Loops & Legs in QFT, April 2000

RacoonWW:
Radiative corrections on $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f$ *

Stefan Dittmaier

Universität Bielefeld, Germany

in collaboration with

A. Denner, M. Roth and D. Wackeroth

Contents

---

*Nucl. Phys. **B560** (1999) 33; Phys. Lett. **B475** (2000) 127; hep-ph/9912447; BI-TP 2000/06, in prep.

1 Introduction

Recent progress for $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f$

...experimentally by LEP2:

- W-pair cross section σ_{WW} reaches 1% accuracy
- W-boson mass M_{W} exceeds $50\,\mathrm{MeV}$ accuracy
- analysis of $4f+\gamma$ final states
  $\to$ first direct bounds on quartic gauge-boson couplings (QGCs)
  OPAL '99

...theoretically:

- inclusion of $\mathcal{O}(\alpha)$ correction into event generators
  (RacoonWW, YFSWW)
- full matrix-element calculations for $4f+\gamma$ production
  (Jegerlehner/Kolodziej, GRACE, WRAP, RacoonWW)
- various numerical studies
  (corrections, γ recombination, QGCs, etc.)

$\Rightarrow$ Issue of this talk is

- to explain the strategy of the RacoonWW approach
- to present first numerical results of RacoonWW

Relevance of radiative corrections

Procedure for predictions in the past

Event generators for $\mathrm{ee} \to \mathrm{WW} \to 4f$ included
leading corrections to tree-level predictions: CERN report 96-01

- leading universal effects: $\Delta\alpha$, $\Delta\rho$
- Coulomb singularity at WW threshold
- leading-log initial-state radiation (ISR)

Size of neglected non-leading corrections ?

Estimate by non-leading $\mathcal{O}(\alpha)$ corrections to on-shell process:

δ_{IBA} : univ. corrections, Coulomb sing., ISR — Böhm, Denner, S.D. '92

δ : full $\mathcal{O}(\alpha)$ correction to $\mathrm{ee}\to\mathrm{WW}$ — Böhm et al. '88; Fleischer, Jegerlehner, Zralek '89

Impact on integrated cross-section:

$$\delta - \delta_{\mathrm{IBA}} \quad \sim \quad \begin{cases} 1\text{–}2\% & \text{at LEP2} \\ 10\text{–}20\% & \text{in TeV range} \end{cases}$$

CERN report 96-01
Denner, S.D. '97
Jadach et al. '98

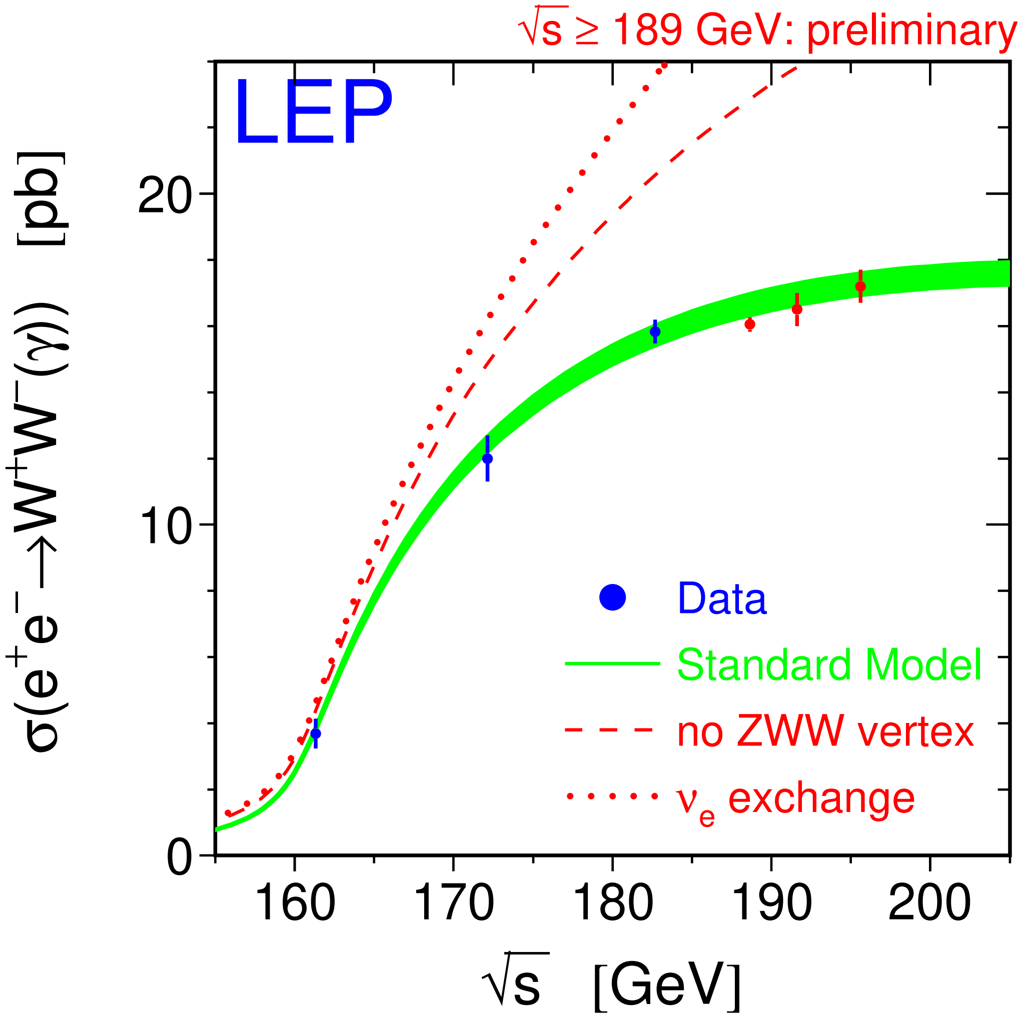
Effect even much larger in angular distributions.

$\Rightarrow$ Inclusion of non-leading corrections important !

Remark: dominance of vertex + box corrections at high energies
[Sudakov logs like $\alpha \ln^2(s/M_{\mathrm{W}}^2)$] — Beenakker et al. '93

Total WW cross section at LEP2 — status of 1999

LEPEWWG '99



GENTLE prediction
with theoretical uncertainty of $\sim \pm 2\%$

$\uparrow$

non-leading electroweak corrections

2 $\mathcal{O}(\alpha)$ corrections to $\mathrm{e^+e^-}\to\mathrm{WW}\to 4f$

Virtual corrections — $\mathrm{e^+e^-} \to 4f$ at one loop

Problems in full calculation:

- enormous technical complications:
  $\mathcal{O}(10^3$–$10^4)$ diagrams per $4f$ state, many $4f$ states, numerical instabilities, etc.

  Nevertheless there is some progress . . . Vicini '97–'99

- no convincing solution to maintain gauge invariance in practice

Possible solution: double-pole approximation (DPA)

$\Rightarrow$ Take only diagrams for $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f$
with two nearly resonant W bosons !

- Considerable reduction in number of Feynman graphs
- On-shell production and decay of W's as building block
- Generic calculation for all final states possible
- Expected uncertainty not too close to threshold:

$$\sim \mathcal{O}\left(\frac{\Gamma_\mathrm{W}}{M_\mathrm{W}}\frac{\alpha}{\pi}\ln(\cdots)\right) \lesssim 0.5\%$$

Real corrections — $\mathrm{e^+e^-} \to 4f + \gamma$ at tree level

Full calculations for all final states exist.

$\Rightarrow$ DPA for real corrections can be controlled.

Note: error estimate of DPA for real corrections
not obvious for $E_\gamma \sim \Gamma_\mathrm{W}$!

The RacoonWW approach

Denner, S.D., Roth, Wackeroth '99

$e^+e^- \to 4f$ at tree level

Full matrix-element calculation with massless fermions

$\mathcal{O}(\alpha)$ radiative corrections (RCs) to $e^+e^- \to WW \to 4f$

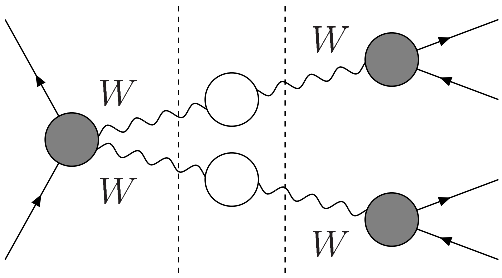
virtual

$e^+e^- \to WW \to 4f$ at one loop:
Double-pole approximation

real

$e^+e^- \to 4f+\gamma$ at tree level:
Full matrix-element calculation

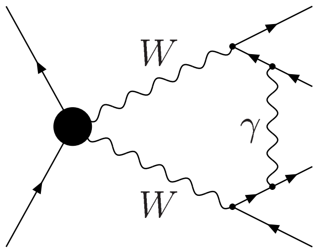
Factorizable corrections



Building blocks:
– RCs to on-shell production
– RCs to on-shell decay
But: respect spin correlations!

Böhm et al. '88
Fleischer, Jegerlehner, Zralek '89
Bardin, S. Riemann, T. Riemann '86
Jegerlehner '86; Denner, Sack '90

Non-factorizable corrections



etc.

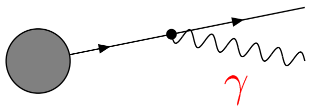
Photon exchange between production and decay subprocesses ($E_\gamma \lesssim \Gamma_W$)

Melnikov, Yakovlev '96
Beenakker, Berends, Chapovsky '97
Denner, S.D., Roth '97

Combination of virtual and real corrections

Corrections involve singularities:

Typical situation:



} Emission angle or $E_\gamma \;\to 0$

$\Rightarrow$ IR- and mass singularies proportional to $|\mathcal{M}_{\mathrm{Born}}|^2$

Note: connection with virtual corrections
$\rightarrow$ cancellations

$\Rightarrow$ Careful treatment necessary, since

- virtual corrections related to $\mathcal{M}^{\mathrm{e^+e^-\to WW\to 4}f}_{\mathrm{Born,DPA}}$
- real corrections related to $\mathcal{M}^{\mathrm{e^+e^-\to 4}f}_{\mathrm{Born}}$

Application of two methods:

1. "phase-space slicing"
   $\rightarrow$ separation of singularities by cuts
2. "dipole subtraction formalism":
   - QCD with massless partons — Catani, Seymour '96
   - γ radiation off massive fermions — S.D. '99, Roth '99

   $\rightarrow$ separation with subtraction function

“Master formula”:

$$
\begin{aligned}
\int \mathrm{d}\sigma \;=\; \frac{1}{2s}\Bigg\{ \int \mathrm{d}\Phi_{4f} \Bigg[& \, |\mathcal{M}^{\mathrm{e}^+\mathrm{e}^-\to 4f}_{\mathrm{Born}}|^2 \\
& + 2\,\mathrm{Re}\Bigg((\mathcal{M}^{\mathrm{e}^+\mathrm{e}^-\to \mathrm{WW}\to 4f}_{\mathrm{Born,DPA}})^* \, \delta\mathcal{M}^{\mathrm{e}^+\mathrm{e}^-\to \mathrm{WW}\to 4f}_{\mathrm{virt,fact,DPA}} \\
& \qquad + |\mathcal{M}^{\mathrm{e}^+\mathrm{e}^-\to \mathrm{WW}\to 4f}_{\mathrm{Born,DPA}}|^2 \, \delta_{\mathrm{virt,nonfact,DPA}} \Bigg) \\
& \Bigg] \\
+ \int \mathrm{d}\Phi_{4f\gamma} \quad & |\mathcal{M}^{\mathrm{e}^+\mathrm{e}^-\to 4f\gamma}_{\mathrm{Born}}|^2 \Bigg\}
\end{aligned}
$$

non-singular $\left\{ \quad + \, |\mathcal{M}_{\mathrm{Born,DPA}}^{\mathrm{e^+e^-\to WW\to 4}f}|^2 \, \delta_{\mathrm{sub},1}^{4f} \right.$

explicit mass singularities $\{ \quad + \, |\mathcal{M}_{\mathrm{Born}}^{\mathrm{e^+e^-\to 4}f}|^2 \otimes \delta_{\mathrm{sub},2}^{4f}$

$$\underbrace{\left[\qquad - |\mathcal{M}_{\mathrm{Born}}^{\mathrm{e^+e^-\to 4}f}|^2 \, \delta_{\mathrm{sub}}^{4f\gamma} \right]}_{\text{non-singular}}$$

Singular structures:

- $\delta_{\mathrm{sub}}^{4f\gamma}$: IR and collinear poles in $4f\gamma$ phase space (no regulators: $m_\gamma = m_f = 0$)
- $\delta_{\mathrm{sub},1}^{4f}$: IR and mass singularities
  $\alpha \ln(m_\gamma)\ln(m_f)$, $\alpha \ln(m_\gamma)$, $\alpha \ln^2(m_f)$, $\alpha \ln(m_f)$
  related to $4f$ kinematics
  $\rightarrow$ full compensation by virtual counterparts
- $\delta_{\mathrm{sub},2}^{4f}$: physical ISR singularities $\alpha \ln(m_{\mathrm{e}}/E)$
  associated with $\mathrm{e} \to \mathrm{e}\gamma$ splitting function
  $\rightarrow$ full Born matrix element kept !

Further features of RacoonWW

Input: different input schemes, e.g. G_μ-scheme

ISR beyond $\mathcal{O}(\alpha)$:

soft-γ exponentiation and leading $\mathcal{O}(\alpha^2)$ via structure function

Monte Carlo integration:

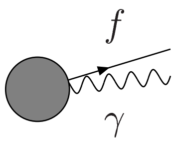
- multi-channel Monte Carlo approach
- weighted events

Massless final-state fermions:

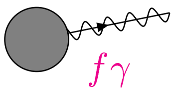
$\rightarrow$ avoid final-state mass singularities ...

- for full set of $4f$ graphs:
  cuts on $\mathrm{e}^\pm$ production angles and $f\bar{f}$ invariant masses
  (only relevant for background diagrams)
- for γ emission:
  recombination of soft and collinear γ's with fermions

  Possible procedure:
  select fermion with smallest invariant mass $(p_f + p_\gamma)^2$, then:



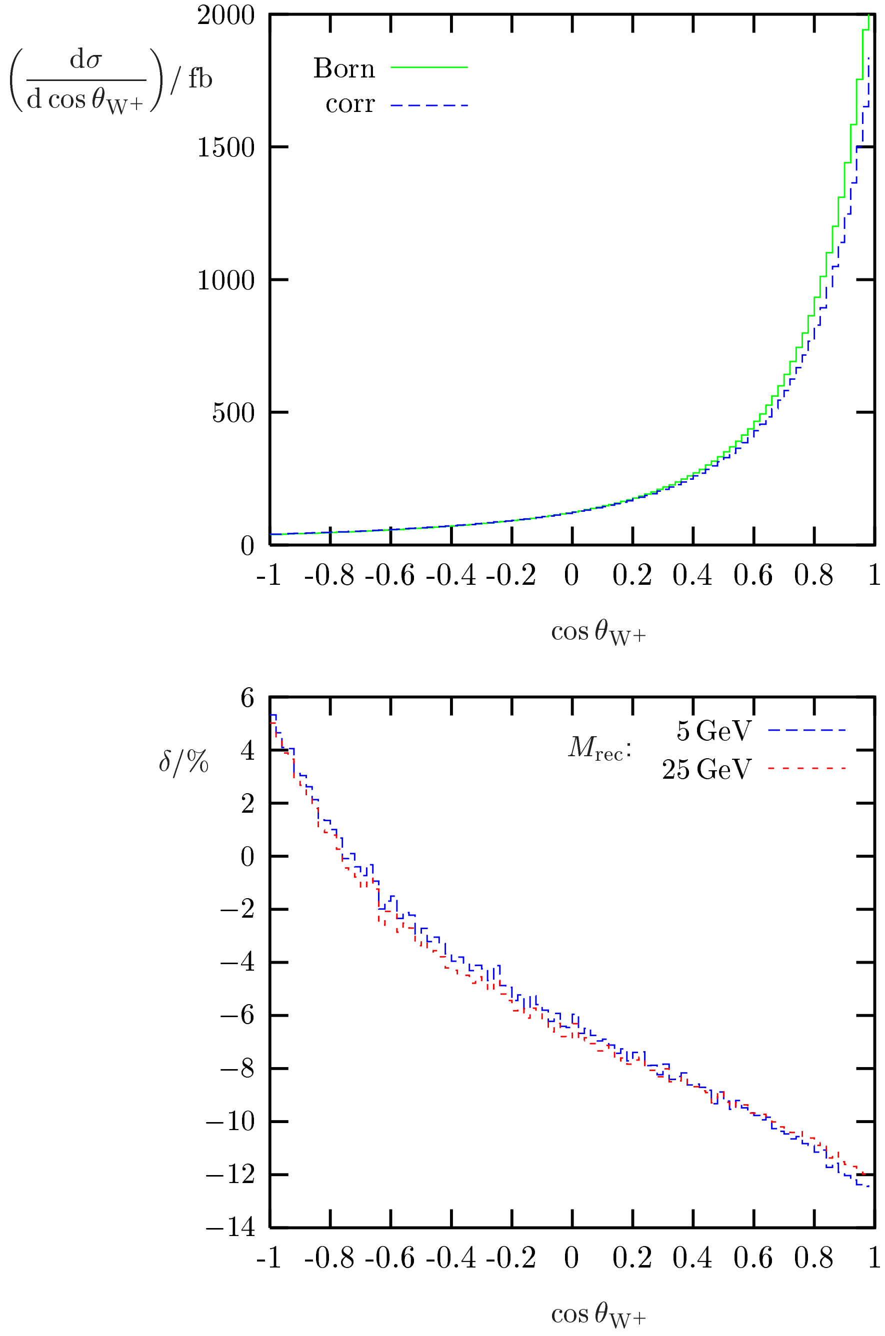
$\}\ (p_f + p_\gamma)^2 < M^2_{\mathrm{rec}} \quad \Rightarrow$



$p_{f\gamma} = p_f + p_\gamma$

3 Numerical results of RacoonWW

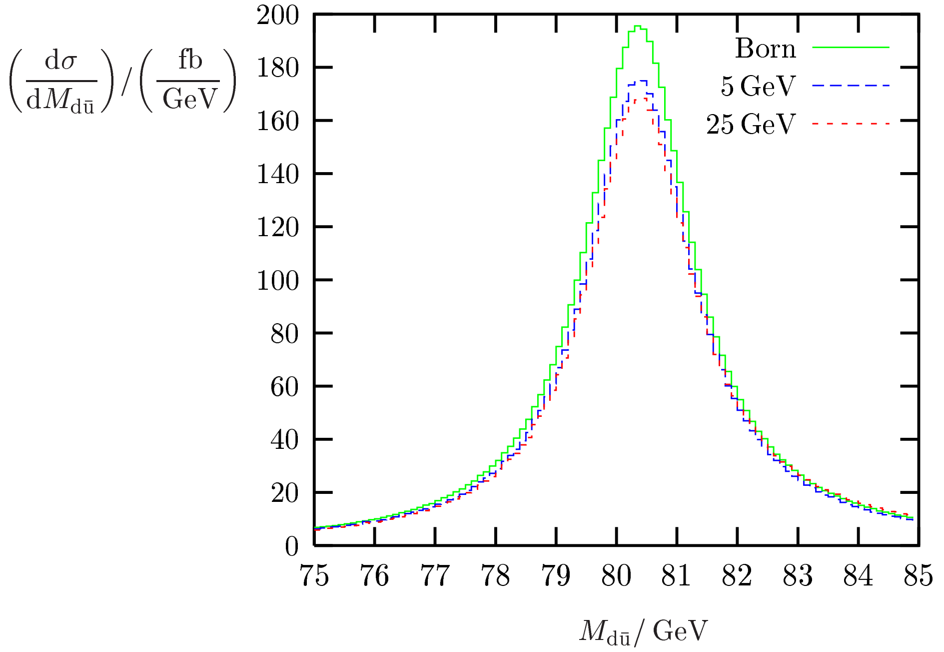
W-production angle distribution:



$e^+e^- \to \mu^+\nu_\mu d\bar{u}(\gamma)$

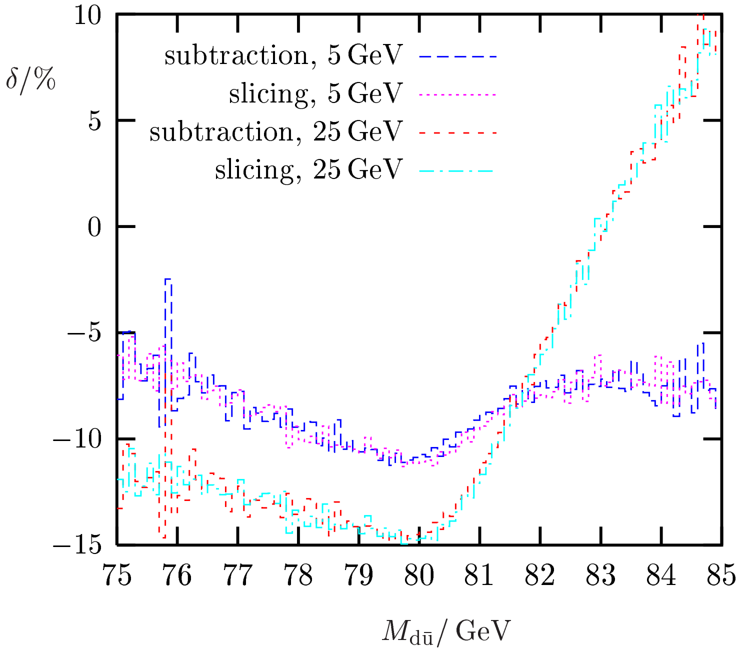
$\sqrt{s} = 200\,\mathrm{GeV}$

W$^-$ invariant-mass distribution:



$e^+e^- \to \mu^+\nu_\mu d\bar{u}(\gamma)$

$\sqrt{s} = 200\,\mathrm{GeV}$

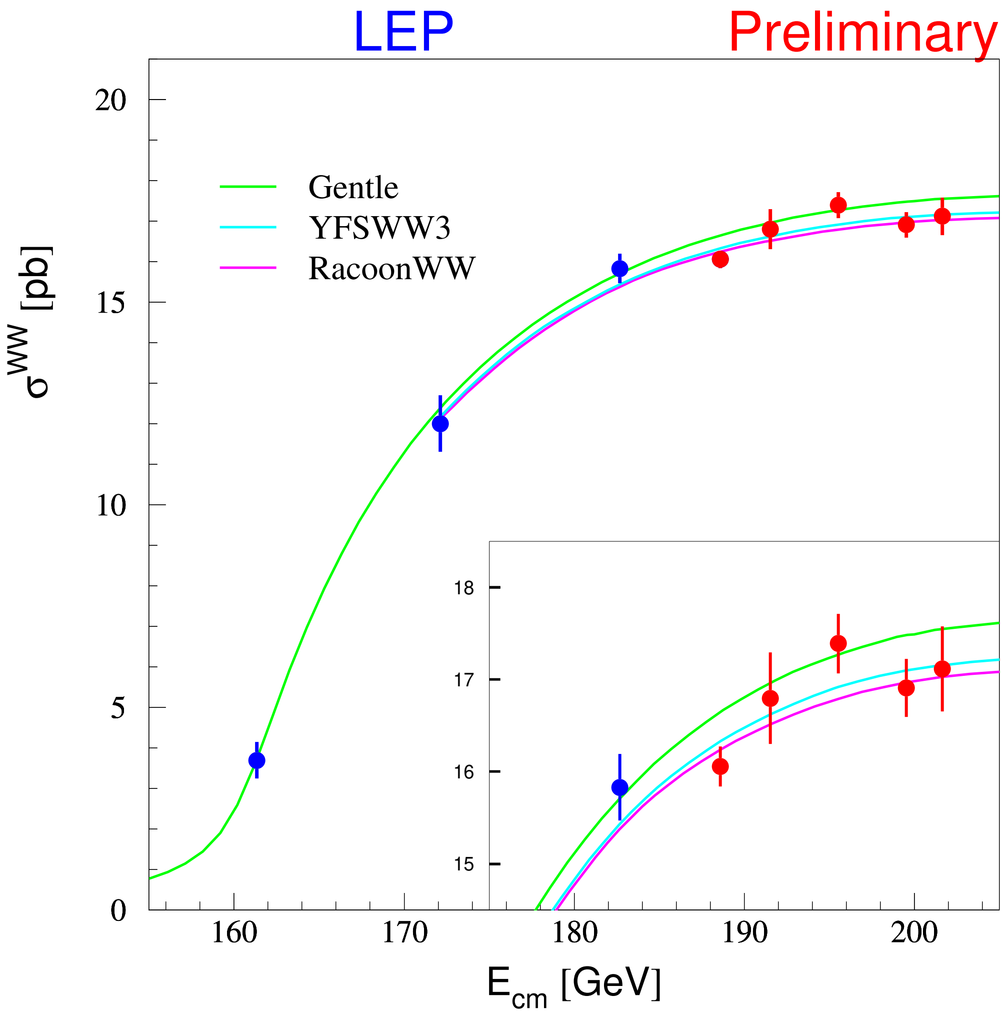


$\Rightarrow$ Strong sensitivity to photon recombination procedure !

Corrections induce $\Delta M_W \sim +30\,\mathrm{MeV}$ for $M_{rec} = 25\,\mathrm{GeV}$

Total WW cross section at LEP2:

LEPEWWG 2000



Theoretical uncertainty:

- naive: $\Delta_{\rm th} \lesssim 0.5\%$
- more sophisticated error estimate in progress

4 Summary and outlook

Event generator RacoonWW:

- lowest order: full amplitude for $\mathrm{e}^+\mathrm{e}^- \to 4f$
- real corr's: full amplitude for $\mathrm{e}^+\mathrm{e}^- \to 4f + \gamma$
  and ISR beyond $\mathcal{O}(\alpha)$
- virtual corr's: consistent DPA for $\mathrm{e}^+\mathrm{e}^- \to \mathrm{WW} \to 4f$

$\Rightarrow$ First event generator with complete DPA for $\mathcal{O}(\alpha)$ corr's

0.5% precision for WW cross section reached by RacoonWW

Work in progress:

- public version of RacoonWW
- comparison to related work $\to$ LEP2 MC workshop
  - MC generator YFSWW (Jadach et al.)
    $\to$ 0.7% difference in total cross section
  - semianalytical approach of Beenakker/Berends/Chapovsky
    $\to$ agreement for leptonic cross section