CERN-TH/2000-357

W-Pair Production with YFSWW/KoralW[†,‡]

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Abstract

A theoretical description of W-pair production in terms of two complementary Monte Carlo event generators `YFSWW` and `KoralW` is presented. The way to combine the results of these two programs in order to get precise predictions for WW physics at LEP2 and LC energies is discussed.

[†] Talk given by W. Płaczek at the Linear Collider Workshop 2000, October 24-28, 2000, Fermilab, Batavia, Illinois, USA.

[‡] Work partly supported by the Maria Skłodowska-Curie Joint Fund II PAA/DOE-97-316 and by the US Department of Energy Contracts DE-FG05-91ER40627 and DE-AC03-76ER00515.

CERN-TH/2000-357
December, 2000

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. Ref [1]. 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 a study, at the tree level, of triple and quartic gauge boson couplings, where small deviations from the subtle SM gauge cancellations can lead to significant effects on physical observables – these can be signals of "new physics".

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:

$$e^+ + e^- \longrightarrow 4f + n\gamma, \quad (n = 0, 1, 2, \ldots), \tag{1}$$

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 multiparticle phase space and a large number of Feynman diagrams to be evaluated. 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 [2]. The full one-loop calculations have not been finished yet, even for the simplest case (doubly plus singly W-resonant diagrams) [3]. 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 extremely sizeable and very 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 are necessary for the required theoretical accuracy (dependent on 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 [4, 5]. Here we present such a solution for the W-pair production process, which consists of two complementary Monte Carlo event generators: `YFSWW3` and `KoralW`. More details on `YFSWW3` can be found in Refs. [6, 7, 8, 9] and on `KoralW` in Refs. [10, 11, 12].

`KoralW` includes the full lowest-order $e^+e^- \to 4f$ 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 at LEP2. For 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`. 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, as will be shown later, allows us to combine the results of the two programs to achieve the desired theoretical precision for WW observables. The ISR effects in both programs are based on the Yennie–Frautschi–Suura (YFS) exclusive exponentiation procedure [13, 14], with an arbitrary number of non-zero p_T radiative photons. The Coulomb correction is implemented in the standard version according to Ref. [15] and also in the form of the "screened" Coulomb ansatz of Ref. [16], which is an efficient approximation of non-factorizable corrections. The full 4f matrix element with non-zero fermion masses for `KoralW` has been generated using the GRACE system of the MINAMI-TATEYA collaboration [17]. For an efficient event generation, two independent 4f phase-space presamplers have been developed [18]. In this way `KoralW` is able to provide the important 4f-background correction to the WW-process in the form of MC events. However, as was already shown in Ref. [2], the pure universal radiative corrections and the 4f-background corrections are not sufficient for a final theoretical precision tag of 0.5% for LEP2 experiments. By using the exact $\mathcal{O}(\alpha)$ calculations of Refs. [19, 20] for on-shell W-pair production, it was shown that the non-leading electroweak (EW) corrections can be as large as 1–2% at LEP2 energies (as will be seen later, they are even larger at LC energies). These calculations were done, however, in the on-shell-W approximation (stable W), so the question was how to implement (or extend) them in the realistic off-shell WW production. A workable solution to this turned out to be the so-called leading-pole approximation (LPA). The LPA was also needed for other reasons. Namely, the matrix element for the WW production and decay based on three double-resonant Feynman graphs (so-called CC03) is not $\mathrm{SU}(2)_L\times\mathrm{U}_1$ gauge-invariant, and the simplest way to achieve the full gauge invariance is to use the LPA.

There are two approaches within the LPA: the one already discussed in Ref. [2] and employed in the actual calculations for the WW process in Ref. [21], and the second advocated by R. Stuart in Ref. [22]. In the first approach, the whole matrix element is expanded in Laurent series about complex poles corresponding to two resonant W's; then in the LPA only the leading terms of this expansion are retained. In this approach one gets a direct correspondence to the on-shell W-pair production and decay, but the results can differ from the realistic process by several per cent. This can be corrected by adding the difference between the predictions of the full 4f process and this approximation, at least at the Born level; however, it is not obvious how to do it on an event-by-event basis. We have implemented in `YFSWW3` this solution and it is called the LPA_b option – it can be useful for some tests/cross-checks. In the second approach, the gauge-invariant matrix element is first decomposed into a sum of Lorentz scalar functions multiplied by spinor and Lorentztensor factors according to the standard S-matrix theory [23]. Then, only the Lorenz scalar functions, which describe the finite-range W propagation, are expanded about their complex poles. In the LPA, as previously done, only the leading terms in (Γ_W/M_W) are retained. In this approach the results are very close to the predictions based on the minimum gauge-invariant subset of Feynman diagrams including the WW production (so-called CC11), e.g. for the total cross section the differences are below 0.1% at 200 GeV and $\sim 0.5\%$ at 500 GeV. This solution is implemented in `YFSWW3` as the LPA$_a$ option and it is *recommended* for the event generation. The non-universal (non-leading) corrections are included in both LPAs through the YFS exponentiation for the WW production stage including photon radiation off the W bosons (split in a gauge-invariant way into the radiation in the production and decay stages). Here we employ the exact $\mathcal{O}(\alpha)$ calculations for the on-shell WW production of Ref. [20]. In the on-pole LPA residuals we make the approximation $s_p \approx M_W^2$, where s_p is the complex pole position and M_W is the on-shell W mass, which means neglecting terms $\sim (\alpha/\pi)(\Gamma_W/M_W)$ – unimportant for the aimed theoretical accuracy. For the radiation in the W decays, we use in the current version of `YFSWW3` the leading-log-type program PHOTOS [24], normalized to the radiatively corrected W branching ratios; however, the YFS exponentiation for this process is in progress. The non-factorizable corrections (interferences between various stages of the process) have been included only via the so-called screened Coulomb ansatz [16] (which is a sufficient approximation for LEP2), but can be implemented to their full extent in the future.

Having these two MC event generators, we can combine their results, in order to obtain precise predictions for the WW process, in two ways. Either we can take the best prediction from `YFSWW3` and correct it for the 4f background using `KoralW`, which can be symbolically denoted by:

$$\sigma_{Y/K} = \sigma_Y \oplus \delta_K^{4f} , \tag{2}$$

or we can take the best prediction from `KoralW` and correct it for the non-leading (NL) effects to the "signal" process from `YFSWW3`, which we can write symbolically as:

$$\sigma_{K/Y} = \sigma_K \oplus \delta_Y^{NL} . \tag{3}$$

This can be done easily at the level of the total cross section as well as for the differential distributions. Recently, reweighting interfaces have been developed for the two programs so that it can also be done on an event-by-event basis [25, 26]. All this is possible because both programs have some common basic distribution, which is the WW signal process with the universal radiative correction, and it has been checked that they agree very well at this level [9].

`YFSWW3` was also compared with an independent MC program, RacoonWW [27], which includes the non-universal $\mathcal{O}(\alpha)$ corrections for the W-pair production. The two programs were found to agree for the total WW cross section $< 0.4\%$ at LEP2 energies [5] and $< 0.5\%$ at 500 GeV [9]. Numerically, the non-universal $\mathcal{O}(\alpha)$ corrections as calculated by `YFSWW3` are $\sim$ 1–2% at LEP2 energies and $\sim$ 5–10% at LC energies (0.5–1.5 TeV), and they are always negative. On the other hand the ISR corrections change their sign from being large negative near the WW threshold to being large positive at LC energies (thus cancelling partially the effects of non-universal corrections).

Acknowledgements

One of us (W.P.) thanks the organizers of the LCWS 2000 at Fermilab for their kind hospitality and their financial support. We also acknowledge the support of the CERN Theory Division, all the LEP Collaborations and the DESY Directorate.

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