STANDARD AND NON-STANDARD PRECISION TESTS OF THE STANDARD MODEL*

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The present status of the Standard Model Precision Tests is shortly reviewed.

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1. Standard Model Precision Tests

In this paper we present a short discussion on the present status of the Standard Model Precision Tests (SMPT). In the first part we summarize the standard LEP 1 SMPT to continue with a brief discussion on the fine points of future SMPT at LEP 2 energies. This will cover the following items:

- non-standard SMPT: 2f — the twofold way;
- non-standard SMPT: 4f — the fourfold way;
- the twofold way versus the fourfold way;
- measurement of the W boson mass;
- background to Higgs boson searches at LEP 2.

Standard LEP 1 SMPT involve a rather standard procedure where one starts with Pseudo-Observables and performs a fit to the standard model parameters at the Z peak. The relatively new fact is that m_t has now the rank of a precision measurement and this will be accounted in the fit by

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including the proper penalty function. Adopting the most recent set of the available data [1] (*i.e.* LEP+SLD+D0+CDF+...), we obtain [2]

$$m_t = 172 \pm 7\,\text{GeV} \qquad (\text{Th. error} \quad < 150\,\text{MeV}),$$
$$\alpha_s(M_Z) = 0.12043 \pm 0.00411^{+0.00075}_{-0.00037}\,(\text{th}),$$
$$M_H = 143 \pm 13\,(\text{th})\,\text{GeV}, \qquad M_H < 430\,\text{GeV} \quad \text{at} \quad 95\% \quad \text{CL},$$

where the theoretical uncertainty has been estimated along the lines described in [3].

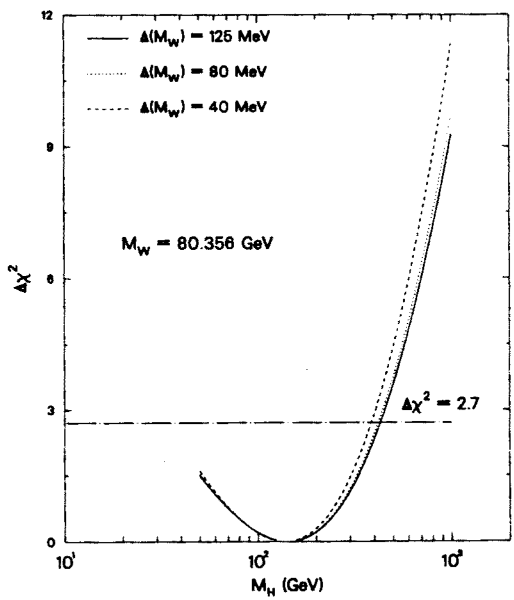

Fig. 1. The $\Delta\chi^2$ distribution as a function of M_H for different $\Delta(M_W)$.

The impact of the M_W measurement on the fit is illustrated in Fig. 1 where we have reported the $\delta\chi^2(M_H)$ curve relative to the present experimental error of 125 MeV and to some projected error.
Once we have taken the data and derived the standard model parameters $m_t, \alpha_s(M_Z)$ and M_H with their errors then we proceed in computing the Pseudo-Observables, $\sigma_H, R_l, A^l_{FB}, \ldots$, at the Z peak with propagation of the $\Delta(m_t)$ *etc.* errors and with some rough estimate of the corresponding theoretical uncertainty as derived in TOPAZ0 by considering different options on the implementation of higher order electroweak corrections. Some of the results are shown in Figs 2–3 where the theoretical uncertainty has been scaled by a factor 10.

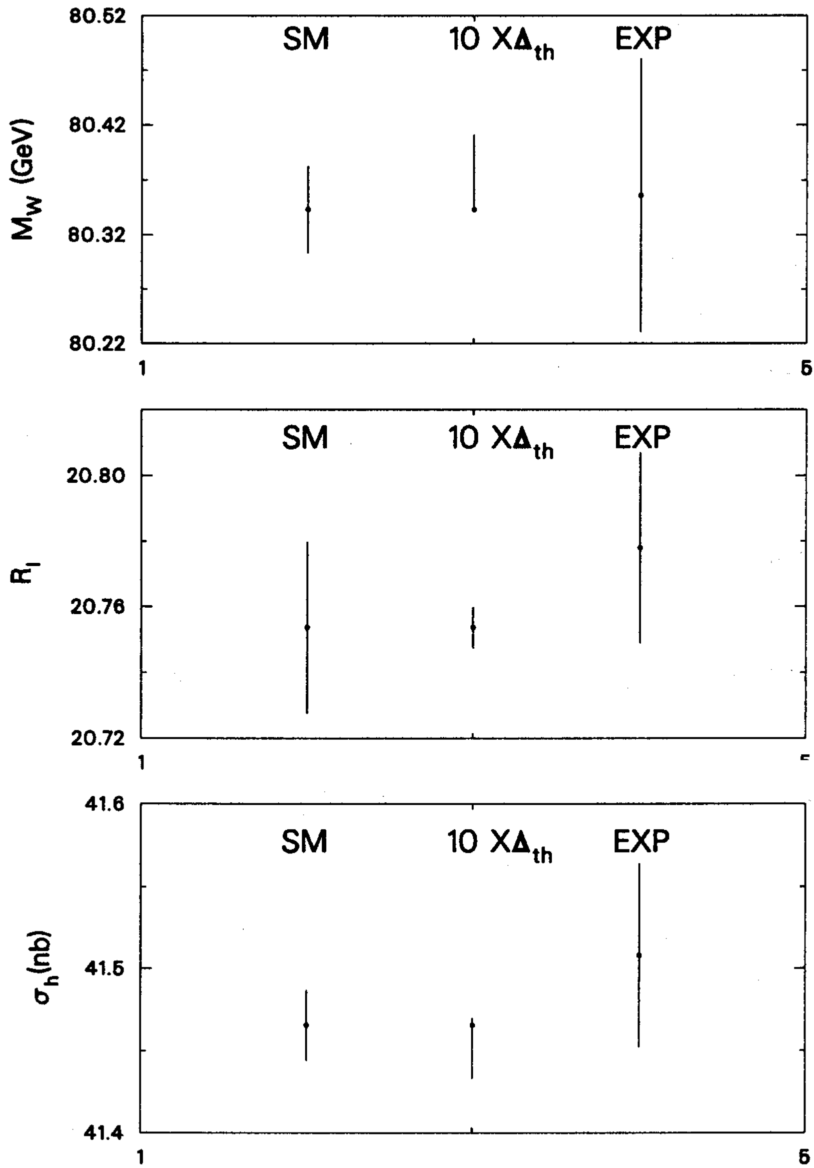

Fig. 2. Pseudo-Observables at the Z peak as compared to the standard model prediction with propagation of errors and with an estimate of the theoretical uncertainty ($\Delta_{\rm th}$).

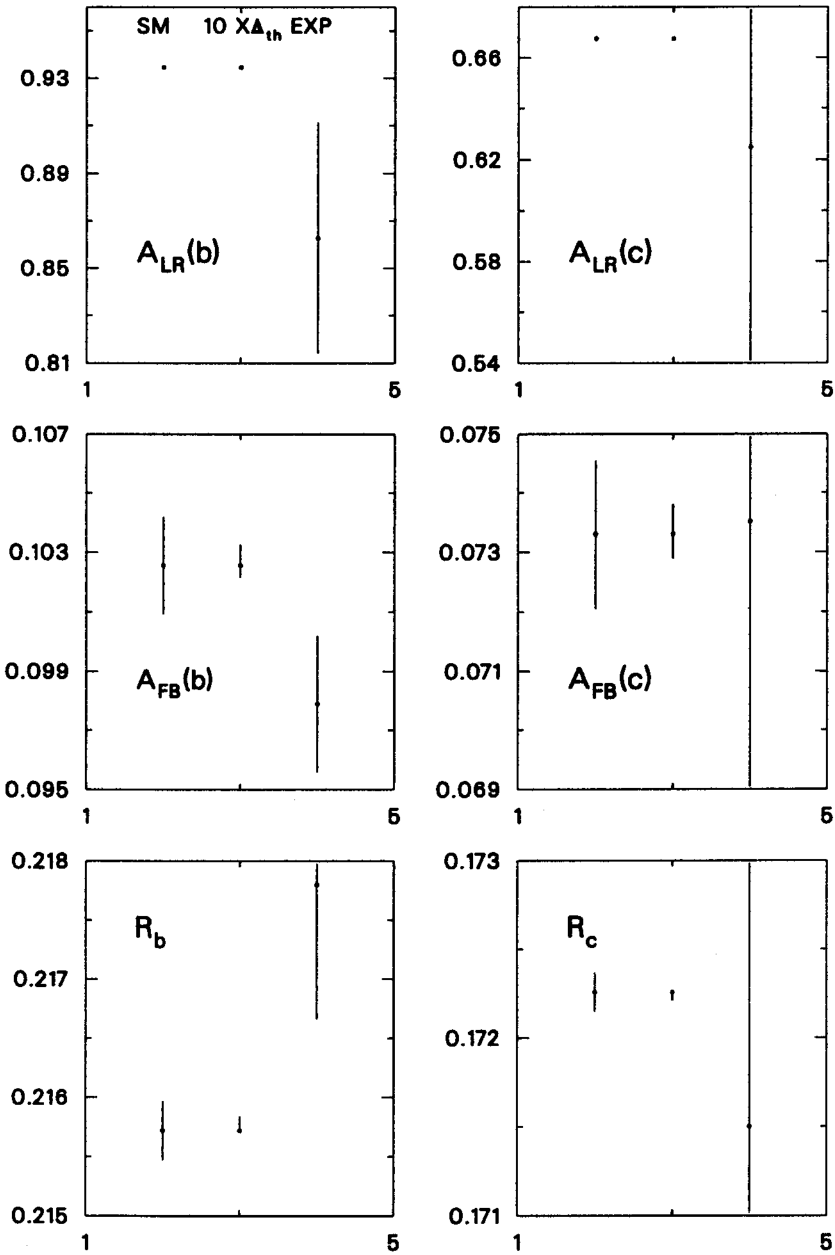

Fig. 3. The same as in Fig. 2

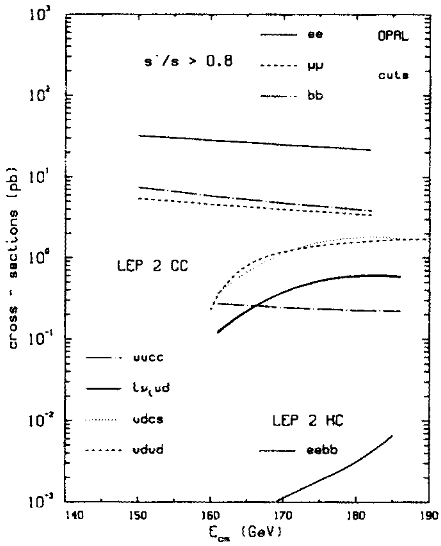

Fig. 4. 2f and 4f cross-sections in the LEP 2 energy range

The natural comment emerging from this study is that the MSM around the Z resonance is in a very good shape. There is a quest for extending (or disproving) this statement away from the Z resonance with the same standard of high precision.

The accurately measured σ, A_{FB} at the resonance allow a precise determination of the effective Z couplings which, including the knowledge of the γ-couplings, will give the complete behavior of the theory at any other energy, if no new physics is there. Presently any other energy means 161, 170, 172 GeV and before we move on in our discussion it is worth to have a rough idea of the order of magnitude of the LEP 2 cross-sections. This is shown in Fig. 4 where we have shown the 2f cross-sections with s' cut, the 4f ones with canonical LEP 2 cuts [4] and a sample relative to the Higgs boson searches [5].

2. $e^+e^- \to$ 2f, the twofold way

The theoretical analysis of the 2f final states, *i.e.* $e^+e^- \to \overline{f}f$, has been extended to higher energies [6]. To achieve this goal both TOPAZ0 [2] and ZFITTER [7] have been upgraded by including the most recent developments made available in the literature. In this way precise measurements and accurate predictions, away from resonance, allow to control the energy evolution of the MSM, to constrain the size of the γZ-interference and to control the energy behavior of R_b — after the Warsaw restoration.

When we talk about measurements and predictions we usually refer to two different criteria. One can use the same criteria as in earlier — on-resonance — studies or a correction to the phase-space limit can be imposed by the so called s' cut in order to avoid the radiative return to the Z peak.

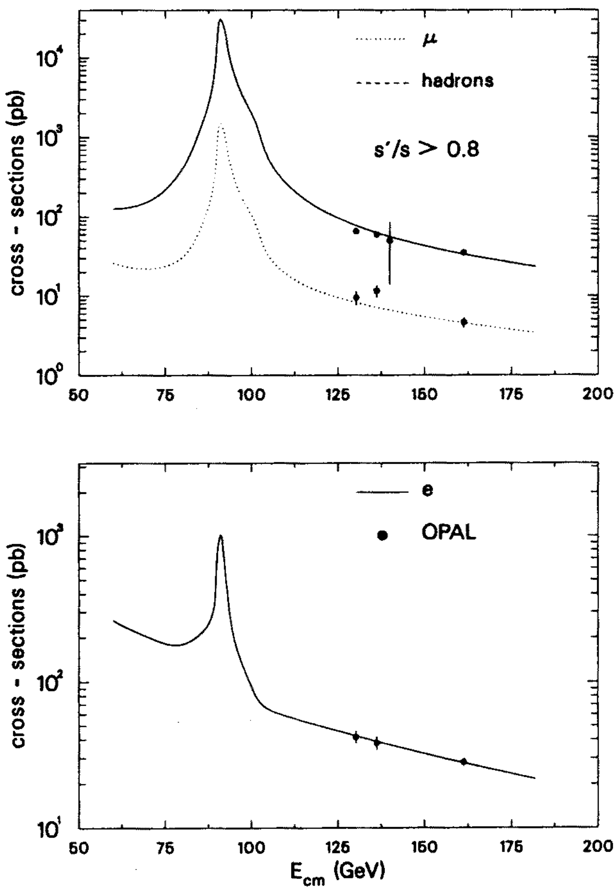

Fig. 5. Cross-sections for $e^+e^- \to e^+e^-, \mu^+\mu^-$ and hadrons with $s'/s > 0.8$.

Both situations have been analyzed with the help of TOPAZ0 and the resulting comparison at LEP 2 energies is shown with the OPAL data [8] in Figs 5–6.

In the following we will discuss something related to the interplay between 2f and 4f final states in e^+e^- annihilation at LEP 2. There are several components in the radiative corrections to 2f final states, among which the

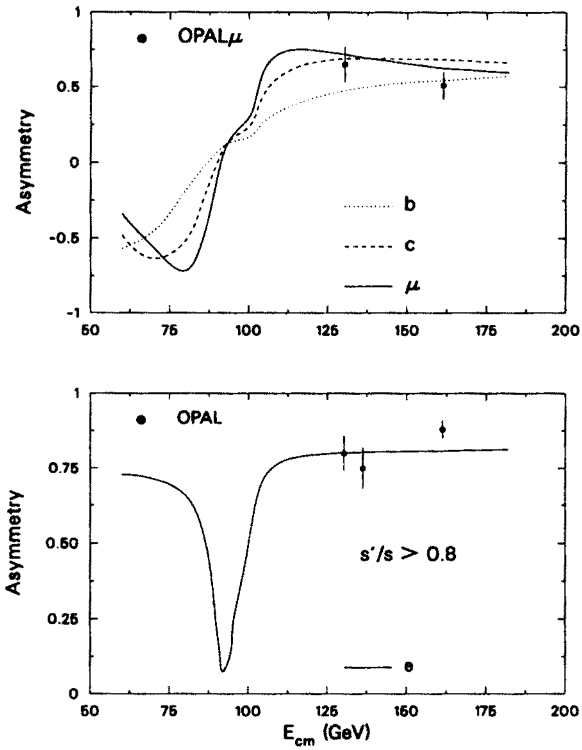

Fig. 6. Forward–Backward asymmetries for $e^+e^- \to e^+e^-, \mu^+\mu^-$ and hadrons with $s'/s > 0.8$.

less satisfactory from a theoretical point of view is initial state (or final state) pair production. After making a cut for non-radiative events the hadronic cross-section at $\sqrt{s} = 161.3$ Gev is 35.3 pb (with an OPAL-like cut of $s'/s > 0.8$). The principal background is an estimated 2.6 pb arising from 4f events. What is really meant by this statement?

For definiteness we will consider $e^+e^- \to \bar{b}b$ with radiation of an e^+e^- pair. The background is therefore represented by the full 4f process $e^+e^- \to e^+e^-\bar{b}b$, the so called NC48 process, which consists of 48 diagrams. For studies around the Z resonance [3] we only included pairs from initial state — e, μ hadronic pairs — and a cut was selected so that

$$M^2(\bar{b}b) > 0.25\,\mathrm{s}\,. \tag{1}$$

At LEP 2 and at even higher energies we need a more precise separation between radiative corrections to 2f and real 4f events. Why? We try to answer this question by presenting an easy-to-use catalog of pairs in 2f. First of all the soft pairs $\gamma^* \to e^+e^-$ are divergent in the limit of zero e^+e^- invariant mass and therefore any simulation of very soft pairs with massless 4f codes is bound to produce craziness. Are massive 4f codes enough? No because if pairs are soft enough — we are going down to m_e^2 — then we must include virtual pairs as well. Are soft + virtual initial/final pairs in 2f codes enough? No, no upper cut is imposed on $M(e^+e^-)$ so that all pairs compatible with $M^2(\bar{b}b) > 0.8\,s$ are accepted. Thus there is more in life than soft + virtual initial/final pairs, there are many topologies for hard pairs and some of them requires finite m_e also for hard pairs — there are multi-peripheral diagrams which diverge in the $m_e \to 0$ limit. What is the solution?

A Include virtual+soft(up to some invariant mass Δ) Initial/Final state pairs with a complete 2f code.

B The contributions to $e^+e^- \to e^+e^-\bar{b}b$ not in [A] are included with $M^2(\bar{b}b) > 0.8\,s$, no further restriction on $M^2(e^+e^-)$ with a full 4f code (massive m_e).

C The contributions to $e^+e^- \to e^+e^-\bar{b}b$ already in [A] are included with $M^2(\bar{b}b) > 0.8\,s$, $M(e^+e^-) > \Delta$.

TABLE I

Effect of e^+e^- Pair Production, $s' = M^2(\bar{b}b)$ and $M(e^+e^-) < \Delta$

	$\sqrt{s}$ (GeV)	161.3	170	172	182
	pb				
	$\sigma(\bar{b}b), s'/s > 0.8$	5.701	4.785	4.609	3.875
IS	V+S $s'/s > 0.8$, $\Delta = 1$ GeV	-0.020	-0.017	-0.017	-0.015
IS	V+S $s'/s > 0.8$, $\Delta = 5$ GeV	-0.017	-0.015	-0.015	-0.013
IS	V+S $s'/s > 0.8$	-0.017	-0.015	-0.014	-0.013
	fb				
FS	V+S $s'/s > 0.8$, $\Delta = 1$ GeV	-0.8	-0.7	-0.7	-0.6
FS	V+S $s'/s > 0.8$, $\Delta = 5$ GeV	-0.6	-0.5	-0.5	-0.4
FS	V+S $s'/s > 0.8$	-0.5	-0.5	-0.5	-0.4

TABLE II

Complete Effect of e^+e^- Pair Production, including Virtual/Soft($\Delta = 5$ GeV) Initial and Final state pairs and Hard (complete) pairs.

$\sqrt{s} = 161.3$ GeV $M^2(\bar{b}b) > 0.8\,s$, $\Delta = 5$ GeV	
$\sigma(\bar{b}b)$	5.701 pb
IS V+S	−17.2 fb
FS V+S	−0.6 fb
H	+0.8 fb
Total	−17 fb (−0.3%)

There is a caveat. This works for μ-pairs too, for hadrons however the recipe is unclear. We have shown the result of our investigation in Table I–II for different soft-hard separators Δ.

3. Towards the fourfold way, $e^+e^- \to 4$f

In this part of the paper we will be mostly concerned with a newfoundland — precision physics of the fourfold way — discovery physics doesn't require sophisticated tools, after all! The following items will be covered. Marginally the M_W-measurements for which we refer to [9] and [10]. Next we will discuss some subtle points about CC20, the $e^+e^- \to e^-\overline{\nu}_e u\overline{d}$ process, in the low-scattering-angle region. Finally we present some preliminar discussion about the background to Higgs production at LEP 2, essentially to $e^+e^- \to \nu\overline{\nu}b\overline{b}$ — the so called single W events. The quest for radiative corrections in 4f physics and in particular the case of the Fermion Loop scheme will not be addressed here, see instead [11].

For the M_W-measurement we only make one quantitative (multiple) statement on the effect of neutral current (NC) processes on WW distributions: at the parton level we can compute distributions for 7 processes, to understand the complete background to $WW \to \overline{q}q\overline{q}q$. The NC background, $u\overline{u}c\overline{c}$ *etc*, is completely negligible whenever we apply a ± 10 Gev cut around the W mass. The only small but not negligible background is coming from non-leading contributions of the CC and MIX($u\overline{d}d\overline{u}$) families. moreover the leading contribution of the CC family is completely dominated by the double-resonant diagrams, the so-called CC03 approximation, at least for some cuts.

The only improvement on the standard presentation will be an estimate of the theoretical error for the CC03 WW cross-section performed with WTO [12], as shown in Fig. 7.

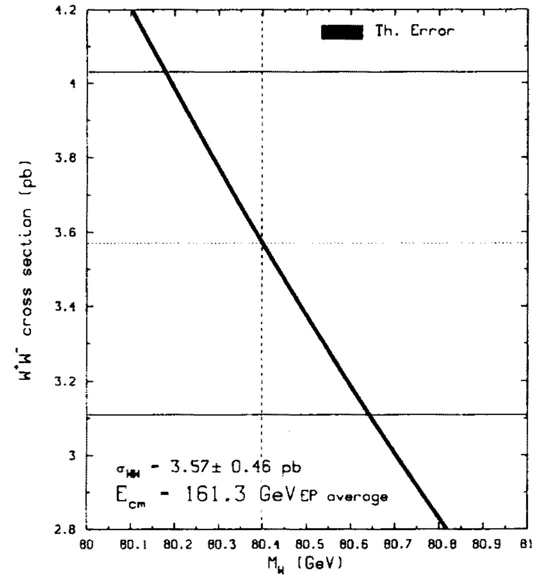

Fig. 7. The CC03 σ_{WW} with an estimate of the theoretical uncertainty.

In CC20 there is a issue of gauge-invariance [11]. A breakdown of the relevant Ward identities of the theory in the $e^+e^- \to e^-\overline{\nu}_e\nu_\mu\mu^+(u\overline{d})$ case results into a numerical catastrophe. The solution could be a pragmatic one, to use a fixed width for W's both in the s and t channels. Otherwise one has to adopt the Fermion Loop scheme [11].
The small scattering angle region for CC20 and/or different schemes is shown in Fig. 8.

Finally we shortly discuss some fine points in standard Higgs boson searches at LEP 2. All cross-sections for $e^+e^- \to \overline{b}b\overline{f}f$ are available but $\overline{b}b+$ neutrinos represent 20% of the signal at LEP 2 energies. We stress that for precision physics production $\otimes$ decay is not adequate enough. With an increasing degree of complexity one goes through the following ladder of approximations. First $e^+e^- \to Z^*H^*$, $\otimes$ $Z^* \to \overline{f}f$ and $H^* \to \overline{b}b$. Under the assumption that the Higgs production at LEP 2 is dominated by the Higgsstrahlung process the latter factorization is justified by the small Higgs width but the former one is not good enough because of the much larger Z width. Differential distributions are not accessible. $e^+e^- \to \overline{f}fH^* \otimes H^* \to \overline{b}b$. This works under the hypothesis that the fusion diagrams can be neglected. Again differential distributions are not accessible. At the top of the scale we have the full tree-level calculation $e^+e^- \to \overline{b}b\overline{f}f$.
No approximation is made, differential distributions are available and the

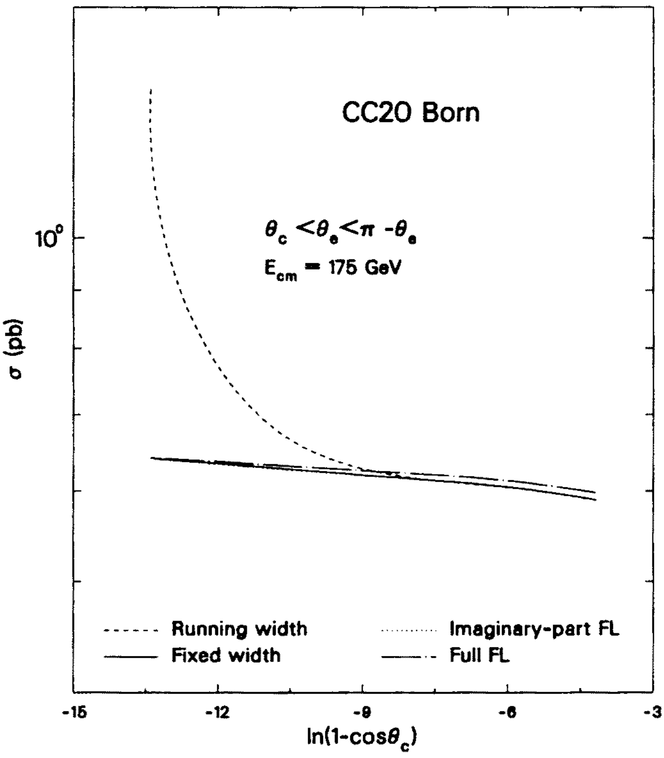

Fig. 8. The Born cross section for the CC20 process at small scattering angles for the electron.

background is under control. Cross-sections for different final states have been computed and presented in [5] while the relevance in $\bar{b}b\overline{\nu}_e\nu_e$ of the fusion production mechanism is illustrated in Fig. 9.

Since at LEP 2 a large fraction of Higgs events will be of the type $\bar{b}b\overline{\nu}\nu$ ($\approx$ 20%) we can concentrate in analyzing the corresponding background. There are potentially large backgrounds in $e\nu_e cs$ with flavor mis-identification and the e lost in the beam-pipe. A safe estimate requires including m_e in the calculation since we go down to $\theta_e = 0$ where moreover gauge invariance is in danger. Also important is $l^+l^-\bar{b}b$ with the leptons lost in the beam-pipe; again it requires a finite lepton mass because of divergent multi-peripheral diagrams.

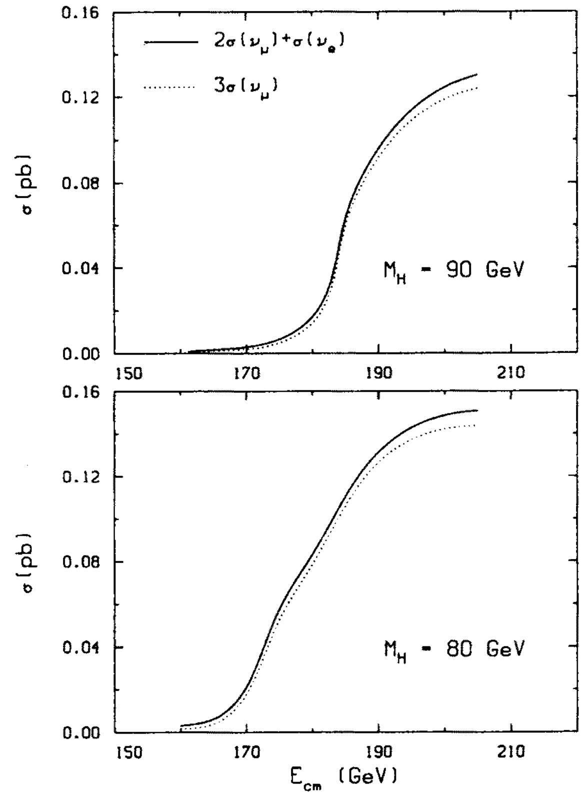

Fig. 9. The effect of the fusion production mechanism in $e^+e^- \to \bar{b}b+$ neutrinos.

TABLE III

Signal is $\sigma(e^+e^- \to \bar{b}b\bar{\nu}\nu)$ for $M_H = 80\,\text{GeV}$. BCKG I[II] is $\sigma(e^+e^- \to e\nu_e[\mu\nu_\mu]cs)$. Here $M_W = 80.356\,\text{GeV}$.

$P_0 = P_{bb}^2$	$P = P_{cb} \cdot P_{sb}$		
$\sqrt{s}$ (GeV)	Signal (fb)	BCKG I (fb)	BCKG II (fb)
170	$16.261(1) \cdot P_0$	$34.0(2) \cdot P$	$7.12(6) \cdot P$
172	$33.095(2) \cdot P_0$	$34.8(4) \cdot P$	$8.00(6) \cdot P$
186	$121.22(4) \cdot P_0$	$39.7(6) \cdot P$	$12.6(3) \cdot P$

A rather preliminary analysis has been performed with WTO giving the results of Table III where we have indicated that the probabilities of a light quark, a c-quark or a b-quark jet to be confused with a b-quark are non zero.

4. Conclusions

LEP 1 has represented the age of high precision, requiring the highest standards on the theoretical side. On the other end the first phase of the LEP 2 programme seems to be less demanding. Despite the spectacular success of the whole operation some criticism must be expressed. It has become customary to record LEP 1 deconvoluted pseudo-observables, like deconvoluted peak cross-sections and forward-backward asymmetries. The the main question is what can we do when — LEP collaborations dissolved — new ideas will come into play? The new habit, although partly justified by the relatively low statistics is to consider $e^+e^- \to 4\,\mathrm{fermions}$, where one evaluates the FULL — CC03 cross-section at fixed M_W with some X-code estimating the error on the subtraction by comparing some X/Y-codes. Then M_W is derived from a fit to $\sigma(\mathrm{CC03})$ with the help of some other Z-code. For today precision this is fine but for tomorrow high precision phase?

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