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# Impact of $\mathcal{O}(\alpha)$ radiative corrections on CC03 physics at LEP

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**Abstract.** In this work we report about the effect that the improved knowledge of electroweak radiative corrections, via the recent calculations of four-fermion processes with $\mathcal{O}(\alpha)$ corrections in double pole approximation, has on $WW$ physics at LEP2. Particular emphasis is given to the effects on differential distributions and their impact on the experimental observables. This study is based on generator comparisons using the new codes from the 2000 LEP2 Montecarlo workshop and allows new, important insights on the effects full radiative corrections have on $W$ physics observables. The results presented here explain why it is so important to take these new calculations into account for precision measurements at LEP2.

## 1 Introduction

The high accuracy reached by LEP in the CC03 cross-section measurement during the years 1996–1999 (roughly 1%) has imposed new levels of precision to the theory. Most part of the theoretical uncertainty on $\sigma_{\mathrm{CC03}}$ with the codes used before the 2000 LEP2 Montecarlo Workshop [1] was due to the contribution of non-leading radiative corrections. This has led to a big effort from the theoretical community in order to reduce this error; even though the full calculation of $\mathcal{O}(\alpha)$ electroweak corrections to 4-fermion processes is not available yet, the approach of the so-called double-pole approximation (DPA) allowed a substantial improvement of the theoretical accuracy on the total cross-section [1]. The new predicted value for $\sigma_{\mathrm{CC03}}$ is about 2% below the predictions by GENTLE [2], run in the recommended configuration described in [3]. The new cross-section was found to be in better agreement with the experimental data.

What has not been studied in detail is the effect that the improved knowledge of radiative corrections on CC03 has on differential distributions. This study, reported here, is important for understanding whether these more precise radiative corrections have a relevant effect on the experimental observables, and not only on the total cross-section.

In what follows we use YFSWW [4] and RacoonWW [5] as the two generators with DPA. The first one is a $e^+e^- \to W^+W^- \to 4f$ generator (CC03 diagrams only) with $\mathcal{O}(\alpha)$ factorizable electroweak corrections and non-factorizable corrections implemented via the so-called Khoze–Chapovsky ansatz (KC) [6], whereas the second one implements DPA rigourously and also includes real corrections with the exact $e^+e^- \to 4f\gamma$ matrix elements of the CC11 class. The matching between real and virtual corrections is done in such a way as to exactly cancel all the infrared divergencies.

These codes are compared to typical improved Born approximation (IBA) calculations, like those used for LEP2 generators. KoralW [7] (or YFSWW in equivalent IBA settings) is used in this paper. As will be described in the text, the comparisons are done with a coherent choice of the input parameter settings in the generators.

This text is organized as follows: in Sect. 2 the input parameter settings are described and consistency checks based on total cross-section comparisons shown. Section 3 illustrates the distortion introduced by DPA on the main $W$ physics observables as compared to the previous IBA calculations, trying to disentangle the effect that different parts of the radiative corrections have. The effect of the introduction of realistic experimental cuts in the comparisons is discussed, and in Sect. 4 our conclusions are crosschecked by comparing YFSWW and RacoonWW.

## 2 Technical checks and input parameter settings

In order to investigate the effects of the radiative corrections in all their components the generators have to be run in different configurations, which will be explained where relevant, making sure to use everywhere the same input parameter settings. As far as radiation is concerned, KoralW implements Coulomb corrections (CC), initial state radiation (ISR) via the YFS exponentiation $\mathcal{O}(\alpha^3)$ (like in YFSWW) and final state radiation (FSR) $\mathcal{O}(\alpha^2)$ with PHOTOS [8]. In YFSWW and KoralW the same version of PHOTOS is used, which also allows radiation off quarks. RacoonWW complements the exact $\mathcal{O}(\alpha)$ in the produc-

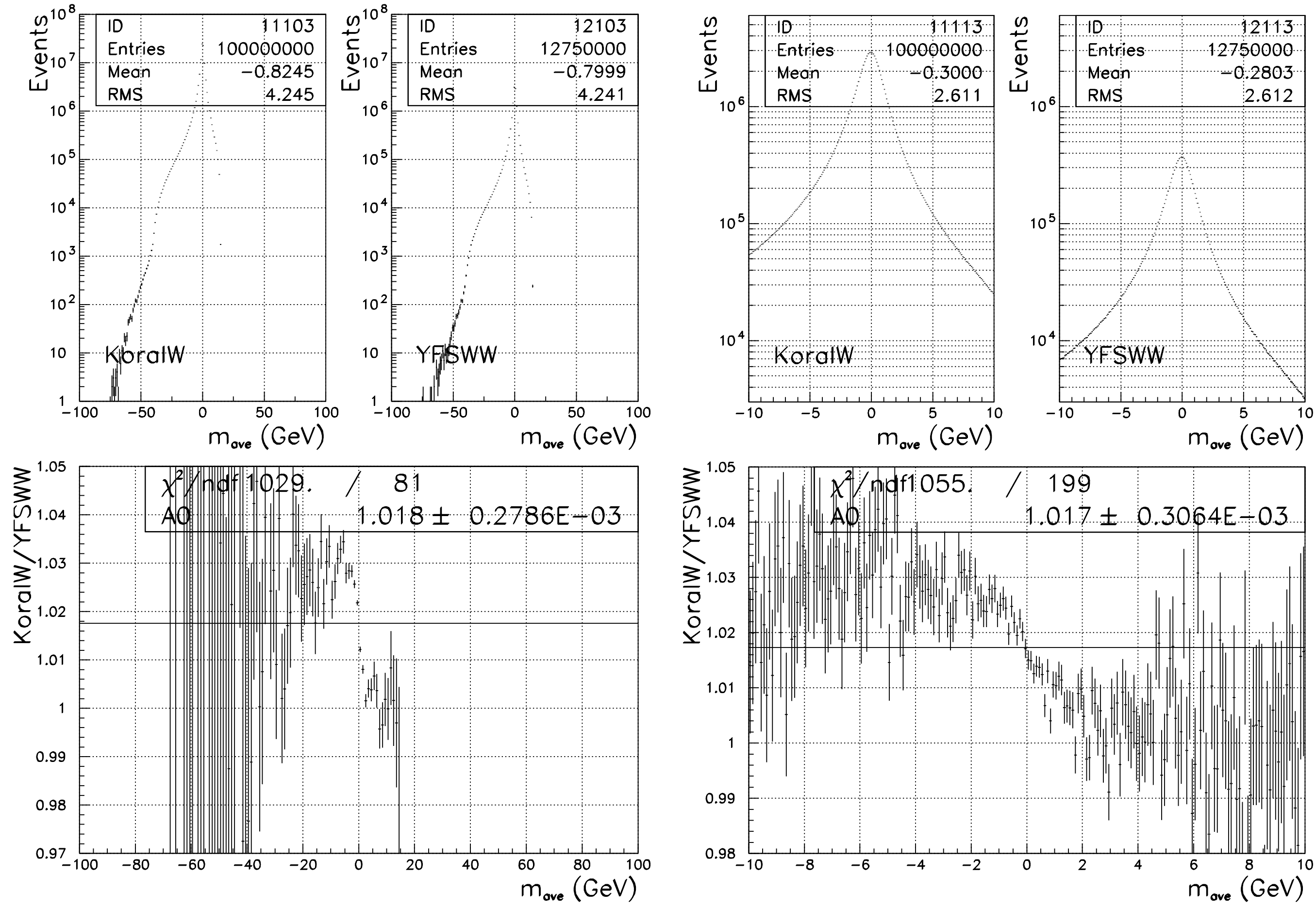


**Fig. 1.** KoralW and YFSWW comparison for the difference between the average difermion invariant mass in the event and the nominal $W$ mass for two different mass ranges. The lower plots show the ratio between the two distributions, fitted with a constant term indicated as A0

tion and decay phase with collinear ISR $\mathcal{O}(\alpha^3)$ with structure functions (SF).

The chosen reference final state is $u\bar{d}\mu\bar{\nu}_\mu$, with only the CC03 diagrams included. The center of mass energy in which the calculations are performed is 189 GeV, and the $G_\mu$ scheme is used. All the programs have the same input parameter settings: namely they have the same input constants, the running width scheme is used for the $W$ and the $Z$ boson propagators in KoralW and YFSWW, naive QCD corrections are included, and the CKM matrix is set as diagonal.
Table 1 shows the relevant information concerning the precision of our comparisons in this work; the number of generated events and the typical relative uncertainty on total cross-section and differential distributions at the double pole are indicated. To check the correctness of the input parameter settings and the reproducibility of the results in the LEP2 MC yellow report, numerical checks on the values of the total cross-sections were performed. In Table 2 the CC03 cross-sections (for the $u\bar{d}\mu\bar{\nu}_\mu$ channel) obtained by running the generators are shown for different configurations; the Born cross-sections, Born with ISR and Coulomb corrections, DPA without cuts (DPA0) and DPA with the “bare” photon recombination scheme explained in Sect. 4 and a 10 degrees cut in the polar angle of the final charged fermions (DPA1). The numbers with DPA confirm a relative decrease of the cross-section of about $-1.5\%$, in perfect agreement with the results of the LEP2 workshop. From the comparison of the DPA numbers with the same cuts it is also confirmed that RacoonWW and YFSWW agree at the 0.2% level, as expected and within the associated theoretical error.

## 3 The effects of DPA on $W$ observables

### 3.1 DPA and differential distributions

Modification of differential distributions induced by $\mathcal{O}(\alpha)$ corrections as compared to the IBA calculations are investigated by comparing KoralW and YFSWW in their best settings. The two codes basically differ for the inclusion of the $\mathcal{O}(\alpha)$ electroweak corrections to on-shell $WW$ production, the non-leading part of the radiation and for the approximate inclusion of the non-factorizable corrections, correlating initial and final state and the decay of

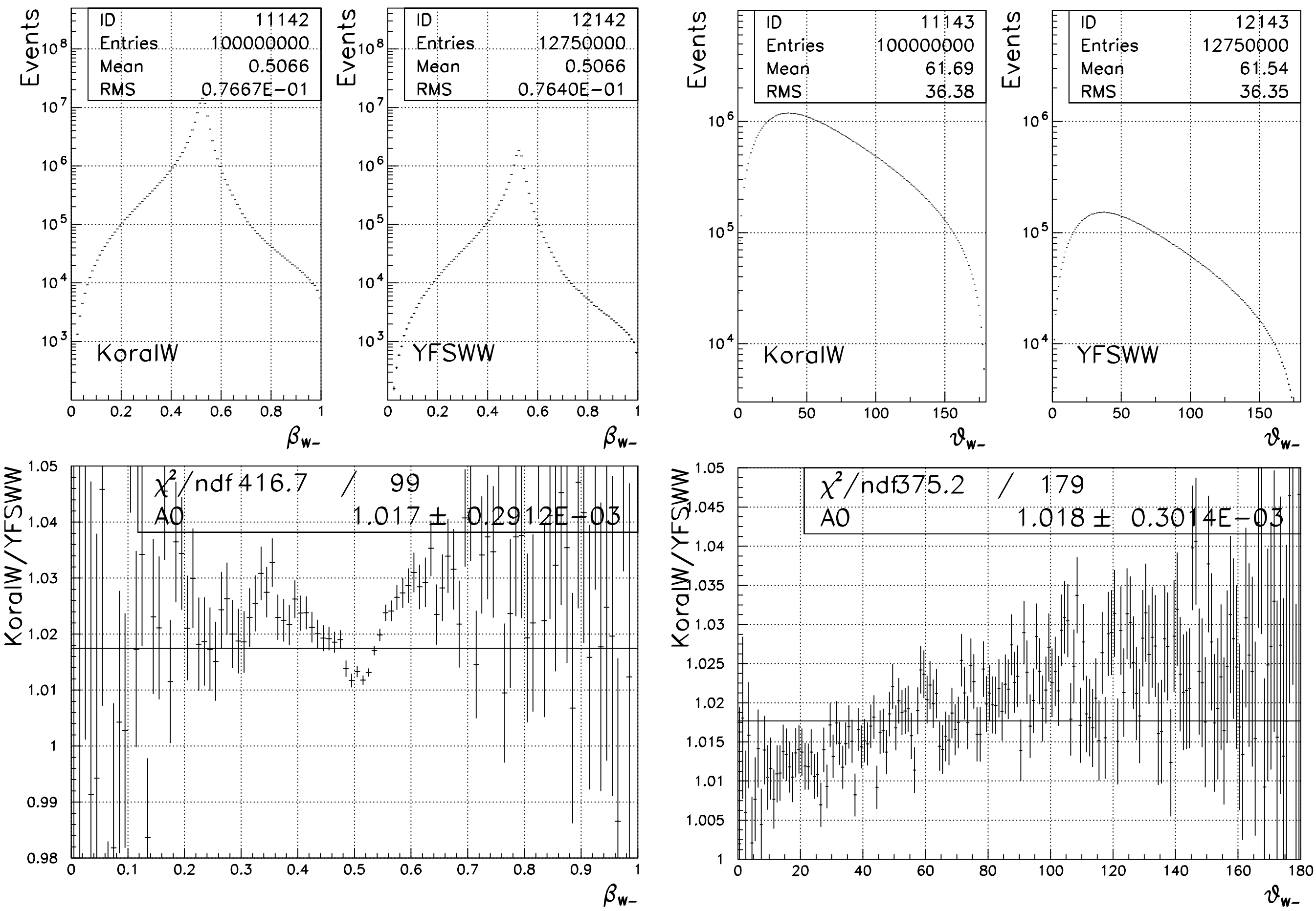


**Fig. 2.** KoralW and YFSWW comparison for the $W$ boost (left) and the $W$ polar angle (right). The lower plot shows the ratio between the two distributions, fitted with a constant term indicated as A0

**Table 1.** Number of generated events and achieved precision, in our set-up, on total cross-section and differential cross-section in mass. $\sigma_m$ is the differential cross-section as a function of the average mass $(m_{u\bar{d}} + m_{\mu\bar{\nu}_\mu})/2$

| Generator | Generated events | $\delta\sigma/\sigma$ | $\delta\sigma_m/\sigma_m\vert_{m_W}$ |
|---|---|---|---|
| KoralW | $10^8$ unweighted | $6 \times 10^{-5}$ | $3 \times 10^{-4}$ |
| YFSWW | $10^7$ unweighted | $2 \times 10^{-4}$ | $10^{-3}$ |
| RacoonWW | $5 \times 10^7$ weighted | $2 \times 10^{-4}$ | $10^{-3}$ |

**Table 2.** Cross-section values for the process $u\bar{d}\mu\bar{\nu}_\mu$ in different settings and for the different codes. In brackets the statistical integration error is indicated

| | KoralW/YFSWW | RacoonWW |
|---|---|---|
| Born (pb) | 0.66763(2) | |
| ISR+CC (pb) | 0.60687(3) | |
| DPA0 (pb) | 0.59625(7) | 0.5952(1) |
| DPA1 (pb) | 0.5696(1) | 0.5684(1) |

the two $W$ bosons. As a result differences arise in the radiation, especially at higher photon transverse momenta. There KoralW is found to overestimate the total radiated energy, but the total effect is anyway very small since the averages of the two spectra have been calculated to differ only by 40 MeV.

The important question is to verify whether these differences have also effects directly on the observables to be experimentally measured. This can be investigated by looking at differential cross-sections which are sensitive to radiation and are relevant for the event reconstruction. Figure 1 shows the distribution of the difference between the average event mass, determined as $(m_{u\bar{d}} + m_{\mu\bar{\nu}_\mu})/2$, and the generation $W$ mass. In the figures the distributions from KoralW, YFSWW and the ratio are shown, for different ranges of the mass. The ratios are fitted with a constant term, whose value represents then the ratio between the total cross-sections. The comparison clearly indicates a change of the trend at the double pole. This is mainly due to real and virtual photons connecting the two $W$ bosons and their decay products. From the right-hand plot it can be seen that the difference in the average of the distributions in the 10 GeV range around the pole is $20.0 \pm 0.7$ MeV. On the contrary, a $W$ mass estimator like the mass parameter of a Breit–Wigner function changes its value by about 5 MeV. Therefore the introduction of more complete radiative correction distorts the whole mass spectrum towards higher mass values, affecting both the $W$ mass and width measurements. In interpreting these results the reader should remember that the DPA approximation is valid only in a range of a few decay widths around the resonance pole, becoming unreliable outside this range.

Therefore one can conclude that a reasonable estimate for the shift in the fitted $W$ mass introduced by the DPA calculation compared to the previous IBA ones is conservatively of the order of $\mathcal{O}(\leq 10\,\mathrm{MeV})$. We will investigate in the next subsections in more detail what the cause is for this relevant distortion of the mass spectra and how conclusive this result is.

Because of the presence of radiation off $W$s, a change in the distribution of the $W$ angles and momenta is to be expected as well. In Fig. 2 the comparison between the generators with and without DPA for the $W$ boost, defined as $p_W/E_W$, and the $W$ polar angle, is shown. The relative difference on the boost induced by DPA, in the left-hand part of the figure, is of the order of 1%, with a narrowing of the momentum distribution of about 0.5%. The $W$ polar angle, which is shown in the right-hand part of the figure, is the variable which is affected by DPA in the most spectacular – and dangerous – way; the ratio shows a net 2% tilt in the angular distribution, due both to hard photon emission from the $W$s and to differences in the treatment of virtual corrections, which were not taken into account in LEP generators before. This effect can cause significant changes in the analysis performance and introduces big systematic shifts to those measurements which are very sensitive to the $W$ production polar angle, like the anomalous gauge couplings measurements.

### 3.2 The effect of non-factorizable radiative correction

It is interesting to study separately the effects, on distributions, of different parts of the $\mathcal{O}(\alpha)$ corrections. Hints of possible spectra distortions or mass shifts due to the non-factorizable radiative corrections via the Khoze–Chapovsky Coulomb screening are already suggested in [6]. In order to better understand their role and importance YFSWW has been run in IBA mode (i.e. with ISR and the Coulomb correction) with and without the KC Coulomb screening. The results on distributions are shown in Fig. 3, where the upper and the lower-left plots show the effect on the $W$ boost and mass (shifted by the input value) of the inclusion of the Khoze–Chapovsky Coulomb screening in the IBA calculation, whereas the lower-right plot compares, as a function of the shifted mass, the full DPA YFSWW with the IBA calculation with KC. It is possible to notice that the effect on the momenta is large and results in a relative increase of the $W$ boosts of 0.08%, corresponding to a 25 MeV momentum shift at a constant typical energy. On the other hand the sizeable distortion of the mass spectrum completely disappears (within the small statistical errors) when comparing the best YFSWW calculation with the simple IBA with non-factorizable corrections. The difference in total cross-section is of the expected order from DPA. Almost unchanged is the situation of the polar angle distributions.

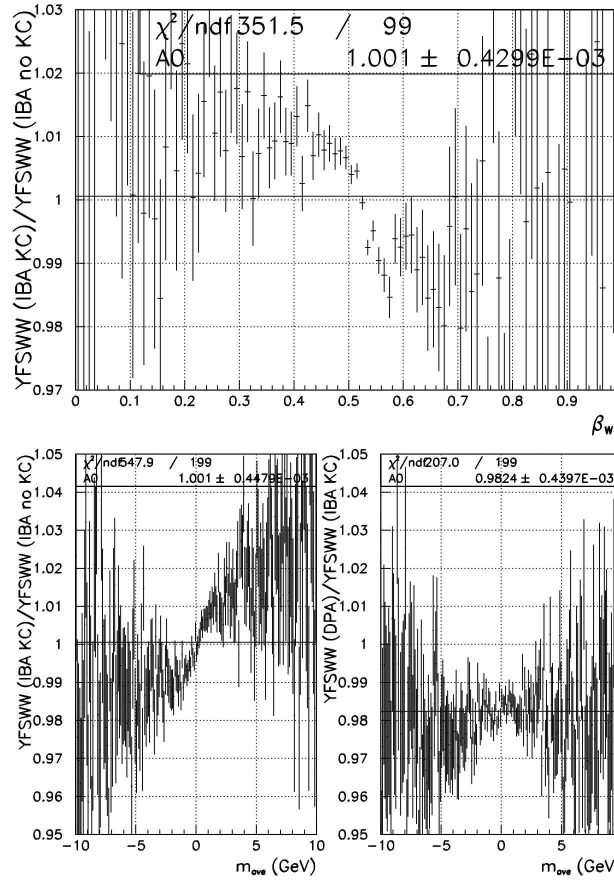


**Fig. 3.** Ratio of the distributions of the $W$ boost (upper plot) and the difference between nominal and average $W$ mass (lower-left plot) of YFSWW in the IBA setting with and without the non-factorizable virtual corrections implemented via KC. The lower-right plot shows the invariant mass ratio of YFSWW with its best settings and YFSWW in IBA including KC. All plots are fitted with constant terms

This result leads to the important – and in part expected – conclusion that most of the distortion in the mass distributions with respect to the IBA calculation using the standard Coulomb correction [6] is induced by the virtual non-factorizable corrections, approximated with the screened Coulomb ansatz, in particular those involving photons which connect the two $W$ systems, representing a momentum transfer between the two. This is a sort of electroweak reconnection never accounted for in the LEP2 analyses. The $W$ angular distribution are, on the contrary, more influenced by hard real photon emission from the $W$ themselves.

### 3.3 Experimental cuts and photon recombination

To study the possible interplay between the effect of the new DPA approach on distributions and experimental cuts (including the recombination of photons to fermions, mandatory when in the presence of jets, for instance), the same comparisons were done in the presence of experi-

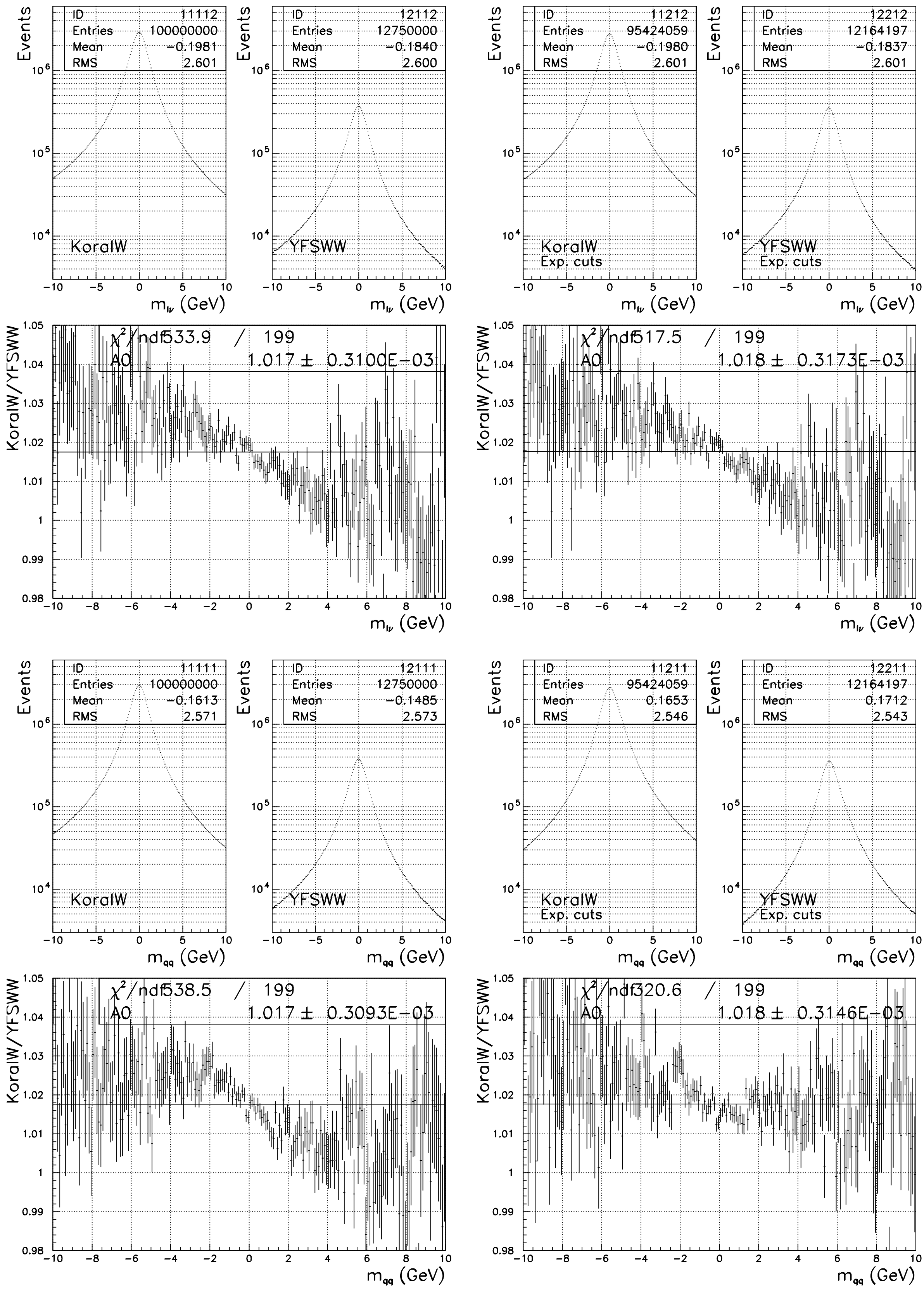


**Fig. 4.** KoralW and YFSWW comparison for the $\mu\bar{\nu}_\mu$ invariant mass (upper figures) and $u\bar{d}$ invariant mass (lower figures) in $u\bar{d}\mu\bar{\nu}_\mu$ events. The first column is the bare comparison, whereas the second is with the experimental cuts and the recombination of photons to fermions applied as described in the text. The lower plots in each of the figures show the ratio between the two distributions, fitted with a constant term indicated as A0

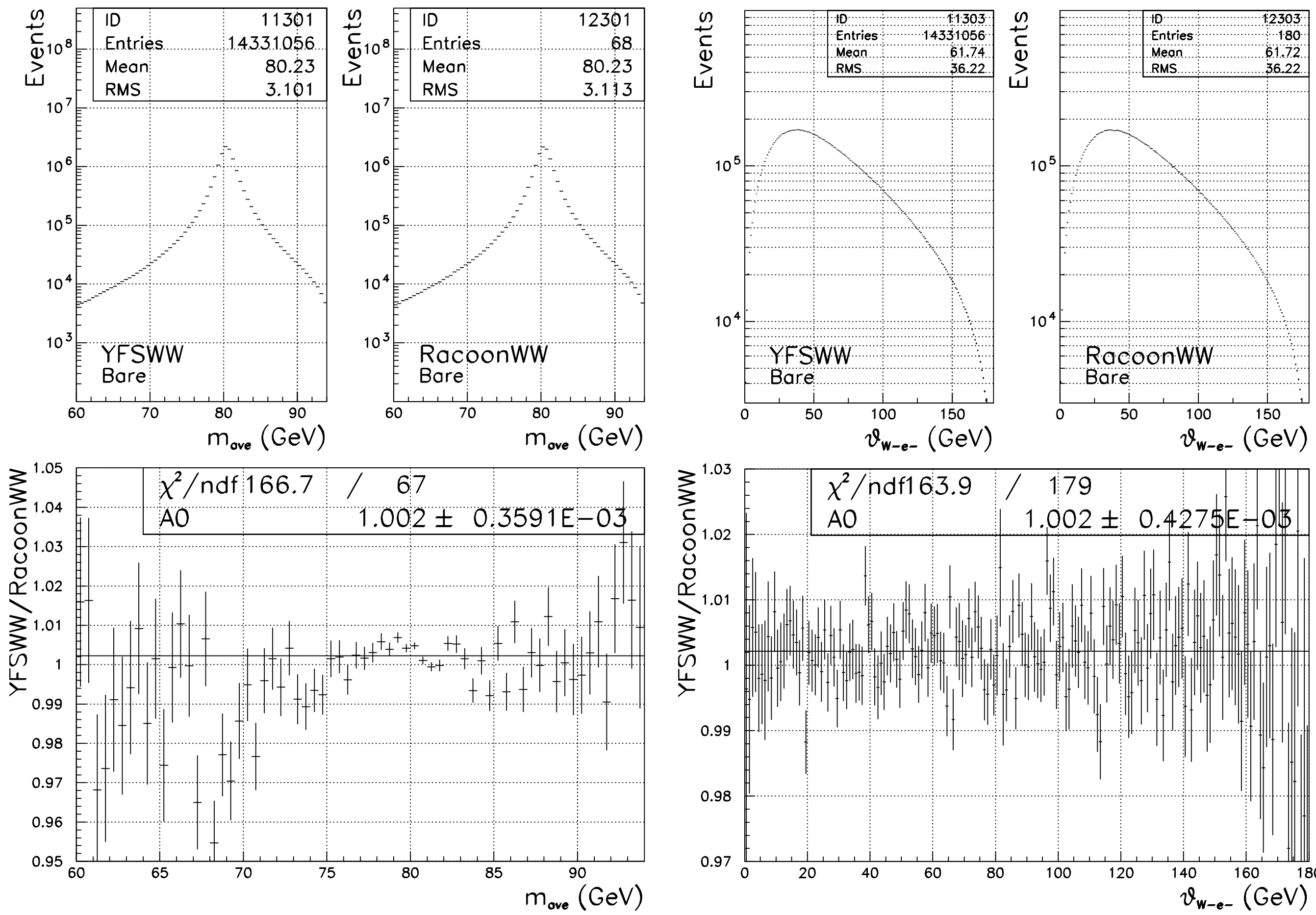


**Fig. 5.** YFSWW and RacoonWW comparisons for the average $W$ mass (left) and the $W^-$ polar angle with respect to the incoming electron (right). The lower plots show the ratio between the two distributions, fitted with a constant term indicated as A0

mental-like cuts (including also the FSR from final state fermions with PHOTOS). They are summarized here:

(1) jets (quarks) are visible everywhere, if their energy is greater than 5 GeV;
(2) charged leptons are required to have an angle of at least 10 degrees from the beams and an energy greater than 5 GeV;
(3) the invariant mass of a lepton and any quark is required to be above 10 GeV;
(4) the invariant mass of any couple of quarks is required to be above 30 GeV;
(5) photons are visible if they have energy above 300 MeV and polar angle between 2 and 178 degrees;
(6) photons are non-distinguishable from a quark if their invariant mass is below 10 GeV and non-distinguishable from an electron if they form an angle lower than 5 degrees. In these cases the photon four-momentum is reassociated to the fermion.

The application of the experimental cuts and the photon reassociation brings a negligible effect on the $W$ angular and momentum distribution, whereas the invariant mass reconstruction is affected. This is a confirmation that the change in the $W$ polar angle is mainly due to hard photon emission, whereas soft and semi-soft radiation also influences the mass reconstruction. Figure 4 shows the comparison between KoralW and YFSWW for the leptonic and hadronic invariant masses in generated $u\bar{d}\mu\bar{\nu}_\mu$ events, with and without the experimental cuts. What can be noticed is that, where the photon recombination takes place (in the hadronic part), the difference in the reconstructed $W$ mass is decreased by almost 50%. This is of course to be expected since the photons become indistinguishable from the quark and are reassociated to it. In this respect it is clear that it is very hard to reach any conclusion about the effects that DPA has on the invariant mass reconstruction from a generator study, and that an exercize at full reconstruction level is mandatory. These preliminary studies also tend to point towards an effect of radiation which is also different in hadronic and leptonic events. The resulting systematic uncertainties could then be final state dependent.

## 4 RacoonWW and YFSWW

The confirmation of the results shown in the previous sections comes from the comparisons with another code like

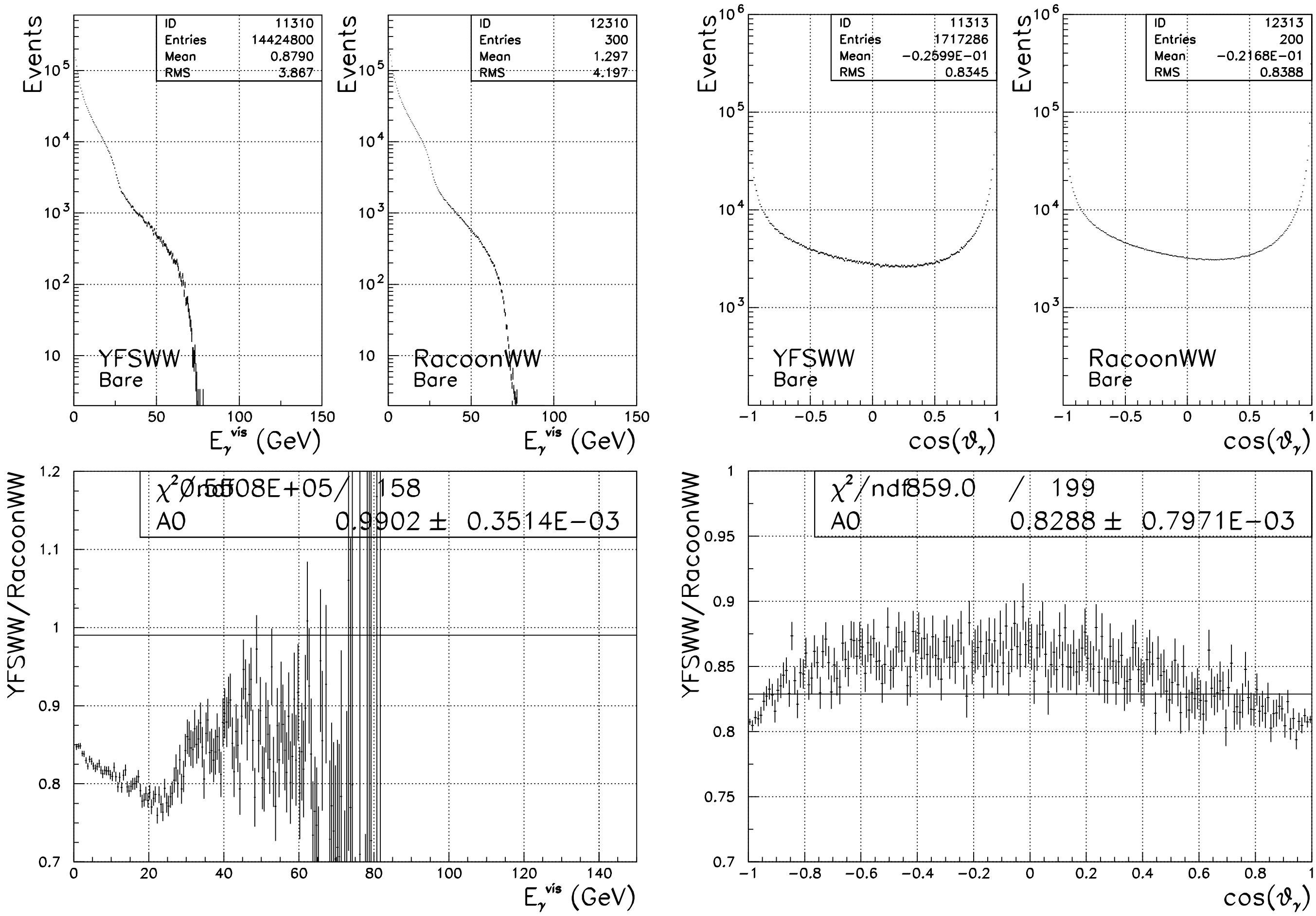


**Fig. 6.** YFSWW and RacoonWW comparison for the energy (left) and the cosine of the polar angle (right) of the visible photons. The lower plots show the ratio between the two distributions, fitted with a constant term indicated as A0

RacoonWW, where the DPA approach is more rigorous. To realize a tuned comparison, in YFSWW the fixed $W$ width scheme was used, to be consistent with the treatment in RacoonWW. Also the same angular cuts on final charged fermions were applied and the same bare photon recombination scheme used. This scheme consists in considering the emitted photons visible only if their polar angle is at least 2 degrees away from the beam pipe direction and to recombine the photon four-momentum to the closest fermion whenever its energy is below 300 MeV or the mass with the fermion below 5 GeV. In YFSWW, where more than one photon can be present, the recombination procedure is applied to all the real photons. It must be said that the application of the Khoze–Chapovsky ansatz for the non-factorizable corrections in YFSWW ignores photon recombination since the photon phase space is integrated out.

When comparing this study to the similar one presented in [1], the reader should keep in mind that although our comparison is very close to the "bare" one presented there, the inputs are not strictly the same, and in particular the cuts on the photon(s) polar angle(s) are different.

The average invariant mass distributions from YFSWW and RacoonWW are compatible within about 1%, as shown in the left-hand plots of Fig. 5; the fit to the distributions of a relativistic Breit–Wigner shows an excellent agreement of the fitted masses (within 1 MeV) and a very reduced effect on the fitted value of the $W$ width (order of 10 MeV).

Also the boost distributions are in reasonable agreement between the two codes. In the right-hand plot of Fig. 5 the polar angle of the $W^-$ with respect to the same charge initial fermion is shown: a remarkable agreement in the whole angular region is visible. All these comparisons essentially confirm the distortions with respect to non-DPA calculations and that some approximations used in YFSWW, like the Khoze–Chapovsky ansatz for the non-factorizable corrections, do not lead to appreciable effects in terms of distributions. The last important things to be compared are the properties of the real emitted photon(s) in the event. The plots in Fig. 6 show the comparison between the two codes for the energy and the polar angle of the visible photons – after the photon recombination –, correctly normalized to the total number of photons in the event (in YFSWW all the photons that are not recombined are considered). As one could expect, major differences (up to 20%) can be seen in the hard part of the spectrum and for collinear photons. This is explained by the different implementation of the radiative correction by the two codes: for RacoonWW the exact $\mathcal{O}(\alpha)$ in the production and decay phase is taken into account, extended to $\mathcal{O}(\alpha^3)$ for collinear ISR via SF. KoralW, on the contrary, includes ISR LL $\mathcal{O}(\alpha^3)$ via YFS and FSR LL $\mathcal{O}(\alpha^2)$ via PHOTOS. Therefore one can expect the two calculations to be more trustworthy in different regions of the photon phase space: RacoonWW is more reliable in the hard, high $p_{\mathrm{T}}$, regions, where matrix elements are known to be more correct, whereas YFSWW might give a better description of the quasi-collinear multiphoton radiation at very low $p_{\mathrm{T}}$.

More recently an IBA option has been implemented in RacoonWW where the $\mathcal{O}(\alpha^3)$ collinear ISR radiation is implemented on top of the Born $4f+\gamma$ final state [11]. Using this calculation the agreement with YFSWW in the visible photon distributions improves significantly. At present the RacoonWW configuration where DPA is used for the $4f$ part, which has been used for the above comparison, does not directly include also this improvement, which for this reason is not used in this paper.

## 5 Conclusions and outlook

In this work we have studied in detail what the effects are due to the introduction of $\mathcal{O}(\alpha)$ corrections to $WW$ physics in terms of distributions at generator level. This work complements what has been done for the LEP2 MC workshop and has the main aim of answering the question whether the introduction of $\mathcal{O}(\alpha)$ electroweak corrections to $WW$ physics in DPA at LEP2 may have an effect at the level of analyses when comparing with the old IBA calculations.

Our conclusions are that DPA, known to change the total cross-section by a relative amount of almost 2%, has also very important effect on distributions. In particular DPA influences the $W$ distributions in two ways: real photon emission from the $W$s and the different treatment of virtual corrections significantly change the shape of the angular distributions, with effects up to 1.5%, whereas non-factorizable virtual corrections, especially the one linking the decay phase of the two $W$ systems, distort the reconstructed mass distributions, shifting it towards higher mass by $\mathcal{O}(\leq 10\,\mathrm{MeV})$. In addition, the first of the two effect seems independent upon the implementation of experimental cuts or photon recombination to fermions.

Another important aspect of the better knowledge of radiative corrections on CC03 is the more correct treatment of real radiation, of special relevance for the correct mass reconstruction and the study of CC03 physics when in hard photons are present (for instance in the quartic gauge couplings measurements).

The results obtained in this work, which in part were unexpected even after the end of the LEP2 MC workshop, point out that neglecting part of the $\mathcal{O}(\alpha)$ corrections introduces new systematic effects on our LEP2 physics precision observables, which were unknown before and that can be in principle very relevant. This is confirmed by the first preliminary results on the triple gauge couplings measurements obtained by the ALEPH collaboration [10], showing shifts of the parameters larger than the measurements themselves and comparable with the total systematic error on them. This makes it necessary to take into account the new EW radiative corrections in DPA for $W$ physics precision measurements at LEP2. This, in turn, tells us that the old way to look at systematics due to radiation simply by different implementation of ISR or FSR, is not adequate to precision CC03 physics and that a new way to consider systematics due to radiation is needed.

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