Loopfest, BNL, May 2002

Four-fermion production at future e^+e^- linear colliders

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Contents

1 Introduction

Physical goals for $e^+e^- \to 4f\,(+\gamma)$ and relevant observables ?

Main interest & largest cross sections:

$$e^+e^- \to WW \quad \text{and} \quad e^+e^- \to e\nu_e W$$

Standard-Model precision test:

e.g.: $\frac{\Delta\sigma_{WW}}{\sigma_{WW}}(\text{LEP2}) \sim 1\%, \qquad \frac{\Delta\sigma_{WW}}{\sigma_{WW}}(\text{TESLA}) < 0.5\%$

W-mass measurement in $ee \to WW$:

$\Rightarrow$ Better constraints on M_H and new physics !

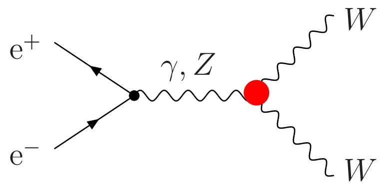
Relevant observables for M_W:

- σ_{tot} for W pairs at threshold
  $\Delta M_W(\text{LEP2}) \sim 150\,\text{MeV}, \quad \Delta M_W(\text{“MegaW”}) \sim 6\,\text{MeV}$
- invariant-mass distributions of W-decay products
  $\Delta M_W(\text{LEP2}) \sim 30\,\text{MeV}, \quad \Delta M_W(\text{TESLA}) \sim 15\,\text{MeV}$

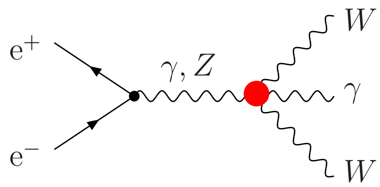
Gauge-boson self-interactions:

Constraints on anomalous gauge-boson self-couplings

- γWW, ZWW: angular distributions



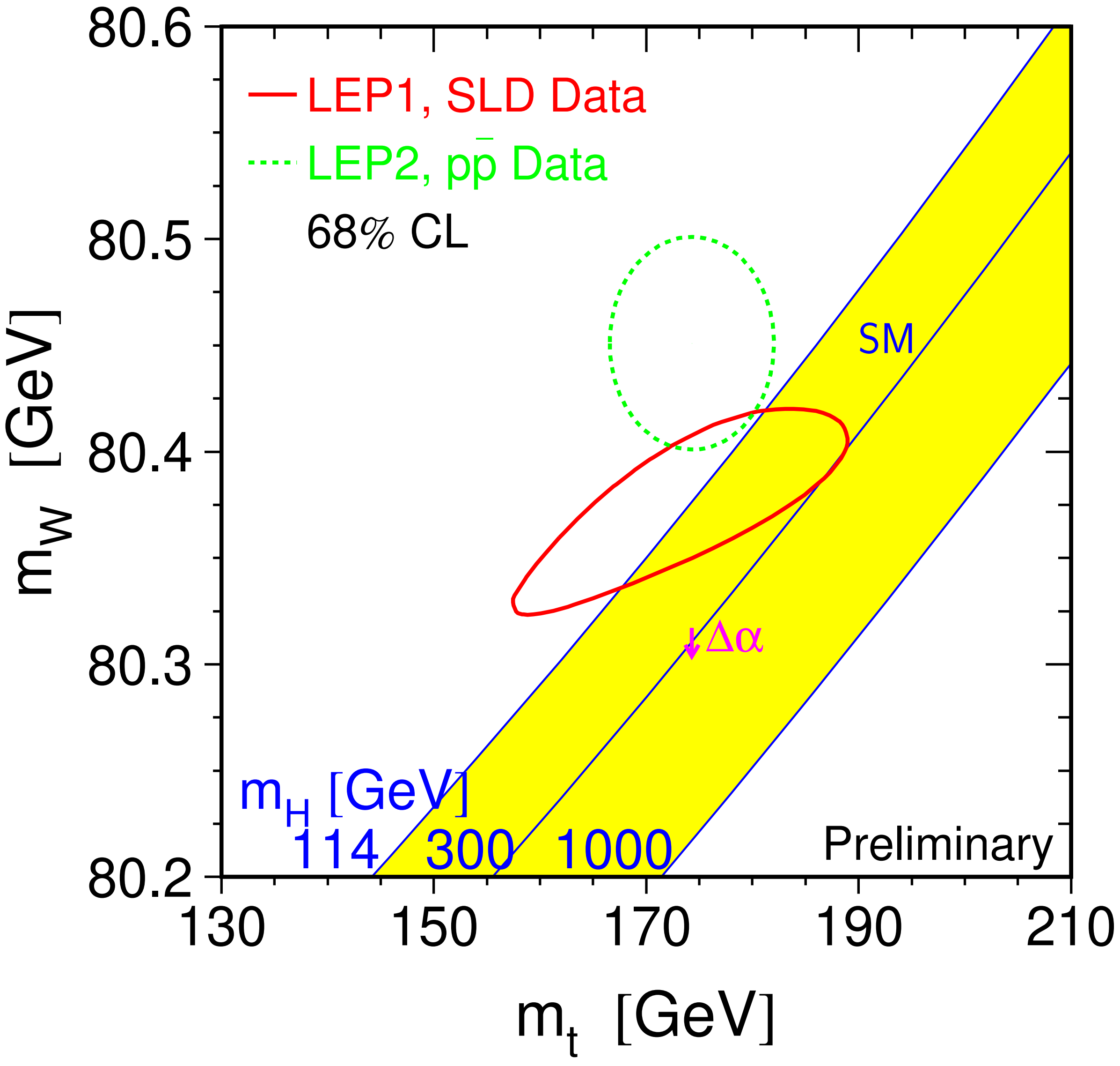
- $\gamma\gamma$WW, γZWW: e.g. E_γ distribution



... other interesting issues

Direct and indirect determination of M_{W} and m_{t}

LEPEWWG '02



$\Rightarrow$ Reasonable agreement, but...

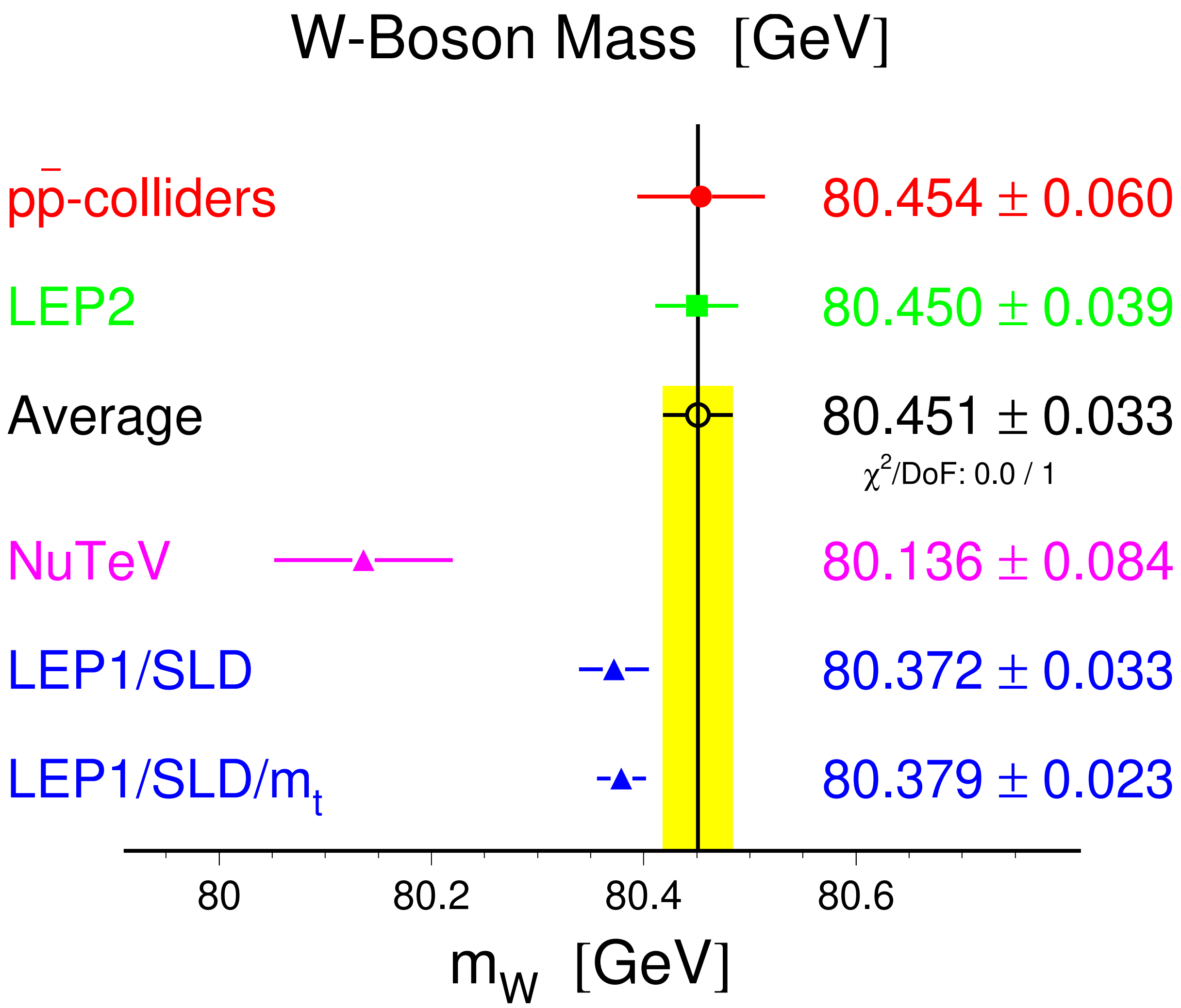
higher precision in M_{W} and m_{t} highly desribale:

$\hookrightarrow\ \mathrm{e}^+\mathrm{e}^- \to \mathrm{WW} \to 4f(+\gamma)$

- further constraints of M_{H} in SM
- (dis-)favour SUSY models

Present experimental status for M_{W}:

LEPEWWG '02



Progress for $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f$ in recent years

... experimentally by LEP2:

- W-pair cross section σ_{WW} reaches 1% accuracy
- W-boson mass M_{W} reaches $39\,\mathrm{MeV}$ accuracy
- analysis of $4f + \gamma$ final states
  $\longrightarrow$ first direct bounds on quartic gauge-boson couplings (QGCs)
  OPAL '99, L3 '00

... theoretically:

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

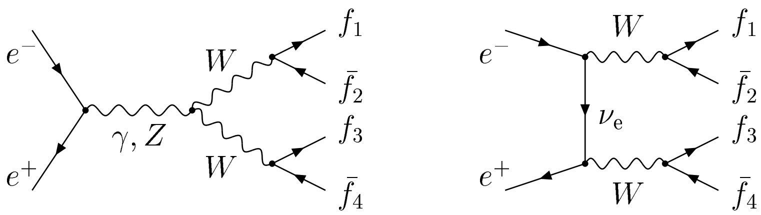
$\Rightarrow$ Issue of this talk is

- to briefly review the state of the art for $\mathrm{ee}\to\mathrm{WW}\to 4f(+\gamma)$
- to explain the main physical and technical problems in precision calculations $\longrightarrow$ role of loop calculations
- to give an outlook on our homework for a future $\mathrm{e^+e^-}$ collider

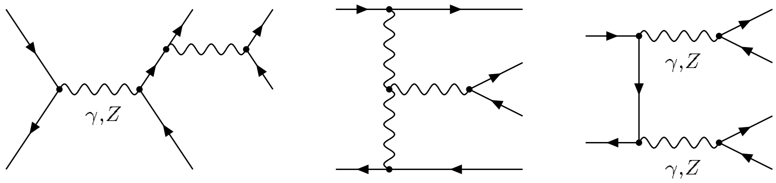
2 $4f$ and $4f+\gamma$ production in lowest order

Diagrams for $\mathrm{e}^+\mathrm{e}^- \to 4f$:

three WW "signal diagrams": two resonant W's



"background diagrams": at most one resonant W



etc.

Number of background diagrams:

$$\begin{array}{ll} \mathrm{e}^+\mathrm{e}^- \to \mu^-\bar{\nu}_\mu\tau^+\nu_\tau : & 6 \\ \vdots & \vdots \\ \mathrm{e}^+\mathrm{e}^- \to \mathrm{e}^-\bar{\nu}_\mathrm{e}\mathrm{e}^+\nu_\mathrm{e} : & 53 \end{array}$$

Impact of background diagrams $\sim \frac{\Gamma_\mathrm{W}}{M_\mathrm{W}} \sim 3\%$, but

- systematic enhancement effects (e.g. by $\mathrm{e}^\pm$ in final state)
- reduction by cuts possible

Full inclusion of background diagrams necessary !

Inflation of expense for $\mathrm{e}^+\mathrm{e}^- \to 4f + \gamma$:

	$\mathrm{e}^+\mathrm{e}^- \to 4f$	$\mathrm{e}^+\mathrm{e}^- \to 4f+\gamma$
# diagrams: (lowest order)	9–144	14–1008
dimension of phase space:	8	11
programs for		
single final states:	ERATO, GENTLE, HIGGSPV, KORALW, WTO, WWF, WWGENPV	WRAP, GRACE, CompHEP, "JK", PHEGAS
all final states:	ALPHA, CompHEP, Excalibur, grc4f, WPHACT, RacoonWW	RacoonWW

Main complications:

- fast evaluation of diagrams
  $\hookrightarrow$ spinor techniques or recursive algorithms
- extremely rich peaking structure of integrand
  $\hookrightarrow$ mainly treated by "multi-channel" Monte Carlo integration
  Berends,Daverveldt,Kleiss '85
  Hilgart,Kleiss,Le Diberder '93
- gauge invariance in presence of unstable particles
  $\hookrightarrow$ compare different schemes

Tuned comparison between programs (mainly PHEGAS, WRAP, RacoonWW)

$\Rightarrow$ Predictions fully under control

LEP2 MC workshop report
hep-ph/0005309

Gauge-invariance violation at high energies

Some cross sections $\sigma/\,\mathrm{fb}$ as given by RacoonWW

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

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

$\sqrt{s} =$	189 GeV	500 GeV	2 TeV	10 TeV
constant width	703.5(3)	237.4(1)	13.99(2)	0.624(3)
running width	703.4(3)	238.9(1)	34.39(3)	498.8(1)
complex mass	703.1(3)	237.3(1)	13.98(2)	0.624(3)

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

$\sqrt{s} =$	189 GeV	500 GeV	2 TeV	10 TeV
constant width	224.0(4)	83.4(3)	6.98(5)	0.457(6)
running width	224.6(4)	84.2(3)	19.2(1)	368(6)
complex mass	223.9(4)	83.3(3)	6.98(5)	0.460(6)

Important: separation cuts for "visible" γ $(E_\gamma, \theta_{\gamma f} > \text{cut})$

- Running width $\longrightarrow$ totally wrong at high energies !

  Reason: violation of gauge invariance

- Constant width / complex masses $\longrightarrow$ consistent results

  $\uparrow$

  preserves gauge invariance

Remarks on the gauge-invariance problem:

Amplitude $\mathcal{M}$ with *one* resonance:

$$\mathcal{M} \;=\; \underbrace{\frac{R(k^2)}{k^2 - M^2}}_{\text{resonant}} \;+\; \underbrace{N(k^2)}_{\text{non-resonant}}$$

Consequences of gauge invariance:

- $\mathcal{M}$ is independent of gauge parameters
- $\mathcal{M}$ obeys Ward identities

Introduction of decay width $\Gamma(k^2)$:

$$\frac{1}{k^2 - M^2} \;\to\; \frac{1}{k^2 - M^2 + \mathrm{i}M\Gamma(k^2)}$$

$\Rightarrow$ in general violation of gauge invariance !

Solutions for gauge bosons and lowest order:

- "fermion-loop scheme" Baur, Zeppenfeld '95, Argyres et al. '95, Beenakker et al. '96

  $\to$ introduction of $\Gamma(k^2)$ in propagators and vertices by fermion-loop resummation

- "complex-mass scheme" Denner, S.D., Roth, Wackeroth '99

  $\to$ consistent analytical continuation of amplitudes to complex masses ($\Rightarrow$ complex couplings)

- "non-local effective Lagrangian" Beenakker, Berends, Chapovsky '99

  $\to$ gauge-invariant introduction of $\Gamma(k^2)$ in propagators and vertices

But: no practical gauge-invariant solution for radiative corrs.

3 Radiative corrections to $\mathrm{ee} \to \mathbf{WW} \to 4f$

3.1 Calculation of radiative corrections

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.
- no practical solution to maintain gauge invariance

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 !

- gauge invariance
- 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:
  $$\sim \mathcal{O}\left(\frac{\Gamma_\mathrm{W}}{M_\mathrm{W}}\frac{\alpha}{\pi}\ln(\cdots)\right) \lesssim 0.5\%$$
- drawback: DPA uncertainty out of control at threshold

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

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

Full matrix-element calculation with massless fermions

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

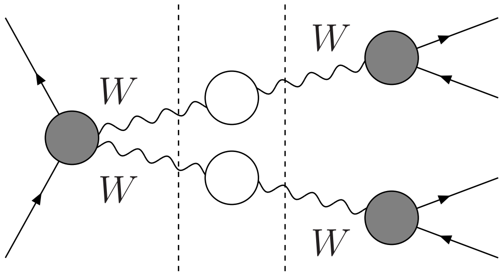
virtual

real

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

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

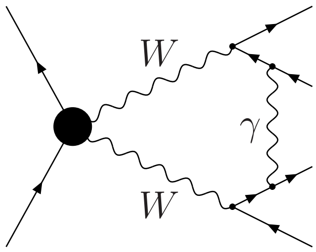
Factorizable corrections



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 ($E_\gamma \lesssim \Gamma_{\mathrm{W}}$)

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

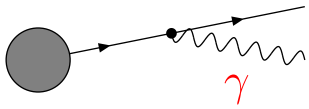
Beyond $\mathcal{O}(\alpha)$

Soft-γ exponentiation and leading-log ISR up to $\mathcal{O}(\alpha^3)$

Combination of virtual and real corrections in RacoonWW

Corrections involve singularities:

Typical situation:



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

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

Note: connection with virtual corrections
$\to$ cancellations

$\Rightarrow$ Careful treatment necessary, since

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

Application of two methods:

1. "phase-space slicing"
   $\to$ 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
   - QCD with massive partons — Phaf, Weinzierl '01; Catani, S.D., Seymour, Trócsányi '02

   $\to$ separation with subtraction function

The KoralW & YFSWW approach

Jadach et al. '98–'01

Tandem of two event generators: KandY

$\Downarrow$ $\Downarrow$

KoralW

$e^+e^- \to 4f$

$\oplus$

universal corrections

- full tree-level amplitudes
- Coulomb singularity
- FSR via PHOTOS
- YFS exp. & LL $\mathcal{O}(\alpha^3)$ ISR

YFSWW

DPA for $e^+e^- \to WW \to 4f$

$\oplus$

$\mathcal{O}(\alpha)$ correction

- DPA for virtual and real corrections to $ee \to WW$
- approximation for non-factorizable corrs.
- corrs. to decays via BR's
- FSR via PHOTOS
- YFS exp. & LL $\mathcal{O}(\alpha^3)$ ISR

cross talk via reweighting of events

Agreement between YFSWW and RacoonWW results at LEP2:

- total cross sections within 0.3%
- angular and invariant-mass distributions within 1%
- photon spectra within $\sim 5\%$

Comparison to related work

$\hookrightarrow$ Details also in LEP2 MC workshop report hep-ph/0005309

Semianalytical approach of Beenakker/Berends/Chapovsky '98

- DPA for virtual and real $\mathcal{O}(\alpha)$ corrections
- idealized situations (e.g. no photon recombination)
- numerical results for $\mathrm{e^+e^-} \to \mathrm{WW} \to 4\,$leptons

Comparison with RacoonWW results at LEP2 energies

$\hookrightarrow$ agreement for total cross section within some 0.1%

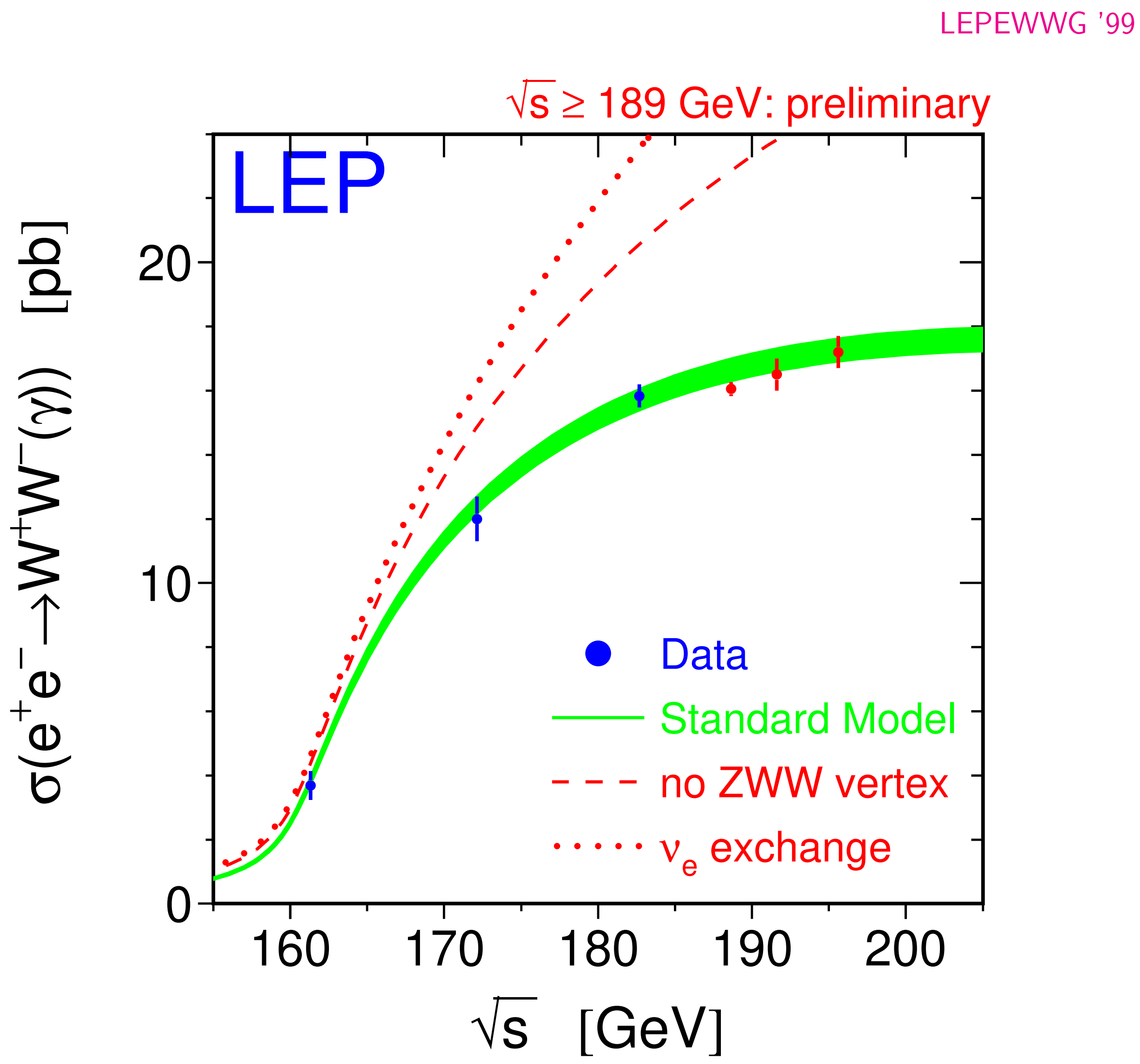
DPA of Kurihara/Kuroda/Schildknecht '01

- DPA for virtual and real $\mathcal{O}(\alpha)$ corrections
  (neglect of non-factorizable corrections)
- numerical results at LEP2 energies for total cross sections only

Comparison with RacoonWW results $\quad \to$ deviation of $\sim 0.6\%$

3.2 Results for total cross sections

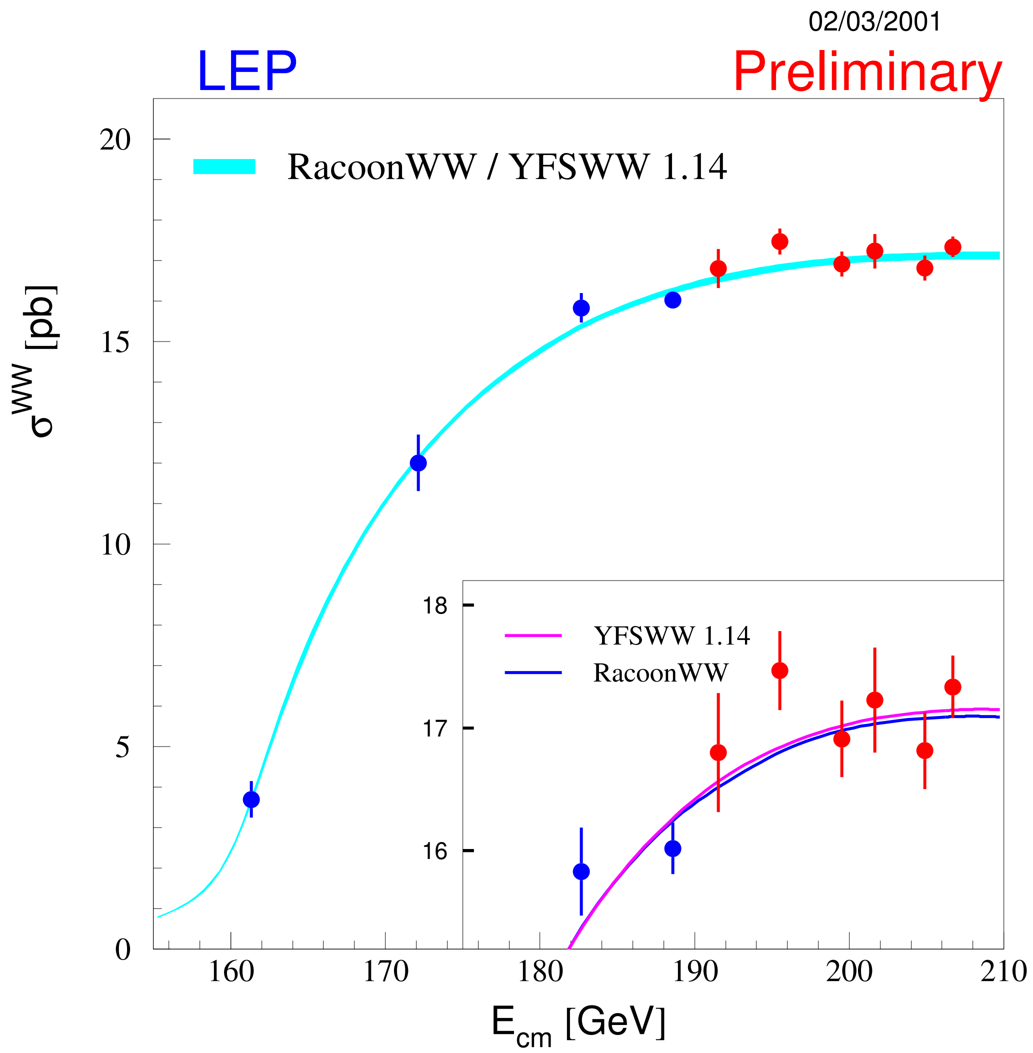
Total WW cross section at LEP2 — status of 1999



GENTLE prediction (Bardin et al.)
with theoretical uncertainty of $\sim \pm 2\%$
$\uparrow$
non-leading electroweak corrections

Total WW cross section at LEP2:

LEPEWWG
Winter 2001



$\Rightarrow$ Evidence for non-universal electroweak corrections !

RacoonWW versus YFSWW3 results at LEP2 and a future LC

Total cross sections:

no cuts		$\sigma_{\rm tot}[\rm fb]$	
final state	program	$\sqrt{s} = 200\,\rm GeV$	$\sqrt{s} = 500\,\rm GeV$
$\nu_\mu\mu^+\tau^-\bar{\nu}_\tau$	YFSWW3	$199.995(62)$	$89.607(32)$
	RacoonWW	$199.551(46)$	$90.018(27)$
	(Y–R)/Y	$0.22(4)\%$	$-0.46(5)\%$
$\rm u\bar{d}\mu^-\bar{\nu}_\mu$	YFSWW3	$622.71(19)$	$279.086(97)$
	RacoonWW	$621.06(14)$	$280.149(86)$
	(Y–R)/Y	$0.27(4)\%$	$-0.38(5)\%$
$\rm u\bar{d}s\bar{c}$	YFSWW3	$1937.40(61)$	$868.14(31)$
	RacoonWW	$1932.20(44)$	$871.66(27)$
	(Y–R)/Y	$0.27(4)\%$	$-0.41(5)\%$

Impact of non-leading electroweak corrections ?

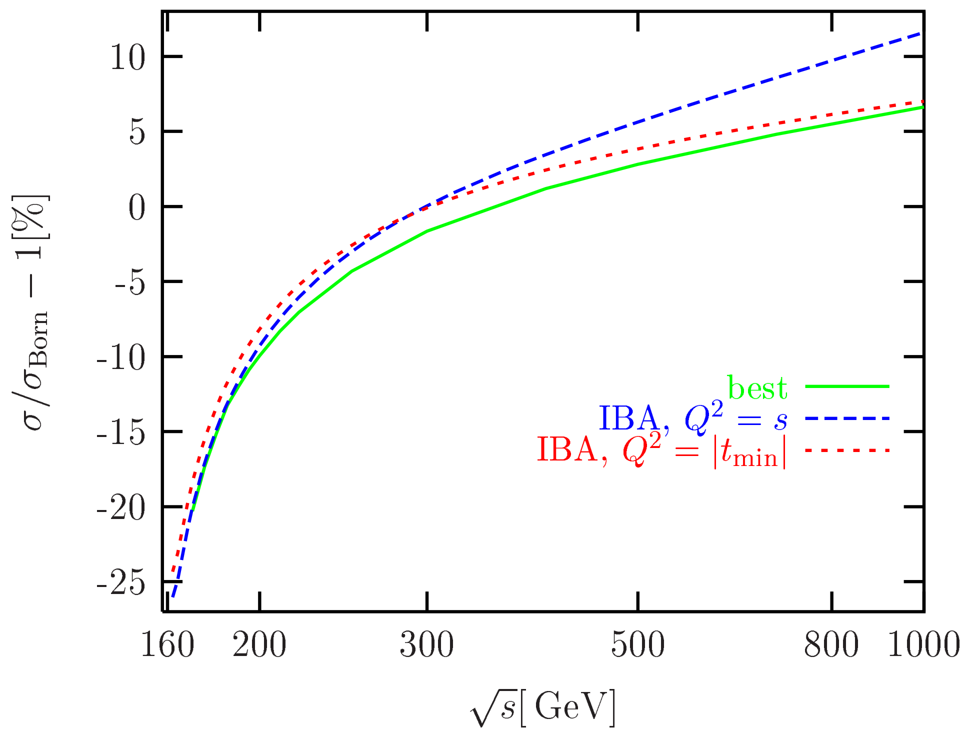
$\longrightarrow$ Compare full RCs with improved Born approximation (IBA) !

IBA includes:

- leading universal effects: $\Delta\alpha$, $\Delta\rho$
- Coulomb singularity at WW threshold
- leading-log ISR
  $\longrightarrow$ scale dependence via $\alpha^n \ln^n(m_\mathrm{e}^2/Q^2)$

Corrections to total $\mathrm{e^+e^-} \to \mathrm{u\bar{d}}\mu^-\bar{\nu}_\mu(\gamma)$ cross section:

Denner, S.D., Roth, Wackeroth '00



IBA uncertainty ~ 1–2% for $\sqrt{s} < 200\,\mathrm{GeV}$

$\sim 5\%$ for $\sqrt{s} \sim 500$–$1000\,\mathrm{GeV}$

From LEP2 to future $\mathrm{e^+e^-}$ colliders ("MegaW" at TESLA?)

Radiative corrections

...in the threshold region ($\sqrt{s} \lesssim 170\,\mathrm{GeV}$)

- DPA uncertainty runs out of control
- only approximation by leading universal corrections available (LL ISR, Coulomb singularity, effective couplings)
- theoretical uncertainty (TU):
  - cross section: $\sim 2\%$
  - distributions: $\gtrsim 2\%$

$\Rightarrow$ Full 1-loop calculation for $\mathrm{e^+e^-} \to 4f$ necessary !

...in the high-energy range ($\sqrt{s} \gtrsim 500\,\mathrm{GeV}$)

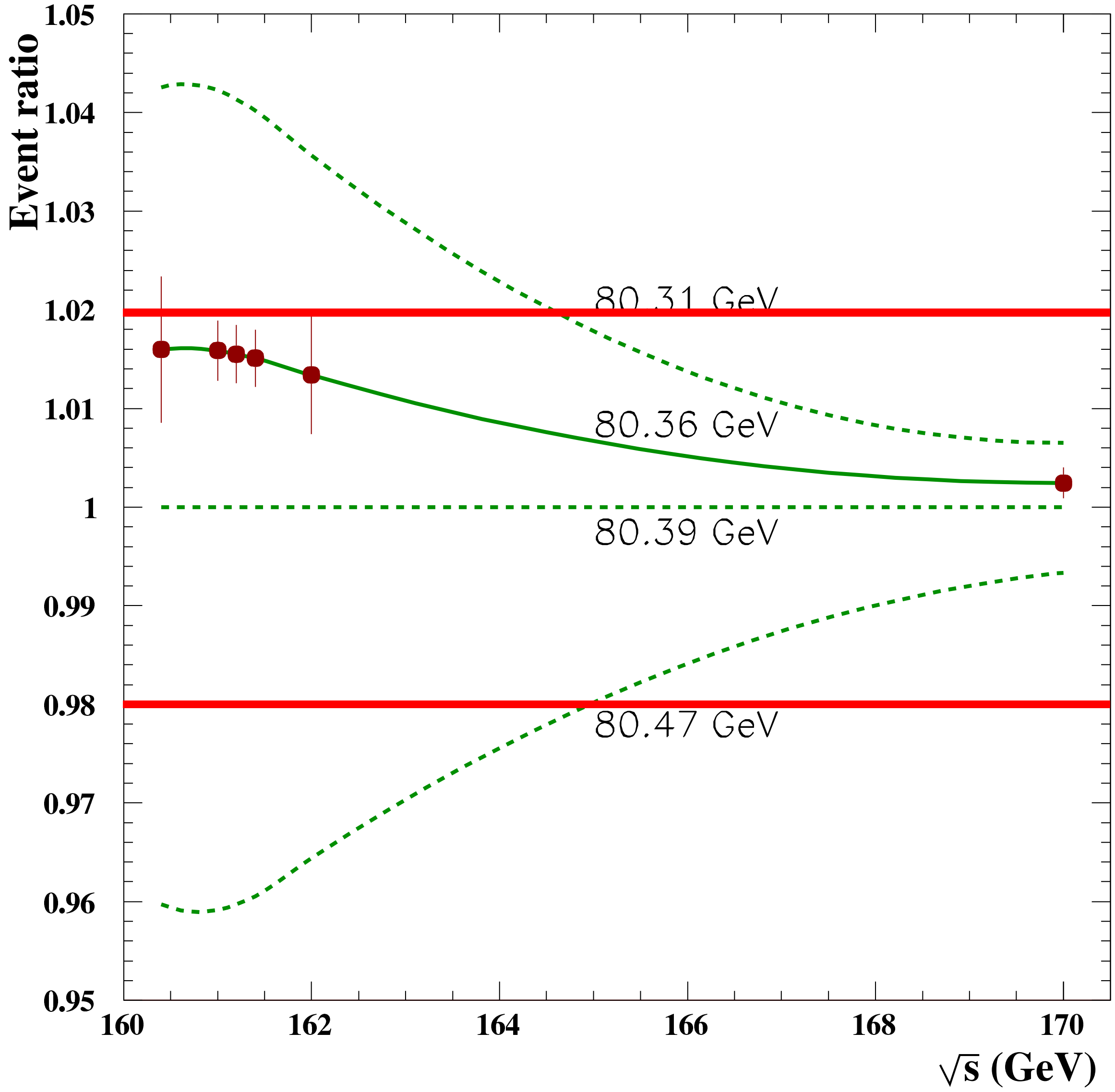
- procedure as in intermediate energy range
- TU worse due to missing higher orders (mainly two-loop electroweak Sudakov logs)

$\Rightarrow$ Inclusion of leading corrections beyond $\mathcal{O}(\alpha)$ necessary !

M_{W} measurement from threshold scan:

Experimental sensitivity: $\Delta M_{\mathrm{W}}(\mathrm{exp}) \sim 6\,\mathrm{MeV}$

TESLA-TDR '01



$\pm 2\%$ TU on cross section (no better estimate available)

$\Rightarrow$ Precise prediction of threshold slope necessary (with reliable TU)

3.3 W-invariant-mass distribution

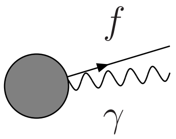
Mass singularities versus photon recombination

Recombination of soft and collinear γ's with fermions

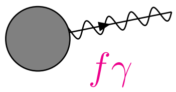
$\rightarrow$ compensation of final-state singularities

Possible procedure:

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



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

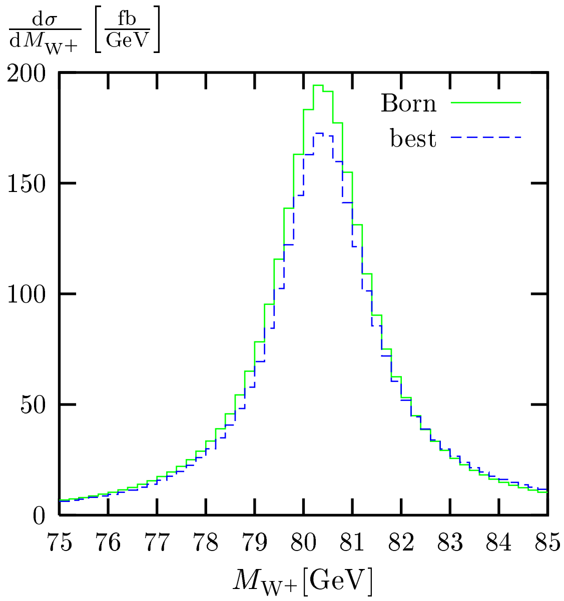


$$p_{f\gamma} = p_f + p_\gamma$$

$\rightarrow$ Qualitative simulation of imperfect detector resolution

W^+-invariant-mass distribution

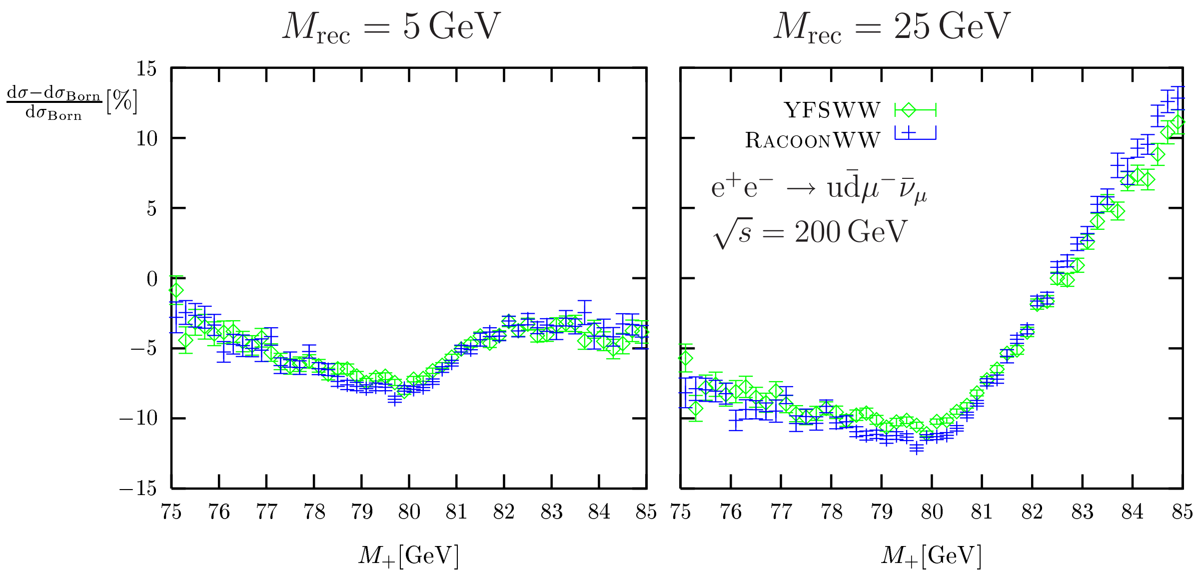
$\hookrightarrow$ Relevance for M_{W} reconstruction



$$\mathrm{e^+e^-} \rightarrow \mathrm{u\bar{d}}\mu^-\bar{\nu}_\mu$$

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

Corrections from RacoonWW and YFSWW3:



$\Rightarrow$ Good agreement,
but strong sensitivity to γ recombination

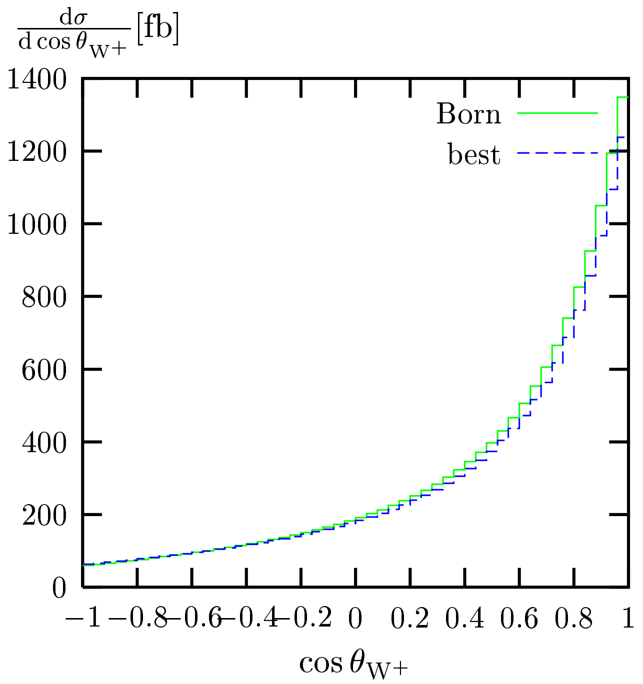
Estimate of TU for $M_{\rm W}$ reconstruction at LEP2: Jadach et al. '01

$$\Delta M_{\rm W}(\mathsf{TU}) \lesssim 5\,{\rm MeV}$$

3.4 W-production angular distribution

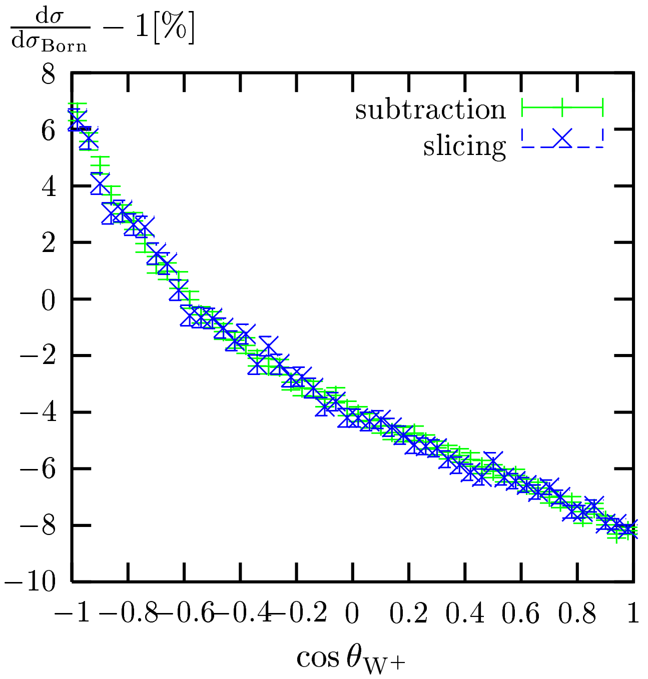
Corrections to the W-production angular distribution

$\hookrightarrow$ relevance for analysis of anomalous TGCs



$\mathrm{e}^+\mathrm{e}^- \to \mathrm{u}\bar{\mathrm{d}}\mu^-\bar{\nu}_\mu$

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



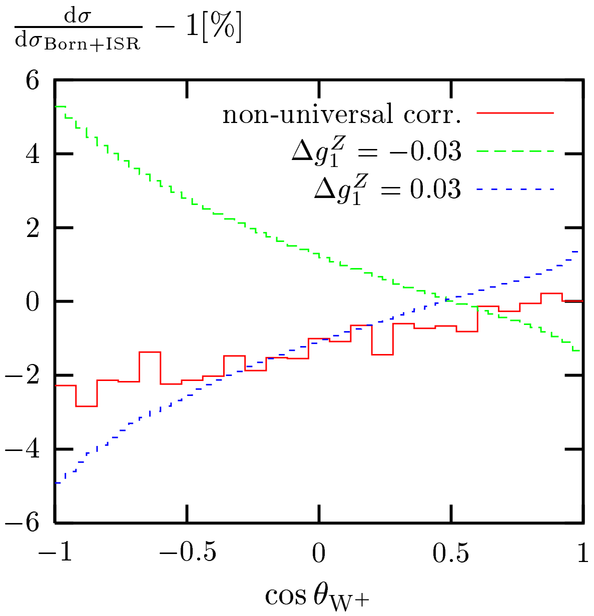
RacoonWW

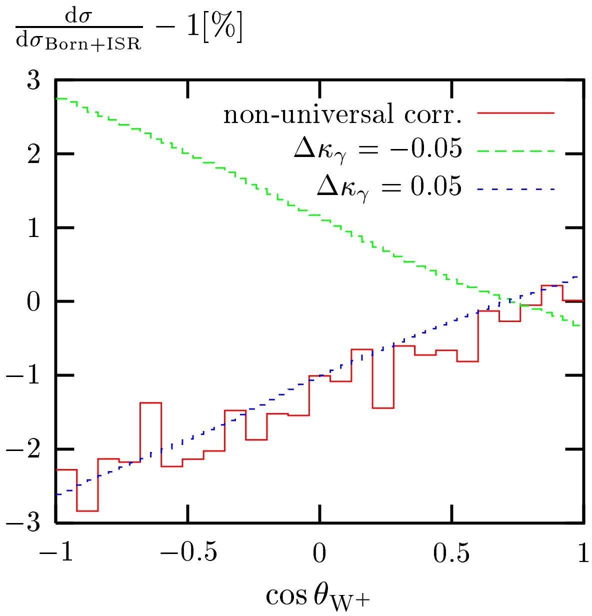
$M_{\mathrm{rec}} = 25\,\mathrm{GeV}$

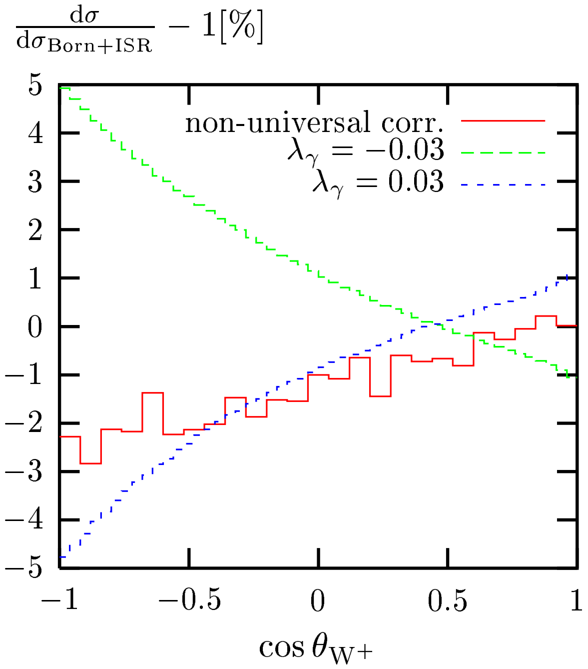
Only weak

M_{rec} dependence

Anomalous TGC versus electroweak corrections:







RacoonWW

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

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

$\lambda_Z = \lambda_\gamma$

$\Delta\kappa_Z = \Delta g_1^Z + \tan^2\theta_W \Delta\,\kappa_\gamma$

Neglected corrections
mimic anomalous TGC !

Sensitivity to anomalous TGCs at LEP2 and a future LC:

- LEP2:
  - experimental sensitivity (68% C.L.):

    $$\Delta\lambda \sim 0.025, \quad \Delta g_1^Z \sim 0.024, \quad \Delta\kappa_\gamma \sim 0.058$$

    LEPEWWG/TGC/2002-01
  - impact of non-univ. corrections on fit:

    $$\Delta\lambda \sim -0.015, \quad \Delta g_1^Z \sim -0.015, \quad \Delta\kappa_\gamma \sim -0.039$$

    LEPEWWG/TGC/2002-01
  - present theoretical uncertainty due to missing corrections:

    $\Delta\lambda \sim 0.005$ Brunelière et al. '02
- future LC:

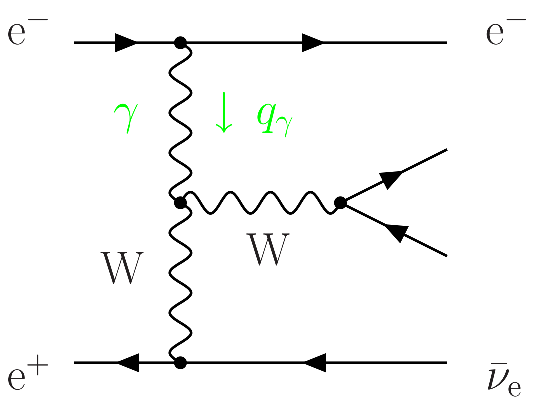
  experimental sensitivity:

  $\Delta g_1^Z, \Delta\kappa_\gamma, \Delta\lambda < 10^{-3} \ll$ impact of non-univ. corrections

  $\Rightarrow$ theoretical improvements necessary !

4 Features of single-W production

Typical dominating diagram:

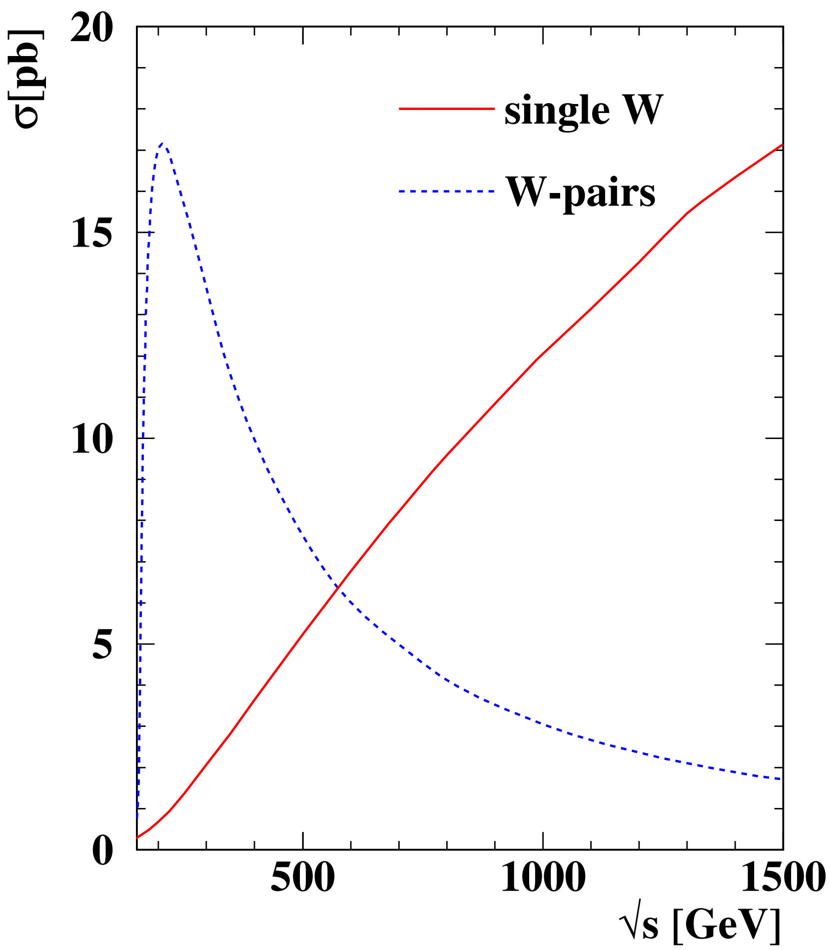


(strongly forward-scattered)

$q_\gamma^2 \to 0$

Finite electron mass required!

Total cross sections for single-W and W-pair production:



TESLA-TDR '01

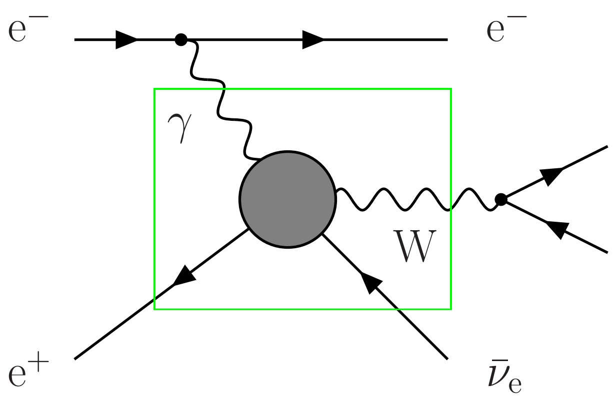
Present state-of-the-art: CERN 2000-009,
WPHACT (Accomando et al.), NEXTCALIBUR (Berends et al.), GRACE (Kurihara et al.), SWAP (Montagna et al.), WTO (Passarino)

- Consistent lowest-order predictions with finite fermion masses
- leading-log ISR
  (complicated by γ emission at low scale q_γ^2)
- running coupling $\alpha(q_\gamma^2)$
  (including non-perturbative domain $q_\gamma^2 \to 0$)
- fermion-loop corrections
- NO non-leading electroweak corrections
- TU for cross section: $\sim 5\%$
  (at $\sqrt{s} \sim 200\,\mathrm{GeV}$, larger for higher energy)

Required improvements in the future:

- required precision similar to W pairs for $\sqrt{s} \sim 400 - 800\,\mathrm{GeV}$
- possible first step:

  "DPA-like" approach for non-leading $\mathcal{O}(\alpha)$ corrections



Subprocess:
$\mathrm{e}^+\gamma \to \mathrm{W}^+\bar{\nu}_\mathrm{e}$

Feasible in due time! (Most building blocks exist.)

- finally: full $\mathcal{O}(\alpha)$ correction for $\mathrm{e}^+\mathrm{e}^- \to \bar{\nu}_\mathrm{e}\mathrm{e}^- f\bar{f}'$
  with finite m_e
- higher-order effects as for W pairs

5 Summary and outlook

State-of-the-art for $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f$:

- lowest order: full amplitudes for $\mathrm{e^+e^-} \to 4f$
- real corr's: full amplitudes for $\mathrm{e^+e^-} \to 4f+\gamma$ and leading-log ISR up to $\mathcal{O}(\alpha^3)$
- virtual corr's: consistent DPA for $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f$

$\to$ Fully implemented in RacoonWW,
partially in KandY (=KoralW and YFSWW)

Present theoretical uncertainty (TU):

- WW cross section
  TU $\lesssim 0.5\%$ (0.7%) for $500\,\mathrm{GeV} > \sqrt{s} > 180\,\mathrm{GeV}$ $(170\,\mathrm{GeV})$

  DPA not applicable near WW threshold
  $\to$ IBA used for $\sqrt{s} < 170\,\mathrm{GeV}$: TU $\sim 2\%$
- agreement between RacoonWW and YFSWW3 at LEP2 energies
  - within $\sim 0.3\%$ for total cross sections
  - within $\sim 1\%$ in angular and invariant-mass distributions

Relevance of electroweak corrections at LEP2:

- WW cross section
  $\to$ significance of non-universal weak corrections
- W-mass reconstruction
  $\to$ importance of photon recombination
- Triple gauge-boson couplings
  $\to$ significant distortion of angular distributions by corrections

Outlook: from LEP2 to future e^+e^- colliders (TESLA?)

New situation: higher energies and higher luminosity !

Estimated experimental uncertainties for W-pairs at TESLA:

- $< 0.5\%$ for total WW cross section and distributions
  (also for energies $> 500\,\mathrm{GeV}$)
- $6\,\mathrm{MeV}$ in M_W from threshold scan
- $15\,\mathrm{MeV}$ in M_W from direct reconstruction

$\Rightarrow$ Theoretical requirements:

- full treatment of $e^+e^- \to 4f$ at one loop
  $\to$ many technical difficulties,
  requires practical solution of gauge-invariance problem
  for radiative corrections to resonances
- treatment of "non-WW" channels on equal footing,
  e.g. single-W production $e^+e^- \to \bar{\nu}_e e^- W^+ \to \bar{\nu}_e e^- f\bar{f}'$
- leading two-loop effects,
  e.g. Sudakov log's at high energies, such as $\left[\alpha \ln^2(s/M_\mathrm{W}^2)\right]^2$
- better control of QCD corrections,
  e.g. matching of matrix elements with hadronization

Lot of homework + great challenges !