MASS OF THE b-QUARK AT LEP

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The effect of the heavy b-quark mass is studied measuring the normalized n-jet rates of b-quarks with respect to light-quarks ($\ell = uds$), $R_n^{b\ell}$ (n=2-4), using the CAMBRIDGE jet clustering algorithm with LEP data collected by the Delphi experiment at the Z peak. Results are compared with generators (at hadron level) and massive NLO calculations. $R_3^{b\ell}$ is used to extract values for the b-quark mass at the M_Z energy scale defined in the $\overline{MS}$ scheme, $m_b(M_Z)$ and to test α_s universality. The validity of approximating massive NLO corrections by their corresponding massless ones is investigated with the aim to measure the b-quark mass in four-jet events.

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 and SLC. The main effect is a slight reduction of the emission of gluons from b-quarks, mainly in the collinear region. 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.[1]

The b-quark mass is a fundamental parameter in the Standard Model Lagrangian. Because of confinemet, quarks are not observed as free particles and to define the mass a theoretical convention is needed. The most commonly used definitions are the pole mass, M_b (defined as the pole of the renormalized quark propagator), and the *running* mass, $m_b(Q^2)$ (the renormalized mass in the $\overline{MS}$ scheme). Both definitions are equivalent and are related perturbatively[2], but have different convergence properties. A combination[3] of b-mass measurements at the production threshold led to the value $m_b(m_b) = 4.24 \pm 0.11\,\mathrm{GeV/c^2}$. NLO massive calculations[4,5,6,7] exist for several event shape type observables at the M_Z energy scale. They allow for an independent measurement of the b-quark mass from three-jet observables.[8,9,10,11] We extend these studies to cover from two to four-jet rates. These measurements can be compared to those obtained at low energy to test the *running* of the b-mass as predicted by QCD.

It has also important implications on Higgs searches [12,13,14] and in theories beyond the Standard Model as those predicting $m_b - m_\tau$ unification at the GUT scale. In addition, mass effect studies on multijet topologies serve as a testbench for the different event generators. This allows for the study and validation of the different models implemented and will be important for understanding the production mechanism and the experimental backgrounds at LHC.

2 Experimental strategy

The DELPHI data collected between the years 1994 and 2000 at a center-of-mass energy of $\sqrt{s} \approx M_Z$ were analyzed. The CAMBRIDGE [15] jet reconstruction algorithm was used to define jets, as it is expected to give a smaller theoretical uncertainty.[7,16] The observable studied was:

$$R_n^{b\ell}(y_{cut}) = \frac{[\Gamma_n(y_{cut})/\Gamma_{tot}]^{Z\to b\bar{b}}}{[\Gamma_n(y_{cut})/\Gamma_{tot}]^{Z\to \ell\bar{\ell}}}, \qquad n = 2,3,4 - jets, \tag{1}$$

where $\ell \equiv uds$ are light flavours and $[\Gamma_n(y_{cut})/\Gamma_{tot}]^{Z\to q\bar{q}}$ represents the normalized n-jet cross-section for a flavour q. In this definition, the flavour of the event is given by the pair of quarks coupling to the Z boson. Experimentally, b and ℓ-events were separated through methods exploiting the longer B hadron life time. [17,18] The measured rates were corrected for experimental effects as detector acceptance, resolution and flavour identification, in order to be expressed in terms of hadrons.

For $n = 2, 3$-jets we measured simultaneously the number of events tagged as b or light in the inclusive and n-jet samples. [8] For $n = 4$ only the n-jet samples were classified by flavour and a double-jet tag technique was used. This procedure measures the flavour-tagging efficiencies from data reducing experimental uncertainties. The global normalisation for the observable was obtained from the latest world combination [19] of R_b and R_c.

To compare with massive ME calculations (at parton level), we further corrected the experimental results to take into account non-perturbative effects in the hadronization phase.

3 $R_n^{b\ell}$ at hadron level

The preliminary $R_n^{b\ell-had}$ ($n = 2, 3, 4$) results at hadron level obtained as a function of y_{cut} are compared to the predictions from PYTHIA 6.131, HERWIG 6.1 and ARIADNE 4.08 event generators [20,21,22] in Figure 1. None of the three models describes all the measurements simultaneously, and the worst description is that of $R_2^{b\ell}$. Experimental results are consistent with generator predictions if the spread of the three generators is taken as the uncertainty of the prediction.

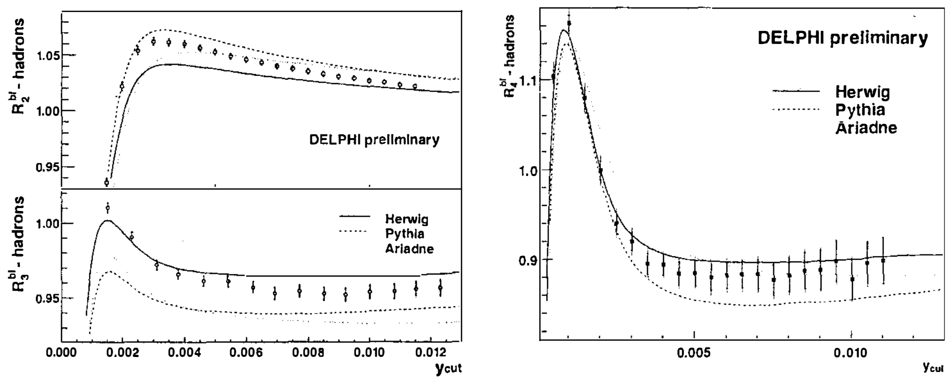

Figure 1: Comparison between measured $R_n^{b\ell-had}$ rates and predictions from the PYTHIA 6.131, HERWIG 6.1 and ARIADNE 4.08 generators. None of the three models describes all the measurements simultaneously.

4 Mass extraction from $R_3^{b\ell}$

A detailed study of how mass effects in the hadronization process are implemented in the event generators led to a better control of the hadronization correction. A cut on the b-quark jet energy, $x_e^b(\text{jet}) = E_{b-jet}/E_{beam} \geq 0.55$, was applied in order to correct the experimental measurement for hadronization effects in a restricted phase-space region where the hadronization models from PYTHIA and HERWIG give a similar correction. The comparison between the observed three-jet result and the massive NLO calculations (see Fig. 2) allowed to extract both the *running* and the pole b-quark masses by assuming α_s universality (see Table 1). In addition, the flavour independence of α_s was tested by fixing the value of m_b to the combined value from low energy measurements [3] evolved to the M_Z scale using Renormalization Group Equations (RGE).

The dominant systematical uncertainty comes from the modelling of hadronization. It was evaluated by propagating the uncertainties in the M_b parameter in the generator (which was identified as the pole mass) through the correction procedure and by comparing the final result when the fragmentation models from Peterson[23] and Bowler[24] were used in PYTHIA. Experimental uncertainties include flavour, jet identification and gluon splitting. Theoretical uncertainties include the μ-dependence of the calculation and the uncertainty on α_s. In addition, two different procedures were used to translate the pole mass calculations into *running* mass calculations (with and without RGE) and the difference between the two results is considered as an additional source of systematic uncertainty. The measured b-quark masses from $R_3^{b\ell}$ are summarized in Table 1.

5 Consistency with $R_4^{b\ell}$

Existing calculations for jet-rates including mass effects are only $\mathcal{O}(\alpha_s^2)$. However, if most of the mass correction to the observable is already at LO, the four-jet observable description may be improved using $\mathcal{O}(\alpha_s^3)$ massless corrections.[25,26,27] This procedure has been successfully tested for $R_3^{b\ell}$, for which the genuine massive NLO corrections exist. As for the case of $R_3^{b\ell}$,[7] it was found that the NLO corrections using the pole and *running* mass definitions were both within the uncertainty band defined by the two LO curves and that the *running* mass definition gave a smaller correction at NLO than the pole mass. Such a correction method can be considered plausible for $R_4^{b\ell}$, although one cannot estimate the size of the theoretical uncertainty in a precise way. The measured b-quark masses from $R_4^{b\ell}$ are summarized in Table 2. The consistency of the b-quark m_b results with the ones obtained from $R_3^{b\ell}$ and with the QCD predicted values is swhown in Figure 3.

Table 1: Mass results from $R_3^{b\ell}$ (parton level) at $y_{cut} = 0.0085$ (CAMBRIDGE).

	$R_3^{b\ell} - part$	$m_b(M_Z)$ GeV/c^2	M_b GeV/c^2	${\alpha_s}^b/{\alpha_s}^\ell$
value	0.9646	2.85	4.47	0.996
stat	± 0.0042	$^{+0.18}_{-0.19}$	± 0.23	± 0.004
exp	± 0.0030	± 0.13	± 0.25	± 0.006
had	± 0.0045	$^{+0.19}_{-0.20}$	$^{+0.16}_{-0.17}$	-
theo	-	± 0.12	$^{+0.70}_{-0.83}$	± 0.003

6 Summary and conclusions

Effects from the b-quark mass in DELPHI were measured and compared at hadron level with existing Monte Carlo generators. Massive NLO calculations enabled tests of the flavour inde-

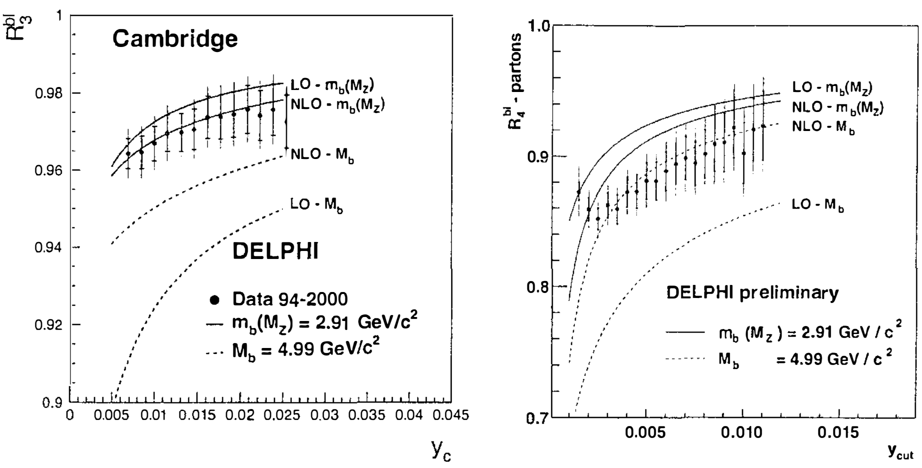

Figure 2: Experimental results for $R_n^{b\ell}$ obtained at parton level as a function of y_{cut}, for n = 3-jets (left) and n = 4-jets (right). Results are compared with the LO and NLO theoretical predictions calculated in terms of M_b and $m_b(M_Z)$ (in the case of $R_4^{b\ell}$ the NLO calculatios are massless).

Table 2: Mass results from $R_4^{b\ell}$ (hadron level) at $y_{cut} = 0.0065$ (CAMBRIDGE).

CAMBRIDGE	$R_4^{b\ell}$ − *had*	$m_b(M_Z)$ GeV/c^2	M_b GeV/c^2
value	0.883	3.60	5.20
stat	±0.013	±0.32	±0.41
exp	±0.015	±0.28	±0.36
had	-	±0.20	±0.30
theo	-	±0.40	±0.50

pendence of α_s to a precision of 1%, and determinations of $m_b(M_Z)$ and M_b. Results agree with existing measurements both at the M_Z scale (see Figure 4) and at low energy, including a recent measurement [28] from DELPHI from semileptonic B-decays which gave the result $m_b(m_b) = 4.26 \pm 0.13$ GeV/c^2. New studies on mass effects and the hadronization process allowed for a reduction in systematic uncertainties from previous analysis[8] and the uncertainty to the M_b parameter in the generators was studied for the first time. The measured value of $m_b(M_Z)$ from $R_3^{b\ell}$ was:

$$m_b(M_Z) = 2.85^{+0.18}_{-0.19}\ (stat) \pm 0.13\ (exp)\ ^{+0.19}_{-0.20}\ (had) \pm 0.12\ (theo)\ \ \mathrm{GeV/c^2} \qquad (2)$$

The validity of approximating massive NLO corrections to $R_4^{b\ell}$ by their corresponding massless ones was shown. The measured value of $m_b(M_Z)$ was:

$$m_b(M_Z) = 3.60 \pm 0.32\ (stat) \pm 0.28\ (exp) \pm 0.20\ (had) \pm 0.40\ (theo)\ \ \mathrm{GeV/c^2} \qquad (3)$$

The dominant source of uncertainty is theoretical, and it is due to the use of approximate massless NLO corrections. This uncertainty is three times larger than the corresponding uncertainty in the mass extracted from $R_3^{b\ell}$, where massive NLO corrections exist.

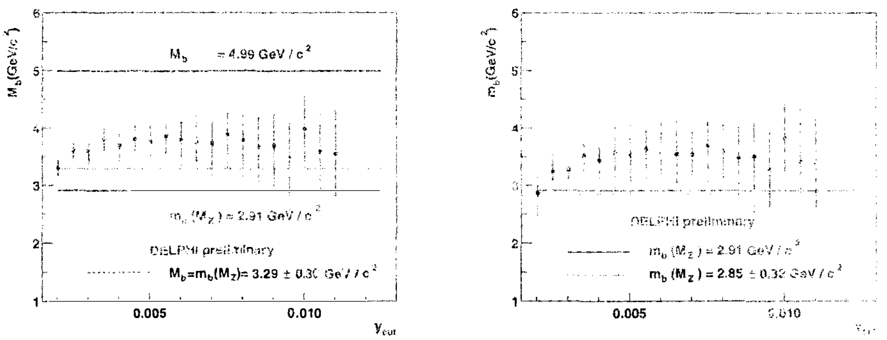

Figure 3: Comparison of the *running* mass result obtained from $R_4^{b\ell}$ with the measured mass from the $R_3^{b\ell}$ analysis (colour band) and $m_b(M_Z)$ from the QCD prediction from $m_b(m_b)$ evolved to the M_Z scale using RGE. The comparison is done with LO (left) and massless NLO calculations (right).

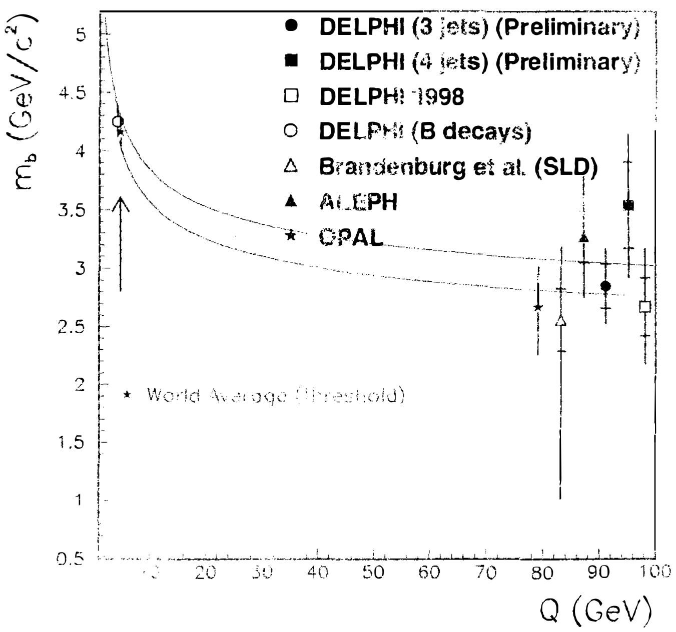

Figure 4: Comparison of $m_b(M_Z)$ and $m_b(m_b)$ measured at LEP and SLC with $m_b(Q)$ from the combination [3] of threshold measurements of $m_b(m_b)$ evolved using Renormalization Group Equations. Results are consistent with each other.

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