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Measurement of b-quark mass effects in the four-jet rate at LEP

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Abstract

The effect of the heavy b-quark mass on the four-jet rate is studied for the first time at LEP. A preliminary measurement of R_4^{bl}, the normalized four-jet rate of b-quarks with respect to light ℓ-quarks ($\ell = u, d, s$), using the DURHAM jet clustering algorithm is presented. The data sets collected by the DELPHI experiment at the Z peak in 1994 and 1995 are analyzed and results are compared with existing LO massive calculations and with PYTHIA and HERWIG generators.

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1 Introduction

Mass corrections to the $Z \to b\bar{b}$ coupling are of order (m_b^2/M_Z^2), which is too small to measure at LEP. For some inclusive observables, like jet-rates, the effect is enhanced as $(m_b^2/M_Z^2)/y_{cut}$, where $y_{cut} \ll 1$ is the jet resolution parameter. The effect of the b-quark mass in the production of three jet event topologies at the Z peak has already been measured at LEP [1, 2, 3]. This study presents for the first time the effect of the heavy b-quark mass on the four-jet rate.

1.2 million hadronic events collected by DELPHI during the years 1994 and 1995 at a the Z peak have been analysed. The DURHAM algorithm [7] was used to cluster the events into jets. The experimental results are compared to leading order (LO) massive matrix element (ME) predictions [6] and to the PYTHIA 6.131 [8] and HERWIG 6.1 [9] event generators. The observable used is:

$$R_4^{b\ell} = \frac{[\Gamma_4(y_{cut})/\Gamma_{tot}]^{Z\to b\bar{b}}}{[\Gamma_4(y_{cut})/\Gamma_{tot}]^{Z\to \ell\bar{\ell}}} \tag{1}$$

where $[\Gamma_4(y_{cut})/\Gamma_{tot}]^{Z\to b\bar{b}}$ and $[\Gamma_4(y_{cut})/\Gamma_{tot}]^{Z\to \ell\bar{\ell}}$ represent the normalised four-jet cross sections for b- and ℓ=uds-quarks for the y_{cut} considered. In this definition, the flavours used are those of the pair of quarks coupled to the Z boson at tree level. With respect to $R_3^{b\ell}$, this observable has the advantage of having a higher suppression (the mass effect is about 10% in $R_4^{b\ell}$ compared to about 5% in the three-jet observable) which compensates for the loss of data events.

In this study, the comparison is done between data corrected for detector effects and theory (LO ME or event generators) *after* the hadronisation phase. In the case of the LO ME, the parton level predictions are corrected to the hadron level via factors computed with PYTHIA 6.131 and HERWIG 6.1.

2 The experimental method

Events are selected in the same way as in the published $R_3^{b\ell}$ analysis [1]. They are then forced to a four-jet topology using the DURHAM jet algorithm. If N_{4B} and N_{4L} are respectively the total number of four-jet events tagged as b- and ℓ=uds-quarks, $R_4^{b\ell}$ can be expressed at hadron level as:

$$(R_4^{b\ell})^{hadrons} = \frac{\Gamma_{tot}(Z\to \ell\bar{\ell})}{\Gamma_{tot}(Z\to b\bar{b})} D_4^{b\ell}\frac{N_{4B}}{N_{4L}} = \left(\frac{1-R_c-R_b}{R_b}\right) D_4^{b\ell}\frac{N_{4B}}{N_{4L}} \tag{2}$$

where R_b and R_c are the partial decay widths of the Z to b and c quark pairs and $D_4^{b\ell}$ are detector correction factors.

In this way, the experimental measurement of the $R_4^{b\ell}$ observable is divided respectively into two parts:

- First, the ratio N_{4B}/N_{4L} is measured with the DELPHI data collected in 1994 and 1995 and corrected for detector effects. About 1.15×10^6 hadronic Z decays are selected. Only events reconstructed into four jets at each y_{cut} are considered.

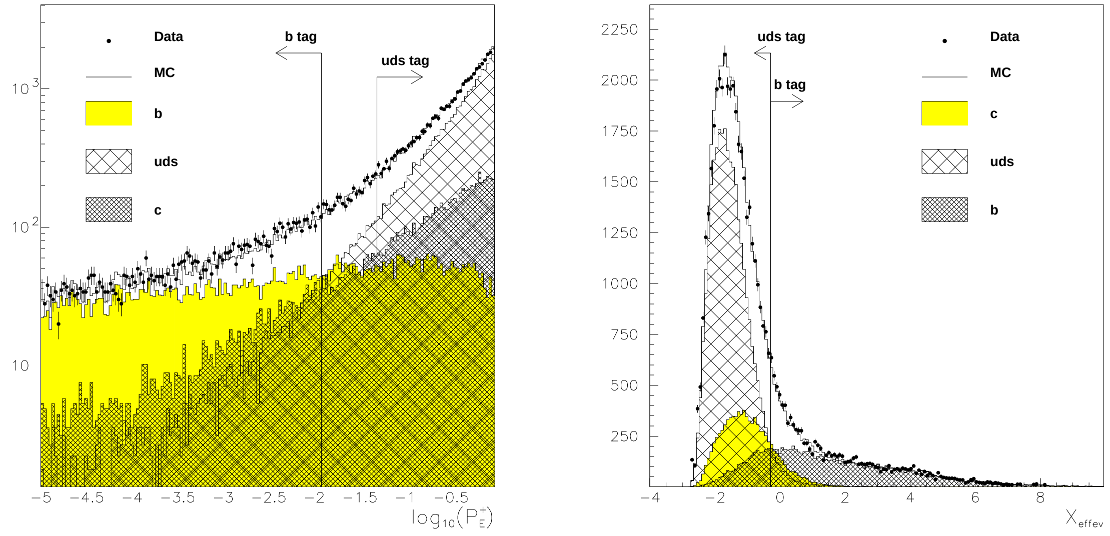
- Second, the global normalisation factor $\frac{\Gamma_{tot}(Z\to\ell\bar{\ell})}{\Gamma_{tot}(Z\to b\bar{b})}$ is calculated from the latest combination performed for the R_b and R_c values ($R_b = 0.21646 \pm 0.00065$, $R_c = 0.1719 \pm 0.0031$)[4]. Taking into account correlations between the two measurements, the following value was found:

$$\left(\frac{1 - R_c - R_b}{R_b}\right) = (2.826 \pm 0.017) \tag{3}$$

With this procedure the flavour-tagging can be used optimally in the context of the four-jet topology while benefiting from the precise R_b and R_c determinations.

2.1 Flavour tag

To identify the flavour of events, two algorithms are available in DELPHI: the lifetime-signed impact parameter of the charged particles [11] and the combined tagging technique [12]. The first method discriminates the flavour of the event by calculating the probability P_E^+ of having all particles in the event generated at the interaction point. For the second technique, a global estimator X_{effev} is built as an optimal combination of P_E^+ and three additional discriminating variables. The P_E^+ and X_{effev} distributions obtained in data and Monte Carlo are compared in Figure 1 for the four-jet sample. Both variables were obtained by combining the flavour information calculated for each of the four reconstructed jets.



(a) Lifetime-signed impact parameter

(b) Combined tagging

Figure 1: Event distribution of the probability P_E^+ (a) and X_{effev} (b) for events classified as four-jet at y_{cut}=0.009. The real (points) and simulated (histogram) data are compared. The specific contribution of each quark flavour is displayed for the simulated data. The cuts used to tag the b-quark and ℓ-quark samples are also indicated.

The cuts used to select b and ℓ-quark samples (see Figure 1 and Table 1) are chosen to minimize the total uncertainty on the measurement while keeping detector corrections small in the full range of y_{cut} studied. Both methods are used and compared throughout the analysis.

Method	#4-jet events	Type Q	cut	Purity	Efficiency
Combined	10815	B	$X_{effev} \geq -0.28$	74%	65%
Combined	35869	L	$X_{effev} < -0.28$	75%	60%
Impact parameter	9787	B	$\log P_E^+ \leq -1.92$	74%	58%
Impact parameter	33527	L	$\log P_E^+ > -1.31$	76%	58%

Table 1: Flavour composition of the samples tagged as b-quark (B) and ℓ-quark events (L) for the two techniques used in the analysis. A total number of 46684 four-jet events (y_{cut}=0.009) was found in the data sample.

2.2 Detector corrections

The detector corrections $D_4^{b\ell}(y_{cut})$ take into account the flavour identification procedure, kinematic biases, the acceptance and other detector effects. They are calculated with $\sim 4.3 \times 10^6$ hadronic events generated using JETSET 7.3 [10] and treated by the full simulation of the DELPHI detector (DELSIM) and by the standard data reconstruction chain. The simulation was reweighted in order to reproduce the measured gluon splitting rates [5]:

$$\begin{aligned} g_{c\bar{c}} &= 0.0296 \pm 0.0038 \\ g_{b\bar{b}} &= 0.00254 \pm 0.00051 \end{aligned} \tag{4}$$

The detector correction factors are shown in Figure 2. For the combined tagging technique the corrections are slightly smaller and are almost independent of the chosen y_{cut}.

2.3 Hadronisation corrections

To compare the parton-level LO ME massive calculations [6] of $R_4^{b\ell}$ with the experimental results, they are corrected for hadronisation effects:

$$(R_4^{b\ell})^{hadrons} = H_4^{b\ell}(R_4^{b\ell})^{partons} \tag{5}$$

The factors $H_4^{b\ell}(y_{cut})$ are computed using both PYTHIA 6.131 and HERWIG 6.1 tuned to DELPHI data [13], taking the average of the two (see Figure 2). An independent generation of $180M$ $b\bar{b}$ and $130M$ $\ell\bar{\ell}$ events was done for this purpose. For y_{cut} larger than 0.015 the hadronisation corrections obtained are very small ($\sim$ 1%) compared to the expected suppression from the b-quark mass ($\sim$ 10%).

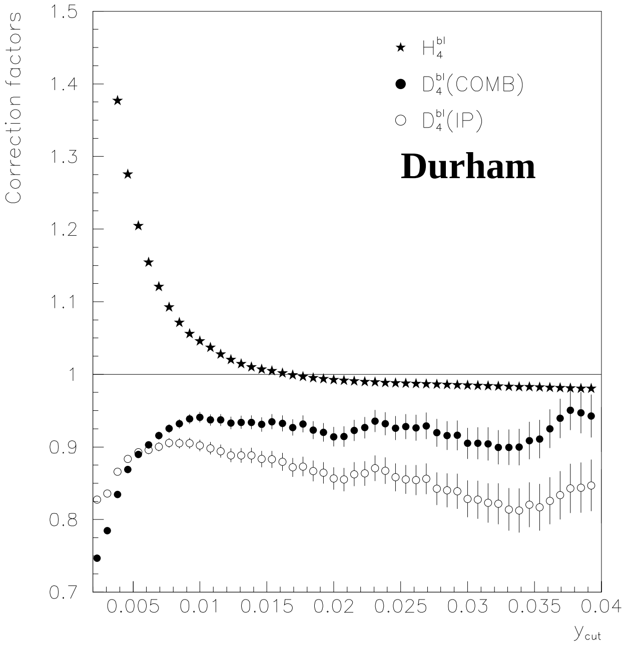


Figure 2: Detector and hadronisation corrections applied in the measurement.

3 Results

The preliminary $R_4^{b\ell}$ measurements obtained as a function of y_{cut} by combining the 1994 and 1995 data samples[1] are displayed at hadron level in Figures 3a and 3b. The combined flavour tagging technique is used here since it has a better perfomance (see Table 1) [2].

Figure 3a shows the comparison with LO ME calculations for two different values of the perturbative pole mass ($M_b = 4.8\ GeV/c^2$ and $M_b = 3.1\ GeV/c^2$), both including and not including the hadronisation corrections calculated with Pythia 6.131 and Herwig 6.1. NLO ME massive calculations are not available, but are expected to be bounded by these two LO curves in a way analogous to the $R_3^{b\ell}$ observable [6]. The measurements obtained for $y_{cut} = 0.009$ and $y_{cut} = 0.015$ are:

$$\begin{aligned} R_4^{b\ell}(y_{cut} = 0.009) &= 0.924 \pm 0.009(\text{stat}) \pm 0.010(\text{exp syst}) \\ R_4^{b\ell}(y_{cut} = 0.015) &= 0.916 \pm 0.015(\text{stat}) \pm 0.012(\text{exp syst}) \end{aligned}$$

where the second error represents the experimental systematic uncertainty affecting the measurements.

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[1] Some discrepency was found between the measurements in 1994 and 1995, reaching up to 3 sigma in the low y_{cut} region ($y_{cut} < 0.01$). The differences are still under investigation. In the context of these preliminary results, the experimental systematic uncertainties affecting the measurements (see Section 4) were treated as fully correlated in the combination.

[2] The results obtained with the life-time impact parameter technique are compatible (see Figure 4)

For all values of y_{cut} the result is bounded by the two LO ME predictions, as expected. This is the case both for the combined 1994-1995 measurement shown in Figure 3a and for each of the years analysed separately. At $y_{cut} = 0.015$ the measured value results entirely from the suppression due to the b-quark mass, since hadronisation corrections are very small. At $y_{cut} = 0.009$ both the computed suppression from the b-quark mass and fairly large hadronisation effects are needed to explain the data.

The results are also compared to the predictions from the PYTHIA 6.131 and HERWIG 6.1 generators (see Figure 3b). For y_{cut} values smaller than 0.025 the measured $R_4^{b\ell}$ is better described by the HERWIG 6.1 generator. With the PYTHIA 6.131 string model, both the Peterson and the Bowler fragmentation functions were studied. The difference between the two is found to be very small.

4 Systematics

Two different sources of systematics have been considered: experimental and modelling systematics. Experimental uncertainties arise in the process of correcting the detector-level measurement to hadron level. Modelling uncertainties appear in the process of correcting parton-level theoretical calculations to hadron level.

The following sources of experimental uncertainties have been studied:

- Gluon splitting: the gluon splitting rates $g_{c\bar{c}}$ and $g_{b\bar{b}}$ were varied in the range of their quoted uncertainties (5). The observed changes in $R_4^{b\ell}$ were added in quadrature and taken as the gluon splitting uncertainty.

- Flavour tagging: the analysis was redone with the calibration file for data used in the Monte Carlo, following the procedure outlined in [14]. The change in $R_4^{b\ell}$ was taken as the tagging uncertainty.

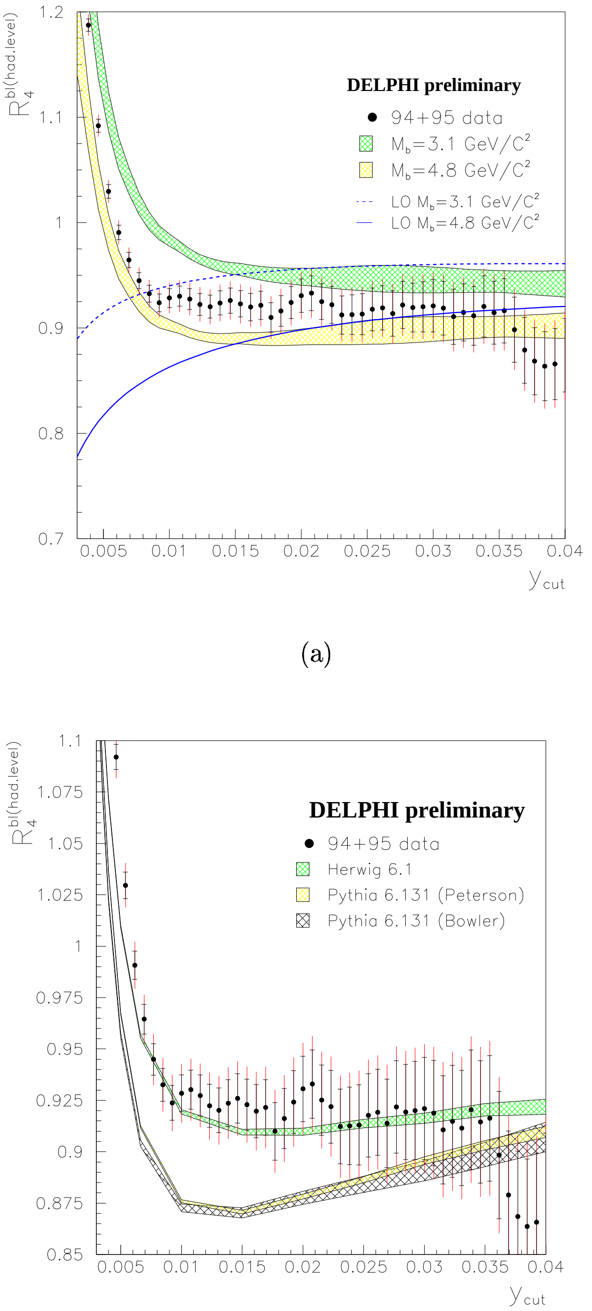
- Simulation error: The generated events were passed through the full analysis chain as if they were data. The statistical fluctuations in the final result was taken conservatively as the simulation error.

As an additional cross-check, the purities of the b- and ℓ-quark tagged samples are varied over a wide range to test the stability of the result (see Figure 4). No important dependence with the purity is found and the chosen working points are within the stability regions.

The following sources of modelling uncertainties have been studied:

- The parameters of the PYTHIA 6.131 Monte Carlo which are relevant in the fragmentation process (Λ_{QCD}, Q_0, σ_q, ϵ_b, a) were varied within one standard deviation from their tuned central values [13]. The quadratic sum of the deviations was taken as the tuning uncertainty taking into account correlations.

- As mentioned in Section 2.3, two different hadronisation models were studied: PYTHIA 6.131 with the Peterson fragmentation function and HERWIG 6.1. Half the difference between the two models was taken as the systematic uncertainty due to the hadronisation model.



(a)

(b)

Figure 3: (a) Final $R_4^{b\ell}$ at hadron level as a function of y_{cut} compared with the LO theoretical predictions calculated in terms of a pole mass of $M_b = 4.8\ GeV/c^2$ (light) and $M_b = 3.1\ GeV/c^2$ (dark). The modelling uncertainties (see the text) are represented by the grey shadings. The LO predictions are also shown without hadronisation corrections for $M_b = 4.8\ GeV/c^2$ (continuous) and $M_b = 3.1\ GeV/c^2$ (dashed). (b) Final $R_4^{b\ell}$ at hadron level as a function of y_{cut} compared with the generator predictions from PYTHIA 6.131 and HERWIG 6.1. The difference between the Peterson and Bowler fragmentation functions in PYTHIA 6.131 is seen to be very small. For small y_{cut} $R_4^{b\ell}$ is better described by the HERWIG 6.1 generator. The width of the bands reflects the statistical errors.

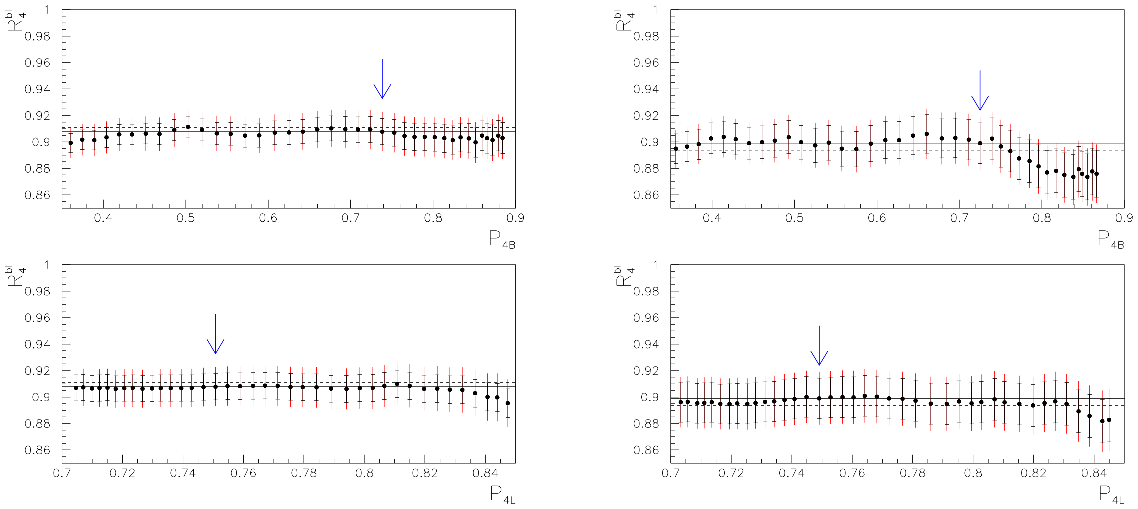
The contributions of the different sources of systematic uncertainty to each measurement are listed in Table 2. The dominant experimental uncertainty arises from the knowledge in the gluon splitting rates. The contributions of the modelling uncertainties to the LO ME predictions are listed in Table 3. The two modelling uncertainties considered are comparable. An additional modelling uncertainty arises from the precision with which the perturbative pole mass in the LO ME calculation can be identified with the mass in the perturbative part of the generator (PYTHIA 6.131 and HERWIG 6.1) used to compute the hadronisation corrections. This uncertainty is of the order of $\Lambda_{QCD} \sim 200\ MeV$ [15]. In the absence of ME predictions at NLO, it was however not considered here.

DURHAM	$R_4^{b\ell}(y_{cut}=0.009)$	$R_4^{b\ell}(y_{cut}=0.015)$
Value	0.924	0.916
Statistical (data)	±0.008	±0.013
Statistical (simulation)	±0.005	±0.007
Tagging	±0.002	±0.003
Normalisation	±0.005	±0.005
Gluon splitting	±0.008	±0.011
Total systematics	±0.010	±0.012
Total statistical	±0.009	±0.015
Total experimental error	±0.014	±0.019

Table 2: Statistical and systematic errors affecting the measurements of R_4^{bl} performed at hadron level, for the two working points y_{cut}=0.009 and y_{cut}=0.015.

	LO ME ($M_b = 4.8\ GeV/c^2$)		LO ME ($M_b = 3.1\ GeV/c^2$)	
DURHAM	$R_4^{b\ell}(y_{cut}=0.009)$	$R_4^{b\ell}(y_{cut}=0.015)$	$R_4^{b\ell}(y_{cut}=0.009)$	$R_4^{b\ell}(y_{cut}=0.015)$
Value	0.906	0.890	0.990	0.954
Tuning	±0.005	±0.005	±0.005	±0.005
Hadronisation	±0.004	±0.003	±0.004	±0.003
Total modelling error	±0.006	±0.006	±0.006	±0.006

Table 3: Systematic uncertainties in the translation of the LO ME predictions from parton to hadron level, computed using the PYTHIA 6.131 and HERWIG 6.1 event generators.



(a) Stability at y_{cut}=0.009

(b) Stability at y_{cut}=0.015

Figure 4: Stability plots of $R_4^{b\ell}$ at hadron level for 1994, as a function of the purities P_{4B}, P_{4L} of the four-jet sample (for the combined flavour tagging technique). The arrows mark the position of the working points.The horizontal line corresponds to the measured values of $R_4^{b\ell}$ with the combined tagging technique (continuous line) and with the life-time impact parameter technique (dashed). The two tagging techniques are stable for a wide range of purities and compatible inside statistical errors.

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