ELECTRO-WEAK COUPLINGS FROM HEAVY FLAVORS AT LEP

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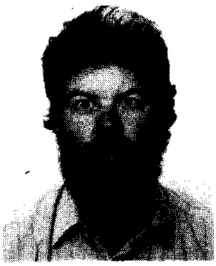

ABSTRACT

This talk presents the results of the four LEP experiments, Aleph, Delphi, L3 and Opal, on the partial widths for $Z^0 \to c\bar{c}$ and $Z^0 \to b\bar{b}$ ($\Gamma_{c\bar{c}}$ and $\Gamma_{b\bar{b}}$), and the forward-backward asymmetries $A_{c\bar{c}}$ and $A_{b\bar{b}}$.

INTRODUCTION

The determination of the couplings of quarks to the Z^0 provides tests of the Standard Model. The forward-backward asymmetry for b- and c-quarks is sensitive to the weak mixing angle $\sin^2\theta_W$.[1-3] The partial width of $Z^0 \rightarrow b\bar{b}$ is relatively independent of the top quark mass,[2,4] and thus a precise measurement can be a decisive test for the Standard Model.

This talk presents the results of the four LEP experiments, Aleph, Delphi, L3 and Opal, on the partial widths for $Z^0 \rightarrow c\bar{c}$ and $Z^0 \rightarrow b\bar{b}$ ($\Gamma_{c\bar{c}}$ and $\Gamma_{b\bar{b}}$), and the forward-backward asymmetries $A_{c\bar{c}}$ and $A_{b\bar{b}}$. Most results are based on the 1989 and 1990 data samples, which consist of between 100k and 175k hadrons.

The Aleph, L3 and Opal collaborations[5-9] tag events containing b- or c-quarks by identifying a lepton coming from the semi-leptonic decay of the quark. For the case of the b-quark, the high mass of the quark and its hard fragmentation tend to produce leptons with high momentum and high transverse momentum with respect to the jet axis. For c-quarks, both the momentum and transverse momentum tend to be lower.

Both Aleph and Opal use the JADE[10] algorithm to form jets. L3 uses a geometric algorithm based on a cone with 30° opening angle.[11] L3 removes the lepton when calculating the jet direction, whereas both Aleph and Opal include the lepton. Thus, the $p_\perp$ calculated by L3 tends to be overestimated. However, they have found that this method increases the sensitivity to b-quark events.

Figure 1 shows the $p_\perp$ distributions determined by the 3 experiments. Shown are the comparisons between the data and the Monte-Carlo expectations for the signal and background processes. As can be seen, the leptons from the semi-leptonic decay of b-quarks (labeled "prompt b", "primary b", or "b-→ μ") have a higher $p_\perp$ than leptons from other sources. Also the effect of including or excluding the lepton from the jet calculation is clearly visible.

By using inclusive leptonic events, both the partial widths and the forward-backward asymmetry can be studied. The ratio of the number of hadronic events containing leptons to the total number of hadronic events can be used to determine the quantity

$$\Gamma_{x\bar{x}} \cdot \mathrm{Br}(x \rightarrow \ell X)/\Gamma_{had} \qquad (x = b \text{ or } c). \tag{1}$$

To extract the partial width, the semi-leptonic branching ratio, as well as the total hadronic width, must be known. To measure the asymmetry, the charge of the lepton is used to

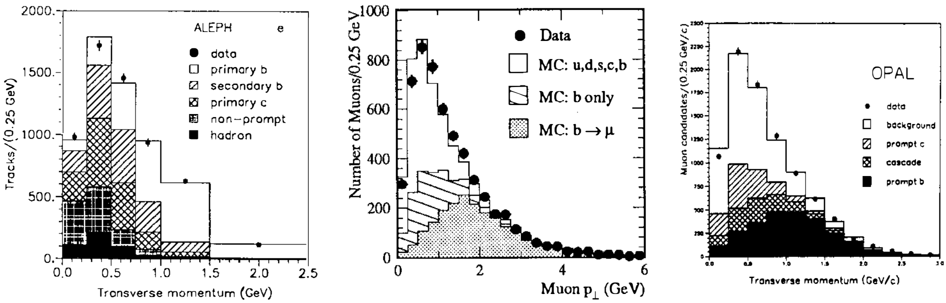

Figure 1. The $p_\perp$ distributions for Aleph electron, L3 muon and Opal muon events. Events at high-$p_\perp$ are clearly dominated by b-quark decay.

determine the charge of the quark. The thrust axis of the event is used to approximate the direction of the quark.

The Delphi collaboration uses different approaches to measure $\Gamma_{b\bar{b}}$ and $\Gamma_{c\bar{c}}$. For $\Gamma_{b\bar{b}}$ they the method of boosted sphericity[12,13] to separate $b\bar{b}$ events from other events. This method relies on the fact that since b-quarks are heavier than u, d, s, and c quarks, they move slower in the lab frame. If one transforms each of the two jets to its own center-of-mass frame, using the boost for b-quarks, then the b-quark jets will be more spherical than for the other quarks. The product of the sphericities of the two jets is used to separate b-quark events from other events.

For $\Gamma_{c\bar{c}}$, Delphi use low-$p_\perp$ π's to tag the decay $D^{*\pm} \rightarrow \pi^\pm D^0$.[14] They count the number of such π's, and use measurements from lower center-of-mass energy experiments for the probability of a c-quark to fragment into a $D^{*\pm}$, to determine $\Gamma_{c\bar{c}}/\Gamma_{had}$. (Note that Aleph and Opal have reported measurements using reconstructed D^*'s. See Reference 15.)

DETERMINATION OF $\Gamma_{b\bar{b}}$

Aleph has measured $\Gamma_{b\bar{b}} \cdot \text{Br}(b \dashrightarrow \ell X)/\Gamma_{had}$ counting high $p_\perp$ electrons and muons in their 1989 data sample.[5] They have not yet reported a measurement using their 1990 data. Their value is $0.0224 \pm 0.0016(\text{stat}) \pm 0.0010(\text{sys})$. The results for electrons and muons alone are consistent with each other: $0.0217 \pm 0.0019 \pm 0.0010$ and $0.0238 \pm 0.0028 \pm 0.0012$, respectively.

L3's measurement is based on a two-dimensional fit in p and $p_\perp$ for electrons and muons with $p_\perp > 1.0$ GeV.[8] The cut in $p_\perp$ reduces the contribution due to c-quarks, and thus reduces the systematic error due to uncertainties in the c-quark semi-leptonic branching ratio. They quote the result in terms of $\Gamma_{b\bar{b}}$, which can be converted back into $\Gamma_{b\bar{b}} \cdot \mathrm{Br}(b \to \ell X)/\Gamma_{had}$. Their result is $0.0259 \pm 0.0005 \pm 0.0007$. Measurements for electrons and muons separately yield $0.0249 \pm 0.0008 \pm 0.0010$ and $0.0265 \pm 0.0006 \pm 0.0007$.

The Opal measurement[9] uses a fit in p and $p_\perp$ over the full range. Their result is $0.0226 \pm 0.0007 \pm 0.0013$. If they count only the high-$p_\perp$ muons the result is $0.0218 \pm 0.0007 \pm 0.0026$.

The measurements are summarized in Table 1. There is a possible problem in that the L3 and Opal results disagree by almost 2 standard deviations. The average of the three measurements is

$$\Gamma_{b\bar{b}} \cdot \mathrm{Br}(b \to \ell X)/\Gamma_{had} = 0.0247 \pm 0.009. \tag{2}$$

An attempt has been made to take into account common sources of systematic errors. Examples are the effects of fragmentation, since all three experiments use the Lund[16] Monte-Carlo. Another source is the uncertainties in the rate of high-mass D-mesons in the decay of B-mesons.[8] A conservative estimate is that these sources contribute 0.006 to the error.

To extract $\Gamma_{b\bar{b}}$ we now need Γ_{had} and $\mathrm{Br}(b \to \ell X)$. The total hadronic width has been reported at this conference:[17] $\Gamma_{had} = 1740 \pm 9$ MeV, using the results of all four LEP experiments.

The situation with the semi-leptonic branching ratio is more complicated. Measurements of $\mathrm{Br}(b \to \ell X)$ have been performed at CESR and DORIS[18] for low-mass B-mesons, which are produced at the $\Upsilon(4S)$. These results are not directly applicable to $Z^0 \to b\bar{b}$ events, where a large spectrum of B-mesons and b-baryons is produced in the fragmentation process. The semi-leptonic branching fractions measured at PETRA and PEP can be used, but the world average value has an error of about 6%[19] and is thus the dominant error on $\Gamma_{b\bar{b}}$. Independent measurements of $\mathrm{Br}(b \to \ell X)$ from $Z^0 \to b\bar{b}$ are needed to improve the precision.

One new measurement of $\mathrm{Br}(b \to \ell X)$ comes from the L3 Collaboration.[8] They have used the ratio of the number of high-$p_\perp$ dilepton events to high-$p_\perp$ single lepton events. To first order, after correcting for backgrounds, this ratio is proportional to $\mathrm{Br}(b \to \ell X)$, and is independent of $\Gamma_{b\bar{b}}$. Their result is $\mathrm{Br}(b \to \ell X) = 0.113 \pm 0.010 \pm 0.006$. Combining this result with the world average PEP/PETRA value (0.120 ± 0.007) yields the new average:

$$\mathrm{Br}(b \dashrightarrow \ell X) = 0.118 \pm 0.006. \tag{3}$$

Using results (2) and (3) we obtain 0.209 ± 0.013 for $\Gamma_{b\bar{b}}/\Gamma_{had}$, averaged over the results from Aleph, L3 and Opal. Including the preliminary Delphi result using boosted sphericity,[13,20] $\Gamma_{b\bar{b}}/\Gamma_{had} = 0.208 \pm 0.015 \pm 0.020$, and using the LEP average for Γ_{had}, we obtain:

$$\Gamma_{b\bar{b}} = 364 \pm 19 \text{ MeV}, \tag{4}$$

in good agreement with the Standard Model prediction of 377 MeV. The results are summarized in Table 1.

	$\Gamma_{b\bar{b}} \cdot \mathrm{Br}(b \to \ell X)/\Gamma_{had}$	$\Gamma_{b\bar{b}}/\Gamma_{had}$	$\Gamma_{b\bar{b}}$
Aleph	$0.0224 \pm 0.0016 \pm 0.0010$		
L3	$0.0259 \pm 0.0005 \pm 0.0007$		
Opal	$0.0226 \pm 0.0007 \pm 0.0013$		
Average	0.0247 ± 0.0009	0.209 ± 0.013	
Delphi		$0.208 \pm 0.015 \pm 0.020$	
Average		0.209 ± 0.011	364 ± 19 MeV

Table 1. Summary of the LEP results on $\Gamma_{b\bar{b}}$.

DETERMINATION OF $\Gamma_{c\bar{c}}$

The determination of $\Gamma_{c\bar{c}}$ has been done in a similar manner as for $\Gamma_{b\bar{b}}$. However, the measurement using inclusive leptons is more difficult, since the leptons from c-quark decay have lower p and $p_\perp$, and populate a region that has more background than in the b-quark case. Only Aleph and Opal have reported results using leptons, whereas Delphi has used the method of low-$p_\perp$ π's. The results are summarized in Table 2.

The Aleph result is $\Gamma_{c\bar{c}} \cdot \mathrm{Br}(c \dashrightarrow \ell X)/\Gamma_{had} = 0.0133 \pm 0.0040^{+0.0038}_{-0.0031}$[5] using inclusive electrons from their 1989 data only. They have made a fit to the full p and $p_\perp$ spectrum.

Opal has used a fit to the full p and $p_\perp$ spectrum for inclusive muons to obtain the result $0.0176 \pm 0.0025 \pm 0.0042$.[9]

The world average semi-leptonic branching ratio from the PEP and PETRA data is $\mathrm{Br}(c \to \ell X) = 0.096 \pm 0.006$.[19] Using this value yields $\Gamma_{c\bar{c}}/\Gamma_{had} = 0.163 \pm 0.040$ for the average of the Aleph and Opal results. Including the Delphi result, $\Gamma_{c\bar{c}}/\Gamma_{had} = 0.163 \pm 0.030 \pm 0.050$,[14] and the LEP average for Γ_{had}, we obtain

$$\Gamma_{c\bar{c}} = 283 \pm 57 \text{ MeV} \tag{5}$$

as the LEP average. This should be compared to the Standard Model value of 296 MeV. The LEP result is in good agreement with the Standard Model, but one can see that much work (and statistics!) is needed to make a precise test.

	$\Gamma_{c\bar{c}} \cdot \mathrm{Br}(c \to \ell X)/\Gamma_{had}$	$\Gamma_{c\bar{c}}/\Gamma_{had}$	$\Gamma_{c\bar{c}}$
Aleph	$0.0133 \pm 0.0040^{+0.0038}_{-0.0031}$		
Opal	$0.0176 \pm 0.0025 \pm 0.0042$		
Average	0.0157 ± 0.0037	0.163 ± 0.040	
Delphi		$0.162 \pm 0.030 \pm 0.050$	
Average		0.163 ± 0.033	283 ± 57 MeV

Table 2. Summary of the results for $\Gamma_{c\bar{c}}$.

Determination of the Forward-Backward Asymmetry

The forward-backward asymmetry is defined as

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}, \tag{6}$$

where σ_F and σ_B are the forward and backward cross-sections. The angular distribution is

$$\frac{1}{N}\frac{dN}{d\cos\theta_q} = 1 + \cos^2\theta_q + \frac{8}{3}A_{FB}\cos\theta_q, \tag{7}$$

where θ_q is the direction of the quark.

The thrust axis of the event is used to approximate the direction of the quark, and the charge of the lepton from the semi-leptonic decay is used to determine the charge of the quark. Thus, for b-quarks, the direction of the quark is

$$\cos\theta_b = -q_\ell \cos\theta_{thrust},$$

whereas for c-quarks it is

$$\cos\theta_c = \quad q_\ell \cos\theta_{thrust}.$$

One must correctly take into account the effects of backgrounds, including the cascade decay, $b \to c \to \ell X$, as this process yields a lepton with the opposite charge compared to the direct $b \to \ell X$ decay.

For b-quarks, there is the additional complication of B^0-$\bar{B}^0$ mixing which reduces the observed asymmetry:

$$A_{FB}^{obs} = A_{FB} \cdot (1 - 2\chi),$$

where χ is the mixing parameter. For χ of 0.14 this amounts to a 39% correction. The error on χ is one of the dominant errors in the determination of A_{FB}.

Both Aleph and L3 determine $A_{FB}(b)$ using inclusive electrons and muons. A fit is made to the data as a function of $-q_\ell \cos\theta$, p and $p_\perp$, with A_{FB} as a free parameter. In addition, Aleph also fits for $A_{FB}(c)$. Both groups use the complete data sample, including the data not on the Z^0 peak. Aleph corrects the off-peak data to the peak energy, using the energy dependence of A_{FB} from the Standard Model. L3 gives the effective center-of-mass energy for which their result is valid. The difference between the actual peak energy and the effective energy is very small, and can be neglected. Both experiments give their result including the correction for mixing, however, they use different values of χ. Thus, to compare results, the mixing correction must be removed.

The result from Aleph[6] is $A_{FB}(b) = 0.126 \pm 0.028 \pm 0.012$, where they have used a value for χ of $0.132^{+0.027}_{-0.026}$. Removing the correction for χ yields $0.0927 \pm 0.0206 \pm 0.0056$. Their result for $A_{FB}(c)$ is $0.064 \pm 0.039 \pm 0.030$.

L3's result[7] is $A_{FB}(b) = 0.130^{+0.044}_{-0.042} \pm 0.02$ for $\chi = 0.178^{+0.049}_{-0.040} \pm 0.02$. For $\chi = 0.0$, their result is $0.084 \pm 0.025 \pm 0.015$.

Opal uses only high-$p_\perp$ muons from their on-peak data sample to determine $A_{FB}(b)$.[9] They fit the $-q_\ell \cos\theta_{thrust}$ distribution, and correct for the effects of background. Their result is $A_{FB}(b) = 0.072 \pm 0.042 \pm 0.010$, with no correction for mixing.

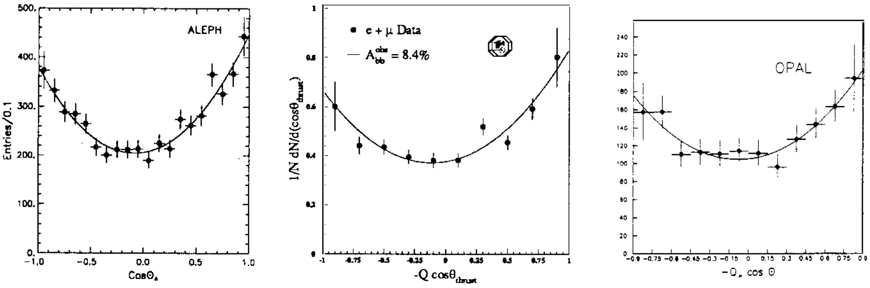

Figure 2. The angular distribution of the signed thrust axis for Aleph, L3 and Opal. The curves are from the fits that the individual experiments have performed.

The average over the three measurements is $A_{FB} = 0.087 \pm 0.016$, without the mixing correction. The angular distributions are shown in Figure 2 for the three experiments.

To correct for mixing, we use the average of the Aleph[21] and L3[22] χ measurements, which yields $\chi = 0.144 \pm 0.023$.★ We then obtain for the LEP average

$$A_{FB}(b) = 0.122 \pm 0.024, \qquad (8)$$

at $\sqrt{s} = 91.22$ GeV. The results are summarized in Table 3.

	$A_{FB}(b)$ (no mixing)	$A_{FB}(b)$ corrected	$A_{FB}(c)$
Aleph	$0.0927 \pm 0.0206 \pm 0.0056$		$0.064 \pm 0.039 \pm 0.030$
L3	$0.084 \pm 0.025 \pm 0.015$		
Opal	$0.072 \pm 0.042 \pm 0.010$		
Average	0.087 ± 0.016	0.122 ± 0.024	0.064 ± 0.049

Table 3. Summary of the forward-backward asymmetry results.

★ If we include the preliminary Aleph result using the jet charge method,[15] the average changes to $\chi = 0.123 \pm 0.017$.

DETERMINATION OF $\sin^2\theta_W$

In the Standard Model, using the improved Born approximation framework,[1-4] the forward-backward asymmetry on the peak is given by

$$A_{FB}^{Born} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b, \tag{9}$$

where

$$\mathcal{A}_i = \frac{2v_ia_i}{v_i^2 + a_i^2} = \frac{2(1 - 4|Q_i|\sin^2\overline{\theta}_W}{1 + (1 - 4|Q_i|\sin^2\overline{\theta}_W)^2}. \tag{10}$$

Here v_i, a_i and Q_i are the vector and axial-vector coupling constants of the electron and b-quark, and $\sin^2\overline{\theta}_W$ is the effective weak mixing angle. To compare the measured asymmetry to this Born level calculation, QED and QCD corrections as well as the shift between the Z^0 mass and the effective center-of-mass energy must be taken into account. These corrections amount to a change of 0.007 to the asymmetry. Including these corrections, the asymmetry measurement of $A_{FB}(b) = 0.122 \pm 0.024$ corresponds to

$$\sin^2\overline{\theta}_W = 0.227 \pm 0.004. \tag{11}$$

Alternatively, we can compare the prediction of the Standard Model for the top quark mass as a function of the asymmetry. For this we have used the ZFITTER[23] program with the following ranges of parameters: $50 < M_{Higgs} < 1000$ GeV, $M_{Z^0} = 91.174 \pm 0.020$ GeV, $\sqrt{s} = M_{Z^0} + 0.040$ GeV, and $\alpha_s = 0.115 \pm 0.009$. The asymmetry as a function of m_{top} is shown in Figure 3. As can be seen, with the present statistics the error on the asymmetry is still a little too large to set a limit on the mass of the top quark.

SUMMARY AND OUTLOOK

After the first year and a half of data-taking at LEP, much has been accomplished. We now know the partial width of $Z^0 \to b\bar{b}$ with an error of 5%: $\Gamma_{b\bar{b}} = 364 \pm 19$ MeV. The main contribution to the error is the knowledge of the semi-leptonic branching ratio. This should improve when the other LEP experiments complement the L3 measurement.

The partial width of $Z^0 \to c\bar{c}$ is not nearly as well measured: $\Gamma_{c\bar{c}} = 283 \pm 57$ MeV. Here the main problems are the separation of the signal and the background. More work is needed to reduce the error.

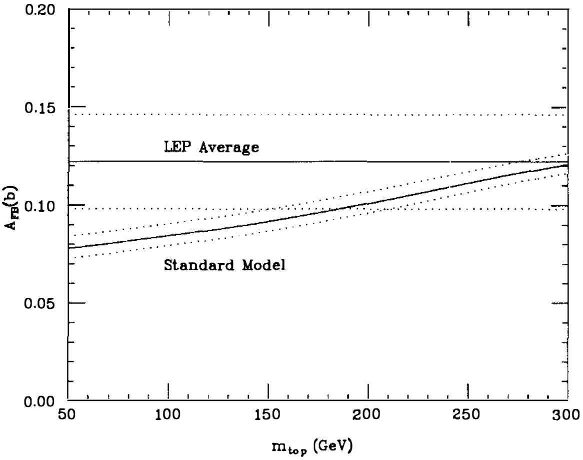

Figure 3. The prediction of the Standard Model for $A_{FB}(b)$ as a function of the top quark mass. The range shown for the prediction is due to the variations of the input parameters as described in the text. Shown also is the LEP average value for $A_{FB}(b)$.

The forward-backward asymmetry for $b\bar{b}$ is known to 20%: $A_{FB}(b) = 0.122 \pm 0.024$. The main errors come from statistics and the error on the mixing, which in turn is mainly statistical. Thus, improvements on this measurement should be straight-forward: just get more data! Even so, this value alone allows a very good determination of the weak mixing angle: $\sin^2 \overline{\theta}_W = 0.227 \pm 0.004$.

The $c\bar{c}$ asymmetry is not very well measured yet: $A_{FB}(c) = 0.069 \pm 0.049$. Here also, improvements should be straight-forward, as only Aleph has reported a measurement. A factor four in statistics is immediately available when the other experiments report their measurements.

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