Heavy Flavours Forward-Backward Asymmetries at LEP

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The four LEP experiments have measured the forward-backward asymmetry for the processes $e^+e^- \to Z \to b\bar{b}$ and $e^+e^- \to Z \to c\bar{c}$ with very high precision. The various and very sophisticated methods providing largely independent determinations of $A^b_{\rm FB}$ and $A^c_{\rm FB}$ are briefly presented. The results yield a very precise determination of the electroweak effective mixing angle $\sin^2\theta^{\,lept}_{eff}$, probing the Standard Model prediction for the electroweak radiative corrections. LEP measurements of $A_{\rm FB}$ and their interpretation are also presented at centre-of-mass energies above the Z resonance.

1. Introduction

In the process $e^+e^- \to Z, \gamma \to b\bar{b}$, $c\bar{c}$ observed at LEP, the polar angle distribution of the b, c quark is forward-backward asymmetric [1]. This asymmetry $A_{\rm FB} = (\sigma_{\sf forw.} - \sigma_{\sf backw.})/\sigma_{\sf tot}$ arises from the parity-violating structure of the Z-exchange and its interference with the photon exchange. At centre-of-mass energies close to m_Z, the latter is suppressed so that $A^{q,0}_{\rm FB}(\sqrt{s} = m_Z)$ determines the ratio between vector and axial vector couplings:

$$A^{q,0}_{\rm FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_q = \frac{3}{4}\frac{2g_{Ae}g_{Ve}}{g^2_{Ae}+g^2_{Ve}}\frac{2g_{Aq}g_{Vq}}{g^2_{Aq}+g^2_{Vq}} \qquad (1)$$

Higher order electroweak corrections are taken into account by means of an improved Born approximation which relates the coupling ratio to the effective electroweak mixing angle $\sin^2\theta^{\,f}_{eff}$. With $\mathcal{A}_q$ being close to 1 for heavy flavours, the forward-backward asymmetry is basically sensitive to the *leptonic* $\sin^2\theta^{\,lept}_{eff}$ and can be compared directly to other measurements that determine this quantity. The most precise one among them is the measurement from $A_{\rm LR}$ at SLC, which has been disagreeing with $\sin^2\theta^{\,lept}_{eff}$ from $A^b_{\rm FB}$ on a 3σ level since the two observables are measured while precision has improved continously. Even long after the LEP 1 running it is therefore of very high interest to provide as precise and reliable asymmetry measurements as possible.

2. Forward-backward asymmetries near the Z resonance

Measuring heavy flavour asymmetries requires knowing the quark flavour as well as the quark / antiquark direction. On the large data sets near the Z resonance, asymmetries can be measured either by exclusive reconstruction of a decay mode with a clear charge information or by inclusive analysis of all decay types on a flavour-pure data set. Both principles demand sophisticated techniques to restore the missing other bit of information, i.e. the production flavour for exclusive analyses and the disctinction of quark and antiquark by their charge in case of the flavour-pure approach.

According to these possibilities, the LEP $A_{\rm FB}$ analyses can be classified in three groups. (1) The exclusive reconstruction of D meson decays provides access to mainly $A^c_{\rm FB}$. (2) By identifying leptons in $b, c \to l$ decays both $A^b_{\rm FB}$ and $A^c_{\rm FB}$ can be measured simultaneously. (3) On a very pure $b\bar{b}$ sample, the jet charge and recently also more sophisticated observables provide an inclusive and precise determination of the b asymmetry.

2.1. $A^c_{\rm FB}$ with exclusively reconstructed D^* mesons

Charged D mesons are produced in $c\bar{c}$ events as well as B meson decays and are identified by the invariant mass of their decay products. Anal-

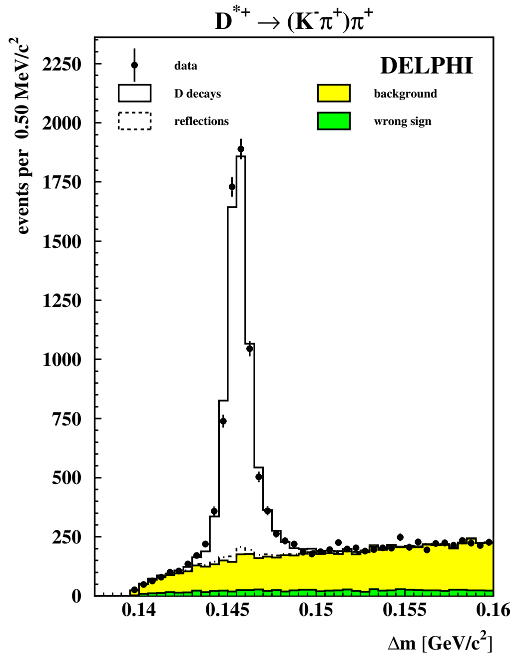

Figure 1. The $D^{*+} - D^0$ mass difference distribution for the decay mode $D^{*+} \to (K^-\pi^+)\pi^+$ as measured in DELPHI

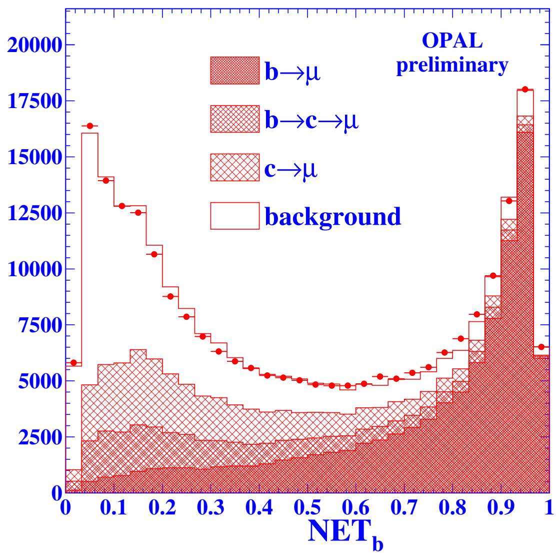

Figure 2. Distribution of the separating variable NET$_b$ used in the OPAL lepton A_{FB} analysis. It enriches $b \to \mu$ signal at output values near 1, as illustrated by the Monte Carlo truth information.

yses using 6 to 9 different D decay modes like the one shown in Fig. 1 have been published by ALEPH [2], DELPHI [3] and OPAL [4]. A fit to the observed asymmetry is done in bins of $\cos\theta$ and one or two b-c separator variables, taking into account the different contributions from A^b_{FB} and A^c_{FB} and the combinatorial background of the reconstructions.

2.2. A^b_{FB} and A^c_{FB} with Leptons

All LEP experiments provide measurements of A^b_{FB} and A^c_{FB} using prompt leptons that are produced with large p and $p_\perp$ in weak B and D meson decays [5–8]. The key feature of all methods is then to distinguish between $b \to l$, $c \to l$, $b \to c \to l$ decays and background using again p, $p_\perp$ either as the direct discriminator or the main ingredient to a lepton ID neural net like the one displayed in Fig. 2. The simultaneous fit in bins of these decay type identifiers and in $\cos\theta$ then yields A^b_{FB} and A^c_{FB}. However, analyses are subject to $B-\overline{B}$-mixing and a reliable description of $b \to c \to l$ cascade decays, which may create a wrong sign correlation between lepton and initial quark. Here the tools have been optimised to reduce modelling dependence also from the lepton $p_\perp$ spectra. ALEPH has added an extra NN$_{b\to c\to l}$ identification while DELPHI calls in the jet charge of the opposite hemisphere to reduce the number of wrong-sign decays.

2.3. Inclusive jet charge and new neural net analyses for A^b_{FB}

All four LEP experiments exploit also an inclusive approach to measure A^b_{FB} from a large size b-tagged sample whith usually very low backgrounds [9–12]. This allows the use of the jet charge to obtain a correlation to the primary quark charge, however this correlation is diluted by fragmentation and subsequent decays.

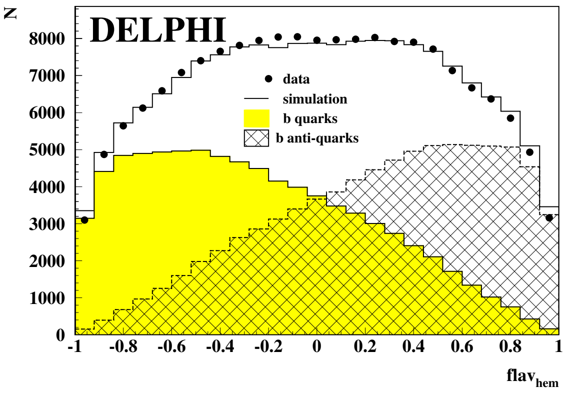

Figure 3. The DELPHI charge tagging neural network output for the data of 1994 in comparison with simulation.

2.3.1. New neural network techniques

ALEPH and DELPHI have improved their techniques by combining more information about B-jets than just the plain jet charge, using neural networks [9,13]. The inputs are in detail:

- jet charges at various weighting powers κ,
- the secondary vertex charge,
- B_x charge tags that weight the charge at the secondary and primary vertex depending on the B hadron hypothesis,
- identified particles (p, K, π),
- exclude leptons (in DELPHI only indirectly used) in order to reduce correlations to the lepton A_{FB} analyses.

The output of such a network improves on charge tagging performance by about 10% and is displayed for the DELPHI data of 1994 in Fig. 3. In order to be able to discuss later the quality of the two most precise contributions [9,13] to the LEP combined b asymmetry, these measurements are explained in more detail in the following.

2.3.2. The analyses

ALEPH exploits the proportionality between A^b_{FB} and the average charge flow

$$\langle Q_{\mathsf{F}} - Q_{\mathsf{B}} \rangle = \sum_f \mathcal{P}_f(\theta)\delta_f(\theta)A^f_{\mathrm{FB}}(\theta) \qquad , \qquad (2)$$

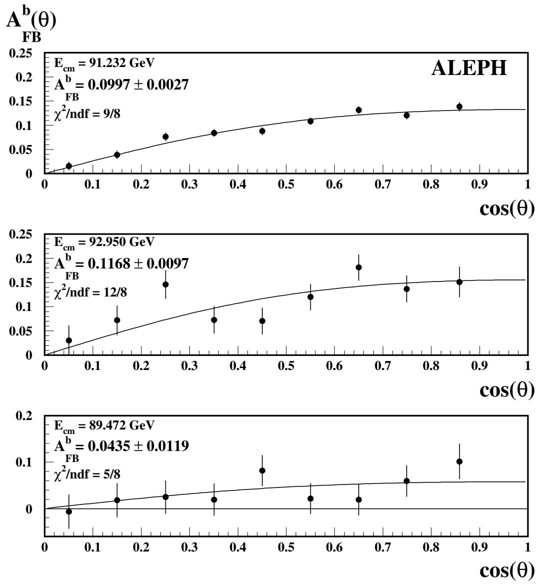

Figure 4. A^b_{FB} as a function of the thrust polar angle at peak, peak+2 and peak-2 centre-of-mass energy. The errors shown are statistical only.

using very inclusive hemisphere tags to build $Q_{\mathsf{F}} - Q_{\mathsf{B}}$. DELPHI uses the counting method

$$\frac{N_{\mathsf{F}} - N_{\mathsf{B}}}{N_{\mathsf{F}} + N_{\mathsf{B}}} = \sum_f (2w_f - 1)\mathcal{P}_f A^f_{\mathrm{FB}}(\theta) \qquad (3)$$

with a cut-based selection of hemispheres. The measurements work on b-enriched samples with purities of $\mathcal{P}_b \sim 88\,\%$ (A) and $\mathcal{P}_b \sim 96\,\%$ (D), with both experiments extracting flavour efficiencies from the data. Of utmost importance for being independent from B-physics modelling in the simulation is the calibration of the charge correlation to the initial b quark. Therefore ALEPH calibrates the charge separation δ_f by measuring

$$\bar{\delta}^2 = \sigma^2(Q_{\mathsf{FB}}) - \sigma^2(Q_{\mathsf{tot}}) \approx \sum_f \mathcal{P}_f \delta_f^2 \qquad (4)$$

and DELPHI calibrates the probability w_b to identify the quark charge correctly from the numbers of like and unlike sign charged hemisphere pairs.

A^b_{FB} is then extracted from a fit to the differential asymmetry, as illustrated by Fig. 4.

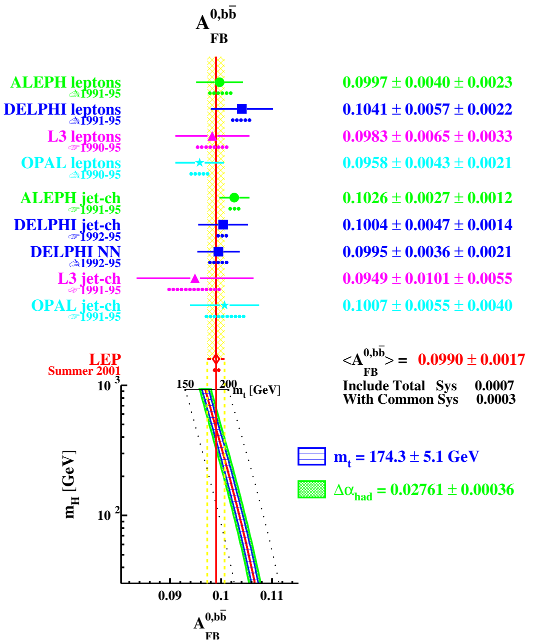

Figure 5. The LEP results for $A_{\rm FB}^{b,0}$. The average takes into account correlated errors and off-peak measurements.

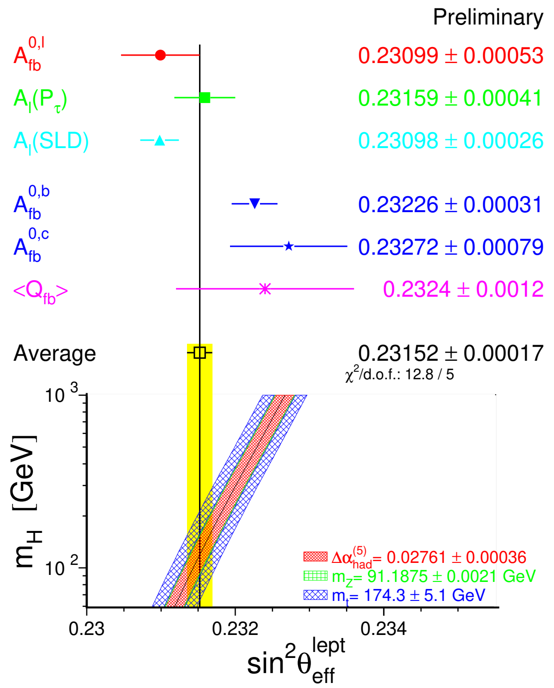

Figure 6. Comparison of several determinations of $\sin^2\theta_{eff}^{lept}$ from asymmetries. [14]

2.3.3. Modelling dependence and checks

The remaining corrections that have to be taken from simulation are the individual sensitivity to the QCD correction and the hemisphere correlations. The latter arise mainly from charge conservation and amount to $k_f \sim 10\,\%$ in the correction $[w_b,\, \delta_f] \cdot (1 + k_f)$. The stability versus $\mathcal{P}_b$ has been checked in both experiments. DELPHI, who takes also the charm background contribution from simulation, has verified the c efficiency on data by means of a double hemisphere tag to agree within 20 % with simulation. The charge identification probability for background, w_c, has been checked with opposite hemisphere D^* finding no significant deviation. Also ALEPH has reproduced δ_b by means of high-p_T leptons.

3. Asymmetry results in the light of the Standard Model

As the b quark asymmetry contributes much more to the precise testing of electroweak theory, a detailed discussion of the c quark results will be omitted here. It can be found in [14]. The results for the b pole asymmetry $A_{\rm FB}^{b,0}$ from the four lepton and five inclusive analyses are shown in Fig. 5. They represent the status of summer 2001 and are very consistent with each other. By taking into account correlations and common systematic errors as well as off-peak measurements in case where available one obtains the LEP combined result of

$$< A_{\rm FB}^{b,0} >= 0.0990 \pm 0.0017 \quad . \tag{5}$$

According to Eqn. 1 the measurement of $A_{\rm FB}^{b,0}$ can be used together with direct lepton measurements and also with $A_{\rm LR}$ from SLC to determine $\sin^2\theta_{eff}^{lept}$, which itself is sensitive to m_h via higher order electroweak corrections. This combination – as illustrated in Fig. 6 – shows that the lepton and heavy quark results are not very consistent with each other: the probability for the fit is only

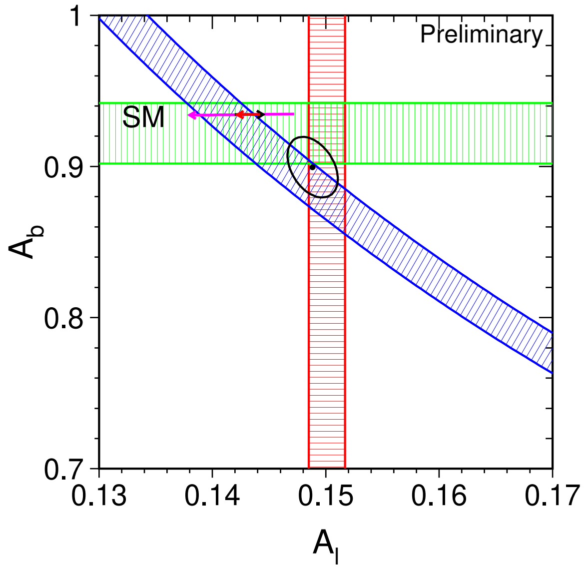

Figure 7. The measurements of the combined LEP+SLD $\mathcal{A}_l$ (vertical band), SLD $\mathcal{A}_b$ (horizontal band) and LEP $A_{\rm FB}^{b,0}$ (diagonal band), compared to the Standard Model expectation (arrow). For more details see [14].

$\approx 2.5\,\%$! However, this does not necessarily point to a problem within the heavy flavour asymmetries: such a poor agreement might still happen on average in one of 40 measurements. Interestingly, $A_{\rm FB}^b$ is then the only quantity that prefers a high higgs mass, thus making the electroweak fit more compatible with the direct exclusion limit on m_h [14,15].

Fig. 7 shows that LEP's $A_{\rm FB}^{b,0}$ is not incompatible with the SM, but the lepton sector represented by the vertical band could have a problem instead. On the other hand, LEP and SLD results for $\mathcal{A}_b$ are not inconsistent, but agree within 1σ:

$$\mathcal{A}_b(\text{LEP only}) = 0.891 \pm 0.022 \qquad (6)$$
$$\mathcal{A}_b(\text{SLD}) = 0.921 \pm 0.020 \qquad (7)$$

There are more arguments that the results for $A_{\rm FB}^{b,0}$ have to be taken seriously and are neither easy to ignore [15] nor subject to largely underestimated experimental uncertainties [16].

Table 1
Error breakdown for $A_{\rm FB}^{b,0}$ from LEP

stat. error $\Delta A_{\rm FB}^{b,0}$	0.00156
uncorr. syst.	0.00061
corr. syst.	0.00039
total syst.	0.00071

The main reason for continued preliminarity or very recent publication comes from the careful work on model-independence and self-calibration methods. Additionally, final detector calibrations are only available for a few years, and the powerful tools like the charge neural networks have been developed lately, with steady feedback from analyses. Some measurements even see still room for improvement, given the fact that LEP's $A_{\rm FB}^{f,0}$ will outlast at the next decade. Only little changes are expected when the LEP $A_{\rm FB}^b$ measurements become final because even the combined b pole asymmetry is statistics dominated. The correlated systematic error as shown in Tab. 1 turns out to be very small. It arises from mainly physics like QCD correction and light quark fragmentation and again demonstrates the good quality of the experimental methods.

4. Asymmetries above the Z resonance

At LEP 2 the $Z-\gamma$ interference leads to large forward-backward asymmetries, so that the focus of interest moves towards verifying the electroweak theory at high energies and searching for new processes that might interfere with the SM graphs and affect $A_{\rm FB}$. Asymmetry measurements at LEP 2 have to cope with a decreasing signal cross-section and the presence of non-negligible backgrounds like radiative Z-returns and four-fermion events. The small number of events does neither allow the application of double tagging techniques nor the analysis of exclusive decay channels. On the other hand the simulation can safely be used to determine b and c purities as well as charge tagging probabilities.

As there has not been any inclusive approach to $A_{\rm FB}^c$ at LEP 1, there are only very few charm measurements up to now. For $A_{\rm FB}^b$, the LEP collaborations have supplied results at various energy

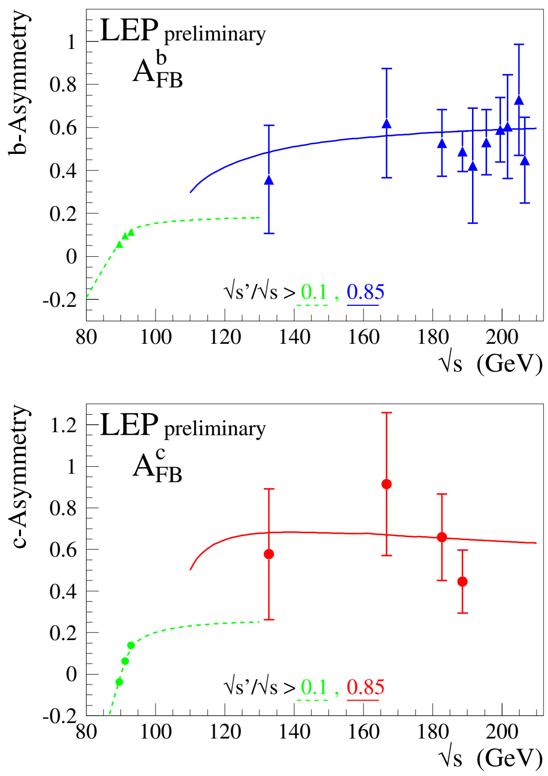

Figure 8. Preliminary combined LEP measurements for A^b_{FB} and A^c_{FB} as a function of the centre-of-mass energy. See details in [17].

points between 130 and 207 GeV, which are combined by the LEP difermion working group [17]. The results for A^b_{FB} and A^c_{FB} at 130–207 GeV are displayed in Fig. 8, showing a good agreement with the SM prediction obtained from Zfitter. The precision for A^b_{FB} averaged over all energy points amounts to $\Delta A^{b\bar{b}}_{\mathrm{FB}} = 0.06$.

4.1. LEP 2 contact interaction fits

The LEP 2 results are used to search for contact interactions between electrons and heavy quarks. Contact interactions are parameterised by adding an extra term to the SM Lagrangian [17] that is governed by the energy scale Λ and takes into account different helicity states of electrons and outgoing quarks. Different settings of the helicity couplings define several models, each of which can interfere constructively or destructively with

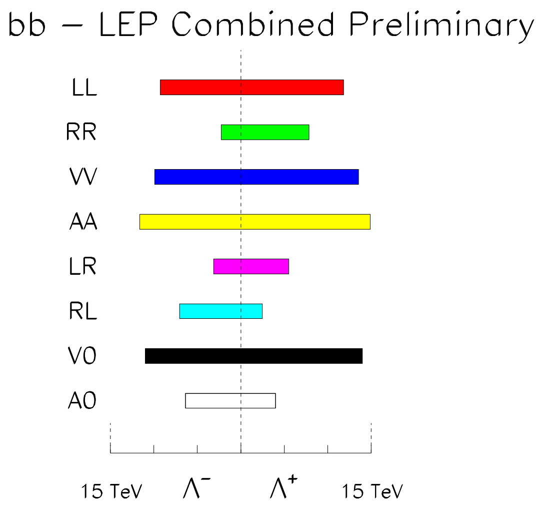

Figure 9. The 95 % CL limits on the scale of contact interactions in $e^+e^- \to b\bar{b}$ using LEP combined results from 130 to 207 GeV.

the SM. Assuming that the contact interaction affects only one flavour, one obtains for each model 95% confidence lower limits on Λ (Fig. 9) from the measured $\sigma_{b\bar{b}}$ and $A^{b\bar{b}}_{\mathrm{FB}}$, or $\sigma_{c\bar{c}}$ and $A^{c\bar{c}}_{\mathrm{FB}}$ respectively.

5. Concluding remarks

Heavy flavour foward-backward asymmetries have been measured at LEP with various powerful and sophisticated techniques, giving very precise and consistent results. Partly motivated by the fact that their final results will not be superseded by new experiments for many years, they are still very interesting to study and are often dealt with by papers on the electroweak fit in the light of theories beyond the Standard One.

The close-up view on the most precise contributions to A^b_{FB} and the discussion of its reliability have not left much room for a systematic error causing the disagreement in $\sin^2\theta^{lept}_{eff}$, so the question remains if it is a statistical fluctuation or new physics. A question that LEP and SLC will probably leave open.

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