Forward-backward asymmetry of b-$\bar{b}$ events at the Z

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Forward/Backward asymmetry of $b-\bar{b}$ events ($A_{\mathrm{FB}}^{\mathrm{b\overline{b}}}$) provides the most precise measurement of $\sin^2\theta_{eff}^{lept}$ at LEP I. In this note we will review :

- The different techniques used to measure $A_{\mathrm{FB}}^{\mathrm{b\overline{b}}}$.
- The recent improvements implemented by the LEP experiments in their $A_{\mathrm{FB}}^{\mathrm{b\overline{b}}}$ analysis.
- The corrections applied to $A_{\mathrm{FB}}^{\mathrm{b\overline{b}}}$ to extract $\sin^2\theta_{eff}^{lept}$.

The value obtained for $\sin^2\theta_{eff}^{lept}$ from $A_{\mathrm{FB}}^{\mathrm{b\overline{b}}}$ is in favour of a high value for the Higgs mass compared to what is obtained with other observables like A_{LR} or m_W . This difference is commented.

1 Introduction

Particles not produced at LEP, like the top or the Higgs, can have measurable effects on electroweak observables through the radiative corrections they induce. In the same way than LEP was able to predict the top mass with a precision of $\sim 10\,\mathrm{GeV}$ before its discovery at the TEVATRON, the present electroweak data give throng constrains on the Higgs mass (m_H= 88 $^{+53}_{-35}$ GeV , m_H< 196 GeV at 95% cl)[a]. All measurements sensitive to the fermions couplings to the Z play an important role in these constrains. The asymmetric forward-backward production of fermions in the Z decays are among them. In this paper the measurement of the forward-backward b asymmetry performed at LEP I will be presented. It provides today, with m_W and A_{LR} , the main constrain on m_H.

1.1 *Fermions asymmetries and* $\sin^2\theta_{eff}^{lept}$

In the Standard Model (SM) the differential cross-section in function of the polar angle θ between the e^- and the fermion f directions for the process $e^+e^- \to f\overline{f}$ at $\sqrt{s}=m_Z$ is

$$\frac{d\sigma}{d\cos\theta} \sim 1+\cos^2\theta+\frac{8}{3}A_{\mathrm{FB}}^{f,0}\ \cos\theta$$

[a] All the results/numbers quoted in this note are updated to their summer 2001 values

with

$$A_{\rm FB}^{f,0} = \frac{3}{4}\mathcal{A}_e\,\mathcal{A}_f$$

which can be expressed in terms of the real part of the effective vector and axial-vector neutral current couplings of fermion f, g_{v_f} and g_{a_f} :

$$\mathcal{A}_f = \frac{2g_{v_f}g_{a_f}}{{g_{v_f}}^2+{g_{a_f}}^2} = 2\frac{\frac{g_{v_f}}{g_{a_f}}}{\left(\frac{g_{v_f}}{g_{a_f}}\right)^2+1}$$

In the case of the left-right cross section asymmetry ($A_{\rm LR}$) or τ polarisation measurements, the results can be directly expressed in term of $\mathcal{A}_e$ alone.

At first $\sin^2\theta_{eff}^{lept}$ was introduced for Z pole analysis as the ratio of effective vector and axial-vector couplings of μ, including loops, for the on mass shell $Z \rightarrow \mu^+\mu^-$ vertex :

$$\frac{g_{v_l}}{g_{a_l}} = 1-4\sin^2\theta_{eff}^{lept}$$

Then for each fermion, $\sin^2\theta_{eff}^{f}$ is:

$$\frac{g_{v_f}}{g_{a_f}} = 1-4\,|Q_f|\sin^2\theta_{eff}^{f}$$

Within the SM $\sin^2\theta_{eff}^{f}$ can be corrected to $\sin^2\theta_{eff}^{lept}$. All the measurements, like asymmetries, expressed in term of ratio of these effective vector and axial-vector couplings, can be translated in a value of $\sin^2\theta_{eff}^{lept}$. It can be noticed than $\sin^2\theta_{eff}^{lept}$, in the SM, is the most sensitive quantity to m_H. For example with $m_H \sim 100\mathrm{GeV}$

$$\frac{\delta m_H}{m_H} \sim 440\frac{\delta\sin^2\theta_{eff}^{lept}}{\sin^2\theta_{eff}^{lept}}$$

to be compared to

$$\frac{\delta m_H}{m_H} \sim 1300\frac{\delta m_W}{m_W}$$

All fermions asymmetries don't have the same sensitivity to $\sin^2\theta_{eff}^{lept}$,m_H. $\mathcal{A}_q$ for the quarks is large ($\mathcal{A}_b \sim$ 0.93 and $\mathcal{A}_c \sim$ 0.67) compared to $\mathcal{A}_l$ for the leptons ($\mathcal{A}_l \sim$ 0.15). For this reason the quarks, and more precisely the high b quark asymmetry, provide a better sensitivity to $\sin^2\theta_{eff}^{lept}$: $\delta A_{\rm FB}^{\rm l\bar{l}} \sim 1.8\delta\sin^2\theta_{eff}^{lept}$, $\delta A_{\rm FB}^{\rm c\bar{c}} \sim 4.4\delta\sin^2\theta_{eff}^{lept}$ and $\delta A_{\rm FB}^{\rm b\bar{b}} \sim 5.7\delta\sin^2\theta_{eff}^{lept}$. Nevertheless the sensitivity to $\sin^2\theta_{eff}^{lept}$ for

$A_{\rm FB}^{\rm b\overline{b}}$ comes from $\mathcal{A}_e$. In the SM $\mathcal{A}_b$ is some how saturated/almost independent of the radiative correction : it is $\sim$ 7 time less sensitive to a change in $\sin^2\theta_{eff}^{lept}$ than $\mathcal{A}_e$. From the SM model point of view $A_{\rm FB}^{\rm b\overline{b}}$, $A_{\rm FB}^{\rm l\overline{l}}$, the τ polarisation and $A_{\rm LR}$ measure the same things : the value of $\sin^2\theta_{eff}^{lept}$ through $\mathcal{A}_l$ or $\mathcal{A}_e$ according to lepton universality.

1.2 The $\sin^2\theta_{eff}^{lept}$ measurements

In regard of the previous section, the different values of $\sin^2\theta_{eff}^{lept}$ extracted form the data are not really satisfactory in the SM frame work. As shown in figure 1, there is a poor agreement ($\sim 2.5\%$) between the leptonic measurements of $\mathcal{A}_l$ (like in $A_{\rm FB}^{\rm l\overline{l}}$ or $A_{\rm LR}$) and the indirect hadronic measurements of $\mathcal{A}_l$ (like in $A_{\rm FB}^{\rm b\overline{b}}$). Fixing $\mathcal{A}_l$ to its leptonic measurements underline further this point : the b couplings extracted that way are quite away from the SM prediction (see figure 2).

2 $A_{\rm FB}^{\rm b\overline{b}}$ ($A_{\rm FB}^{\rm c\overline{c}}$) measurements

2.1 Experimental techniques

To perform the $A_{\rm FB}^{\rm b\overline{b}}$ measurement the following informations are required :

- A flavour tag to select the $b-\bar{b}$ event
- The polar angle/"axis" of the $b-\bar{b}$ production
- A charge tag to sign this $b-\bar{b}$ "axis" along the b direction

Among the quarks only the b and c quarks can be easily tagged. Many methods to tag Z decays in $c\bar{c}$ or $b\bar{b}$ quarks have been developed. They rely on different properties of the heavy quarks production and decay:

- The b hadrons have a long fly distance ($\gamma c\tau_b \sim 2.$ mm). The charm, present in the b decay products, further increases the distance between the interaction region and the secondary vertices. Such decay chain gives vertices clearly shifted from the primary vertex and produces tracks with high impact parameters (see figure 4). Typical working point in $A_{\rm FB}^{\rm b\overline{b}}$ analysis using lifetime tag corresponds to an efficiency in $b \sim$ 0.7 - 0.9 for a purity $\sim$ 0.7 - 0.9. This working point is slightly different to the one used in R_b analysis for which a higher purity is required.

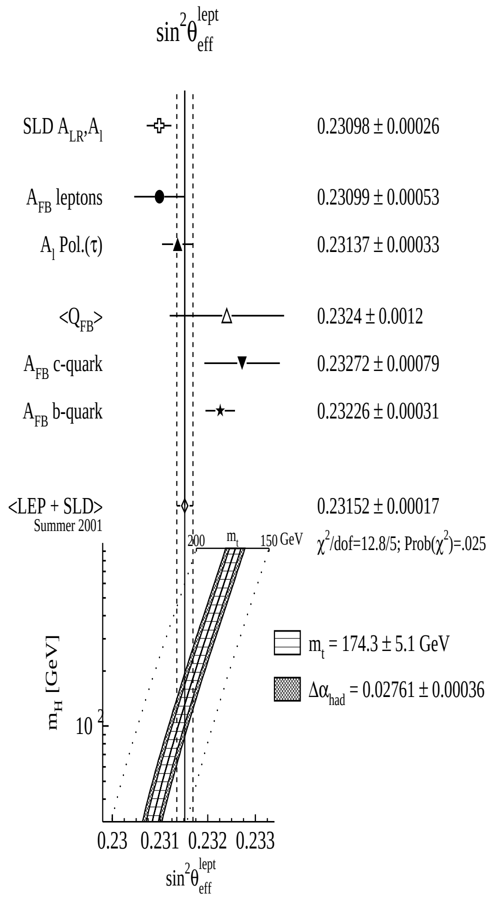

Figure 1: *Values of $\sin^2\theta_{eff}^{lept}$ extracted from different measurements. If in average this subsample of electroweak observables predicts a Higgs mass slightly above 100 GeV , the mass preferred by each measurement cover a large range. The main discrepancy is observed between the A_{LR} measurement at SLC and the $A_{\mathrm{FB}}^{\mathrm{b\bar{b}}}$ measurement at LEP I. The overall compatibility between all these measurements is only 2.5%.*

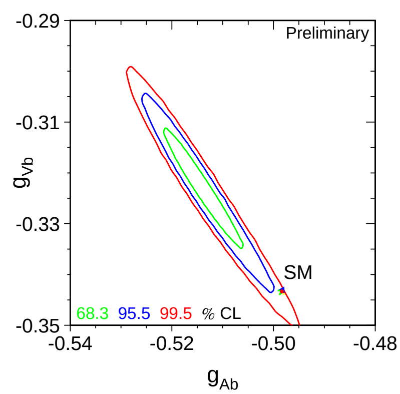

Figure 2: *Values of g_{a_b} and g_{v_b} extracted from $\mathcal{A}_l$, R_b ($\sim g_{v_b}^2 + g_{a_b}^2$) and $A_{\mathrm{FB}}^{\mathrm{b\bar{b}}}$ ($\sim g_{v_b}/g_{a_b}$). The SM is excluded at almost 99.5 % cl.*

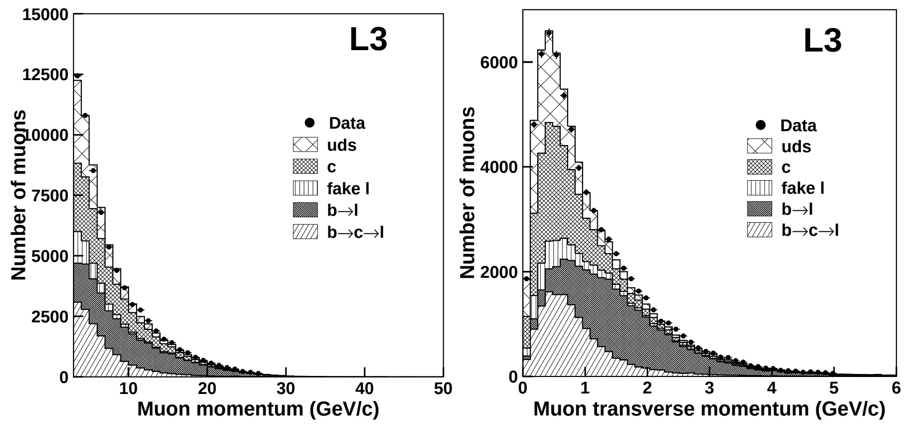

Figure 3: *Distribution of the μ momentum, p, (left) and transverse momentum relative to the closest jet, p_T, (right) for different sources. Due to the hard fragmentation and high mass of the b, an excess of events at high p or p_T from $b \rightarrow \mu$ is observed. In the μ $A_{\mathrm{FB}}^{\mathrm{b\bar{b}}}$ L3 analysis*[1] *the following cuts are applied :* $p > 4\mathrm{GeV}/c$ *and* $p_T > 1\mathrm{GeV}/c$.

- The B and D hadrons have high semi-leptonic branching ratios ($\sim$ 10% for prompt decay in μ or e), they take most of the beam energy ($< X_E >_B \sim 0.7$ and $< X_E >_D \sim 0.5$), and, due to their high mass, they produce leptons with a high transverse momentum (p_T). For these reasons semi-leptonic tagging using the p and p_T of the leptons can give pure sample of b or c quarks (see figure 3).
- The charm content of b and c events can be directly identified by exclusive reconstruction of D^*/D decays. The energy and fly distance of these D^*/D allow a distinction between b and c events.

The usual choice for the polar angle is the thrust axis. This choice induces specific QCD corrections but doesn't result in any significant systematics.
The charge of the initial quark can be extracted :

- in a exclusive way using the correlation between the quark and its decay products ($b \rightarrow e^- + X$, $c \rightarrow D^{*+}$, etc).
- in an inclusive way by a jet charge method where the sign of the quark charge is estimated by a momentum weighted mean of the charged tracks present in the Forward/Backward hemispheres : $Q_{F(B)} = \sum_{F(B)} q_i P_i^K / \sum_{F(B)} P_i^K$ where K is typically chosen between 0.5 and 1 (see figure 5). This method uses the fact than tracks of high momentum in a b jet are more likely coming from the b decay itself.

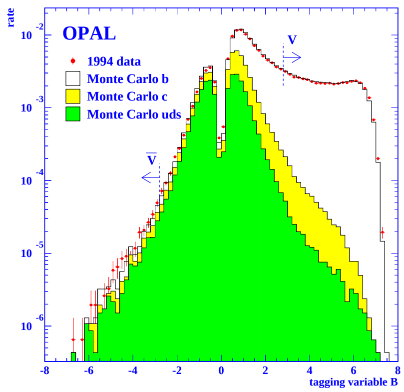

Figure 4: *This OPAL b-tag variable which includes decay length significance of a secondary vertex, shows at high value a strong b enrichment. The events with a b-tag value below zero are the results of resolution effects. This last type of events can be used to tune the simulation to the data resolution.*

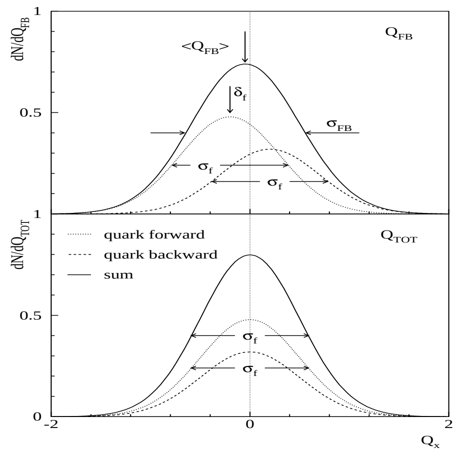

Figure 5: *Three experimental observables are used in jet charge analysis : $Q_{FB} = Q_F - Q_B$ which holds informations on the asymmetry and the charge separation (δ_f) , $Q_{tot} = Q_F + Q_B$ which holds informations on charge bias and resolution (σ_f) and $Q_F \times Q_B$ (not plotted here) which holds informations on the charge separation and correlation. Such distributions allow to perform a fine tuning of the simulation before extracting the b asymmetry itself.*

- in a semi-inclusive way by selecting a sub sample of tracks with a given property: for example with all the tracks associated to a secondary vertex a "vertex charge" can be built holding information on the charge of the particle at the origin of this vertex.

2.2 Improved $A_{\rm FB}^{\rm b\overline{b}}$ measurements

Many combinations of the different flavour and charge tagging techniques described in the previous section have been used. In this section the last developments in the usage of these tools will be presented.

New lepton analysis

In lepton analysis a few observables have been used on top of the pure p,p_T tags. Improved b sample purity has been obtained using missing energy/ neutrino tag (ALEPH [3],OPAL [4]) or b lifetime tag (ALEPH [3],DELPHI [2],OPAL [4]). Better charge tagging has

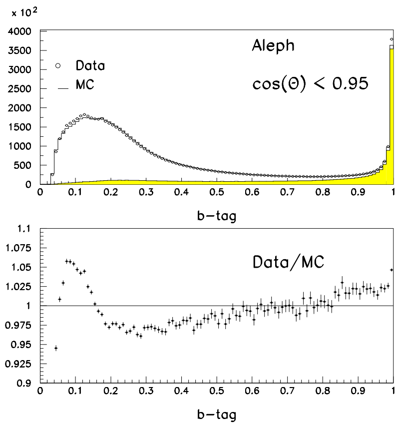

Figure 6: *The distribution of the b-tag variable used in the ALEPH inclusive analysis shows before tuning of the simulation a clear excess of events in the b region (shadowed area).*

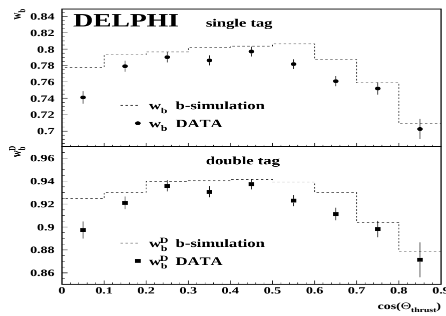

Figure 7: *The probability to identify correctly the charge of the b quark in the DELPHI inclusive analysis for events where only one hemisphere has been tagged (upper plot) and when the two hemispheres have been tagged with opposite charge (lower plot). The difference between data and simulation shows the difficulty for the simulation to describe correctly all the information used. The direct calibration in the data of the charge tagging power overcomes this problem.*

been reached using differences between $b \rightarrow \ldots \rightarrow l^-$ and $b \rightarrow \ldots \rightarrow l^+$ in observables like the jet charge of the opposite hemisphere to the lepton (DELPHI [2]) or the energy taken by the tracks nearer the lepton (OPAL [4]). If all these observables improved the statistical precision of the results, they require in general specific measurements/calibrations to keep the systematics under control.

Such improved techniques decreased the statistical error up to 20% (50%) for $A_{\rm FB}^{\rm b\overline{b}}$ ($A_{\rm FB}^{\rm c\overline{c}}$) with in general constant if not better systematics.

New inclusive analysis

ALEPH [5] and DELPHI [6] provided in 2001 results with highly inclusive techniques. The interest of these approaches is to measure directly in the data both ,the b sample purity and the charge separation, using more of the available information than the usual “b-tagging + jet charge” techniques.

For the same sample, the total error on $A_{\rm FB}^{\rm b\overline{b}}$ is reduced by 1.2 in DELPHI and 1.7 in ALEPH compared to the classical jet charge analysis. These results are obtained by :

- adding charge/b flavour informations like secondary vertex charge or lepton/K identification combined with their reconstructed p,p_T and charge.

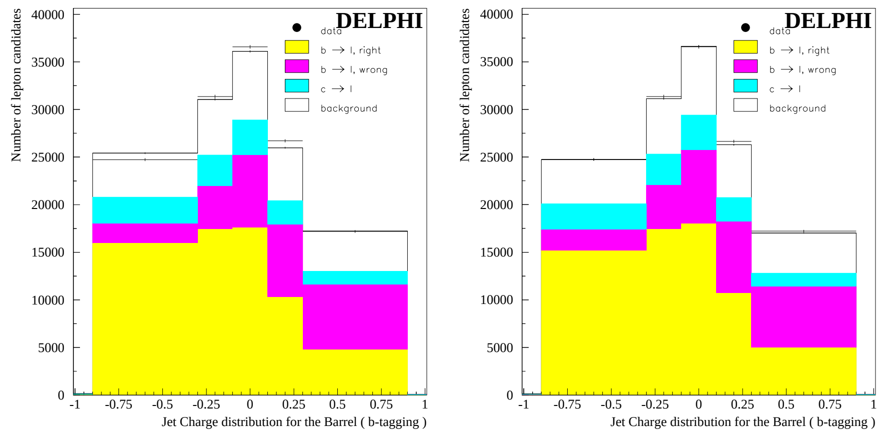

Figure 8: *Distribution for b-tagged event in the DELPHI lepton analysis of "the jet-charge opposite hemisphere" $\times$ "the charge of the lepton". Prompt leptons from b produce events with a negative value for such product : the two hemispheres have a b with opposite charge. Nevertheless $b-\bar{b}$ mixing or $b \to c \to l^+$ events (quoted as "$b \to l$,wrong" in the plot) may end up to events with a positive value for such product. Figure on the left : before calibration of the jet charge shape. Figure on the right : after calibration.*

- "distinguishing" between the different B hadrons to take advantage of differences in their decay/charge properties : B^+ has a good vertex charge information instead B^0 has some charge information in the fragmentation tracks to tag the sign of the $b/\bar{b}$ quark.

The $A_{\rm FB}^{\rm b\bar{b}}$ obtained with such analysis have statistical correlations with other $A_{\rm FB}^{\rm b\bar{b}}$ measurements performed on the same data sample. Such correlations have been taken into account in the LEP average, for example a statistical correlation of $\sim$ 20% is observed between such analysis and lepton analysis.

Calibration in the data

Of course the simulation cannot describe properly all the variables used in these analysis : sample composition or charge separation have to be measured directly in the data. The interest in the analysis described above rely not only on their improved statistical sensitivity but even more on their relative low sensitivity to the availability of a precise simulation description.

For example all LEP experiments observe a $\sim 2-5$ % data/MC discrepancy in the distribution of the b-tagging variable (see figure 6). To extract the sample composition in different bins of b-tag, an analysis of the number of single ($\sim \epsilon_f$) /double ($\sim \epsilon_f^2$) b-

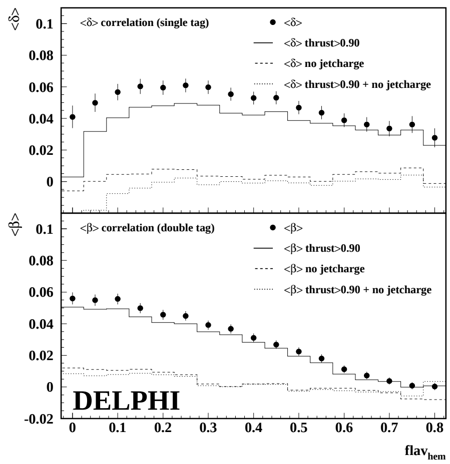

Figure 9: *The hemisphere charge correlation as predicted by the simulation when one hemisphere (upper plot) or two hemispheres with opposite charge (lower plot) are tagged. The correlations are plotted as a function of the neural net variable used to select b with a defined charge. Beside the full flavour network (point) results using modified flavour network are shown.*

tagged hemispheres can be performed to extract the efficiency (ϵ_f) to tag each flavour f.

In the DELPHI lepton analysis, the jet charge of the opposite hemisphere to the lepton is used. The shape of the jet charge (σ_b,δ_b) like always is measured in the data (see figure 5). The calibration gives, almost by construction, a good data/MC agreement (see figure 8) for the overall sample but also for subsamples with different lepton-b charge correlation selected by a given p,p_T cuts. This last point is interesting as it indicates than the origin of the different leptons is well understood.

On important point in the new ALEPH/DELPHI inclusive analysis is the measurement of the charge separation in the data them self. In DELPHI only hemispheres with a good b charge separation are used. The charge tagging power is measured in the data by a single/double tag techniques. Up to 93% right charge tagging has been obtained (see figure 7). In ALEPH all b-tagged events have been used and a charge separation up to 74% has been observed. In this last analysis a classical (see figure 5) calibration of the shape of the jet charge has been performed.

In analysis using such kind of self-calibration (for the jet charge , b-tagging , ...) the dominant systematics are in general still coming from what has to be taken from the simulation. For example the hemisphere correlations or the behaviour of non-b events induce the main contribution to the systematics in the inclusive analysis.

Nevertheless lots of efforts have been done to define correctly the size of such systematics. For example (see figure 9) in the new DELPHI inclusive analysis the source of the charge correlation between the hemispheres has been investigated in the simulation and identified to the jet charge information. Such correlation in the jet charge being well understood and studied in data as shown in the pure jet charge

Table 1: *Corrections applied to the QCD corrected asymmetry ($A_{\rm FB}^{QCD}$) :*
$A^0_{\rm FB} = A_{\rm FB}^{QCD} + \sum_i (\delta A_{\rm FB})_i$

Source	$\delta\ A_{\rm FB}^{\rm b\overline{b}}$	$\delta\ A_{\rm FB}^{\rm c\overline{c}}$
$\sqrt{s} =\ m_Z$	-0.0013	-0.0034
QED corr.	+0.0041	+0.0104
$\gamma,\ \gamma Z$	-0.0003	-0.0008
Total	+0.0025	+0.0062

Table 2: *The following reduction coefficients, α_b, of the theoretical QCD correction, C_b^{had}, have been estimated (example of summer 97 analysis): $C_b^{meas} = \alpha_b C_b^{had}$ and $A_{\rm FB}^{measured} = (1 - C_b^{meas}) A_{\rm FB}^{QCD}$*

Exp.	μ/e	D^*	Jet Ch.
ALEPH	.74±.07		
DELPHI	.52±.06	.46±.14	.24±.46
OPAL	.69±.13	.29±.13	.36±.32

DELPHI analysis [7], a systematic associated to this hemisphere correlation can be correctly defined.

3 The corrections : $A_{\rm FB}^{\rm b\overline{b}} \rightarrow A_{\rm FB}^{b,0}$

To extract from the measured asymmetries the pole asymmetry/$\sin^2\theta_{eff}^{lept}$, corrections have to be applied (see table 1) :

- energy shift from 91.26 $\rm GeV$ (energy used to average the $A_{\rm FB}^{\rm b\overline{b}}$) to m_Z
- initial state radiation
- γ and $\gamma\ Z$ interference
- QCD corrections (done separately for each measurement)

The effect of the QCD corrections received lots of attention over the last years. This effort converged only in 1999. The main conclusion of these studies is than the visibility of the hard gluon emission, which dominate the theoretical QCD corrections, is a function of the experimental method used to extract the asymmetry. For example

- experimental cuts (ex : lower cut on the lepton momentum remove events with hard gluon)
- event weight (ex : events with hard gluon may end up in "area" of high background and get a lower weight in the $A_{\rm FB}^{\rm b\overline{b}}$ extraction)

generate changes in the QCD corrections to apply. As shown table 2 the scaling down of the QCD corrections due to these effects is not negligible. For this reason, even if the theoretical QCD corrections for the b (c) is $C_b^{had} = 0.0377 \pm 0.0059$ ($C_c^{had} = 0.0413 \pm 0.0063$), the common error in the LEP average from the QCD corrections is only $\sim$ 0.0002 for $A_{\rm FB}^{b,0}$ ($\sim$ 0.00005 for $A_{\rm FB}^{c,0}$).

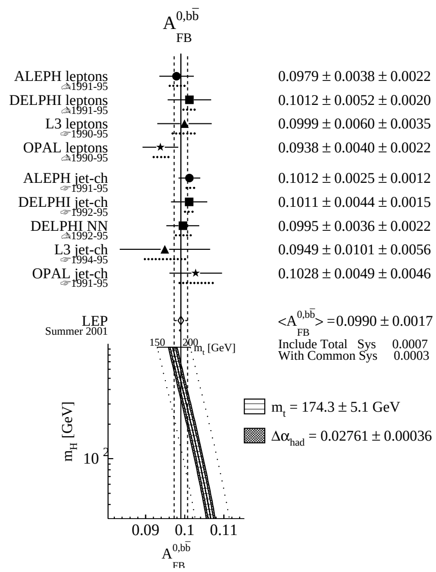

Figure 10: *The 9 most precise measurements of $A^{b\bar{b}}_{\rm FB}$ and the overall LEP I average. The total (full line) and systematic (doted line) errors are plotted. The first printed error corresponds to the statistic the second to the systematic. The different measurements of $A^{b\bar{b}}_{\rm FB}$ are in very good agreement and give an average of 0.0982 ± 0.0017. The error of 0.0017 include a total systematic of only 0.0007 with a common part (systematics present in more than one measurement) of 0.0003 : the individual measurements and the final average are dominated by the statistical error. This final $A^{b\bar{b}}_{\rm FB}$ is not significantly correlated to any other quantity than $A^{c\bar{c}}_{\rm FB}$ and even there the correlation is small : 16 %.*

3.1 Results summary

There is eleven different measurements of $A^{b\bar{b}}_{\rm FB}$ performed at LEP I by the four LEP experiments. To take into account correctly in the average the statistical and systematical correlations of these results, the LEP/SLD Heavy Flavour Working group has developed an averaging procedure [8] which includes many measured quantities connected to the electroweak measurements in the b and c sectors at the Z . In practice the average is performed for 18 observables and for a total of 99 measurements. The main measurements and the LEP average for $A^{b\bar{b}}_{\rm FB}$ are quoted in figure 10.

4 Conclusion

Since 1994-1995 some discrepancies between $\sin^2\theta^{lept}_{eff}$ extracted from $A_{\rm LR}$ and $A^{b\bar{b}}_{\rm FB}$ measurements have been observed. Over the last 10 years, LEP I data collected between 1990 and 1995 have been analysed and re-analysed to improve the $A^{b\bar{b}}_{\rm FB}$ measurement and to further check its associated systematics. Nevertheless, today , using $A^{b\bar{b}}_{\rm FB}$, R_b and the measurement of $\mathcal{A}_l$ in the leptonic sector[b], the value extracted for the effective g_{v_b} and g_{a_b} are compatible with the Standard Model prediction by less than 1% (see figure 2). If this is not enough to claim a discovery, this should trig our

[b] dominated by the $\mathcal{A}_e$ /$A_{\rm LR}$ measurement at SLC

attention.

Even if some $A_{\rm FB}^{\rm b\overline{b}}$ measurements are still preliminary no significant change or improvement are expected with the LEP and SLC data.

The present m_W and $A_{\rm LR}$ measurements are compatible with the SM, even if both predict a "too" low Higgs mass, $\sim$ 1.5 sigma below the LEP II 95% exclusion limit of 114.1 $\rm GeV$. If SUSY could explain such low m_H prediction, no discrepancy between the $\sin^2\theta_{eff}^{lept}$,$m_H$extracted from $A_{\rm LR}$ and $A_{\rm FB}^{\rm b\overline{b}}$ are expected in the usual theoretical frame works.

Before the start of LHC, to investigate further these results, improved measurement of m_W (LEP II+ TEVATRON : δm_W 34 $\rightarrow$ 25 $\rm MeV$) , m_{top} (TEVATRON : δm_{top} 5.1 $\rightarrow$ 2 $\rm GeV$) and $\Delta\alpha_{had}^5(M_Z)$ (BES +"QCD" : 0.00036 $\rightarrow$ 0.0002-0.0001) are expected.

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