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A Search for the Top and b' Quarks in Hadronic Z^0 Decays

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Abstract

We report on a search for new quarks in hadronic Z^0 decays. From the event shape analysis of a data sample containing 2185 multihadronic annihilation events, we observe no evidence for the top or b' quarks. We derive limits for the top and b' quark masses under the assumption of various possible standard model and non-standard model decay schemes. Our search is sensitive to quark masses larger than $23 \text{ GeV}/c^2$; it yields the following lower limits at a 95 % confidence level: $44.5 \text{ GeV}/c^2$ for the top quark mass and $45.2 \text{ GeV}/c^2$ for the b' quark mass.

The standard model with three fermion families includes the top quark as the isodoublet partner of the b quark. While the top quark has not yet been found, its existence is supported by the measured forward-backward charge asymmetry of the b quark in e^+e^- annihilation experiments [1] and by the absence of b quark neutral current decays [2]. The standard model provides no prediction for the fermion masses and does not require the existence of additional fermion families. If a fourth family exists, the b' or "down-quark" member of that family could be lighter than the top quark. In this case the charged current decay $b' \rightarrow cW$ might be inhibited by a small value of the mixing matrix element $V_{cb'}$, and flavour changing neutral current decays, $b' \rightarrow b\gamma$ or $b' \rightarrow bg$, could play a competitive or even dominant role [3]. Furthermore, looking beyond the standard model, one is led to consider an extended scalar sector with several Higgs doublets [4]. If the charged Higgs components of those doublets are not too heavy, the decay of top and b' via the channels $t \rightarrow bH^+$ and $b' \rightarrow cH^-$ would dominate both the standard charged current and the flavour changing neutral current decays.

We describe a search for top and b' in the hadronic decays of the Z^0 resonance. Our aim is to consider all three possibilities: (1) charged current, (2) flavour changing neutral current and (3) decay through a charged Higgs. As a consequence, we have adopted a general technique based on event shape variables. In contrast to the case of the known light quarks, the final states produced by slowly moving heavy quarks are rather spherical. Shape variables such as acoplanarity, thrust, sphericity and many others are thus sensitive measures for the presence of new heavy quarks [5]. The OPAL apparatus with its full geometrical coverage (98% of the solid angle), high granularity and good energy-momentum resolution is well suited for the study of global event shape distributions. Methods based on the detection of high $p_\perp$ leptons from semi-leptonic quark decays have been employed in the past, especially in hadron collider experiments [6] [7], resulting in mass limits for the top quark as high as 77 GeV/ c^2 . These mass limits rely, however, on the standard model assumption for the semi-leptonic decay branching ratios. An analysis based on event shape distributions, well known from previous e^+e^- experiments [8] [9], does not suffer from this restriction, but it must deal with uncertainties inherent to quark fragmentation. These are, however, reasonably well understood for the purpose of the present analysis, as will be discussed below.

The data have been collected with the OPAL detector at the CERN e^+e^- collider LEP. The present analysis is restricted to data collected near the peak of the Z^0 resonance, at a centre of mass energy of 91.26 GeV, corresponding to an integrated luminosity of 72.4 nb $^{-1}$. The main features of the OPAL detector have already been described in detail [10]. Here we shall briefly describe the central tracking chamber, the time-of-flight scintillation counter array and the electromagnetic calorimeter, which are the components of the OPAL facility relevant to the present analysis. The tracking of charged particles relies principally on a cylindrical drift chamber with jet chamber geometry [10], covering an angular range of $|\cos\theta| \leq 0.92$ and positioned inside a magnet solenoid which provides an axial field for momentum measurement. The time-of-flight counter array is a cylinder composed of 160 scintillator bars, which covers an angular range of $|\cos\theta| \leq 0.82$. Particles emerging from the interaction point are recognized by their proper timing with respect to the collision time. The electromagnetic calorimeter consists of a cylindrical array of 9,440 lead glass blocks, 25 radiation lengths in depth, covering the angular range $|\cos\theta| \leq 0.82$, and of two endcap arrays of 2,264 blocks, 20 radiation lengths, covering the angular range $0.81 \leq |\cos\theta| \leq 0.98$.

The total solid angle coverage of the electromagnetic calorimeter is thus 98% of 4π , while its average granularity is approximately 40×40 mrad². For a typical multihadronic Z^0 event about 60% of the total energy is observed in the electromagnetic calorimeter.

The data acquisition system was triggered if one of the following conditions was fulfilled: 1) the energy deposited in the electromagnetic calorimeter exceeded 6 GeV in either the barrel or the endcaps; 2) there was a signal in at least three non-adjacent scintillator slabs in the time-of-flight counter array; 3) specialized trigger logic utilizing the tracking information signaled the presence of at least two charged tracks with transverse momentum greater than 450 MeV/c, pointing in the (r,z) plane towards the collision point. A fast online event analysis using the lead-glass and time-of-flight information permitted the separation of genuine hadronic Z^0 decays from background. The data sample obtained in this manner, on which the present analysis is based, contains 2240 multihadronic decay candidates. The efficiency of our trigger and event selection criteria (97.1 ± 0.6 %) and the residual background from tau pairs, two-photon processes, beam-pipe interactions and cosmic radiation (< 1 %) have been determined by various methods which are described in detail in ref.[11]. The selected multihadronic events were next processed through the full offline event reconstruction, which made use of a precise calibration of the various detector components.

For the event shape analysis, further event selection criteria were applied to the hadronic sample. At least 8 separated deposits of energy ("clusters"), with energy greater than 200 MeV in the barrel part or greater than 500 MeV in the endcap part, were required to be present in the electromagnetic calorimeter. To insure a good containment of the events, the thrust axis calculated from the electromagnetic clusters was required to be within the range $|\cos\theta| \leq 0.96$ and the energy summed over all clusters was required to exceed 10 GeV. These additional selection criteria reduced the data sample to $N_0=2185$ events.

Various distributions which characterize the global properties of events in e^+e^- annihilations have been considered as possible indicators for the presence of a new quark flavour. Our studies have shown that acoplanarity is amongst the most effective of these for this purpose, yielding the most favourable signal to background ratios for quark masses between 25 and 45 GeV/c². Acoplanarity is defined [5] as

$$A = 4 \text{Min}(\sum |P_{i,\perp}| / \sum |P_i|)^2$$

where the sum runs over all final-state particles and $P_{i,\perp}$ is the momentum component of particle i , perpendicular to the plane which minimizes the expression in brackets. Acoplanarity, like other shape variables, exhibits some dependence on quark fragmentation; this has been assessed during our analysis by comparing the predictions of two well known Monte Carlos which model fragmentation, namely JETSET [12] and HERWIG [13], as discussed below.

In the following we examine various distributions as measured by the electromagnetic calorimeter alone and as measured by the jet chamber alone. The possibility to study multihadronic event shapes using these two independent measurements permits us to cross check the consistency of our observations and to convince ourselves that there are no significant systematic biases. The comparison of the measured distributions with the Monte Carlo simulations, with and without a sixth quark, allows us to assess the quality of the simulation and to demonstrate the sensitivity of the variables to the presence of a new heavy quark.

In Fig.1 (a) and (b) and in Fig. 2 (a) we show the acoplanarity, thrust and sphericity distributions, as measured by our electromagnetic calorimeter. The solid histograms are the predictions of the JETSET parton shower Monte Carlo with five quark flavours. The generated events were processed through the simulation of the OPAL detector and were subjected to the same trigger requirements, event selection and analysis procedure as were the data. These considerations apply to all the Monte Carlo distributions which we present in this paper. The signal from a heavy quark anti-quark pair would appear as an enhancement at low values of thrust and at high values of acoplanarity and sphericity; these are indicated by the dashed and dotted histograms for top and for b' , respectively. For these distributions we have chosen a top and b' mass of $35 \text{ GeV}/c^2$, where the sensitivity is large. Also, we have considered standard charged current decays only. The data agree well with the five-quark-flavour Monte Carlo. The good agreement between the data and the Monte Carlo with five flavours leads us to the conclusion that there is no compelling evidence for the production of a new quark flavour in hadronic Z^0 decays. The $p_{T,in}$, $p_{T,out}$ and x_E distributions in Fig. 2 (b), (c) and (d), which depend on the number and energy of individual clusters, also show good agreement between data and simulation. These distributions are not particularly sensitive to the presence of a sixth quark. The definitions of $p_{T,in}$, $p_{T,out}$ and x_E are given in the figure captions.

While the calorimeter is sensitive to electromagnetic energy, the tracking chamber provides a good measurement for charged particles. Of the sample of 2185 events previously defined, 2021 events were collected during a time when the tracking chamber was active. For our examination of event shape variables using charged tracks, we required that at least 5 good tracks be present in the event, each with at least 20 measured space points, a momentum component transverse to the beam direction larger than $150 \text{ MeV}/c$ and a distance of closest approach to the interaction point of less than 5 cm in the (r,ϕ) plane and of less than 30 cm along the beam direction. We further required that the thrust axis determined from the charged tracks lie within the angular range $|\cos\theta| \leq 0.86$ and that the scalar sum of all charged track momenta exceed $10 \text{ GeV}/c$. These requirements reduced the number of events for our charged particle analysis to 1739. The acoplanarity and thrust distributions for this sample are shown in Fig.1, parts (c) and (d). The agreement with the five flavour Monte Carlo simulation is again very good. Thus, from our measurement of the charged component of hadronic Z^0 decays we again conclude that we observe no compelling evidence for the production of new heavy quark flavours.

We emphasize that by performing the above comparisons using our electromagnetic calorimeter by itself, and by repeating those comparisons using only the jet chamber, we obtain two independent measures for the hadronic event shape in our data sample. We are thus confident that the Monte Carlo curves shown in Figs. 1 and 2 are not systematically biased by imperfections in the event simulation or by a misunderstanding of detector performance, to a significant level.

In the following, we derive mass limits for the top and b' quarks. For that purpose we choose to utilize the acoplanarity distribution as measured by the electromagnetic calorimeter. This leads to a simple and straightforward analysis while providing us with a sensitive measure by which to obtain stringent results. Our results rely upon the fidelity of our simulation of the electromagnetic calorimeter, which has been demonstrated above.

We have calculated mass limits separately for the various charged current, flavour changing neutral current and charged Higgs decay modes which we consider. To this end the expected number of events having *acoplanarity* > 0.25 has been determined for both the standard five flavour case (N_5) and for the case where a sixth quark flavour, either top or b' , is present in the mass range between 25 and 45 GeV/c² (N_6). Normalizing to $N_0 = 2185$ which is the number of multihadronic events in our sample, N_5 and $N_6(m)$ are given by

$$N_5 = N_0 \epsilon_5$$

and by

$$N_6(m) = N_0 [(1 - R_6(m)) \epsilon_5 + R_6(m) \epsilon_6(m)].$$

In these expressions, m is the mass of the sixth quark, $R_6(m) = \sigma_6(m)/\sigma_{had}(m)$ is the fraction of hadronic Z^0 decays into the sixth quark, while ϵ_5 and $\epsilon_6(m)$ are the fractions of events satisfying the acoplanarity requirement ($A > 0.25$) for five flavours and for the sixth flavour, respectively.

The branching fraction $R_6(m)$ was calculated using the program ZHADRO [14], for a centre of mass energy of 91.26 GeV, assuming the validity of the standard model adapted to the case of four generations. Standard electroweak corrections were included, as were first order QCD corrections. The following set of parameters was used for these calculations: $m(Z^0) = 91.01$ GeV/c² [11], $m(H^0) = 100$ GeV/c² and $\alpha_s = 0.12$. Furthermore, for the case of b' , the top and t' masses were both fixed to 100 GeV/c². The influence of the low lying heavy quarkonium bound states [15] on the mass limits were not considered. The limits we obtain may therefore be interpreted as conservative bounds. The cross sections and branching ratios which we obtain are listed in Table 1 for various top and b' quark masses. They are subject to a number of systematic errors of which the most important is due to an insufficient knowledge of higher order QCD corrections. The latter has been estimated [16] to be $\pm 30\%$ of the first order correction; this translates into an uncertainty on $R_6(m)$ which varies with the quark mass. In the case of top, for masses of 25, 30, 35, 40, 43 and 44 GeV/c², one obtains $\Delta R_6(m)/R_6(m) = 5, 6, 8, 12, 18$ and 21% , respectively, while in the case of b' the uncertainties are smaller by a factor of approximately 0.6.

To determine the efficiencies ϵ_5 and $\epsilon_6(m)$ for the various quark masses and decay mode hypotheses, we generated Monte Carlo samples using JETSET [12] (modified by us for the flavour changing neutral current decays) and then applied the acoplanarity requirement, $A > 0.25$. The selection efficiencies $\epsilon_6(m)$ so determined are given in Table 2. For the decay into charged Higgs, we have considered Higgs masses between 18 and 41 GeV/c² (note that the experimental lower limit for the charged Higgs mass is 19 GeV/c² [17]). In Table 2 we list the numbers which correspond to a Higgs mass of 23 GeV/c² and we assume that $H^\pm$ decays exclusively into cs quark states. This assumption is model dependent: for instance cb and $\tau\nu$ decays could also be significant. While the inclusion of the cb final state would not alter the efficiencies significantly, the inclusion of the $\tau\nu$ final state would lead to lower efficiencies and to a softening of our mass limits as will be discussed later. All numbers in Table 2 are affected by small uncertainties due to the Monte Carlo statistics (5%) and the trigger and selection criteria (2%) as well as by a significant systematic error due to the uncertainties of quark fragmentation. The latter has been estimated by comparing the acoplanarity distributions predicted by the JETSET and HERWIG Monte Carlos. The HERWIG Monte Carlo produces

more events at high acoplanarity than does JETSET. However, this tendency is present for both light and heavy quark species leading to a calculated signal to background ratio which is fairly model independent. For the efficiencies ϵ_5 and $\epsilon_6(m)$, we use the values predicted by JETSET and assign an uncertainty equal to 50% of the difference between the JETSET and HERWIG results. This is a conservative approach. Were we to use HERWIG values for the efficiencies yet higher mass limits would be obtained.

In Table 3 the expected number N_6 of events having acoplanarity > 0.25 , including top or b' as a sixth quark flavour, is listed for the various decay possibilities. For the Higgs channels we again quote the numbers obtained for a Higgs of mass $23 \text{ GeV}/c^2$ decaying exclusively into cs quark states. The errors were obtained by adding in quadrature the statistical error and the various theoretical and systematic uncertainties which affect the calculation of the cross sections and efficiencies, as discussed above. Mass limits for top and b' were obtained by comparing the numbers in Table 3 to the experimentally observed number of events having acoplanarity > 0.25 , which equals 15 (note that for the five flavour case, JETSET and HERWIG predict 20.5 ± 3.3 and 27.9 ± 4.5 events, respectively).

The extraction of the mass limits is illustrated in Fig. 3(a), where we have considered the case of top and b' decaying via the standard charged current channels. The figure shows the number of events expected as a function of the mass of the sixth quark, after subtraction of the global uncertainty as given in Table 3. The 95% confidence level upper limit [18] for the observed number of events is indicated by the horizontal dashed line. The intersection of this line with the curves delimits the mass range excluded by the present measurement at the 95% confidence level. The Monte Carlo curves in Fig. 3 (a) thus represent a lower limit for the expectations which accounts for theoretical uncertainties, for uncertainties in the fragmentation and for fluctuations in the Monte Carlo statistics. The rise at low mass is due to the larger sensitivity of the acoplanarity distribution to the presence of a new quark as the mass approaches the kinematic limit. The decrease at high mass is due to the production threshold factor which affects top and b' differently. The steepness of the decrease at high mass makes our mass limits insensitive to the manner in which we treat the theoretical uncertainties and to the particular choice of our acoplanarity cut. This same procedure was used to extract mass limits for the flavour changing neutral current and charged Higgs decays, as illustrated in Figs. 3 (b), (c) and (d). The mass limits we obtain for top and b' , assuming 100% decay into the channels we consider, are given in Table 4. For the flavour changing neutral current decays of b' into $b\gamma$ and bg we have used several values for the decay branching ratio $BR = \Gamma(b\gamma)/[\Gamma(bg) + \Gamma(b\gamma)]$, which are also listed. For the decays into charged Higgs, the inclusion of the $H \rightarrow \tau\nu$ final state, with a branching ratio of 50 % (100 %) was found to reduce the upper limit of the excluded mass range by 0.4 (0.9) GeV/c^2 .

In summary, we have described a search for top and for b' in the hadronic decays of the Z^0 , based on the analysis of event shape distributions in e^+e^- annihilations. The good agreement between the measured distributions and those of the five flavour Monte Carlo demonstrates that there is no compelling evidence in our data for the presence of a new heavy quark. The consistency of our measurement with the expectations for five quark flavours has been demonstrated for distributions as measured by two independent detectors of the OPAL facility. Mass limits have been derived using the acoplanarity distribution measured by the electromagnetic calorimeter. Our search is sensitive to new quarks with masses larger than 23

GeV/c² and is sufficiently general to include the possibilities of various standard model and non-standard model decay channels such as charged current decays, flavour changing neutral current decays of the b' quark and decays of the top and b' quarks into charged Higgs particles. For the top quark, the least stringent mass limit is obtained if one assumes standard charged current decays. For the b' quark, the least stringent mass limit is obtained if $b\gamma$ is the only final state (BR=1); however, this assumption is highly improbable given that the expected branching ratio for $b' \rightarrow b\gamma$ is only about 0.2 [3]. Extracting the mass limits from Table 4, and taking into account previous e^+e^- experiments [8] at lower energies which have excluded the low mass range not covered by the present search, we conclude at the 95% confidence level that the top quark is heavier 44.5 GeV/c² and that the b' quark, if it exists, is heavier than 45.2 GeV/c².

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References

- [1] See e.g. B. Naroska, Phys. Rep. 148 (1987) 68.
- [2] A. Bean et al., Phys. Rev. D35 (1987) 3533.
- [3] V. Barger, R.J.N. Phillips and A. Soni, Phys. Rev. Lett. 57 (1986) 1516, W.S. Hou and R.G. Stuart, Nucl. Phys. B320 (1989) 227, W.S. Hou and R.G. Stuart, Phys. Rev. Lett. 62 (1989) 617.
- [4] S.L. Glashow and S. Weinberg, Phys. Rev. D15 (1977) 1958, H.E. Haber, G.L. Kane and T. Sterling, Nucl. Phys. B161 (1979) 493.
- [5] A. De Rujula, J. Ellis, E.G. Floratos and M.K. Gaillard, Nucl. Phys. B138 (1978) 387.
- [6] UA1 collaboration, C. Albajar et al., Z. Phys. C37 (1988) 505. The results quoted in this reference have been analysed and updated by G. Altarelli et al., Nucl. Phys. B308 (1988) 724.
- [7] UA2 collaboration, T. Akesson et al., to be published in Z. Phys. C. CDF collaboration, F. Abe et al., UPR-0172 E (1989).
- [8] TOPAZ collaboration, I. Adachi et al., Phys. Lett. B229 (1989) 427. AMY collaboration, S. Eno et al., Phys. Rev. Lett. 63 (1989) 1910. AMY collaboration, S. Eno et al., KEK report No. 88-47 (1988), to be published. VENUS collaboration, K. Abe et al., Phys. Rev. D39 (1989) 3524. AMY collaboration, T. Mori et al., KEK report 88-43 (1988), to be published. TOPAZ collaboration, I. Adachi et al., Phys. Rev. Lett. 60 (1988) 97. For earlier e^+e^- experiments, see e.g. references quoted in [1].
- [9] MARK II collaboration, G. S. Abrams et al., SLAC-PUB 5106 (1989), to be published.
- [10] The OPAL Detector, to be published. See also: The OPAL Detector Technical Proposal, CERN/LEPC/83-4 (1983).
- [11] Measurement of the Z^0 Mass and Width with the OPAL Detector at LEP, M.Z. Akrawy et al., Phys. Lett. B231 (1989) 530.
- [12] T. Sjostrand, Comp. Phys. Comm. 39 (1986) 347; JETSET, Version 7.1. We used the parameter values given in Braunschweig et al., Z. Phys. C41 (1988) 375.
- [13] G. Marchesini and B.R. Webber, Nucl. Phys. B310 (1988) 461; HERWIG, Version 3.2. The HERWIG parameters have been adjusted by us to describe the data of A. Petersen et al., Phys. Rev. D37 (1988) 1.
- [14] G. Burgers, Shape and size of the Z resonance, in Polarization at LEP, CERN 88-06, edited by G. Alexander, G. Altarelli, A. Blondell, G. Coignet, E. Keil, D.E. Plane and D. Treille (1988).
- [15] J.H. Kühn and P.M. Zerwas, Phys. Rep. 167 (1988) 321.
- [16] J.H. Kühn, A. Reiter and P.M. Zerwas, Nucl. Phys. B272 (1986) 560.

- [17] "The Higgs Hunter's Guide", J. F. Gunion, H. E. Haber, G. L. Kane and S. Dawson, BNL-41644 (1989), submitted to Phys. Rep.
- [18] Review of Particle Properties, Phys. Lett. B204 (1988) 74.

Mass [GeV/c ²]		25	30	35	40	43	44
<i>top</i>	$\sigma_{had.}[nb]$	29.15	29.35	29.57	29.80	29.93	29.97
	$\sigma_6[nb]$	3.10	2.56	1.91	1.17	0.701	0.543
	$R_6[\%]$	10.6	8.7	6.5	3.9	2.3	1.8
<i>b'</i>	$\sigma_{had.}[nb]$	28.73	28.94	29.20	29.51	29.73	29.81
	$\sigma_6[nb]$	4.13	3.65	3.03	2.26	1.68	1.43
	$R_6[\%]$	14.4	12.6	10.4	7.7	5.7	4.8

Table 1: The six flavour hadronic cross-section and branching ratio for various top and *b'* quark masses calculated for a centre of mass energy of 91.26 GeV. The five-flavour hadronic cross-section obtained with the same parameter values is 30.24 nb.

Mass [GeV/c ²]	25	30	35	40	43	44
$t \rightarrow bW^*$	9.2	21.9	32.3	41.2	40.9	41.0
$t \rightarrow bH^+$	-	31.2	56.3	68.7	70.1	64.0
$b' \rightarrow cW^*$	7.6	18.0	28.3	40.4	35.0	34.9
$b' \rightarrow cH^-$	4.0	23.8	47.0	66.1	61.2	55.8
$b' \rightarrow bg$	9.4	22.8	40.2	52.3	52.7	45.1
$b' \rightarrow b\gamma$	5.3	11.9	13.3	8.4	1.0	1.0

Table 2: The fraction ϵ_6 , expressed in per cent, of events satisfying the acoplanarity requirement $\Lambda > 0.25$ for various top and *b'* quark masses and decay modes. For the decays into charged Higgs, we list the numbers which correspond to a Higgs of mass 23 GeV/c² decaying exclusively into *cs* quark states. For five flavours, we obtain the number $\epsilon_5 = 0.94 \pm 0.15\%$, using the same simulation.

Mass [GeV/c ²]	25	30	35	40	43	44
$t \rightarrow bW^*$	39.7 $\pm$ 5.5	60.4 $\pm$ 8.9	65.1 $\pm$ 9.9	54.9 $\pm$ 8.5	40.6 $\pm$ 6.3	36.3 $\pm$ 5.6
$t \rightarrow bH^+$	-	78.1 $\pm$ 12.3	99.2 $\pm$ 16.6	78.3 $\pm$ 13.6	55.3 $\pm$ 9.1	45.3 $\pm$ 7.8
$b' \rightarrow cW^*$	41.5 $\pm$ 5.7	67.5 $\pm$ 10.3	82.7 $\pm$ 13.1	86.9 $\pm$ 14.1	63.0 $\pm$ 10.0	55.2 $\pm$ 9.0
$b' \rightarrow cH^-$	30.2 $\pm$ 5.0	83.5 $\pm$ 13.2	125.2 $\pm$ 21.2	130.2 $\pm$ 22.4	95.6 $\pm$ 16.6	78.1 $\pm$ 13.7
$b' \rightarrow bg$	47.2 $\pm$ 6.7	80.7 $\pm$ 12.7	109.8 $\pm$ 18.3	107.0 $\pm$ 17.9	85.0 $\pm$ 14.5	66.9 $\pm$ 11.3
$b' \rightarrow b\gamma$	34.3 $\pm$ 4.7	50.7 $\pm$ 7.2	48.6 $\pm$ 6.9	33.1 $\pm$ 4.3	20.6 $\pm$ 3.3	20.6 $\pm$ 3.3

Table 3: The expected number of events $N_6 \pm \delta_{N_6}$ for various top and *b'* masses and decay modes. For the decays into charged Higgs, we list the numbers which correspond to a Higgs of mass 23 GeV/c² decaying exclusively into *cs* quark states. The number of events expected for the five-flavour case is 20.5 ± 3.3 .

Decay channel		Excluded mass range [GeV/c^2]
$t \rightarrow bW^*$		23.4 - 44.5
$b' \rightarrow cW^*$		23.2 - 45.2
$b' \rightarrow bg$	BR=0.00	22.5 - 45.4
	BR=0.25	22.9 - 45.2
	BR=0.50	23.6 - 44.5
	BR=1.00	23.6 - 41.4
$t \rightarrow bH^+$	$m_{H^+} = 23$	28.2 - 45.2
	$m_{H^+} = 28$	33.2 - 45.2
	$m_{H^+} = 33$	38.2 - 45.2
	$m_{H^+} = 38$	43.2 - 45.2
$b' \rightarrow cH^-$	$m_{H^-} = 26$	27.5 - 45.5
	$m_{H^-} = 31$	32.5 - 45.5
	$m_{H^-} = 36$	37.5 - 45.5
	$m_{H^-} = 41$	42.5 - 45.5

Table 4: Mass limits obtained for the top and the b' quarks for the decay modes we consider. For the flavour changing neutral current decays of b' , the limits have been calculated for different values of the branching ratio $BR=\Gamma(b\gamma)/[\Gamma(bg) + \Gamma(b\gamma)]$. For the channels with charged Higgs, various Higgs masses have been considered and it was assumed that the Higgs particle decays exclusively into cs quark states. We have used 5.0 and 1.35 GeV/c^2 for the b and c quark masses, respectively.

Figure Captions

FIGURE 1: Acoplanarity and thrust as measured by the electromagnetic calorimeter [(a) and (b)] and by the jet chamber [(c) and (d)]. The comparison of the data and the five flavour Monte Carlo (solid histogram) yields the following χ^2 values: (a) $\chi^2 = 17.7$ (24 bins), (b) $\chi^2 = 14.9$ (19 bins), (c) $\chi^2 = 14.0$ (23 bins) and (d) $\chi^2 = 8.3$ (17 bins). The dashed and dotted histograms represent the expectations including a sixth quark, either top or b' , with a mass of 35 GeV/c^2 . There are approximately 5000 events in the Monte Carlo samples.

FIGURE 2: The (a) sphericity, (b) $p_{T,in}$, (c) $p_{T,out}$ and (d) x_E distributions as measured by the electromagnetic calorimeter. The variables $p_{T,in}$ and $p_{T,out}$ are the absolute values of the momentum components of the particles, in and out of the event plane, defined by the two sphericity eigenvectors associated with the two largest eigenvalues; x_E is the energy of a cluster measured in the electromagnetic calorimeter, divided by the beam energy. The solid histograms represent the five flavour Monte Carlo prediction.

FIGURE 3: The expected number of events with $acoplanarity > 0.25$ (N_6), minus its uncertainty (δ_{N_6}), as a function of the top or b' quark mass, for the various decay modes we consider: (a) standard charged current top and b' decays, (b) flavour changing neutral current decays of the b' quark, (c) the $t \rightarrow bH^+$ decay and (d) the $b' \rightarrow cH^-$ decay. The experimental number of events and its 1σ statistical error (hatched area) are also shown. The

horizontal dashed line represents the 95 % confidence level upper limit for the measurement; its intersection with the full curves delimits the quark mass interval which we exclude.

Fig. 1. Dependence of the quark mass ratio m_s/m_c on the parameter $\alpha_s(M_Z)$. The solid curves are the theoretical predictions for the quark mass ratio m_s/m_c and m_s/m_c^2 calculated in the $\overline{MS}$ scheme. The horizontal dashed line represents the 95 % confidence level upper limit for the measurement. The intersection of the dashed line with the curves defines the excluded interval for the quark mass ratio m_s/m_c .

The solid curves represent the theoretical predictions for the quark mass ratio m_s/m_c and m_s/m_c^2 calculated in the $\overline{MS}$ scheme. The horizontal dashed line represents the 95 % confidence level upper limit for the measurement. The intersection of the dashed line with the curves defines the excluded interval for the quark mass ratio m_s/m_c .

For the quark mass ratio m_s/m_c the excluded interval is $m_s/m_c < 0.08$. For the quark mass ratio m_s/m_c^2 the excluded interval is $m_s/m_c^2 < 0.08$.

The quark mass ratio m_s/m_c is a function of the parameter $\alpha_s(M_Z)$. The quark mass ratio m_s/m_c is a function of the parameter $\alpha_s(M_Z)$.

Figure 1

Figure 2

Figure 3