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The Monte Carlo program KORALZ, version 3.8, for the lepton or quark pair production at LEP/SLC energies

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ABSTRACT

The Monte Carlo program for τ pair production and decay applicable to the experiments in e^+e^- colliders in the Z resonance energy range is presented. The program includes initial state bremsstrahlung corrections up to the $\mathcal{O}(\alpha^2)$ (with exclusive exponentiation), final state $\mathcal{O}(\alpha)$ bremsstrahlung and $\mathcal{O}(\alpha)$ electroweak corrections. The following τ decay modes can be generated: $\tau^\pm \to \bar\nu\nu e^\pm$, $\bar\nu\nu\mu^\pm$, $\nu\pi^\pm$, $\nu\rho^\pm$, $\nu K_1^\pm$, $\nu K^{*\pm}$, $\nu a_1^\pm$, $\nu 4\pi^{\pm,0}$, $\nu 5\pi^{\pm,0}$, $\nu 6\pi^{\pm,0}$ including leading logarithmic radiative corrections in decays. The program can be also used for generation of the final states different from $\tau^+\tau^-$ pairs, i.e., is able to generate $\mu^+\mu^-$, $\nu\bar\nu$, $u\bar u$, $d\bar d$, $c\bar c$, $s\bar s$ and $b\bar b$ final states.

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PROGRAM SUMMARY

Title of the program: KORALZ, version: 3.8

Computer: IBM 3090; *Installation:* CERN, SLAC

Operating system: VM/CMS

Programing language used: FORTRAN 77

High speed storage required: 45000 words

No. of bits in a word: 32

Peripherals used: Line printer

No. of cards in combined program and test deck: about 15000

Keywords: Radiative corrections, heavy lepton τ, Monte Carlo simulation, quantum electrodynamics, spin polarization, electro-weak theory.

Nature of the physical problem: Spin polarization of τ in the process $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$, $\tau^\pm \rightarrow X^\pm$ will be used as an important data point for precise tests of the standard electroweak theory. The effects due to QED bremsstrahlung and apparatus efficiency have to be subtracted from the data. The program may be also applied for the production of u, d, s, c, b quarks and neutrinos after appropriate redefinition of the coupling constants and masses. It may be used, as well, to simulate the muon pair production process. The application of the program to the b quark mode requires an electro-weak library which includes effects due to the relatively big mass of b.

Method of solution: The Monte Carlo simulation of the combined τ production and decay process is used to calculate the spin effects and effects of radiative corrections, including hard bremsstrahlung, simultaneously. Any experimental cut and apparatus efficiency may be introduced easily by rejecting some of the generated events.

Restrictions on the complexity of the problem: The incoming $e^\pm$ and outgoing $\tau^\pm$ may have only longitudinal polarizations. The total center of mass energy is restricted to the range from about 20 GeV to 150 GeV. High precision of the program is assured only in the region of the Z where interference of bremsstrahlung from initial and final states can be neglected.

Typical running time: Efficiency is 0.006-0.057 CPU sec. (IBM 3090) per event, in the multi-bremsstrahlung mode and including τ decay.

LONG WRITE-UP

1. Introduction

The production of the τ lepton pair in the SLC/LEP experiment is recognized [1], [2] as a process which will provide important experimental data for precise tests of the Standard Electroweak Theory [3].

The unique property of the process $e^+e^- \to \tau^+\tau^-$ is that it is possible to measure spin polarization of the final state lepton τ. This can be done by inspection of the energy distributions of τ decay products.

The unstable nature of the τ, which on one hand constitutes its powerful virtue, on the other hand complicates the data analysis. The presented Monte Carlo program is aimed as a helpful tool in the τ pair data analysis in SLC/LEP experiments.

In addition, after switching off τ decays the program can be used to simulate the process of other fermion pair production in electron-positron annihilation $e^+e^- \to f^+\bar{f}^-(n\gamma)$, where the fermion may be a lepton, $f = \mu, \nu$, or a quark, $q = u, d, s, c$, and under certain restrictions the quark b.

The following important effects are taken into account:

1. Multiple QED hard bremsstrahlung from the initial state $e^\pm$ and single photon bremsstrahlung from the final state fermion.
2. $O(\alpha)$ radiative corrections from the standard electroweak model [3].
3. Longitudinal spin polarization of the beams.
4. The most frequent decays of the τ lepton $\tau^\pm \to \bar{\nu}\nu e^\pm$, $\bar{\nu}\nu\mu^\pm$, $\nu\pi^\pm$, $\nu\rho^\pm$, $\nu K_1^\pm$, $\nu K^{*\pm}$, $\nu a_1^\pm$, $\nu 4\pi^{\pm,0}$, $\nu 5\pi^{\pm,0}$, $\nu 6\pi^{\pm,0}$.
5. Spin polarization effects in τ decay process (except of multi-pion decays).
6. Single bremsstrahlung in the most important τ decay modes: $\bar{\nu}\nu e^\pm$, $\bar{\nu}\nu\mu^\pm$, $\nu\pi^\pm$, $\nu\rho^\pm$ $\nu K_1^\pm$, $\nu K^{*\pm}$ (in the leading logarithmic approximation).

The program has some limitations. Let us list them in the order of their importance:

1. The QED initial-final state bremsstrahlung interference is not included in the case of the multiple QED hard bremsstrahlung in the initial state.
2. QED $O(\alpha)$ corrections to the τ decay are included in the leading logarithmic approximation and only for the $\bar{\nu}\nu e^\pm$, $\bar{\nu}\nu\mu^\pm$, $\nu\pi^\pm$, $\nu\rho^\pm$, $\nu K_1^\pm$, $\nu K^{*\pm}$ decay modes.

3. There is no possibility to vary, from event to event, the flavour of the final state fermion and the energy of the beams.
4. The multi-pion τ decay modes (four π's and more) in τ decay do not include spin effects and are generated with an over-simplified matrix element.
5. The incoming $e^{\pm}$ and outgoing $\tau^{\pm}$ may have only longitudinal polarizations.

The KORALZ program has a modular structure. All of its basic parts, YFS2 [4], MUSTRAAL [5], TAUOLA [6], PHOTOS [7], DIZET [8], were already published and are included in KORALZ either directly or with only minor changes. This separation assures clear structure of the program. It is especially important in the case of electroweak corrections.

Let us remind the reader that the program KORAL-B of ref. [10] for τ pair production at $\sqrt{s} \leq 30$GeV includes all effects due to the finite mass of τ and due to transverse polarizations of $\tau^{\pm}$ and $e^{\pm}$. KORALZ neglects the unimportant transverse spin correlations in τ decays. KORALB may serve for checks on the importance of these correlations. KORALB includes Z exchange in the low energy approximation limit and single bremsstrahlung only.

KORALZ includes spin polarization of the beams and the complete $\mathcal{O}(\alpha)$ virtual corrections from the (electroweak) standard model [8,11], also hadronic and gluonic corrections. In the multi-bremsstrahlung mode KORALZ uses a new multi-photon algorithm for QED bremsstrahlung [4]. In the single bremsstrahlung mode KORALZ emulates the program MUSTRAAL of ref. [5]. In our case, however, the massive kinematics is implemented in a better way than in the MUSTRAAL.

Users interested in a more detailed information on the implementation of spin effects in KORALZ are referred to paper [12]. Ref. [13] provides more information on the generation of the single final state bremsstrahlung and the way of combining the electroweak and final state bremsstrahlung corrections with the rest of QED corrections.

The τ decay library TAUOLA, used in KORALZ, is described in ref. [6] and corresponding leading-log radiative corrections in decays are generated as described in ref [7].

A few remarks on the limitations of the program: The total center of mass energy is restricted to the range from about 20 GeV to 150 GeV. One should keep in mind that the interference of bremsstrahlung from initial and final states can be neglected only close to the Z resonance [14].* The use of the program for production of u, d, s, c quarks and neutrinos requires an appropriate redefinition of the coupling constants and masses. The same is true for the muon pair production

* For a precision better than 1%, in general, the size of the interference correction should be checked with the help of the single bremsstrahlung mode of KORALZ, as explained in ref. [15]

process. The application of the program to the b quark mode requires a nontrivial modification of the electroweak correction library in order to include effects due the to the relatively large mass of b and t quarks (the latter in the virtual corrections only).

The outline of the paper is the following: in Chapter 2 we describe the functional structure of the program. In Chapter 3 it is explained how to use the program. Finally, in Chapter 4 the future developments of the program are discussed. In addition Appendix A covers a detailed description of the interface between electroweak libraries and, the rest of KORALZ and Appendix B explains modifications of the algorithm necessary in the quark and ν modes. In Appendix C it is explained how to reweight already generated (and analyzed) events and, in this way, change effectively the value of some input parameters. In Appendix D, we collect published important tests of the program and benchmarks. Finally, an extract from the output of the demonstration program is included at the end of the paper.

2. The structure of the program

The program consists of three distinct parts which are playing a different role and are, by the authors' intention, well separated into corresponding modules with the well-defined flow of information. They are as follows:

(A) The part of the program which simulates fermion pair production (no decay) including QED bremsstrahlung. In this part the inclusion of all spin effects and electroweak corrections is administered. Two types of the QED bremsstrahlung generators are employed: the YFS2 generator of ref. [4] and a modified version of MUSTRAAL [5] of ref. [12].

(B) The library TAUOLA [6] of the M.C. programs for simulating the exclusive decays of the polarized τ's.

(C) Two libraries of the $\mathcal{O}(\alpha)$ electroweak radiative corrections in the standard electroweak theory according to ref. [8] and refs. [11,16].

The four momenta of final state fermions and of additional bremsstrahlung photons are generated in part (A). The basic generator in this part is the YFS2 program of ref. [4] which generates the fermion pair and multiple initial state photons. The algorithm of ref. [13] is used subsequently in order to include the final state bremsstrahlung and the electroweak corrections. The other, single bremsstrahlung generator, similar to that of MUSTRAAL, is included for backward compatibility reasons (it is not precise enough for Z resonance). It was intensively used as a basic program for fermion pair production at PETRA/PEP. A rather detailed description may be found in ref. [5]. Three important modifications are made with respect to the original program: longitudinal spin polarization of $e^{\pm}$ and $\tau^{\pm}$ is introduced according to the prescription of ref. [12]. The final state fermions may have a mass comparable to beam energy (improved kinematics but not matrix element). In the case of the multiphoton generator YFS2 the initial-final state bremsstrahlung interference is neglected. This is well justified in the region of the Z peak [14] and in the absence of strong cut-offs. The production part of the program is supplemented with the subroutine `TRALOR4` which performs the Lorentz transformation from the final fermion rest frame ($\tau^{\pm}$) to the laboratory CMS frame. This subprogram is used in TAUOLA library.

In the present version the τ decay part (B) consists of the TAUOLA library which is able to simulate τ decays into seven exclusive channels: $\bar{\nu}e\nu$, $\bar{\nu}\mu\nu$, $\bar{\nu}\pi$, $\bar{\nu}\rho$, $\bar{\nu}a_1$, $\bar{\nu}K$, $\bar{\nu}K^*$, and into multi-pion decay channels. Radiative QED corrections in decays are included in the leading logarithmic approximation. A more detailed description of TAUOLA and its interface to KORALZ is available separately [6].

The electroweak corrections in part (C) (two options) are described in refs. [8] (see also. [9]) and [11,16]. These libraries of electroweak radiative corrections from the standard model should include also the gluonic (hadronic) effects (see e.g. refs. [18,17]). The interface between electroweak libraries and KORALZ is described in Appendix A.

Let us now comment briefly on the interrelation among the above three parts of the program. The spin amplitudes from (C) are used in (A), in the final stage on the M.C. shaping of the τ^+, τ^- and γ's samples. The effects due to GSW corrections are added by a rejection technique. The programs in the decay part (B) use, in the simulation of the τ decay, the spin polarization vectors of τ^+ and τ^- provided by the production part (A)*. In fact, most of the exchange of the information among the parts (A)-(C) goes through routine KORALZ which plays a role of the central manager subprogram. In particular all initializations necessary to initiate the work of (A), (B) and (C) are administrated by KORALZ. The calculation of $\sin^2\theta_W$ (using the definition $\cos\theta_W = M_W/M_Z$) out of the muon lifetime and the mass M_Z is also administrated within KORALZ during the initialization mode.

* Note the difference with respect to the KORALB program, where the full spin correlations are taken into account. In KORALZ the terms of the $\mathcal{O}(m_\tau^2/s)$ are neglected in the matrix element and only the helicities of the $\tau^{\pm}$ are passed to the decay routines.

3. How to use the program

A Monte Carlo event, i.e., a complete set of final state momenta and flavours, is generated by a single call to routine `KORALZ`. For example a complete sequence of calls which generates 1000 M.C. events may look like

```
      REAL*4 PB1(4),PB2(4),E1(3),E2(3),XPR(40)
      INTEGER*4 NPR(40)
      CALL KORALZ(-1,KFB,PB1,E1,-KFB,PB2,E2,XPR,NPR)
      DO 300 IEV=1,1000
      CALL KORALZ(0,KFB,PB1,E1,-KFB,PB2,E2,XPR,NPR)
300   filling histograms
      CALL KORALZ(1,KFB,PB1,E1,-KFB,PB2,E2,XPR,NPR)
```

Here, the first call (obligatory) on `KORALZ` sets the $e^{\pm}$ beam momenta and transfers other input parameters (so far no event generation), the second call generates a M.C. event, and the third call (optional) terminates the generation by printing some useful output and calculating the total cross section, partial widths in τ decays etc., corresponding to a generated sample. Generally, the input parameters are transferred as `KORALZ` parameters and the output results (momenta, flavours) are encoded in certain common blocks, described later in this Section.

Let us explain now in more detail the parameters of `KORALZ`. As is obvious from the above example the first parameter `MODE` in `KORALZ(MODE,...)` is simply saying whether `KORALZ` is called in initialization mode (`MODE=-1`), generation mode (`MODE=0`), or postgeneration mode (`MODE=1`).

3.1. Initialization mode

In the initialization mode (`MODE=-1`) the meaning of the parameters in
`KORALZ(MODE,KFB,PB1,E1,-KFB,PB2,E2,XPR,NPR)`
is the following: `REAL*4 PB1(4), PB2(4)` are four-momenta of the first and second beam (with `PB1(4)` and `PB2(4)` being the energy). Both momenta are necessarily along a third axis in the laboratory system (CMS) and `PB1` is required to have a positive third component. `INTEGER*4 KFB` is a flavour identifier of the first beam (ie. associated with `PB1`). `KFB=7,-7` denotes electron and positron respectively (the old Lund notation*). Two four vectors `REAL*4 E1(3), E2(3)` are spin polarization vectors of the first and second beam in the corresponding $e^{\pm}$ rest frames. For the first beam (`PB1,E1`), the rest frame used to define its spin polarization vector `E1` has its third axis directed along its line of flight, i.e., it is a standard helicity

⋆ This convention governs only the most external part of the program. It will be straightforward to apply new conventions like PDG codes [19] .

axis. For E2, the direction of the corresponding third axis is opposite to its line of flight, i.e., opposite to its helicity axis. For example `KFB=-7, E1=(0.0,0.0,1.0), E2=(0.0,0.0,1.0)`, means that the user asks for first beam being a right-handed positron and the second being a left-handed electron. Partial polarization is allowed, i.e., `E2=(0.0,0.0,0.5)` would represent a 50% polarized second beam. The flavour of the first beam defines also the flavour of the first τ. In the following, we will assume that `KFB=-7` and we will call the first τ the τ^+. If the first beam was chosen to be e^- (`KFB=7`) the first τ will be automatically defined as τ^- and not as τ^+. In this case, the user of KORALZ should keep in mind this redefinition when reading the rest of the paper. No transverse beam polarization is allowed, however. The other input parameters are transferred through matrices `REAL*4 XPR(40)` and `INTEGER NPR(40)`.

In the table below we give a short summary of all input parameters.

Parameter	Meaning
KFB	Flavour identifier of the first beam, KFB=7,-7 denotes electron and positron respectively (Lund notation).
PB1	Four momentum of the first beam. PB1(3)>0 necessarily.
E1	Spin polarization vector of the first beam. E1(3)=twice helicity.
PB2	Four momentum of the second beam.
E2	Spin polarization vector of the second beam. $-$E2(3)=twice helicity.
NPR(1)=ISPIN	Switch for spin effects in τ decay. Normally the user should set ISPIN=1, and when ISPIN=0 spin polarization effects in the decays are absent.
NPR(2)=INRAN	Initialization constant, INRAN$\geq$1, for random number generator used in the τ pair production part of M.C., obsolete.
NPR(3)=KEYGSW	Implementation level of the GSW standard electroweak model. For KEYGSW=0 there is no γ exchange in the s channel at all (only Z). For KEYGSW=1, γ and Z exchange is included (also in the presence of hard bremsstrahlung) but no vacuum polarization is included. KEYGSW=2,3 are obsolete. For KEYGSW=4 QED and electroweak corrections are combined together using a leading-log inspired approach [13].

Parameter	Meaning
NPR(4)=KEYRAD	Switch for the QED bremsstrahlung. KEYRAD=0 means no QED bremsstrahlung. KEYRAD=1 denotes single bremsstrahlung. KEYRAD=10 denotes single initial state bremsstrahlung with an "ad hoc" exponentiated photon spectrum. KEYRAD=11 provides $\mathcal{O}(\alpha)$ exponentiated initial state bremsstrahlung according to the algorithm of [4]. KEYRAD=12 denotes $\mathcal{O}(\alpha^2)$ initial state bremsstrahlung according to the algorithm of [4]. KEYRAD=111,112 differs from KEYRAD=11,12 by the inclusion of single final state bremsstrahlung.
NPR(5)=JAK1	The variable JAK1=1,2,3,4,5,6,7,8 defines the decay channel of τ^+ as being $\bar{\nu}e^+\nu$, $\bar{\nu}\mu^+\nu$, $\bar{\nu}\pi^+$, $\bar{\nu}\rho^+$, $\bar{\nu}a_1^+$, $\bar{\nu}K^+$, $\bar{\nu}K^{*+}$, $\bar{\nu}(n\pi)^+$, respectively. Furthermore, setting JAK1=0 causes the τ^+ to decay into all eight channels inclusively according to predefined branching ratios (see routine JAKER), and setting JAK1=−1 inhibits the decay completely.
NPR(6)=JAK2	The assignments of JAK2, for τ^-, are the same as of JAK1.
NPR(7)=ITFIN	This switch key allows to generate final state fermion pairs other than τ pairs. The τ pairs are produced with ITFIN=1, μ pairs with ITFIN=2, ν pairs with ITFIN=3. The quarks are produced with ITFIN=501-506. Quark masses are taken directly from KORALZ input. For ITFIN $>$ 1 the τ decay is automatically suppressed.
NPR(8)=ITDKRC	Switch for bremsstrahlung in the τ^- decay. 1/0= on/off.
NPR(9)=KEYWLB	Type of the Electroweak library in use: first library for KEYWLB=1 and second library for KEYWLB=2 (it can be used only for ITFIN=1,2).
NPR(11)=NNEUT	Number of the neutrino species. Relevant only in the neutrino mode, it has however no effect on the width.
XPR(1)=AMZ	Mass of the Z.
XPR(2)=AMH	Mass of the Higgs boson.
XPR(3)=AMTOP	Mass of the top quark.

Parameter	Meaning
`XPR(4)=GV`	Vector coupling constant g_V and
`XPR(5)=VA`	Axial coupling constant g_A of the τ to the W in the τ decay. Note that $g_V = 1$, $g_A = -1$ represent the standard $V - A$ assignment.
`XPR(6)=SWSQ`	$\sin^2\theta_W$. One has to assign SWSQ and GAMMZ for KEYGSW= 0.1
`XPR(7)=GAMMZ`	Width of the Z.
`XPR(8)=AMNUTA`	Mass of the ν_τ, It cannot be set exactly zero because of numerical stability.
`XPR(9)=AMNEUT`	Mass of the ν's in the ν generation mode, or the final state quark mass in the quark mode. Because of the massive kinematics used in the program it cannot be set exactly to zero.
`XPR(11)=XK0`	Soft/Hard photon cut-off for the final state bremsstrahlung mode or for the KEYRAD=1 mode.
`XPR(12)=VVMIN`	Minimal energy of the photon to be generated; typically below 10^{-5}. It should be at least a factor of 10 smaller than the detector energy detectability threshold.
`XPR(13)=VVMAX`	Maximum energy to be taken by the photon system XPR(13) ≤ 1.
`XPR(14)=XK0DEC`	Soft/Hard photon cut-off for the bremsstrahlung in the decay.

3.2. Generation/production mode

In this mode all parameters of `KORALZ`, except for `MODE=0`, are ignored. The produced Monte Carlo event is stored in the common block

```
COMMON / LUJETS / N,K(2000,2),P(2000,5)
```

The common block `LUJETS` contains a complete set of all initial and final state flavours and four-momenta encoded in the standard conventions of the Lund programs, see for more details the original reference [20]. It contains information on the $e^{\pm}$ beams, on the τ^+, τ^-, γ and finally on all the $\tau^{\pm}$ decay products including neutrinos. Conservation of total energy and momentum is explicitly obeyed. The intermediate particles like $W^{\pm}$ and $\rho^{\pm}$ are kept in the record, like in the Lund programs. If the user wants the π^0 to decay, it is done by means of `CALL LUEXEC`. Every event may be edited using `LUEDIT` and displayed using `LULIST`. These three routines belong to the Lund package JETSET [20]. In `KORALZ` itself, however, there is no explicit call to any Lund subprogram and KORALZ can be run without loading the Lund library.

In addition the final state momenta for the production process only may be found in
`COMMON / UTIL4 / QP(4),QM(4),PH(4)`
or in,
`COMMON / MOMSE4 / AQF1(4),AQF2(4), ASPHUM(4),ASPHOT(100,4),NPHOTA`
where `REAL*4 QP,QM (AQF1,AQF2)` are four-momenta of τ^+, and τ^- respectively and `REAL*4 PH (ASPHUM)` is the momentum of the bremsstrahlung photon in the case of single bremsstrahlung or the sum of all photon momenta (in GeV units). `NPHOTA` denotes the number of the generated photons. `REAL*4` matrix `ASPHOT` stores the four momenta of the photons. `QP` and `QM` are the momenta of the final state fermion $\bar{f}$ and f, the `PH=ASPHUM`. Helicities of τ^+ and τ^- are stored in the `COMMON / TAUHEL / HELT1,HELT2` as `REAL*8` variables.

3.3. Postgeneration mode

A call on `KORALZ` in this mode (`MODE=1`) may be optionally used in order to obtain information on the value of the integrated cross section and the list of the partial τ decay widths. They are obtained with a finite statistical error depending on the number of generated M.C. events and they correspond strictly to the production and decay matrix elements used in the actual M.C. generation*. All this information is printed in the output file and it is also provided to the user through parameter matrices `XPR` and `NPR`, see table below.

* For generation, however, different values of the branching ratios given in the `COMMON /TAUBRA/` and `/TAUNPI/` (see subroutine `INITDK`) are used. The values given here are not determining the proportion of the different channels in the decay sample but rather monitor properties of the matrix element used in the decay routines.

Parameter	Meaning
NPR(10)	Number of generated τ pairs.
XPR(10)	Total cross section in cm^2.
XPR(16)	Total cross section in cm^2 (the same as XPR(10)).
XPR(17)	Total cross section in nb.
XPR(18)	Statistical error on the total cross section in nb units.
XPR(21)	Partial width of $\tau \to \nu e \bar{\nu}$.
XPR(22)	Partial width of $\tau \to \nu \mu \bar{\nu}$.
XPR(23)	Partial width of $\tau \to \nu \pi$.
XPR(24)	Partial width of $\tau \to \nu \rho$.
XPR(25)	Partial width of $\tau \to \nu a_1$.
XPR(26)	Partial width of $\tau \to \nu K$.
XPR(27)	Partial width of $\tau \to \nu K^*$.
XPR(28-31)	Partial width of $\tau \to \nu n\pi$.

4. Possible future developments

As is clear from the list of the limitations in the Introduction a number of developments may be still desirable, e. g.

- Complete exponentiation of all QED bremsstrahlung: initial, final and interference.
- Complete $\mathcal{O}(\alpha)$ radiative corrections in the τ decay, or proof that presently available corrections are precise enough.
- Inclusion of missing τ decay modes.

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APPENDIX A

Interface of electroweak libraries to KORALZ

The interface between part (A) and part (B) or (C) of KORALZ has to be clearly defined. Physics of weak interactions and many details of τ decays were not so far probed experimentally with very high precision, and thus it may be necessary to change or replace parts (B) or (C). The interface between τ decay library TAUOLA and KORALZ is explained in detail in Ref. [6]. Here, let us concentrate on the interface between KORALZ and electroweak libraries.

In principle, the QED corrections are part of the Electroweak corrections, and as such, have to be calculated in the broader theory of Glashow-Weinberg-Salam. In fact such a separation can be done only up to the $\mathcal{O}(\alpha)$ and at higher orders to next-to-leading-log approximation. Starting from the non-logarithmic terms of $\mathcal{O}(\alpha^2)$ pure QED corrections alone do not have any phenomenological value at LEP, unless they are combined with the terms of the same order coming from the complete electroweak theory. Fortunately such terms are anyway expected to be too small to be seen.

In addition, it should be kept in mind, that one of the goals of the LEP experiments is to check the Standard Model. As a matter of fact, the electroweak non-QED corrections will be rather measured than predicted.

One of the convenient ways of dealing with the electroweak corrections is the following [13]:

– Construct the Monte Carlo program for QED, including only this part of electroweak corrections which can be absorbed into redefinition of the coupling constants and Z width (crude differential cross section).

– Provide an electroweak library which calculates all electroweak corrections, but excluding QED bremsstrahlung. Define routine calculating the two-body differential cross section $d\sigma/d\Omega(s,\Theta)$ with all non-QED corrections.

– Design an algorithm (reduction procedure) which combines photon momenta with incoming and outgoing fermion momenta in such a way that the effective two-body hard scattering process is defined [13].

In the KORALZ we follow the outline described above, and the electroweak corrections are implemented by means of rejection. For every event we first generate a M.C. event assuming a simplified form of the (crude) cross section, that is we include only those electroweak corrections which can be absorbed into energy independent coupling constants and Z width.

In the second step, by means of rejection, we introduce the remaining and numerically small part of the electroweak corrections. To this end we calculate for each event a weight (with the help of hard scattering process variables) equal to the ratio of the complete electroweak cross section calculated in a particular point of the phase space and the previously used crude one. In principle there is no restriction on the crude cross section. If it is close to the corrected one then the efficiency of the algorithm gets improved. However, the angular distribution of the crude cross section due to technical reasons must have always the following form: $1+\cos^2\theta + \mathrm{Const}\cdot\cos\theta$. More precisely such an algorithm can be used for implementation of relatively small corrections e.g. of the $\mathcal{O}(\alpha)$. The error in their implementation, due to approximations used in reduction procedure, is of the $\mathcal{O}(\alpha^2)$. The overall normalization is an exception, there is no error in its implementation by the method described above.

To interface any new electroweak library to KORALZ the following routines have to be replaced with the new ones:

```
SUBROUTINE MASET(AMZ,AMH,AMT)
IMPLICIT REAL*8 (A-H,O-Z)
COMMON /BEAMPM/ ENE,AMIN,AMFIN,IDE,IDF
CALL GIVIZO(IDE,1,AIZOR,QE,KDUMM)
CALL GIVIZO(IDF,1,AIZOR,QF,KOLOR)
.......
END
```

```
SUBROUTINE PRMOUT(ZMASS,GAMZ0,GAMZ,WMASS,GAMW0,GAMW,SIN2W)
IMPLICIT REAL*8 (A-H,O-Z)
.......
END
FUNCTION BORNR(MODE,SVAR,TA,TB)
IMPLICIT REAL*8 (A-H,O-Z)
COMMON /INSPIN/ SEPS1,SEPS2
.......
END
FUNCTION ALFSPI(S)
IMPLICIT REAL*8 (A-H,O-Z)
.......
END
```

Calls to all those routines are already defined within the KORALZ library and the only communication between KORALZ and electroweak libraries is the following: `SUBROUTINE MASET` initialize electroweak library. Variables `AMZ,AMH,AMT,` denote the values (in GeV) of Z, Higgs and top masses which are transmitted from KORALZ to the electroweak library. Also the content of the common `/BEAMPM/` is predefined in KORALZ before any call on the electroweak library. The variables `ENE,AMIN,AMFIN,IDE,IDF` denote respectively beam energy, electron and final state masses (all in GeV), and flavour identifiers for the beams and final state fermions `IDF(IDE)`$= 1,2,3,4$ denote respectively neutrino, lepton, up-type quark and down-type quark. The routine `GIVIZO` calculates from the flavour identifiers `IDE,IDF` charges `QE,QF` and color factor `KOLOR`. All these parameters may be needed to initialize the electroweak library.

KORALZ calls on routine
`PRMOUT(ZMASS,GAMZ0,GAMZ,WMASS,GAMW0,GAMW,SIN2W)`,
of the electroweak part which transmits some parameters of electroweak corrections wherever they may turn out to be needed. The (output) parameters of routine `PRMOUT` denote respectively: Z mass, lowest order and including corrections width, W mass, lowest order and including corrections width, and finally $\sin^2\theta_W$. The function `ALFSPI(S)`$=\alpha_s(s)/\pi$ is used in KORALZ, where it is needed in the quark mode in order to calculate final state gluonic corrections as described later in Appendix B.

Functionally, the most important part of the interface is the function
`BORNR(MODE,SVAR,COSTHE,TA,TB)` which calculates two-body cross section. The meaning of its parameters is the following: `MODE` denote the mode of the operation. For `MODE`$=0$ a crude distribution should be calculated, otherwise complete electroweak corrections should be included. The `SVAR`$=s$ denotes a Mandelstam variable of the reduced process, `COSTHE`$=\cos\theta$ an angle between directions of τ^+ and e^+. Variables `TA,TB` denote polarization states of the final state fermions. They

denote respectively twice helicity of τ^+ and minus twice helicity of τ^- (in general first and second final state fermions). In KORALZ only values `TA,TB=`$\pm1,0$ are used. According to the same conventions spin polarization states `SEPS1,SEPS2` of the beams are defined. In this case any value between -1 and $+1$ can be provided from KORALZ.

Let us note that if it would be necessary to change/add an electroweak library in the future, the overall normalization of the function `BORNR` has to be chosen in such a way that for the unpolarized muon cross section (in the massless limit), and pure γ s-channel, the cross section is given by the following formula: $1+\cos^2\theta$. Finally, for the sake of tests and backward compatibility the interface to the electroweak library should be organized in such way that, once input of KORALZ `KEYGSW` is chosen to be 1 (no electroweak corrections), the interface returns exactly the same distribution as the one presently available in KORALZ. For this purpose it is compulsory that additional input parameters are transmitted from KORALZ to the electroweak library interface. Consequently the common blocks

```
/GSWPRM/ SWSQ,AMW,AMZ,AMH,AMTOP,GAMMZ
/KEYSET/ KEYGSW,KEYRAD,KEYTAB
```

should be used in routine `BORNR`. Variable `SWSQ` denotes $\sin^2\theta_W$, and `AMZ,GAMMZ` respectively Z mass and width. Z coupling constants are calculated from $\sin^2\theta_W$ following conventions defined in [5]. In this last case the call on the routine `MASET` initializing the electroweak library is *not executed.*

At present, KORALZ is interfaced with the two electroweak libraries; by the Dubna-Zeuthen group [8], see also [9], and by W. Hollik [11,16]. Note that the interface of KORALZ to the electroweak library by R. Stuart [21] is also available.

APPENDIX B

Extension of the program to the q and ν cases*

In order to switch from the $e^+e^-\to\mu^+\mu^-$ process to $e^+e^-\to\nu\bar{\nu}$, we change the final state couplings (i.e., reverse the weak isospin, set the charge to 0), and add the W exchange in the t-channel graph, to the Z exchange in the s-channel graph.

Because the W exchange contribution is small, it is enough to use the following leading logarithmic approximation. We neglect emission of the photons from the W and we assume the t-channel $\gamma-W$ boxes can be described by the same function as the $Z-e-e$ vertex corrections. The first approximation has been proved to be very good [22]. In the crude cross section we use contact approximation for the

* The extension of KORALZ to the ν case was developed with the active collaboration from Laurent Mirabito and Paul Colas.

W exchange. The remaining very small correction to the contact approximation is introduced later by rejection. See refs. [23,24] for more details.

The case of the light quark production is very simple. We change the charge and isospin of the final state fermions, add color factor and an overall factor $1 + \alpha_S(M_Z^2)/\pi + \alpha_S^2(M_Z^2)(1.98 - N_F \cdot 0.115)$, in order to obtain proper normalization of the cross section.[⋆] The trivial b quark mass terms in kinematics and Born matrix element are included. The electroweak libraries (like DIZET [8]) must also include top mass dependent vertex corrections.

APPENDIX C

The algorithm saving CPU time

A definite drawback of the Monte Carlo programs generating series of events for the physical processes is the limited possibility of playing with input parameters and looking into their influence on the quantities directly related with the measurements in a given experiment. It is particularly true for full scale detector simulation when the computer time needed by Long Chain (LC)[*] to process one event, is sometimes more than 1 min. of the typical mainframe CPU time. Thus, physical events are generated only once, then are processed through the Long Chain and are archived on the tape for any further usage.

This leaves very little room (if any) for the analysis of the influence of variation of the input parameters (such as Higgs or top masses or addition of another heavy fermion family or second heavy boson) on the generated sample of events. Let us sketch a possible *solution of the problem*, using as an example the process $e^+e^- \to \tau^+\tau^-$.

The differential cross section after inclusion of the radiative corrections differs significantly from the Born cross section. Completely new final states, such as $\tau^+\tau^-\gamma$, which cannot be obtained by any means from (LC) events, generated using the Monte Carlo program for the cross section in Born approximation. Fortunately, at LEP energies appearance of the extra particles (in practice only photons) in the final state is caused by the best known (and to some extent non-interesting) and well-established part of the Standard Model, i.e., by QED.

On the contrary the effects of the modifications in the *non*-QED part of the Standard Model can be represented as,

---

⋆ Note that this overall scaling factor does not take into account terms which distinguish between QCD corrections to axial and and vector couplings of the Z [25].

* This name is used to describe the procedure of: (1) digitalization, i.e., complete simulation of the detector response to the particular event (to get an event in a form identical to the one registered in the experiment); (2) evaluation back of the physical content of the event by means of the reconstruction programs (i.e., procedures prepared for the reconstruction of the events registered in the experiment).

$$\frac{d\sigma^{modif}}{d\Omega} = \frac{d\sigma^{ORIGINAL}}{d\Omega} w^{modif}(\Omega)$$

with positive function $w^{modif}(\Omega)$ which is close to 1 essentially* all over the phase space.

This opens a possible way of dealing with the modification in the Standard Model in a way which does not require repetition of the Long Chain analysis.

The complete scenario would look as follows:

(1) The series of events are generated according to certain configuration of parameters in the Physics Monte Carlo event generator.

(2) The Long Chain analysis is performed on those events.

(3) All events which passed the Long Chain (LC events) are archived on the tape.

(4) A new set of input parameters (or modified version of electroweak model) is chosen.

(5) For every LC event, at the corresponding point in the phase space we recalculate the value of the differential cross section which was used in the original generation. At the same point we calculate a new value of the differential cross section corresponding to modified parameters. We assign the ratio of these two cross sections, w^{modif}, to every LC event. With this weight we treat the entire series of old LC events as if it was generated with the new parameters.

Applicability of such a scenario requires some precautions and prearrangements. From the user side, the stored LC event has to include enough information to recalculate the value of the differential cross section at the corresponding point of the phase space.

On the other hand, in the Physics Monte Carlo program there should exist a clearly defined function, easy for further modifications and extensions, which calculates the (QED reduced) differential cross section out of momenta of final state particles.

In the case of KORALZ, the function `BORNS(MODE,SVAR,COSTHE,T1,T2)` of the same parameters as function `BORNR` described in Appendix A may be used for this purpose. For every generated event parameters of the function `BORNS` have to

* This statement is not valid only in the small regions ($\cos\theta = \pm 1$ and $\sqrt{s} \simeq M_Z \mp 15GeV$) of the phase space where the differential cross section approaches zero. Change in the input parameters may shift position of this zero and there the function $w^{modif}(\Omega)$ may differ significantly from 1. These regions (of cross section very close to 0) give a negligible contribution to observables and may be excluded from this consideration.

be stored. The numerical value of `T1,T2` may be picked up from the common block `TAUHEL`, `T1=HELT1`, `T2=-HELT2`. The `SVAR,COSTHE` can be obtained by the additional call to routine `BDRESS(1,PPBT,PMBT,SVAR,COSTHE)` after an event is generated. The `PPBT(4),PMBT(4)` are declared as `REAL*8`. Then, for each archived LC event the weight w^{modif} can be calculated using the `BORNS` function and initializing KORALZ once with the old and once with the new set of the input parameters. The function BORNS calculates the differential distribution of the final state fermions without QED bremsstrahlung corrections but including weak corrections.

In an analogous although a bit more involved way, the nontrivial transverse spin correlations between decay products of τ^+ and τ^- can be included into series of LC events. This topic will be covered elsewhere.

APPENDIX D

Numerical tests of the program

The present version of KORALZ differs from the previously available (unpublished) version 3.7 in the following respect:

- improvements on the top mass dependence of the electroweak corrections are introduced.
- final state fermion mass terms are included; important for b quarks.
- the sign of the parity violating term in a_1 decay of τ^- that is a sign of the determinant built up from the momenta of $\pi^-\pi^-\pi^+$ is corrected.
- the ν_τ mass terms are included in all decay modes.
- the ρ and a_1 form factors are improved. Present form factors are identical to the ones described in [26].
- the change of the *internal* order of particles was introduced. Contrary to the version 3.7 where the first τ (or μ etc.) stored in the common blocks was always τ^+, it is now the τ of the same charge as the *first* beam. The direction of the first beam (which can be electron or positron) is now fixed and has to be always in the direction of the z-axis.
- the mass of the final state, if it is chosen to be a quark pair is now initialized through parameters of the `KORALZ` routine.
- the random number generator RANMAR was replaced by the official version [27].

The program of the size and complexity, as is the case with KORALZ, requires exhausting testing before it can be considered reliable. So far the following tests and groups of tests were performed which can be reproduced by the user of the program.

1. In Ref. [6] tests on the τ decays are reported.
2. In the description of the YFS2 [4] generator for the initial state multiphoton bremsstrahlung, some tests are reported.
3. Comparison of results by KORALZ with other ν generator can be found in refs. [23,24].
4. The prediction of KORALZ for the forward backward asymmetry of muons was compared with the analytical calculations in refs. [28], see also [15].
5. The τ polarization observables were compared with semi-analytical calculations, including also the leading logarithmic bremsstrahlung corrections in decay, in ref. [29].
6. A multitude of other comparisons with the semi-analytical program CALASY [30], in particular for the total cross section, can also be found in [31].
7. The further options of calculations of electroweak corrections were compared [9,15] with the ones actually used in KORALZ.

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