Predictions for $e^+e^- \rightarrow WW \rightarrow 4f(\gamma)$ at a future linear collider

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Abstract

We describe the salient features of precise predictions for the processes $e^+e^- \rightarrow WW \rightarrow 4f(\gamma)$ as obtained with the Monte Carlo generator RacoonWW$^4$, including the complete $\mathcal{O}(\alpha)$ electroweak radiative corrections in the double-pole approximation. Numerical results for some distributions are given at the typical linear-collider energy $\sqrt{s} = 500$ GeV. Moreover, we study the impact of the non-universal electroweak corrections by comparing with results of an improved Born approximation.

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$^4$ Program available from http://www.hep.psi.ch/racoonww/racoonww.html
Predictions for $\text{e}^+\text{e}^- \rightarrow \text{WW} \rightarrow 4\text{f}(\gamma)$ at a future linear collider

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Abstract. We describe the salient features of precise predictions for the processes $\text{e}^+\text{e}^- \rightarrow \text{WW} \rightarrow 4\text{f}(\gamma)$ as obtained with the Monte Carlo generator RACOONWW, including the complete $\mathcal{O}(\alpha)$ electroweak radiative corrections in the double-pole approximation. Numerical results for some distributions are given at the typical linear-collider energy $\sqrt{s} = 500$ GeV. Moreover, we study the impact of the non-universal electroweak corrections by comparing with results of an improved Born approximation.

INTRODUCTION

The measurements of the W-boson mass and the gauge-boson self-interactions in W-pair production at a future $\text{e}^+\text{e}^-$ linear collider (LC) will provide further important precision tests of the Electroweak Standard Model. To match the experimental accuracy, which will exceed the per-cent level, the predictions for the observed cross sections of $\text{e}^+\text{e}^- \rightarrow \text{WW} \rightarrow 4\text{f}(\gamma)$ have to reach an accuracy at the level of some 0.1%. Thus, the inclusion of higher-order effects in perturbation theory is crucial. Moreover, at the LC for the first time a precise direct measurement of quartic gauge-boson couplings can be performed, and predictions for all processes $\text{e}^+\text{e}^- \rightarrow 4\text{f}\gamma$ are needed. Already at LEP2 with only a few $\text{WW}\gamma$ events, first direct bounds on the quartic gauge-boson couplings have been obtained [1].

Full results for the processes $\text{e}^+\text{e}^- \rightarrow 4\text{f}$ at the one-loop level are out of sight at present. Fortunately, for W-pair production at LEP2 and at not too high LC energies\(^1\), it is sufficient for the envisioned theoretical precision to take into account only radiative corrections to those contributions that are enhanced by two resonant W-boson propagators. Different versions of this so-called double-pole approximation (DPA) for the radiative corrections to off-shell W-pair production have been described in the literature [2–5]. Two of them have been implemented in the

\(^1\) Above 0.5–1 TeV at least the leading electroweak logarithms at the two-loop level should also be taken into account.
state-of-the-art Monte Carlo generators YFSWW [3] and RACOONWW [5]. The MC program RACOONWW also provides tree-level predictions for all processes $e^+e^- \rightarrow 4f\gamma$ for massless fermions [6].

Here we briefly describe the radiative corrections to off-shell W-pair production in the DPA as implemented in RACOONWW and study their impact on some distributions at a typical LC energy $\sqrt{s} = 500$ GeV. Moreover, we discuss the effect of the non-universal electroweak corrections by comparing the full calculation in the DPA with an improved-Born approximation (IBA) [7] as implemented in RACOONWW. More results for LEP2 and LC energies are provided in Refs. [5,8,9] and [7,10], respectively. Refs. [5,9] also contain a discussion of the intrinsic theoretical uncertainty of our version of the DPA as well as comparisons to results of other authors.

**PRECISE PREDICTIONS FOR $e^+e^- \rightarrow WW \rightarrow 4f(\gamma)$**

The $O(\alpha)$-corrected cross section to off-shell W-pair production in DPA as implemented in RACOONWW can be written as follows [5]:

$$d\sigma_{WW} = d\sigma_{\text{Born}}^{e^+e^- \rightarrow 4f} + d\sigma_{\text{virt,finite,DPA}}^{e^+e^- \rightarrow WW \rightarrow 4f} + d\sigma_{\text{virt+real,sing}}^{e^+e^- \rightarrow 4f} + d\sigma_{\text{finite}}^{e^+e^- \rightarrow 4f\gamma}.$$  \hspace{1cm} (1)

Here $d\sigma_{\text{Born}}^{e^+e^- \rightarrow 4f}$ is the full lowest-order cross section to $e^+e^- \rightarrow 4f$, and $d\sigma_{\text{finite}}^{e^+e^- \rightarrow 4f\gamma}$, which describes real photon radiation away from IR and collinear regions, is the full lowest-order cross section to $e^+e^- \rightarrow 4f\gamma$ as described in Ref. [6]. The IR-finite sum of virtual and real soft and collinear photonic corrections is denoted by $d\sigma_{\text{virt+real,sing}}^{e^+e^- \rightarrow 4f}$. The matching of IR and collinear singularities in the virtual and real corrections is performed in two different ways: by using phase-space slicing or alternatively a subtraction method [11]. Apart from non-mass-singular terms, $d\sigma_{\text{virt+real,sing}}^{e^+e^- \rightarrow 4f}$ contains only collinear singularities associated with the initial state, i.e. leading logarithms of the form $\alpha \ln(s/m_e^2)$, at least for sufficiently inclusive observables. Since the contribution $d\sigma_{\text{virt+real,sing}}^{e^+e^- \rightarrow 4f}$ is not treated in DPA, those logarithms are included in our approach exactly. In RACOONWW, the DPA is only applied to the finite (non-leading) part of the virtual corrections, denoted by $d\sigma_{\text{virt,finite,DPA}}^{e^+e^- \rightarrow WW \rightarrow 4f}$ including the full set of the remaining factorizable and non-factorizable virtual $O(\alpha)$ corrections. Beyond $O(\alpha)$, RACOONWW includes soft-photon exponentiation and leading higher-order initial-state radiation (ISR) up to $O(\alpha^3)$ via the structure-function approach (see Ref. [12] and references therein). The leading higher-order effects from $\Delta\rho$ and $\Delta\alpha$ are included by using the $G_\mu$ scheme. QCD corrections are taken into account either by a multiplicative factor $(1 + \alpha_s/\pi)$ for each hadronically decaying W boson or by evaluating the $O(\alpha_s)$ corrections directly from Feynman diagrams with real or virtual gluons.

For the numerical results we use the setup of Ref. [5], choosing the calo recombination procedure. Our “best” results comprise the CC03 Born cross section, $d\sigma_{\text{Born}}$, and all radiative corrections briefly described above. We compare these “best” results with an IBA that has been implemented in RacoonWW as described
FIGURE 1. The CC03 Born, IBA, and “best” predictions of the W$^+$ invariant-mass distribution for $e^+e^- \rightarrow u\bar{d}\mu^+\bar{\nu}_\mu$ at $\sqrt{s} = 500$ GeV when calo cuts are applied (l.h.s). The corresponding relative corrections are shown for different normalizations $d\sigma_0$ (r.h.s).

FIGURE 2. The CC03 Born, IBA, and “best” predictions of the distribution in the cosine of the $W^+$ production angle at 500 GeV when calo cuts are applied (l.h.s). The corresponding relative corrections are shown for different normalizations $d\sigma_0$ (r.h.s).

in detail in Ref. [7]. The IBA takes into account the universal electroweak corrections [13]: the running of the electromagnetic coupling, corrections connected to the $\rho$ parameter, the Coulomb singularity, and leading-logarithmic ISR.

In Figs. 1 and 2 we show the $W^+$-invariant-mass and $W^+$-production-angle distributions, respectively, and the corresponding relative corrections, $d\sigma/d\sigma_0 - 1$, to $e^+e^- \rightarrow u\bar{d}\mu^+\bar{\nu}_\mu(\gamma)$ at 500 GeV. Here $d\sigma$ denotes the “best” prediction and $d\sigma_{IBA}(Q^2)$ the IBA for two different scales in the structure functions, $Q^2 = s$ and
\[ t_{\text{min}} = s \left( 1 - \sqrt{1 - 4M_W^2/s} \right)/2 - M_W^2. \]

In contrast to the LEP2 case, the radiative corrections at 500 GeV mostly increase the Born cross sections.

The invariant masses are obtained from the four-momenta of the decay fermions of the W bosons after eventual photon recombinations. As discussed in Refs. [5,8], they are very sensitive to the treatment of the photons, i.e. different results are obtained when using bare cuts. The observed distortion of the W-invariant-mass distributions is of particular interest when the W-boson mass is reconstructed from the W-decay products. As can be seen when comparing the “best” with IBA results, this distortion cannot be described by the used IBA, since the IBA does not account for radiation from the W-decay processes. The universal corrections mainly affect the normalization of the invariant-mass distributions.

For the angular distributions, we define all angles in the centre-of-mass system of the initial state. In contrast to the invariant-mass distributions, the angular distributions hardly depend on the recombination procedure. Thus, similar results are obtained when bare recombination cuts are used [5,8]. The dramatic increase of the relative corrections is due to hard ISR which causes a redistribution of events to a phase-space region where the Born cross section \( d\sigma_{\text{Born}} \) is very small. Thus, the effect is less pronounced when \( d\sigma_0 = d\sigma_{\text{IBA}} \), since the IBA accounts for the leading ISR effects. For very small angles, where the \( t \)-channel pole dominates the cross section, the IBA predictions approach the “best” results within a few per cent. For large and intermediate angles, where the cross section is small, the IBA predictions depend strongly on the scale in the structure functions.

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