On Theoretical Precision of W Mass and Triple-Gauge Couplings Measurement at LEP2

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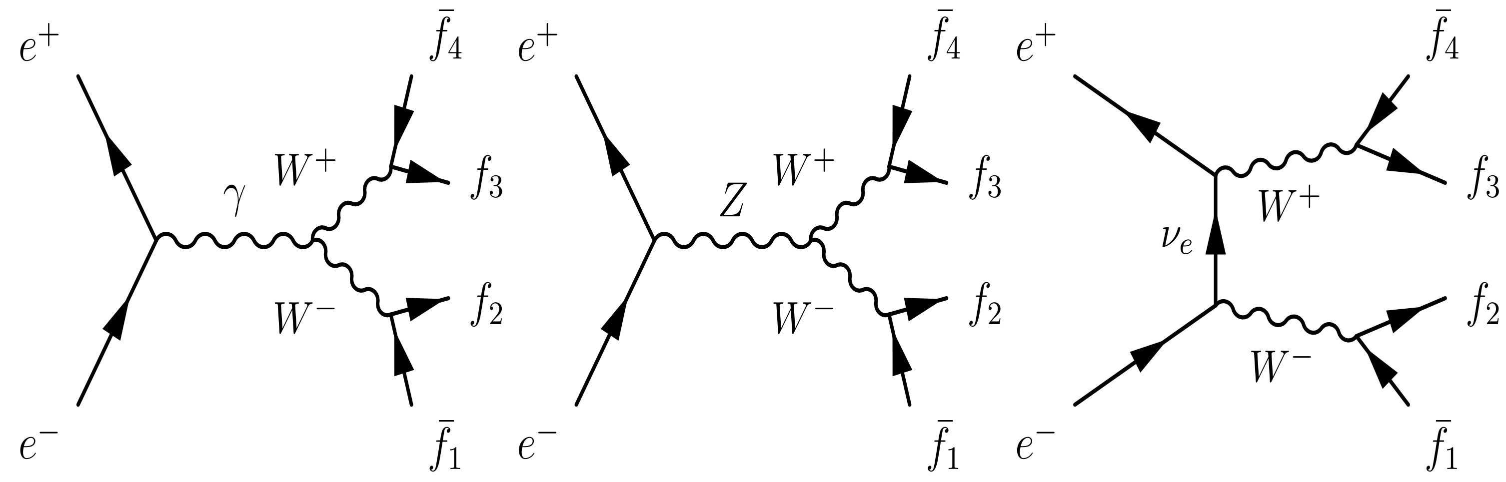
Outline:

- **Introduction.**
- **Theoretical Precision of W Mass measurement.**

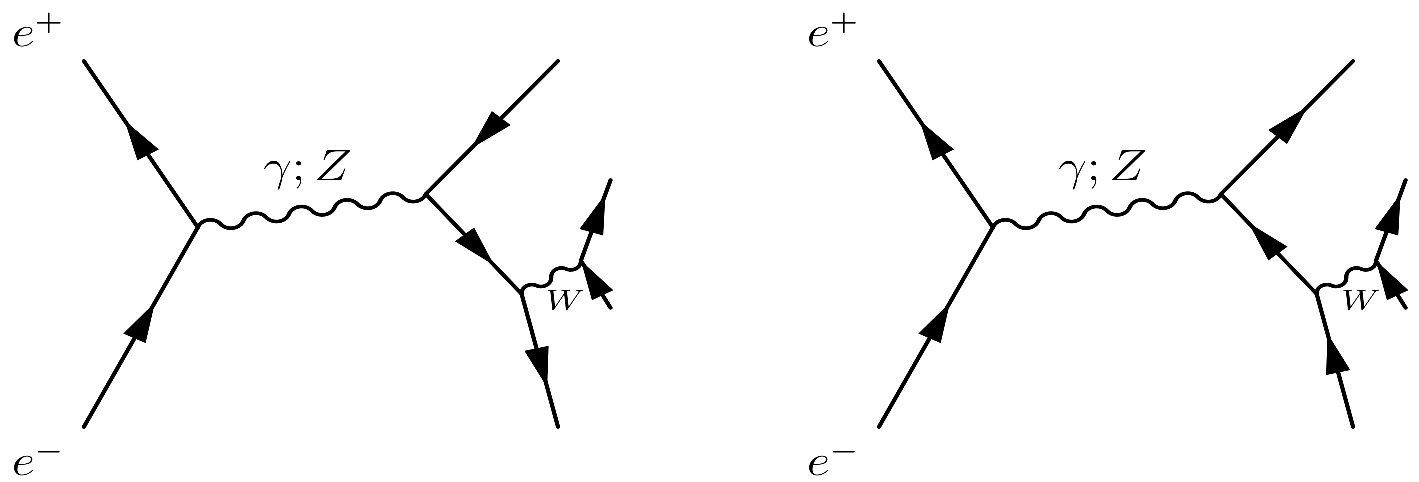
  → **S. Jadach, W.P., M. Skrzypek, B.F.L. Ward, Z. Wąs, hep-ph/0109072, Phys. Lett. B, in press.**
- **Theoretical Precision of Triple-Gauge Couplings (TGC) measurement.**

  → **R. Brunelière, A. Denner, S. Dittmaier, S. Jadach, S. Jézéquel, W.P., M. Roth, M. Skrzypek, D. Wackeroth, B.F.L. Ward, Z. Wąs, CERN-TH/2001-274, to be submitted to Phys. Lett B.**

Introduction

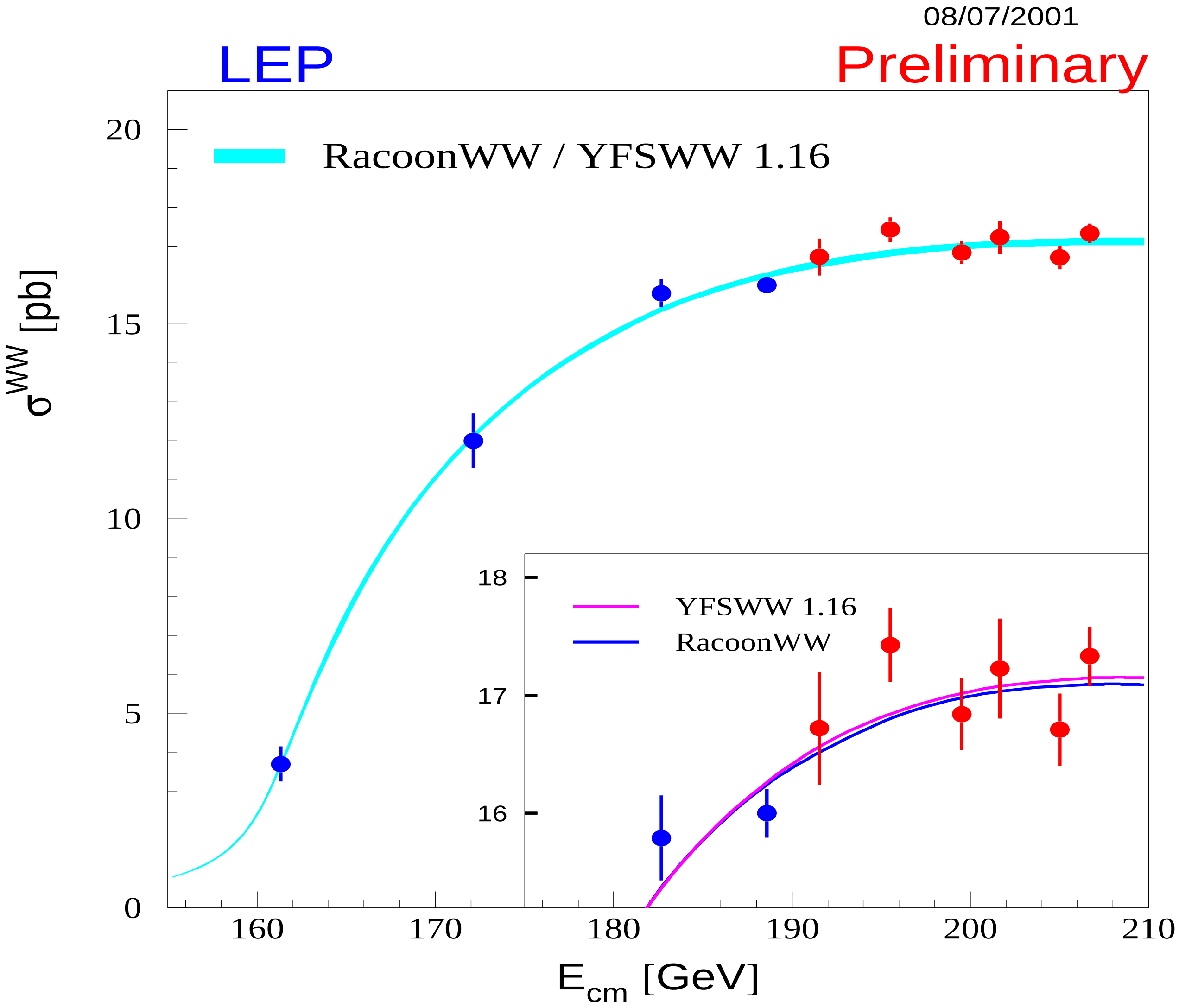


Feynman diagrams for $\mathbf{W}^+\mathbf{W}^-$ Production and Decay (CC03)



Single-$\mathbf{W}$-Resonant (background) diagrams of CC11 class

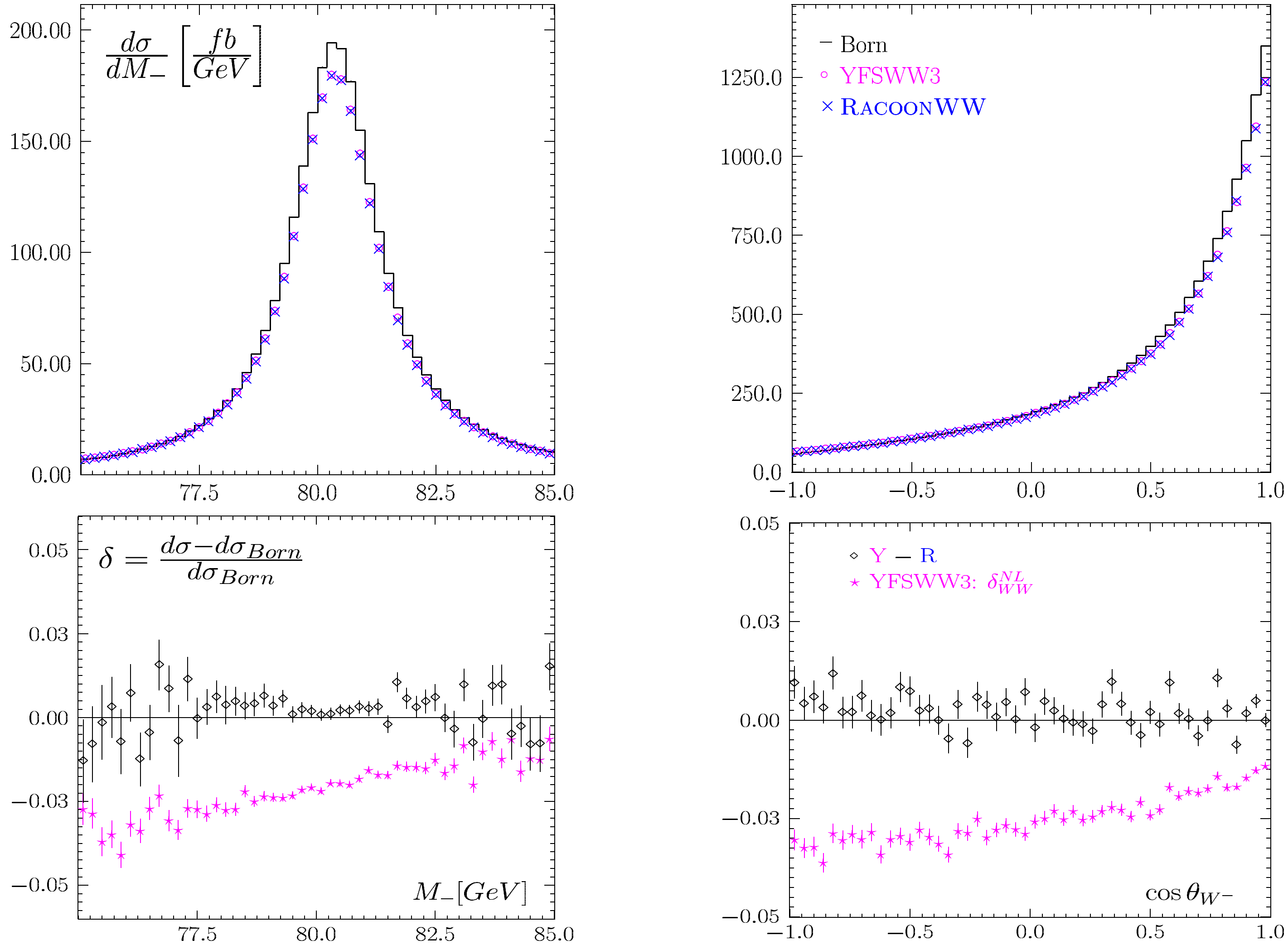
Total WW cross section



TH Precision $\simeq 0.5\%$

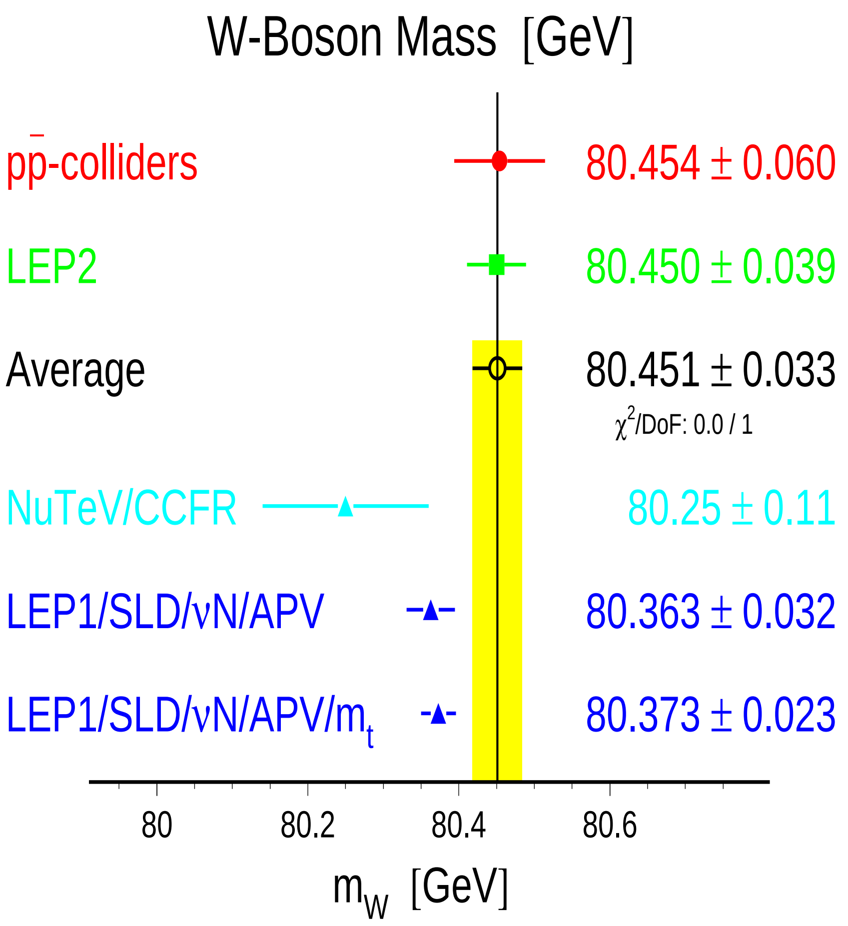
Introduction

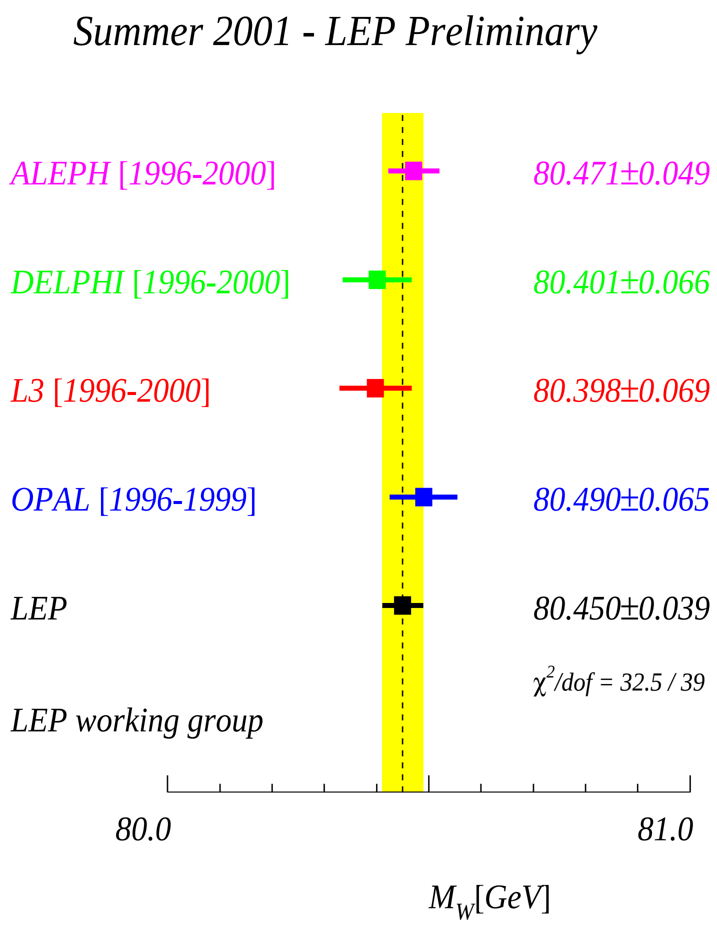
$$e^+e^- \longrightarrow W^+W^- \longrightarrow u\bar{d}\mu^-\bar{\nu}_\mu$$



$\Rightarrow$ **$\mathbf{M_W}$** $\qquad\qquad$ $\Rightarrow$ **TGC**

W Mass measurement





$\mathbf{W}$ Mass measurement

- $\mathrm{M_W}$ **at LEP2 measured by direct fit to $\mathbf{W}$ invariant mass distribution**:

  Level-1: Constrained kinematic fit $\Rightarrow$ two $\mathbf{W}$ invariant masses $+$ auxiliary parameters (controlling the detector energy resolution, etc.)

  Level-2: Actual $\mathrm{M_W}$ fit using MC Event Generator (ALEPH, L3, OPAL) or analytical function (DELPHI)

- **Final LEP2 Experimental Precision:** $\Delta\mathrm{M_W} \simeq \mathbf{30}$ **MeV**

- **Theoretical Untertainty (TU) should be:** $\leq \mathbf{15}\,(\mathbf{10})$ **MeV**

- **Missing detailed study on TU of $\mathrm{M_W}$ (before this work)**

  $\Rightarrow$ **TU of $\mathrm{M_W}$ is almost completely independent of TU on σ_{WW}** (studied in detail during 2000 LEP2 MC Workshop, cf. Yellow Report CERN 2000-009)

$\mathrm{M_W}$ Fitting

Assumptions:

- Semileptonic process: $\mathbf{e^+e^- \to W^+W^- \to u\bar{d}}\mu^-\bar{\nu}_\mu$
- Parton level with simplified cuts/acceptances
- One-dimensional fit of a single $\mathbf{W}$ invariant mass
- Mass of $\mathbf{W}^- \to \mu^-\bar{\nu}_\mu$ considered
- Invariant mass distributions from MCs: YFSWW3-KoralW (Jadach et al.) and RacoonWW (Denner et al.)
- Fitting function (FF) from semi-analytical program KorWan (Jadach et al.)

Notation:

Born – Born level

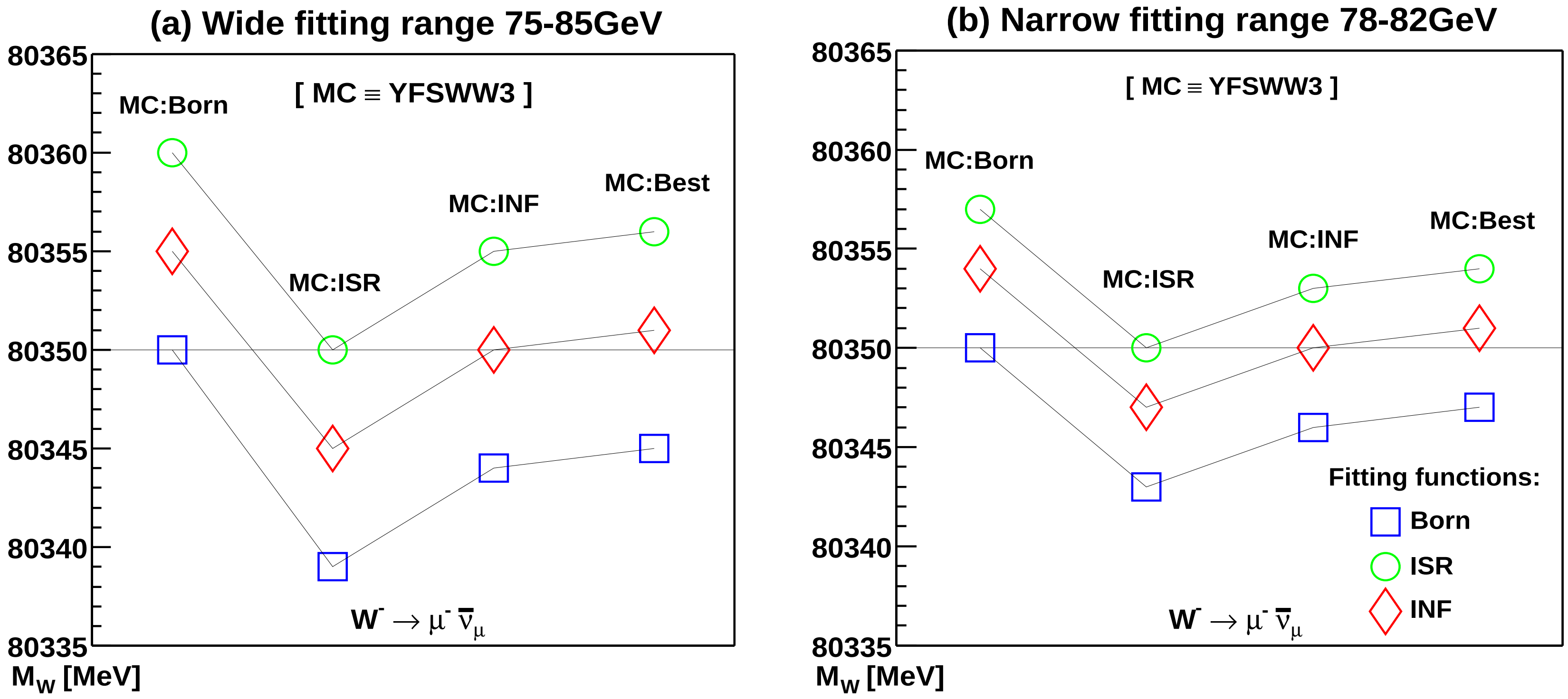
ISR – $\mathcal{O}(\alpha^3)$ LL YFS exponentiation for ISR and Coulomb correction

INF – the above plus non-factorizable corrections (NF) in the inclusive approx. of Chapovsky & Khoze ("screened" Coulomb ansatz)

Best – best predictions from YFSWW3, i.e. all the above plus the $\mathcal{O}(\alpha^1)$ EW non-leading (NL) corrections (Fleischer et al.)

$\mathrm{M_W}$ Fitting

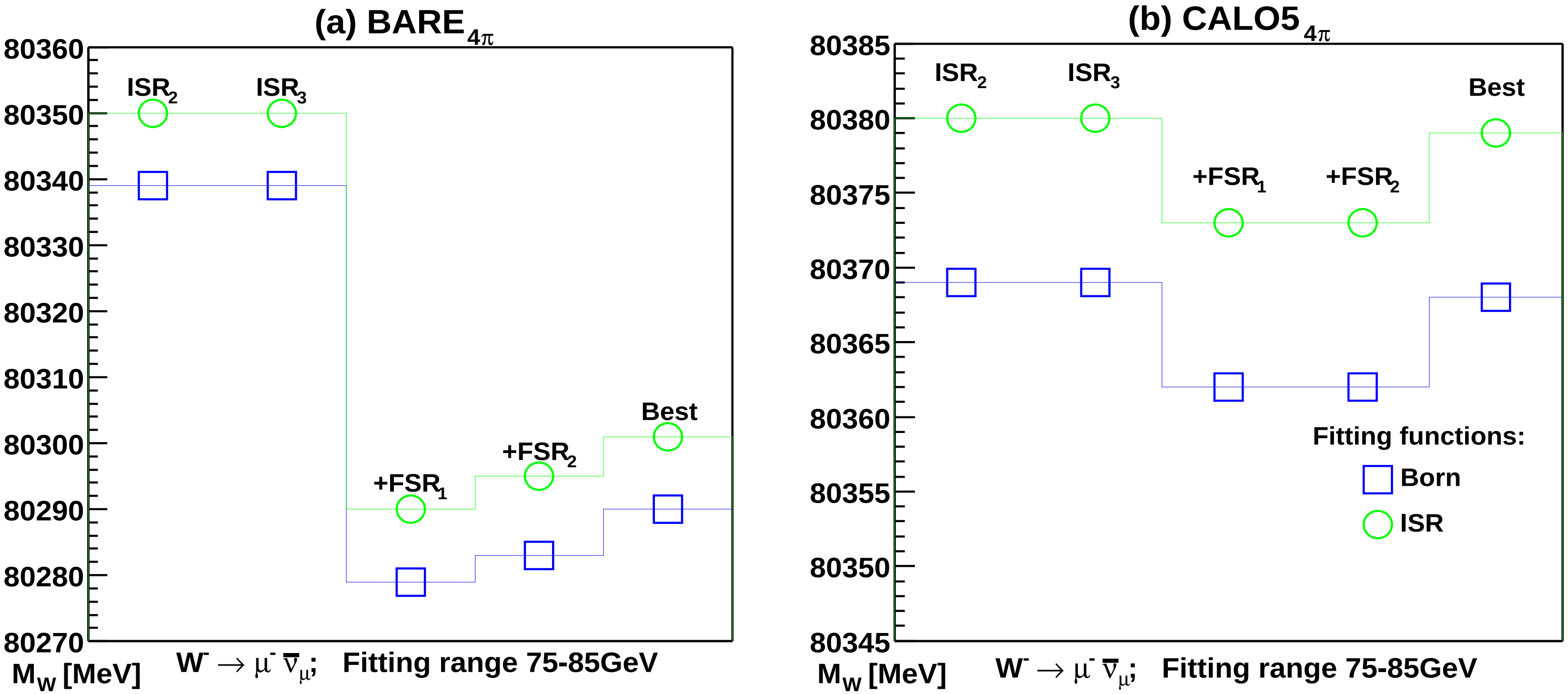
"Calibration" fits (No Cuts):



- The fitted $\mathrm{M_W}$ exactly agrees with the input $\mathrm{M_W}$ in the case when the same effects are included both in FF and the MC.
- If one is interested only in the shift of $\mathrm{M_W}$, then any FF can be used.
- 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!).

M_W Fitting

Effects of ISR and FSR on M_W:



Acceptances:

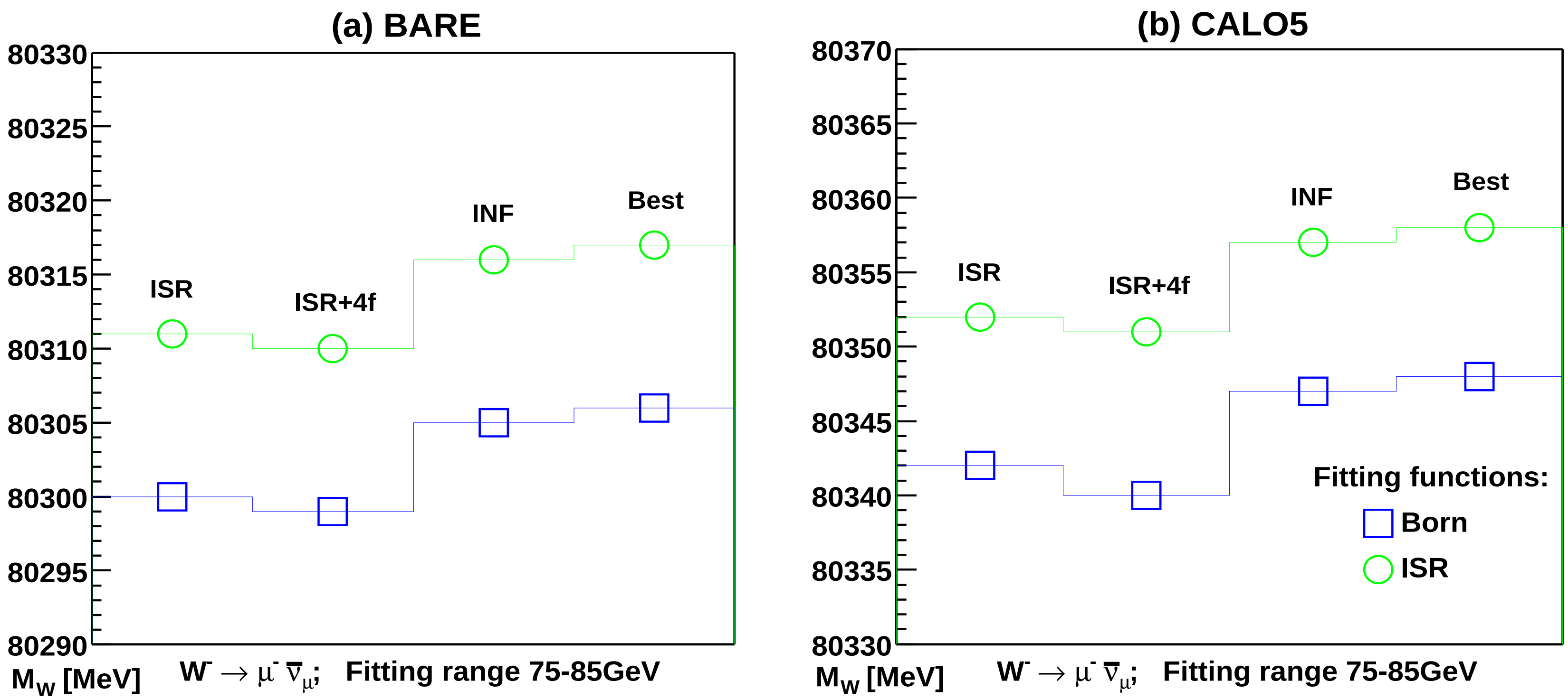
BARE$_{4\pi}$ – "bare" parton level with full solid-angle coverage

CALO5$_{4\pi}$ – photons for which the invariant mass with a final-state charged fermion was < 5 GeV were recombined with that fermion

$\longrightarrow$ **FSR** from **PHOTOS** (Wąs et al.)

M_W Fitting

Effects of $4f$ background on M_W:



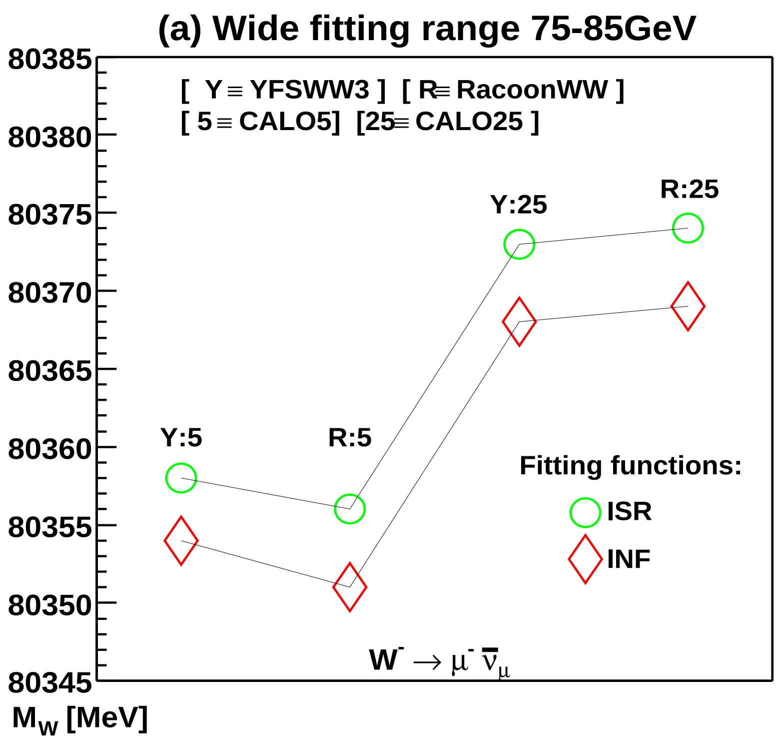
Acceptances: (2000 LEP2 MC Workshop)

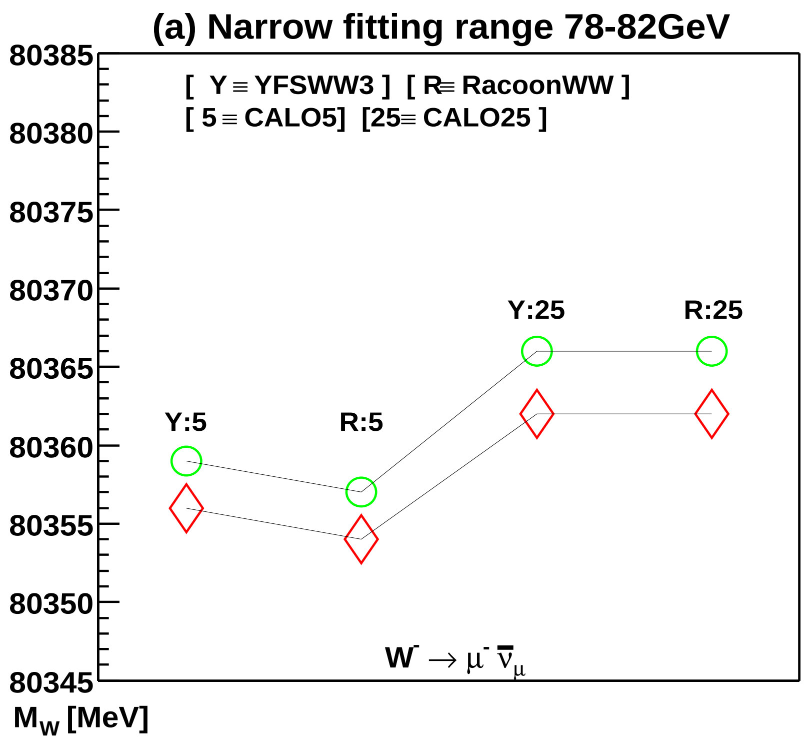
1. $\theta_{f_{ch}} > 10^\circ$; 2. $\theta_\gamma > 5^\circ$;

3. $M_{rec}^{\gamma f} \leq$
- 0 GeV: **BARE**
- 5 GeV: **CALO5**
- 25 GeV: **CALO25**

M_W Fitting

Comparison of YFSWW3 and RacoonWW:





- The comparison of **YFSWW3** with **RacoonWW** is very interesting because the two calculations differ in almost every aspect of the implementation of the ISR, FSR, NL and NF corrections.
- The results of **YFSWW3** and **RacoonWW** differ, in terms of the fitted mass, by only $\lesssim 3$ **MeV**, slightly more for **CALO5** than for **CALO25.**

Semi-quntitative estimates of ΔM_W

- **Linearized M_W Shift due to Correction Function $f(M^2)$:**

$$\frac{d\sigma}{dM} \simeq |BW(M)|^2 \times f(M^2) \;\Rightarrow\; \Delta M_W \simeq \frac{1}{8}\Gamma_W^2 \frac{\partial \ln f(M^2)}{\partial M}\Big|_{M=M_W}$$

Main Effects:

a) $\Delta_{ISR} M_W \simeq -\Gamma_W \frac{\Gamma_W M_W}{2s\beta_W^2} \times 4\frac{\alpha}{\pi}\ln(s/m_e^2) \simeq -6$ MeV

b) $\Delta_{FSR} M_W \simeq -\Gamma_W \frac{\pi}{8}\frac{\alpha}{\pi}\ln(M_W^2/M_{rec}^{\gamma f}) \simeq -8$ MeV for CALO5

c) $\Delta_{INF} M_W \simeq -\Gamma_W \frac{\alpha}{4}\frac{(1-\beta_W)^2}{\beta_W} \simeq -1$ MeV

Note: $\Delta_{Coul.} M_W \simeq -\Gamma_W \frac{\alpha}{4}\frac{1}{\beta_W} \simeq -6$ MeV

$\Rightarrow \Delta_{INF} M_W - \Delta_{Coul.} M_W \simeq 5$ MeV (cf. Figs)

In Agreement with Fit results

Semi-quntitative estimates of ΔM_W

Estimation of the missing effects in the K-Y MC tandem:

ΔM_W			
Error Type	Scale Param. $\Delta M_W = \Gamma \times \epsilon$	Numerical cross-check	ΔM_W
WW production			
ISR $\mathcal{O}(\alpha^4 L_e^4)$	$\epsilon \simeq \frac{\Gamma_W M_W}{s\beta_W^2} (\frac{\alpha}{\pi})^4 L_e^4 \sim 5 \cdot 10^{-6}$	$[\mathcal{O}(\alpha^3 L_e^3) - \mathcal{O}(\alpha^2 L_e^2)]_{\mathrm{KoralW}}$	$\ll 1$ 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

- **TU due to LPA:** $\Delta M_W = 1$ **MeV (LPA options in YFSWW3)**

Summary on $\delta_{\rm th} M_W$

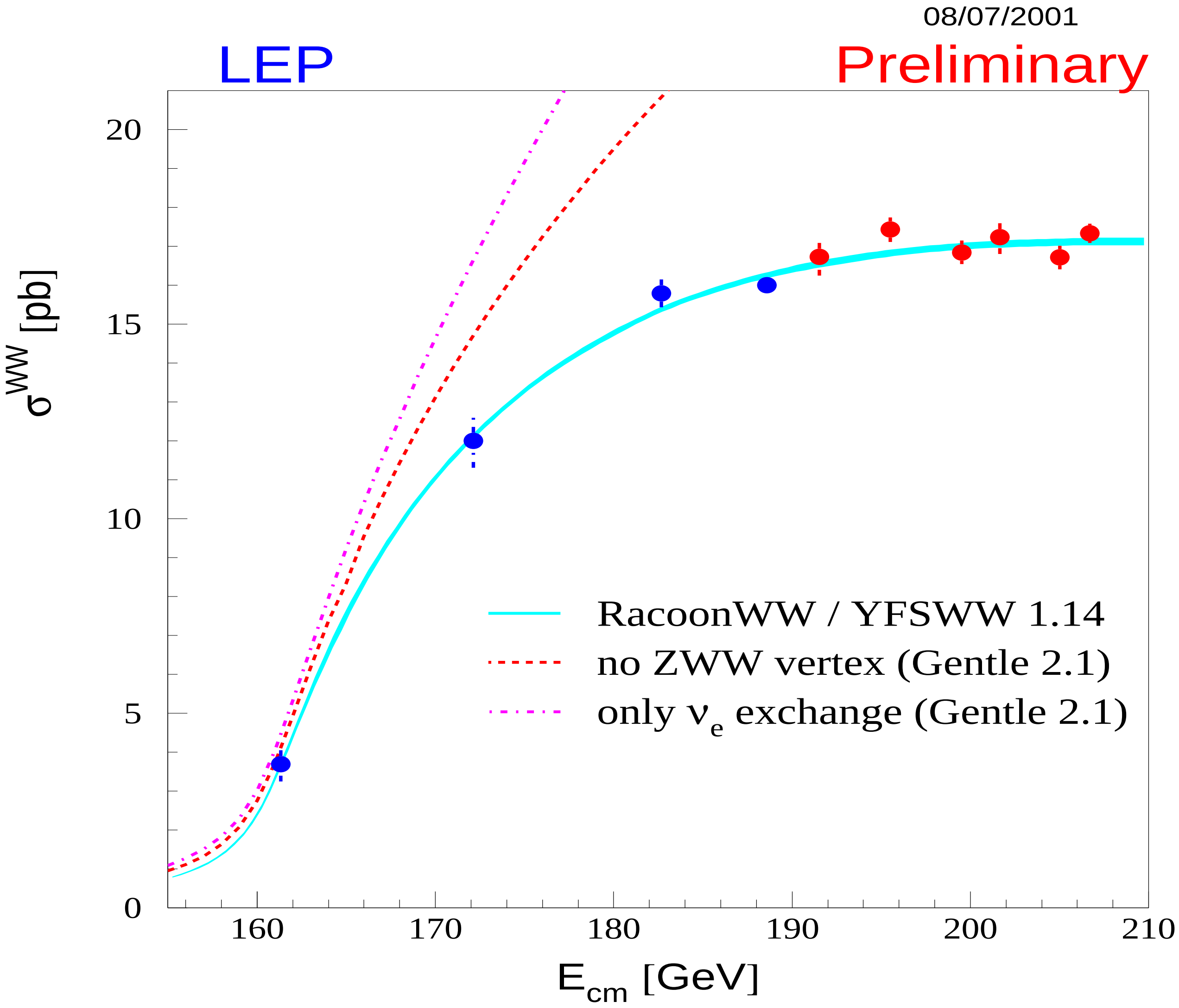
- **The Electroweak Theoretical Uncertainty in M_W of the KoralW-YFSWW3 MC tandem at LEP2 energies is** $\boxed{\sim 5 \text{ MeV}}$
  (< 10 MeV – targeted TU for LEP2)

- **The above conclusion is strengthened by the smallness of the differences between YFSWW3 and RacoonWW (≤ 3 MeV).**
  We attribute it to the standard *factorizable* corrections (ISR, FSR, etc.) and purely technical/numerical effects.

- **In the above estimate we included a "safety factor" of 2, corresponding to the fact that our fits of M_W were done for 1-dimensional effective W mass distributions.**
  In order to eliminate it, our analysis should be repeated for the realistic measurements of the LEP2 experiments.

Triple-Gauge Couplings measurement

Total WW cross section



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

Anomalous Triple-Gauge Couplings

Effective Lagrangian With Anomalous WWV, $(\mathrm{V}=\gamma,\mathrm{Z})$ Couplings:

[K. Hagiwara et al., Nucl. Phys. **B282** (1987) 253]

$$\begin{aligned}\mathcal{L}_{\mathrm{WWV}}/g_{\mathrm{WWV}} = & i g_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} \\ & + \frac{i\lambda_V}{M_W^2} W^\dagger_{\rho\mu} W^\mu{}_\nu V^{\nu\rho} - g_4^V W^\dagger_\mu W_\nu \left(\partial^\mu V^\nu + \partial^\nu V^\mu\right) \\ & + g_5^V \epsilon^{\mu\nu\rho\sigma} \left(W^\dagger_\mu \overleftrightarrow{\partial_\rho} W_\nu\right) V_\sigma + i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} + \frac{i\tilde{\lambda}_V}{M_W^2} W^\dagger_{\rho\mu} W^\mu{}_\nu \tilde{V}^{\nu\rho}\end{aligned}$$

where:

$$A_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad \tilde{A}_{\mu\nu} = \tfrac{1}{2}\epsilon_{\mu\nu\rho\sigma} A^{\rho\sigma},$$

$$g_{\mathrm{WW}\gamma} = -e, \quad g_{\mathrm{WWZ}} = -e\cot\theta_{\mathrm{W}}.$$

⇒ Anomalous Electric Charge of $\mathbf{W}$: $|q_{\mathrm{W}}| = e g_1^\gamma$

⇒ Anomalous Magnetic Moment of $\mathbf{W}$:

$$\mu_{\mathrm{W}} = \frac{e}{2\mathrm{M_W}}\left(1 + \kappa_\gamma + \lambda_\gamma\right)$$

⇒ Anomalous Electric Quadrupole Moment of $\mathbf{W}$:

$$Q_{\mathrm{W}} = -\frac{e}{\mathrm{M_W^2}}\left(\kappa_\gamma - \lambda_\gamma\right)$$

Anomalous Triple-Gauge Couplings

- Standard Model: $g_1^V = \kappa_V = 1, \quad \lambda_V = g_4^V = g_5^V = \tilde{\kappa}_V = \tilde{\lambda}_V = 0.$
- In general: $g_1^V, \kappa_V, \lambda_V, g_4^V, g_5^V, \tilde{\kappa}_V, \tilde{\lambda}_V \in \mathbb{C}$,

  and depend on $(s/\Lambda^2)^n$, where Λ – scale of New Physics.

Thus, measurement of Anomalous TGC $\Rightarrow$ scale of New Physics

Our aim:

Project TU of $\cos\theta_{\mathbf{W}}$ distribution into TU of Anomalous TGC

- 14 Complex-number Couplings – too many Parameters!

$\longrightarrow$ Usually investigated only **Three** C and P Conserving Anomalous Couplings:

$$\Delta g_1^Z,\ \Delta\kappa_\gamma,\ \lambda = \lambda_\gamma = \lambda_Z \quad \in \mathbb{R}$$

$\Rightarrow$ Measured at LEP2 using 5 observables: $\cos\theta_{\mathbf{W}}, \mathbf{cos}\theta_{\mathbf{l}}^*, \phi_{\mathbf{l}}^*, \cos\theta_{\mathbf{jet}}^*, \phi_{\mathbf{jet}}^*$

$*$ λ **sensitive mainly to** $\cos\theta_{\mathbf{W}}$ $(\sim 70\%)$

$*$ $\Delta g_1^Z,\ \Delta\kappa_\gamma$ sensitive to all observables!

We consider only λ

Fitting of λ

Monte Carlo Parametric Fit (MPF):

Instead of using semi-analytical formula of (with limited choice of cuts) we parametrize normalized Monte Carlo distribution (with any cuts) $D(\cos\theta_W, \lambda) = (1/\sigma)(d\sigma/d\cos\theta_W)$ as a function of $\cos\theta_W$ and λ.

$\longrightarrow$ We use the following 9-parameter fitting function (MPFF):

$$\rho(\cos\theta_W, \lambda) = \frac{D(\cos\theta_W, \lambda)}{D(\cos\theta_W, 0)} = \sum_{i=0}^{2} \left(a_i\lambda^i + b_i\lambda^i \cos\theta_W + c_i\lambda^i \cos^2\theta_W \right)$$

(ρ is a very smooth function of $\cos\theta_W$ and λ at LEP2 energies)

a_i, b_i, c_i are determined by fitting ρ distributions obtained from YFSWW or RacoonWW for three values of $\lambda = -0.2, 0, 0.2$.

We checked that the constructed MPFFs reproduce the input values of λ within the fit error of ~ 0.001.

$\Rightarrow$ **We project changes in $\cos\theta_{\mathbf{W}}$ distribution due to various EW corrections into shifts of λ**

- Final LEP2 Experimental Precision: $\delta_{exp}\lambda \simeq 0.01$

Fitting of λ

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

Shifts of λ from fits to $\cos\theta_{\mathbf{W}^-}$ (Y=YFSWW, R=RacoonWW)

Fitting procedure		Fitted data			
Fitting function	Accept.	Y: Best−ISR	R: Best−ISR	Best: R−Y	Accept.
1. KorWan	BARE	$0.0114\,(6)$	—	—	CALO5
2. KorWan	BARE	$0.0115\,(6)$	—	—	CALO25
3. MPF: Y-ISR	CALO5	$0.0112\,(7)$	$0.0097\,(8)$	$0.0008\,(9)$	CALO5
4. MPF: Y-ISR	CALO5	$0.0115\,(7)$	$0.0161\,(8)$	$0.0008\,(9)$	CALO25
5. MPF: R-ISR	CALO5	$0.0112\,(7)$	$0.0097\,(8)$	$0.0008\,(9)$	CALO5
6. MPF: R-ISR	CALO5	$0.0115\,(7)$	$0.0161\,(8)$	$0.0008\,(10)$	CALO25
7. MPF: Y-Best	CALO5	$0.0113\,(7)$	$0.0098\,(8)$	$0.0008\,(10)$	CALO5
8. MPF: Y-Best	CALO5	$0.0116\,(7)$	$0.0162\,(8)$	$0.0008\,(9)$	CALO25
9. MPF: R-Best	CALO5	$0.0110\,(7)$	$0.0096\,(8)$	$0.0007\,(9)$	CALO5
10. MPF: R-Best	CALO5	$0.0113\,(7)$	$0.0158\,(8)$	$0.0008\,(9)$	CALO25
11. MPF: KoralW	ALEPH	$0.0118\,(7)$	$0.0103\,(9)$	$0.0008\,(10)$	CALO5
12. MPF: KoralW	ALEPH	$0.0122\,(7)$	$0.0172\,(9)$	$0.0009\,(10)$	CALO25

Final LEP2 Experimental Precision: $\delta_{exp}\lambda \simeq 0.01$

Fitting of λ

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

$\Delta\lambda$ from Various Effects

YFSWW

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 definition	CALO5	$0.0005\,(10)$
	CALO25	$0.0005\,(10)$

Deviations from “Best” predictions $\lesssim 0.002$

Fitting of λ for Other Channels

Other-Channel MPFFs fitted to MC Data for Channel $u\bar{d}\mu^-\bar{\nu}_\mu$

(TRUE – Parton level, RECO – Full ALEPH Detector Reconstruction)

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

$\longrightarrow$ For channels $\tau\nu_\tau qq$ and $qqqq$ Detector Effects (jet resolution, jet pairing, jet charge and τ reconstruction, etc.) imposed on MC data through Transfer Matrices

Summary on $\delta_{\mathrm{th}}\lambda$

- The Non-Leading EW Corrections shift λ by $\mathbf{0.01}$–$\mathbf{0.02}$, which is comparable to the combined Experimental LEP2 Accuracy.
  $\Rightarrow$ They Have to be Taken into Account in Experimental Analyses!

- The Electroweak Theoretical Uncertainty in $\lambda = \lambda_\gamma = \lambda_{\mathbf{Z}}$ of the MC tandem KoralW&YFSWW3 and of the MC RacoonWW at LEP2 energies is estimated to be $\sim \mathbf{0.005}$, which is $\sim \mathbf{1/2}$ of the expected combined Experimental Error on λ at LEP2.

- We used a safety factor of 2 to account for the $\sim 30\%$ sensitivity loss due to the single-distribution fit and for possible higher order effects missing in both programs.