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Search for the t and b′ Quarks in Hadronic Decays of the Z^0 Boson

DELPHI Collaboration

Abstract

We present a search for the third generation up type quark *t* and a possible fourth down type quark *b′* in hadronic Z^0 decays observed in DELPHI at the LEP collider. For any scenario with a decay through the charged current or into a charged Higgs with a mass at least 6 GeV/c^2 below the *t* and 3 GeV/c^2 below the *b′* mass, we set a lower limit for the *t* quark mass at 44.0 GeV/c^2 and for the *b′* mass at 44.5 GeV/c^2. For specific scenarios the mass limits are slightly higher, eg. for charged current decays the limits are 44.5 and 45.0 GeV/c^2 respectively, where all limits are given at a 95% confidence level.

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Hadronic events are selected by requiring that

- the total energy of charged particles seen in the event E_{ch} exceeds 10 GeV,
- there are at least 5 charged particles with momenta above 0.2 GeV/c,
- the polar angle θ of the sphericity axis is in the range $40^0 \leq \theta \leq 140^0$.

After these cuts, 2175 hadronic events remain with negligible contamination of $\tau^+\tau^-$, beam gas or $\gamma\gamma$ events.

4. Search strategy

Several decay schemes of the new quarks can be envisaged. We search for charged current decays as given within the Standard Model, $t \rightarrow bW^*, b' \rightarrow cW^*$, which will produce aplanar, spherical multijet events with usually 6 jets or 4 jets together with a fast lepton. But our main aim is to search for decays to a charged Higgs: $t \rightarrow bH^+, b' \rightarrow cH^-$. Only a small extension of the minimal Standard Model is necessary to allow for such decay modes: the introduction of two instead of one Higgs doublets, which both develop vacuum expectation values v_1 and v_2 [4]. As already mentioned, this decay mode would provide a possible scenario in which the t or b' is undiscovered at hadron colliders but light enough to be discovered at LEP [5] [10]. Here the decay mode and the mass of the charged Higgs particle would strongly influence the event shape. Assuming Yukawa couplings and the standard Kobayashi–Maskawa quark mixing, one can estimate that 95% of the charged Higgs scalars H^+ will decay into the $c\bar{s}$ or $\tau^+\nu_\tau$ channel, leaving 5% for other hadronic decay channels like $c\bar{b}$, $c\bar{d}$ [4]. The ratio v_1/v_2 of the vacuum expectation values of the Higgs fields governs the decay modes of the charged Higgs. If this ratio is close to zero, the Higgs decays hadronically, while for a ratio greater than unity the τ decay will dominate. We can therefore subdivide the possible events into 3 classes:

- $e^+e^- \rightarrow \bar{t}t \rightarrow H^+H^-b\bar{b} \rightarrow q_i\overline{\bar{q}_j q_k}q_l b\bar{b}$ (class 6q)
- $e^+e^- \rightarrow \bar{t}t \rightarrow H^+H^-b\bar{b} \rightarrow q_i\bar{q}_j\tau^-\bar{\nu}_\tau b\bar{b}$ (class 4q)
- $e^+e^- \rightarrow \bar{t}t \rightarrow H^+H^-b\bar{b} \rightarrow \tau^-\bar{\nu}_\tau\tau^+\nu_\tau b\bar{b}$ (class 2q)

- $e^+e^- \rightarrow b'\overline{b'} \rightarrow H^+H^-c\bar{c} \rightarrow q_i\overline{\bar{q}_j q_k}q_l c\bar{c}$ (class 6q)
- $e^+e^- \rightarrow b'\overline{b'} \rightarrow H^+H^-c\bar{c} \rightarrow q_i\bar{q}_j\tau^-\bar{\nu}_\tau c\bar{c}$ (class 4q)
- $e^+e^- \rightarrow b'\overline{b'} \rightarrow H^+H^-c\bar{c} \rightarrow \tau^+\nu_\tau\tau^-\bar{\nu}_\tau c\bar{c}$ (class 2q)

The event shape distributions of events with hadronically decaying Higgs particles would be similar to those of charged current decays of the t or b'. One expects again aplanar spherical multijet events. Due to the large missing energy carried away by the neutrinos, event shapes are different in the case of τ decays of the Higgs. For these decay modes, selecting aplanar events does not provide good discrimination. Instead one may look for an isolated particle coming from the τ decay. Even if the Higgs decays hadronically, selecting aplanar events is inefficient if the t and b' mass and the Higgs mass are near their maximum kinematically accessible values, because the events then appear like planar 4–jet events.

In this search for new heavy quarks we follow the usual strategy of using event shape variables. Several variables may be used for such a search. We have found that the event shape variables thrust, minor

1. Introduction

During the last few years several experiments have reported on searches for new heavy quarks. No direct evidence has been found so far for their existence. The searches at $p\bar{p}$ colliders have relied on the charged current decays of the third generation up type quark t and a fourth down type quark b' [1] [2] [3]. Those searches exclude a t and b' that can be pair produced at LEP I by the process $e^+e^-\rightarrow t\bar{t}$ or $e^+e^-\rightarrow b'\bar{b}'$ and subsequently decays through the charged current as given in the minimal Standard Model. However small extensions of the Higgs sector of this model would lead to the existence of charged Higgs scalars and result in t or b' decays being dominated by the modes $t\rightarrow bH^+$ or $b'\rightarrow cH^-$ if they are kinematically accessible [4] [5]. The $p\bar{p}$ collider mass limits become much weaker in that case.

We have made a search for heavy quarks with a special emphasis on their charged Higgs decay modes, putting almost no constraints on the decay modes of the charged Higgs. In particular we want to allow for leptonic decays of the charged Higgs $H^+\rightarrow\tau^+\nu_\tau$; in these decays a large fraction of the total energy in the event is carried away by neutrinos. Our measurement of the hadronic width of the Z^0 [6] and our lower limit on the charged Higgs boson mass [7] constrain the possible scenarios to masses of the t or b' quark above 33 GeV/c^2 and of the charged Higgs above 30 GeV/c^2. Therefore we will focus on that mass range.

2. The DELPHI detector

A detailed description of the DELPHI detector has been given elsewhere [8]. The detector components used are identical to those used in our study of hadronic events [9]. The essential components for this study are:

- the time projection chamber TPC, used for measuring charged particles. Up to 16 space points are used for reconstructing tracks with a momentum resolution of $\delta p/p^2 = 0.02\,(GeV/c)^{-1}$ in a field of 0.7 T,
- the inner detector (ID), a jet chamber providing 24 $r\phi$ coordinates, and the outer tracking detector (OD), both used for a track trigger in the barrel region with polar angle $40^0 \leq \theta \leq 140^0$,
- the electromagnetic calorimeter (HPC) with its scintillation counters and the time of flight (TOF) scintillator system covering an angular region of $40^0 \leq \theta \leq 140^0$ used for the trigger.

3. Event sample

The analysis uses the events accumulated in late 1989 on the peak of the Z^0 resonance at 91.0−91.5 GeV which were used for our previous study of hadronic events [9]. Only charged particle tracks are used. These tracks are retained only if:

- they extrapolate back to within 5 cm of the beam axis in the radial distance r and to within 10 cm of the nominal crossing point along the beam direction,
- their momentum p is larger than 0.1 GeV/c,
- their measured track length is above 50 cm,
- their polar angle is between 25^0 and 155^0.

and major which are linear in the momenta provide a better signal to noise ratio than the variables coming from the momentum tensor such as sphericity or aplanarity. We will therefore use:

- the thrust $T = \Sigma|p_{\parallel i}| \,/\, \Sigma|p_i|$, where $p_\parallel$ refers to the momentum component along the axis for which the value of T is maximal, called the thrust axis;
- the major $M = \Sigma|p_{\parallel i}| \,/\, \Sigma|p_i|$, a thrust-like parameter where $p_\parallel$ refers to the momentum component along the axis perpendicular to the thrust axis that gives the largest value of M, called the major axis;
- the similarly defined minor value m where $p_\parallel$ refers to the momentum component along the so-called minor axis which is perpendicular both to the thrust axis and to the major axis.

To account for the different decay possibilities, we search for the new heavy quarks applying three sets of cuts.

Selection 1 is tuned to search for aplanar multijet events. For the hadronic events selected before, we require:

- the minor m to be ≥ 0.2
- the thrust T to be ≤ 0.9
- the total energy of charged particles seen in the event E_{ch} to be ≥ 30 GeV

The energy cut improves the signal to noise ratio in the events we are seeking, but does not significantly affect the mass limits obtained.

Selection 2 is equally efficient for all t and b' decays including planar events and events containing $H^+ \rightarrow \tau^+ \nu_\tau$ but over much of the parameter space the signal to noise ratio is worse than in Selection 1. We require:

- the major M to be ≥ 0.35
- the thrust T to be ≤ 0.85

Selection 3 is efficient for events with at least one charged Higgs decaying into $\tau\nu_\tau$. Here we will look for isolated particles coming from the τ decays. The separation angle is defined as $\theta_{sep} = Max_i(Min_j(\theta_{ij}))$, where θ_{ij} are the angles between a particle i with momentum higher than p_{sep} and any other particle j. We require in this selection:

- the separation angle θ_{sep} to be $\geq 35^0$
- the momentum of the isolated particle p_{sep} to be ≥ 4 GeV/c
- the thrust T to be ≤ 0.85
- the total energy of charged particles seen in the event E_{ch} to be ≤ 30 GeV.

Note that because of the energy cuts Selection 1 and 3 will lead to independent event samples.

Assuming the existence of a new heavy quark, the number of events within our selected sample is given by:

$$N_{had} = \varepsilon_5 N_5 + \varepsilon_6 N_6 \,, \qquad N^{sel} = \frac{\varepsilon_5^{\;sel} + \varepsilon_6^{\;sel} R(m)}{\varepsilon_5 + \varepsilon_6 R(m)} \, N_{had}$$

with

N_{had} the number of hadronic events in our hadronic selection,
N_5 the number of hadronic events of type u,d,s,c,b produced,
ε_5 the efficiency of those u,d,s,c,b events to be in our sample,
N_6 the number of t and b' events produced,
ε_6 the efficiency of those t,b' events to be in our sample,
$R(m) = N_6/N_5$, with m being the t,b' mass,
$N^{sel},\varepsilon_5{}^{sel},\varepsilon_6{}^{sel}$ the expected number of events and the efficiencies inside the search selections.

We have calculated all efficiencies by generating events with our full detector Monte Carlo and then analyzing them with the same programs as we used for analyzing the data. For the 5−flavour background Monte Carlo we have used the Lund 6.3 parton shower Monte Carlo [11], which was found to model our data very well [9]. In the case of the t and b', Monte Carlo samples were generated for different t and b' masses and different charged Higgs masses and decay modes.

Figure 1 shows some of the event shape distributions which were used for the search, before the signal to noise was improved by the cuts on the other variables. The expected distributions assuming the existence of a t or b' with a mass of 40 GeV/c^2 are compared with the LUND 5−flavour Monte Carlo and the data. Figure 2 shows the momentum distribution of isolated tracks after all cuts of Selection 3 except the momentum cut on the isolated particle for the same Monte Carlo samples as used for Figure 1.

The computed efficiencies $\varepsilon_6{}^{sel}$ for detecting t or b' quark events after application of the selections 1,2 and 3 described above, are given in Table 1 for selected mass values for t, b' and the charged Higgs. We want to stress that the main contribution to a drop in efficiency for higher masses comes from a high Higgs mass and not from a high quark mass. Thus the attainable limits are strongly constrained by the mass of the charged Higgs.

In the case of the charged Higgs decay scenario we compute the expected number of events in our search selections using the Higgs branching ratio dependence as given in [4]. As already mentioned, the hadronic decay modes should be strongly dominated by the $c\bar{s}$ channel, which we therefore use as a representative for all the $q_i\bar{q}_j$ decays of the Higgs. This introduces negligible systematic uncertainties for the distributions used.

The computation of the expected number of events within our selected sample is subject to a statistical uncertainty and to a number of systematic errors. Detector and fragmentation effects have to be considered. In addition, the estimation of $R(m) = N_6/N_5$ has some theoretical uncertainties.

To compute $R(m)$ we follow a conservative approach taking into account normal threshold behaviour corrected for electroweak and QCD effects to first order, but not accounting for any resonance structure which should increase $R(m)$ [10]. The $R(m)$ values used are shown in Table 2. They have been evaluated with the program ZHADRO [12] and found to be consistent with results presented in [13]. The uncertainty in the estimation of $R(m)$ is due to the lack of knowledge of higher order QCD corrections and the uncertainty of α_S used in the calculations. Assuming an error in the order of 30% on these corrections we assign an error $\delta R(m)/R(m)$ in the range of 8% to 21% for t or b' masses from 35 to 44 GeV/c^2.

We estimate the uncertainty in the calculated background after our search selections, by comparing the results from different models; the Lund parton shower model, the Marchesini−Webber Monte Carlo and two QCD second order matrix element Monte Carlos with Lund string fragmentation, which had been tuned at low energy as we have discussed elsewhere [9]. This comparison shows a strong difference in the uncertainty for different variables. The thrust and major distributions differ much less between the models than the minor distribution. We thus assign different errors due to fragmentation model uncertainties to the different selections. In Selection 1 we assign 15% to this systematic uncertainty, while an uncertainty of 7% is used in Selections 2 and 3.

For background estimation, we do not consider the two matrix element models as they clearly need retuning to describe our data, as was best seen in the rapidity distribution [9]. This leaves the Lund parton shower model and the Webber Monte Carlo. The latter predicts higher backgrounds and therefore leads to stronger mass limits. To be conservative, we use the LUND Monte Carlo predictions. These are shown in Table 3 together with the numbers of real events in the three search selections.

5. Results

In Figure 3 the data are compared with the expected numbers of events in the three selections arising from a t quark of 44 GeV/c^2 decaying through charged currents or into a charged Higgs of 35 GeV/c^2 and from a b' quark of 43 GeV/c^2 decaying through charged currents or into a charged Higgs of 37 GeV/c^2, as a function of v_1/v_2. The 95% CL shown is to be compared to the prediction of decays into the charged Higgs. The expected number of charged current decay events in our selections can be compared to the 95% CL given at $v_1/v_2 = 0$. The intersection of the line showing the estimated number of events and the 95% CL delimits the v_1/v_2 range we can exclude with a given selection. One can clearly see the complementary information given by the 3 selections. For the computation of the confidence level we use the method proposed by the particle data group [15] to account for the background. The uncertainties in the background, the fragmentation, the efficiencies and in $R(m)$ are taken into account by averaging over them. For this reason the 95% CL shows a dependence on the number of expected events, thus a dependence on v_1/v_2. The 95% CL limits we obtain in the different decay scenarios are listed in Table 4.

The limits for the charged current decays of the t and b' are determined using Selection 1: the lower limit is 44.5 GeV/c^2 for the top mass and 45.0 GeV/c^2 for the mass of the fourth down type quark b'.

In the case of the decay of the heavy quarks through the charged Higgs we use either Selection 2 or Selection 1 and 3 combined. If we suppose that the Higgs mass is at least 6 GeV/c^2 below the t mass and 3 GeV/c^2 below the b' mass we get for any scenario with a decay through the charged Higgs and/or charged currents a lower limit for the t quark mass at 44.0 GeV/c^2 and for the b' mass at 44.5 GeV/c^2. Because of the complementary information in the three selections, the final limits don't depend any more on the branching ratio dependence of the Higgs decay channels on v_1/v_2, which was used in the computation of the different expected signals.

6. Discussion

Comparable limits on the t and b' masses from the analysis of Z^0 decays have been obtained recently [16] [17] [18]. Reference [17] does not refer to the charged Higgs decay. Reference [16] has looked for various channels but was statistics limited. The limits in reference [18] refer also to the possible decays into charged Higgs particles. They are based on a cut in the acoplanarity variable, which is closely related to the minor value which we use (together with thrust and energy) in Selection 1. They use similar statistics but appear slightly tighter in some channels than the limits we quote because we have calculated our limits using a more conservative method that takes account of the physical boundary conditions.

We have not treated here the possibility of b' decaying through flavour changing neutral currents $b' \rightarrow bg$ or $b' \rightarrow b\gamma$. However our previous measurement [6] of the total hadronic width $\Gamma_{Had} = 1741 \pm 61$ MeV may be compared with the Standard Model prediction of $\Gamma_{Had} = 1735 \pm 25$ MeV for 5 quarks to exclude a b' of mass below 40.5 GeV/c^2 at a 95% CL decaying in such modes. The same argument excludes a t mass below 33.5 GeV/c^2. In both cases we use the same expected branching ratio R(m) $\pm\delta$R(m) and the same method for setting a limit in a physical bound region as in our direct search. The limits hold for all channels with a detection efficiency comparable to that of standard 5−flavour hadronic events, like the flavour changing neutral current decays, but are slightly lower for decays like the Higgs decay with the Higgs decaying in the τ channel.

7. Summary

We have searched for new heavy quarks produced at the e^+e^- collider LEP. The lower mass limit in the charged current decay channel is found to be 44.5 GeV/c^2 for the top quark and 45.0 GeV/c^2 for the fourth down type quark. Allowing for any combination of charged current decays of a t or b' quark and a decay into a charged Higgs, we set a lower mass limit of 44.0 GeV/c^2 for the t and of 44.5 GeV/c^2 for the b', where we require for the Higgs mass that $m_t - m_H \geq 6$ GeV/c^2 and $m_{b'} - m_H \geq 3$ GeV/c^2. The limits for specific decay channels are slightly better, as can be seen in Table 4.

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Table 1: Efficiencies of the different top and b′ decay channels.

Channel	t,b' mass [GeV/c^2]	H mass [GeV/c^2]	Selection 1 [%]	Selection 2 [%]	Selection 3 [%]
t - bW	35	-	33	58	2.9
t - bW	40	-	42	65	1.7
t - bW	43	-	40	65	2.4
t class 6q	35	20	46	68	0
t class 6q	40	33	40	67	1.3
t class 6q	43	37	34	61	.4
t class 6q	44	35	41	62	.3
t class 4q	35	20	30	62	2.4
t class 4q	40	33	20	58	6.4
t class 4q	43	37	13	39	2.1
t class 4q	44	35	21	51	4.8
t class 2q	35	20	6	50	12
t class 2q	40	33	1.5	45	14
t class 2q	43	37	0.5	40	13
t class 2q	44	35	3.2	55	21
b' - cW	35	-	29	61	4.6
b' - cW	40	-	35	64	2.1
b' - cW	43	-	29	52	2.7
b' class 6q	35	20	54	72	.4
b' class 6q	40	33	34	70	0
b' class 6q	43	37	25	53	.4
b' class 6q	44	41	11	37	.3
b' class 4q	35	20	25	63	4.6
b' class 4q	40	33	14	57	6
b' class 4q	43	37	12	45	4.5
b' class 4q	44	41	1.9	27	4
b' class 2q	35	20	7	47	11
b' class 2q	40	33	3	39	15
b' class 2q	43	37	1	42	19
b' class 2q	44	41	0	19	9.2

Table 2: R(m) for t and b′

This table shows the ratio $R(m) = N_6/N_5$ for various top and b′ masses as obtained for a centre of mass energy of 91.25 GeV. The following values were used in the computation: α_S = 0.12, m_{H^0} = 50 GeV/c^2, m_Z = 91.15 GeV/c^2 and m_{top} = 100 GeV/c^2 for the b' scenario.

Mass [GeV/c^2]	30.	35.	40.	42.	43.	44.
top R(m)	8.7%	6.5%	4.0%	2.9%	2.4%	1.87%
b' R(m)	12.6%	10.4%	7.6%	6.3%	5.6%	4.8%

Table 3: Events in our selections.

For the Lund Monte Carlo the error given is the statistic error and the systematic error due to fragmentation added in quadrature.

Event set	Selection 1	Selection 2	Selection 3
Data	48	175	2
5-flavour Lund MC	59±10	212±16	2±0.5

Table 4: Mass limits in the different decay schemes at 95% CL.

Selection 1 looks for aplanar events, Selection 2 uses thrust and major and Selection 3 uses the isolated particle criterion.

Channel	Higgs decay	Higgs mass [GeV/c^2]	Search selection	Excluded range [GeV/c^2]
$t \to bW^+$	–	–	1	≤ 44.5
$t \to bH^+$	hadronic	≤ m(t)-6	1,2	≤ 44.0
$t \to bH^+$	τ	≤ m(t)-6	3	≤ 44.0
$t \to bH^+$	any	≤ m(t)-6	1,2,3	≤ 44.0
$b' \to cW^-$	–	–	1	≤ 45.0
$b' \to cH^-$	hadronic	≤ m(b')-3	1,2	≤ 44.5
$b' \to cH^-$	τ	≤ m(b')-3	3	≤ 45.0
$b' \to cH^-$	any	≤ m(b')-3	1,2,3	≤ 44.5

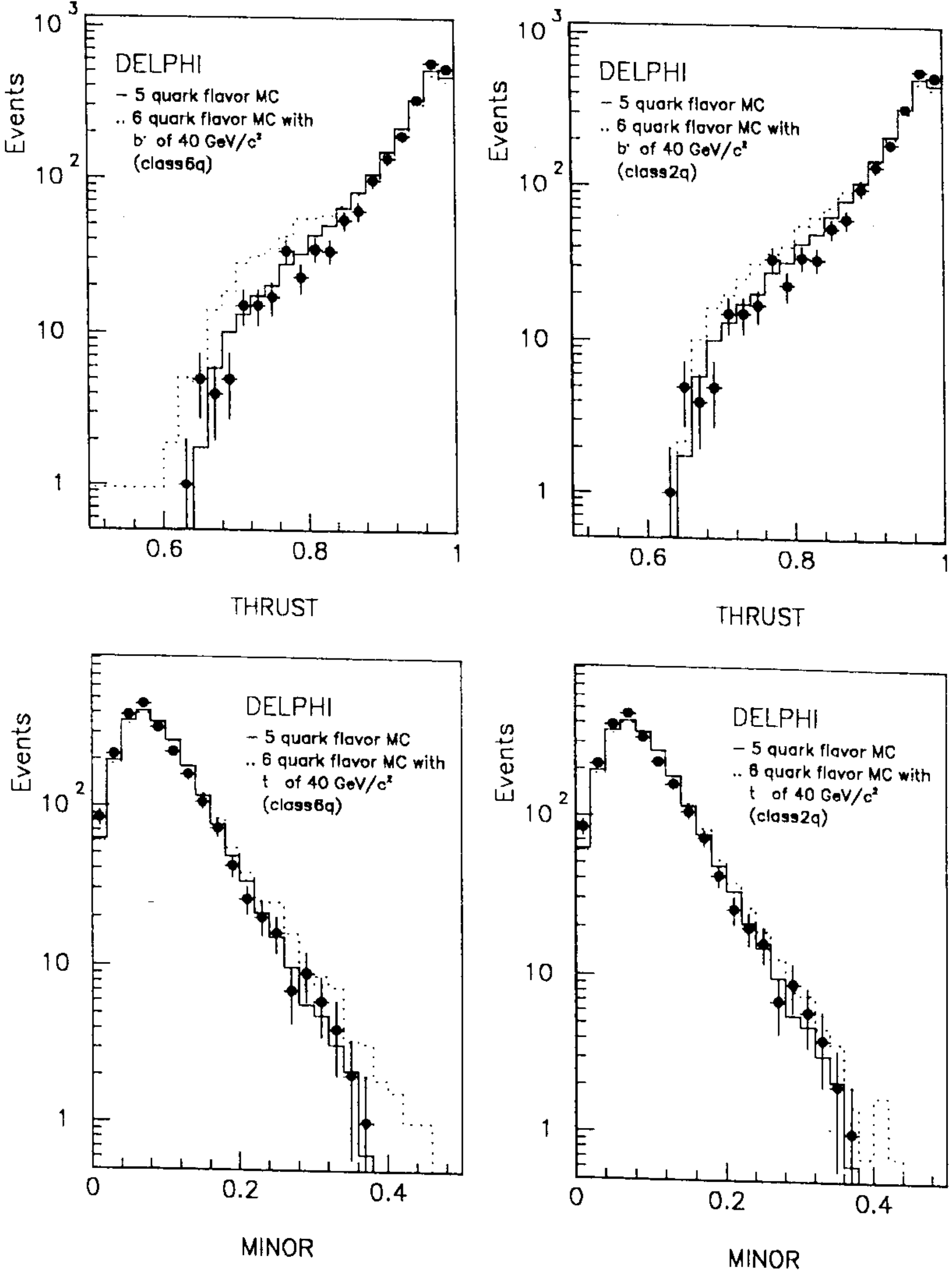

Figure 1: Thrust and minor distributions as expected for 5 quark flavours (full line) are compared to the 6 quark flavour distributions as expected for a b′ (upper thrust plots) and a top (lower minor plots) of 40 GeV/c^2 mass decaying into a charged Higgs with a mass of 33 GeV/c^2. The distributions are normalized to the 2175 hadronic events we find in our data (points). On the left side we assume that both Higgs particles decay hadronically (class 6q), while on the right side both Higgs particles in the event decay through the τ channel (class 2q).

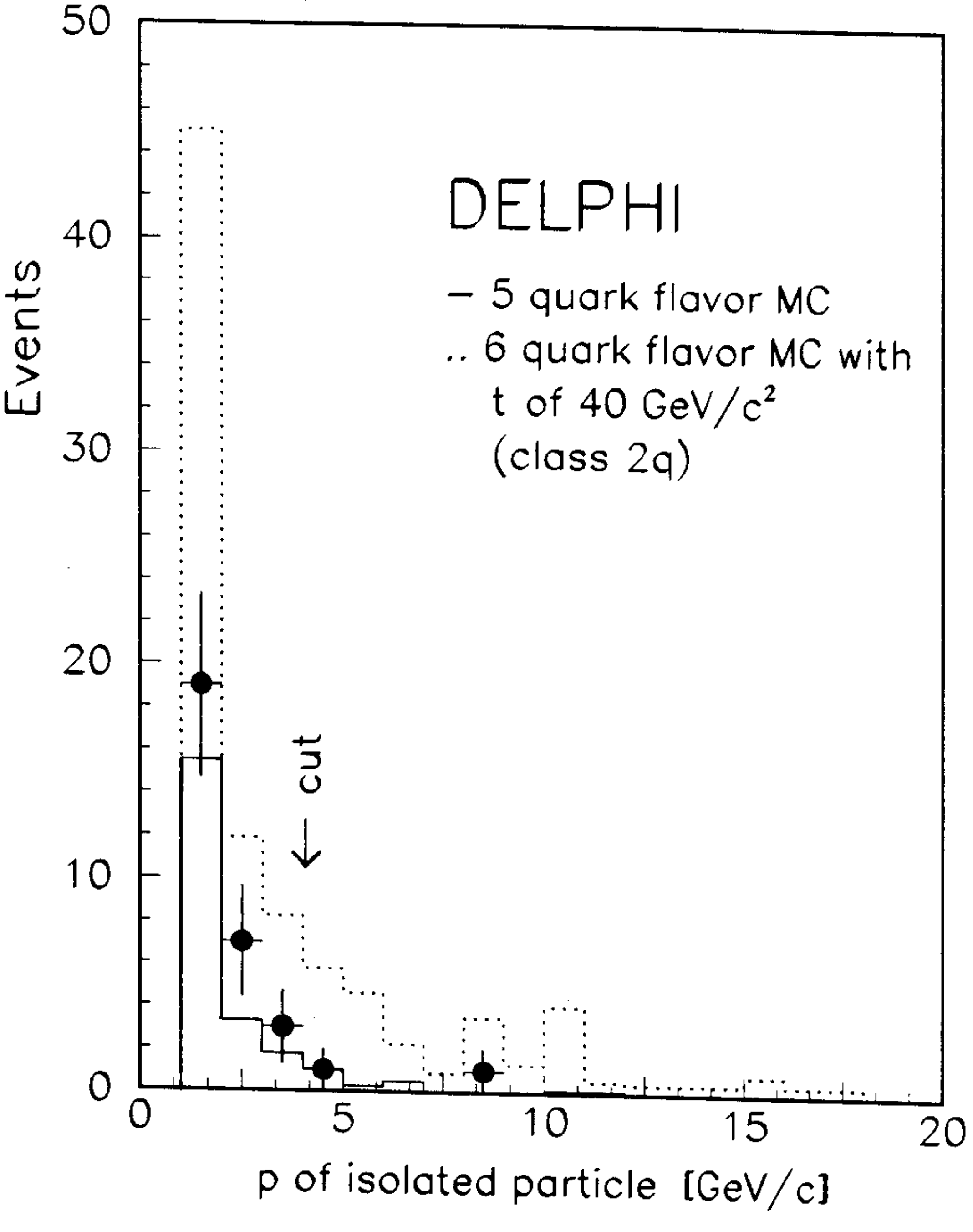

Figure 2: The momentum distribution of isolated particles after all other cuts of Selection 3 for 5 quark flavours (full line) is compared to the 6 quark flavour distribution for a top of 40 GeV/c^2 mass decaying into a charged Higgs with a mass of 33 GeV/c^2 which then decays through the τ channel (class 2q). The Monte Carlo distributions are normalized to the total number of hadronic events in the data (points) before applying the cuts.

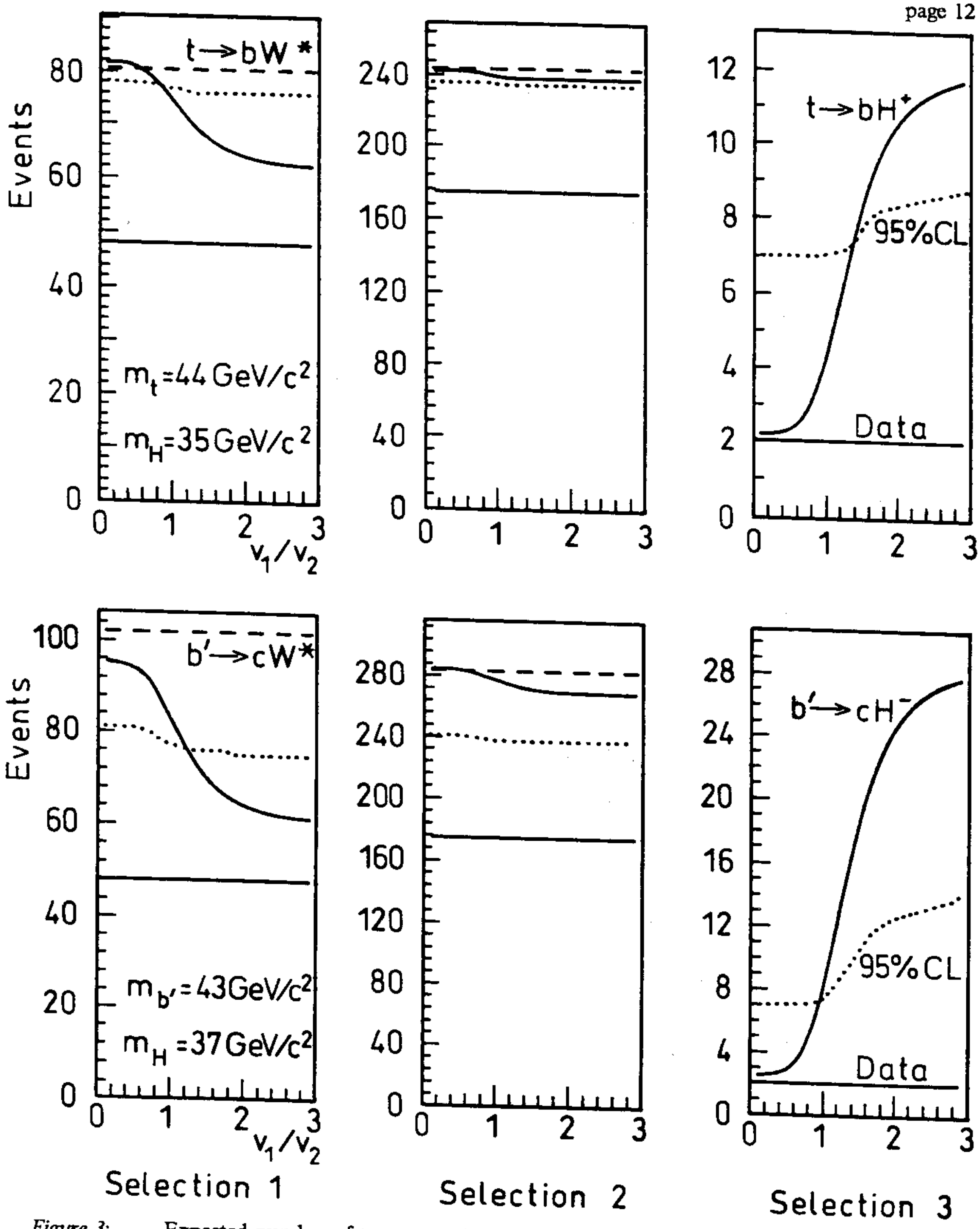

Figure 3: Expected number of top events (upper plots) and b′ events (lower plots) in our 3 selections against ν_1/ν_2. The expected number in the scenario with a charged Higgs decay (full line) is compared to the one with a charged current decay (dashed line) and data (full horizontal line). The dotted line indicates the 95% CL in the Higgs decay scenario. As we have taken the uncertainty of the number of expected events into account in the calculation of the CL, this 95% CL shows a ν_1/ν_2 dependence. In the case of the charged current decay the confidence level has to be taken from the dotted line at $\nu_1/\nu_2 = 0$