W-Pair Production With YFSWW/KORALW

WIESŁAW PŁACZEK
Jagiellonian University, Cracow, Poland
and
CERN, Geneva, Switzerland

Outline:

- **Introduction.**
- **WW Physics with YFSWW/KORALW.**
- **Numerical results.**
- **Conclusions and outlook.**

People:

S. Jadach, W.P., M. Skrzypek, B.F.L. Ward, Z. Wąs

Papers:

KORALW: Comput. Phys. Commun. **94** (1996) 215;

Phys. Lett. **B372** (1996) 289;

Comput. Phys. Commun. **119** (1999) 272.

YFSWW: Phys. Rev. **D54** (1996) 5434;

Phys. Lett. **B417** (1998) 326;

Phys. Rev. **D61** (2000) 113010;

hep-ph/0007012.

⇒ **EXPERIMENTALLY:**

W-pairs observed through **4f** final states + radiative photons

- **GENERAL PROCESS:**

$$e^+ + e^- \longrightarrow f_1 + \bar{f}_2 + f_3 + \bar{f}_4 + n\gamma\,, \; (n = 0, 1, \ldots)$$

⇒ **THEORETICALLY:** also LOOP corrections necessary!

- **Exclusive Yennie-Frautschi-Suura Exponentiation:**

$$\sigma = \sum_{n=0}^{\infty} \frac{1}{n!} \int \prod_{j=1}^{4} \frac{d^3 q_j}{q_j^0} \left\{ \prod_{i=1}^{n} \frac{d^3 k_i}{k_i^0} \tilde{S}(\{p\},\{q\},k_i) \Theta\left(\frac{2k_i^0}{\sqrt{s}} - \epsilon \right) \right\}$$
$$\times \delta^{(4)} \left(p_1 + p_2 - \sum_{j=1}^{4} q_i - \sum_{j=1}^{n} k_i \right) \; e^{Y(\{p\},\{q\};\epsilon)}$$
$$\times \left[\bar{\beta}_0^{(m)}(\{p\},\{q\}) + \sum_{i=1}^{n} \frac{\bar{\beta}_1^{(m)}(\{p\},\{q\},k_i)}{\tilde{S}(\{p\},\{q\},k_i)} + \ldots \right],$$

where

$\tilde{S}(\{p\},\{q\},k)$ — Soft Photon Radiation Factor

$Y(\{p\},\{q\};\epsilon)$ — YFS FormFactor

$\bar{\beta}_n^{(m)}(\ldots)$ — $\mathcal{O}(\alpha^m)$ YFS Residuals for n Real Photons

$\boxed{\textbf{COMPLICATED !!!}}$

Introduction

$\Rightarrow$ **PROBLEMS:**

- ~ 80 Different Channels
- Complicated Peaking Behaviour in $8 + (3n - 4)$ Dim. Phase Space
- Large Number of Feyman Diagrams

  # of Feynman Graphs/Channel (WW-type, $m_f = 0$)

BORN	9 — 56
1-LOOP	3,579 — 15,948

$\longrightarrow$ **Practical Problems** – A Few Examples:

- **BORN:** e.g. KORALW $(m_f \neq 0)$

  Source Code: $\sim$ 0.5M Lines $\longrightarrow$ $\sim$ 20MB

  Exec. Code: $\sim$ 10MB

  Compilation Time: $\sim$ 1h On Fast PC

- **1-LOOP:** Rough Estimate – Mupltiply by 100

  Source Code: $\sim$ 50M Lines $\longrightarrow$ $\sim$ 2GB

  Exec. Code: $\sim$ 1GB

  Compilation Time: $\sim$ 100h On Fast PC

  $\longrightarrow$ **Very Slow Event Generation!** $\sim 100 \times$ Born

EFFICIENT APPROXIMATIONS NEEDED !

$\Rightarrow$ **OUR SOLUTION:**

TWO MC EVENT GENERATORS

$\Downarrow$	$\Downarrow$
YFSWW	**KORALW**
Simplified Process	**Full Process**
(Double-Resonant W)	(All 4f Channels)
$\bigoplus$	$\bigoplus$
As Much Rad. Corr. As Possible (Needed)	**Simplified Rad. Corr. (ISR, Coulomb, ...)**

δ_{WW}^{NL}

- $\ast$ $\mathcal{O}(\alpha)$ NL EW Corr.
- $\ast$ "Screened" Coul. Corr. (Approximation For Non-Factorizable Corr.)

WW-Process

- $\ast$ YFS $\mathcal{O}(\alpha^3)$LL ISR
- $\ast$ Coulomb Correction
- $\ast$ "Naive" QCD Corr.
- $\ast$ Full CKM Matrix
- $\ast$ W-BR's Incl. Rad Corr.
- $\ast$ Anomalous TGC's
- $\ast$ FSR by PHOTOS
- $\ast$ τ Decays by TAUOLA
- $\ast$ Hadronization by JETSET
- $\ast$ Semi-An. Code: KORWAN

δ_{4f}

- $\ast$ Non-WW 4f Contrib.
- $\ast$ YFS $\mathcal{O}(\alpha^3)$LL ISR

⇒ **TWO POSSIBILITIES:**

1. $\boldsymbol{\sigma_{Y/K} = \sigma_{Y} \oplus \delta_{4f}}$ ← For WW-Physics
2. $\boldsymbol{\sigma_{K/Y} = \sigma_{K} \oplus \delta_{WW}^{NL}}$ ← When $\delta_{4f} > \delta_{WW}^{NL}$

WW Physics With YFSWW

Double-Resonant Feyman Graphs (CC03)

Non Gauge-Invariant!

⇒ **POSSIBLE SOLUTION:**

Leading Pole Approximation (LPA):

- Matrix Element (For Gauge-Invariant Set of Feynman Graps) Can Be Decomposed:

$$\mathcal{M} = \sum_i T_i(\ldots, p_j, \ldots, p_k, \ldots)\, M_i(\ldots, p_j \cdot p_k, \ldots)$$

$\boldsymbol{T_i}$ ← Spinor and Lorentz Tensor Structure of M.E.

(External Wave Functions, etc.)

$\boldsymbol{M_i}$ ← Lorentz Scalar Functions

(e.g. Describe Finite-Range W-Propagation)

⇒ **TWO APPROACHES:**

a) R. G. Stuart, Nucl. Phys. **B498** (1997) 28 and Refs. therein

M_i Expanded About Complex Poles (Laurent Series)

Corresponding to Unstable Particles (Here: W's)

T_i Untouched by Laurent Expansion!

$\longrightarrow$ **LPA:** Only Leading-Pole Terms Kept!

IMPLEMENTED IN YFSWW: LPA$_a$ $\longleftarrow$ RECOMMENDED

b) Yellow Report CERN 96-01, Vol. 1, p. 79 and Refs. therein[a]

The Whole Matrix Element $\mathcal{M}$ Expanded About Poles!

(Connection to On-Shell WW Production and Decay)

$\longrightarrow$ **LPA:** Only Leading-Pole Terms Kept!

IMPLEMENTED IN YFSWW: LPA$_b$ $\longleftarrow$ For Tests

- NUMERICAL DIFFERENCES :

Level	LPA$_a$/LPA$_b$ − 1
Born	Several Per Cent
δ_{ISR}	A Few Per Mille
δ_{WW}^{NL}	$\leq 0.1\%$

⇒ Born: LPA$_a$ Very Close to CC11 (Min. Gauge-Invariant Set of Feynman Diagrams)

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

Results

YFSWW3-1.14 $\leftrightarrow$ KORALW-1.42

(CC09/CC10/CC11 Channels)

$\sqrt{s} = 161$ GeV		σ_{WW} [fb]		δ_{4f} [%]		δ_{WW}^{NL} [%]
Final state	Program	Born	ISR	Born	ISR	
$u\bar{d}\mu^-\bar{\nu}_\mu$	YFSWW	156.670 (16)	122.832 (08)	—	—	−1.41 (4)
	KORALW	156.601 (24)	122.836 (11)	0.29	0.25	—
	(Y−K)/Y	0.04 (2)%	0.00 (1)%	—	—	—

$\sqrt{s} = 200$ GeV		σ_{WW} [fb]		δ_{4f} [%]		δ_{WW}^{NL} [%]
Final state	Program	Born	ISR	Born	ISR	
$\nu_\mu\mu^+\tau^-\bar{\nu}_\tau$	YFSWW	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)%	—	—	—
$u\bar{d}\mu^-\bar{\nu}_\mu$	YFSWW	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)%	—	—	—
$u\bar{d}s\bar{c}$	YFSWW	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)%	—	—	—

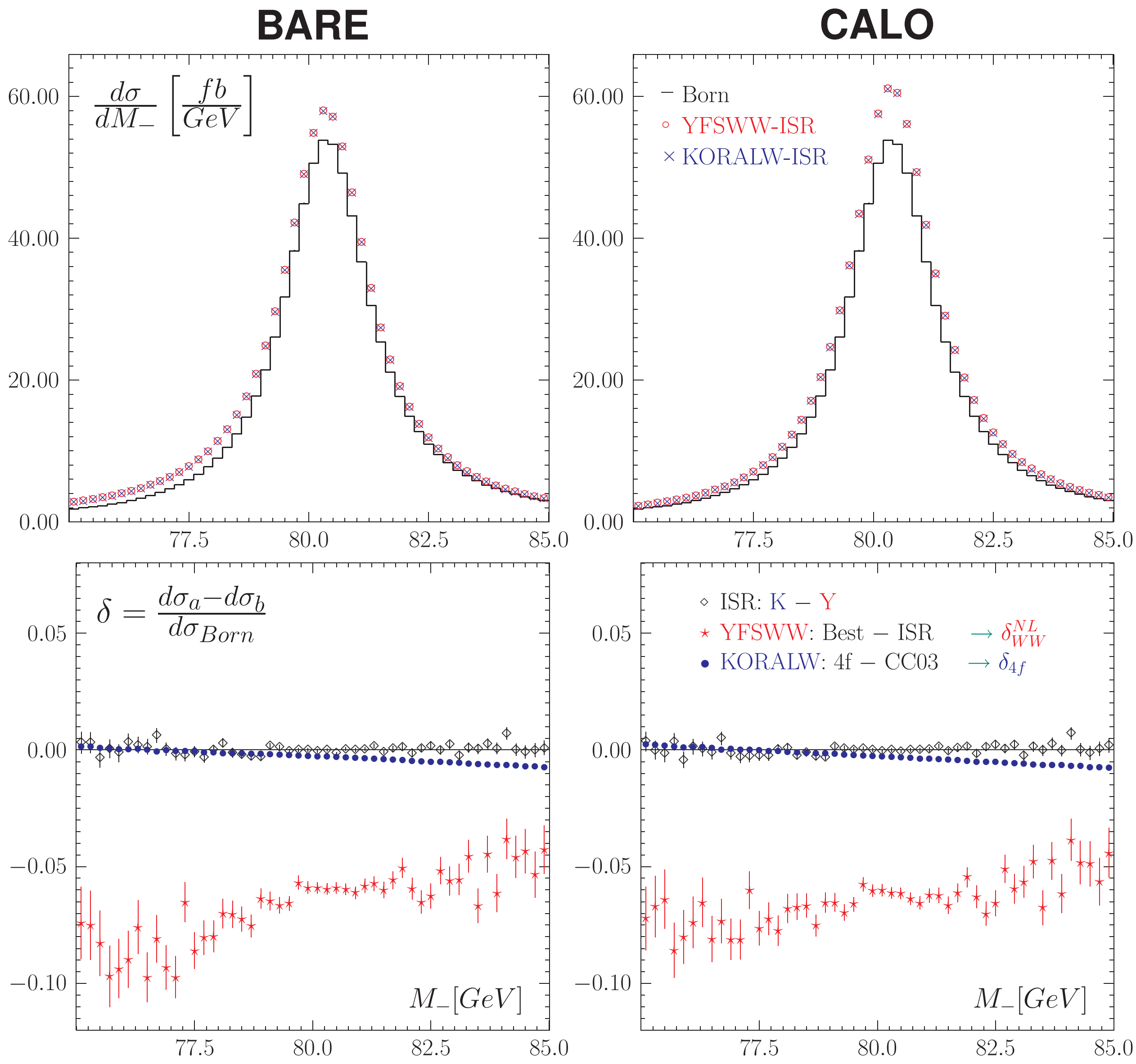
$\sqrt{s} = 500$ GeV		σ_{WW} [fb]		δ_{4f} [%]		δ_{WW}^{NL} [%]
Final state	Program	Born	ISR	Born	ISR	
$u\bar{d}\mu^-\bar{\nu}_\mu$	YFSWW	261.368 (23)	292.029 (18)	—	—	−4.95 (4)
	KORALW	261.348 (17)	291.979 (19)	−0.51	−0.51	—
	(Y−K)/Y	0.01 (1)%	0.02 (1)%	—	—	—

$\boldsymbol{\delta_{WW}^{NL}}$ Much Bigger Than $\boldsymbol{\delta_{4f}}$!

Results

YFSWW3-1.14 $\leftrightarrow$ KORALW-1.42

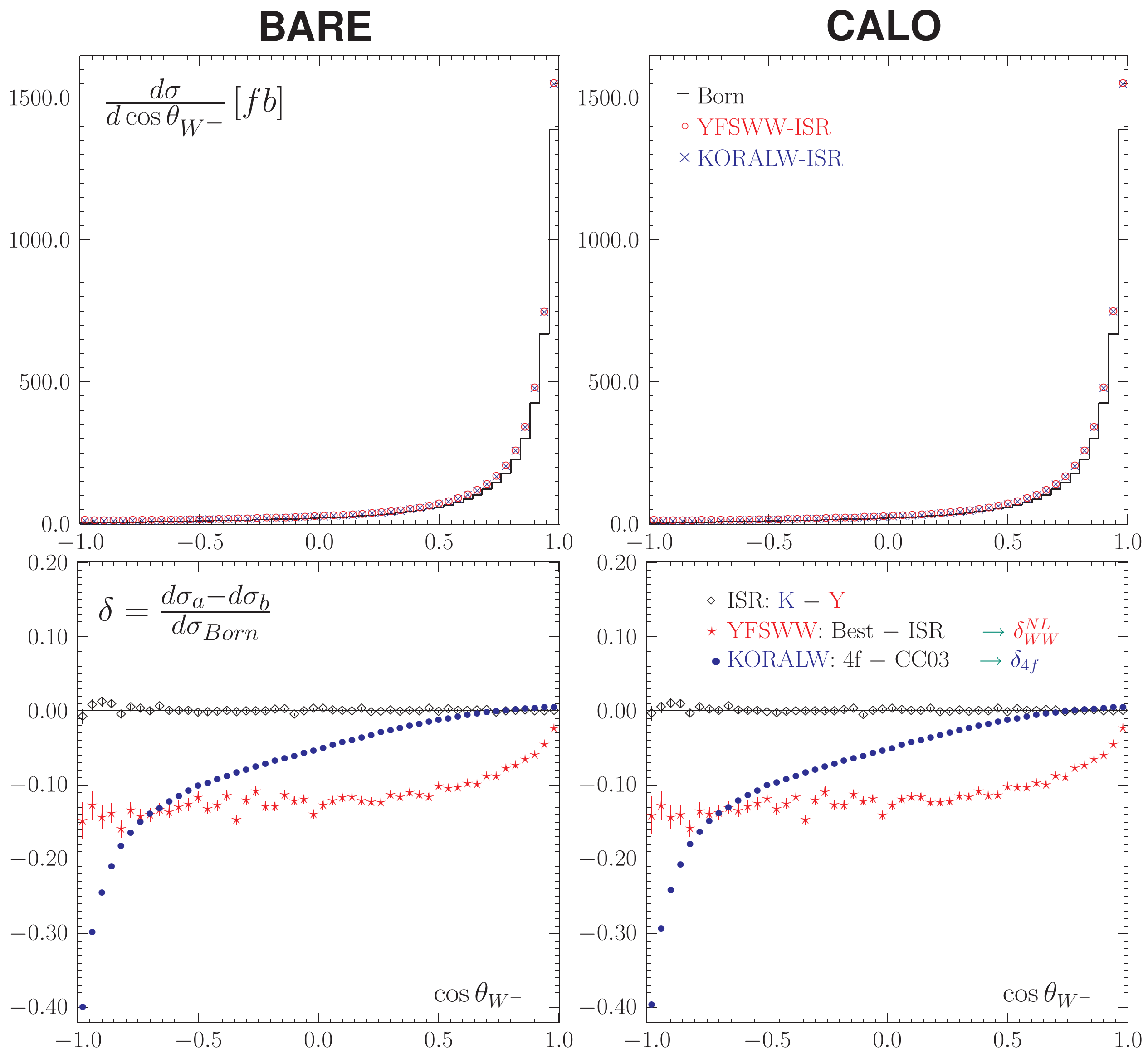
$$e^+e^- \longrightarrow W^+W^- \longrightarrow u\bar{d}\mu^-\bar{\nu}_\mu$$



$M_{W^-}^{inv}$ @ $\sqrt{s} = 500$ GeV

YFSWW3-1.14 $\leftrightarrow$ KORALW-1.42

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



$\cos\theta_{W^-}$ @ $\sqrt{s} = 500$ GeV

Results

YFSWW3-1.14 $\leftrightarrow$ RacoonWW A. Denner, S. Dittmaier, M. Roth, D. Wackeroth

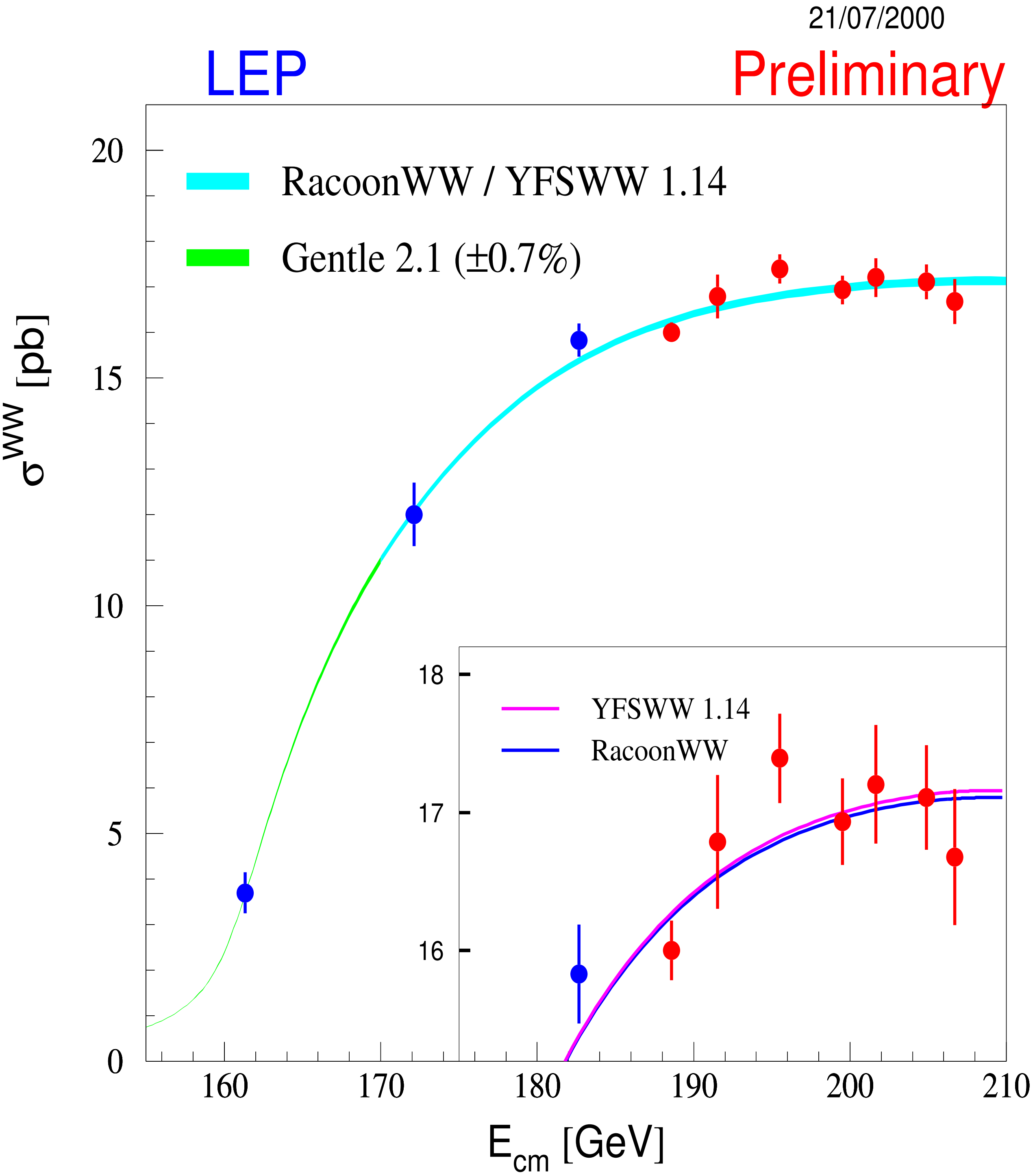
@ LEP2 Energies

$\sqrt{s}\,[GeV]$	$\sigma_{WW}\,[pb]$		(Y − R)/Y [%]
	YFSWW3	RacoonWW	
168.000	9.8302 (34)	9.8392 (49)	−0.09 (6)
172.086	12.0988 (41)	12.0896 (76)	0.08 (7)
176.000	13.6360 (45)	13.6271 (66)	0.07 (6)
180.000	14.7791 (49)	14.7585 (72)	0.14 (6)
182.655	15.3610 (50)	15.3684 (76)	−0.05 (6)
185.000	15.7755 (48)	15.7716 (78)	0.25 (6)
188.628	16.2664 (53)	16.2486 (111)	0.11 (8)
191.583	16.5680 (57)	16.5188 (85)	0.30 (6)
195.519	16.8409 (61)	16.8009 (87)	0.24 (6)
199.516	17.0167 (68)	16.9791 (88)	0.22 (6)
201.624	17.0755 (62)	17.0316 (89)	0.26 (6)
205.000	17.1279 (55)	17.0792 (89)	0.28 (6)
208.000	17.1507 (67)	17.0942 (90)	0.33 (7)
210.000	17.1467 (66)	17.0858 (91)	0.34 (7)
215.000	17.0786 (70)	17.0378 (91)	0.24 (7)

Agreement Within 0.4%

Results

Versus LEP2 Data

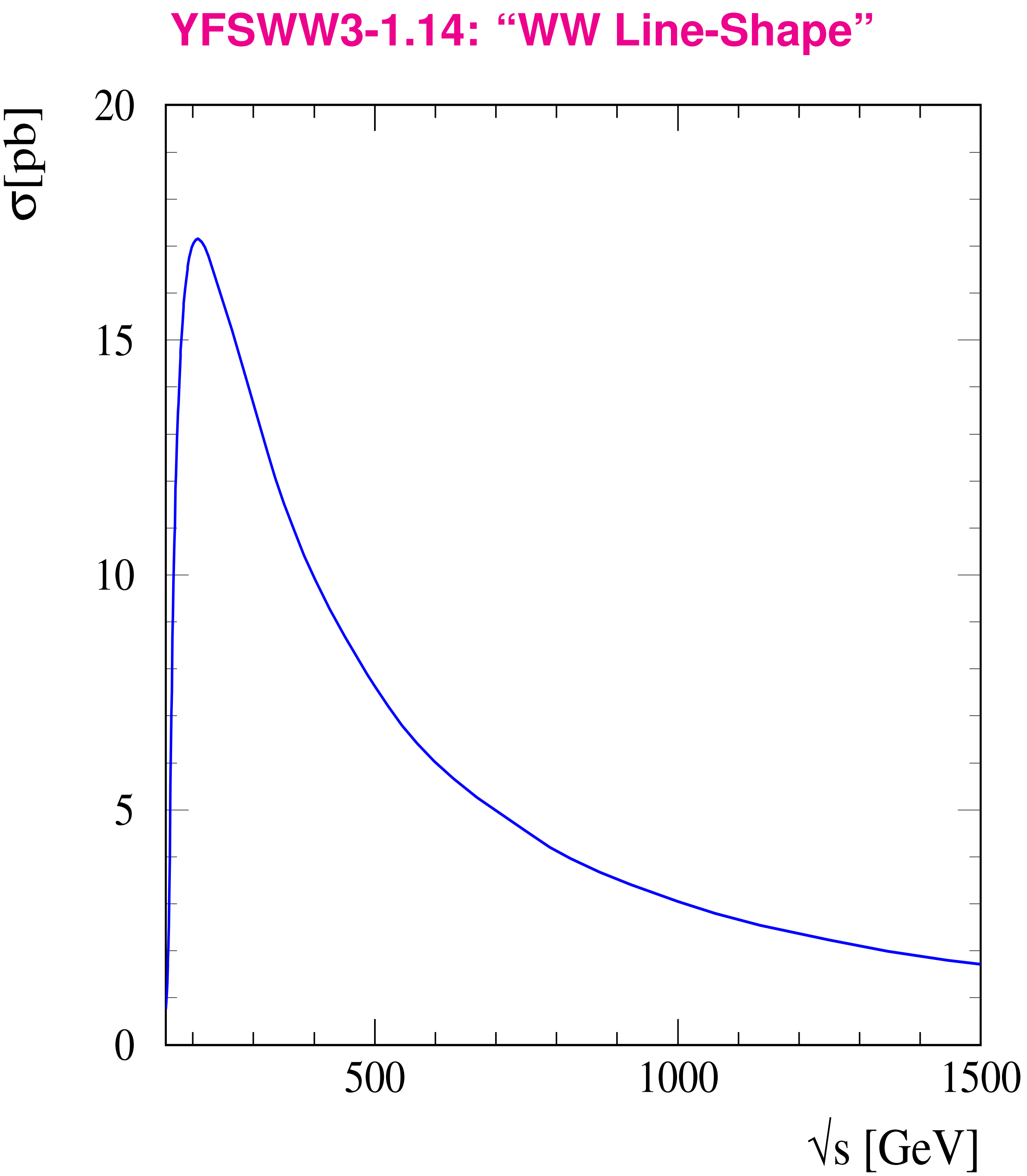


Results

YFSWW3-1.14: Total WW Cross Section

$\sqrt{s}\,[GeV]$	$\sigma_{WW}\,[pb]$ Born	ISR	Best	$\frac{\text{ISR}-\text{Born}}{\text{Born}}$ [%]	$\frac{\text{Best}-\text{ISR}}{\text{Born}}$ [%]
155.000	0.94585 (17)	0.76497 (14)	0.75478 (35)	−19.12 (3)	−1.08 (5)
157.000	1.38578 (25)	1.10298 (19)	1.08686 (48)	−20.41 (3)	−1.16 (5)
159.000	2.30412 (40)	1.79141 (30)	1.76254 (80)	−22.25 (3)	−1.25 (5)
161.000	4.4138 (7)	3.3579 (5)	3.2969 (14)	−23.92 (3)	−1.38 (5)
163.000	7.3264 (10)	5.6178 (7)	5.5219 (22)	−23.32 (3)	−1.31 (4)
165.000	9.7343 (11)	7.6385 (9)	7.5073 (27)	−21.53 (3)	−1.35 (4)
167.000	11.5788 (14)	9.2903 (10)	9.1367 (31)	−19.76 (3)	−1.33 (4)
168.000	12.3391 (14)	10.0020 (11)	9.8302 (34)	−18.94(3)	−1.39 (4)
170.000	13.6124 (15)	11.2392 (12)	11.0504 (37)	−17.43 (3)	−1.39 (4)
172.086	14.6717 (16)	12.3114 (14)	12.0988 (41)	−16.09 (3)	−1.45 (4)
176.000	16.1293 (17)	13.8760 (15)	13.6360 (45)	−13.97 (3)	−1.49 (4)
180.000	17.1207 (18)	15.0325 (16)	14.7791 (49)	−12.20 (3)	−1.48 (4)
182.655	17.5852 (19)	15.6190 (17)	15.3610 (50)	−11.18 (3)	−1.47 (4)
185.000	17.8981 (19)	16.0422 (18)	15.7755 (48)	−10.37 (3)	−1.49 (4)
188.628	18.2391 (20)	16.5540 (18)	16.2664 (53)	−9.24 (3)	−1.58 (4)
191.583	18.4179 (20)	16.8649 (18)	16.5680 (57)	−8.43 (3)	−1.61 (4)
195.519	18.5466 (19)	17.1651 (19)	16.8409 (61)	−7.45 (3)	−1.75 (4)
199.516	18.5828 (19)	17.3608 (19)	17.0167 (68)	−6.58 (3)	−1.85 (4)
201.624	18.5696 (21)	17.4284 (19)	17.0755 (62)	−6.15 (3)	−1.90 (4)
205.000	18.5162 (21)	17.4968 (20)	17.1279 (55)	−5.51 (3)	−1.99 (4)
208.000	18.4399 (21)	17.5216 (20)	17.1507 (67)	−4.98 (3)	−2.01 (4)
210.000	18.3767 (21)	17.5219 (20)	17.1467 (66)	−4.65 (2)	−2.04 (4)
215.000	18.1833 (21)	17.4773 (20)	17.0786 (70)	−3.88 (2)	−2.19 (4)
250	16.2477 (16)	16.2293(14)	15.7952 (44)	−0.11 (2)	−2.67 (3)
350	11.3812 (12)	11.9325 (12)	11.5255 (39)	4.84 (2)	−3.58 (4)
500	7.3621 (8)	7.9823 (9)	7.6324 (30)	8.42 (2)	−4.75 (4)
750	4.2885 (6)	4.7993 (6)	4.5349 (21)	11.91 (2)	−6.17 (5)
1000	2.8598 (4)	3.2679 (4)	3.0543 (16)	14.27(2)	−7.47 (5)
1250	2.0714 (3)	2.4017 (4)	2.2263 (13)	15.95 (2)	−8.47 (6)
1500	1.5865 (2)	1.8615 (3)	1.7095 (11)	17.33 (2)	−9.58 (7)
				δ_{ISR}	δ_{WW}^{NL}

Results



CONCLUSIONS

- **Our Solution for WW Physics:**

  Two MC Event Generators

  (Weighted/Unweighted Events)

  YFSWW **KORALW**

  WW Signal **4f Background**

- **Good Agreement With** RacoonWW ($< 0.5\%$) **and LEP2 Data**

- $\mathcal{O}(\alpha)$ **Non-LL EW Radiative Corrections:**

  1% — 2% at LEP2

  Up to 10% at LC (Higer Orders Needed!)

- **ISR Corrections Change:**

  From Large Negative at LEP2

  To Large Positive at LC (Partial Cancellation With EWC)

To Be Done

- $\mathcal{O}(\alpha)$ **YFS Exponentiation In W Decays** (In Progress)

- **Non-Factorizable Corrections**

- **Tests, ...**