RECENT THEORETICAL DEVELOPMENTS IN LEP 2 PHYSICS

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Recent theoretical developments in e^+e^--annihilation into fermion pairs are summarized. In particular, two-fermion production, DPA for $W-W$ signal, single-W production and $Z-Z$ signal

After an illustrious career LEP stops running rather soon so it is unlikely there will be any more data in this energy region and we all must try to do the best we can to get the most accurate measurements and the most precise predictions we can.

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, but it is surely a useful target as the theory error has to be added in quadrature in looking for deviations from the standard model.

In this talk the most recent theoretical developments connected with LEP 2 physics will be shortly reviewed. As the LEP 2 community has written a report that has just come out I refer the interested reader to that report [1] where one of the goals was to summarize and review critically the progress made in theoretical calculations and their implementation in computer programs since the 1995 workshop on *Physics at LEP2*.

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

On the basis of comparisons of various calculations, theoretical uncertainties have been estimated and compared with those for the final LEP 2 data analysis. In the following list we summarize the present status of theoretical and experimental accuracy as given in the report of the 2f Working Group of the LEP 2/MC Workshop [2] to which we refer for more details:

1. $e+e^- \to \overline{q}q(\gamma)$ 0.3% / 0.1%-0.2%
2. $e+e^- \to \mu^+\mu^-(\gamma)$ 0.4% / 0.4%-0.5%
3. $e+e^- \to \tau^+\tau^-(\gamma)$ 0.4% / 0.4%-0.6%
4. $e+e^- \to e^+e^-(\gamma)$ (endcap) 0.5% / 0.1%
5. $e+e^- \to e^+e^-(\gamma)$ (barrel) 2.0% / 0.2%
6. $e+e^- \to e^+e^-(\gamma)$ 3.0% / 1.5%
7. $e+e^- \to \mathrm{l}^+\mathrm{l}^-$ 1.0% / 0.5%
8. $e+e^- \to \overline{\nu}\nu(\gamma)$ 4.0% / 0.5%

First entry is the present theoretical uncertainty, second one is the experimental precision tag. The total hadronic and leptonic cross-sections are now predicted to the total precision tag of 0.2%, (excluding pairs) by ZFITTER [3] and KKMC [4].

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

Shortly before and during this workshop a lot of new codes for pair corrections at LEP 2 were developed. Before 1999, only the diagram-based pair correction with $s' = M^2_{\mathrm{prop}}$ could be calculated by ZFITTER and TOPAZ0 [5].

Common exponentiation of IS-γ and ISNS$_\gamma$ pairs for energies away from the Z-peak as well as optional ISS$_\gamma$ pairs were implemented in both codes in 1999 (see [2] for their definition). Now ZFITTER has been upgraded to include explicit FS$_\gamma$ with the possibility of mass cuts. Furthermore, the new GENTLE/4fan [6] offers even more options with mass cuts on all pairs and inclusion of pairs from virtual Z and swapped FS diagrams and a new combination of KKMC and KORALW is being developed.

The main achievements in this area can be summarized as follows: 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 [17] to a precision of 0.1%, from a comparison of real pair cross-sections with GENTLE. However, problems of pairing ambiguities for four 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. Furthermore, differences for pair corrections between s' definitions via the propagator or primary pair mass in the diagram-based approach have been determined and GENTLE – 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. Compared to the LEP-combined statistical precision of the measurements all these differences are small. Even the 1.7 per mill difference is only about half of the expected LEP-combined statistical error.

Finally, a first complete calculation of pair corrections for Bhabha scattering has been done by LABSMC [7].

The conclusion for the inclusion of pair effects in the two-fermion cross-section are as follows: 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. Note that improvements are still expected in GENTLE, TOPAZ0 and KKMC + KORALW.

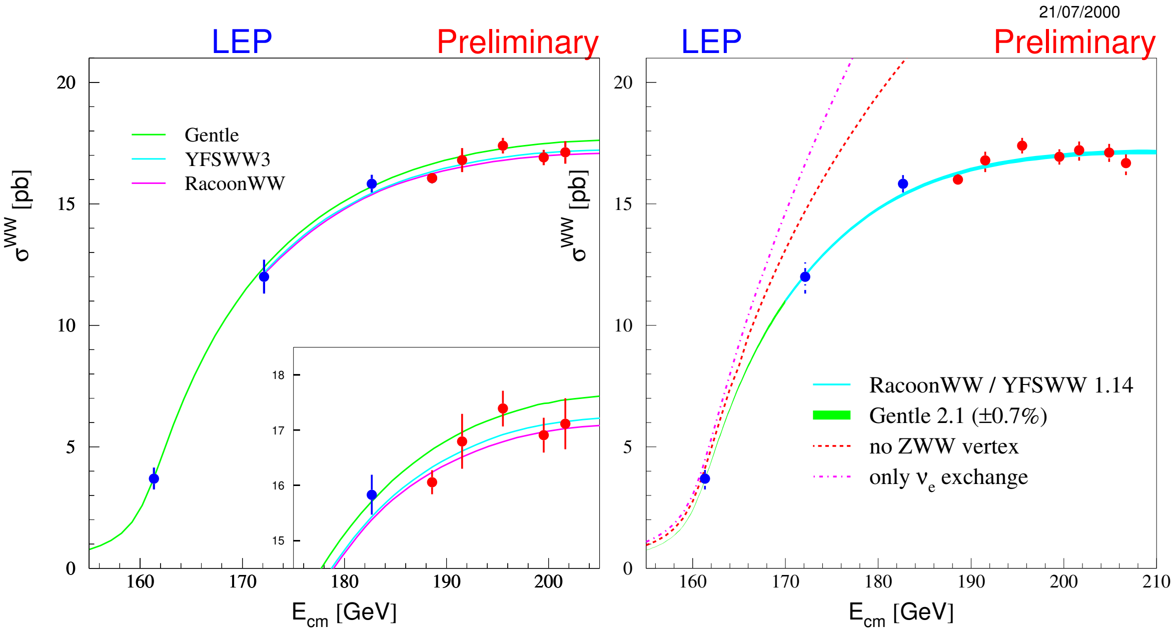
In the following we will discuss items that are related to four-fermion production.

- WW signal: the CC03 class

While the CC03 cross-section is not an observable, it is nevertheless a useful quantity at LEP 2 energies where it can be classified as a pseudo-observable. It contains the interesting physics, such as the non-abelian couplings and the sensitivity of the total cross-section to M_W near the W-pair threshold. The goal of this common definition is to be able to combine the different final state measurements from different experiments so that the new theoretical calculations can be checked with data at a level better than 1%.

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 in some sort of Improved Born Approximation (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 standard model prediction with a $\pm 2\%$ systematic error assigned to it. However, we have clear indications that non-universal electroweak corrections for WW(CC03) cross-section are not small and even larger than the experimental LEP accuracy. Furthermore, one should stress the importance of photon reconstruction at LEP 2 accuracy.

Recently [8], a new electroweak $\mathcal{O}(\alpha)$ CC03 cross-section has become available, in the framework of double-pole approximation (DPA), showing a result that is $2.5 \div 3\%$ smaller than the old CC03 cross-section. This is a big effect since the combined experimental accuracy of LEP experiments is even smaller.



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 should not be applied for Born-level calculations. Summarizing we may say that the at present only workable approach for evaluating the radiative corrections to resonance-pair-production processes, involves the so-called leading-pole approximation. This approximation restricts the complete pole-scheme expansion to the term with the highest degree of resonance.

Conclusions for CC03 are as follows: the data are in good agreement with the predictions of RacoonWW [9] and YFSWW3 [10] (see also BBC [11]). 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 for total cross-sections and within 1 % in angular and invariant-mass distributions. There is a general satisfaction with the progress induced by new DPA calculations. Nevertheless, the theoretical uncertainty could probably be improved somewhat in the future.

- single-W production

A fairly large amount of work has been done in the last years on the topic of single-W production. The experimental community agreed on some setup to define the single-W production and now this has been formalized in one of the `LEP EWWG` meetings; there, it was decided to have a signal definition as follows:

1. $e e \nu \nu$, t-channel only, $E(e^+) > 20\,\mathrm{GeV}$, $|\cos\theta(e^+)| < 0.95, |\cos\theta(e-)| > 0.95$;
2. $e \nu \mu \nu$, t-channel only, $E_(\mu^+) > 20\,\mathrm{GeV}$;
3. $e \nu \tau \nu$, t-channel only, $E_(\tau^+) > 20\,\mathrm{GeV}$;

4. $e\nu ud$, t-channel only, $M(ud) > 45GeV$;
5. $e\nu cs$, t-channel only, $M(cs) > 45GeV$.

The main problems in dealing with single-W production are the correct choice of the energy scale in couplings and the proper treatment of QED radiation in processes that are not dominated by annihilation diagrams..

For the energy scale in couplings we have now an exact calculation [12] based on the massive formulation of the Fermion-Loop scheme (FL) which, at the Born-level (no QED)is known to be at the 1 % level of accuracy (see WTO [13]). No program includes $\mathcal{O}(\alpha)$ electroweak radiative corrections. Note that the FL-scheme developed in [14] and refined in [15] makes the approximation of neglecting all masses for the incoming and outgoing fermions in the processes $e^+e^- \to n$ fermions. The recent development, however, goes beyond this approximation.

A description of single-W processes by means of the FL-scheme is mandatory because FL is the only known QFT consistent scheme that preserves gauge invariance and, moreover, single-W production is a process that depends on several scales: the single-resonant s-channel exchange of W-bosons, the exchange of W-bosons in t-channel, the small scattering angle peak of outgoing electrons.

A correct treatment of the multi-scale problem can only be achieved via FL-scheme and a naive rescaling cannot reproduce the full answer for all situations, all kinematical cuts.

The effect of QED on the total cross-sections are between 7% and 10% at LEP 2 energies. Furthermore, grc4f and SWAP [8] have estimated that if one uses the wrong energy scale s in the IS structure functions, the ISR effect is overestimated of about 4 %. SWAP [16] 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 [17].

Conclusions for single-W are as follows: although we register substantial improvements upon the standard treatment of QED ISR, 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. At the moment, a total upper bound of ± 5 % th. uncertainty should be assigned to single-W.

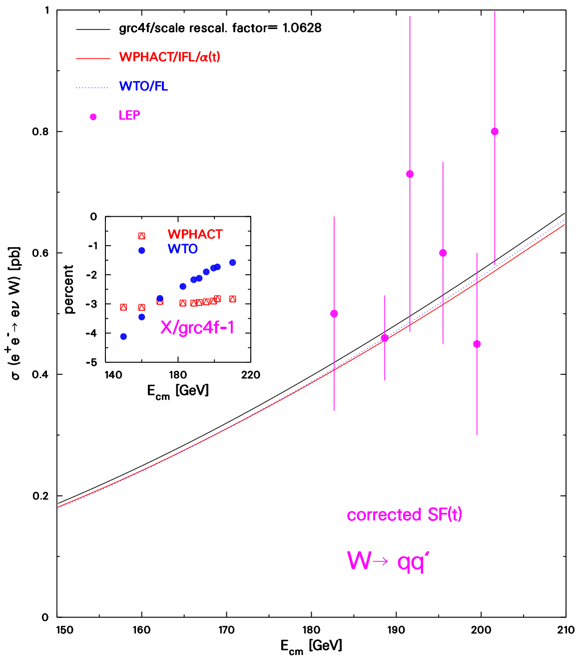
We could say that QED in single-W is understood at a level better than 4 % but we are presently unable to quantify this assertion.

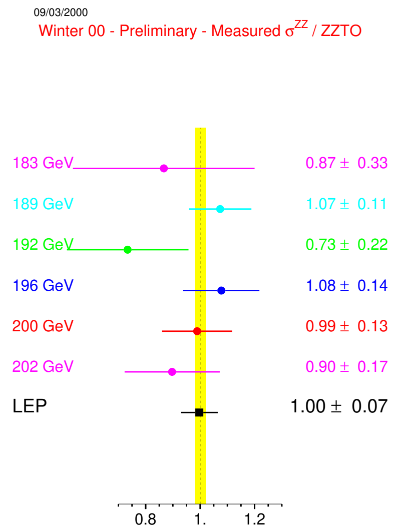
- ZZ signal

NC02 is $e^+e^- \to ZZ$, (t and u channel), with all Z decay modes allowed. Since the interferences between the crossings are not double-resonant, it is customary to consider them as background and to define the ZZ signal from the absolute squares of the double-resonant diagrams only. The choice is based on the observation that $R_{uucc/uuuu} = 2.06$, $R_{ddss/dddd} = 2.08$.

Compared to the experimental uncertainty [18] on the NC02 ZZ cross-section a difference of about 1% between theoretical predictions is acceptable. The global estimate of theoretical uncertainty is 2%, again acceptable. However, it would be nice to improve upon the existing calculations.

Conclusions for NC02 are as follows: for the NC02 cross-section we have a 1% variation, obtained by changing the input parameter set in GENTLE and in ZZTO [20] 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 (with universal ISR, $\mathrm{FSR}_{\mathrm{QED}}$ $\mathrm{FSR}_{\mathrm{QCD}}$ and running masses) agrees rather well with YFSZZ [19], roughly below the typical DPA accuracy of 0.5%, and the latter features leading pole approximation, on $\mathcal{O}(\alpha^2)$ leading-logarithms YFS exponentia-





tion (EEX).

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

- Conclusions

To gauge the priorities of this rather short summary one should remember that the experimental situation [21] is rather different for WW when compared to other processes. For W-pairs, LEP (ADLO) is able to test the theory to below 1%, i.e. , below the old uncertainty of $\pm 2\%$ established in 1995. Thus the CC03-DPA, including non-leading electroweak corrections, constitutes a very important theoretical development. However, ADLO cannot test single-W or ZZ-signal to an equivalent level, since their total cross-section is of the order of 1 pb or less, 20 times smaller than that of W-pair production.

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