ZFITTER: a semi-analytical program for fermion pair production in $e^+e^-$ annihilation, from version 6.21 to version 6.42

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Abstract

ZFITTER is a Fortran program for the calculation of fermion pair production and radiative corrections at high energy $e^+e^-$ colliders; it is also suitable for other applications where electroweak radiative corrections appear. ZFITTER is based on a semi-analytical approach to the calculation of radiative corrections in the Standard Model. We present a summary of new features of the ZFITTER program version 6.42 compared to version 6.21. The most important additions are: (i) some higher-order QED corrections to fermion pair production, (ii) electroweak one-loop corrections to atomic parity violation, (iii) electroweak one-loop corrections to $\bar{\nu}_e\nu_e$ production, (iv) electroweak two-loop corrections to the $W$ boson mass and the effective weak mixing angle.

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New version summary

Title of program: ZFITTER version 6.42 (18 May 2005)

Authors of original program: D. Bardin, P. Christova, M. Jack, L. Kalinovskaya, A. Olchevski, S. Riemann, T. Riemann

Program obtainable from:
http://www-zeuthen.desy.de/theory/research/zfitter/ (main web site),
/afs/cern.ch/user/b/bardindy/public/ZF6.42


Operating system: UNIX/LINUX, program tested under, e.g., HP-UX and PC/Linux

Programming language used: FORTRAN 77

High speed storage required: < 2 MB

No. of cards in combined program and test deck: about 26,200

Keywords: Quantum electrodynamics (QED), Standard Model, electroweak interactions, heavy boson Z, $e^+e^-$-annihilation, fermion pair production, radiative corrections, initial state radiation (ISR), final state radiation (FSR), QED interference, SLD, LEP, ILC.

Nature of the physical problem: Fermion pair production is an important reaction for precision tests of the Standard Model, at LEP/SLC and future linear colliders at higher energies. For this purpose, QED, electroweak and QCD radiative corrections have to be calculated with high precision, including higher order effects. Multi parameter fits used to extract model parameters from experimental measurements require a program of sufficient flexibility and high calculational speed. ZFITTER combines these two aspects by employing analytical integrations of matrix elements and at most one one dimensional numerical integration, as well as a variety of flags defining the physics content used. The calculated predictions are typically at the per mille precision level, sometimes better.

Method of solution: Numerical integration of analytical formulae.

Restrictions on the complexity of the problem: Fermion pair production is described below the top quark pair production threshold. Photonic corrections are taken into account with simple cuts on photon energy, or the energies and acollinearity of the two fermions, and one fermion production angle. The treatment of Bhabha scattering is less advanced.

Typical running time: On a Pentium IV PC installation (2.8 GHz) using
g77 under Linux 2.4.21, approximately 23 sec are needed to run the standard test of subroutine ZFTEST. This result is for a default/recommended setting of the input parameters, with all corrections in the Standard Model switched on. ZFTEST computes 12 cross-sections and cross-section asymmetries for 8 energies with 5 interfaces, i.e. about 360 cross-sections in 23 seconds.
1 Introduction

The Fortran program ZFITTER is based on a semi-analytical approach to the calculation of fermion pair production in $e^+e^-$ annihilation at a wide range of centre-of-mass energies, including SLC/LEP1, LEP2, and ILC energies below the $t\bar{t}$-threshold. ZFITTER allows the calculation of several quantities needed for precision studies of the Standard Model:

- $M_W$ — the $W$ boson mass;
- $\Gamma_Z$, $\Gamma_W$, — total (and also partial) $Z$ and $W$ boson decay widths;
- $d\sigma/d\cos \vartheta$ — differential cross-sections;
- $\sigma_T$ — total cross-sections;
- $A_{FB}$ — forward-backward asymmetries;
- $A_{LR}$ — left-right asymmetries;
- $A_{pol}, A_{pol}^{\mu}$ — final state polarisation effects for $\tau$ leptons.

All observables are calculated including radiative corrections using the (running) fine structure constant $\alpha$, the muon decay constant $G_\mu$, the $Z$ mass $M_Z$ as well as the fermion masses and the Higgs mass $M_H$ as input.

ZFITTER version 6.21 and higher was mainly intended for the use at LEP1/SLC energies, and versions since 6.30 are also adapted to the LEP2 kinematics. Various interfacing subroutines (short: interfaces) allow the user to calculate observables, e.g., for fits to the experimental data with different sets of free parameters.

The Fortran package DIZET, a library for the calculation of electroweak radiative corrections, is part of the ZFITTER distribution. It can also be used in a stand-alone mode. On default, DIZET performs the following calculations:

- by call of subroutine DIZET: $W$ mass, $Z$ and $W$ partial and total decay widths;
- by call of subroutine ROKANC: four weak neutral-current (NC) form factors, running electromagnetic and strong couplings needed for the calculation of effective NC Born cross sections for the production of massless fermions (however, the mass of the top quark appearing in the virtual state of loop diagrams for the process $e^+e^- \rightarrow f\bar{f}$ is not ignored);
- by call of subroutine RH0CC: the corresponding form factors and running strong coupling for the calculation of effective CC Born cross sections;
- by call of subroutine ZUAPV: $Q_W(Z, A)$ — the weak charge used for the description of parity violation in heavy atoms.

If needed, the form factors of cross sections may be made to contain the contributions from $WW$ and $ZZ$ box diagrams thus ensuring the correct kinematic behaviour over a larger energy range compared to the $Z$ pole.
ZFITTER version 6.21 [1] was released in July 1999 and was described in [2]. Since then, there were several important developments of the program. The current release is that of ZFITTER version 6.42, dated 18 May 2005. This article describes the changes and additions in ZFITTER from version 6.21 to version 6.42. Other sources of information on ZFITTER and its use are given by the previous program description and the references therein, the ZFITTER webpage [3], the studies [4, 5], the 1999/2000 CERN LEP2 workshop proceedings [6], and the studies of the LEPEWGG (LEP electroweak working group) [7].

The essential changes from ZFITTER v. 6.21 to v. 6.42 in terms of physics topics are:

- Higher order QED corrections to fermion-pair production, of importance at energies off the Z boson peak;
- Electroweak corrections to the weak charge $Q_W$, describing the parity violation effects in atoms, of importance for so-called global Standard Model fits;
- Electroweak corrections to $\bar{\nu}_e\nu_e$ production, of importance for a precise description of $\bar{\nu}_\mu\gamma$ production;
- Electroweak two-loop corrections to $M_W$ and the effective weak mixing angle $\sin^2\theta_W^{\text{eff}}$, of importance for global Standard Model fits and for precise predictions of the Higgs mass $M_H$.

Further, an option to change the strength of the Wtb vertex, $|V_{tb}|$, was implemented in DIZET since version 6.30: $|V_{tb}|$ is now one of the parameters of subroutine DIZET. The default is the Standard Model calculation with $|V_{tb}| = 1$. Several new interface routines deal with this case, see Appendix C for the details.

This program description update is organized as follows. In Sections 2 to 5, we describe the improved or new physics issues. Section 6 contains a description of the input parameters and pseudo observables, and Section 7 reproduces reference outputs from a running of the sample program package. A Summary closes this update note. In Appendices A to C we collect, for the convenience of the user, updated ZFITTER and DIZET user guides and an overview of the user interfaces. The presentation assumes, of course, a familiarity of the reader with [2].

With the present update of ZFITTER and its description, the maintenance of the program has been migrated to a group of volunteers, the ZFITTER support group. The main webpage has been migrated to: http://www-zeuthen.desy.de/theory/research/zfitter/

The decision to do so was taken together with the original authors of the program. Since we did not want to change the list of authors in view of the long-standing history of the program, the idea to create a ZFITTER support
group was considered to be an appropriate way to handle the maintenance situation requiring permanent care about the program. The ZFITTER support group is composed of authors of ZFITTER version 6.21, long-term users of the program, and colleagues who contributed substantially to its present state. We hope that a kernel of us will stay with ZFITTER as long as the code is needed by the community.

A correct citation of the ZFITTER package will include reference [2], together with the present update.

2 Higher order QED corrections

Measurements at LEP1/SLC were performed in the vicinity of the $Z$ resonance so that many of the photonic corrections were suppressed. Cross sections at energies away from the $Z$ resonance peak have a much stronger dependence on higher order photonic corrections and their inclusion is of numerical importance at LEP2. Several improvements in this respect have been performed since ZFITTER version 6.21 and will be described in the following subsections. They have also been discussed in [6].

2.1 Second order initial state fermion pair corrections

Since ZFITTER version 6.21 there is an improved treatment of second order corrections for angular distributions and $A_{FB}$. These corrections were applied in the leading logarithmic approximation as described in Ref. [2]. The option is accessed by a new flag:

- \texttt{FBH0} = 0 – old treatment with photonic corrections only,
- \texttt{FBH0} = 1 – leading log fermion pair corrections are added.

The non-singlet and singlet fermion pair contributions to the electron (positron) structure function of [8] (see Eq. (11) in [9] and Eq. (47) in [8]) are used (with different options according to the values of the flags ISPP, IPFC and IPSC). They are directly added to the corresponding photonic contributions [10, 11], which are governed by the flag FUNA. For pair corrections in general, the new value of flag IPT0 = −1 is added. It allows to calculate pure virtual pair contributions separately. This option can be used for comparisons or in the case, when the contribution of real pair emission is taken from another program.
2.2 Second order initial state QED corrections with acceptance cuts

Since ZFITTER version 6.30, the second order initial state radiation (ISR) QED corrections in presence of angular cuts are improved [12]. A new option governed by a new flag FUNA is implemented, with:

FUNA=0 – old treatment,
FUNA=1 – new treatment.

The corrected treatment of these corrections takes the angular acceptance cuts ANG0, ANG1 into account. The corrections are relevant for the angular distribution and for the integrated forward-backward asymmetry. We use the leading logarithmic approximation by means of the electron structure function formalism [8,9]. In fact the differential angular distribution of the electron–positron annihilation process can be represented in a form analogous to that of the Drell–Yan process:

$$
\frac{d\sigma(s,c)}{dc} = \int_0^1 dx_1 D(x_1, L_e) \int_0^1 dx_2 D(x_2, L_e) \frac{d\hat{\sigma}(\hat{s}, \hat{c})}{d\hat{c}} J(\hat{s} - s'), \quad (2.1)
$$

with $c = \cos \vartheta$ and

$$
\hat{s} = x_1 x_2 s, \quad (2.2)
\hat{J} = \frac{4 x_1 x_2}{[x_1 + x_2 - c(x_1 - x_2)]^2}, \quad (2.3)
$$

where the structure functions $D(x_1, L_e)$ give the probability to find an electron (positron) with a reduced energy fraction $x_{1(2)}$ in the initial electron (positron). The Born–level annihilation cross section $d\sigma(\hat{s}, \hat{c})/d\hat{c}$ is defined in the center–of–mass reference frame of electron and positron with reduced energy fractions. The Jacobian $J$ is coming from the relation to the angles in the laboratory reference frame. The structure functions are taken in the leading logarithmic approximation keeping the first and second order photonic contributions:

$$
D(x, L_e) = \delta(1 - x) + \frac{\alpha}{2\pi}(L_e - 1)P^{(1)}(x) + \frac{1}{2} \left( \frac{\alpha}{2\pi}(L_e - 1) \right)^2 P^{(2)}(x), (2.4)
$$

with
\[ L_e \equiv \ln \frac{s}{m_e^2} \]  
\[ P^{(1)}(x) = \lim_{\Delta \to 0} \left\{ \delta(1 - x) \left( 2 \ln \Delta + \frac{3}{2} \right) + \Theta(1 - \Delta - x) \frac{1 + x^2}{1 - x} \right\}, \]  
\[ P^{(2)}(x) = \lim_{\Delta \to 0} \left\{ \delta(1 - x) \left[ \left( 2 \ln \Delta + \frac{3}{2} \right)^2 - \frac{2\pi^2}{3} \right] \right. 
+ \left. \Theta(1 - \Delta - x)2 \left[ \frac{1 + x^2}{1 - x} \left( 2 \ln(1 - x) - \ln x + \frac{3}{2} \right) \right. 
+ \left. \frac{1 + x}{2} \ln x - 1 + x \right]\right\}. \]  

In order to avoid a double counting, we expanded formula (2.1) in \( \alpha \) and take only the \( \mathcal{O}(\alpha^2) \) terms, which are then added to the full first order corrections. Where possible, we performed integrations over the angle and the energy fractions analytically. This allows to get a relatively fast code for these corrections. The calculation is realized with subroutine \texttt{funang.f}. It is compatible with the use of \texttt{ICUT} = 1,2,3. We just mention that for the contribution to the total cross section the complete \( \mathcal{O}(\alpha^2) \) formulae are used.

2.3 Higher order photonic corrections from the initial-final state interference

The exponentiation of photonic initial-final-state interference corrections was implemented according to Ref. [13]. It allows to take into account the most significant part of higher order corrections coming from the initial-final state interference. The corrections are relevant for the angular distribution and for the integrated forward-backward asymmetry. A combination of the one-loop initial-final interference corrections with the corresponding higher order effects from the exponentiation can be computed in \texttt{ZFITTER} by using flag \texttt{INTF} = 2. The old options are:
- \texttt{INTF} = 0: the initial-final state interference in photonic corrections is omitted;
- \texttt{INTF} = 1: the interference is taken in the one-loop approximation.

The numerical effect of the exponentiation was discussed in Ref. [6]. It was found to be close to the one obtained by a slightly different exponentiation procedure [14].

2.4 Final state fermion pair production corrections

Since \texttt{ZFITTER} version 6.30, the corrections from final state radiation (FSR) of fermion pairs are implemented [12], according to the formulae given in [15]. The option is governed by a new flag:
FSPP = 0 – without FSR pairs,
FSPP = 1 – with FSR pairs, additive,
FSPP = 2 – with FSR pairs, multiplicative.
For the best approximation, the FSR pair corrections should be treated mul-
tiplicative (FSPP = 2) with respect to the ISR photonic corrections (see Eq. (2.1)
in [12]). The additive treatment of FSR pairs (FSPP = 1) can be used for a
comparison. For the FSR corrections, a cut on the invariant mass of the sec-
dondary pair is accessible. In order to accommodate this cut value, the variable
SIPP of the
SUBROUTINE ZUCUTS(INDF, ICUT, ACOL, EMIN, S_PR, ANG0, ANG1, SIPP)
is now used. The dependence on this cut for realistic event selections was
shown to be rather weak [12]. Therefore, the meaning of variable SIPP has
been changed. Now it has nothing to do with cutting of the initial state pairs.
In fact, there is no possibility to directly cut the initial state secondary pairs.
The primary pair invariant mass cut (S_PR) is taken into account in the phase
space of secondary pairs.

3 Improved Born approximation for $e^+e^- \rightarrow \bar{\nu} \nu$ in ZFITTER version
6.34

For a study of the reaction

$$e^+e^- \rightarrow \bar{\nu}\nu(n\gamma), \quad \nu = \nu_e, \nu_\mu, \nu_\tau$$

one needs the effective Born approximation for

$$\frac{d\sigma}{d\cos \vartheta} = \sum_{t=e,\mu,\tau} \frac{d\sigma(e^+e^- \rightarrow \bar{\nu}_t\nu_t)}{d\cos \vartheta} = 3 \sigma_s + \sigma_{sl} + \sigma_t. \quad (3.2)$$

The specific property of this reaction is due to the interference of $s$ channel $Z$
boson and $t$ channel $W$ boson exchange for $\bar{\nu}_e\nu_e$ production. For an application
in KKMC [16], the corresponding formulae have been derived [17] from a
related study [18,19] and implemented in ZFITTER version 6.34 (05 Feb 2001).
The changes in the program consist of a modification of the weak charged
current form factor (variable ROW) in subroutine coscut in zfbib6_34.f. The
addition is \(^{1}\):

$$\delta_{cc-nc} = \text{QEDCC-QEDNC} = \frac{\alpha}{2\pi} Q_c^2 \left[ \frac{3}{2} \ln \frac{M_W^2}{s} + \frac{1}{2} \ln \frac{t}{s} - 4 \text{Li}_2(1) + \frac{1}{2} \ln \frac{t}{s} \right]. \quad (3.3)$$

\(^{1}\) In the Fortran code until version 6.42, the factor of 4 at the r.h.s. of Equation
(3.3) is lacking.
The variables SIGST and SIGT are influenced by this, they correspond to $\sigma_{st}$ and $\sigma_t$. Depending on the setting of flag ENUE there, part or all of them contribute to the prediction of $d\sigma / d\cos \theta$; see also Section B.2.

In ZFITTER version 6.42, the file zfbin6_34.f is replaced by zfbin6_40.f. The latter file contains a subroutine coscut where the described features are not accessible. The file zfEENN_34.f is no longer part of the distribution.

4 Atomic parity violation

The global precision tests of the Standard Model may include an experimental input from atomic parity violation measurements in heavy atoms. The observable quantity of interest is the so-called weak charge $Q_W$:

$$Q_W(Z, A) = -2 [2Z + N) C_{1u} + (Z + 2N) C_{1d}] . \quad (4.1)$$

Here, $Z$ and $N$ are the numbers of protons and neutrons in the nucleus. The weak couplings involved are those which parameterize the electron-quark parity-violating Hamiltonian at zero momentum transfer:

$$H_{PV} = \frac{G_F}{\sqrt{2}} (C_{1u} \bar{e} \gamma_\mu \gamma_5 \bar{u} \gamma_\mu u + C_{2u} \bar{e} \gamma_\mu \gamma_5 \bar{u} \gamma_\mu u + C_{1d} \bar{d} \gamma_\mu \gamma_5 \bar{\gamma}_\mu d \right) + C_{2d} \bar{d} \gamma_\mu \gamma_5 \bar{\gamma}_\mu d) . \quad (4.2)$$

In Born approximation, $C_{1u} = -\frac{1}{2} (1 - 8/3 \sin^2 \theta_W)$ and $C_{1d} = \frac{1}{2} (1 - 4/3 \sin^2 \theta_W)$; generally, $C_{1q} = 2a_{e\gamma q}$ and $C_{2q} = 2a_{\gamma q}$, $q = u, d$. In [20], using the results of [21], the higher order corrections to atomic parity violation in the on-mass-shell renormalization scheme have been derived and the corresponding expressions were used for ZFITTER version 6.34 (26 Jan 2001) onwards. The formulae given in [22] were also reproduced.

In subroutine ZU_APV the corresponding expressions for $C_{1u}, C_{1d}, C_{2u}, C_{2d}$ are calculated. In fact, the sign conventions have been changed compared to [20] in order to share the definitions of the particle data group \(^2\). A sample use is prepared with subroutine ZF_APV, with $N = 78$ and $Z = 55$ for Caesium. Flag TUPV may be used for a study of the theoretical uncertainty, the default value is TUPV=1.

\(^2\) We just mention that the signs of Equations (4) in [20] are not in accordance with Equation (3) there, while those of Equation (14) are.
5 Higher order electroweak corrections to Standard Model observables

In ZFITTER version 6.42, all known two- and three loop corrections of the Standard Model observables $M_w$, $\sin^2 \theta_{\text{eff}}$ and $\Gamma_z$ have consistently been included. The corresponding changes began with version 6.33, with subsequent additions until version 6.42. They are described to some detail in this section.

5.1 The W boson mass

ZFITTER, version 6.36 (21 July 2001), contained only the leading and next-to-leading corrections to $\Delta r$, obtained through an expansion in the heavy top quark mass. They were applied according to [23–28] and have been implemented in the package m2tcorn.f. The W boson mass was then evaluated with the relation:

$$ M_W = \frac{M_Z}{\sqrt{2}} \sqrt{1 + \frac{4\pi \alpha}{\sqrt{2} M_Z^2 G_F (1 - \Delta r)}}, \quad (5.1) $$

by an iterative procedure, since $\Delta r$ also depends on $M_W$. More accurate results on the electroweak corrections to muon decay, which successively appeared in [29–38], were found in terms of exact one-dimensional integral representations at the order $O(\alpha^2)$. However, since the computation of general two loop integrals is rather slow, only fitting formulas as published in [32,37] were implemented in ZFITTER. Furthermore, since typical resummation prescriptions for $\Delta r$ (see [39] and references therein) are problematic once the complete two-loop contributions are included, the new result has been directly applied to $M_W$.

With the option AMT4 = 5 the complete fermionic two loop corrections to the $W$ boson mass [32] are used. Here the fermionic corrections encompass all two-loop contributions with at least one closed fermion loop. In addition to electroweak corrections, this setting also includes the leading $O(\alpha\alpha_s)$ [40–46] and next-to-leading $O(\alpha_s^2)$ [47–49] QCD corrections. Contrary to the settings AMT4 \leq 4, the $O(\alpha_s^2)$ corrections are incorporated exactly according to [49]. Previously, only the leading term in $m_t^2$ was used.

The assignment AMT4 = 6, which is used from Summer 2004 onwards, enables the calculation of $M_W$ including complete (fermionic and bosonic) $O(\alpha^2)$ corrections [34,37], $O(\alpha\alpha_s)$ [40–46] and $O(\alpha_s^2)$ [49,50] QCD corrections, as well as leading three-loop corrections in an expansion in $m_t^2$ of order $O(\alpha^3)$ and $O(\alpha^2\alpha_s)$ [51]. These contributions were implemented into a fitting formula of the following form [37]:

14
\[ M_w = M_{w}^0 - c_1 dH - c_2 dH^2 + c_3 dH^4 + c_4 (dh - 1) - c_5 d\alpha + c_6 dt \]  
\[ - c_7 dt^2 - c_8 dh dt + c_9 dh dt - c_{10} d\alpha_s + c_{11} dZ, \]  
where
\[ dH = \log \left( \frac{M_{\mu}}{100 \text{ GeV}} \right), \quad dh = \left( \frac{M_{\mu}}{100 \text{ GeV}} \right)^2, \]
\[ dt = \left( \frac{m_t}{174.3 \text{ GeV}} \right)^2 - 1, \quad dZ = \frac{M_z}{91.1875 \text{ GeV}} - 1, \]  
\[ d\alpha = \frac{\Delta \alpha}{0.05907} - 1, \quad d\alpha_s = \frac{\alpha_s(M_z)}{0.119} - 1, \]  
and the coefficients \( M_{w}^0, c_1, \ldots, c_{11} \) take the following values
\[ M_{w}^0 = 80.3799 \text{ GeV}, \quad c_1 = 0.05429 \text{ GeV}, \quad c_2 = 0.008939 \text{ GeV}, \]
\[ c_3 = 0.0000890 \text{ GeV}, \quad c_4 = 0.000161 \text{ GeV}, \quad c_5 = 1.070 \text{ GeV}, \]
\[ c_6 = 0.5256 \text{ GeV}, \quad c_7 = 0.0678 \text{ GeV}, \quad c_8 = 0.00179 \text{ GeV}, \]
\[ c_9 = 0.0000659 \text{ GeV}, \quad c_{10} = 0.0737 \text{ GeV}, \quad c_{11} = 114.9 \text{ GeV}. \]  
(5.4)

With eq. (5.2) the full result for \( M_w \) is approximated to better than 0.5 MeV over the range of \( 10 \text{ GeV} \leq M_{\mu} \leq 1 \text{ TeV} \) if all other experimental input values vary within their combined 2\( \sigma \) region around the central values, as being used in eq. (5.3).

For the new options \( \text{AMT4} = 5, 6 \) the algorithm used by ZFITTER for the estimation of the theory error due to the calculation of \( M_w \), based on applying different resummation procedures (see eq. (2.104) of [2]) cannot be used anymore, since the next term in the \( m_t \) expansion, which is of order \( O(G_{\mu}^2 m_t^0 M_z^2) \), is now known exactly. In contrast, for these options the uncertainties from unknown higher order contributions in the calculation of \( M_w \) have been estimated in [32,37] and are set here to \( \pm 5 \text{ MeV} \) and \( \pm 4 \text{ MeV} \), respectively. They can be simulated by varying the flag DMWW between \( -1 \) and \( 1 \), which is the only relevant flag to simulate theoretical uncertainties for \( M_w \) for \( \text{AMT4} = 5, 6 \), whereas \( \text{EXPR}, \text{HIGS}, \text{HIG2}, \text{SCRE} \) and \( \text{SCAL} \) are ignored. Furthermore, the use of \( \text{AMT4} = 5, 6 \) is not compatible with the setting IMOMS > 1.

5.2 The effective leptonic weak mixing angle

The amplitude for the decay of the \( Z \) boson into a pair of fermions is parameterized in ZFITTER as:
\[ V_{\mu}^{Zff} \left( M_z^2 \right) = (i \cdot 2\pi)^4 i \sqrt{\sqrt{2} G_{\mu} M_z^2} \sqrt{p_f \cdot f^{(8)}_{\mu} \left[ (1 + \gamma_5) - 4 |Q_f| s_w^2 \kappa_{z_f} \right]}. \]  
(5.5)
This formula allows to define the effective weak mixing angle as:

\[ \sin^2 \theta^l_{\text{eff}} = \text{Re} \left( \kappa^l_z \right) s_w^2, \]

(5.6)

where the coefficients \( \rho^l_z \) and \( \kappa^l_z \) are called effective couplings of Z-decay.

Complete fermionic two-loop corrections to the leptonic effective weak mixing angle \( \sin^2 \theta^\text{lept}_{\text{eff}} \) \cite{52-54} are included with the option AMT4 = 6. They improve the realizations for AMT4 \( \leq 5 \) by including all electroweak two-loop contributions with at least one closed fermion loop and go beyond the leading \cite{55-58} and next-to-leading \cite{59} terms in an expansion in \( m_t^2 \). The corrections have been implemented directly using the numerical fitting formula as published in \cite{52}, thereby assuring a fast evaluation:

\[
\sin^2 \theta^\text{lept}_{\text{eff}} = s_0 + d_1 L_H + d_2 L_H^2 + d_3 L_H^4 + d_4 (\Delta_H^2 - 1) + d_5 \Delta_\alpha \\
+ d_6 \Delta_t + d_7 \Delta_t^2 + d_8 \Delta_t (\Delta_H - 1) + d_9 \Delta_\alpha_s + d_{10} \Delta_Z,
\]

(5.7)

with

\[ L_H = \log \left( \frac{M_H}{100 \, \text{GeV}} \right), \quad \Delta_H = \frac{M_H}{100 \, \text{GeV}}, \]

\[ \Delta_\alpha = \frac{\Delta \alpha}{0.05907} - 1, \quad \Delta_t = \left( \frac{m_t}{178.0 \, \text{GeV}} \right)^2 - 1, \]

\[ \Delta_\alpha_s = \frac{\alpha_s(M_Z)}{0.117} - 1, \quad \Delta_Z = \frac{M_Z}{91.1876 \, \text{GeV}} - 1, \]

(5.8)

and

\[ s_0 = 0.2312527, \quad d_1 = 4.729 \times 10^{-4}, \quad d_2 = 2.07 \times 10^{-5}, \]

\[ d_3 = 3.85 \times 10^{-6}, \quad d_4 = -1.85 \times 10^{-6}, \quad d_5 = 0.0207, \]

\[ d_6 = -0.002851, \quad d_7 = 1.82 \times 10^{-4}, \quad d_8 = -9.74 \times 10^{-6}, \]

\[ d_9 = 3.98 \times 10^{-4}, \quad d_{10} = -0.655. \]

(5.9)

In addition to the electroweak one- and two-loop corrections, this formula also includes two-loop \( \mathcal{O}(\alpha \alpha_s) \) \cite{40-46} and three-loop \( \mathcal{O}(\alpha \alpha_s^2) \) \cite{49,50} QCD corrections, as well as leading three-loop corrections in an expansion in \( m_t^2 \) of order \( \mathcal{O}(\alpha^3) \) and \( \mathcal{O}(\alpha^2 \alpha_s) \) \cite{51}. In contrast to the settings AMT4 < 6, the three-loop QCD corrections are incorporated exactly according to \cite{49}, which goes beyond the leading term in \( m_t^2 \) used previously. Equation (5.7) reproduces the exact calculation with maximal and average deviations of \( 4.5 \times 10^{-6} \) and \( 1.2 \times 10^{-6} \), respectively, as long as the input parameters stay within their \( 2\sigma \) ranges and the Higgs boson mass in the range \( 10 \, \text{GeV} \leq M_H \leq 1 \, \text{TeV} \).
With the new option $\text{AMT4} = 6$ the theory error in the calculation of $\sin^2 \theta^\text{lept}_\text{eff}$ is no longer obtained through different resummation formulas (see eq. (2.134) of [2]). Instead, the value of $\pm 4.9 \times 10^{-5}$, as estimated in [52], is used. For this case the theory uncertainty can be simulated by varying the flag $\text{DSWW}$ between $-1$ and $1$.

### 5.3 Partial and total $Z$ boson widths

The $Z$ boson decay width is defined through the effective couplings, $\kappa^l_z$ and $\rho^l_z$, of eq. (5.5). The form factor $\kappa^l_z$ is obtained from the effective weak mixing angle $\sin^2 \theta^\text{eff} \text{lept}$, as presented in subsection 5.2. For $Z$ boson decays into a pair of fermions $f$, $f \neq l$, the two-loop corrections to $\kappa^l_z$ are currently implemented in an approximate way only, while for $\Gamma(Z \to b\bar{b})$, no two-loop corrections beyond the leading $m^4$ term are available. For the form factor $\rho^l_z$, the two-loop corrections beyond the next-to-leading $m_t^2$ expansion are still missing. This quantity is therefore computed identically for the choices $\text{AMT4} = 4, 5, 6$.

### 5.4 Electroweak form factors for $e^+ e^- \to f \bar{f}$

The radiative corrections to the cross-sections and asymmetries for the process $e^+ e^- \to f \bar{f}$ are parameterized in ZFITTER by electroweak form factors, $\rho_{ef}, \kappa_e, \kappa_f$ and $\kappa_{ef}$, defined through a $Z$-boson exchange amplitude:

$$A_Z(s, t) = i e^2 4 \frac{f_f^{(3)} f_f^{(3)} \chi_Z(s)}{s} \rho_{ef}(s, t) \left\{ \gamma_\mu (1 + \gamma_5) \otimes \gamma_\mu (1 + \gamma_5) - 4 |Q_e| s^2 W^2 \kappa_e(s, t) \gamma_\mu (1 + \gamma_5) - 4 |Q_f| s^2 W^2 \kappa_f(s, t) \gamma_\mu (1 + \gamma_5) \otimes \gamma_\mu \right\},$$

$$+ 16 |Q_e Q_f| s^4 W^2 \kappa_{ef}(s, t) \gamma_\mu \otimes \gamma_\mu \right\}. \quad (5.10)$$

where

$$\chi_Z(s) = \frac{G_F M_Z^2}{\sqrt{2} 8 \pi \alpha} \frac{s}{s - m_Z^2}, \quad \text{and} \quad m_Z^2 = M_Z^2 - i M_Z \Gamma_Z(s). \quad (5.11)$$

In the leading pole approximation, the following relations hold:

$$\rho_{ef} = \sqrt{\rho^e_Z \rho^f_Z}, \quad \kappa_e = \kappa^e_Z, \quad \kappa_f = \kappa^f_Z, \quad \kappa_{ef} = \kappa^e_Z \kappa^f_Z. \quad (5.12)$$

However, generally, $\rho_{ef}$, $\kappa_e$, $\kappa_f$, and $\kappa_{ef}$ also include $\gamma-Z$ interference effects, corrections from non-resonant $Z$ and $\gamma$ exchanges, and non-factorizable box
contributions. With the option $\text{AMT4} = 6$ the coefficients $\kappa_c$ and $\kappa_f$, for $f \neq b$, are calculated with all known two- and three-loop effects, as discussed in the previous sections. The corresponding factorizable vertex corrections to $\kappa_{ef}$ are incorporated similarly. The electroweak box contributions to the form factors include the complete one-loop order correction, which is sufficient for present precision. For the form factor $\rho_{ef}$, complete two-loop corrections are still missing, and it is computed including two-loop corrections of the order $O(G^2_\mu m^2_t M^2_Z)$ only for all options $\text{AMT4} = 4, 5, 6$.

For the $Z \rightarrow b\bar{b}$ channel, no two-loop electroweak corrections beyond the leading $m^4_t$ terms are available so far. Furthermore, in ZFITTER versions before 6.42, a mismatch occurred in the treatment of the $b\bar{b}$ final state. The subroutine GDEGNL, which computes the leading two-loop corrections, is called at two places in the program: (i) in subroutine ZWRATE the effective couplings introduced in section 5.2 are used for the computation of $Z$ partial widths; (ii) the interfaces ZUTHSM, ZUTPSM, ZULRSM and ZUATSM, on the other hand, calculate the cross-sections and asymmetries from the weak form factors $\rho_{ef}(s,t)$, $\kappa_c(s,t)$, $\kappa_f(s,t)$ and $\kappa_{ef}(s,t)$ in the subroutine ROKANC. For $\text{INDF} = 9$, i.e. the $b\bar{b}$ final state, all these form factors were calculated in one-loop approximation with the leading $m^4_t$ two-loop term. As a result, in ROKANC the initial-state $Ze^+e^-$ form factors for all other final states are generated including next-to-leading two-loop corrections, while for the $b\bar{b}$ final state these corrections were missing. This mismatch also affects the ZFITTER interfaces ZUXSA, ZUTAU and ZUXSA2, which use the language of effective couplings [2], since they are defined to coincide as close as possible with the complete Standard Model prediction in ROKANC if the effective couplings coincide with their Standard Model analogue.

The problem has been alleviated since ZFITTER version 6.41 (15 October 2004). In contrast to the older implementations, $\kappa_c(s,t)$ and $\kappa_f(s,t)$ are not treated symmetrically anymore for $\text{INDF} = 9$, but two-loop electroweak corrections are included in $\kappa_c(s,t)$ for $\text{AMT4} \geq 4$, not yet in $\kappa_b(s,t)$. The treatment of $\rho_{ef}(s,t)$ and $\kappa_{ef}(s,t)$ has been changed accordingly. Here one can use the fact that the presently known two-loop contributions factorize into initial-state and final-state corrections. For a more detailed discussion see [60].

---

3 In ZFITTER version 6.41 an error occurred in the treatment of a form factor $\rho_{ef}(s,t)$. It affected the $b\bar{b}$ cross-section only, and was corrected in ZFITTER version 6.42.
6 Input parameters and pseudo observables

For the calculations of pseudo observables (POs), such as partial $Z$ decay widths or effective coupling constants, ZFITTER uses the DIZET package which calculates such quantities employing the on-mass-shell (OMS) renormalization scheme [61,62] within the Standard Model. The user has to provide a set of values for the so-called input parameter set, which are then used by ZFITTER and DIZET to calculate the POs. A standard set of input parameters is given by:

- The electromagnetic coupling constant at the $Z$ pole, or, more precisely, its shift due to the $5$-quark flavour hadronic vacuum polarisation, $\Delta\alpha_{\text{had}}^{(5)}$ at the $Z$ pole;
- The strong coupling constant at the $Z$ pole, $\alpha_{S}$;
- The pole masses of $Z$ boson, top quark and Higgs boson.

These variables are the main physics values to be provided to ZFITTER and DIZET by the user. The Fermi constant is treated as a constant in the program (see flag GFER). In order to use the user-supplied value of the hadronic vacuum polarisation, flag ALEM=2 must be used. In order to use the latest set of electroweak radiative corrections (see [37,52] and Section 5), flag AMT4=6 must be used.

Selected POs calculated by ZFITTER and DIZET are listed in Tab. 6.1, namely: (i) the $W$ boson mass and the on-shell electroweak mixing angle $s_{w}^{2} = 1 - M_{W}^{2}/M_{Z}^{2}$; (ii) the partial $Z$ decay widths, including the invisible width, simply equal to $3\Gamma_{\nu}$, and the total hadronic width, equal to the sum of the five-flavour quarkonic widths, and the total width; (iii) ratios of widths and pole cross-sections as used by, e.g., the LEP EWWG; (iv) the effective electroweak mixing angle $\sin^{2} \theta_{\text{eff}}^{f}$ according to Eq. (5.6) and the $\rho_{f}$ parameter $\rho_{f} = \text{Re}(\rho_{Z}^{f})$, for leptons and heavy fermions $b$ and $c$; and (v) the asymmetry parameter $A_{f}$ and the forward-backward pole asymmetries $A_{\nu_{f}}^{0}$ for leptons and heavy fermions $b$ and $c$.

The partial decay widths are defined inclusively, i.e., they contain all real and virtual corrections. The ratios for leptons $l$ and quarks $q$ are defined as:

$$R_{l}^{0} = \frac{\Gamma_{l}}{\Gamma_{h}}, \quad R_{q}^{0} = \frac{\Gamma_{q}}{\Gamma_{h}}, \quad (6.1)$$

while the hadronic and leptonic pole cross-sections are defined as:

$$\sigma_{h}^{0} = 12\pi \frac{\Gamma_{e}\Gamma_{h}}{M_{Z}^{2}\Gamma_{Z}^{2}}, \quad \sigma_{l}^{0} = 12\pi \frac{\Gamma_{e}\Gamma_{l}}{M_{Z}^{2}\Gamma_{Z}^{2}}. \quad (6.2)$$
The complex variable $g_Z^f$ is defined as the ratio:

$$g_Z^f = \frac{v_f}{a_f} = 1 - 4|Q_f|\kappa_Z^f s_w^2$$  \hspace{1cm} (6.3)

of the complex effective vector and axial couplings of the Z boson to the fermion $f$:

$$v_f = \sqrt{\rho_Z^f (T_3^f - 2Q_f\kappa_Z^f s_w^2)},$$  \hspace{1cm} (6.4)$$

$$a_f = \sqrt{\rho_Z^f T_3^f}.$$  \hspace{1cm} (6.5)

Hence one may write:

$$\text{Re}(g_Z^f) = 1 - 4|Q_f|\sin^2\theta_{\text{eff}}^f.$$  \hspace{1cm} (6.6)

The complex form factors $\rho_Z^f$, $\kappa_Z^f$ are defined through the amplitude of the Z boson decay into a pair of fermions, as in eq. (5.5).

With these definitions, the asymmetry parameters are then given in terms of the real part of $g_Z^f$:

$$A_f = 2 \frac{\text{Re} g_Z^f}{1 + \left(\text{Re} g_Z^f\right)^2}.$$  \hspace{1cm} (6.7)

The forward-backward pole asymmetries are mere combinations of these asymmetry parameters:

$$A_{\text{FB}}^o = \frac{3}{4} A_e A_f.$$  \hspace{1cm} (6.8)

In terms of the real part of the complex $\rho_Z^f$ parameter, $\rho_f = \text{Re}(\rho_Z^f)$, and the (real) effective electroweak mixing angle $\sin^2\theta_{\text{eff}}^f$ defined earlier, the real effective vector and axial-vector coupling constants as quoted by the LEP EWWG are then defined as:

$$g_{Af} = \sqrt{\rho_f T_3^f}$$  \hspace{1cm} (6.9)$$

$$g_{VF} = \sqrt{\rho_f (T_3^f - 2Q_f\sin^2\theta_{\text{eff}}^f)}.$$  \hspace{1cm} (6.10)

With these definitions, it follows that:

$$\frac{g_{VF}}{g_{Af}} = \text{Re}(g_Z^f),$$  \hspace{1cm} (6.11)

so that the asymmetry parameters are then equivalently given as:

$$A_f = 2 \frac{g_{VF}/g_{Af}}{1 + (g_{VF}/g_{Af})^2}.$$  \hspace{1cm} (6.12)
<table>
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<tr>
<th>Observable</th>
<th>Value</th>
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<td>$M_W$ [GeV]</td>
<td>80.3613</td>
<td>$R_t^0$</td>
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<td>$s_w^2$</td>
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<td>$\mathcal{A}_b$</td>
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<td>$R_c^0$</td>
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<td>$\mathcal{A}_c$</td>
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<td>$\Gamma_e$ [MeV]</td>
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<td>$\sigma_{b}^{\beta}$ [nb]</td>
<td>41.4826</td>
<td>$A_{FB}^{0b}$</td>
<td>0.016166</td>
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<tr>
<td>$\Gamma_\mu$ [MeV]</td>
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<td>$\rho_c$</td>
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<tr>
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<td>$\rho_b$</td>
<td>0.993943</td>
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<tr>
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<td>$\rho_c$</td>
<td>1.005860</td>
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</table>

Table 6.1
Predictions for pseudo observables calculated with ZFITTER and DIZET for $\Delta \alpha_{\text{had}}^{(5)} = 0.02758$, $\alpha_s = 0.118$, $M_Z = 91.1875$ GeV, $M_t = 175$ GeV and $M_H = 150$ GeV, and flags ALEM=2 and AMT4=6.

6.1 Pseudo observables in common blocks of DIZET

The channel dependent quantities are stored in common block COMMON/CDZRKZ/ and in array PARTZ(0:11):

```
COMMON/CDZRKZ/AROFZ(0:10),ARKAFZ(0:10),ARVEFZ(0:10),ARSEFZ(0:10)
&
  ,AROTFZ(0:10),AIROFZ(0:10),AIKAFZ(0:10),AIVEFZ(0:10)
*---
DIMENSION NPAR(25),ZPAR(30),PARTZ(0:11),PARTW(3)
*---
SUBROUTINE DIZET(NPAR,AMW ! NPAR : FLAGS; AMW : INPUT/OUTPUT
&
  ,AMZ,AMT,AMH,DALSH,V_TBA,ALSTR ! INPUT
&
  ,ALQED,ALSTRT,ZPAR,PARTZ,PARTW) ! OUTPUT
```

The correspondences have not been changed compared to Section 2.5.1 of [2]:

21
ARROFZ(0:10) = (ρ_z^f)', (6.13)
AROTFZ(0:10) = Re ρ_z^f, (6.14)
ARKAFZ(0:10) = Re κ_z^f, (6.15)
ARVEFZ(0:10) = Re g_z^f, (6.16)
AIROFZ(0:10) = Im ρ_z^f, (6.17)
AIKAFZ(0:10) = Im κ_z^f, (6.18)
AIVEFZ(0:10) = Im g_z^f, (6.19)
ARSEFZ(0:10) = sin^2 θ_{eff}, (6.20)
PARTZ(0:11) = Γ_f, (6.21)

The usual ZFITTER channel assignments as given in Figure 5 of [2] are used, and all quantities but (ρ_z^f)' have been introduced already. The (ρ_z^f)' is discussed in Section 2.5.1 of [2]. We mention also here that both options MISC=1.0 (with (ρ_z^f)' or with |ρ_z^f|) are used in the Model Independent interfaces of ZFITTER, see Appendix C.

Note that since the convention of the LEP EWWG is to use the real parameter ρ_f = Re(ρ_z^f), not (ρ_z^f)', the array AROTFS is generally used, while ARROFZ, RENFAC and SRENFAC are usually ignored.

7 Subroutine ZFTEST

The ZFITTER distribution includes subroutine ZFTEST. With ZFTEST the user may test whether ZFITTER has been properly installed. The subroutine calculates cross-sections and asymmetries as functions of √s near the Z peak, below, and above. A sample file zfmai6_42.f runs ZFTEST:

* MAIN to call ZFTEST with version 6.42
* CALL ZFTEST(0)
END

The numerical output should reproduce the Tables given in Subsection 7.1.

7.1 ZFTEST results

This Section contains the standard test-outputs, produced by a call to ZFTEST(0). The argument of ZFTEST sets the flag MISC. The default value is MISC=0. The
user’s result should be identical to the sample output, apart from a possible flip in the last digit.
**************************
*** This is FITTTER ver#4 6.43 ***
*** 05/04/18   ***
**************************
*** http://www.ifn.it/3vacapo/biblior.html ***

UNIT= FITTTER default=:

FITTTER fit= value=:
AFCR: 1; SCA: 0; SCR: 0; AMT: 4; BURH: 0
BHRB: 1; CONR: 1; FHRB: 1; FRET: 3; CAMR: 1
DIAG: 1; DSTR: 1; BASS: 3; PSTR: 0; MVR: 1
FINR: 0; ALXR: 3; QCQCR: 3; VMPL: 1; WEAK: 1
PTFR: 1; PARR: 0; NMPR: 0; MTN: 0; AMT: 3
CRAK: 1; PREC: 10; HUC: 0; ALER: 0; CPER: 2
IBHP: 2; FERS: 1; HCD: 0; MZD: 1; DPC: 5
IVBC: 0; IDTC: 3; FBHC: 0; FERS: 0; FLA: 0
ASCR: 1; SFEP: 1; FERF: 1; DMAR: 0
DSW: 0

FITTTER init parameters:
DAKX = 0.02800388693
ALQEM = 128.866183
BNAG = 81.187607; TNAG = 178.0000
MMAG = 100.0000
DAK = 0.0304; ALQEM = 128.866183
AINAG = 0.11700; AFINAG = 0.15679
FITTTER intermediate results:
VMAS = 80.30957; SD72 = 0.2270
ALQEM = 0.11700;
QCQCR = 1.00000; 1.03928; 1.04639; 1.03877; 1.03177; 1.03941; 1.04681; 1.03877; 1.03838; 1.04639; 1.03897; 1.03936-0.00003 0.19883

Michael  With  REL. F.N.  REL. F.T  S/N eff
--------  -------  --------  ---------  ---------
A 167.399 1.008646 1.008646 0.231036
B 94.037 1.007999 1.005849 0.231417
C 83.947 1.007999 1.005849 0.231417
D 300.128 1.006890 1.006833 0.231310
E 383.033 1.007854 1.007806 0.231813
F 383.033 1.007854 1.007806 0.231813
G 0.000 0.000000 0.000000 0.000000
H 375.593 0.993858 0.993858 0.232004
I 1741.064
total 5495.694
$$s^2_\text{QT}(S) = 0.1879929$$

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8 Summary

The description of the ZFITTER package has been updated to version 6.42. Besides a short introduction to the physics contents of the program additions, we reproduce, in Appendices, also the technical details like user flags and interface subroutines as complete as necessary for a convenient use of the program.

ZFITTER covers most of the radiative corrections of a practical relevance in the foreseeable future. Yet, several corrections are still needed to close the two loop program of data analysis with ZFITTER:

- cross section (or decay rate) asymmetries, with the $Z$ boson coupling to light quarks or $b$ quarks;
- electroweak corrections to the $Z$ boson width;
- bosonic electroweak corrections to all asymmetries and the effective weak mixing angle.

The inclusion of the two loop electroweak corrections to the $Zb\bar{b}$ vertex will additionally require to account for the mass of the $b$ quark in the one loop electroweak corrections. Nonetheless, it was checked that the one loop corrections with a massive $b$ quark would give negligible effects for the accuracy reached at LEP.

Some bug reports concerning ZFITTER versions between version 6.21 and version 6.42 will be found at the webpage [3].

Acknowledgements

For many years, the support of the user community of ZFITTER by the authors of the program was substantial for the numerous applications of the program by the LEP collaborations, the LEP EWWG (LEP Electroweak Working Group), and many other user groups.

We greatly appreciate the readiness of those authors of ZFITTER who decided not to join the ZFITTER support group, Dima Bardin, Pena Christova, Mark Jack, Lida Kalinovskaya, Alexandre Olshesvki, to transfer the support of the program with full responsibility to the ZFITTER support group, thus allowing the program to survive in a rapidly changing physics world.

We would like to thank Georg Weiglein for discussions.

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A DIZET user guide

This Appendix describes technical details of the DIZET package. Not all of them have been influenced by the updates over the years. For the convenience of the user, we nevertheless decided to give a complete overview and will repeat a substantial part of the material, which was already presented in Section 4.1 of [2].

A.1 Structure of DIZET

A first call of subroutine DIZET returns various pseudo-observables, the W-boson mass, weak mixing angles, the Z-boson width, the W-boson width and other quantities. After the first call to DIZET, several subroutines of DIZET might be used for the calculation of form factors and couplings. This is described in Section 4.1.1 of [2].

A.2 Input and output of DIZET

The DIZET argument list contains Input, Output and Mixed (I/O) types of arguments:

```
CALL DIZET(NPAR,AMW,AMZ,AMT,AMH,DALSH,ALQED,ALSTR,ALSTR,TPAR,PARTZ,PARTW)
```

A.2.1 Input and I/O parameters to be set by the user

Input:

- `NPAR(1:25)`, INTEGER*4 vector of flags
- `AMT = m_t - t-quark mass`
\[ \text{AMH} = M_H - \text{Higgs boson mass} \]
\[ \text{ALSTR} = \alpha_s(M_Z^2) - \text{strong coupling at } s = M_Z^2 \]

**I/O:**

\[ \text{AMW} = M_W, \ W \text{ boson mass, input if NPAR(4) = 2,3, but is being calculated for NPAR(4) = 1} \]
\[ \text{AMZ} = M_Z, \ Z \text{ boson mass, input if NPAR(4) = 1,3, but is being calculated for NPAR(4) = 2} \]
\[ \text{DAL5H} = \Delta \alpha_h^5(M_Z^2), \text{ hadronic vacuum polarization} \]

The \( M_Z^2, M_W^2, \) and \( \Delta \alpha_h^5(M_Z^2) \) cannot be assigned by a parameter statement (input/output variables).

### A.2.2 Output of the DIZET package

\[ \text{ALQED} = \alpha(M_Z^2), \text{ calculated from } \Delta \alpha_h^5(M_Z^2), \text{ see description of flag ALEM in Subsection A.3} \]
\[ \text{ALSTRT} = \alpha_s(m_Z^2) \]
\[ \text{ZPAR(1) = DR} = \Delta r, \text{ the loop corrections to the muon decay constant} \]
\[ \text{ZPAR(2) = DRREM} = \Delta r_{\text{rem}}, \text{ the remainder contribution } \mathcal{O}(\alpha) \]
\[ \text{ZPAR(3) = SW2} = s_w^2, \text{ squared of sine of the weak mixing angle defined by weak boson masses} \]
\[ \text{ZPAR(4) = GMUC} = G_\mu, \text{ muon decay constant, if NPAR(4) = 1,2, is set in CONST1 depending on flag NPAR(20), see Subsection A.3. (It should be calculated if NPAR(4)=3 from } M_Z, M_W, \text{ but then it will deviate from the experimental value.)} \]
\[ \text{ZPAR(5–14)} \ - \text{ stores effective sines for all partial Z-decay channels:} \]
- 5 - neutrino
- 6 - electron
- 7 - muon
- 8 - \( \tau \) lepton
- 9 - up quark
- 10 - down quark
- 11 - charm quark
- 12 - strange quark
- 13 - top quark (presently equal to up quark)
- 14 - bottom quark
\[ \text{ZPAR(15) = ALPHST} \equiv \alpha_s(M_Z^2) \]
\[ \text{ZPAR(16–30)} = \text{QCDCOR(0–14), QCDCOR(I)} \ - \text{ array of QCD correction factors for quark production processes and/or } Z \text{ boson partial width (channel } i) \]
into quarks. Enumeration as follows:
\[
\begin{align*}
\text{QCD\text{COR}(0)} &= 1 \\
\text{QCD\text{COR}(1)} &= R_\nu^\mu(M_Z^2) \\
\text{QCD\text{COR}(2)} &= R_\nu^\mu(M_Z^2) \\
\text{QCD\text{COR}(3)} &= R_\ell^\mu(M_Z^2) \\
\text{QCD\text{COR}(4)} &= R_\ell^\mu(M_Z^2) \\
\text{QCD\text{COR}(5)} &= R_\nu^\mu(M_Z^2) \\
\text{QCD\text{COR}(6)} &= R_\ell^\mu(M_Z^2) \\
\text{QCD\text{COR}(7)} &= R_\ell^\mu(M_Z^2) \\
\text{QCD\text{COR}(8)} &= R_\ell^\mu(M_Z^2) \\
\text{QCD\text{COR}(9)} &= R_\nu^\mu(M_Z^2) \text{ foreseen for } \bar{t}\bar{t}-\text{channel} \\
\text{QCD\text{COR}(10)} &= R_\ell^\mu(M_Z^2) \text{ foreseen for } \bar{t}\bar{t}-\text{channel} \\
\text{QCD\text{COR}(11)} &= R_\ell^\mu(M_Z^2) \\
\text{QCD\text{COR}(12)} &= R_\ell^\mu(M_Z^2) \\
\text{QCD\text{COR}(13)} &= R_\ell^\mu-\text{singlet vector correction} \\
\text{QCD\text{COR}(14)} &= f_1, \text{ corrections to } A_{FB} \ [63]
\end{align*}
\]

\textbf{PARTZ(I)} – array of partial decay widths of the Z-boson:
\begin{itemize}
  \item I = 0 neutrino
  \item I = 1 electron
  \item I = 2 muon
  \item I = 3 tau
  \item I = 4 up
  \item I = 5 down
  \item I = 6 charm
  \item I = 7 strange
  \item I = 8 top (foreseen, not realized)
  \item I = 9 bottom
  \item I = 10 hadrons
  \item I = 11 total
\end{itemize}

\textbf{PARTW(I)} – array of partial decay widths of the W-boson \(^4\) for the channels:
\begin{itemize}
  \item I = 1 one leptonic
  \item I = 2 one quarkonic
  \item I = 3 total
\end{itemize}

\textbf{A.3 The flags used by DIZET}

Since the DIZET package may be used as stand-alone in order to compute POs we present here a short description of all flags in DIZET. The flag values

\(^4\) The calculation of the W width [64] follows the same principles as that of the Z width and is realized in subroutine \textbf{ZW RATE} of DIZET. Since the W width is not that important for the description of fermion pair production, we do not go into details.
must be filled in vector \textbf{NPAR}(1:25) by the user. Most of these flags overlap with the flags set in user subroutine \textbf{ZUFLAG} called by \textbf{ZFITTER}, however, in the stand-alone mode \textbf{ZUFLAG} need not be called. We will show the correspondence between the flag names \textbf{CHFLAG} and the flag values \textbf{IVALUE} used inside \textbf{DIZET}, called with
\begin{verbatim}
CALL ZUFLAG('CHFLAG', IVALUE).
\end{verbatim}

The description is given in the order of the vector \textbf{NPAR}(1:25). Flag values marked as \textbf{presently not supported} are not recommended. For instance, they may be chosen for backward compatibility with respect to earlier versions of the code.

\textbf{NPAR}(1) = \textbf{IHVP} \rightarrow \textbf{ZUFLAG}('VPOL', \textbf{IHVP}) – Handling of hadronic vacuum polarization:
\begin{itemize}
  \item \textbf{IHVP} = 1 (default) by the parameterization of [65]
  \item \textbf{IHVP} = 2 by effective quark masses of [66,67] \textbf{presently not supported}
  \item \textbf{IHVP} = 3 by the parameterization of [68] \textbf{supported}
\end{itemize}

\textbf{NPAR}(2) = \textbf{IAMT4} \rightarrow \textbf{ZUFLAG}('AMT4', \textbf{IAMT4}) – Re-summation of the leading \( \mathcal{O}(G_\mu m_t^2) \) electroweak corrections, see Section 5:
\begin{itemize}
  \item \textbf{IAMT4} = 0 \textbf{no re-summation}
  \item \textbf{IAMT4} = 1 with re-summation recipe of [69] \textbf{presently supported}
  \item \textbf{IAMT4} = 2 with re-summation recipe of [43] \textbf{not supported}
  \item \textbf{IAMT4} = 3 with re-summation recipe of [70] \textbf{supported}
  \item \textbf{IAMT4} = 4 (default) with two-loop sub-leading corrections and re-summation recipe of [23–28]
  \item \textbf{IAMT4} = 5 with fermionic two-loop corrections to \( M_W \) according to [29,30,32]
  \item \textbf{IAMT4} = 6 with complete two-loop corrections to \( M_W \) [37] and fermionic two-loop corrections to \( \sin^2 \theta_{\text{eff}} \) [52]
\end{itemize}

\textbf{NPAR}(3) = \textbf{IQCD} \rightarrow \textbf{ZUFLAG}('QCDC', \textbf{IQCD}) – Handling of internal QCD corrections of order \( \mathcal{O}(\alpha_s) \):
\begin{itemize}
  \item \textbf{IQCD} = 0 \textbf{no internal QCD corrections}
  \item \textbf{IQCD} = 1 by Taylor expansions (fast option) of [71]
  \item \textbf{IQCD} = 2 by exact formulae of [71]
  \item \textbf{IQCD} = 3 (default) by exact formulae of [42]
\end{itemize}

\textbf{NPAR}(4) = \textbf{IMOMS} – Choice of two input/output parameters from the three parameters \( \{G_\mu, M_z, M_W\} \):
\begin{itemize}
  \item \textbf{IMOMS} = 1 (default) input \( G_\mu, M_z \); output \( M_W \), see Eq. (5.1)
  \item \textbf{IMOMS} = 2 input \( G_\mu, M_W \); output \( M_z \), \textbf{foreseen, not realized}
  \item \textbf{IMOMS} = 3 input \( M_z, M_W \); output \( G_\mu \), \textbf{foreseen, not realized}
\end{itemize}

\textbf{NPAR}(5) = \textbf{IMASS} – Handling of hadronic vacuum polarization in \( \Delta r \); for tests only:
IMASS = 0 (default) uses a fit to data
IMASS = 1 uses effective quark masses

\textbf{NPAR(6) = ISCRE \rightarrow ZUFLAG(\textasciitilde SCRE}, ISCRE) – Choice of the scale of the two-loop remainder terms of $\Delta r$ with the aid of a conversion factor $f$, for details see [2].

\begin{itemize}
  \item ISCRE = 0 (default) scale of the remainder terms is $K_{\text{scale}} = 1$
  \item ISCRE = 1 scale of the remainder terms is $K_{\text{scale}} = f^2$
  \item ISCRE = 2 scale of the remainder terms is $K_{\text{scale}} = \frac{1}{f^2}$
\end{itemize}

\textbf{NPAR(7) = IALEM \rightarrow ZUFLAG(\textasciitilde ALEM}, IALEM) – Controls the usage of $\alpha(M_Z^2)$, see flowchart in [2]. Inside DIZET, however, its meaning is limited:

\begin{itemize}
  \item IALEM = 0 or 2 $\Delta \alpha_s^{(5)}(M_Z^2)$ must be supplied by the user as input to the DIZET package
  \item IALEM = 1 or 3 $\Delta \alpha_s^{(5)}(M_Z^2)$ is calculated by the program using a parameterization IHPV (default: IALEM=3)
\end{itemize}

For details see the complete discussion about this flag in Sections 2.8 and 4.2.2 of [2].

\textbf{NPAR(8) = IMASK – Historical relict of earlier versions. Presently unused.}

\textbf{NPAR(9) = ISCAL \rightarrow ZUFLAG(\textasciitilde SCAL}, ISCAL) – Choice of the scale of $\alpha_s(\xi m_t)$:

\begin{itemize}
  \item ISCAL = 0 (default) exact AFMT correction [47]
  \item ISCAL = 1,2,3 options used in [72], \textbf{presently not supported}
  \item ISCAL = 4 Sirlin’s scale $\xi = 0.248$ [73]
\end{itemize}

\textbf{NPAR(10) = IBARB \rightarrow ZUFLAG(\textasciitilde BARB}, IBARB) – Handling of leading $O\left(G_\mu^2 m_t^4\right)$ corrections:

\begin{itemize}
  \item IBARB = 0 corrections are not included
  \item IBARB = 1 corrections are applied in the limiting case: Higgs mass negligible with respect to the top mass, [74]
  \item IBARB = 2 (default) analytic results of [75] approximated by a polynomial [76]
\end{itemize}

These options are inactive for AMT4 = 4.

\textbf{NPAR(11) = IFTJR \rightarrow ZUFLAG(\textasciitilde FTJR}, IFTJR) – Treatment of $O(G_\mu \alpha_s m_t^2)$ FTJR corrections [77],

\begin{itemize}
  \item IFTJR = 0 without FTJR corrections
  \item IFTJR = 1,2 with FTJR corrections (default IFTJR=1)
\end{itemize}

Inside DIZET its meaning is limited. See complete discussion about this flag in [2].

\textbf{NPAR(12) = IFACR \rightarrow ZUFLAG(\textasciitilde EXPR}, IFACR) – Realizes different expan-
sions of $\Delta r$ [26, 59]:

- **IFACR = 0** (default) realizes the so-called OMS-I renormalization scheme
- **IFACR = 1** intermediate step from OMS-I to OMS-II renormalization scheme
- **IFACR = 2** approaches the spirit of the OMS-II renormalization scheme, a fully expanded option

- **NPAR(13) = IFACT → ZUFLAG('EXPF', IFACT)** – To simulate theoretical uncertainties different expansions of the formfactors $\rho$ and $\kappa$ are realized in complete analogy to the flag IFACR:
  - **IFACT = 0** (default) OMS-I renormalization scheme
  - **IFACT = 1** intermediate step from OMS-I to OMS-II renormalization scheme
  - **IFACT = 2** approaches the OMS-II renormalization scheme

- **NPAR(14) = IHIGS → ZUFLAG('HIGS', IHIGS)** – Switch on/off resummation of the leading Higgs contribution:
  - **IHIGS = 0** (default) leading Higgs contribution is not re-summmed
  - **IHIGS = 1** leading Higgs contribution is re-summmed

- **NPAR(15) = IAFMT → ZUFLAG('AFMT', IAFMT)** – Includes the three-loop corrections $\Delta^{(2)}_{\text{AFMT}} \sim \delta^{\alpha_s}$ [47] (see also description of flag SCAL):
  - **IAFMT = 0** without AFMT correction
  - **IAFMT = 1** correction $O(G_f m^2 \alpha_s^2)$ is included
  - **IAFMT = 2** corrections $O(G_f m^2 \alpha_s^2)$ and $O(G_f M_2^2 \alpha_s^2 + \log(m_t^2))$ are included
  - **IAFMT = 3** (default) corrections $O(G_f m^2 \alpha_s^2)$, $O(G_f M_2^2 \alpha_s^2 + \log(m_t^2))$ and $O(G_f M_2^2 / m_t^2 \alpha_s^2)$ are included

- **NPAR(16) = IEWLC** – Treatment of the remainder terms of $\rho$ and $\kappa$ (used in ROKAPP together with obsolete option AMT4 = 1-3):
  - **IEWLC = 0** all remainders are set equal to zero
  - **IEWLC = 1** (default) standard treatment

- **NPAR(17) = ICZAK → ZUFLAG('CZAK', ICZAK)** – Treatment of the CKHSS non-factorizable $O(\alpha_s)$ corrections $\Delta_{\text{EW/QCD}}$ to the quarkonic width, $\Gamma_q$ [78, 79]:
  - **ICZAK = 0** without CKHSS corrections
  - **ICZAK = 1** (default) with CKHSS corrections
  - **ICZAK = 2** with CKHSS for pseudoobservables and without CKHSS in case of realistic observables

Inside the weak library DIZET the meaning of ICZAK is limited. See also discussion about this flag in Subsection B.2.

- **NPAR(18) = IHIG2 → ZUFLAG('HIG2', IHIG2)** – Handling of the quadratically enhanced two-loop Higgs contributions to $\Delta r$ [80, 81]:
  - **IHIG2 = 0** without Higgs corrections

33
IHIG2 = 1 with Higgs corrections

\[ \text{NPAR}(19) = \text{IALE2} \rightarrow \text{ZUFLAG('ALE2', IALE2) - Treatment of leptonic corrections to } \Delta \alpha: \]
\[ \text{IALE2} = 0 \text{ for backward compatibility with versions up to v.5.12} \]
\[ \text{IALE2} = 1 \text{ with one-loop corrections} \]
\[ \text{IALE2} = 2 \text{ with two-loop corrections [82]} \]
\[ \text{IALE2} = 3 \text{ (default) with three-loop corrections [83]} \]

\[ \text{NPAR}(20) = \text{IGFER} \rightarrow \text{ZUFLAG('GFER', IGFER) - Handling of QED corrections to the Fermi constant:} \]
\[ \text{IGFER} = 0 \text{ for backward compatibility with versions up to v.5.12} \]
\[ \text{IGFER} = 1 \text{ one-loop QED corrections for Fermi constant [84–86]} \]
\[ \text{IGFER} = 2 \text{ two-loop QED corrections for Fermi constant [87,88]} \]

\[ \text{NPAR}(21) = \text{IDDZZ - Used in ZWRATE for internal tests:} \]
\[ \text{IDDZZ} = 0 \text{ RQCDV(A) are set to 0} \]
\[ \text{IDDZZ} = 1 \text{ (default) standard treatment of FSR QCD corrections} \]

\[ \text{NPAR}(22) = \text{IAMW2} \rightarrow \text{ZUFLAG('AMW2', IAMW2) - incorporates the fermionic two-loop contributions to the prediction for the W boson mass [29,30,32]:} \]
\[ \text{IAMW2} = 0 \text{ (default) no two-loop corrections to } M_W \]
\[ \text{IAMW2} = 1 \text{ with two-loop corrections to } M_W \]

\[ \text{NPAR}(23) = \text{ISFSR} \rightarrow \text{ZUFLAG('SFSR', ISFSR) - allows to switch the final state radiation} \]
\[ \text{ISFSR} = -1 \text{ both, QED and QED } \otimes \text{QCD final state radiation are excluded} \]
\[ \text{ISFSR} = 0 \text{ final state QED radiation is excluded, QED } \otimes \text{QCD is included} \]
\[ \text{ISFSR} = 1 \text{ (default) both, QED and QED } \otimes \text{QCD final state radiation are included} \]

\[ \text{NPAR}(24) = \text{IDMWW} \rightarrow \text{ZUFLAG('DMWW', IDMWW) - Simulation of the theoretical error on } M_W \text{ for AMT4 = 5,6:} \]
\[ \text{IDMWW} = -1 \text{ minimal value for } M_W \]
\[ \text{IDMWW} = 0 \text{ (default) no shift on } M_W \text{ applied} \]
\[ \text{IDMWW} = 1 \text{ maximal value for } M_W \]

\[ \text{NPAR}(25) = \text{IDSWW} \rightarrow \text{ZUFLAG('DSWW', IDSWW) - Simulation of the theoretical error on } \sin^2 \theta_{\text{eff}}^{\text{opt}} \text{ for AMT4 = 6:} \]
\[ \text{IDSWW} = -1 \text{ minimal value for } \sin^2 \theta_{\text{eff}}^{\text{opt}} \]
\[ \text{IDSWW} = 0 \text{ (default) no shift on } \sin^2 \theta_{\text{eff}}^{\text{opt}} \text{ applied} \]
\[ \text{IDSWW} = 1 \text{ maximal value for } \sin^2 \theta_{\text{eff}}^{\text{opt}} \]
A.4 Calculation of $\alpha(s)$. Function XFOTF3

the running QED coupling at scale $s$ is calculated with function XFOTF3 as follows:

\[
\alpha(s) = \frac{\alpha}{1 - \frac{\alpha}{4\pi} \text{DREAL}(\text{XFOTF3}(\text{IALEM}, \text{IALE2}, \text{IHVP}, \text{IQCD}, 1, \text{DAL5H}, -S))}. 
\]

(A.2)

B ZFITTER user guide

This Appendix describes technical details of the ZFITTER package. Not all of them have been influenced by the updates over the years. For the convenience of the user, we nevertheless decided to give a complete overview and will repeat a substantial part of the material, which was already presented in Section 4.2 of [2].

ZFITTER is coded in FORTRAN 77. Double-precision variables have been used throughout the program. The package consists of the following FORTRAN files:

zf630_aux.f  
zfbib6_40.f  
zfmai6_42.f  
zfusr6_42.f  
aco16_1p.f  
bcqcdl5_14.f  
bhang4_640.f  
bkqcdl5_14.f  
dizet6_42.f  
expifi6_30.f  
funang6_30.f  
m2tcor5_11.f  
pairho6_40.f  
APV_lib.f
The following routines are normally called in the initialization phase of programs using the ZFITTER package in the order listed below: ZINIT, ZIFLAG, ZUWEAK, ZUCUTS, ZUINFO. An example of different use is described in Section 2.5 of [2].

B.1 Subroutine ZINIT

Subroutine ZINIT is used to initialize variables with their default values. This routine must be called before any other ZFITTER routine.

CALL ZINIT

B.2 Subroutine ZIFLAG

Subroutine ZIFLAG is used to modify the default values of flags which control various ZFITTER options.

CALL ZIFLAG(CHFLAG,IVALUE)

Input Arguments:

CHFLAG is the character identifier of a ZFITTER flag.
IVALUE is the value of the flag. See Tab. C.2 for a list of the defaults.

Possible combinations of CHFLAG and IVALUE are listed below:

In Tab. C.2 an overview over all flags used in DIZET and ZFITTER is given. The DIZET flags (vector NPAR(1:25) in DIZET corresponds to NPARD(1:25) in ZFITTER) are described in Subsection A.

AFBC – Controls the calculation of the forward backward asymmetry for interfaces ZUTHSM, ZUXSA, ZUXSA2, and ZUXAFB:

IVALUE = 0 asymmetry calculation is inhibited (can speed up the program if asymmetries are not desired)

5 It is worth noting that not for all flags the default value is necessarily the preferred value. A typical example is flag FINR, distinguishing two different treatments of FSR, which are relevant in different experimental setups.
IVALUE = 1 (default) both cross-section and asymmetry calculations are done

AFMT – see NPAR(15) in subsection A.3

ALEM – Controls the treatment of the running QED coupling $\alpha(s)$:
ivalue = 0 or 2 $\Delta \alpha_h^{(5)}(M_Z^2)$ must be supplied by the user as input to the
DIZET package; using this input DIZET calculates ALQED = $\alpha(M_Z^2)$
ivalue = 1 or 3 $\Delta \alpha_h^{(5)}(M_Z^2)$ and $\alpha(M_Z^2)$ are calculated by the program
using a parameterization IHVP.

The scale of $\alpha$(scale) is governed in addition by the flag CONV, see description
below and the flowchart, Figure 6 of [2]. Values ALEM = 0,1 are accessible
only at CONV = 0. Then for ALEM = 0,1 $\alpha(M_Z^2)$ and for ALEM = 2,3 $\alpha(s)$ are
calculated. Values ALEM = 2,3 are accessible for CONV = 0,1,2. Then for CONV
= 0 $\alpha(s)$ and for CONV = 1,2 $\alpha(s')$ are calculated. Recommended values: ALEM
= 2,3.

ALE2 – see NPAR(19) in subsection A.3

AMT4 – see NPAR(2) in subsection A.3

ASCR – is a hidden flag that handles the treatment of contributions to $A_{FB}$:
ivalue = 0 treatment as in versions 5 up to version 6.23
ivalue = 1 (default) new (and very old) treatment

BARB – see NPAR(10) in subsection A.3

BORN – Controls calculation of QED and Born observables:
ivalue = 0 (default) QED convoluted observables
ivalue = 1 electroweak observables corrected by Improved Born Approx-
imation

BOXD – Determines calculation of ZZ and WW box contributions, (see Section
3.3.2 of [2]):
ivalue = 0 no box contributions are calculated
ivalue = 1 (default) the boxes are calculated as additive separate contrib-
tion to the cross-section
ivalue = 2 box contributions are added to all four form factors

CONV – Controls the energy scale of running $\alpha$ and EWRC, see Figure 6 of [2]:
ivalue = 0 $\alpha(s)$
ivalue = 1 (default) $\alpha(s')$ convoluted
ivalue = 2 both electroweak radiative correction and $\alpha_s$ are convoluted

CZAK – Treatment of CKHSS non-factorized corrections, [78], [79], see Figure
6 of [2]:
IVALUE = 0 without CKHSS corrections
IVALUE = 1 (default) with CKHSS corrections everywhere
IVALUE = 2 CKHSS corrections are taken into account only in POs, this
option is used for tests only

DIAG – Selects type of diagrams taken into account:
IVALUE = -1 only Z- exchange diagrams are taken into account
IVALUE = 0 Z and γ - exchange diagrams are taken into account
IVALUE = 1 (default) Z and γ exchange and Zγ interference are included

EXPF – see NPAR(13) in subsection A.3

EXPR – see NPAR(12) in subsection A.3

ENUE – Treatment of the improved Born approximation for the process e⁺e⁻ →
νν. This option is only available via subroutine COSCUT in zbib6._34.f
and using zfeNN_34.f. This flag is presently not supported, see also Section
3.
IVALUE = -1 s-channel only
IVALUE = 0 s- and t-channels
IVALUE = 1 (default) s+t complete with s-t interference

DMWW – see NPAR(24) in subsection A.3

DSSW – see NPAR(25) in subsection A.3

FBHO – treatment of second order corrections to angular distributions and AF_B
IVALUE = 0 (default) treatment as in version 6.21 and before
IVALUE = 1 modified treatment; photonic radiative corrections are improved
and O(α²) contributions from pairs are included in leading-log approxi-
mation, see Section 2.1

FINR – Controls the calculation of final-state radiation,
IVALUE = -1 final-state QED and QCD correction are not applied;
IVALUE = 0 by s' cut, final-state QED correction is described with the
factor 1 + 3α(s)/(4π)Q²
IVALUE = 1 (default) M_f² cut, includes complete treatment of final-state
radiation with common soft-photon exponentiation

FOT2 – Controls second-order leading log and next-to-leading log QED cor-
rections:
IVALUE = -1 no initial state radiation QED convolution at all
IVALUE = 0 complete α additive radiator
IVALUE = 1 with logarithmic hard corrections
IVALUE = 2 complete α² additive radiator
IVALUE = 3 (default) complete $\alpha^2$ additive radiator
IVALUE = 4 optional $\alpha^3$ additive radiator for estimation of theoretical errors [89]
IVALUE = 5 “pragmatic” LLA third order corrections in a factorized form [8]

FSPP – correction due to final state radiation into pairs, see Section 2.4:
IVALUE = 0 (default) no final state state pair corrections
IVALUE = 1 final state state pair contributions are implemented as additive corrections
IVALUE = 2 final state state pair contributions are implemented as multiplicative corrections

FSRS – Final state radiation scale:
IVALUE = 0 $\alpha(0)$, preferred for tight cuts
IVALUE = 1 (default) $\alpha(s)$, preferred for loose cuts

FTJR – Treatment of FTJR corrections [77]:
IVALUE = 0 without FTJR corrections
IVALUE = 1 (default) with FTJR corrections everywhere
IVALUE = 2 FTJR corrections are taken into account only in POs, the option is used for tests only

FUNA – implementation of higher order photonic corrections to the angular distribution, see Section 2.2:
IVALUE = 0 (default) no higher order corrections
IVALUE = 1 higher order photonic LLA corrections are included

GAMS – Controls the $s$ dependence of $G_Z$, the $Z$-width function, see Section 3.2 of [2]:
IVALUE = 0 forces $G_Z$ to be constant
IVALUE = 1 (default) allows $G_Z$ to vary as a function of $s$ [90].

GFER – see NPAR(20) in subsection A.3

HIGS – see NPAR(14) in subsection A.3

HIG2 – see NPAR(18) in subsection A.3

INTF – Determines if the $O(\alpha)$ initial-final state QED interference (IFI) is calculated; see Section 2.3:
IVALUE = 0 the interference term is ignored
IVALUE = 1 (default) with IFI in the $O(\alpha)$
IVALUE = 2 with one-loop IFI corrections and corresponding higher order effects from the exponentiation

IPFC – Pair flavour content for the pair production corrections:
IVALUE = 1  only electron pairs
IVALUE = 2  only muon pairs
IVALUE = 3  only tau-lepton pairs
IVALUE = 4  only hadron pairs
IVALUE = 5  (default) all channels summed
IVALUE = 6  leptonic pairs (without hadrons)

IPSC – Pair production singlet-channel contributions (works with ISPP = 2):
   IVALUE = 0  (default) only non-singlet pairs
   IVALUE = 1  LLA singlet pairs according to [91]
   IVALUE = 2  complete $O(\alpha^2)$ singlet pairs, *ibid*
   IVALUE = 3  singlet pairs up to order $(\alpha L)^3$, *ibid*

IPTO – Third (and higher) order pair production contributions [12] (works
   with ISPP = 2):
   IVALUE = 1  allows to calculate the pure virtual pair contributions sepa-
               rately
   IVALUE = 0  only $O(\alpha^2)$ contributions
   IVALUE = 1  $O(\alpha^3)$ pairs
   IVALUE = 2  some ”non-standard” $O(\alpha^3)$ LLA pairs added
   IVALUE = 3  (default) $O(\alpha^4)$ LLA electron pairs added

ISPP – Treatment of ISR pairs:
   IVALUE = 1  pairs are treated with a “fudge” factor as in versions up to
             v.5.14
   IVALUE = 0  without ISR pairs
   IVALUE = 1  with ISR pairs, [92] with a re-weighting
   IVALUE = 2  (default) with ISR pairs according to [12]
   IVALUE = 3  with ISR pairs according to [93]
   IVALUE = 4  with ISR pairs [93] with extended treatment of hadron pair
               production

MISC – Controls the treatment of scaling of $\rho$ in the Model Independent
   approach, see discussion in Subsection 6.1:
   IVALUE = 0  (default) non-scaled $\rho$’s are used, ARQTFZ-array
   IVALUE = 1  scaled $\rho$’s, absorbing imaginary parts, are used, ARROFZ-array

MISD – Controls the $s$ dependence of the Model Independent approach
   IVALUE = 0  fixed $s = M_Z^2$ in EWRC, old treatment
   IVALUE = 1  (default) ensures equal numbers from all interfaces and for all
               partial channels but INDF=10 for a large range of $\sqrt{s}$ and for INDF=10 up
               to 100 GeV

PART – Controls the calculation of various parts of Bhabha scattering:
   IVALUE = 0  (default) calculation of full Bhabha cross-section and asym-
               metry
IVALUE = 1 only s channel
IVALUE = 2 only t channel
IVALUE = 3 only s – t interference

POWR – Controls inclusion of final-state fermion masses in kinematical factors, see Figure 6 of [2]. It acts differently for quarks and leptons. For leptons:
IVALUE = 0 final state lepton masses are set equal to zero
IVALUE = 1 (default) final state lepton masses are retained in all kinematical factors
For quarks it is active only for FINR = -1 and then:
IVALUE = 0 final state quark masses are set equal to zero
IVALUE = 1 (default) final state quark masses are set to their running values (that is, for $\bar{\tau}$ and $b\bar{b}$ channels) and retained in all kinematical factors

PREC – is an integer number which any precision governing any numerical integration is divided by, increasing thereby the numerical precision of computation:
IVALUE = 10 (default)
IVALUE = 1 – 99 in some cases when some numerical instability while running v.5.10 was registered, it was sufficient to use PREC = 3, in some other cases (e.g. with $P_{t}$) only PREC = 30 solved the instability

PRNT – Controls ZUWEAK printing:
IVALUE = 0 (default) printing by subroutine ZUWEAK is suppressed
IVALUE = 1 each call to ZUWEAK produces some output

QCDC – see NPAR(3) in subsection A.3

SCAL – see NPAR(9) in subsection A.3

SCRE – see NPAR(6) in subsection A.3

SFSR – see NPAR(23) in subsection A.3

TUPV – simulates theoretical uncertainties in APV, see Sect. 4:
IVALUE = 1 (default)
IVALUE = 2, 3 for variation, see Sect. 4

VPOL – see NPAR(1) in subsection A.3

WEAK – Determines if the weak loop calculations are to be performed
IVALUE = -1 is only valid for INDF=-1 and represents the options
WEAK=1, 2 without electroweak corrections for W boson exchange in the t-channel
IVALUE = 0 no weak loop corrections to the cross-sections are calculated and weak parameters are forced to their Born values, i.e. $\rho_{ef} = \kappa_{e,f,\epsilon f} = 1$
IVALUE = 1 (default) weak loop corrections to the cross-sections are calculated
IVALUE = 2 weak loop corrections are calculated but some higher order corrections that do not propagate via DIZET are switched off (ADDIME, ADDIMF; these corrections are small at LEP2 and they are not included by using DIZET with other codes

B.3 Subroutine ZUWEAK

Subroutine ZUWEAK is used to perform the weak sector calculations. These are done internally with DIZET, see Section A. The routine calculates a number of important electroweak parameters which are stored in common blocks for later use (see Section 6.1). If any ZFITTER flag has to be modified this must be done before calling ZUWEAK.

CALL ZUWEAK(ZMASS, TMASS, HMASS, DAL5H, ALFAS)

Input Arguments:

ZMASS is the Z mass $M_z$ in GeV.
TMASS is the top quark mass $m_t$ in GeV, [10-400].
HMASS is the Higgs mass $M_H$ in GeV, [10-1000].
DAL5H is the value of $\Delta \alpha_s^{(5)}(M_Z^2)$.
ALFAS is the value of the strong coupling constant $\alpha_s$ at $q^2 = M_Z^2$ (see factors QCDCOR in Tab. A.1).

Computing time may be saved by performing weak sector calculations only once during the initialization of the ZFITTER package. This is possible since weak parameters are nearly independent of $s$ near the $Z$ peak, e.g. $\sim \ln s/M_Z^2$. However, the incredible precision of LEP1 data forced us to give up this option, see description of flag MISP.

B.4 Subroutine ZUCUTS

Subroutine ZUCUTS is used to define kinematic and geometric cuts for each fermion channel: it selects the appropriate QED calculational chain.

CALL ZUCUTS(INDF, ICUT, ACOL, EMIN, S_PR, ANGO, ANG1, SIPP)
**Input Arguments:**

**INDF** is the fermion index (see Tab. C.1 and Figure 5 of [2]).

**ICUT** controls the kinds of cuts (chain) to be used.
- **ICUT = -1**: (default) allows for an $s'$ cut (a cut on $M^2_{ff}$, the fermion and antifermion invariant mass); the fastest branch based on [94]
- **ICUT = 0**: **not recommended**; branch is known to contain bugs. It allows for a cut on the acollinearity $\text{ACOL}$ of the $f \bar{f}$ pair, on the minimum energy $\text{EMIN}$ of both fermion and antifermion, and for a geometrical acceptance cut [95] \(^6\)
- **ICUT = 1**: $s'$ or $M^2_{ff}$ cuts and geometrical acceptance cut, based on [99]
- **ICUT = 2**: new branch, replaces ICUT = 0 for realistic cuts $\text{ACOL}$ and $\text{EMIN}$, based on [96]
- **ICUT = 3**: the same branch, using $\text{ACOL}$ cut and $\text{EMIN}$ cut but also with possibility to impose an additional acceptance cut [98]

**ACOL** is the maximum acollinearity angle $\xi_{\text{max}}$ of the $f \bar{f}$ pair in degrees (ICUT = 0, 2, 3).

**EMIN** is the minimum energy $E^\text{min}_{f\bar{f}}$ of the fermion and antifermion in GeV (ICUT = 0, 2, 3).

**SPR** is the minimum allowed invariant $f \bar{f}$ mass $M^2_{ff}$ in GeV (ICUT = -1, 1) or, with some approximations, the minimum allowed invariant mass of the propagator after ISR \(^7\)

**ANG0** (default = 0°) is the minimum polar angle $\vartheta$ in degrees of the final-state antifermion.

**ANG1** (default = 180°) is the maximum polar angle $\vartheta$ in degrees of the final-state antifermion.

**SIPP** is a parameter for cuts on the invariant mass of secondary pairs for FSRP = 1, 2 (see subsection 2.4). In older versions before v.6.30 the parameter SIPP governed the calculation of corrections due to initial state pairs and was recommended to be chosen equal to $s'$.

**B.5 Subroutine ZUINFO**

Subroutine ZUINFO prints the values of ZFITTER flags and cuts.

```plaintext
CALL ZUINFO(MODE)
```

---

\(^6\) As was shown recently [96–98], the old results of [95] contained bugs which occasionally didn’t show up in comparisons as e.g. in [39]. The option is retained for back-compatibility with older versions only.

\(^7\) The invariant mass of the propagator is not an observable quantity unless specific assumptions on ISR and FSR are made.
Input Argument:

**MODE** controls the printing of ZFITTER flag and cut values.
- **MODE = 0**: Prints all flag values.
- **MODE = 1**: Prints all cut values.

## C  Interface routines of ZFITTER

This Appendix describes technical details of the interface routines of ZFITTER. Not all of them have been influenced by the updates over the years. For the convenience of the user, we nevertheless decided to give a complete overview and will repeat a substantial part of the material, which was already presented in Section 4.3 of [2].

Note that subroutine **ZUWEAK** must be called prior to the interfaces. As a consequence, the flags used in **ZUWEAK** may influence the calculation of cross-sections and asymmetries in the interfaces described now.

All subroutines need the following input arguments:

- **INDF** is the fermion index (see Tab. C.1).
- **SQRs** is the centre-of-mass energy $\sqrt{s}$ in GeV.
- **ZMASS** is the Z mass $M_Z$ in GeV.

We just mention that the interface using an S-matrix inspired language is realized with the **SMATASY** package [100-103].

### C.1 Subroutine ZUTHSM

Subroutine **ZUTHSM** is used to calculate Standard Model cross-sections and forward-backward asymmetries.

```fortran
CALL ZUTHSM (INDF, SQRs, ZMASS, TMASS, HMASS, DAL5H, ALFAS, XS*, AFB*)
```

Input Arguments:

- **TMASS** is the top quark mass $m_t$ in GeV, [10-400].
- **HMASS** is the Higgs mass $M_H$ in GeV, [10-1000].
DAL5H is the value of $\Delta \alpha_h^{(5)}(M_Z^2)$.
\textbf{ALFAS} is the value of the strong coupling constant $\alpha_s$ at $q^2 = M_Z^2$ (see also flag QCD and factors QCDCOR).

\underline{Output Arguments}^{8}:

\textbf{XS} is the total cross-section $\sigma_T$ in nb.
\textbf{AFB} is the forward-backward asymmetry $A_{FB}$.

\underline{Output Internal Flag}:

\textbf{INTRF}=1

\textbf{C.2 Subroutine ZUATSM}

Subroutine \textit{ZUATSM} is used to calculate differential cross-sections, $d\sigma/d\cos\theta$, in the Standard Model.

\begin{verbatim}
CALL ZUATSM(INDF,SQRS,ZMASS,TMASS,HMASS,DAL5H,ALFAS,CSA*,DXS*)
\end{verbatim}

\underline{Input Arguments}:

\textbf{TMASS} is the top quark mass $m_t$ in GeV, [10-400].
\textbf{HMASS} is the Higgs mass $M_H$ in GeV, [10-1000].
\textbf{ALQED} is the value of the running electromagnetic coupling constant.
\textbf{ALFAS} is the value of the strong coupling constant $\alpha_s$ at $q^2 = M_Z^2$ (see factors QCDCOR).
\textbf{CSA} is the cosine of the scattering angle.

\underline{Output Arguments}:

\textbf{DXS} is the theoretical differential cross-section.

\underline{Output Internal Flag}:

\textbf{INTRF}=1

\footnote{An asterisk (*) following an argument in a calling sequence is used to denote an output argument.}
C.3 Subroutine ZUTPSM

Subroutine ZUTPSM is used to calculate the tau polarization and tau polarization asymmetry in the Standard Model.

```
CALL ZUTPSM(SQRS,ZMASS,TMASS,HMASS,DAL5H,ALFAS,TAUPOL*,TAUAFB*)
```

Input Arguments:

- **HMASS** is the Higgs mass $M_H$ in GeV, [10-1000].
- **DAL5H** is the value of $\Delta\alpha_h^{(5)}(M_Z^2)$.
- **ALFAS** is the value of the strong coupling constant $\alpha_s$ at $q^2 = M_Z^2$ (see factors QCDCOR).

Output Arguments:

- **TAUPOL** is the tau polarization $A_{pol}$ of Equation 3.312 of [2].
- **TAUAFB** is the tau polarization forward-backward asymmetry $A_{pol}^{FB}$ as defined in Equation 3.313 of [2].

Output Internal Flag:

**INTRF=1**

C.4 Subroutine ZULRSM

Subroutine ZULRSM is used to calculate the left-right asymmetry in the Standard Model.

```
CALL ZULRSM(INDF,SQRS,ZMASS,TMASS,HMASS,DAL5H,ALFAS,POL,XSPL*,XSMI*)
```

Input Arguments:

- **TMASS** is the top quark mass $m_t$ in GeV, [40-300].
- **HMASS** is the Higgs mass $M_H$ in GeV, [10-1000].
- **DAL5H** is the value of $\Delta\alpha_h^{(5)}(M_Z^2)$. 

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ALFAS is the value of the strong coupling constant $\alpha_s$ at $q^2 = M_Z^2$ (see also flag ALST).

POL is the degree of longitudinal polarization of electrons.

Output Arguments:

XSPL is the cross-section for POL $> 0$
XSMI is the cross-section for POL $< 0$

Output Internal Flag:

INTRF=1

C.5 Subroutine ZUXSA

Subroutine ZUXSA is used to calculate cross-section and forward-backward asymmetry as described in Section 3.7.5 of [2] as functions of $\sqrt{s}$, $M_Z$, $\Gamma_Z$.

CALL ZUXSA(INDF,SQRS,ZMASS,GAMZ0,MODE,GVE,XE,GVF,XF,XS*,AFB*)

Input Arguments:

GAMZ0 is the total Z width $\Gamma_Z$ in GeV.
MODE determines which weak couplings are used:
   MODE = 0: XE (XF) are effective axial-vector couplings $\tilde{a}_{e,f}$ for electrons (final-state fermions).
   MODE = 1: XE (XF) are the effective weak neutral-current amplitude normalizations $\tilde{\rho}_{e,f}$ for electrons (final-state fermions).
GVE is the effective vector coupling for electrons $g_e$.
XE is the effective axial-vector coupling $\tilde{a}_e$ or weak neutral-current amplitude normalization $\tilde{\rho}_e$ for electrons (see MODE).
GVF is the effective vector coupling for the final-state fermions $g_f$.
XF is the effective axial-vector coupling $\tilde{a}_f$ or the weak neutral-current amplitude normalization $\tilde{\rho}_f$ for the final-state fermions (see MODE).

Output Arguments:

XS is the cross-section $\sigma_x$ in nb.
AFB is the forward-backward asymmetry $A_{FB}$. 

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Output Internal Flag:

INTRF=3

C.6 Subroutine ZUXSA2

Subroutine ZUXSA2 is used to calculate lepton cross-section and forward-backward asymmetry as functions of $\sqrt{s}$, $M_z$, $\Gamma_z$, and of the weak couplings assuming lepton universality. This routine is similar to ZUXS except that the couplings are squared.

CALL ZUXSA2(INDF,SQRS,ZMASS,GAMZ0,MODE,GV2,X2,XS*,AFB*)

Input Arguments:

GAMZ0 is the total Z width $\Gamma_z$ in GeV.
MODE determines which weak couplings are used:
MODE = 0: X2 is the square of the effective axial-vector coupling $\tilde{a}_l$ for leptons.
MODE = 1: X2 is the square of the effective neutral-current amplitude normalization $\tilde{p}_l$ for leptons.
GV2 is the square of the effective vector coupling $\tilde{g}_l$ for leptons.
X2 is the square of the effective axial-vector coupling $\tilde{a}_l$ or neutral-current amplitude normalization $\tilde{p}_l$ for leptons (see MODE).

Output Arguments:

XS is the cross-section $\sigma_x$ in nb.
AFB is the forward-backward asymmetry $A_{FB}$.

Output Internal Flag:

INTRF=4

C.7 Subroutine ZUTAU

Subroutine ZUTAU is used to calculate the $\tau^+$ polarization as a function of $\sqrt{s}$, $M_z$, $\Gamma_z$, and the weak couplings.
CALL ZUTAU(SQRS, ZMASS, GAMZ0, MODE, GVE, XE, GV F, XF, TAUPOL*, TAUAFB*)

Input Arguments:

GAMZ0 is the total Z width $\Gamma_z$ in GeV.
MODE determines which weak couplings are used:
- $\text{MODE} = 0$: XE (XF) is the effective axial-vector coupling $\tilde{a}_{e,f}$ for electrons (final-state fermions).
- $\text{MODE} = 1$: XE (XF) is the effective weak neutral-current amplitude normalization $\tilde{\rho}_{e,f}$ for electrons (final-state fermions).
GVE is the effective vector coupling for electrons $\bar{g}_e$.
XE is the effective axial-vector coupling $\tilde{a}_e$ or weak neutral-current amplitude normalization $\tilde{\rho}_e$ for electrons (see MODE).
GV F is the effective vector coupling for the final-state fermions $\bar{g}_f$.
XF is the effective axial-vector coupling $\tilde{a}_f$ or weak neutral-current amplitude normalization $\tilde{\rho}_f$ for the final-state fermions (see MODE).

Output Arguments:

TAUPOL is the $\tau$-lepton polarization $\lambda_\tau$
TAUAFB is the forward-backward asymmetry for polarized $\tau$-leptons $A_{FB}^{pol}$

Output Internal Flag:

INTRF=3

C.8 Subroutine ZUXSEC

Subroutine ZUXSEC is used to calculate the cross section as a function of $\sqrt{s}$, $M_z$, $\Gamma_z$, $\Gamma_e$ and $\Gamma_f$.

CALL ZUXSEC(INDF, SQRS, ZMASS, GAMZ0, GAMEE, GAMFF, XS*)

Input Arguments:

GAMZ0 is the total Z width $\Gamma_z$ in GeV.
GAMEE is the partial Z decay width $\Gamma_e$ in GeV.
GAMFF is the partial Z decay width $\Gamma_f$ in GeV; if INDF=10, GAMFF=$\Gamma_h$. 

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Output Internal Flag:

\texttt{INTRF=2}

\textbf{C.9 Subroutine ZUXAFB}

Subroutine ZUXAFB is used to calculate the cross section as a function of $\sqrt{s}$, $M_Z$, $\Gamma_Z$, $\Gamma_e$ and $\Gamma_f$.

\begin{verbatim}
CALL ZUXAFB(INDF, SQRS, ZMASS, GAMZ0, PFOUR, PVAE2, PVAF2, XS*, AFB*)
\end{verbatim}

Input Arguments:

- \texttt{GAMZ0} is the total $Z$ width $\Gamma_Z$ in GeV.
- \texttt{PFour} is the product of vector and axial-vector couplings $g_v a_v g_f \bar{a}_f$.
- \texttt{PVAE2} is $g_v^2 + \bar{a}_v^2$.
- \texttt{PVAF2} is $g_f^2 + \bar{a}_f^2$.

Output Argument:

- \texttt{XS} is the cross-section $\sigma_x$ in nb.
- \texttt{AFB} is the forward-backward asymmetry $A_{FB}$.

Output Internal Flag:

\texttt{INTRF=5}

\textbf{C.10 Subroutine ZUALR}

Subroutine ZUALR is reserved for the fit of $A_{LR}$.

\begin{verbatim}
CALL ZUALR(SQRS, ZMASS, GAMZ0, MODE, GVE, XE, GVF, XF, TAUPOL*, TAUAFB*)
\end{verbatim}

Output Internal Flag:

\texttt{INTRF=6}
C.11 Subroutine ZVWEAK

The strength of the Wtb vertex, \(|V_{tb}|\), can be changed by using the subroutine ZVWEAK instead of ZUWEAK; see Section 1.

```
CALL ZVWEAK(ZMASS, TMASS, HMASS, DAL5H, V_TB, ALFAS)
```

Input Arguments:

- \( V_{TB} \) is the value of \(|V_{tb}|\); the Standard Model calculation of ZUWEAK corresponds to \(|V_{tb}| = 1\).

ZVWEAK has to be complemented with new interface routines, all now with the additional input argument \( V_{TB} \):

- ZVTHSM(INDF, SQR5, ZMASS, TMASS, HMASS, DAL5H, V_TB, ALFAS, XS*, AFB*)
- ZVTPSM(SQR5, ZMASS, TMASS, HMASS, DAL5H, V_TB, ALFAS, TAUPOL*, TAUAFB*)
- ZVLRSM(INDF, SQR5, ZMASS, TMASS, HMASS, DAL5H, V_TB, ALFAS, POL, XSPL*, XSMI*)
- ZVATSM(INDF, SQR5, ZMASS, TMASS, HMASS, DAL5H, V_TB, ALFAS, CSA, DXS*)

These subroutines replace ZUTHSM, ZUTPSM, ZULRSM and ZUATSM.

C.12 Subroutine ZU_APV

With subroutine ZU_APV measurements of the weak charge, \( Q_W \), (see Section 4) can be included into the global tests of the Standard Model.

```
CALL ZU_APV(ZMASS, TMASS, HMASS, SIN2TW, UMASS, DMASS, C1U*, C1D*, C2U*, C2D*)
```

Input Arguments:

- \( \text{SIN2TW} \) is the sin of the weak mixing angle.
- \( \text{UMASS} \) is the u-quark mass (constituent).
- \( \text{DMASS} \) is the d-quark mass (constituent).

Output Argument:

- \( C1U \) – coupling parameter, \( C_{1u} = 2a_e v_u \)
- \( C1D \) – coupling parameter, \( C_{1d} = 2a_e v_d \)
$C_{2u}$ - coupling parameter, $C_{2u} = 2v_e a_u$

$C_{2d}$ - coupling parameter, $C_{2d} = 2v_e a_d$
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Table C.1
Indices for the selection of final states. Note that INDF=0 returns values for one neutrino species, while INDF=10 returns values for the five-flavour inclusive (udscb) hadronic channel. Also note that INDF = 0,1 includes only s-channel calculations while INDF = 8 always returns zero.
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<th>Position in ZFITTER NPAR(1:30)</th>
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Table C.2
Flag settings for ZFITTER and DIZET; the flags are listed in the order of vector IFLAGS. The corresponding names used internally in the programs, the position of the flags in vector NPAR(1:25) of DIZET (called NPARD in ZFITTER) and NPAR(1:30) of ZFITTER and the default values are given.

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References


[27] G. Degrassi, Fortran program m2tcor (Oct 1996).


