$Z \rightarrow \bar{b}b$ Decay Asymmetry: Lose-Lose for the Standard Model

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Combining precision measurements and the Higgs boson search limit, the electroweak data have evolved to a point where new physics is favored whether the 3.2σ $A_{\rm FB}^b$ anomaly is genuine or not. Such new physics could greatly alter the inferred value of the Higgs boson mass.

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Introduction.—A decade of beautiful experiments has provided increasingly precise tests of the standard model (SM) of elementary particle physics. The data test the SM, probe for new physics, and are sensitive to m_H, the mass of the still undiscovered Higgs boson which gives mass to the elementary particles. Currently they imply an upper bound on m_H of the order of 200 GeV, while direct searches have established a lower limit of 113.5 GeV [1].

In the most recent analysis of the electroweak data the $Z \rightarrow \bar{b}b$ front-back asymmetry, $A_{\rm FB}^b$, differs by 3.2σ (99.9% C.L.) from the SM fit [1]. It could represent new physics, but a few red flags suggest caution: (1) the direct determination of A_b from the front-back left-right asymmetry, $A_{\rm FBLR}^b$, is consistent with the SM (0.7σ) while A_b extracted from $A_b = 4A_{\rm FB}^b/3A_l$ (where A_l is the leptonic asymmetry) disagrees by 3.5σ (99.95% C.L.); (2) $Z \rightarrow \bar{b}b$ measurements have proven notoriously difficult in the past; and (3) there is no hint of an R_b anomaly to match the A_b anomaly, requiring a degree of tuning of the left- and right-handed $Z\bar{b}b$ couplings with an extremely large shift in the right-handed coupling.

The situation is then quite puzzling. The result could be a statistical fluctuation, but statistical criteria reviewed below tell us this is very unlikely. The remaining two possibilities are new physics or subtle systematic error. While great care and effort have been focused on understanding and reducing the systematic uncertainties, further work is needed before we can choose clearly between the two possibilities. If the explanation is systematic error and $A_{\rm FB}^b$ is omitted, the global SM fit, which is poor with $A_{\rm FB}^b$ included, becomes excellent, but the predicted value of m_H, the Higgs boson mass, falls to low values in conflict with the direct search limit, $m_H > 113.5$ at 95% C.L. [2] To remove the inconsistency new physics would be required to modify the predictions based on the radiative corrections. New physics is then favored whether $A_{\rm FB}^b$ is affected by systematic error or not, and m_H cannot be predicted without disentangling the effect of the new physics.

Though less precise, it is striking that the values of $x_W^l = \sin^2\theta_W^l$, the effective leptonic mixing angle, extracted from the two other hadronic asymmetry measurements, $A_{\rm FB}^c$ and $Q_{\rm FB}$, agree with x_W^l from $A_{\rm FB}^b$ and deviate from the SM fit. Combined, the three measurements differ from the SM fit at 99.5% C.L. At the same time they are the only precision measurements that raise the predicted value of m_H toward the range required by the direct search limit. We show below that all other m_H-sensitive precision measurements favor values much lower than 113.5 GeV. The measurements that are consistent with the global fit are inconsistent with the search limit, while the measurements that are essential for consistency with the search limit are inconsistent with the global fit.

The data.—In the latest data the 3.5σ difference in the SM determinations of x_W^l from $A_{\rm LR}$ and $A_{\rm FB}^b$ drives a poor fit of the 7 asymmetries used to determine x_W^l, with $\chi^2/{\rm dof} = 15.5/6$ and C.L. $= 0.013$. The four leptonic measurements, $A_{\rm LR}$, $A_{\rm FB}^l$, A_e, A_τ, agree very well with one another, $\chi^2/{\rm dof} = 2.7/3$, as do the three hadronic determinations from $A_{\rm FB}^b$, $A_{\rm FB}^c$, $Q_{\rm FB}$, $\chi^2/{\rm dof} = 0.1/2$, while the aggregated leptonic and hadronic determinations of x_W^l differ by 3.6σ (99.97% C.L.).

The four leptonic asymmetries provide the first, third, fourth, and fifth most precise of the 7 determinations of x_W^l. Because they are consistent, large systematic errors would have to conspire to affect each measurement in a similar way, which is very unlikely because they are measured by three very different methods. The same cannot be said of the hadronic asymmetries, which share common systematic issues. All three hadronic measurements require similar QCD corrections and make common use of fragmentation and decay models. As in the R_b anomaly, $\bar{b}b$ and $\bar{c}c$ events constitute backgrounds for one another [3]. In the most recent analysis the $A_{\rm FB}^b$ and $A_{\rm FB}^c$ measurements are assigned a 16% correlation [1].

Taking a wider perspective, it is useful to consider the 15 degrees of freedom in the global SM fit of all data reported in Ref. [1]. Even in that framework a $\geq 3.2\sigma$ discrepancy is very unlikely, with probability $1 - 0.9986^{15} = 0.021$. As noted above, $A_{\rm FB}^b$ also drives the poor χ^2 of that fit, $\chi^2/{\rm dof} = 26/15$ and C.L. $= 0.038$. With the contribution of $A_{\rm FB}^b$ removed the same fit parameters yield $\chi^2/{\rm dof} = 15.8/14$ corresponding to a robust C.L. $= 0.33$. If instead the second most deviant measurement, $A_{\rm LR}$, is omitted, the improvement is much smaller, with $\chi^2/{\rm dof} = 23.2/14$ and C.L. $= 0.057$.

Another feature of the data also points to A_{FB}^b as the "odd man out." The $Z\bar{b}b$ vertex factor, A_b, is predicted very precisely in the SM and agrees well (0.7σ) with the direct determination at the SLC from A_{FBLR}^b. But the determination from $A_b = 4A_{FB}^b/3A_l$ disagrees with the SM by 3.5σ and from the directly measured A_{FBLR}^b by 1.8σ.

The evidence for new physics in the $Z\bar{b}b$ vertex is compelling on a purely statistical level, and the third generation quarks are a plausible venue for new physics connected to the symmetry breaking sector. But the disagreement with A_{FBLR}^b and the past history of $Z \to \bar{b}b$ measurements suggest caution. While the lessons of the R_b anomaly have been refined and applied to A_{FB}^b, the latter measurement involves additional subtleties. Systematic error could in principle provide an escape path for the SM. But we will see in the next section that the path is rather narrow if it is open at all.

Results.—In this section we present χ^2 fits of m_H and compare them with the search limit. To confront the predictions of the SM as directly as possible we focus on the directly measured, m_H-sensitive observables. The observables with the greatest impact are x_W^l and m_W. The other directly measured, m_H-sensitive Z-pole observables are the total width $\Gamma_Z = 2.4952(23)$ GeV and the ratio of hadronic to leptonic partial widths, $R_l = \Gamma_h/\Gamma_l = 20.767(25)$ [1]. For m_Z, m_W, and m_t we use the directly measured values, currently $m_Z = 91.1875(21)$ GeV, $m_W = 80.448(34)$ GeV, and $m_t = 174.3(5.1)$ GeV [1].

The strong coupling is taken to be $\alpha_S(m_Z) = 0.118(3)$. The greatest parametric uncertainty is from the electromagnetic coupling at the Z pole, $\alpha(m_Z)$, in particular from $\Delta\alpha_5$, the five flavor hadronic contribution to $\Delta\alpha$, which renormalizes α by $\alpha(m_Z) = \alpha(0)/(1 - \Delta\alpha)$. We use five determinations: two experiment-driven [4,5] based on the most recent data and three theory-driven [6–8]. (The older theory-driven determinations [6,7] are included because they are consistent with the new data.) Gaussian errors are assumed for all experimental quantities. We use the two loop radiative correction package from ZFITTER [9], version 6.30, to compute the SM values of the four observables as a function of m_H and the four experimentally determined parameters, m_Z, m_t, $\alpha(m_Z)$, and $\alpha_S(m_Z)$. Taking as inputs the all-data fit values [1] for m_Z, m_t, $\Delta\alpha_5$, α_S, and m_H, we reproduce the results (from ZFITTER V6.35) in [1] as follows: x_W^l: 0.23142/0.23142; m_W: 80.394/80.393; Γ_Z: 2.4960/2.4962; and R_l: 20.737/20.740. The effect of such differences on χ^2 is negligible.

For two reasons we first consider just m_W and the Z-pole measurements, Γ_Z and R_l: (1) they are not affected by the issues affecting the asymmetries and (2) the determination of m_H from them is less sensitive to the uncertainty from $\alpha(m_Z)$. The results are striking. Figure 1 shows $\Delta\chi^2 = \chi^2 - \chi^2_{\min}$ as a function of m_H obtained from m_W alone and in combination with Γ_Z and R_l. At each value of m_H the experimental parameters m_t, $\alpha(m_Z)$, and $\alpha_S(m_Z)$ are

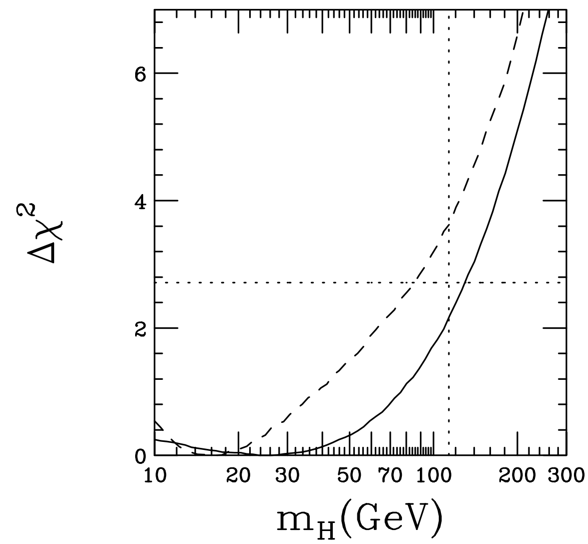

FIG. 1. χ^2 distributions as a function of m_H. The solid line is obtained from m_W alone and the dashed line from the combined fit of m_W, Γ_Z, and R_l. The vertical dotted line indicates the direct search lower limit and the horizontal dotted line indicates the value of $\Delta\chi^2$ corresponding to a 95% C.L. upper limit. $\alpha(m_Z)$ is from [5].

chosen to minimize the sum of the χ^2 contributions from m_W, m_t, $\alpha(m_Z)$, and α_S (and also from Γ_Z and R_l in the case of the second fit). (We have checked that varying m_Z has negligible effect on χ^2.) The results are summarized in Table I for the five choices of $\alpha(m_Z)$. For the fit based just on m_W the central value of m_H falls between 21 and 28 GeV, with $m_H < 113.5$ GeV favored at 94% to 92% C.L. For the fit with Γ_Z and R_l included, the results are even less sensitive to $\alpha(m_Z)$ and are shifted to lower m_H, 15–17 GeV, with C.L. ($m_H < 113.5$ GeV) increased to between 98% and 97%.

We next consider the effect of the asymmetry measurements in the framework of the hypothesis that the A_{FB}^b anomaly results from undetected systematic error. As discussed above, A_{FB}^b, A_{FB}^c, and Q_{FB} share common systematics so that the most reliable determination of x_W^l would in this case be provided by the four leptonic asymmetry measurements, which are very unlikely to have common systematic uncertainties. Results based on the leptonic asymmetries, which yield $x_W^l = 0.23113(20)$, combined with m_W, Γ_Z, and R_l are shown in Fig. 2 and summarized in Table II where they are labeled "$+L4$." The central values are in the range 27–44 GeV, with C.L. ($m_H < 113.5$ GeV) from 98% to 94%. As in Table I there is a significant conflict with the search limit, though with more dependence on $\alpha(m_Z)$.

For completeness we also consider the effect of the two lower precision hadronic asymmetry measurements, combining Q_{FB} [$x_W^l = 0.23118(20)$] and A_{FB}^c [$x_W^l = 0.23127(19)$] sequentially with the previously considered observables. The results, in Fig. 2 and Table II, conflict with the search limit, though less decisively. Finally, we

TABLE I. Fit results without asymmetry measurements for five determinations of $\alpha(M_Z)$. For each fit the central value of m_H is shown in GeV and the confidence level (C.L.) for $m_H > 113.5$ GeV. Results for m_W alone are shown in the first two rows, and for the combination of m_W, Γ_Z, and R_l in the last two.

	$\Delta\alpha_5$	J [4] 0.027 896 (395)	BP [5] 0.027 61(35)	MOR [8] 0.027 426 (190)	DH [6] 0.027 63(16)	KS [7] 0.027 75(17)
m_W	m_H	21	26	28	25	23
	C.L.	0.057	0.071	0.080	0.068	0.062
$+\Gamma_Z, R_l$	m_H	15	17	15	17	15
	C.L.	0.023	0.028	0.032	0.027	0.024

exhibit the results with all seven asymmetry measurements included, denoted "$+A_{\rm FB}^b$" in Table II, with $x_W^l = 0.231\,56(17)$. As for the usual global SM fits, m_H is centered around 100 GeV and the fits are consistent with the search limit for all $\alpha(m_Z)$.

To summarize, each fit with $A_{\rm FB}^b$ omitted is in conflict with the search limit, and the fits based on the data that are most reliable if the $A_{\rm FB}^b$ anomaly is a systematic effect—Table I and the "$+L4$" fit of Table II—have the most significant conflicts.

Discussion.—The greatest source of uncertainty is the sensitivity to $\alpha(m_Z)$ of the fits that include asymmetry data, which makes the lack of asymmetry data in Table I especially interesting. The theoretical uncertainty from uncalculated diagrams is smaller than from $\alpha(m_Z)$, as can be seen in Fig. 13 of [1] where the "blue band" estimating the theoretical uncertainty is less than the difference resulting from $\alpha(m_Z)$ for [5] compared to [8]. The figure also shows that the prediction of ZFITTER as employed in [1] lies near the large- m_H edge of the blue band. Since, as noted above, our ZFITTER calculations closely reproduce those of [1], our estimates of the conflict with the search limits are conservative relative to the other libraries/settings used to generate the blue band.

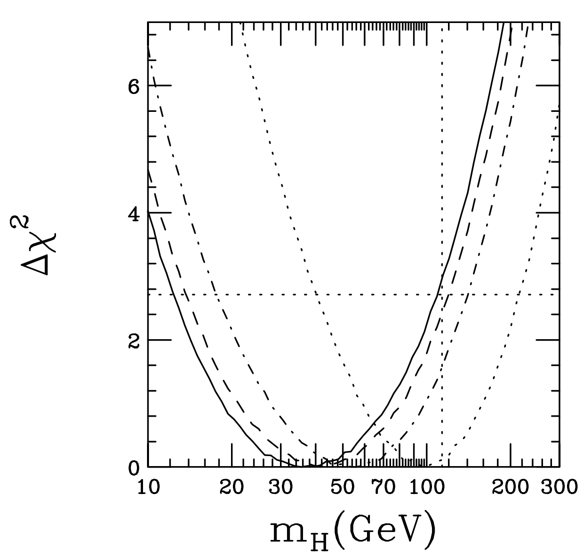

FIG. 2. χ^2 distributions as in Fig. 1. The lines correspond to fits of m_W, Γ_Z, and R_l, combined incrementally, as in Table II, with the four leptonic asymmetry measurements (solid), plus $Q_{\rm FB}$ (dashes), plus $A_{\rm FB}^c$ (dot-dashes), plus $A_{\rm FB}^b$ (dots).

We have found that new physics is favored by the data whether the $A_{\rm FB}^b$ anomaly reflects new physics or systematic error. An important consequence is that the evidence from the SM fit favoring a light Higgs boson becomes less credible. It can be maintained only if the $A_{\rm FB}^b$ anomaly turns out to be a statistical fluctuation. (If the discrepancies in the SM fit are statistical fluctuations, the appropriate fits are those in the bottom line of Table II, and the measurements of all the m_H-sensitive observables, not just $A_{\rm FB}^b$, must have fluctuated significantly from their true values.) The most generous estimate of the likelihood of this possibility is the poor 3.8% χ^2 C.L. of the global SM fit [1], which is due almost entirely to the deviation of $A_{\rm FB}^b$ from the fit as noted above. Otherwise, whether the anomaly is a genuine signal of new physics or a systematic artifact, $A_{\rm FB}^b$ cannot be used to determine x_W^l, and the resulting conflict with the search limit favors new physics contributions to remove the contradiction.

We can get a rough idea of the new physics contributions that would be needed by considering just x_W^l and m_W, using the deviation from the SM for any given value of m_H, δx_W^l, and δm_W, to compute the corresponding oblique parameters [10] S and T. Taking x_W^l from the 4 leptonic asymmetries and using the direct measurement of m_W, we find, e.g., for $m_H = 114$, 300, 1000, and 2000 GeV that the corresponding values are $(S,T) = (-0.02, 0.16)$, $(-0.08, 0.27)$, $(-0.11, 0.48)$, and $(-0.09, 0.65)$, where $m_H = 2000$ GeV is a "stand-in" for dynamical symmetry breaking. The existing data cannot choose among these possibilities.

The unexpected emergence of evidence for new physics at the end of the LEP/SLC decade is a cautionary signal to keep an open mind as to the ultimate explanation. If the $A_{\rm FB}^b$ anomaly is genuine, it signals new physics not anticipated by popular theoretical models. If the anomaly is genuine and unique to the third generation, it will also affect $\bar{b}s$, $\bar{b}d$, and $\bar{s}d$ neutral currents via non-SM Z penguin amplitudes, though the precise effects are not readily predicted. If the anomaly is not genuine, the conflict with the search limit is for now our only evidence of the new physics and we are left with even fewer clues as to its nature.

TABLE II. Fit results with asymmetry measurements included. The format is as in Table I. The first fit reflects the combination of m_W, Γ_Z, and R_l together with the four leptonic asymmetry measurements "$L4$." Successive fits incrementally include $Q_{\rm FB}$, $A_{\rm FB}^c$, and $A_{\rm FB}^b$

	$\Delta\alpha_5$	J [4] 0.027 896 (395)	BP [5] 0.027 61(36)	MOR [8] 0.027 426 (190)	DH [6] 0.027 63(16)	KS [7] 0.027 75(17)
$+L4$	m_H	27	37	44	39	34
	C.L.	0.019	0.041	0.060	0.033	0.023
$+Q_{\rm FB}$	m_H	33	43	57	46	39
	C.L.	0.028	0.058	0.087	0.049	0.034
$+A_{\rm FB}^c$	m_H	43	53	61	61	55
	C.L.	0.053	0.10	0.14	0.091	0.069
$+A_{\rm FB}^b$	m_H	86	110	114	102	89
	C.L.	0.26	0.36	0.50	0.40	0.38

The evidence for new physics presented here may be weakened or strengthened by future measurements, not only of $A_{\rm FB}^b$ and the other asymmetries but also of m_W and m_t. New facilities will be needed to answer the questions posed by the current data, including a second generation Z factory. Better measurements of $R_{e^+e^-}$ would be needed to determine $\alpha(m_Z)$ with enough precision to realize the potential precision of a new Z factory for x_W^l [4]. This will be important even after the Higgs sector is discovered, since precise comparisons of the electroweak data with predictions based on the observed Higgs sector will provide invaluable guidance on whether additional new physics exists at yet higher scales. The evidence of the present data for unspecified new physics underscores the importance of framing the search for the Higgs sector in the most general form.

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Note added.—Data presented after this work was completed [11] differ slightly from the data considered above: $A_{\rm FB}^b$ disagrees with the SM fit by 2.9σ (C.L. = 99.6%), and the leptonic and hadronic SM determinations of x_W^l disagree by 3.3σ (C.L. = 99.9%). The likelihood of the statistical fluctuation hypothesis increases to a still small probability, e.g., from 3.8% to 6.7% as gauged by the global fit. The analysis of the systematic error hypothesis is unaffected since the fits which omit $A_{\rm FB}^b$ change very little, and the contradiction with the search limit persists at the levels quoted above.

[1] LEP Collaborations ALEPH, DELPHI, L3, OPAL, LEP Electroweak Working Group, and SLD Heavy Flavour and Electroweak Groups, Report No. LEPEWWG/2001-01.

[2] N.B., the 95% lower limit does *not* imply a 5% chance that the Higgs boson is lighter than 113.5 GeV; rather it means that if m_H were actually 113.5 GeV there would be a 5% chance for it to have escaped detection. The likelihood for $m_H < 113.5$ GeV from the direct searches is much smaller than 5%. See, for instance, the discussion in M. Chanowitz, Phys. Rev. D **59**, 073005 (1999), Sec. 5.

[3] It is suggestive that the signs of both the $A_{\rm FB}^b$ and $A_{\rm FB}^c$ anomalies are as would be expected if c's were misidentified as $\bar{b}$'s and vice versa, although the systematic error currently budgeted to this effect is much smaller [1] than the anomalies.

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