# Precision W-pair Physics

# with YFSWW3 and KoralW Monte Carlos

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**Outline**:

- **Introduction**
- **Concurrent Monte Carlo KoralW&YFSWW3** ***[CPC 140 (2001) 432 and 475]***
- **Theoretical precision - $W$ mass** ***[PLB 523 (2001) 117]***
- **Theoretical precision - $W$ angular distrib.** ***[R. Brunelière et al. PLB 533 (2002) 75]***
- **Improvements for single $W$ process** ***[CERN-TH 2002-195, August 2002]***
- **Summary**

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## Main $W$ observables at LEP2 and their precision:

- Total $WW$ cross section $\sigma_{WW}$

  $\longrightarrow$ 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: $\delta_{th}\lambda \lesssim 0.005$

- Single $W$ cross section $\sigma_{We\nu} \Rightarrow$ TGCs measurement

  $\longrightarrow$ Experimental precision: $\delta_{ex}\sigma_{We\nu} \sim 7\%$

  $\longrightarrow$ Required theoretical precision: $\delta_{th}\sigma_{We\nu} \sim 3.5\%$

## 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 $W$s
- Non-factorizable corr. in inclusive approx. of "screened-Coulomb" ansatz
- Anomalous TGCs (three parametrisations)
- FSR by PHOTOS up to $\mathcal{O}(\alpha^2)$ LL
- $\tau$ decays by TAUOLA; quark fragmentation and hadronization by JETSET
- Semi-Analytical program KorWan for $WW$ process including leading corr.

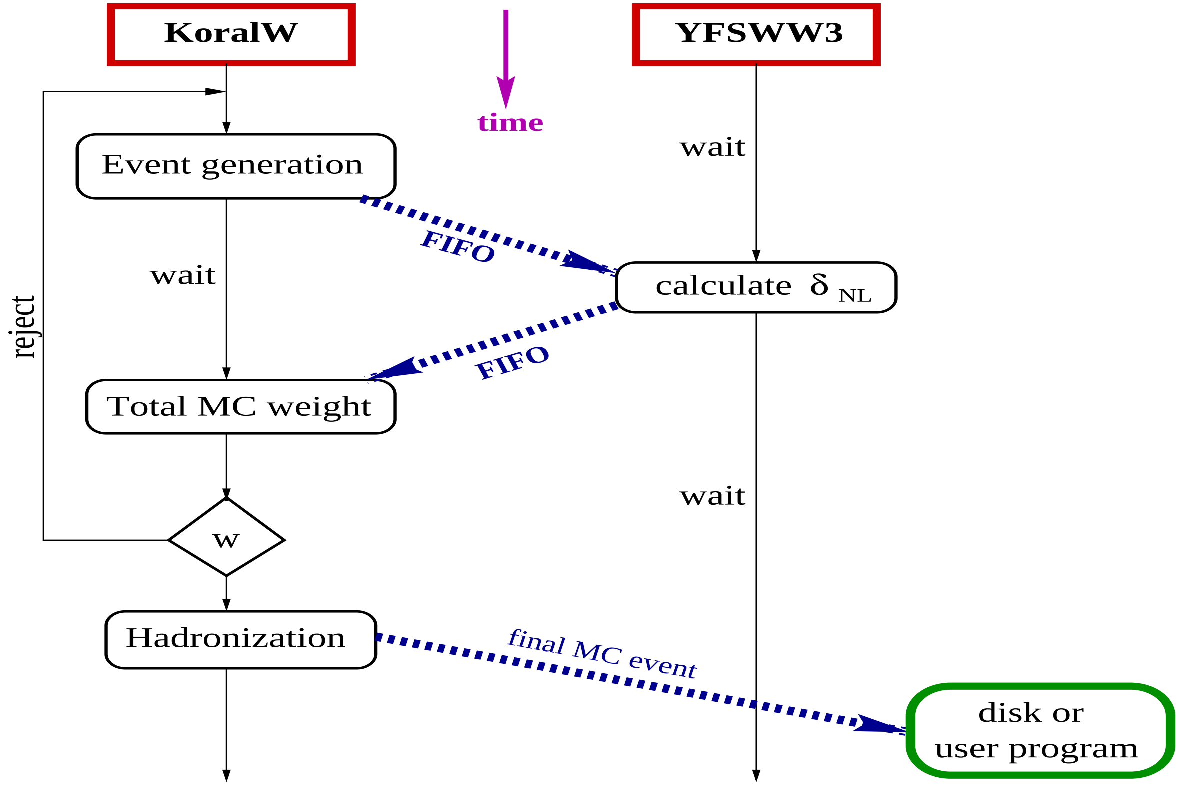
# How to combine KoralW and YFSWW3

## Solution: Concurrent Monte Carlo

Two independent codes run in parallel and exchange data in real time through UNIX/LINUX operating system (via FIFO special files)

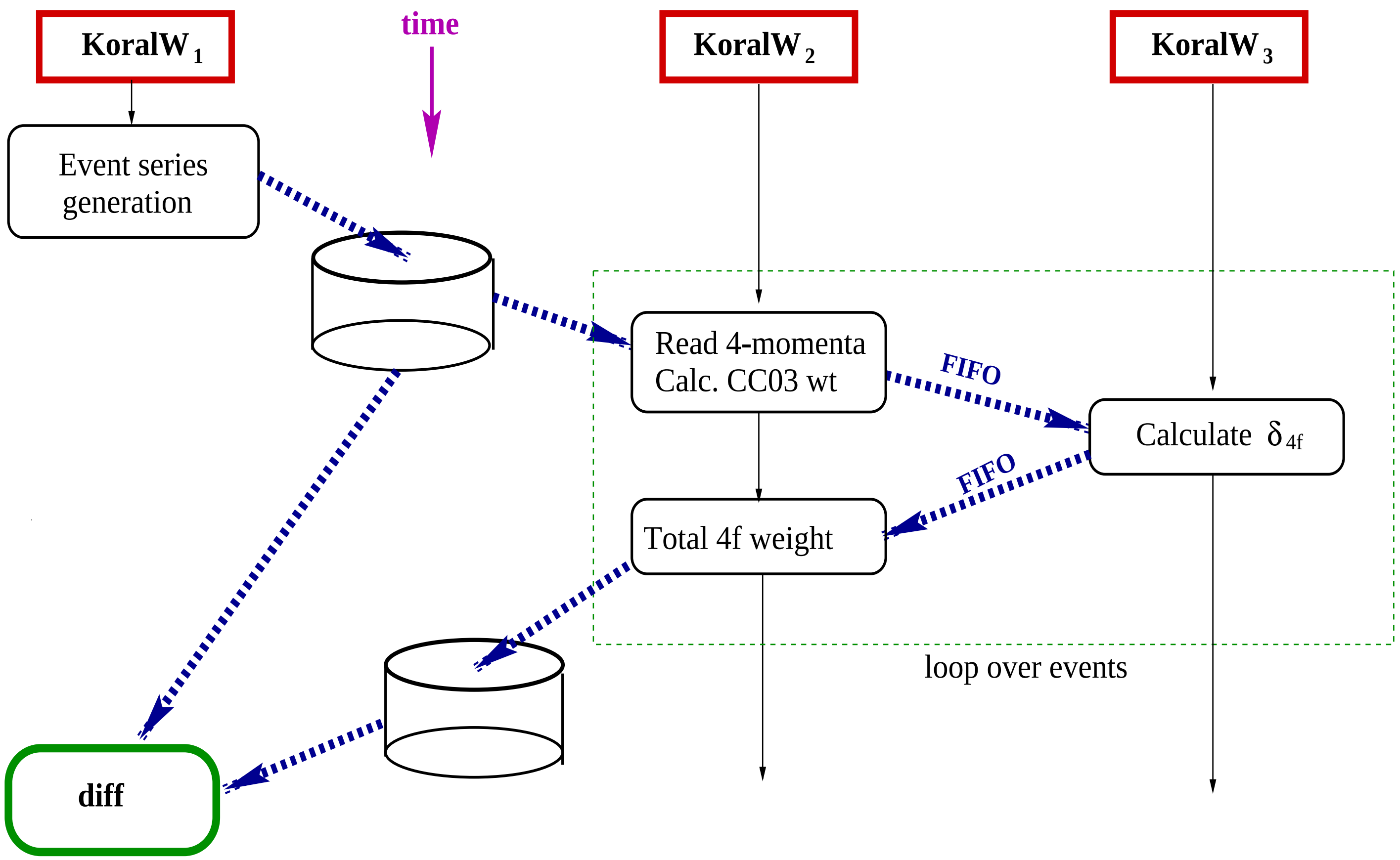
## Advantages of CMC

▷ "Encapsulation" (any codes/languages) – no need to merge/modify source codes



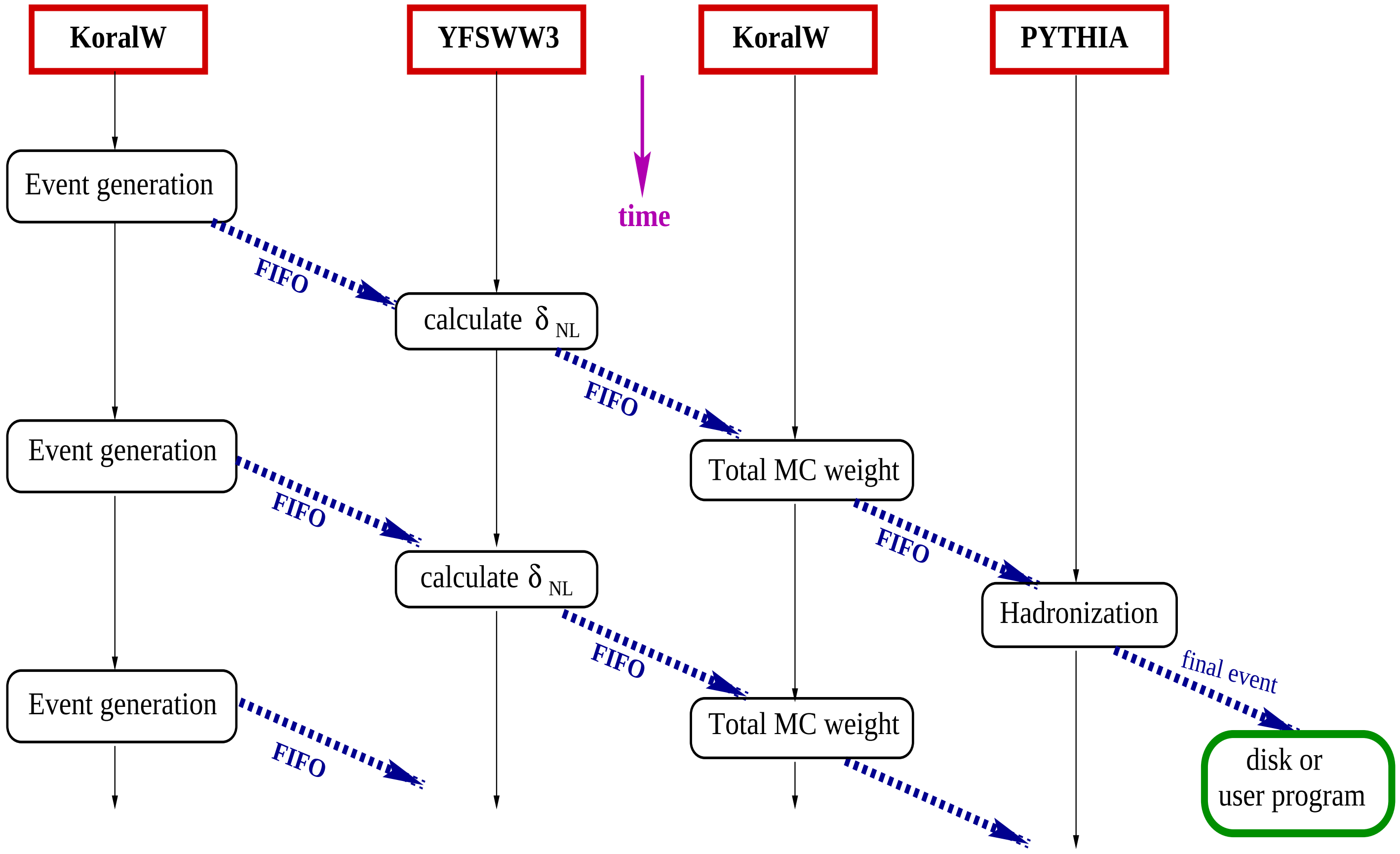
# Advantages of CMC

▷ “Lego blocks” structure – many possible arrangements (e.g. reprocessing data)



# Advantages of CMC

- ▷ common input data cards
- ▷ efficient use of multi-processor CPU



## Theoretical precision – $M_W$

- $M_W$ **measurement very different from** $\sigma_{tot}$ **– extracted from 3-D fits**
- **Our strategy:**

→ Use simplified 1-D fits ($u\bar{d}\mu^-\bar{\nu}_\mu$ final state) Fig. A

→ Check size of known corrections Fig. B

→ Compare KoralW+YFSWW3 results with RacoonWW data Fig. C

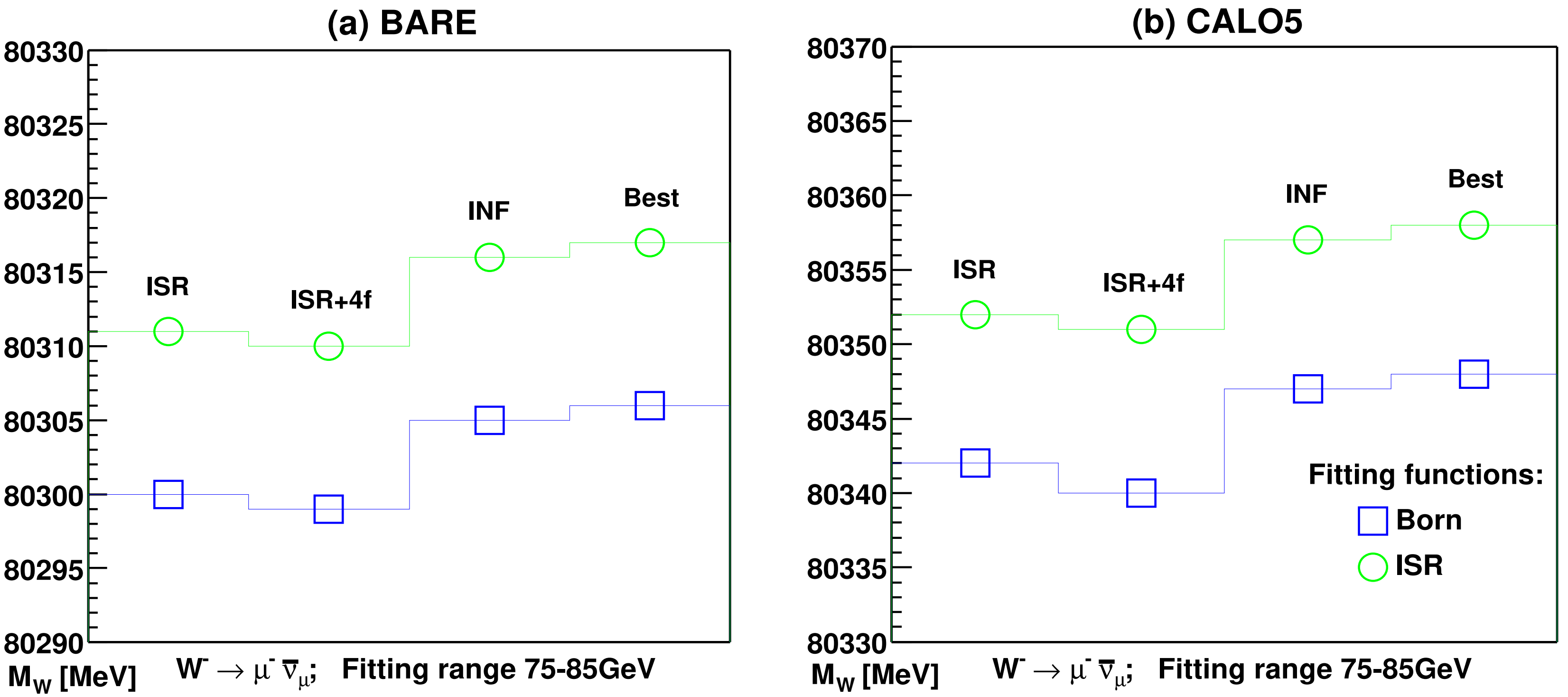
→ Estimate missing corrections Fig. D

- **Conclusions:**

  - The Electroweak Theoretical Uncertainty in $\mathbf{M_W}$ of the **KoralW-YFSWW3 MC tandem** at LEP2 energies is $\boxed{\sim \mathbf{5}\ \textbf{MeV}}$
(< $\mathbf{30}$ **MeV** – EXP precision for LEP2)

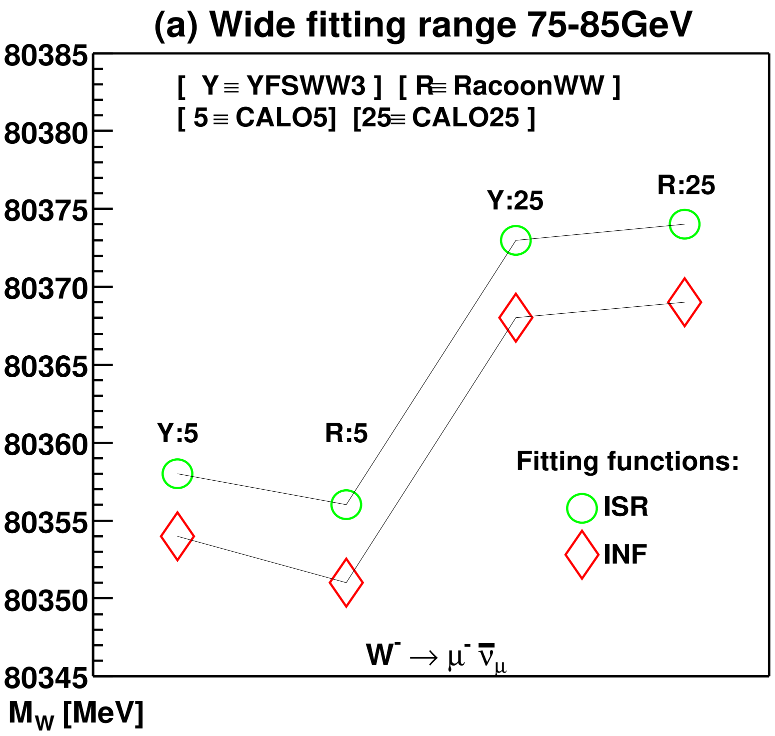
  - In the above estimate we included a "safety factor" of $\mathbf{2}$, corresponding to the fact that our fits of $\mathbf{M_W}$ were done for 1-dimensional effective $\mathbf{W}$ mass distributions.

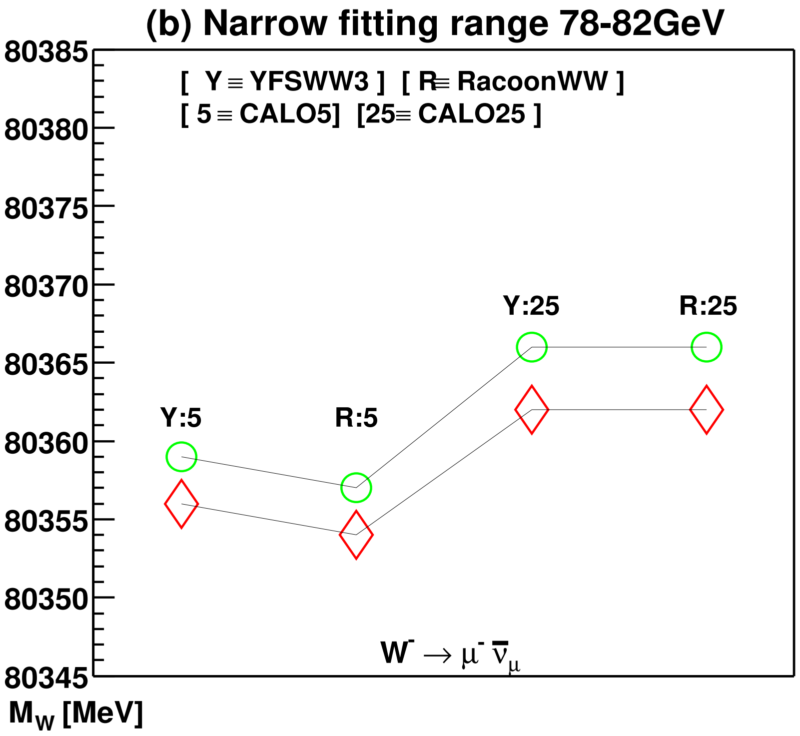
## B. Size of $4f$ background and non-factorizable corrs. on $M_W$:




- Size of 4f background $\sim 1$ MeV, may be larger in non-CC11 channels (strongly cut-off dependent, needs full-scale analysis)
- INF+NL $\sim 5$ MeV with resp. to ISR with non-screened Coulomb corr. but NL only $\sim 1$ MeV with resp. to screened Coulomb corr. (INF).
- NF itself only $\sim 1$ MeV (non-screened Coulomb shifts $M_W$ by $-5$ MeV). To enhance this genuine NF effect one would need large $\ln(\Gamma_W/E_{max})$, ie. veto on photons above very small $E_{max}$ – unlikely scenario

## C. 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 $\leq 3$ **MeV**, slightly more for **CALO5** than for **CALO25**.

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

| $\Delta M_W$ | | | |
|---|---|---|---|
| Error Type | Scale Param. $\Delta M_W = \Gamma \times \epsilon$ | Numerical cross-check | $\Delta M_W$ |
| $WW$ 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 | $\sim 2$ 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 $2\gamma$ in PHOTOS | $\ll 1$ MeV |
| Non-factorizable QED interferences (between production and 2 decays) | | | |
| $\mathcal{O}(\alpha^1)^{inclusive}_{miss.}$ | $\epsilon \simeq 0.1\left(\frac{\alpha}{4}\frac{(1-\beta)^2}{\beta}\right) \sim 10^{-4}$ | Chapovsky & Khoze | $< 1$ MeV |
| $\mathcal{O}(\alpha^2)^{inclusive}$ | $\epsilon \simeq \frac{1}{2}\left(\frac{\alpha^2}{4}\frac{(1-\beta)^2}{\beta}\right)^2 \sim 10^{-7}$ | None | $\ll 1$ MeV |

- **TU due to LPA: $\Delta \mathrm{M_W} = 1$ MeV (LPA options in YFSWW3)**
- **TU due to $\mathcal{O}(\alpha^1)_{miss.}$ NF with typical cuts on photons $\leq 2$ MeV**

# Theoretical precision - gauge coupling $\lambda$

▷ Distribution of cosine of $W$ production angle used to extract TGCs

▷ **Our strategy:**

$\longrightarrow$ Concentrate on $\lambda = \lambda_\gamma = \lambda_Z$ (simple, strong dependence on $\cos\theta_W$)

$\longrightarrow$ Perform fits to semianalytical $\cos\theta_W$ distributions from KorWan (no cuts!)

$\longrightarrow$ Use realistic “Monte Carlo parametric fitting functs” from fits to MC data (cuts!):

$$\rho(\cos\theta_W, \lambda) = \frac{d\sigma(\cos\theta_W, \lambda)}{d\cos\theta_W} \Big/ \frac{d\sigma(\cos\theta_W, 0)}{d\cos\theta_W} = \sum_{i=0}^{2} (a_i + b_i \cos\theta_W + c_i \cos^2\theta_W)\lambda^i$$

$\longrightarrow$ Include detector effects by applying ”transfer matrices” to MC data

$\longrightarrow$ Compare KoralW&YFSWW3 fits with RacoonWW fits — Fig. A

$\longrightarrow$ Check size of known corrections and estimate missing ones — Fig. B

▷ **Conclusions:**

- The Electroweak Theoretical Uncertainty in $\lambda$ of the **RacoonWW MC** and **KoralW&YFSWW3 MC** at LEP2 energies is $\boxed{\sim \mathbf{0.005}}$ (0.01 – exp. prec.)
- The above estimate includes a “safety factor” of $\mathbf{2}$, due to sensitivity loss due to single-distribution fit and possible missing higher order effects
- The above conclusions hold true also after realistic detector effects are included

## A. TH precision of an. TGC $\lambda$ (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 $\sim$ 0.01–0.02 !**

## Single $W$ – Electric Charge Screening effect in KoralW

▷ **ISR alone inadequate for FS particles collinear to beams:**

● too many photons with large $p_T$ ● too strong overall energy loss ●

▷ **fixed when ISR $\otimes$ FSR interference added** (ISR $\otimes$ FSR interf. $\equiv$ ECS effect) Fig. A

▷ **Our strategy:**

$\Rightarrow$ introduce weight: $W_{\mathrm{ECS}} = \prod_{photons} \frac{\tilde{S}_{abcd}(k)}{\tilde{S}_{ab}(k)+\tilde{S}_{cd}(k)}$; $\tilde{S}$= soft one-photon distr.

●Effective reintroduction of ISR $\otimes$ FSR interference ●Does NOT reintroduce FSR●

●Suppresses transverse radiation ●Well behaved weight (no tail) ● Fig. B

$\Rightarrow$ $\langle W_{\mathrm{ECS}} \rangle$ alone is infrared (IR) divergent ($\simeq \log \epsilon$, $\epsilon$ = dummy IR cut-off).

Cancelled by virtual+soft form-factor (YFS theorem). We calculate IR violation and introduce weight: $W_{ECS}^{norm} = \exp\left[\frac{3}{4}(\bar{\gamma}_t - \gamma_s) \int_{\epsilon\sqrt{s}/2}^{\sqrt{s}} \frac{d^3k}{k^0} \tilde{S}_{ab}(k)(1 - w_{ECS})\right]$ Fig. C

▷ **Scale of $\alpha_{QED}$ should be $t^{\pm}$, not $M_W$.** We add it "naively" as overall factor:

$W_{Run} = \left(\alpha(t^{\pm})/\alpha_{G_\mu}\right)^2$ or $W_{Run} = \left(\alpha(t^{+})\alpha(t^{-})/\alpha_{G_\mu}^2\right)^2$ Fig. D

▷ **Theoretical precision: 3%** (experimental precision at LEP2 $\sim 7\%$)

●ECS implementation (NLO): 2% ● Naive $\alpha_{QED}$: 2% [G. Passarino, NPB578, 3 (2000)] ●

# ECS: suppression of transv. phots.

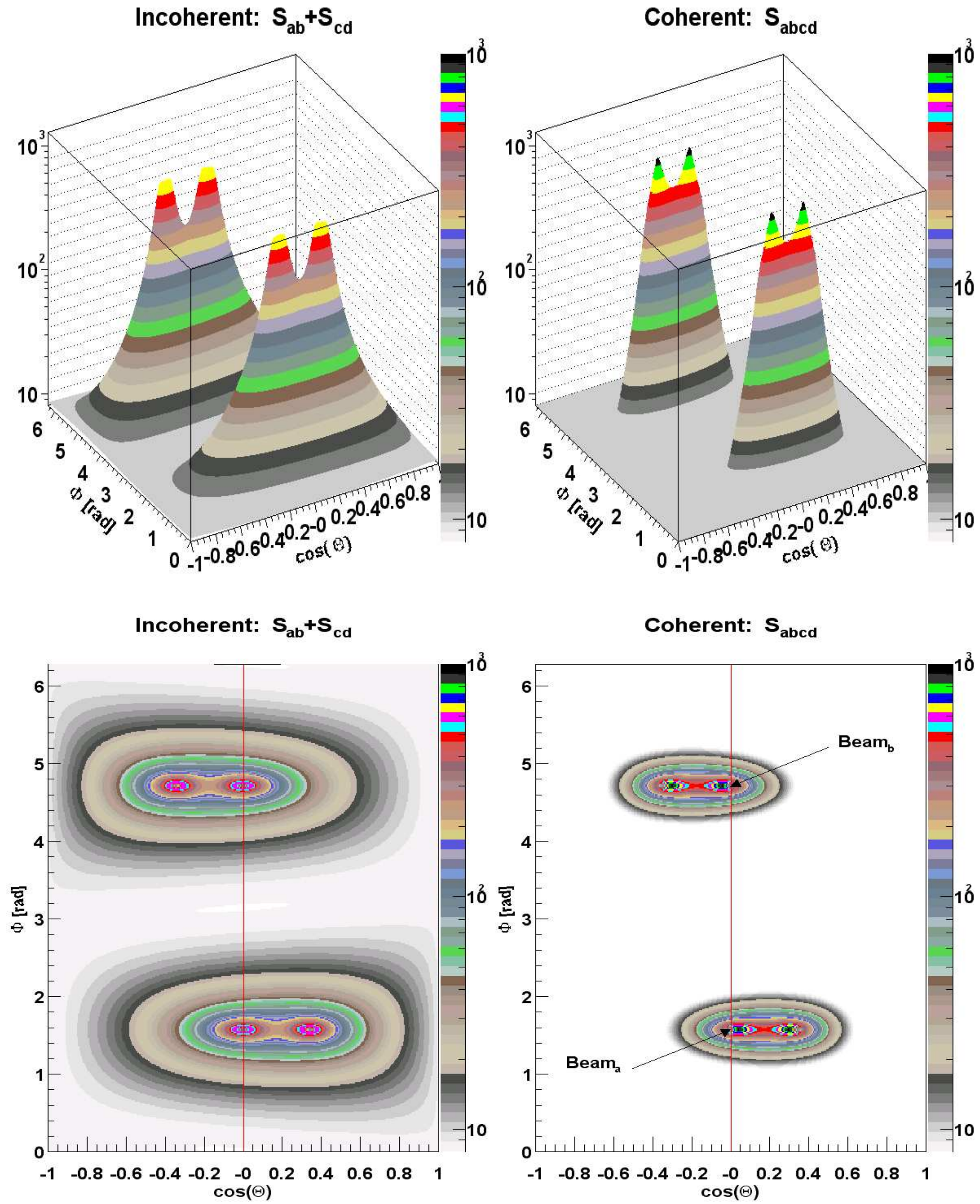



Fig. A Photon angular distribution. The difference between left and right hand side plots illustrates ECS effect.

## Summary

- Theoretical precision for quantities other than total cross section has been established:

  $M_W$ precision $\sim 5$ MeV (EXP precision $\sim 30$ MeV) *[PLB 523 (2001) 117]*

  $\lambda$ coupling precision $\sim 0.005$ (EXP precision $\sim 0.01$) *[PLB 533 (2002) 75,*

  *with R. Brunelière, A. Denner, S. Dittmaier, S. Jézéquel, M. Roth, D. Wackeroth, ]*

  This precision meets the LEP2 experimental requirements

- KoralW and YFSWW3 have been combined into one Monte Carlo code by means of novel technique of "Concurrent Monte Carlo" to provide complete $4f + \mathcal{O}(\alpha)$ predictions for $WW$ physics *[CPC 140 (2001) 432 and 475]*

- KoralW has been upgraded in the kinematical domain of single-$W$ to better emulate $t$-channel dominated photonic radiation with total precision of 3%, sufficient for LEP2 physics (EXP precision $\sim 7\%$) *[CERN-TH 2002-195, Sept. 2002]*