Precision Predictions for WW/4f Production in e^+e^- Annihilation: YFSWW3/KoralW1.42/YFSZZ

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Outline:

- **Introduction**
- **YFSWW3-1.14**
- **KoralW1.42**
- **YFSZZ**
- **Results**
- **Conclusions**

with S. Jadach, W. Placzek, M. Skrzypek and Z. Was

The EEX solution: YFSWW3-1.14/KoralW1.42/YFSZZ

Application of YFS3(PLB**274**,470(1992)) to the WW pair production and decay in YFSWW3, PLB**417**,326(1998), CERN-TH-99-222, PRD**61** (2000) 113010, UTHEP-00-0101, hep-ph/0007012, of YFS2(CPC**56**,351 (1990)), extended to $\mathcal{O}(\alpha^3)$ LL, to all-4f production in KoralW1.42(CPC**119**, 272 (1999)) and to ZZ pair production in YFSZZ(PRD**56**,6939 (1997) - only $\mathcal{O}(\alpha^2)$ LL:

Exclusive Exponentiation (EEX) technique, as implemented in KORALZ/YFS3, BHLUMI, BHWIDE, KORALW:

- Exact $\mathcal{O}(\alpha)$ YFS exponentiation of production process (YFSWW3)
- FSR treated (YFSWW3/KoralW1.42) via PHOTOS to $\mathcal{O}(\alpha^2)$ LL Finite P_T in FSR correct for soft limit in $\mathcal{O}(\alpha)$
- Ratio of BR's used to correct decay rate through $\mathcal{O}(\alpha)$ accordingly

The CEEX solution: For the Future in 4f

SEE THE NEXT TALK BY Z. WAS FOR ITS APPLICATION TO 2f

INTRODUCTION

Comparison with Other Calculations

YFSWW3-1.14/KoralW1.42/YFSZZ

- RacoonWW, Dittmaier *et al.*

  Exact $O(\alpha)$ LPA, complete $O(\alpha)$ $e^+e^- \rightarrow 4f + \gamma$

  Soft Photon KF exponentiation

  for $O(\alpha^3)$LL ISR via structure fns.

  hep-ph/9912261, 9912290, 9912447;

  Phys. Lett. **B475** (2000) 127; BI-TP 2000/06, hep-ph/0006307

- Beenakker *et al.* SEMIANALYTICAL APPROACH

  Exact $O(\alpha)$ LPA, NO HIGHER ORDER RESUMMATION

  hep-ph/9902333,9811481

INTRODUCTION

- ZZTO, G. Passarino

  Universal ISR, FSR$_{QED}$, FSR$_{QCD}$, running masses

  and Fermion Loop Scheme,

  in hep-ph/0005309 and references therein

- GENTLE, D. Bardin *et al.*

  All 4f as well as NC02, SF ISR QED, FSR,

  in hep-ph/0005309 and references therein

YFSWW3-1.14

Process of interest

$$e^-(p_1) + e^+(p_2) \rightarrow f_1(r_1) + \bar{f}_2(r_2) + f_1'(r_1') + \bar{f}_2'(r_2') + \gamma(k_1), ..., \gamma(k_n)$$

$$\sigma_n = \frac{1}{flux} \int d\tau_{n+4}(p_1 + p_2; r_1, r_2, r_1', r_2', k_1, ..., k_n)$$

$$\sum_{ferm.\ spin} \ \sum_{phot.\ spin} |\mathcal{M}_{4f}^{(n)}(p_1, p_2, r_1, r_2, r_1', r_2', k_1, ..., k_n)|^2 \qquad (1)$$

W^+W^- production and decay

$$e^-(p_1) + e^+(p_2) \rightarrow W^-(q_1) + W^+(q_2),$$

$$W^-(q_1) \rightarrow f_1(r_1) + \bar{f}_2(r_2), \quad W^+(q_2) \rightarrow f_1'(r_1') + \bar{f}_2'(r_2'),$$

$$\sigma_n = \frac{1}{flux}\int d\tau_{n+4}(p_1+p_2; r_1, r_2, r_1', r_2', k_1, ..., k_n)$$
$$\sum_{ferm.\ spin}\ \sum_{phot.\ spin} |\mathcal{M}^{(n)}_{LPA}(p_1, p_2, r_1, r_2, r_1', r_2', k_1, ..., k_n)|^2 \qquad (2)$$

LPA$_{a,b}$**:**

$$\mathcal{M}^{(n)}_{4f}(p_1,p_2,r_1,r_2,r_1',r_2',k_1,...,k_n)\ \overset{LPA}{=>}\ \mathcal{M}^{(n)}_{LPA}(p_1,p_2,r_1,r_2,r_1',r_2',k_1,...,k_n)$$
$$=\sum_{Phot.\ Partitions}\mathcal{M}^{(n),\lambda_1\lambda_2}_{Prod}(p_1,p_2,q_1,q_2,k_1,...,k_a)$$
$$\times\frac{1}{D(q_1)}\mathcal{M}^{(n)}_{Dec_1,\lambda_1}(q_1,r_1,r_2,k_{a+1},...,k_b)$$
$$\times\frac{1}{D(q_2)}\mathcal{M}^{(n)}_{Dec_2,\lambda_2}(q_2,r_1',r_2',k_{b+1},...,k_n),$$
$$D(q_i)=q_i^2-M^2,\quad M^2=({M_W}^2-i\Gamma_W M_W)(1-{\Gamma_W}^2/{M_W}^2+\mathcal{O}(\alpha^3)),$$
$$q_1=r_1+r_2+k_{a+1}+...+k_b;\ \ q_2=r_1'+r_2'+k_{b+1}+...+k_n, \tag{3}$$

⇒**LPA**$_{a,b}$**:Eden** ***et al.*****, Stuart, hep-ph/9706431, etc.**

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

We do both.

Standard YFS Methods(EEX-Type)$\Rightarrow$

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

where

$$D = \int \frac{d^3k}{k_0} \tilde{S} \left[e^{-iy\cdot k} - \theta(K_{max} - |\vec{k}|) \right]$$
$$2\alpha\tilde{B} = \int \frac{d^3k}{k_0} \theta(K_{max} - |\vec{k}|) \tilde{S}(k). \quad (6)$$

$K_{max} \Longleftrightarrow$ **Dummy**

SCHEMES: RELATED BY RENORMALIZATION GROUP

- **Version 1.13:** G_μ**-Scheme of Fleischer** ***et al.*****, Z. Phys. C42 (1989) 409, etc.**
- **Version 1.14: Scheme A – ONLY HARD EW CORR. HAS** α_{G_μ}**;**
  Scheme B – ENTIRE $\mathcal{O}(\alpha)$ **HAS** $\alpha(0)$

$\Rightarrow -0.3 \div -0.4\%$ **SHIFT OF NORMALIZATION of 1.14 RELATIVE TO 1.13**

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

with

$\beta = \frac{2\alpha}{\pi}(L-1)$

$\Rightarrow$ shift

$[(\alpha(0) - \alpha_{G_\mu})(\frac{3}{2}L - 2) \sim -0.33\%$

See Dittmaier's Talk for More Details and References

KoralW-1.42

Process of interest

$$e^-(p_1) + e^+(p_2) \rightarrow f_1(r_1) + \bar{f}_2(r_2) + f_1'(r_1') + \bar{f}_2'(r_2') + \gamma(k_1), ..., \gamma(k_n)$$

Use KoralW1.42 for $\mathcal{O}(\alpha^3)$ LL YFS exponentiated ISR for the input GRACE v. 2 (J. Fujimoto *et al.*, MINAMI-TATEYA Coll., GRACE User's Manual, v. 2.0) all 4f library of Born matrix elements or our independent CCO3 Born matrix elements

$\Rightarrow$ Combine YFSWW3-1.14 and KoralW1.42 to correct for background diagram effects: Using LPA$_a$ in YFSWW3-1.14, $\sigma(Y_a)$, we get

$$\sigma_{Y/K} = \sigma(Y_a) + \Delta\sigma(K), \tag{8}$$

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

$$\Delta\sigma(K) = \sigma(K_1) - \sigma(K_3). \tag{9}$$

Here, $\sigma(K_1) \Leftrightarrow$ 4-f KoralW-1.42 result

$\sigma(K_3) \Leftrightarrow$ CC03 KoralW-1.42 result

$\Rightarrow \sigma_{Y/K}$ is accurate to $\mathcal{O}(\frac{\alpha}{\pi}\frac{\Gamma_W}{M_W})$

Alternatively, using LPA$_b$ in YFSWW3-1.14,$\sigma(Y_b)$, we get

$$\sigma_{K/Y} = \sigma(K_1) + \Delta\sigma(Y) \tag{10}$$

where

$$\Delta\sigma(Y) = \sigma(Y_b) - \sigma(Y_4), \tag{11}$$

and $\sigma(Y_4) \Leftrightarrow$ YFSWW3-1.14 result with
NL $\mathcal{O}(\alpha)$ corrections to $\bar{\beta}_n$, $n = 0, 1$, switched off.
$\Rightarrow \sigma_{K/Y}$ 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**
$\sigma(K_2)\Leftrightarrow$ **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.

YFSZZ-1.02

Process of interest

$$e^-(p_1)+e^+(p_2)\rightarrow Z(q_1)Z(q_2)+(\gamma(k_1),...,\gamma(k_m))$$
$$\rightarrow f_1(r_1)+\bar{f}_1(r_2)+f'_1(r'_1)+\bar{f}'_1(r'_2)+\gamma(k_1),...,\gamma(k_n)$$

- **Use LPA_a as described above for the NC02 process $\mathcal{O}(\alpha^2)$ LL YFS exponentiated ISR for the input Hagiwara,** *et al.***(NPB282, 253 (1987)) NCO2 Born matrix elements**

- **Anomalous Couplings Are Supported Following Hagiwara,** *et al.* **— THIS IS ALSO TRUE FOR YFSWW3/KORALW**

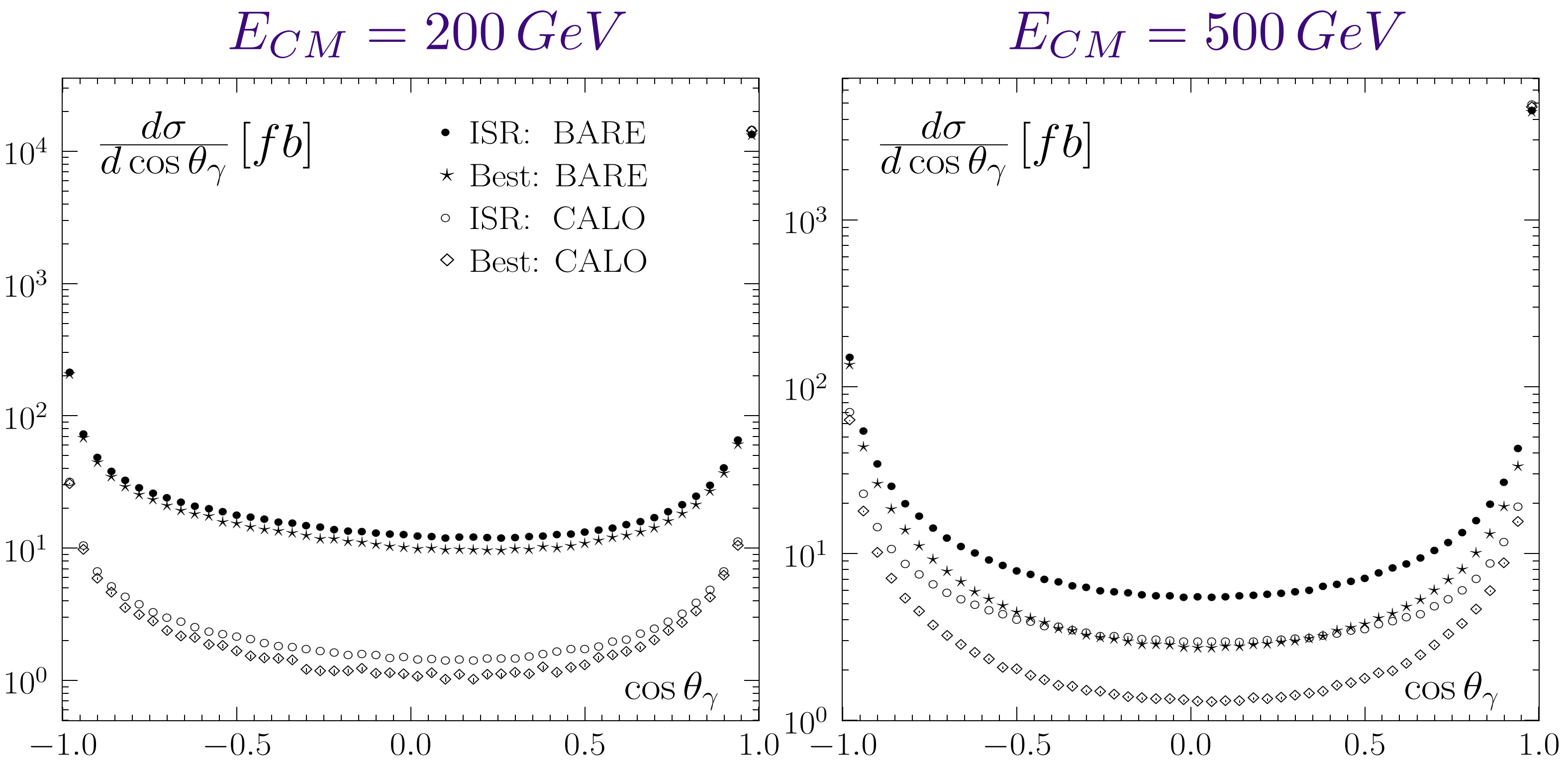
- **YFSZZ Tested In LEP2 MC Workshop, Just As YFSWW3-1.14 Was Tested**

$\Rightarrow$ **WE NOW TURN TO SUCH RESULTS**

RESULTS: YFSWW3-1.14

Hardest Photon Angular Distribution

$$e^+e^- \longrightarrow W^+W^- \longrightarrow u\bar{d}\mu^-\bar{\nu}_\mu$$



$E_{CM} = 200\,GeV$

$E_{CM} = 500\,GeV$

$cos\theta_\gamma$ w.r.t. e^+ beam ⇒ NL away from beams, etc.

Comparison with RacoonWW

no cuts		$\sigma_{\rm tot}\,[{\rm fb}]$	
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)%
$\mathrm{u\bar{d}}\mu^- \bar{\nu}_\mu$	`YFSWW3`	659.64(07)	622.71(19)
	`RacoonWW`	659.51(12)	621.06(14)
	(Y–R)/Y	$0.02(2)$%	0.27(4)%
$\mathrm{u\bar{d}s\bar{c}}$	`YFSWW3`	1978.18(21)	1937.40(61)
	`RacoonWW`	1978.53(36)	1932.20(44)
	(Y–R)/Y	$-0.02(2)$%	0.27(4)%

Total cross sections, CC03 from `RacoonWW`, `YFSWW3`, $\sqrt{s} = 200\ \mathrm{GeV}$ without cuts. Statistical errors – last digits in $(\ )$, etc.$\Rightarrow$ 0.4% TU.

RESULTS: YFSWW3/KORALW

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	$0.02\ (1)\%$	$0.02\ (1)\%$	—	—	—

Total WW YFSWW3 and KoralW xsect.: Born and ISR level, KoralW $4f$ corr., YFSWW3 $\mathcal{O}(\alpha)$ NL cor., at $200\,GeV$, no cuts – (-) $\Leftrightarrow$ last digits stat. err.

WW/4f Cross Section

WITH CUTS		$\sigma_{WW}\ [fb]$		$\delta_{4f}\ [\%]$		$\delta^{NL}_{WW}\ [\%]$
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	$0.03\,(2)\%$	$0.02\,(1)\%$	—	—	—

Total WW YFSWW3 and KoralW xsect.: Born and ISR level, KoralW $4f$ corr., YFSWW3 $\mathcal{O}(\alpha)$ NL cor., at $200\,GeV$, with cuts – (-) ⇔ last digits stat. err.

RESULTS: YFSZZ

Comparison with ZZTO

channel	YFSZZ	ZZT0 G_F-scheme	ZZT0 α-scheme
$qqqq$	294.6794(490)	298.4411(60)	294.5715(59)
$qq\nu\nu$	175.4404(302)	175.5622(35)	174.9855(35)
$qq\mathrm{ll}$	88.1805(134)	88.7146(18)	87.9881(18)
$\mathrm{ll}\nu\nu$	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)

NC02, YFSZZvs ZZT0, 188.6 GeV, in fb., stat. err. – last digits in $(\ )$, etc. $\Rightarrow$ 2% TU.

Conclusions: YFSWW3-1.14

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:

- **Mass Distributions: FSR – Peak Position and Height Shifts**
- **W Angular Distributions: LL AND NL**
- **ℓ Angular Distributions: LL AND NL**
- **Photon Angular Distributions: LL AND NL**
- **Photon Energy Distributions: LL**
- **Normalization: LL AND NL**

  Current 200 GeV TU: 0.4% $\{$**YFSWW3/RacoonWW**$\}$

Conclusions: YFSWW3/KORALW

- **Two different combinations reach total precision $\mathcal{O}(\frac{\alpha}{\pi}\frac{\Gamma_W}{M_W})$**

- **Size of the $4f$ correction to YFSWW3-1.14 is $\sim 0.1\%$, as expected**

- **Future extension to a single platform possible**

$YFSWW3/KoralW$**: complete MC event generator solution for precision WW/4f production at LEP2 (and LC's)**

Conclusions: YFSZZ

- Multiple photon MC event generator for NC02 – $\bar{\beta}_0$ level LPA YFS exponentiation (EEX)
- Tested in the LEP2 MC Workshop vs ZZTO and GENTILE to $\sim 2\%$ TU
- Upgrade to higher precision possible but not needed, apparently