W and Z Pair Production In Electron-Positron Collisions

WIESŁAW PŁACZEK
Institute of Computer Science
Jagiellonian Univesity, Cracow, Poland

Outline:

- **Introduction.**
- **Some results from LEP2.**
- WW **Physics with YFSWW/KoralW.**
- ZZ **Physics with YFSZZ/KoralW.**
- **Conclusions and outlook.**

$\Rightarrow$ Why to investigate W and Z Pair production?

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

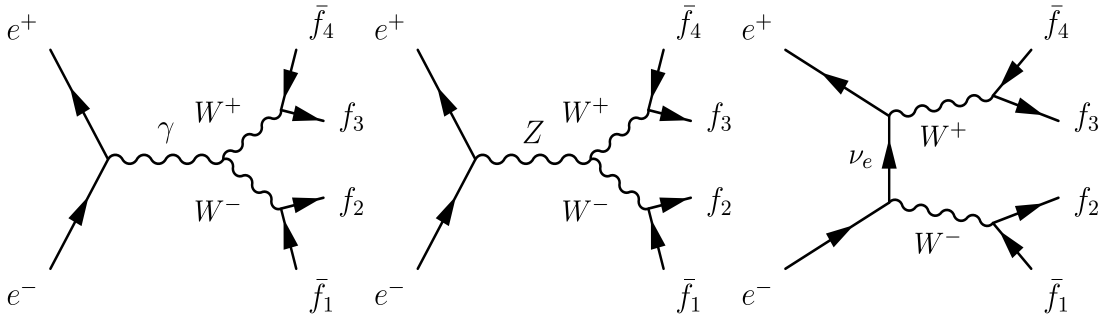
  $\rightarrow$ Before LEP2 (1995): $\Delta M_W \approx 160$ MeV,

  while: $\Delta M_Z \approx 2$ MeV
- To test the Standard Model, e.g. Triple-Gauge Couplings (TGC): $WW\gamma$ and WWZ

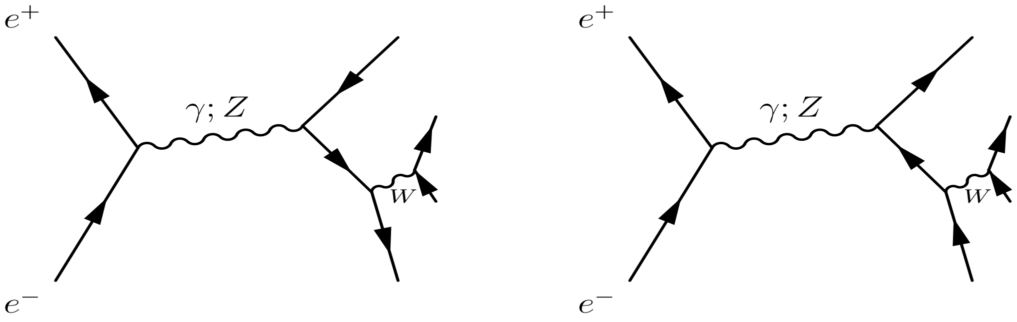
  Note: For the first time at the Born level in e^+e^- collisions
- To get better constraints on the **Higgs mass**

  $\rightarrow$ Indirectly from other SM parameters
- To search for **“new physics”**, e.g. anomalous TGCs, etc.
- WW and ZZ processes – important background for **Higgs boson** searches.

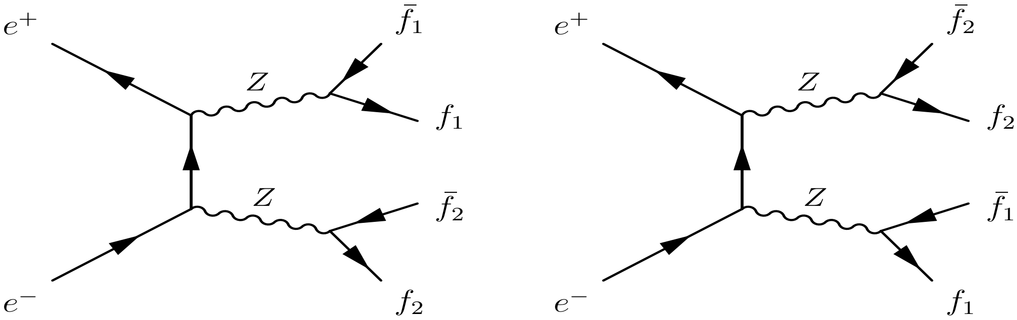
Introduction



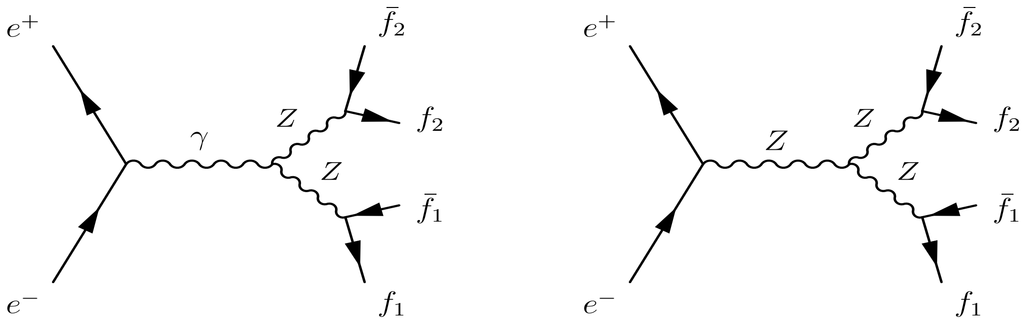
Feynman diagrams for W^+W^- Production and Decay (CC03)



Single-W-Resonant diagrams of CC11 class



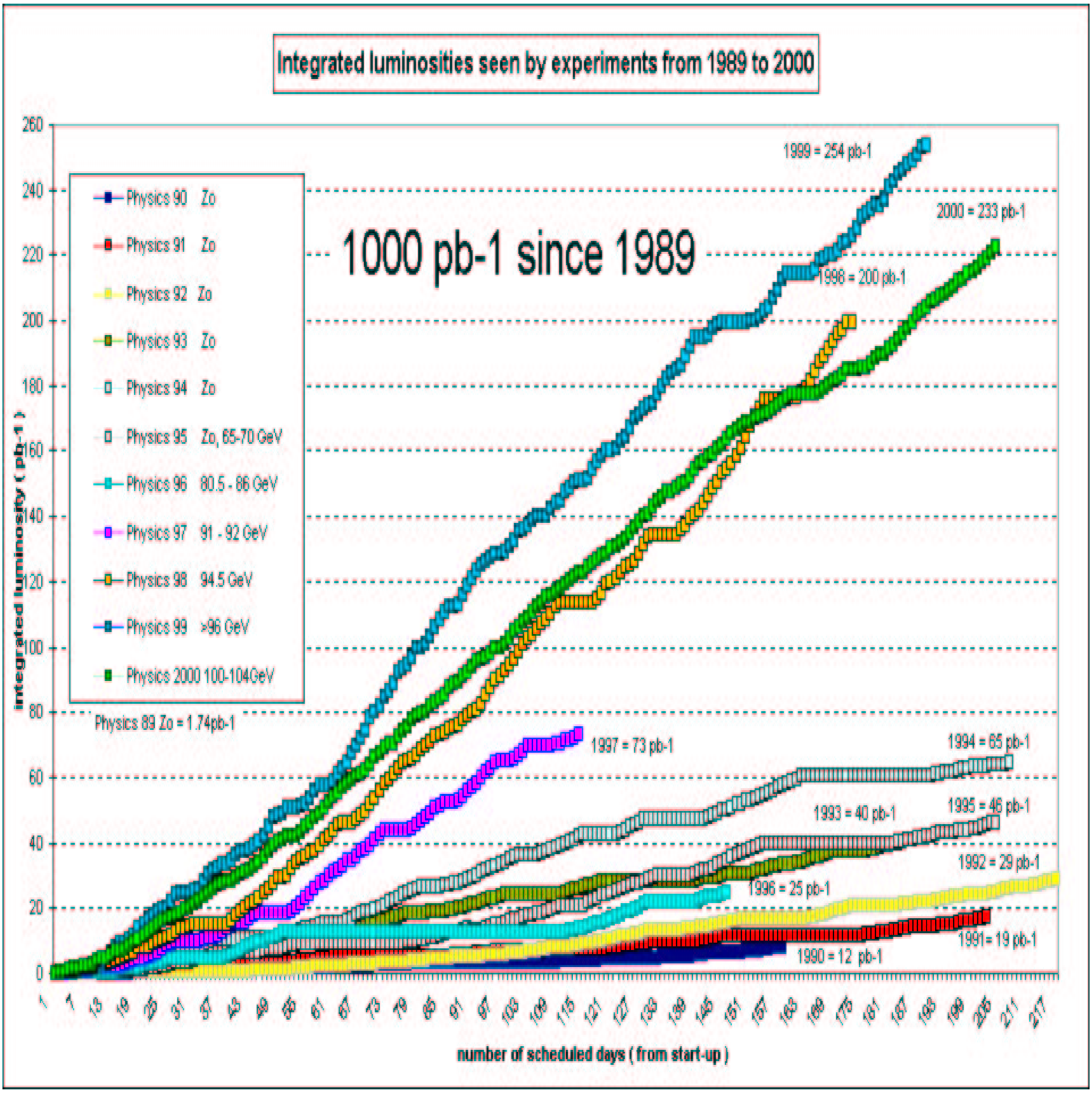
Feynman diagrams for ZZ Production and Decay (NC02)



Non-SM ZZ diagrams with Anomalous TGCs

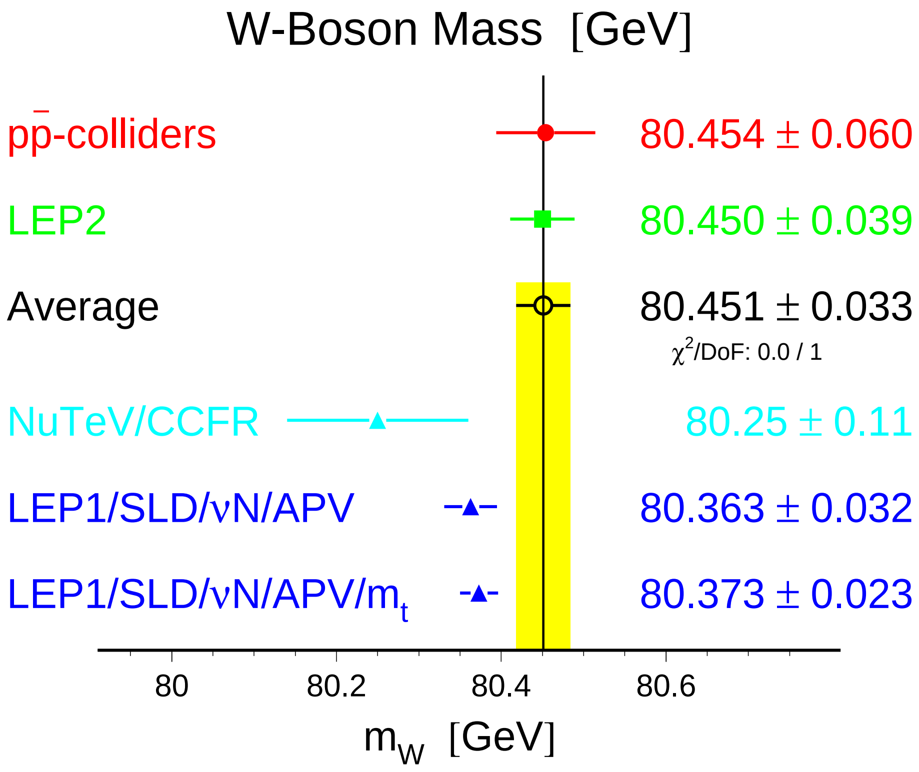
Some results from LEP2

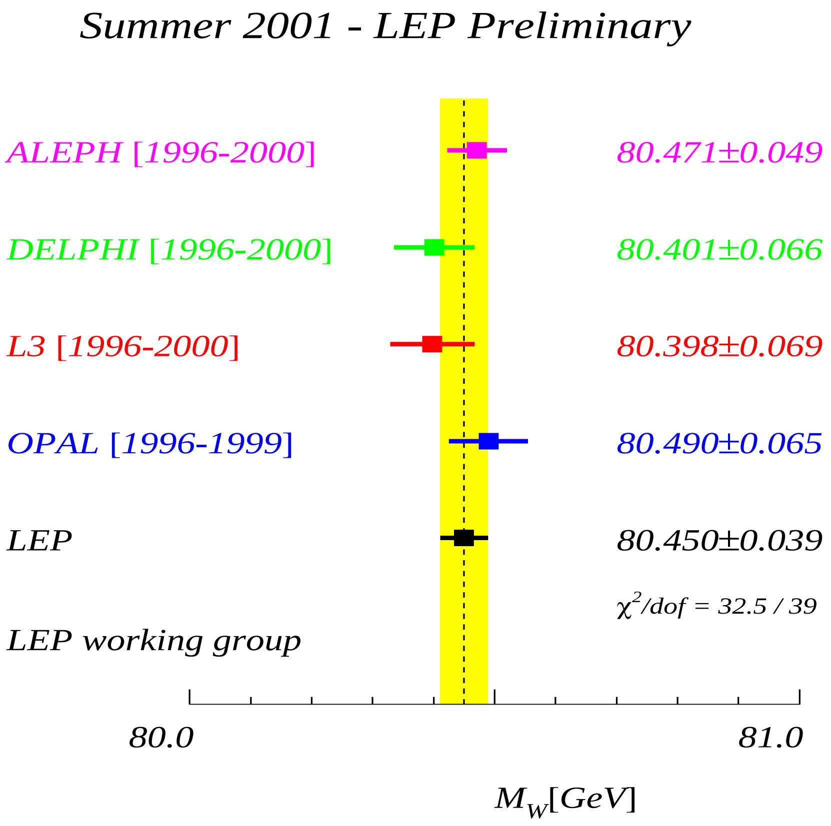
LEP Integrated Luminosity



LEP2: ~ 800 **pb**$^{-1}$

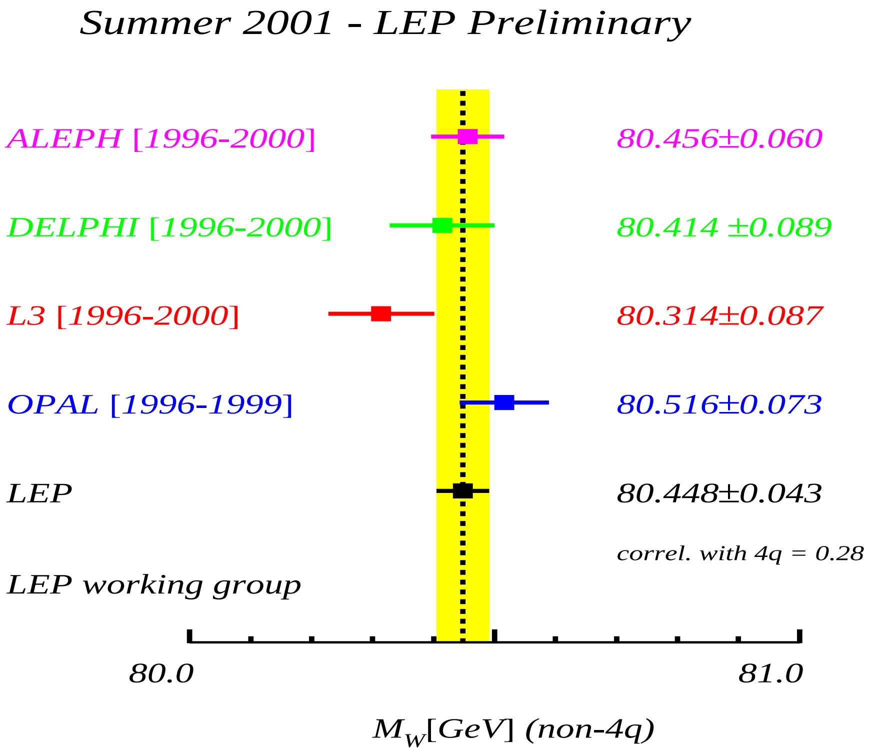
Some results from LEP2



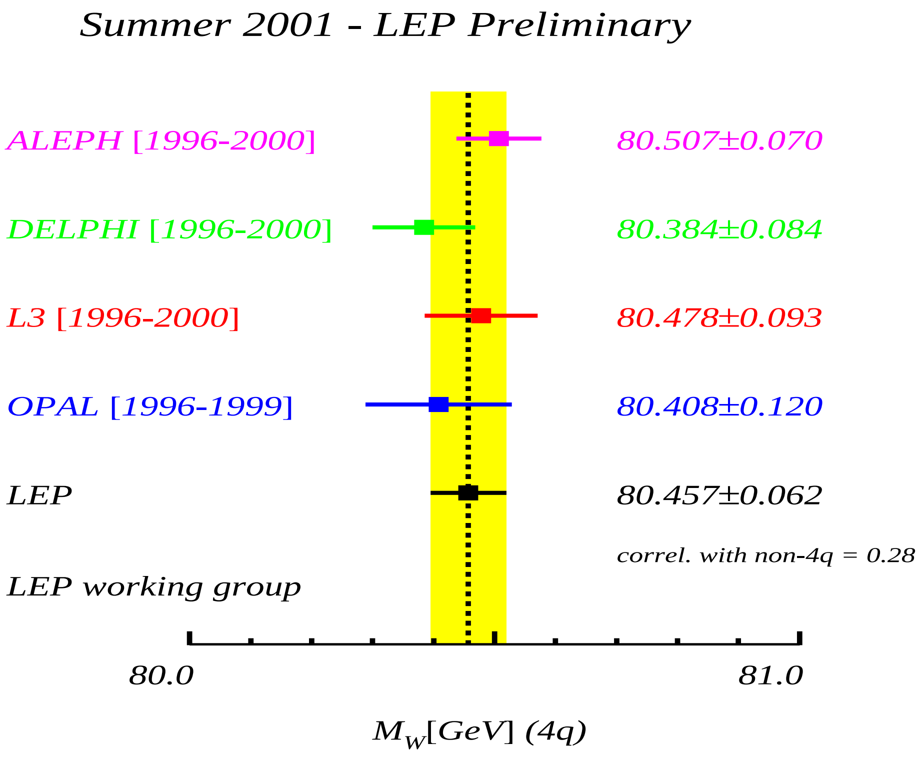


Some results from LEP2

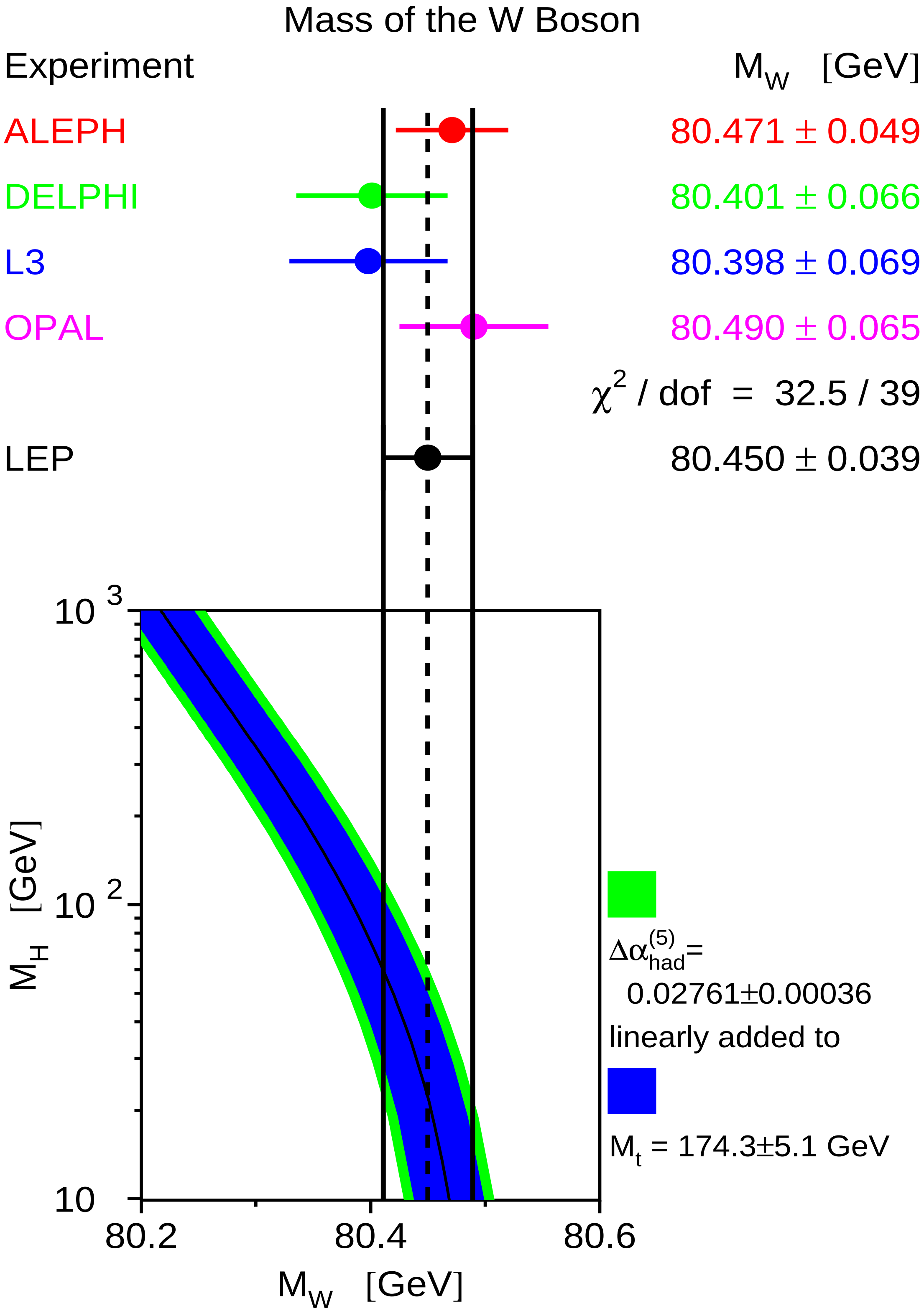
Semi-leptonic



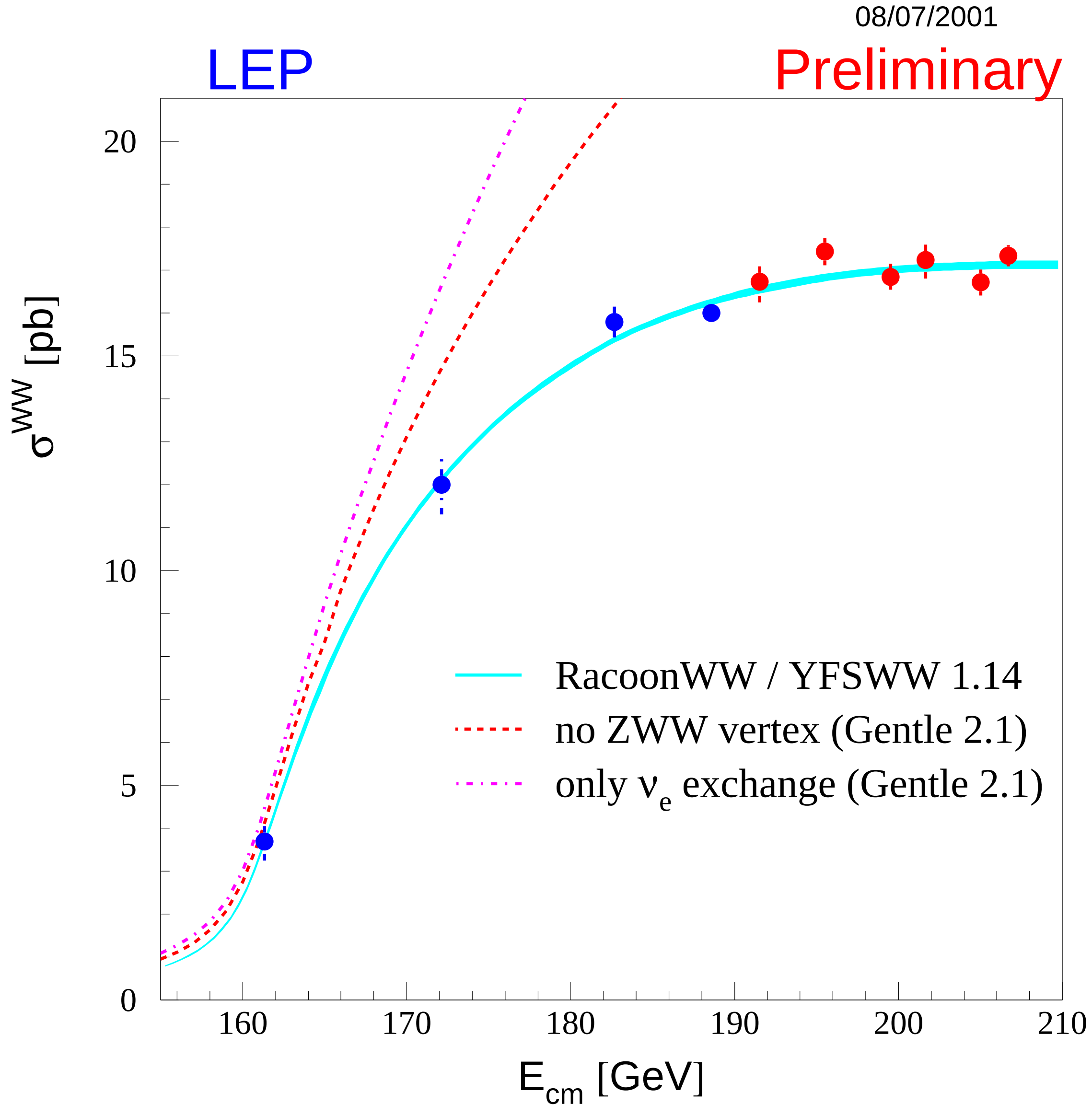
Hadronic



Some results from LEP2



WW Total Cross Section



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

WW Physics with YFSWW/KoralW

People:

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

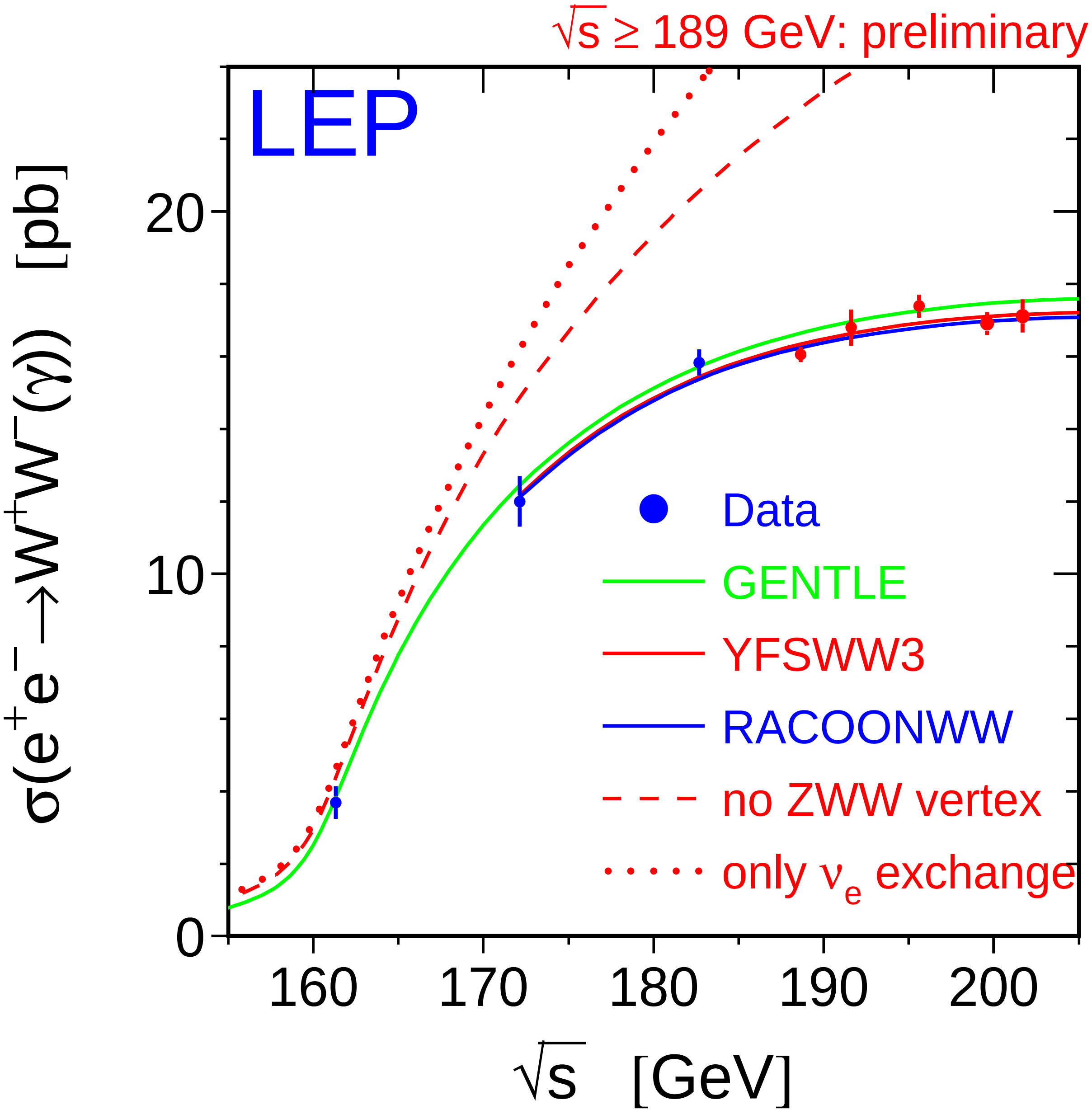
MC Programs	Papers
KoralW:	Comput. Phys. Commun. **94** (1996) 215
	Phys. Lett. **B372** (1996) 289;
	Comput. Phys. Commun. **119** (1999) 272
	Comput. Phys. Commun. **125** (2000) 8
	Comput. Phys. Commun. **140** (2001) 475
YFSWW3:	Phys. Rev. **D54** (1996) 5434
	Phys. Lett. **B417** (1998) 326
	Phys. Rev. **D61** (2000) 113010
	Comput. Phys. Commun. **140** (2001) 432
	CERN-TH/2000-337, hep-ph/0007012
	→ submitted to Phys. Rev. **D**
YFSZZ:	Phys. Rev. **D56** (1997) 6939

→ **Programs available at:**

`http://cern.ch/placzek`

LEP2 Needs $\mathcal{O}(\alpha)$ Corrections!

$\mathcal{O}(\alpha^1)$ Genuine EW Corr. ~ 1–2% at LEP2 Energies



GENTLE: No $\mathcal{O}(\alpha^1)$ EW Corrections (D. Bardin *et al.*)

YFSWW3 and RACOONWW: Include $\mathcal{O}(\alpha^1)$ EW Corrections

WW Physics with YFSWW/KoralW

$\Rightarrow$ **EXPERIMENTALLY:**

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

- **GENERAL PROCESS:**

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

$\Rightarrow$ **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

EW Loop Corrections enter through $\bar{\beta}$-functions.

Theoretical Predictions needed in terms of

Monte Carlo Event Generator !

$\Rightarrow$ **PROBLEMS:**

- CC03 set of Feynman diagrams Not Gauge-Invariant;
  At least CC11 needed for Gauge Invariance
  $\rightarrow$ **In practice, full $e^+e^- \rightarrow 4f$ process to be considered**
- ~ 80 different $4f$ channels
- Complicated Peaking behaviour in $8 + 3n$ 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

- Problem of including Finite W boson Width in $4f$ processes in Gauge-Invariant way
  $\rightarrow$ Practical solution – Complex-Mass Scheme:

$$M_V^2 \longrightarrow \tilde{M}_V^2 = M_V^2 + iM_V\Gamma_V$$

$$\sin^2\theta_W \longrightarrow \sin^2\tilde{\theta}_W = 1 - \frac{\tilde{M}_W^2}{\tilde{M}_Z^2}$$

Problems:

$\ast$ Also Space-like propagators aquire Width (Non-Physical)

$\ast$ CP structure of process may be Changed (Complex Couplings)

$\longrightarrow$ **Computing Problems** – a few examples:

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

  Source code: $\sim$ 0.5M Lines $\rightarrow$ $\sim$ 20MB

  Exec. code: $\sim$ 10MB

  Compilation time: $\sim$ 0.5h on fast PC

- **1-LOOP:** Rough estimate – mupltiply by 100

  Source code: $\sim$ 50M Lines $\rightarrow$ $\sim$ 2GB

  Exec. code: $\sim$ 1GB

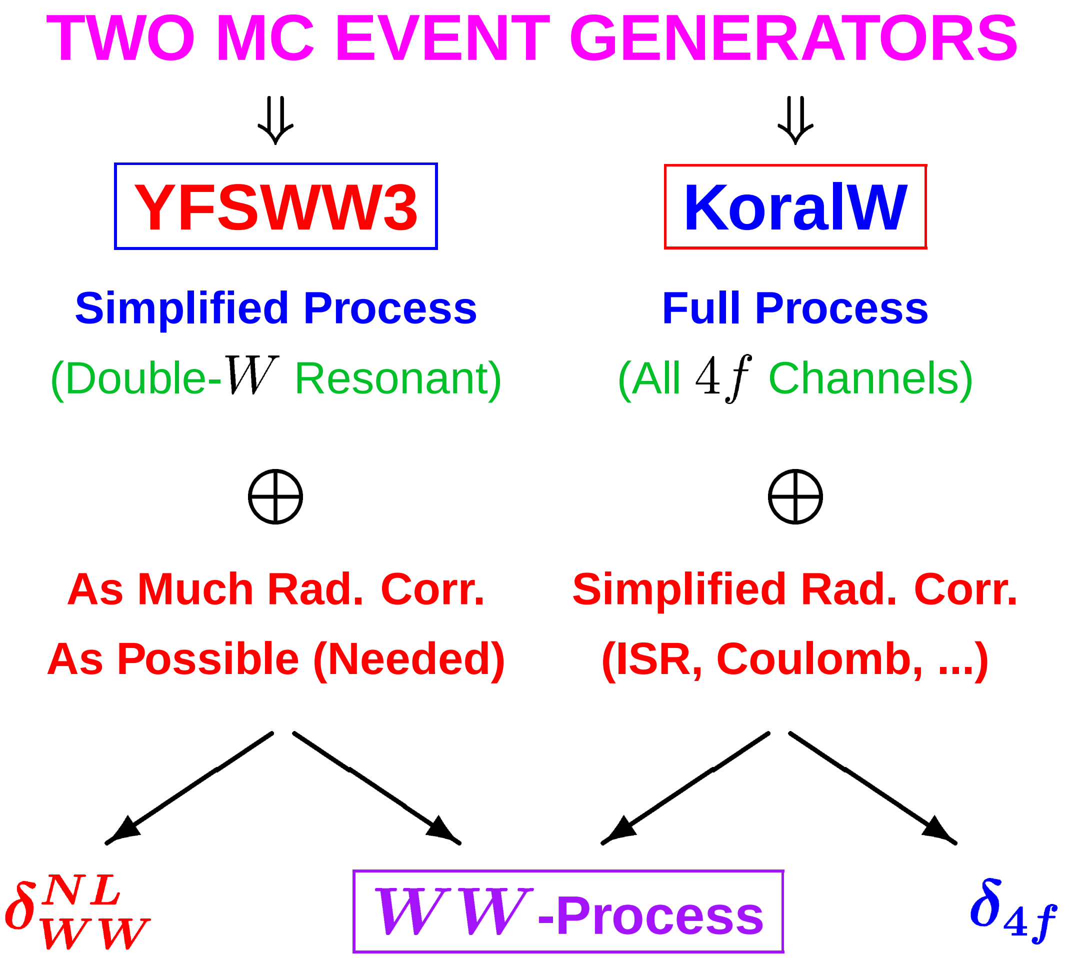
  Compilation time: $\sim$ 50h on fast PC

  $\rightarrow$ **Very Slow event generation!** $\sim$ 100 × Born

EFFICIENT APPROXIMATIONS NEEDED !

WW Physics with YFSWW/KoralW

$\Longrightarrow$ **OUR SOLUTION:**



TWO MC EVENT GENERATORS

$\Downarrow$ $\Downarrow$

YFSWW3

Simplified Process

(Double-W Resonant)

$\bigoplus$

As Much Rad. Corr.
As Possible (Needed)

KoralW

Full Process

(All $4f$ Channels)

$\bigoplus$

Simplified Rad. Corr.
(ISR, Coulomb, ...)

δ_{WW}^{NL}

- $\ast$ $\mathcal{O}(\alpha)$ NL EW Corr.
- $\ast$ γ Radiation from WW
  (in YFS Expon. Scheme)

WW-Process

- $\ast$ YFS $\mathcal{O}(\alpha^3)$LL ISR
- $\ast$ Coulomb Correction
- $\ast$ “Naive” QCD Corr.
- $\ast$ Full CKM Matrix
- $\ast$ W BRs with Rad Corr.
- $\ast$ Anomalous TGCs
- $\ast$ 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

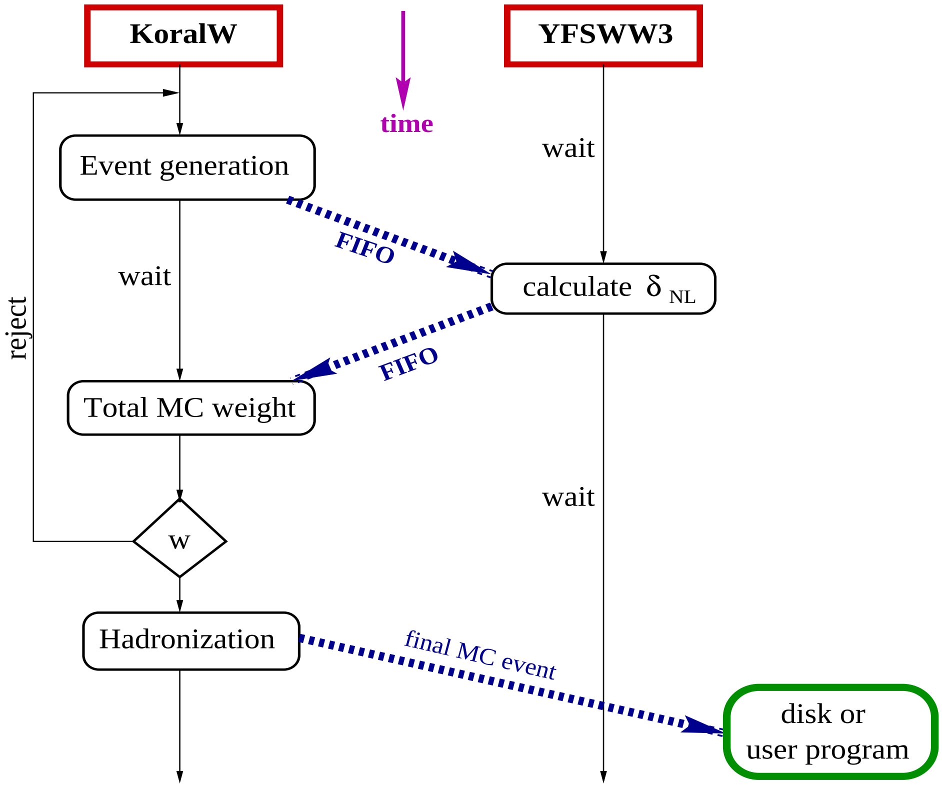
$\Rightarrow$ TWO POSSIBILITIES:

1. $\sigma_{Y/K} = \sigma_Y \oplus \delta_{4f}$ $\leftarrow$ When $\delta_{WW}^{NL} > \delta_{4f}$
2. $\sigma_{K/Y} = \sigma_K \oplus \delta_{WW}^{NL}$ $\leftarrow$ When $\delta_{4f} > \delta_{WW}^{NL}$

$\Rightarrow$ NEW:

Concurrent relalization of $\sigma_{K/Y}$: CMC KoralW&YFSWW3

Based on Unix FIFO special file (named pipe) mechanism



$\rightarrow$ Works effectively as a single MC event generator!

$4f$ Physics with KoralW

- Two independent, efficient MC Presamplers for general $4f$ Phase Space
  $\rightarrow$ Multibranch MC Algorithms (~ 50 Main Branches)
- Two dedicated MC Presamplers for W-Pair and Z-Pair Production and Decay
- YFS MC Algorithm for Arbitrary number of ISR Photons (wiht Non-Zero p_T)
- Fully-Massive $4f$ Born Matrix Element generated with GRACE System, MINAMI-TATEYA Collaboration, J .Fujimoto *et al.*
  ($\rightarrow$ It can be easily replaced by any other M.E. – due to modularity of KoralW)

WW Physics with YFSWW

Double-Resonant Graphs (CC03) – Non Gauge-Invariant!

$\Rightarrow$ **POSSIBLE SOLUTION:**

Leading-Pole Approximation (LPA):

$\frac{\Gamma_W}{M_W} \sim \frac{1}{40}$ **is Important Expansion Parameter!**

- Matrix Element (For Gauge-Invariant set of Feynman graps) can be decomposed:

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

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

(External Wave-Functions, etc.)

$\boldsymbol{M_i}$ $\leftarrow$ Lorentz-Scalar Functions

(e.g. describe finite-range W-propagation)

⇒ **TWO APPROACHES:**

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

$\boldsymbol{M_i}$ Expanded about Complex Poles (Laurent series)

corresponding to Unstable Particles (here: Ws)

$\boldsymbol{T_i}$ Untouched by Laurent expansion!

⟶ **LPA:** Only Leading-Pole terms kept!

IMPLEMENTED IN YFSWW: LPA$_a$ ← 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)

⟶ **LPA:** Only Leading-Pole terms kept!

IMPLEMENTED IN YFSWW: LPA$_b$ ← 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)

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

WW Physics with YFSWW/KoralW

- Photon Radiation Off Internal Ws
  $\longrightarrow$ Decomposition of W Propagator: $(Q' = Q - k)$

$$\frac{1}{Q^2 - M^2}\frac{1}{Q'^2 - M^2} = \frac{1}{2kQ' + k^2}\frac{1}{Q'^2 - M^2} - \frac{1}{Q^2 - M^2}\frac{1}{2kQ - k^2}$$

$\Rightarrow$ Gauge-Invariant decomposition of Radiative Corr. into Factorizable (separately in Production and Decays) and Non-Factorizable (Interferences between different stages)

- Non-Fatorizable Corrections Approximated with Screened Coulomb Ansatz: A.P. Chapovsky and V.A. Khoze, Eur. Phys. J. **C9** (1999) 449. $\longrightarrow$ Sufficient for LEP2

- Radiation in W Decays generated by PHOTOS (Z. Wąs *et al.*) $\longrightarrow$ up to two photons

- Radiative Correction at WW Production stage:
  - $\ast$ Full YFS FormFactor for $e^+e^- \to W^+W^-$
  - $\ast$ YFS MC Algorithm for Photon Radiation from WW-state (WSR)
  - $\ast$ Interferences between ISR and WSR properly included
  - $\ast$ $\mathcal{O}(\alpha)$ NL Electroweak Correcions based on:
    J. Fleischer, F. Jegerlehner and M. Zrałek, Z. Phys. **C42** (1989) 409,
    K. Kołodziej and M. Zrałek, Phys. Rev. **D43** (1991) 3619,
    (For On-Shell WW Production)

YFSWW3 ↔ KoralW

(CC09/CC10/CC11 channels)

$\sqrt{s}=161$ GeV		$\sigma_{WW}\,[fb]$		δ_{4f} [%]		δ^{NL}_{WW} [%]
Final state	Program	Born	ISR	Born	ISR	
$u\bar{d}\mu^-\bar{\nu}_\mu$	YFSWW3	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)%	—	—	—

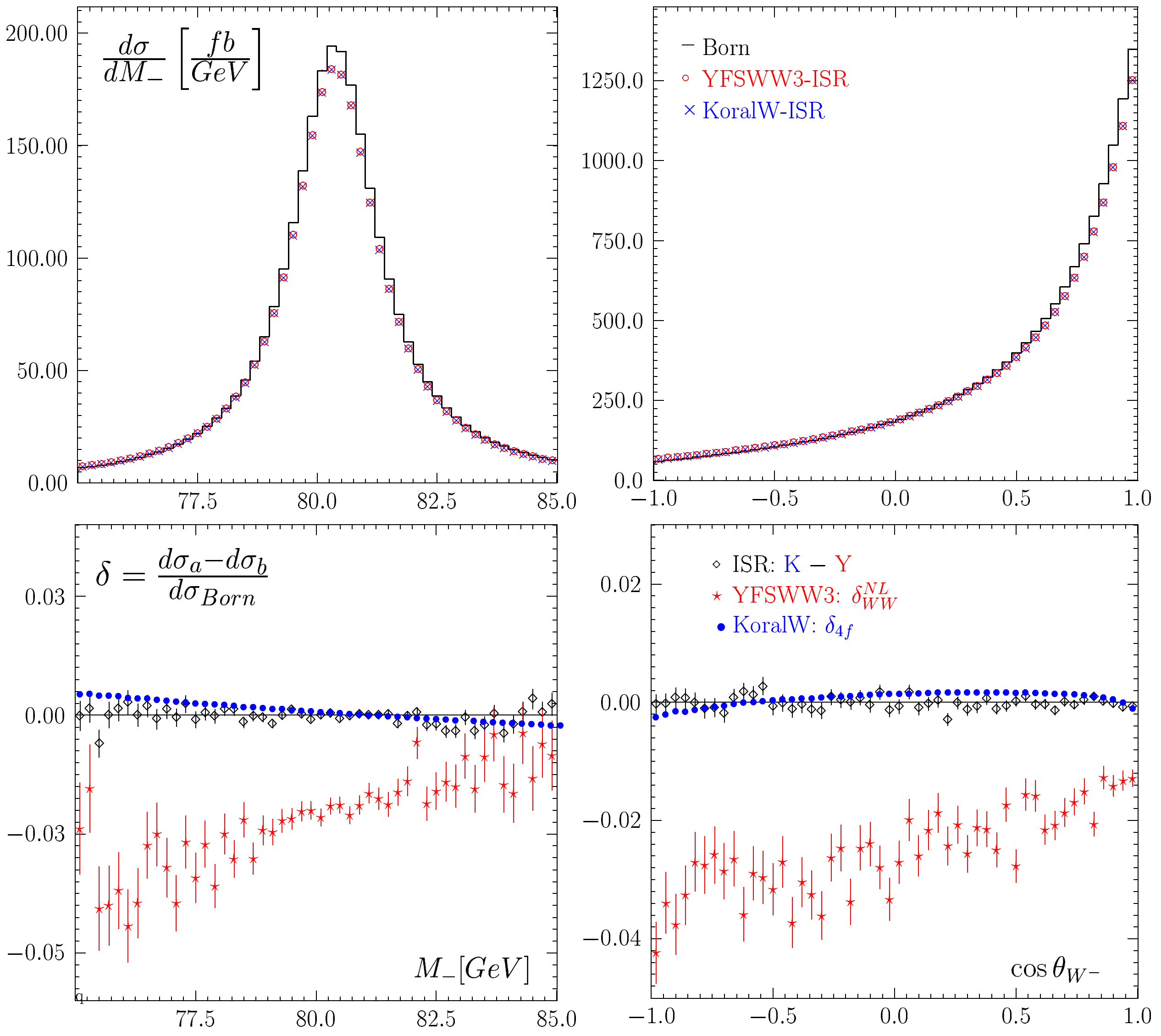
$\sqrt{s}=200$ GeV		$\sigma_{WW}\,[fb]$		δ_{4f} [%]		δ^{NL}_{WW} [%]
Final state	Program	Born	ISR	Born	ISR	
$\nu_\mu\mu^+\tau^-\bar{\nu}_\tau$	YFSWW3	219.793 (16)	204.198 (09)	—	—	−1.92 (4)
	KoralW	219.766 (26)	204.178 (21)	0.041	0.044	—
	(Y−K)/Y	0.01 (1)%	0.01 (1)%	—	—	—
$u\bar{d}\mu^-\bar{\nu}_\mu$	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)%	—	—	—

$\sqrt{s}=500$ GeV		$\sigma_{WW}\,[fb]$		δ_{4f} [%]		δ^{NL}_{WW} [%]
Final state	Program	Born	ISR	Born	ISR	
$u\bar{d}\mu^-\bar{\nu}_\mu$	YFSWW3	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)%	—	—	—

$\boldsymbol{\delta^{NL}_{WW}}$ much bigger than $\boldsymbol{\delta_{4f}}$!

YFSWW3 ↔ KoralW

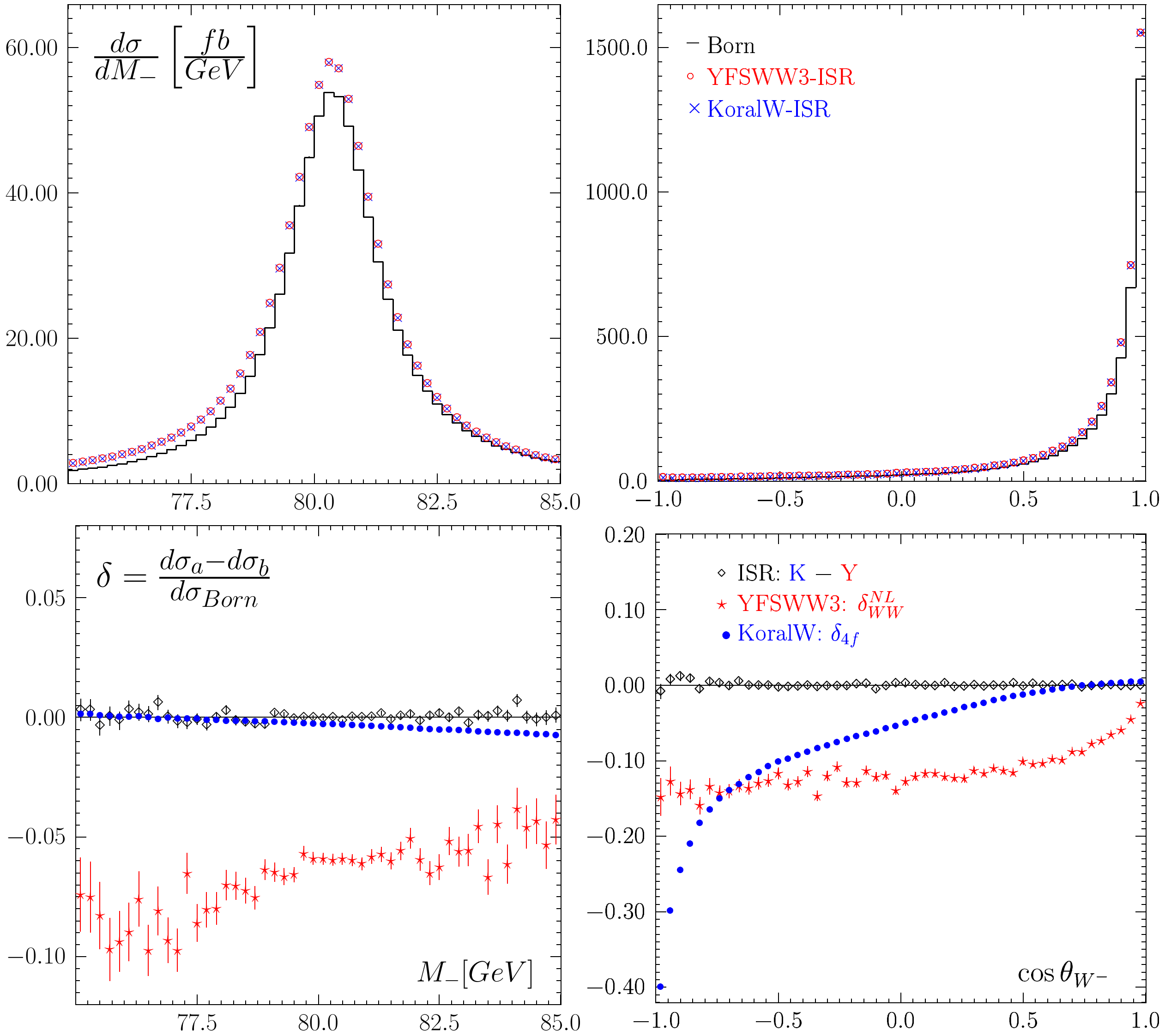
$$e^+e^- \longrightarrow W^+W^- \longrightarrow u\bar{d}\mu^-\bar{\nu}_\mu$$



$M^{inv}_{W^-}$, $\cos\theta_{W^-}$ @ $\sqrt{s} = 200$ GeV

YFSWW3 ↔ KoralW

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



$$M^{inv}_{W^-}, \cos\theta_{W^-} \text{ @ } \sqrt{s} = 500 \text{ GeV}$$

YFSWW3 ↔ RacoonWW @ LEP2 Energies

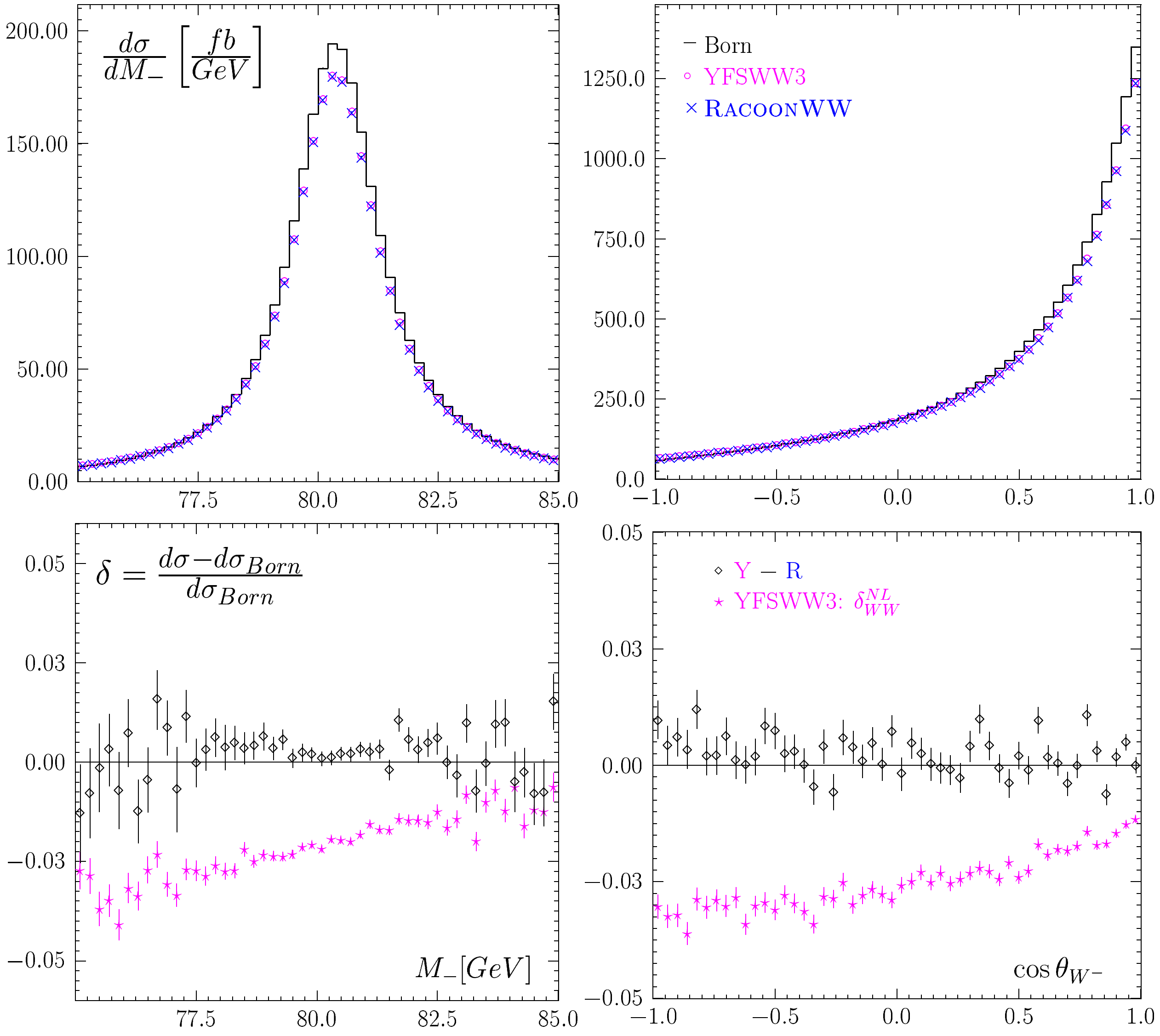
A. Denner, S. Dittmaier,
M. Roth, D. Wackeroth

$\sqrt{s}\,[GeV]$	$\sigma_{WW}\,[pb]$ YFSWW3	$\sigma_{WW}\,[pb]$ RacoonWW	(Y − R)/Y [%]
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%

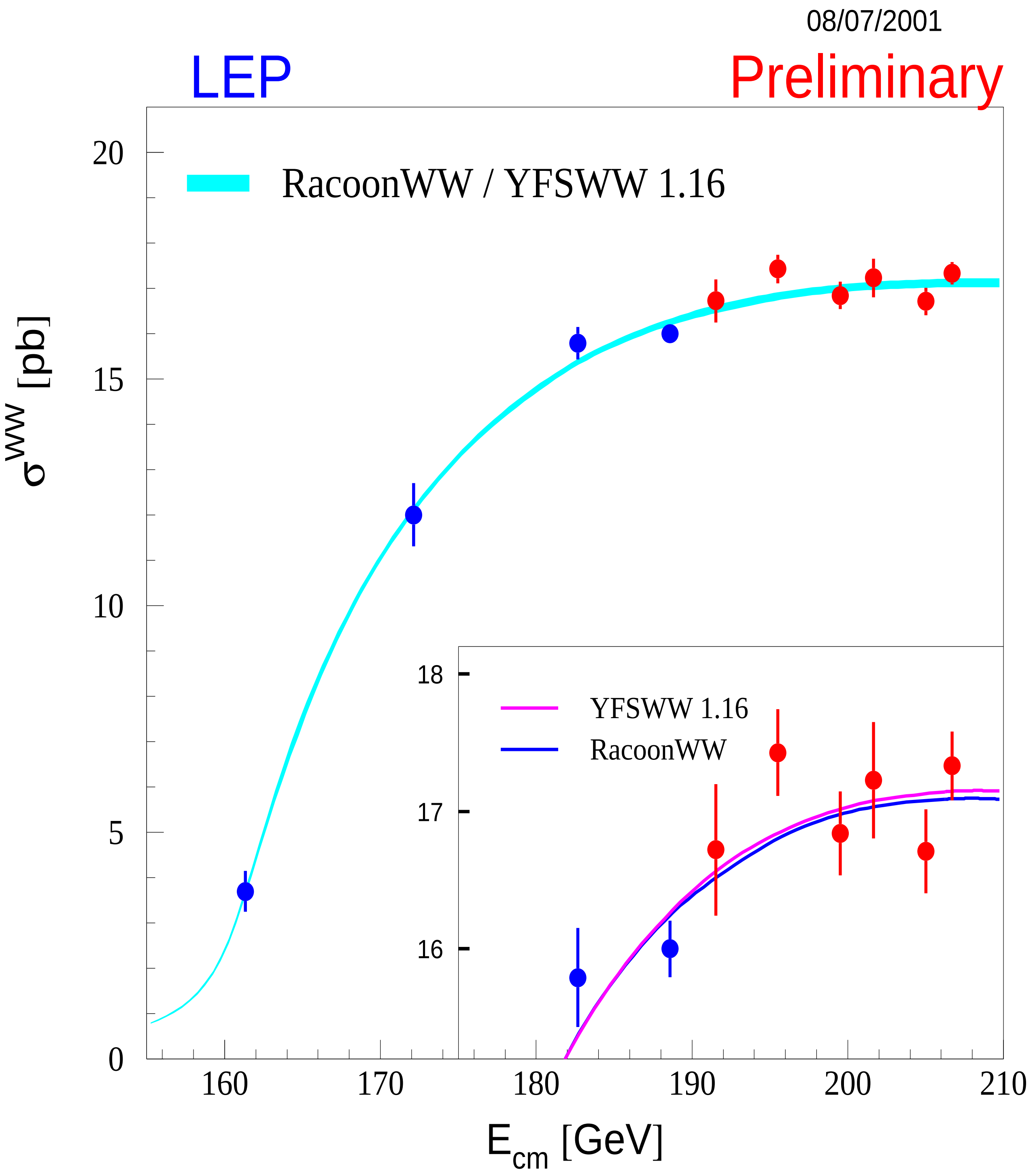
YFSWW3 ↔ RACOONWW

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



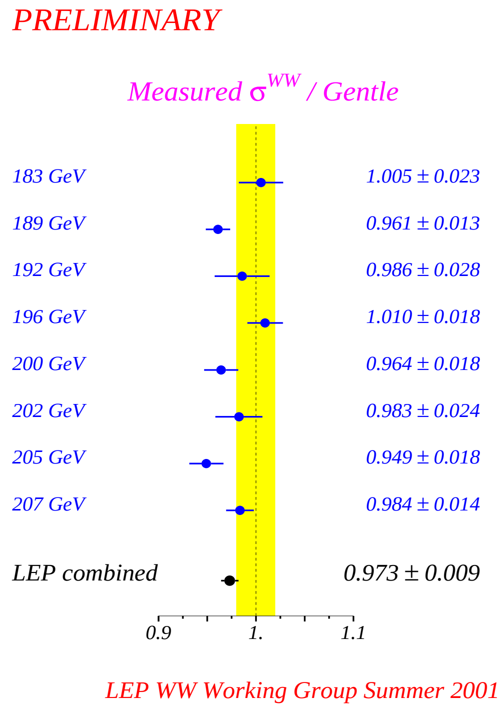
$$M^{inv}_{W^-}, \cos\theta_{W^-} \;@\; \sqrt{s} = 200 \text{ GeV}$$

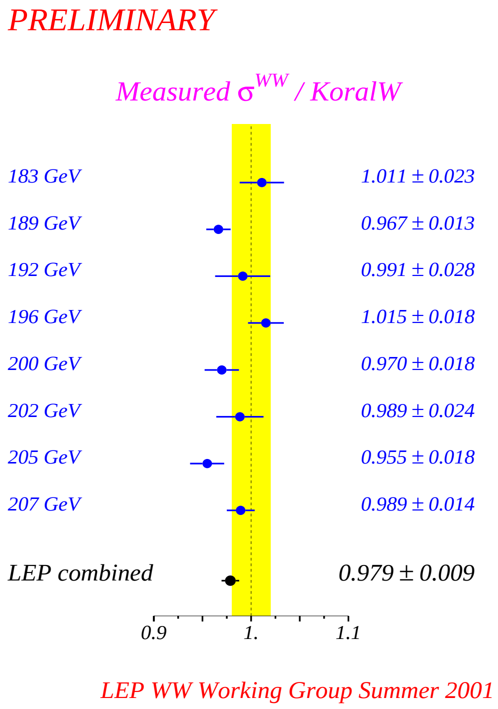
Versus LEP2 Data



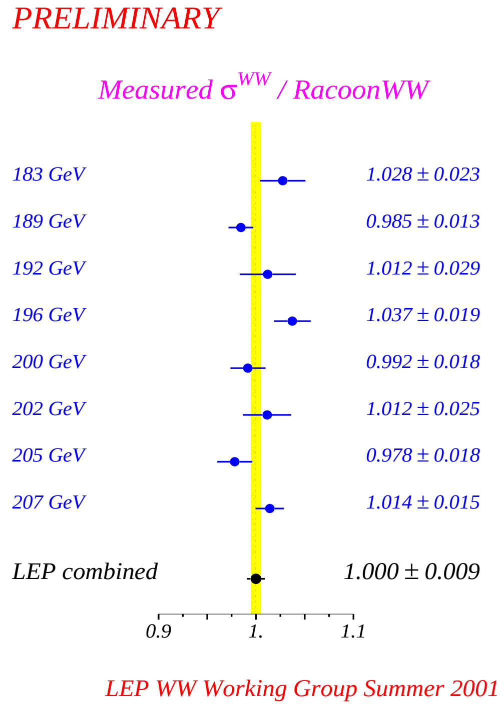
TH Precision $\simeq 0.5\%$

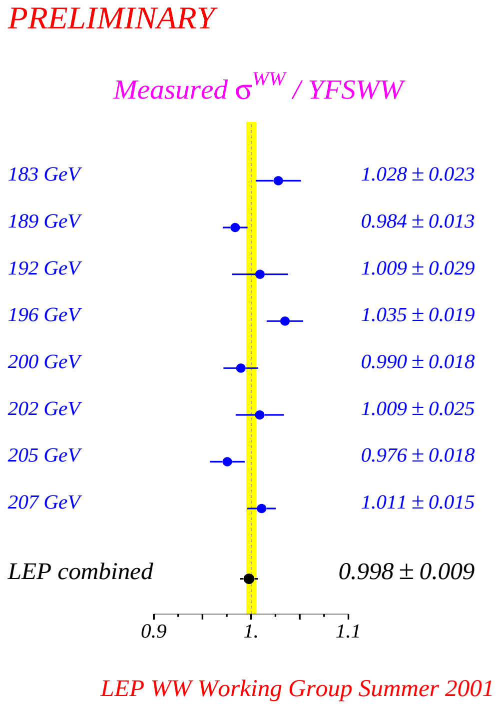
Leading Corrections Only





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





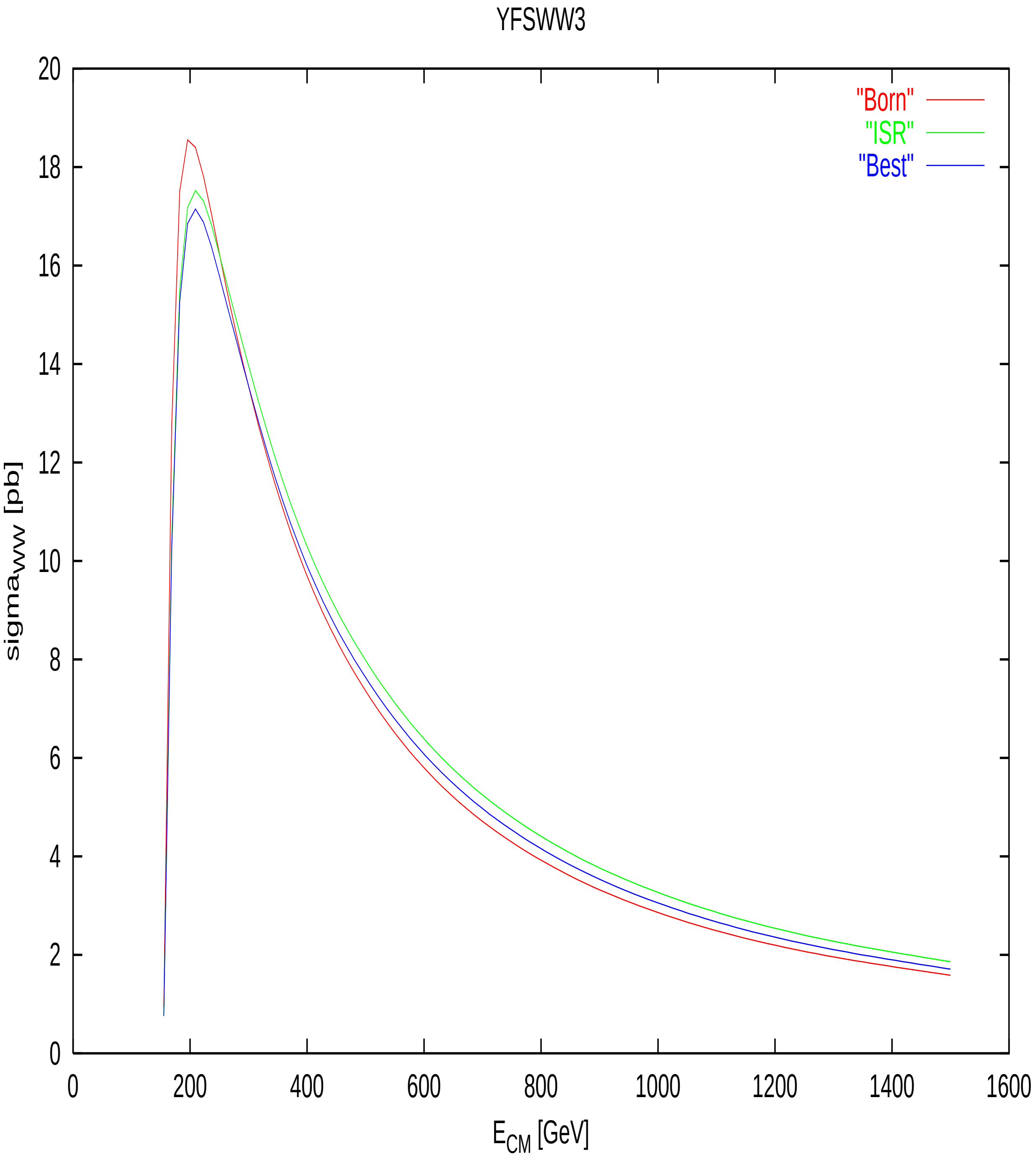
YFSWW3: Total WW Cross Section

$\sqrt{s}\,[GeV]$	$\sigma_{WW}\,[pb]$			$\frac{\text{ISR}-\text{Born}}{\text{Born}}\,[\%]$	$\frac{\text{Best}-\text{ISR}}{\text{Born}}\,[\%]$
	Born	ISR	Best		
155.000	0.94585 (17)	0.76497 (14)	0.75444 (26)	−19.12 (3)	−1.13 (4)
157.000	1.38578 (25)	1.10298 (19)	1.08636 (42)	−20.41 (3)	−1.21 (4)
159.000	2.30412 (40)	1.79141 (30)	1.76197 (69)	−22.25 (3)	−1.28 (4)
161.000	4.4138 (7)	3.3579 (5)	3.2953 (12)	−23.92 (3)	−1.43 (5)
163.000	7.3264 (10)	5.6178 (7)	5.5198 (18)	−23.32 (3)	−1.35 (4)
165.000	9.7343 (11)	7.6385 (9)	7.5059 (23)	−21.53 (3)	−1.37 (4)
167.000	11.5788 (14)	9.2903 (10)	9.1348 (26)	−19.76 (3)	−1.35 (4)
168.000	12.3391 (14)	10.0020 (11)	9.8342 (29)	−18.94(3)	−1.35 (4)
170.000	13.6124 (15)	11.2392 (12)	11.0476 (31)	−17.43 (3)	−1.42 (4)
172.086	14.6717 (16)	12.3114 (14)	12.0982 (34)	−16.09 (3)	−1.45 (4)
176.000	16.1293 (17)	13.8760 (15)	13.6360 (38)	−13.97 (3)	−1.49 (4)
180.000	17.1207 (18)	15.0325 (16)	14.7790 (42)	−12.20 (3)	−1.48 (4)
182.655	17.5852 (19)	15.6190 (17)	15.3584 (43)	−11.18 (3)	−1.49 (4)
185.000	17.8981 (19)	16.0422 (18)	15.7691 (46)	−10.37 (3)	−1.53 (4)
188.628	18.2391 (20)	16.5540 (18)	16.2578 (47)	−9.24 (3)	−1.63 (4)
191.583	18.4179 (20)	16.8649 (18)	16.5523 (47)	−8.43 (3)	−1.70 (4)
195.519	18.5466 (19)	17.1651 (19)	16.8282 (49)	−7.45 (3)	−1.83 (4)
199.516	18.5828 (19)	17.3608 (19)	17.0099 (49)	−6.58 (3)	−1.89 (4)
201.624	18.5696 (21)	17.4284 (19)	17.0643 (51)	−6.15 (3)	−1.97 (4)
205.000	18.5162 (21)	17.4968 (20)	17.1213 (53)	−5.51 (3)	−2.03 (4)
208.000	18.4399 (21)	17.5216 (20)	17.1361 (53)	−4.98 (3)	−2.10 (4)
210.000	18.3767 (21)	17.5219 (20)	17.1229 (52)	−4.65 (2)	−2.18 (4)
215.000	18.1833 (21)	17.4773 (20)	17.0651 (54)	−3.88 (2)	−2.27 (4)
250	16.2477 (16)	16.2293(14)	15.7730 (55)	−0.11 (2)	−2.81 (4)
350	11.3812 (12)	11.9325 (12)	11.5100 (47)	4.84 (2)	−3.71 (4)
500	7.3621 (8)	7.9823 (9)	7.6091 (37)	8.42 (2)	−5.07 (4)
750	4.2885 (6)	4.7993 (6)	4.5157 (25)	11.91 (2)	−6.61 (5)
1000	2.8598 (4)	3.2679 (4)	3.0375 (20)	14.27(2)	−8.07 (5)
1250	2.0714 (3)	2.4017 (4)	2.2105 (16)	15.95 (2)	−9.23 (6)
1500	1.5865 (2)	1.8615 (3)	1.6992 (14)	17.33 (2)	−10.23 (7)

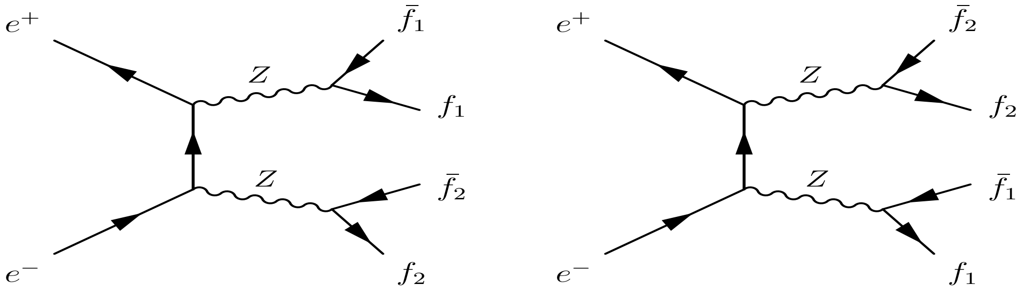
δ_{ISR} δ^{NL}_{WW}

In TESLA TDR (2001)

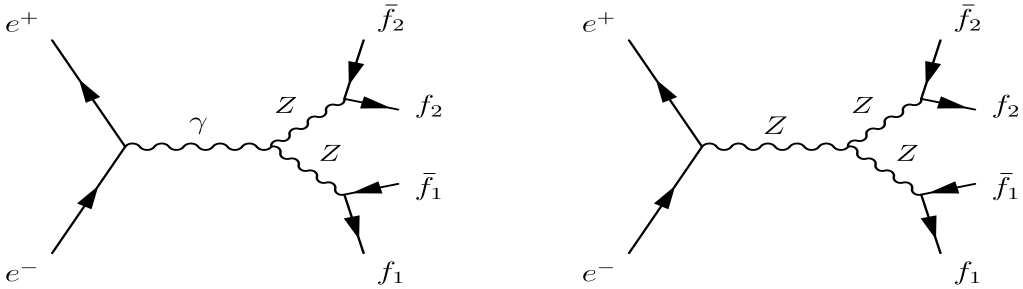
YFSWW3: “WW Line-Shape”



ZZ Production and Decay



Standard Model diagrams (NC02)



Non-SM diagrams with Anomalous TGCs

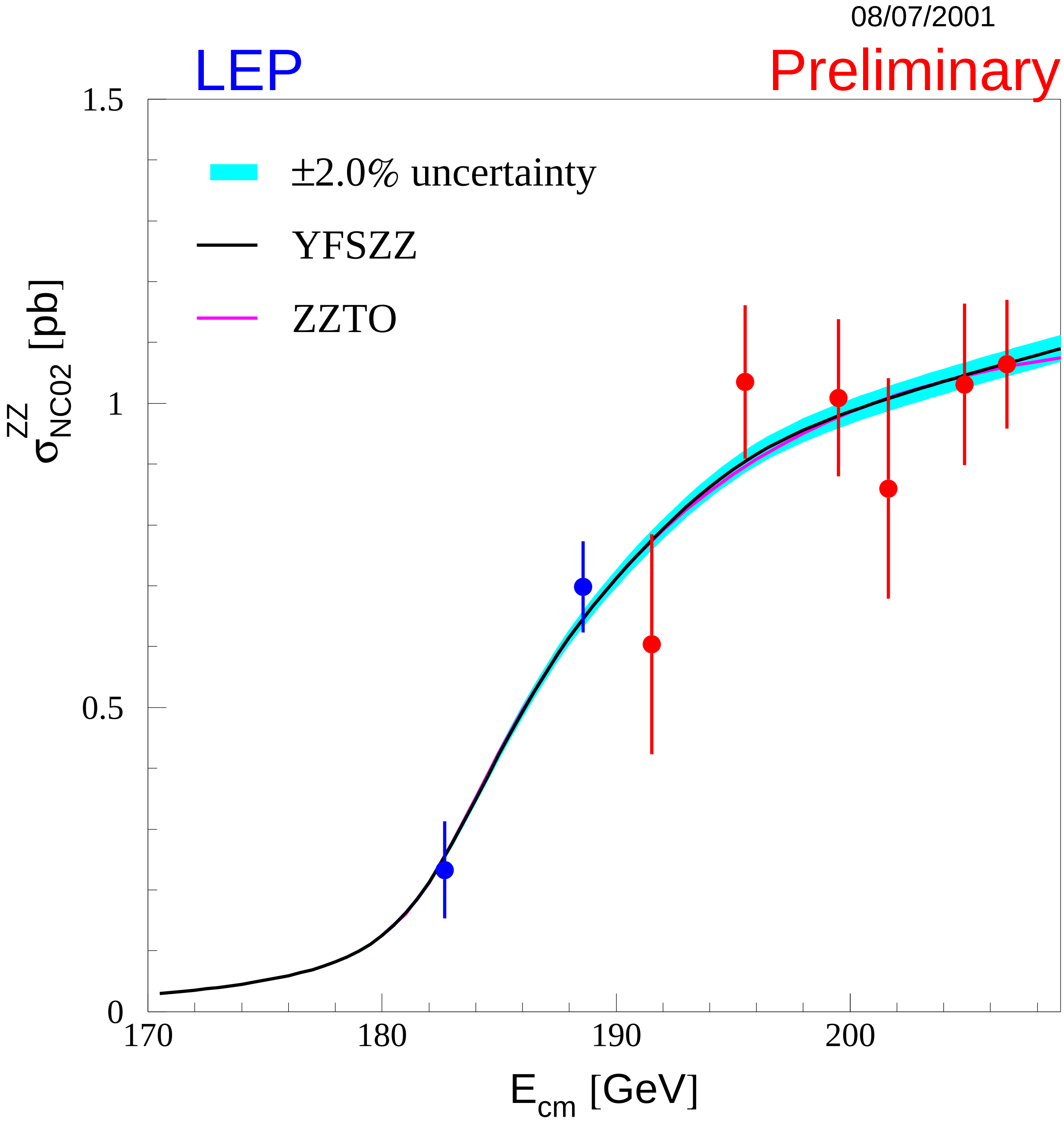
$\Rightarrow$ **Two MC Event Generators:**

- **YFSZZ** for Signal ZZ Process – including Anomalous Triple-Gauge Couplings: $ZZ\gamma$ and ZZZ
- **KoralW** for Standard Model $4f$ Background

Both include ISR Corrections in YFS Scheme (with Mulptiple Photons)

$\Rightarrow$ **TH Precision for σ_{ZZ} at LEP2 Energies $\simeq \mathbf{2\%}$**

ZZ Total Cross Section



YFSZZ: S. Jadach, W.P., B.F.L. Ward

ZZTO: G. Passarino (semi-analytical program)

Conclusions & Outlook

CONCLUSIONS – WW:

- **Our Solution for WW Physics:**

Two MC Event Generators

YFSWW3 **KoralW**

WW **Signal** $4f$ **Background**

- **Works from WW Threshold to LC Energies**
- **Combination on Event-by-Event basis possible:**
  - $\ast$ by Reweighting generated events
  - $\ast$ through Unix FIFO Pipes:

    $\longrightarrow$ **Concurrent MC KoralW&YFSWW3**
- **Good Agreement with** RacoonWW ($< 0.3\%$) **and LEP2 Data**

& OUTLOOK – WW:

- $\mathcal{O}(\alpha)$ **YFS Exponentiation in W Decays** (in progress)
- **Non-Factorizable Corrections**
- **Coherent Exclusive Exponentiation (CEEX) for W-Pair Production and Decay** (Expon. on Spin-Amplitude level)
- **Higer-order EW Corrections for LC** (Sudakov logs, etc.)
- **Beamstrahlung, Beam Polarization, ...**

CONCLUSIONS – ZZ:

- **Our solution for ZZ Physics:**

Two MC Event Generators

YFSZZ **KoralW**

ZZ **Signal** $4f$ **Background**

- **Good Agreement with ZZTO** ($< 1\%$) **and LEP2 Data**

& OUTLOOK – ZZ:

- **Combination on Event-by-Event basis:**

  $\rightarrow$ **Concurrent MC KoralW&YFSZZ**

- $\mathcal{O}(\alpha)$ **NL EW Corrections**
- $\mathcal{O}(\alpha)$ **YFS Exponentiation in Z Decays**
- **Coherent Exclusive Exponentiation (CEEX) for Z-Pair Production and Decay** (Expon. on Spin-Amplitude level)
- **Higer-order EW Corrections for LC** (Sudakov logs, etc.)
- **Beamstrahlung, Beam Polarization, ...**