TOPAZ0 4.0 - A new version of a computer program for evaluation of de-convoluted and realistic observables at LEP 1 and LEP 2

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Program classification: 11.1

\begin{abstract}
The program TOPAZ0 was developed for computing a variety of physical observables which are related to the $e^+e^-$ annihilation into fermion pairs and to the large angle Bhabha scattering around the $Z$ resonance. Among them, the $Z$ parameters or pseudo-observables, the de-convoluted cross sections and those dressed with QED radiation, and finally the forward-backward asymmetries. The calculations are performed both for a completely inclusive experimental set-up and for a realistic one, i.e. a set-up with cuts on the acollinearity angle, on the energy of the outgoing fermions or on their invariant mass and angular acceptance. The new version, 4.0, includes several innovative features. First of all, the most important new capabilities since previous versions are recently computed electroweak and QCD correction factors that are relevant at the $Z$ resonance in the light of the present experimental accuracy. Among them, the effect of the next-to-leading $\mathcal{O}(\alpha^2 m_t^2)$ corrections and those radiative corrections to the hadronic decay of the $Z$ which provide complete corrections of $\mathcal{O}(\alpha\alpha_s)$ to $\Gamma(Z \to q\bar{q})$ with $q = u,d,s,c$ and $b$. Secondly, the program has been upgraded to cover two-fermion final states at LEP 2 energies, where some of the assumptions made for earlier versions are no longer valid. In particular, to this aim all the electroweak radiative corrections that are negligible at the $Z$ peak, but relevant far from it, have been added for $s$-channel processes, e.g. purely weak boxes, next-to-leading $\mathcal{O}(\alpha^2)$ and leading $\mathcal{O}(\alpha^3)$ QED corrections.
\end{abstract}
NEW VERSION SUMMARY

Title of program: TOPAZ0 4.0

Catalogue number:

Program obtainable from: CPC Program Library, Queen’s University of Belfast, N. Ireland (see application form in this issue); also upon request to one of the authors.


Catalogue number of previous version: ACNT

The new version supersedes the previous ones

Licensing provisions: none

Computers on which this or another recent version has been tested: DEC-ALPHA 3000, HP-UX 9000;

Operating system under which the new version has been tested: VMS, UNIX

Installations: INFN, Sezione di Pavia, via A. Bassi 6, 27100 Pavia, and Sezione di Torino, via P. Giuria 1, 10125 Turin, Italy

Programming language used: FORTRAN 77; exception to standard: use of REAL*16 variables

Memory required to execute with typical data: \( \approx 300 \) kbyte as evaluator of observables in seven energy points

No. of bits in a word: 32

No. of processors used: one

Subprograms used: NAGLIB [?]

\[
\text{No. of lines:} \begin{cases} \text{PROGRAM} & 15472 \\ \text{FORTRAN job-control file} & 180 \end{cases}
\]

Keywords: \( e^+e^- \) annihilation, Bhabha scattering, LEP, \( Z \) resonance, electroweak, extrapolated and realistic experimental set-up, QCD corrections, QED corrections, pure weak corrections, radiative corrections, Minimal Standard Model, de-convoluted and realistic observables.
Nature of physical problem
An accurate theoretical description of $e^+e^-$ annihilation processes and of Bhabha scattering for centre of mass energies at the $Z$ resonance (LEP 1) and above (LEP 2) is necessary in order to compare theoretical cross sections and asymmetries with the experimental ones as measured by the LEP collaborations (realistic observables). In particular a realistic theoretical description, i.e. a description in which the effects of experimental cuts, such as maximum acollinearity, energy or invariant mass and angular acceptance of the outgoing fermions, are taken into account, allows the comparison of the Minimal Standard Model predictions with experimental raw data, i.e. data corrected for detector efficiency but not for acceptance. The program takes into account all the corrections, pure weak, QED and QCD, which allow for such a realistic theoretical description. The program offers also the possibility of computing the $Z$ parameters (pseudo-observables) including the state-of-the-art of radiative corrections, which is important for the indirect determination of the fundamental Standard Model parameters.

Method of solution
Same as in the original program. A detailed description of the theoretical formulation and of a sample of physical results obtained can be found in [?].

Summary of revisions

- In 1995 the CERN Report on Precision Calculations for the $Z$ resonance [?] provided as basic documentation the theoretical basis for upgrading existing calculations and FORTRAN programs.

  Although the '95 analysis remains quite comprehensive, an update of the discussion of radiative corrections has become necessary for one very good reason: a sizeable amount of theoretical work has appeared following ref. [?]. In particular, a crucial amount of work has been performed in providing higher-order corrections.

  In ref. [?] the two-loop $\mathcal{O}(\alpha^2 m_t^2)$ are incorporated in the theoretical calculation of $M_w$ and $\sin^2\theta_{\text{eff}}$. More recently the complete calculation of the decay rate of the $Z$ have been made available [?]. The only case which is not covered is the one of final $b$ quarks, because it involves specific $\mathcal{O}(\alpha^2 m_t^2)$ vertex corrections. For simplicity the above correction factors will be referred as sub-leading. Another recent development in the computation of radiative corrections to the hadronic decay of the $Z$ is contained in two papers which together provide complete corrections of $\mathcal{O}(\alpha \alpha_s)$ to $\Gamma(Z \rightarrow q\bar{q})$ with $q = u,d,s,c$ and $b$. In the first reference of [?] the decay into light quarks is treated. In the second one the remaining diagrams contributing to the decay into $b$ quarks are considered.
and thus the mixed two-loops corrections are complete.

TOPAZO [?], which was involved in the analysis of refs. [?], has been constantly updated and we focus, in this note, on a short description of the most important new capabilities since the '95 version.

- The crucial upgrading refers to the allowed values for $OU_0$, a flag contributing to the estimate of the theoretical error. The old option $OU_0 = 'Y'/'N'$ has now 3 different entries. The effect of the old choice $'N'$ (no re-summation at all of the bosonic corrections, the extreme option) is disappeared. Instead we have now $OU_0 = 'N'$ or $'L'$ or $'S'$. If one wants to compare with the old default then $OU_0 = 'N'$ (new default) should be selected, $OU_0 = 'L'$ is a new variant of the re-summation without sub-leading and could be used to estimate the uncertainty before the introduction of sub-leading, finally $OU_0 = 'S'$ includes the implementation of the [?] correction factors and represents the recommended choice. TOPAZO is based on a series of theoretical options $OU_n$, $n = 0,\ldots,7$. All these options ($n > 0$) are still active for $OU_0 = 'N'$ or $'L'$ but most of them are internally de-activated for $OU_0 = 'S'$, thus decreasing the overall uncertainty. The default setting remains

$$OU_1 = 'Y'$, $OU_2 = 'N'$, $OU_3 = 'Y'$, $OU_4 = 'N'$,
$$OU_5 = 'N'$, $OU_6 = 'Y'$, $OU_7 = 'N'$

Changing the parameters is governed by a FORTRAN job-control file, typical example is:

```fortran
CHARACTER*1 OVAL
CHARACTER*3 OFFS
OFFS= 'OU0'
OVAL='S'
CALL TCFLAG(OFFS,OVAL)
```

- There is a major change with respect to the internal philosophy of TOPAZO. A new subroutine has been introduced, TBASIC(NT,ST,FVECMS,IFLAG)

Once TOPAZO is called then the first step is governed by an internal call to subroutine TWIDHTO. Here, as a primitive calculation, both $M_W$ – the $W$ boson mass – and $s^2$ – the improved one-loop solution
for the sinus of the weak mixing angle – are obtained as iterative solutions of the two relevant renormalization equations. After that, all $Z$-parameters are computed. As a matter of fact, most of the users are solely interested in deriving pseudo-observables. For this reason, it is now possible to call TOPAZ0 with $\text{OEXT} = 'P'$ where the calculation of the realistic observables is skipped with a considerable gain in CPU time.

- In computing $M_W, \hat{s}^2$ and the rest of the pseudo-observables there are essentially five functions which are touched by the inclusion of the sub-leading. Each of these functions depends on $M_H, m_t, \hat{s}^2$ and $M_W$. As a function of the ratio $M_H/m_t$ they are given in [?] in terms of two expansions, $M_H/m_t \gg 1$ and $M_H/m_t \ll 1$. In between it is up to the reader to decide what to do. In between, however, is exactly where the the present experimental data would like to see the Higgs boson. In order to avoid any kink in the evaluation of pseudo-observables one has to interpolate numerically. The origin of the kink is related to the two-loop correction factor, $\Delta \rho^{(2)}$, which in the hierarchy of the effects is the dominant one. We decided to interpolate with some accuracy for this function.

- The most important upgrading in the electroweak/QCD interplay is represented by non-factorizable QCD and EW corrections to the hadronic $Z$ boson decay rate. The Born result receives both QCD and EW corrections and, so far, one used factorization

$$\Gamma = \Gamma_{\text{EW}} \left(1 + \frac{\alpha_s}{\pi}\right)$$

However the correct implementation of the new result [?] is giving us

$$\Delta \Gamma (Z \rightarrow u, d, s, c) \approx -0.59(3) \text{ MeV},$$

or

$$\Delta \alpha_s(M_Z) \approx -\pi \frac{\Delta \Gamma (Z \rightarrow \text{hadrons})}{\Gamma (Z \rightarrow \text{hadrons})} \approx \pi \frac{0.50}{1743} \approx 0.001.$$

There is no space enough here to account for a complete description of the QCD corrections implemented in TOPAZ0. We simply note that subroutine TCORRQCD has been completely re-designed and function RRUNM allows the running quark masses to be computed at the corresponding pole mass. For instance subroutine TCORRQCD computes
- the running of the s-quark mass up to the c- and b-quark threshold
- the c-quark mass at the c-quark threshold
- the c-quark mass at the b-quark threshold
- and finally the running c-quark mass at any scale.
- The b-quark mass at b-quark threshold
- and finally the running b-quark mass at any scale.

In the following we present a list of the relevant corrections:

1. The \( \mathcal{O}(\alpha_s) \) corrections including non-vanishing quark masses.
2. Flavor non-singlet corrections in the massless limit are the same as those for the vector current. Whereas flavor singlet contributions for vector currents arise only at order \( \alpha_s^3 \) they are present already in second order for the axial part.
4. Quadratic massive corrections.
5. Quartic massive corrections.
6. Power suppressed top-quark mass correction.
7. Singlet axial corrections.
8. Singlet vector correction.

It is important to discuss the most relevant variations in the prediction for pseudo-observables. We refer to the situation presented in refs. [? , ?]. For this reason we have taken again \( M_Z = 91.1888 \text{ GeV}, \)

\[
\begin{array}{|c|c|c|c|}
\hline
\text{NEW versus OLD} & \text{TOPAZ0 2.0} & \text{TOPAZ0 4.0} & \text{Abs. shift(per-mil)} \\
\hline
M_W \ [\text{GeV}] & 80.310 & 80.308 & -0.03 & -2.1 \ \text{[MeV]} \\
\sin^2 \theta_{\text{eff}} & 0.23200 & 0.23209 & 0.39 & 8.9 \times 10^{-5} \\
\Gamma_Z \ [\text{MeV}] & 2497.4 & 2496.1 & -0.052 & -1.29 \ \text{[MeV]} \\
\hline
\end{array}
\]

Table 1: Comparison of two TOPAZ0’s versions. Here \( M_Z = 91.1888 \text{ GeV}, \)

\[
m_t = 175 \ \text{GeV}, \ \alpha_s(M_Z^2) = 0.125 \ \text{and} \ M_H = 300 \ \text{GeV} \ \text{the ’95 input parameter set} \ \text{and compared some of the predictions in Table 1.}
\]

- Purely weak boxes have been introduced for s-channel processes. Their effect has been already discussed at length in [?].

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• QED corrections — For both the cross sections and forward-backward asymmetry, new QED corrections have been added. They include both corrections that are relevant at the $Z$ peak, in view of the present accuracy of experimental data, and correction that are negligible at the $Z$ peak, but become relevant for centre of mass energies above it.

- Cross sections – New corrections, already known in the literature, but not implemented in the previous versions, and completely new ones have been inserted. They are:

  * initial-state next-to-leading $\mathcal{O}(\alpha^2)$ corrections to the radiator, according to eqs. (3.19) and (3.20) in [?]; this radiator is selected by $\text{OHC} = Y$ and $\text{ORAD} = A$;
  
  * additional initial-state higher-order corrections to the radiator, according to eqs. (3.29) and (3.30) in [?]; this radiator is selected by $\text{OHC} = Y$ and $\text{ORAD} = D$;
  
  * additional initial-state higher-order corrections to the radiator, including part of the leading $\mathcal{O}(\alpha^3)$ corrections, according to eqs. (3.31) and (3.32) in [?]; this radiator is selected by $\text{OHC} = Y$ and $\text{ORAD} = E$;
  
  * the full radiator including initial-state next-to-leading $\mathcal{O}(\alpha^2)$ and complete leading $\mathcal{O}(\alpha^3)$ corrections, according to the analytical results obtained in [?]; this radiator is selected by $\text{OHC} = Y$ and $\text{ORAD} = F$ (recommended choice).

For each of these choices, also the primitives have been computed analytically and implemented in FUNCTION TPRAD. Moreover, also the $\mathcal{O}(\alpha^3)$ contributions to the electron structure function and its primitive, according to [?], have been implemented in SUBROUTINE TSTRUCFUN and SUBROUTINE TPDFUN.

- Forward-backward asymmetries – For $\text{OHC} = Y$, additional contributions to the forward-backward radiator, that become relevant above the $Z$ peak, are included, according to eqs. (43), at the $\mathcal{O}(\alpha)$, and (46), at the $\mathcal{O}(\alpha^2)$, in [?]. These contributions are active only for $s$-channel asymmetries. Also in this case, the primitive has been computed analytically and implemented in FUNCTION TPRAD.

$\text{OHC} = N$ sets automatically the radiator adopted in the previous versions of the program, both for cross sections and asymmetries.

The effects of the above QED corrections have been investigated in [?]. They can be summarized as follows: at LEP 1 the initial-state next-to-leading
\( \mathcal{O}(\alpha^2) \) corrections are negligible, whereas the leading \( \mathcal{O}(\alpha^3) \) ones introduce a negative shift of the total cross section of about 0.07\%. At LEP 2, the two corrections tend to compensate one another, leaving a net effect of around 0.2–0.4\% when the \( Z \) radiative return is included and about 0.1\% otherwise.

It is worth emphasizing, that in order to implement the new radiators and their primitives, a new library of Nielsen’s polylogarithms has been created,

```
SUBROUTINE TPOLYL(X,EP,S11,S12,S13,S21,S22)
```

It returns \( S_{1,1}(x), \ldots S_{2,2}(x) \).

The running is governed by a FORTRAN job-control file, where the necessary input parameters are fixed. The program calls `SUBROUTINE TINIT` (see below), where all the flags are initialized to their default value. It is allowed to change the default settings by calling the auxiliary `SUBROUTINES TCUTSET`, `TCFLAG` and `TCOPT`. In particular, the theoretical options `OUun` are re-set by subroutine `TCOPT`, kinematical cuts by subroutine `TCUTSET` and all the remaining `TOPAZ0`'s flags by subroutine `TCFLAG`. A change of a non-existing flag is signalled by a warning message:

```
TOPFLAG: FLAG NOT RECOGNISED: FLAGNAME
```

Then `SUBROUTINE TOPAZ0` is called, according to the following calling statement:

```
SUBROUTINE TOPAZ0(NRTS,RTS,ZMT,TQMT,HMT,ALST,OTPPO,OTPRO).
```

The first six entries are input parameters, whose meaning is:
- **NRTS**: number of energies;
- **RTS**: array dimensioned as \( \text{RTS(NRTS)} \), containing the values of the energies;
- **ZMT**: the \( Z \)-boson mass (GeV);
- **TQMT**: the top-quark mass (GeV);
- **HMT**: the Higgs-boson mass (GeV);
- **ALST**: the value of \( \alpha_s(M_Z^2) \).

The last two variables are output quantities:
- **OTPPO**: array dimensioned as \( \text{OTPPO(24)} \), containing the values of the pseudo-observables; the internal ordering is:

```
<table>
<thead>
<tr>
<th>mass of the W (1)</th>
<th>( M_W )</th>
</tr>
</thead>
<tbody>
<tr>
<td>hadronic peak cross-section (16)</td>
<td>( \sigma_{\text{had}} )</td>
</tr>
<tr>
<td>partial leptonic widths (17)</td>
<td>( \Gamma_\nu(2), \Gamma_e(3), \Gamma_\mu(4), \Gamma_\tau(5) )</td>
</tr>
</tbody>
</table>
```

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partial hadronic widths \( \Gamma_u(6), \Gamma_d(7), \Gamma_c(8), \Gamma_s(7), \Gamma_b(9) \)
the total width \( \Gamma_z(14) \)
the total hadronic width \( \Gamma_h(19) \)
the total invisible width \( \Gamma_{inv}(20) \)
ratios \( R_l(15), R_b(17), R_c(22) \)
asymmetries and polarization \( A_{FB}^l(12), A_{LR}^l(13), A_{FB}^b(18), A_{FB}^c(21), A_{LR}^b(23), A_{LR}^c(24) \)
effective sinuses \( \sin^2 \theta_{eff}^l(10), \sin^2 \theta_{eff}^b(11) \)

\textbf{OTPRO}: array dimensioned as \texttt{OTPRO(26*NRTS)}, containing the values of the realistic observables and relative numerical errors:

\[
\text{RO} = \begin{cases} 
\sigma_e \pm \Delta \sigma_e & \sigma_\mu \pm \Delta \sigma_\mu & \sigma_\tau \pm \Delta \sigma_\tau \\
\sigma_{\text{had}} \pm \Delta \sigma_{\text{had}} & R_b \pm \Delta R_b & \sigma_c \pm \Delta \sigma_c & R_c \pm \Delta R_c \\
A_{FB}^e \pm \Delta A_{FB}^e & A_{FB}^\mu \pm \Delta A_{FB}^\mu & A_{FB}^\tau \pm \Delta A_{FB}^\tau \\
A_{FB}^c \pm \Delta A_{FB}^c & A_{FB}^b \pm \Delta A_{FB}^b 
\end{cases}
\]

Results are stored in array \texttt{OTPRO(K)} according to \( K = 13(2(I-1)+J-1)+L \)
with \( I = 1, NRTS \) running over energy points, \( L = 1, 13 \) running over the type of realistic observable (\( \sigma_e, \sigma_\mu \) etc.) and \( J = 1, 2 \) for the central value and the numerical error.

The output is still governed by the job-control file, by means of the printing of the arrays \texttt{OTPPO(24)} and \texttt{OTPRO(26*NRTS)}, to be declared in \texttt{COMMON}. The output from the program is self-explanatory.

All the internal flags of the program are initialized by means of \texttt{SUBROUTINE TINIT}, which is called by the job-control file. Here the complete list of inputs is given, devoting particular care in commenting the meaning of the new flags. For more details concerning flags already present in earlier versions, the reader is referred to the documentation of the previous releases.

\textbf{SE}: scaling factor for numerical integration error;
\textbf{OWEAK}: residual weak corrections: running (R) or fixed (F); at LEP 2 the correct choice is R;
\textbf{OWBOX}: weak boxes included (Y) or not (N). Away from the Z-resonance the correct choice is Y;
\textbf{OU0}: includes (S) the sub-leading two-loop \( \mathcal{O}(\alpha^2 m_t^2) \) corrections according to [?]. It is the \textit{recommended} choice;
\textbf{OHC}: next-to-leading and higher order hard photon contribution included (Y) or not (N);
ORAD: selects the type of next-to-leading and higher order hard photon contributions to be included (A,D,E,F). F is the recommended choice;

OAL: selects the value of \( \alpha_{em}^{-1}(M_Z^2) \): 128.896 (Y), 128.87 (N), user-defined (V); if OAL = 'V' then a new value for \( \alpha_{em}^{-1}(M_Z^2) \) is selected through the calling procedure CALL TCAQED(ALPHANEW).

OAAS: the scale in \( \alpha_s \) in mixed \( \alpha_s \) corrections;

ONP: array dimensioned as ONPT(NRTS) selecting (Y) or not (N) the pair production correction for each energy;

ONIF: array dimensioned as ONIF(NRTS) selecting (Y) or not (N) the effect of initial-finale state QED interference for each energy;

OEXT: selects the extrapolated (E) or cut (C) branch for \( \mu \) and \( \tau \). With OEXT = 'P' pseudo-observables are computed and control is returned;

OFB: selects (Y) or not (N) different treatment of cuts for cross sections and forward-backward asymmetries for \( \mu \) and \( \tau \);

OCUTS: array dimensioned as OCUTST(NRTS); if OFB = Y selects (Y) or not (N) a cut on the invariant mass after initial-state radiation for \( \mu \) and \( \tau \) cross sections;

OCHAN: selects the full Bhabha scattering matrix element (F) (default) or only the s-channel part (S);

OCUT: array dimensioned as OCUT(NRTS); selects a cut on \( s' \) : no cut (NC), cut on hadronic channels only (HC), cut on all channels (FC). Here \( s' \) is the invariant mass of the \( e^+e^- \) system after initial state radiation;

OCUF: as OCUT, but for final-state fermions invariant mass;

OTHMT: if OEXT = C, selects invariant mass (M) or energy (E) threshold for \( \mu \) and \( \tau \);

OCREE: if OEXT = E and OCHAN = S, i.e. for s-channel electrons, it allows for an \( s' \) cut;

OCUTES: array dimensioned as OCUTES(NRTS); if OCREE = Y, it allows (C) or not (N) for an \( s' \) cut for each energy point;

OTHER: selects invariant mass (M) or energy (E) threshold for electrons;

OFS: selects the treatment of higher order final-state QED corrections; default (D) or perturbative (Z);

OCN: includes (Y) or not (N) the contribution of electromagnetic jets for final-state calorimetric electrons;

XMED: fictitious separator for 1-dimensional integrations to improve numerical convergence;

OVNAL: if OAL = V, enters the user-defined value \( \alpha_{em}^{-1}(M_Z^2) = OVNAL; \)

SC: if OAAS = Y, defines the scale in \( \alpha_s \) in mixed \( \alpha_s \) corrections;

ZPCUT: the minimum fraction of squared invariant mass of the final state after radiation of the additional initial-state pair;

OXCUTS: if OCUTS = Y, it enters the value of the \( s' \) cut, \( s_0/s; \)
OXCUT: if $OCUT = Y$, it enters the value of the $s'$ cut, $s_0/s$;

$OCUTF$: if $OCUTF = Y$, it enters the cut on the value of invariant mass squared of the final-state fermions;

$SOCUT$: array dimensioned as $SOCUT(3)$; $SOCUT(1)$ is the minimum invariant mass (GeV) of the final-state electrons, used if $OTHRE = M$; $SOCUT(2)$ and $SOCUT(3)$ are the same as $SOCUT(1)$ for $\mu$ and $\tau$ respectively, used if $OTHRTMT = M$;

$E0$: array dimensioned as $E0(3)$; $E0(1)$ is the minimum energy (GeV) of the final-state electrons, used if $OTHRE = E$; $E0(2)$ and $E0(3)$ are the same as $E0(1)$ for $\mu$ and $\tau$ respectively, used if $OTHRTMT = E$;

$THMIN$: array dimensioned as $THMIN(3)$; it enters the minimum scattering angle (deg) for electrons, $\mu$ and $\tau$, respectively ($symmetrical$ $angular$ $acceptance$ is understood); $THMIN(2)$ and $THMIN(3)$ used only if $OEXT = C$;

$THMINP$: the same as $THMIN$, for the antiparticles;

$ACOLL$: array dimensioned as $ACOLL(3)$; it enters the maximum acollinearity angle (deg) for electrons, $\mu$ and $\tau$, respectively; $ACOLL(2)$ and $ACOLL(3)$ used only if $OEXT = C$;

$OCUTES$: if $OCUTES(I) = C$, it enters the $s_0/s$ threshold for the $I$-th energy point;

$DEL$: the semi-aperture of the electromagnetic jet (deg); used only if $OCN = 'Y'$.

The internal default has been set to the following choices:

$$OWEAK = 'R', OWBOX = 'Y', OHC = 'Y', ORAD = 'F'$$

$$XMED = 0.98D0, OAL = 'Y', OCN = 'Y', DEL = 0.5D0$$

$$ZPCUT = 0.8D0, OFS = 'D', ONF(I) = 'Y', ONF(I) = 'Y'$$

A change for some of the kinematical cuts is illustrated by the following calling sequence:

```fortran
IND= 1
DMY= -1.D0
ANG= 40.D0
ACL= 10.D0
ETH= 5.D0
CALL TCUTSET(IND,DMY,ANG,DMY,ACL,ETH,DMY,DMY,DMY)
```

With $IND = 1$ only cuts for the electron will be touched and moreover $DMY = -1$, i.e. $DMY < 0$ implies that variables $SOCUT(1)$, $THMINP(1)$, $OXCUT$, 

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OXCUTF and ZPCUT keep the default value, while variables THMIN(1), ACOLL(1)
and E0(1) are reset to new values 40°, 10° and 5 GeV.

After initialization a call is performed to subroutine TWIDTHO after which
the control is returned if OEXT = 'P', otherwise subroutine TEWEXT and TWCUT
are called and the evaluation of realistic observables starts. In TEWEXT weak
corrections are computed and the physical quantities are convoluted when no
cuts (but on the invariant mass) are applied. In TWCUT weak corrections are
computed and the physical quantities are convoluted for leptons, when cuts
are applied.

The previous versions of TOPAZ0 can be used to compute Z-parameters and
de-convoluted observables but also to obtain predictions for QED-dressed dis-
tributions, over some realistic set-up, resembling the experimental raw data.
The most severe limitation of those versions is that they have been developed
by having in mind the accurate evaluation of theoretical observables at the
Z peak. The new version of the program, TOPAZO 4.0, offers remarkable im-
provements in two directions. First, towards the goal of taking into account
all those radiative corrections that can become relevant, when we consider the
experimental accuracy reached at present by the LEP 1 experiments. Of the
same relevance is the effort of adding those radiative corrections that are negli-
gible for a centre-of-mass energy around the Z peak, but that become relevant
for energies above it.

Restrictions on the complexity of the problem

Analytic formulas have been developed for an experimental set-up with sym-
metrical angular acceptance. Moreover the angular acceptance of the scat-
tered antifermion has been assumed to be larger than the one of the scattered
fermion. The prediction for Bhabha scattering is understood to be for the
large-angle regime. Initial-state next-to-leading $O(\alpha)$ QED corrections are
treated exactly for an $s'$ cut, in the soft photon approximation otherwise. This
means that for center of mass energies sensibly above the $Z^0$ peak (typically in
the LEP 1.5 – LEP 2 regime), the theoretical accuracy of the $C$ branch is un-
der control (theoretical error $\leq 0.3\%$) when excluding the $Z$ radiative return,
whereas including it the theoretical error can grow up to some % depending
on the final state selected [7]. In the same energy range, large angle Bhabha
scattering becomes a $t$-channel dominated process: since all the QED correc-
tions implemented are strictly valid for $s$-channel processes, this means that
large angle Bhabha scattering off the $Z$ resonance is treated at the leading
logarithmic level.

Typical running time

This depends strongly on the particular experimental set-up studied and on
the energy range. As evaluator of realistic observables in seven energy points around the $Z^0$ peak, between 10 (extrapolated set-up) and 270 (realistic set-up) CPU seconds for HP-UX 9000. Anyway, for the realistic observables the CPU time depends strongly on being at LEP 1 or LEP 2, and on the scaling factor $SE$ controlling the accuracy of numerical integrations. For the evaluation of pseudo-observables the program runs much faster.

Unusual features of the program
Subroutines from the library of mathematical subprograms NAGLIB [?] for the numerical integrations are used in the program.

Acknowledgements
We would like to express special thanks to many colleagues. Without their contributions the program would not be what it is now. We have received a great support from the experimental community, but among them we take the pleasure to acknowledge the active role of Robert Clare, Peter Clarke, Manel Martinez, Alexander Olshevsky and Frederic Teubert. Essential, in the development of TOPAZ0, has been the constant support of Martin Gruenewald, Christoph Pauss and Gunter Quast. Among our theorist friends we would like to thank Wim Beenakker, Wolfgang Hollik, Hans Kühn and Roberto Pittau.

We acknowledge the important role played by Giuseppe Degrassi and by Paolo Gambino in helping us with the implementation of the two-loop sub-leading corrections and for sharing with us the result of their work prior to publication. Finally we express our gratitude to Dmitri Bardin. It is only due to the constant exchange of information and to the continuous cross-checks between TOPAZ0 and ZFITTER that we have reached the present level of confidence in our results. Perhaps it is not that frequent that competitors forget about competition and sit down until they understand everything about their respective work before publication of the work itself.
Test Run Output

The typical calculations that can be performed with the new version of the program are illustrated in the following example. The FORTRAN job-control file computes both pseudo-observables and realistic observables with $\text{OEXT} = 'E'$. For the large angle Bhabha observables we use the following selection criterion:

- minimum scattering angle for the $e^-$, $|\cos \theta_e^-| < 0.7$;
- maximum acollinearity, $\theta_{\text{acol}} = 10^\circ$;
- energy thresholds, $E(e^\pm) = 1$ GeV.

The realistic observables are computed for three typical energies, $\sqrt{s} = M_Z$, 136.22 GeV and 172.12 GeV. The input parameter set is $M_Z = 91.1867$ GeV, $m_t = 175.6$ GeV, $M_H = 300$ GeV and $\alpha_s(M_Z^2) = 0.120$.

\[
\begin{align*}
\text{W MASS (GEV)} & = 0.803121E+02 \\
\text{NU} & = 0.167123E+00 \\
\text{ELECTRON} & = 0.839180E-01 \\
\text{MUON} & = 0.839173E-01 \\
\text{TAU} & = 0.837263E-01 \\
\text{UP} & = 0.299863E+00 \\
\text{DOWN(STRANGE)} & = 0.382626E+00 \\
\text{CHARM} & = 0.299806E+00 \\
\text{SIN}^2(E) & = 0.375542E+00 \\
\text{SIN}^2(B) & = 0.232068E+00 \\
\text{A_FB(L) EFF.} & = 0.152848E-01 \\
\text{A_LR EFF.} & = 0.142757E+00 \\
\text{TOTAL WIDTH (GEV)} & = 0.249338E+01 \\
\text{G_H/G_E} & = 0.207399E+02 \\
\text{SIGMA0_H (NB)} & = 0.414744E+02 \\
\text{G(B)/G(HAD)} & = 0.215772E+00 \\
\text{A_FB(B)} & = 0.999354E-01 \\
\text{HADRONIC WIDTH (GEV)} & = 0.174045E+01 \\
\text{INVISIBLE} & = 0.501370E+00 \\
\text{A_FB(C)} & = 0.713261E-01 \\
\text{G(C)/G(HAD)} & = 0.172258E+00 \\
\text{A_LR(B) EFF.} & = 0.934328E+00 \\
\text{A_LR(C) EFF.} & = 0.665952E+00
\end{align*}
\]
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{CM}$ (GeV)</td>
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<td>SIGMA(E) (NB)</td>
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<td>SIGMA(MU) (NB)</td>
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<td>Parameter</td>
<td>Value 1</td>
<td>Value 2</td>
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