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ELECTROWEAK CORRECTIONS UNCERTAINTY ON THE W MASS MEASUREMENT AT LEP

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Abstract

The systematic uncertainty on the W mass and width measurement resulting from the imperfect knowledge of electroweak radiative corrections is discussed. The intrinsic uncertainty in the 4-f generator used by the DELPHI Collaboration is studied following the guidelines of the authors of `YFSWW`, on which its radiative corrections part is based. The full DELPHI simulation, reconstruction and analysis chain is used for the uncertainty assessment. A comparison with the other available 4-f calculation implementing DPA $\mathcal{O}(\alpha)$ corrections, `RacoonWW`, is also presented. The uncertainty on the W mass is found to be below 10 MeV for all the WW decay channels used in the measurement.

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1 Introduction

Precision tests of the Standard Model in the W sector have been one of the main issues of the LEP2 physics program. In this context the measurement of the W mass is one of the most interesting tests. Due to the high precision which is experimentally achievable, about 0.05% in the LEP combination, it is important to have a robust estimate of all the possible systematic uncertainties.

Electroweak radiative corrections on WW events, which are used for the W mass and width measurements, and more generally on 4-f events, have been an important issue since LEP2 beginning. After the LEP2 Workshop of 1995 [1] it has been clear that the simple radiative corrections approach based on the Improved Born Approximation (IBA) is not sufficient to obtain a theoretical precision smaller than the experimental foreseen one in precise W physics measurements.

At the 2000 LEP2 Monte Carlo workshop [2] calculations implementing full $\mathcal{O}(\alpha)$ electroweak radiative corrections for 4-f events in the so called Double Pole Approximation (DPA) [3–5], i.e. reliable around the double resonant W pole, have been available as the result of an effort from the theory community. There are two Monte Carlo generators implementing these calculations, `YFSWW` [6] and `RacoonWW` [7].

Initially the studies on the theoretical precision of these calculations have been devoted to the inclusive WW cross section, showing a satisfactory 0.4% agreement between the two codes. Studies of differential distributions at generator level have been shown by both the theoretical groups and by others (for instance [8]), but a full attempt of assessing the theoretical precision on W related observables has been presented only later for the W mass [9] and for the TGC [10].

In the TGC related study the possible sources of uncertainties in both generators are considered and the calculations compared one to the other. Moreover a detector effect parameterization (based on the ALEPH simulation and analysis) is used to mimic the dominant effects beyond the pure electroweak generator.

The W mass study is a pure 4-$f+\gamma$ generator one based on a pseudo-observable (the $\mu\nu$ mass with some photon recombination) not directly comparable with the real observable measured by the experiments. It is based on an internal precision study of `YFSWW` plus a comparison with `RacoonWW`.

These studies provide a complete discussion of all the basic ingredients of the systematic uncertainty related to electroweak corrections, but the authors themselves recognize that for the W mass a study at full analysis level is needed for a complete final determination to be used by LEP experiments.

The purpose of the present work is to use the above mentioned studies as a guideline to perform a complete estimation of this systematic uncertainty for the W mass analysis in the frame of the full DELPHI event and detector simulation, reconstruction and analysis chain.

In section 2 the study of the intrinsic uncertainty of the DELPHI 4-f generator [11], based on `YFSWW` as far as radiative corrections are concerned, is discussed. In section 3 the comparison with `RacoonWW` is presented. Section 4 shows the global results and conclusions on the systematic uncertainty on the W mass and width.

Although the target of the present study is the assessment of the uncertainty on the W mass, the techniques and the Monte Carlo samples presented can be used for similar studies on other observables, in particular the TGC.

2 The uncertainty of the DELPHI 4-f generator

2.1 Description of the setups and samples

The 4-f generator used for this study is the standard DELPHI one, based on `WPHACT` [12] with the YFS-exponentiated ISR from `KoralW` [13] and with additional radiative corrections implemented for WW like events through `YFSWW`, using a reweighting technique as in the `KandY` "Monte Carlo tandem" [14]: IBA based events are reweighted in order to reproduce with good approximation the result of the DPA calculation. For simplicity it will be referred to as `WandY`. For single W events and non WW-like final states an IBA approach is adopted, using the `QEDPS` parton shower generator [15] in order to describe ISR, suitably adapted in the energy scale used for the radiation.

The version used for this study, as well as for the final DELPHI W mass analysis (internal DELPHI version 2.4) differs from [11] in the treatment of the final state radiation (FSR) from leptons, which is implemented with `PHOTOS` [16]: `PHOTOS` version 2.5 is used, implementing non leading logarithm (NLL) corrections which bring it quite close to the full matrix element calculation [17].

The study has been performed at the centre of mass energy of $\sqrt{s} = 188.6$ GeV, corresponding to the 1998 data sample. It has been chosen since it represents the highest single-energy data statistics available.

The wide range of sources of systematic uncertainties and possible studies discussed in [9] implies the need for several distinct Monte Carlo samples. Several sources can in fact be studied by simple event reweighting, applying as event weight the ratio of the modified matrix element squared and the standard one, where the modifications are related to the uncertainty source to be studied. All the possible weights have been implemented in the production of the standard WW-like 4-f samples.

Some studies cannot be performed by event reweighting and require dedicated samples. In the standard `WandY` the Leading Pole Approximation (LPA) expansion around the double resonant pole is made using the approach that in `YFSWW` is called the LPA$_A$ scheme [18]; the other available approach, the so called LPA$_B$ scheme [19], must be generated directly with `YFSWW`. Another case is the possible change of order in leptonic FSR: this would require distinct samples with $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha^2)$ matrix elements.

Furthermore the need to compare `WandY` to `RacoonWW`, which has some remarkable differences with respect to the normal DELPHI code, has suggested to produce a dedicated `WandY` sample suitably modified to be as close as possible to `RacoonWW` itself. Since `RacoonWW` cannot produce directly samples with several final states at the same time, and the statistical precision needed for a meaningful comparison ($\Delta m_W(\texttt{Wandy - RacoonWW}) \simeq \mathcal{O}(5\,\mathrm{MeV})$) requires about 1 million events per channel to be produced, two final states have been chosen as representatives of the fully hadronic and semileptonic channels for these special event samples.

In order to minimize as much as possible 4-f background contamination to CC03 diagrams, CC11 final states have been selected; the 4-f background effect is better studied in the standard `WandY` sample, with massive kinematics and dedicated radiative corrections not present in `RacoonWW` and where inter-channel migration effects, in which the 4-f background can also play a role, can be studied. For the fully hadronic channel the $udsc$ final state has been chosen, and for the semileptonic channel $ud\mu\nu$ has been preferred due to the presumably higher sensitivity to FSR corrections: photons are likely to be seen, while in final states with electrons most of them are merged in the calorimetric shower of the electron itself, and in taus they are generally merged in the jet of particles coming from the decay, which play a dominant role making all the studies more complex.

In order to be directly comparable with `RacoonWW`, these dedicated samples have been produced with the following modifications (compared to the standard settings):

- diagonal CKM matrix;
- fixed W and Z widths;
- $\mathcal{O}(\alpha)$ final state radiation from leptons with `PHOTOS` version 2.5. It is closer to `RacoonWW` than the original version in the lack of higher orders FSR;
- no Coulomb correction, Khoze-Chapovsky ansatz Coulomb correction [20] implemented through reweighting.

Since in the normal production the standard Coulomb correction is already included, the reweighting would allow to study only the difference between this one and the approximated version of the full non-factorizable $\mathcal{O}(\alpha)$ correction, the so called Coulomb correction in the Khoze-Chapovsky ansatz. In order to study the net $\mathcal{O}(\alpha)$ correction effect with respect to the tree level (known to be significantly smaller than the previously mentioned difference), no Coulomb correction is implemented in the special samples generation.

The main concern of possible systematic differences in the results from the dedicated samples and the standard ones is linked to the propagators' width treatment. A test has been performed with a small (100k events) dedicated $ud\mu\nu$ sample produced with the above modification but the W and Z width, kept running. The W mass difference with respect to the main $ud\mu\nu$ sample was:

$$\Delta(\text{running}\,\Gamma_W - \text{fixed}\,\Gamma_W) \quad = \quad -28 \pm 16\,\text{MeV} \tag{1}$$

well compatible with the known simple shift of -27 MeV of the mass value when moving from the fixed to the running width definition [1,21]. This known shift has been verified at generator level with a precision of about 2 MeV.

The `WandY` code has been extensively compared to `YFSWW` (see [11]), and for CC03 events it has been shown to be equivalent to `KandY`. Anyway, as a further consistency cross check, in order to allow the generalization of the results of this study, a dedicated `YFSWW` $udsc$ sample using LPA$_A$ scheme has been produced at pure "4-f + n γ" level (including FSR from quarks) to compare with a similar `WandY` sample and with `RacoonWW` at a corresponding level. In appendix A the input parameters set for `YFSWW`, equivalent to what used in `WandY`, is given.

In the cross check only the CC03 part of `WandY` has been used to be consistent with `YFSWW`. The total cross sections are found to be in agreement at the (0.03 ± 0.06) % level. In the event analysis photons forming an angle with the beam axis smaller than 2 degrees are discarded, and those with a bigger angle are recombined with the charged fermion with which they form the smallest invariant mass if their energy is below 300 MeV or if this mass is below 5 GeV. Several observables have been checked, among which the most interesting ones for this study are invariant mass distributions. They have been fitted using a fixed width like Breit-Wigner function:

$$BW(s) \quad = \quad \frac{P_3\ s}{(s-(P_1+80.4)^2)^2+(P_1+80.4)^2P_2^2} \tag{2}$$

where the parameters P_1 and P_2 are the (shifted) W mass and width (P_1 actually represents the shift of the W mass with respect to 80.4 GeV/c^2). The absolute value obtained in the fit depends on the fit function form and it is not particularly relevant. What matters for this check is the level of agreement between different codes when using the same analysis and fit procedure.

Fig. 1 shows the result of the fits on the average of the ud and sc invariant masses. The agreement both in the mass and in the width is satisfactory. An approach closer to the real analysis is to look at the average of the masses from the pairing in which the difference of the di-fermion masses is smallest (a criterion inspired by the equal masses constraint used in constrained fits); the result is shown in fig. 2, and also here the agreement is good. An observable that is very interesting, as will be seen in the comparison with `RacoonWW`, is the invariant mass rescaled by the ratio of the beam energy and di-fermion energy: it is the simplest way to mimic at pure generator level the energy-momentum conservation which is usually imposed in constrained fits and which is responsible for the sensitivity of the results to photon radiation, ISR in particular. Differences in the radiation structure are likely to cause visible effects in this kind of mass distributions, even if the previous ones are in good agreement. In fig. 3 the average of the invariant masses computed as in fig. 2 but rescaled by the ratio $E_{beam}/E_{f\bar{f}}$ is shown: also in this case, despite the sizeable effect of the rescaling on the fitted parameters compared to the previous fits, the agreement is very satisfactory.

This check proves that the results based on `WandY` can be considered valid for similar analysis using `YFSWW` (possibly except for specific non CC03 diagrams related features).

2.2 Technique of the uncertainty study

The systematic uncertainty on the W mass and width measurement due to the electroweak radiative corrections is the effect of the approximations and of the missing terms in the theoretical calculation used for the analysis. Its exact knowledge would imply the full computation of the missing corrections. The evaluation of the systematic uncertainty means estimating the order of magnitude of the effect of these not yet computed terms on the analysis.

This goal is practically achieved by splitting the calculations in different parts (ISR, FSR, etc.), whose limited knowledge introduces a source of uncertainty in the electroweak radiative corrections as implemented in `WandY`. The size of the uncertainty from each of these sources can be estimated by repeating the full W mass (and width) analysis with changes in the part of the radiative corrections related to this source, whose effect should reasonably be of the same order of magnitude (or bigger) than the missing terms, and comparing with the standard calculation. This study can be performed on both the dedicated high statistics samples and on the standard ones.

The purely numerical precision from the fit algorithm is 0.1 MeV for the mass value and 0.3 MeV for the mass error. On the width, due to the very slow variation of the likelihood curve around the minimum, the numerical accuracy on the fit result is about 1

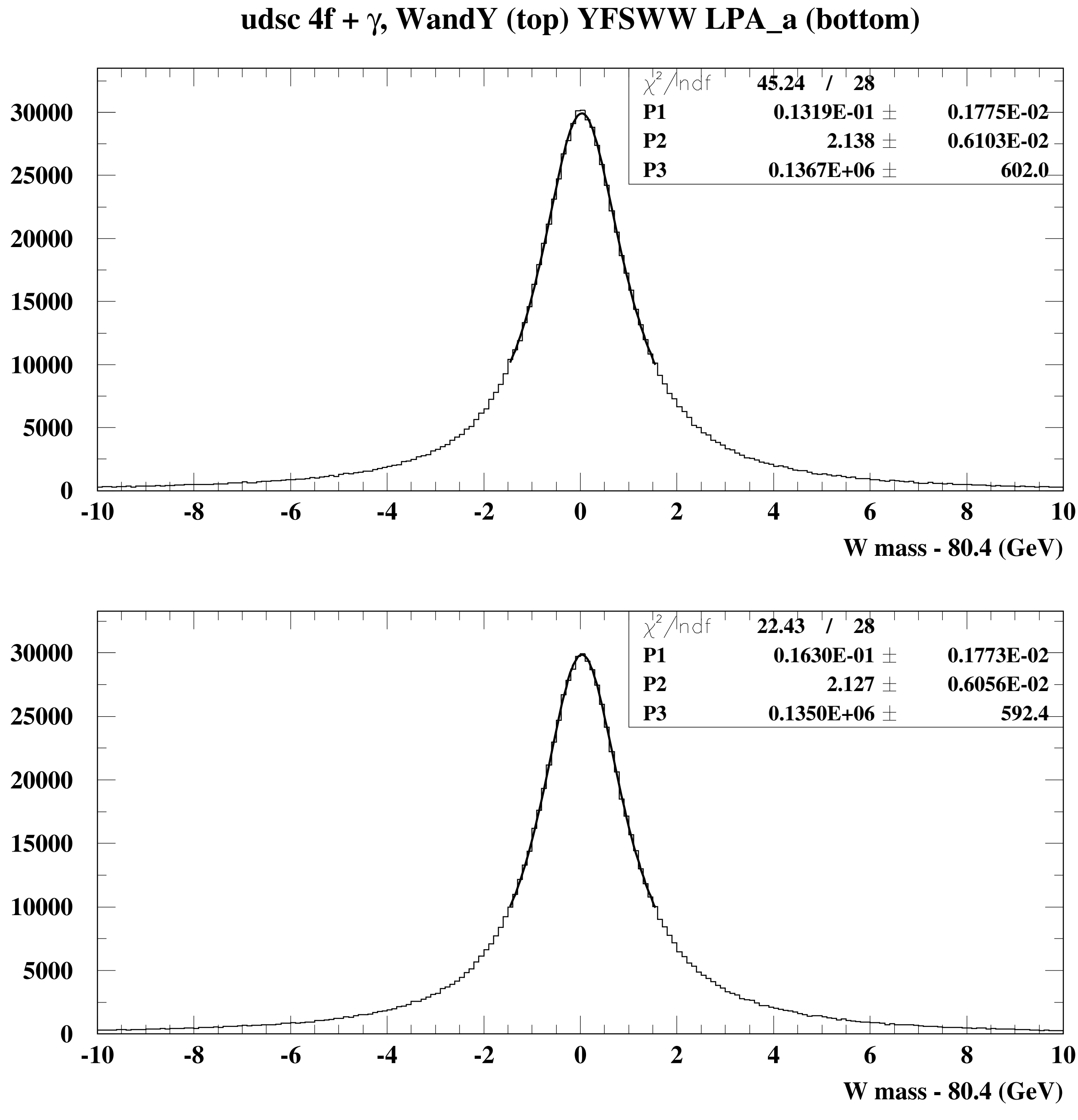

Figure 1: Average of ud and sc invariant masses (after photons cuts and recombination). Upper plot shows the result of a Breit-Wigner fit (eq. 2) to the `WandY` distribution, the lower one refers to `YFSWW`.

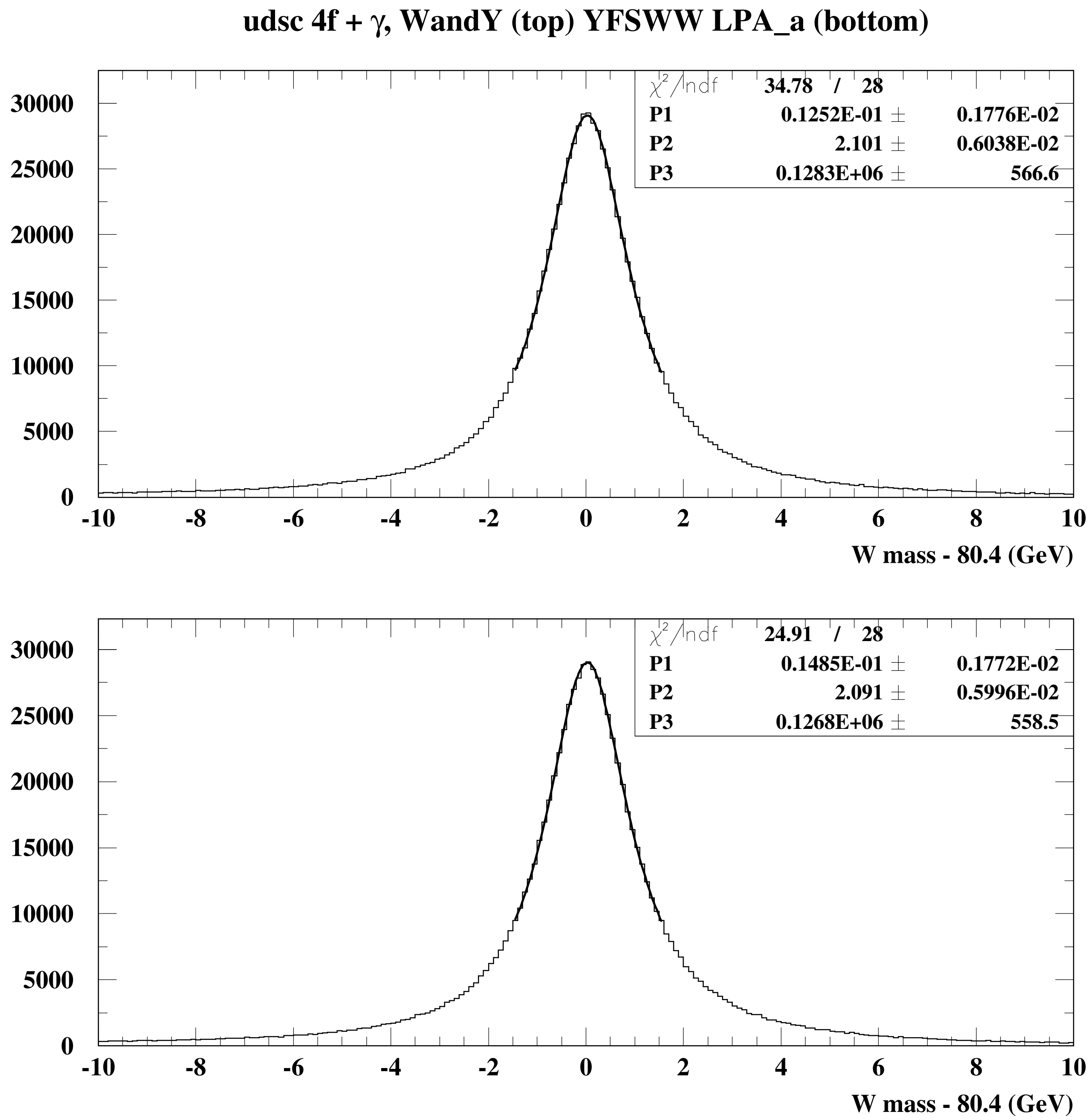

Figure 2: Average of the invariant masses obtained in the fermion pairing with the smallest masses difference (after photons cuts and recombination). Upper plot shows the result of a Breit-Wigner fit (eq. 2) to the `WandY` distribution, the lower one refers to `YFSWW`.

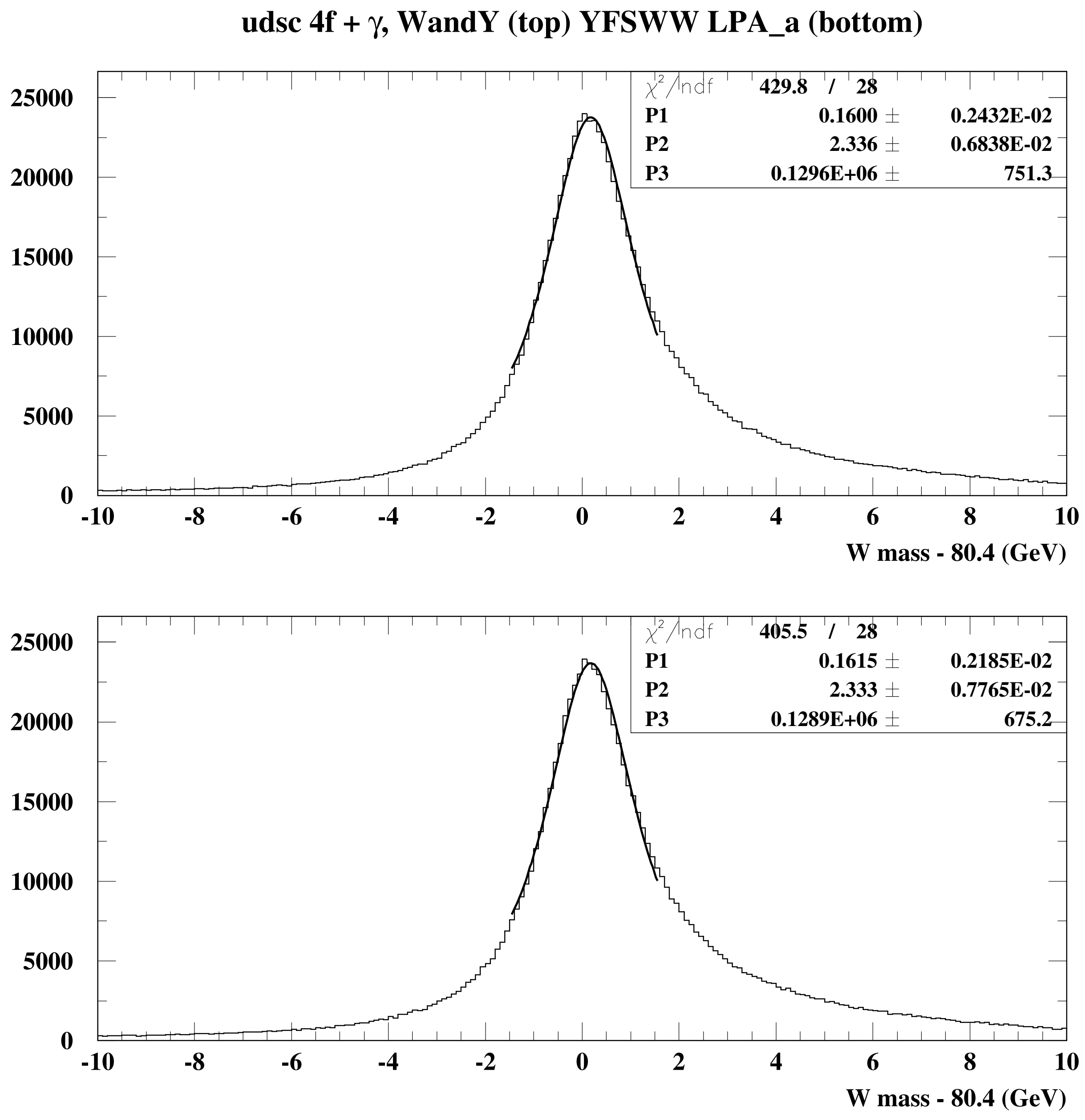

Figure 3: Average of the invariant masses obtained in the fermion pairing with the smallest masses difference after rescaling masses for the energies ratio $E_{beam}/E_{f\bar{f}}$ (after photons cuts and recombination). Upper plot shows the result of a Breit-Wigner fit (eq. 2) to the `WandY` distribution, the lower one refers to `YFSWW`.

MeV.

As already mentioned in the previous section, for several sources of uncertainty it is possible to use a reweighting technique, which allows to reuse the same event sample for several studies, minimizing the simulation needed. When using the reweighting technique, the statistical error on the difference between the results of the fits on the standard and the modified sample has to take into account the correlation existing between the samples: the same events are used, simply with a different weight in the fit. This correlation allows to strongly reduce the error on the difference itself, with respect to comparisons of statistically uncorrelated samples.

In order to take into account the correlation the total sample for one channel has been divided into several subsamples, and the difference has been computed for each subsample. The RMS of the subsamples differences distribution, divided by the square root of the number of subsamples, is an estimate of the uncertainty which naturally includes the correlation between the original and reweighted samples. This way of computing the errors has been cross checked for the mass (where numerical fluctuations are generally negligible compared to the statistical ones) with the "Jackknife" [22] one, subtracting each time one subsample, and a very good agreement in the error estimate has been found.

The study has been performed only on 4-f WW-like events, omitting all the remaining background processes. The rate and nature of the total selected events which are discarded in this way strongly depends on the channel [23]:

$q\bar{q}'e\nu$: $\simeq$ 5%

$q\bar{q}'\mu\nu$: $<$ 1%

$q\bar{q}'\tau\nu$: $\simeq$ 9%

$q\bar{q}'Q\bar{Q}'$: $\simeq$ 24%

For semileptonic events they are both $q\bar{q}'ll$ and $q\bar{q}\gamma$, the relative rate depending on the channel, while for fully hadronic events practically only the latter class of events weighs and is not considered. Other processes give anyway a negligible contribution. The uncertainty from the radiative corrections on these events is taken into account in the uncertainty on the background.

2.3 Analysis of the sources of systematic uncertainties

Following the approach of ref. [9], several distinct categories of uncertainty sources common to all WW channels can be identified, corresponding to different parts of the electroweak corrections:

- WW production: initial state radiation (ISR);
- W decay: final state radiation (FSR);
- Non-factorizable QED interference (NF) $\mathcal{O}(\alpha)$ corrections;
- Ambiguities in LPA definition: non leading factorizable (NL) $\mathcal{O}(\alpha)$ corrections.

Moreover, due to the importance of the single W diagrams in the semileptonic electron channel and the relatively sizeable uncertainty on the radiative corrections on them, a dedicated study has been performed for semileptonic channels.

The uncertainty for each of the categories is studied by testing the effect of activating/deactivating or modifying the relative corrections, in order to have an estimate of the potential effect of used approximations and non-calculated missing terms.

Table 1 and 2 show the results of the studies for m_W and Γ_W respectively on the dedicated samples, while table 3 and 4 show the results on the standard samples.

Δm_W (MeV)		
Numerical test	$ud\mu\nu$	$udsc$
Full DPA effect		
Best - IBA	-10.6 ± 0.7	-10.1 ± 1.0
WW production (ISR)		
Best - $\mathcal{O}(\alpha^2)$	< -0.1	< -0.1
Best - $\mathcal{O}(\alpha)$	-0.7 ± 0.1	-0.3 ± 0.1
W decay (FSR)		
Best - LL FSR	< -0.1	-
Non-factorizable QED interference (NF $\mathcal{O}(\alpha)$)		
Best - no KC Coulomb	-0.7 ± 0.1	-1.9 ± 1.0
Ambiguities in LPA definition (NL $\mathcal{O}(\alpha)$)		
Best - EW scheme B	0.1 ± 0.1	< 0.1
Best - no NL (LPA$_A$)	-9.9 ± 0.7	-8.2 ± 1.0
NL Δ(no LPA$_A$ $-$ no LPA$_B$)	0.0 ± 1.1	1.3 ± 1.0

Table 1: Summary of the studies on the uncertainties on m_W performed on the dedicated $ud\mu\nu$ and $udsc$ samples. The quoted errors are statistical, and rounded to 0.1 MeV.

2.3.1 WW production: initial state radiation

ISR is playing a key role in the W mass analysis since it is one of the main sources of the bias on the fit result with respect to the true value, due to the energy-momentum

$\Delta\Gamma_W$ (MeV)		
Numerical test	$ud\mu\nu$	$udsc$
Full DPA effect		
Best - IBA	-9.4 ± 1.4	-17.0 ± 1.0
WW production (ISR)		
Best - $\mathcal{O}(\alpha^2)$	< -0.1	< -0.1
Best - $\mathcal{O}(\alpha)$	-1.0 ± 0.1	-0.7 ± 0.1
W decay (FSR)		
Best - LL FSR	-0.5 ± 0.1	-
Non-factorizable QED interference (NF $\mathcal{O}(\alpha)$)		
Best - no KC Coulomb	1.6 ± 0.1	-0.4 ± 0.1
Ambiguities in LPA definition (NL $\mathcal{O}(\alpha)$)		
Best - EW scheme B	-0.1 ± 0.1	0.1 ± 0.1
Best - no NL (LPA$_A$)	-11.1 ± 1.4	-16.6 ± 1.0
NL Δ(no LPA$_A$ $-$ no LPA$_B$)	3.9 ± 2.8	-1.6 ± 4.0

Table 2: Summary of the studies on the uncertainties on Γ_W performed on the dedicated $ud\mu\nu$ and $udsc$ samples. The quoted errors are statistical, and rounded to 0.1 MeV.

conservation constraint used in the kinematical constrained fits. The ISR is computed in the YFS exponentiation approach, using a leading logarithm (LL) $\mathcal{O}(\alpha^3)$ matrix element.

The difference between the best result, implementing the $\mathcal{O}(\alpha^3)$ ISR matrix element and the $\mathcal{O}(\alpha^2)$ one gives an order of magnitude of the effect of the missing higher orders in the matrix element, i.e. to use a wrong description of events with more than three hard photons or more than one photon with high p_t. As can be seen from the tables, this effect is below the fit sensitivity for all the channels.

The difference between the best result and the $\mathcal{O}(\alpha)$ includes the previous study, and can be used for estimating an upper limit of the effect of the missing non leading logarithm (NLL) terms at $\mathcal{O}(\alpha^2)$, which should be smaller than the LL component removed. From the tables it is seen that the effect is below 1 MeV both for the mass and the width in all the channels.

Taking into account also the study performed in [9], the ISR related uncertainty can be conservatively estimated at 1 MeV for the mass and 2 MeV on the width.

2.3.2 W decay: final state radiation

The FSR description and uncertainty is tightly linked to the final state considered. QED FSR from quarks is embedded in the parton shower describing the first phase of the hadronization process. It is therefore essentially impossible to separate it from the rest of the hadronization process, and the relative uncertainty is considered as included in the jet and fragmentation related ones.

FSR from leptons is described by `PHOTOS`. The difference between the best result, based on the new NLL treatment, and the previous LL one can give an estimate of the effect of the missing part of the $\mathcal{O}(\alpha)$ FSR correction. It depends on the semileptonic channel, but it is always within 1 MeV.

In [9] the effect of the missing higher orders beyond $\mathcal{O}(\alpha^2)$ has been found to be negligible at generator level. Since a full study of this uncertainty would require a high statistics dedicated simulation, and simple perturbative QED considerations suggest that the size of the effect should not exceed the size of the previous one, conservatively the previous error can be doubled to take into account also this component of the uncertainty.

Δm_W (MeV)					
Numerical test	$q\bar{q}'e\nu$	$q\bar{q}'\mu\nu$	$q\bar{q}'\tau\nu$	$q\bar{q}'l\nu$	$q\bar{q}'Q\bar{Q}'$
Full DPA effect					
Best - IBA	2.1 ± 2.9	6.3 ± 2.0	1.6 ± 3.4	4.0 ± 1.6	5.6 ± 1.0
WW production (ISR)					
Best - $\mathcal{O}(\alpha^2)$	< -0.1	< -0.1	< -0.1	< -0.1	< -0.1
Best - $\mathcal{O}(\alpha)$	-0.8 ± 0.1	-0.6 ± 0.1	-0.9 ± 0.1	-0.8 ± 0.1	-0.3 ± 0.1
W decay (FSR)					
Best - LL FSR	< -0.1	< -0.1	-0.6 ± 0.1	-0.2 ± 0.1	-
Non-factorizable QED interference (NF $\mathcal{O}(\alpha)$)					
Best - no KC Coulomb	16.5 ± 0.2	15.6 ± 0.1	17.6 ± 0.2	16.3 ± 0.1	13.3 ± 0.1
Ambiguities in LPA definition (NL $\mathcal{O}(\alpha)$)					
Best - EW scheme B	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
Best - no NL (LPA$_A$)	-14.4 ± 2.9	-9.6 ± 2.0	-16.1 ± 3.4	-12.3 ± 1.6	-7.7 ± 1.0

Table 3: Summary of the studies on the uncertainties on m_W performed on the standard (all WW-like final states) sample. The quoted errors are statistical, and rounded to 0.1 MeV.

2.3.3 Non-factorizable QED interference: NF $\mathcal{O}(\alpha)$ corrections

Non factorizable $\mathcal{O}(\alpha)$ corrections have to be treated with care. It is known (see for instance [8,9,20]) that the net effect of the $\mathcal{O}(\alpha)$ QED interference between Ws on the W mass is small if compared with Born level, and the apparent sizeable effect seen when

$\Delta\Gamma_W$ (MeV)					
Numerical test	$q\bar{q}'e\nu$	$q\bar{q}'\mu\nu$	$q\bar{q}'\tau\nu$	$q\bar{q}'l\nu$	$q\bar{q}'Q\bar{Q}'$
Full DPA effect					
Best - IBA	-16.3 ± 7.7	-17.7 ± 5.3	-23.0 ± 7.5	-18.8 ± 3.7	-4.3 ± 1.0
WW production (ISR)					
Best - $\mathcal{O}(\alpha^2)$	< -0.1	< -0.1	< -0.1	< -0.1	< -0.1
Best - $\mathcal{O}(\alpha)$	-1.0 ± 0.1	-1.0 ± 0.1	-1.4 ± 0.1	-1.1 ± 0.1	-0.8 ± 0.1
W decay (FSR)					
Best - LL FSR	-0.3 ± 0.1	-0.4 ± 0.1	-0.9 ± 0.2	-0.4 ± 0.1	-
Non-factorizable QED interference (NF $\mathcal{O}(\alpha)$)					
Best - no KC Coulomb	-9.8 ± 0.3	-10.3 ± 0.3	-10.2 ± 0.4	-9.7 ± 0.2	2.9 ± 0.2
Ambiguities in LPA definition (NL $\mathcal{O}(\alpha)$)					
Best - EW scheme B	-0.1 ± 0.1	-0.1 ± 0.1	0.0 ± 0.1	-0.1 ± 1.1	0.1 ± 0.1
Best - no NL (LPA$_A$)	-6.8 ± 7.7	-7.9 ± 5.3	-14.0 ± 7.5	-8.6 ± 3.7	-7.2 ± 1.0

Table 4: Summary of the studies on the uncertainties on Γ_W performed on the standard (all WW-like final states) sample. The quoted errors are statistical, and rounded to 0.1 MeV.

comparing new DPA calculations with the old IBA ones is an artifact due to the use of the standard Coulomb correction.

This can be seen by comparing the results in tables 1 and 2, where the effective implementation of DPA NF corrections through the Khoze-Chapovsky (KC) ansatz is compared to the Born level (i.e. no correction at all), and the results in tables 3 and 4. Here the comparison is done with the standard Coulomb correction, part of the traditional IBA setup used before DPA.

The effect of using the KC ansatz with respect to Born can be considered as an upper limit of the missing part of the full $\mathcal{O}(\alpha)$ calculation and of the higher order terms. Since the effect on the W mass and width in comparing with the standard Coulomb correction on all the final states is approximately the same for all the channels, the values found on the special samples are used for all the final states without further studies.

2.3.4 Ambiguities in LPA definition: NL $\mathcal{O}(\alpha)$ corrections

The effect of the NL factorizable $\mathcal{O}(\alpha)$ corrections in LPA is shown in all the tables. As it is seen, its almost complete compensation with the change from standard Coulomb to KC Coulomb correction is the reason for the small net effect of the full DPA correction on the W mass in comparison to the IBA. For the W width on the contrary the effects are in the same sense and add up.

Two sources of uncertainties are considered, following the study in [9]. Missing higher orders effect can be, at least partly, evaluated by changing the electroweak scheme used in the $\mathcal{O}(\alpha)$ calculation. The standard one in `YFSWW` and `WandY`, conventionally called A, corresponds to the G_μ scheme, the other available one is called B, and it corresponds to the choice of `RacoonWW`. This essentially means changing the definition of the QED fine structure constant used in the $\mathcal{O}(\alpha)$ matrix element (see for instance the explanation in [6]). The effect is very small, at the limit of the fit sensitivity, both for the mass and the width.

It is worthwhile to notice here that in `YFSWW` and `WandY` the $\mathcal{O}(\alpha)$ implementation beyond the standard IBA can be technically splitted in two stages, the first one involving the introduction of the WSR and ISR-WSR interference in the YFS form factor and infrared $\tilde{S}$ factors, and the second one where the electroweak virtual and soft $\mathcal{O}(\alpha)$ corrections and the hard $\mathcal{O}(\alpha)$ matrix element are used to replace the pure QED LL calculation. In this context it is interesting to notice that the effect on the W mass of the second phase is quite small when compared to the total effect of the LPA correction, at most $\mathcal{O}(5-10\%)$ of it. This allows to conclude that the introduction of the ISR-WSR interference in the YFS form factor and infrared $\tilde{S}$ factors plays a key role. For the W width on the contrary the effect of the second part is found to be much more important.

The second, more relevant, source of uncertainty connected to the LPA is its possible definition, i.e. the ambiguity present in the way of expanding the amplitude around the double resonant W pole. The standard `YFSWW` and `WandY` use the so called LPA$_A$ definition; a comparison with the LPA$_B$ one can give an estimate of the effect from the instrinsic ambiguity in the LPA definition. Unfortunately LPA$_B$ cannot be reproduced through reweighting, and it gives sizeable changes in comparison to LPA$_A$ already at Born (or IBA) level. Therefore in order to evaluate only the effect on the $\mathcal{O}(\alpha)$ correction a separate LPA$_B$ sample has been generated with `YFSWW`, and the effect has been estimated as the double difference:

$$\Delta\mathcal{O}(\alpha)\ (\text{LPA}_A - \text{LPA}_B) = \quad \Delta(\text{Best LPA}_A - \text{no NL LPA}_A) - \Delta(\text{Best LPA}_B - \text{no NL LPA}_B)$$

on the special samples. The size of the effect is within 1 MeV for the mass, within 4 MeV for the width, dominated by the statistical uncertainty (statistically independent samples are used). This result will be used for all the final states and channels, since LPA is applied on the CC03 part of the matrix element and therefore the estimate obtained here should be approximately valid for all the final states.

2.3.5 Radiative corrections on 4-f background diagrams: single W

At Born level the full 4-f diagrams set for WW-like final states is computed with a very high precision, at least for LEP2 energies and in the phase space regions relevant for the W mass and width measurements. This was shown already by the studies in [1]. Therefore the systematic uncertainties associated to it are linked essentially to the electroweak corrections.

The DPA is known to be valid in a few Γ_W interval around the double resonant pole. The study of the previous section takes into account the ambiguity in its definition and the effects caused by this ambiguity far from the pole. Since the so called "additive approach" is used in `WandY` for the DPA implementation through reweighting, e.g. the DPA correction is applied only to the CC03 part of the matrix element (and partly to the interference, see [11]), non CC03 diagrams contributions are not directly affected by the DPA uncertainty (except for possible effects in the interference term which is relevant for the electron channel).

It is clear that this still leaves the problem of the approximated radiative corrections treatment for the non CC03 part of the matrix element (and the interference).

The ISR studies previously discussed can reasonably cover the most relevant part of the electroweak radiative corrections uncertainties present also for the WW-like 4-f background diagrams, e.g. the non CC03 part. There is a noticeable exception represented by the so called single W diagrams for the $q\bar{q}'e\nu$ final state (see [1,2] for their definition and a basic discussion of the problem).

The bulk of single W events is rejected in the W mass and width analysis, since the electron in these events is lost in the beam pipe. But the CC03 - single W interference is sizeable, and it has a strong impact on the W mass result in the electron channel. This can be easily seen from the variation of the W mass result for the electron channel when only the CC03 part of the matrix element is used in the simulation (inter-final state cross talk is included):

$$\Delta m_W\,(\text{electron})\,\text{Best - CC03 only} \quad = \quad 106.6 \pm 1.9\,\text{MeV}$$

and comparing with the variation when only the CC03/non CC03 interference is excluded from the simulation:

$$\Delta m_W\,(\text{electron})\,\text{Best - no interference} \quad = \quad 106.3 \pm 2.2\,\text{MeV}$$

It can be noticed that the big effect of moving from a full 4-f calculation to the CC03 only is almost entirely due to the interference between the CC03 and the non CC03 part.

The situation is different in the W width analysis, where in $qqe\nu$ events reconstructed as electrons the effects of non CC03 diagrams and the CC03 - non CC03 interference are opposite in sign and almost completely canceling.

The situation is made even more complex by the cross talk between channel, e.g. events belonging in reality to one channel but reconstructed as belonging to another one. This cross talk is particularly relevant between electrons and taus, and this explains why also the τ channel is sensitive to this uncertainty source.

The effect is particularly relevant for the width, where variations of the non CC03 parts of the $qqe\nu$ matrix element give different results with respect to the electron channel: the pure non CC03 diagrams give again an effect opposite in sign to the interference, but much bigger, so in the width analysis the tau channel is more sensitive to this systematic effect than the electron one:

$$\begin{aligned} \Delta\Gamma_W\,(\text{tau})\,\text{Best - CC03 only} &= 190.7 \pm 12.3\,\text{MeV} \\ \Delta\Gamma_W\,(\text{tau})\,\text{Best - no interference} &= -9.8 \pm 10.7\,\text{MeV} \end{aligned}$$

Studying separately real $qq\tau\nu$ events from the $qqe\nu$ ones reconstructed as taus clearly shows that this behaviour is due to the cross talk.

Theoretical studies [2] show that the standard IBA calculations suffer from several problems for the single W process, ranging from gauge invariance issues to the scale to be used for the ISR (the t-channel scale should be preferred to the s-channel one), problems which can globally lead to a $\mathcal{O}(4\%)$ uncertainty on the cross section.

It should be noticed that `WandY` implements several improvements in this sector with respect to fixed width based IBA calculations (see [11,12]). Nevertheless, in order to give an estimate of the uncertainty related to the radiative corrections for the single W part, the non CC03 part of the matrix element, assumed dominated by the single W contribution, has been scaled by a factor 1.04 for $q\bar{q}'e\nu$ final states.

The effect on the mass and width measurement is shown in table 5.

Another possible source of uncertainty related to 4-f background is represented by partly applying the DPA correction to the interference term (see the discussion in [11]). The effect of this way of computing the corrections is shown in table 5, and can be considered as another estimate of the uncertainty related to the 4-f background presence.

3 The DELPHI 4-f generator - RacoonWW comparison

The generator chosen by the LEP collaborations for implementing electroweak radiative corrections in WW-like events is `YFSWW`, used together with another full 4-f generator (either `KoralW` or `WPHACT`). `RacoonWW` is the other, completely independent Monte Carlo

Numerical test	$q\bar{q}'e\nu$	$q\bar{q}'\mu\nu$	$q\bar{q}'\tau\nu$	$q\bar{q}'l\nu$	$q\bar{q}'QQ'$
		Δm_W (MeV)			
Best - non CC03 $\times$ 1.04	-4.2 ± 0.1	< -0.1	0.6 ± 0.1	-1.2 ± 0.1	-
Best - no DPA in int.	-1.3 ± 0.2	0.2 ± 0.1	0.1 ± 0.3	-0.3 ± 0.1	< 0.1
		$\Delta\Gamma_W$ (MeV)			
Best - non CC03 $\times$ 1.04	0.2 ± 0.2	< -0.1	-6.4 ± 0.4	-1.2 ± 0.1	-
Best - no DPA in int.	1.8 ± 0.5	-0.4 ± 0.1	0.5 ± 0.7	0.5 ± 0.2	< 0.1

Table 5: Summary of the studies related to the uncertainties on m_W and Γ_W due to 4-f background radiative corrections performed on the standard (all WW-like final states) sample. The quoted errors are statistical, and rounded to 0.1 MeV.

generator which implements radiative corrections in DPA on top of a (massless) 4-f generator.

Its use has been fundamental in assessing the DPA precision on the WW cross section, by comparing it with `YFSWW`. It looks therefore interesting to try to use it also for a completely independent cross check of the `YFSWW` based results on the W mass and width (and possibly on other W related measurements). This check has been already done in [9], finding a good agreement between the two codes, but as previously explained on an observable which is not directly linked to the real analysis.

In appendix B the input options set used for `RacoonWW` in this study is shown, and the output of one of the runs is given to show the values of all the relevant parameters adopted for the tuned comparison with `WandY` and `YFSWW`. The phase space slicing approach has been adopted for the implementation of the radiative corrections, in the version suggested for unweighted events production (`smc = 3`). The DELPHI version of `PYTHIA` has been used for the quark hadronization.

There is anyway a number of challenges in this test to be taken into account. Real photon emission is handled in a completely different way with respect to `YFSWW`. In particular real emission in the detector acceptance (i.e. with finite p_t) is computed only at $\mathcal{O}(\alpha)$, although with a full 4-f + γ matrix element. Higher order ISR is present only through collinear structure functions on events where there is no hard $\mathcal{O}(\alpha)$ emission, a very different situation compared to the YFS exponentiation for ISR and WSR and the $\mathcal{O}(\alpha^3)$ LL ISR matrix element. No FSR beyond the one already included in the $\mathcal{O}(\alpha)$ is present, while in `YFSWW` the FSR is independent from the remaining part of the $\mathcal{O}(\alpha)$ calculation and introduced at $\mathcal{O}(\alpha^2)$ for leptons through `PHOTOS` and, merged with gluon emission, in the parton shower for quarks. These differences have been investigated in the literature (see for instance [2,7,8]) and are known to give sizeable discrepancies in the photon related observables.

Therefore it is difficult to disentangle differences arising from a different way of computing the same corrections from those due to the use of different sets of corrections.

Since it is known that RacoonWW in its DPA mode does not compare well with YFSWW on photonic spectra, the RacoonWW authors have developed a 4-$f + \gamma$ IBA mode which combines the $\mathcal{O}(\alpha)$ matrix element and collinear structure functions. The photonic energy and angular spectra produced in this mode are in much better agreement with the YFSWW ones at LEP2 energies, but it is not possible at present to combine it with the DPA corrections for the virtual and soft emission part in a consistent way.

Moreover the energy and angle cutoffs for the soft/hard photon emission separation in RacoonWW are in practice quite higher than the YFSWW ones, due to the quite different techniques adopted in the two calculations. The phase space slicing approach for matching virtual, soft and hard corrections has been used for this test, and these cutoffs are an integral part of the approach itself. The values used, shown in appendix B, correspond roughly to a minimum real photon energy of about 95 MeV and a minimum real photon-fermion angle of about 1.8 degrees, and are a compromise between the reliability of the calculation and the attempt to avoid merging with fermions photons which could be detected separately by the detector. Moreover, in contrast to what has been suggested by the authors, to avoid results which are dependent on the specific cutoff chosen, no further photon recombination is applied in the sample production. This choice is motivated by the fact that in a realistic simulation of a detector any recombination has to be determined by the detector granularity and analysis procedure itself, and due to the already big values of the cutoffs adopted, any further recombination would risk to suppress photons that would be detectable.

For final states with quarks, where the hadronization phase has to be described beyond the electroweak radiative corrections, the use of a full 4-$f + \gamma$ matrix element, in principle more correct than a parton shower, creates in practice a problem: photons are systematically emitted before gluons, which is unphysical and most probably incompatible with the hadronization packages tunings used (PYTHIA [24] is the standard choice for the analysis and this study).

The suggestion of the authors of RacoonWW to switch off the photon radiation in the parton shower to compensate for the photon emission in the matrix element has been adopted in this study, but it does not seem a real solution to the problem, and of course it can potentially spoil the validity of the hadronization tuning used. In case of need this problem might be studied with the WandY setup, trying to emulate the RacoonWW situation, i.e. calling PHOTOS also for quark pairs before the call to PYTHIA, and switching off photon emission inside PYTHIA itself. This presumably would overestimate the effect of FSR, since the photon emission would be performed independently from the two fermion pairs.

A third potential problem in the comparison is represented by RacoonWW generating massless fermions in the final state. Fermion masses are added *a posteriori* using the routine provided by the authors, which conserves obviously the total 4-momentum and the di-fermion masses. It is clear that when a sizeable mass, compared to the fermion energy, is added, as in the case of the cs quark pair, this could lead to distortions in the final state distributions.

All these features suggest that the comparison results must be considered with care, if serious discrepancies are found (as it is the case). On the other hand no special tuning has been prepared for the hadronization package, in order to avoid mixing problems concerning different sectors of the event description.

Table 6 shows the result of the comparison between WandY and RacoonWW 1.3. A sizeable discrepancy can be seen for the mass in the $ud\mu\nu$ channel, and, to a minor extent, for the width in the $udsc$ channel.

Numerical test	$ud\mu\nu$	$udsc$
Δm_W (MeV)		
WandY - RacoonWW 1.3	-38 ± 5	-4 ± 5
$\Delta\Gamma_W$ (MeV)		
WandY - RacoonWW 1.3	4 ± 10	27 ± 10

Table 6: Summary of the WandY - RacoonWW comparison on the uncertainties for m_W and Γ_W for the dedicated $ud\mu\nu$ and $udsc$ final states. The quoted errors are statistical, and rounded to 1 MeV.

Extensive studies have been performed in order to investigate the discrepancies, in particular the one on the W mass.

The different hadronization due to the treatment of FSR from quarks in RacoonWW has of course an influence on the jet characteristics, and can affect the results, in particular the ones for the width. Optimizing the interface of the hadronization with the electroweak full matrix element to circumvent possible problems arising from the simple minded approach followed goes beyond the scope of this study.

A generator level analysis analogous to the one whose results are shown in fig. 1, 2 and 3, has been used for a 4-f + γ level comparison of WandY with RacoonWW 1.3 for the $ud\mu\nu$ channel (all the 4-f diagrams are included here, not only the CC03 part). This study has been used to investigate the discrepancy on the W mass trying to disentangle the genuine electroweak part from possible problems connected to the implementation of the hadronization phase.

This study has clearly shown the crucial role played by the photon clustering, in particular around the muon. The different treatment of the soft, but mainly of the collinear photons in the two codes implies a strong difference in the radiation around the fermions. In `RacoonWW` no visible photon is generated in a cone of 1.8 degrees around a fermion, no matter which energy it has, and the radiation is reassociated to the lepton. This is not true in `WandY`, were the energy and angle cutoffs (for FSR from leptons the `PHOTOS` ones) are quite smaller, closer to a real situation.

For quarks this is not a big problem since experimentally FSR photons cannot be disentangled from jets, and they are naturally clustered to the jets themselves. But the treatment of photons around leptons is a different problem. While in the reconstruction of high energy electrons a clustering of photons is done in order to take into account the bremsstrahlung due to the interaction with the detector, muons can be quite cleanly separated from photons, unless they are strictly collinear. In the latter case the photon energy is anyway lost, since the muon momentum is used, not the energy deposited in the calorimeters possibly associated to it. $ud\mu\nu$ is therefore a good final state to study in detail differences in the visible photon radiation, mainly FSR.

In the real analysis visible photons, which have passed the quality selection criteria, are clustered to the muon if in a cone of 3 degrees around it, otherwise are associated to the jets. This procedure can partly reabsorb the difference in the collinear radiation mentioned above, even if not completely, because of limited photon reconstruction efficiency, resolution, selection cutoffs, etc. The effect of this photon clustering is of improving the agreement between the two calculations on the fitted mass, without it the difference in table 6 would be about -50 MeV.

The W mass difference obtained on the beam energy rescaled average mass (like in fig. 3) is -6 MeV if photons are clustered to the charged fermion with which they have the smallest p_t. If on the contrary the clustering to the muon is done only for photons in a 3 degrees cone around it, associating all the others to the quarks, the difference becomes -23 MeV.

Increasing the opening angle of the cone for the clustering improves the agreement, but of course in the real analysis such a procedure would rapidly cluster photons coming from the hadronization of the quarks (mainly π^0 decay products). Although the opening angle might be tuned to minimize the rate of photons from jets clustered and optimize the `WandY` - `RacoonWW` agreement, such a procedure would introduce further systematic uncertainties due to the imperfect knowledge of the photon distributions in jets.

The residual discrepancy is presumably linked to the known differences between the two calculations in the description of the radiation beyond the treatment of the strictly collinear region in this study. The good agreement for the mass found in the hadronic channel seems due to the smaller sensitivity of the analysis to the detailed description of the photonic radiation, since the photon clustering is implicit in the analysis procedure itself. This looks anyway an encouraging result for the general confidence in the study.

In this situation using the difference between the prediction of the two calculations to estimate the systematic uncertainty on the W mass and width does not seem appropriate.

4 Results and conclusions

The results of all the studies presented have to be combined in a single uncertainty for each channel. Tables 7 and 8 present an estimate of the different sources of uncertainties as it can be deduced from the studies presented in the section 2.1. Where the numerical or statistical uncertainty on the estimate is comparable with the estimate itself, they are added linearly to take them conservatively into account.

Δm_W (MeV)				
Uncertainty source	$q\bar{q}'e\nu$	$q\bar{q}'\mu\nu$	$q\bar{q}'\tau\nu$	$q\bar{q}'Q\bar{Q}'$
ISR	1	1	1	1
FSR	0.5	0.5	1	-
NF $\mathcal{O}(\alpha)$	1	1	1	2
NL $\mathcal{O}(\alpha)$	1	1	1	1
4-f background	5.5	0.5	1	0.5
Total	9	4	5	4.5

Table 7: Summary of the systematic uncertainties on the W mass. The total is computed adding linearly the values of all the contributions.

The total uncertainty per channel is computed summing linearly the values of the contributions. This choice is conservatively motivated by the fact that several contributions are more maximal upper limits than statistical errors. All the numbers have been rounded to 0.5 MeV.

As can be seen, the uncertainty on the W mass is within the 10 MeV level.

$\Delta\Gamma_W$ (MeV)				
Uncertainty source	$q\bar{q}'e\nu$	$q\bar{q}'\mu\nu$	$q\bar{q}'\tau\nu$	$q\bar{q}'Q\bar{Q}'$
ISR	2	2	2	2
FSR	1	1	2	-
NF $\mathcal{O}(\alpha)$	2	2	2	2
NL $\mathcal{O}(\alpha)$	4	4	4	4
4-f background	2	1	6	1
Total	11	10	16	9

Table 8: Summary of the systematic uncertainties on the W width. The total is computed adding linearly the values of all the contributions.

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A Appendix: YFSWW input parameters

The YFSWW samples used for the study, whose settings are the same as those used in WandY special samples, have been generated with version 3-1.17. The input for the LPA_A sample ($udsc$ final state) is:

```
*//////////////////////////////////////////////////////////////////////////////
*//                                                                          //
*//                  Input data for YFSWW3: ISR + EW + FSR                   //
*//                      For Simple DEMO Program                             //
*//                                                                          //
*//////////////////////////////////////////////////////////////////////////////
BeginX
*<-i><----data-----><-------------------comments------------------------------>
    1        188.6d0 CMSEne =xpar( 1) ! CMS total energy [GeV]
    2     1.16639d-5 Gmu    =xpar( 2) ! Fermi Constant
    4       91.187d0 aMaZ   =xpar( 4) ! Z mass
    5     2.506693d0 GammZ  =xpar( 5) ! Z width
    6       80.400d0 aMaW   =xpar( 6) ! W mass
    7     -2.08699d0 GammW  =xpar( 7) ! W with, For gammW<0 it is RECALCULATED
   11          115d0 amh    =xpar(11) ! Higgs mass
   13       0.1255d0 alpha_s=xpar(13) ! QCD coupling const.
  111            1d0 vckm(1:1)
  112            0d0 vckm(1:2)
  113            0d0 vckm(1:3)
  114            0d0 vckm(2:1)
  115            1d0 vckm(2:2)
  116            0d0 vckm(2:3)
  117            0d0 vckm(3:1)
  118            0d0 vckm(3:2)
  119            1d0 vckm(3:3)
*<-i><----data-----><-------------------comments------------------------------>
* YFSWW3 SPECIFIC PARAMETERS !!!
*=============================================================================
 2001            5d0 KeyCor =xpar(2001)   Radiative Correction switch
*                    KeyCor   =0: Born
*                             =1: Above + ISR
*                             =2: Above + Coulomb Correction
```

```
*                             =3: Above + YFS Full Form-Factor Correction
*                             =4: Above + Radiation from WW
*                             =5: Above + Exact O(alpha) EWRC (BEST!)
*                             =6: As Above but Apporoximate EWRC (faster)
 2002            0d0 KeyLPA   =0: LPA_a
*=================================================================================
 1011            1d0 KeyISR  =0,1  initial state radiation off/on (default=1)
*
 1013            1d0 KeyNLL  =0 sets next-to leading alpha/pi terms to zero
*                            =1 alpha/pi in yfs formfactor is kept (default)
 1014            2d0 KeyCul =xpar(1014)
*                    =0 No Coulomb correction
*                    =1 "Normal" Coulomb correction
*                    =2 "Screened-Coulomb" Ansatz for Non-Factorizable Corr.
 1021            2d0 KeyBra =xpar(1021)
*                    = 0 Born branching ratios, no mixing
*                    = 1 branching ratios from input
*                    = 2 branching ratios with mixing and naive QCD
*                       calculated in IBA from the CKM matrix (PDG 2000);
*                       see routine filexp for more details (file filexp.f)
 1023            1d0 KeyZet =xpar(1023)
*                    = 0, Z width in z propagator: s/m_z *gamm_z
*                    = 1, Z width in z propagator:   m_z *gamm_z
*                    = 2, Z zero width in z propagator.
 1026            1d0 KeyWu  =xpar(1026)
*                    = 0 w width in w propagator: s/m_w *gamm_w
*                    = 1 w width in w propagator:   m_w *gamm_w
*                    = 2 no (0) w width in w propagator.
 1031            0d0 KeyWgt =xpar(1031)
*                    =0, unweighted events (wt=1), for apparatus Monte Carlo
*                    =1, weighted events, option faster and safer
 1041            1d0 KeyMix =xpar(1041)
*                    KeyMix EW "Input Parameter Scheme" choices.
*                    =0 "LEP2 Workshop '95" scheme (for Born and ISR only!)
*                    =1 G_mu scheme (RECOMMENDED)
* W decays: 1=ud, 2=cd, 3=us, 4=cs, 5=ub, 6=cb, 7=e, 8=mu, 9=tau, 0=all chan.
 1055            4d0 KeyDWm =xpar(1055)    W- decay: 7=(ev), 0=all ch.
```

```
 1056            1d0 KeyDWp =xpar(1056)    W+ decay: 7=(ev), 0=all ch.
 1057           16d0 Nout   =xpar(1057)    Output unit no, for Nout<0, Nout=16
*==============================================================================
*                  TAUOLA, PHOTOS, JETSET
*   >>> If you want to switch them OFF, uncomment the lines below <<<
*<-i><----data-----><-------------------comments------------------------------>
 1071            0d0 Jak1   =xpar(1071)   Decay mode tau+
 1072            0d0 Jak2   =xpar(1072)   Decay mode tau-
 1073            0d0 Itdkrc =xpar(1073)   Bremsstrahlung switch in Tauola
 1074            2d0 IfPhot =xpar(1074)   PHOTOS switch
 1075            0d0 IfHadM =xpar(1075)   Hadronization W-
 1076            0d0 IfHadP =xpar(1076)   Hadronization W+
  516        0.01d0       mass [GeV] (3-9 MeV in PDG)
  526        0.005d0      mass [GeV] (1.5-5 MeV in PDG)
  536        0.2d0        mass [GeV] (60-170 MeV in PDG)
  546        1.30d0       mass [GeV] (1.1-1.4 GeV in PDG)
  556        4.8d0        mass [GeV] (4.1-4.4 GeV in PDG)
  566        175.0d0      mass [GeV] (174.3 GeV in PDG 1999)
EndX
*///////////////////////////////////////////////////////////////////////////////
```

The LPA_b sample input, used for fully simulated events, differed in the following parameters:

```
 2002            1d0 KeyLPA   =0: LPA_a
 1073            1d0 Itdkrc =xpar(1073)   Bremsstrahlung switch in Tauola
 1074            1d0 IfPhot =xpar(1074)   PHOTOS switch
 1075            1d0 IfHadM =xpar(1075)   Hadronization W-
 1076            1d0 IfHadP =xpar(1076)   Hadronization W+
```

The YFSWW version used for the full simulation implemented the PYTHIA version and tuning and the TAUOLA version used in [11].

B Appendix: RacoonWW input options and parameters

The RacoonWW samples used for the study, with input options and parameters tuned to give the best agreement with the WandY and YFSWW samples used, have been generated both with version 1.2 and 1.3. The input for the 1.3 sample ($udsc$ final state) is:

```
udsc.out     ! name of output file
188.6d0      ! energy: CMF energy (in GeV)
100000       ! neventsw: number of weighted events
3            ! smc: choice of MC branch: 1(or 3):slicing 2:subtraction
1            ! sborn4: include Born ee->4f: 0:no 1-3:yes
1            ! sborn5: include Born ee->4f+photon: 0:no 1:yes
0            ! sborng5: include Born ee->4f+gluon: 0:no 1:yes
1            ! sisr: include higher-order ISR: 0:no 1:yes
1            ! src: include radiative corrections: 0:no 1:DPA 2:IBA-4f 3:IBA-4fa
0            ! scoul5: Coulomb singularity for ee->4f+photon: 0:no 1,2:yes
3            ! qnf: Coulomb singularity for ee->4f: 1,2, or 3
0            ! qreal: neglect imaginary part of virt. corr.: 0:no 1:yes
2            ! qalp: choice of input-parameter scheme: 0,1, or 2
4            ! qgw: calculate the W-boson width: 0:no 1-4:yes
1            ! qprop: choice of width scheme: 0,1,2,3 or 4
0            ! ssigepem4: choice of diag. for Born ee->4f: 0:all 1-5:subsets
5            ! ssigepem5: choice of diag. for Born ee->4f+ga: 0:all 1-5:subsets
0            ! ssigepemg5: choice of diag. for Born ee->4f+gl: 0:all 1,5:subsets
2            ! qqcd: include QCD radiative corr.: 0:no 1:CC03 2:naive 3:CC11
0            ! sqcdepem: include gluon-exch. diag. in Born: 0:no 1:yes 2:only
u            ! fermion 3
d            ! anti-fermion 4
s            ! fermion 5
c            ! anti-fermion 6
0d0          ! pp: degree of positron beam polarization [-1d0:1d0]
0d0          ! pm: degree of electron beam polarization [-1d0:1d0]
0            ! srecomb: recombination cuts: 0:no 1:TH 2:EXP
1.7d0        ! precomb(1): angular rec. cut between photon and beam
0.1d0        ! precomb(2): rec. cut on photon energy
1.32d0       ! precomb(3): inv.-mass rec.(TH) or angular rec. cut for lept.(EXP)
0d0          ! precomb(4): angular rec. cut for quarks(EXP)
0            ! srecombg: gluon recombination cuts: 0:no 1:TH 2:EXP
```

```
0d0          ! precombg(1): rec. cut on gluon energy
0d0          ! precombg(2): inv.-mass (TH) or angular (EXP) recombination cut
0            ! satgc: anomalous triple gauge couplings (TGC): 0:no 1:yes
0d0          ! TGC Delta g_1^A
0d0          ! TGC Delta g_1^Z
0d0          ! TGC Delta kappa^A
0d0          ! TGC Delta kappa^Z
0d0          ! TGC lambda^A
0d0          ! TGC lambda^Z
0d0          ! TGC g_4^A
0d0          ! TGC g_4^Z
0d0          ! TGC g_5^A
0d0          ! TGC g_5^Z
0d0          ! TGC tilde kappa^A
0d0          ! TGC tilde kappa^Z
0d0          ! TGC tilde lambda^A
0d0          ! TGC tilde lambda^Z
0d0          ! TGC f_4^A
0d0          ! TGC f_4^Z
0d0          ! TGC f_5^A
0d0          ! TGC f_5^Z
0d0          ! TGC h_1^A
0d0          ! TGC h_1^Z
0d0          ! TGC h_3^A
0d0          ! TGC h_3^Z
0            ! qaqgc: anomalous quartic gauge couplings (QGC): 0:no 1:yes
0d0          ! QGC a_0/Lambda^2
0d0          ! QGC a_c/Lambda^2
0d0          ! QGC a_n/Lambda^2
0d0          ! QGC tilde a_0/Lambda^2
0d0          ! QGC tilde a_n/Lambda^2
10           ! scuts: separation cuts: 0:no 1,2:default(ADLO,LC) 10,11:input
0d0          ! photon(gluon) energy cut
1d0          ! charged-lepton energy cut
2d0          ! quark energy cut
2d0          ! quark-quark invariant mass cut
0d0          ! angular cut between photon and beam
```

```
0d0          ! angular cut between photon and charged lepton
0d0          ! angular cut between photon(gluon) and quark
0d0          ! angular cut between charged leptons
0d0          ! angular cut between quarks
0d0          ! angular cut between charged lepton and quark
0d0          ! angular cut between charged lepton and beam
0d0          ! angular cut between quark and beam
```

and the corresponding output is:

```
      smc= 3: Phase-space-slicing branch of RacoonWW
              ======================================

 technical cutoff parameters (photon):
  delta_s =    1.0000000000000000E-003
  delta_c =    5.0000000000000000E-004

 Input parameters:
 -----------------
    CMF energy = 188.60000 GeV,    Number of events =     100000,

  alpha(0) = 1/ 137.0359895, alpha(MZ) = 1/128.88700,   alpha_s = 0.12550,
        GF = .1166390E-04,
        MW =  80.40000,            MZ =  91.18700,          MH = 115.00000,
        GW =   2.09372,            GZ =   2.50669,
        me = .51099906E-03,       mmu =   0.105658300,    mtau =   1.77700,
        mu =   0.00500,            mc =   1.30000,          mt = 175.00000,
        md =   0.01000,            ms =   0.20000,          mb =   4.80000.

 Effective branching ratios:
 leptonic BR =  0.32476, hadronic BR =  0.67524, total BR =  1.00000

 Process:  anti-e e -> u anti-d s anti-c (+ photon)

       pp= 0.0: degree of positron beam polarization.
       pm= 0.0: degree of electron beam polarization.
     qalp= 2: GF-parametrization scheme.
```

```
      qgw= 4: one-loop W-boson width calculated (with QCD corr.).
    qprop= 1: constant width.

   sborn4= 1: tree-level process ee -> 4f.
 ssigepem4= 0: all electroweak diagrams included.
     qqcd= 2: naive QCD corrections included.

      src= 1: virtual corrections in DPA and real corrections included.
 ssigepem5= 5: real photon corr. : only CC11 class of diagrams included.
     qqcd= 2: naive QCD corrections included
    qreal= 0: imaginary part of virtual corrections included.
      qnf= 3: off-shell Coulomb singularity with off-shell Born included.
     sisr= 1: initial-state radiation up to order alpha^3 included.

    scuts=10: with separation cuts:
 energy(3)  >   2.00000 GeV
 energy(4)  >   2.00000 GeV
 energy(5)  >   2.00000 GeV
 energy(6)  >   2.00000 GeV
 mass(3,4)  >   2.00000 GeV
 mass(3,5)  >   2.00000 GeV
 mass(3,6)  >   2.00000 GeV
 mass(4,5)  >   2.00000 GeV
 mass(4,6)  >   2.00000 GeV
 mass(5,6)  >   2.00000 GeV

    events  :  intermediary results   :  preliminary results
   1000000  : 1846.54692 +- 11.43978  : 1846.54692 +- 11.43978
   2000000  : 1833.80408 +- 11.11287  : 1840.17550 +-  7.97440
   3000000  : 1852.08809 +- 11.09372  : 1844.14636 +-  6.47590
   4000000  : 1839.58697 +- 11.05121  : 1843.00651 +-  5.58773
   5000000  : 1834.96514 +- 10.89130  : 1841.39824 +-  4.97266
   6000000  : 1843.06512 +- 11.03453  : 1841.67605 +-  4.53366
   7000000  : 1840.81013 +- 10.93956  : 1841.55235 +-  4.18847
   8000000  : 1832.80339 +- 10.87736  : 1840.45873 +-  3.90900
 Warning: weight=-1            1       19685
   9000000  : 1836.94865 +- 10.94773  : 1840.06872 +-  3.68143
```

```
Warning: weight>weighttotmax           1       21733
         weight/weighttotmax=.21913D+01
         Redefining weighttotmax=weight
  10000000  : 1844.61537 +- 11.08916  : 1840.52339 +-  3.49394
  11000000  : 1851.84340 +- 11.08708  : 1841.55248 +-  3.33239
  12000000  : 1841.10316 +- 10.94892  : 1841.51504 +-  3.18804
  13000000  : 1837.82755 +- 10.94003  : 1841.23138 +-  3.06077
  14000000  : 1846.96380 +- 10.97894  : 1841.64084 +-  2.94835
  15000000  : 1830.80012 +- 10.84000  : 1840.91813 +-  2.84510
  16000000  : 1854.14538 +- 11.11172  : 1841.74483 +-  2.75621
  17000000  : 1841.29479 +- 10.91541  : 1841.71836 +-  2.67237
  18000000  : 1841.08998 +- 10.99218  : 1841.68345 +-  2.59673
  19000000  : 1844.23691 +- 10.97313  : 1841.81784 +-  2.52694
  20000000  : 1859.00710 +- 11.16467  : 1842.67730 +-  2.46465
  21000000  : 1834.41218 +- 10.92653  : 1842.28373 +-  2.40426
  22000000  : 1854.21070 +- 11.12994  : 1842.82586 +-  2.35007
 Warning: weight=-1            2       35285
  23000000  : 1841.83930 +- 10.95617  : 1842.78297 +-  2.29782
  24000000  : 1828.49319 +- 10.88035  : 1842.18756 +-  2.24825
  25000000  : 1849.61925 +- 11.05529  : 1842.48483 +-  2.20316
  26000000  : 1840.99837 +- 10.98930  : 1842.42766 +-  2.16018
 Warning: weight=-1            3       39352
  27000000  : 1839.23779 +- 10.87842  : 1842.30951 +-  2.11883
  28000000  : 1850.36220 +- 10.97517  : 1842.59711 +-  2.08042
  29000000  : 1842.48313 +- 10.89208  : 1842.59318 +-  2.04349
  30000000  : 1843.99336 +- 11.02637  : 1842.63985 +-  2.00928
  31000000  : 1846.22236 +- 10.88435  : 1842.75542 +-  1.97591
  32000000  : 1844.43879 +- 10.92402  : 1842.80802 +-  1.94436
  33000000  : 1855.61815 +- 10.91623  : 1843.19621 +-  1.91424
  34000000  : 1838.22596 +- 10.89012  : 1843.05002 +-  1.88535
  35000000  : 1838.40827 +- 10.94610  : 1842.91740 +-  1.85799
  36000000  : 1854.60202 +- 11.09578  : 1843.24197 +-  1.83249

 Result:
 -------
 Number of weighted events   =         36942025
 Average            =  1843.0071014423 fb
```

```
Standard deviation =     1.8086070041 fb
Maximal weight     =     0.0442221449 fb

Tree-level four-fermion cross section:
Average            =  1932.5509695232 fb
Standard deviation =     2.9415853629 fb


Number of events
----------------
Unweighted events            =     50000
Events with weight=-1        =         3
Events with weight>weightmax =         1
```

References

[1] Physics at LEP2, G. Altarelli, T. Sjöstrand and F. Zwirner eds., CERN 96-01 (1996).

[2] M. Grünewald *et al.*, *Four-Fermion Production in Electron-Positron Collisions*, in *Report of the Working Groups on precision calculations for LEP2 physics*, S. Jadach, G. Passarino and R. Pittau eds., CERN 2000-009 (2000) 1 [hep-ph/0005309].

[3] M. Veltman, Physica **29** (1963) 186;
R.G. Stuart, Phys. Lett. **B262** (1991) 113;
A. Aeppli, G.J. van Oldenborgh and D. Wyler, Nucl. Phys. **B428** (1994) 126.

[4] W. Beenakker, F.A. Berends and A.P. Chapovsky, Nucl. Phys. **B548** (1999) 3.

[5] A. Denner, Fortschr. Phys. **41** (1993) 307;
A. Denner, G. Weiglein and S. Dittmaier, Nucl. Phys. **B440** (1995) 95;
A. Denner, S. Dittmaier and M. Roth, Nucl. Phys. **B519** (1998) 39.

[6] S. Jadach, W. Placzek, M. Skrzypek and B.F.L. Ward, Phys. Rev. **D54** (1996) 5434;
S. Jadach, W. Placzek, M. Skrzypek, B.F.L. Ward and Z. Was, Phys. Lett. **B417** (1998) 326;
S. Jadach, W. Placzek, M. Skrzypek, B.F.L. Ward and Z. Was, Phys. Rev. **D61** (2000) 113010;
S. Jadach, W. Placzek, M. Skrzypek, B.F.L. Ward and Z. Was, Comp. Phys. Commun. **140** (2001) 432;
S. Jadach, W. Placzek, M. Skrzypek, B.F.L. Ward and Z. Was, Phys. Rev. **D65** (2002) 093010.

[7] A. Denner, S. Dittmaier, M. Roth and D. Wackeroth, Nucl. Phys. **B560** (1999) 33;
A. Denner, S. Dittmaier, M. Roth and D. Wackeroth, Nucl. Phys. **B587** (2000) 67;
A. Denner, S. Dittmaier, M. Roth and D. Wackeroth, Eur. Phys. J. **C20** (2001) 201;
A. Denner, S. Dittmaier, M. Roth and D. Wackeroth, Comp. Phys. Commun. **153** (2003) 462.

[8] R. Chierici and F. Cossutti, Eur. Phys. J. **C23** (2002) 65.

[9] S. Jadach, W. Placzek, M. Skrzypek, B.F.L. Ward and Z. Was, Phys. Lett. **B523** (2001) 117.

[10] R. Brunelière *et al.*, Phys. Lett. **B533** (2002) 75.

[11] A. Ballestrero, R. Chierici, F. Cossutti and E. Migliore, Comp. Phys. Commun. **152** (2003) 175.

[12] E. Accomando and A. Ballestrero, Comp. Phys. Commun. **99** (1997) 270;
E. Accomando, A. Ballestrero and E. Maina, Comp. Phys. Commun. **150** (2003) 166.

[13] S. Jadach, W. Placzek, M. Skrzypek, B.F.L. Ward and Z. Was, Comp. Phys. Commun. **119** (1999) 272.

[14] S. Jadach, W. Placzek, M. Skrzypek, B.F.L. Ward and Z. Was, Comp. Phys. Commun. **140** (2001) 475.

[15] Y. Kurihara, J. Fujimoto, T. Munehisa and Y. Shimizu, Progress of Theoretical Physics **96** (1996) 1223.

[16] E. Barberio and Z. Was, Comp. Phys. Commun. **79** (1994) 291.

[17] G. Nanava and Z. Was, Acta Phys. Polon. **B34** (2003) 4561.

[18] R. G. Stuart, Nucl. Phys. **B498** (1997) 28, and references therein.

[19] W. Beenakker *et al.*, *WW Cross-Sections and Distributions*, in Ref. [1], Vol. 1, 79.

[20] A.P. Chapovsky and V.A. Khoze, Eur. Phys. J. **C9** (1999) 449.

[21] D. Bardin, A. Leike, T. Riemann and M. Sachwitz, Phys. Lett. **B206** (1988) 539.

[22] B. Efron, “Computers and the Theory of Statistics”, SIAM Rev. **21** (1979) 460;
B. Efron and R. Tibshirani, “An Introduction to the Bootstrap”, Chapman & Hall 1993, ISBN 0-412-04231-2.

[23] DELPHI Collab., P. Abreu *et al.*, Phys. Lett. **B511** (2001) 159.

[24] T. Sjöstrand *et al.*, Comp. Phys. Commun. **135** (2001) 238.