

The Monte Carlo Event Generator
YFSW3 version 1.16
for W -Pair Production and Decay
at LEP2/LC Energies[†]

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Abstract

We present the Monte Carlo event generator YFSW3 version 1.16 for the process of W -pair production and decay in electron-positron collisions. It includes $\mathcal{O}(\alpha)$ electroweak radiative corrections in the WW production stage together with the $\mathcal{O}(\alpha^3)$ initial-state-radiation (ISR) corrections in the leading-logarithmic (LL) approximation, implemented within the Yennie-Frautschi-Suura (YFS) exclusive exponentiation framework. The photon radiation in the W decays is generated by the dedicated program PHOTOS up to $\mathcal{O}(\alpha^2)$ LL, normalised to the W branching ratios. The program is interfaced with the τ decay library TAUOLA and the quark fragmentation/hadronization package JETSET. The semi-analytical code KorWan for the calculations of the differential and total cross-sections at the Born level and in the ISR approximation is included.

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PROGRAM SUMMARY

Title of the program: YFSWW3, version 1.16 .

Computer: any with the FORTRAN 77 compiler and the UNIX/Linux operating system

Operating system: UNIX/Linux

Programming language used: FORTRAN 77

High speed storage required: < 10 MB

Size of distributed program: 3,237 kB

Distribution format: tar gzip file (size of 1,103 kB)

No. of cards in combined program and test deck: about 23,000 plus about 48,000 of auxiliary packages: KorWan, FF, JETSET, TAUOLA, PHOTOS.

Keywords:

Standard Model (SM), LEP2, linear colliders (LC), quantum electrodynamics (QED), quantum chromodynamics (QCD), boson W , W -pair production, W decay, W branching ratio (BR), triple gauge boson couplings (TGC), quartic gauge boson couplings (QGC), four-fermion ($4f$) background, radiative corrections, Yennie-Frautschi-Suura (YFS) exponentiation, initial state radiation (ISR), leading-log (LL) approximation, Coulomb effect, final state radiation (FSR), electroweak (EW) corrections, leading-pole approximation (LPA), Monte Carlo (MC) simulation/generation.

Nature of the physical problem:

The process of the W -pair production is important for precise tests of the Standard Model as well as searches for “new physics” at LEP2 and future linear colliders. In order to match the experimental precision necessary for a successful physics programme, quantum effects (the so-called radiative corrections) have to be included into a theoretical description of this process. It turns out that not only the so-called universal corrections (initial state radiation, the Coulomb effect, “naive” QCD correction, etc.) are necessary, but also the $\mathcal{O}(\alpha)$ electroweak corrections in the WW production are needed for the desired theoretical accuracy. All these effects should, preferably, be included in a Monte Carlo event generator in order to account for realistic experimental set-ups.

Method of solution:

The Monte Carlo event generator for the combined W -pair production and decay process including $\mathcal{O}(\alpha^3)$ LL ISR effects, the Coulomb correction (usual or screened), the “naive” QCD effect, the $\mathcal{O}(\alpha)$ EW corrections in the WW production stage, implemented within the YFS exclusive exponentiation framework is provided. Multi-photon radiation in the WW production is generated according to the YFS MC method. The photon radiation in the W decays, normalized to the W BR’s, is generated by the LL-type MC program PHOTOS (up to two photons). The decays of τ ’s including radiative corrections are done by the dedicated package TAUOLA. The quark fragmentation/hadronization is performed with the help of the Lund program JETSET. The program can provide both weighted and

unweighted (weight=1) events. 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 leading pole approximation (LPA) is used (in two versions) to describe the signal WW production process. Multi-photon radiation according to the YFS exponentiation scheme is generated only for the WW production stage. $\mathcal{O}(\alpha)$ EW corrections (in LPA) are included only in the WW production stage. The ISR effects beyond $\mathcal{O}(\alpha)$ are included in the LL approximation. Non-factorizable corrections (interferences between the production and decay stages) are approximated by the so-called screened Coulomb ansatz. Spin correlations between the WW production and decays are fully included only at the Born and the ISR levels. Radiative corrections in the W decays are included into an overall normalisation through the W BR's, and the real photon radiation is generated in the LL approximation (up to two photons) by the program PHOTOS. Anomalous triple gauge boson couplings are included in the Born-like matrix element, i.e. with the universal SM corrections only. Quartic gauge boson couplings are implemented according to the Standard Model only (no anomalous couplings). The τ -decays and quark hadronization are performed, respectively, with the help of the dedicated packages: TAUOLA and JETSET. No $4f$ background processes are included.

Typical running time:

200 CPU seconds of a PC Intel Pentium III @ 550MHz per 1000 unweighted events, for the parameter settings as they are given in the demonstration program.

1 Introduction

The process of W -pair production in electron–positron colliders is very important for testing the Standard Model (SM) and searching for signals of possible “new physics”; see e.g. Refs. [1,2]. One of the main goals of investigating this process at present and future e^+e^- experiments is to measure precisely the basic properties of the W boson, such as its mass M_W and width Γ_W . This process also allows for a study of the triple and quartic gauge boson couplings at the tree level, where small deviations from the subtle SM gauge cancellations can lead to significant effects on physical observables – these can be signals of “new physics”.

In this work we present the Monte Carlo (MC) event generator which simulates the production and decay of the W -pair at e^\pm colliders. The integrated cross sections and arbitrary differential distributions can be calculated from a series of the constant-weight fully inclusive MC events. The program embodies the Standard Model scattering matrix element with the $\mathcal{O}(\alpha)$ radiative corrections for the double-resonant component of the scattering matrix element. The basics of the model used in the program and selected numerical results were already presented in the earlier publications [3–6]. The important components of the presented program/calculation are the complete $\mathcal{O}(\alpha)$ radiative correction for on-shell W -pair production, which are implemented according to¹, Refs. [7–9], see also Ref. [10].

Let us discuss briefly the basic physics properties of the W -pair production and decay process. Since the W 's are unstable and short-lived particles, the W -pairs are not observed directly in the experiments but through their decay products: four-fermion ($4f$) final states (which may then also decay, radiate gluons/photons, hadronize, etc.). As high energy charged particles are involved in the process, one can also observe energetic radiative photons. So, at the parton level, one has to consider a general process:

$$e^+ + e^- \longrightarrow 4f + n\gamma, \quad (n = 0, 1, 2, \dots), \quad (1)$$

where also some background (non- WW) processes contribute. In a theoretical description of this process – according to quantum field theory – one also has to include virtual effects, the so-called loop corrections. This general process is very complicated since it involves ~ 80 different channels ($4f$ final states) with complex peaking behaviour in multi-particle phase space and a large number of Feynman diagrams. Even in the massless-fermion approximation the number of Feynman graphs grows up from 9–56 per channel at the Born level to an enormous 3579–15948 at the one-loop level [11]. The full one-loop calculations have not been finished yet, even for the simplest case (doubly plus singly W -resonant diagrams) [12]. But even if they existed one would be faced with problems in their numerical evaluations in practical applications, particularly within Monte Carlo event generators – they would be prohibitively huge and slow. These are the reasons why efficient approximations in the theoretical description of this process are necessary. These approximations should be such that on the one hand they would include all contributions/corrections that

¹We are grateful to the authors of these works for providing us the relevant parts of the computer code.

are necessary for the required theoretical accuracy (dependent on the experimental precision) and on the other hand they would be efficient enough for numerical computations. Given the complicated topologies of the $(4f + n\gamma)$ final states, such calculations should be, preferably, given in terms of a Monte Carlo event generator that would allow one to simulate the process directly [13, 14].

Our solution to this consists of two complementary Monte Carlo event generators: `YFSWW3` and `KoralW`. `KoralW` includes the full lowest-order $e^+e^- \rightarrow 4f$ process but with simplified radiative corrections – the universal ones such as initial-state radiation (ISR), the Coulomb effect, etc. In `YFSWW3`, on the other hand, the lowest-order process is simplified – only the doubly W -resonant contributions are taken into account, but inclusion of the radiative corrections in this process goes beyond the universal ones. In the current version of `YFSWW3` only those non-universal (non-leading) corrections are included that are necessary to achieve the theoretical precision for the total WW cross section of 0.5% required for LEP2². In order to achieve a gauge-invariant description of the signal WW -process and employ the existing $\mathcal{O}(\alpha)$ electroweak corrections for the on-shell W -pair production, we use the so-called leading-pole approximation (LPA) – see Refs. [6, 15]. The important thing is that the two programs have a well established common part, which is the doubly W -resonant (WW) process with the same universal radiative corrections. This allows us to combine the results of the two programs to achieve the desired theoretical precision for WW observables. Detailed descriptions of `KoralW` were published in Refs. [16–19]. Here, we present a documentation of the program `YFSWW3`; physical aspects together with some numerical results are discussed in Refs. [3–6, 15]. Possible scenarios of combining the results of the two programs are presented in Refs. [6, 15, 20].

The outline of the paper is as follows. In Section 2, we define our notation and describe the physics content of the program. In Section 3, we discuss the MC algorithm. In Section 4, we present the structure of the program, important routines, etc. Details about the practical use of the program are given in Section 5. Appendices contain useful technical information on the structure of the program, its input/output, etc.

²For the future linear colliders (LC) this may not be sufficient, so even some higher-order corrections would have to be added, which is possible within the framework of `YFSWW3`.

2 Physics Content of YFSWW3

In this section we describe the physics content of YFSWW3, that is we define differential distributions used to calculate the cross section and generate events for the W -pair production and decay process. These distributions we define rather completely, because they were not defined in every detail in the past publications. On the other hand we shall skip the detailed discussion of the physics models which they represent. This will be done in a separate publication [21]. First, we discuss our notation. Then, we present the master formula and its ingredients. And finally, we give some details on the MC algorithms implemented in the program.

2.1 Notation

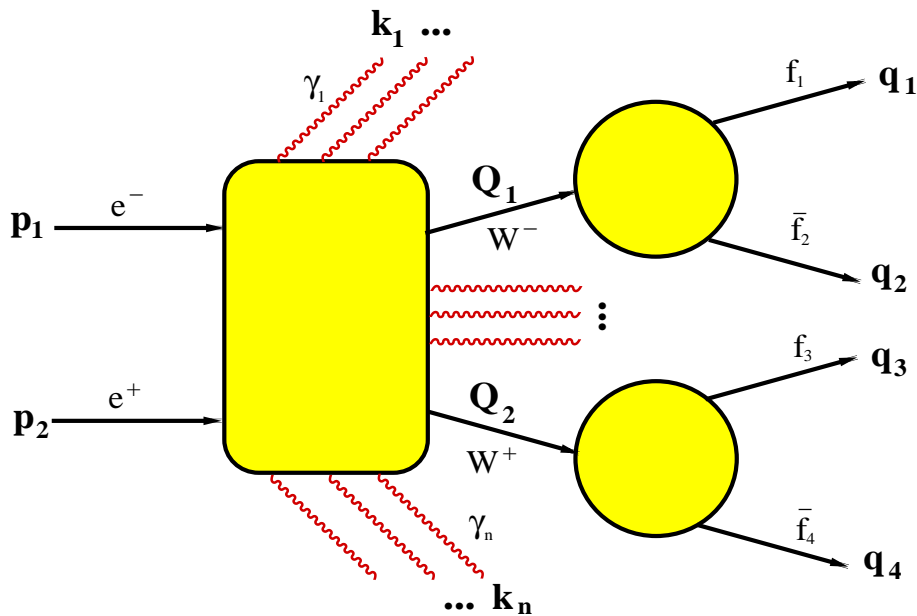


Figure 1: Kinematics of the W -pair production and decay process with multiple photons in the production stage.

In YFSWW3 we adopt the notational convention similar to the one used in KoralW. The variables p_1, p_2 are the incoming e^-, e^+ four-momenta, respectively:

$$p_1 = (E_e, 0, 0, p_e), \quad p_2 = (E_e, 0, 0, -p_e), \quad (2)$$

where E_e is the beam energy and $p_e = \sqrt{E_e^2 - m_e^2}$, with m_e being the electron mass. The variables Q_1, Q_2 are the four-momenta of the W^- and W^+ bosons; their invariant masses are denoted by M_1 and M_2 , respectively. q_1, q_2 and m_1, m_2 are the four-momenta and masses of the W^- decay products; q_3, q_4 and m_3, m_4 are the analogous four-momenta and masses of the W^+ decay products, with the first component of each pair corresponding to a

fermion and the second to an anti-fermion. By k_i we denote the four-momenta of radiative photons. See also fig. 1 for a pictorial representation. The components of a four-vector are denoted by $p = (p_0, p_x, p_y, p_z)$, with the metric convention of $\{1, -1, -1, -1\}$. We also use the following Lorentz invariants: $s = (p_1 + p_2)^2$, $s_1 = Q_1^2 = M_1^2$ and $s_2 = Q_2^2 = M_2^2$.

2.2 Master Formula

Here, we consider the process:

$$e^- + e^+ \longrightarrow \{W^- \rightarrow f_1 + \bar{f}_2\} + \{W^+ \rightarrow f_3 + \bar{f}_4\} + n\gamma, \quad (n = 0, 1, 2, \dots), \quad (3)$$

where the radiative photons are emitted only at the WW -production stage. The photon radiation in W decays (FSR) in this version of YFSWW3 is done, in the $\mathcal{O}(\alpha^2)$ leading-logarithmic (LL) approximation, by the dedicated program PHOTOS [22] – in the same way as in KoralW. Since this is done externally on fully generated events (it does not change event weights), we do not include the FSR in our discussion of the master formula. It should be remembered that the use of PHOTOS in YFSWW3 is a temporary solution before the advent of the YFS-exponentiated MC for W decays.

As it was already mentioned in Introduction, we use the LPA to describe this process respecting the $SU(2)_L \times U(1)$ gauge invariance. In YFSWW3, we implemented two options of the LPA, called LPA_a and LPA_b . The first one, which is the default (recommended) option, is based on the approach of R. Stuart [23], where only the Lorentz scalar functions in the S-matrix are expanded about poles corresponding to unstable W 's. In the lowest order, the LPA_a matrix element coincides with the so-called CC03 (see e.g. Ref. [11] for explanation of this notation) matrix element in the 't Hooft-Feynman gauge. In the following we shall use the notion ‘‘CC03’’ in that sense. The second option, intended for some dedicated tests, follows the method suggested in Ref. [11], where the whole S-matrix residuals are expanded about poles³; see Refs. [6, 15] for more details. In the following we shall describe explicitly the LPA_a scheme; LPA_b can be obtained from this by taking the W 's on-shell (i.e. $Q_1^2, Q_2^2 \rightarrow M_W^2$) everywhere, except for the Breit-Wigner denominators and the phase-space integration.

In the framework of the Yennie-Frautschi-Suura (YFS) exclusive exponentiation (EEX), the cross section for the process (3) can be written as

$$\begin{aligned} \sigma_{\text{Best}} = & \sum_{n=0}^{\infty} \frac{1}{n!} \int ds_1 ds_2 \frac{d^3 Q_1}{Q_1^0} \frac{d^3 Q_2}{Q_2^0} \prod_{l=1}^4 \frac{d^3 q_l}{q_l^0} \prod_{i=1}^n \frac{d^3 k_i}{k_i^0} \delta^{(4)} \left(p_1 + p_2 - Q_1 - Q_2 - \sum_{i=1}^n k_i \right) \\ & \delta^{(4)} (Q_1 - q_1 - q_2) \delta^{(4)} (Q_2 - q_3 - q_4) \rho_n^{\text{Best}}(p_1, p_2; q_1, \dots, q_4, k_1, \dots, k_n), \end{aligned} \quad (4)$$

³We do not apply, however, the pole approximation to the phase space as it was done in semi-analytical calculations of Ref. [24].

where ρ_n^{Best} is the following fully exclusive multi-photon differential distribution:

$$\begin{aligned} \rho_n^{\text{Best}}(p_1, p_2; q_1, \dots, q_4, k_1, \dots, k_n) &= \prod_{i=1}^n \tilde{S}(p_1, p_2, Q_1, Q_2, k_i) \theta(k_i^0 - k_\epsilon) \\ &\times e^{Y'(p_1, p_2, Q_1, Q_2; k_\epsilon)} [1 + \delta_C(Q_1, Q_2, M_W, \Gamma_W)] \sum_{\varphi \in \{I, W\}^n} p_\varphi \mathcal{B}(\{p, Q, q, k\}^{\mathcal{R}_\varphi}), \end{aligned} \quad (5)$$

with \mathcal{B} being the contribution from the infrared-finite YFS residuals⁴:

$$\begin{aligned} \mathcal{B}(\{p, Q, q, k\}^{\mathcal{R}_\varphi}) &= [1 + \delta_{An}^{\text{TGC}}(\{p, Q, q\}^{\mathcal{R}_\varphi})] \\ &\times \left\{ \bar{\beta}_0^{(1)}(\{p, Q, q\}^{\mathcal{R}_\varphi}) + \sum_{i=1}^n \frac{\bar{\beta}_1^{(1)}(\{p, Q, q, k_i\}^{\mathcal{R}_\varphi})}{\tilde{S}(\{p, Q, k_i\}^{\mathcal{R}_\varphi})} + \Delta \bar{\beta}_{0,ISR}^{(3)}(\{p, Q, q\}^{\mathcal{R}_\varphi}) \right. \\ &+ \sum_{\varphi_i=I} \frac{\Delta \bar{\beta}_{1,ISR}^{(3)}(\{p, Q, q\}^{\mathcal{R}_\varphi}, k_i)}{\tilde{S}_I(\{p\}^{\mathcal{R}_\varphi}, k_i)} + \frac{1}{2!} \sum_{\varphi_{i,j}=I} \frac{\bar{\beta}_{2,ISR}^{(3)}(\{p, Q, q\}^{\mathcal{R}_\varphi}, k_i, k_j)}{\tilde{S}_I(\{p\}^{\mathcal{R}_\varphi}, k_i) \tilde{S}_I(\{p\}^{\mathcal{R}_\varphi}, k_j)} \\ &\left. + \frac{1}{3!} \sum_{\varphi_{i,j,l}=I} \frac{\bar{\beta}_{3,ISR}^{(3)}(\{p, Q, q\}^{\mathcal{R}_\varphi}, k_i, k_j, k_l)}{\tilde{S}_I(\{p\}^{\mathcal{R}_\varphi}, k_i) \tilde{S}_I(\{p\}^{\mathcal{R}_\varphi}, k_j) \tilde{S}_I(\{p\}^{\mathcal{R}_\varphi}, k_l)} \right\}, \end{aligned} \quad (6)$$

where we use a short-hand notation of the type $\{p, Q, q\} \equiv \{p_1, p_2, Q_1, Q_2, q_1, q_2, q_3, q_4\}$.

The sum \sum_φ in Eq. (5) runs over the photon partitions, i.e. all possible photon associations to the initial-state radiation (ISR) or the W -state radiation (WSR). For n photons we identify every of the 2^n partitions φ with a vector $\varphi \equiv (\varphi_1, \dots, \varphi_n)$, where $\varphi_i = I, W$, and I, W denote the ISR or the WSR photons, respectively. The partition weight p_φ is given by

$$p_\varphi = \frac{\prod_{\varphi_i=I} \tilde{S}_I(k_i) \prod_{\varphi_j=W} \tilde{S}_W(k_j)}{\sum_\varphi \prod_{\varphi_i=I} \tilde{S}_I(k_i) \prod_{\varphi_j=W} \tilde{S}_W(k_j)} = \frac{\prod_{\varphi_i=I} \tilde{S}_I(k_i) \prod_{\varphi_j=W} \tilde{S}_W(k_j)}{\prod_{i=1}^n (\tilde{S}_I(k_i) + \tilde{S}_W(k_i))}, \quad (7)$$

where $\tilde{S}_I(k)$ and $\tilde{S}_W(k)$ are the real photon infrared (IR) factors for the ISR and the WSR, respectively:

$$\begin{aligned} \tilde{S}_I(p_1, p_2, k) &= -\frac{\alpha}{4\pi} \left(\frac{p_1}{kp_1} - \frac{p_2}{kp_2} \right)^2, \\ \tilde{S}_W(Q_1, Q_2, k) &= -\frac{\alpha}{4\pi} \left(\frac{Q_1}{kQ_1} - \frac{Q_2}{kQ_2} \right)^2. \end{aligned} \quad (8)$$

It is worth to stress that the partition dependence for the first two terms proportional to $\bar{\beta}_0^{(1)}$ and $\bar{\beta}_1^{(1)}$ cancels out, when truncated to $\mathcal{O}(\alpha)$ (as it should), thanks to special

⁴In the sums like $\sum_{\varphi_{i,j}=I}$ we include all pairs of indices (i, j) such that $i \neq j$, $\varphi_i = I$ and $\varphi_j = I$.

normalisation choice for the partition weights: $\sum_{\wp \in \{I, W\}^n} p_\wp = 1$. See also the definition of $\bar{\beta}_1^{(1)}$ and the discussion on the partition-dependent “reduction procedure” \mathcal{R}_\wp in the following. The purpose of the sum over partitions is to help the introduction of the LL corrections *beyond* the $\mathcal{O}(\alpha)$.

In Eq. (6) the two components proportional to $\bar{\beta}_0^{(1)}$ and $\bar{\beta}_1^{(1)}$ represent explicitly the complete $\mathcal{O}(\alpha)$ contribution to the WW -production process while the remaining $\bar{\beta}$'s and $\Delta\bar{\beta}$'s collect the second and third order ISR corrections in the LL approximation; see Section 2.2.4 for more details. The dependence of the $\bar{\beta}$ -functions on the photon partitions enters through the so-called reduction (extrapolation) procedures which take into account the CMS energy shift induced by the ISR; for more details see Subsection 2.2.4.

2.2.1 YFS Infrared Factors

The real photon IR factor

$$\tilde{S}(p_1, p_2, Q_1, Q_2, k) = -\frac{\alpha}{4\pi^2} \left(\frac{p_1}{kp_1} - \frac{p_2}{kp_2} - \frac{Q_1}{kQ_1} + \frac{Q_2}{kQ_2} \right)^2 \quad (9)$$

includes the ISR, the WSR and the interferences between them.

The step function $\theta(k^0 - k_\epsilon)$, where $k_\epsilon = \epsilon\sqrt{s}/2$, cuts out the singular IR region, already included to all orders in the YFS form factor $e^{Y'}$, where

$$Y'(p_1, p_2, Q_1, Q_2; k_\epsilon) = 2\alpha\Re B'(p_1, p_2, Q_1, Q_2) + 2\alpha\tilde{B}(p_1, p_2, Q_1, Q_2; k_\epsilon). \quad (10)$$

The IR functions $\Re B'$ and \tilde{B} , correspond to virtual and real photons, respectively, and are defined explicitly in Ref. [3].

2.2.2 Coulomb Correction

The correction δ_C is the Coulomb effect, included both (two options): in its standard form as given in Ref. [25] and in terms of the so-called screened Coulomb ansatz of Ref. [26], which is an efficient approximation of the non-factorizable corrections for singly-inclusive distributions [26]. It reads

$$\delta_C^{\{\text{Std}, \text{Scr}\}}(Q_1, Q_2, M_W, \Gamma_W) = \frac{\alpha\pi}{2\beta} \left[1 - \{1, (1 - \beta)^2\} \frac{2}{\pi} \arctan \left(\frac{|\kappa|^2 - p^2}{2p\Re\kappa} \right) \right], \quad (11)$$

with

$$\begin{aligned} \beta &= \sqrt{1 - 2(s_1 + s_2)/s_Q + [(s_1 - s_2)/s_Q]^2}, \quad p = \frac{1}{2}\beta\sqrt{s_Q}, \quad s_Q = (Q_1 + Q_2)^2, \\ \kappa &= \sqrt{\frac{M_W}{2} \left(\sqrt{E^2 + \Gamma_W^2} - E \right)} - i\sqrt{\frac{M_W}{2} \left(\sqrt{E^2 + \Gamma_W^2} + E \right)}, \quad E = \frac{s_Q - 4M_W^2}{4M_W}, \end{aligned} \quad (12)$$

where M_W and Γ_W are the on-shell W -mass and W -width, respectively. The first term in the curly brackets in Eq. (11) corresponds to the standard (Std) while the second one to the screened (Scr) Coulomb correction. This correction is properly matched with the YFS form-factor, where the Coulomb-like singularity appears in the virtual IR function $\mathfrak{R}B$. After matching it with the full Coulomb correction δ_C , the original YFS function $\mathfrak{R}B$ is replaced by $\mathfrak{R}B'$ as described in Ref. [3]. M_W and Γ_W are the on-shell W -mass and W -width, respectively.

2.2.3 Anomalous triple-gauge couplings

The anomalous corrections to the triple-gauge couplings (TGC) WWV ($V = Z, \gamma$) are included multiplicatively through

$$1 + \delta_{An}^{\text{TGC}} = \frac{|\mathcal{M}_{\text{Born}}^{\text{AnTGC}}|^2}{|\mathcal{M}_{\text{Born}}^{\text{SM}}|^2}, \quad (13)$$

where $\mathcal{M}_{\text{Born}}^{\text{AnTGC}}$ is the Born level matrix element with the anomalous TGC's, while $\mathcal{M}_{\text{Born}}^{\text{SM}}$ is the corresponding SM matrix element. In YFSWW3 we use the same conventions (routines) for the TGC's as they are given in KorallW [18]. The anomalous couplings are included in the event generation only if an appropriate switch in the input parameters is on and the parameters corresponding to these couplings (in a given parametrisation) are set up to the non-SM values; see Appendix A for details.

2.2.4 $\bar{\beta}$'s for W -pair Production

In the IR-finite $\bar{\beta}$ -functions of Eq. (5) we see the superscripts \mathcal{R}_φ in the four-momenta arguments like $\{p, Q, q\}^{\mathcal{R}_\varphi}$ or $\{p, Q, q, k\}^{\mathcal{R}_\varphi}$. This means that these arguments are subject to the ‘‘reduction (extrapolation) procedures’’. These reductions procedures are partition-dependent – this is why they are denoted with the subscripts φ . The partition-dependence enters through accounting for the ISR energy shift $s \rightarrow s'$, where $s' = (p_1 + p_2 - \sum_{\varphi_i=I} k_i)^2$ in the evaluation of the $\bar{\beta}$ -functions. For more discussion on the meaning of the reduction/extrapolation procedures see Subsection 2.3. In YFSWW3, we use the reduction procedures of the YFS2 and YFS3 programs of KORALZ [27–29], with some modifications: in constructing the reduced W four-momenta, we take into account that, in general, $M_1 \neq M_2$. We perform appropriate transformations of the W^\pm decay products, that is we boost them to W 's rest-frames before the reduction, and then, we make the inverse boost transformation to the reduced frame. In general, in these reduction procedures the effects of the CMS energy shift $s \rightarrow s'$ (recoil) is taken due to the ISR photons only. This procedure is well justified for the ISR corrections beyond $\mathcal{O}(\alpha)$ where we take $\{p, Q, q\}^{\mathcal{R}_\varphi}$ and for each photon we may say whether it belongs to the ISR or to the WSR. For the $\mathcal{O}(\alpha)$ -specific corrections, in the corresponding $\bar{\beta}$'s we cannot make a distinction between the ISR and the WSR, and the $\{p, Q, q, k_i\}^{\mathcal{R}_\varphi}$ in their arguments means that, (i), the reduced $\{p, Q, k_i\}^{\mathcal{R}_\varphi}$ are within the 3-body phase space and, (ii), the photon k_i is excluded from the energy shift $s \rightarrow s'$ calculation. For more discussion on this non-trivial point see Subsections 2.3 and 2.4.

Let us now describe in detail the $\mathcal{O}(\alpha)$ -complete⁵ functions $\bar{\beta}_0^{(1)}$ and $\bar{\beta}_1^{(1)}$. The first one, which includes the $\mathcal{O}(\alpha)$ electroweak (EW) virtual corrections, reads as follows:

$$\bar{\beta}_0^{(1)}(\{p, Q\}) = \bar{\beta}_0^{(0)}(\{p, Q\}) \left[1 + \delta_{v+s}^{(1)}(\{p, Q\}; k_\epsilon) - Y(\{p, Q\}; k_\epsilon) \right], \quad (14)$$

where $\bar{\beta}_0^{(0)}$ is the lowest order matrix element squared for the W -pair production and decay, and is identical to the corresponding $\bar{\beta}_0^{(0)}$ -function in `KoralW` [16, 18]. In fact, the $\bar{\beta}_0^{(1)}$ -function comes in two variants. The first one, referred to as *the scheme (A)* [6], reads as follows:

$$\begin{aligned} \bar{\beta}_{0,A}^{(1)}(\{p, Q\}) = & \bar{\beta}^{(0)}(\{p, Q\}) \left[1 + \delta_{ISR}^{(1)}(p_1, p_2) \right] \\ & + \bar{\beta}^{(0)}(\{p, Q\}) \left[\delta_{v+s}^{(1)}(\{p, Q\}; k_\epsilon) - Y(\{p, Q\}; k_\epsilon) - \delta_{ISR}^{(1)}(p_1^{eff}, p_2^{eff}) \right]_{G_\mu} \end{aligned} \quad (15)$$

where $\delta_{ISR}^{(1)} = (\alpha/\pi)[\ln(s/m_e^2) - 1]$ is the LL pure QED $\mathcal{O}(\alpha)$ ISR correction, and the subscript G_μ means that the whole correction is calculated in the so-called G_μ -scheme [7] as explained in Ref. [6]. Another option, referred to as *the scheme (B)*, similar to the one used in the program `RACONWW` [30], is defined as follows:

$$\begin{aligned} \bar{\beta}_{0,B}^{(1)}(\{p, Q\}) = & \bar{\beta}^{(0)}(\{p, Q\}) \left[1 + \delta_{ISR}^{(1)}(p_1, p_2) \right] \\ & + \bar{\beta}^{(0)}(\{p, Q\}) \left[\delta_{v+s}^{(1)}(\{p, Q\}; k_\epsilon) - Y(\{p, Q\}; k_\epsilon) - \delta_{ISR}^{(1)}(p_1^{eff}, p_2^{eff}) \right]_{G_\mu} \left(\frac{\alpha}{\alpha_{G_\mu}} \right), \end{aligned} \quad (16)$$

where α is the fine structure constant and $\alpha_{G_\mu} = (\sqrt{2}G_\mu M_W^2 \sin^2 \theta_W)/\pi$. Here, although the $\mathcal{O}(\alpha)$ corrections are calculated in the G_μ -scheme, their relative coefficient is α instead of α_{G_μ} . Our recommended option is *the scheme (A)* which is inspired by the renormalization group equations (RGE) [31, 6].

The $\mathcal{O}(\alpha)$ virtual and soft photon corrections for the WW -production stage are included in $\delta_{v+s}^{(1)}$. In the current version of the program, we use the calculations of Ref. [7] for the on-shell WW -production. Since in our case the W 's are off-shell we have to perform some transformations/extrapolations (which can be viewed as an analytic continuation of the S-matrix) in order to employ these calculations. We do it in the following way. After performing the reduction procedure for the $\bar{\beta}_0$ function, as described above, we find $\cos \theta_{eff}$ and the velocity β_{eff} of the W 's in the reduced frame, where

$$\begin{aligned} \beta_{eff} &= \sqrt{1 - 2(s_1 + s_2)/s' + [(s_1 - s_2)/s']^2}, \\ \cos \theta_{eff} &= (\vec{p}_1^{\mathcal{R}\varphi} \cdot \vec{Q}_1^{\mathcal{R}\varphi}) / (|\vec{p}_1^{\mathcal{R}\varphi}| |\vec{Q}_1^{\mathcal{R}\varphi}|). \end{aligned} \quad (17)$$

Then, for this value of β_{eff} we calculate the effective CMS energy squared for on-shell W 's:

$$s_{eff} = 4M_W^2 / (1 - \beta_{eff}^2). \quad (18)$$

⁵In the early version of the present program called `YFSWW2`, corrections beyond the ISR were included only through the function Y' and \tilde{S} -factors [3].

Having $(s_{eff}, \beta_{eff}, \cos \theta_{eff})$, we construct the four-momenta $(p_1^{eff}, p_2^{eff}, Q_1^{eff}, Q_2^{eff})$ for the on-shell process $e^+e^- \rightarrow W^+W^-$ and use them to calculate the respective EW corrections. The same four-momenta are used to calculate the IR form factor Y according to Eq. (10), where now the Coulomb-like singularity in the virtual IR function \mathfrak{RB} is kept in order to cancel the corresponding singularity in $\delta_{v+s}^{(1)}$, and to calculate the $\mathcal{O}(\alpha)$ ISR correction:

$$\delta_{ISR}^{(1)}(p_1^{eff}, p_2^{eff}) = \frac{\alpha}{\pi} \left(\ln \frac{s_{eff}}{m_e^2} - 1 \right). \quad (19)$$

Such a procedure allows us to use the EW corrections also in the WW -threshold region, however, in this region the LPA becomes less precise. Since no other calculation with the $\mathcal{O}(\alpha)$ EW corrections for the W -pair production and decay process exists for the WW -threshold region, we estimate, for the moment, the precision of YFSWW3 in that region conservatively at 2%, just as for the ISR approximation. This can be improved in the future when more calculations/tests are done.

Two comments are in order about approximation used in evaluation of Eqs. (14-16):

1. In the LPA_{a,b}, the 1-loop corrections should be evaluated “on-pole”, i.e. for the complex W mass: $M^2 = M_W^2 - iM_W\Gamma_W$. This would, however, require the analytic continuation of the on-shell 1-loop corrections to the second Riemann sheet. We avoid this by using in the LPA residuals the approximation $M \simeq M_W$. Since this is done for the $\mathcal{O}(\alpha)$ corrections the error introduced by this approximation is of the order of $(\alpha/\pi)(\Gamma_W/M_W) < 10^{-4}$, which is negligible for our aimed precision.
2. A coherent sum over W spins between the production and decay stages is included in Eq. (14) in the $\bar{\beta}_0^{(0)}$ function, but not in the non-leading (NL) $\mathcal{O}(\alpha)$ EW correction. This should be sufficient for the LEP2 precision as the total EW correction in the LEP2 energy range is typically ~ 1 –2%. However, the W -spin effects can be included also in the NL $\mathcal{O}(\alpha)$ EW correction, if necessary.

The $\mathcal{O}(\alpha)$ real photon ISR and photon emission in the WW -production stage are included through the following IR-finite function:

$$\bar{\beta}_1^{(1)}(\{p, Q, q, k\}^{\mathcal{R}_\varphi}) = D_\gamma^{(1)}(\{p, Q, q, k\}^{\mathcal{R}_\varphi}) - \tilde{S}(\{p, Q, q, k\}^{\mathcal{R}_\varphi}) \bar{\beta}_0^{(0)}(\{p, Q, q\}^{\mathcal{R}_\varphi}) \quad (20)$$

where $D_\gamma^{(1)}$ is the differential cross section for the single hard photon radiation in the WW -production stage and the non-radiative W -decays. For this we use the calculations of Ref. [32], where the W 's are taken on-shell. In order to accommodate them in our off-shell process, we use general formulae for W -polarisation vectors in terms of their off-shell four-momenta [33] in the spin amplitude calculations, and perform a coherent summation over the W 's polarisations of the production and decay amplitudes. In fact, the hard-photon amplitudes of Ref. [32] are given in the massless-fermion approximation, so they become inaccurate when a photon is emitted close to a fermion direction. To correct this, we supplement these amplitudes with the mass terms according to the CALKUL prescription of Ref. [34].

In Eqs. (4-5) we use the IR-finite $\bar{\beta}$ -functions for the ISR $\bar{\beta}_{0,ISR}^{(3)}$, $\bar{\beta}_{1,ISR}^{(3)}$, $\bar{\beta}_{2,ISR}^{(3)}$ and $\bar{\beta}_{3,ISR}^{(3)}$, calculated up to $\mathcal{O}(\alpha^3)$ LL. They are exactly the same as in `KoralW`, see Ref. [18]. We define in addition:

$$\Delta\bar{\beta}_{0,ISR}^{(3)} = \bar{\beta}_{0,ISR}^{(3)} - \bar{\beta}_{0,ISR}^{(1)}, \quad \Delta\bar{\beta}_{1,ISR}^{(3)} = \bar{\beta}_{1,ISR}^{(3)} - \bar{\beta}_{1,ISR}^{(1)}. \quad (21)$$

In Eqs. (4-5) they are evaluated only for the ISR photons. In principle, these ISR residuals could be calculated for all photons – it is still consistent with the LL ISR approximation.

2.2.5 Pre-tabulated EW Corrections

We have implemented also the pre-tabulated (or “fast”) version of the EW corrections. In this mode, a pre-tabulation of the NL $\mathcal{O}(\alpha)$ EW corrections

$$\delta_{EW}^{NL}(\{p, Q\}) = \delta_{v+s}^{(1)}(\{p, Q\}; k_\epsilon) - Y(\{p, Q\}; k_\epsilon) - \delta_{ISR}^{(1)}(p_1, p_2) \quad (22)$$

is done in the initialisation stage of the program. Then, during the event generation, a linear interpolation of the pre-tabulated values is performed for each event. The pre-tabulation is done as a function of $\cos\theta$ of the W^- for fixed values of the CMS energy \sqrt{s} (set-up to the nominal energy) and of the W invariant masses (set-up to M_W). This means that in this approach the ISR energy shift $s \rightarrow s'$ as well as off-shellness of the W 's are not taken into account (the latter prevents this method from being used below the WW -threshold). In that respect, the pre-tabulated version of the EW corrections should be regarded as some approximation of the `YFSWW3` “best” prediction. The main advantage of this version is that it is much faster in computing time than the exact (“best”) one, because here the time consuming EW library is invoked only at the beginning of the program run for some number of equally spaced points instead of calling it for each generated event. We have checked that at $\sqrt{s} = 200$ GeV, the results for the total cross section and main distributions of the pre-tabulated version differ from the corresponding results of the “best” one by only 0.1%, which is well below the required theoretical precision for the LEP2 data analysis.

2.2.6 Fixed-Order Calculation

By truncating the master formula (4) at some power of the coupling constant α one can obtain a fixed order calculation, e.g. $\mathcal{O}(\alpha^0)$, $\mathcal{O}(\alpha^1)$.

At $\mathcal{O}(\alpha^0)$ (the Born approximation), one gets the differential distribution

$$\rho_0^{(0)}(\{p, Q, q\}) = \bar{\beta}_0^{(0)}(\{p, Q, q\}). \quad (23)$$

At $\mathcal{O}(\alpha^1)$, there are two contributions: (1) from the one-loop virtual corrections and the real soft photon radiation

$$\rho_0^{(1)}(\{p, Q, q\}; k_\epsilon) = \bar{\beta}_0^{(0)}(\{p, Q, q\}) \left[1 + \delta_{v+s}^{(1)}(\{p, Q\}; k_\epsilon) \right], \quad (24)$$

and (2) from the real hard photon radiation

$$\rho_1^{(1)}(\{p, Q, q\}, k) = D_\gamma^{(1)}(\{p, Q, q\}, k). \quad (25)$$

We have implemented the above fixed order calculations in **YFSWW3**. They are available through the parallel weights as explained in Table 9 of Appendix A.

2.2.7 Radiative Corrections for W -Decays

Radiative corrections in W decays are not included in the above formulae explicitly. However, we include them in the overall normalisation of the cross section by normalising the W decay amplitudes to the W branching ratios (BR), which can be provided through the input parameters of the program. This means that in the $\bar{\beta}$ -functions of Eq. (6) for the (i, j) -th W^-W^+ decay channel, we use the normalisation constant

$$\mathcal{N}_{ij} = \frac{B_i B_j}{B_{ref}^2}, \quad (26)$$

with

$$B_{ref} = \frac{\alpha_W M_W}{12\Gamma_W \sin^2 \theta_W}, \quad (27)$$

where θ_W is the weak mixing angle, and $\alpha_W = \alpha_{G_\mu}$ in our recommended G_μ -scheme while in the so-called α -scheme we set $\alpha_W = \alpha$. B_i is the BR for the i -th W -decay channel, while B_{ref} is the reference BR used for the normalisation of the actual matrix element; see Ref. [16] for more details. For the fully inclusive process (all channels), the normalisation constant is

$$\mathcal{N}_{all} = \frac{1}{B_{ref}^2}. \quad (28)$$

It turns out that the BR's calculated at the Born level in the G_μ -scheme – the so-called improved-Born approximation (IBA) – agree within 0.1% with the full one-loop results [11]. Such an IBA option is also included in the program – for this one needs only to supply (through the input parameters) the values of the CKM matrix elements. In that case

$$B_i = \begin{cases} B_{ref} : & \text{for leptons,} \\ 3 |V_i^{\text{CKM}}|^2 \left(1 + \frac{\alpha_s(M_W^2)}{\pi}\right) B_{ref} : & \text{for quarks,} \end{cases} \quad (29)$$

where V_i^{CKM} is the CKM matrix element for the i -th W -decay channel, and $\alpha_s(M_W^2)$ is the QCD coupling constant at the M_W scale.

The real photon radiation in W decays which is generated by **PHOTOS**, by construction does not affect the overall normalisation of the cross section – this is of course motivated by the KLN theorem [35, 36].

2.2.8 ISR Reference Differential Distribution

Eqs. (4-5) define the so-called “best” physics model of YFSWW3 and if the corresponding weight is used as a rejection weight in order to generate unweighted (constant-weight) events, then we say that YFSWW3 is run in the “best” mode. For the purpose of combining the fully exclusive (multi-photon) differential distributions from YFSWW3 and KoralW, such that the resulting distributions contain both the LPA $\mathcal{O}(\alpha)$ EW corrections (missing in KoralW) and $4f$ -background diagram corrections (missing in YFSWW3), using event-per-event correction-weights, it is necessary to define a certain simplified auxiliary fully exclusive differential distribution $d\sigma_R$, which is *common to both programs*, and to implement the corresponding MC weight w_R . In YFSWW3 the weight w_R can be used also optionally as a main rejection weight – this is the so-called “ISR mode”. Otherwise, w_R is one of many alternative weights calculated simultaneously with the “best mode” and is available to the user, and/or it is used to calculate the correction-weight which serves for the purpose of introducing the missing $\mathcal{O}(\alpha)$ EW corrections in events generated by KoralW.

In the reference distribution $d\sigma_R$ only the *numerically leading* corrections, that is the ISR, the Coulomb correction, etc. are taken into account. It includes the CC03 matrix element defined identically in YFSWW3 and KoralW. We say also sometimes that this is the distribution of the ISR-type model. The corresponding fully exclusive reference differential distribution, replacing ρ_n of Eq. (5), we define as follows:

$$\begin{aligned} \rho_n^R(p_1, p_2; q_1, \dots, q_4, k_1, \dots, k_n) &= \prod_{i=1}^n \tilde{S}_I(p_1, p_2, k_i) \theta(k_i^0 - k_\epsilon) \\ &\times e^{Y_I(p_1, p_2; \epsilon)} [1 + \delta_C(Q_1, Q_2, M_W, \Gamma_W)] [1 + \delta_{An}^{\text{TGC}}(\{p, Q, q\}^{\mathcal{R}})] \\ &\left\{ \bar{\beta}_{0,ISR}^{(3)}(\{p, Q, q\}^{\mathcal{R}}) + \sum_{i=1}^n \frac{\bar{\beta}_{1,ISR}^{(3)}(\{p, Q, q\}^{\mathcal{R}}, k_i)}{\tilde{S}_I(\{p\}^{\mathcal{R}}, k_i)} + \sum_{i>j}^n \frac{\bar{\beta}_{2,ISR}^{(3)}(\{p, Q, q\}^{\mathcal{R}}, k_i, k_j)}{\tilde{S}_I(\{p\}^{\mathcal{R}}, k_i) \tilde{S}_I(\{p\}^{\mathcal{R}_\varphi}, k_j)} \right. \\ &\left. + \sum_{i>j>l}^n \frac{\bar{\beta}_{3,ISR}^{(3)}(\{p, Q, q\}^{\mathcal{R}}, k_i, k_j, k_l)}{\tilde{S}_I(\{p\}^{\mathcal{R}}, k_i) \tilde{S}_I(\{p\}^{\mathcal{R}}, k_j) \tilde{S}_I(\{p\}^{\mathcal{R}}, k_l)} \right\}, \end{aligned} \quad (30)$$

where with respect to Eq. (5) we have made the following replacements:

$$\begin{aligned} Y' &\longrightarrow Y_I(p_1, p_2; \epsilon) = 2 \frac{\alpha}{\pi} \left[\left(\ln \frac{s}{m_e^2} - 1 \right) \ln \epsilon + \frac{1}{2} \ln \frac{s}{m_e^2} - 1 + \frac{\pi^2}{2} \right], \\ \tilde{S} &\longrightarrow \tilde{S}_I(p_1, p_2, k), \end{aligned} \quad (31)$$

and we include the pure ISR LL $\bar{\beta}$'s only. The WSR in the above distribution is just absent, which means that there is only one photon partition (where all photons are associated to the ISR) with the weight $p_\varphi = 1$. In the actual MC program, ρ_n^R should be implemented with a MC weight in the operational mode when the WSR is switched off – through the parallel weights. Both these possibilities are included in YFSWW3. However, it can also be

also implemented as a MC weight when the WSR is switched on. In such a case the sums over $\bar{\beta}$'s should extend to all photons.

The above ISR reference cross section is also used in this and other works to define the so-called non-leading (NL) corrections

$$\sigma_{NL} \equiv \sigma - \sigma_R = \int (d\sigma - d\sigma_R). \quad (32)$$

The subscript NL (non-leading) expresses the fact that these corrections are numerically smaller than the leading ISR corrections. It does not mean, however, that these corrections are free of logarithmic contributions, such as e.g. $\ln(s/M_W^2)$, but these logarithms are numerically much smaller than the ISR basic logarithm $\ln(s/m_e^2)$.

As already indicated, the same reference ISR differential distribution of Eq. (30) (for the same CC03 matrix element) is also implemented in `KoralW`, and it has been checked numerically to a very high accuracy [6, 20] that its `KoralW` implementation agrees with the one implemented in the present `YFSWW3` program. Having done that, it is possible to combine the results of the `KoralW` and `YFSWW3` programs by re-weighting the MC events, in order to include both the effects of the $4f$ -background and the LPA $\mathcal{O}(\alpha)$ NL corrections in the MC predictions for the W -pair production and decay process. This is done in practice by re-weighting the MC events produced by `KoralW` with the correction-weight provided by `YFSWW3`. The correction δ_{NL}^R to be used by `KoralW` is defined as follows

$$1 + \delta_{NL}^R = \frac{\rho_n^{\text{Best}}(p_1, p_2; q_1, \dots, q_4, k_1, \dots, k_n)}{\rho_n^R(p_1, p_2; q_1, \dots, q_4, k_1, \dots, k_n)}, \quad (33)$$

where the numerator and denominators are defined in Eq. (5) and (30). A few remarks are in due order. The above ratio is, in fact, calculated as a ratio of the corresponding MC weights. The `YFSWW3` program has to be run in the mode with the WSR switched on, because ρ_n^{Best} includes the summation over the ISR–WSR photon partitions, see Eq. (5), through the multi-channel reduction procedure \mathcal{R}_φ . Under these conditions the above correction includes the complete $\mathcal{O}(\alpha)$ correction, which can be used to correct the fully exclusive distributions generated by `KoralW`, on the event-per-event basis. As we shall see in Subsection 4.12, the `YFSWW3` program provides at present only a numerically efficient approximation of the above δ_{NL}^R .

2.3 YFS Reduction/Extrapolation Procedures

It is characteristic and inherent feature of the YFS exponentiation that the IR-finite $\bar{\beta}_i$ distributions require extrapolation to a larger phase space with the additional “spectator” photons. For instance function $\bar{\beta}_0$ is in our case originally defined at the $(\{q_1, q_2, q_3, q_4\}) = (\{q\})$ point of the 4-particle phase space and it has to be also defined at every $(\{q\}, k_1, \dots, k_n)$ point of the $(4+n)$ -particle phase space. The procedure of extending the domain of the $\bar{\beta}_0$ function $\bar{\beta}_0(\{q\}) \rightarrow \bar{\beta}_0^E(\{q\}, k_1, \dots, k_n)$ we call the “extrapolation procedure”. The only true limitation in the choice of the extrapolation procedure is that $\bar{\beta}_0^E(\{q\}, 0, \dots, 0) =$

$\bar{\beta}_0(\{q\})$ must hold. Typically, $\bar{\beta}_0(\{q\})$ is defined in terms of dot-products of the four-momenta $p_i \cdot q_j$ (or inner spinor products). Extrapolation may be done in a natural way by using exactly the same algebraic expressions in the larger phase space that were originally obtained from the Feynman diagrams in the smaller phase space. In the smaller phase space the dot-products obey certain relations due to the four-momentum conservation, which in the presence of the additional photons do not hold any more – this is the main mechanism in the realization of such an extrapolation. Another useful method of implementing the extrapolation (especially in the case when $\bar{\beta}_0(\{q\})$ is implemented in a form of a black-box procedure, which requires as the input the four-momenta in the 4-particle phase space) is to project the $(\{q\}, k_1, \dots, k_n)$ point into the “reduced” point $\{q\}^{\mathcal{R}}$ using some kinematical manipulations (boosts, rotations, re-scalings) on the four-momenta, and subsequently plugging it into $\bar{\beta}_0^E(\{q\}, k_1, \dots, k_n) \equiv \bar{\beta}_0(\{q\}^{\mathcal{R}})$. The above “reduction procedure” is, of course, less general than the extrapolation procedure. Last but not least, let us note that the extrapolation procedure $(\{q\}) \rightarrow (\{q\}, k_1, \dots, k_n)$ is the reverse procedure to the procedure of defining the residua at the IR divergent points/poles $(\{q\}, k_1, \dots, k_n) \rightarrow (\{q\}) = (\{q\}, 0, \dots, 0)$ in the derivation of the resummation of the IR divergences to the infinite order (i.e. the derivation of the YFS exponentiation). The extrapolation procedure $\bar{\beta}_1(\{q\}, k_j) \rightarrow \bar{\beta}_1^E(\{q\}, k_1, \dots, k_j, \dots, k_n)$ is quite analogous. It has to obey the relation $\bar{\beta}_1(\{q\}, k_j) \rightarrow \bar{\beta}_1^E(\{q\}, 0, \dots, 0, k_j, 0, \dots, 0)$. All photons except the j -th one are here the spectators.

2.4 Multichannel YFS Reduction/Extrapolation

Sometimes it is useful to split the $\bar{\beta}$'s into several components and introduce a different extrapolation/reduction procedure for each component. This is perfectly within the freedom which we have. For instance, in YFS3 in the centre-of-mass of the Z -boson neither the initial beams nor the final fermion pairs have the momenta back-to-back. There are four possible definitions of the scattering angles in this frame. One defines $\bar{\beta}_0$ as a sum of four differential Born-level distributions, each for a different scattering angle. They might be summed up with the same weight 1/4, but, in fact, also a more sophisticated mixture is implemented [37]. A similar multichannel extrapolation procedure is used in BHLUMI [38, 39]. In the present work we employ another kind of the multichannel extrapolation, introduced for the first time in the unpublished program BHWIDE [40].

Let us elaborate on that method. Our exponentiation model is based on the real soft photon factor \tilde{S} and the corresponding virtual photon function \mathfrak{RB} to which photons emitted from the beams and from the W 's contribute coherently. One cannot, therefore, say whether a given photon is emitted from the initial state or from the W 's. One may, however, say something about that in a probabilistic way. If we split \tilde{S} as follows:

$$\begin{aligned} \tilde{S}(k) &= -\frac{\alpha}{4\pi^2} \left(\frac{p_1}{kp_1} - \frac{p_2}{kp_2} - \frac{Q_1}{kQ_1} + \frac{Q_2}{kQ_2} \right)^2 = \tilde{S}_I(k) + \tilde{S}_W(k) + \tilde{S}_{int}(k), \\ \tilde{S}_I(k) &= \left(\frac{p_1}{kp_1} - \frac{p_2}{kp_2} \right)^2, \quad \tilde{S}_W(k) = \left(\frac{Q_1}{kQ_1} - \frac{Q_2}{kQ_2} \right)^2, \end{aligned} \tag{34}$$

Then we may define for each photon a probability

$$p_I(k) = \frac{\tilde{S}_I(k)}{\tilde{S}_I(k) + \tilde{S}_W(k)}, \quad (35)$$

that it was emitted from the beams, and the probability $p_W(k) = 1 - p_I(k)$ that it was emitted from the W 's. The above probabilities are a kind of the LL concept which has to be used with care. It may help to sum up higher order QED corrections in the LL approximation. In particular, it may allow us to construct a multichannel type of the reduction/extrapolation in which we may say for the spectator photons whether they were emitted by the beams (ISR) or by the W bosons (WSR). This is done as follows. For each phase space point we split the differential distributions into 2^n components corresponding to 2^n possible associations of n photons to the ISR or the WSR, with the weight being the product $P(k)$ of the corresponding $p_I(k_i)$ or $p_W(k_i)$. This product is exactly the partition weight p_ϕ in eqs. (4) and (7). For each component we may apply a separate reduction procedure which “knows” whether a given spectator photon belongs to the ISR or the WSR. The above procedure is, in practice, simpler than is said above, because in the MC realization we start from the YFS3 differential distribution in which $\tilde{S}_{int}(k)$ is neglected, and the sum over the association of the photons to the ISR or the WSR is “randomised”. In other words, we generate only one of the 2^n possible associations and therefore, for a given event, we work with only one component (association), for which we may immediately employ its “native” reduction procedure – that is we may use the information on the photon associations directly from the YFS3 MC generator, see also the following Section for additional discussion. Let us stress again that this solution should be used with great care, especially for the non-spectator photons.

3 Monte Carlo Algorithm

In constructing the MC algorithm for the cross section calculation and the event generation, we start from the master formula of Eq. (4) and perform step-by-step simplifications in the differential distribution, compensating them with appropriate weights. We do this until we reach a differential distribution, which is simple enough to be generated by using the standard MC techniques. The MC algorithm of YFSWW3 for the Born-like WW production and decay is identical to the one used in KORALW for the so-called CC03 option [16], while the algorithm for the multi-photon radiation in the $e^+e^- \rightarrow W^+W^-$ process is based on the one implemented in the program YFS3 of KORALZ [29] for the process $e^+e^- \rightarrow f\bar{f}$. Since W 's are much heavier than light fermions and, in general, have different invariant masses, we had to make a few modifications in the latter algorithm. The most important of them are:

- generalisation of the photon radiation formulae to allow for large and different masses of radiating particles⁶,

⁶This extension is also included in the YFS3 of $\mathcal{K}\mathcal{K}$ MC program [37].

- inclusion of interferences between the radiation from the initial state and from the WW state, both in the YFS IR functions \tilde{S} and Y and in the IR finite residuals $\bar{\beta}$.

The algorithm of YFS3, although used for a decade as part of other programs, was not documented until recently. Its first full description can be found in two recent works [37, 41]. We therefore do not describe it here in detail, but refer the interested reader to the above two papers. Below we explain only the main steps in the YFSWW3 algorithm that lead to the algorithms of YFS3 and KoralW, and then comment on the YFS reduction/extrapolation procedures.

3.1 Main Steps in Construction of the MC Weight

The MC algorithm of YFSWW3 is based on the importance sampling method. In constructing it, we start from the master formula (4) and make a series of simplifications compensating them with appropriate weights until we reach a distribution that is simple enough to be generated using the basic MC methods (see e.g. Refs. [42, 43]), as we indicated above. Here, we describe only the main simplifications in Eq. (4) that lead to the formula which can be generated with the help of the MC algorithms used in the programs YFS3 and KoralW. They are:

1. $\bar{\beta}$ -functions:

For the aggregate of the $\bar{\beta}$ -functions we do the following replacement:

$$\mathcal{B}(\{p, Q, q, k\}^{\mathcal{R}_\varphi}) \longrightarrow b_0(\{p, Q, q\}^{\mathcal{R}_\varphi}), \quad (36)$$

which is compensated with the “model” weight

$$w_\beta^\varphi = \frac{\mathcal{B}(\{p, Q, q, k\}^{\mathcal{R}_\varphi})}{b_0(\{p, Q, q\}^{\mathcal{R}_\varphi})}, \quad (37)$$

where $b_0 = \bar{\beta}_0^{(0)}$ is the Born-level differential cross section for the W -pair production and decay process as given in Eq. (4) of Ref. [16]. To evaluate the model weight w_β^φ , we use the partition-dependent reduction procedures described in Subsection 2.2.4.

2. YFS form factor:

The YFS form-factor we simplify with the replacement:

$$Y'(p_1, p_2, Q_1, Q_2; k_\epsilon) \longrightarrow Y_I(p_1, p_2; \epsilon) + Y_W(Q_1, Q_2; k_\epsilon), \quad (38)$$

which is compensated with the weight

$$w_Y = \exp[Y' - Y_I - Y_W], \quad (39)$$

where Y_I is given in Eq. (31) and Y_W is the YFS IR function corresponding to the photon radiation from the W^-W^+ electric dipole:

$$Y_W(Q_1, Q_2; k_\epsilon) = 2\alpha\Re B(Q_1, Q_2) + 2\alpha\tilde{B}(Q_1, Q_2, k_\epsilon). \quad (40)$$

The explicit formulae for the above \mathfrak{RB} and \tilde{B} are given in Ref. [3]; we do not repeat them here because they are rather lengthy. This simplification corresponds to neglecting the ISR-WSR interference terms in the YFS form factor.

3. \tilde{S} -factors:

In the \tilde{S} -factors we also neglect the ISR-WSR interferences:

$$\tilde{S}(p_1, p_2, Q_1, Q_2, k) \longrightarrow \tilde{S}_I(p_1, p_2, k) + \tilde{S}_W(Q_1, Q_2, k), \quad (41)$$

and compensate this with the weight

$$w_{\tilde{S}} = \prod_{i=1}^n \frac{\tilde{S}(p_1, p_2, Q_1, Q_2, k)}{\tilde{S}_I(p_1, p_2, k) + \tilde{S}_W(Q_1, Q_2, k)}, \quad (42)$$

where \tilde{S}_I and \tilde{S}_W are given in Eq. (8).

After these simplifications, from Eq. (4) we obtain the formula for the first-level ‘‘crude’’ cross section:

$$\begin{aligned} \sigma_{\text{Crude}} = & \sum_{n=0}^{\infty} \frac{1}{n!} \int ds_1 ds_2 \frac{d^3 Q_1}{Q_1^0} \frac{d^3 Q_2}{Q_2^0} \prod_{l=1}^4 \frac{d^3 q_l}{q_l^0} \left[\prod_{i=1}^n \frac{d^3 k_i}{k_i^0} \left\{ \tilde{S}_I(k_i) + \tilde{S}_W(k_i) \right\} \theta(k_i^0 - k_\epsilon) \right] \\ & \delta^{(4)} \left(p_1 + p_2 - Q_1 - Q_2 - \sum_{i=1}^n k_i \right) \delta^{(4)}(Q_1 - q_1 - q_2) \delta^{(4)}(Q_2 - q_3 - q_4) \\ & e^{Y_I + Y_W} \sum_{\wp \in \{I, W\}^n} p_\wp b_0(\{p, Q, q\}^{\mathcal{R}_\wp}). \end{aligned} \quad (43)$$

The above distribution can be generated using the MC algorithms of **YFS3** and **KoralW**. To make this more transparent, we shall write this formula in a slightly different but equivalent form.

The product of the \tilde{S} -factors in the square brackets in Eq. (43) together with the sum over the photon partition can be written as

$$\begin{aligned} & \prod_{i=1}^n \frac{d^3 k_i}{k_i^0} \left\{ \tilde{S}_I(k_i) + \tilde{S}_W(k_i) \right\} \theta(k_i^0 - k_\epsilon) \sum_{\wp \in \{I, W\}^n} p_\wp b_0(\{p, Q, q\}^{\mathcal{R}_\wp}) = \\ & \sum_{\wp \in \{I, W\}^n} \prod_{\wp_i = I} \frac{d^3 k_i}{k_i^0} \tilde{S}_I(k_i) \theta(k_i^0 - k_\epsilon) \prod_{\wp_j = W} \frac{d^3 k_j}{k_j^0} \tilde{S}_W(k_j) \theta(k_j^0 - k_\epsilon) b_0(\{p, Q, q\}^{\mathcal{R}_\wp}) \end{aligned} \quad (44)$$

where we have substituted Eq. (7) for the partition weight p_\wp .

After some algebra, and exploiting the Bose-Einstein symmetry for photons, the formula of Eq. (43) can be written as

$$\begin{aligned}
\sigma_{\text{Crude}} = & \sum_{n_I=0}^{\infty} \sum_{n_W=0}^{\infty} \int ds' \frac{d^3 P'}{P'^0} \delta^{(4)} \left(p_1 + p_2 - \sum_{i=1}^{n_I} k_i - P' \right) ds_1 ds_2 \frac{d^3 Q_1}{Q_1^0} \frac{d^3 Q_2}{Q_2^0} \\
& \left[\frac{1}{n_I!} \prod_{i=1}^{n_I} \frac{d^3 k_i}{k_i^0} \tilde{S}_I(k_i) \theta(k_i^0 - k_\epsilon) \right] \left[\frac{1}{n_W!} \prod_{j=1}^{n_W} \frac{d^3 k_j}{k_j^0} \tilde{S}_W(k_j) \theta(k_j^0 - k_\epsilon) \right] \\
& \delta^{(4)} \left(P' - Q_1 - Q_2 - \sum_{j=1}^{n_W} k_j \right) \prod_{l=1}^4 \frac{d^3 q_l}{q_l^0} \delta^{(4)}(Q_1 - q_1 - q_2) \delta^{(4)}(Q_2 - q_3 - q_4) \\
& e^{Y_I} e^{Y_W} b_0(\{p, Q, q\}^{\mathcal{R}_\varphi}),
\end{aligned} \tag{45}$$

where $s' = P'^2$ is the CMS energy squared in the ISR-reduced (effective) frame, and n_I and n_W are the multiplicities of the ISR and WSR photons, respectively.

To generate the ISR and WSR according to Eq. (45), we can use the MC algorithm of YFS3 (see Refs. [37, 41]) for multi-photon radiation in the fermion-pair production, where the initial-final state interferences were neglected. The only modification we had to do in this algorithm was to extend it to the case of heavy particles of unequal masses (see Ref. [37]). Generating particular values of n_I and n_W corresponds to choosing a given photon partition for $n = n_I + n_W$ in the sum of Eq. (44). This means that the sum over partitions is “randomised” in the program, i.e. not evaluated directly but generated using the MC methods. For the given-generated photon partition, we then calculate the weights w_β^φ , w_Y and $w_{\tilde{S}}$. Such a solution can be regarded as a multi-branch MC algorithm, see Ref. [43], where each branch corresponds to a particular photon partition.

3.2 MC Weights and Absolute Normalisation

In the process of simplifying the fully differential distribution of Eq. (4)

$$\sigma_{\text{Best}} = \sum_{n=0}^{\infty} \frac{1}{n!} \int d\text{Lips}_n(\{p; q\}, k_1, \dots, k_n) \rho_n^{\text{Best}}(\{p; q\}, k_1, \dots, k_n) \tag{46}$$

described in the previous section we have finished with the “crude differential distribution” ρ^{Crude} inside the integral

$$\sigma_{\text{Crude}} = \sum_{n_I=0}^{\infty} \sum_{n_W=0}^{\infty} \frac{1}{n_I!} \frac{1}{n_W!} \int d\text{Lips}_n(\{p; q\}, k_1, \dots, k_n) \rho_{n_I, n_F}^{\text{Crude}}(\{p; q\}, k_1, \dots, k_n), \tag{47}$$

where $n = n_I + n_F$. Using the above notation, the total correcting weight is defined as follows:

$$w^{(1)} = \frac{\rho_n^{\text{Best}}(\{p; q\}, k_1, \dots, k_n)}{\rho_{n_I, n_F}^{\text{Crude}}(\{p; q\}, k_1, \dots, k_n)} = w_\beta^\varphi w_Y w_{\tilde{S}}. \tag{48}$$

In the actual program it comes in several versions, because for the purpose of the technical tests, and for the discussion of the physical precision, we need to switch off/on certain contributions in the full distribution ρ_n^{Best} .

However, in the actual MC program we do not actually generate the distribution ρ^{Crude} , but a certain more primitive “primary” distribution ρ^{Prim} . For its definition and full description, and the description how events are generated according to this distribution, starting from the uniform random numbers, we refer the reader to the most complete documentation of the YFS3 Monte Carlo algorithm in Ref. [37]; Refs. [16] and [27] can also be helpful. The weight correcting for the transition from the primary to crude distribution is given by

$$w^{(2)} = \frac{\rho_{n_I, n_F}^{\text{Crude}}(\{p; q\}, k_1, \dots, k_n)}{\rho_{n_I, n_F}^{\text{Prim}}(\{p; q\}, k_1, \dots, k_n)} \quad (49)$$

and is fully defined in Ref. [37]. The total MC weight is of course equal to the product

$$w = w^{(1)} w^{(2)} \quad (50)$$

or

$$w = w^{\text{Model}} w^{\text{Crude}}, \quad (51)$$

with

$$w^{\text{Model}} = w_\beta^\varphi b_0, \quad w^{\text{Crude}} = w^{(2)} w_Y w_{\bar{S}} b_0^{-1}, \quad (52)$$

where w^{Model} is called in the program the “model weight” (this weight and its many variants are provided in the `WtSet` array; see Section 5), and w^{Crude} is called the “crude weight” (in the program it is equal to the product `WtCrud1*WtCrud2`; see Section 5).

The integrated cross section is given by the product of the average weight and the integrated primary cross section

$$\sigma = \langle w \rangle \sigma^{\text{Prim}} = \langle w \rangle \int d\sigma^{\text{Prim}}. \quad (53)$$

The integrated primary cross section we also call a “normalisation cross section”, because it provides the absolute normalisation for the whole MC calculation.

4 Structure of the Program

In this section we provide the reader with a brief guide of the YFSWW3 program. We shall describe its main routines, libraries and interfaces. We want to note here that the program, in the distribution version, is prepared for a UNIX/Linux-type operating system that supports directories and the `make` utility. The source code is distributed over a number of subdirectories, in order to make the structure of the program more transparent and

easier to handle. Also a system of the `Makefile`'s is provided, for compilation, execution and other auxiliary functions (e.g. clean-up). (Of course, this organization, which is in fact rather simple, can be avoided and the whole source code can be put into a single FORTRAN file.) In the following we give a review of all YFSWW3 subdirectories. We start from the directories that are most interesting from the user's point of view and then go to the ones with more technical contents. In the distribution package, all these subdirectories are located in the main YFSWW3 directory: `yfsww3-1.16-export`. This directory also comprises two important files: `README` and `RELEASE.NOTES`, which we recommend the user to look through before using the program. They contain some basic information about YFSWW3: how to compile/link and run the program, a brief documentation of the code, etc.

4.1 demo – Demonstration Program

The subdirectory `demo` contains a demonstration program in the file `demo.f`. Generally, the user is supposed to provide his/her own main program, nevertheless, the file quoted here provides a simple example of such a program. It has a double role: (1) as a useful template, and (2) as a first cross-check that the MC generator YFSWW3 runs correctly on a given installation. The essential part of this program is a loop in which a series of MC events is generated. It also reads the input from a disk file, but no histogramming is performed and most of the output comes from the generator itself. At the end of the program, a MC integrated cross section of YFSWW3 is compared with the Born-level and ISR results from the semi-analytical program `KorWan`. The program is compiled/linked and executed, with the help of the `Makefile`, for the input data set given in the files `demo.input`. The program also reads the default settings provided in the file `data_DEFAULTS` located in the directory `data_files` – some of these default settings are overridden by data from `demo.input`. The demonstration program is run for unweighted events with the external libraries `PHOTOS`, `TAUOLA` and `JETSET` switched on. The output, written into the disk file `demo.output`, can then be compared with the one provided in the file `demo.output.linux`. It was obtained on a PC Intel Pentium III under the Linux RedHat 6.1 operating system.

4.2 data_files – Default Input Data

The subdirectory `data_files` contains the input data file `data_DEFAULTS` with the defaults settings for YFSWW3. It is *identical* with the one used in the program `Kora1W`, so the two programs can be set-up from the same input data file! This facilitates considerably combining the results of both programs; see Ref. [20] for more details. Some entries in this data file are dummy for YFSWW3 and are kept only for compatibility with `Kora1W`, while some of them are specific to YFSWW3 and are treated as dummy parameters in `Kora1W`. They are denoted by appropriate comments. This file can also be used by the user as a template to create his/her own input data file, where only those entries that will have different settings than in the default data file may be included. The user input file should be read after reading the file `data_DEFAULTS`, so that the user settings would override

the default ones; see the example in the `demo.f` file described in the previous subsection. This directory comprises also some older data files kept for backward compatibility. Their names contain, after a dot, the two last digits of the year of their creation. The newest one is identical with the file `data_DEFAULTS`.

4.3 `yfsww` – Master Unit

The subdirectory `yfsww` contains the actual Monte Carlo event generator. Subprograms used directly by the user are the following:

- `YFSWW_ReadDataX` – the subprogram used to read, from the disk file, the default input data of `YFSWW3` and subsequently the data of the user into the array `xpar` at the very beginning of the use of `YFSWW3`.
- `YFSWW_Initialize` – the subprogram that does all initialisations of internal variables. First, it sets-up the main parameters of the program (through the routine `filexp`) according to the values in the input data files, then it calls several *initialisers* of the main internal modules of the generator, such as `KarLud(-1, ...)`, and of external packages, such as `TAUOLA`, etc. It prints out directly or indirectly all the input parameters.
- `YFSWW_Make` – the most important subprogram of `YFSWW3`. It generates single MC events. Functionally, it is a high-level management subprogram in the event generation. It invokes (through the routine `yfsww3`) other routines that perform specific tasks, such as: generation of ISR photons (`KarLud`), generation of radiative photons from W 's (`KarFin`), generation of the W 's and final $4f$ four-momenta (`WW_Presam`), evaluation of the Coulomb correction (`WTCoul`), calculation of the matrix element (`Model`), of the YFS form factor, of the interference corrections, etc. It builds up the total MC weight from the weights supplied by these routines. This weight is then returned, in the weighted-event mode, as the main event weight, or used in the rejection loop (in the routine `yfsww3`), in the unweighted-event mode, for constructing the `weight=1` event. It also calls `PHOTOS` which generates photon radiation in the W decays, `TAUOLA` for decaying of the final state τ 's (if they appear), and `JETSET` to perform fragmentation/hadronization of the final state quarks. It keeps track, through special monitoring routines, of all information necessary for the final results from the MC event generation.
- `YFSWW_Finalize` does all final bookkeeping, including the calculation of the integrated (total) cross section. It prints a summary output on the whole sample of generated MC events.

The first subprogram is located in the file `readata.f`, while the following three are in the file `yfsww3.f`.

This directory contains also a collection of utility routines which can be used e.g. to access information on particle flavours and four-momenta, on event weights, etc. They are located in the file `ww_get.f` (see the comments in this file for more details).

4.4 model – Matrix Elements

The routines for the “model” weights calculations are located in the subdirectory `model`. The master routine here is the subroutine `Model` (in the file `model.f`), which by calling some other routines, evaluates the “model” weights w^{Model} as defined in Eq. (52).

1. For the **Born-level matrix element** we use the same routines as in the program `KoralW` – they are collected in the file `born.f`. The same is for the ISR corrections, located in the file `betas.f`.
2. The $\mathcal{O}(\alpha)$ **virtual and real soft photon corrections** are evaluated with the help of a special interface – the routine `VirSof` – in the file `virsof.f`. In the first call, this routine makes all the necessary initialisations, and then calculates the EW corrections by calling appropriate routines from the EW library for each generated event. The pre-tabulated (or “fast”) version of the EW correction is invoked through the routine `Dn1Fast` (in the file `dn1fast.f`). This routine makes a pre-tabulation of the EW corrections in the initialisation stage of the program and then, during the event generation, it performs the linear interpolation of the pre-tabulated values to calculate the EW corrections for each event as described in Section 2.2.5.
3. The $\mathcal{O}(\alpha)$ **hard photon matrix element** in the WW production, which contributes to the function $\bar{\beta}_1$, see Eq. (20), is calculated with the help of the routine `eewwg`, located in the file `eewwg.f`. This routine evaluates appropriate spin amplitudes for the process $e^+e^- \rightarrow W^+W^-\gamma$ according to the formulas of Ref. [32], which are then combined coherently with the spin amplitudes for W decays.

In order to calculate all these contributions to the $\bar{\beta}$ -functions, the subroutine `Model` calls the routines that perform appropriate “reduction” procedures as described in Section 2. Except for calculating the contributions to the YFS exponentiated cross section, this routine provides also the weights corresponding to the strict $\mathcal{O}(\alpha^0)$ and $\mathcal{O}(\alpha^1)$ calculations. In the end, the subroutine `Model` fills the array of weights with the weights corresponding to: (i) various variants of the SM models (for example different orders of QED ISR) (ii) and various components in the differential cross section for a give variant of the SM (for example contributions from various $\bar{\beta}$'s). The subroutine `Model` returns the best “model” weight.

The routine `WTCoul` – in the file `coulco.f` – for the Coulomb (both the “standard” and “screened”) correction calculation is also located in this directory.

4.5 ewc – Electroweak Library

The subdirectory `ewc` contains the routines for the calculation of the electroweak (virtual plus soft photon) corrections in the on-shell WW production process according to Refs. [7, 10]. For the evaluation of one-loop integrals they use the package `FF` of Ref. [44], which is located in a separate directory (see below).

4.6 `interfs` – Interfaces to External Libraries

Interfaces to some external libraries are collected in the directory `interfs`. The most important routines are:

- `inietc` – in the file `tauola_photos_ini.f` – sets up some parameters of PHOTOS and TAUOLA.
- `tohep` – in the file `hepface.f` – fills in the `/HEPEVT/ COMMON` block, calls PHOTOS for photon radiation in W decays and TAUOLA for τ decays.
- `tohad` – in the file `lundface.f` – calls JETSET for the quark fragmentation/hadronization.

Note that the `COMMON` block `/HEPEVT/` is expected to contain single-precision (`REAL*4`) variables.

4.7 `wdeclib` – External Libraries for W Decay

The subdirectory `wdeclib` provides the following programs:

- PHOTOS [22] for photon radiation in the W decays (up to two photons).
- TAUOLA [45] for τ decays with radiative corrections.
- JETSET version 7.4 [46] for quark fragmentation/hadronization.

located in the files: `photos.f`, `tauola.f` and `jetset74.f`, respectively.

In YFSWW3 1.16 we use the recently modified PHOTOS, where also the photon radiation from quarks can be activated with the help of a special input parameter switch; see the tables with the input parameters in Appendix A. Note that in the distribution version of TAUOLA the parameters in the τ decay modes are not adjusted to the recent experimental data. We recommend the user to replace this version of TAUOLA with the one accepted within his/her own collaboration. The technical update explained in Refs. [47, 48] will resolve this inconvenience in the future releases of the program.

4.8 `glib` – Histogramming and Numerical Library

A handy FORTRAN histogramming package, GlibK [49], is provided in the subdirectory `glib` (the file `glibk.f`). It is used by YFSWW3 both for hard-coded internal bookkeeping and for some optional “external” tests. The package is similar in its usage to the classic HBOOK of CERNLIB. This subdirectory also contains the useful numerical package `yfslib.f` with the routines for weight monitoring, random number generation, numerical integration, one and two-dimensional adaptive MC sampling, Lorentz transformations, etc.

4.9 semian – Semi-analytical Program KorWan

The subdirectory `semian` contains the package `KorWan` for the semi-analytical calculations of the cross section for the off-shell WW production and decay at the Born level and with the ISR corrections (using the structure function formalism). Also the Coulomb effect is included in `KorWan` in both versions: the “standard” and the “screened” ones. The package is described in detail in Refs. [16–18]. It can be used for a quick consistency check of the `YFSWW3` results.

4.10 ff – FF Package

In the subdirectory `ff` is located the `FF` package [44] for the evaluation of one-loop integrals needed to calculate the $\mathcal{O}(\alpha)$ EW virtual corrections.

4.11 dok – Related Papers

In the subdirectory `dok`, we include some of our papers related to `YFSWW3`. They are in the form of gzip’ed PostScript files.

4.12 rewt – Re-weighting Tools

The subdirectory `rewt` contains routines that are not needed for the standard MC event generation but for various event re-weighting purposes. We provide here the tools for two kinds of re-weighting: (1) the re-weighting of the `KoralW` generated events to correct for $\mathcal{O}(\alpha)$ NL effects in WW production, and (2) the re-weighting of the `YFSWW3` generated events to take into account effects due to some input parameters (typically W -mass) changes. All these tools are described in detail in the following, see also the file `README` provided in this subdirectory.

4.12.1 Re-weighting KoralW Events by YFSWW3

The main tool for this kind of re-weighting is the function `YFSWW_WtNL` located in the file `rewt_K.f`. For the events, in terms of flavours and four-momenta of the final state fermions and the ISR photons, provided through its parameters, this function calculates and returns the corresponding correction weight from `YFSWW3`. This weight is a ratio of the fully differential distribution. In practice, we calculate the ratio of the MC weights corresponding to two distributions – this is more convenient. We can do it because the common crude distribution entering both weights cancels out. For a given number of real photons of Eq. (5), to the reference distribution in the “ISR approximation” defined in Eq. (30), which is the same as in `KoralW` in the `CC03` mode (Eq. (4) of Ref. [18]). It is defined in Eq. (33). In the re-weighting mode of `YFSWW3`, we implement an approximate version of this weight:

$$w_{NL}^- \equiv \frac{\rho_n^{\text{Best-}}(\{p, Q, q\}^{\mathcal{R}_I}, k_1, \dots, k_n)}{\rho_n^R(\{p, Q, q\}^{\mathcal{R}_I}, k_1, \dots, k_n)} = 1 + \delta_{NL-}^R, \quad (54)$$

where $\rho_n^{\text{Best-}}$ is a variant of ρ_n^{Best} in which the sum over the photon partitions is reduced to only one term in which all photons are associated to the ISR with the partition probability $p_\varphi = 1$, and \mathcal{R}_I means the respective reduction procedure. Unfortunately, we loose in this way a (small) part of the genuine $\mathcal{O}(\alpha)$ corrections. The full $\mathcal{O}(\alpha)$ correction can be included only if YFSWW3 is run in the event-generation mode, and the correction-weight for re-weighting (accounting for the $4f$ -background) is supplied from KoralW. (This leads, however, to large MC weight fluctuations, see below.) We have checked, however, that at the LEP2 energy range the bias introduced by this approximation is within 0.1%, both for the total cross section and for distributions. This can be explained by the fact that the W 's, as heavy and slowly moving particles, do not radiate much at these energies. Of course, the main weight of YFSWW3 based on ρ_n^{Best} does not have this bias. In this way, by assigning this correction-weight to the KoralW events, one can include, in a simple way, the $\mathcal{O}(\alpha)$ NL correction δ_{NL-}^R into the KoralW results. How to do it in practice, we explain in detail in Ref. [20].

4.12.2 Re-weighting YFSWW3 Events by YFSWW3

This kind of re-weighting can be useful in some data analyses, when e.g. one has a large sample of simulated events for a given input parameter set-up and one wants to asses the effects of changing some of the input parameters on the results, but without a necessity of repeating the full simulation with the new parameter set-ups. The tools for such a re-weighting are collected in the file `rewt_Y.f`. We provide two methods: “exact” and “approximate”. They differ in that, that in the exact method the partition vector for photons is stored along with their four-momenta, while in the approximate method the partition information is not recorded.

(a) The exact method:

The tool for the exact method is SUBROUTINE `YFSWW_WME(WtME)`, where `WtME` corresponds to the weight w^{Model} of Eq. (52). It requires storing on the disk/tape the entire content of four COMMON blocks: `/MOMINI/`, `/MOMFIN/`, `/MOMDEC/` and `/DeChan/` during the event generation run of YFSWW3. We assume that the appropriate tools for writing the above information on the disk/tape as well as for reading it in the re-weighting run of the program are provided by the user of the code (see the source code for more details).

How to use it:

1. *The primary run generating/storing events:*
 - Run YFSWW3 and store on the disk/tape the whole content of the COMMON blocks: `/MOMINI/`, `/MOMFIN/`, `/MOMDEC/`, `/DeChan/`.
This is done for some input parameters set-up (A).
2. *The secondary run re-weighting events:*
 - Initialise the program with the input parameters set-up (A) used for the event generation.
 - Instead of generating events, call `YFSWW_WME(WtME_A)` for all stored events and

- save the computed matrix element weight $WtME_A$ (in some arbitrary units).
- Initialise the program with a different input parameters set-up (B).
- Calculate the weight $WtME_B$ and save as above.
- For each event calculate the ratio $Wt = WtME_B/WtME_A$ and use it as the weight for re-weighting the original sample of events.
- This procedure can be repeated for any new input parameters set-up (B).

Example of running the program in the re-weighting mode:

```
CALL YFSWW_ReaDataX('./data_DEFAULTS',1,10000,xpar) ! reading general defaults
CALL YFSWW_ReaDataX('./user.input',0,10000,xpar) ! reading user input
CALL YFSWW_Initialize(xpar) ! initialize generator
NevTot = 1000 ! number of events to be re-weighted
DO Iev = 1, NevTot
  CALL YFSWW_WME(WtME) ! calculate matrix element weight for stored events
ENDDO
```

For more information about running YFSWW3 see Section 5.

(b) The approximate (simpler) version:

In the case when one does not have all the information needed for the exact (recommended) method of re-weighting (because of the lack of disk/tape space or some other reasons), one can use

```
WtME = YFSWW_WME_Smpl(Iflav,pf1,pf2,pf3,pf4,Phot,Nphot)
```

instead of `CALL YFSWW_WME(WtME)`. In this case one needs to store for each event only the flavours and the four-momenta of the final state fermions and the number and the four-momenta of all photons. *Important:* They should come from YFSWW3 itself, not from PHOTOS after the FSR. These four-momenta and flavours are available from two COMMON blocks:

```
COMMON / DECAYS / Iflav(4),amdec(4)
COMMON / MOMDEC / pf1(4),pf2(4),pf3(4),pf4(4),Phot(100,4),Nphot
```

(the fermion mass array `amdec(4)` does not need to be stored). They can be alternatively accessed with the help of two getter-routines:

```
SUBROUTINE YFSWW_Get4f(flav,p1,p2,p3,p4)
SUBROUTINE YFSWW_GetPhotAll(NphAll,PhoAll)
```

located in the file `ww_get.f` in the subdirectory `yfsww`. The first one provides the flavours and the four-momenta of the final state 4-fermions, while the second one provides the number and the four-momenta of the radiative photons (excluding the ones from PHOTOS).

The FUNCTION `YFSWW_WME_Smpl` fills the appropriate COMMON blocks and calculates (returns) the matrix element weight (corresponding to $WtME$ in the previous method). This method is *approximate* because it does not use the information on the photon partitions

but assigns all the photons to the ISR in performing the partition-dependent reduction procedure (described in Section 2.2). Our tests show, however, that the differences between this and the exact method are numerically negligible, e.g. $< 0.01\%$ for the total cross section at $\sqrt{s} = 200$ GeV.

4.12.3 Re-weighting YFSWW3 Events by KoralW

Similar re-weighting tools are provided in the new version of KoralW [20]. They can be used for re-weighting events generated by YFSWW3 with the weight provided by the KoralW in order to correct for the missing $4f$ background contribution to the the signal WW process. The relevant re-weighting routines in KoralW require as an input the events from YFSWW3, which are generated according to the ISR-type reference differential distribution. Such events are provided by YFSWW3 in the standard generation mode with the help of the getter-routine `YFSWW_GetEvtISR`, located in the file `ww_get.f` of the directory `yfsww`. The correction-weight provided by KoralW can be used to re-weight the constant-weight (unweighted) events from YFSWW3 or to correct the YFSWW3 weights in the variable-weight (weighted-event) mode; see Ref. [20] for more details.

5 How to use the Program

In this section we provide a short guide on how to use the current version of YFSWW3, and we describe the input parameters of the program and its output.

5.1 Principal Entries of YFSWW3

The principal entries of the YFSWW3 package, which the user has to call in his/her application in order to generate a series of the MC events, were already listed and described briefly in Subsection 4.3. Here we shall add more information on their functionality. The calling sequence constituting a typical Monte Carlo run will look as follows:

```
CALL YFSWW_ReaDataX('./data_DEFAULTS',1,10000,xpar) ! reading general defaults
CALL YFSWW_ReaDataX('./user.input',0,10000,xpar) ! reading user input
CALL YFSWW_Initialize(xpar) ! initialize generator
DO loop = 1, 10000 ! loop over MC events
  CALL YFSWW_Make ! generate single MC event
ENDDO
CALL YFSWW_Finalize ! final book-keeping, print
CALL YFSWW_GetXSecMC(XSecMC,XErrMC) ! get total cross section
```

In the first call of `YFSWW_ReaDataX`, default data are read into the `REAL*8` array `xpar(10000)`. The YFSWW3 has almost no data hidden in the source code (this is not true for TAUOLA and JETSET). The file `data_DEFAULTS`, which is read first, is placed in the distribution subdirectory `data_files`. This file provides necessary initial default values of *all* input parameters. The user should *never modify it*. It can be copied to a local directory or,

better, a symbolic link should be created to the original `data_files/data_DEFAULTS`. This file is quite sizable and the user is usually interested only in changing some subset of these data. In the second call of `YFSWW_ReadDataX`, the user can overwrite the default data with his/her own smaller set of input data which are placed in the `user.input` file. For example, the simplest input data which defines only the CMS energy would look like this:

```
BeginX
*<ia><-----data-----><-----comments----->
  1          190d0 CMSEne =CMS total energy [GeV]
EndX
```

As we see, data cards begin with the keyword `BeginX` and end with the keyword `EndX`. The comment lines are allowed – they begin with `*` in the first column. The data themselves are in a fixed format, with the index `i` of the array `xpar(i)` followed by the data value and a trailing comment. The example of the input data set for the demonstration program `demo.f` in the subdirectory `demo` provides a useful template for a typical user’s data. The complete set of the data in `data_DEFAULTS` is described in detail in Tables 1–5. Obviously, the user is interested in manipulating only some of them and will retain the default values in most of the cases.

The `YFSWW_Initialize` is invoked to initialise the generator. It reads the input data from the array `xpar`, prints them out and sends them down to the various modules and auxiliary libraries. The programs have to be called in strictly the same order as in the above example. At this point one is ready to generate the series of the MC events. The generation of a single event is done with the help of `YFSWW_Make`. After the generation loop is completed, we may invoke `YFSWW_Finalize`, which does the final book-keeping, prints out various pieces of information on the MC run, and calculates the total MC integrated cross section (in pb). In order to obtain this cross section the user may call the routine `YFSWW_GetXSecMC(XSecMC, XErrMC)`.

5.2 Input/Output Parameters

As we have already explained in the previous section, the input parameters enter through the `xpar` array, being a parameter of the routine `YFSWW_Initialize`. The meaning of all of them is explained in Tables 1–5.

The principal output of `YFSWW3` is the Monte Carlo *event*, which is just a list of final-state four-momenta (in GeV) and flavours, encoded in the standard `/HEPEVT/` event record. At the present version we still provide the `REAL*4` version of `/HEPEVT/` of the dimension of 2000. If the user is interested in the parton momenta before hadronization, then, in addition to `/HEPEVT/`, they are available (see also Table 8) through

```
CALL YFSWW_Get4f(p1,p2,p3,p4)      ! get final 4f flavours and 4-momenta
CALL YFSWW_GetBeams(q1,q2)        ! get beam 4-momenta
CALL YFSWW_GetPhotAll(NphAll,PhoAll) ! get photons multiplicity and 4-momenta
```

Alternatively, all the four-momenta are available from the internal COMMON blocks /MOMWWP/ and /MOMDEC/, see Tables 6 and 7 for details.

In the case of a MC run with weighted events, the user is provided with the main weight (see also Table 10) through

```
CALL YFSWW_GetWtMain(WtMain)           ! get main Monte Carlo weight
```

Of course, for unweighted event generation runs `WtMain=1`. For special purposes the user may also be interested in auxiliary weights, which are provided (see also Table 10) with the help of

```
CALL YFSWW_GetWtAll(WtMain,WtCru,WtSetAll) ! get all Monte Carlo weights
```

where `REAL*8 WtSetALL(100)` is an array of the weights described in Table 9. The definition of the main weight `WtMain` depends on the input switches `KeyCor` and `KeyLPA`, see Table. 9, for instance, the best model for `KeyCor = 5` and `KeyLPA = 0` corresponding to Eq. (4) is defined as follows:

$$WtMod = Wtcru1*Wtcru2*(WtSet(41)-WtSet(2)+WtSet(4)).$$

Alternatively, the auxiliary weights `WtSet` defined in Eq. (48) are available from the COMMON /WGSTALL/, see Table 9. The total auxiliary weight should be defined as:

$$WtAuxEWC(i) = WtCru1*WtCru2*WtSetAll(i)$$

for $\mathcal{O}(\alpha)$ EW corrections, and

$$WtAuxISR(i) = WtCru1*WtCru2*WtSetAll(i)$$

for the ISR corrections. The corresponding integrated cross section is simply obtained by multiplying the average of the total weight by the *normalisation* cross section of Eq. (53) (or the “primary cross section” in the terminology of Ref. [37]), which is provided through

```
CALL YFSWW_GetXSecNR(XSecNR,XErrNR)    ! get normalization x-section
```

Note that we expect from the user to use the auxiliary weights in the variable-weight mode only. It is, however, not impossible to use them also for the constant-weight events. In such a case we recommend the user to contact the authors for more instructions on how to do it correctly.

The complete description of the post-generation output parameters from `YFSWW_Finalize` is collected in Table 11.

5.3 Printouts of the Program

In this section we describe a printout of the demonstration program `demo` in the “best” mode, shown in Appendix B. The printout starts with the detailed specification of the actually used input parameters. Also, logos of some of the activated subprograms (`KarLud`, `KarFin`) and libraries (`PHOTOS`, `TAUOLA`, `JETSET`) are printed here. Next, the printout of one full event (in the standard PDG convention) is shown (in the actual `demo.output` file,

five events can be seen). Then, the printouts from the post-generation mode, i.e. `CALL YFSWW_Finalize`, appear. First, one can see summary reports from the subprograms `KarLud` and `KarFin`. Their meaning is rather technical, so the average user of `YFSWW3` does not have to worry about them (unless something unusual appears there). One thing that the user may check from time to time there is the entry `B5` in the `KarFin` window `B`: the average value of the `WCTRL` weight should be equal to 1 within the statistical error (if it is not, notify the authors!). After these technical printouts from the `YFSWW3` subprograms, there are several summary reports from `TAUOLA` on the τ decays. The final reports of the main `YFSWW3` MC generator are collected in three windows: `A`, `B` and `C`.

The window `A` contains the most important information from from the user's point of view. It provides the values of:

`A0` : the CMS energy in GeV;

`A1` : the best-order total cross section with its absolute statistical error for the generated statistics sample (in pb) ;

`A2` : the relative error of the above cross section;

`A3` : the total number of generated events;

`A4` : the number of accepted events;

`A5` : the number of the events with negative weights;

`A6` : the relative contribution to the total cross section from the events with the negative weights;

`A7` : the number of over-weighted events;

`A8` : the relative contribution to the total cross section from the over-weighted events;

`A9` : the value of the maximum weight for the event rejection;

`A10` : the average weight.

The numbers in the entries `A5`, `A6`, `A7`, `A8` should be as small as possible. In particular, the relative contributions to the cross section from the negative weights and the over-weights should be much smaller than the expected accuracy of the MC calculations. If there is a large contribution from the over-weighted events, one should try to increase the value of the maximum weight `WtMax`, see Table 1. In the case of the large negative weight contribution, one should contact the authors. The ratio of the average weight (entry `A10`) to the maximum weight (entry `A9`) shows the efficiency of the MC algorithm in the unweighed events generation, i.e. the event acceptance rate. In the example given in the demo program it is $\sim 20\%$.

The window `B` is devoted to the technical information on the ISR corrections in different orders in α within the `YFS` framework. This information is quite important, because it

shows how big the contributions of subsequent orders of the perturbative series are, and thus allows us to estimate the missing higher-order effects. The entries B1–B4 provide the values of the total cross section (in pb) in the orders $\mathcal{O}(\alpha^0)_{exp}$ – $\mathcal{O}(\alpha^3)_{exp}$ of the ISR, while the entries B15–B17 give the differences of these values in subsequent orders. The entries B5–B14 contain the information on the contributions from the individual YFS ISR residuals $\bar{\beta}_{i,ISR}$, also in different orders in α . The differences between various residuals and various orders for a given residual are provided in the entries B18–B26.

The window C contains the information on the exact $\mathcal{O}(\alpha^1)_{exp}$ corrections to the WW production stage. The first entry (C1) shows the total $\mathcal{O}(\alpha^1)_{exp}$ cross section for the exact EW corrections calculation, the second one (C2) shows the same for the approximate (“fast”) EW corrections, and the third one (C3) contains the $\mathcal{O}(\alpha^1)_{exp}$ LL cross section. The second part of this window shows the differences between the exact and approximate EW corrections (C4), and between the exact and the LL results (C5). The final part (entries C6–C8), contains the differences of various $\bar{\beta}_i$ contributions. All these values are given in pb.

This completes the description of the output of YFSWW3. The remaining entries shown in the `demo.output` file (e.g. histograms) are produced by the `demo` main program.

6 Summary

We presented Monte Carlo event generator YFSWW3 version 1.16 for the combined W -pair production and decay process. It includes the complete $\mathcal{O}(\alpha)$ EW corrections in the WW production process in the leading pole approximation, in addition to other numerically sizeable but physically less interesting effects like for instance up to $\mathcal{O}(\alpha^3)$ QED ISR effects in the LL approximation. The program is precise enough for obtaining Standard Model prediction for the total cross section and any distribution at LEP2, understanding that contribution from the background diagrams are included in the calculation with help of KoralW (or removed from the data). YFSWW3 includes programming tools for communicating with KoralW in the process of generating single MC event. The program was also tested and is applicable for the Linear Collider energy range. The next possible improvement in the program is the introduction of the YFS exponentiation in the MC simulation of the W decays.

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A Program Parameters and Their Settings

Parameter	Position and meaning
CMSEne	xpar(1) (=200.0): \sqrt{s} , centre-of-mass (CMS) energy [GeV]
Gmu	xpar(2) (=1.16639d-5): G_F , Fermi constant in [GeV ⁻²]
alfWin	xpar(3) (=128.07d0): $1/\alpha_W$ inverse QED coupling constant at M_W scale
aMaZ	xpar(4) (=91.1882): M_Z , mass of Z boson, [GeV]
GammZ	xpar(5) (=2.4952): Γ_Z , width of Z boson in [GeV]
aMaW	xpar(6) (=80.419): M_W , mass of W boson [GeV]
GammW	xpar(7) (=-2.120): Γ_W , width of W boson [GeV], for (gammw < 0) Γ_W is recalculated from G_μ , M_W and α_S
VVmin	xpar(8) (=1d-6): Minimum v -variable (dimensionless), infra-red cut-off
VVmax	xpar(9) (=0.99): Maximum value of v -variable
WtMax	xpar(10) (=2.0): Maximum weight for rejection, for wtmax < 0 redefined inside the program
aMH	xpar(11) (=115.0): Higgs mass [GeV]
aGH	xpar(12) (=1.0): Higgs width [GeV]
alpha_s	xpar(13) (=0.1185): QCD coupling constant
	xpar(14-19): Dummy parameters in YFSW3 (specific to KoralW)

Table 1: The list of input parameters of the YFSW3 generator in the xpar vector. The default values are in brackets.

Parameter	Position and meaning
KeyCor	xpar(2001) (=5): Radiative corrections switch =0: Born =1: Above + ISR =2: Above + Coulomb correction =3: Above + Full YFS Form-Factor for WW production =4: Above + Radiation from WW =5: Above + Exact $\mathcal{O}(\alpha)$ EW corrections in WW production (BEST!) =6: Same as 5 but with pre-tabulated EWC (approximate but faster!)
KeyLPA	xpar(2002) (=0): LPA mode switch =0/1: LPA _a /LPA _b (LPA _a recommended , LPA _b for test only)

Table 2: The list of input parameters in the xpar vector specific to the YFSW3 generator (not used in KoralW). The default values are in brackets.

Parameter	Position and meaning
	xpar(21-57): Values of TGC's: Set 1, most general set – complex numbers, default values are wild random, not shown
g1(1)	=DCMPLX(xpar(21), xpar(31)) = g_1^z , for WWZ vertex
kap(1)	=DCMPLX(xpar(22), xpar(32)) = κ_z , for WWZ vertex
lam(1)	=DCMPLX(xpar(23), xpar(33)) = λ_z , for WWZ vertex
g4(1)	=DCMPLX(xpar(24), xpar(34)) = g_4^z , for WWZ vertex
g5(1)	=DCMPLX(xpar(25), xpar(35)) = g_5^z , for WWZ vertex
kapt(1)	=DCMPLX(xpar(26), xpar(36)) = $\tilde{\kappa}_z$, for WWZ vertex
lamt(1)	=DCMPLX(xpar(27), xpar(37)) = $\tilde{\lambda}_z$, for WWZ vertex
g1(2)	=DCMPLX(xpar(41), xpar(51)) = g_1^g , for $WW\gamma$ vertex
kap(2)	=DCMPLX(xpar(42), xpar(52)) = κ_g , for $WW\gamma$ vertex
lam(2)	=DCMPLX(xpar(43), xpar(53)) = λ_g , for $WW\gamma$ vertex
g4(2)	=DCMPLX(xpar(44), xpar(54)) = g_4^g , for $WW\gamma$ vertex
g5(2)	=DCMPLX(xpar(45), xpar(55)) = g_5^g , for $WW\gamma$ vertex
kapt(2)	=DCMPLX(xpar(46), xpar(56)) = $\tilde{\kappa}_g$, for $WW\gamma$ vertex
lamt(2)	=DCMPLX(xpar(47), xpar(57)) = $\tilde{\lambda}_g$, for $WW\gamma$ vertex
	xpar(61-65): Values of TGCs: Set 2, see CERN 96-01, Vol. 1, p. 525
delta_Z	=xpar(61) = δ_Z
x_gamma	=xpar(62) = x_γ
x_Z	=xpar(63) = x_Z
y_gamma	=xpar(64) = y_γ
y_Z	=xpar(65) = y_Z
	xpar(71-73): Values of TGCs: Set 3, see CERN 96-01, Vol. 1, p. 525
alpha_Wphi	=xpar(71) = $\alpha_{W\phi}$
alpha_Bphi	=xpar(72) = $\alpha_{B\phi}$
alpha_W	=xpar(73) = α_W
amel	=xpar(100) (=0.510998902d-3): beam (electron) mass
AlfInvl	=xpar(101) (=137.03599976): $1/\alpha_{\text{QED}}$ at the Thomson limit
gpicob	=xpar(101) (=389.379292d6): GeV^{-2} to picobarn translation constant
BR(1:20)	xpar(131-139): W branching ratios (BR); the numbering of entries is: 1 = ud , 2 = cd , 3 = us , 4 = cs , 5 = ub , 6 = cb , 7 = $e\nu_e$, 8 = $\mu\nu_\mu$, 9 = $\tau\nu_\tau$
amafin(20)	xpar(500 +10*KF +6): Masses of the W decay products; the used entries KF (in PDG notation) are: 1 = d , 2 = u , 3 = s , 4 = c , 5 = b , 6 = t , 11 = e , 12 = ν_e , 13 = μ , 14 = ν_μ , 15 = τ , 16 = ν_τ ; Note: The masses of τ and ν_τ have to be independently set to the same numerical values in the initialisation of TAUOLA
VCKM(1:3,1:3)	xpar(111-119): CKM matrix elements (PDG 2000)

Table 3: The list of input parameters of the YFSWW3 generator in the xpar vector (cont.). The default values are in brackets.

Parameter	Position and meaning
KeyCul	xpar(1011-1013): Dummy parameters in YFSWW3 (specific to KoralW) xpar(1014) (=2): Coulomb correction switch =0: Coulomb correction is OFF =1: “Standard” Coulomb correction is ON =2: “Screened” Coulomb correction is ON
KeyBra	xpar(1021) (=2): Sets W branching ratios (BR), used for normalisation of the matrix element =0: Born values (no mixing) with “naive” QCD (if $\alpha_S = 0$: $ud, cs = 1/3$, $e\nu, \mu\nu, \tau\nu = 1/9$, others = 0) =1: Values of BR’s taken from the input =2: With CKM mixing and “naive” QCD, calculated in the IBA from the CKM matrix (PDG 2000)
KeyMas	xpar(1022): Dummy parameter in YFSWW3 (specific to KoralW)
KeyZet	xpar(1023) (=1): Z width choice =0: Z width in Z propagator: $(s/M_Z)\Gamma_Z$ =1: Z width in Z propagator: $M_Z\Gamma_Z$ =2: no Z width in Z propagator
KeySpn	xpar(1024) (=1): Spin effects in W decays =0: Spin effects OFF (for tests only) =1: Spin effects ON (recommended)
KeyRed	xpar(1025): Dummy parameter in YFSWW3 (specific to KoralW)
KeyWu	xpar(1026) (=1): W width choice =0: W width in W propagator: $(s/M_W)\Gamma_W$ =1: W width in W propagator: $M_W\Gamma_W$ =2: No W width ($\Gamma_W = 0$) in W propagator (dangerous!)
KeyWgt	xpar(1031) (=0): Unweighted/Weighted choice =0: Unweighted events $WtMod=1$, for apparatus Monte Carlo =1: Weighted events (variable weights)
KeyRnd	xpar(1032) (=1): Random number generator switch =1: RANMAR random number generator =2: ECURAN random number generator =3: CARRAN random number generator
KeySmp	xpar(1033): Dummy parameter in YFSWW3 (specific to KoralW)
KeyMix	xpar(1041) (=1): Input-Parameter-Scheme (IPS) switch =0: LEP2 '95 Workshop scheme (only for Born and ISR) =1: G_μ -scheme (recommended ; the only choice for $\mathcal{O}(\alpha)$ EW corrections) =2: α -scheme (“pure” Born; for tests)
Key4f	xpar(1042): Dummy parameter in YFSWW3 (specific to KoralW)

Table 4: The list of input parameters of the YFSWW3 generator in the xpar vector (cont.). The default values are in brackets.

Parameter	Position and meaning
KeyAcc	xpar(1043) (=0): Anomalous TGCs switch =0: Anomalous WWV couplings OFF >0: Anomalous WWV couplings ON =1: The most general (complex number) TGCs in the notation of K. Hagiwara et al., Nucl. Phys. B282 (1987) 253 =2 Parametrization of CERN 96-01, Vol. 1, p. 525: $\delta_Z, x_\gamma, x_Z, y_\gamma, y_Z$ =3: Parametrization of CERN 96-01, Vol. 1, p. 525: $\alpha_{W\phi}, \alpha_{B\phi}, \alpha_W$
KeyZon	xpar(1044): Dummy parameter in YFSWW3 (specific to KoralW)
KeyWon	xpar(1045): Dummy parameter in YFSWW3 (specific to KoralW)
KeyDwm	xpar(1055) (=0): Sets decay channel of W^- =0: Inclusive, otherwise the exclusive modes for the W are: $\begin{bmatrix} = & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\ & ud & cd & us & cs & ub & cb & e\nu & \mu\nu & \tau\nu \end{bmatrix}$
KeyDwp	xpar(1056) (=0): Sets the decay channel of W^+ , similar assignments as for W^-
Nout	xpar(1057) (=-1): Output unit number for the generator (if < 0 then Nout=16)
Jak1	xpar(1071) (=0): Input for TAUOLA, defines decay mode of the τ^+ in W^+ decay
Jak2	xpar(1072) (=0): Input for TAUOLA, defines decay mode of the τ^- in W^- decay Jak1, Jak2 = -1: TAUOLA is switched OFF Jak1, Jak2 = 0: Requests all τ^\pm decay channels to be simulated Jak1, Jak2 > 0: Single specific τ^\pm decay channel, see TAUOLA manual
Itdkrc	xpar(1073) (=1): Input for TAUOLA, radiative corrections in leptonic τ decays switch Itdkrc = 1: Corrections are ON Itdkrc = 0: Corrections are OFF
IfPhot	xpar(1074) (=1): PHOTOS activation switch =0: PHOTOS is OFF =1: Radiation in leptonic W decays is ON =2: Radiation in both leptonic and quarkonic W decays is ON (for tests)
IfHadM	xpar(1075) (=1): W^- hadronization activation switch (JETSET)
IfHadP	xpar(1075) (=1): W^+ hadronization activation switch (JETSET) IfHadM, ifhadP=0: Hadronization is OFF IfHadM, ifhadP=1: Hadronization is ON In the present version IfHadM and IfHadP have to be equal!
Umask	xpar(1101-1302): Dummy parameters in YFSWW3 (specific to KoralW)
BE params	xpar(4061-4070): Dummy parameters in YFSWW3 (specific to KoralW)

Table 5: The list of input parameters of the YFSWW3 generator in the xpar vector (cont.). The default values are in brackets.

Parameter	Meaning
Q1(4)	Four-momentum of W^-
Q2(4)	Four-momentum of W^+
SPhum(4)	Sum of four-momenta of photons from the WW production stage
SPhot(100,4)	Four-momenta of photons from the WW production stage
Nphot	Number of photons from the WW production stage

Table 6: The list of four-momenta in the COMMON /MOMWWP/ of the YFSWW3 generator. They are given in GeV in the CMS of the incoming beams.

Parameter	Meaning
pf1(4)	Four-momentum of the fermion from the W^- decay
pf2(4)	Four-momentum of the antifermion from the W^- decay
pf3(4)	Four-momentum of the fermion from the W^+ decay
pf4(4)	Four-momentum of the antifermion from the W^+ decay
Phot(100,4)	Four-momenta of photons from the WW production stage
Npho	Multiplicity of photons from the WW production stage

Table 7: The list of four-momenta in the COMMON /MOMDEC/ of the YFSWW3 generator. They are given in GeV in the CMS of the incoming beams.

Routine	Parameter	Meaning
YFSWW_GetBeams	q1(4)	Four-momentum of the e^- beam
	q2(4)	Four-momentum of the e^+ beam
YFSWW_Get4f	flav(4)	Flavours of the final $4f$ -state in the PDG convention
	p1(4)	Four-momentum of the fermion of flav(1)
	p2(4)	Four-momentum of the fermion of flav(2)
	p3(4)	Four-momentum of the fermion of flav(3)
	p4(4)	Four-momentum of the fermion of flav(4)
YFSWW_GetPhotAll	NphAll	Number of photons from the WW production stage
	PhoAll(100,4)	Four-momenta of these photons

Table 8: The list of output parameters of the YFSWW3 generator transferred through parameters of the getter-routines: YFSWW_GetBeams(q1,q2), YFSWW_Get4f(flav,p1,p2,p3,p4) and YFSWW_GetPhotAll(NphAll,PhoAll).

Parameter	Meaning
WtCru1 WtCru2 WtMod	Crude weight for ISR, Crude weight for the rest. They are necessary to build the total weight out of WtSet The “best” weight corresponding to eq. (4), e.g. for KeyCor=5: $WtMod = Wtcru1*Wtcru2*(WtSet(41)-WtSet(2)+WtSet(4))$
WtSet(1-19)	Various ISR-type contributions to the matrix element (β -functions) – to get the total weight they must be multiplied by WtCru1
WtSet(1)	Zero-order ($\bar{\beta}_0$)
WtSet(2)	First-order ISR ($\bar{\beta}_0 + \bar{\beta}_1$)
WtSet(3)	Second-order ISR ($\bar{\beta}_0 + \bar{\beta}_1 + \bar{\beta}_2$)
WtSet(4)	Third-order ISR ($\bar{\beta}_0 + \bar{\beta}_1 + \bar{\beta}_2 + \bar{\beta}_3$)
WtSet(10)	$\mathcal{O}(\alpha^0)$ contribution from $\bar{\beta}_0$
WtSet(11)	$\mathcal{O}(\alpha^1)$ ISR contribution from $\bar{\beta}_0$
WtSet(12)	$\mathcal{O}(\alpha^1)$ ISR contribution from $\bar{\beta}_1$
WtSet(13)	$\mathcal{O}(\alpha^2)$ ISR contribution from $\bar{\beta}_0$
WtSet(14)	$\mathcal{O}(\alpha^2)$ ISR contribution from $\bar{\beta}_1$
WtSet(15)	$\mathcal{O}(\alpha^2)$ ISR contribution from $\bar{\beta}_2$
WtSet(16)	$\mathcal{O}(\alpha^3)$ ISR contribution from $\bar{\beta}_0$
WtSet(17)	$\mathcal{O}(\alpha^3)$ ISR contribution from $\bar{\beta}_1$
WtSet(18)	$\mathcal{O}(\alpha^3)$ ISR contribution from $\bar{\beta}_2$
WtSet(19)	$\mathcal{O}(\alpha^3)$ ISR contribution from $\bar{\beta}_3$
WtSet(41-52)	Contributions to the matrix element from $\mathcal{O}(\alpha)$ EW corrections in the WW production stage – to get the total weight they must be multiplied by WtCru1*WtCru2
WtSet(41)	$\mathcal{O}(\alpha^1)$ EW corrections ($\bar{\beta}_0 + \bar{\beta}_1$)
WtSet(51)	Pretabulated (“fast”) $\mathcal{O}(\alpha^1)$ EW corrections ($\bar{\beta}_0 + \bar{\beta}_1$)
WtSet(42)	$\mathcal{O}(\alpha^1)$ contribution from $\bar{\beta}_0$
WtSet(43)	$\mathcal{O}(\alpha^1)$ contribution from $\bar{\beta}_1$
WtSet(52)	Pretabulated $\mathcal{O}(\alpha^1)$ contribution from $\bar{\beta}_0$
WtSet(65-68)	Fixed order (no exponentiation) contributions (for tests)
WtSet(65)	$\mathcal{O}(\alpha^0)$, no exponentiation
WtSet(66)	$\mathcal{O}(\alpha^1)$, no exponentiation
WtSet(67)	$\mathcal{O}(\alpha^1)$ virtual + soft real photon only, no exponentiation
WtSet(68)	$\mathcal{O}(\alpha^1)$ real hard photon only, no exponentiation

Table 9: The list of output weights in the COMMON /WGTALL/ of the YFSWW3 generator.

Routine	Parameter	Meaning
YFSWW_GetWtMain	WtMain	<i>Principal</i> best MC event weight
YFSWW_GetWtISR	WtISR	Best ISR-type weight
YFSWW_GetWtAll	WtMain WtCrud WtSetAll(100)	<i>Principal</i> best MC event weight Crude MC event weight: $WtCrud=WtCru1*WtCru2$ Model weights (the same as in <code>WtSet(100)</code> in COMMON /WGTALL/)

Table 10: The list of output parameters of the YFSWW3 generator transferred through parameters of the getter-routines: `YFSWW_GetWtMain(WtMain)`, `YFSWW_GetWtISR(WtISR)` and `YFSWW_GetWtAll(WtMain,WtCrud,WtSetAll)`.

Routine	Parameter	Meaning
YFSWW_GetXSecMC	XSecMC XErrMC	<i>Principal</i> total MC cross section [pb] Its absolute error [pb]
YFSWW_GetXSecNR	XSecNR XErrNR	Normalisation (primary) cross section, see Sect. 5.2: For <code>KeyWgt=0</code> , the principal cross section <code>XSecMC</code> [pb], For <code>KeyWgt=1</code> , the crude cross section <code>XCrude</code> [pb] Its absolute error [pb]
YFSWW_GetNevMC	NevMC	Total number of generated Monte Carlo events

Table 11: The list of output parameters of the YFSWW3 generator transferred through parameters of the getter-routines: `YFSWW_GetXSecMC(XSecMC,XErrMC)`, `YFSWW_GetXSecNR(XSecNR,XErrNR)` and `YFSWW_GetNevMC(NevMC)`.

B Output of the Demo Program

```

*****
*          YFSW3 version 1.16,  January 2001
*          S. Jadach, W. Placzek, M. Skrzypek,
*          B.F.L. Ward, Z. Was
*
*          INPUT PARAMATERS:
*
*          200.0000000    CMS energy total          CMSEne    I.0
*          *****
*          5              Rad. Corr. switch        KeyCor     IR1
*          *****
*          2101          QED super-switch          KeyRad     IQ1
*          1              Init. state Rad.         KeyISR     IQ2
*          0              Final state Rad.         KeyFSR     IQ3
*          1              Next-To-Leading          KeyNLL     IQ4
*          2              Coulomb corr.            KeyCul     IQ5
*          *****
*          101112        Physics super-switc      KeyPhy     IP1
*          0              FS mass reduction        KeyRed     IP2
*          1              Spin in W decays          KeySpn     IP3
*          1              Z propag.                KeyZet     IP4
*          1              Mass kinematics.         KeyMas     IP5
*          2              Branching Rat.           KeyBra     IP6
*          1              W propag.                KeyWu      IP7
*          *****
*          10           Technical super-swi       KeyTek     IT1
*          0           LPA_a or LPA_b mode         KeyLPA     IT2
*          0           Presampler type             KeySmp     IT3
*          1           Rand. Numb. Gen.            KeyRnd     IT4
*          0           Weighting switch           KeyWgt     IT5
*          *****
*          10001        Miscelaneous              KeyMis     IM1
*          1           EW Input Par. Schem         KeyMix     IM2
*          0           4 fermion matr el          Key4f      IM3
*          0           Anomalous couplings        KeyAcc     IM4
*          1           WW type final state        KeyWon     IM5
*          0           ZZ type final state        KeyZon     IM6
*          *****
*          0           W- decay mode              KeyDwm     ID1
*          0           W+ decay mode              KeyDwp     ID2
*          *****
*          1.16639000    G_mu * 1d5              Gmu        I.1
*          132.50494581  Inverse alpha_w          alfWin     I.2
*          91.18820000    Z mass [GeV]             aMaZ       I.3
*          2.49520000    Z width [GeV]            GammZ      I.4
*          80.41900000    W mass [GeV]             aMaW       I.5
*          2.09957845    W width [GeV]            GammW      I.6
*          0.00000100    Dummy infrared cut        VVmin      I.7
*          0.99000000    v_max ( =1 )          VVmax      I.8
*          4.00000000    Max wt for rejectn.        WtMax      I.9
*          4.00000000    Max wt for CC03 rej        WtMax      I10
*          0.11850000    alpha_s: QCD coupl.         alphas     I11
*          0.00000000    Color Re-Con. Prob.        PReco     I12
*          *****
*          0.22224994    sin(theta_w)**2          sinW2      I13
*          *****
*          Z width in Z propagator:  M_Z *GAMM_Z
*          *****
*
*          CKM matrix elements:
*
*          0.97493000    V_ud      VCKM(1,1)    IV1
*          0.22250000    V_us      VCKM(1,2)    IV2
*          0.00350000    V_ub      VCKM(1,3)    IV3
*          -0.22246000    V_cd      VCKM(2,1)    IV4

```

```

*      0.97412000      V_cs  VCKM(2,2)      IV5 *
*      0.04000000      V_cb  VCKM(2,3)      IV6 *
*      0.00549000      V_td  VCKM(3,1)      IV7 *
*     -0.03978000      V_ts  VCKM(3,2)      IV8 *
*      0.99920000      V_tb  VCKM(3,3)      IV9 *
*      Unitarity check of the CKM matrix:
*      VV+ =   1.00001   0.00000   0.00000
*             0.00000   1.00000   0.00000
*             0.00000   0.00000   1.00001
*
*      Branching ratios of W decays:
*      0.32071536      ud      BR(1)      IB1 *
*      0.01669847      cd      BR(2)      IB2 *
*      0.01670448      us      BR(3)      IB3 *
*      0.32018266      cs      BR(4)      IB4 *
*      0.00000413      ub      BR(5)      IB5 *
*      0.00053987      cb      BR(6)      IB6 *
*      0.10838559      e       BR(7)      IB7 *
*      0.10838559      mu      BR(8)      IB8 *
*      0.10838559      tau     BR(9)      IB9 *
*
*      fermion masses:
*      0.00600000      d      amafin(1)  IM1 *
*      0.00300000      u      amafin(2)  IM2 *
*      0.12250000      s      amafin(3)  IM3 *
*      1.25000000      c      amafin(4)  IM4 *
*      4.20000000      b      amafin(5)  IM5 *
*     174.30000000     t      amafin(6)  IM6 *
*      0.00051100      e      amafin(11) IM7 *
*      0.00000000      ve     amafin(12) IM8 *
*      0.10565836      mu     amafin(13) IM9 *
*      0.00000000      vmu    amafin(14) IM10 *
*      1.77703000      tau    amafin(15) IM11 *
*      0.00000000      vtau   amafin(16) IM12 *
*
*      Higgs mass:
*     115.00000000     Higgs  aMHig  IMH *
*
*      DECAy LIBRARIES
*      0      TAUOLA for W+      Jak1  IL1 *
*      0      TAUOLA for W-      Jak2  IL2 *
*      1      TAUOLA Ord(alpha)  Itdkrc IL3 *
*      1      PHOTOS              IfPhot IL4 *
*      1      JETSET for W-      IfHadM IL5 *
*      1      JETSET for W+      IfHadP IL6 *
*
*****

```

```

*****
* ##### ##### ##### ##### ##### ##### ##### ##### *
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* ##### ##### ##### ##### ##### ##### ##### ##### *
* ##### ##### ##### ##### ##### ##### ##### ##### *
*****

```

```

*****
*      Initialize KarLud start
*      19.33542764      xs_crude VESKO      XCVESK
*      19.19161478      xs_crude GAUSS     XCGAUS
*      0.00749353      XCVESK/XCGAUS-1
*      Initialize KarLud end
*****

```

```

*****
*      Initialize KarFin start
*      Initialize KarFin end
*****

```

```

*****TAUOLA LIBRARY: VERSION 2.6 *****
*****August 1995*****
**AUTHORS: S.JADACH, Z.WAS*****
**R. DECKER, M. JEZABEK, J.H.KUEHN*****
**AVAILABLE FROM: WASM AT CERNVM *****
**PUBLISHED IN COMP. PHYS. COMM.***
*****CERN-TH-5856 SEPTEMBER 1990*****
*****CERN-TH-6195 SEPTEMBER 1991*****
*****CERN-TH-6793 NOVEMBER 1992*****
**5 or more pi dec.: precision limited
*****DEXAY ROUTINE: INITIALIZATION****
0 JAK1 = DECAY MODE FERMION1 (TAU+)
0 JAK2 = DECAY MODE FERMION2 (TAU-)
*****

```

----- YFSW demo -----
NevTot = 1000 events to be generated ...

.... skipped

Event listing (standard)

I	particle/jet	K(I,1)	K(I,2)	K(I,3)	K(I,4)	K(I,5)	P(I,1)	P(I,2)	P(I,3)	P(I,4)	P(I,5)
1	!e-!	21	11	0	3	4	0.00000	0.00000	100.00000	100.00000	0.00051
2	!e+!	21	-11	0	3	4	0.00000	0.00000	-100.00000	100.00000	0.00051
3	(W-)	11	-24	1	5	6	-58.15061	0.61540	33.01304	95.19679	67.75468
4	(W+)	11	24	1	7	8	58.15061	-0.61540	-33.01304	104.80321	80.69684
5	(d)	14	1	3	3	6	10	0	0	10	0.00600
6	(u-)	14	-2	3	0	0	11	3	5	11	4.05017
7	(u)	14	2	4	3	8	29	0	0	29	18.03726
8	(d-)	14	-1	4	0	0	30	3	7	30	40.11335
9	(CMshower)	11	94	5	10	11	-58.15062	0.61540	33.01304	95.19679	67.75468
10	(d)	14	1	9	3	5	13	0	5	12	-60.91610
11	(u-)	14	-2	9	0	6	14	3	6	15	2.76548
12	(d)	14	1	10	3	13	17	0	10	16	-46.33492
13	(g)	14	21	10	3	10	18	3	12	19	-14.58117
14	(u-)	14	-2	11	0	11	20	3	15	21	2.79517
15	(g)	13	21	11	2	14	0	2	11	0	-0.02970
16	(d)	13	1	12	2	17	0	0	12	0	-12.64723
17	(g)	13	21	12	2	12	0	2	16	0	-33.68769
18	(g)	13	21	13	2	13	0	2	19	0	-9.68361
19	(g)	13	21	13	2	18	0	2	13	0	-4.89756
20	(u-)	14	-2	14	0	14	22	3	21	23	4.17251
21	(g)	14	21	14	3	20	24	3	14	25	-1.37734
22	(u-)	14	-2	20	0	20	26	3	23	27	4.29870
23	(g)	13	21	20	2	22	0	2	20	0	-0.12619
24	(g)	13	21	21	2	21	0	2	25	0	-1.25460
25	(g)	13	21	21	2	24	0	2	21	0	-0.12274
26	(u-)	13	-2	22	0	22	0	2	27	0	2.89930
27	(g)	13	21	22	2	26	0	2	22	0	1.39939
28	(CMshower)	11	94	7	29	30	58.15061	-0.61540	-33.01304	104.80321	80.69683
29	(u)	14	2	28	3	7	32	0	7	31	23.86922
30	(d-)	14	-1	28	0	8	33	3	8	34	34.28139
31	(u)	13	2	29	2	32	0	0	29	0	2.06978
32	(g)	14	21	29	3	29	35	3	31	36	21.79944
33	(d-)	14	-1	30	0	30	37	3	34	38	9.91990
34	(g)	14	21	30	3	33	39	3	30	40	24.36149
35	(g)	14	21	32	3	32	41	3	36	42	24.19235
36	(g)	14	21	32	3	35	43	3	32	44	-2.39291
37	(d-)	13	-1	33	0	33	0	2	38	0	7.66346
38	(g)	13	21	33	2	37	0	2	33	0	2.25644
39	(g)	14	21	34	3	34	45	3	40	46	11.13057
40	(g)	14	21	34	3	39	47	3	34	48	13.23092
41	(g)	13	21	35	2	35	0	2	42	0	6.51083
42	(g)	14	21	35	3	41	49	3	35	50	17.68152
43	(g)	13	21	36	2	36	0	2	44	0	-2.15456
44	(g)	13	21	36	2	43	0	2	36	0	-0.23835
45	(g)	13	21	39	2	39	0	2	46	0	9.54865
46	(g)	13	21	39	2	45	0	2	39	0	1.58193
47	(g)	13	21	40	2	40	0	2	48	0	1.41318
48	(g)	13	21	40	2	47	0	2	40	0	11.81774
49	(g)	13	21	42	2	42	0	2	50	0	14.75801
50	(g)	13	21	42	2	49	0	2	42	0	2.92351
51	(d)	A	12	1	16	73	73	-12.64723	-1.30492	1.82179	12.84423
52	(g)	I	12	21	17	73	73	-33.68769	-7.65337	4.40528	34.82587
53	(g)	I	12	21	19	73	73	-4.89756	-1.19512	0.49355	5.06537
54	(g)	I	12	21	18	73	73	-9.68361	-4.03725	-0.24096	10.49428
55	(g)	I	12	21	15	73	73	-0.02970	-0.14691	0.54657	0.56675
56	(g)	I	12	21	25	73	73	-0.12274	1.39016	3.91159	4.15309
57	(g)	I	12	21	24	73	73	-1.25460	0.15914	3.44828	3.67287
58	(g)	I	12	21	23	73	73	-0.12619	0.81281	2.38321	2.52117

59	(g)	I	12	21	27	73	73	1.39939	5.08227	7.51962	9.18327	0.00000
60	(u ⁻)	V	11	-2	26	73	73	2.89930	7.50857	8.72410	11.86990	0.00560
61	(u)	A	12	2	31	91	91	2.06978	-3.05418	-5.61577	6.71930	0.00560
62	(g)	I	12	21	44	91	91	-0.23835	0.13849	1.08896	1.12330	0.00000
63	(g)	I	12	21	43	91	91	-2.15456	-0.80571	0.13785	2.30441	0.00000
64	(g)	I	12	21	50	91	91	2.92351	0.47380	2.41516	3.82157	0.00000
65	(g)	I	12	21	49	91	91	14.75801	5.72986	14.60889	21.54181	0.00000
66	(g)	I	12	21	41	91	91	6.51083	2.61590	3.06918	7.65857	0.00000
67	(g)	I	12	21	48	91	91	11.81774	-6.56210	-18.85316	23.19831	0.00000
68	(g)	I	12	21	47	91	91	1.41318	-1.20728	-3.26543	3.75734	0.00000
69	(g)	I	12	21	46	91	91	1.58193	-0.22443	-2.48869	2.95744	0.00000
70	(g)	I	12	21	45	91	91	9.54865	-1.43393	-9.90045	13.82938	0.00000
71	(g)	I	12	21	38	91	91	2.25644	0.88705	-1.73723	2.98268	0.00000
72	(d ⁻)	V	11	-1	37	91	91	7.66346	2.82714	-12.47235	14.90909	0.00990
73	(string)		11	92	51	74	90	-58.15062	0.61539	33.01305	95.19680	67.75468
74	(eta)		11	221	73	123	125	-10.24036	-1.30218	1.37509	10.42839	0.54750
75	n0		1	2112	73	0	0	-18.93694	-4.18797	2.49748	19.57721	0.93960
76	p ⁻		1	-2212	73	0	0	-14.20916	-3.08438	1.25868	14.62458	0.93830
77	(rho0)		11	113	73	126	127	-6.22881	-2.31614	1.02168	6.76712	0.76646
78	K+		1	321	73	0	0	-3.92215	-0.97100	0.06270	4.07107	0.49360
79	(Lambd0)		11	3122	73	128	129	-3.01880	-0.44703	0.30808	3.26381	1.11560
80	n ⁰		1	-2112	73	0	0	-3.75048	-1.33794	0.39685	4.11053	0.93960
81	(eta')		11	331	73	130	131	-0.12766	0.40474	0.85328	1.35133	0.95807
82	(pi0)		11	111	73	132	133	-0.50601	-0.14221	0.41852	0.68531	0.13500
83	(omega)		11	223	73	134	136	-0.63008	0.00890	3.96938	4.09435	0.78145
84	(pi0)		11	111	73	137	138	0.12911	0.68122	0.54176	0.89020	0.13500
85	(rho0)		11	113	73	139	140	0.01639	1.31382	3.53153	3.84545	0.76771
86	pi-		1	-211	73	0	0	-0.25161	-0.09021	0.25972	0.39798	0.13960
87	(rho+)		11	213	73	141	142	0.28192	1.27522	2.20383	2.67551	0.77191
88	pi-		1	-211	73	0	0	-0.03182	1.50185	1.71206	2.28193	0.13960
89	K+		1	321	73	0	0	1.10097	1.59131	2.64052	3.31065	0.49360
90	(K*-)		11	-323	73	143	144	2.17486	7.71740	9.96190	12.82138	0.92739
91	(string)		11	92	61	92	122	58.15061	-0.61540	-33.01305	104.80321	80.69683
92	(rho+)		11	213	91	145	146	1.55024	-2.13893	-3.14091	4.17312	0.75586
93	pi-		1	-211	91	0	0	-0.17159	0.04685	0.08614	0.24196	0.13960
94	pi+		1	211	91	0	0	0.24570	-0.03059	-0.39588	0.48733	0.13960
95	(rho0)		11	113	91	147	148	-0.05235	0.18826	-0.45908	0.89626	0.74455
96	(rho0)		11	113	91	149	150	-0.32546	-0.90485	-0.78443	1.47577	0.79869
97	(rho-)		11	-213	91	151	152	-0.25670	-0.63219	-0.01561	1.05392	0.80308
98	(Delta++)		11	2224	91	153	154	0.88891	0.12972	0.83826	1.74275	1.23593
99	K-		1	-321	91	0	0	-0.03388	0.33010	0.05701	0.59750	0.49360
100	(Sigma ⁻)		11	-3222	91	155	156	0.07562	-0.53240	0.50627	1.40005	1.18940
101	p+		1	2212	91	0	0	3.33352	2.05592	4.01892	5.68958	0.93830
102	(rho+)		11	213	91	157	158	1.90521	0.28713	1.53127	2.54161	0.63461
103	p ⁻		1	-2212	91	0	0	1.36015	0.95944	1.70996	2.56416	0.93830
104	(eta)		11	221	91	159	161	5.08637	0.98859	3.62885	6.34955	0.54750
105	(rho-)		11	-213	91	162	163	4.25581	2.04714	3.53767	5.93431	0.63108
106	(rho+)		11	213	91	164	165	2.21954	0.96066	3.02820	3.94127	0.71724
107	(eta)		11	221	91	166	168	1.47892	0.23889	0.82782	1.79702	0.54750
108	(pi0)		11	111	91	169	170	1.98223	0.39680	0.15178	2.03174	0.13500
109	(rho-)		11	-213	91	171	172	0.67407	0.00155	-1.27522	1.61024	0.71575
110	(rho+)		11	213	91	173	174	3.49583	-1.53409	-4.96288	6.33350	0.95327
111	(Delta0)		11	2114	91	175	176	1.66564	-1.34819	-2.37829	3.39981	1.14476
112	(eta)		11	221	91	177	179	0.86265	-0.26884	-1.72434	2.02226	0.54750
113	(Delta ⁻)		11	-2214	91	180	181	3.12720	-1.49499	-4.64393	5.91198	1.17091
114	(eta)		11	221	91	182	183	4.40704	-1.97240	-6.96861	8.49551	0.54750
115	pi+		1	211	91	0	0	0.73868	-0.26451	-0.84399	1.16078	0.13960
116	(pi0)		11	111	91	184	185	0.19280	-0.10577	-0.69190	0.73845	0.13500
117	(rho-)		11	-213	91	186	187	3.50644	-0.39157	-3.81033	5.24824	0.75957
118	(Sigma ⁺⁺)		11	3224	91	188	189	3.62885	-0.37994	-4.27561	5.78618	1.37332
119	(Xi ^{*0})		11	-3324	91	190	191	4.58324	0.53697	-5.60459	7.42030	1.53458
120	K-		1	-321	91	0	0	4.83667	1.54290	-6.58041	8.32582	0.49360
121	(rho0)		11	113	91	192	193	0.81491	0.29522	-1.28553	1.68575	0.66175
122	pi+		1	211	91	0	0	2.07437	0.37776	-3.09369	3.74648	0.13960
123	(pi0)		11	111	74	194	195	-2.10779	-0.28820	0.21802	2.14280	0.13500
124	(pi0)		11	111	74	196	197	-2.68848	-0.44180	0.33111	2.74790	0.13500
125	(pi0)		11	111	74	198	199	-5.44409	-0.57218	0.82596	5.53769	0.13500
126	pi+		1	211	77	0	0	-4.66494	-1.98637	0.59457	5.10689	0.13960
127	pi-		1	-211	77	0	0	-1.56387	-0.32977	0.42711	1.66022	0.13960
128	n0		1	2112	79	0	0	-2.67232	-0.46645	0.20868	2.87841	0.93960
129	(pi0)		11	111	79	200	201	-0.34648	0.01942	0.09940	0.38540	0.13500
130	gamma		1	22	81	0	0	0.15036	0.06694	0.20410	0.25359	0.00000
131	(rho0)		11	113	81	202	203	-0.27802	0.39780	0.64919	1.09774	0.74030
132	gamma		1	22	82	0	0	-0.37766	-0.11643	0.38142	0.54924	0.00000
133	gamma		1	22	82	0	0	-0.12835	-0.02578	0.03709	0.13607	0.00000
134	pi-		1	-211	83	0	0	-0.55143	-0.02633	2.19196	2.26471	0.13960
135	pi+		1	211	83	0	0	0.03016	-0.02559	0.23412	0.27544	0.13960
136	(pi0)		11	111	83	204	205	-0.10881	0.06083	1.54330	1.55420	0.13500
137	gamma		1	22	84	0	0	0.10429	0.28346	0.17781	0.35049	0.00000
138	gamma		1	22	84	0	0	0.02482	0.39776	0.36395	0.53971	0.00000
139	pi-		1	-211	85	0	0	-0.02925	0.81104	1.19718	1.45305	0.13960
140	pi+		1	211	85	0	0	0.04564	0.50278	2.33435	2.39240	0.13960
141	pi+		1	211	87	0	0	-0.10049	0.97231	1.66839	1.93869	0.13960
142	(pi0)		11	111	87	206	207	0.38241	0.30290	0.53544	0.73682	0.13500
143	(K ⁰)		11	-311	90	208	208	1.63227	5.30466	6.44776	8.52203	0.49770
144	pi-		1	-211	90	0	0	0.54259	2.41274	3.51414	4.29935	0.13960
145	pi+		1	211	92	0	0	0.37519	-0.42730	-1.16477	1.30366	0.13960
146	(pi0)		11	111	92	209	210	1.17505	-1.71164	-1.97614	2.86946	0.13500

147	pi-	1	-211	95	0	0	-0.02511	-0.25130	-0.27599	0.39931	0.13960
148	pi+	1	211	95	0	0	-0.02724	0.43956	-0.18308	0.49696	0.13960
149	pi+	1	211	96	0	0	0.01872	-0.34856	-0.70919	0.80267	0.13960
150	pi-	1	-211	96	0	0	-0.34419	-0.55629	-0.07524	0.67311	0.13960
151	pi-	1	-211	97	0	0	-0.31262	-0.28175	-0.33663	0.55671	0.13960
152	(pi0)	11	111	97	211	212	0.05592	-0.35044	0.32102	0.49721	0.13500
153	p+	1	2212	98	0	0	0.71834	-0.11831	0.72858	1.39328	0.93830
154	pi+	1	211	98	0	0	0.17057	0.24802	0.10968	0.34947	0.13960
155	n0	1	-2112	100	0	0	0.16668	-0.28801	0.46995	1.10201	0.93960
156	pi-	1	-211	100	0	0	-0.09107	-0.24439	0.03632	0.29804	0.13960
157	pi+	1	211	102	0	0	1.74927	0.13762	1.23164	2.14833	0.13960
158	(pi0)	11	111	102	213	214	0.15594	0.14950	0.29963	0.39328	0.13500
159	pi+	1	211	104	0	0	1.81616	0.41035	1.28781	2.26821	0.13960
160	pi-	1	-211	104	0	0	2.55951	0.39048	1.74498	3.12538	0.13960
161	(pi0)	11	111	104	215	216	0.71070	0.18776	0.59605	0.95596	0.13500
162	pi-	1	-211	105	0	0	3.62668	1.80466	3.22112	5.17733	0.13960
163	(pi0)	11	111	105	217	218	0.62913	0.24248	0.31655	0.75699	0.13500
164	pi+	1	211	106	0	0	2.01360	0.65080	2.44717	3.23825	0.13960
165	(pi0)	11	111	106	219	220	0.20593	0.30985	0.58104	0.70303	0.13500
166	(pi0)	11	111	107	221	222	0.68124	0.15877	0.32632	0.78359	0.13500
167	(pi0)	11	111	107	223	224	0.15443	0.08805	0.11955	0.25322	0.13500
168	(pi0)	11	111	107	225	226	0.64325	-0.00793	0.38194	0.76022	0.13500
169	gamma	1	22	108	0	0	0.52260	0.07609	0.09222	0.53610	0.00000
170	gamma	1	22	108	0	0	1.45963	0.32071	0.05956	1.49564	0.00000
171	pi-	1	-211	109	0	0	0.17198	-0.28518	-0.30458	0.47240	0.13960
172	(pi0)	11	111	109	227	228	0.50209	0.28673	-0.97064	1.13784	0.13500
173	pi+	1	211	110	0	0	2.93956	-1.28882	-3.54111	4.78132	0.13960
174	(pi0)	11	111	110	229	230	0.55627	-0.24528	-1.42177	1.55218	0.13500
175	n0	1	2112	111	0	0	1.56887	-1.33211	-2.20490	3.15916	0.93960
176	(pi0)	11	111	111	231	232	0.09677	-0.01608	-0.17339	0.24065	0.13500
177	gamma	1	22	112	0	0	0.01295	0.04499	-0.05018	0.06863	0.00000
178	pi+	1	211	112	0	0	0.55623	-0.35914	-1.18580	1.36528	0.13960
179	pi-	1	-211	112	0	0	0.29347	0.04532	-0.48835	0.58835	0.13960
180	p'-	1	-2212	113	0	0	2.40690	-1.27183	-3.45434	4.49706	0.93830
181	(pi0)	11	111	113	233	234	0.72030	-0.22316	-1.18960	1.41492	0.13500
182	gamma	1	22	114	0	0	3.72994	-1.81174	-6.19765	7.45692	0.00000
183	gamma	1	22	114	0	0	0.67710	-0.16066	-0.77096	1.03858	0.00000
184	gamma	1	22	116	0	0	0.09058	-0.06419	-0.15700	0.19229	0.00000
185	gamma	1	22	116	0	0	0.10222	-0.04158	-0.53489	0.54616	0.00000
186	pi-	1	-211	117	0	0	0.43395	-0.27180	-0.52830	0.74885	0.13960
187	(pi0)	11	111	117	235	236	3.07249	-0.11977	-3.28203	4.49939	0.13500
188	(Lambda0)	11	3122	118	237	238	3.42267	-0.30045	-3.79719	5.24101	1.11560
189	pi+	1	211	118	0	0	0.20618	-0.07949	-0.47842	0.54517	0.13960
190	(Xi'+)	11	-3312	119	239	240	4.23992	0.59179	-5.04930	6.75043	1.32130
191	pi-	1	-211	119	0	0	0.34332	-0.05482	-0.55529	0.66986	0.13960
192	pi+	1	211	121	0	0	0.34304	0.26564	-1.03898	1.13455	0.13960
193	pi-	1	-211	121	0	0	0.47188	0.02957	-0.24655	0.55120	0.13960
194	gamma	1	22	123	0	0	-0.59562	-0.14153	0.07625	0.61694	0.00000
195	gamma	1	22	123	0	0	-1.51217	-0.14667	0.14177	1.52587	0.00000
196	gamma	1	22	124	0	0	-1.59588	-0.32397	0.22387	1.64375	0.00000
197	gamma	1	22	124	0	0	-1.09260	-0.11784	0.10724	1.10415	0.00000
198	gamma	1	22	125	0	0	-1.44943	-0.10471	0.25587	1.47557	0.00000
199	gamma	1	22	125	0	0	-3.99466	-0.46746	0.57009	4.06212	0.00000
200	gamma	1	22	129	0	0	-0.26109	0.07007	0.05160	0.27521	0.00000
201	gamma	1	22	129	0	0	-0.08540	-0.05065	0.04780	0.11019	0.00000
202	pi+	1	211	131	0	0	-0.24040	0.45140	0.11596	0.54266	0.13960
203	pi-	1	-211	131	0	0	-0.03762	-0.05360	0.53323	0.55507	0.13960
204	gamma	1	22	136	0	0	-0.04084	0.06750	1.27167	1.27412	0.00000
205	gamma	1	22	136	0	0	-0.06797	-0.00668	0.27163	0.28008	0.00000
206	gamma	1	22	142	0	0	0.12366	0.02444	0.13402	0.18398	0.00000
207	gamma	1	22	142	0	0	0.25876	0.27847	0.40142	0.55284	0.00000
208	K_LO	1	130	143	0	0	1.63227	5.30466	6.44776	8.52203	0.49770
209	gamma	1	22	146	0	0	0.72737	-1.07804	-1.14781	1.73456	0.00000
210	gamma	1	22	146	0	0	0.44768	-0.63360	-0.82833	1.13490	0.00000
211	gamma	1	22	152	0	0	0.05817	-0.13211	0.05850	0.15575	0.00000
212	gamma	1	22	152	0	0	-0.00225	-0.21834	0.26252	0.34146	0.00000
213	gamma	1	22	158	0	0	0.00265	-0.02338	0.03177	0.03954	0.00000
214	gamma	1	22	158	0	0	0.15328	0.17289	0.26786	0.35374	0.00000
215	gamma	1	22	161	0	0	0.13516	0.03401	0.18738	0.23353	0.00000
216	gamma	1	22	161	0	0	0.57554	0.15374	0.40867	0.72242	0.00000
217	gamma	1	22	163	0	0	0.30126	0.04572	0.12559	0.32958	0.00000
218	gamma	1	22	163	0	0	0.32786	0.19676	0.19096	0.42741	0.00000
219	gamma	1	22	165	0	0	0.09395	0.05367	0.23060	0.25473	0.00000
220	gamma	1	22	165	0	0	0.11198	0.25618	0.35043	0.44830	0.00000
221	gamma	1	22	166	0	0	0.49958	0.11652	0.30257	0.59557	0.00000
222	gamma	1	22	166	0	0	0.18167	0.04226	0.02376	0.18802	0.00000
223	gamma	1	22	167	0	0	-0.02210	-0.00142	0.00028	0.02215	0.00000
224	gamma	1	22	167	0	0	0.17653	0.08947	0.11927	0.23107	0.00000
225	gamma	1	22	168	0	0	0.08815	0.01534	0.10957	0.14146	0.00000
226	gamma	1	22	168	0	0	0.55510	-0.02327	0.27237	0.61876	0.00000
227	gamma	1	22	172	0	0	0.12712	0.11287	-0.19308	0.25725	0.00000
228	gamma	1	22	172	0	0	0.37498	0.17386	-0.77756	0.88059	0.00000
229	gamma	1	22	174	0	0	0.28732	-0.10621	-0.87647	0.92846	0.00000
230	gamma	1	22	174	0	0	0.26895	-0.13907	-0.54530	0.62372	0.00000
231	gamma	1	22	176	0	0	0.12088	-0.04281	-0.11611	0.17299	0.00000
232	gamma	1	22	176	0	0	-0.02411	0.02673	-0.05729	0.06766	0.00000
233	gamma	1	22	181	0	0	0.37690	-0.05568	-0.65663	0.75915	0.00000
234	gamma	1	22	181	0	0	0.34340	-0.16748	-0.53297	0.65577	0.00000

235	gamma	1	22	187	0	0	0.08510	-0.01401	-0.06558	0.10835	0.00000
236	gamma	1	22	187	0	0	2.98739	-0.10576	-3.21645	4.39104	0.00000
237	p+	1	2212	188	0	0	2.76880	-0.33055	-3.14146	4.30403	0.93830
238	pi-	1	-211	188	0	0	0.65387	0.03010	-0.65573	0.93698	0.13960
239	(Lambda ⁰)	11	-3122	190	241	242	3.97897	0.50910	-4.80418	6.35736	1.11560
240	pi+	1	211	190	0	0	0.26095	0.08270	-0.24512	0.39307	0.13960
241	p ⁻	1	-2212	239	0	0	3.53794	0.36931	-4.30069	5.65949	0.93830
242	pi+	1	211	239	0	0	0.44102	0.13979	-0.50348	0.69787	0.13960
sum charge:		0.00	sum momentum and inv. mass:		-0.00001						

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*****
*                               KarLud FINAL REPORT                               *
*                               window A                                           *
*                               4537 total no of events NEVTOT A0 *
*                               0 WT<0 events NEVNEG A1 *
*                               19.33542764 xs_cru VESKO [pb] XCVESK A2 *
*                               19.17361574 +- 0.01754039 xs_est VESKO [pb] XSVE A3 *
*                               19.19161478 +- 0.00001919 xs_est Gauss [pb] XSGS A4 *
*                               -0.00093786 +- 0.00091582 XCVE/XCGS-1 A5 *
*                               251.14598768 +- 0.24820021 <WTKARL> WTKARL A6 *
*****

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*****
*                               KarFin output - window A                               *
*                               Weight Statistics                                   *
*                               0.99643450 +- 0.00368336 general weight WT A1 *
*                               4263 generated events NEVGEN A2 *
*                               0.08139808 aver. ph. multi. AVMULT A3 *
*                               0 Marked photons MARTOT A4 *
*                               0.99108609 +- 0.00145252 Kinematics, smin WT1 A5 *
*                               0.99999743 +- 0.00000168 Jacobian WT2 A6 *
*                               1.00534843 +- 0.00335486 Photon ang. dist. WT3 A7 *
*****

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*****
*                               KarFin output - window B                               *
*                               on mass weights                                   *
*                               0.96568167 +- 0.00245351 removal wgt WTREM WT6 B1 *
*                               4263 no. of raw events B2 *
*                               0 WT6=0 events B3 *
*                               0.08139808 raw ph. multipl. B4 *
*                               0.99951442 +- 0.00245437 control wgt WCTRL WT5 B5 *
*                               0.10000000E-05 epsilon B6 *
*                               0.10000000E-08 delta B7 *
*****

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*****
*                               ***** DADMEL FINAL REPORT *****                               *
*                               48 NEVRAW = NO. OF EL DECAYS TOTAL *
*                               18 NEVACC = NO. OF EL DECS. ACCEPTED *
*                               0 NEVOVR = NO. OF OVERWEIGHTED EVENTS *
*                               0.48927E-12 PARTIAL WTDTH ( ELECTRON) IN GEV UNITS *
*                               1.207993507 IN UNITS GFERMI**2*MASS**5/192/PI**3 *
*                               0.128391966 RELATIVE ERROR OF PARTIAL WIDTH *
*                               COMPLETE QED CORRECTIONS INCLUDED *
*                               BUT ONLY V-A CUPLINGS *
*****

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*****
*                               *****TAUOLA LIBRARY: VERSION 2.6 *****                               *
*                               *****August 1995*****                               *
*                               **AUTHORS: S.JADACH, Z.WAS*****                               *
*                               **R. DECKER, M. JEZABEK, J.H.KUEHN*****                               *
*                               **AVAILABLE FROM: WASM AT CERNVM *****                               *
*                               ***** PUBLISHED IN COMP. PHYS. COMM.*****                               *
*                               *****CERN-TH-5856 SEPTEMBER 1990*****                               *
*                               *****CERN-TH-6195 SEPTEMBER 1991*****                               *
*                               *****CERN-TH-6793 NOVEMBER 1992*****                               *
*                               *****DEXAY ROUTINE: FINAL REPORT*****                               *

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*          105      NEV1 = NO. OF TAU+ DECS. ACCEPTED      *
*          91      NEV2 = NO. OF TAU- DECS. ACCEPTED      *
*          196      NEVTOT = SUM                          *
* NOEVTS  PART.WIDTH  ERROR  ROUTINE  DECAY MODE          *
* 9      1.2079935    0.1283920  DADMEL  ELECTRON          *
* 4      0.8730308    0.2060235  DADMMU  MUON            *
* 6      0.6106793    0.0000000  DADMPI  PION            *
* 9      1.2446948    0.0659817  DADMRO  RHO (->2PI)     *
* 9      0.7094790    0.1167541  DADMAA  A1 (->3PI)     *
* 10     0.0400228    0.0000000  DADMKK  KAON            *
* 10     0.0698563    0.0652813  DADMKS  K*              *
* 7      0.0798995    0.1472948  TAU- --> 2PI-, PI0, PI+ *
* 12     0.0178338    0.0767882  TAU- --> 3PI0, PI-    *
* 13     0.0580654    0.1190726  TAU- --> 2PI-, PI+, 2PI0 *
* 11     0.0267028    0.1478714  TAU- --> 3PI-, 2PI+,    *
* 8      0.0042604    0.1847376  TAU- --> 3PI-, 2PI+,    *
* 6      0.0029619    0.2054046  TAU- --> 2PI-, PI+, 3PI0 *
* 9      0.0063946    0.1197646  TAU- --> K-, PI-, K+   *
* 7      0.0051756    0.2002329  TAU- --> KO, PI-, KOB  *
* 11     0.0005735    0.1100686  TAU- --> K-, KO, PIO   *
* 8      0.0059857    0.1026906  TAU- --> PIO, PIO, K-   *
* 11     0.0325313    0.0894969  TAU- --> K-, PI-, PI+  *
* 10     0.0291474    0.1199303  TAU- --> PI-, KOB, PIO  *
* 9      0.0106989    0.1192819  TAU- --> ETA, PI-, PIO  *
* 7      0.0028271    0.0911550  TAU- --> PI-, PIO, GAM  *
* 10     0.0172013    0.1098466  TAU- --> K-, KO       *
*          THE ERROR IS RELATIVE AND PART.WIDTH          *
*          IN UNITS GFERMI**2*MASS**5/192/PI**3          *
*****

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*****
*          YFSWW3 Final Report                          *
*          Window A                                     *
* 200.0000000    CMS energy total      CMSENE      A0 *
* 16.96445667 +- 0.24052939    xs_tot [pb]    XSMCPB      A1 *
* 0.01417843    relative error          EREL          A2 *
* 4537          total no of events        NEVTOT      A3 *
* 1000          accepted events          NEVACC      A4 *
* 0            WT<0 events                NEVNEG      A5 *
* 0.00000000 +- 0.00000000    xsec/xtot: WT<0    XSNEG      A6 *
* 17           WT>WTMAX events            NEVOVE      A7 *
* 0.00096638 +- 0.00028479    xsec/xtot:WT>WTMAX  XSOVE      A8 *
* 4.00000000          WTMAX                WTMAX      A9 *
* 0.87737685 +- 0.01243983    <WT>          AWTOT      A10 *
*****

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*****
*          YFSWW3 final report                          *
*          Window B:                                     *
*          ISR                                           *
* 16.71805108 +- 0.20216719    xsec total      0(alf0)      B1 *
* 17.20746824 +- 0.21080089    xsec total      0(alf1)      B2 *
* 17.22391080 +- 0.21107044    xsec total      0(alf2)      B3 *
* 17.22440793 +- 0.21107682    xsec total      0(alf3)      B4 *
* 16.71805108 +- 0.20216719    xsec(beta00)     0(alf0)      B5 *
* 17.67935928 +- 0.21379205    xsec(beta01)     0(alf1)      B6 *
* -0.47189104 +--0.01736687    xsec(beta10)     0(alf1)      B7 *
* 17.70699748 +- 0.21412627    xsec(beta02)     0(alf2)      B8 *
* -0.48533564 +--0.01785827    xsec(beta11)     0(alf2)      B9 *
* 0.00224896 +- 0.00031913    xsec(beta20)     0(alf2)     B10 *
* 17.70752722 +- 0.00002720    xsec(beta03)     0(alf3)     B11 *
* -0.48528352 +- 0.00008275    xsec(beta12)     0(alf3)     B12 *
* 0.00216423 +- 0.00033020    xsec(beta21)     0(alf3)     B13 *
* 0.00000000 +- 0.01265929    xsec(beta30)     0(alf3)     B14 *
*          xsec_tot differences *
* 0.48941716 +- 0.01874270    xstot(alf1-0)  0(alf1)     B15 *

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*      0.01644256 +- 0.00052593      xstot(alf2-1)      0(alf2)      B16 *
*      0.00049713 +- 0.00001292      xstot(alf3-2)      0(alf3)      B17 *
*                                     betas differences
*      0.96130820 +- 0.01162486      xs(beta01-00)      0(alf1)      B18 *
*     -0.47189104 +--0.01736687      xs(beta10)         0(alf1)      B19 *
*      0.02763819 +- 0.00033422      xs(beta02-01)      0(alf2)      B20 *
*     -0.01344459 +--0.00049160      xs(beta11-10)      0(alf2)      B21 *
*      0.00224896 +- 0.00031913      xs(beta20)         0(alf2)      B22 *
*      0.00052974 +- 0.00000641      xs(beta03-02)      0(alf3)      B23 *
*      0.00005212 +- 0.00000324      xs(beta12-11)      0(alf3)      B24 *
*     -0.00008473 +--0.00001141      xs(beta21-20)      0(alf3)      B25 *
*      0.00000000 +- 0.01265929      xs(beta30)         0(alf3)      B26 *
*****

```

```

*****
*                                     YFSWW3 final report
*                                     Window C:
*                                     0(alf1) EWRC in WW-prod.
*
*      16.94721804 +- 0.24020843      xs_tot: EW-ex      0(alf1)      C1 *
*      16.92711416 +- 0.24008944      xs_tot: EW-ap      0(alf1)      C2 *
*      17.20746824 +- 0.21080089      xs_tot: ISR-LL     0(alf1)      C3 *
*                                     xsec_tot differences
*      0.02010388 +- 0.00091149      EW-ex - EW-ap     0(alf1)      C4 *
*     -0.26025020 +--0.11286284      EW-ex - ISR-LL    0(alf1)      C5 *
*                                     betas differences
*      0.02010388 +- 0.00091149      bet01(ex - ap)    0(alf1)      C6 *
*     -0.40008677 +--0.00639368      bet01(ex - LL)    0(alf1)      C7 *
*     -0.02807084 +--0.00454222      bet10(ex - LL)    0(alf1)      C8 *
*****

```

..... skipped

```

===== demo =====
16.96445667 +- 0.24052939      MC Best, XPAR, YFSWW3
18.96537427 +- 0.00085125      SemiAnal Born, KorWan
17.42293229 +- 0.00255375      SemiAnal 0(alf3)exp.LL, KorWan
===== End demo =====

```

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