Coherent exclusive exponentiation for precision Monte Carlo calculations of fermion pair production/ Precision predictions for (un)stable W^+W^- pairs

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Outline:

- **Introduction**
- **KKMC**
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- **YFSWW3-1.14**
- **Results: YFSWW3-1.14**
- **Conclusions**

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

INTRODUCTION

The CEEX solution: KKMC

Documented in CERN-TH-99-235, DESY-99-106, UTHEP-99-0901, CERN-TH-2000-087, UTHEP-99-0901

- ISR/FSR interferences are included in a natural way. Spin amplitudes for ISR and FSR summed squared numerically. (The BHWIDE approach gets cumbersome beyond first order)
- Exact treatment of fermion spin polarizations (transv.&longitudinal). Numerical Wigner rotations of spin density matrices available. (Necessary for interfacing with decay M.C. simulating fermion de cays).
- Exact matrix element for 2 and 3 and more photons using Kleiss-Stirling (KS) spinor technique.

The EEX solution: YFSWW3-1.14

Application of YFS3(PLB**274**,470(1992)) to the WW pair production and decay, YFSWW3, PLB**417**,326(1998), CERN-TH-99-222, PRD**61** (2000) 113010, UTHEP-00-0101, hep-ph/0007012: **Exclusive Exponentiation** (EEX) technique, as implemented in KORALZ/YFS3, BHLUMI, BHWIDE, KORALW:

- Exact $\mathcal{O}(\alpha)$ YFS exponentiation of production process
- FSR treated 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 $\mathcal{O}(\alpha)$

INTRODUCTION

Comparison with Other Calculations

KKMC

- EEX: $\mathcal{O}(\alpha^3)$ LL (KORALZ4.X-type)
- IEX: $\mathcal{O}(\alpha^2)_{prag}$
- ZFITTER 6.21: $\mathcal{O}(\alpha^3)$ LL, Bardin *et al.*,hep-ph/9908433

YFSWW3-1.14

- RacoonWW, Dittmaier *et al.*
  Exact $O(\alpha)$ LPA, complete $O(\alpha)$ $e^+e^- \to 4f + \gamma$
  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

KKMC

Main Difference: Old EEX/YFS vs CEEX for

$$e^-(p_1,\lambda_1)+e^+(p_2,\lambda_2)\rightarrow$$
$$f(q_1,\lambda_1')+\bar{f}(q_2,\lambda_2')+\gamma(k_1,\sigma_1)+...+\gamma(k_n,\sigma_n). \quad (1)$$

EEX total cross section

$$\sigma=\sum_{n=0}^{\infty}\int_{m_\gamma} d\Phi_{n+2}\, e^{Y(m_\gamma)} D_n(q_1,q_2,k_1,...,k_n) \quad (2)$$

$\mathcal{O}(\alpha^1)$ **distributions for** $n_\gamma=0,1,2$

$$D_0=\bar{\beta}_0$$
$$D_1(k_1)=\bar{\beta}_0\tilde{S}(k_1)+\bar{\beta}_1(k_1)$$
$$D_2(k_1,k_2)=\bar{\beta}_0\tilde{S}(k_1)\tilde{S}(k_2)$$
$$+\bar{\beta}_1(k_1)\tilde{S}(k_2)+\bar{\beta}_1(k_2)\tilde{S}(k_1) \quad (3)$$

Real Soft Factors as usual

$$4\pi\tilde{S}(k) = \sum_{\sigma} |\mathfrak{s}_{\sigma}(k)|^2 = |\mathfrak{s}_{+}|^2(k) + |\mathfrak{s}_{-}(k)|^2$$
$$= -\frac{\alpha}{\pi}\left(\frac{q_1}{kq_1} - \frac{q_2}{kq_2}\right)^2. \quad (4)$$

Important: the IR-finite building blocks

$$\bar{\beta}_0 = \sum_{\lambda} |\mathcal{M}_{\lambda}|^2,$$
$$\bar{\beta}_1(k) = \sum_{\lambda\sigma} |\mathcal{M}_{\lambda\sigma}^{1-\mathrm{phot}}|^2 - \sum_{\sigma} |\mathfrak{s}_{\sigma}(k)|^2 \sum_{\lambda} |\mathcal{M}_{\lambda}^{\mathrm{Born}}|^2 \quad (5)$$

in the multiphoton distributions are all in terms of $\sum_{spin} |...|^2$!! Here, $\lambda =$ fermion helicities and $\sigma =$ photon helicity.

Contrast: the analogous $\mathcal{O}(\alpha^1)$ case of CEEX

$$\sigma = \sum_{n=0}^{\infty} \int_{m_\gamma} d\Phi_{n+2} \sum_{\lambda,\sigma_1,\dots,\sigma_n} |e^{B(m_\gamma)} \mathcal{M}^{\lambda}_{n,\sigma_1,\dots,\sigma_n}(k_1,\dots,k_n)|^2 \quad (6)$$

Differential Distributions for $n_\gamma = 0, 1, 2$ photons:

$$\mathcal{M}^{\lambda}_{0} = \hat{\beta}^{\lambda}_{0}, \quad \lambda = \text{fermion helicities},$$

$$\mathcal{M}^{\lambda}{}_{1,\sigma_1}(k_1) = \hat{\beta}^{\lambda}{}_{0}\mathfrak{s}_{\sigma_1}(k_1) + \hat{\beta}^{\lambda}{}_{1,\sigma_1}(k_1),$$

$$\mathcal{M}^{\lambda}{}_{2,\sigma_1,\sigma_2}(k_1,k_2) = \hat{\beta}^{\lambda}{}_{0}\mathfrak{s}_{\sigma_1}(k_1)\mathfrak{s}_{\sigma_2}(k_2) + \hat{\beta}^{\lambda}{}_{1,\sigma_1}(k_1)\mathfrak{s}_{\sigma_2}(k_2) + \hat{\beta}^{\lambda}{}_{1,\sigma_2}(k_2)\mathfrak{s}_{\sigma_1}(k_1) \quad (7)$$

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IR-finite building blocks

$$\hat{\beta}^{\lambda}{}_0 = \left(e^{-B}\mathcal{M}_{\lambda}^{\text{Born+Virt.}}\right)\Big|_{\mathcal{O}(\alpha^1)},$$
$$\hat{\beta}^{\lambda}_{1,\sigma}(k) = \mathcal{M}^{\lambda}{}_{1,\sigma}(k) - \hat{\beta}^{\lambda}{}_0 \mathfrak{s}_{\sigma}(k). \tag{8}$$

Explicitly,this time everything is in terms of $\mathcal{M}$-spin-amplitudes! THE BASIC DIFFERENCE BETWEEN EEX/YFS AND CEEX.

Complete expressions for spin amplitudes with CEEX exponentiation, n_γ arbitrary, in Phys. Lett. **B449**, 97 (1999) for the $\mathcal{O}(\alpha^1)$ case and in CERN-TH/2000-087,UTHEP-99-09-01, for the $\mathcal{O}(\alpha^2)$ case, all based on GPS spinor conventions in CERN-TH-98-235, hep-ph/9905452.

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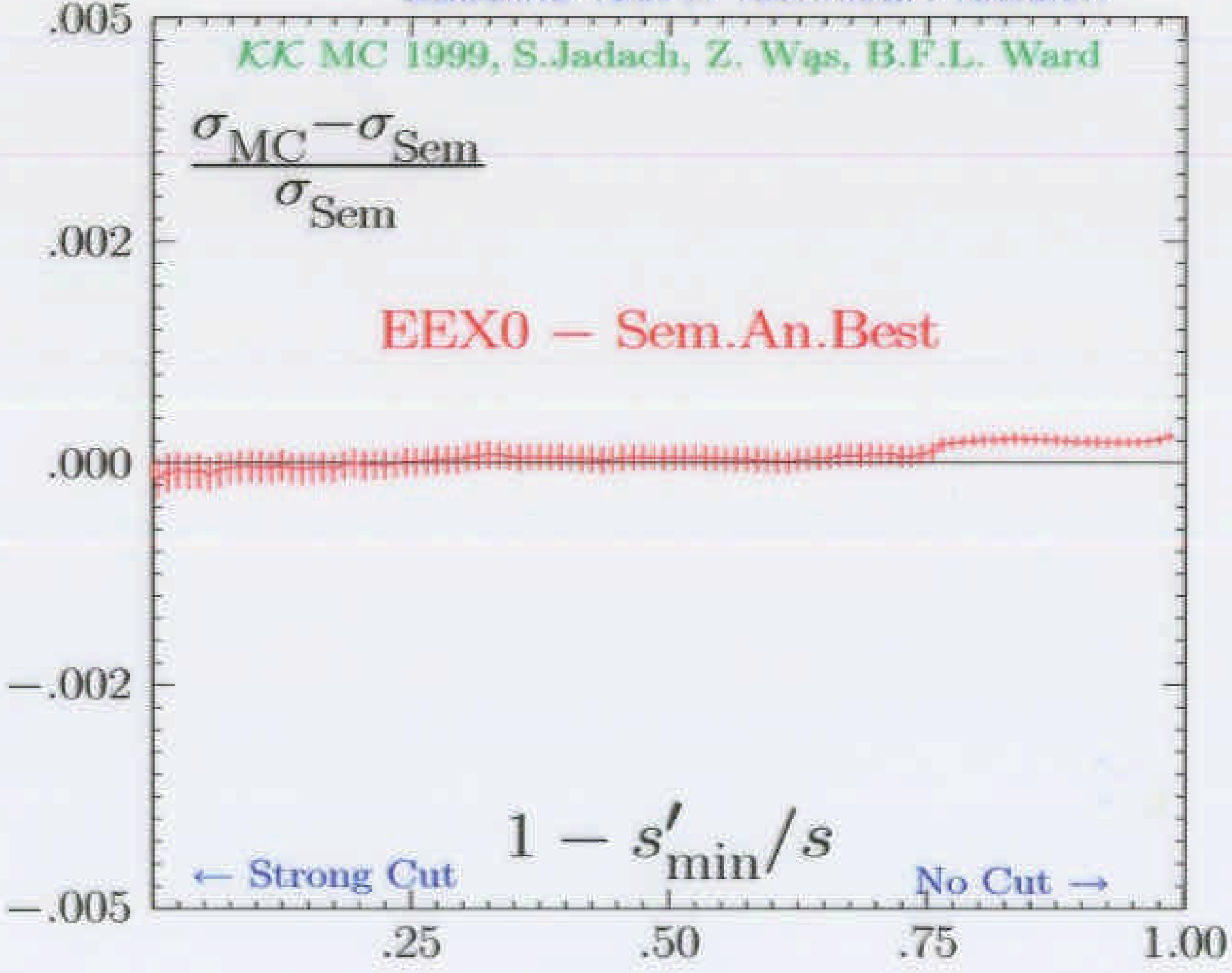
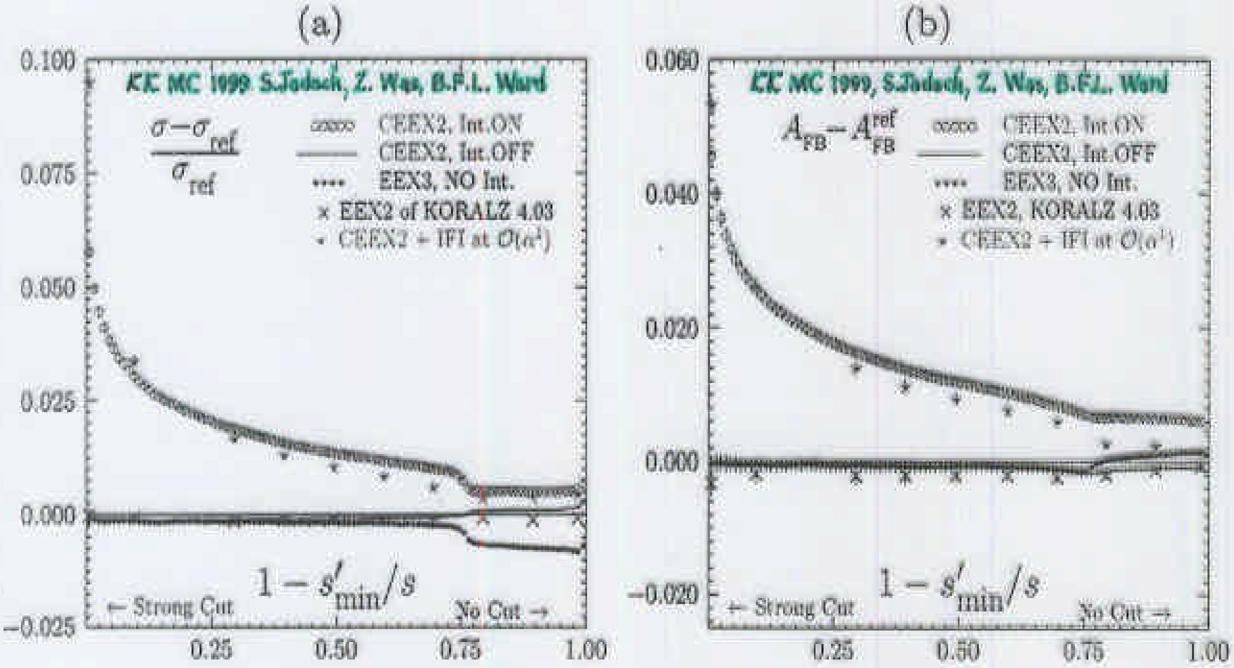
RESULTS: CEEX

Baseline Test of Technical Precision



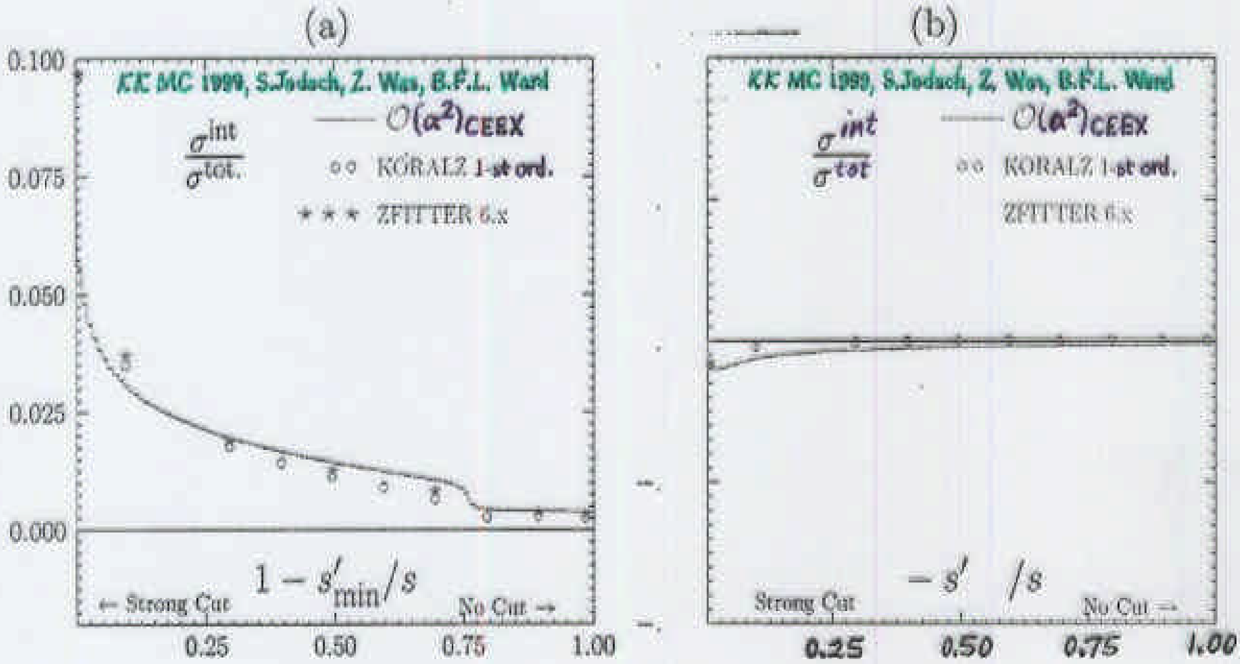
⇒ 0.02% TTU, $v < 0.999$, etc.

Physical Precision Tests



Absolute predictions for σ_{tot}, A_{FB} : $\mu\bar{\mu}$, 189GeV
⇒ 0.2% (0.2–0.4%) TU for σ_{tot} (A_{FB}) at LEP2, etc.

Physical Precision Tests



s'-cut dependence of $\delta\sigma$, No θ cut: (a), 189GeV (b), M_Z ⇒ IFI ≅ 1.5% for energy cut 0.3, $|\cos\theta| < 0.9$ reduces IFI by 25%, IFI very small at Z return, etc.

YFSWW3-1.14

Process of interest

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

$$\sigma_n = \frac{1}{flux} \int d\tau_{n+4}(p_1 + p_2; r_1, r_2, r_1', r_2', k_1, ..., k_n) \sum_{ferm.\ spin} \sum_{phot.\ spin} |\mathcal{M}_{4f}^{(n)}(p_1, p_2, r_1, r_2, r_1', r_2', k_1, ..., k_n)|^2 \quad (9)$$

W^+W^- **production and decay**

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

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

$$\sigma_n = \frac{1}{flux} \int d\tau_{n+4}(p_1 + p_2; r_1, r_2, r_1', r_2', k_1, ..., k_n) \sum_{ferm.\ spin} \sum_{phot.\ spin} |\mathcal{M}^{(n)}_{LPA}(p_1, p_2, r_1, r_2, r_1', r_2', k_1, ..., k_n)|^2 \quad (10)$$

LPA$_{a,b}$:

$$\mathcal{M}^{(n)}_{4f}(p_1,p_2,r_1,r_2,r'_1,r'_2,k_1,...,k_n) \overset{LPA}{=>} \mathcal{M}^{(n)}_{LPA}(p_1,p_2,r_1,r_2,r'_1,r'_2,k_1,...,k_n)$$

$$= \sum_{Phot.\ Partitions} \mathcal{M}^{(n),\lambda_1\lambda_2}_{Prod}(p_1,p_2,q_1,q_2,k_1,...,k_a)$$

$$\times \frac{1}{D(q_1)} \mathcal{M}^{(n)}_{Dec_1,\lambda_1}(q_1,r_1,r_2,k_{a+1},...,k_b)$$

$$\times \frac{1}{D(q_2)} \mathcal{M}^{(n)}_{Dec_2,\lambda_2}(q_2,r'_1,r'_2,k_{b+1},...,k_n),$$

$$D(q_i) = q_i^2 - M^2, \quad M^2 = ({M_W}^2 - i\Gamma_W M_W)(1 - {\Gamma_W}^2/{M_W}^2 + \mathcal{O}(\alpha^3)),$$

$$q_1 = r_1 + r_2 + k_{a+1} + ... + k_b; \quad q_2 = r'_1 + r'_2 + k_{b+1} + ... + k_n, \tag{11}$$

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

$$\mathcal{M} = \sum_j \ell_j A_j\left(\{q_k q_l\}\right), \tag{12}$$

We do both.

Standard YFS Methods(EEX-Type)⇒

$$d\sigma = e^{2\Re\alpha B' + 2\alpha\tilde{B}} \frac{1}{(2\pi)^4}$$

$$\int d^4y e^{iy(p_1+p_2-q_1-q_2)+D} [\bar{\beta}_0 + \sum_{n=1}^{\infty} \frac{d^3k_j}{k_j^0} e^{-iyk_j} \bar{\beta}_n(k_1, ..., k_n)] \quad (13)$$

$$\times \frac{d^3r_1}{\bar{E}_1} \frac{d^3r_2}{\bar{E}_2} \frac{d^3r_1'}{\bar{E}_1'} \frac{d^3r_2'}{\bar{E}_2'},$$

where

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

$$2\alpha\tilde{B} = \int \frac{d^3k}{k_0} \theta(K_{max} - |\vec{k}|) \tilde{S}(k). \quad (14)$$

K_{max} ⇐⇒ **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

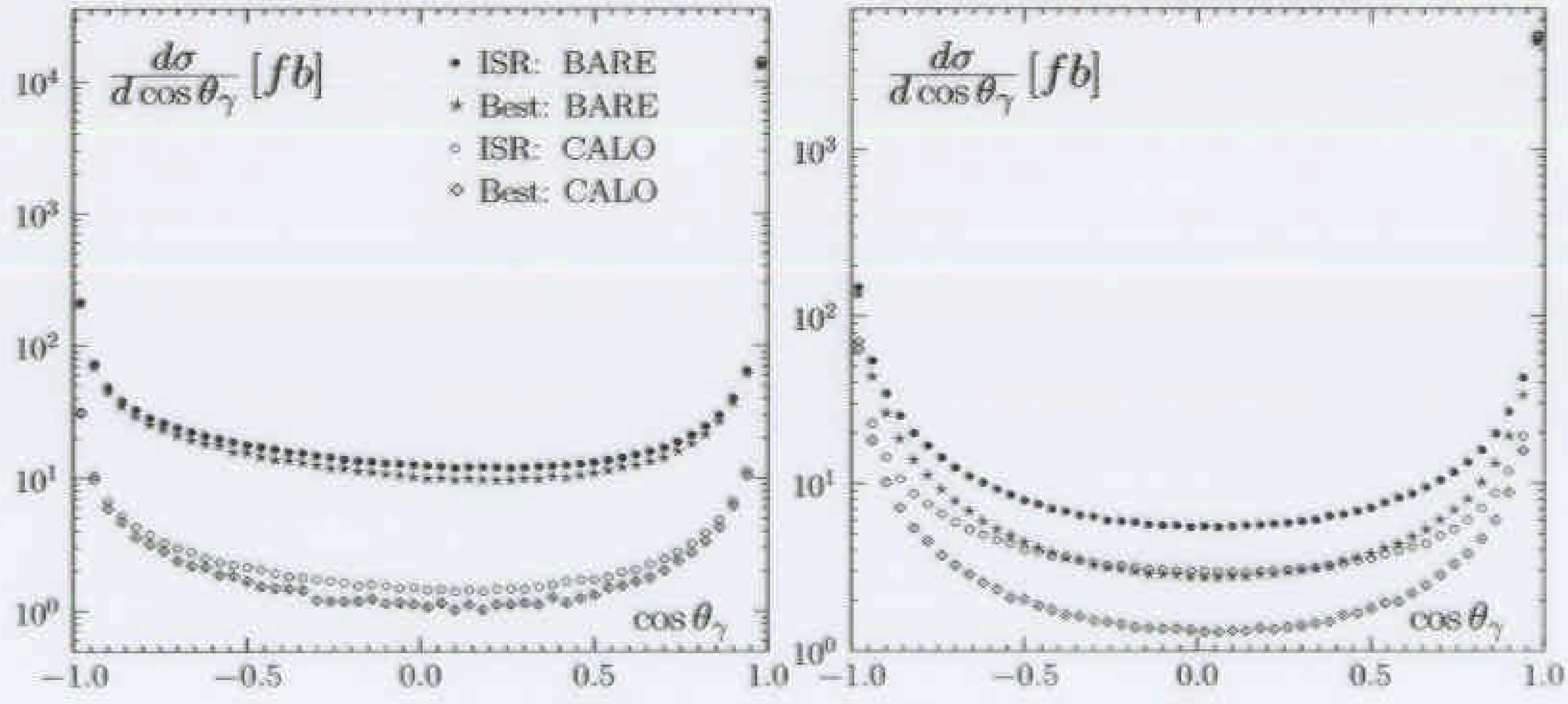
See Passarino's Talk for Details and References

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.

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Comparison with RacoonWW

no cuts		$\sigma_{tot}[\mathrm{fb}]$	
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)%
$\mathrm{u}\bar{\mathrm{d}}\mu^- \bar{\nu}_\mu$	YFSWW3	659.64(07)	622.71(19)
	RacoonWW	659.51(12)	621.06(14)
	(Y–R)/Y	0.02(2)%	0.27(4)%
$\mathrm{u}\bar{\mathrm{d}}\mathrm{s}\bar{\mathrm{c}}$	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.⇒ 0.4% TU.

Conclusions: KKMC(CEEX)

CEEX: clear upgrade path for EEX in a spin amplitude level MC.

- IFI (ISR$\otimes$FSR) included and under firm control -- (see below).
- All coherence effects, including narrow resonances.
- All spin-spin effects ($\| \oplus \perp$) for beams and final (unstable) fermions.
- Exact M.E. for 2 high hard photons (3 photons pending).
- Extension to $\nu\bar{\nu}$ in progress.
- Future extension to all-angle second order Bhabha is possible.
- For LEP2, total TU is 0.2%(0.2-0.4%) for $\sigma_{tot}(A_{FB})$, for typical cuts. For the LC at 0.5 TeV, these are a factor of 2 worse.
- For $\gamma\gamma^*$, the TU is 0.3% for LEP2 (no firm result for LC)

$\mathcal{KKMC}$: first MC implementation for 2f production at LEP, LC's, μ-colliders, τ and b factories.

Conclusions: KKMC(IFI)

CEEX: firm control of IFI

- For a typical energy cut of 0.3 IFI is about 1.5% in σ_{tot} and A_{FB}.
- For the energy cut of 0.1 it is a factor 2 bigger.
- The cut $|cos\theta| < 0.9$ makes it 25% smaller.
- $\mathcal{O}(\alpha^1)$ IFI controlled using KORALZ and KKMC for arbitrary cuts.
- Effects beyond $\mathcal{O}(\alpha^1)$ are negligible, $(< 20\%$ of $\mathcal{O}(\alpha^1))$, except for energy cuts stronger than 0.1.
- IFI at the Z radiative return is very small, as expected.
- Changing from s' to Q^2-propagator in the energy cut has no effect.

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}