LEP ELECTROWEAK PHYSICS

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ABSTRACT

The LEP Collaborations have been taking data for over 10 years. In this talk just a small number of hopefully interesting results on electroweak physics will be presented. These are neutrino counting, heavy flavor (b quark) cross-sections and asymmetries, final-state interaction effects in W pair events, and results on the global electroweak fit: where do we stand on the Higgs boson.

1 Introduction

The LEP experiments, ALEPH, DELPHI, L3 and OPAL, accumulated data at the Z resonance between 1989 and 1995. In this time, more than 16 million Z decays were recorded by the four experiments. The bulk of the data was at the peak of the Z resonance; however, significant fractions were also accumulated approximately 2 GeV below and above the peak. These data were used to determine the so-called "Z lineshape", that is, the mass, width of the Z boson and its couplings to fermion pairs.

In 1995, the LEP machine left the Z resonance for higher energies. The energy has been increased in steps, by the addition of new RF cavities, starting at 130 GeV in the last half of 1995 to 208 GeV in 2000 (well, actually a *very* small amount of data has been recorded at 209 GeV). These data have been used to study fermion-pair production at high energy. Since 1996, the LEP energy has been greater than 160 GeV, above the threshold for pair-production of W bosons. With these data the properties of the W boson have been studied. An example of the various cross-sections that have been measured at LEP is shown in Figure 1.

Of course, additional measurements have been made using the LEP data sets, such as QCD studies, and searches for new phenomena. These measurements are beyond the scope of this talk, although the latest results on new particle searches was presented at this conference.[1]

Rather than giving a whirlwind tour of all of the electroweak results that have been made at LEP, I'll concentrate on just a few measurements which I think are interesting and important. These are: neutrino counting (particularly relevant for this conference); the measurements in the heavy quark sector, especially R_{b} and $A_{\mathrm{FB}}^{\mathrm{b}}$; the effects on the W mass measurement of final state interactions in fully-hadronic W decays; and finally the global fit: what do we know about the Higgs boson.

2 Neutrino Counting

At LEP, the number of neutrino species is measured by determining the invisible width of the Z boson. The width of the Z into a pair of fermions is given by the formula:

$$\Gamma_{\mathrm{f\bar{f}}} = \frac{G_F m_{\mathrm{Z}}^3}{6\pi\sqrt{2}}(g_{\mathrm{Vf}}^2 + g_{\mathrm{Af}}^2) \tag{1}$$

where

$$g_{\mathrm{Af}} = I_{3\mathrm{f}} \tag{2}$$

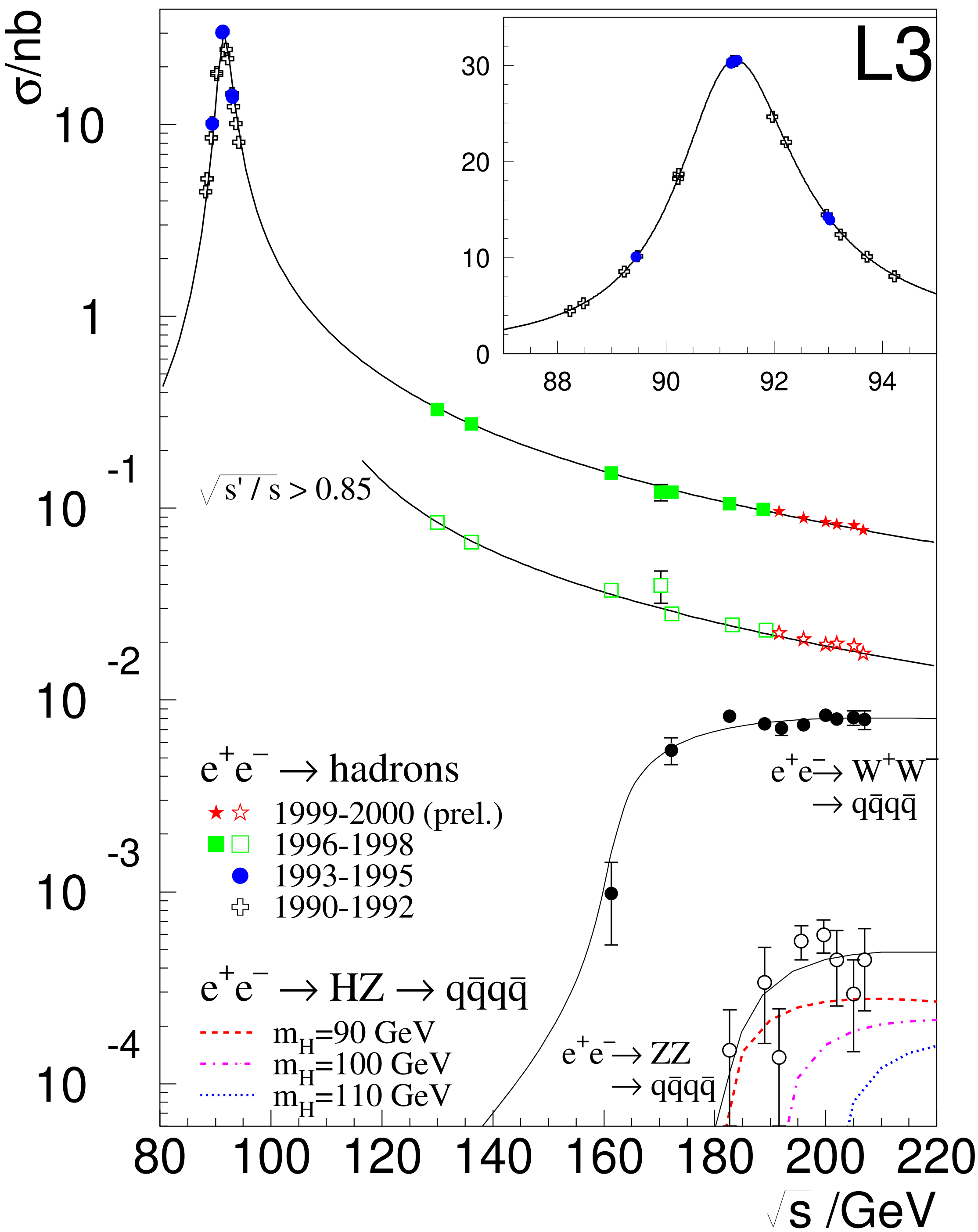

Fig. 1. Hadronic cross-sections as measured by L3 at LEP. Shown are the $\mathrm{q\bar{q}}$, the W-pair and Z-pair (with all W's and Z's decaying hadronically) cross-sections, compared with the Standard Model expectations as a function of the center-of-mass energy, $\sqrt{s}$. Also shown is the expected cross-section for a Higgs boson with various masses.

$$g_{\mathrm{Vf}} \quad = \quad I_{3\mathrm{f}} - 2Q\sin^2\theta_{\mathrm{W}}. \tag{3}$$

Thus, the width of the Z into a pair of neutrinos, $\Gamma_{\nu\bar{\nu}}$, is approximately 167 MeV (which can be compared to 84 MeV for the width into a pair of charged leptons). To determine the number of neutrino species, one simply divides the measured invisible width by $\Gamma_{\nu\bar{\nu}}$.

There are two techniques to measure the invisible width, each with their advantages and disadvantages. The first is the "direct" method which actually measures the rate of invisible Z decays. The Z decays are tagged using a photon from initial state radiation. The second is more indirect, as it derives the invisible width by taking the measured total width and subtracting off the measured partial widths. All that is left over is "invisible".

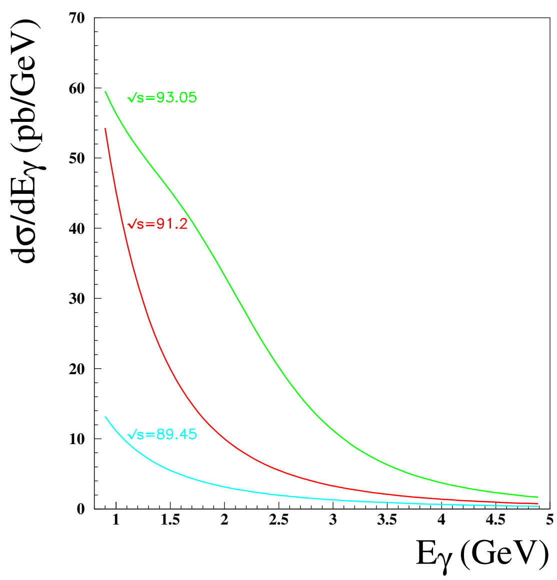

Fig. 2. The differential cross-section for $\mathrm{e^+e^-} \to \gamma\mathrm{Z} \to \gamma\nu\bar{\nu}$ for three different center-of-mass energies.

For the "direct" method, it is important to tag using photons with as small an energy as possible, as the photon energy follows a bremsstrahlung distribution. This can be seen in Figure 2 which shows the differential cross-section for center-of-mass energies around the Z peak. As can also be seen, although the measurement is best performed above the Z peak, it is still possible, albeit difficult, to measure the cross-section *below* the peak, because of the width of the Z resonance.

One must also take into account t-channel W exchange and W–Z interference (Figure 3). Although W exchange also produces neutrinos in the final state, only the electron neutrino is produced, and thus this process yields no information about the number of species. At the Z resonance, the W exchange and W–Z interference contribute about 5% to the total cross-section.[2]

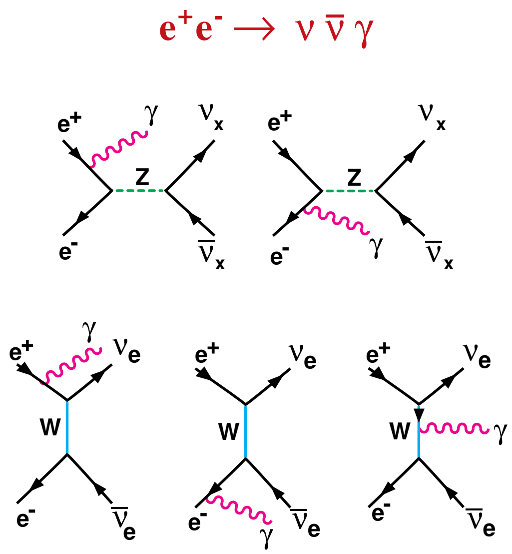

Fig. 3. The lowest order diagrams contributing to $e^+e^- \rightarrow \nu\bar{\nu}\gamma$.

Examples of measured single γ spectra are shown in Figure 4, with comparisons of the data to the expectations of $\nu\bar{\nu}\gamma$ production with 3 neutrino species. One can see the importance of accepting photons with very low energies.

The final results of the LEP experiments[3–6] using the direct technique is shown in Figure 5. The LEP average results in a 3% measurement of the number of neutrino species.

The "indirect" method relies on the knowledge of the measured cross-section as a function of center-of-mass energy, the so-called "Z lineshape". The bulk of the information is contained in the hadronic cross-section, shown in Figure 6. That the cross-section depends on the number of neutrinos can be seen by examining the form of the peak cross-section:

$$\sigma^0_{\rm had} = \frac{12\pi}{m_{\rm Z}^2}\frac{\Gamma_{\rm ee}\Gamma_{\rm had}}{\Gamma_{\rm Z}^2}.$$

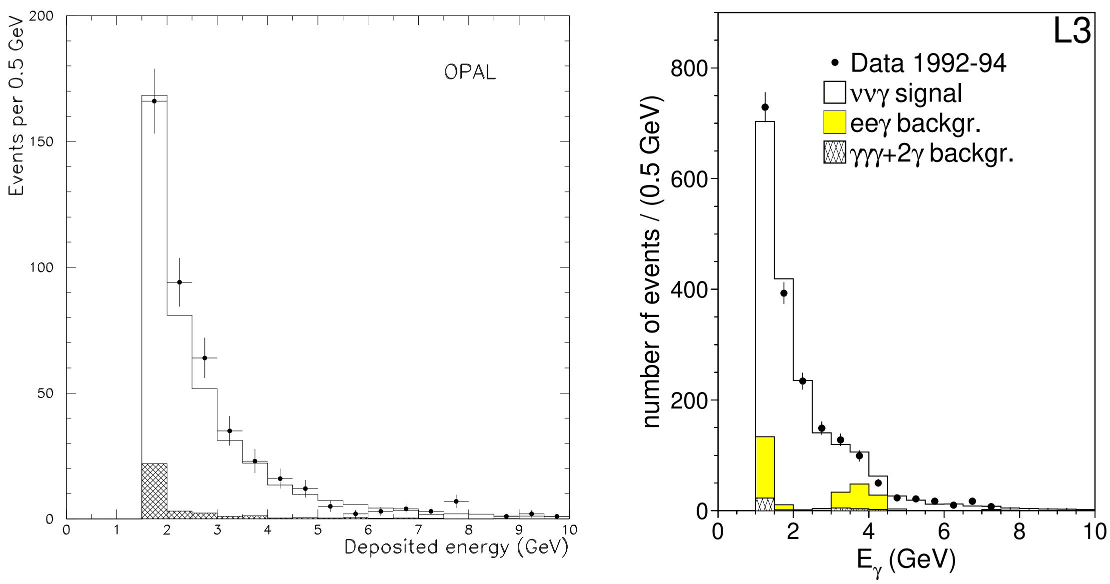

Fig. 4. The measured single photon energy spectra for OPAL (left) and L3 (right). The open histograms are the expectations for $\nu\bar{\nu}\gamma$ production with 3 neutrino species. The solid histograms are the background.

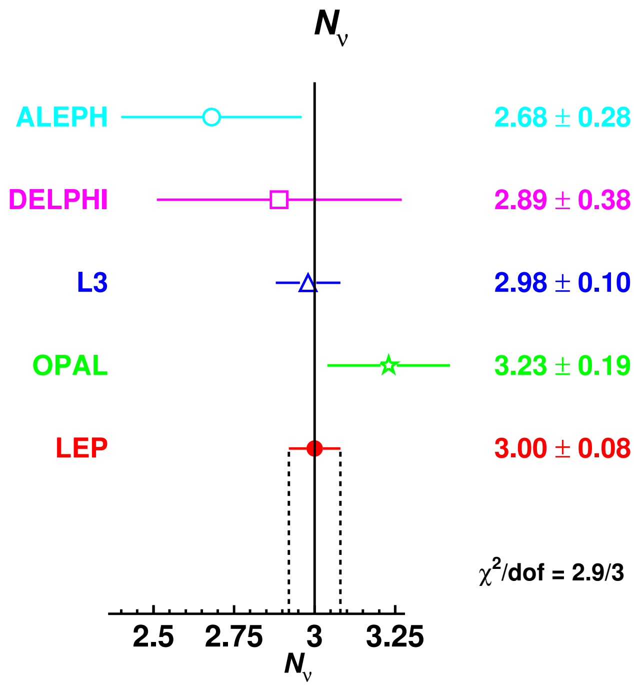

Fig. 5. The results of the four LEP collaborations, as well as the combination, on the direct measurements of N_ν at the Z.

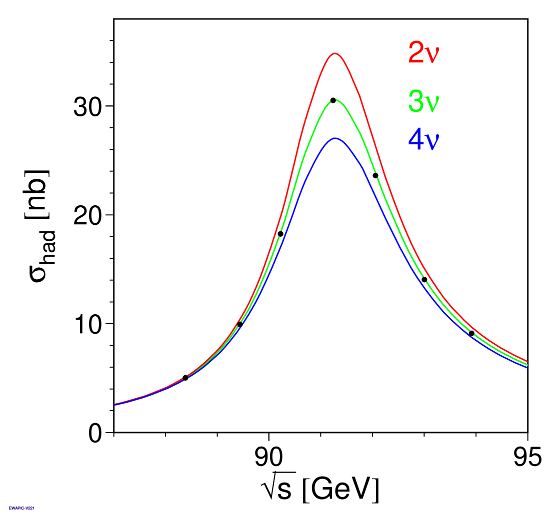

Fig. 6. The measured hadronic cross-section (all 4 experiments combined) compared to the expectations for 2, 3 and 4 neutrino families.

As the number of neutrino families decreases, the invisible width decreases, decreasing the total width and increasing the peak cross-section. The detailed shape of the cross-section is critical for this measurement. Radiative corrections are large: the first order corrections change the peak cross-section by 25%. However, they appear to be under control at better than 0.1%, as shown in Figure 7.

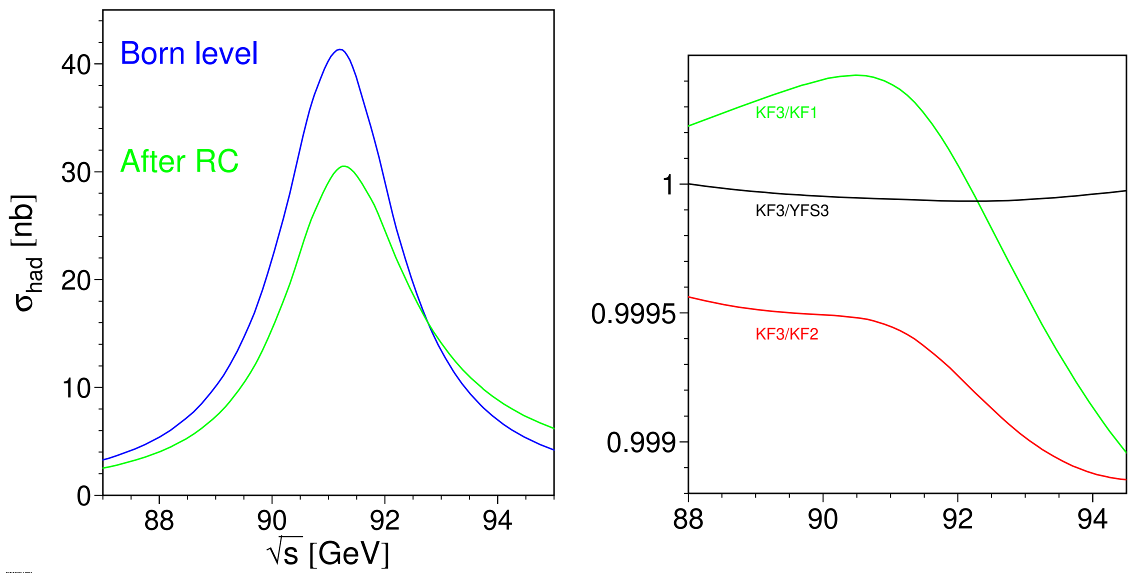

Fig. 7. On the left, the Born-level and first-order-corrected hadronic cross-section; on the right, the ratio of first, second and third order corrections.

From the combined LEP lineshape fit results,[7]

$$\sigma^0_{\mathrm{had}} = 41.540 \pm 0.037 \ \text{ nb} \tag{4}$$

$$\Gamma_{\mathrm{Z}} = 2495.2 \pm 2.3 \ \ \mathrm{MeV} \tag{5}$$

$$m_{\mathrm{Z}} = 91187.5 \pm 2.1 \ \ \mathrm{MeV} \tag{6}$$

$$R_\ell \equiv \Gamma_{\mathrm{had}}/\Gamma_{\ell\ell} = 20.767 \pm 0.025, \tag{7}$$

the experiments derive

$$\frac{\Gamma_{\mathrm{inv}}}{\Gamma_{\ell\ell}} = 5.942 \pm 0.016. \tag{8}$$

Using the Standard Model expectation of $\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{\ell\ell}} = 1.992 \pm 0.0012$, one finally arrives at

$$N_\nu = 2.984 \pm 0.008. \tag{9}$$

This is a bit below an integral value of three, due mainly to the fact that all four collaborations measure a hadronic cross-section higher than the Standard Model prediction.

If, on the other hand, one assumes that there are 3 neutrino families, then this result can be translated into a limit on additional invisible width:

$$\Gamma_{\rm inv}^{\rm new} < 2.0 \ \ {\rm MeV}, \tag{10}$$

or about 1% of the width of a "standard" neutrino family.

3 Electroweak Heavy Flavor Physics

There are a few aspects of the b-quark that make electroweak studies using b-quarks both interesting as well as possible. First of all, because the b-quark has a relatively long lifetime, the use of displaced vertices allows for efficient and effective tags. In addition, about 20% of the time, a b-quark will decay semi-leptonically resulting in a high momentum electron or muon. Finally, the large mass of the b-quark allows a separation of b- and c-quark events based on the invariant mass of the particles associated with the displaced vertex.

The rate for Z$\rightarrow$ $\rm b\bar{b}$ is interesting because of the extra diagrams involved (Figure 8). Because of these diagrams, the ratio $R_{\rm b} \equiv \Gamma_{\rm b\bar{b}}/\Gamma_{\rm had}$ is uniquely sensitive to the top-quark mass, and is practically insensitive to other parameters of the Standard Model, including the Higgs mass.

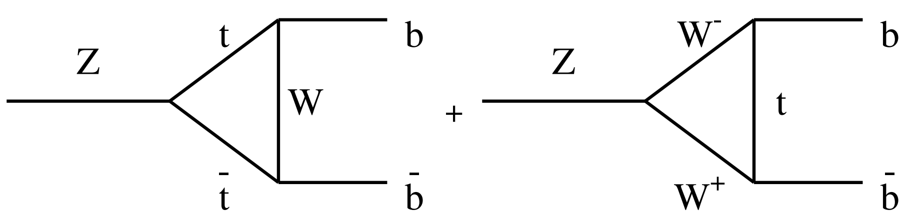

Fig. 8. The extra diagrams for the $\rm Zb\bar{b}$ vertex involving the t-quark.

The current status[8] of the $R_{\rm b}$ measurements is shown in Figure 9. The results are quite consistent with each other, and with the expectations of the Standard Model. It should be noted that $R_{\rm b}$ all by itself yields a prediction of $m_{\rm t}$ of 150 ± 25 GeV, in very good agreement with the measured value of 174.3 ± 5.1 GeV. This was not always the case, as also shown in Figure 9. There have been a number of changes in the last five years.

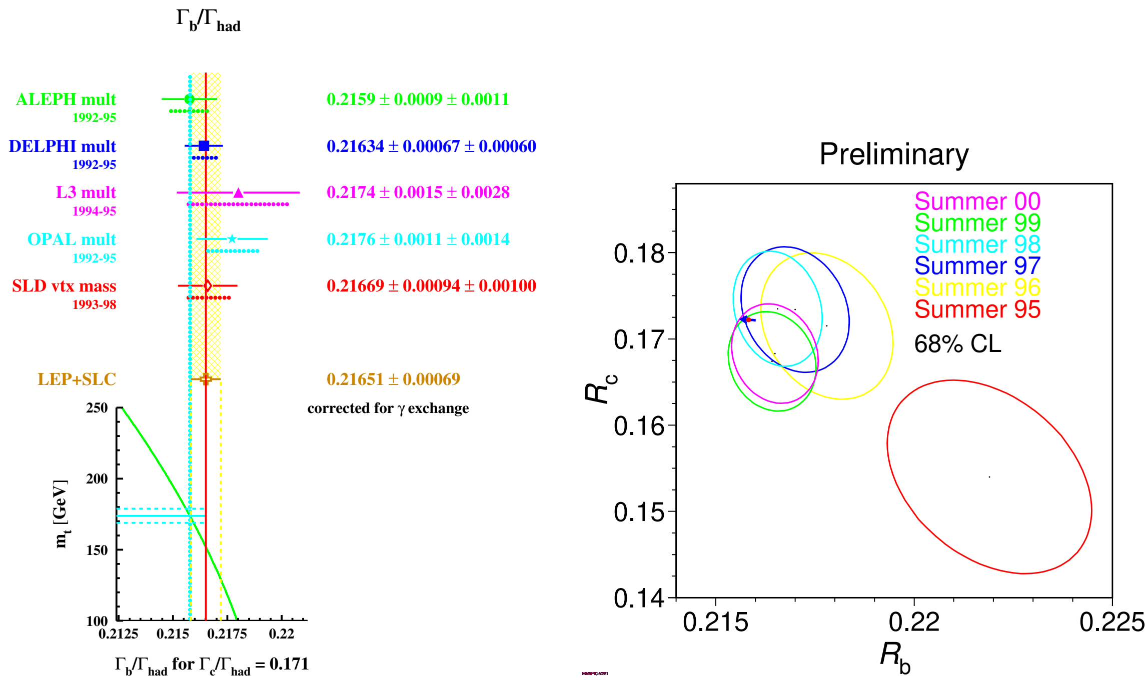

Fig. 9. On the left, the current measurements of R_b. On the right, the history over the last few years of R_b and R_c, compared to the Standard Model prediction (small arrow).

In 1995, only about one half of the full LEPI data set had been analysed. Thus, the current values, which are very close to the final results, include twice the statistics.

The techniques used to measure R_{b} have improved significantly. In 1995, only a few measurements used multiple-tags. The use of multiple-tags allows the determination of many efficiencies directly from the data, reducing significantly the reliance on Monte-Carlo models. This has made the results more robust.

Much work has gone into studying correlations between hemispheres. These correlations can arise through the underlying physics, for example through gluon radiation which can reduce the available phase-space for both b quarks, or can even flip both quarks into the same hemisphere. They can also arise through experimental measurement systematics, for example mis-measuring the primary event vertex and thus affecting the measured decay length of both b's. These effects are also under better control, also partially through the use of multiple types of tags which are affected differently by the various systematic uncertainties.

Finally, a very important element in the measurement of R_{b} has been improvements in related measurements. As can be seen, in 1995 there was a strong correlation between R_{b} and R_{c}. The correlation is much smaller now (due to the improved R_{b} techniques), but measurement of R_{c} has also improved at the same time, also through the use of new methods. In addition, some ancillary measurements, such as D meson branching ratios and gluon splitting fractions ($g \to \mathrm{b\bar{b}}$ and $g \to \mathrm{c\bar{c}}$) have been better measured, or in some cases measured for the first time, again reducing the reliance on Monte-Carlo.

The upshot is that R_{b} appears to no longer be a concern. However, the b sector is not completely out of the woods yet, as the forward-backward asymmetries are making life interesting now.

The b-quark asymmetry has always provided an interesting and important measurement of $\sin^2\theta_{\mathrm{W}}$. This can be seen by examining the structure of the forward-backward asymmetry on the Z peak:

$$A_{\mathrm{FB}} = \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_{\mathrm{f}} \tag{11}$$

where

$$\mathcal{A}_{\mathrm{f}} = \frac{2g_{\mathrm{Vf}}g_{\mathrm{Af}}}{g_{\mathrm{Vf}}^2 + g_{\mathrm{Af}}^2} \tag{12}$$

or, equivalently

$$\mathcal{A}_{\mathrm{f}} = \frac{2(1-4|Q_f|\sin^2\theta_{\mathrm{W}})}{1+(1-4|Q_f|\sin^2\theta_{\mathrm{W}})^2}. \tag{13}$$

Since the b-quark has charge $-\frac{1}{3}$, $\mathcal{A}_{\rm b}$ is fairly *insensitive* to $\sin^2\theta_{\rm W}$. On the other hand, $A_{\rm FB}^{\rm b}$ is *more* sensitive than $A_{\rm FB}^{\ell}$ to $\sin^2\theta_{\rm W}$, as shown in Figure 10. Thus, $A_{\rm FB}^{\rm b}$ provides an excellent measurement of $\sin^2\theta_{\rm W}$ at the *electron* vertex.

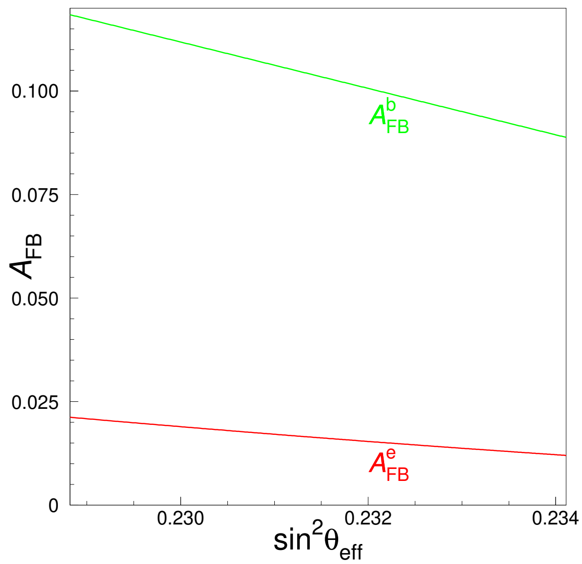

Fig. 10. The forward-backward asymmetry as a function of $\sin^2\theta_{\rm W}$. As can be seen, $A_{\rm FB}^{\rm b}$ is more sensitive to $\sin^2\theta_{\rm W}$ than the electron (or any other unit charged particle) asymmetry.

The measurement of $A_{\rm FB}^{\rm b}$ is conceptually very simple: one tags $\rm b\bar{b}$ events, measures the charge of at least one of the quarks, and then counts the number of b quarks and $\rm\bar{b}$ quarks in the forward hemisphere and takes the difference. The tagging techniques are similar to those used for the $R_{\rm b}$ measurement, relying on high p_t leptons and lifetime information. To measure the quark charge, the charge of the lepton is used for the leptonic tags. For the lifetime tags, as well as for the leptonic tags, one can use the "jet charge". The idea here is that the charge of the primordial quark is "remembered" by the sum of the charges of all particles in the jet, especially if one weights the particles according to their momentum.

There are a number of corrections which must be applied to the measured asymmetry. One source which has been studied in some detail in the recent past arises from QCD radiative corrections. Examples of the effects of QCD corrections are shown in Figure 11. There have been a number of recent calculations.[9] The current understanding is that these effects result in a 1 – 2.5% correction which is somewhat dependent on the analysis and experimental cuts. The correction is larger for the leptonic tags than

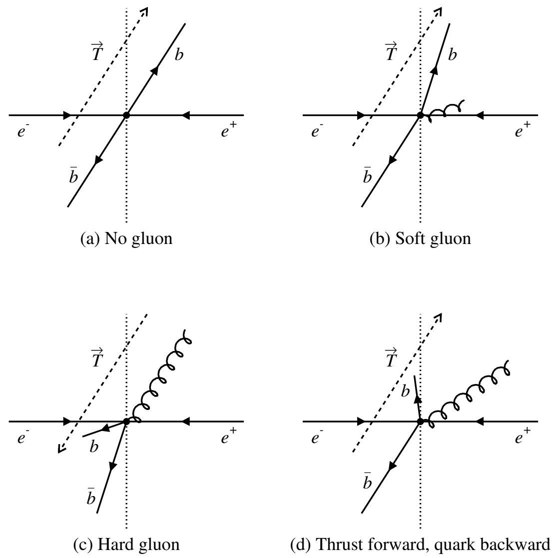

Fig. 11. Examples of event distortions due to QCD radiative corrections. As can be seen, in some cases the quark can be "flipped" to the wrong hemisphere.

for the jet-charge tags, as the jet-charge method compensates for some of the effects.

The resulting measurements[10–13] are shown in Figure 12 (Ref. 14), grouped by measurement type. As can be seen, there is very good agreement among the experiments as well as between the two methods. The average of all leptonic tags yields $A_{\rm FB}^{\rm b} = 0.0971 \pm 0.0026$ whereas the average jet-charge tag is $A_{\rm FB}^{\rm b} = 0.1021 \pm 0.0031$, consistent with the overall average of $A_{\rm FB}^{\rm b} = 0.0990 \pm 0.0020$. Note that because of correlations, these results are not a straight-forward average of the individual measurements.

Although the measurements of $\rm b\bar{b}$ asymmetry are consistent with each other, one can ask whether they are consistent with other measurements. This can be seen graphically in Figure 13. On the left, the $A_{\rm FB}^{\rm b}$ measurements (diagonal band) are compared to the $\mathcal{A}_\ell$ measurements from the leptonic asymmetries, tau polarization and $A_{\rm LR}$ (vertical band) and the direct $\mathcal{A}_{\rm b}$ measurements (horizontal band). There *is* a region where all measurements overlap; it is, however, not where the Standard Model would like to have them. Viewed another way, if one assumes that the b couplings are those given by the Standard Model, then the $\mathcal{A}_\ell$ value extracted from $A_{\rm FB}^{\rm b}$ does not agree with that from the leptonic asymmetries. This is the "standard" interpretation when using $A_{\rm FB}^{\rm b}$ to extract $\sin^2\theta_{\rm W}$ which yields significantly different values for the two. On the other

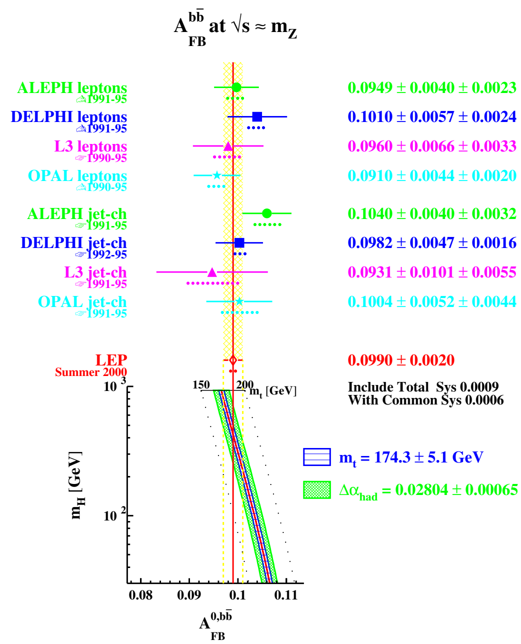

Fig. 12. The various measurements of $A^{\mathrm{b}}_{\mathrm{FB}}$, compared to the Standard Model expectation as a function of the Higgs mass.

hand, if one assumes that the leptonic asymmetries are correct, and uses $\mathcal{A}_\ell$, $A^{\mathrm{b}}_{\mathrm{FB}}$, $\mathcal{A}_{\mathrm{b}}$ and R_{b} to extract the b couplings (the right half of Figure 13), the agreement between the measured b couplings and the Standard Model is not very good.

This is one of the very few sets of measurements that disagree with the Standard Model. Is this physics or just a statistical (or systematic) effect? We will probably have to wait a while to discover this, as essentially all of the available data have been analysed, and all of the results are now final or close to final, and both the LEP and SLC programs are finished.

4 Final State Interactions in W decays

When both W bosons in $\mathrm{e}^+\mathrm{e}^- \to \mathrm{W}^+\mathrm{W}^-$ decay hadronically, the two hadronic systems may interfere. This is because the typical hadronization scale is about 1 fm, whereas the typical separation between the W's at the time of their decay (at LEP energies) is about 0.1 fm. Because of this, the two systems have the potential to cross-talk, which might influence the measured W mass distributions. Only the fully hadronic (qqqq)

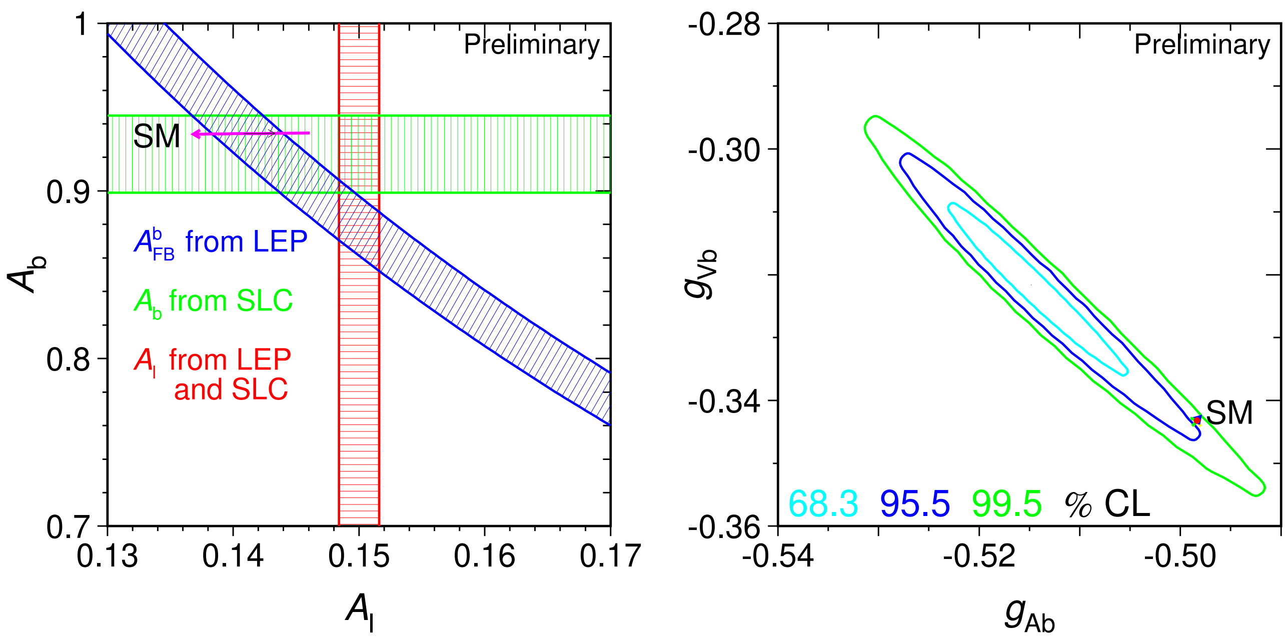

Fig. 13. On the left, the comparison of the $A_{\rm FB}^{\rm b}$ (diagonal band), $\mathcal{A}_{\rm b}$ (horizontal band) and $\mathcal{A}_{\ell}$ (vertical band) measurements. On the right, the extracted b couplings using all available measurements. In both cases, the arrow indicates the Standard Model expectation for Higgs masses between 100 GeV (back end of arrow) to 1000 GeV (head of arrow).

events are affected; events where only one W decays hadronically ($qq\ell\nu$) events are not affected.

There are two sources of final state interactions which might affect the W mass, "color reconnection"[15] and Bose-Einstein correlations.[16] They are schematically represented in Figure 14. Color reconnection involves a change of the color flux, which

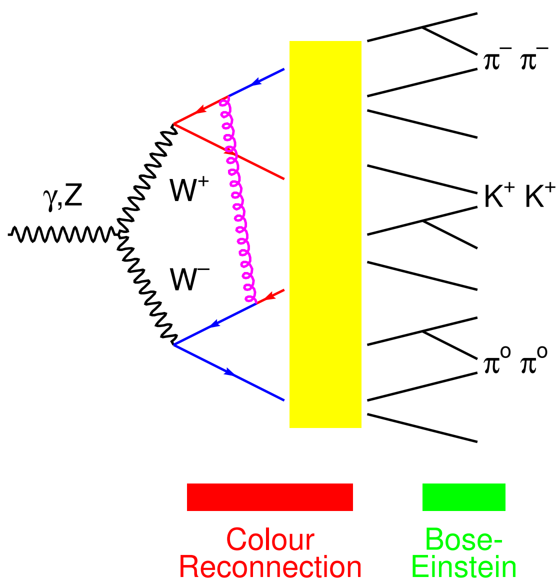

Fig. 14. The different types of final state interactions which can affect the W mass measurements.

could be brought about by the exchange of low energy gluons between quarks from different W decays. Bose-Einstein correlations which affect the distributions of final state pions and kaons are only bad if particles from different W decays are involved.

As all of these processes occur at low momentum transfer, perturbative QCD cannot be used to evaluate them. Until recently, the only available method was to use various Monte-Carlo models. This was not a good situation, as the various models gave a wide range of results: one[17] predicted mass shifts of several hundred MeV! As the final statistical uncertainty on the W mass is expected to be 25 MeV, this could be a show-stopper.

However, with the increasing statistics available, the collaborations are now reporting measurements of these effects using data. These can be used to constrain the available models, placing a limit on the size of any mass shift.

There is ample evidence for Bose-Einstein correlations (BEC) in Z decays.[18] Thus BEC should also occur within a single W decay (*intra*-W BEC). Furthermore, given the arguments above, they could also occur between the two W decay products (*inter*-W BEC).

All four experiments have studied BEC in W decays.[19] All see indications for intra-W BEC. An example of this evidence is shown in Figure 15. However, the fact

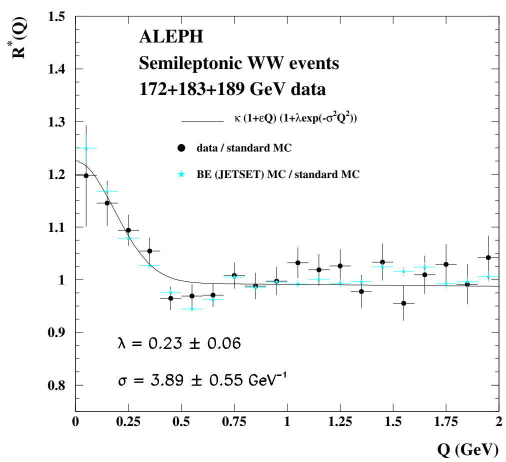

Fig. 15. An example of the evidence for Bose-Einstein correlations in W boson decays.

that BEC do exist makes it more difficult to see if the dangerous inter-W BEC also exist. The experiments have gotten around this by comparing distributions of pions with those from qq$\ell\nu$ events (with only intra-W BEC) or from pions from completely different qq$\ell\nu$ events (with no BEC at all by construction).

The results at the moment are inconclusive.[20] ALEPH disfavor inter-W BEC by about 2 sigma; DELPHI favor inter-W, but also only at 2 sigma. L3 disfavor them at 4 sigma (see Figure 16), whereas OPAL can not say either way (the data are compatible with no inter-W BEC). Clearly more work is needed on this. Fortunately the experiments have not yet analyzed the full data set. With the current situation, the experiments have estimated that BEC effects contribute a systematic uncertainty on the W mass of about 25 MeV.

Color reconnection can be viewed as a situation where the QCD string between the two quarks in one W decay flips to connect two quarks from different W's, as shown diagrammatically in Figure 17. Predicted effects include a change of particle multiplicities, as the dynamics of the fragmentation process have changed, and a change of particle and energy flow between jets, following the string. Also here, with only

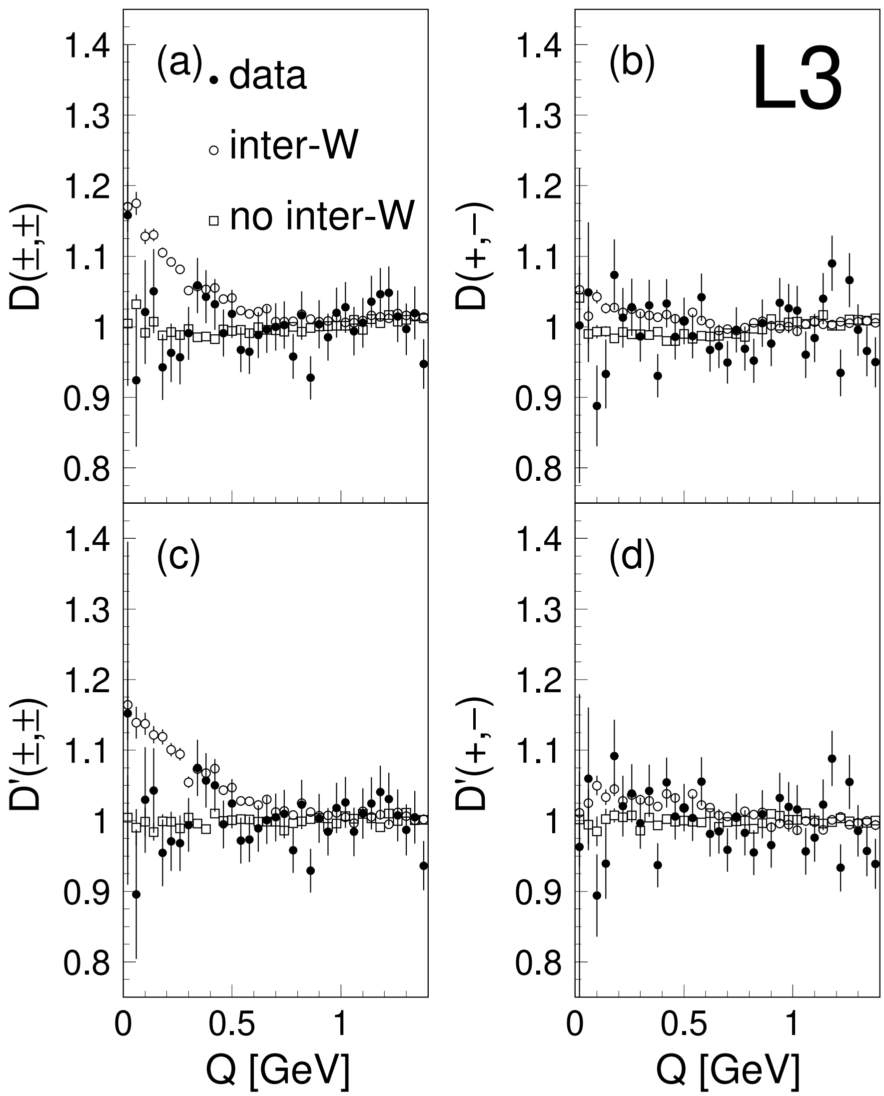

Fig. 16. Distributions of the variables D and D' as a function of Q, the 4-momentum difference between pairs of particles. D and D' are constructed to be one in the absence of inter-W BEC. The data are in agreement with no inter-W BEC (a and c). The control samples of unlike-sign particles (b and d) show no effect.

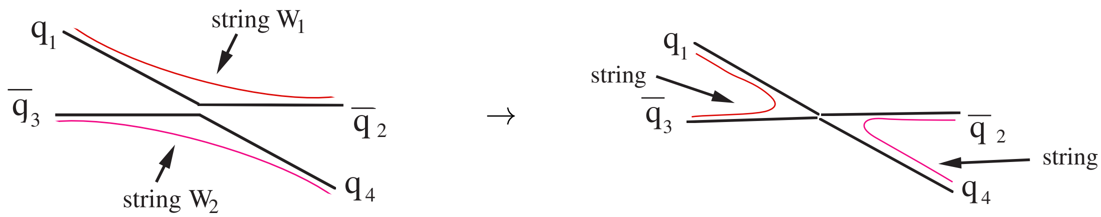

Fig. 17. A diagrammatic view of color reconnection.

models to rely on, the experimenters have tried to infer as much as possible by studying the data, comparing qqqq events to qq$\ell\nu$ or to mixed events.

The study of particle multiplicities has been inconclusive to date.[21] The experiments have compared the inclusive multiplicity in qqqq to twice the multiplicity in qq$\ell\nu$ (after correcting for the leptons). Most models predict a shift between -0.3 and 0.2. As can be seen in Figure 18, it will be very difficult to exclude any models using this method. There is ongoing work to study heavy hadrons (K, p) which are expected[22] to show

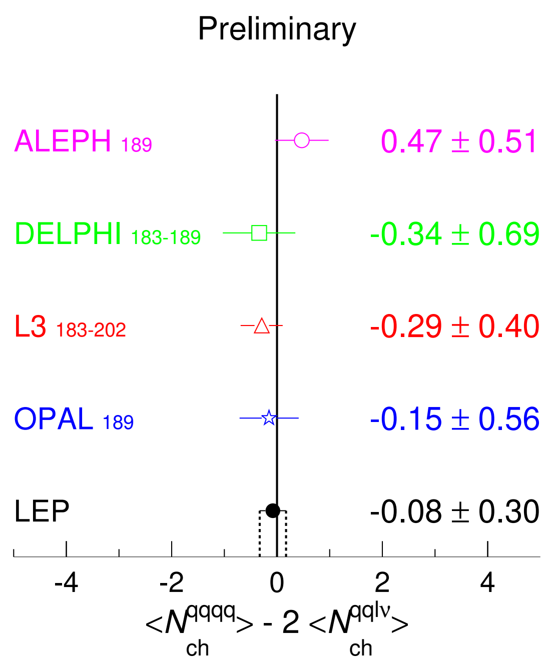

Fig. 18. The difference between the multiplicities in fully hadronic WW decays and semileptonic WW decays.

larger effects.

A more promising method is the study of the inter-jet particle and energy flows,[23] which was successfully used to establish the "string effect". Here one takes fully hadronic WW events and applies a very tight selection, requiring a very clean and well defined 4 jet topology. With these requirements, one can achieve a very high probability ($\approx$ 87%) of pairing the jets to the correct W boson. After normalizing the inter-jet angles, the energy or particle flow is plotted as a function of the normalized angle, as shown in Figure 19. One then takes the ratio of the intra-W regions to the inter-W

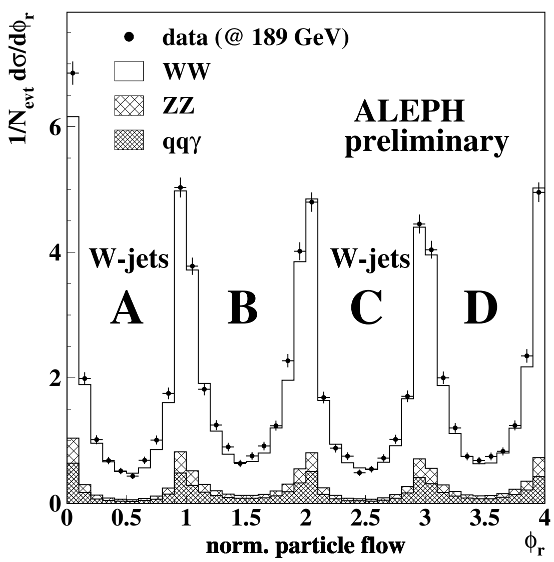

Fig. 19. The particle flow as a function of normalized inter-jet angle. The events are oriented such that regions A and C correspond to the region between the quarks arising from a W (intra-W).

regions, to better isolate the effects of color reconnection. This analysis has been performed by L3,[24] ALEPH[25] and OPAL.[26] Examples are shown in Figure 20. As can be seen, this quantity can be used to distinguish the various models. The experiments have parameterized their results as a function of the reconnection probability: 0% means that reconnection never occurs (the two W's decay independently) and 100% means that reconnection always occurs. The L3 data prefer a 40% reconnection probability and disfavors no reconnection at the 1.7 sigma level. ALEPH prefer 15% reconnection and put the 1 sigma limit at 45%. The OPAL results are inclusive, with one analysis preferring some reconnection and another preferring no reconnection.

The experiments have also studied the relationship between the reconnection probability and the expected mass shift. This is shown in Figure 21. With the current results indicating around 40% reconnection probability, the current estimate is at most 50 MeV

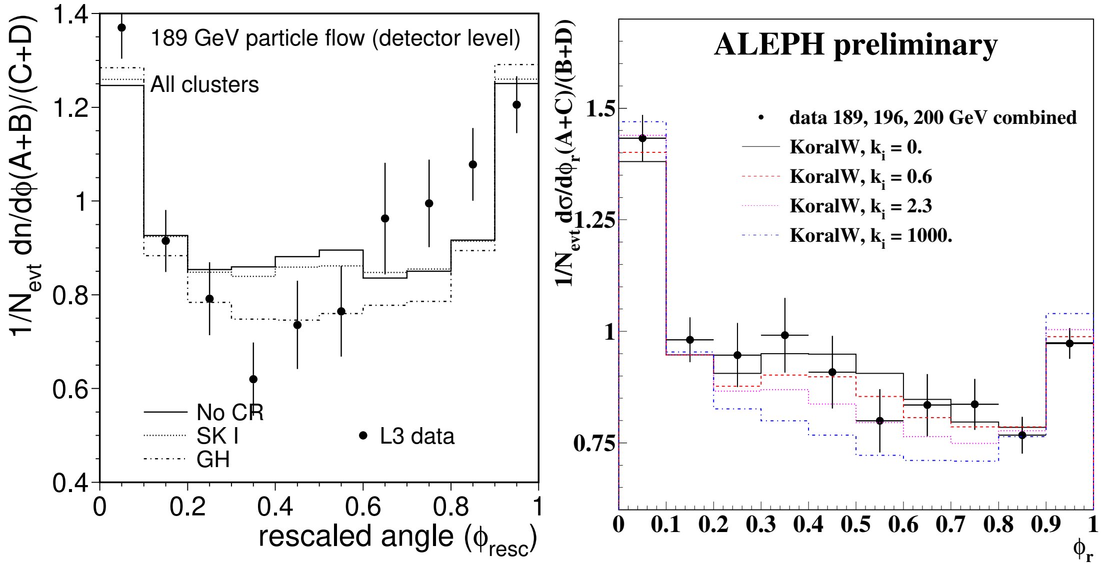

Fig. 20. The ratio of intra-W to inter-W particle flows as a function of the angle for L3 (left) and ALEPH (right). The points are the data and the lines various Monte-Carlo models with varying reconnection probabilities. In each plot, the solid line corresponds to no color reconnection.

for the difference in masses. On the other hand, the mass shift can also be experimentally determined by comparing the difference in masses using fully hadronic events and semileptonic events, as also shown in Figure 21. The result is currently consistent with no mass shift, as well as a 50 MeV shift. With more statistics all results will improve.

5 The Global Fit

The many electroweak measurements performed at LEP, SLC and elsewhere can be used to test the Standard Model. Within the Standard Model they can be used to extract information about the Higgs boson mass through the effects of radiative corrections. An example of the comparison of measurement to SM predictions is shown in Figure 22. There are several things that can be gleaned from this figure. Firstly, electroweak radiative corrections are indeed needed; secondly, the SM appears in good shape, and thirdly, the uncertainty on the running of α directly affects the ability of the data to say something about the Higgs mass.

The fine structure coupling "constant", α, runs because of virtual fermion loops in

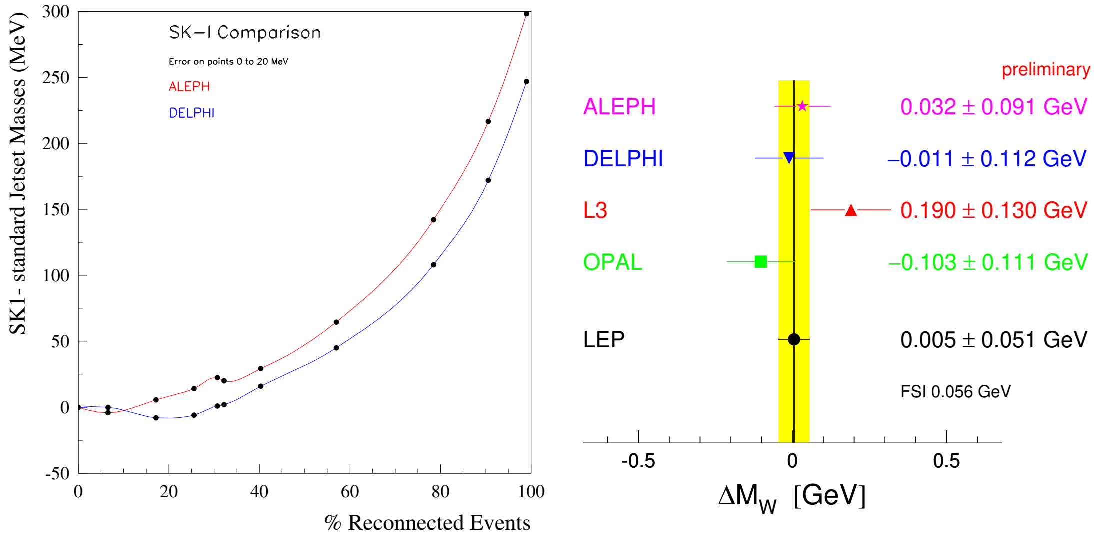

Fig. 21. On the left, the W mass difference as a function of the reconnection probability. On the right, the experimentally determined mass shifts.

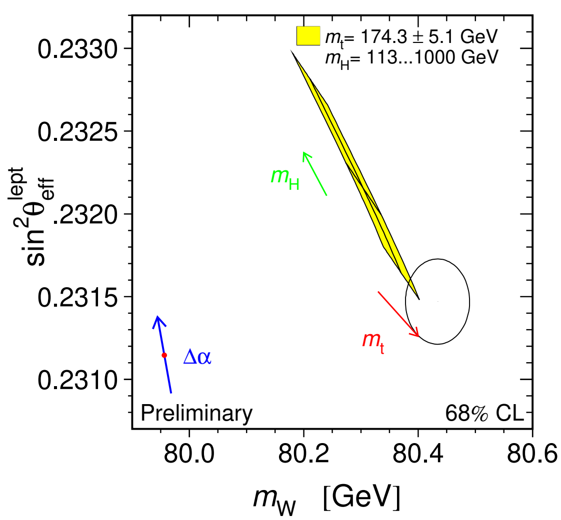

Fig. 22. The measurement of m_{W} and $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ (contour) compared to the SM prediction (shaded region). The size of the region reflects the uncertainty on the top quark mass, and the range allowed for the Higgs mass, with the arrows indicating the regions of higher mass. Also shown is the prediction if only the effects of the running of α are considered. The size of the arrow on that point reflects the uncertainty on $\Delta\alpha$.

the photon propagator, resulting in

$$\alpha(m_{\mathrm{Z}}) = \frac{\alpha(0)}{1 - \Delta\alpha}. \tag{14}$$

For leptonic loops, QED can be used, and the radiative corrections are known to high order.[27] On the other hand, the contributions from quark loops are more problematic, since QCD at low energy is non-perturbative. One can get around this by relating the hadronic component of $\Delta\alpha$ to the hadronic cross-section measured in $\mathrm{e}^+\mathrm{e}^-$ annihilation (R):

$$\Delta\alpha_{\mathrm{had}}(m_{\mathrm{Z}}^2) = -\frac{\alpha m_{\mathrm{Z}}^2}{3\pi}\int_{4m_\pi^2}^{\infty} ds \frac{R(s)}{s(s - m_{\mathrm{Z}}^2 - i\epsilon)}. \tag{15}$$

There have been two choices for evaluating R: using the data[28] or using QCD.[29] The

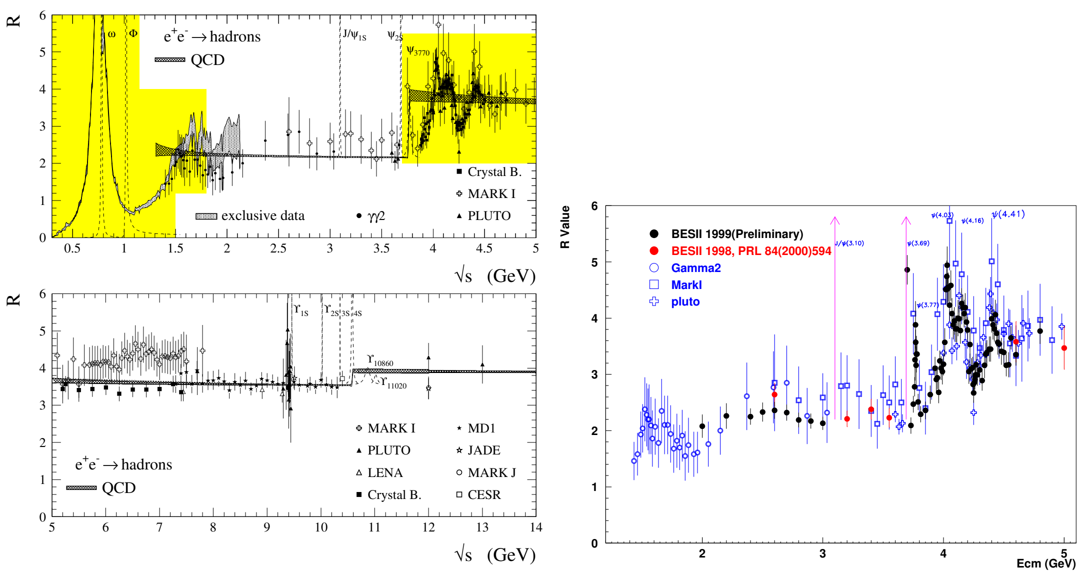

Fig. 23. On the left, the measurements (points) of R as a function of the center of mass energy compared to the QCD calculations (narrow hatched band). On the right, the new measurements from the BES experiment (solid points) compared to older results (open points).

situation until this year has not been very satisfactory, as seen in Figure 23. The data below 10 GeV, which is important, is not very consistent, and the uncertainties are often rather large. The uncertainties from the QCD calculations are much smaller, but QCD and the data do not always agree. The value of $\Delta\alpha$ determined from data is larger, with a larger uncertainty than that from QCD. This in turn yields a smaller value of the Higgs mass, but also with a larger uncertainty (*i.e.*, higher mass limit).

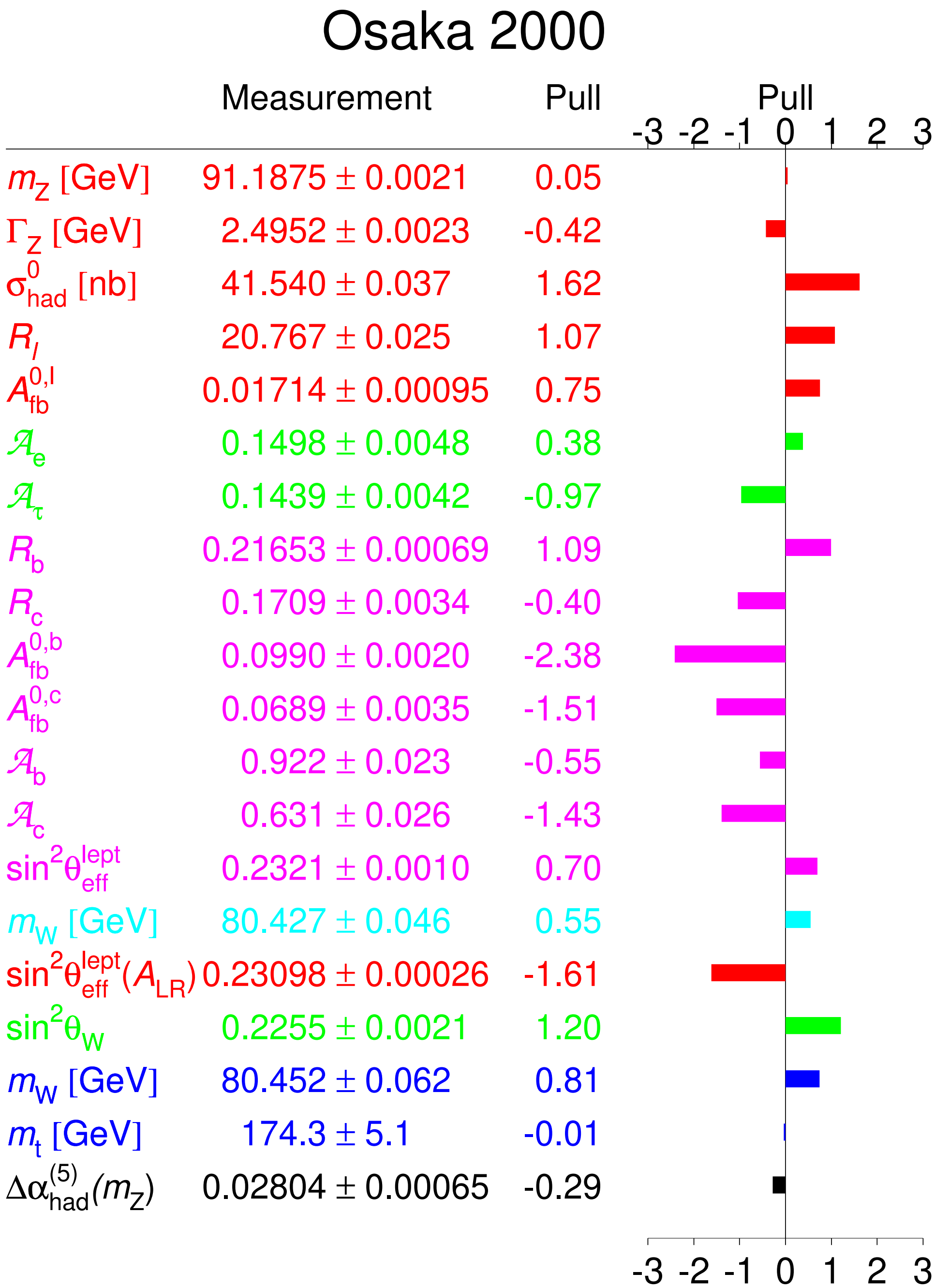

Fig. 24. The data measurements used in the global SM fit for the Higgs mass. Also shown is the deviation from the SM fit (labeled "pull").

Fortunately, there has been a significant improvement in the data this year, with the new preliminary BES results,[30] as also shown in Figure 23. The data uncertainties have been reduced significantly, and the results seem to agree with QCD better. The preliminary value of $\Delta\alpha$ obtained with the new data is 0.02755 ± 0.00046[31] compared to the old data result of 0.02804 ± 0.00065.[28]

The complete data set used for the fit to determine the Higgs mass in the context of the SM is shown in Figure 24. As can be seen, the biggest deviations occur for $A_{\rm FB}^{0,\,\rm b}$ and $A_{\rm LR}$, as discussed earlier.

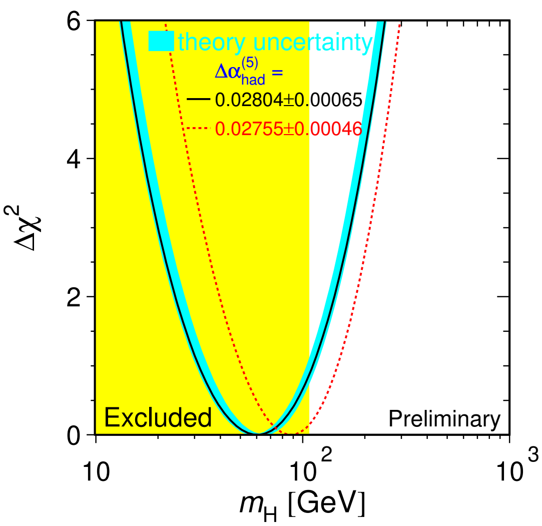

Fig. 25. The χ^2 of the SM fit as a function of the Higgs mass. The solid curve shows the result using the older value of $\Delta\alpha$; the dashed curve results from the new preliminary value. The band around the solid curve indicates the theoretical uncerntainties in the fit. The shaded region below about 113 GeV indicates the limit from the direct searches at LEP.[1]

The resulting fit for the Higgs mass is shown in Figure 25, for the old and new data evaluations of $\Delta\alpha$. Using the old $\Delta\alpha$, the central value for the Higgs mass is 60 GeV, with the 95% confidence level limit of 165 GeV. Using the new value of $\Delta\alpha$, these numbers move up to 88 GeV and 210 GeV, respectively. This shows how important the low energy $\rm e^+e^-$ data is! Nevertheless, it is clear that the electroweak measurements prefer a low mass Higgs.

6 Summary

The LEP program has been fantastically successful. The LEP machine has performed both as a Z factory as well as a W factory. A wealth of information has been obtained concerning the Standard Model. This talk has just focused on a very small number of these results:

- The number of light neutrino families has been determined to be three at the sub-percent level, from measurements of the width of the Z. Any additional "invisible" contributions to the Z width are limited to the per-mil level. Perhaps more relevant for this conference, any new invisible particles are limited to have less than one percent of a standard neutrino coupling.
- The heavy flavor electroweak sector has been and continues to be very interesting. The only relatively significant deviations from the Standard Model are in the b quark couplings, driven by a combination of the $A_{\mathrm{FB}}^{\mathrm{b}}$ measurements and the leptonic asymmetries (A_{FB}, τ polarization and SLD's A_{LR}). Unfortunately, all of the available data has been analyzed, the experiments have stopped taking data, and the results are essentially final. It will be a while before we learn anything new here.
- Final state interactions were once seen as potential "show-stoppers" in the determination of the W mass. New studies, and especially new techniques using the data, indicate that FSI is probably not a problem.
- The Higgs boson appears to be light.

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