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Precision Predictions for (Un)Stable
 $WW/4f$ Production in e^+e^- Annihilation:
YFSWW3/KoralW-1.42/YFSZZ*

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We present precision calculations of the processes $e^+e^- \rightarrow 4\text{-fermions}$ in which the double resonant W^+W^- and ZZ intermediate states occur. Referring to these latter intermediate states as the 'signal processes', we show that, by using the YFS Monte Carlo event generators [YFSWW3-1.14](#) and [KoralW-1.42](#) in an appropriate combination, we achieve a physical precision on the WW signal process, as isolated with LEP2 MC Workshop cuts, [below 0.5%](#). We stress the full gauge invariance of our calculations and we compare our results with those of other authors where appropriate. In particular, sample Monte Carlo data are explicitly illustrated and compared with the results of the program [RacoonWW](#) of Denner *et al.*. In this way, we cross check that the total (physical \oplus technical) precision tag for the WW signal process cross section is [0.4% for 200 GeV](#), for example. Results are also given for 500 GeV with an eye toward the LC. For the analogous ZZ case, we cross check that our [YFSZZ](#) calculation yields a total precision tag of [2%](#), when it is compared to the results of [ZZTO](#) and [GENTLE](#) of Passarino and Bardin *et al.*, respectively.

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1 Introduction

The theoretical paradigm affirmed by the award of the 1999 Nobel Prize to G. 't Hooft and M. Veltman for the success of the predictions of their formulation [1] of the renormalised non-Abelian quantum loop corrections for the **Standard Model** [2] of the electroweak interaction focuses our efforts on the need to continue to test this theory at the quantum loop level in the gauge boson sector itself. This then emphasises the importance of the on-going (the data are under analysis and will be for some time even though the LEP2 accelerator was recently shutdown) precision studies of the processes $e^+e^- \rightarrow W^+W^-(ZZ) + n(\gamma) \rightarrow 4f + n(\gamma)$ at LEP2 energies [3,4,5], as well as the importance of the planned future higher energy studies of such processes in LC physics programs [6,7,8,9]. We need to stress also that hadron colliders also have considerable reach into this physics and we hope to come back to their roles elsewhere [10].

In what follows, we present precision predictions for the event selections (ES) of the LEP2 MC Workshop [11] for the processes $e^+e^- \rightarrow W^+W^- + n(\gamma) \rightarrow 4f + n(\gamma)$ based on our new exact $\mathcal{O}(\alpha)_{prod}$ YFS exponentiated LL $\mathcal{O}(\alpha^2)$ **FSR leading pole approximation (LPA)** formulation as it is realized in the MC program **YFSWW3-1.14** [12,13] in combination with the all four-fermion processes MC event generator **KoralW-1.42** [14] so that the respective four-fermion background processes are taken into account in a gauge invariant way. In addition, we also present the current status of the predictions of our YFS MC approach to the processes $e^+e^- \rightarrow ZZ + n(\gamma) \rightarrow 4f + n(\gamma)$ as it was also illustrated in the **2000 LEP2 MC Workshop** [11] using the MC event generator YFSZZ [15], which realizes **YFS exponentiated LL $\mathcal{O}(\alpha^2)$ ISR in the LPA** in a gauge invariant way. Indeed, gauge invariance is a crucial aspect of our work and we stress that we maintain it through-out our calculations. Here, **ISR** denotes initial state radiation, **FSR** denotes final-state radiation and LL denotes leading-log as usual.

This realization which we present of the YFS MC approach is the **exclusive exponentiation (EEX)** [16] and it is already well established in its applications to the **MC event generators for LEP1 physics calculations in the MC's KORALZ/YFS3** [17,18], **BHLUMI** [19,20] and **KoralW** [14]. In our applications in YFSWW3-1.14 and in KoralW-1.42, the **FSR is implemented using the program PHOTOS** [21], so that not only is the FSR calculated to the LL $\mathcal{O}(\alpha^2)$ but the **FSR photons have the correct finite p_T in the soft limit to $\mathcal{O}(\alpha)$** . We always use the ratio of branching ratios (BR's) to correct the respective decay rates through $\mathcal{O}(\alpha)$ accordingly. Recently, we have introduced the **coherent exclusive exponentiation (CEEX)** [22] approach to the YFS MC event generator calculation of radiative corrections and we will present the application of this new approach to the $4f$ production processes elsewhere [10]. For a description of its application to the $2f$ production processes see Ref. [23].

Recently, the authors in Refs. [24,25] have also presented MC program results for

the processes $e^+e^- \rightarrow W^+W^- + n(\gamma) \rightarrow 4f + n(\gamma)$, $n = 0, 1$ in combination with the complete background processes which feature the exact LPA $\mathcal{O}(\alpha)$ correction, the complete $\mathcal{O}(\alpha)$ result for $e^+e^- \rightarrow 4f + \gamma$, and soft photon KF [26] exponentiation for the LL $\mathcal{O}(\alpha^3)$ ISR via structure functions. Thus, we will compare our results where possible with those in Refs. [24] in an effort to check the over-all precision of our work. As we argue below, the two sets of results should agree at a level below 0.5% on observables such as the total cross section. The authors in Refs. [5] have used **semi-analytical methods** to compute the exact LPA $\mathcal{O}(\alpha)$ correction $e^+e^- \rightarrow W^+W^- \rightarrow 4f$ with no higher order resummation. Thus, while we have compared our results with theirs in Ref. [13] for example, here we do not present such comparisons because the expected precision tag of their results is larger than the desired 0.5% needed by the LEP2 experiments [11].

For the processes $e^+e^- \rightarrow ZZ + (n\gamma) \rightarrow 4f + (n'\gamma)$, the authors in Refs. [27,28] have presented calculations in the LEP2 MC Workshop [11] at the NC02 and all-4f level [28] as well. The calculations in Ref. [27] are done with the program ZZTO and feature universal ISR corrections, $\mathcal{O}(\alpha)$ FSR_{QED} corrections, $\mathcal{O}(\alpha_s)$ FSR_{QCD} corrections, and running masses in the fermion loop scheme of Ref. [29]. The results in Ref. [28] feature the structure function approach to the ISR QED corrections and the $\mathcal{O}(\alpha)$ FSR_{QED} corrections. We will compare our YFSZZ results with these two sets of results as well, as the three approaches should agree at the level of the 2% precision needed by the LEP2 experiments [11] on observables such as the total cross section.

Our presentation is organised as follows. In the next Section, we discuss the current status YFSWW3-1.14. In Section 3, we present the current status of KoralW-1.42 from the standpoint of its use to calculate the 4f background processes in combination with YFSWW3-1.14. In Section 4, we present the current status of YFSZZ. In Sections 5, 6 and 7, we illustrate the results we have obtained with our calculations for YFSWW3, KoralW-1.42 and YFSZZ, respectively, for the ES of the LEP2 MC Workshop [11], wherein we include comparisons with the respective results in Refs. [24,27,28]. Section 8 contains our summary remarks.

2 YFSWW3-1.14

In this section we present the current status of **YFSWW3-1.14**. We start with the **process of interest and its cross section**,

$$\begin{aligned}
e^-(p_1) + e^+(p_2) &\rightarrow f_1(r_1) + \bar{f}_2(r_2) + f'_1(r'_1) + \bar{f}'_2(r'_2) + \gamma(k_1), \dots, \gamma(k_n), \\
\sigma_n &= \frac{1}{flux} \int d\tau_{n+4}(p_1 + p_2; r_1, r_2, r'_1, r'_2, k_1, \dots, k_n) \\
&\quad \sum_{\text{ferm. spin}} \sum_{\text{phot. spin}} |\mathcal{M}_{4f}^{(n)}(p_1, p_2, r_1, r_2, r'_1, r'_2, k_1, \dots, k_n)|^2,
\end{aligned} \tag{1}$$

and the corresponding expressions for the **W^+W^- production and decay in the leading pole approximation (LPA)**,

$$\begin{aligned}
e^-(p_1) + e^+(p_2) &\rightarrow W^-(q_1) + W^+(q_2), \\
W^-(q_1) &\rightarrow f_1(r_1) + \bar{f}_2(r_2), \quad W^+(q_2) \rightarrow f'_1(r'_1) + \bar{f}'_2(r'_2), \\
\sigma_n &= \frac{1}{flux} \int d\tau_{n+4}(p_1 + p_2; r_1, r_2, r'_1, r'_2, k_1, \dots, k_n) \\
&\quad \sum_{\text{ferm. spin}} \sum_{\text{phot. spin}} |\mathcal{M}_{LPA}^{(n)}(p_1, p_2, r_1, r_2, r'_1, r'_2, k_1, \dots, k_n)|^2.
\end{aligned} \tag{2}$$

Here, we realize the **LPA_{a,b}** as follows:

$$\begin{aligned}
\mathcal{M}_{4f}^{(n)}(p_1, p_2, r_1, r_2, r'_1, r'_2, k_1, \dots, k_n) &\stackrel{LPA}{\Rightarrow} \mathcal{M}_{LPA}^{(n)}(p_1, p_2, r_1, r_2, r'_1, r'_2, k_1, \dots, k_n) \\
&= \sum_{\text{Phot. Partitions}} \mathcal{M}_{Prod}^{(n), \lambda_1 \lambda_2}(p_1, p_2, q_1, q_2, k_1, \dots, k_n) \\
&\times \frac{1}{D(q_1)} \mathcal{M}_{Dec1, \lambda_1}^{(n)}(q_1, r_1, r_2, k_{a+1}, \dots, k_b) \\
&\times \frac{1}{D(q_2)} \mathcal{M}_{Dec2, \lambda_2}^{(n)}(q_2, r'_1, r'_2, k_{b+1}, \dots, k_n), \\
D(q_i) &= q_i^2 - M^2, \quad M^2 = (M_W^2 - i\Gamma_W M_W)(1 - \Gamma_W^2/M_W^2 + \mathcal{O}(\alpha^3)), \\
q_1 &= r_1 + r_2 + k_{a+1} + \dots + k_b; \quad q_2 = r'_1 + r'_2 + k_{b+1} + \dots + k_n,
\end{aligned} \tag{3}$$

where the two formulations of the **LPA, LPA_{a,b}**, are based on the results in **Eden Refs. [30,31]** as one can see from the representation of our amplitudes \mathcal{M} as

$$\mathcal{M} = \sum_j \ell_j A_j(\{q_k q_l\}). \tag{4}$$

Here, the $\{\ell_j\}$ are a complete set of spinor covariants and the $\{A_j\}$ are the respective scalar functions. For **LPA_{(a)b}**, we do (not) evaluate the

spinor covariants on-pole in realizing the respective $\mathcal{M}_{LPA}^{(n)}$. We do both in YFSWW3-1.14.

We use standard YFS methods(EEX-Type)to write

$$d\sigma = e^{2\Re\alpha B' + 2\alpha\tilde{B}} \frac{1}{(2\pi)^4} \int d^4y e^{iy(p_1+p_2-q_1-q_2)+D} [\bar{\beta}_0 + \sum_{n=1}^{\infty} \frac{d^3k_j}{k_j^0} e^{-iyk_j} \bar{\beta}_n(k_1, \dots, k_n)] \times \frac{d^3r_1}{E_1} \frac{d^3r_2}{E_2} \frac{d^3r'_1}{E'_1} \frac{d^3r'_2}{E'_2}, \quad (5)$$

where

$$D = \int \frac{d^3k}{k_0} \tilde{S} [e^{-iy \cdot k} - \theta(K_{max} - |\vec{k}|)]$$

$$2\alpha\tilde{B} = \int \frac{d^3k}{k_0} \theta(K_{max} - |\vec{k}|) \tilde{S}(k). \quad (6)$$

Here, K_{max} is a dummy parameter of which eq.(5) is independent. In realizing eq.(5) in YFSWW3, we employ the following schemes, which are related by the renormalization group:

- Version 1.13: G_μ -Scheme of Fleischer *et al.* [32]
- Version 1.14: Scheme A – only the hard EW correction has α_{G_μ} ; Scheme B – the entire $\mathcal{O}(\alpha)$ correction has $\alpha(0)$

As it was shown in the LEP2 MC Workshop [11], there is a $\Rightarrow -0.3 \div -0.4\%$ shift of the normalisation of version 1.14 relative to that of version 1.13. This can be seen as follows. The universal LL ISR $\mathcal{O}(\alpha)$ soft plus virtual correction is

$$\delta_{ISR,LL}^{v+s} = \beta \ln k_0 + \frac{\alpha}{\pi} \left(\frac{3}{2}L + \frac{\pi^2}{3} - 2 \right), \quad (7)$$

with $\beta = \frac{2\alpha}{\pi}(L-1)$ and with k_0 equal to the usual soft cut-off and $L = \ln s/m_e^2$. From eq.(7), we get the estimate of the shift in normalisation between version 1.13 and version 1.14 at 200 GeV as

$$(\alpha(0) - \alpha_{G_\mu}) \left(\frac{3}{2}L - 2 \right) \sim -0.33\%. \quad (8)$$

This is consistent with what is observed as reported in Ref. [11]. See Dittmaier's talk [25] for more details and references.

3 KoralW-1.42

For the **process of interest**, $e^-(p_1) + e^+(p_2) \rightarrow f_1(r_1) + \bar{f}_2(r_2) + f'_1(r'_1) + \bar{f}'_2(r'_2) + \gamma(k_1), \dots, \gamma(k_n)$, we use **KoralW-1.42** which realizes the $\mathcal{O}(\alpha^3)$ **LL YFS exponentiated ISR**. The respective input Born matrix elements are the **GRACE v. 2 [33]** all 4f library of Born matrix elements and **our independent CC03 Born matrix elements**. This allows us to **combine YFSWW3-1.14 and KoralW-1.42 to correct for background diagram effects**: using LPA_a in YFSWW3-1.14, whose cross section we denote by $\sigma(Y_a)$, we get

$$\sigma_{Y/K} = \sigma(Y_a) + \Delta\sigma(K), \quad (9)$$

where $\Delta\sigma(K)$ is defined by

$$\Delta\sigma(K) = \sigma(K_1) - \sigma(K_3). \quad (10)$$

Here, $\sigma(K_1)$ is the 4-f KoralW-1.42 result and $\sigma(K_3)$ is the CC03 KoralW-1.42 result. This means that $\sigma_{Y/K}$ is accurate to $\mathcal{O}(\frac{\alpha}{\pi} \frac{\Gamma_W}{M_W})$.

Alternatively, using LPA_i , $i = a, b$ in YFSWW3-1.14, whose cross section we denote by $\sigma(Y_i)$, we get

$$\sigma_{K/Y} = \sigma(K_1) + \Delta\sigma(Y) \quad (11)$$

where

$$\Delta\sigma(Y) = \sigma(Y_i) - \sigma(Y_4), \quad (12)$$

and $\sigma(Y_4)$ is the respective YFSWW3-1.14 result with **NL $\mathcal{O}(\alpha)$ corrections to $\bar{\beta}_n$, $n = 0, 1$, switched off**. This means that $\sigma_{K/Y}$ is also accurate to $\mathcal{O}(\frac{\alpha}{\pi} \frac{\Gamma_W}{M_W})$.

Above WW threshold, $\sigma_{K/Y}$ and $\sigma_{Y/K}$ agree to the 0.1% level. We advocate the latter as our best result in the following.

Note that we sometimes identify $\sigma(Y_1) = \sigma(Y_a)$, $\sigma(Y_2) = \sigma(Y_b)$, $\sigma(Y_3) = \sigma(K_3)$ with $\sigma(K_2)$ equal to the cross section from KoralW-1.42 with the **on-pole CC03 Born level matrix element with YFS exponentiated $\mathcal{O}(\alpha^3)$ LL ISR** – this $\sigma(K_2)$ should be available soon. It is useful for further cross checks on our work.

4 YFSZZ

In our calculation in YFSZZ-1.02 [15] the **process of interest** is $e^-(p_1) + e^+(p_2) \rightarrow Z(q_1)Z(q_2) + (\gamma(k_1), \dots, \gamma(k_m)) \rightarrow f_1(r_1) + \bar{f}_1(r_2) + f'_1(r'_1) + \bar{f}'_1(r'_2) + \gamma(k_1), \dots, \gamma(k_n)$. We proceed as follows in realizing the MC **YFSZZ-1.02**:

- We use LPA_a as described above for the NC02 process to calculate $\mathcal{O}(\alpha^2)$ LL YFS exponentiated ISR for the input NCO2 Born matrix elements of Ref. [34].
- Anomalous couplings are supported following the conventions of Ref. [34] – this is also true for YFSWW3/KORALW.

We stress that YFSZZ is in wide use at LEP and that it was tested in the LEP2 MC Workshop, just as YFSWW3-1.14 was tested. We now turn to such results.

5 Results-YFSWW3-1.14

In this section we illustrate the effects of the NL $\mathcal{O}(\alpha)$ correction as it is calculated in YFSWW3-1.14. We do this with the hardest photon angular distribution. Similar calculations of other observables can be found in Ref. [13,11].

Specifically, in Fig. 1, we show the distribution of the cosine of the production angle of the hardest photon in the cms system with respect to the e^+ beam. We see that away from the beams the NL $\mathcal{O}(\alpha)$ correction is important for precision studies of this photonic observable. Similar conclusions follow from the more complete set of observables studied in Refs. [13,11].

Indeed, in the LEP2 MC Workshop, we compared our results with those of RacoonWW by the authors in Ref. [24]. For a complete description of these comparisons we refer the reader to Ref. [11]. Here, we show in Table 1 the comparison of the total cross sections at 200 GeV with no cuts as defined Ref. [11].

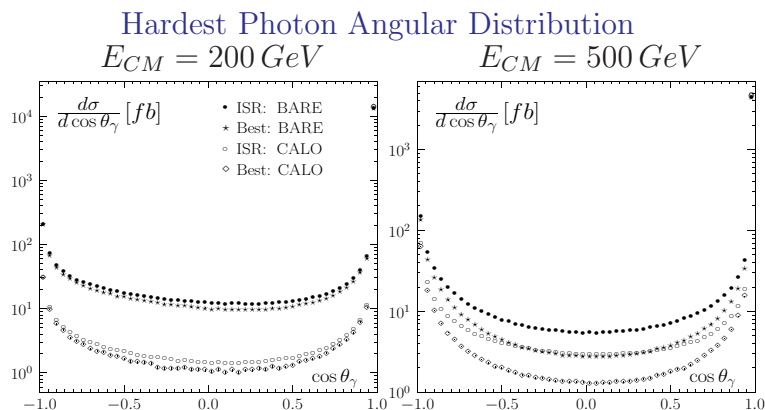


Figure 1: $\cos\theta_\gamma$ w.r.t. the e^+ beam in the cms system for $e^+e^- \rightarrow W^+W^- \rightarrow u\bar{d}\mu^-\bar{\nu}_\mu$. We see that NL corrections are important away from the beams, for example.

Comparison with RacoonWW

no cuts		$\sigma_{\text{tot}}[\text{fb}]$	
final state	program	Born	best
$\nu_{\mu}\mu^{+}\tau^{-}\bar{\nu}_{\tau}$	YFSWW3	219.770(23)	199.995(62)
	RacoonWW	219.836(40)	199.551(46)
	(Y-R)/Y	-0.03(2)%	0.22(4)%
$u\bar{d}\mu^{-}\bar{\nu}_{\mu}$	YFSWW3	659.64(07)	622.71(19)
	RacoonWW	659.51(12)	621.06(14)
	(Y-R)/Y	0.02(2)%	0.27(4)%
$u\bar{d}s\bar{c}$	YFSWW3	1978.18(21)	1937.40(61)
	RacoonWW	1978.53(36)	1932.20(44)
	(Y-R)/Y	-0.02(2)%	0.27(4)%

Table 1: Total cross sections, CC03 from RacoonWW, YFSWW3, $\sqrt{s} = 200 \text{ GeV}$ without cuts. Statistical errors correspond to the last digits in ().

From the results in Table 1 and the related results given in Ref. [11] we conclude that the TU of the calculations is 0.4% at 200 GeV for the total signal cross section. This is a considerable improvement over previously quoted precision of 2% in Ref. [35].

6 Results-YFSWW3/KoralW

One of the important aspects of the isolation and study of the WW signal processes is the control of the corresponding background $4f$ processes. This we do with our all- $4f$ MC KoralW-1.42 as we described above. Here, we illustrate the size of the corresponding $4f$ background corrections to the YFSWW3-1.14 cross sections.

Specifically, in Tabs. 2 and 3, we show the size of this $4f$ background correction in comparison to the NL correction of YFSWW3-1.14 for the total cross section, for example, both for the case of no cuts and the case of cuts, respectively, as defined in Ref. [11]. These results show that the $4f$ background correction at 200 GeV to the total YFSWW3-1.14 cross section is below 0.1%.

7 Results-YFSZZ

In this section we show the results of our comparison with ZZTO for the total ZZ pair signal processes as carried out in Ref. [11]. In that same set of comparisons, ZZTO was also compared with the results of GENTLE by the authors in Refs. [28]. In this way, a cross check was made on all three calculations.

WW/4f Cross Section

NO CUTS		$\sigma_{WW} [fb]$		$\delta_{4f} [\%]$		$\delta_{WW}^{NL} [\%]$
Final state	Program	Born	ISR	Born	ISR	
$\nu_\mu \mu^+ \tau^- \bar{\nu}_\tau$	YFSWW3	219.793 (16)	204.198 (09)	—	—	-1.92 (4)
	KoralW	219.766 (26)	204.178 (21)	0.041	0.044	—
	(Y-K)/Y	0.01 (1)%	0.01 (1)%	—	—	—
$u\bar{d}\mu^-\bar{\nu}_\mu$	YFSWW3	659.69 (5)	635.81 (3)	—	—	-1.99 (4)
	KoralW	659.59 (8)	635.69 (7)	0.073	0.073	—
	(Y-K)/Y	0.02 (1)%	0.02 (1)%	—	—	—
$u\bar{d}s\bar{c}$	YFSWW3	1978.37 (14)	1978.00 (09)	—	—	-2.06 (4)
	KoralW	1977.89 (25)	1977.64 (21)	0.060	0.061	—
	(Y-K)/Y	0.02 (1)%	0.02 (1)%	—	—	—

Table 2: Total *WW* YFSWW3 and KoralW cross sections: Born and ISR level, KoralW *4f* correction, YFSWW3 $\mathcal{O}(\alpha)$ NL correction, at 200 GeV, no cuts. The last digits in (...) correspond to the statistical errors.

Specifically, we show in Table 4 the ZZ signal cross section at 188.6 GeV as predicted by YFSZZ and ZZTO for the case of no cuts as defined in Ref. [11]. For ZZTO, results are shown for two schemes, the G_μ and α schemes [27]. The agreement between the programs in this comparison and between the programs in the other related comparisons carried out in Ref. [11] show that the TU for the respective NC02 signal process is 2% at the respective LEP2 energies.

8 Conclusions

We are currently at an exciting point in the tests of the EW Theory in gauge boson physics. The WW pair production is an important aspect of these tests. The radiative corrections which we realize in YFSWW3-1.14 play a significant role in these tests as follows:

- Mass distributions: these are affected by FSR, yielding peak position and height shifts
- W Angular distributions: these are affected by LL and NL corrections
- ℓ Angular distributions: these are affected by LL and NL corrections
- Photon Angular distributions: these are affected by LL and NL corrections

WW/4f Cross Section

WITH CUTS		$\sigma_{WW} [fb]$		$\delta_{4f} [\%]$		$\delta_{WW}^{NL} [\%]$
Final state	Program	Born	ISR	Born	ISR	
$\nu_\mu \mu^+ \tau^- \bar{\nu}_\tau$	YFSWW3	210.938 (16)	196.205 (09)	—	—	-1.93 (4)
	KoralW	210.911 (26)	196.174 (21)	0.041	0.044	—
	(Y-K)/Y	0.01 (1)%	0.02 (1)%	—	—	—
$u\bar{d}\mu^-\bar{\nu}_\mu$	YFSWW3	627.22 (5)	605.18 (3)	—	—	-2.00 (4)
	KoralW	627.13 (8)	605.03 (7)	0.074	0.074	—
	(Y-K)/Y	0.01 (1)%	0.02 (1)%	—	—	—
$u\bar{d}s\bar{c}$	YFSWW3	1863.60 (15)	1865.00 (09)	—	—	-2.06 (4)
	KoralW	1863.07 (25)	1864.62 (21)	0.065	0.064	—
	(Y-K)/Y	0.03 (2)%	0.02 (1)%	—	—	—

Table 3: Total *WW* YFSWW3 and KoralW cross sections: Born and ISR level, KoralW *4f* correction, YFSWW3 $\mathcal{O}(\alpha)$ NL correction, at 200 GeV, with cuts. The last digits in (...) correspond to the statistical errors.

Comparison with ZZTO

channel	YFSZZ	ZZTO G_F -scheme	ZZTO α -scheme
$qqqq$	294.6794(490)	298.4411(60)	294.5715(59)
$qq\nu\nu$	175.4404(302)	175.5622(35)	174.9855(35)
$qqll$	88.1805(134)	88.7146(18)	87.9881(18)
$ll\nu\nu$	26.2530(463)	26.0940(5)	26.1342(5)
$llll$	6.5983(15)	6.5929(1)	6.5706(1)
$\nu\nu\nu\nu$	26.1080(71)	25.8192(5)	25.9868(5)
total	617.2596(755)	621.2241(124)	616.2366(123)

Table 4: NC02 cross sections, YFSZZ vs ZZTO, 188.6 GeV, in fb. The statistical errors correspond to the last digits in ().

- Photon Energy distributions: these are affected by LL corrections
- Normalisation: this is affected by LL AND NL corrections; the current 200 GeV TU is 0.4% from the {YFSWW3/RacoonWW} results.

Concerning our results on calculating the *4f* background to YFSWW3-1.14 using KoralW-1.42, we have shown the following:

- Two different combinations of YFSWW3 and KoralW-1.42 cross sections reach the total precision $\mathcal{O}(\frac{\alpha}{\pi} \frac{\Gamma_W}{M_W})$.

- The size of the $4f$ correction to **YFSWW3-1.14** is $\lesssim 0.1\%$, as expected.
- The future extension to a single platform is possible.

It follows that **YFSWW3/KoralW** is a complete MC event generator solution for precision **WW/4f** production at **LEP2** (and **LC's**).

From our studies of the **NC02** signal process we conclude that **YFSZZ**, a multiple photon MC event generator for **NC02** with $\bar{\beta}_0$ level LPA YFS exponentiation (**EEX**), is tested in the **LEP2 MC Workshop vs ZZTO** and **GENTLE** to 2% TU. An upgrade to higher precision is possible but is not needed, apparently?

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