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# Precise predictions for $e^+e^- \to 4f(+\gamma)$ with anomalous couplings*

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Abstract: The relevance of radiative corrections to $4f$ production at LEP2 and future $e^+e^-$ colliders is emphasized, and their treatment in the event generator RacoonWW is briefly discussed. In particular, the non-universal corrections are compared with the signature of anomalous triple gauge-boson couplings. For $4f+\gamma$ production the influence of anomalous quartic gauge-boson couplings on photon-energy distributions is illustrated.

## 1. Relevance of radiative corrections

From 1996 to 2000, LEP2 has operated very successfully above the W-pair threshold allowing for a thorough investigation of W-pair production (see e.g. Ref. [1] and references therein). The results of the four LEP experiments provide accurate tests of the non-Abelian structure of the Electroweak Standard Model (SM) and a precise measurement of

*RacoonWW can be downloaded from http://ltpth.web.psi.ch/racoonww/racoonww.html.

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the W-boson mass. While the precision of the W-pair production cross section at LEP2 has reached the per-cent level, the final LEP2 precision for the W-boson mass will be 30–35 MeV. At a future $e^+e^-$ linear collider, the accuracy of the cross-section measurement will be at the per-mille level, and the precision of W-mass determination is expected to be 15 MeV by reconstructing the W bosons from their decay products [2] and about 6 MeV from a threshold scan [3] of the total W-pair cross section.

In order to account for the experimental precision at LEP2, considerable theoretical effort was undertaken in the past years, as it is reviewed in Refs. [4, 5]. In the present calculations, the W bosons are treated as resonances in the full 4-fermion processes, $e^+e^- \to 4f\,(+\gamma)$, and radiative corrections are taken into account in a proper way. These can be split into universal and non-universal corrections. The former comprise leading-logarithmic corrections (LL) from initial-state radiation (ISR), higher-order corrections included upon a proper choice of the input-parameter scheme (running or effective couplings), and the Coulomb singularity. The remaining corrections are called non-universal since they depend on the process under investigation. The full $\mathcal{O}(\alpha)$ corrections to the $4f$ processes are not necessary to match the accuracy of LEP2, and it is sufficient to take only those corrections into account that are enhanced by two resonant W bosons. The leading term of an expansion about the two W poles provides the so-called *double-pole approximation* (DPA) [6]. In this approximation, there are *factorizable corrections*, which are the ones to on-shell W-pair production and on-shell W decay, and *non-factorizable corrections*, which originate from soft-photon exchange between the production and decay stages. Different versions of such a pole expansion have been used in the literature [7, 8, 9]. Although several Monte Carlo programs exist that include universal corrections, only two event generators, YFSWW3 [9, 10] and RacoonWW [8, 11], include non-universal corrections.

While the DPA approach is sufficient for the LEP2 accuracy [5, 12], the extremely high experimental precision at a future linear collider is a great challenge for future theoretical predictions, in particular since the DPA is not reliable near the W-pair threshold. The full $\mathcal{O}(\alpha)$ corrections have to be known for all $4f$ final states, and leading effects beyond $\mathcal{O}(\alpha)$ have to be included in the theoretical predictions properly. For instance, leading and sub-leading Sudakov logarithms become important and amount to several per cent in the TeV range [13].

## 2. Non-universal corrections vs. anomalous triple gauge-boson couplings

As already mentioned, one of the main goals at LEP2 is the investigation of the non-Abelian structure of the SM. A proper way to study possible deviations from the SM is the measurement of anomalous couplings. Recently, anomalous quartic [14] and triple gauge-boson couplings have been incorporated in RacoonWW. A general parametrization of charged anomalous triple gauge-boson couplings has been suggested in Ref. [15]. We have implemented these couplings in RacoonWW in the conventions of Ref. [16], which differ from the former by a sign in the parity-violating terms. The implementation of neutral triple gauge-boson couplings in RacoonWW follows the general parametrizations of Ref. [17].



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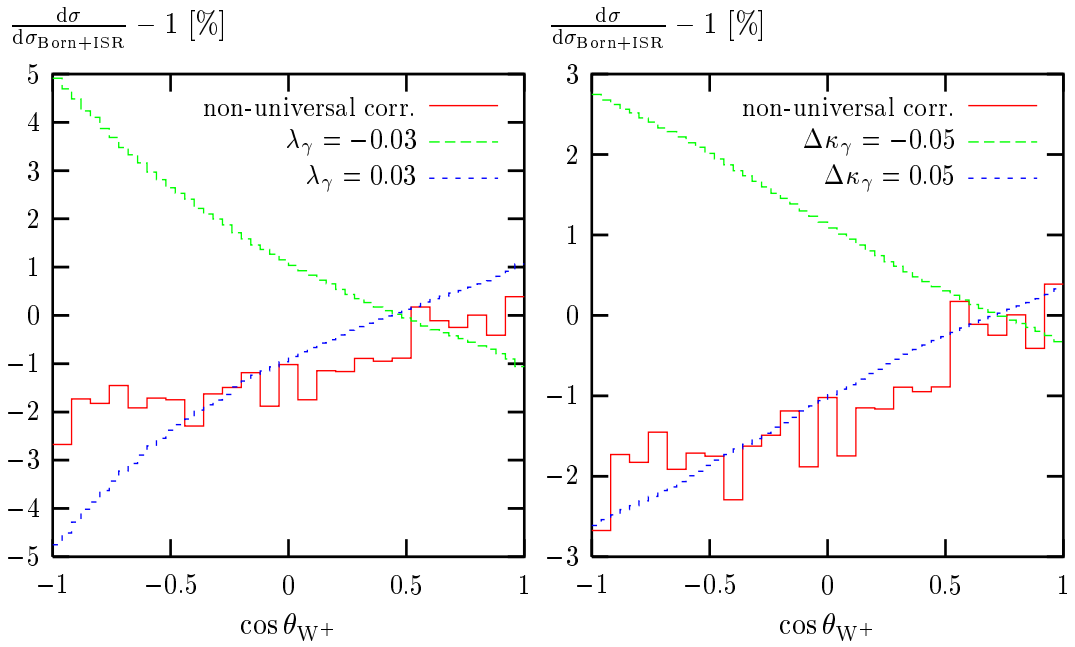


**Figure 1:** Influence of anomalous triple gauge-boson couplings and non-universal corrections in the $W^+$-production-angle distribution for the process $e^+e^- \to u\bar{d}\mu^-\bar{\nu}_\mu$ at $\sqrt{s} = 200\,\mathrm{GeV}$

In the numerical discussion, we compare the influence of the anomalous charged gauge-boson couplings with the effect of the non-universal corrections. We adopt the same SM input parameters and the same set of phase-space cuts as in Refs. [5, 8]. In particular, we use the "bare" recombination scheme, where the photon is recombined with a charged fermion if their invariant mass is smaller than 5 GeV. Following a convention widely used in the LEP2 data analysis, we consider only the P- and C-conserving anomalous coupling operators with the coupling constants $g_1^Z$, $\kappa_Z$, $\kappa_\gamma$, $\lambda_Z$, and $\lambda_\gamma$, which are further constrained by

$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_w, \qquad \lambda_Z = \lambda_\gamma,$$

where $\theta_w$ is the weak mixing angle and $\Delta$ indicates the deviation from the corresponding SM values $g_1^Z = \kappa_Z = \kappa_\gamma = 1$ and $\lambda_Z = \lambda_\gamma = 0$. Hence, we are left with the three independent parameters $\Delta g_1^Z$, $\Delta\kappa_\gamma$, and $\lambda_\gamma$.

In Figures 1 and 2 we study the influence of the anomalous couplings on the $W^+$-production-angle distribution for the process $e^+e^- \to u\bar{d}\mu^-\bar{\nu}_\mu$ at the centre-of-mass energy of $\sqrt{s} = 200$ GeV, as predicted by RacoonWW. All numbers are normalized to the tree-level cross section including higher-order LL ISR up to order $O(\alpha^3)$ via structure functions. The relative deviations for different values of the anomalous couplings are compared with the corresponding predictions including non-universal $\mathcal{O}(\alpha)$ corrections instead of anomalous couplings. The labels indicate the values of the corresponding anomalous coupling constants, which are chosen to be of the order of the actual accuracy achieved by the LEP experiments. The comparison shows clearly that the non-universal corrections are of the same size as the contributions from anomalous couplings and, thus, have to be taken into



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account in the determination of the anomalous couplings at LEP2.

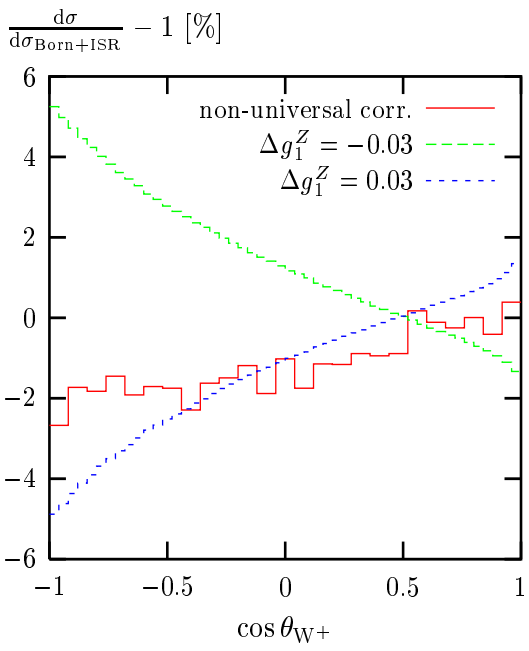


**Figure 2:** As in Figure 1

## 3. Anomalous quartic gauge-boson couplings in $4f + \gamma$ production

Finally, we study the effects of anomalous quartic gauge-boson couplings in $4f + \gamma$ production. Specifically, we consider the P-conserving couplings $a_0$, $a_c$, and $a_n$, which have been investigated in Ref. [18], and the P-violating couplings $\tilde{a}_0$ and $\tilde{a}_c$, which have been recently introduced in Ref. [14]. In this analysis we use the improved Born approximation mode [14] of RacoonWW for $4f + \gamma$ production which includes corrections from higher-order ISR and from the Coulomb singularity. We adopt the same SM input parameters as in Refs. [5, 8]; in particular, we apply the ADLO/TH cuts.

Figure 3 shows the photon-energy spectrum (l.h.s.) and the corresponding relative deviation from the SM (r.h.s.) for different values of the anomalous couplings. The

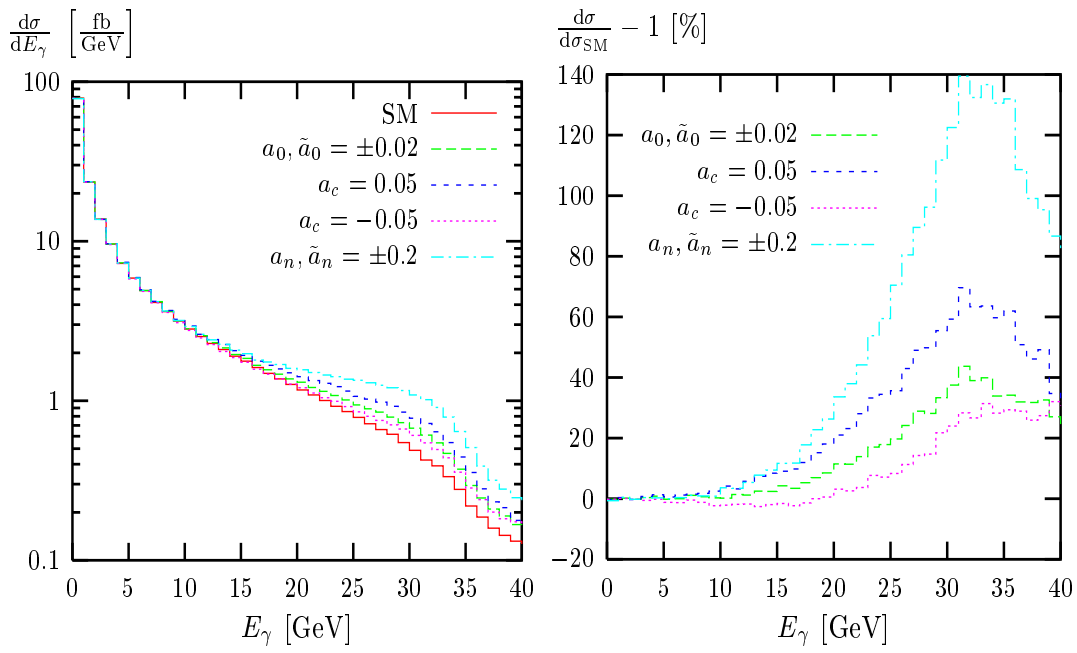


**Figure 3:** Influence of anomalous quartic gauge-boson couplings on the photon-energy distribution for the process $e^+e^- \to u\bar{d}\mu^-\bar{\nu}_\mu\gamma$ at $\sqrt{s} = 200\,\mathrm{GeV}$



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values of the anomalous couplings are of the order of the present experimental accuracy. Only one curve for the coupling $a_0$ and the corresponding P-violating coupling $\tilde{a}_0$ (also for $a_n$ and $\tilde{a}_n$) is plotted since the respective results are indistinguishable. Within the statistical error, the contributions from $a_0$, $a_n$, $\tilde{a}_0$, and $\tilde{a}_n$ are symmetric under a change in sign, signalling that the quadratic anomalous terms are dominating the squared amplitude. However, an effect from changing the sign is visible for $a_c$, where the interference of anomalous and SM contributions becomes visible. Since the deviations from the SM are largest for hard photons, effects from anomalous quartic gauge-boson couplings can be observed best near the kinematical threshold for W-pair production in the $E_\gamma$ distribution.

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