UNIBAB, Version 2.2: Monte Carlo Event Generation for Large Angle Bhabha Scattering at LEP and SLC Energies*

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Abstract

This manual describes version 2.2 of the Monte Carlo event generator UNIBAB for large angle Bhabha scattering at LEP and SLC. UNIBAB implements higher order electromagnetic radiative corrections and the effects of soft photon exponentiation in a photon shower approach. Weak corrections are included through the use of an electroweak library.

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Program Summary:

- **Title of program:** UNIBAB, Version 2.2 (December 1995)
- **Program obtainable from:**
  [ftp://crunch.ikp.physik.th-darmstadt.de/pub/anlauf/unibab](ftp://crunch.ikp.physik.th-darmstadt.de/pub/anlauf/unibab)
- **Programming language used:** FORTRAN-77
- **Computer/Operating System:** Any with a FORTRAN-77 environment
- **Number of program lines in distributed program, including test data, etc.:** \( \approx 9000 \) (Including comments)
- **Keywords:** radiative corrections, large angle Bhabha scattering, multiphoton radiation
- **Nature of physical problem:** Higher order leading logarithmic QED radiative corrections to large angle Bhabha scattering \((e^+e^- \rightarrow e^+e^- + n\gamma)\) including weak corrections at Z energies and beyond
- **Method of solution:** Monte Carlo event generation
- **Restrictions on the complexity of the problem:** The program assumes dominance of the \( s \)-channel Z exchange contribution and does not include the interference between initial and final state radiation. Therefore, the program is primarily designed to be used in the vicinity of the Z peak and only for not too small and not too large scattering angles \((10^\circ < \theta^* < 170^\circ)\). With somewhat limited accuracy, the program is also useful for LEP2 energies. For cross checks, the contributions of the \( t \)-channel diagrams may be switched off, so that the program effectively simulates \( e^+e^- \rightarrow \mu^+\mu^- \). However, the latter mode is not very efficient.
- **Typical running time:** Strongly dependent on the energy and the chosen cuts. The test run took approximately 55 CPU seconds on a DEC Alpha 3000-600 running Digital Unix, 65 CPU seconds on an SGI Challenge running IRIX, 80 CPU seconds on an HP 9000/735 running HP/UX, 355 CPU seconds on an IBM RS/6000-520 running AIX, and 485 CPU seconds on an Intel 486DX50 running Linux.
1 Introduction

The study of electroweak physics in \( e^+e^- \)-collisions close to the Z resonance has proven to be extremely fruitful \cite{1-3}. The precision measurements of the Z parameters are very powerful in constraining the as yet unknown electroweak parameters and allow to put stringent limits on potential physics beyond the standard model.

In the context of these precision measurements, small angle Bhabha scattering plays a major role because all LEP/SLC experiments use it for their luminosity measurements. Consequently, from the beginning much effort has gone into the construction of semi-analytical programs \cite{4} and Monte Carlo event generators \cite{4} for Bhabha scattering in the small angle regime. With improved statistics, systematic errors begin to dominate, to which the theoretical uncertainties in the calculation of cross sections give an important, by now even sometimes dominating, contribution. At the level of a required precision of the order of 0.1\%, the inclusion of higher order electromagnetic corrections is indispensable and is taken care of in state-of-the-art calculations and Monte Carlo programs, as reviewed in \cite{2, 6}.

In contrast, the situation for large angle Bhabha scattering is less favorable. In the vicinity of the Z peak, s-channel Z exchange and t-channel photon exchange are of similar importance, thus the calculation of radiative corrections is more involved than in the case of fermion pair production or small angle Bhabha scattering. For typical experimental cuts, the radiative corrections to large angle Bhabha scattering are numerically much larger than to small angle Bhabha scattering, and higher order electromagnetic corrections are of much higher importance. Nevertheless, large angle Bhabha scattering at LEP1 and SLC in principle provides a sensitivity to the parameters of the electroweak sector of the Standard Model comparable to the other charged lepton final states, \( \mu^+\mu^- \), \( \tau^+\tau^- \). In the energy regime of LEP2, the contribution of Z exchange to the Bhabha cross section is much smaller than at LEP1/SLC, hence it can be considered essentially as a general QED test.

The state-of-the-art for large angle Bhabha scattering is reviewed in \cite{6}. While semi-analytical calculations \cite{7-12} provide reliable predictions for a predefined set of cuts, it is nevertheless experimentally desirable to provide a comparable precision in a full Monte Carlo event generator, which will then allow to impose arbitrary cuts, and to simulate the response of the detector to \( e^+e^- \rightarrow e^+e^- \) events.

The present paper describes the implementation and status of the Monte Carlo event generator \texttt{UNIBAB} 2.2 that provides a level of precision comparable to semi-analytical programs. It is an update of the first published version 2.0 \cite{13}, and has been compared with other available Monte Carlo event generators (\texttt{BHAGENE3} \cite{14} and \texttt{BHWIDE} \cite{15}) as well as available semi-analytical calculations \cite{6} both for LEP1 and LEP2 energies.

The distinguishing feature of \texttt{UNIBAB} from fixed order Monte Carlo event generators...
is that it handles the leading logarithmic contributions
\[ \frac{\alpha}{\pi} \log \left( \frac{s}{m_e^2} \right) \approx 6\% \quad \text{(at LEP/SLC energies)} \] (1)
to the electromagnetic radiative corrections to all orders in a Monte Carlo parton shower algorithm, which includes the very important exponentiation of the soft photon contributions automatically, as well as the contributions from multiple emission of hard collinear photons. In addition, UNIBAB contains the full kinematics from multiphoton emission, since the radiated photons are generated explicitly.

The first version of the Monte Carlo generator, UNIBAB89 [16,17], was a “QED dresser” in the sense of [1], i.e. it contained only the QED corrections to an effective Born cross section. It also suffered from several serious limitations (see appendix B). In version 2.0 of UNIBAB, most of these limitations were overcome using the experiences with the Monte Carlo event generators KRONOS [18] and KROWIG [19] for deep inelastic scattering at HERA. Weak corrections are included through the use of an electroweak library.

This write-up is organized as follows: In section 2 we outline the physics underlying the algorithms implemented in UNIBAB. The actual implementation is described in section 3. The parameters controlling the execution of UNIBAB are discussed in detail in section 4, and the FORTRAN-77 interface is presented in section 5. Section 6 contains our conclusions. Distribution rules, the revision history, a listing of all external symbols and an example can be found in the appendices.

## 2 Bhabha Scattering at High Energies

In the structure function formalism [6,20–22] the factorized expression for the differential cross section for the process
\[ e^+(p_+)e^-(p_-) \rightarrow e^+(p'_+)e^-(p'_-) [\gamma(k_1) \cdots ] \] (2)
reads
\[
\frac{d^4\sigma}{dt_+dt_-du_+du_-} = \int_0^1 dx_+dx_-dy_+dy_- \Gamma(x_+, Q^2)\Gamma(x_-, Q^2)D(y_+, Q^2)D(y_-, Q^2)
\times \frac{d^4\hat{\sigma}}{\partial(t_+, \hat{t}_-, \hat{u}_+, \hat{u}_-)} \frac{d^4\hat{\sigma}}{d\hat{t}_-d\hat{u}_+d\hat{u}_-} \quad (3)
\]
where \( \hat{\sigma} \) is the Born level cross section of the hard process, \( \Gamma(x_i, Q^2) \) are the structure functions for initial state radiation, \( D(y_i, Q^2) \) are the fragmentation functions used for final state radiation, and \( Q^2 \) is the factorization scale. The invariants are defined as
follows

\[ s = (p_+ + p_-)^2 \]  
\[ \hat{s} = (x_+ p_+ + x_- p_-)^2 = x_+ x_- s \]  
\[ t_\pm = \left( p_\pm - p'_\pm \right)^2 \]  
\[ \hat{t}_\pm = \left( x_\pm p_\pm - \frac{p'_\pm}{y_\pm} \right)^2 = \frac{x_\pm}{y_\pm} t_\pm \]  
\[ u_\pm = \left( p_+ - p'_+ \right)^2 \]  
\[ \hat{u}_\pm = \left( x_+ p_+ - \frac{p'_+}{y_+} \right)^2 = \frac{x_+}{y_+} u_+ \]  

where the electron mass has been neglected. In the absence of photon radiation we have of course \( t_+ = t_- \) and \( u_+ = u_- \).

Here we restrict ourselves to the leading log approximation (LLA) where the structure functions \( \Gamma(x, Q^2) \) and \( D(x, Q^2) \) are identical. The structure functions \( D \) satisfy the evolution equation [20, 23, 24]

\[ Q^2 \frac{\partial}{\partial Q^2} D(x, Q^2) = \frac{\alpha}{2\pi} \int \frac{dz}{z} [P_{ee}(z)] D \left( \frac{x}{z}, Q^2 \right) \]  

with initial condition

\[ D(x, m_e^2) = \delta(1 - x) \]  

An explicitly regularized version of (10) which is used in the Monte Carlo implementation is given by

\[ Q^2 \frac{\partial}{\partial Q^2} D(x, Q^2) = \frac{\alpha}{2\pi} \int \frac{dz}{z} P_{ee}(z) D \left( \frac{x}{z}, Q^2 \right) - \frac{\alpha}{2\pi} \left[ \int_0^{1-\epsilon} dz P_{ee}(z) \right] D(x, Q^2). \]  

2.1 The Algorithms for Multiphoton Radiation

2.1.1 Initial State Radiation

From (11) it is obvious that the implementation of (8) in a Monte Carlo event generator amounts to solving (13) by iteration and taking into account the energy loss in the hard cross section.
The initial state branching algorithm, which is implemented as a photon shower algorithm, has already been described in ref. [18]. It has been taken over essentially unchanged, the only modification is that we require conservation of four-momentum at every emission vertex and allow the electron momentum to take on off-shell values after initial state radiation. The off-shell momenta of the electron and positron after initial state branching are then used as the input momenta for the subgenerator of the hard Bhabha cross section. In the present version, the factorization scale used for initial state radiation is fixed to $Q^2 = s$.

### 2.1.2 Final State Radiation

In the vicinity of the $Z$ peak and for not too small scattering angles, the cross section is dominated by $s$-channel $Z$ exchange. Therefore we use the following approach. If we neglect interference between initial- and final-state radiation, the radiative corrections in the final state will then be well approximated by the radiative corrections to $Z$ decay.

The differential decay rate for one-photon emission $Z \to e^+e^-\gamma$ is related to the decay $Z \to e^+e^-$ at lowest order [25]:

$$\frac{d\Gamma^{(3)}}{dx_1dx_2d\Omega_{1,2}} = C_1(x_1, x_2) \cdot \frac{d\Gamma^{(2)}}{d\Omega_1} + C_2(x_1, x_2) \cdot \frac{d\Gamma^{(2)}}{d\Omega_2}$$

(14)

where

$$C_1(x_1, x_2) = \frac{\alpha}{2\pi} \frac{x_1^2}{(1 - x_1)(1 - x_2)}$$

$$C_2(x_1, x_2) = \frac{\alpha}{2\pi} \frac{x_2^2}{(1 - x_1)(1 - x_2)}$$

Here $d\Gamma^{(2,3)}$ denotes the differential decay width of $Z$ into $e^+e^-$ ($e^+e^-\gamma$), $d\Omega_{1,2}$ refers to the direction of the outgoing $e^+$ ($e^-$) in the $Z$ rest frame, and $x_1$ and $x_2$ are the energy fractions of $e^+$ and $e^-$ for the radiative decay. For a more detailed description we refer the reader to [25].

It is easily verified that, in the limit of emission of soft photons or photons (almost) collinear with the outgoing fermions, eq. (14) reduces to

$$\frac{1}{\Gamma^{(2)} dx_1dx_2} \sim s^2 \frac{x_1^2 + x_2^2}{(2p^+_\gamma \cdot k)(2p^-_\gamma \cdot k)},$$

(15)

which exhibits the leading soft and collinear singularities that have to be resummed to all orders.

We choose the phase space boundary such that the leading logarithms are correctly reproduced,

$$1 - x_3(1 - \eta) < x_{1,2} < 1 - x_3\eta, \quad \epsilon < x_3 < 1$$

(16)

with
\[ x_1 + x_2 + x_3 = 2. \]

The parameter \( \eta \) is therefore related to the factorization scale \( Q^2 \) associated with final state radiation:

\[ \ln \left( \frac{1}{\eta} \right) = \ln \left( \frac{Q^2}{m_e^2} \right) - 1 \] (17)

In the case of multiphoton final state radiation approximations are necessary. Our main concern is the proper infrared and collinear limit of the effective radiation matrix element, plus a good approximation for the photon that carries the largest transverse momentum relative to the outgoing fermions, while we want to neglect the interference between successive emissions, and assume that the radiated photons are widely separated in phase space. One can easily see that iteration of the single photon emission algorithm satisfies these criteria and reproduces the leading logarithms, provided the following virtuality ordering conditions are met. Denote by \( x_1^{(i)}, x_2^{(i)}, i = 1, \ldots, n \), the phase space variables for the case of emission of \( n \) photons. The phase space variables are then required to satisfy

\[ \min \left[ 1 - x_1^{(1)}, 1 - x_2^{(1)} \right] > \min \left[ 1 - x_1^{(2)}, 1 - x_2^{(2)} \right] > \cdots > \min \left[ 1 - x_1^{(n)}, 1 - x_2^{(n)} \right] \] (18)

which are the analogue of the ordering conditions (15) resp. (17) of ref. \[18\], except that they are reversed. This, together with the phase space (16), guarantees the proper normalization of the leading logarithmic terms.

\[
\int_{\text{PS}} \prod_{i=1}^{n} dx_1^{(i)} dx_2^{(i)} \left[ C_1(x_1^{(i)}, x_2^{(i)}) + C_2(x_1^{(i)}, x_2^{(i)}) \right] = \frac{1}{n!} \left\{ \int dx_1 dx_2 \left[ C_1(x_1, x_2) + C_2(x_1, x_2) \right] \right\}^n \\
= \frac{1}{n!} \left\{ \frac{\alpha}{\pi} \left[ \ln \frac{1}{\eta} \left( 2 \ln \frac{1}{\epsilon} - \frac{3}{2} \right) - \frac{1}{2} \right] \right\}^n \\
= \frac{1}{n!} (\bar{n}_f)^n \] (19)

The algorithm for final state multiphoton radiation is thus defined as follows. i) Determine the number of photons \( \bar{n}_f \) emitted from the final state according to (19). ii) In the case of single-photon emission, use distribution (14), with phase space limits (16). iii) For emission of multiple photons, iterate the algorithm for single photon radiation, taking into account the phase space conditions (18).

### 2.2 The Effective Born Amplitude

The calculation of the effective Born amplitude follows the BHM/WOH approach as described in \[2,28\]. The amplitude for \( e^+e^- \to e^+e^- \) including virtual corrections can be
cast into a form close to the lowest order amplitude:

\[ A(e^+e^- \rightarrow e^+e^-) = A_s^{(\gamma)} + A_s^{(Z)} + A_i^{(\gamma)} + A_i^{(Z)} + (\text{box}) , \] (20)

where \( A^{(\gamma)} \) denotes the dressed photon, \( A^{(Z)} \) the dressed Z exchange amplitudes, and \( (\text{box}) \) the terms from box diagrams, which can be essentially neglected around the Z peak.

The dressed photon exchange amplitude is written as

\[
A_s^{(\gamma)} = \frac{e^2}{1 + \Pi^{\gamma}(s)} \frac{Q_e^2}{s} \left[ (1 + F_V^{\gamma e}) \gamma_\mu - F_A^{\gamma e} \gamma_\mu \gamma_5 \right] \otimes \left[ (1 + F_V^{\gamma e}) \gamma^\mu - F_A^{\gamma e} \gamma^\mu \gamma_5 \right] ,
\]

while the Z exchange amplitude is given by

\[
A_s^{(Z)} = e^2 D_Z(s) \left[ (v_e + F^{Ze}_V + Q_e \hat{\Pi}^{\gamma Z}(s)) \gamma_\mu - (a_e + F^{Ze}_A) \gamma_\mu \gamma_5 \right] \otimes \left[ (v_e + F^{Ze}_V + Q_e \hat{\Pi}^{\gamma Z}(s)) \gamma^\mu - (a_e + F^{Ze}_A) \gamma^\mu \gamma_5 \right] .
\]

2.3 QED Virtual Corrections

Besides the weak virtual corrections that are easily included in the effective Born amplitude (20), we have to include the QED virtual corrections (vertex corrections, box corrections). In addition, we have to properly include the contributions from soft-photon emission beyond leading logs.

The method of inclusion of nonleading QED corrections in the structure function formalism is well known (see e.g. ref. [29]). However, to preserve a fully factorized form of the cross section similar to (3), which is mandated by our implementation of initial- and final-state radiation, we refrain from introducing \( K \)-factors and proceed as follows.

The effective Born amplitude is multiplied by (helicity-dependent) form-factors, as given explicitly e.g. in the appendix of ref. [7]. The photon-mass singularities in the form-factors are explicitly canceled against the soft-photon contribution. The infrared-singular parts are factored out and absorbed into the structure functions and fragmentation functions, thus uniquely determining an infrared-finite nonleading correction.

The cross section determined by this matching procedure in principle fully reproduces the \( O(\alpha) \) corrections in the soft limit. However, since the actual photon shower algorithms do not yet include initial-final interference, we have to drop the infrared-finite pieces of the QED boxes and corresponding terms from the soft-photon corrections for a consistent treatment.
2.4 Implementation of the Bhabha Cross Section

The differential cross section for the hard subprocess is implemented in a standard way, using importance sampling techniques. As a majorant function for the differential cross section, we use ($\tau \equiv -t/s = (1 - \cos \theta_{\text{cma}})/2$)

$$\frac{d\bar{\sigma}}{d\tau}(s, \tau) = A(s) + \frac{B(s)}{\tau^2}.$$  \hspace{1cm} (23)

The functions $A(s)$ and $B(s)$ are chosen such that the peaking behaviour of the full cross section for small angles as well as the resonant behaviour for large angles in the vicinity of the Z peak is efficiently reproduced:

$$A(s) = \frac{4\pi\alpha(s)^2}{s^2} \cdot \frac{\chi_Z^2(s)}{2} \left( \left( v_e^2 - a_e^2 + \frac{s - M_Z^2}{s} \right)^2 + \frac{M_Z^2 \Gamma_Z^2}{s^2} \right)$$  \hspace{1cm} (24)

$$B(s) = \frac{4\pi\alpha(s)^2}{s^2} \cdot \left[ 1 + C\chi_Z^2(s) \left( v_e^2 + a_e^2 \right) \left| \frac{s - M_Z^2}{s} \right| \right]$$  \hspace{1cm} (25)

where

$$\chi_Z^2(s) = \frac{s^2}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}.$$  \hspace{1cm} (26)

Here $\alpha(s)$ is the running QED coupling constant, and $v_e$ and $a_e$ denote the vector and axial vector couplings of the electron to the Z. The parameter $C \approx 0.1$ has been empirically adjusted so that $d\bar{\sigma}/d\tau$ is a majorant of the effective Born cross section.

The angular distribution is generated by a combined mapping and rejection algorithm with mapping function

$$\frac{A(s)}{B(s)} \tau - \frac{1}{\tau} = \chi(\tau) = \chi(\tau_{\text{max}}) \cdot \rho + \chi(\tau_{\text{min}}) \cdot (1 - \rho),$$  \hspace{1cm} (27)

and corresponding event weight,

$$w = \frac{d\sigma(s, \tau)}{d\bar{\sigma}(s, \tau)},$$  \hspace{1cm} (28)

where $d\sigma$ is calculated using the effective Born amplitude, as described in the previous sections.

3 Implementation of UNIBAB 2.2

Like almost all Monte Carlo event generators, UNIBAB is divided into three parts: initialization, generation, termination. These are described in this section.
3.1 Initialization of UNIBAB

The initializations in UNIBAB are used for computing the value of variables that will be used frequently during event generation. The primary example is the calculation of electroweak couplings, widths, and masses from a set of input parameters. To this end, the generic initialization routine ubinit calls the subroutine ubigsw which contains a simple interface to the initialization routine of the electroweak library.

Furthermore, internal steering parameters are derived from the cuts specified by the user. Finally, a standard /hepevt/ initialization record is written [1], which can be read by the analysis program.

3.2 Event Generation

The routine ubgen produces an event on every call. The four momenta are written to a standard /hepevt/ [1] event record, where they can be read by user supplied analyzers (the default configuration uses hepawk [2]). See section 5 for details on UNIBAB’s use of /hepevt/.

After generation of the initial state radiation by the branching routine ubbini, a raw Bhabha event corresponding to the approximate cross section \( \bar{\sigma} (\text{ubxtot}) \) is generated at reduced lepton energies with the corresponding angular distribution (ubgt). This event will be given a weight according to the ratio of the full differential cross section including weak corrections (ubxdif) to the approximate one (ubxtri).

Next, the routine ubgppr constructs the four-vectors of the leptons after the hard scattering in the effective c.m.s. frame. Finally, after generation of the final state radiation by the branching routine ubbfin, the event will be accepted in ubgacc if it passes the given experimental cuts, otherwise it will be rejected and the above algorithm repeated.

3.3 Termination

The cross section for the generated events, and its error, are obtained from the standard formulae

\[
\sigma_{\text{tot}}(s) = \max_{s' > s_0} \{ \bar{\sigma}(s') \} \cdot \frac{\text{# of successful trials}}{\text{total # of trials}} \quad (29)
\]

\[
\Delta \sigma_{\text{tot}}(s) = \max_{s' > s_0} \{ \bar{\sigma}(s') \} \cdot \sqrt{\frac{(\text{total # of trials} - \text{# of successful trials}) \cdot \text{# of successful trials}}{(\text{total # of trials})^3}} \quad (30)
\]

(where \( s_0 \) is the minimal invariant mass squared of the outgoing electron positron pair as determined from the given cuts) and placed into /hepevt/ for inspection by the analysis program, which might use it to normalize its histograms at this point.
4 Parameters

The parameters controlling UNIBAB version 2.2 are summarized in table 1.

4.1 Electroweak Parameters

Starting with UNIBAB version 2.0, the electroweak corrections are included through calls to an electroweak library.

The electroweak library of UNIBAB 2.2 is based on the library that is distributed with ALIBABA 2.0 [7] and assumes the minimal standard model. This library is based on ref. [27], which uses the on-shell renormalization scheme [28]. The input parameters are the masses of the Z (mass1z), the top-quark (mass1t) and the Higgs (mass1h). During initialization, the mass of the W (mass1w) as well as $\Gamma_Z$ (gamm1z) and $\sin^2 \theta_W$ (sin2w) are calculated from these parameters. As of version 2.2, the electroweak library has been updated to include QCD-corrections to the $\Gamma_Z$ and the leading $m_t^4$-corrections to the $\rho$-parameter (see e.g., [2]).

UNIBAB has several switches that control the “physics” entering the hard scattering cross section. The first, tchann, may be used to switch off the contributions of the $t$-channel diagrams to the cross section, which is useful for the application of the so-called “$t$-channel subtraction” to experimental data, and to compare with programs that describe the process $e^+ e^- \rightarrow \mu^+ \mu^-$ including higher order QED corrections, like e.g. KORALZ [30]. With tchann set to .false., the program effectively simulates the process $e^+ e^- \rightarrow \mu^+ \mu^-$; however, this mode of operation is not very efficient.

The switches qedvtx and qedbox control the inclusion of the finite pieces of the QED vertex and box corrections. The QED vertex corrections are enabled by default, however, as explained in section 2.3, the box corrections are disabled. The box corrections may be switched on to estimate the size of the neglected initial-final interference effects, but should not be used for physics simulations, since initial-final interference is not included for hard photon emission.

The next switch, weak, may be used to switch off the pure weak corrections in the electroweak library. According to standard terminology, this includes the propagator corrections to the exchanged photon and Z. It should be noted, however, that $\Gamma_Z$ as well as $\sin^2 \theta_W$ are computed from the input parameters even if the weak corrections are switched off. A final switch, boxes, controls the inclusion of the pure weak box diagrams. The relative contribution of these diagrams is of the order of at most 0.1–0.2% in the energy range of LEP, whereas their computation may be quite time consuming.

4.2 Control of QED corrections

The photon shower algorithms are controlled by the following switches:

- **isrtypr**: Key for initial state radiation
| Variable name | semantics                                      | Default value               |
|---------------|-----------------------------------------------|------------------------------|
| ahpla         | $1/\alpha_{\text{QED}}$                     | 137.0359895                 |
| mass1e        | $m_e$                                         | $0.51099906 \cdot 10^{-3}$ GeV |
| mass1z        | $M_Z$                                         | 91.1887 GeV                 |
| mass1t        | $m_t$                                         | 174.0 GeV                   |
| mass1h        | $M_H$                                         | 300.0 GeV                   |
| alphas        | $\alpha_S(M_Z)$                               | 0.124                       |
| ebeam         | $e^\pm$ beam energy                          | 46 GeV                      |
| epol          | $e^-$ beam polarization                       | 0                           |
| ppol          | $e^+$ beam polarization                       | 0                           |
| ctsmin        | minimum $\cos \theta^*$                      | $-0.9$                      |
| ctsmax        | maximum $\cos \theta^*$                      | $+0.9$                      |
| acocut        | maximum $e^+e^-$ acollinearity angle          | $20^\circ$                  |
| ecut          | minimum outgoing $e^\pm$ energy              | 20 GeV                      |
| evisct        | minimum invariant mass of final state         | 0                           |
| nevent        | Number of events                              | 1000                        |
| tchann        | Switch for $t$-channel diagrams               | .true.                      |
| qedvtx        | Switch for QED vertex corrections             | .true.                      |
| qedbox        | Switch for QED box corrections                | .false.                     |
| weak          | Switch for weak corrections                   | .true.                      |
| boxes         | Switch for weak box diagrams                  | .true.                      |
| isrty       | Key for initial state radiation               | 1                           |
| fsrty         | Key for final state radiation                 | 3                           |
| epsiln        | Internal infrared cutoff                     | $10^{-5}$                   |
| rseed         | Random number seed                            | 54217137                    |
| errmax        | maximum error count                           | 100                         |
| verbos        | verbosity                                     | 0                           |
| runid         | run identification                            |                             |
| stdin         | standard input                                | 5                           |
| stdout        | standard output                               | 6                           |
| stderr        | standard error                                | 6                           |

Table 1: Parameters controlling UNIBAB. These range from standard model parameters ($M_Z, m_t, M_H, \ldots$), over experimental cuts to purely technical parameters like input/output units.
0 Initial state radiation disabled.
1 Initial state radiation enabled, factorization scale $Q^2 = s$.

- **fsrtypl**: Key for final state radiation

0 Final state radiation enabled, factorization scale $Q^2 = \hat{s}$ (c.f. (17)).
1 Final state radiation enabled, factorization scale $Q^2 = -\hat{t} \cdot e$, so that $\ln(1/\eta) = \ln(-\hat{t}/m_e)$
2 Same, but with $Q^2 = \hat{s} \hat{t}/\hat{u}$

The different choices for the factorization scale for final state radiation, which are of course completely equivalent at the leading logarithmic level, can be used to estimate the effect of the missing initial-final interference effects in UNIBAB.

The remaining QED corrections (vertex, boxes) are described in subsection 4.1.

The former switch **bsyle** (UNIBAB versions 2.0 and 2.1) is no longer available, it has been superseeded by **isrtyp** and **fsrtypl**.

### 4.3 Cuts

The region of phase space where UNIBAB generates events is controlled by specifying kinematical cuts. For the sake of simplicity and efficiency, there are five parameters:

- **ctsmint**: minimum $\cos \theta^*$ (see below),
- **ctsmaxt**: maximum $\cos \theta^*$,
- **acocut**: maximum acollinearity angle of the outgoing leptons,
- **ecut**: minimum energy of either of the outgoing leptons,
- **evisct**: minimum invariant mass of final state.

The meaning of the angle $\theta^*$ is the following. Let $\theta_+$ and $\theta_-$ be the angle between the outgoing positron and electron and the incoming electron beam, respectively. The angle $\theta^*$ is then defined by

$$\cos \theta^* = \frac{\cos\left[\frac{1}{2}(\theta_+ + \pi - \theta_+ + \theta_-)\right]}{\cos\left[\frac{1}{2}(\theta_- - \pi + \theta_-)\right]} \quad (31)$$

If all emitted photons are emitted strictly collinearly with respect to the radiating lepton, $\theta^*$ equals to the scattering angle in the partonic subsystem.

Since UNIBAB is designed for the calculation of QED corrections in the LLA in the large angle regime, the angular cuts are restricted by the requirement that the factorization scale
be the c.m.s. energy \( s \), so that terms of the order \( \alpha/\pi \cdot \log(-t/s) \) and \( \alpha/\pi \cdot \log(-u/s) \) remain small compared to the leading logarithmic terms \( \alpha/\pi \cdot \log(s/m_e^2) \). We require (cf. eqs. (4–9))

\[
\left| \alpha/\pi \cdot \log(-\hat{t}/\hat{s}) \right|, \left| \alpha/\pi \cdot \log(-\hat{u}/\hat{s}) \right| < 1\% .
\] (32)

Therefore, the angular cuts in \textsc{unibab} are restricted to the range

\[-0.985 \leq \cos \theta^*_\text{min} < \cos \theta^*_\text{max} \leq 0.985 ,\] (33)

which corresponds to

\[10^\circ < \theta^* < 170^\circ \] (34)

While the parameter \texttt{ecut} has a physical meaning, the cut \texttt{evisct} has a technical interpretation and is to be understood in the following way. Due to the implementation, each radiated photon may be associated with either initial state or final state. Thus one can define an “invariant mass of the final state”. It should be noted, however, that this quantity is unphysical and should be used only for optimization of the Monte Carlo speed for a given set of physical cuts. An example is the calorimetric measurement of the Bhabha cross section, where one does not discriminate between the outgoing lepton and an accompanying photon if the latter lies within a narrow cone of the former, but where one cuts on the sum of their energies.

Although most of the above-mentioned cuts have a simple physical meaning, their implementation in the Monte Carlo generator is not without problems. For strictly collinear photon emission, the relations (4–9) between laboratory variables and the variables for the hard scattering subprocess allow a straightforward derivation of the Monte Carlo’s internal steering parameters from these cuts in a strict manner. If one allows for finite angles between the photon and the radiating lepton, these relations get modified, and one has to weaken the internal cuts; in fact, one cannot even derive these parameters any more in a strict manner, since the multi-particle phase space becomes too complicated. In the actual implementation, we have used empirical relations to derive these internal steering parameters from those valid for collinear emission, so that the contribution to the systematic error on inclusive observables like cross sections is well below the overall precision, which is of the order of 1%. For less inclusive observables, we would recommend that the user convinces himself by a variation of the cuts that the generated distribution does not change in the region of interest.

It should be noted that setting the lepton energy cut \texttt{ecut} to very small values or setting the acollinearity cut \texttt{acocut} close to 180\(^\circ\) makes the Monte Carlo generator very slow. The latter also implies that non-logarithmic terms, which are not implemented in \textsc{unibab}, become more important.
4.4 Monte Carlo Parameters

The remaining, more technical Monte Carlo parameters should be almost self-explaining. Since our photon shower algorithm automatically includes soft photon exponentiation, the results will not depend on the value of the internal infrared cutoff $\epsilon$ (which is measured in units of the beam energy), provided it is kept well below the experimental energy resolution. However, it is not advisable to set it many orders of magnitude lower than the default value, because this may result in too high photon multiplicities which will overflow internal tables.

5 FORTRAN-77 Interface

UNIBAB version 2.2 provides two application program interfaces on different levels. The higher (preferred) level consists of the command interpreter `ubdcmd` which accepts commands in form of `character(*)` strings. This driver communicates with the analyzer `hepawk` by default. The lower level consists of two FORTRAN-77 subroutine calls: `ubpsrv` and `unibab`.

5.1 Higher Level Interface

The simple commands understood by `ubdcmd` are (here keywords are typeset in typewriter font and variables in italics; vertical bars denote alternatives)

- `initialize`
  
  Force initialization of UNIBAB and write an initialization record into the `/hepevt` event record, which should trigger the necessary initializations in the analyzer.

- `generate [n]`
Generate `nevent` events and call `hepawk` to analyze them. If the optional parameter `n` is supplied, `nevent` is set to its value.

- **close**
  Write a termination record to `/hepevt/`, which should trigger the necessary cleanups in the analyzer.

- **statistics**
  Print performance statistics (this is usually only useful for the `UNIBAB` developers, who are tuning internal parameters).

- **quit**
  Terminate `UNIBAB` without writing a termination record.

- **exit|bye**
  Write a termination record and terminate `UNIBAB`.

- **set variable ival|rval**
  Set physical or internal parameters. See the table for a comprehensive listing of all variables. For example, the command `set ahpla 128.0` will set the QED fine structure constant to $1/128$.

- **print variable|all**
  Print the value of physical or internal variables. Specifying the special variable `all` causes a listing of all variables known to `UNIBAB`.

- **debug|nodebug flag**
  Toggle debugging flags.

- **testran**
  Test the portability of the random number generator. We use a generator of the Marsaglia-Zaman variety [31], which should give identical results on almost all machines.

- **banner**
  Print a string identifying this version of `UNIBAB`.

- **echo message**
Figure 2: Event generation loop

Print message on standard output.

Unique abbreviations of the keywords are accepted, i.e. 'g 1000' generates 1000 events. The tokens are separated by blanks. Blank lines and lines starting with a # are ignored and may be used for comments. For portability, only the first 72 characters of each line are considered.

On UNIX systems UNIBAB reads default startup files .unibab in the user’s home directory and the current directory, if they exist.

5.2 Lower Level Interface

The subroutine unibab(code) has a single integer parameter. The parameter code is interpreted as follows:

- 0: initialize the generator and write an initialization record to /hepevt/.
- 1: generate an event and store it in /hepevt/. If UNIBAB has not been initialized yet, the necessary initializations are performed, but no initialization record is written.
- 2: perform final calculations and write the results to /hepevt/.
UNIBAB's parameters can be accessed on the lower level by the subroutine ubpsrv (result, action, name, type, ival, rval, dval, lval). The parameter is specified by its (lowercase) name in the character*(*) string name. The string action is either 'read' or 'write' corresponding to whether the parameter is to be inspected or modified. The type of the parameter ('int', 'real', 'dble', or 'lgcl') is returned in type, if action is set to 'read'; if action='write', the type must be specified in type. Depending on this type the value is passed in ival, rval, dval, or lval, respectively. The following error codes will be returned in the string result: ' ': no error, 'enoarg': invalid action, 'enoent': no such parameter, 'enoperm': permission denied, and 'enotype': invalid type.

The protection scheme implemented with this parameter handling has been described in [18]. Its main purpose is to guarantee consistency of user defined and computed parameters in the generation phase of the Monte Carlo.

5.3 Additional information in /hepevt/

Because UNIBAB uses since version 2.2 the standard /hepevt/ event record internally, not only stable particles with isthep(i) = 1 will be present. Adapting the conventions of the HERWIG Monte Carlo [32], we use the following status codes

- 101: e\textsuperscript{−} beam,
- 102: e\textsuperscript{+} beam,
- 103: e\textsuperscript{+}e\textsuperscript{−} center of mass system,
- 110: e\textsuperscript{+}e\textsuperscript{−} hard scattering center of mass system,
- 111: e\textsuperscript{−} before hard scattering,
- 112: e\textsuperscript{+} before hard scattering,
- 113: e\textsuperscript{−} after hard scattering,
- 114: e\textsuperscript{+} after hard scattering.

However, these entries have no physical significance and should never be used in any analysis. An exception to this rule are the beam particles 101 and 102, which are convenient for defining the reference frame (positive z axis pointing in the direction of the incoming electron) and are used e.g. by hepawk [20] for this purpose. Only the particles with status code 1 belong to the final state as predicted by UNIBAB.
6 Conclusions

We have presented the new version 2.2 of the Monte Carlo event generator UNIBAB for Bhabha scattering at LEP/SLC. The distinguishing feature of UNIBAB is the inclusion of higher order electromagnetic corrections, including exponentiated soft photons, in a photon shower approach. In contrast to fixed order calculations which have to be exponentiated by hand, UNIBAB handles the multiphoton effects explicitly.

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A Availability

The latest release of UNIBAB is available from the authors upon request. In addition, UNIBAB is available by anonymous ftp from the directory

tftp://crunch.ikp.physik.th-darmstadt.de/pub/anlauf/unibab

It is nevertheless recommended to notify the authors, in order to be informed of future bug fixes and enhancements.

UNIBAB is distributed in PATCHY/CMZ card format [34, 35], but machine specific and plain FORTRAN-77 versions are made available on request. A more modern (auto-configuring) and self-contained version of the Monte Carlo generator will be made available in a future release.

B Revision History

Version 2.2, December 1995

- Update of the electroweak library.
- Improved final state photon shower algorithm.
- Different choices of factorization scale for final state radiation.
- QED virtual corrections.
- Speed-up of electroweak corrections.
- Fixed minor bug in initial-state photon shower.
Version 2.1, September 1994
• Beam polarization.

Version 2.0, June 1993
• weak corrections included.
• problems with energy non-conservation of old final-state radiation algorithm fixed.
• more user-friendly: physical cuts replace “bare” Monte Carlo steering parameters.

Version 1.3, September 1992
• improved form of initial state radiation, as implemented in [18].
• final state radiation.

Version 1.2, July 1992
Complete internal rewrite
• /hepevt/ support (also used internally now),
• double precision arithmetic (which is the native floating point mode on most modern machines),
• new driver program (using KRONOS [18] routines).

The physics algorithms have not changed from version 1.1. The purpose of this release is to provide a usable baseline for further improvements.

Version 1.1, September 1989
Maintenance release.

Version 1.0, July 1989
First official release.
C Common Blocks and Subroutines

To avoid possible name clashes with other packages, all external symbols exported by UNIBAB proper begin with the two letters UB, except for the routine unibab itself and the /hepevt/ common block. The names of the subroutines and common blocks of the provided electroweak library have been taken over unchanged.

- Common Blocks:
  - /ubpcom/: Main parameter common block, holds all physical parameters. Application programs should access this common block through the ubpsrv routine (cf. section 5.2).
  - /ubcbrn/: holds the maximum Born cross section in the available energy interval.
  - /ubcevt/: passes the particle momenta between subroutines.
  - /ubcmsc/: internal parameters.
  - /ubcsta/: holds statistics on UNIBAB’s performance.
  - /ubctri/: lookup table for driver keywords.

- Primary entry point:
  - unibab: main entry point, described in section 5.2.

- Branching:
  - ubbini: initial state branching for one lepton.
  - ubbfin: final state radiation for one lepton.

- Cross sections:
  - ubxdif: differential cross section $d\sigma/d\cos\theta$ (in pbarn). This function contains a very simple interface to the electroweak library.
  - ubxtri: approximate differential cross section used for mapping.
  - ubxtot: integral of the approximate cross section used for mapping.
  - ubxcof: coefficients of the approximate cross section.
  - ubffac: QED vertex form factors and box corrections.

- Initialization:
  - ubinit: initialize UNIBAB.
– ubigsw: setup standard model parameters. This subroutine also calls the initialization routines of the electroweak library and transfers parameters between these two modules.
– ubibmx: calculate the maximal Born cross section in the considered energy interval.
– ubibn: negative Born cross section.
– ubeeni: enters an initialization record into /hepevt/.

• Event generation:
  – ubgen: main event generation routine.
  – ubgppr: construct four momenta of hard subprocess in the effective c.m. system.
  – ubgt: generate momentum transfer in the hard subprocess.
  – ubgacc: checks if current raw event satisfies physical cuts.
  – ubeent: enter a particle in /hepevt/.
  –ubenew: start a new /hepevt/ record.
  – ubenul: zero a /hepevt/ entry.

• Termination:
  – ubclos: write a final record to /hepevt/.
  – ubeens: enters a termination record into /hepevt/.
  – ubstat: print statistics on UNIBAB’s performance.

• Driver program:
  – ubdriv: main driver program, calling the command loop.
  – ubdloo: command loop, reading commands from the terminal or from files.
  – ubdcmd: execute a single command (cf. section 5.1).
  – ubdlxs: get the next string from the command line.
  – ubd1xd: get the next floating point number from the command line.
  – ubd1xi: get the next integer from the command line.

• Parameter management:
  – ubpsrv: inspect or modify parameters (cf. section 5.2).
  – block data ubpini: initialize parameters with their default values.
- **ubpprn**: print parameters.

- **General utility routines:**
  - **ubrgen**: random number generator of the Marsaglia-Zaman type \[31\].
  - **ubrstst**: selftest routine for **ubrgen**.
  - **ububoo**: boost a four-vector.
  - **ubulwr**: convert string to lower case.
  - **ubumin**: minimize function.
  - **ubumsg**: print a message.
  - **ubuort**: construct three orthogonal three-vectors for a given \( z \) direction.
  - **ubupro**: project a pair of four-vectors onto mass shell.
  - **ubutim**: check remaining CPU time.

- **Keyword search (using the dynamic tries described in \[30\]):**
  - **ubtins**: insert a new keyword.
  - **ubtlup**: look up a (possibly abbreviated) keyword.
  - **ubtnew**: insert a new node into the trie.
  - **ubtlen**: calculate length of keyword.
  - **ubtc2a**: convert keyword from `character(*)` to `integer(*)`.

- **Electroweak library entry points:**
  - **ewinit**: initialize electroweak library.
  - **eeeew**: effective cross section including virtual corrections.
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Test Run

UNIBAB version 2.2 is distributed together with a sample command file and hepawk script, which are given below. To run this example, the user will need to link UNIBAB with the CERN library, because histogramming is done by HBOOK [37].

The file sample.unibab is read from standard input (unit stdin, which is initialized to 5), and sample.hepawk is read from the file SCRIPT (i.e. under MVS from the file which has been allocated to the DDNAME SCRIPT and under UNIX from the file script or from the value of the environment variable SCRIPT).

After UNIBAB has been successfully built and linked with hepawk on a supported UNIX system, running either make check or make test should validate the build.

sample.unibab

Here is a simple UNIBAB command file, setting up parameters and generating 10000 events.

```
# sample.unibab -- sample UNIBAB command file

# kinematical cuts (e+e-)
set ctsmin -0.8
set ctsmax 0.8
set ecut  20
set acocut 30
set ebeam 48

# run
init
gen 10000
close
quit
```
sample.hepawk

This is a small hepawk script that plots the acollinearity distribution for Bhabha events, for which the acollinearity is larger than 0.01 radians.

# sample.hepawk -- sample HEPAWK analyzer for UNIBAB.

BEGIN
{
    printf ("Welcome to the UNIBAB test:\n");
    printf ("***************************\n");
    printf ("Monte Carlo Version: %s", REV);
    printf ("\n Run: %d", RUN);
    printf (" Date: %s\n", DATE);

    lower_angle_cut = 20/DEG;
    upper_angle_cut = PI - lower_angle_cut;
    minimum_acollinearity_cut = 0.01;

    h_acollinearity
    = book1 (0, "electron acollinearity", 50, 0, PI/6);

    incut = 0;  # initialize counter
}

{
    # Collect the outgoing electron and positron
    $electron = $positron = $NULL;
    for (@l in LEPTONS)
        if (@l:id == _pdg_electron)
            $electron = @l:p;
        else if (@l:id == - _pdg_electron)
            $positron = @l:p;
}

lower_angle_cut <= angle ($electron, @B1:p) <= upper_angle_cut
&& lower_angle_cut <= angle ($positron, @B1:p) <= upper_angle_cut
{
    # sample the acollinearity, but cut out Born-like events
    acollinearity = PI - angle ($electron, $positron);
    if (acollinearity > minimum_acollinearity_cut)
    {
        incut++;
        fill (h_acollinearity, acollinearity);
END
{
    # Dump some numbers
    printf ("\nRESULTS:\n");
    printf ("\n\n");
    printf ("generated events: %d, generated cross section: %gnb\n", NEVENT, XSECT * 1e6);
    printf ("events within cuts: %d, cross section: %g nb\n", incut, (incut/NEVENT) * XSECT * 1e6);

    printf ("\nHISTOGRAMS:\n");
    printf ("\n\n");
    scale (XSECT/NEVENT*1e6);
    plot ();  # plot the histograms
    printf ("\ndone.\n");
}
sample.output

The following output should result from the input files above, modulo small roundoff errors.

ubdcmd: message: Starting UNIBAB, Version 2.01/08, (build 951206/1241)
hepawk: message: starting HEPAWK, Version 1.6

Welcome to the UNIBAB test:
***************************

Monte Carlo Version: v02.01 (Dec 06 00:00:00 1995)
Run: 1035996352
Date: Dec 06 13:07:00 1995

RESULTS:
*******
generated events: 10000, generated cross section: .2484 nb
events within cuts: 5904, cross section: .1467 nb

HISTOGRAMS:
************

1 electron acollinearity

| ID | DATE |
|----|------|
| 1  | 06/12/95 |

1.36 I
1.32 I I
1.28 0 II
1.24 I II
1.2 0 I
1.16 I
1.12 I
1.08 II 0
1.04 00 I
1  II
.96 I
.92 I I
.88 II I
.84 00 I
.8  II I
done.

ubdriv: message: bye.