ALEPH 93 - 68
PHYSIC 93 - 57
F. Saadi et al.
13.4.93

A measurement of $\Gamma(Z \to b\bar{b})/\Gamma(Z \to hadrons)$ using single and double tagged events with high $p_\perp$ leptons

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Abstract

The partial decay width of the Z boson into $b\bar{b}$ has been measured by a double tag counting method using high $p_\perp$ leptons. The probability to tag a b quark with a lepton is extracted directly from the data which makes this measurement independent of the various b physics aspects, essentially the branching ratio $b \to l$ and the b fragmentation process. Using $429,000$ hadronic Z events collected by ALEPH in 1990 and 1991, we find:

$$\Gamma_{b\bar{b}}/\Gamma_{had} = 0.2270 \pm 0.0087 \text{ (stat.)} \pm 0.0073 \text{ (syst.)}$$

1 Introduction

In this note we present a measurement of the partial decay width of the Z into $b\bar{b}$. The b quarks are characterized by a large mass compared to the u, d, s, and c quarks (light quarks). This leads to a hard fragmentation of the b quarks so that their semileptonic decays produce leptons with high momentum p. The large mass of the b is also reflected by large transverse momentum $p_\perp$ of the produced leptons. These leptons are used as signature for $b\bar{b}$ events. The b tagging efficiency using cuts on p and $p_\perp$ depends on various parameters:

- the fragmentation of the heavy quark. The simulation of this problem depends on the QCD parton shower process (which represent the first step in the b desintegration) and the parameter of the Peterson *et al* model used to describe the distribution of the fraction of the b energy carried by the B hadron produced.
- The lepton production in the B hadrons decay requires the knowledge of different branching ratios $BR(b \to l)$, $BR(b \to c \to l)$, $BR(b \to \tau \to l)$....
- The lepton energy spectrum in the B center of mass is not well known and depends on the type of hadron produced and on the modelization used. Furthermore, the rate of D^{**} mesons produced in semileptonic decay is not yet precisely measured.
- In addition the lepton identification efficiencies for the different runs are also needed.

The principle of the method described in this note is to measure simultaneously $\Gamma_{b\bar{b}}/\Gamma_{had}$ and a global b tagging efficiency directly from data which permits to be independent of the different points described above.

2 Method

This method uses two types of events: single tagged hadronic events where only one quark is tagged and double tagged events where both the b and $\bar{b}$ quarks are tagged. Each event is divided in two hemispheres with respect to the plane perpendicular to the thrust axis. High $p_\perp$ leptons sign the quark flavour. Events in which all the tagged leptons belong to the same hemisphere give the single tagged sample, whereas in the double tagged sample each hemisphere contains at least one high $p_\perp$ lepton. Then we simply count the numbers N_{st} and N_{dt} of single tagged and double tagged events to derive the value of $\Gamma_{b\bar{b}}/\Gamma_{had}$. These two numbers are related by the following relations:

$$\left\{ \begin{array}{lclcll} N_{st} & = & 2P_b(1-CP_b)N_{b\bar{b}} & + & N_{st}^{light} & (1) \\ N_{dt} & = & CP_b^2 N_{b\bar{b}} & + & N_{dt}^{light} & (2) \end{array} \right.$$

Where:

$N_{b\bar{b}}$ is the number of $Z \rightarrow b\bar{b}$ produced events in the hadronic sample.

P_b is the probability to tag one hemisphere of a $b\bar{b}$ event. It is the sum of the different b decay mode tagging probabilities. For a given mode like $b \rightarrow l$ *or* $b \rightarrow c \rightarrow l$, this probability is the product of the lepton identification efficiency in the detector by the efficiency to satisfy some kinematical cuts and by the branching ratio of the decay mode.
P_b and $N_{b\bar{b}}$ are the two unknowns.

C is a correction factor. $C = P_{b\bar{b}}/P_b^2$ where $P_{b\bar{b}}$ is the probability to tag the two hemispheres in a $b\bar{b}$ event. This factor takes into account for possible correlations between the tagging efficiencies of the b and $\bar{b}$ hemispheres. This correction is mainly due to geometrical effects.

N_{st}^{light} and N_{dt}^{light} are the number of single and double *udsc* tagged events respectively. C, N_{st}^{light} and $N_{dt}^{light}$are estimated from Monte Carlo and hence they are subject to systematic errors.

3 Event selection

The full sample of Z hadronic events collected by ALEPH during 1990 and 1991 is analysed. The standard selection criteria used by the Heavy Flavour Lepton group are required (see [1] for more details).

– In SCANBOOK the selection flags DEDX, ECAL, HCAL AND MUONS are required to be 'good'.

– The hadronic events are selected by using the CLASS 16 flag.

– The energy flow tracks (charged + neutral) are used in the jet clusterisation including leptons. Then the lepton is excluded when calculating its $p_\perp$ with respect to the jet axis.

This selection leads to 148,541 hadronic events in 1990 and 280,600 in 1991.

– For the electron identification, cuts on the electromagnetic shower estimators are used: $-1.6 < R_T < 999.0$ and $-1.8 < R_L < 3.0$. To improve the background rejection we impose cut on the dE/dx estimator $-2.5 < R_I < 1000$. (more than 50 isolated wires are required).

– The electrons coming from conversion are rejected by using the routine QPAIRFD with the cuts :

$$|D_{xy}| < 1.0\ cm,\ |D_z| < 1.0\ cm \text{ and } M_{e^+e^-} < 20\ MeV.$$

– For the muon identification, we use QMUIDO with $IDF = 13$ *or* $IDF = 14$.

4 Monte Carlo simulation and corrections

The simulation of $Z \rightarrow q\bar{q}$ is based on the program HVFL02 which includes several improvements compared to the standard JETSET7.3 (see [2]). The event selection induces a small increase of the $b\bar{b}$ fraction in the hadronic events. For instance, the CLASS 16 efficiency is 98% for $b\bar{b}$, 97.5% for $c\bar{c}$ and 97% for *uds* events. So the measured b fraction in the data has to be corrected by a factor $C_b = 0.992 \pm 0.004$ where the error reflects the Monte Carlo statistics used to evaluate this effect.

For this analysis some corrections were applied to the simulation for the lepton identification [2]:

– The electron identification efficiency with the ECAL is directly measured in the data by using a pure sample of electrons produced by photon materialization in the material. It is calculated for various ranges of the polar angle, p and $p_\perp$ values and is determined with an accuracy of 3%.

– The dE/dx efficiency is also taken from the data with a study made on all the 'good' TPC tracks. It essentially corresponds to the efficiency to have 50 isolated wires associated to a track.

– The contamination of electrons by hadrons in the ECAL is estimated by analysing the R_I estimator in the data; the Monte Carlo is then corrected accordingly.

– The rate of conversion is found higher in the data than in the Monte Carlo. These corrections are evaluated to be 5.2% for 1990 and 5.7% in 1991.

5 Tag of the hemispheres using high $p_\perp$ leptons

As the aim of this method is to reduce the influence of the Monte Carlo inputs, the contribution of the light quarks needs to be small. The light quarks will be rejected by using kinematical cuts on leptons. The momentum of a track identified as a lepton is required to be greater than 3 GeV/c; the $b\bar{b}$ purity after this cut is 60% (this cut is mainly imposed for the muon identification).

The purity is increased by using $p_\perp$ cuts. With 550,590 fully reconstructed $Z_{q\bar{q}}$ simulated events, we estimate the b-purity for different $p_\perp$ cuts. The results are summarized in table 1.

$p_\perp$ cut (Gev/c)	0.75	1.0	1.25	1.5
$b\bar{b}(st)$	0.75	0.82	0.870	0.900
$c\bar{c}(st)$	0.15	0.11	0.075	0.055
$uds(st)$	0.10	0.07	0.055	0.045
$b\bar{b}(dt)$	0.960	0.980	0.996	0.997
$c\bar{c}(dt)$	0.036	0.013	0.004	0.003
$uds(dt)$	0.004	0.007	0.000	0.000

Table 1: Fractions of events from various sources in the single (st) and double (dt) tagged samples as a function of the $p_\perp$ cut.

A $b\bar{b}$ purity of 87% in the single tag sample can be achieved for $p_\perp \geq 1.25\ GeV/c$, for which the b purity of the double tagged sample is almost 100%. Later on, the results are given for the cuts used in table 1.

5.1 Extraction of the correction factor C

This factor has been estimated by using 175,215 $Z_{b\bar{b}}$ events simulated with the '91 geometry and 89,524 $Z_{b\bar{b}}$ events simulated with the '90 geometry. From equations (1) and (2) applied to $b\bar{b}$ events, one gets:

$$C = \frac{4N_{dt}N_{b\bar{b}}}{(N_{st} + 2N_{dt})^2}. \tag{3}$$

This gives a correction C = 1.038 ± 0.024 for the '91 simulation and C= 0.983 ± 0.035 for the '90 simulation. These values are compatible within the errors. This factor is mainly due to the geometrical acceptance efficiency. To reduce this effect, we apply a cut on the thrust axis: $|\cos\theta_{thrust}| < 0.9$ and we obtain C = 0.986 ± 0.020. Furthermore, we have checked that C does not depend on the $p_\perp$ cut (this dependence is in fact absorbed by P_b). Table 2 shows that within the errors, C is always compatible with 1.0. For this analysis we have used the average of C(90) and C(91) to reduce the statistical error.

$p_\perp$ *cut* (GeV/c)	0.75	1.0	1.25	1.5
$bb(st)$ MC 90	17645	14982	12422	9932
$b\bar{b}(dt)$ MC 90	1285	882	570	336
C	0.968±0.023	0.969±0.029	0.955±0.036	0.920±0.046
P_b	13.13± 0.10	10.87± 0.08	8.81± 0.07	6.89± 0.06
$bb(st)$ MC 91	36928	31264	25831	20842
$b\bar{b}(dt)$ MC 91	3096	2092	1357	820
C	0.991±0.015	0.999±0.019	1.000±0.024	0.975±0.031
P_b	14.36± 0.08	11.80± 0.07	9.50± 0.06	7.48± 0.05
C(90+91)	0.984±0.013	0.990±0.016	0.986±0.020	0.958±0.026

Table 2: Correction factor: C=$P_{b\bar{b}}/P_b^2$. The errors are due to the limited Monte Carlo statistics.

5.2 Data results

This method applied to the 127,299 $Z_{q\bar{q}}$ events selected in 1990 and to the 240,474 $Z_{q\bar{q}}$ selected in 1991 (events with $|cos(\theta_{thrust})| < 0.9$) leads to the following numbers (see table 3 and table 4):

	'91 data				'90 data			
$p_\perp$ cut (GeV/c)	0.75	1.0	1.25	1.5	0.75	1.0	1.25	1.5
N^e_{st}	7519	5834	4525	3504	3761	2921	2272	1770
N^μ_{st}	11608	8841	6857	5319	5598	4274	3319	2552
N_{st}	17812	13839	10865	8486	8782	6813	5376	4179
N^e_{dt}	185	76	67	40	104	75	48	37
N^μ_{dt}	409	263	176	107	190	123	82	41
N_{dt}	1132	734	478	296	534	369	232	144

Table 3: Numbers of tagged hemispheres and double tagged events obtained by using only electrons $N^e_{st}(N^e_{dt})$, only muons $N^\mu_{st}(N^\mu_{dt})$ or both electrons and muons $N_{st}(N_{dt})$.

The double tagged sample represents 4.21% of all the tagged events for 1991 data and 4.14% for 1990 for $p_\perp \geq 1.25$ GeV/c.

	'91 data			'90 data		
N_{lep}	0 tag	1 tag	2 tags	0 tag	1 tag	2 tags
1	35867	8426		18220	4242	
2	3541	2198	405	1717	1013	201
3	230	220	65	113	109	30
4	10	21	8	2	12	1
total	39648	10865	478	20052	5376	232

Table 4: Origin of the single and double tagged events with $p_\perp \geq 1.25\ GeV/c$. N_{lep} is the number of identified leptons in an event. The events are classified in three categories: the '0 tag' are events where all leptons fail the cuts, the '1 tag' are event where only one hemisphere is tagged and '2 tags' are events where the two hemispheres are tagged.

5.3 Extraction of P_b and $\Gamma_{b\bar{b}}/\Gamma_{had}$

The system of two equations (1) and (2) was solved by using the contribution of light quarks and the value of C obtained for different $p_\perp$ cuts. The results are plotted in fig. 1 and fig. 2. and show that the values obtained for $\Gamma_{b\bar{b}}/\Gamma_{had}$ are stable within the errors. The values obtained for $\Gamma_{b\bar{b}}/\Gamma_{had}$ and P_b with $p_\perp \geq 1.25\ GeV/c$ are listed in table 5 for electrons and muons separately. In fact, this cut has been chosen since it gives the smallest overall error after the systematic errors evaluation (see tables 6 and 7). Note that the acceptance correction factor C_b has been taken into account.

	'91 data		'90 data		data: '90 + '91	
	$\Gamma_{b\bar{b}}/\Gamma_{had}$ (%)	P_b (%)	$\Gamma_{b\bar{b}}/\Gamma_{had}$ (%)	P_b (%)	$\Gamma_{b\bar{b}}/\Gamma_{had}$ (%)	P_b (%)
e	24.50 ± 2.85	3.67 ± 0.40	19.46 ± 2.89	4.41 ± 0.61	21.63 ± 2.08	3.80 ± 0.34
μ	22.49 ± 1.74	5.71 ± 0.41	21.43 ± 2.43	5.49 ± 0.57	22.11 ± 1.41	5.64 ± 0.33
l	23.68 ± 1.08	9.15 ± 0.38	22.51 ± 1.47	9.01 ± 0.54	23.29 ± 0.87	9.10 ± 0.31

Table 5: $\Gamma_{b\bar{b}}/\Gamma_{had}$ and P_b for 1991 and 1990 data for electrons, muons and leptons (e + μ). Note that for these results, N^{light} was estimated by using the JETSET modelization for the $c \rightarrow l$ transition.

The average of $\Gamma_{b\bar{b}}/\Gamma_{had}$ (e) and $\Gamma_{b\bar{b}}/\Gamma_{had}$ (μ) is different from $\Gamma_{b\bar{b}}/\Gamma_{had}$ (l) because of events tagged by both electrons and muons.

6 Systematics

The systematic errors of this measurement are essentially due to the charm contribution which is taken from the simulation. The different sources of uncertainties are listed in table 6 and are described in the following sections for $p_{\perp} \geq 1.25\ GeV/c$.

6.1 Geometrical efficiency variation

For different ranges of the thrust polar angle, we calculate the fraction of the tagged hemispheres for '90 and '91 data. The distribution of this fraction is showed in fig. 3 for events tagged by electrons, muons or both electrons and muons. For $|cos(\theta_{thrust})| < 0.9$, this distribution is flat and shows that an eventual bias due to detector effect is small. With more statistics, we will be able to evaluate this effect by measuring $\Gamma_{b\bar{b}}/\Gamma_{had}$ for different bins of $cos(\theta_{thrust})$.

6.2 Charm fragmentation

The parametrization of the charm fragmentation in the simulation is done according to the Peterson et al. distribution with $\epsilon_c = 0.04$. Leptons coming from $c \longrightarrow l$ transitions are weighted according to this distribution with $\epsilon_c = 0.052$ (this value is measured by the D^* analysis [3]). Changing ϵ_c by ± 20% gives an error of ± 0.13% on $\Gamma_{b\bar{b}}/\Gamma_{had}$.

6.3 $c \longrightarrow l$ modelisation and $\Gamma_{c\bar{c}}/\Gamma_{had}$

The JETSET modelisation of $c \longrightarrow l$ is changed after the simulation by using the model of Altarelli et al. optimized on the DELCO data [4]. The lepton energy is weighted a posteriori in the D rest frame. This results in a harder spectrum (fig.4) and induces a shift on $\Gamma_{b\bar{b}}/\Gamma_{had}$ of -0.6% . The systematic error is then set to pm 0.3%. Furthermore, a variation of the $c\bar{c}$ partial width by ±10% induces an error of ± 0.3%. So the overall systematic error due to the charm physics is ±0.44% on $\Gamma_{b\bar{b}}/\Gamma_{had}$.

6.4 Background uncertainty

The lepton identification efficiencies were varied within the errors determined in section 3.

The uncertainty on γ conversions and electron misidentification probability have a minor effect on this measurement. The μ decay and the punch through contamination represent a fraction of 35% in the light sample and affect $\Gamma_{b\bar{b}}/\Gamma_{had}$ with an error of ± 0.27%.

6.5 Monte Carlo statistics

The limited Monte Carlo statistics used in this analysis is reflected by a statistical error on N_{st}^{light} and a more important error in the determination of the correction factor C. So, these two errors can be significantly reduced in the future.

Source	Variation	$\Delta\Gamma_{b\bar{b}}/\Gamma_{had}$ (%)		
		$p_\perp \geq 1.00$	$p_\perp \geq 1.25$	$p_\perp \geq 1.50$
Charm fragmentation ϵ_c	20 %	± 0.09	± 0.13	± 0.07
$c \rightarrow l$ modelisation	50 %	± 0.46	± 0.30	± 0.27
$\Gamma_{c\bar{c}}/\Gamma_{had}$	10 %	± 0.58	± 0.30	± 0.25
Lepton id. efficiency	3 %	± 0.19	± 0.12	± 0.05
e misidentification	10 %	± 0.09	± 0.02	± 0.00
γ conversion	10 %	± 0.08	± 0.01	± 0.00
Punch through + μ decay	20 +10%	± 0.60	± 0.27	± 0.20
Monte Carlo statistics	1σ	± 0.16	± 0.16	± 0.16
$C = \frac{P_{b\bar{b}}}{P_b^2}$	1σ	± 0.46	± 0.46	± 0.46
Selection correction C_b	1σ	± 0.09	± 0.09	± 0.09
Total		± 1.10	± 0.073	± 0.65

Table 6: Systematic errors on $\Gamma_{b\bar{b}}/\Gamma_{had}$ for different $p_\perp$ cuts (in GeV/c).

With the statistics used in this analysis, the overall smallest error on $\Gamma_{b\bar{b}}/\Gamma_{had}$ (stat. + syst.) is obtained for $p_\perp \geq 1.25$ GeV/c. Note that this cut is not the optimum for the systematic error and with more statistics this measurement can be improved by increasing the $p_\perp$ cut.

$p_\perp$ *cut* (GeV/c)	$\Delta\Gamma_{b\bar{b}}/\Gamma_{had}$ (stat.)	$\Delta\Gamma_{b\bar{b}}/\Gamma_{had}$ (syst.)	$\Delta\Gamma_{b\bar{b}}/\Gamma_{had}$ (stat.+syst.)
1.00	± 0.70%	± 1.10 %	± 1.30%
1.25	± 0.87%	± 0.73 %	± 1.14%
1.50	± 1.11%	± 0.65 %	± 1.29%

Table 7: $\Gamma_{b\bar{b}}/\Gamma_{had}$ statistical and systematic errors for different $p_\perp$ cuts.

6.6 Conclusion

We have measured the partial decay width $\Gamma_{b\bar{b}}/\Gamma_{had}$ by using a double tag method:

$$\Gamma_{b\bar{b}}/\Gamma_{had} = 0.2270 \pm 0.0087 \text{ (stat.)} \pm 0.0073 \text{ (syst.)}.$$

This method allows to measure $\Gamma_{b\bar{b}}/\Gamma_{had}$ independently of the various b physics aspects. It is limited by the double tagged sample statistics. Our dominant systematic error comes from the charm contribution. With more statistics, this error can be reduced by increasing the $p_\perp$ cut. Also an improvement of the knowledge of the charm parameters are expected with a higher statistics. A preliminary study [5] adding the b lifetime information to reject the light quarks, showed that the systematic errors can be reduced by about a factor four.

References

[1] D. Abbaneo *et al.*, Aleph Note 92-101

[2] A. Falvard *et al.*, Aleph Note 93-30

[3] D. Decamp *et. al.*, ALEPH Collab., *Production of Charmed Mesons in Z decays*, Contributed paper to the $XXVI^{th}$ International Conference on High Energy Physics, 6-12 August 1992, Dallas.

[4] Mark. A. Worris PhD Dissertation Univesity. CLNS THESIS 91-05

[5] F. Saadi - Talk given to Leptons Group Meeting on 2 june 1992.

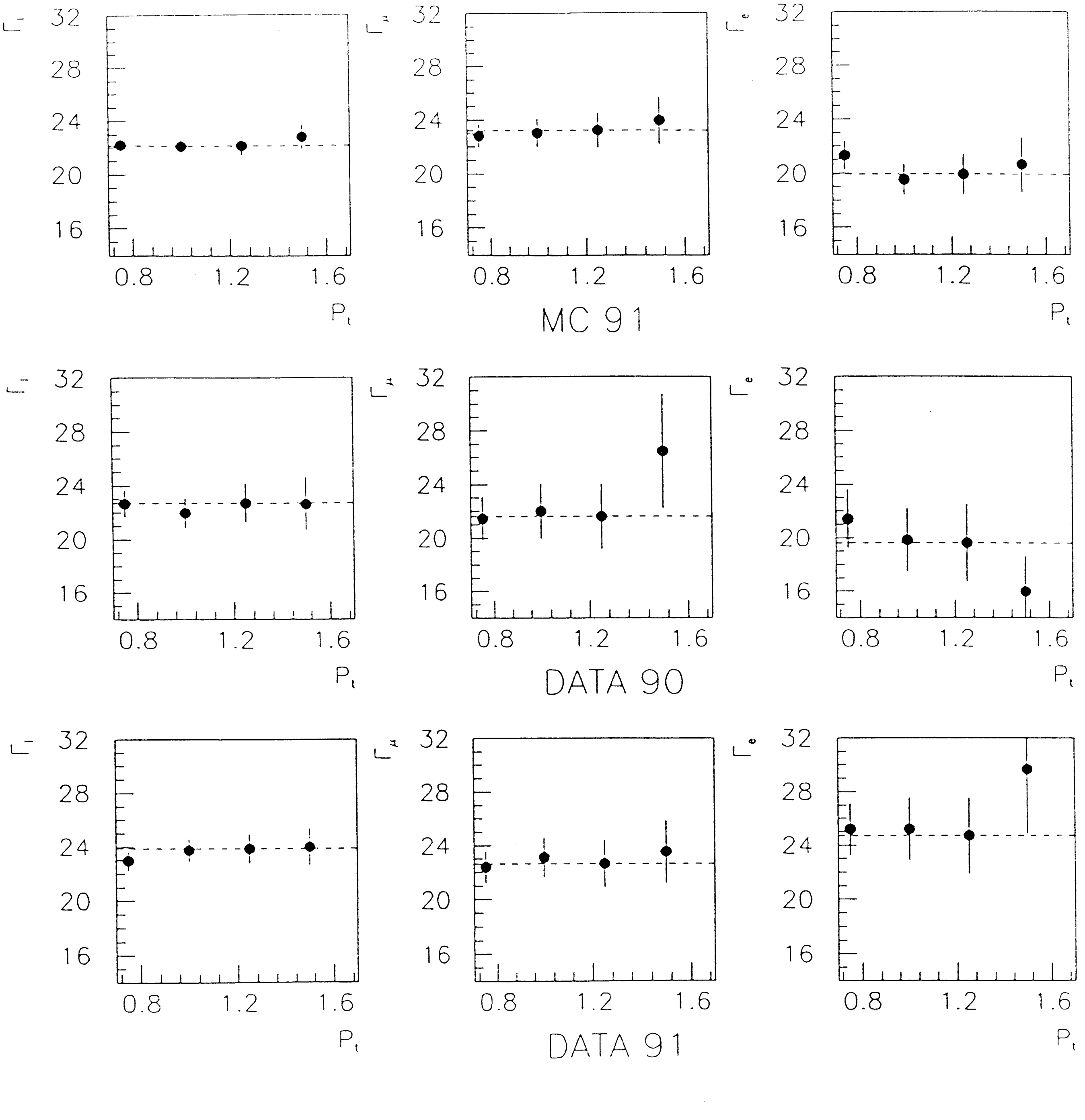

Figure 1: Measured values of $\Gamma_{b\bar{b}}/\Gamma_{had}$ for different $p_\perp$ cuts for electrons Γ^{e}. muons Γ^{μ} and both electrons and muons Γ^{l} with the correction C=0.99.

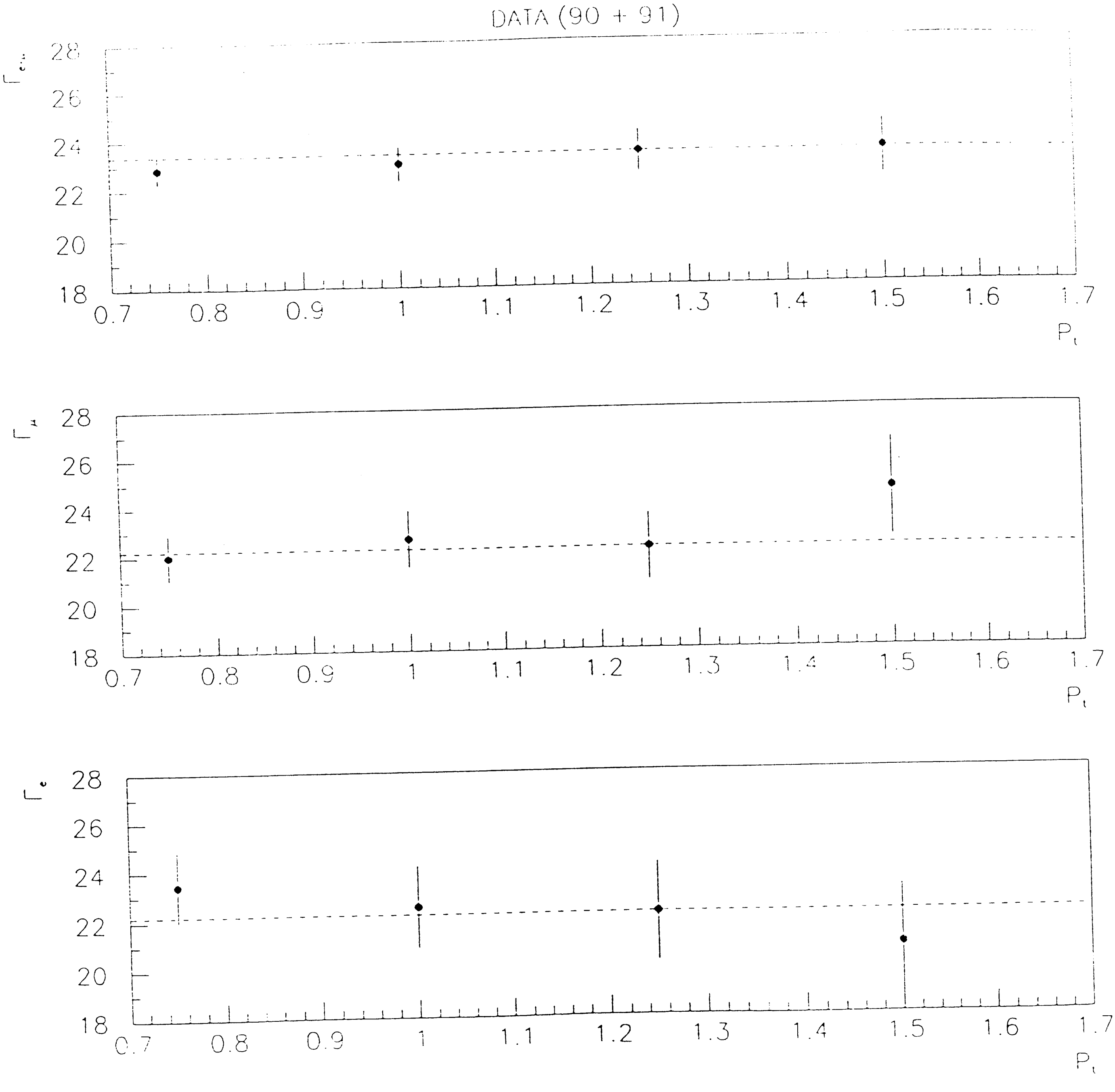

Figure 2: Measured values of $\Gamma_{b\bar{b}}/\Gamma_{had}$ for different $p_\perp$ cuts for all the data (90 +91).

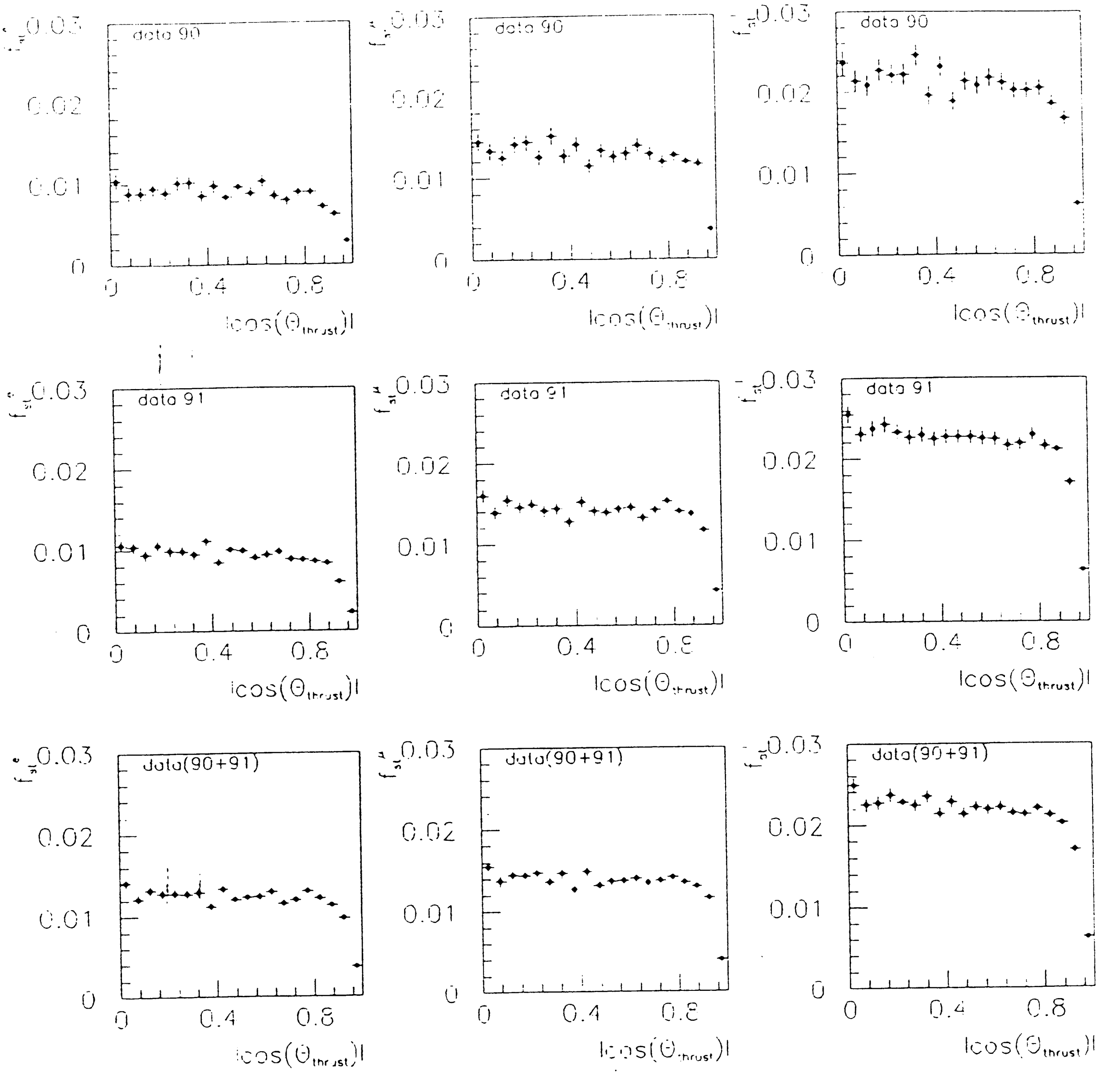

Figure 3: The variation of the fraction of tagged hemispheres in different bins of | $cos(\theta_{thrust})$ |. The hemispheres are tagged by electrons f^e_{st},muons f^{μ}_{st} or by both electrons and muons.

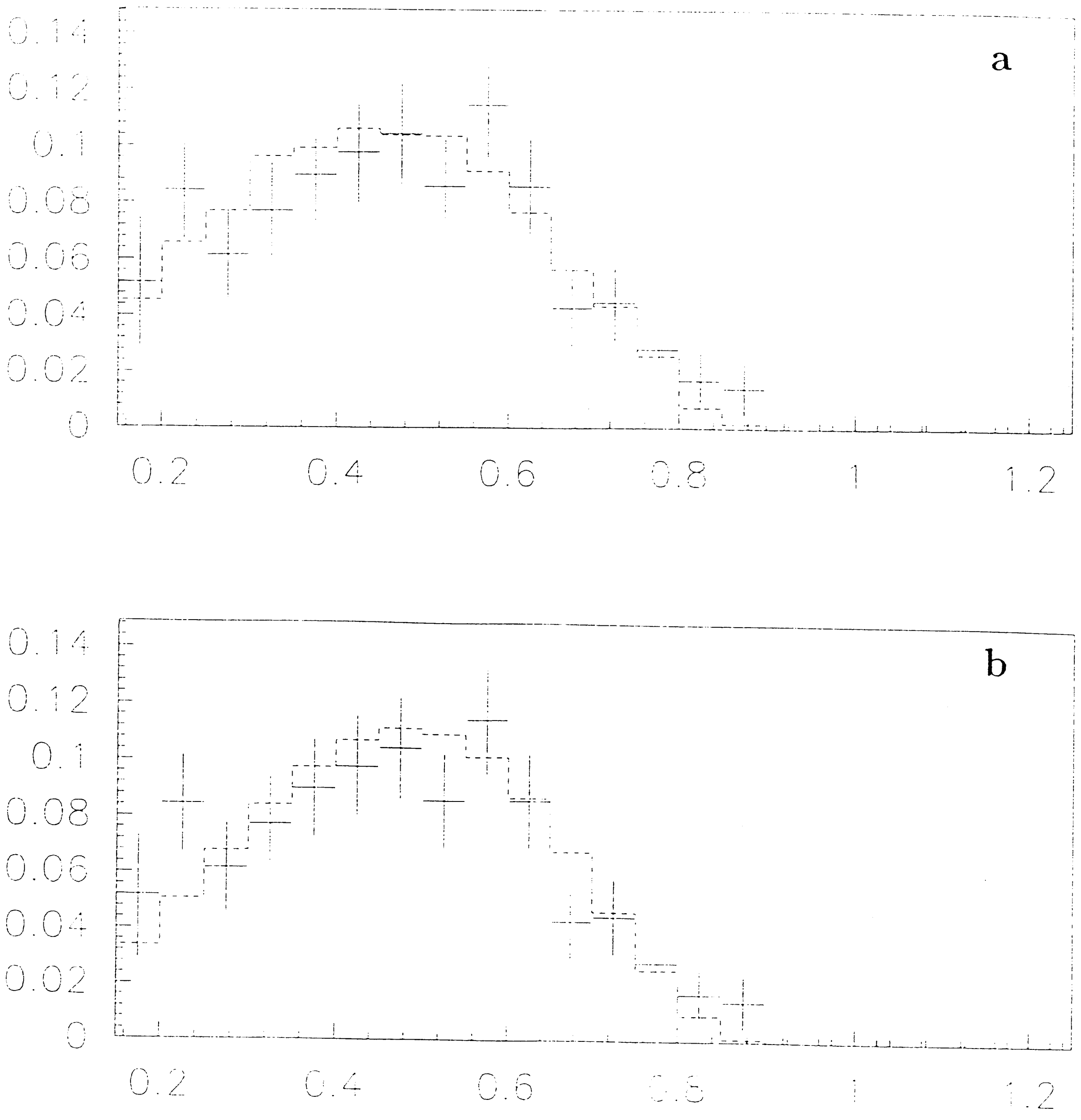

Figure 4: Lepton energy spectrum in c-hadron rest frame for $c \to l$ transitions; comparison between the Monte Carlo predictions (dotted histogram) and the data from DELCO: a) JETSET prediction, b) model of Altarelli *et al.*