SLAC–PUB–7649
September 1997

Production of Heavy Flavors at the Z^0 and Electroweak Couplings*

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Abstract

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Invited talk presented at 7th International Symposium on Heavy Flavor Physics,
Santa Barbara, CA, USA,
July 7 - 11, 1997

*Work supported by Department of Energy contract DE–AC03–76SF00515.

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1 Introduction

The electroweak (EW) couplings of heavy quarks to the Z^0 have been aggressively studied since data was first taken at LEP and SLC eight years ago. These couplings are of interest as c and b are the only charge $\frac{2}{3}$ and $-\frac{1}{3}$ quarks which can be cleanly isolated in hadronic Z^0 decay. New physics, which might couple to heavy mass, could stand out against the precise predictions of the EW theory. Originally R_b held the most interest due to its sensitivity to m_t, but this has since been resolved by direct measurement of m_t.

Except where noted, averages presented in this paper are those of the LEP EW Working Group [1] as compiled from LEP and SLD publications and contributions to conferences through Winter/Spring 1997. As the quoted results include various modifications, the original papers (listed in Ref 1) should be consulted for further detail. And remember, many of the measurements cited are preliminary conference submissions, and may change significantly.

In the EW standard model (SM) at tree level, the coupling of a fermion f to the Z^0 is given by two parameters, its axial coupling $a_f = \pm\frac{1}{2}$ and its vector coupling $v_f = a_f - 2Q_f \sin^2\theta_W^{eff}$. The fermion right-handed coupling $g_R = \frac{1}{2}(v_f - a_f)$ and left-handed coupling $g_L = \frac{1}{2}(v_f + a_f)$ to the Z^0 is another way to express these two parameters. For heavy quarks, the two measured quantities used to determine (to sign ambiguities[†]) these parameters are

$$R_Q^{SM} = \frac{v_Q^2 + a_Q^2}{\sum_q (v_q^2 + a_q^2)} = \frac{g_{LQ}^2 + g_{RQ}^2}{\sum_q (g_{Lq}^2 + g_{Rq}^2)} = \frac{\Gamma_{QQ}}{\Gamma_{had}} \tag{1}$$

and

$$A_Q^{SM} = \frac{2v_Q a_Q}{v_Q^2 + a_Q^2} = \frac{g_{LQ}^2 - g_{RQ}^2}{g_{LQ}^2 + g_{RQ}^2}. \tag{2}$$

[†]These sign ambiguities are resolved with off-resonance data.

Table 1: b and c quark electroweak parameters *at tree level* for $\sin^2\theta_W^{eff} = 0.2315$.

	a	v	g_L	g_R	R^{SM}	A^{SM}	$\partial A_f/\partial \sin^2\theta_W$
c	0.5	+0.19	+0.35	-0.15	0.17	0.67	-3.5
b	-0.5	-0.35	-0.42	+0.08	0.22	0.94	-0.6

For b quarks, R_b (A_b) is most sensitive to the left-(right-)handed coupling:

$$\delta R_b/R_b \sim -3.57\delta g_L + 0.65\delta g_R, \quad \delta A_b/A_b \sim -0.31\delta g_L + 1.72\delta g_R. \tag{3}$$

The left-handed Wtb coupling changes g_{Lb}, so SM prediction for R_b^{SM} and R_c^{SM} become 0.2158 and 0.172, while A_b^{SM} and A_c^{SM} change very little.

The production rate ratios R_b and R_c are used since large QCD and other corrections mostly cancel. A_b and A_c are measured from forward-backward (FB) asymmetries in $e^+e^- \to Z^0 \to f\overline{f}$. For an e^- beam of polarization $P_e = \frac{N_R - N_L}{N_R + N_L}$ interacting with an unpolarized e^+ beam at the Z^0 resonance:

$$d\sigma_f/d\cos\theta \propto (1 - A_e P_e)(1 + \cos\theta) + 2(A_e - P_e)A_f \cos\theta. \tag{4}$$

The FB asymmetry derived from this angular distribution is:

$$A_{FB}^f(P_e) = \frac{\sigma^f(\cos\theta > 0) - \sigma^f(\cos\theta < 0)}{\sigma^f(\cos\theta > 0) + \sigma^f(\cos\theta < 0)} = \frac{3}{4}\frac{A_e - P_e}{1 - A_e P_e}A_f. \tag{5}$$

For $P_e = 0$ (LEP), $A_{FB}^f = \frac{3}{4}A_e A_f$. For $P_e \neq 0$ (SLC), another asymmetry independent of A_e can be formed:

$$\tilde{A}^f = \frac{\sigma_L^f(>) - \sigma_L^f(<) - \sigma_R^f(>) + \sigma_R^f(<)}{\sigma_L^f(>) + \sigma_L^f(<) + \sigma_R^f(>) + \sigma_R^f(<)} = \frac{3}{4}|P_e|A_f, \tag{6}$$

where L and R denote the predominant helicity of the e^- beam. Examples of unpolarized and polarized FB asymmetries are shown in Fig 1.

Along with lepton asymmetries (A_{LR}, P_τ, A_{FB}^ℓ), A_{FB}^b is quite sensitive to $\sin^2\theta_W^{eff}$, though A_b is not. While this gives added impetus to measuring A_{FB}^b at LEP, it does couple this measurement tightly to the others.

In many ways LEP and SLD measurements of R_Q and A_Q are complimentary. While they share many of the same physics systematic errors, some dominant ones are very different. SLD needs a factor of $(|P_e|/A_e)^2 \sim (0.75/0.15)^2 \sim 25$ fewer events for same statistical error on A_Q. The situation is not as favorable for R_Q measurements, though fundamental differences between linear

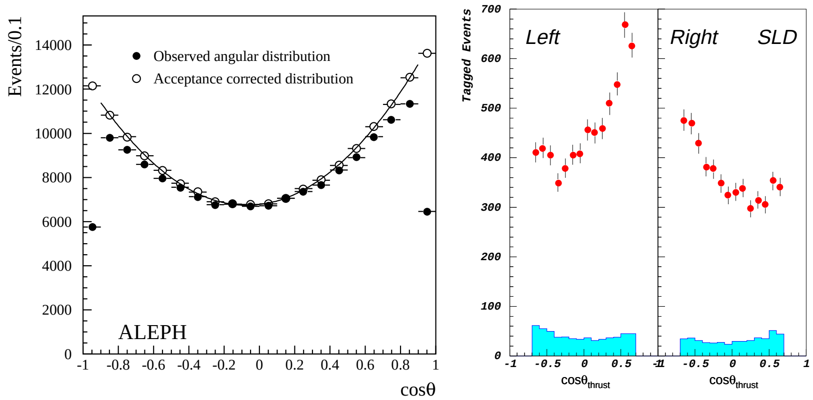

Figure 1: The polar angle distributions for $Z^0 \to b\bar{b}$ events tagged with a) high-p_T leptons by ALEPH and b) lifetime and jet-charge by SLD (shown separately for left- and right-handed polarized electrons).

colliders and storage rings allow SLD to make up some of the large difference in integrated luminosity ($\sim$ 4.1M Z^0/experiment at LEP vs $\sim$ 0.2M for SLD). The stable, micron-size interaction region gives SLD the B or D production point essentially independent of tracks in the event (less correlations between hemispheres and less uncertainty in the B or D flight direction). The beam focusing and background masking allows Si vertex detectors at smaller radii, and the much lower collision rate allows the use of thin CCDs for true 3D measurements.

2 Tagging

There are many tags of heavy flavor (HF) production, such as high p and p_T leptons. However, there are many sources of these leptons to be accounted for: $b \to \ell^-$, $b \to c \to \ell^+$, $c \to \ell^+$, $b \to \overline{b} \to \ell^+$, and $b \to \overline{c} \to \ell^-$, in addition to Dalitz decays, γ conversions, decays in flight, and mis-identifications.

All of the experiments have Si vertex detectors which allow tagging based on the long lifetimes ($< \gamma\beta c\tau >\sim$ 3mm) of B and D particles. For example, impact parameter resolutions[‡] with the new SLD VXD3 are 13 and 20 μm in $r\phi$ and rz (constant terms) and 38 μm (momentum-dependent terms) while those for DELPHI are 21 μm (constant) and 66 μm (momentum-dependent).

[‡]Impact parameter resolutions are often parametrized as $A \oplus Bp^{-1}\sin^{-3/2}\theta$.

Large numbers of event shape variables, such as directed sphericity, are generally combined in neural net analyses to provide tags. Exclusively and semi-exclusively reconstructed $D^\star$ and D decays are also useful tags of $c \to D$ and $b \to c \to D$, along with the inclusive slow π_s^+ from $D^{\star +} \to \pi_s^+ D^0$. And while tags of B and D decays are very similar, there are numerous ways to differentiate them (p and p_T, vertex mass, multiplicity, or momentum, directionality to the primary vertex, ...).

3 Double Tagging

Most modern measurements of R_b (and many of R_c) use double tags. For R_b the two measured quantities are the number of hemispheres which are tagged (N_{ST}), and the number of events where both hemispheres are tagged (N_{DT}) :

$$N_{ST}/(2N_{HAD}) = \epsilon_b R_b + \epsilon_c R_c + \epsilon_{uds}(1 - R_b - R_c), \tag{7}$$

$$N_{DT}/N_{HAD} = \epsilon_b^D R_b + \epsilon_c^D R_c + \epsilon_{uds}^D (1 - R_b - R_c), \tag{8}$$

where ϵ_i (ϵ_i^D) is the efficiency to tag (double tag) a hemisphere (event) produced by an $i-$ type quark. The efficiency to tag an $i-$ type quark in one hemisphere is correlated with the efficiency to tag one in the *other* hemisphere, so $\epsilon_i^D = \epsilon_i^2 + \lambda_i(\epsilon_i - \epsilon_i^2)$. There are many notations for this correlation in use: $\rho_b^{ALEPH} = C_b - 1 = \frac{\lambda_b(1-\epsilon_b)}{\epsilon_b}$. To extract R_b, MC programs tuned to many experimental constraints are used to estimate ϵ_c, ϵ_{uds}, and λ_b, R_c is set to SM predictions, λ_c and λ_{uds} are ignored, and then R_b and ϵ_b are solved for. As $N_{DT} \propto \epsilon_b^2$, the R_b statistical error is $\propto \frac{1}{\epsilon_b}$. While double tags are "clean," in that large uncertainties in B decays are removed by measuring ϵ_b directly, charm decays and hard-to-determine correlation factors due to effects like $Z^0 \to b\bar{b}g$ become dominant systematic errors. $\frac{\delta R_c}{R_c}$ and $\frac{\delta \epsilon_c}{\epsilon_c}$ contribute to $\frac{\delta R_b}{R_b}$ with a factor $\frac{2\epsilon_c R_c}{\epsilon_b R_b}$, and $\frac{\delta \lambda_b}{\lambda_b}$ contributes with a factor $\frac{\lambda_b(1-\epsilon_b)}{\epsilon_b}$. So to minimize systematic errors, one maximizes ϵ_b and minimizes ϵ_c and λ_b.

4 R_b Measurement

The values for the measurements described here are shown in Fig 2a. The only pure event shape tag is the L3 one from their 1991 data. The pure lepton-tag R_b measurements have been combined by the LEP EWWG into one average. This number represents all of the L3 data (though recent measurements are still preliminary), and data from the other experiments *before* they installed their Si vertex detectors. Until recently this was a very significant contribution to the world average, and is noticeably above the SM expectation. *If* this is

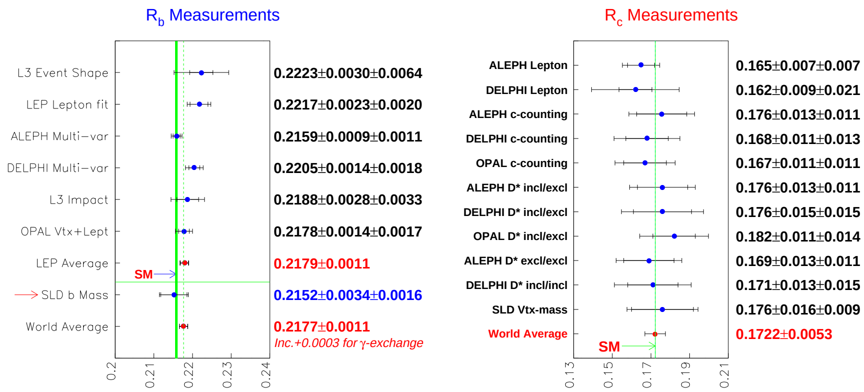

Figure 2: Measurements of a) R_b and b) R_c by the LEP and SLD experiments.

due to common systematic error, one potential source could be high p and p_T leptons from D decay not being properly accounted for. If there are more of these in the data than are represented in MCs tuned to Mark III and DELCO $c \to \ell^+$ spectra, it would result in the lepton-tagged R_b being measured high.

For LEP experiments other than L3, the lepton tags in their newer data are included in their multi-tag measurements. These multi-tags generally mix (neural net) event shape tags, leptons tags, and lifetime tags; the lifetime tags are the dominant contribution. L3 also has a pure lifetime tag with its 1994 data. This tag is similar to the *old* ALEPH lifetime tag, and the lifetime part of the DELPHI multi-tag used for their pre-1994 data is also similar. The probability that all tracks in a hemisphere with positive impact parameter significance b/σ_b come from the primary vertex (PV) is calculated and cut on; tracks with negative b/σ_b are used for calibration. As tracks from both hemispheres are used to calculate the PV, there is a large correlation through the PV. For the L3 analysis this is estimated to be $\sim -8\%$.

The lifetime tag part of the OPAL Vtx+Lept measurement fits a secondary vertex (SV) in each hemisphere, and uses a cut on decay length significance ($L/\sigma_L > 8$) as the tag (they also use negative L/σ_L to calibrate the tag). The lifetime part of the DELPHI Multi-var analysis on their 1994 data is similar to this tag. With this tag there is much less correlation through the PV ($< 0.5\%$). The OPAL, DELPHI, and L3 lifetime tags don't include their 1995 data yet, and only use $r\phi$ information from their Si vertex detectors, even though they also have rz measurements, so there is significant room for improvement for

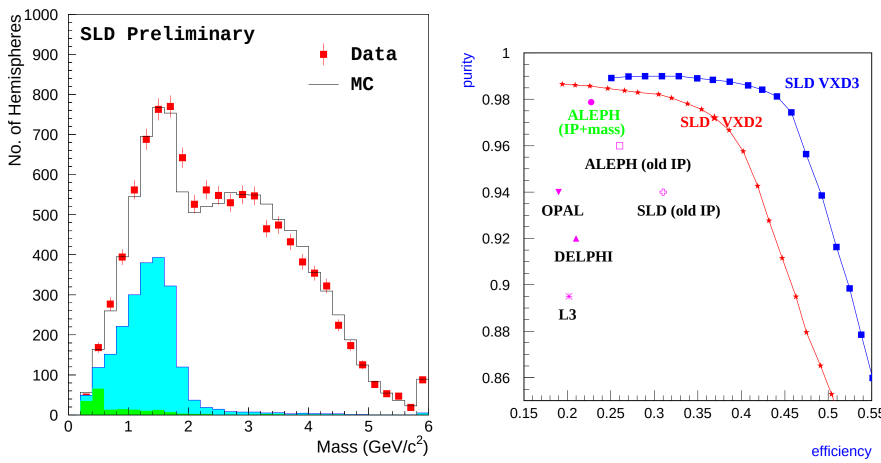

Figure 3: a) The missing-p_T corrected mass distribution for the SLD 1996 data, taken with VXD3. The shaded histograms are MC expectations for c and uds. b) A comparison of hemisphere b-tag performance.

the last 3 LEP measurements shown in Fig 2a.

ALEPH has analyzed and published R_b from their full LEP I data sample. For their hemisphere probability tag, they now find the PV separately in each hemisphere, which results in a much smaller correlation. They combine their lifetime tag with a mass tag designed to suppress long-lived charm BG, and then combine this analysis with four other tags (leptons, event shape neural nets, ...) for one number. This is the most significant measurement so far, and is in excellent agreement with the SM prediction.

SLD also uses a combination lifetime-mass tag. Their PV is the SLC interaction region, so their PV correlation is negligible. They search for a high probability SV in each hemisphere and require $L > 1$ mm. Unused tracks are assigned to the SV if the track distance-of-closest-approach to the flight path is < 1mm and is $> 25\%$ of the way to the SV. The SV mass is corrected for missing p_T with respect to the flight path (π^0s, νs, ...): $M_{corr} = \sqrt{M_{raw}^2 + p_T^2} + |p_T|$. A cut of $M_{corr} > 2.0$ GeV/c^2 separates the b signal from the $udsc$ BG. The result from their 1993-95 data (VXD2) is in Fig 2a. This week SLD reported a *preliminary* $R_b = 0.2102 \pm 0.0034 \pm 0.0021$ based on data taken in 1996 with VXD3. The M_{corr} distribution for this data (Fig 3a) shows its power at rejecting BG.

The average of all measurements shown in Fig 2a is $R_b^0 = 0.2177 \pm 0.0011$, or $\sim 1.7\sigma$ from the SM prediction. For comparison, efficiencies and purities of the various (enhanced) lifetime tags are shown in Fig 3b.

5 R_c Measurement

ALEPH and DELPHI report R_c measurements for lepton tags (Fig 2b). The ALEPH lepton tag analysis uses some lifetime information.

ALEPH, DELPHI and OPAL perform single-tagged charm-counting measurements. Here they exclusively reconstruct signature decay modes for the different charmed hadrons (D^0, D^+, D_s^+, and Λ_c), and using branching ratios and production rates measured at LEP and elsewhere, account for all direct charm production. ALEPH also performs a double-tagged measurement with exclusively reconstructed charm hadrons.

A series of measurements (ALEPH, DELPHI, OPAL) uses one hemisphere tagged by an exclusively reconstructed D decay and the other hemisphere tagged by inclusive identification of the low p_T pion from $D^{\star+} \to \pi_s^+ D^0$. In these measurements they also determine $P(c \to D^{\star+}) BR(D^{\star+} \to \pi_s^+ D^0) = 0.162 \pm 0.007$. This is lower than that measured by PEP/PETRA/ARGUS experiments, and one of the important reasons for the increase in the average measured R_c from 0.1540 ± 0.0074 (Summer 1995) to 0.1722 ± 0.0053. [2]

The SLD lifetime-mass tag (Fig 3a) provides a good charm tag for $0.55 < M_{corr} < 2.0$ GeV/c^2. They take advantage of a large difference between reconstructed momentum (p_D) for c and b at a given M_{corr} and require $p_D > 7.5$ GeV/c and $p_D + 10 > 15 M_{corr}$. This results in an efficiency of $11.2 \pm 1.0\%$ with a purity of 68.4% for their 1993-95 data (Fig 2b). This week they announced a *preliminary* measurement with their 1996 data of $R_c = 0.187 \pm 0.019 \pm 0.008$. This particular R_c measurement is not yet systematics limited, while lepton and π_s^+ BG modeling and D BRs are the major systematic errors for the LEP measurements.

6 A_c Measurement

Asymmetry measurements use single tags and need a way to identify the f (as opposed to $\overline{f}$) direction. For $D^{\star+}$ and D^+ tags this comes naturally for c; for b one has to worry about mixing. Lepton tags also directly give the f direction ($c \to \ell^+$), but beware of mis-assigned $\overline{b} \to \ell^+$. It carries $-A_b$ (~ -0.94), not A_c ($\sim +0.67$) (A_b has a similar effect). Lepton-tagged A_c and A_b measurements are generally the result of combined fits to lepton (p, p_T) spectra.

Lepton-tagged A_c measurements (Fig 4a) tend to be systematics dominated (lots of BG from $b \to \ell$), though OPAL has reduced theirs by including lifetime and event shape information. The $D^{\star+}$ tagged A_c measurements tend

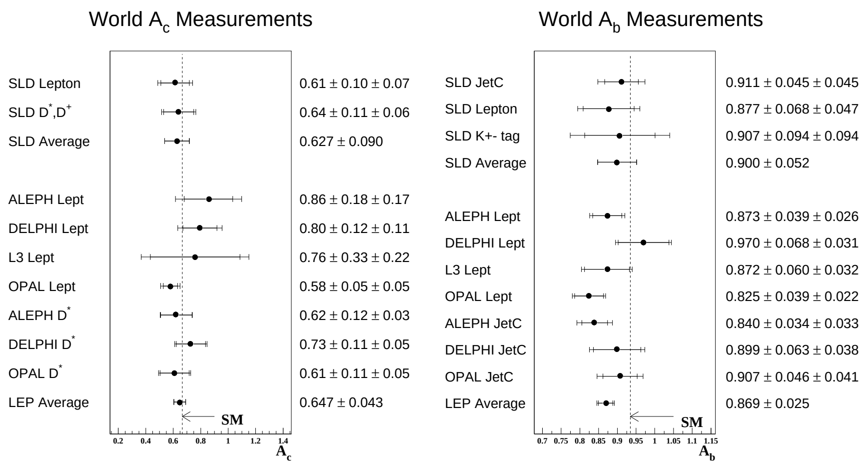

Figure 4: Measurements of a) A_c and b) A_b by LEP experiments and SLD. For LEP measurements, $A_{FB}^{0,f}$ has been converted into A_f using $A_e = 0.1512 \pm 0.0023$, the combined SLD A_{LR} and LEP A_ℓ.

to be statistics limited (low BRs for exclusive final states). For the future, SLD is investigating measuring A_c with the inclusive c tag used to measure R_c. In Fig 4 the measured LEP FB asymmetries have been corrected for A_e and the SLD ones for P_e. The world average $A_c = 0.643 \pm 0.038$ is in good agreement with SM predictions.

7 A_b Measurement

OPAL and DELPHI measure A_b with $D^{\star +}$ tags, but these have little weight in the average. All experiments use $b \to \ell^-$ tags to measure A_b. The effect of mixing is corrected for by measuring $\overline{\chi}$ with opposite sign and same sign di-lepton tags. The ALEPH event angular distribution is shown in Fig 1a for events which have been tagged with a $p_T > 1.25$ GeV/c lepton. All of their LEP I data is included in this measurement. Dominant systematic errors are the $\overline{\chi}$ correction, c fragmentation, and R_c. The error due to $b \to \overline{c} \to \ell^-$ is estimated to be small.

Most experiments measure A_b with a lifetime b tag, assigning the b direction on the basis of momentum-weighted jet-charge (vertex charge is often also used). A typical analysis forms the sum

$$Q = \Sigma q_i |\vec{p}_i \cdot \hat{T}|^\kappa \mathbf{sgn}(\vec{p}_i \cdot \hat{T}), \qquad (9)$$

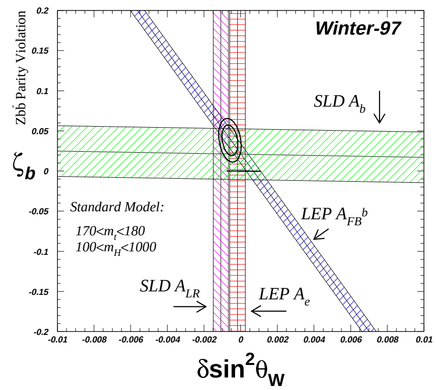

Figure 5: Plot of the TGR parameters ζ_b vs δs^2 for LEP and SLD measurements. The origin is determined by $m_t = 175$, $m_H = 300$, $\alpha_s = 0.117$, and $\alpha_{EM} = 1/128.96$, and the black band through the origin is determined by the values of m_t and m_H shown on the plot.

where $\kappa \sim 0.5$ and the thrust direction $\hat{T}$ (signed so that Q is negative) is the estimator of the b direction. Using the jet-charge analyzing power determined from a MC would bring in many B decay systematics, so the jet-charge in both hemispheres is used to self-calibrate the analyzing power. The SLD lifetime/jet-charge tagged angular distributions are shown in Fig 1b.

Both SLD and DELPHI have ring-imaging $\check{C}$ counters, and so can also assign b direction to lifetime tagged b events using $b \to c \to K^-$. Only SLD has reported this measurement so far, and it suffers from not being self-calibrated, resulting in large B physics systematic errors.

The values of A_b extracted from the measurements is shown in Fig 4b, and the LEP measurements average to a number 2.6σ below the SM prediction. How can this be, when the LEP averaged value of $A_{FB}^{0,b} = 0.0985 \pm 0.0022$ is perfectly consistent with reasonable values of SM parameters? The answer is easiest seen in Fig 5, which is an update of an analysis by Takeuchi, Grant, and Rosner.[3] The two most precise types of $\sin^2\theta_W^{eff}$ measurement (A_{LR} and A_{FB}^b) differ by $> 3\sigma$ if the one-Higgs-Boson SM is assumed. A_{LR} prefers a very light Higgs and A_{FB}^b prefers a much heavier one.

It's tempting to argue that one or more of the measurements are wrong, but difficult to find a culprit. Except for some 1995 data (OPAL JetC and DELPHI Lept and JetC), almost all LEP I data is used, though many analyses are still preliminary. If the conjecture that A_b is contaminated by unaccounted-for

$\overline{c} \to \ell^-$ and $\overline{b} \to \overline{c} \to \ell^-$ is proposed (the effect is in the right direction), one can ask if the lepton-tagged and jet-charge tagged asymmetries are consistent. Naive averages yield $A_b = 0.868 \pm 0.032$ for lepton tags and $A_b = 0.871 \pm 0.041$ for lifetime/jet-charge tags; quite good agreement for completely different systematic errors. To bring A_{LR} in agreement with A^b_{FB} would take a shift of many times the quoted A_{LR} systematic error. The LEP average A_e lies between A_{LR} and A^ℓ_{FB} in the SM, but is made up of measurements in good agreement with A_{LR} (A^ℓ_{FB}) and those in good agreement with A^b_{FB} (P_τ).

8 Conclusions

The progress in heavy quark EW measurements in the past eight year has been impressive; fractional errors are now $\frac{\delta R_b}{R_b} \sim 0.5\%$, $\frac{\delta A_b}{A_b} \sim 2.5\%$, $\frac{\delta R_c}{R_c} \sim 3\%$, and $\frac{\delta A_c}{A_c} \sim 6\%$. R_b is now 1.7σ above SM, and we eagerly await DELPHI, OPAL, L3, and SLD updates. But why did it come down? Tags with smaller correlations? Mass tags with less charm contamination? Statistics? R_c is now dead on the SM. A_c is also fine, but A_b is far too low. This doesn't necessarily mean anything's wrong with A^b_{FB}; the extraction of A_b couples in other EW measurements. But something (or things) are inconsistent; possibly the one-Higgs-Boson SM. The resolution of this inconsistency will be most interesting.

Acknowledgments

I would like to thank Su Dong and Masahiro Morii for sharing their expertise and evaluations of HF EW measurements, and the members of the LEP EW and the SLD HF Working Groups for their conscientious cataloging and averaging of the results presented here. This work was supported by Department of Energy contract DE-AC03-76SF00515.

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