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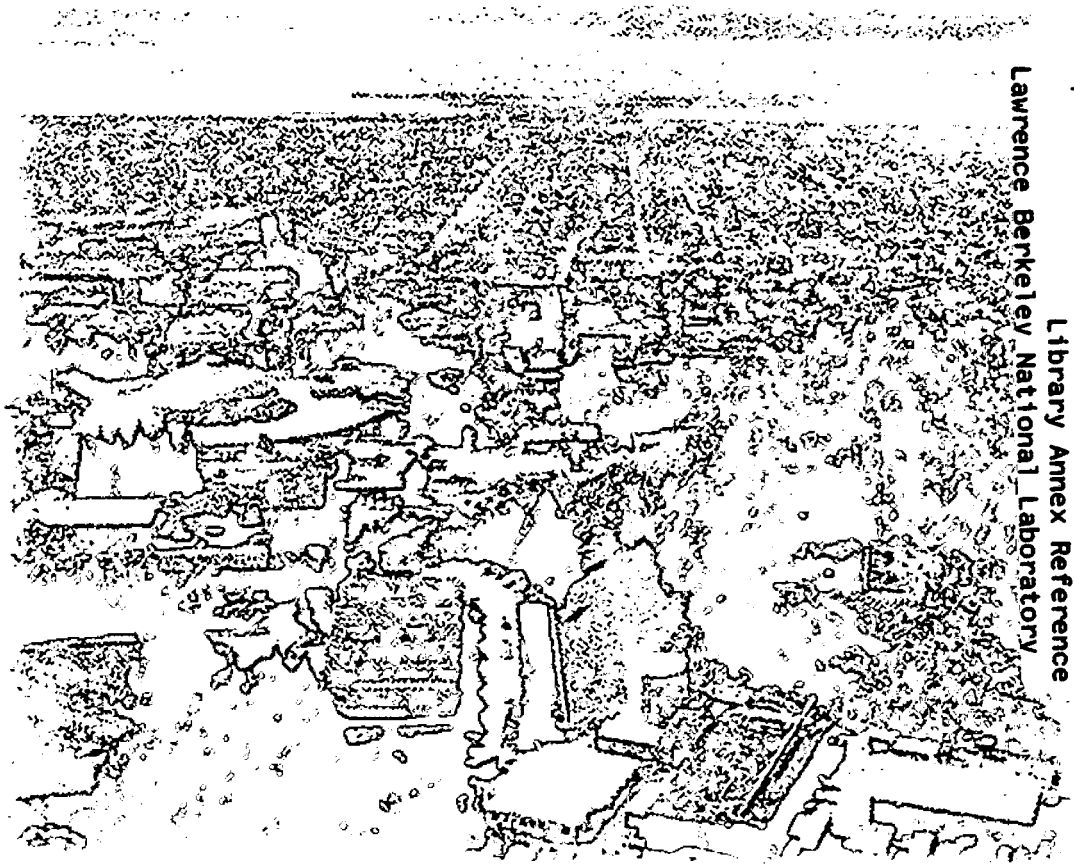

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The $Z \to \bar{b}b$ decay asymmetry: lose-lose for the Standard Model [1]

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Abstract

Whether the reported value of A^b_{FB} is correct or not, the Standard Model is disfavored and the prediction of a light Higgs boson is lost.

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Introduction

In the most recent analysis of the precision electroweak data[1] the $Z \to \bar{b}b$ front-back asymmetry is $A^b_{FB} = 0.0982(17)$, which is 3.2σ (99.9% CL) from the SM (Standard Model) fit value. By several criteria the result is statistically significant evidence for new physics beyond the SM. However there are also a few red flags suggesting caution: (1) the direct determination of A_b from the front-back left-right asymmetry, A^b_{FBLR}, is quite consistent with the SM (0.7σ) while A_b extracted from $A_b = 4A^b_{FB}/3A_l$ (where A_l is the leptonic asymmetry) conflicts with the SM by 3.1σ (99.8% CL), (2) $Z \to \bar{b}b$ 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.

The resulting picture presented by the data is quite puzzling. The result could be a statistical fluctuation, but statistical criteria reviewed below tell us that this is very unlikely. The remaining two possibilities are new physics or subtle systematic error. While great care and effort has been focused on understanding and reducing the systematic uncertainties, further work is needed before we can choose clearly between the two possibilities. We show here that whether the explanation is systematic error or new $Z\bar{b}b$ physics, the SM fit of m_H is disfavored.

If A^b_{FB} is affected by systematic error, it cannot be used to determine $x^l_W = \sin^2\theta^{l,eff}_W$, the effective leptonic weak interaction mixing angle, and other hadronic asymmetry measurements may also be tainted. It is then most reliable to use the leptonic asymmetries to determine x^l_W. The resulting fit is quite self consistent, but it implies $m_H < 113$ GeV at 99 to 97% CL (depending on $\alpha(m_Z)$), in conflict with the 95% lower limit[3] from the direct searches, $m_H > 113.5$ GeV.[1] Even if the other hadronic asymmetries are retained (or if all asymmetries, both leptonic and hadronic, are omitted), the conflict persists at a significant level.

If new physics affects the $Z\bar{b}b$ interaction, the SM fails and the SM analysis of the radiative corrections is *a priori* not a reliable probe of the Higgs sector. Going farther, even if we hypothesize that new physics affects A^b_{FB} but somehow does not significantly affect the Higgs sector analysis, we reach a contradiction with the search limits, similar to what follows from the hypothesis of systematic error. Thus whether the A^b_{FB} anomaly is a systematic effect or new physics, we find that new physics is likely to affect the fit of m_H from the radiative corrections. Without knowing more about this new physics there is no definite prediction for m_H and the preference for a light Higgs boson is lost.

[3]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 the Higgs mass were 113.5 GeV there would be a 5% chance for it to have escaped detection. The likelihood for $m_H < 113$ GeV from the direct searches is much smaller than 5%. See for instance the discussion in section 5 of [2]

The data

For ten years the two most precise SM determinations of x_W^l, from A_{LR} and A_{FB}^b, have disagreed by $\sim 3\sigma$. In the most recent analysis[1] they differ by 3.5σ (99.95% CL), which drives a poor SM fit of the 7 asymmetries used to determine x_W^l, with $\chi^2/dof = 15.5/6$ and CL $= 0.013$. The four leptonic measurements, $A_{LR}, A_{FB}^l, A_e, A_\tau$, agree very well with one another as do the three hadronic determinations from $A_{FB}^b, A_{FB}^c, Q_{FB}$, while the aggregated leptonic and hadronic determinations of x_W^l differ by 3.6σ. If A_{FB}^b is excluded the χ^2 CL of the remaining 6 determinations rises by an order of magnitude, with $\chi^2/dof = 8.2/5$ and CL $= 0.15$. If only A_{LR} is excluded the fit remains problematic, with $\chi^2/dof = 10.5/5$, CL $= 0.06$. Q_{FB} and especially A_{FB}^c also have deviant central values, but they are the least precise, with relatively little weight in the fits.

The leptonic determinations of x_W^l are valid in general, assuming only lepton universality, while the hadronic determinations are not. The front-back asymmetry of a fermion f is given by

$$A_{FB}^f = \frac{3}{4} A_e A_f \tag{1}$$

where $A_f = (g_{fL}^2 - g_{fR}^2)/(g_{fL}^2 + g_{fR}^2)$ and $g_{fL,R}$ are the left and right-handed $Z\overline{f}f$ couplings. For quarks the factor A_f is very insensitive in the SM to the various parameters of the theory. For instance, for Higgs boson mass in the interval $10 \leq m_H \leq 1000$ GeV, A_b only varies within the range $0.9347^{+0.0006}_{-0.0008}$, with little sensitivity to the top quark mass m_t or $\alpha(m_Z)$. The usually reported determinations[1, 3] of x_W^l from A_{FB}^q for quark q assume SM values for A_q. If new physics affects A_q, those determinations are invalid.

The four leptonic asymmetries provide the first, third, fourth, and fifth most precise of the 7 determinations of x_W^l. Because they agree well ($\chi^2/dof = 2.7/3$), large systematic errors would have to conspire to affect each measurement in a similar way, which is unlikely because they are measured by three very different methods. The same cannot be said of A_{FB}^b and A_{FB}^c, which share common systematic issues.[4]

Taking a wider perspective, it is useful to consider the 15 observables in the global SM fit of all data reported in reference [1]. Even in that framework a $\geq 3.2\sigma$ discrepancy is very unlikely, with probability $1 - 0.9986^{15} = 0.021$. A_{FB}^b also drives the poor χ^2 of that fit, $\chi^2/dof = 26/15$ and CL $= 0.038$. If A_{FB}^b is removed the CL rises by an order of magnitude, to CL $= 0.33$, $\chi^2/dof = 15.8/14$. If instead the second most deviant measurement, A_{LR}, is omitted, there is little improvement, with $\chi^2/dof = 23.2/14$ and CL $= 0.057$.

By all these measures the A_{FB}^b anomaly is statistically significant. Another feature of

[4]It is suggestive that the sign of both the A_{FB}^b and A_{FB}^c anomalies are as would be expected if c's were misidentified as $\bar{b}$'s and vice-versa, but the systematic error budgeted to this effect is much smaller[4] than the anomalies.

the data also points to A^b_{FB} as the 'odd man out.' Using $A_l = 0.1501(16)$ from the four combined leptonic measurements, the experimental value of A^b_{FB} implies from Eq. (1) that $A_b = 0.872(18)$, which is 3.5σ from the SM value (CL = 0.9995). It also differs by 1.8σ (CL = 0.07) from the direct measurement of $A_b = 0.921(20)$ from A^b_{FBLR}, the latter being within 0.7σ of the SM.[5] Combining the two determinations we have $A_b = 0.894(13)$, and the anomaly persists at 3.1σ (99.8% CL).

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^b_{FBLR} 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^b_{FB}, the latter requires distinguishing the b and $\bar{b}$ quarks in their respective hemispheres, which could give rise to 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.

Likelihood fits

In this section we derive likelihood distributions for m_H and compare them with the search limit. To confront the predictions of the SM as directly as possible with the data, the likelihood distributions are obtained from directly measured, m_H-sensitive observables. The observables with the greatest impact are x^l_W and the W boson mass m_W. The other relevant observables[6] 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_W and m_t we use the directly measured values, currently[1] $m_W = 80.448(34)$ GeV and $m_t = 174.3(5.1)$ GeV.

The strong coupling is taken to be $\alpha_S = 0.118(3)$. The greatest parametric uncertainty is from $\alpha(m_Z)$. We use five determinations which span the range of choices: a conservative experiment-driven determination based on pre-1995 data[5], two theory-driven determinations[6, 7], and two[8, 9] that incorporate the latest data.

We use the two loop radiative correction package from ZFITTER[10] to compute the SM values of the four observables as a function of m_H. Assuming Gaussian errors for the four observables we then obtain likelihood distributions for m_H from each of the observables, normalized to unity in the interval $10 \leq m_H \leq 1000$ GeV. For each distribution the experimental uncertainty in the measurement of the observable is combined in quadrature with

[5] Even taking $A_l = 0.1467(13)$ from the fit to all seven asymmetries, the result for A_b from A^b_{FB} differs from the SM by 2.53σ with CL = 0.01.

[6] Partial widths, such as Γ_h and Γ_l, are also sensitive to m_H, but they are not directly determined from the data.[3] For instance, Γ_l is obtained from $\Gamma_l = \sqrt{\sigma_h m_Z^2/12\pi R_l}\Gamma_Z$ where σ_h is the peak hadronic cross section. Since σ_h has negligible sensitivity to m_H, the sensitivity of the experimental value of Γ_l (and Γ_h) is actually due to Γ_Z and R_l which we consider directly.

the parametric uncertainty (from $\alpha(m_Z)$, m_t, and α_S) in the calculation of the observable as a function of m_H. The distributions obtained from x_W^l are approximately Gaussian in $\log(m_H)$ as are the distributions from m_W above, but not below, the likelihood maximum, while those from Γ_Z and R_l are decidedly nonGaussian. The combined distribution is then obtained from the normalized product of the individual distributions. Examples of the individual and combined distributions are shown in Figure 1. The kinks in the combined distribution are due to the nonGaussian shape of the distribution from Γ_Z.[7] A more detailed presentation and discussion of the fits will be given elsewhere.[12]

In table 1 the fits are compared with the search limit. Before considering the effect of x_W^l we consider the likelihood of consistency with the search limit from m_W alone, denoted CL_{m_W} in table 1, as well as the combined likelihood from m_W, Γ_Z, and R_l, denoted $CL_{no\ x_W}$. Each indicate a serious conflict with the search limit. From figure 1 we see that all three observables favor m_H below 113 GeV, and indeed that they would have significant likelihood below 10 GeV if we were to relax the lower limit chosen for the distributions. From the W mass alone, CL_{m_W} ranges from 0.050 to 0.066 depending on $\alpha(m_Z)$, while for $CL_{no\ x_W}$ the corresponding range goes from 0.032 to 0.049. In addition to being independent of the ambiguities affecting x_W^l, these fits are much less sensitive to the systematic uncertainty from $\alpha(m_Z)$.

Next we consider the effect of x_W^l on the fits. We entertain three hypotheses: (1) that the A_{FB}^b measurement is a statistical fluctuation, (2) that it reflects systematic error, and (3) that it represents new physics. The likelihood of case (1) can be assessed by statistical criteria and, as discussed in the previous section, is very unlikely. Therefore either case (2) or (3) are likely to be true, though statistics may not help us to decide between them.

For case (1) the combination of the seven asymmetry measurements in the SM yields $x_W^l = 0.23156(17)$. The corresponding CL's for $m_H > 113$ GeV from the four-observable fits are denoted in table 1 by CL_{all}. They resemble the usual global SM fits, and except for the case of $\alpha(m_Z)$ from [5] they are consistent with the search limit. Also shown for these fits is the maximum likelihood value of m_H and the corresponding χ^2 and CL, all of which are acceptable. As a consistency check we have also verified that using the global fit parameters given in [1] we reproduce the fit value of m_H reported there.

It is less clear how to proceed in case (2), since systematic errors in A_{FB}^b might well affect A_{FB}^c and perhaps even Q_{FB}. We therefore consider several possibilities. As discussed in the preceding section, the safest choice is to consider x_W^l from the four leptonic asymmetry measurements, which are least likely to be affected by systematic errors. From their combined

[7] D. Bardin and G. Passarino have verified, with ZFITTER and TOPAZ0 respectively, that Γ_Z as a function of m_H has a local maximum at $\sim$ 40 to 50 GeV (depending on parameters), which causes the unexpected twin peak likelihood distribution in the figure.[11]

value, $A_l = 0.1501(16)$, we obtain $x_W^l = 0.23113(20)$. This choice, denoted CL_l in table 1, gives the strongest contradiction with the search limits, with the likelihood for consistency ranging from 0.009 to 0.034. For these fits we have also indicated the most likely values for m_H along with the corresponding χ^2's and CL's, all of which are acceptable.

We also consider two other fits that may be relevant to case (2). The fit denoted $CL_{l,Q}$ in table 1 combines Q_{FB} and the four leptonic asymmetries, with $x_W^l = 0.23118(20)$. The CL for consistency with the search limit ranges from 0.012 to 0.048. Though it seems unlikely that A_{FB}^c would not also be affected if A_{FB}^b were affected by systematic error, we also consider this possibility and record the fit where only A_{FB}^b is excluded. In this case $x_W^l = 0.23127(19)$, and the CL for consistency, denoted by $CL_{l,c,Q}$, ranges from 0.019 to 0.085.[8]

For new physics, case (3), we can imagine two possibilities: that the new physics involves only the third generation quarks (and for some reason is small or absent in the third generation leptons), or that it is a leptophobic phenomenon affecting all three quark generations. For the first possibility the SM determinations of x_W^l from both A_{FB}^b and Q_{FB} are affected. Excluding them, the corresponding fit yields $x_W^l = 0.23123(19)$. Indicated by $CL_{l,c}$ in table 1, the CL for consistency with the search limit varies from 0.015 to 0.067. If the new physics affects all quark generations we can again consider the fit based on the four leptonic asymmetries, CL_l.

For case(3) we also consider a model independent extraction of x_W^l from A_{FB}^b which does not assume the SM. Instead we use Eq. (1) with A_b taken directly from A_{FBLR}^b. The experimental uncertainty of A_{FBLR}^b then reduces the precision of the x_W^l determination and therefore reduces the weight of A_{FB}^b in the fit of m_H. We find $x_W^l = 0.23214(50)$ (cf. 0.23240(31) from the SM determination). Combined with the four leptonic asymmetries and the SM determination from A_{FB}^c (the method is not readily applied to Q_{FB}), the result is $x_W^l = 0.23135(18)$, with $\chi^2/dof = 8.8/5$ and CL $= 0.12$. This value of x_W^l and the experimental value of A_{FB}^b then imply $A_b = 0.882(17)$, which is 3.1σ from the SM value and 1.5σ from the direct measurement. Denoted CL_{MI} (for model independent) in table 1, the resulting fits leave the widest opening for consistency with the search limit. A very similar result follows if we also extract x_W^l from A_{FB}^c by the analogous procedure.[12]

Discussion

The likelihood distributions for m_H were normalized on the interval between 10 and 1000 GeV. This may be regarded as a type of 'Bayesian prior' to the analysis. If we enlarge the interval both below and above, the fits are driven to lower values of m_H and the conflict with the search limit increases, because, as can be seen from Figure 1, the combined likelihood is

[8]The values for x_W^l corresponding to $CL_{l,Q}$, $CL_{l,c}$, and $CL_{l,c,Q}$ neglect common errors and correlations, and may differ slightly from the properly combined values, but the differences are negligibly small. E.g., naive combination of the 7 measurements gives 0.23158(16) compared with the reported 0.23156(17).

already negligible at 1 TeV but has appreciable weight at 10 GeV. The region below 10 GeV in the SM fit would correspond in the context of BSM (beyond the SM) fits to a perfectly allowed physical region, reflecting the sum of the contributions to the radiative corrections from the actual Higgs sector (presumeably > 113 GeV) and the new physics.

We can get a rough idea of the new physics contributions that would be required by considering just x_W^l and m_W, using the deviations from the SM for any given value of m_H, δx_W^l and δm_W, to compute the corresponding oblique parameters[13] 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 $m_H = 300, 1000, 2000$ GeV that the corresponding values are $S = -0.13, -0.15, -0.13$ and $T = 0.21, 0.43, 0.60$, where $m_H = 2000$ GeV is a 'stand-in' for dynamical symmetry breaking. A more complete discussion will be given elsewhere.[12]

If new physics unique to the third generation is the cause of the A_b anomaly, it will also affect $\bar{b}s$, $\bar{b}d$, and $\bar{s}d$ FCNC (flavor changing neutral currents) via non-SM Z penguin amplitudes. The precise effects would depend on details of the fermion-Higgs Yukawa coupling matrix and are not readily predicted. If the new physics were understood, the FCNC could be used to analyze the Yukawa matrix.[12]

The usual SM fit of m_H averages a collection of measurements that form a sharply bimodal distribution. The more precise lower wing consists principally of the four leptonic asymmetries and m_W, and appears to be the most reliable. The upper wing contains only one high precision measurement, A_{FB}^b, which deviates significantly from the SM and is likely to reflect new physics or systematic error. Excluding A_{FB}^b or following a model independent fitting procedure which reduces its weight, we found that the resulting fits conflicted with the search limit, signalling the presence of new physics affecting the SM determination of m_H from the precision data. This conclusion also follows from fits, dominated by the W mass, in which all the asymmetries are omitted.

It may require new facilities 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 of a new Z factory. 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 contributions to the radiative corrections underscores the importance of framing the search for the Higgs sector in the most general form.

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Table 1. Confidence levels for $m_H > 113$ GeV from various fits (see text). For the fits corresponding to CL_l and CL_{all}, the likelihood maximum for m_H and the corresponding χ^2 minimum and CL are also shown.

	EJ[5]	DH[6]	KS[7]	MOR[8]	BP[9]
$\Delta\alpha_5$	0.02804(65)	0.02763(16)	0.02775(17)	0.02743(19)	0.02761(36)
CL_l	0.0090	0.017	0.011	0.034	0.021
$CL_{l,Q}$	0.012	0.025	0.017	0.048	0.030
$CL_{l,c}$	0.015	0.036	0.024	0.067	0.041
$CL_{l,Q,c}$	0.019	0.047	0.032	0.085	0.052
CL_{MI}	0.029	0.081	0.057	0.14	0.083
CL_{all}	0.080	0.25	0.20	0.35	0.23
CL_{m_W}	0.050	0.058	0.054	0.066	0.060
$CL_{no\ x_W}$	0.032	0.041	0.037	0.049	0.043
$m_{H,l}$(GeV)	30	42	36	56	43
$\chi^2_{MIN,l}$	0.85	1.2	1.1	1.4	1.2
$CL(\chi^2/3\ dof)_l$	0.84	0.75	0.78	0.71	0.75
$m_{H,all}$(GeV)	60	93	84	105	84
$\chi^2_{MIN,all}$	2.3	3.0	2.9	3.2	2.8
$CL(\chi^2/3\ dof)_{all}$	0.51	0.39	0.41	0.36	0.42

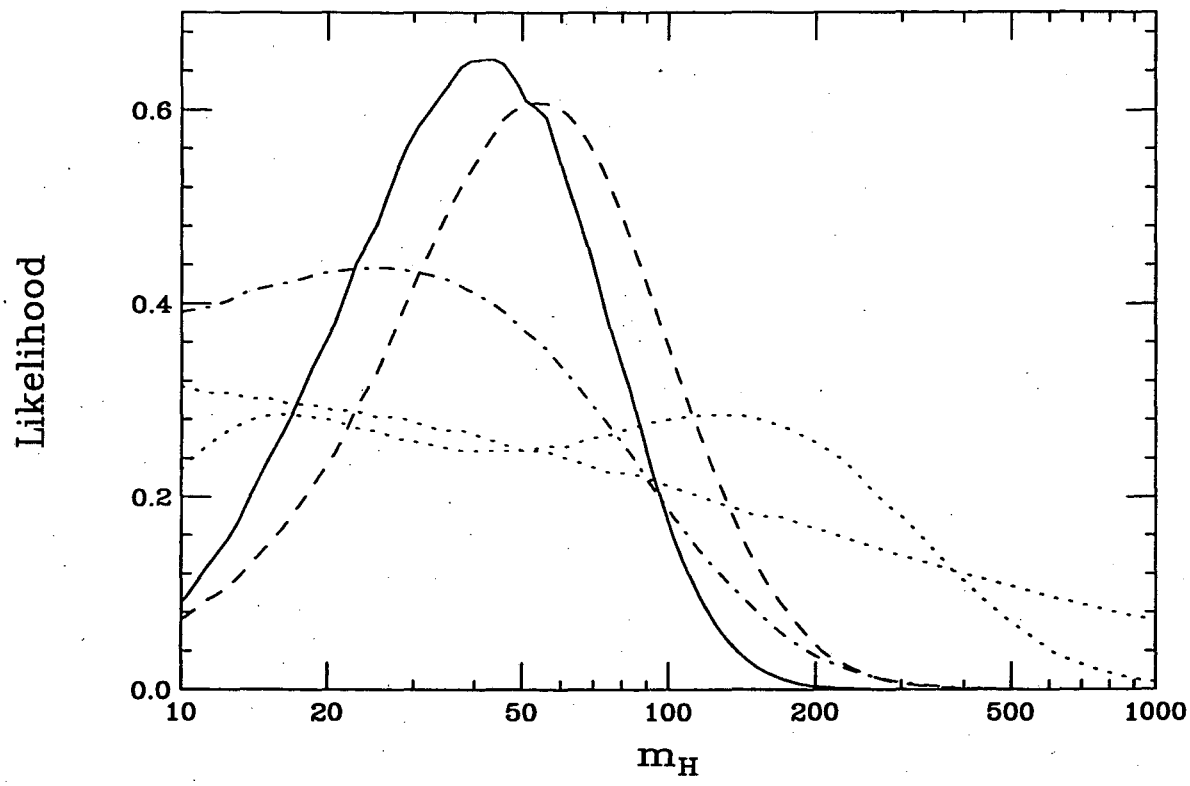

Figure 1: Likelihood distributions obtained from (1) x_W^l from four leptonic asymmetries (dashes), (2) m_W (dot-dash), (3) Γ_Z (dots with twin peaks), (4) R_l (dots), and (5) all four combined (solid). $\alpha(m_Z)$ is from [9].

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