Hadronic Width of the Z from a Global Fit to $e^+e^- \to$ Hadrons Data

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A global analysis of the $e^+e^- \to$ hadrons data is presented to extract an effective value for the strong-interaction correction to the quark-parton-model approximation to be used for the Z hadronic width. We obtain $\Gamma_h = 1782 \pm 17(\text{fit}) \pm 15$[electroweak (EW) theory] MeV, and a ratio $\Gamma_h/\Gamma_l = 21.32 \pm 0.24$, in good agreement with the results from the CERN collider LEP, and different from the two-loop QCD predictions, $\Gamma_h = 1735 \pm 6(\alpha_s) \pm 15$(EW theory) MeV and $\Gamma_h/\Gamma_l = 20.74 \pm 0.12$, corresponding to $\Lambda_{\overline{\rm MS}}^{(5)} = 140^{+100}_{-80}$ MeV, where $\overline{\rm MS}$ denotes the modified minimal-subtraction scheme.

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The present experiments at the CERN e^+e^- collider LEP open a new era of precision tests in the area of strong and electroweak interactions. The results from LEP (Refs. 1-4) after the first two runs are summarized below[5] ($\Gamma_l = \Gamma_e = \Gamma_\mu = \Gamma_\tau$)

$$M_Z = 91.171 \pm 0.012 \pm 0.030 \text{ GeV},$$

$$\Gamma_Z = 2538 \pm 26 \text{ MeV}, \quad \Gamma_h = 1792 \pm 23 \text{ MeV},$$

$$\Gamma_l = 83.6 \pm 1.0 \text{ MeV}, \quad \Gamma_{\rm inv} = 500 \pm 21 \text{ MeV}.$$

The purely leptonic observables Γ_l and $\Gamma_{\rm inv}$ were in good agreement with the predictions of the standard model[6] including radiative corrections, $\Gamma_l = 83.6 \pm 0.7$ MeV, $\Gamma_{\rm inv} = 3\Gamma_\nu = 500 \pm 5$ MeV, in the range of the unknown top-quark and Higgs-boson masses

$$80 \text{ GeV} \le m_t \le 200 \text{ GeV}, \quad 25 \text{ GeV} \le m_H \le 1 \text{ TeV}, \qquad (1)$$

as favored by the present experimental situation[7-9] and suggested by a consistent weak-coupling interpretation of the theory. The hadronic width, however, is somewhat larger than the standard-model (SM) predictions when considering the same range (1) given above and the QCD correction corresponding to the scale parameter $\Lambda_{\overline{\rm MS}}^{(5)} = 140^{+100}_{-80}$ MeV.[10] Indeed in this case one obtains

$$\Gamma_h = 1735 \pm 6 \pm 15 \text{ MeV},$$

where the former error reflects the uncertainty in $\Lambda_{\overline{\rm MS}}^{(5)}$ ($\overline{\rm MS}$ denotes the modified minimal-subtraction scheme), and the latter derives from varying m_t and m_H in the range (1) as well as from the small uncertainty in the Z mass.

At the same time, the hadronic observables (after taking into account the 2.3% correction in L3 luminosity)

$$\sigma^h_{\rm peak} = \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_h}{\Gamma_Z^2} = 41.0 \pm 0.5 \text{ nb},$$

$$R_h \equiv \Gamma_h/\Gamma_l = 21.4 \pm 0.4$$

were correlated as required by the purely electroweak sector of the standard model with three light neutrinos.[11] This observation suggests that the rather large experimental value of Γ_h might be due, rather than to some new physics effect, to an inaccurate description of the strong-interaction sector.

The most recent data from LEP have, somewhat, changed the central value of Γ_h (see Ref. 12),

$$\Gamma_h = 1764 \pm 14 \text{ MeV},$$

but, as discussed in Ref. 13, the ratio Γ_h/Γ_l is still substantially larger than the SM prediction, including the two-loop QCD corrections. In fact, from Ref. 13, one obtains (by analyzing more than 98% of the LEP statistics available so far)

$$\Gamma_h/\Gamma_l = 21.24 \pm 0.20,$$

to be compared with the theoretical prediction

$$\frac{\Gamma_h}{\Gamma_l} = \frac{\Gamma_h^{(0)}}{\Gamma_l} A_{\rm QCD} = 20.74 \pm 0.12 \qquad (2)$$

obtained from the quark-model approximation, including higher-order electroweak effects, $\Gamma_h^{(0)}/\Gamma_l = 19.98 \pm 0.04$ and $A_{\rm QCD} = 1.038 \pm 0.004$, the two-loop QCD correction (taking into account small effects due to the b-quark mass) associated with $\Lambda_{\overline{\rm MS}}^{(5)} = 140^{+100}_{-80}$ MeV.[10]

To separate out the effect of the strong interactions from potential modifications of $\Gamma_h^{(0)}/\Gamma_l$ due to new physics, we have decided to analyze the experimental data for $e^+e^- \to$ hadrons, which contain exactly the same physical effects. This kind of analysis has been addressed in Ref. 14 with the conclusion that the strong-interaction correction is substantially larger than the perturbative QCD predictions at $\Lambda_{\overline{\rm MS}}^{(5)} = 150$ MeV. Our result will be presented in the following.

Since our main interest is on the value of the correction to the hadronic width, we have discarded in our analysis the quark masses as in Ref. 10, as, in this case, the two correction factors coincide. For this reason our analysis starts from $\sqrt{s}=22$ GeV. Our sample of 98 data is taken from Refs. 15–24. Systematic errors are treated in the usual way, i.e., by introducing in the χ^2 a penalty function which takes into account the normalization of the various experiments. We are aware of the fact that in the past different kinds of radiative corrections have been applied to the data. QED corrections (vacuum polarization, vertex corrections, initial-state radiation, etc.) are common to all experiments. Purely weak corrections, on the other hand, are only implemented in Refs. 22–24. Therefore, the electroweak Born approximations for $R(e^+e^-\to \text{hadrons})$, which are quoted by the various experimental groups, are different for the two sets of data, from the DESY and SLAC storage rings PETRA and PEP and from the KEK collider TRISTAN. For this reason it may be misleading to fit all the data with the same value of $\sin^2\theta_W$. Indeed, when weak corrections are not applied to the data, the strength of the amplitude for the Z exchange should be expressed in terms of the Z mass and the Fermi constant as discussed in Refs. 25 and 26. Therefore, for the sample of 60 experimental data from 22 up to 46.6 GeV, one should describe the Z exchange by means of $[\mu^2=\pi\alpha/G_F\sqrt{2}=(37.2802\text{ GeV})^2]$

$$\chi(s)=\left(\frac{M_Z}{\mu}\right)^2\frac{s}{s-M_Z^2+iM_Z\Gamma_Z}$$

and the effective value of $\sin^2\theta_W$, $\sin^2\bar\theta$, which, as discussed in Refs. 25 and 27–29, correctly describes the coupling of the Z to the quarks and leptons in the presence of weak radiative corrections, only appears in the vector couplings. For $M_Z=91.17$ GeV and in the range (1) of m_H and m_t one obtains $\sin^2\bar\theta=0.232\pm0.005$.

On the other hand, the data from 50 to 61.4 GeV, where purely weak radiative corrections (in the on-shell scheme) are implemented on the data, should be analyzed by using rather

$$\chi(s)=\frac{1}{\sin^2\theta_W\cos^2\theta_W}\frac{s}{s-M_Z^2+iM_Z\Gamma_Z}$$

and $\sin^2\theta_W$ in the couplings. In this case we could take full advantage of the very complete analysis of Ref. 8, updated in Ref. 30, which gives

$$1-M_W^2/M_Z^2=\sin^2\theta_W=0.2275\pm0.0035\,,$$

but we have allowed $0.22\le\sin^2\theta_W\le0.23$. We have performed two types of fit on the two different samples of data.

(i) A fit in perturbative QCD where the normalizations of the various experiments and $\Lambda^{(5)}_{\overline{\rm MS}}$ are the free parameters. The strong-interaction correction has been computed up to and including the term α_s^2, because, right now, there is no agreement on the value of the coefficient of the term α_s^3. At the same time, the comparison with the low-energy processes (quarkonia decays, deep-inelastic scattering, γ-structure functions, etc.), where only the two-loop corrections are implemented, would be difficult.

(ii) A fit which modifies the quark-parton-model approximation by a simple, energy-independent multiplicative factor A, in order to give a quantitative precise estimate of the strong-interaction correction in a model-independent way,

$$\sigma(e^+e^-\to\text{hadrons})=A\sum_{i=1}^{5}\sigma(e^+e^-\to q_i\bar q_i)\,. \qquad (3)$$

When considering the 60 low-energy data from $\sqrt{s}=22$ GeV up to $\sqrt{s}=46.6$ GeV, we have divided them into two bins of 30 data from 22 to 35 GeV and from 35 to 46.6 GeV. We have fixed $\sin^2\bar\theta=0.233$ in the vector couplings. The two fits give the following results: 22–35 GeV,

$$\text{(i)}\ \Lambda^{(5)}_{\overline{\rm MS}}=833^{+684}_{-500}\text{ MeV},\quad \chi^2/N_{\rm DF}=32.4/29\,,$$

$$\text{(ii)}\ A=1.067\pm0.013,\quad \chi^2/N_{\rm DF}=32/29\,,$$

35–46.6 GeV,

$$\text{(i)}\ \Lambda^{(5)}_{\overline{\rm MS}}=420^{+687}_{-349}\text{ MeV},\quad \chi^2/N_{\rm DF}=15.1/29\,,$$

$$\text{(ii)}\ A=1.052\pm0.013,\quad \chi^2/N_{\rm DF}=15.1/29\,.$$

We have then combined the 60 data all together (22–46.6 GeV) with the results

$$\text{(i)}\ \Lambda^{(5)}_{\overline{\rm MS}}=878^{+621}_{-473}\text{ MeV},\quad \chi^2/N_{\rm DF}=50.1/59\,,$$
$$\text{(ii)}\ A=1.0644\pm0.011,\quad \chi^2/N_{\rm DF}=49.8/59\,. \qquad (4)$$

The very low χ^2 of the fit to the 30 data from 35 to 46.6 GeV is probably due to an overestimate of the experimental errors in this range. For this reason the combined determinations for the whole sample of 60 data are very close to the first set. As a check that the global average is giving the correct indication we note the very good agreement with the analysis performed in Ref. 21 where the value of the constant $A=1.062\pm0.011$ (at $\sqrt{s}=34$ GeV) is obtained.

Then we have allowed for variations of $\sin^2\bar\theta$ with the whole sample of 60 data. For $\sin^2\bar\theta=0.227$ we obtain $A=1.0675\pm0.011$ ($\chi^2/N_{\rm DF}=49.9/59$) and for $\sin^2\bar\theta=0.237$, $A=1.063\pm0.011$ ($\chi^2/N_{\rm DF}=50.1/59$).

When considering the 38 data from the 50 up to 61.4 GeV we have obtained, fixing $\sin^2\theta_W=0.2275$,

$$\text{(i)}\ \Lambda^{(5)}_{\overline{\rm MS}}=3274^{+3418}_{-2529}\text{ MeV},\quad \chi^2/N_{\rm DF}=31.6/37\,,$$

$$\text{(ii)}\ A=1.0795\pm0.026,\quad \chi^2/N_{\rm DF}=31.7/37\,.$$

Allowing $\sin^2\theta_W$ to vary, we obtain $A=1.076\pm0.026$ ($\chi^2/N_{\rm DF}=32.3/37$) for $\sin^2\theta_W=0.22$ and $A=1.0805\pm0.026$ ($\chi^2/N_{\rm DF}=31.6/37$) for $\sin^2\theta_W=0.23$.

Let us now discuss the implications of our analysis on the hadronic width of the Z. Assuming no new threshold in the range $61.4\text{ GeV}\le\sqrt{s}\le M_Z$ and averaging the various values of A, which are consistent with each other, we find the value of the strong-interaction correction to apply to the quark-parton-model approximation for the Z hadronic width

$$A=1.067\pm0.01 \tag{5}$$

or

$$\Gamma_h=A\Gamma_h^{(0)}=1782\pm17\pm15\,, \tag{6}$$

where, again, the former error reflects the uncertainty in A and the latter derives from varying m_H and m_t in the range (1). To test the consistency of this procedure we have fitted the 98 data from 22 to 61.4 GeV together, obtaining ($\sin^2\bar{\theta}=0.233$, $\sin^2\theta_W=0.2275$)

$$\begin{aligned}&\text{(i) } \Lambda_{\overline{\rm MS}}^{(5)}=1074^{+629}_{-558}\ \text{MeV},\quad \chi^2/N_{\rm DF}=82.4/97\,,\\ &\text{(ii) } A=1.0673\pm0.01,\quad \chi^2/N_{\rm DF}=81.7/97\,.\end{aligned} \tag{7}$$

Note that Eq. (6) is in very good agreement with the OPAL result, presented at Singapore,[12] $\Gamma_h=1778\pm26$ MeV.

As discussed in Ref. 31, no particular evidence for the presence of an energy-dependent strong-interaction correction is found in the data. The fit with an energy-independent constant is always as good as in QCD where, however, it produces anomalously large scale parameters $\Lambda_{\overline{\rm MS}}^{(5)}$. On the other hand, the value of the constant fitted in Ref. 31 is not reported. The value of $\Lambda_{\overline{\rm MS}}^{(5)}$ obtained from the full fit ($22<\sqrt{s}<61.4$ GeV) is not compatible, at the two-loop level, with the other determinations from low-energy processes (see Ref. 10). Moreover, in a more recent analysis[32] in the range 14–61 GeV, at the two-loop level, the value

$$\Lambda_{\overline{\rm MS}}^{(5)}=650^{+450}_{-340}\ \text{MeV}$$

is obtained by employing, however, the three-loop relation between α_s and $\Lambda_{\overline{\rm MS}}^{(5)}$.

The results of Ref. 32 can be easily transformed into a completely consistent two-loop estimate

$$\Lambda_{\overline{\rm MS}}^{(5)}=700^{+480}_{-370}\ \text{MeV}\,.$$

We think that, as in our case, the lower value of 370 MeV is obtained for consistency with the low-energy data (i.e., at 14 GeV), the mean value 700 MeV in the region $\sqrt{s}\sim34$ GeV, and the upper value 1180 MeV at $\sqrt{s}=61$ GeV. The corresponding values of α_s are $[A_{\rm QCD}^{\text{two-loop}}\sim1+\alpha_s/\pi+1.41(\alpha_s/\pi)^2]$

$$\begin{aligned}&\sqrt{s}=14\ \text{GeV},\quad \alpha_s=0.180,\quad A_{\rm QCD}^{\text{two-loop}}\sim1.062,\quad \Lambda_{\overline{\rm MS}}^{(5)}=330\ \text{MeV}\,,\\ &\sqrt{s}=34\ \text{GeV},\quad \alpha_s=0.174,\quad A_{\rm QCD}^{\text{two-loop}}\sim1.060,\quad \Lambda_{\overline{\rm MS}}^{(5)}=700\ \text{MeV}\,,\\ &\sqrt{s}=61\ \text{GeV},\quad \alpha_s=0.172,\quad A_{\rm QCD}^{\text{two-loop}}\sim1.059,\quad \Lambda_{\overline{\rm MS}}^{(5)}=1180\ \text{MeV}\,.\end{aligned}$$

Therefore, also in Ref. 32, the effective correction seen in the e^+e^- data is constant. This explains why we always obtain the same χ^2 as in QCD. It is nontrivial to discover this puzzling result, but the strong asymmetry of the errors in the fitted values of $\Lambda_{\overline{\rm MS}}^{(5)}$ provides the key to understand what is going on.

Returning to our results, we note that the fitted normalization coefficients are remarkably independent (up to the third or fourth digit) of the way in which the strong-interaction effects are described, but they differ by about 2% when the value $\Lambda_{\overline{\rm MS}}^{(5)}=140$ MeV is fixed (see Table I).

By using the value $A=1.067\pm0.010$ as a model-independent estimate of $A_{\rm QCD}$ from 22 to 61 GeV and by computing $\Gamma_h^{(0)}/\Gamma_l$ in the SM we obtain the prediction to be tested at LEP, and in very good agreement with the analysis of Ref. 13,

$$\frac{\Gamma_h}{\Gamma_l}=\frac{\Gamma_h^{(0)}}{\Gamma_l}A=21.32\pm0.24\,. \tag{8}$$

By restricting our analysis to the PETRA-PEP range ($A=1.0644\pm0.011$) we obtain the slightly smaller value $(\Gamma_h^{(0)}/\Gamma_l)A=21.27\pm0.26$ in excellent agreement with the OPAL result,[12] $\Gamma_h/\Gamma_l=21.26\pm0.32$.

Summarizing, we have performed a fit of 98 $e^+e^-\to$ hadrons data from $\sqrt{s}=22$ up to 61.4 GeV. The strong-interaction correction to the quark-parton model is well reproduced by an energy-independent constant $A=1.067\pm0.01$. This correction yields a Z hadronic width and a ratio Γ_h/Γ_l in very good agreement with the LEP results. The fit in perturbative QCD yields a value

TABLE I. The normalization coefficients of the various experiments obtained from the global fit ($22<\sqrt{s}<61.4$ GeV) and the corresponding normalization errors. In the first column we report the result obtained with an energy-independent constant ($A=1.067\pm0.010$, $\chi^2/N_{\rm DF}=81.7/97$); in the second column, the fit in QCD with $\Lambda_{\overline{\rm MS}}^{(5)}=140$ MeV, $\chi^2/N_{\rm DF}=88.2/98$.

Experiment	$A=1.067\pm0.010$	$\Lambda_{\overline{\rm MS}}^{(5)}=140$ MeV
HRS (7%)	0.936 ± 0.012	0.915 ± 0.010
MAC (2.1%)	0.985 ± 0.011	0.965 ± 0.010
CELLO (1.7%)	1.019 ± 0.012	1.004 ± 0.010
JADE (2.5%)	0.990 ± 0.015	0.972 ± 0.011
Mark J (2.1%)	1.021 ± 0.012	1.003 ± 0.010
PLUTO (6%)	0.966 ± 0.027	0.948 ± 0.026
TASSO (4%)	0.976 ± 0.014	0.956 ± 0.011
AMY (3.2%)	0.971 ± 0.016	0.959 ± 0.015
TOPAZ (5.5%)	0.966 ± 0.018	0.947 ± 0.016
VENUS (3.8%)	1.020 ± 0.017	1.001 ± 0.015

for the scale parameter $\Lambda_{\overline{\rm MS}}^{(5)}$ that is too large, and does not improve the agreement with the data. Despite the fact that we cannot exclude the presence of new physics (an additional Z', as suggested in Ref. 33 to explain the TRISTAN data) we believe that our analysis gives a strong indication for the presence of nonperturbative effects. Such a situation could be similar to what happens in the analysis of the various jet multiplicities[34] (at low y_c) and the energy-energy correlation[35] where, in order to obtain a reasonable value for $\Lambda_{\overline{\rm MS}}^{(5)}$ from the experimental data, one has to choose a strong-interaction scale $\mu^2 = fs$ with $f \simeq 0.01$. Since in the energy-energy correlation asymmetry[36] there is a very small-scale sensitivity (for $f=1$, $\Lambda_{\overline{\rm MS}}^{(5)} = 104^{+50}_{-40}$ MeV), we conclude that large nonperturbative effects are associated with the two-jet final-state component which is the bulk of the $e^+e^- \rightarrow$ hadrons events.

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