel}|/E_{vis} < 0.4$,

(3) $E_{\perp}/E_{vis} < 0.7$,

where E_{vis} is the total energy observed in the detector. We defined the energy imbalance as the vector sum of the energy clusters in the BGO crystals and the hadron calorimeter towers, with the direction of the vector defined relative to the center of the interaction region. $E_{\parallel}$ is the component of the energy imbalance vector along the beam direction, and $E_{\perp}$ is the projection of this vector onto a plane through the interaction region which is perpendicular to the beam direction.

The number of jets was found using a two step algorithm which groups the energy deposited in the BGO crystals and in the hadron calorimeter towers into clusters, before collecting the clusters into jets. We required:

(4) At least one jet above 10 GeV.

The clustering algorithm normally reconstructs only one cluster for each electron or photon shower, and a few clusters for τ's. We were therefore able to reject $\tau^+\tau^-$ events, by a cut on the number of clusters:

(5) $N_{cluster} > 10$.

The cuts above serve to select a clean sample of hadronic events. Inclusive muon events are then selected by requiring:

(6) At least one track in the muon detector, with momentum greater than 3 GeV. The track had to have reconstructed segments in at least two of the three layers of momentum measuring drift chambers, and at least one track segment in the chambers measuring along the beam direction.

To reduce punch through background, we required that the muon track point back to the interaction point. This was measured in terms of the expected error from multiple scattering in the plane perpendicular to the beam line σ_{xy}, and in the direction along the beam σ_z. We required that

(7) The distance of closest approach was less than $3\sigma_{xy}$ in the transverse plane, and less than $4\sigma_z$ along the beam.

To ensure that the angle of the jet axis, and hence the transverse momentum of the muon with respect to the nearest jet was accurately determined, the thrust axis of the event had to be well inside the detector acceptance. We required:

(8) $|\cos\theta_T| < 0.7$,

where θ_T is the angle between the thrust axis and beam line.

After cuts, we were left with a sample of 944 inclusive muon events. The background from $\tau^+\tau^-$ final states was determined to be negligible.

4. Measurement of $Z^0 \to b\bar{b}$

To determine the acceptance for inclusive muons after cuts, we used the Lund parton shower program JETSET 6.3 [7] and the L3 detector simulation [#1]. This has been shown to provide an accurate description of hadronic events from Z^0 decays [3]. In our analysis of $\Gamma_{b\bar{b}}$ we have used the average of the semimuonic branching ratios measured by previous experiments [5]: $Br(D \to \mu) = 10.0\%$ (averaged over the charged and neutral D's produced) and $Br(B \to \mu) = (11.8 \pm 1.1)\%$.

Fig. 2 shows the momentum spectrum of the inclusive muons passing the selection cuts given above. For the final analysis of $\Gamma_{b\bar{b}}$ only events with a muon momentum larger than 4 GeV were used. Fig. 3 shows the measured transverse momentum of the muon with respect to the nearest jet, $p_{\perp}$, for $p_{\mu} > 4$ GeV. The good agreement between the data and Monte Carlo demonstrates that the contributions from background (which are small at large p_{μ} and $p_{\perp}$), and the detector resolution are well simulated.

In order to obtain a clean data sample which is predominantly from $Z^0 \to b\bar{b}$, we selected inclusive muons

[#1] The L3 detector simulation is based on GEANT Version 3.13, September, 1989. See ref. [8]. The simulation includes the effects of energy loss, multiple scattering, interactions and decays in the detector materials and the beam pipe. The GHEISHA program [9] is used to simulate hadronic interactions.

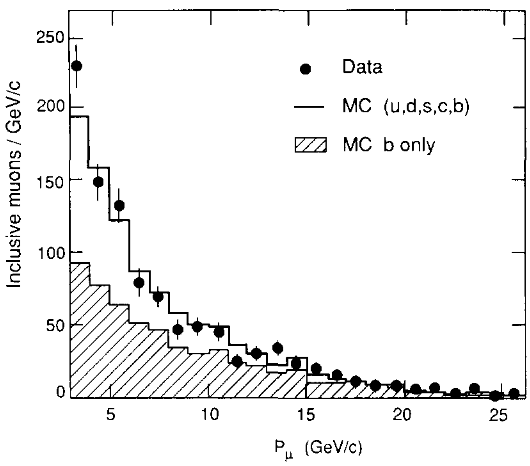

Fig. 2. The measured muon momentum distribution in inclusive muon events, compared to the Monte Carlo simulation. The contribution of $b\bar{b}$ events calculated by the simulation is indicated by the hatched area. The data with $p_\mu > 4$ GeV are dominated by $b\bar{b}$ decays.

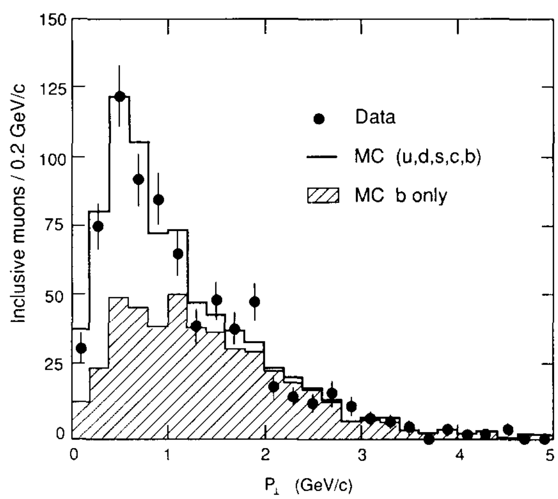

Fig. 3. The measured distribution of the transverse momentum $p_\perp$ of the muon with respect to the nearest jet, for inclusive muons with $p_\mu > 4$ GeV. The data are compared to the Monte Carlo simulation. The contribution of $b\bar{b}$ events calculated by the simulation is indicated by the hatched area. The data with $p_\perp > 1.6$ GeV are dominated by $b\bar{b}$ decays.

with $4\ \text{GeV} < p_\mu < 25$ GeV and $1.6\ \text{GeV} < p_\perp < 3.5$ GeV [#2]. Because the average $p_\perp$ of muons from heavy quark decays is approximately $m_q/4$, a cut in $p_\perp$ should be an efficient way to separate the signal due to b-quarks from the background from the lighter quarks (udsc). Using this selection, we obtained a sample of 171 events. Monte Carlo calculations show that 90.8% of this sample is expected to come from $b\bar{b}$ (including 5.2% from the cascade decay $b \to c \to \mu^+$). The contribution from $c\bar{c}$ is expected to be 4.4%. The expected contribution from the punch through and decay in flight of light hadrons (containing u, d, and s quarks) is 4.8%.

Fig. 4 shows the measured distribution of the transverse energy imbalance $E_\perp / E_{vis}$, for $p_\mu > 4$ GeV. This distribution is sensitive to the energy carried away by the neutrino in the semileptonic decay of a heavy quark. The measured distribution agrees well with the Monte Carlo calculation. As seen in the figure, $b\bar{b}$ events dominate in the region of large $E_\perp$.

In order to measure $\Gamma_{b\bar{b}}$ accurately, it is necessary to study the fragmentation functions for b and c quarks [10], since the momentum distribution of the muons observed in the final state is directly related to the B hadron spectrum prior to decay. We therefore determined $\Gamma_{b\bar{b}}$ in a fit to the data which allowed both the fragmentation function for B mesons and $\Gamma_{b\bar{b}}$ to vary. We characterized the fragmentation of b

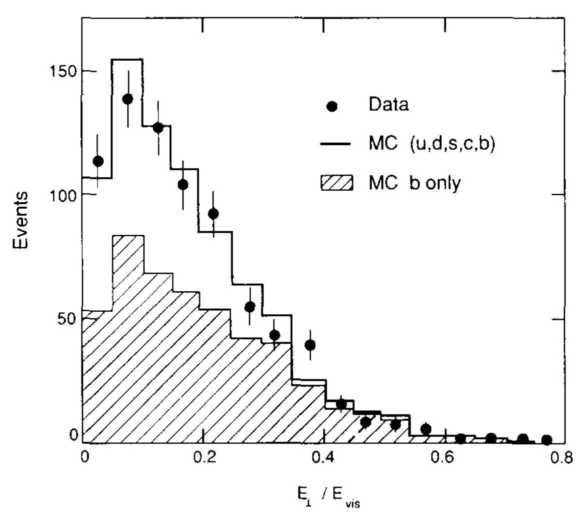

Fig. 4. The measured distribution for the energy imbalance $E_\perp$, compared to the Monte Carlo simulation. The contribution of $b\bar{b}$ events calculated by the simulation is indicated by the hatched area. The data at large $E_\perp / E_{vis}$ values are dominated by $b\bar{b}$ decays.

[#2] The upper cuts on p_μ and $p_\perp$ are made to ensure that there is a well measured, high energy jet in the same hemisphere, so that $p_\perp$ with respect to the nearest jet is well defined.

quarks in terms of the average scaled energy [#3] $x_E = 2E_{\mathrm{hadron}}/\sqrt{s}$, using the functional form given by Peterson et al. [11] which depends on a single fragmentation parameter ϵ_b. As a result of our fragmentation study (see below) we found that $\Gamma_{b\bar{b}}$ is relatively insensitive to the choice of the b quark fragmentation function.

We performed a maximum likelihood fit to the two-dimensional p_μ versus $p_\perp$ distribution, and to the normalized $E_\perp$ distribution, using all inclusive muons with 4 GeV $< p_\mu <$ 25 GeV and no $p_\perp$ cut. The p_μ versus $p_\perp$ distribution is sensitive to both $\Gamma_{b\bar{b}}$ and to ϵ_b. Including the $E_\perp$ distribution in the fit, for events with $p_\perp > 1$ GeV, provides additional sensitivity to ϵ_b and improves the overall precision of the ϵ_b determination.

The distributions in p_μ versus $p_\perp$ and $E_\perp$ were simulated using JETSET 6.3 with $\alpha_s = 0.12$, and various fragmentation functions. The simulated events were generated with the same $\sqrt{s}$ distribution as the data. Distributions for different fragmentation parameters were obtained in the fit by reweighting the Monte Carlo events as a function of x_E, assuming the Peterson functional form. The Monte Carlo predictions were normalized to the same total number of hadronic events as the data.

The direct results of the fits are: $\mathrm{Br}(B \to \mu)\Gamma_{b\bar{b}} = 41.7 \pm 2.9$ (stat) MeV and $\epsilon_b(x_E) = 0.049^{+0.012}_{-0.010}$. This value of $\epsilon_b(x_E)$ corresponds to $\langle x_E \rangle = 0.69 \pm 0.02$.

To check the result of the fit the following tests were performed:

(1) Fits were made with several different cuts in p_μ (between 4 and 6 GeV) and $p_\perp$ (between 0 and 1.6 GeV). We observed changes of typically 4% in $\Gamma_{b\bar{b}}$.

(2) The contribution from the lighter quarks (udsc), and the amount of background from punch through has been varied by $\pm 20\%$. The results of the fits changed by less than 3% in $\Gamma_{b\bar{b}}$ and 0.005 in $\langle x_E \rangle$.

(3) The fit has been repeated by leaving the charm fragmentation and the semileptonic branching ratio $\mathrm{Br}(c \to \mu)$ free. The result changes by 4% in $\Gamma_{b\bar{b}}$ and 0.008 in $\langle x_E \rangle$.

(4) We changed the functional representation of the x_E distribution, by replacing the Peterson form by the "Lund symmetric" form [12]. The result of the fit changes by 2% for $\Gamma_{b\bar{b}}$ and 0.012 in $\langle x_E \rangle$.

From these variations and the error on event selection, we estimate a relative systematic error of $\pm 7\%$ in $\Gamma_{b\bar{b}}$ and 4% in $\langle x_E \rangle$. The final results from the fit are

$$\mathrm{Br}(B \to \mu)\Gamma_{b\bar{b}} = 41.7 \pm 2.9(\mathrm{stat}) \pm 3.0(\mathrm{sys})\ \mathrm{MeV},$$

$$\langle x_E \rangle = 0.69 \pm 0.02 \pm 0.03 .$$

After inserting the semi-leptonic branching ratio, $\mathrm{Br}(B \to \mu) = 0.118 \pm 0.011$ [5], we obtain

$$\Gamma_{b\bar{b}} = 353 \pm 25 \pm 25\ \mathrm{MeV},$$

where the first error is statistical, and the second is systematic. Our measurement agrees with the expected partial width in the standard model, $\Gamma_{b\bar{b}} =$ 379 MeV [13] (for $M_Z = 91.160$ GeV [3], $\alpha_s = 0.12$, $M_{\mathrm{top}} = 100$ GeV, and $M_{\mathrm{Higgs}} = 100$ GeV).

Since $\Gamma_{b\bar{b}} \propto g_A^2(b) + g_V^2(b)$, the measurement of the partial decay width can be used to determine the coupling constants of the b quark. The axial vector coupling has been measured at low energies [4], and is in agreement with the standard model. Inserting the standard model value $g_A(b) = -\frac{1}{2}$ into the expression for $\Gamma_{b\bar{b}}$, we solved for the vector coupling constant, and obtained

$$g_V^2(b) = 0.095 \pm 0.024(\mathrm{stat}) \pm 0.024(\mathrm{sys}) .$$

This agrees with the standard model prediction $g_V^2(b) = 0.12$, for $\sin^2\Theta_w = 0.23$,

Alternatively we can express our result in terms of the ratio of $b\bar{b}$ events to all hadronic events. Our measurements yield

$$\Gamma_{b\bar{b}}/\Gamma_{\mathrm{hadrons}} = 0.204 \pm 0.014(\mathrm{stat}) \pm 0.014(\mathrm{sys}) .$$

Our measured value of this ratio agrees with the standard model expectation $\Gamma_{b\bar{b}}/\Gamma_{\mathrm{hadrons}} = 0.217$.

The uncertainty in the B semi-muonic branching ratio leads to an additional systematic uncertainty of 33 MeV in $\Gamma_{b\bar{b}}$, 0.032 in $g_V^2(b)$, and 0.02 in

[#3] The commonly used fractional "energy" of the primordial heavy hadron, $z_{\mathrm{rec}} = (E + p_\parallel)_{\mathrm{hadron}}/(E+p)_{\mathrm{quark}}$, as reconstructed from the Monte Carlo four-vectors, is not meaningful in parton shower models. Because of the radiation of energetic gluons, values of z_{rec} greater than unity are often observed in the JETSET model at Z^0 energies. The variable $x_E = 2E_{\mathrm{hadron}}/\sqrt{s}$ was chosen because it can be directly measured, and because its definition is independent of fragmentation models.

$\Gamma_{b\bar{b}}/\Gamma_{\rm hadrons}$. Combining all statistical and systematic errors in quadrature, we obtain our final results:

$$\Gamma_{b\bar{b}} = 353 \pm 48 \text{ MeV} ,$$

$$g_V^2(b) = 0.095 \pm 0.047 ,$$

$$\Gamma_{b\bar{b}}/\Gamma_{\rm hadrons} = 0.204 \pm 0.028 .$$

To check the results on $\Gamma_{b\bar{b}}$, another determination was performed by selecting the inclusive muons in the "pure b" events using the cuts mentioned above: 4 GeV $< p_\mu <$ 25 GeV and 1.6 GeV $< p_\perp <$ 3.5 GeV. This corresponds to a selection efficiency of $(4.05 \pm 0.03)\%$ for b events. From the 171 events passing these cuts, the fraction of b events to all hadronic events was determined to be $\Gamma_{b\bar{b}}/\Gamma_{\rm had} = 0.216 \pm 0.018$(stat), in good agreement with the result of the fit.

5. Forward–backward asymmetry $A_{b\bar{b}}$

We measured the forward–backward asymmetry in $Z^0 \to b\bar{b}$ at $\sqrt{s} \approx M_Z$ by using the same inclusive muon event sample used for the determination of $\Gamma_{b\bar{b}}$. In a semi-leptonic decay of a b quark, the charge of the detected muon is directly correlated with the b or $\bar{b}$ quark. Using the thrust axis to define the direction of the quark, and the sign of the muon charge to tag the b or $\bar{b}$, we are able to measure the forward–backward asymmetry $A_{b\bar{b}}$ in $e^+e^- \to b\bar{b}$ [2]. The asymmetry was determined in every bin of the p_t distribution using a fit with $A_{b\bar{b}}$ and $A_{c\bar{c}}$ as free parameters. Contributions from background and the cascade decay $b \to c \to \mu$ were taken into account. From the fit we obtained $A_{b\bar{b}} = (10.6 \pm 7.9)\%$, corresponding to the angular range $|\cos\theta| < 0.7$. By extrapolating $A_{b\bar{b}}$ to the full range $|\cos\theta| < 1$ we obtained the forward–backward asymmetry at $\sqrt{s} \approx M_Z$:

$$A_{b\bar{b}} = (13.3 \pm 9.9)\% ,$$

where the error is statistical only [#4]. (The systematic error is estimated to be smaller than 3%). This result is in agreement with the standard model prediction [#5] for the full angular range $A_{b\bar{b}} = +10.8\%$.

[#4] This result is not corrected for B^0–$\bar{B}^0$ oscillations [2].

[#5] Neglecting B^0–$\bar{B}^0$ mixing, which is expected to reduce the magnitude of the asymmetry, as measured by using the sign of the muon electric charge to tag b and $\bar{b}$ quarks, by a factor of 0.75 ± 0.10 [15].

6. Conclusions

We have analyzed $Z^0 \to b\bar{b}$ decays, using inclusive muon events selected from a sample of 18000 hadron events. From a simultaneous fit to the p_μ, $p_\perp$ and $E_\perp$ distributions we have determined the partial width $\Gamma(Z^0 \to b\bar{b}) = 353 \pm 48$ MeV, and the average fractional energy of hadrons containing b quarks $\langle x_E \rangle = 0.69 \pm 0.04$. From the measurement of $\Gamma_{b\bar{b}}$, the neutral current vector coupling of the b quark has been determined to be $g_V^2(b) = 0.095 \pm 0.047$. Our measurement of the forward–backward asymmetry at $\sqrt{s} \approx M_Z$ yields $A_{b\bar{b}} = (13.3 \pm 9.9)\%$.

Acknowledgement

We wish to thank CERN for its hospitality and help. We want particularly to express our gratitude to the LEP division: it is their excellent achievements which made this experiment possible. We are grateful to T. Sjöstrand, P. Nason, M. Herreiro, H. Steger, and J. Donoghue for useful discussions on heavy quark production and fragmentation. We acknowledge the support of all the funding agencies which contributed to this experiment.

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