Precision predictions for W-pair production at LEP2

WIESLAW PLACZEK
Jagiellonian University, Cracow, Poland
& CERN, Theory Division

Outline:

- **Indroduction.**
- **Theoretical description of W-pair production.**
- **Monte Carlo program RacoonWW.**
- **Monte Carlo programs KoralW & YFSWW3.**
- **Theoretical precision of the main LEP2 WW-observables.**
- **Conclusions.**

Why to investigate W-pair production?

- To measure the Standard Model (SM) parameters, e.g. $M_W, \; \Gamma_W$

  $\longrightarrow$ Before LEP2 (1995): $\Delta M_W \approx 160$ MeV,

  while: $\Delta M_Z \approx 2$ MeV

- To test the SM, in particular its non-Abelian nature through triple-gauge-boson couplings (TGCs): $WW\gamma$ and WWZ

  Note: For the first time at the tree level in e^+e^- collisions

- To get better constraints on the **Higgs mass**

  $\longrightarrow$ Indirectly from SM fits

- To search for **“new physics”**, e.g. anomalous TGCs, etc.

- WW process – important background for **Higgs boson** searches

  (e.g. in “LEP2 Higgs events” @ $m_H \approx 115$ GeV)

Main WW observables at LEP2 and their precision:

- Total WW cross section σ_{WW}

  $\longrightarrow$ Experimental precision: $\delta_{ex}\sigma_{WW} \sim 1\%$

  $\longrightarrow$ Required theoretical precision: $\delta_{th}\sigma_{WW} \lesssim 0.5\%$

- Distribution of W invariant mass $M_{inv} \Rightarrow M_W$ measurement

  $\longrightarrow$ Experimental precision: $\delta_{ex}M_W \sim 30$ MeV

  $\longrightarrow$ Required theoretical precision: $\delta_{th}M_W \lesssim 15$ MeV

- Distribution of cosine of W polar angle $\cos\theta_W \Rightarrow$ TGCs measurement, e.g. for C and P conserving anomalous TGC $\lambda = \lambda_\gamma = \lambda_Z$:

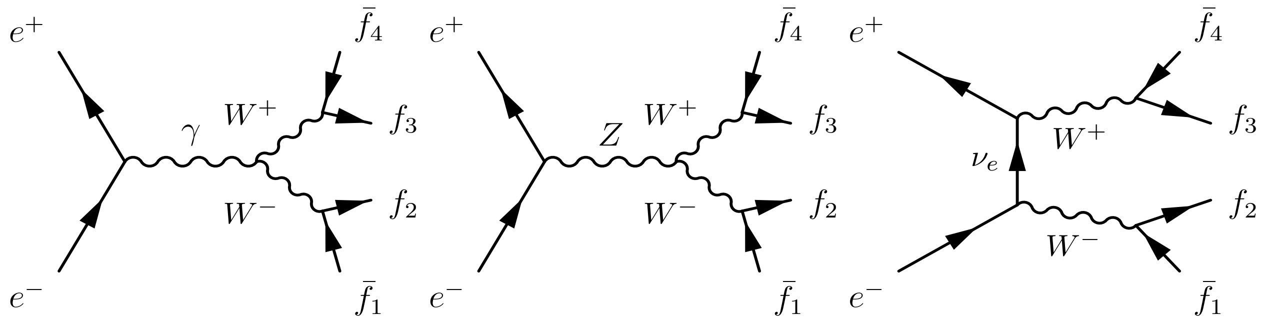
  $\longrightarrow$ Experimental precision: $\delta_{ex}\lambda \sim 0.01$

  $\longrightarrow$ Required theoretical precision: $\delta_{th}\lambda \lesssim 0.005$

LEP2 data analyses require theoretical predictions in terms of Monte Carlo Event Generator (MCEG) that meet the above precision requirements!

Basic process:

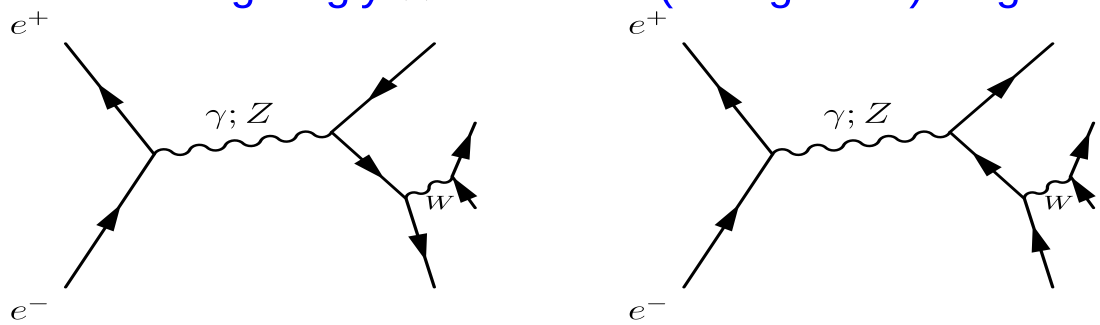
$$e^+ + e^- \longrightarrow W^-W^+ \longrightarrow f_1 + \bar{f}_2 + f_3 + \bar{f}_4$$



Feynman diagrams for W^+W^- Production and Decay (CC03)

Not Gauge Invariant!

After adding singly W-resonant (background) diagrams:



$\Rightarrow$ CC11 subset of $e^+e^- \to 4f$ diagrams – **Gauge Invariant!**

In practice: the whole $e^+e^- \to 4f$ needs to be considered!

- **Another problem: Inclusion of finite W-boson width!**

$\longrightarrow$ "Fixed-Width Scheme" and "Running-Width Scheme" violate Gauge Invariance!

$\longrightarrow$ "Complex-Mass Scheme" – Gauge-Invariant, but space-like propagators acquire unphysical width (also CP structure of a process may be changed)

$\longrightarrow$ "Fermion-Loop Scheme" – includes fermionic loops, misses bosonic loops, etc.

Beyond tree level the above problems increase dramatically!

- At 1-loop level:

$\longrightarrow$ Thousands of Feynman diagrams per $4f$ channel!

$\longrightarrow$ Inclusion of finite W width much more difficult!

Do we need to go beyond the Born level?

▶ Various radiative corrections and their sizes:

- Pure QED

▷ Initial-State Radiation (ISR): $\frac{\delta\sigma_{WW}}{\sigma_{WW}} \sim 5\text{–}20\%$, $\delta M_W \sim 10$ MeV, $\delta\lambda \sim 0.07$

▷ Coulomb correction: $\frac{\delta\sigma_{WW}}{\sigma_{WW}} \sim 2\text{–}6\%$

▷ Final-State Radiadion (FSR): $\delta M_W \sim 10\text{–}80$ MeV (acceptance-dependent!)

▷ Non-Factorizable (NF) corrections: $\delta M_W \sim 1\text{–}5$ MeV (inclusively)

Theoretical description of W-pair production

- Electroweak (EW)

▷ Leading EW corrections (effective scale of hard process):

"G_μ-scheme" ($\alpha \to G_\mu$) accounts for $\frac{\delta\sigma_{WW}}{\sigma_{WW}} \sim 15\%$

▷ $\mathcal{O}(\alpha)$ Non-Leading (NL) EW corrections:

From calculations for WW On-Shell process: $\frac{\delta\sigma_{WW}}{\sigma_{WW}} \sim 1$–$2\%$

$\longrightarrow$ also affect TGCs measurement, e.g. $\delta\lambda \sim 0.01$–0.02

- QCD (for hadronic final states)

▷ "Naive QCD" correction (inclusive):

Normalisation factor $\frac{\alpha_s}{\pi} \simeq 3.8\%$ for each final-state quark-pair and $\frac{2\alpha_s}{3\pi}$ for Γ_W

▷ Exclusive QCD effects – managed by dedicated MC packages (PYTHIA, etc.)

$\Rightarrow$ All the above effects necessary in MC generator for LEP2!

$\longrightarrow$ **The most difficult:** $\mathcal{O}(\alpha)$ NL EW corrections

- Not available yet even for CC11
- If existed – probably too slow numerically for MC generation

Efficient approximation necessary!

We are interested in doubly-resonant WW process:

$\Rightarrow$ **Another expansion parameter:** $\frac{\Gamma_W}{M_W} \sim \frac{1}{40}$ (2.5%)

$\longrightarrow$ **Pole-Epansion:** **expansion about W-pole in increasing powers of $\frac{\Gamma_W}{M_W}$**

$\Leftrightarrow$ **expansion in decreasing powers of resonance**

$\triangleright$ **Leading-Pole Approximation (LPA)**: only highest-pole (resonant) contributions retained, i.e. $\sim (\frac{\Gamma_W}{M_W})^0$ $\longleftarrow$ **Gauge-Invariant!** (R.G. Stuart, NP**B498** (1997) 28)

- **For WW process** – only double-pole contributions retained

  $\longrightarrow$ **Double-Pole Approximation (DPA)**

$\circ$ Not sufficient for Born ($\delta \sim \frac{\Gamma_W}{M_W}$) and Leading corrections ($\delta \sim \frac{\Gamma_W}{M_W} \frac{\alpha}{\pi} \log \frac{Q^2}{m^2}$)

$\longrightarrow$ Lower-pole terms needed – in fact, the full $e^+e^- \rightarrow 4f$ should be considered

$\circ$ OK for $\mathcal{O}(\alpha)$ NL EW corrections: $\delta \sim \frac{\Gamma_W}{M_W} \frac{\alpha}{\pi} < 10^{-4}$

▶ Such solutions implemented in two MCEGs for WW process:

- **RacoonWW**: A. Denner, S. Dittmaier, M. Roth, D. Wackeroth

  $\longrightarrow$ Nucl. Phys. **B587** (2000) 67, and refs. therein.

- **KoralW** & **YFSWW3**: S. Jadach, W. Placzek, M. Skrzypek, B.F.L. Ward, Z. Was

  $\longrightarrow$ Comput. Phys. Commun. **140** (2001) 432 and 475, and refs. therein.

RacoonWW

(A. Denner, S. Dittmaier, M. Roth, D. Wackeroth)

- Matrix element for all $e^+e^- \to 4f$ processes in massless-fermion approximation
- Matrix element for all $e^+e^- \to 4f\gamma$ processes in massless-fermion approxim.
- ISR up to $\mathcal{O}(\alpha^2)$ LL with soft-photon exponentiation through QED structure functions
- Coulomb correction for off-shell Ws
- Non-factorizable QED virtual corrections in DPA
- Virtual $\mathcal{O}(\alpha)$ NL EW corrections in DPA (used 1-loop calculations of on-shell WW production and decay)
- Two methods of treating soft and collinear photon singulatities: dipole subtraction and phase-space slicing $\longrightarrow$ proper matching between virtual and real corrections
- Anomalous Triple and Quartic gauge-boson couplings
- Multi-channel MC algorithm for integration and event generation

KoralW & YFSWW3

(S. Jadach, W. Placzek, M. Skrzypek, B.F.L. Ward, Z. Was)

KoralW:

- Fully massive matrix element for all $e^+e^- \to 4f$ processes (GRACE)
- Two independent efficient multi-channel MC algorithms for $4f$ phase space

YFSWW3:

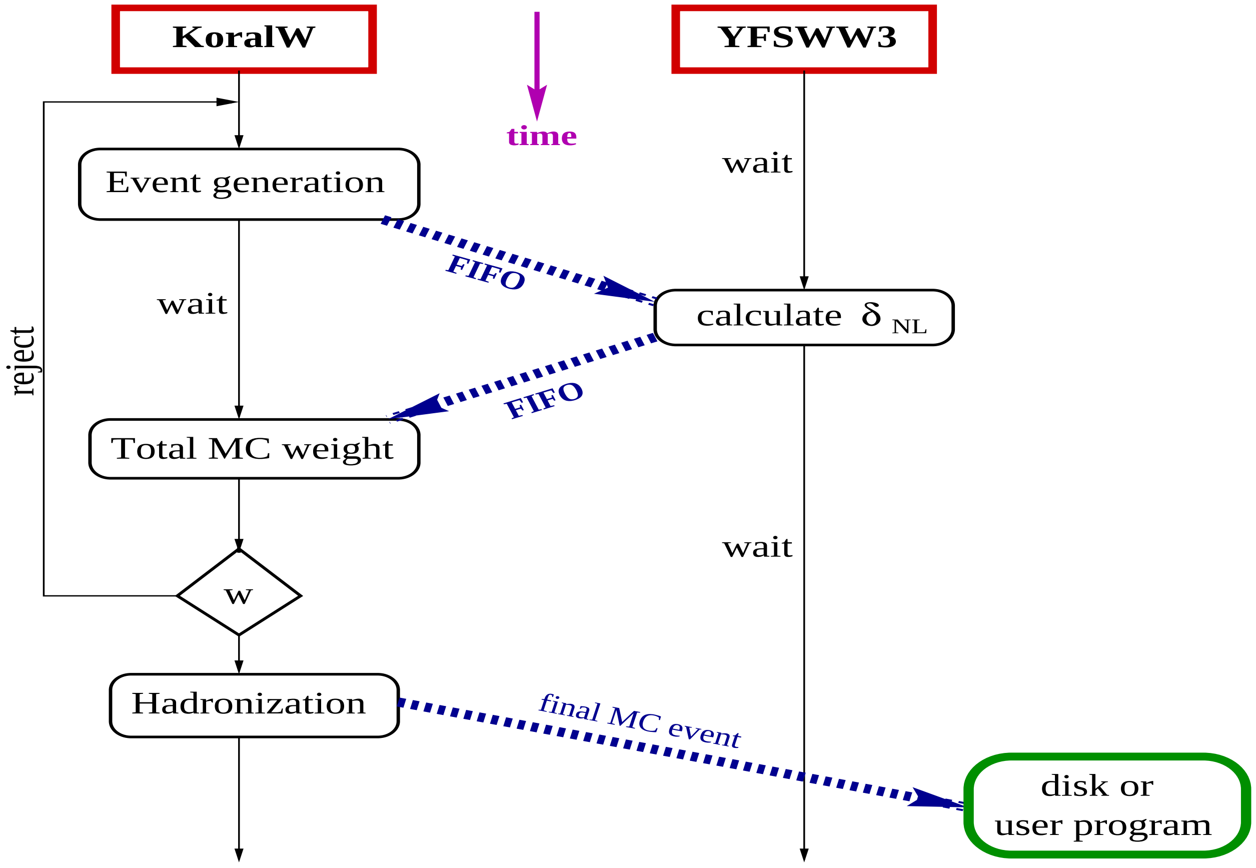
- Multiphoton radiation in WW production stage in the YFS scheme
- $\mathcal{O}(\alpha)$ NL EW corrections in LPA (from on-shell WW production at $\mathcal{O}(\alpha)$: J. Fleischer et al., ZP**C42** (1989) 409, K. Kolodziej & M. Zralek, PR**D43** (1991) 3619)

Both:

- ISR in YFS exponentiation up to $\mathcal{O}(\alpha^3)$ LL with non-zero p_T multi-photons
- Coulomb correction for off-shell Ws
- Non-factorizable corr. in inclusive approx. of “screened-Coulomb” ansatz
- Anomalous TGCs (three parametrisations)
- FSR by PHOTOS up to $\mathcal{O}(\alpha^2)$ LL
- τ decays by TAUOLA; quark fragmentation and hadronization by JETSET
- Semi-Analytical program KorWan for WW process including leading corr.

Results of both programs combined in real-time execution (event-per-event) using Unix FIFO pipes:

⇒ Concurrent Monte Carlo (CMC): KoralW&YFSWW3



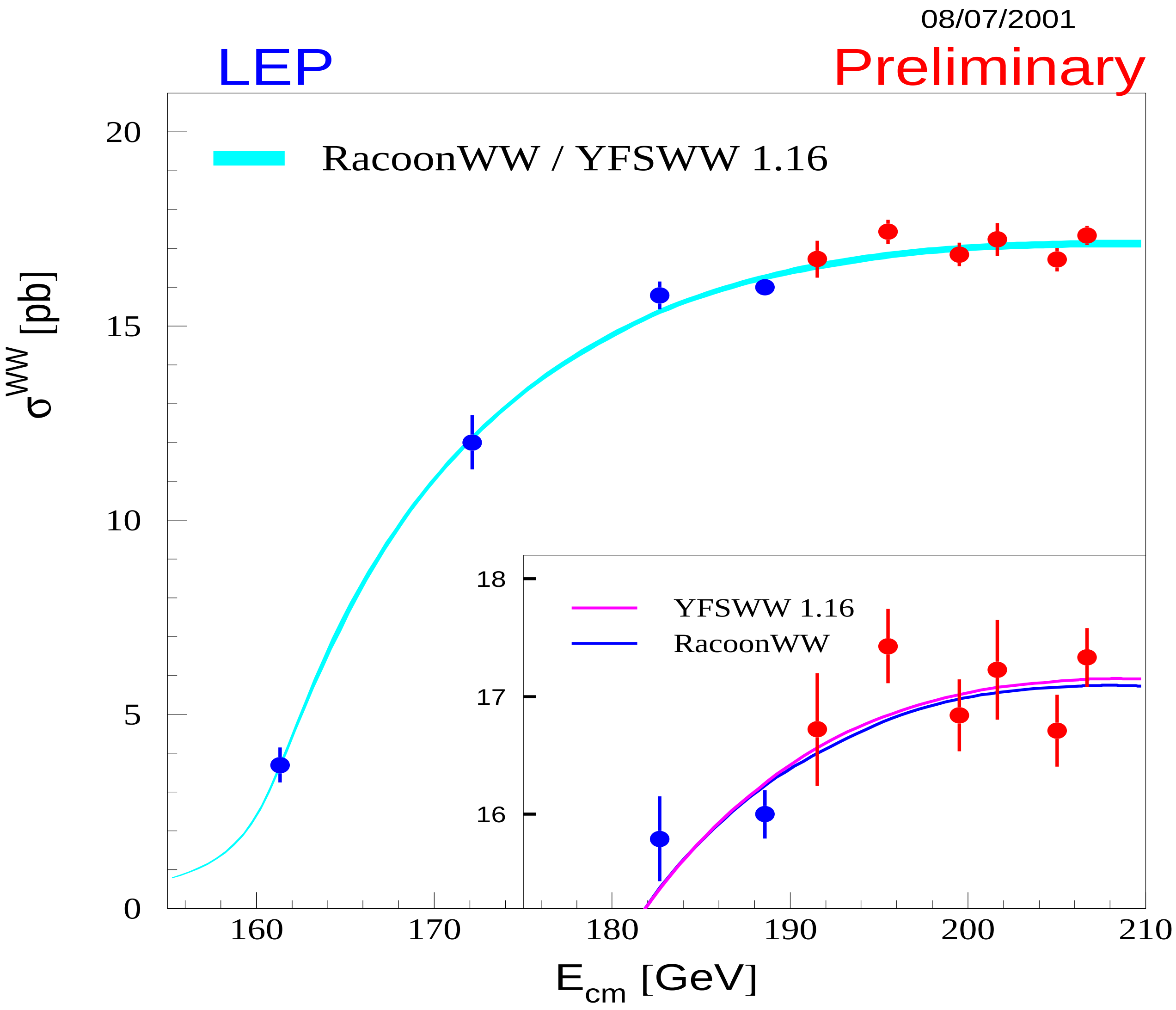
Works effectively as a single MC event generator!

σ_{WW} @ LEP2 Energies: YFSWW3 vs. RacoonWW

$\sqrt{s}\,[GeV]$	$\sigma_{WW}\,[pb]$		(Y − R)/Y [%]
	YFSWW3	RACOONWW	
168.000	9.8342 (29)	9.8392 (49)	−0.05 (6)
172.086	12.0982 (34)	12.0896 (76)	0.08 (7)
176.000	13.6360 (45)	13.6271 (66)	0.07 (6)
180.000	14.7790 (42)	14.7585 (72)	0.14 (6)
182.655	15.3584 (43)	15.3684 (76)	−0.07 (6)
185.000	15.7691 (46)	15.7716 (78)	−0.02 (6)
188.628	16.2578 (47)	16.2486 (111)	0.06 (8)
191.583	16.5523 (47)	16.5188 (85)	0.21 (6)
195.519	16.8282 (49)	16.8009 (87)	0.16 (6)
199.516	17.0099 (49)	16.9791 (88)	0.18 (6)
201.624	17.0643 (51)	17.0316 (89)	0.19 (6)
205.000	17.1213 (53)	17.0792 (89)	0.24 (6)
208.000	17.1361 (53)	17.0942 (90)	0.24 (7)
210.000	17.1229 (52)	17.0858 (91)	0.20 (7)
215.000	17.0651 (54)	17.0378 (91)	0.16 (7)

Agreement within 0.3%

Comparison with LEP2 data (LEP EWWG)

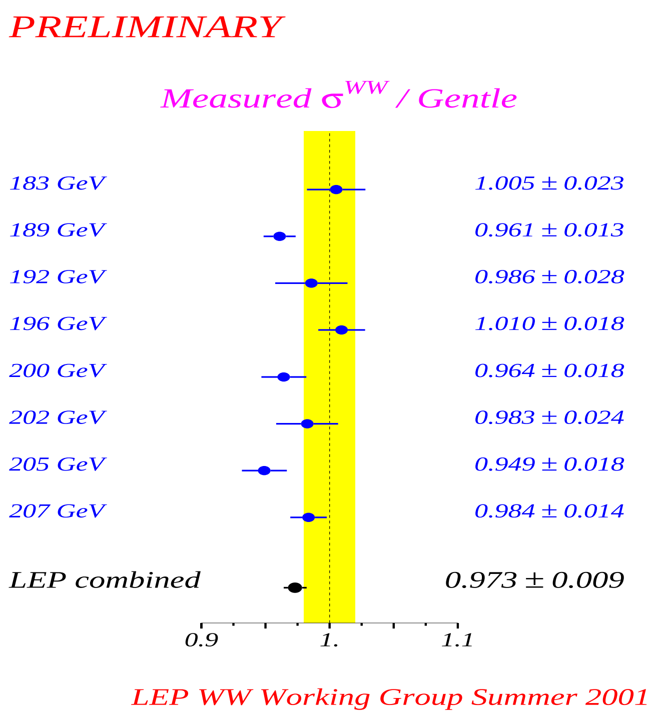


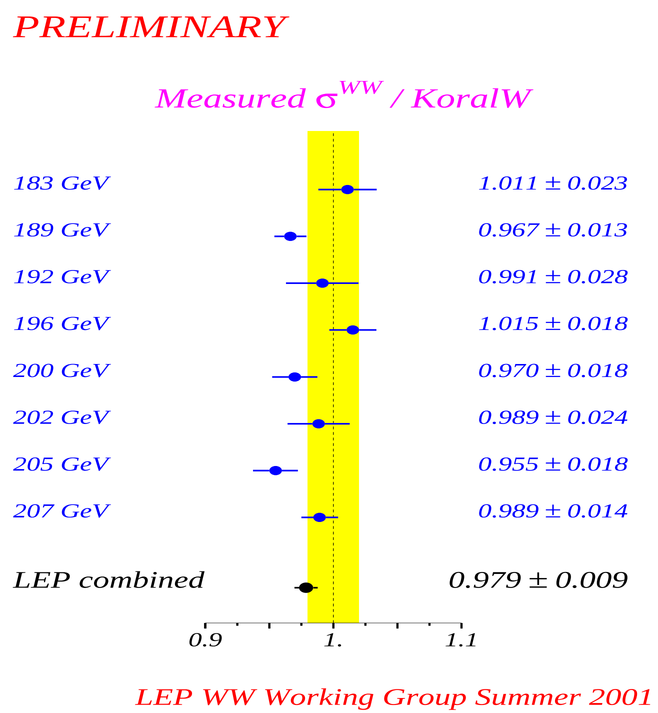
TH Precision $\simeq 0.5\%$

Theoretical precision of the main LEP2 WW-observables

LEP EWWG

Leading Corrections Only



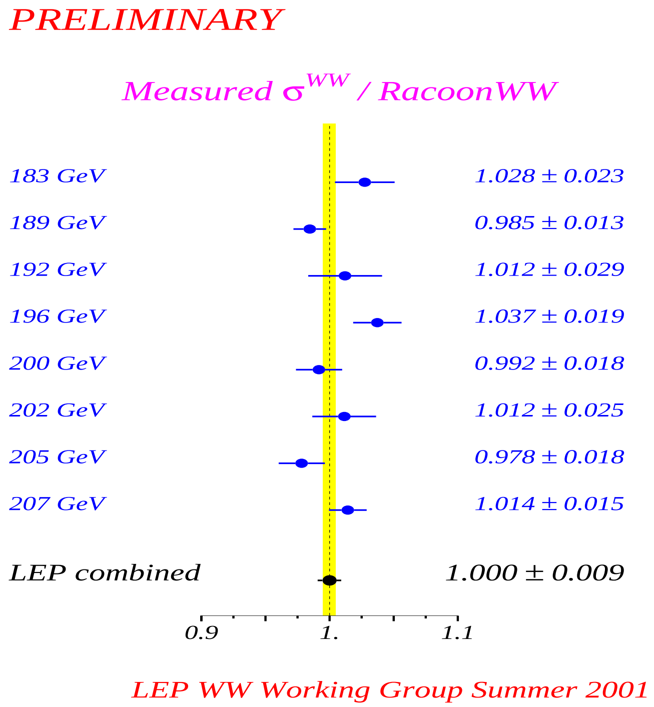


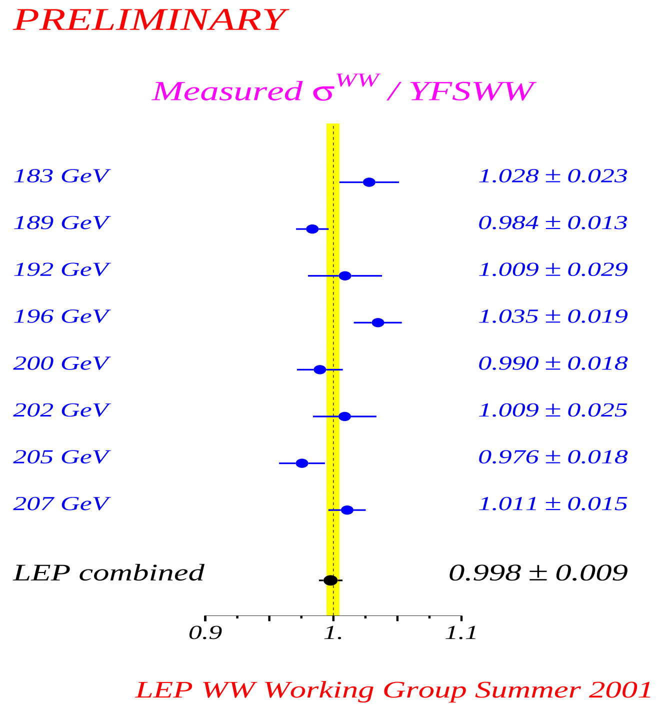
LEP2 data $\sim 3\sigma$ (exp.) away from TH predictions!

Genuine $\mathcal{O}(\alpha)$ EW Corrections needed!

LEP EWWG

Including $\mathcal{O}(\alpha)$ NL EW Corrections





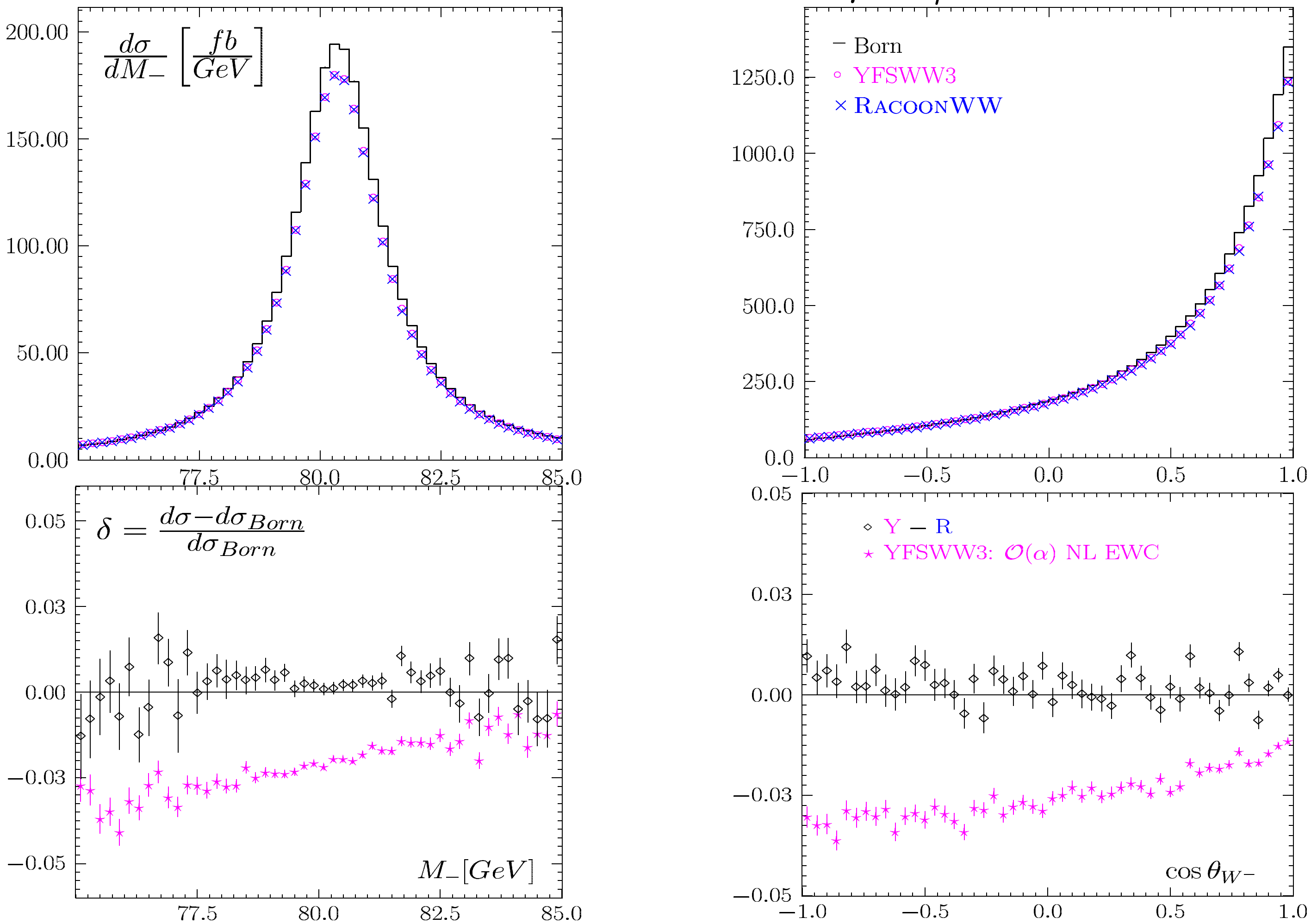
Very good agreement of LEP2 data with YFSWW and RacoonWW predictions!

$\mathcal{O}(\alpha)$ **NL EW Corr.** ~ 1–2% **at LEP2 Energies – Negative!**

Theoretical precision of the main LEP2 WW-observables

YFSWW3 $\leftrightarrow$ RacoonWW

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



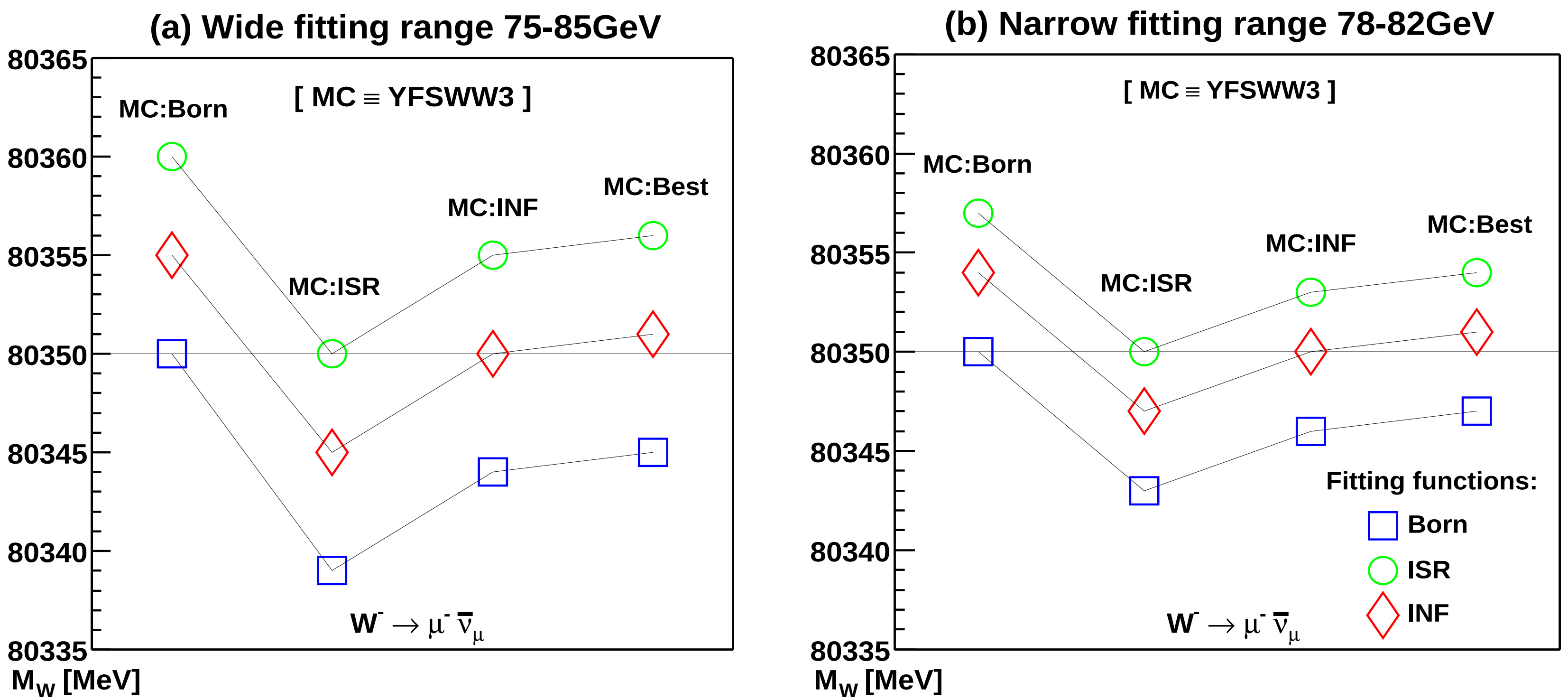
W **invariant mass** $\Rightarrow M_W$ W **polar angle** $\Rightarrow$ **TGC**

RacoonWW and YFSWW3 agree at $\lesssim 1\%$

TH precision of M_W

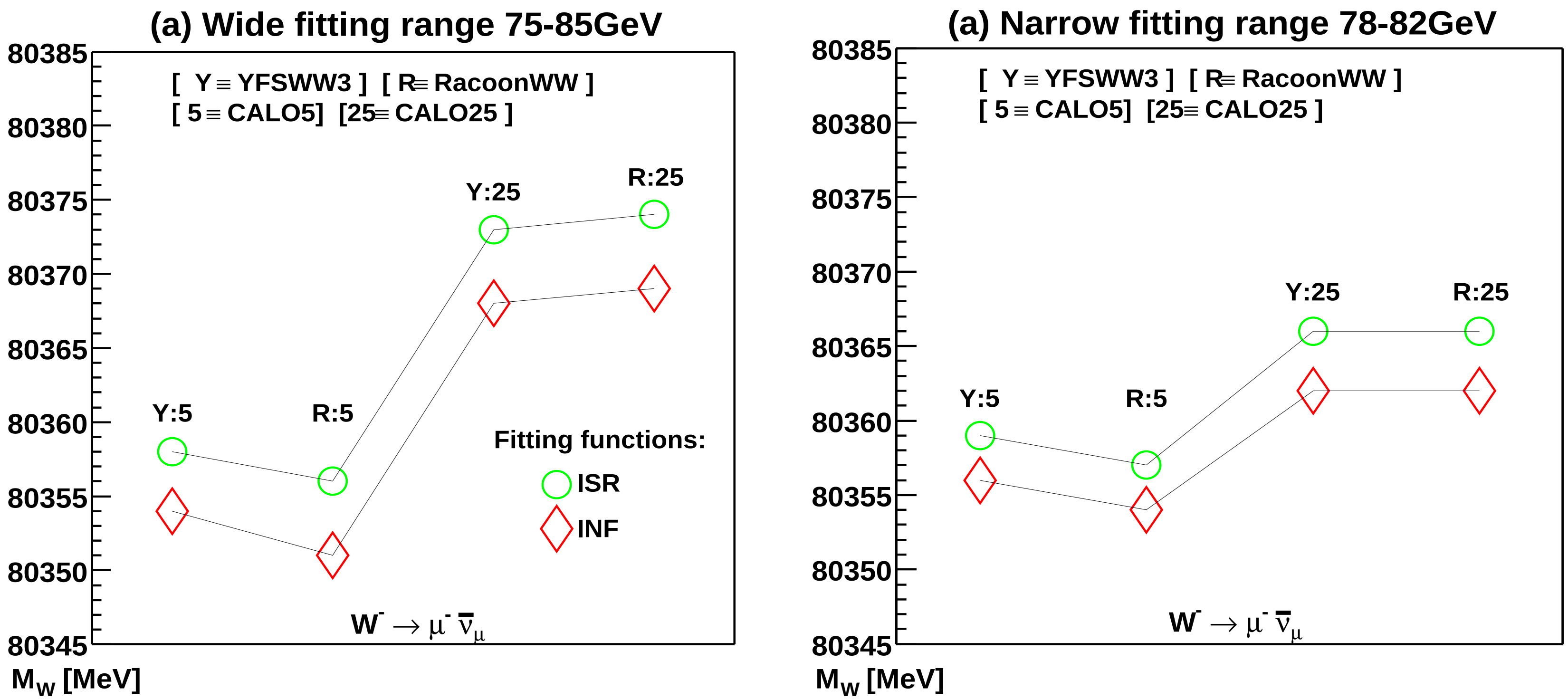
$\longrightarrow$ S. Jadach et al., Phys. Lett. **B523** (2001) 117

Fits of KorWan to W invariant mass distributions from YFSWW3



- The fitted M_W exactly agrees with the input M_W in the case when the same effects are included both in the fitting function and the MC.
- The size of the ISR effect is about -10 **MeV**, that of the INF about $+5$ **MeV**, and the size of the NL corrections ~ 1 **MeV** (negligible!).

Fits of KorWan to W inv. mass distributions from YFSWW3 and RacoonWW



CALO5 and CALO25 – two calorimetric-type acceptances

- Difference between **YFSWW3** and **RacoonWW** in fitted $M_W \lesssim 3$ MeV

$\longrightarrow$ Many more fits for various effects/corrections were performed

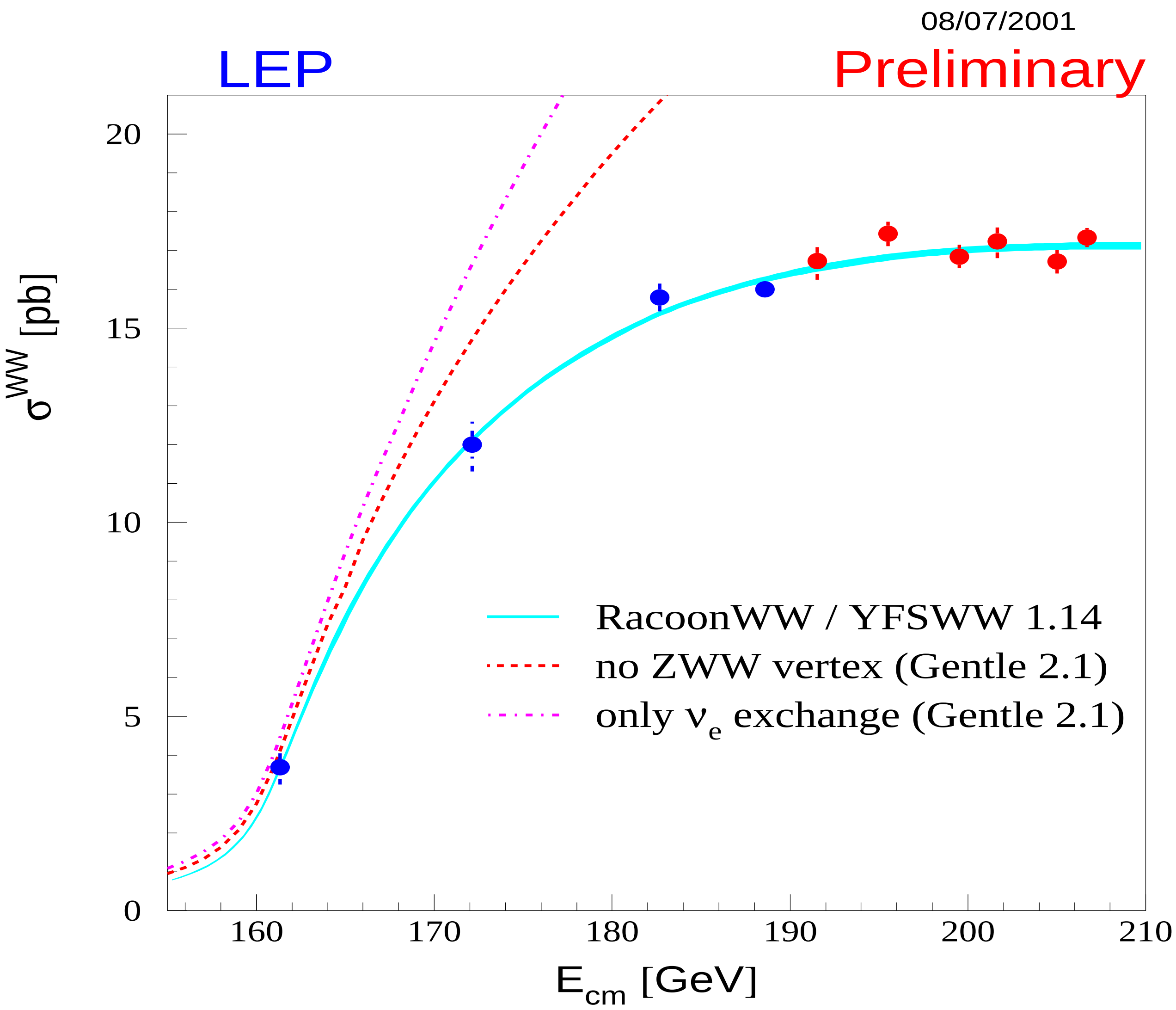
Theoretical precision of the main LEP2 WW-observables

Estimation of the missing effects in KoralW&YFSWW3

ΔM_W			
Error Type	Scale Param. $\Delta M_W = \Gamma \times \epsilon$	Numerical cross-check	ΔM_W
WW production			
ISR $\mathcal{O}(\alpha^4 L_e^4)$	$\epsilon \simeq \frac{\Gamma_W M_W}{s\beta_W^2}(\frac{\alpha}{\pi})^4 L_e^4 \sim 5 \cdot 10^{-6}$	$[\mathcal{O}(\alpha^3 L_e^3) - \mathcal{O}(\alpha^2 L_e^2)]_{\text{KoralW}}$	$\ll 1$ MeV
ISR $\mathcal{O}(\alpha^2 L_e)$	$\epsilon \simeq \frac{\Gamma_W M_W}{s\beta_W^2}(\frac{\alpha}{\pi})^2 L_e \sim 5 \cdot 10^{-6}$	KorWan	$\ll 1$ MeV
ISR $\mathcal{O}(\alpha^2)_{pairs}$	$\epsilon \simeq \frac{\Gamma_W M_W}{s\beta_W^2}(\frac{\alpha}{\pi})^2 L_e^2 \sim 4 \cdot 10^{-4}$	KorWan	< 1 MeV
W decay			
FSR $\mathcal{O}(\alpha)_{miss.}$	$\epsilon \simeq 0.2\left(\frac{\pi}{8}\frac{\alpha}{\pi} 2\ln\frac{M_W}{p_T}\right) \sim 10^{-3}$	Basic tests of PHOTOS	~ 2 MeV
FSR $\mathcal{O}(\alpha^2)_{miss.}$	$\epsilon \simeq \frac{1}{2}\left(\frac{\pi}{8}\frac{\alpha}{\pi} 2\ln\frac{M_W}{p_T}\right)^2 \sim 10^{-5}$	On/off 2γ in PHOTOS	$\ll 1$ MeV
Non-factorizable QED interferences (between production and 2 decays)			
$\mathcal{O}(\alpha^1)_{miss.}$	$\epsilon \simeq 0.1\left(\frac{\alpha}{4}\frac{(1-\beta)^2}{\beta}\right) \sim 10^{-4}$	Chapovsky & Khoze	< 2 MeV
$\mathcal{O}(\alpha^2)$	$\epsilon \simeq \frac{1}{2}\left(\frac{\alpha^2}{4}\frac{(1-\beta)^2}{\beta}\right)^2 \sim 10^{-7}$	None	$\ll 1$ MeV

$\delta_{th} M_W \simeq 5$ MeV

Total WW cross section (LEP EWWG)



Triple-Gauge-Boson Couplings (Non-Abelian) seen at LEP2 !

TH precision of an. TGC λ

(R. Bruneliere et al., Phys. Lett. **B533** (2002) 75)

MC parametric fits to $\cos\theta_W$ distributions from YFSWW3 and RacoonWW

ALEPH fitting function		Fitted data			
Channel	Acceptance	Y: Best−ISR	R: Best−ISR	Best: R−Y	Acceptance
$\mu\nu_\mu qq$	TRUE	0.0118 (7)	0.0102 (9)	0.0008 (10)	CALO5
		0.0121 (7)	0.0170 (9)	0.0009 (10)	CALO25
	RECO	0.0118 (7)	0.0103 (9)	0.0008 (10)	CALO5
		0.0122 (7)	0.0172 (9)	0.0009 (10)	CALO25
$e\nu_e qq$	TRUE	0.0119 (7)	0.0103 (9)	0.0008 (10)	CALO5
		0.0122 (7)	0.0172 (9)	0.0009 (10)	CALO25
	RECO	0.0119 (7)	0.0103 (9)	0.0008 (10)	CALO5
		0.0123 (7)	0.0172 (9)	0.0009 (10)	CALO25
$\tau\nu_\tau qq$	TRUE	0.0115 (7)	0.0100 (8)	0.0008 (10)	CALO5
		0.0118 (7)	0.0166 (8)	0.0009 (10)	CALO25
	RECO	0.0107 (6)	0.0091 (8)	0.0007 (9)	CALO5
		0.0109 (6)	0.0152 (8)	0.0008 (9)	CALO25
$qqqq$	TRUE	0.0118 (7)	0.0102 (9)	0.0008 (10)	CALO5
		0.0120 (7)	0.0169 (9)	0.0009 (10)	CALO25
	RECO	0.0094 (6)	0.0081 (7)	0.0007 (8)	CALO5
		0.0096 (6)	0.0132 (7)	0.0008 (8)	CALO25

(TRUE – parton level, RECO – detector reconstruction; Y=YFSWW3, R=RacoonWW)

Best − ISR $=$ $\mathcal{O}(\alpha)$ NL EW correction $\sim$ $\mathbf{0.01}$–$\mathbf{0.02}$!

Shifts of λ from various effects

YFSWW3

Effect	Acceptance	$\Delta\lambda$
1. Best − ISR	BARE$_{4\pi}$	$0.0108\,(7)$
	CALO5$_{4\pi}$	$0.0110\,(7)$
2. ISR$_3$ − ISR$_2$	BARE$_{4\pi}$	$0.0001\,(2)$
	CALO5$_{4\pi}$	$0.0001\,(2)$
3. FSR$_2$ − FSR$_1$	BARE$_{4\pi}$	$0.0001\,(3)$
	CALO5$_{4\pi}$	$0.0001\,(3)$
4. $4f$-background corr. (Born)	CALO5	$0.0021\,(3)$
	CALO25	$0.0021\,(3)$
5. $4f$-background corr. (with ISR)	CALO5	$0.0005\,(3)$
	CALO25	$0.0005\,(3)$
6. EWC-scheme: $(B) - (A)$	CALO5	$0.0006\,(9)$
	CALO25	$0.0006\,(9)$
7. LPA$_b$ − LPA$_a$	CALO5	$0.0017\,(9)$
	CALO25	$0.0018\,(9)$

RacoonWW

Effect	Acceptance	$\Delta\lambda$
1. Best − ISR	CALO5	$0.0096\,(8)$
	CALO25	$0.0158\,(8)$
2. Off-shell Coulomb effect	CALO5	$0.0001\,(10)$
	CALO25	$0.0001\,(10)$
3. $4f$-background corr. (Born)	CALO5	$0.0029\,(10)$
	CALO25	$0.0029\,(10)$
4. $4f$-background corr. (with ISR)	CALO5	$0.0008\,(10)$
	CALO25	$0.0008\,(10)$
5. On-shell projection	CALO5	$0.0003\,(10)$
	CALO25	$0.0003\,(10)$
6. DPA defi nition	CALO5	$0.0005\,(10)$
	CALO25	$0.0005\,(10)$

$$\delta_{th}\lambda \simeq 0.005$$

Conclusions

- Two independent Monte Carlo programs for precision predictions of W-pair production at LEP2:
  - **RacoonWW**: A. Denner, S. Dittmaier, M. Roth, D. Wackeroth
  - **KoralW&YFSWW3**: S. Jadach, W. Placzek, M. Skrzypek, B.F.L. Ward, Z. Was
- They include $4f$-background contributions as well as all necessary radiative corrections at the precision level required by LEP2.
- The agreement between these programs for the main observables is within the required accuracy of LEP2 experiments.
- Comparisons of these programs, comparisons with other calculations and investigations of various effects $\Rightarrow$ the theoretical precision (δ_{th}) for the main LEP2 observables:
  - ▷ $\delta_{th}\,\sigma_{WW} \sim 0.5\%$ — $\delta_{ex}\,\sigma_{WW} \sim 1\%$
  - ▷ $\delta_{th}\,M_W \sim 5$ MeV — $\delta_{ex}\,M_W \sim 30$ MeV
  - ▷ $\delta_{th}\,\lambda \sim 0.005$ (anomalous TGC) — $\delta_{ex}\,\lambda \sim 0.01$

$\longrightarrow$ To satisfy high-precision requirements of future LC – still long way to go!