ELECTROWEAK PHYSICS 2K†: Experimental Guidance or Theoretical Innovation?

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Summary

- **Present and Past: LEP**
- **Future: LHC, LC**

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HERE IS WHERE WE STAND NOW

For relevent figures

http://lepewwg.web.cern.ch/LEPEWWG/plots

⋈

LEP(theory) past

- $\oplus$ **An extensive collection of theoretical predictions for observables in e^+e^- interactions at LEP 2 energies had been presented in the 1996 CERN** *Report of the Workshop on Physics at LEP2*.

LEP(theory) present

- $\oplus$ **However, an update with improved theoretical prescriptions was needed in order to match the precision achieved by now in the experimental analyses $\Longleftrightarrow$ LEP2/MC Workshop.**

Few people left and only the though problems ....

2f Physics, mostly 2f-4f interplay

- ⊘ Pair corrections can be a very small effect due to the near-cancellation of real and virtual pairs.
- ⊘ Whenever the effect of pairs is of order 0.1%, it is below the LEP combined precision of any 2f cross-section.
- ⊘ Thus, whenever pairs are an issue of order 1% or more this can become important for LEP wide combinations.

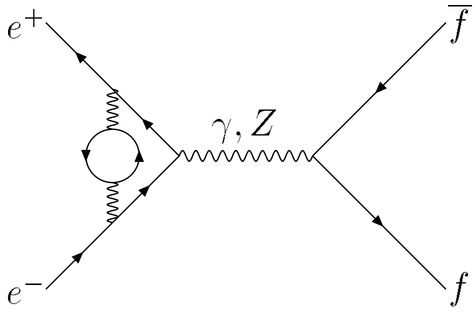
Let's continue with a simple case,

$$e^+e^- \quad \text{PP-corrections to} \quad e^+e^- \to \overline{b}b \tag{1}$$

Diagrams are in Fig. 1. Few definitions

- DIAGRAMS of the first row ≡ Multi-Peripheral or MP;
- DIAGRAMS of the second row ≡ Initial State Singlet, or ISS;
- DIAGRAMS of the third row ≡ Initial State Non-Singlet, or ISNS;
- DIAGRAMS of the fourth row ≡ Final State, or FS.

With both γ and Z exchange, so that there are ISNS$_\gamma$, ISNS$_Z$ and interference. On top of real PP one has virtual e^+e^- pairs:



Till last year, TOPAZ0 and ZFITTER only included ISNS$_\gamma$ plus virtual, with ISS optional. The approximation is well justified around the Z-peak but now we have to move to higher energies.

∇ **Furthermore, one has to add a proper definition of *soft* pairs and of *hard pairs*:**

- **Soft(Hard) Invariant Mass pairs, or SIM(HIM)pairs, according to some pair mass cut.**

∇ **Collaborations are strongly in favour of applying as simple cuts as possible, cuts on IM of the secondary pair only.**

∇ **altenative option: $\rightarrow$ *definition from Feynman diagrams.* Mass cuts can be found, which nearly $1:1$ $\Longleftrightarrow$ choosing certain, e.g. ZZ rejection.**

Strictly related is the quest for an *operative*, universally accepted, separation of various contributions. Consider again the process $e^+e^- \rightarrow \overline{b}be^+e^-$; σ contributes to three different processes:

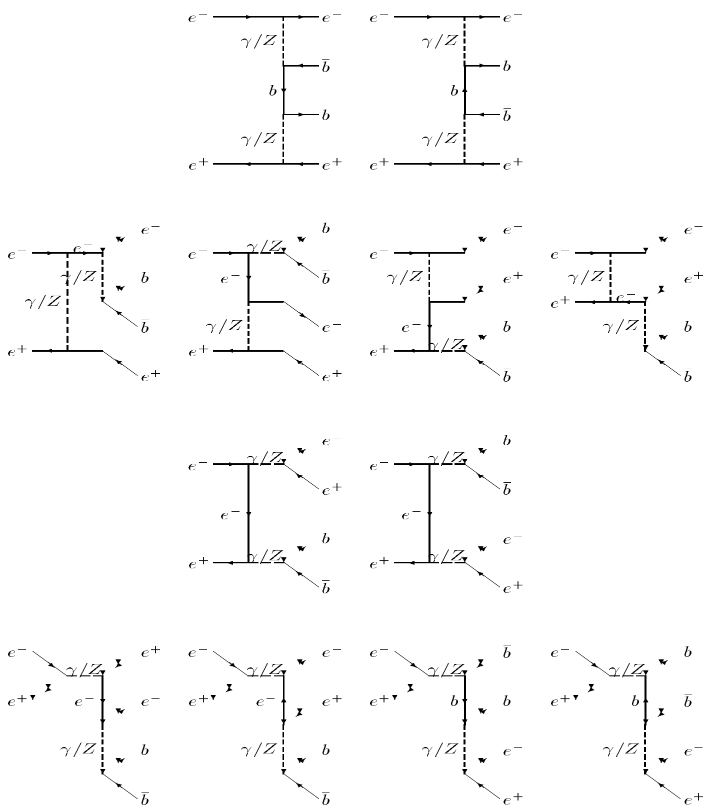


Figure 12: *Complete set of diagrams for the process* $e^+e^- \rightarrow e^+e^-b\bar{b}$.

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Figure 1: The process $e^+e^- \rightarrow \bar{b}be^+e^-$

▷ **genuine 4f events;**

▷ e^+e^- **PP-corr to** $e^+e^- \to \overline{b}b$**;**

▷ $\overline{b}b$ **PP-corr to Bhabha scattering.**

An – easy-to-implement – separation: let the process be specified by

$$e^+e^- \to \overline{b}b(Q2) + e^+e^-(q^2) \tag{2}$$

Integrate and reduce σ **to a two-fold integral with:**

$$\begin{aligned} 4\,m_b^2 &< Q^2 < (\sqrt{s} - 2\,m_e)^2, \\ 4\,m_e^2 &< q^2 < (\sqrt{s} - \sqrt{Q^2})^2. \end{aligned} \tag{3}$$

Introduce two cuts z_p, z_s**, i.e. primary and secondary cuts and define**

♯ e^+e^- **PP-corr to** $e^+e^- \to \overline{b}b$**:**

$$z_p\, s < Q^2 < (\sqrt{s}-2\,m_e)^2, \quad 4\,m_e^2 < q^2 < \min\{z_s\, s\,,\, (\sqrt{s}-\sqrt{Q^2})^2\}. \tag{4}$$

♯ $\overline{b}b$ **PP-corr to Bhabha scattering:**

$$z_p\, s < q^2 < (\sqrt{s}-2\,m_b)^2, \quad 4\,m_b^2 < Q^2 < \min\{z_s\, s\,,\, (\sqrt{s}-\sqrt{q^2})^2\}. \tag{5}$$

♯ **while the remaining portion of the phase space is *background.***

- **At the same time, we must address what *has to go in the calculation* and what is *already subtracted from the data.***

- **Then, you apply a *theory* correction, actually a subtraction obtained from MC, to go to *signal* definitions.**

Typical example?

△ **Using IM cuts $\Rightarrow$ relatively large corrections (5%), most of which are due to MP.**

△ **Here you will have to apply a rather large subtraction, which is rather unnatural.**

△ **Of course, we can take the MP into account, but only if some *reasonable* cut is applied to $M(\overline{b}b)$.**

Finally we come to the most complicate configurations,

$$e^+e^- \to \overline{q}q\bar{Q}Q, \tag{6}$$

or even worst, $e^+e^- \to \overline{q}_1 q_1 \overline{q}_2 q_2$, e.g. $uuuu$ etc. configurations.

Generalization of the separation of the 2f *signal* from the 4f *background*. Two options:

⊙ ***At least* one pair has an IM greater than $z_p\, s$ ($\overline{q}q$ pairs – $\overline{q}Q$ pairs – $qQ, \overline{q}Q$ pairs)**

⊙ ***at least* one pair has an IM greater than $z_p\, s$ while all remaining configurations have IM less than $z_s\, s$.**

Now we come to the really difficult part of the problem.

♯♯ **Since arbitrarily low SIM pairs are allowed, in both cases, a *parton-level* calculation cannot be accurate enough.**

♭ **Under the simplified assumption that one pair (the Q^2 one) is HIM enough and that the remaining one (the q^2 one) is SIM enough we can write σ as**

$$\frac{d\sigma_f}{dq^2 dQ^2} = \left(\frac{\alpha}{\pi}\right)^2 \sigma_f(Q^2)\frac{R_{\rm had}(q^2)}{3\, sq^2}\, f\left(s, Q^2, q^2\right). \qquad (7)$$

♮ **Two problems: The first one will be referred to as the *double-counting problem***

- **At the parton level, $e^+e^- \to \overline{q}q\bar{Q}Q$ and, for instance we want to $\sum_q$ to define the Q-line shape.**

- **However, when we also $\sum_Q$ to have the full hadronic LS, proper care must be taken in order to avoid *double-counting.***

- **At the *parton level* this can be done but we need**

$$e^+e^- \to \bar{Q}Q + \text{hadrons}, \qquad (8)$$

through $R_{\rm had(s)}$, and the problem is, by far, more severe.

- **Thus, yes, we have to agree on what should happen once $R_{\rm had}(s)$ is called for low s.**

- **A black-box-routine for $R_{\rm had}$ is needed. Why this interest in having $R_{\rm had}(s)$?**

- **Well, without it we are bound to KKKS and to the description of hadron radiation in terms of moments. This description is well justified around the** Z**-resonance and for reasonably high values of the** $z_{\min}$ **parameter where one, quite arbitrarily, defines a** ***primary pair*** **and a** ***secondary*** **one.**

- **If** $z_{\min}$ **is high enough,** > 0.25**, there is no overlapping in the hadronic line-shape, i.e. no double-counting. If, however,** $z_{\min} < 0.25$**, we do not know how to deal with** ***double-counting*** **in the KKKS formulation.**

Tentative conclusions:

⌢ The whole 4f must be included to compute the 2f cross-sections;

⌣ The whole 4f is to be divided into two components, *signal* and *background*.

- For our purposes their definition is peculiar, *signal* is what you have implemented into the SA codes.

- *background* is what one subtracts by using a MC, typically GRC4f.

We go from one extreme solution to the other:

- $\boldsymbol{background} = \emptyset$, if everything is included in the SA. MP is an example of something difficult to implement into the SA if low-IM regions are required.

- $\boldsymbol{signal} = \mathbf{ISNS}$, i.e. everything else (large effects) is subtracted by MC. However, using different MC programs would bring to subtractions that differ by some per-cent, which then would have to be regarded as a *theoretical* systematic uncertainty.

4f Physics

- $\otimes$ **One should remember that the experimental situation is rather different for WW with respect to the other processes.**

- $\otimes$ **For W-pairs, LEP (ADLO) is able to test the theory to below 1%, ie, below the old uncertainty of $\pm 2\%$ established in 1995. Thus the CC03-DPA constitutes a very important theoretical development.**

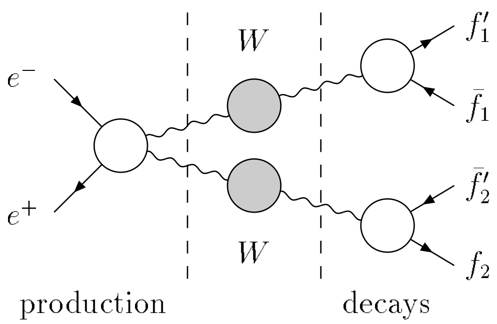

Figure 2: The generic structure of the factorizable W-pair contributions. The shaded circles indicate the Breit–Wigner resonances, whereas the open circles denote the Green functions for the production and decay sub-processes up to $\mathcal{O}(\alpha)$ precision.

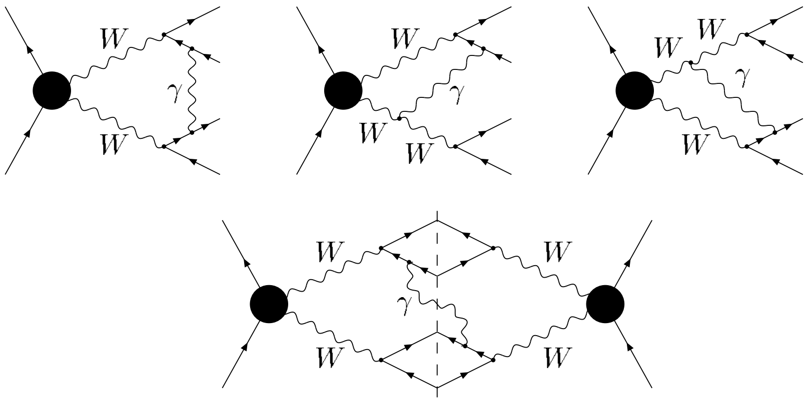

Figure 3: Examples for virtual (top) and real (bottom) non-factorizable corrections to W-pair production. The black circles denote the lowest-order Green functions for the production of the virtual W-boson pair.

CC03

⊗ **However, ADLO cannot test single-W or ZZ-signal to better than $\pm 5 - 10\%$, $\sigma_{\rm tot}$ is $\mathcal{O}(1\,\rm pb)$ or less, 20 times smaller than σ_{WW}.**

⊙ **There is a nice global agreement between the new DPA predictions for CC03, which are $2\% \div 3\%$ lower than the old *official* approach.**

⊙ **However, there remains a discrepancy of 0.8% at $\sqrt{s} = 200\,$GeV.**

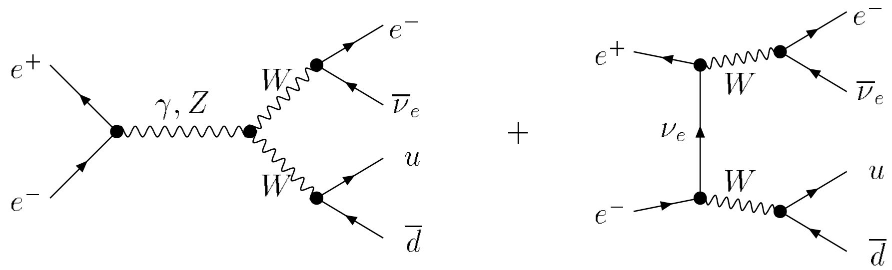

Figure 4: The CC03 family of diagrams, annihilation ⊕ conversion.

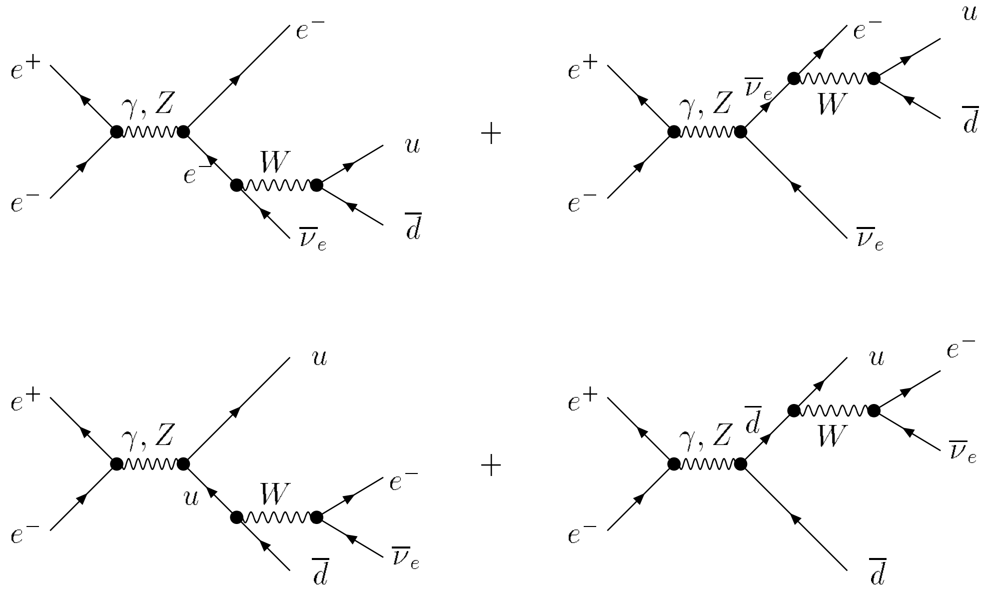

Figure 5: Diagrams belonging to the CC11 $-$ CC03 family.

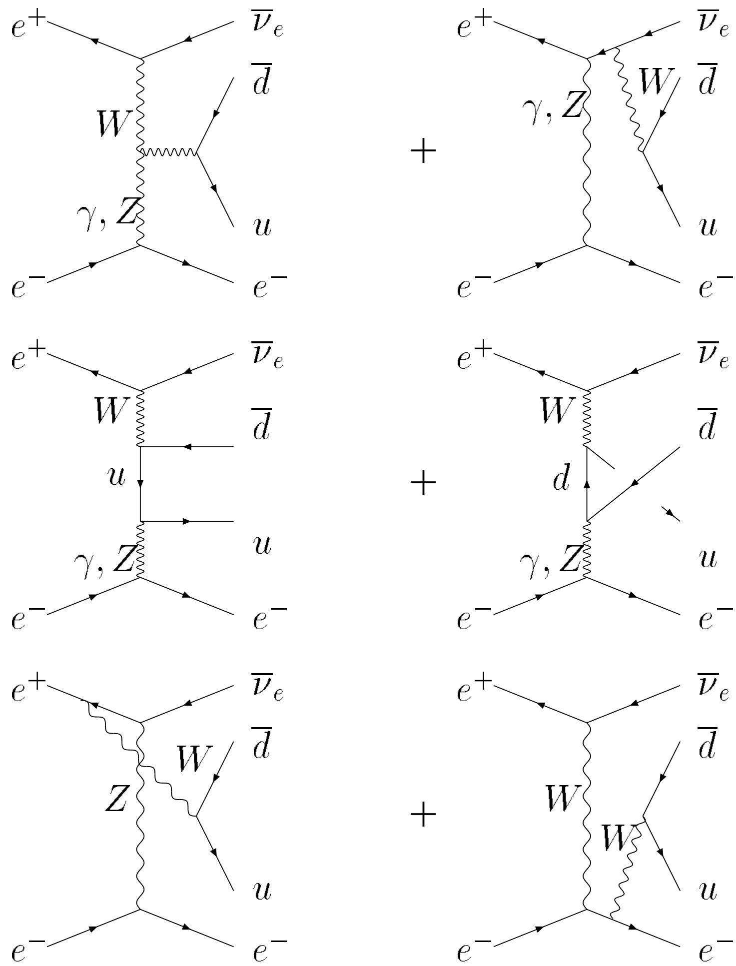

Figure 6: The t-channel component of the CC20 family of diagrams: fusion, bremsstrahlung and multi-peripheral.

Single – W

- ⊙ **In single-W production there are interesting gauge-invariance issues due to unstable particle.**

  The experimentalists however, are asking for ISR and p_t effects, comparisons including PS, SF and exponentiation.

- ⊙ **In single-W production we have a 2% TU associated with the scale of the t-channel γ, with a projected 1% TU when the Fermion-Loop scheme will receive more cross-checks.**

and QED

- ⊙ **For simple processes like e^+e^- annihilation and $\gamma\gamma$ collision, the evolution of the *scale* in the SF/PS algorithms can be determined by the exact perturbative calculations.**

- ⊙ **However, this is not possible for more complicated processes. When no *exact* $\mathcal{O}(\alpha)$ is available then one resorts to the approximate scale from first order *soft* corrections.**

- ⊙ **Therefore we have a conservative 4% TU for ISR from t-channel and p_t for single-W production.**

NC02

- $\odot$ **Compared to the experimental uncertainty on the NC02 σ_{ZZ} a difference of 1% between theoretical predictions is acceptable.**
  However, it would be nice to improve upon the existing calculations.

- $\odot$ **For the σ^{NC02} we have a 1% TU, estimated by varying the IPS in `GENTLE` and in `ZZTO`.**

- $\odot$ **However, given the experimental uncertainty a TU in this order is acceptable and does not seem to require the implementation of missing effects.**

- $\odot$ **The implementation of a DPA calculation, in more than one code, in σ^{NC02} will bring the TU at the level of 0.5%, similar to CC03.**

More details.

- There is now a satisfactory overall agreement between the new DPA predictions for CC03, which are $2\% \div 3\%$ lower than in the old *officiaal* approach.

- However, the discrepancy is 0.8% at $\sqrt{s} = 200\,$GeV. This should be compared with the current experimental precision of $\pm 0.9\%$ with all ADLO data at $183 - 202\,$GeV combined, compatible with the current TU.

- The technical precision for $e^+e^- \to 4\mathrm{f} + \gamma$ has reached high standards but at the moment we are unable to present any overall statement on the TU.
  This is true in particular for the single-W configuration.

- We expect that the present TU of 0.8% on σ^{CC03} will be reduced to a 0.5% when the sources of the differences between `RacoonWW` and `YFSWW` will be better analyzed.

- To go below this level of accuracy would require the complete calculation of one-loop radiative corrections in 4f production,
  a program that does not seem feasible in a forseeable future.

- **In single-W production most of our activity was centered around gauge-invariance issues due to unstable particle.**

- **The net effect of QED is between 8% and 10% for LEP 2, with s-channel SF over-estimating the effect by $\approx 4\%$.**

- **Furthermore, SF with a modified scale seems to agree with PS at the level of 1% when experimental cuts are included or even better for a fully extrapolated setup.**

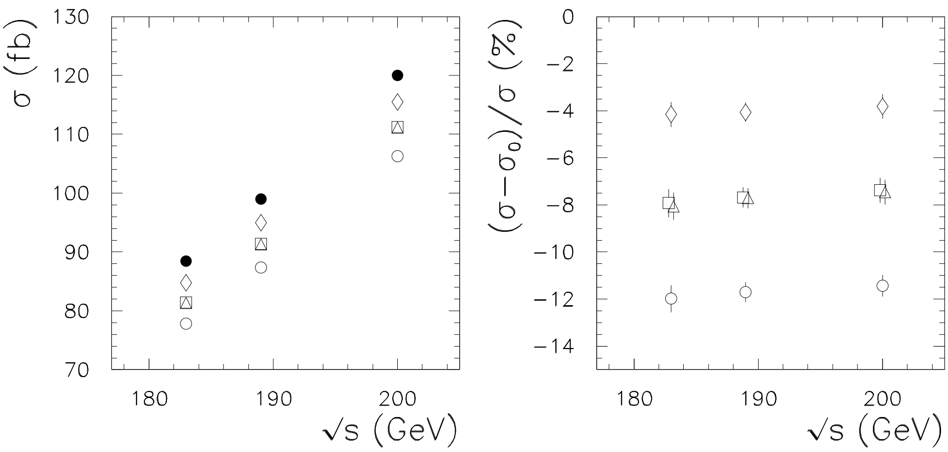

Figure 7: The effect of LL QED corrections to the cross section of the single-W process $e^+e^- \to e^-\bar{\nu}u\bar{d}$ for different choices of the Q^2-scale in the electron/positron SF. Left: absolute cross section values; Right: relative difference between QED corrected cross-sections and the Born one. The marker $\bullet$ represents the Born cross-section, $\circ$ represents the correction given by $Q^2_\pm = s$ scale, $\diamond$ represents the correction given by $Q^2_\pm = |q^2_{\gamma*}|$ scale, $\triangle$ the correction given by the scales of eq. (**??**), the correction given by the naive scales of eq. (**??**). The entries correspond to 183, 189, 200 GeV

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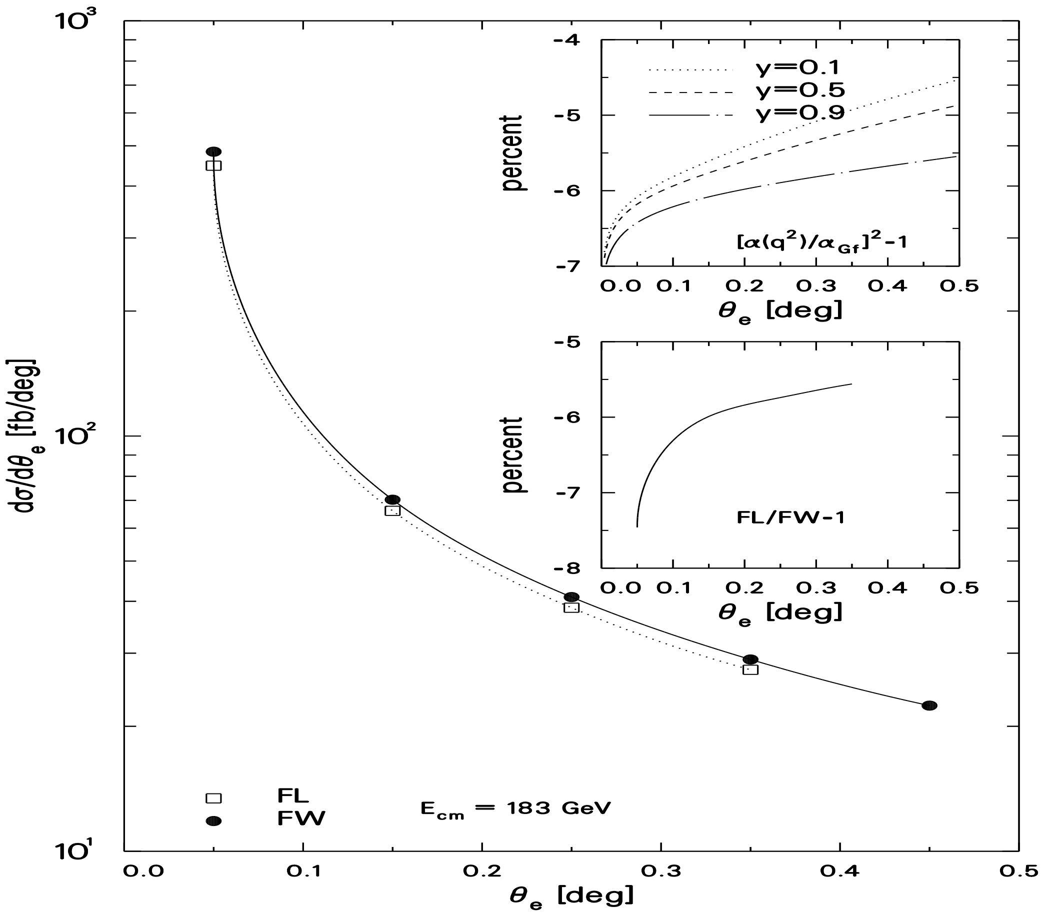

Figure 8: $d\sigma/d\cos\theta_e$ [fb/degrees] for $e^+e^- \to u\overline{d}e^-\overline{\nu}_e$ with $M(u\overline{d}) > 45\,\mathrm{GeV}$ and $\sqrt{s} = 183$ GeV.

- **As far as the scale of $\alpha_{\rm QED}$ is concerned we find that the results with a rescaling of $\alpha_{\rm QED}$ for the t-channel γ that has been implemented in `NEXTCALIBUR`, `SWAP` and `WPHACT`**
  show an agreement with EFL predictions (`WTO`) that is roughly around 2%.

- **The EFL itself usually register an accuracy of 1%.**

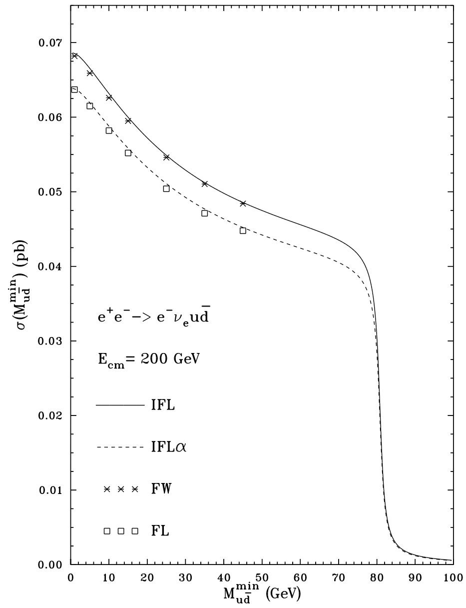

Figure 9: Total cross-section for $e^-e^+ \rightarrow e^-\bar{\nu}_e u\bar{d}$ at $\sqrt{s} = 200$ GeV with $\theta_e < 0.1°$ as a function of the lower cut on $\mathrm{M}_{u\bar{d}}$ in IFL and IFLα schemes. The markers give the results of FW and FL by `WTO`.

- **For single-W, therefore, we register a conservative, overall, upper bound of $\pm 5\%$ for TU.**

- **At the moment the TU for QED ISR is estimated by taking the average of the Born result with the one corrected via s-channel SF,**
  where $\mathrm{SF}(t, p_{tW}^2) > \mathrm{SF}(s)$ by $+5\%$ at $200\,$GeV and Born $> \mathrm{SF}(s)$ by $+12\%$.

- **Implementation of the FL scheme in single-W (in addition to `WTO`) will bring the TU associated with the scale of α_{QED} a 1%, w.r.t. present 2%.**

- **A better understanding of QED ISR in single-W production is certainly needed in order to reduce the corresponding TU, hopefully around 1%.**

- **This, however, requires to go beyond the soft approximation, not an easy task.**

- **Since DPA cannot be applied to single-W production one should include corrections in (improved) Weizsäcker-Williams approximation.**

- **For the moment this is not strictly needed but single-W will be one of the major processes at LC to measure not only TGC but also $M_{_W}$ without color reconnection.**

The future: LC

Extension of DPA

- **The goal of a signal 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%.**

- **Note, however, that $\sigma^{\rm CC03}$ will become very problematic at LC energies, where the background diagrams and the gauge dependences are much larger.**

Sudakov corrections

- **In the SM of EW interactions the W and Z bosons get their masses via the Higgs mechanism,
and the Sudakov logarithms naturally appear in the virtual EW corrections.
There are two *standard* regimes of the Sudakov limit, $s \to \infty$:**

  1. **On-shell massless fermions and gauge bosons with a small, non-zero, mass, $M^2 \ll s$;**

2. **massless gauge bosons and off-shell massless fermions.**

- ⊙ **Sudakov logarithms grow rapidly with energy and become dominant in the TeV region, available at the LC.**

- ⊙ **The analysis of the Sudakov corrections is thus of the high importance for the next generation of accelerators.**

- ⊙ **The two-loop leading and NLO logarithmic corrections in the TeV region have been obtained**

- ⊙ **the corresponding corrections to** $\sigma^{\rm tot}$ **and asymmetries in** $e^+e^- \to \mu^+\mu^-, \overline{q}q$ **have been found to be of a few percent magnitude at the energy of** $1-2$ **TeV.**

- ⊙ **The effect is particularly important for** $e^+{}_L e^-_L \to$ **hadrons, where, at the TeV threshold, the EW corrections are already above QCD corrections.**

Single-W

- Bosonic corrections for single-W are still missing and, very often, our experience has shown, especially at LEP1, that bosonic corrections may become sizeable.

- A large part of the bosonic corrections, as e.g. the leading-logarithmic corrections, factorize and can be treated by a convolution. Nevertheless the remaining bosonic corrections can still be non-negligible, i.e., of the order of one percent at LEP 2.

- For σ^{Born} 1% should, therefore, be understood as the present limit for TU.

- This will have to be improved, soon or later, since bosonic corrections are even larger at higher energies and σ^{1W} will cross over σ^{WW} at 500 GeV.

- Single-W will be one of the major processes at LC to measure not only TGC but also M_W without color reconnection.

The future: LHC electroweak

- **At LHC, substantial improvements in the *precise determination* of EW parameters, such as**

  1. **the W mass;**
  2. **the top quark mass;**
  3. **the EW mixing-angle;**
  4. **vector-boson self-couplings;**
  5. **the mass of the Higgs boson,**

  will become feasible, providing the basis for additional consistency tests of the SM or its extensions, in particular the MSSM.

- **The precise measurement of the production of**

$$W^+W^-, \quad W^\pm Z, \quad ZZ, \quad W^\pm\gamma, \quad Z\gamma, \tag{9}$$

  will provide us with the best test of the non-Abelian structure of the SM. Deviations may come either

  - **from AC (TGC, QGC) or**
  - **production and decay into vector-boson pairs of heavy objects.**

- **Therefore, NLO QCD description of the vector-boson pair production is needed.**

- **Finally, vector-boson vertices can be studied in vector-boson scattering and possible alternative scenarios for the SSB of the EW symmetry can be tested.**