Heavy quark production in e$^+$e$^-$ annihilation above the Z pole.

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At LEPII the study of the forward backward asymmetries of heavy quark production and the ratio of their production cross section with respect to hadrons, allows a further test of the electroweak predictions at the energies above the Z pole. The analysis techniques are discussed and the achieved results are reviewed.

We discuss measurements of heavy quarks production (cross-section fractions R_b and R_c) and forward-backward asymmetry (A^b_{fb} and A^c_{fb}) at LEPII. They are defined as

$$R_b = \frac{\sigma_{b\bar{b}}}{\sigma_{had}}, \qquad A^b_{fb} = \frac{\sigma^f_{b\bar{b}} - \sigma^b_{b\bar{b}}}{\sigma_{b\bar{b}}}, \tag{1}$$

where $\sigma_{had} = \sum_q \sigma_{q\bar{q}}$ is a total hadronic cross section. These quantities were extensively measured at LEPI, where Z-exchange dominates and both the photon contribution and interference are negligible. At LEPII these contributions (Fig.1a) become large, and such measurements provide a new test of the Standard Model. An important feature of measurements at LEPII is the "radiative return to Z": after the emission of a hard Initial State Radiation (ISR) photon (Fig.1b) the center-of-mass energy ($\sqrt{s'}$) of electron-positron equals the Z mass (Fig.2). To investigate genuine high energy events the cut $\sqrt{s'}/\sqrt{s} > 0.85$ is used.

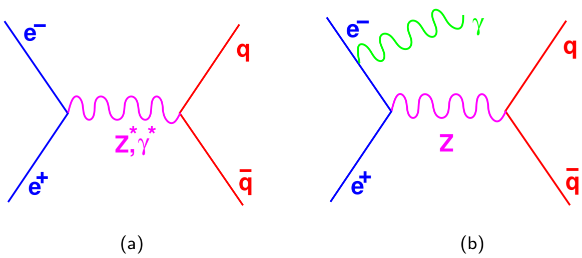

Figure 1. (a) The q$\bar{\text{q}}$ production above Z pole and (b) the "rediative return to the Z".

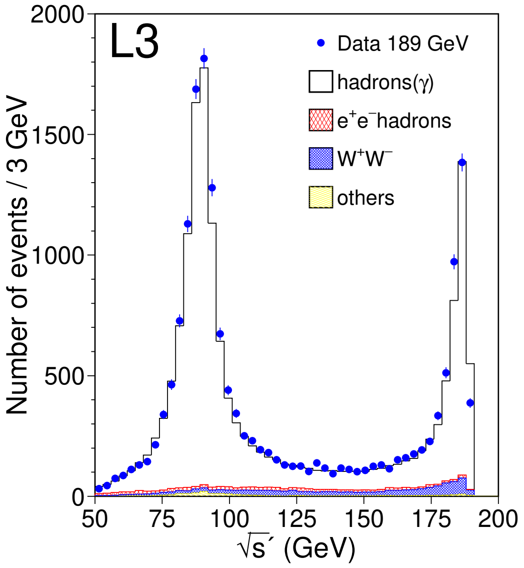

Figure 2. Effective center-of-mass energy $\sqrt{s'}$ for hadron production at LEPII.

Crucial for heavy quark measurements is the identification of hadrons containing b-quarks. This is achieved thanks to their relatively long lifetime (and corresponding decay length) and by possible hard leptons stemming out of their decays. The decay length is the distance between the interaction point (IP) and the decay vertex.

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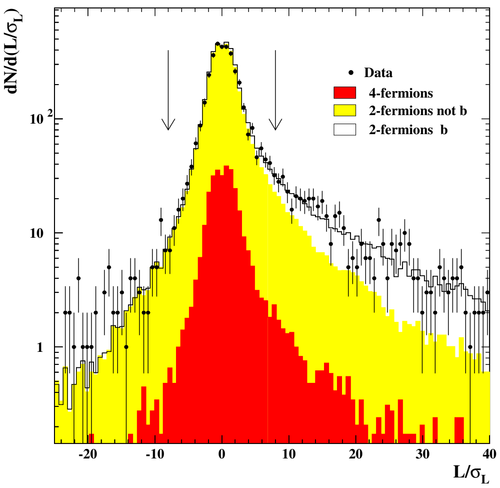

Figure 3. Significance of the decay length measurement by OPAL.

It is assigned a positive sign, if it lays in the same hemisphere relative to the IP as an associated jet, or negative otherwise. The decay length significance, L/σ_L, is defined as a ratio of the decay length to its measurement error. This significance is used by OPAL (Fig.3) for tagging b-events. The selection of secondary vertices with $L/\sigma_L > 8$ gives a purity of about 75%. Another technique is used by ALEPH and L3. Instead of reconstructing the secondary decay vertex, it is possible to use the impact parameter, which is the distance of closest approach between a track and the IP, with a sign defined similar to the decay length. For each reconstructed track, using a distribution in significance of impact parameter, the probability to originate from the IP is calculated, and a combined probability P_{evt} is constructed for the whole event from all its tracks. A discriminant variable $D = -\log_{10}(P_{evt})$ is used to tag b-events (Fig.4). A cut on D is optimized to maximize the ratio of signal to background. The ALEPH efficiency of the b-events selection is about 40% with a purity of 80-90%. For the measurement of R_c ALEPH developed a neural network which is applied to $b\bar{b}$ depleted events with $D < 2$. In L3 a cut $D > 2.5$ gives b purity above 70% for an efficiency in excess of 40%. DELPHI combines the impact parameter lifetime variable with the mass

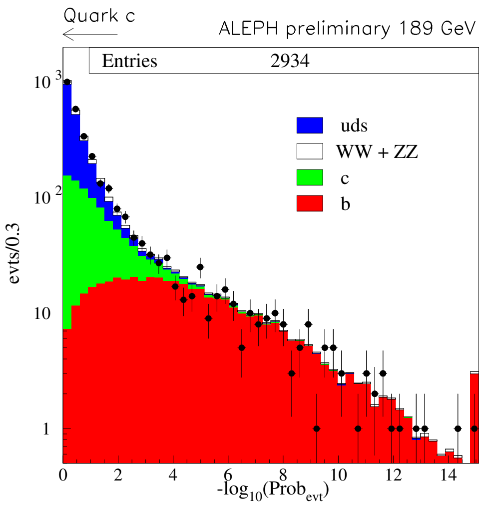

Figure 4. Discriminating variable $D = -\log_{10}(P_{evt})$ used by ALEPH.

of the secondary vertex (if present) and the rapidities of tracks (Fig.5). The selection of events with $btag > 0.625$ produces a sample with purity of about 90%.

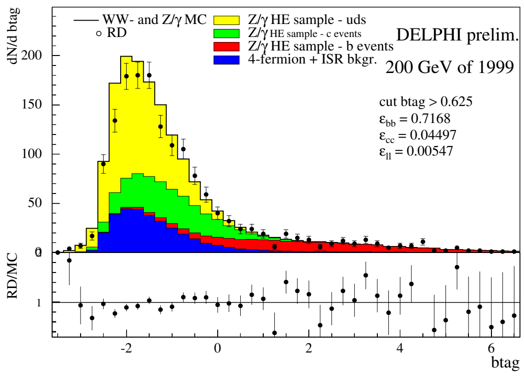

Figure 5. b-tag variable of DELPHI.

For the measurement of forward-backward asymmetry, the charge of the quark, producing a jet, has to be known. It is identified with two methods. One method relies on the jet (or hemisphere) charge. The jet charge is defined as a mean track charge, weighted with the component of the momentum of the track, longitudinal to jet axis, taken in some power. The power is selected to minimize the uncertainty in the final result. Values of this power range from 0.3 to 0.6. The mean charge difference between forward and backward jets (or hemispheres) is calculated, and its sign is sensitive to whether the quark goes in the forward or backward direction. This method is used by ALEPH, DELPHI and OPAL. Another method, which takes a charge of hard prompt lepton from a decay of the quark, is used by L3 and OPAL, which also uses slow pions from charmed mesons decays. The availability of results on R

Table 1
Available $R_{b(c)}$ measurements.

$\sqrt{s}$ (GeV)	R_b				R_c			
	A	D	L	O	A	D	L	O
133	F	F	F	F	-	-	-	-
167	F	F	F	F	-	-	-	-
183	F	P	F	F	F	-	-	-
189	P	P	F	F	P	-	-	-
192 to 202	P	P	P	-	-	-	-	-
205 and 207	-	P	P	-	-	-	-	-

and A_{fb} is summarized in Tables 1 and 2. "F" means final (published) results [1–4], and "P" - preliminary results [5–10].

Table 2
Available A_{fb} measurements.

$\sqrt{s}$ (GeV)	A_{fb}^{bb}				$A_{fb}^{c\bar{c}}$			
	A	D	L	O	A	D	L	O
133	-	F	-	F	-	F	-	F
167	-	F	-	F	-	F	-	F
183	F	-	-	F	P	-	-	F
189	P	P	F	F	P	-	-	F
192 to 202	P	P	-	-	-	-	-	-
205 and 207	-	P	-	-	-	-	-	-

All available results of the four LEP experiments, both published and preliminary, were combined [11]. The preliminary combinations of

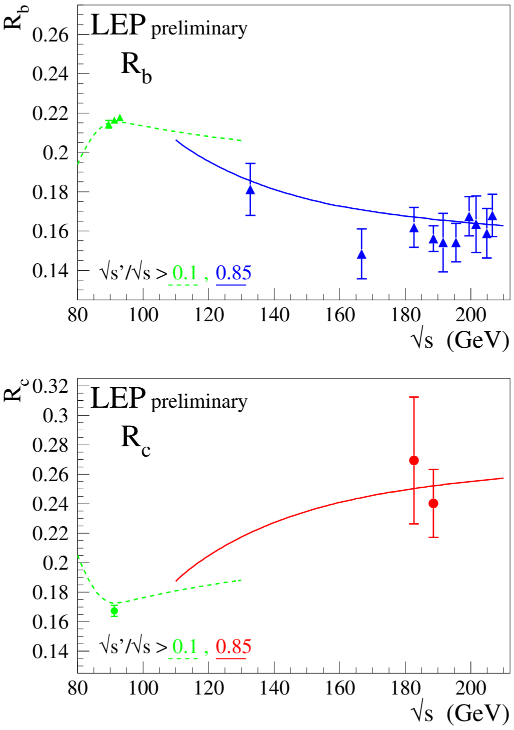

Figure 6. Combined R_b and R_c LEP measurements.

the R_b and R_c measurements are shown in Fig.6, and of the A^b_{fb} and A^c_{fb} measurements in Fig.7. Statistical errors, systematic errors and their correlation are taken into account. The lines represent the predictions of the Standard Model, calculated the with the ZFITTER program [12]. The data are in good agreement with these predictons.

These combined results are used to constrain the contact interactions [13,14] between electrons and b and c quarks . Table 1 summarizes 95% CL upper limits on the scale of contact interactions, Λ, for constructive (+) and destructive (-) interference with the Standard Model.

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Table 3
95% CL limits on the scale of contact interactions Λ (TeV).

	$e^+e^- \to b\bar{b}$		$e^+e^- \to c\bar{c}$	
Model	Λ^-	Λ^+	Λ^-	Λ^+
LL	9.3	11.8	5.3	1.3
RR	2.2	7.7	4.6	1.5
VV	10.0	13.3	7.4	6.7
AA	11.6	14.6	6.6	5.0
LR	3.1	5.5	3.5	2.1
RL	7.0	2.5	2.9	2.6
V0	11.0	13.9	6.9	1.4
A0	6.4	4.0	4.0	2.6

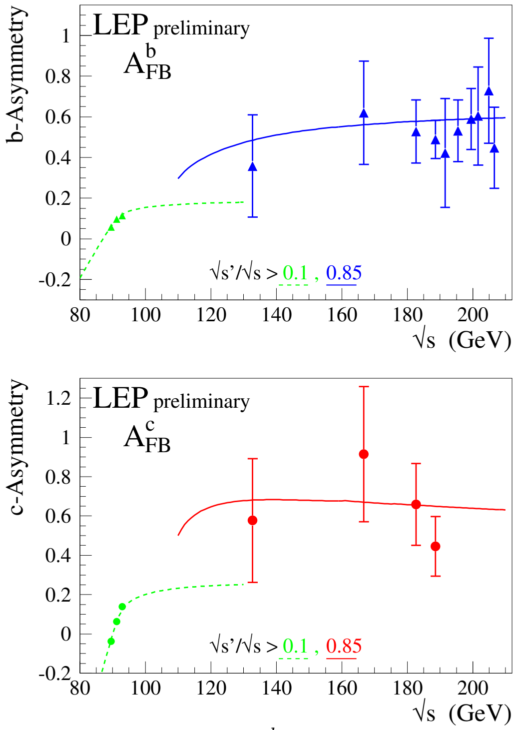

Figure 7. Combined A^b_{fb} and A^c_{fb} LEP measurements.

REFERENCES

1. ALEPH Collaboration, Study of Fermion Pair Production in e^+e^- Collisions at 130-183 GeV, Eur. Phys. J. C12 (2000) 183.
2. DELPHI Collaboration, Measurement and Interpretation of Fermion-Pair Production at LEP energies from 130 to 172 GeV, Eur. Phys. J. C11 (1999) 383.
3. L3 Collaboration, Measurements of the $b\bar{b}$ production cross section and forward-backward asymmetry at center-of-mass energies above the Z pole at LEP, Phys. Lett. B485 (2000) 71.
4. OPAL Collaboration, Measurements of R_b, A^b_{FB} and A^c_{FB} in e^+e^- Collisions at 130-189 GeV, Eur. Phys. J. C16(2000) 41.
5. ALEPH Collaboration, Fermion Pair Production in e^+e^- Collisions at 189 GeV and Limits on Physics beyond the Standard Model, ALEPH 99-018 CONF 99-013 (1999).
6. ALEPH Collaboration, Measurement of R_c at $\sqrt{S} = 189$ GeV/c^2, ALEPH 2000-046 CONF 2000-026 (2000).
7. ALEPH Collaboration, Fermion Pair Production in e^+e^- Collisions from 192 to 202 GeV and Limits on Physics beyond the Standard Model, ALEPH 2000-047 CONF 2000-030 (2000).
8. ALEPH Collaboration, Fermion Pair Production in e^+e^- Collisions at High Energy Limits on Physics beyond the Standard Model, ALEPH 2001-019 CONF 2001-016 (2001).
9. DELPHI Collaboration, A Measurement of the Cross Section Ratio R_b and the Forward-Backward Asymmetry A^b_{fb} for $b\bar{b}$ Events with the DELPHI Detector at LEP2, DELPHI 2001-095 CONF 523 07 (2001).
10. L3 Collaboration, Measurement of R_b at $\sqrt{s} = 192$ - 208 GeV, L3 Note 2640 (2001).
11. LEPEWWG $f\bar{f}$ Subgroup, Combination of the LEP II $f\bar{f}$ Results, LEP2FF/01-02, ALEPH2001-076 PHYSICS 2001-026, DELPHI 2001-128 PHYS 904, L3 note 2712, OPAL TN704 (2001). http://lepewwg.web.cern.ch/LEPEWWG/lep2/summer2001/Welcome.html
12. D. Bardin et al. ZFITTER v.6.21. A Semi-Analitical Program for Fermion Pair Production in e^+e^- Annihilation, DESY-99-070 (hep-ph/9908433), v.2 (02/2000). (Version v.6.23 is used).
13. E. Eichten et al., Phys. Rev. Lett. 50 (1983) 811.
14. H. Kroha, Phys. Rev. D46 (1992) 58.