to see theoretical software in particle physics as an intellectual enterprise like the other inventions of physics research - experimental set-ups, data, hypotheses, models, theories.

We would like to finish the introduction with two quotes.

Several times we all thought that the ZFITTER project is in its final phase of dying out. See for example the remark of Dima Bardin at the symposium "50 Years of Electroweak Physics: a symposium in honour of Professor Alberto Sirlin's 70th Birthday", in the year 2000 [26]:

*"We would like to see the end of the ZFITTER project in the year 2000 and, therefore, a very natural question arises: What's next?"*

In the same year, members of the ZFITTER group were granted the prestigeous "JINR Award in Theoretical Physics" of the Joint Institute for Nuclear Research, Dubna, Russia. For a document, see here: certificate. The referee was Academician Prof. L. B. Okun from ITEP Moscow; he finished his estimate with the statement:[3]

*"Overall, the project "ZFITTER Fortran program" represents a unique theoretical tool of world class. The project formed the basis of a close cooperation of experimetalists and theoreticians (with a series of workshops at CERN). With the accumulation of experimental data, the accuracy of the programs has been increased. The project has always found great interest at conferences. Its importance and the interest to it shows with numerous references in articles, reviews and monographies.*
*In the long term, with the advent of more precise experiments, ZFITTER will allow to take into account all two-loop electroweak corrections.*
*The series of theoretical articles on precision tests of the Standard Model at electron-positron colliders certainly deserves the award of the JINR prize 2000.*
*Academician L.B. Okun"*

Our figures illustrate the development of mass predictions for Z boson (figure 1.3, left), top quark (figure 1.3, right), Higgs boson (figure 1.4). Here, ZFITTER has been useful until now. Okun's proposition that ZFITTER will be used also in future is being fulfilled. We can only hope that our write-up might help to convince the present particle physics community that ZFITTER is worth some support by now and in future.

At the end of the introduction, we would like to reproduce the long(est) authors list of ZFITTER, see also `http://zfitter.com`:

A. Akhundov, A. Arbuzov, M. Awramik, D. Bardin, M. Bilenky, A. Chizhov, P. Christova, M. Czakon, O. Fedorenko (1951-1994), A. Freitas, M. Grünewald, M. Jack, L. Kalinovskaya, A. Olshevsky, S. Riemann, T. Riemann, M. Sachwitz, A. Sazonov, Yu. Sedykh, I. Sheer, L. Vertogradov, H. Vogt.

The list is not complete. According to the conventions of the software library of "Computer Physics Communications", we should also include here all the co-authors who helped to prepare the program descriptions in 1989, 1999, 2005 [9 – 11].

## 2. ZFITTER in a nutshell, or: Is there a ZFITTER approach?

We never used the label "ZFITTER approach". The reason is simple: There is no ZFITTER

[3] The original document is in Russian, see statement.

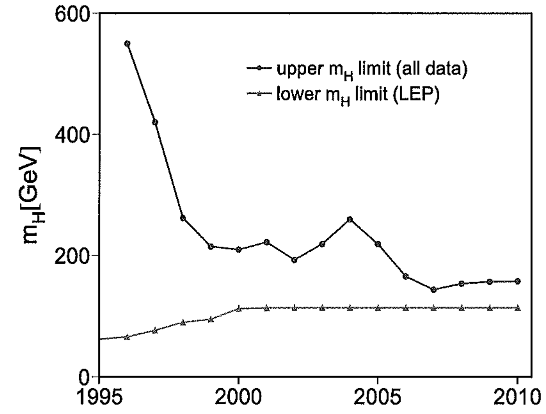


Figure 1.4: *Higgs boson mass measurements. The upper limits and the fit values for $M_H$ derive from a combination of virtual corrections to LEP and similar data, top and W mass measurements, performed by the LEPEWWG. The lower mass limit is due to LEP direct searches. The lower limits from data combinations are not shown.*

software itself to a large extent. Further, without cooperation with ZFITTER authors and with the community of theoreticians, including extensive numerical cross-checks, such a project cannot succeed.[1]

Finally, there is much influence by institutes' directors and by the editors and publishers of physics journals on the engagement of scientists in the development of software. Not all of them seem to mind about proper acknowledgment and quotation of software. Some even say that software has no genuine scientific value by itself and advocate an absolutely free use of any software as common habit. If this would *become* common habit, nobody with inspiration and ambition would invest time to write complicated software for the use by other people, like the ZFITTER group - and other groups as well - does. We live in an academic world and we are valued by our scientific results, their originality, importance, curiosity, usefulness etc. Financing of our projects, of our working positions, our academic prestige depend on all that. We need proper quotation of our scientific results in case they are used. And we can only appeal and hope that the community understands this as a justified expectation, also for software.

As a key feature of user-friendly support, we stored for many years all the relevant versions of ZFITTER at a webpage for anonymous download. We collected about three dozen versions, covering more than 20 years. There are collegues who take the freedom to use ZFITTER as if it were open-source software in the strictest meaning of the word. Despite the facts that academic research deserves strict, proper quotation, and that there are licence regulations (for ZFITTER this includes the CPC licence). In some countries there are even legal regulations.[2]

It is the aim of these notes to give an overview on the ZFITTER project. Maybe they can help

[1]For details see e.g. `http://zfitter.com`.

[2]Due to controversial positions, we closed the links for anonymous download from ZFITTER webpages in 2011, and in 2012 also the links from the Andrew file system at CERN.

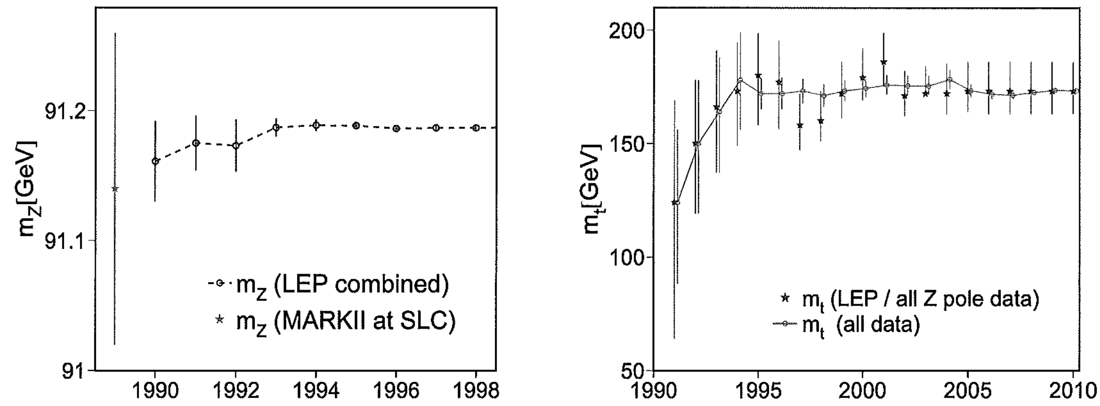


Figure 1.3: *Left: Z boson mass measurements at LEP. Earlier measurements are from UA1, UA2 at SPS (CERN) (see text, not shown in plot) and from MARKII at SLC (SLAC). Right: Top quark mass measurements. After discovery of the top quark, the LEP data were no more competitive. The agreement of direct measurements (in 'all data') and indirect measurements (in 'all Z pole data') supports the validity of the Standard Model at the quantum loop level.*

knowledge, the Big Labs do not plan to support long-term maintenance of software like ZFITTER. We, as authors, theoreticians and phenomenologists, have to mind by ourselves about maintenance of theory/phenomenology software.

Everybody knows that the very details of a data analysis cannot be described by few words. But for precision studies they are truly essential. Sometimes we say: "The description of the program is the program itself." This is a helpful statement if "the program itself" is preserved over a long term in its state of use. ZFITTER did and does a lot to fulfil such a demand. See the webpage `http://zfitter.com`.

Preservation demands effort. In the DESY Data Preservation Project there are 17 people involved. At the other hand, if a theoretician says: I care about the availability of my old software, people start to smile. This aim does not give true credit points for a scientific carrier, in what phase of the carrier ever.

In fact, not only the so-called main author of ZFITTER, Dima Bardin, our "primus inter pares", tends to lose interest in active support of ZFITTER over the decades. This applies to all of us, mainly because of our interest in studying or inventing something new. Nevertheless, we collected in 2005 some volunteers into a ZFITTER support group, which submitted in that year ZFITTER v.6.42 and in 2008 ZFITTER v.6.43 [10, 11].

Encouraged by the decreasing visibility of our ZFITTER support, in 2006 some experimentalists tried to re-program in C++ in a year's time the Standard Model library of ZFITTER from the published literature. Not just for fun, but in order to do better than ZFITTER: use a more modern programming language than Fortran, with more modularity than ZFITTER, a bit updated, with a GUI. In order to retain ZFITTER for a longer term. The project was proprietary until 2012, and it faced two major problems. It proved to be impossible to do so without using the ZFITTER

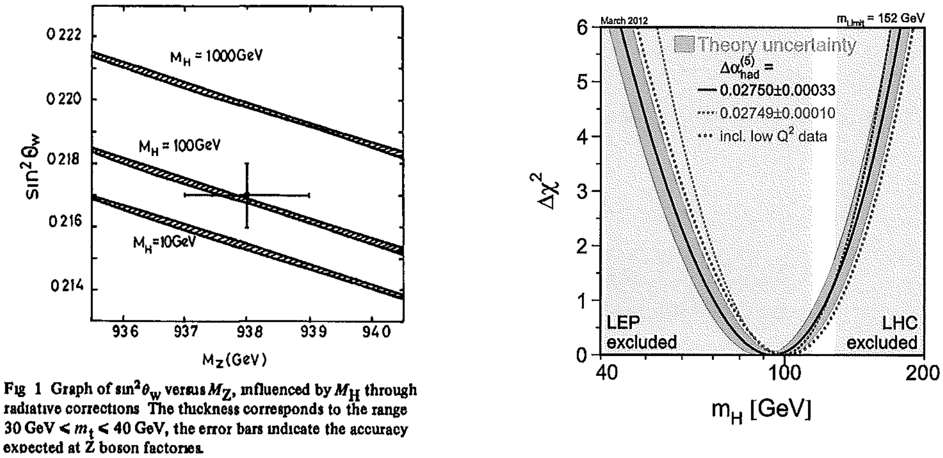


Figure 1.2: *Left: The first ever plotted LEP observables' dependence on the Higgs mass in the Standard Model (reproduced from [1], courtesy Physics Letters B). Right: Blue-band plot of the LEPEWWG [7] with a Standard Model Higgs boson mass prediction based on combined world data from precision electroweak measurements.*

$e^+e^- \to \bar{f}f$. The top quark was predicted by M. Kobayashi and T. Maskawa in 1973 [15] and discovered in 1995 with a mass of about 173 GeV [16, 17]. Top quark mass data from precision electroweak measurements and from direct searches are collected in figure 1.3, right. Over the years the predictive power of the indirect searches for the Higgs boson mass improved considerably, and the discovery of the top quark was a crucial improvement for this. This is described in figure 1.4. In 2012, the LHC collaborations reported the discovery of a scalar particle with a mass of about 125 GeV [18, 19], which fits into these expectations from the indirect searches. It might well be that it is the particle predicted by Peter Higgs in 1964 [20, 21].

We live with the ZFITTER project for more than 20 years now, and ZFITTER is yet in use for a diverse variety of applications, ranging from the global analyses of the LEPEWWG to many graduation papers like e.g. [22]. Twenty years are a long term. It takes similarly long to prepare final results of big experiments at accelerators as LEP 1, LEP 2, HERA. As an example, we mention the final analysis of the LEP 1 data for two-fermion production in 2005 [23] by the LEP collaborations and the LEPEWWG, using ZFITTER v.6.42. The corresponding enterprise for LEP 2 data is yet being finalized, using ZFITTER v.6.43.

The big laboratories invented scientific programs for a dedicated long-term preservation of the experimental data, under the label "ICFA Study Group on Data Preservation and Long Term Analysis in High Energy Physics" [24]. One might assume that this is a self-evident issue of any physics collaboration. Physics is the science of reproducible observations in Nature and of their explanations/descriptions, and reproducibility deserves storage. But long-term storage is an unsolved problem, worth of any (reasonable) effort. DESY, as an example, founded in 2009 a "DESY Data Preservation Project", mainly focusing on the HERA experiments H1, Hermes, ZEUS [25]. If such effort is justified for data, then it is also needed for the analysis tools, which were used for an extraction of the Model with its few parameters from the raw, or not-so-raw, Data. To our

The ZFITTER group members, as well as the authors of other physics software packages used by the LEPEWWG are not members of the LEPEWWG. They are consulted in case.

### 5.3 1995 – The Electroweak Working Group Report

The work of the LEPEWWG and of the four LEP collaborations relied on ZFITTER and TOPAZ0, and also on the BHM/WOH package, and on many other resources. Because of this role of establishing a kind of world standard, the community felt the need of careful numerical checks on their predictions. One is confronted with multi-parameter problems, different calculational schemes, some freedom of input choices, in the presence of approximations and dedicated omissions, of misunderstandings and, sometimes, mistakes.

At a certain moment, the community has to set benchmarks. The result of a year-long workshop is the collection "Reports of the working group on precision calculations for the Z resonance", edited by D. Bardin, W. Hollik, G. Passarino. It was published as Yellow CERN Report, CERN 95-03 (31 March 1995), `http://cdsweb.cern.ch/record/280836/files/CERN-95-03.pdf`.

Part of this document is the "Electroweak Working Group Report", which was two years later submitted to the archive arxive/hep-ph [69].[15] This work is one of the basics for the successful work of the LEP Electroweak Working Group. It is until now one of the most important collections of Standard Model higher order corrections for $e^+e^-$-annihilation.

### 5.4 Higher order corrections in ZFITTER

During the 1995 CERN workshop and shortly after, a lot of additional higher-order corrections were calculated and included into ZFITTER. We give here just a (presumably not complete) list of the references and refer for any detail to the ZFITTER descriptions: [70, 82, 110, 141 – 148]. Later, further improvements were added [149 – 158].

Until now, we did not yet include into ZFITTER the existing parameterization of the rather small *bosonic* two-loop weak corrections to the weak mixing angle [156]. The fermionic corrections are covered, as well as the complete weak two-loop corrections to the $W$ boson mass. For a complete treatment of the weak two-loop corrections to the $Z$ boson width, the correction to the form factor $\rho_Z$ are lacking yet. For this reason, the quite good agreement of the higher-order *approximations* to $\Gamma_Z$ with the so far known pieces of the *complete* two-loop result are an indication that the final answer will be close what we have already.

Generally speaking, we try to control about four to five digits of the predictions aiming at such a *physical* theory precision. One quote from the report [69] is interesting because it sheds some light on the progress of the so-called *technical* precision (precision under fixed, maybe not realistic conditions): " ... compare results of independent calculations. Such a comparison has been done once for $\Delta r$, and an agreement of up to 12 digits (computer precision) was found [14]." Ref. [14] was private communications of Bardin, Kniehl, Stuart, 1992. This has to be compared to a three digits agreement between two Bhabha cross section calculations in a comparison, performed few years earlier in 1990 [52]. Later, in 2002, a precision of up to 12 digits was reached in practice

[15] Now it is also available as a pdf file at CERN, in CERN 95-03.

for complete virtual one-loop calculations, and of 5 digits with inclusion of real corrections [159–161].

## 6. ZFITTER 2013

### 6.1 From ZFITTER v.6.42 to ZFITTER v.6.44beta

The most recent publicly available ZFITTER version is ZFITTER v.6.43 (17 June 2008) [10, 11]. It agrees with ZFITTER v.6.42 up to a correction of a non-influential typo and was released by the ZFITTER support group (A. Arbuzov, M. Awramik, M. Czakon, A. Freitas, M. Grünewald, K. Mönig, S. Riemann, T. Riemann, see `http://zfitter.com`). The ZFITTER group was reorganized in February 2012 and consists now of A. Akhundov, A. Arbuzov, D. Bardin, P. Christova, L. Kalinovskaya, A. Olshevksy, S. Riemann, T. Riemann.

Recently, we have included into ZFITTER v.6.44beta the final results for the $\mathscr{O}(\alpha_s^4)$ QCD corrections to the $Z$-boson and $W$-boson quarkonic partial widths and to the so-called $R$-ratio by P. Baikov et al. [162, 158]. As may be seen from figure 6.1 and from table 6.2 , the numerical shifts in the widths amount to less than 0.3 MeV and are thus well below the experimental errors, e.g. at LEP or at an anticipated GigaZ option of an ILC [163]. A fit formula for the complete electroweak two-loop corrections to the $W$-boson mass [152] was already included in ZFITTER v.6.42. The final exact results for the complete electroweak two-loop corrections to $\sin^2\theta_{\rm eff}^{\rm f\bar{f}}$ for light fermions $f$ [110] and the two-loop electroweak fermionic corrections to $\sin^2\theta_{\rm eff}^{\rm b\bar{b}}$ [157] have to be included yet into ZFITTER. They are known to be small corrections compared to the fit formula [155] covered in ZFITTER since v.6.42. Already these corrections are small compared to the present experimental errors, see table 6.1.

Presently, there are controversial positions concerning ZFITTERS 'conditions of use' and the ZFITTER software licence `http://cpc.cs.qub.ac.uk/licence/licence.html` granted to the authors by Elsevier's Computer Physics Communications Program Library - Programs in Physics & Physical Chemistry. For some details see `http://zfitter.com`. Until the issue is settled, actualized versions of ZFITTER will stay at the beta level and cannot be released.

Sooner or later, the LHC is becoming a precision tool and the community feels some steady need of high-precision Standard Model predictions. Both for use in global fits and for specific cross-section predictions, notably of Drell-Yan processes via the $Z$ resonance. This need would become even more pronounced if the ILC project would substantialize [163].

Regrettably, we see today no alternative project to ZFITTER in the field of precision Standard Model predictions. In the mid-nineteen nineties there were three competing (and cooperating) projects at the disposal [69]: BHM/WOH by W. Hollik et al., TOPAZ0 by G. Passarino et al., and ZFITTER by D. Bardin et al. BHM/WOH was available on request, and the latter two are publicly available. To our knowledge, updating and user support have been minimized for TOPAZ0 and BHM/WOH [136].



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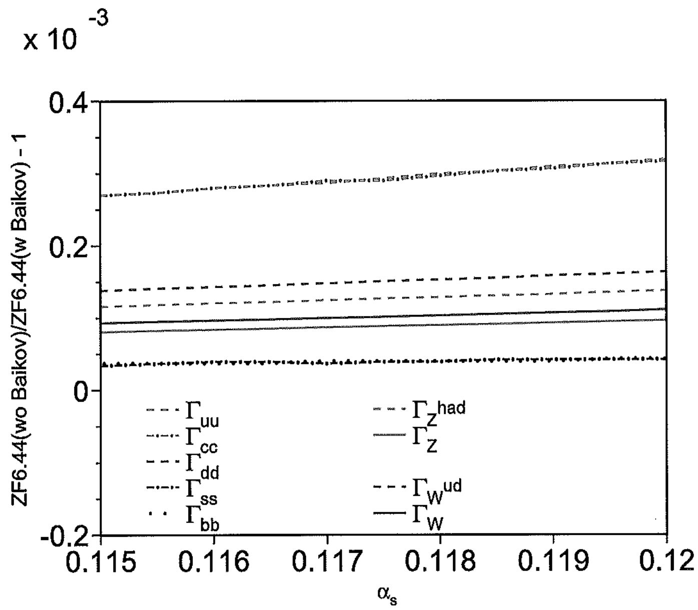


Figure 6.1: *The influence of the $\mathscr{O}(\alpha_s^4)$ QCD corrections [158] on the W and Z boson widths.*

Table 6.1: *ZF6_44, with the input values $\alpha_s$ = 0.1184(7), $M_Z$ = 91.1876(0), $M_W$ = 80.385(15), $M_H$ = 125(0), $m_t$ = 173.5(1). The dependence on electroweak NNLO corrections is studied for IMOMS=1 (input values are $\alpha_{em}, M_Z, G_\mu$). IAMT4= 4: with two-loop sub-leading corrections and re-summation recipe of [23-28] of [11]; IAMT4=5: with fermionic two-loop corrections to $M_W$ according to [29,30,32] of [11]; IAMT4=6: with complete two-loop corrections to $M_W$ [37] and fermionic two-loop corrections to $\sin^2\theta_W^{\mathrm{lept,eff}}$ [52] of [11].*

| IAMT4 | 4 | 5 | 6 | diff. | exp. error |
|---|---|---|---|---|---|
| $\Gamma_Z(\mu\mu)$ | 83.978 | 83.975 | 83.981 | 0.006 | 0.086 |
| $\Gamma_Z$ | 2494.8 | 2494.6 | 2494.9 | 0.3 | 2.3 |
| $\Gamma_W(l\nu)$ | 226.32 | 226.29 | 226.29 | 0.03 | 1.9 |
| $\Gamma_W$ | 2090.3 | 2090.0 | 2090.1 | 0.2 | 42 |
| $M_W$ | 80.358 | 80.354 | 80.355 | 0.004 | 0.015 |

## 6.2 Gfitter

Sometimes the Gfitter project is considered as an independent implementation of Standard Model predictions for some pseudo-observables, and as a true scientific alternative to ZFITTER (for these pseudo-observables). We do not share this opinion and would like to give a short, clarifying comment on the situation. There are several versions of the program Gfitter.

The Gfitter project was started in 2006 and presented to the public in December 2007, at the kick-off meeting of the German "Helmholtz Alliance for Physics at the Terascale", see the slides at `http://indico.desy.de/materialDisplay.py?contribId=36&sessionId=15&materialId=1&confId=477`. Until August 2012, the

Table 6.2: *IBAIKOV=0 (no $\alpha_s^4$ QCD corrections) or IBAIKOV=2012 [158], IAMT4 as described in table 6.1.*

| IBAIKOV=0<br>IAMT4 | 4 | 5 | 6 | Diff. | Exp. Err |
|---|---|---|---|---|---|
| $\Gamma_Z(\mu\mu)$ | 83.9782 | 83.9748 | 83.9807 | | 0.086 |
| $\Gamma_Z$ | 2494.7863 | 2494.0465 | 2494.8688 | | 2.3 |
| $\Gamma_W(l\nu)$ | 226.3185 | 226.2877 | 226.2922 | | 1.9 |
| $\Gamma_W$ | 2090.3308 | 2090.0465 | 2090.0882 | | 42 |
| $M_W$ | 80.3578 | 80.3541 | 80.3546 | | 0.015 |
| s2efflept | 0.231722 | 0.231791 | 0.231670 | | |
| IBAIKOV=2012<br>IAMT4 | 4 | 5 | 6 | Diff. | Exp. Err |
| $\Gamma_Z(\mu\mu)$ | 83.9782 | 83.9748 | 83.9807 | | 0.086 |
| $\Gamma_Z$ | 2494.5591 | 2494.3747 | 2494.6416 | | 2.3 |
| $\Gamma_W(l\nu)$ | 226.3185 | 226.2877 | 226.2922 | | 1.9 |
| $\Gamma_W$ | 2090.1117 | 2089.8274 | 2089.8691 | | 42 |
| $M_W$ | 80.3578 | 80.3541 | 80.3546 | | 0.015 |
| s2efflept | 0.231722 | 0.231791 | 0.231670 | | |

Gfitter software was proprietary, but by private information[16] it became known that the Standard Model library of Gfitter, Gfitter/GSM, was relying on the FORTRAN package ZFITTER v.6.42 and was created to a large extent by copy-paste-adapt. Without any proper citation in the academic meaning of the word.

Gfitter/GSM (Summer 2006 - July 2011) relies essentially and directly on the Standard Model implementation of the ZFITTER software. On top of that, Gfitter/GSM contains few add-ons. The *electroweak add-on* of Gfitter/GSM, compared to ZFITTER v.6.42, are the bosonic two-loop corrections to the weak mixing angle in Amwramik et al. [110]. They are small; see the discussion above. The complete two-loop parameterizations in [110], in turn, have been made with use of ZFITTER v.6.42. As a consequence, it is formally correct to quote for the parameterization only [110], but one should have in mind that there is inside also ZFITTER. There is also a *QCD add-on* of Gfitter/GSM (2011), compared to ZFITTER v.6.42 (2006), based on [164]. It is also numerically small (see the discussion above) and is implemented in ZFITTER v.6.44beta.

Gfitter/GSM (August 2011 till August 2012) relied on a proprietary implementation of Standard Model corrections which were based on a parameterization tracing back to Cho et al. (1999) [165], which in turn is based on an electroweak one-loop calculation published in 1994 [166]. There have been made improvements later, and in a recent article by Cho et al. (2011) [167] the authors confirm the reliability of their parametrization by comparing them with ZFITTER v.6.42 predictions. These parameterizations are used in Gfitter furtheron, and overlayed with the most recent higher-order corrections mentioned.

[16]Private information from and documentation by A. Akhundov, S. Riemann, T. Riemann, March to May 2011.



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Gfitter_1.0 has been released publicly in September 2012. The Standard Model library Gfitter_1.0/gew relies presumably on the same parameterizations as Gfitter/GSM (2012).

The different versions of Gfitter rely in one way or the other on ZFITTER v.6.42. We further remark that without studying the numerical reliability of Gfitter, to four or five significant digits, the scientific value of the inclusion of NNLO weak and $\alpha_s^4$ QCD corrections in Gfitter remains questionable. According to our standards, Gfitter simulates Standard Model predictions with unknown precision. It is a nice tool for the production of figures for the illustration of Standard Model physics. Possibly it is useful for studies beyond the Standard Model.

## 7. Conclusions

This talk was presented at LL2012, the eleventh "Loops and Legs" meeting. This conference was founded by the Zeuthen Theory Group in 1992 when the Zeuthen Institute for High Energy Physics of the (then already former) East German Academy of Sciences became part of DESY. We are glad this this conference attracts since then regularly collegues who contribute to the progress in the field. A field, comprising both the branch of applied calculations and that of development of new theoretical methods.

ZFITTER is certainly one of the oldest source-open software projects in elementary particle physics with a permanent support. It comprises practically all the theoretical knowledge of relevance for a precise description of the Z boson resonance in $e^+e^-$ annihilation and for Z boson's part in global fits in the Standard Model [168]. Certainly, today one would create such a project quite differently. We can only encourage our collegues to try. Complex projects need (independent) duplication.

Higher order quantum field theoretical predictions face another problem: The solutions become so lengthy and complex that the idea of source-open software is, in practice, no longer a realistic option. This happens already with the $\mathcal{O}(\alpha_s^4)$ QCD corrections and the complete NNLO weak corrections in ZFITTER. They are mere parameterizations of huge, unpublished expressions.

The LEP/SLC era gave the scientific community unprecedented precision in several fundamental quantities like $M_Z$, $\Gamma_Z$, the effective weak mixing angle $\sin^2\theta_W^{\rm eff}$, the number of light neutrino flavors $N_\nu$. Of comparable importance is the experimental confirmation of the Standard Model, a gauge theory with spontaneous symmetry breaking, as a consistent quantum filed theory, with inclusion of higher orders of perturbation theory.

We are proud that we are being contributing.

## Acknowledgments

We would like to thank S. Alekhin, J. Blümlein, K. Chetyrkin, A. Freitas, S. Moch for helpful discussions. D. Bardin and L. Kalinovskaya interacted with us when figures and tables were produced. The authors list of this resume of ZFITTER should be much longer, as may be seen from the (quite incomplete) list of references. We are truly thankful to our collaborateurs for many years of common scientific work. Our friendship is stable, while times they were a' changin.

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