# Recent Theoretical Developments in LEP 2 Physics

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**Abstract**

Recent theoretical developments in $e^+e^-$-anninilation into fermion pairs are summarized.

## LEGENDA and ACKNOWLEDGEMENTS:

- **CompHEP** E. Boos, M. Dubinin and V. Ilyin
- **GENTLE** D. Bardin, A. Olchevski and T. Riemann
- **GENTLE-4fan** D. Bardin, J. Biebel, M. Bilenky, D. Lehner, A. Leike, A. Olchevski and T. Riemann
- **GRACE** Y. Kurihara, M. Kuroda and Y. Shimizu
- **KKMC** S. Jadach, B. Ward and Z. Was
- **YFSWW/YFSZZ/KORALW** S. Jadach, W. Placzek, M. Skrzypek,
- **KORALZ** S. Jadach, B. Ward and Z. Was
- **LAMBSMC** A. Arbuzov
- **NEXTCALIBUR** F.A.Berends, C. G. Papadopoulos and R.Pittau
- **PHEGAS/HELAC** C. G. Papadopoulos
- **RacoonWW** A.Denner, S.Dittmaier, M.Roth and D.Wackeroth
- **SWAP/WRAP** G. Montagna, M. Moretti, O. Nicrosini, A. Pallavicini and F. Piccinini
- **TOPAZ0** G. Montagna, O. Nicrosini, G. Passarino, F. Piccinini
- **ZFITTER** D. Bardin, P. Christova, M. Jack, L. Kalinovskaya, A. Olchevski, S. Riemann and T. Riemann
- **WPHACT** E. Accomando, A. Ballestrero and E. Maina
- **WTO/ZZTO** G. Passarino

**LEP** STOPS RUNNING RATHER SOON SO IT IS UNLIKELY THERE WILL BE ANY MORE DATA IN THIS ENERGY REGION

WE ALL MUST TRY TO DO THE BEST WE CAN TO GET THE MOST ACCURATE MEASUREMENTS AND THE MOST PRECISE PREDICTIONS WE CAN

$\nabla$ From the point of view of THEORY there is of course no deep reason why the **theory uncertainty** should be reduced below that of the **experimental precision**,

$\triangleright$ but it is surely a useful target as the **theory error** has to be added in quadrature in looking for **deviations from the SM**.

$$\boxed{e^+e^- \to \overline{f}f(\gamma, \text{pairs})}$$

| PROCESS | TH. UNC.[1] | EXP. PREC. TAG | EXP. EXP.[2] |
|---|---|---|---|
| $e+e^- \to \overline{q}q(\gamma)$ | 0.3 % | 0.1 %-0.2 % | 0.5 % |
| $e+e^- \to \mu^+\mu^-(\gamma)$ | 0.4 % | 0.4 %-0.5 % | 1.2 % |
| $e+e^- \to \tau^+\tau^-(\gamma)$ | 0.4 % | 0.4 %-0.6 % | 1.5 % |
| $e+e^- \to e^+e^-(\gamma)$ (endcap) | 0.5 % | 0.1 % | – |
| $e+e^- \to e^+e^-(\gamma)$ (barrel) | 2.0 % | 0.2 % | 0.5 % |
| $e+e^- \to e^+e^-(\gamma)$ | 3.0 % | 1.5 % | – |
| $e+e^- \to \mathrm{l}^+\mathrm{l}^-$ | 1.0 % | 0.5 % | – |
| $e+e^- \to \overline{\nu}\nu(\gamma)$ | 4.0 % | 0.5 % | – |

1. Report of the **2f WG** of the **LEP 2/MC Workshop**
2. J. Holt & D. Bourilkov, **LEP 2/MC Workshop**

- The total **had** and **lept** cross-sections are now predicted to the total precision tag of 0.2 %, **excluding pairs** (**ZFITTER - KKMC**

## News for Pairs in $e^+e^-$ annihilation

- Shortly before and during this workshop a lot of new code for pair corrections at **LEP 2** were developed.

1. Before 1999, only the diagram-based pair correction with $s' = M^2_{\mathrm{prop}}$ could be calculated by **ZFITTER** and **TOPAZ0**.
2. Common exponentiation of IS-$\gamma$ and $\mathbf{ISNS}_\gamma$ pairs for energies away from the $Z$-peak as well as optional $\mathbf{ISS}_\gamma$ pairs were implemented in both codes in 1999.
3. Now **ZFITTER** has been upgraded to include explicit $\mathbf{FS}_\gamma$ with the possibility of mass cuts.
4. The new **GENTLE/4fan** offers even more options with mass cuts on all pairs and inclusion of pairs from virtual $Z$ and swapped **FS** diagrams.
5. A new combination of **KKMC** and **KORALW** is being developed.

## The main achievements are:

- ♣ A proposal for a **signal definition** which can be, to better than **0.1%** accuracy defined either based on cuts or on diagrams.

- ♢ The determination of **efficiency corrections** using full event generators has been checked for **GRC4f** to a precision of **0.1%**, from a comparison of real pair cross-sections with **GENTLE**.

- ♡ Problems of **pairing ambiguities** for 4 identical fermions become increasingly important with the larger $ZZ$ cross-sections at high energies. From varying pairing algorithms, a worst-case difference of **0.8** per mill was found for inclusive hadrons at **206 GeV**.

♠ Differences for **pair corrections** between $s'$ definitions via the propagator or primary pair mass in the diagram-based approach have been determined.
**GENTLE** and **ZFITTER** both find them to be about **0.3 (1.1)** per mill for high $s'$ hadrons (muons).

♣ Maximum differences for the diagram-based pair correction of **1.7 (1.5)** per mill for inclusive hadrons (muons) and **0.2 (0.4)** per mill for high $s'$ hadrons (muons) between any two of the programs **GENTLE, ZFITTER** and **TOPAZ0** have been found.

♢ A first complete calculation of pair corrections for **Bhabhas** has been done by **LABSMC**.

# Conclusion for Pairs

- With the exception of the **1.7** per mill (tag of **1.1** per mill) difference for inclusive hadrons, all **theoretical uncertainties** are well below the **experimental precision tags**.

- Especially for the case of **Bhabha scattering** it would be highly desirable to have more than one code predicting the effects of secondary pairs. Improvements are still expected in **GENTLE, TOPAZ0** and **KKMC + KORALW**.

# $WW$ signal: CC03

- It is worth summarizing the status of the $WW$ cross-section prior to the **2000 Winter Conferences**:

- Nominally, any calculation for
  $e^+e^- \to WW \to 4f$
  was a **tree level** calculation including as much as possible of the universal corrections (**IBA**).

- A **CC03** cross-section, typically in the $G_F$-**scheme**, with universal **ISR QED** and non-universal **ISR/FSR QED** corrections produces a curve that been used for the definition of the **SM** prediction with a $\pm 2\%$ **systematic error** assigned to it.

- $\nabla$ However, we have clear indications that non-universal EW corrections for $WW$ **(CC03)** cross-section are not small and even larger than the **experimental LEP accuracy**.

- $\nabla$ Recently, a new **EW** $\mathcal{O}(\alpha)$ **CC03** cross-section has become available, in the framework of **DPA**, showing a result that is $2.5 \div 3\%$ smaller than the old **CC03** cross-section.

- $\nabla$ This is a big effect since the **combined experimental accuracy** of LEP experiments is even **smaller**.

# DPA

- **DPA** emerges from the CC03 diagrams upon projecting the $W$-boson momenta in the matrix element to their on-shell values.

- This means that the **DPA** is based on the residue of the double resonance, which is a **gauge-invariant quantity**

- In contrast to the **CC03 cross-section**, the **DPA** is theoretically well-defined. **DPA** provides a convenient framework for the inclusion of **radiative corrections**

(but **NOT** for Born)

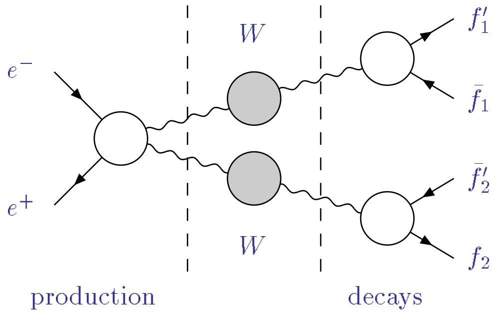



Figure 1: **The generic structure of the virtual factorizable $W$-pair contributions. The shaded circles indicate the Breit–Wigner resonances, whereas the open circles denote the Green functions for the production and decay sub-processes up to $\mathcal{O}(\alpha)$ precision.**

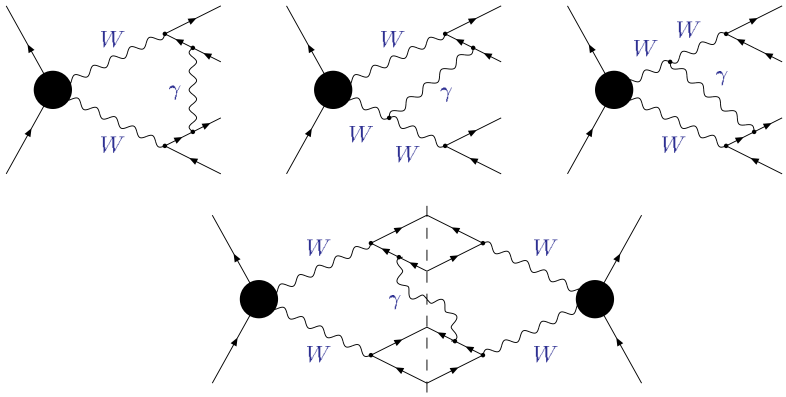
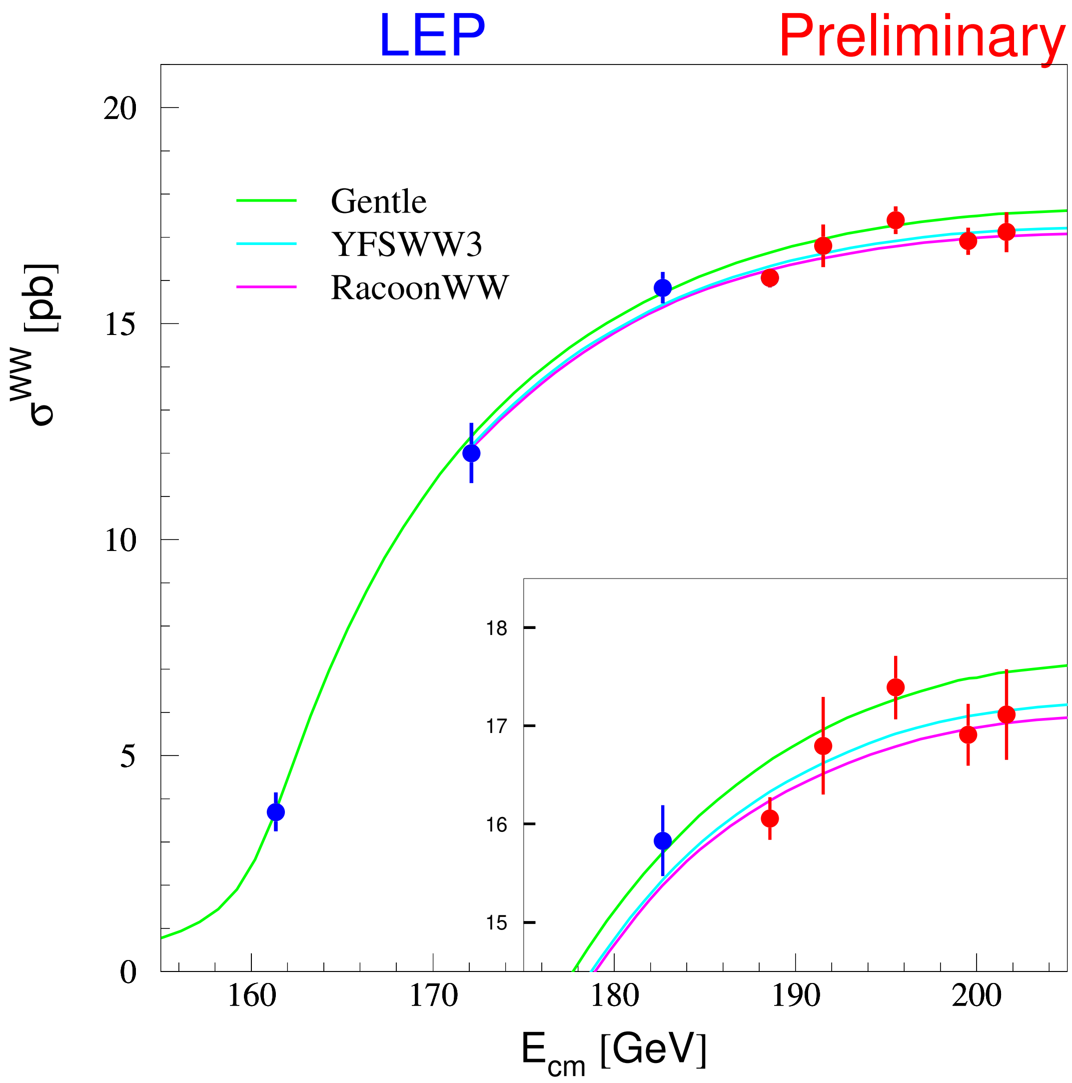



Figure 2: **Examples for virtual (top) and real (bottom) non-factorizable corrections to $W$-pair production. The black circles denote the lowest-order Green functions for the production of the virtual $W$-boson pair.**

# Diagrammatica of DPA




$\boxed{\textbf{CC03 vs } \sqrt{s}}$

# Conclusions for CC03

- The data are in good agreement with the predictions of
  **RacoonWW** and **YFSWW3**
- at the time of **Winter 2000** predictions of **YFSWW3** were about $0.5\,\% - 0.7\,\%$ higher, somewhat larger than intrinsic DPA uncertainty.
- The main source of this discrepancy is found, **RacoonWW** and **YFSWW3** differ only by about $0.3\,\%$ at **LEP 2** energies.

THERE IS EMPIRICAL EVIDENCE OF
**NON-LEADING** EW RC
! abandon calculations without **DPA** !

| no cuts | | $\sigma_{\rm tot}$[fb] | |
|---|---|---|---|
| final state | program | Born | best |
| $\nu_\mu \mu^+ \tau^- \bar{\nu}_\tau$ | YFSWW3 | 219.770(23) | 199.995(62) |
| | RacoonWW | 219.836(40) | 199.551(46) |
| | (Y–R)/Y | −0.03(2)% | 0.22(4)% |
| $\mathrm{u\bar{d}}\mu^- \bar{\nu}_\mu$ | YFSWW3 | 659.64(07) | 622.71(19) |
| | RacoonWW | 659.51(12) | 621.06(14) |
| | (Y–R)/Y | 0.02(2)% | 0.27(4)% |
| $\mathrm{u\bar{d}s\bar{c}}$ | YFSWW3 | 1978.18(21) | 1937.40(61) |
| | RacoonWW | 1978.53(36) | 1932.20(44) |
| | (Y–R)/Y | −0.02(2)% | 0.27(4)% |

Table 1: Total cross-sections for CC03 from RacoonWW and YFSWW3 at $\sqrt{s} = 200\,\mathrm{GeV}$ without cuts. The numbers in parentheses are statistical errors corresponding to the last digits.

**Some comparisons . . . . . .**

# single-$W$ production

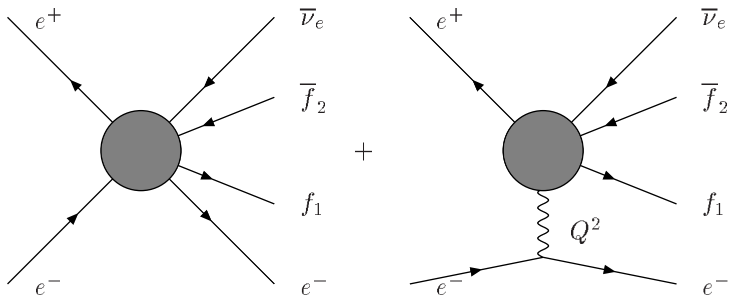



Figure 3: **The CC20 family of diagrams with the explicit component containing a $t$-channel photon.**

| Process | diagrams | cuts |
|---|---|---|
| $e e \nu \nu$ | $t$-channel only | $E(e^+) > 20\,\mathrm{GeV}, \lvert\cos\theta(e^+)\rvert < 0.95, \lvert\cos\theta(e-)\rvert > 0.95$ |
| $e \nu \mu \nu$ | $t$-channel only | $E_(\mu^+) > 20\,\mathrm{GeV}$ |
| $e \nu \tau \nu$ | $t$-channel only | $E_(\tau^+) > 20\,\mathrm{GeV}$ |
| $e \nu u d$ | $t$-channel only | $M(ud) > 45 GeV$ |
| $e \nu c s$ | $t$-channel only | $M(cs) > 45 GeV$ |

Table 2: Signal definition for single-$W$ processes.

A fairly large amount of work has been done in the last years on the topic of **single-$W$**.

♯ **ENERGY SCALE**
we have an exact calculation based on the **FL-scheme** which, at the Born-level (**no QED**) is known to be at the 1 % level of accuracy (**WTO**).

♯ no program includes $\mathcal{O}(\alpha)$ EW RC

♯ A description of **single-$W$** processes by means of the **FL-scheme** is mandatory:

- **FL** is the only known QFT consistent scheme that preserves gauge invariance
- **single-$W$** production is a process that depends on several scales:
  1. the **single-resonant** $s$-channel exchange of $W$-bosons,
  2. the exchange of $W$-bosons in $t$-channel,
  3. the small scattering angle **peak** of outgoing electrons.

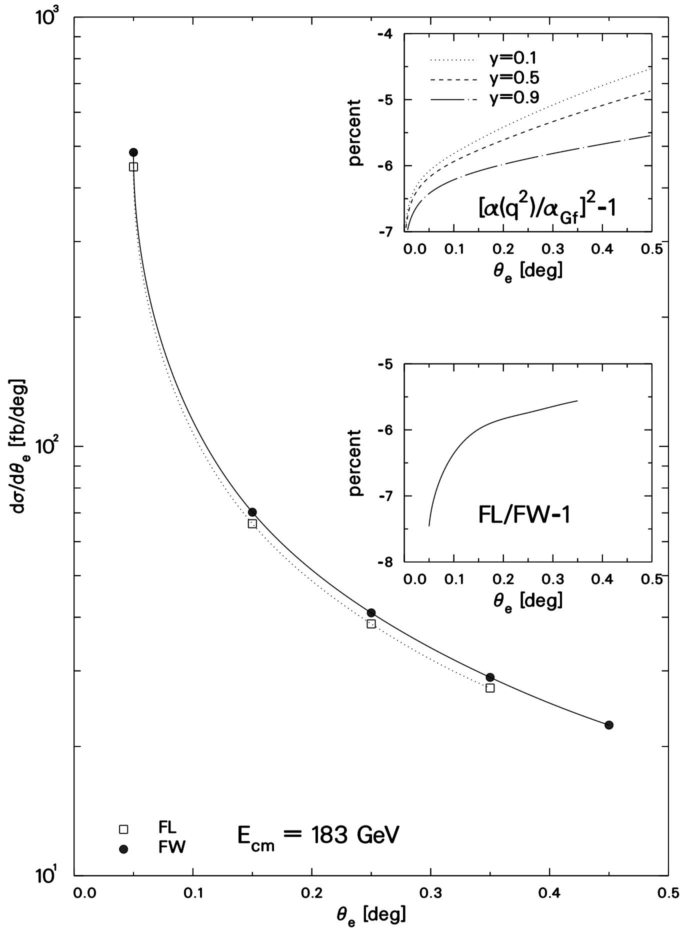



Figure 4: WTO **predictions for** $d\sigma/d\cos\theta_e$ **[fb/degrees] for** $e^+e^- \to u\overline{d}e^-\overline{\nu}_e$ **with** $M(u\overline{d}) > 45\,$**GeV and** $\sqrt{s} = 183\,$GeV**.**

♯ A correct treatment of the **multi-scale** problem can only be achieved via **FL**-scheme.

– a **naive rescaling** cannot reproduce the full answer for all situations, all kinematical cuts.

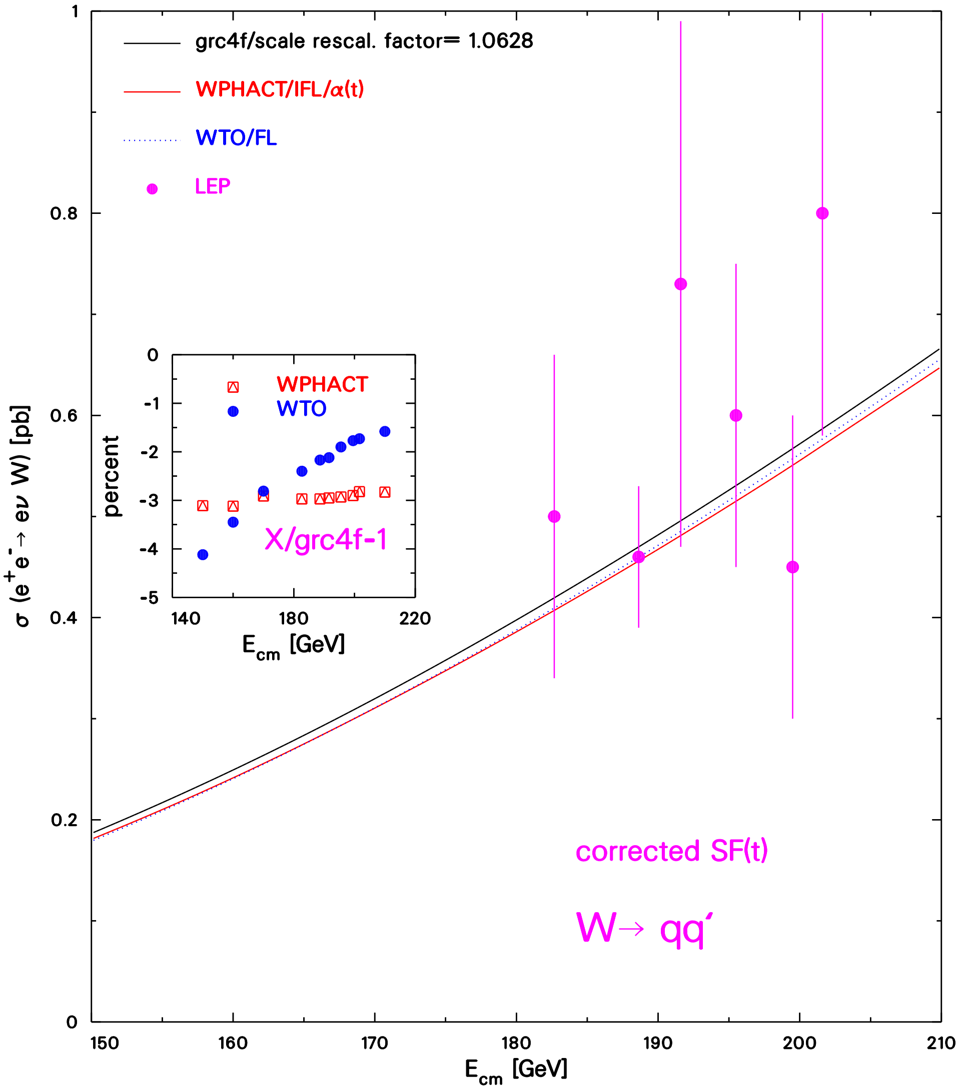



Figure 5: GRC4F, WPHACT, WTO predictions for the single-$W$ hadronic cross-section.

$\boxed{\textbf{hadronic single-}W}$

♯ **QED radiation**

the effect of the **QED** RC on the total cross-sections are between 7% and 10% at **LEP 2** energies.

⊙ **grc4f** and **SWAP** have estimated that if one uses the wrong energy scale $s$ in the **structure functions**, the **ISR** effect is overestimated of about $4\,\%$

⊙ **SWAP** estimates that the effects due to non-$s$-scales predict a lowering of the **Born cross-section** of about $8\,\%$. **SWAP** results show a good agreement with those of **grc4f**.

# Conclusions for single-$W$

- $\smile$ Although we register substantial improvements upon the standard treatment of **QED ISR**,

- $\frown$ the problem is not yet fully solved for processes where the **non-annihilation** component is relevant. A solution of it should rely on the complete calculation of the $\mathcal{O}(\alpha)$ correction

- $\nabla$ At the moment, a total upper bound of $\pm 5\,\%$ **th. uncertainty** should be assigned to $\sigma$(**single-$W$**).

- $\triangle$ We could say that **QED** in **single-$W$** is understood at a level better than $4\,\%$ but we are presently unable to quantify this assertion.

  **ALL LEP** $\to 7.5\,\% \Leftrightarrow$ **tag**$2.5\,\%$

$\boxed{ZZ \text{ signal}}$

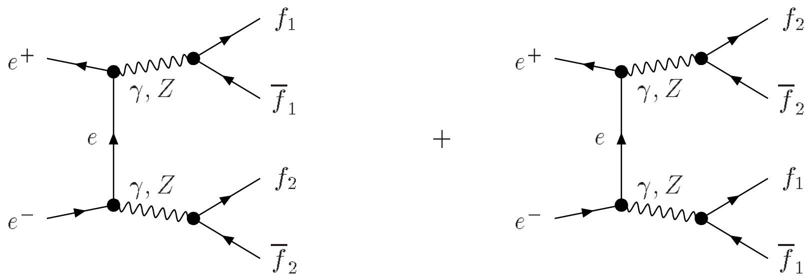
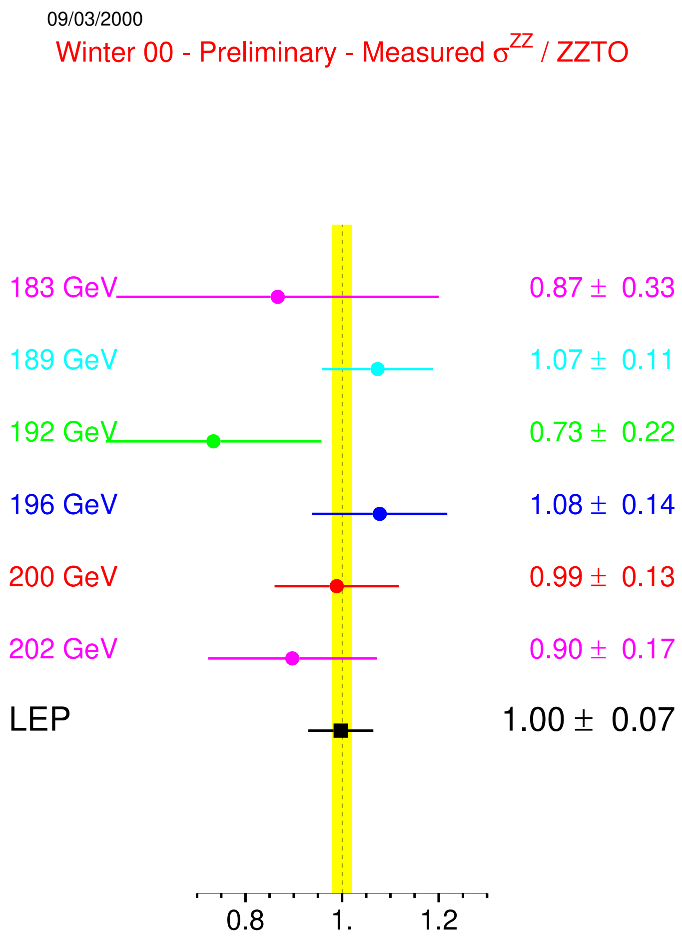



Figure 6: **The NC08 sub-family of diagrams.**

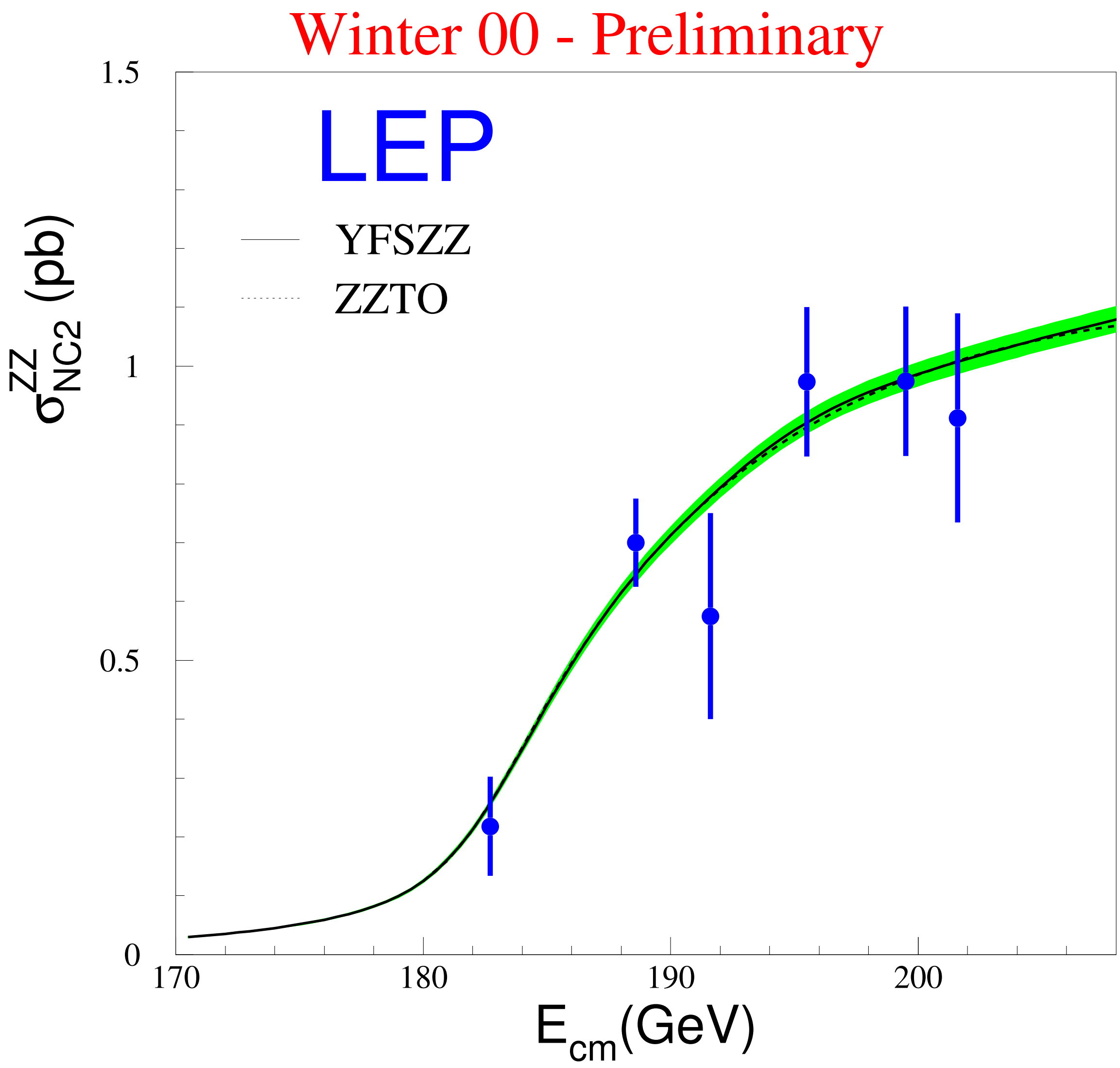
- **NC02** is $e^+e^- \to ZZ$, **(**$t$ **and** $u$ **channel), with all** $Z$ **decay modes allowed. Based on** $R_{uucc/uuuu} = 2.06, R_{ddss/dddd} = 2.08$

- Compared to the experimental **uncertainty** on the **NC02** $ZZ$ $\sigma$ a difference of about 1% between **theoretical predictions** is acceptable.

- The global estimate of **TU** is 2%, again acceptable. However, it would be nice to improve upon the existing calculations.




$\boxed{ZZ \text{ vs SM}}$




$\boxed{ZZ \text{ vs SM}}$

## Conclusions for NC02

- △ For the **NC02** $\sigma$ we have a $1\%$ variation, obtained by changing the **IPS** in **GENTLE** and in **ZZTO** and by varying from the standard **GENTLE** approach for **ISR** to the complete lowest order corrections. We estimate the real **uncertainty** to be $2\%$.

- △ Furthermore, **ZZTO** which is a **FL** calculation agrees rather well with **YFSZZ**, roughly below the typical **DPA** accuracy of $0.5\%$, and the latter features leading pole approximation, on $\mathcal{O}\left(\alpha^2\right)$ **LL YFS** exponentiation.

- △ The implementation of a **DPA** calculation, in more than one code, in the NC02 $Z$-pair $\sigma$ will bring the corresponding accuracy at the level of $0.5\%$, similar to the **CC03** case.