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Precision Physics at the Z Resonance

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Abstract

In this report a short summary is given of the results of the Workshop on Precision Calculations for the Z Resonance (CERN, 1994), published in a new CERN Yellow Report 95-03. It integrates all new results on the precision calculations of the Z-resonance observables, which appeared after the previous CERN Workshop on "Z physics at LEP 1" in 1989. This conference report contains also a brief review of the issue of "evidence for the electroweak (EW) corrections" in the Standard Model (SM).

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PRECISION PHYSICS AT THE Z RESONANCE

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In this report a short summary is given of the results of the Workshop on Precision Calculations for the Z Resonance (CERN, 1994), published in a new CERN Yellow Report 95-03. It integrates all new results on the precision calculations of the Z-resonance observables, which appeared after the previous CERN Workshop on "Z physics at LEP 1" in 1989. This conference report contains also a brief review of the issue of "evidence for the electroweak (EW) corrections" in the Standard Model (SM).

1 Experimental Status

The present experimental status of the precision measurements of Z-resonance observables was thoroughly covered in the parallel session PA1 and summarized in the rapporteur talk [1]. I only want to underline once again what impressive level of precision had the LEP1/ADLO complex reached after six years of very successful operation; this is by far higher than foreseen a few years ago. The SLAC/SLD facility with the polarized electron beam had also provived us with very precise results. In table 1, borrowed from the PA1 talk [2], I list a few of the most precisely measured Z-resonance observables.

Table 1: Several the most precisely measured Z-resonance observables by LEP1 and SLD experiments. In the third column the relative precision in per mille is shown.

a) **LEP**		
Line-shape		
M_Z (GeV)	91.1884 ± 0.0022	.025
Γ_Z (GeV)	2.4963 ± 0.0032	1.3
σ^0_h (nb)	41.488 ± 0.078	1.9
R_ℓ	20.788 ± 0.032	1.5
Results with quarks		
R_b	0.2219 ± 0.0017	7.6
R_c	0.1543 ± 0.0074	
$q\bar{q}$ charge asymmetry		
$\sin^2\theta^{lept}_{eff}$ ($\langle Q_{FB}\rangle$)	0.2325 ± 0.0013	
LEP average, $\sin^2\theta^{lept}_{eff}$	0.23186 ± 0.00034	1.5
b) **SLC**		
$\sin^2\theta^{lept}_{eff}$ (A_{LR})	0.23049 ± 0.00050	2.1
LEP/SLC average, $\sin^2\theta^{lept}_{eff}$	0.23143 ± 0.00028	1.2

These results were prepared by the LEP EW Working Group (*LEPEWWG*) of the four LEP experiments for this conference. They are based on a preliminary analysis of data, including 1994. Already this analysis yields a precision $\approx .15\%$ for systematics free observables. The analysis of all events, collected to the end of 1995, will definitely bring the experimental precision for these observables down to 1 or even below 1 per mille!

Another bright exhibition of the SM consistency at the level of quantum corrections is the impressive agreement between indirect and direct determinations of the mass of the top quark, m_t. The Z-resonance observables are sensitive to it *indirectly*, via loops. The result of [1], based on the analysis of all available world data (LEP1, SLD, $p\bar{p}$, low energy), gives

$$m_t = 178 \pm 8(\text{exp.})^{+17}_{-20}\ \text{GeV}, \tag{1}$$

the second error is due to the Higgs boson mass variation in the interval $M_H = 60-1000$ GeV. This perfectly agrees with the *direct* measurement of m_t by CDF [3]:

$$m_t = 176 \pm 8(\text{stat.}) \pm 10(\text{syst.})\ \text{GeV}, \tag{2}$$

and D0 [4]

$$m_t = 199^{+19}_{-21}(\text{stat.}) \pm 22(\text{syst.})\ \text{GeV}. \tag{3}$$

This amazing progress in precision measurements of the SM parameters triggers a natural question which experimenters address to theoreticians:

- *What is the accuracy with which we are presently able to predict our direct observations in terms of the Standard Model Lagrangian parameters?*

The main goal of the CERN Yellow Report 94-03 [5] was to provide a motivated answer to this question.

2 Status of Precision Calculations

2.1 Theoretical Developments after 1989

All aspects of the Z-resonance physics were comprehensively covered by two CERN Workshops in 1986 and 1989, published in two Yellow Reports [6] and [7].

After the last Workshop in 1989, several groups of theoreticians developed codes supposed to be used for fitting the SM parameters to the experimental data. By the end of 1993 it became clear that the experimental precision had reached the spread among different theoretical predictions which necessitated their critical update.

Another reason, why a new summary of precision calculations for the Z resonance, as in [7], became necessary, was numerous theoretical investigations which appeared after 1989. We present below the most valuable input, which ensured a sizeable improvement in the theoretical precision of the SM predictions.

- Final state QCD/QED corrections: the massless $\mathcal{O}(\alpha_s^3)$ corrections; mixed $\mathcal{O}(\alpha\alpha_s)$ and $\mathcal{O}(\alpha^2)$ corrections; vector and axial-vector massive b and t quark corrections to the process $e^-e^+ \to q\bar{q}$ up to $\mathcal{O}(\alpha_s^3)$. Their present status is exhaustively reviewed in [8].
- Complete 2-loop mixed EW/QCD corrections of $\mathcal{O}(\alpha\alpha_s)$ to self-energies [9–10].
- The leading order, $\mathcal{O}(G_\mu m_t^2 \alpha_s)$, QCD correction to the $Z \to b\bar{b}$ vertex [11–12].
- The next-to-leading (NL) QCD correction to the $Z \to b\bar{b}$ vertex, $\mathcal{O}(\alpha\alpha_s \ln(m_t^2))$ [13].
- The leading 3-loop correction $\mathcal{O}(G_\mu m_t^2 \alpha_s^2)$ to the ρ-parameter [14–15]. This result was important to clarify various controversies about $t\bar{t}$ threshold effects; a review of this subject is given in [16–17].
- Further study of resummation of the leading terms of $\mathcal{O}(G_\mu m_t^2)$ and its implementation into computer codes for definite processes [18]; resummation of the NL terms [19–20].
- The 2-loop EW corrections to the self-energy, $\rho^{(2)}$, and to the $Z \to b\bar{b}$ vertex, $\tau^{(2)}$ [21]. A compact analytic representation for $\rho^{(2)}$ and $\tau^{(2)}$ was given in [22].
- The 2-loop NL correction to $\Delta\rho$ and Δr of $\mathcal{O}(G_\mu^2 m_t^2 M_Z^2)$ [23]. The preliminary results point to a relative importance of this correction.

For more details on recent theoretical results see [24].

2.2 *The Structure of the last Yellow Report*

Within the CERN 1994 Workshop, the three subgroups were working in three fields, EW physics, QCD at the Z resonance and small-angle Bhabha scattering (SABS). Their results comprise the three parts of the Report [5].

The core contribution to Part I is the EW Working Group Report (EWWGR). It contains a description of the present status of precision calculations for the Z resonance, as seen by various independent calculations. Part II summarizes the present status of QCD at the Z resonance, where the largest part of the work seems to be completed. On the contrary, Part III represents an intermediate phase of work on SABS, which was continued within the LEP2 CERN 1995 Workshop [25].

2.3 *Electroweak Working Group Report, EWWGR*

The main aim of the EWWGR, besides updating the predictions of Z-resonance observables, was to estimate the intrinsic theoretical uncertainties of these predictions, which are mainly caused by the neglect of higher-order contributions. We quantified this in the question:

Is theory ready to meet a 10^{-3} *experimental precision with* $\le 0.5 \times 10^{-3}$ *theoretical error in the predictions?*

2.3.1 *Codes for Precision Physics at the Z Resonance*

To answer this question, we used *tools* — codes created by different groups of theorists, based on their own, fully independent investigations. All results of the EWWGR are based on the use of the following five codes:

`BHM` [26] – `Burgers, Hollik, Martinez, Teubert`

`LEPTOP` [27] – ITEP Moscow group
`Novikov, Okun, Rozanov, Vysotsky`

`TOPAZO` [28] – Torino-Pavia group – `Montagna, Nicrosini, Passarino, Piccinini, Pittau`

`WOH` [29] – `Beenakker, Burgers, Hollik`

`ZFITTER` [30] – Dubna-Zeuthen group – `Bardin, Bilenky, Chizhov, Olshevsky, S.Riemann, T.Riemann, Sachwitz, Sazonov, Sedykh, Sheer`

2.3.2 *INPUT/OUTPUT of Precision Calculations*

We used the following set of *input parameters*:

$$\begin{aligned}
\alpha &\equiv \alpha(0) = 1/137.0359895(61),\\
G_\mu &= 1.16639(2)\times 10^{-5}\,\mathrm{GeV}^{-2},\\
M_Z &= 91.1887 \pm 0.0044\,\mathrm{GeV},\\
\Delta\alpha_h &= 0.0282(9) \Longrightarrow \alpha^{-1}(M_Z) = 128.87 \pm 0.12,\\
m_\tau &= 1.7771 \pm 0.0005\,\mathrm{GeV},\\
m_b &= 4.7 \pm 0.3\,\mathrm{GeV},\\
m_c &= 1.55 \pm 0.35\,\mathrm{GeV},\\
\alpha_s(M_Z) &= 0.125 \pm 0.007,\\
m_t &= 100 - 250\,\mathrm{GeV},\\
M_H &= 60 - 1000\,\mathrm{GeV}. \qquad (4)
\end{aligned}$$

Three remarks should be added:

- The importance of $\alpha^{-1}(M_Z)$ in the precision tests of the SM is well known. Its error is one of the dominating theoretical errors (*parametric error*, see below). In our analysis we used the value of [31]. Recently, several new analyses have been published [32–34]. Although they agree within 2σ, this is not satisfactory, given the importance of this value.

- m_b, m_c and m_t are the pole masses which, in the actual calculation, are converted to $\overline{MS}$ masses.
- The masses m_t and M_H are treated as real unknowns varying within certain limits. However, after discovery of the t quark [3-4], one should conclude that the m_t interval we choose is too broad, see Fig.1.

With this *standard input* all codes produced a *standard output* — a theoretical prediction for *observables.* We distinguished *pseudo-observables (PO)* and *realistic observables (RO).* By RO we meant cross-sections $\sigma^f(s)$ and asymmetries $A^f_{FB}(s)$ for the reactions

$$e^+e^- \to (\gamma, Z) \to f\bar{f}(n\gamma)\ , \tag{5}$$

calculated with our best knowledge of QED, EW and QCD corrections, with cuts as realistic as possible. We will not discuss ROs here, referring to [5] and [37] for all details. POs are related to measured cross sections and asymmetries by an additional unfolding (for instance deconvolution of non-interesting QED effects). They could be *parameters*, such as the number of light neutrino species N_ν, or, say the total Z width, Γ_Z, or M_W, or some other parameter-like quantities in which, by definition, some corrections are deconvoluted. We have analysed 25 POs:

mass of the W	M_W
cross-section	$\sigma_h = 12\pi\Gamma_e\Gamma_h/(M^2_Z\Gamma^2_Z)$
partial widths	$\Gamma_\nu, \Gamma_e, \Gamma_\mu, \Gamma_\tau, \Gamma_u, \Gamma_d, \Gamma_c, \Gamma_s, \Gamma_b$
total width	Γ_Z
hadronic width	$\Gamma_h = \Gamma_u + \Gamma_d + \Gamma_c + \Gamma_s + \Gamma_b$
invisible width	$\Gamma_{\rm inv} = \Gamma_Z - \Gamma_e - \Gamma_\mu - \Gamma_\tau - \Gamma_h$
ratios	$R_l = \Gamma_h/\Gamma_e\ , R_{b,c} = \Gamma_{b,c}/\Gamma_h$
asymmetries	$A^\mu_{FB}, A^e_{LR}, A^b_{FB}, A^c_{FB}$
polarizations	P^τ, P^b
effective sines	$\sin^2\theta^{\rm lept}_{\rm eff}, \sin^2\theta^b_{\rm eff}$.

The latter are defined by

$$4\,|Q_f|\sin^2\theta^f_{\rm eff} = 1 - \frac{g^f_V}{g^f_A}\ , \tag{6}$$

with Q_f being the electric charge of the fermion f. By definition, the total and partial widths of the Z boson include EW and final-state QED and QCD corrections, and the deconvoluted hadronic peak cross-section, σ_h, includes only the Z exchange. Unlike the widths, asymmetries and polarizations do not contain, by definition, QED and QCD corrections; they also refer to pure Z exchange. Therefore, they are given by simple combinations of the effective Z couplings:

$$A^f_{FB} = \frac{3}{4}\mathcal{A}^e\mathcal{A}^f,\ A^e_{LR} = \mathcal{A}^e,\ P^f = -\mathcal{A}^f,\ P_{FB}(\tau) = -\frac{3}{4}\mathcal{A}^e$$

where

$$\mathcal{A}^f = \frac{2g^f_V g^f_A}{(g^f_V)^2 + (g^f_A)^2}\ . \tag{7}$$

2.3.3 Parametric and Intrinsic Uncertainties

We begin with a classification of theoretical uncertainties:

- *Parametric uncertainties* are associated with the precision of the input parameters. Typical examples are $|\Delta\alpha^{-1}(M^2_Z)| = 0.12$, $|\Delta m_b| = 0.3\,$GeV, $|\Delta m_c| = 0.35\,$GeV, etc. These uncertainties could be reduced if more accurate measurements became available. They are trivial in a sence.

- *Scheme-dependence uncertainties* are associated with the calculational (renormalization) scheme used [35]. They are present, because in the framework of perturbation theory we are operating with truncated series and in a given calculational scheme this truncation is realized in some specific way. The tools that we have used are based on different renormalization schemes — various realizations of the on-shell scheme in `BHM/WOH`, `ZFITTER`; $\overline{MS}$ scheme in `TOPAZ0`, and an original approach in `LEPTOP`. Therefore, by comparing results of five different approaches, we have an estimate of these uncertainties.

- *Intrinsic uncertainties* inherent in a concrete calculational scheme. Within a given approach, one always has a certain degree of arbitrariness on how to construct the resulting formulae, which again is basically due to unknown higher-order terms. However, it has nothing to do with the scheme dependence, since we are now dealing with one specific realization. Indeed, the predictions of a given approach should always look as bands [36] (similar to experimental error bars) which would reflect this arbitrariness. We invented and realized the concept of *working options*, with the aid of which we simulated this arbitrariness. The typical prediction for a PO with estimated theoretical uncertainties confronted with the present experimental value is given in Fig.1.

2.4 Theoretical Uncertainties, Examples of Options

Three very didactic examples of options are given in [37]. Here I have to limit myself to only one example.

2.4.1 Factorization of QCD and QED FSR corrections

Consider a partial width:

$$\Gamma_f \equiv \Gamma(Z \to f\bar{f})\ . \tag{8}$$

Imagine that we know QED corrections of $\mathcal{O}(\alpha)$ and QCD corrections up to $\mathcal{O}(\alpha^2_s)$, and that we do not know

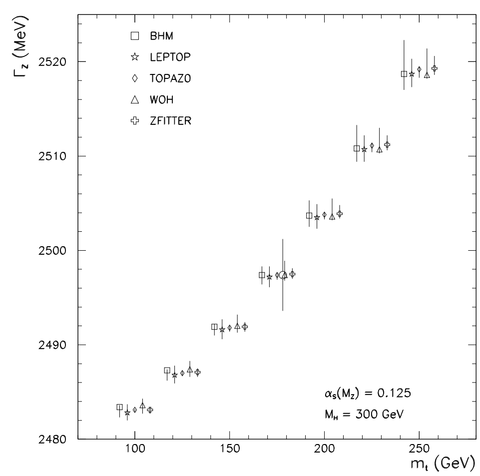

Figure 1: The BHM, LEPTOP, TOPAZO, ZFITTER, WOH predictions for Γ_Z, including an estimate of the theretical error as a function of m_t, for $M_H = 300\,\mathrm{GeV}$ and $\alpha_S(M_Z) = 0.125$

the mixed correction of $\mathcal{O}(\alpha\alpha_s)$. Then the two representations, *factorized*

$$\Gamma_f = \Gamma_f^{EW}\left(1+\frac{3}{4}Q_f^2\frac{\alpha}{\pi}\right)\left[1+\frac{\alpha_s}{\pi}+1.409\frac{\alpha_s^2}{\pi^2}\right], \quad (9)$$

and *expanded*

$$\Gamma_f = \Gamma_f^{EW}\left[1+\frac{3}{4}Q_f^2\frac{\alpha}{\pi}+\frac{\alpha_s}{\pi}+1.409\frac{\alpha_s^2}{\pi^2}\right], \quad (10)$$

are equally correct and one might implement both realizations (9) and (10) into a code, terming them as two *working options*. This implementation would introduce an uncertainty of the order of $\pm(3/4)Q_f^2(\alpha/\pi)Q_f^2(\alpha_s/\pi)$ — a naive estimate of the lack of $\mathcal{O}(\alpha\alpha_s)$ corrections.

Indeed, this correction was calculated in [38], yielding the result $-(1/4)Q_f^2(\alpha/\pi)Q_f^2(\alpha_s/\pi)$. It sizeably reduced the uncertainty, pushing it to $\mathcal{O}((\alpha/\pi)(\alpha_s/\pi)^2)$. The realizations (9) and (10) are no longer options; they should be replaced by a factorized (artificial):

$$\Gamma_f = \Gamma_f^{EW}\left(1+\frac{3}{4}Q_f^2\frac{\alpha}{\pi}-\frac{1}{8}Q_f^2\frac{\alpha}{\pi}\frac{\alpha_s}{\pi}\right) \times\left[1-\frac{1}{8}Q_f^2\frac{\alpha}{\pi}\frac{\alpha_s}{\pi}+\frac{\alpha_s}{\pi}+1.409\frac{\alpha_s^2}{\pi^2}\right], \quad (11)$$

and expanded (natural)

$$\Gamma_f = \Gamma_f^{EW}\left[1+\frac{3}{4}Q_f^2\frac{\alpha}{\pi}-\frac{1}{4}Q_f^2\frac{\alpha}{\pi}\frac{\alpha_s}{\pi}+\frac{\alpha_s}{\pi}+1.409\frac{\alpha_s^2}{\pi^2}\right] \quad (12)$$

options which incorporate the new knowledge of $\mathcal{O}(\alpha\alpha_s)$ corrections. This example shows that the real progress in reducing theoretical uncertainties is achieved whenever a new term in perturbation expansion becomes available.

2.4.2 Other Options

There were many more options suggested:
- *factorization of QCD and EW corrections*;
- *leading–remainder interplay*;
- *scale of remainder corrections*;
- *linearization*;
- *resummation* (several variants);
- *effective scale* (to simulate $t\bar{t}$ threshold corrections);
- *estimates of missing higher-order terms*, etc.

Every team, participating in the project, has designed its own set of working options independently, based on different conceptual principles, described in the EWWGR.

2.5 Main Results and Conclusions of the EWWGR

Based on numerous results for POs and ROs, similar to that of Fig.1, we made the following conclusions:

1) The uncertainties of the theoretical predictions for the Z-resonance are comprehensively studied.

2) The differences between *adapted* results of different codes are small compared to the existing experimental errors.

3) Parametric uncertainty due to $\Delta\alpha_{had}$ dominates. New experimental input is necessary.

4) More theoretical study is welcome, in particular NL EW correction $\mathcal{O}(G_F^2 m_t^2 M_Z^2)$ may reduce the theoretical uncertainty; non-leading $\mathcal{O}(\alpha\alpha_s)$ vertex correction may conceal a surprise.

5) Improving **3)** and clarifying **4)** opens the road to a 0.05% theoretical precision, i.e. two times better than the experimental precision at the end of LEP1.

6) A *considerable* improvement of the experimental errors (2–3 times better than now) will inevitably require a further progress on the road to complete 2-loop EW corrections.

3 Evidence for EW Corrections in the SM

3.1 Are Genuine EWRC seen? If Yes, how many σ's?

One of the most interesting goals of the precision measuments of Z-resonance observables is to see an exhibition of genuine EWRC on top of conventionally considered as 'trivial' running of α from $0 \to M_Z$ [39,40].

Excluding this 'trivial' correction, we have to consider instead of the usual Δr another ERWC Δr_{res}:

$$\frac{\alpha}{1-\Delta r} = \frac{\alpha}{(1-\Delta\alpha)\left(1+\frac{c_W^2}{s_W^2}\Delta\rho\right) - \Delta r_{\rm rem}} = \frac{\alpha(M_Z)}{1-\Delta r_{\rm res}}$$

$$\Delta r_{\rm res} = -\frac{c_W^2}{s_W^2}\Delta\rho + \frac{\Delta r_{\rm rem}}{1-\Delta\alpha} \,. \quad (13)$$

In the table below, I give Δr and $\Delta r_{\rm res}$ for several m_t:

m_t	Δr	$\Delta r_{\rm res}$
113.5	0.0589	0.0000
140.0	0.0510	-0.0055
175.0	0.0391	-0.0152
200.0	0.0293	-0.0239

Using the experimental value of $M_W = 80.26 \pm 0.16$ GeV and $\alpha^{-1}(M_Z)$ of [34], we have
$\Delta r_{\rm res} = -0.0180^{+0.0105}_{-0.0107}$ or 1.7σ deviation from zero

Using instead the value of $M_W = 80.346 \pm 0.052$ GeV, *derived* from the SM with m_t of eq. (1), we have
$\Delta r_{\rm res} = -0.0233 \pm 0.0040$ or 5.9σ deviation from zero

Now consider two more *derived* quantities, [1]:
(1) $\sin^2\theta^{\rm lept}_{\rm eff} = 0.2317 \pm 0.0003^{+0.0001}_{-0.0001}$
(2) $1 - M^2_{\rm W}/M^2_{\rm Z} = 0.2237 \pm 0.0010^{+0.0004}_{-0.0002}$
differing by 6.5σ between themselves and compare them with the $\sin^2\theta_W$ used in the so-called $\bar\alpha$-Born approximation of [27]

$$s^2c^2 = \frac{\pi\alpha(M_Z)}{\sqrt{2}G_\mu M_Z^2} \,. \quad (14)$$

(3) $s^2 = 0.2312 \pm 0.0003$.
The latter differs by 1.3σ from (1) and by 6.2σ from (2).

Since all the three definitions of $\sin^2\theta_W$ should agree at the tree level, the difference must be due to EWRC.

All these considerations might lead to a conclusion that the EWRC are tested with many σ, which was put in the following words "... there is no Born Approximation involving a single mixing angle, whether related to $\alpha(M_Z)$ or not, that can accommodate all the information derived from the data using the full SM" (second ref.[41]).

However, the above conclusions rely on the very small errors for the *derived* quantities, which are derived assuming that the SM is valid. However, we just want to check the SM itself. Leaving out all *derived* quantities, we remain with only 1.7σ test of genuine EWRC.

Since this 1.7σ test via $\Delta r_{\rm res}$ exploits only *one* data point (M_W), we performed [42] the *global* fit of EW data with the $\bar\alpha$-Born approximation [27]. We used the standard *LEPEWWG* fit procedure based on 17 measurements:
5 - line shape parameters: $M_Z, \Gamma_Z, \Gamma_l, R_l, \sigma^0_h$
6 - heavy flavour parameters: R_b, R_c, $A^{0,b}_{FB}$, $A^{0,b}_{FB}$, $\mathcal{A}_b$, $\mathcal{A}_c$
2 - $\mathcal{P}_\tau$ parameters: $\mathcal{A}_e, \mathcal{A}_\tau$
1 - $\langle Q_{FB}\rangle$ the hadronic charge asymmetry
1 - M_W
1 - $R = \sigma_{NC}/\sigma_{CC}$ from νN DIS
1 - A_{LR} from SLAC
We excluded inconsistent $R_{b,c}$ and added two constraints:
CDF/D0 constraint on $m_t = 180 \pm 12$ GeV,
constraint on $\alpha^{-1}(M_Z) = 128.89 \pm 0.09$ [34].
Fitted parameters were: $M_Z, m_t, \alpha_S, \alpha^{-1}(M_Z)$.
We considered two scenarios:
Full SM fit with $M_H = 300^{+200}_{-40}$ GeV ;
$\bar\alpha$-Born, no M_H, m_t, only in FSR QCD corrections.
The results are presented in the following table.

	Scenario 1	Scenario 2
M_Z	91.188 ± 0.002	91.189 ± 0.002
m_t	$172 \pm 7^{+10}_{-4}$	182 ± 12
α_S	$0.122 \pm .004 \pm .002$	$0.125 \pm .004$
$\alpha^{-1}(M_Z)$	$128.90 \pm 0.08^{+0.04}_{-0.02}$	$128.87 \pm 0.08 \pm 0.07$
χ^2/d.o.f.	(13.4, 13.1, 13.5)/13	$24.7/13 \to 2.3\sigma$

As seen from this table the fit to the $\bar\alpha$-Born approximation is substantially worse than the full SM fit yielding a 2.3σ confidence level test of genuine EWRC.[a]

This result, however, tends to rather poor checks of the genuine EWRC. In this connection, I would like to comment that the very small error on m_t at its *indirect* determination from Z-resonance observables means that **genuine EWRC are very important**, indeed. Relatively small c.l. ($\simeq 2.5\sigma$) is an accidental phenomenon. It is in a sense due to bad luck: some EWRC, with respect to $\bar\alpha$-Born, vanish at $m_t \simeq 150 - 160$ GeV. Had nature given us $m_t = 30 - 50$ GeV, we would already have a much better test of genuine EWRC.

3.2 *Evidence for Bosonic EWRC in the SM*

There is a consensus that the present data feel the bosonic EW corrections [39,41] — any attempt at switching them off in a gauge-invariant manner leads to even bigger inconsistency with the experimental data, than in the described above fit to the $\bar\alpha$-Born approximation. This is due to a compensation between fermionic and bosonic corrections. For more details I refer the reader to the existing literature [24,39–41,43].

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[a] Recently D. Schildknecht et al. reported $1.3 - 3.2\sigma$ test of genuine EWRC for different observables[43].

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