STANDARD MODEL AND ELECTROWEAK INTERACTION: PHENOMENOLOGY *

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The status of the LEP 1 results, the LEP 2 perspectives and some recent developments in high energy physics at e^+e^- machines are briefly discussed.

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In the phenomenology of the standard model we have three different phases: yesterday, *i.e.* bounds on standard or new physics from virtual effects, today, *i.e.* direct searches for Higgs particles and new physics and tomorrow, which hopefully will be testing the intimate gauge structure of the theory. If we ask ourselves what has been done since '77 we find that

'77-? The Born-like structure of the MSM, dressed with effective couplings which contain the potentially large radiative corrections has been confronted with the available experimental data, resulting in

1. Stringent bounds on m_t — Top quark discovered.
2. Loose bounds on $M_{\rm H}$ — Higgs boson(s) to be discovered.

But the times they are a-changin'. Now m_t from CDF+D0 is an input parameter in the fits for high precision physics, thus the new frontier is the Higgs boson mass, with or without new physics. At the same time the chief questions remain unaltered, do the experimental data accept the MSM? Are we setting sail for the land beyond the edge of the world, where new physics roam?

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To summarize we present few facts strictly separated from opinions by using the most recent experimental data as presented at ICHEP '96 [1], only few hours ago. As a prelude we want to show a fit to the Higgs boson mass with the uncertainty due to the error on $\alpha(M_Z)$ and m_b fully propagated in the theoretical part of the χ^2 (TOPAZ0 [2], see also BHM [3] and ZFITTER [4]). As a result of the fit we find

$$\begin{aligned} M_{\rm H} &= 143.5\,\text{GeV} \\ M_{\rm H} &\leq 431\,\text{GeV} \quad \text{at} \quad 95\% \quad \text{CL.} \end{aligned} \tag{1}$$

Our results at the minimum of the χ^2 are shown in Table I

TABLE I

Theory versus Experiments around the Z resonance

O	Exp.	Theory	Comments
M_H (GeV)	–	143.5 (fixed)	< 431 at 95% CL
χ^2		18.22/13	
m_t (GeV)	175 ± 6	172 ± 5	penalty in the fit
$\alpha^{-1}_{light}(M_Z)$	128.89 ± 0.09	128.905 ± 0.087	
$\alpha_s(M_Z)$	–	0.1194 ± 0.0037	th. err. not included
m_b (GeV)	4.7 ± 0.2	4.68 ± 0.24	
R_l	20.778 ± 0.029	20.754 ± 0.025	
$\sin^2\theta^e_{eff}$	0.23061 ± 0.00047	0.23159 ± 0.00022	
R_b	0.2178 ± 0.001144	0.2158 ± 0.0002	correlated
R_c	0.1715 ± 0.005594	0.1723 ± 0.0001	"
M_W (GeV)	80.356 ± 0.125	80.350 ± 0.031	
$A^0_{FB}(b)$	0.0979 ± 0.0023	0.1026 ± 0.0012	

In this type of fits — especially in a recent past — the main problems have been to understand

- when the $\chi^2(M_{\rm H})$ shape is unstable with respect to normal fluctuations of the experimental data in the large $M_{\rm H}$ tail. The question of the stability of the high-$M_{\rm H}$ tail in the χ^2 must be constantly addressed.
- That very stringent bounds on $M_{\rm H}$ ($\ll 500\,$GeV) were more a symptom of the clash between LEP and SLD.
- That $\chi^2_{\rm min}(M_{\rm H})$ has an unnatural tendency to be in the forbidden region, thus requiring the unnatural introduction of yet another penalty function.
- The effect of including the theoretical error in the fit [5].

With the new data the situation looks considerably better. For the first time in the LEP 1 history the $\chi^2_{\rm min}(M_{\rm H})$ is in the allowed region, the quality of the fit is more satisfactory than ever, the minimal standard model and the minimal supersymmetric standard model seem to be on – more or less – equal footing in describing the data. In conclusion however it is still premature to give something more precise than an approximate upper bound of $\approx 500\,$GeV at 95% of CL.

Today we have a new perspective anyway. Even though the central value for $M_{\rm H}$ has become a little higher we have a non negligible probability of a Higgs boson within the energy range of LEP 2. Thus we should stop worrying about Tails&Fits and start to understand how a Higgs boson — in the LEP 2 range — looks like in a real environment.

Since we have learned how to deal with unstable particles in a field theoretical context [6] then the properties of the Higgs boson at LEP 2 must be inferred from the complete analysis of the following processes:

$$\begin{aligned} e^+e^- \to\ & \overline{b}b\mu^+\mu^-, \qquad \overline{b}be^+e^-, \\ & \overline{b}b\overline{\nu}\nu, \qquad \overline{b}b\overline{u}u, (\overline{c}c), \\ & \overline{b}b\overline{d}d, (\overline{s}s), \qquad \overline{b}b\overline{b}b \end{aligned} \tag{2}$$

with all the complications arising from flavor mis-identification. Thus the three typical signatures are

- two jets + a charged lepton pair, two jets + missing energy and momentum, four jets

The ideal procedure would be to analyze all channels through some event generator — the ultimate one — which should account for the experimental setup, include a self-consistent set of radiative corrections and be interfaced with some standard hadronization package. A broad separation can be set between the two alternative approaches:

- Dedicated electroweak calculations as described by CompHEP [7], EXCALIBUR [8], GENTLE/4fan [9], HIGGSPV [10], WPHACT [11], WTO [12], ...
- General purpose simulations (PHYTIA [13], ...)

Here we would like to present the point of view of a dedicated EW calculation performed with WTO and which is aimed to discuss the Higgs boson properties by including all diagrams at the 0.1% level of technical precision (or better) with the best available set of radiative corrections, *i.e.*.

1. Initial State QED radiation through the structure function approach [14],
2. Running quark masses [15],
3. Naive QCD (NQCD) final state corrections,

and with a simulation of some quasi-realistic experimental setup. This will allow access to all kind of differential distributions and to a control over the background. To this end we have extended the original version of WTO in order to allow for the generation of unweighed events and for the storage of their four-momenta. The full description of WTO 2.0 and of the methods adopted to generate unweighed events will be given elsewhere.

The degree of complexity of the calculation is shown in Table II by a simple counting of the diagrams which contribute to each channel

TABLE II

Diagrams required (including gluons)

Final state	Class/max # of diagrams
$\bar{b}b\mu^+\mu^-$	NC25
$\bar{b}be^+e^-$	NC50
$\bar{b}b\bar{\nu}_\mu\nu_\mu$	NC25
$\bar{b}b\bar{\nu}_e\nu_e$	NC21
$\bar{b}b\bar{u}u$, $(\bar{c}c)$	NC33
$\bar{b}b\bar{d}d$, $(\bar{s}s)$	NC33
$\bar{b}b\bar{b}b$	NC68

Here we briefly summarize the strategy for the calculation as adopted by WTO. All fermions masses are neglected but for the b-quark mass in the Yukawa coupling and for the b-quark, c-quark and τ masses in the decay width. Quark masses are running and evaluated according to

$$\bar{m}(s) = \bar{m}(m^2) \exp\left\{ - \int_{a_s(m^2)}^{a_s(s)} dx \frac{\gamma_m(x)}{\beta(x)} \right\},$$
$$m = \bar{m}(m^2) \left[1 + \frac{4}{3} a_s(m) + K a_s^2(m) \right], \tag{3}$$

where $m = m_{\text{pole}}$ and $K_b \approx 12.4$, $K_c \approx 13.3$. The Higgs width is computed with the inclusion of the $H \to gg$ channel. The most complete treatment will therefore evolve α_s to the scale $\mu = M_{\text{H}}$, evaluate the running b, c-quark masses and compute

$$\Gamma_H = \frac{G_G M_{\text{H}}}{4\pi} \left\{ 3 \left[m_b^2(M_{\text{H}}) + m_c^2(M_{\text{H}}) \right] \left[1 + 5.67 \frac{\alpha_s}{\pi} + 42.74 \left(\frac{\alpha_s}{\pi} \right)^2 \right] + m_\tau^2 \right\} + \Gamma_{gg},$$
$$\Gamma_{gg} = \frac{G_\mu M_{\text{H}}^3}{36\pi} \frac{\alpha_s^2}{\pi^2} \left(1 + 17.91667 \frac{\alpha_s}{\pi} \right). \tag{4}$$

NQCD is included by evaluating $\alpha_s(M_W)$(input) to $\alpha_s(M_{\text{H}})$ and the Higgs boson signal is multiplied by

$$\delta_{\text{QCD}} = 1 + 5.67 \frac{\alpha_s}{\pi} + 42.74 \left(\frac{\alpha_s}{\pi} \right)^2, \qquad \alpha_s = \alpha_s(M_{\text{H}}). \tag{5}$$

As an example we give in Table III some of the relevant quantities as a function of M_{H}.

TABLE III

Input is $\alpha_s(M_Z) = 0.123$, $m_b = 4.7$ GeV and $m_c = 1.55$ GeV

Parameter	$M_{\text{H}} = 80$ GeV	$M_{\text{H}} = 90$ GeV	$M_{\text{H}} = 100$ GeV
Γ_H	1.8515 MeV	2.0601 MeV	2.2734 MeV
$m_b(M_{\text{H}})$	2.731 GeV	2.702 GeV	2.676 GeV
$m_c(M_{\text{H}})$	0.553 GeV	0.547 GeV	0.542 GeV
$\alpha_s(M_{\text{H}})$	0.12557	0.12323	0.12121

Once we obtain a prediction at a certain level of technical precision still the question of the theoretical uncertainty remains to be addressed. There are several sources for it but no fully reliable estimate of the theoretical error can be given, at most we can produce a rough estimate by applying few options connected with the choices of the Renormalization Scheme (GENTLE/4fan, WTO). To illustrate an example of their effect we have evaluated the Higgs background at 190 GeV and estimated the theoretical error, as shown in Table IV

TABLE IV

Differences in renormalization scheme

Process	1-(G_F scheme)/(α scheme) (per mille)
$\bar{b}b\bar{\nu}_\mu\nu_\mu$	0.86
$\bar{b}b\mu^+\mu^-$	2.23
$\bar{b}b\nu_e\nu_e$	2.44
$\bar{b}be^+e^-$	8.05
$\bar{b}b\bar{u}u$	−3.21
$\bar{b}b\bar{d}d$	−3.03

Roughly speaking the theoretical uncertainty associated with the choice of the RS is most severe whenever low-q^2 photons dominate (WPHACT, WTO). Indeed let us consider the two most popular choices of RS

- The $\alpha(M_Z)$ scheme.

$$s_W^2 = \frac{\pi\alpha}{\sqrt{2}G_\mu M_W^2}, \qquad g^2 = \frac{4\pi\alpha}{s_W^2} \tag{6}$$

- The G_F scheme

$$s_W^2 = 1 - \frac{M_W^2}{M_Z^2}, \qquad g^2 = 4\sqrt{2}G_\mu M_W^2. \tag{7}$$

In the G_F-scheme the e.m. coupling is governed by $\alpha = 1/131.22$ while in the $\alpha(M_Z)$-scheme it is $\alpha = 1/128.89$ which accounts for a 2% difference — about 10% in the two schemes at low-q^2 for diagrams with two photons.

Other additional sources of uncertainty are in the Parametrization of the QED structure functions and in the treatment of the scale in the QCD corrections, especially so for the scale of α_s in the NQCD. The default consists in inserting α_s(fixed) even for internal gluons. A better choice could be α_s at the running virtuality (but cuts are required to avoid the non-perturbative regime).

On top of the theoretical uncertainties there are additional problems, like flavor mis-identification and the correct treatment of the background. Experimentally one must extract the Higgs signal from all final states consisting of a pair of (imperfectly) b-tagged jets + remaining products — including the missing ones. Indeed the probabilities of a light quark, a c-quark or a b-quark jet to be confused with a b-quark are non zero. The effect of flavor mis-identification modifies the original branching ratios. Moreover at LEP 2 a large fraction of Higgs events will be of the type $\bar{b}b\bar{\nu}\nu$ ($\approx 20\%$). There are potentially large backgrounds in

1. $e\nu_e cs$ 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.
2. $l^+l^-\bar{b}b$ with the leptons lost in the beam-pipe. Again it requires a finite lepton mass because of divergent multi-peripheral diagrams.

No reliable estimate has been given so far.

In order to analyze the Higgs signal versus background we fix our set of cuts. They are

1. $M(\bar{b}b) \geq 50\,\text{GeV}$, $\mid M(\bar{f}f) - M_Z \mid \leq 25\,\text{GeV}$. The former is to suppress the photon mediated $\bar{b}b$ production — which decreases for larger $\sqrt{s}$. The latter reduces all contributions which give a broad $M(\bar{f}f)$ spectrum.
2. Lepton momenta $\geq 10\,\text{GeV}$, $E_q \geq 3\,\text{GeV}$.
3. Lepton polar angles with the beams $\geq 15°$.
4. For processes with neutrinos the angle of both b's with the beams $\geq 20°$ or of at least one b. Moreover $\theta(l, q) \geq 5°$.

Next we start by showing the cross sections as a function of $\sqrt{s}$ for $M_{\rm H} = 80\,\text{GeV}, 90\,\text{GeV}, 100\,\text{GeV}$ and ∞. They are shown in Fig. 1.
Our findings confirm the rule of thumb $M_{\rm H} \approx \sqrt{s} - 100\,\text{GeV}$ for LEP 2 feasibility. If the Higgs is above 80 GeV the cross section is too small at $\sqrt{s} = 175\,\text{GeV}$ to allow Higgs discovery, the $\sqrt{s} = 190\,\text{GeV}$ phase of the collider is needed. At $\sqrt{s} = 190\,\text{GeV}$ the ZZ background is not negligible and here is where a dedicated EW calculation becomes useful.

There are several distributions which are of some relevance in the Higgs study. They provide information useful for choosing cuts in the Higgs searches. Among them we have selected:

1. The $M(\bar{b}b)$ distribution for all channels but $\bar{b}b\bar{b}b$. It is useful whenever the direct reconstruction of the invariant mass from the jets in the process is viable.
2. The missing mass recoil. A knowledge of $\sqrt{s}$ and of the leptonic final states is required

$$M^2_{\rm miss} = s - 2\sqrt{s}\,(E_{l^+} + E_{l^-}) + M^2(l^+l^-) \tag{8}$$

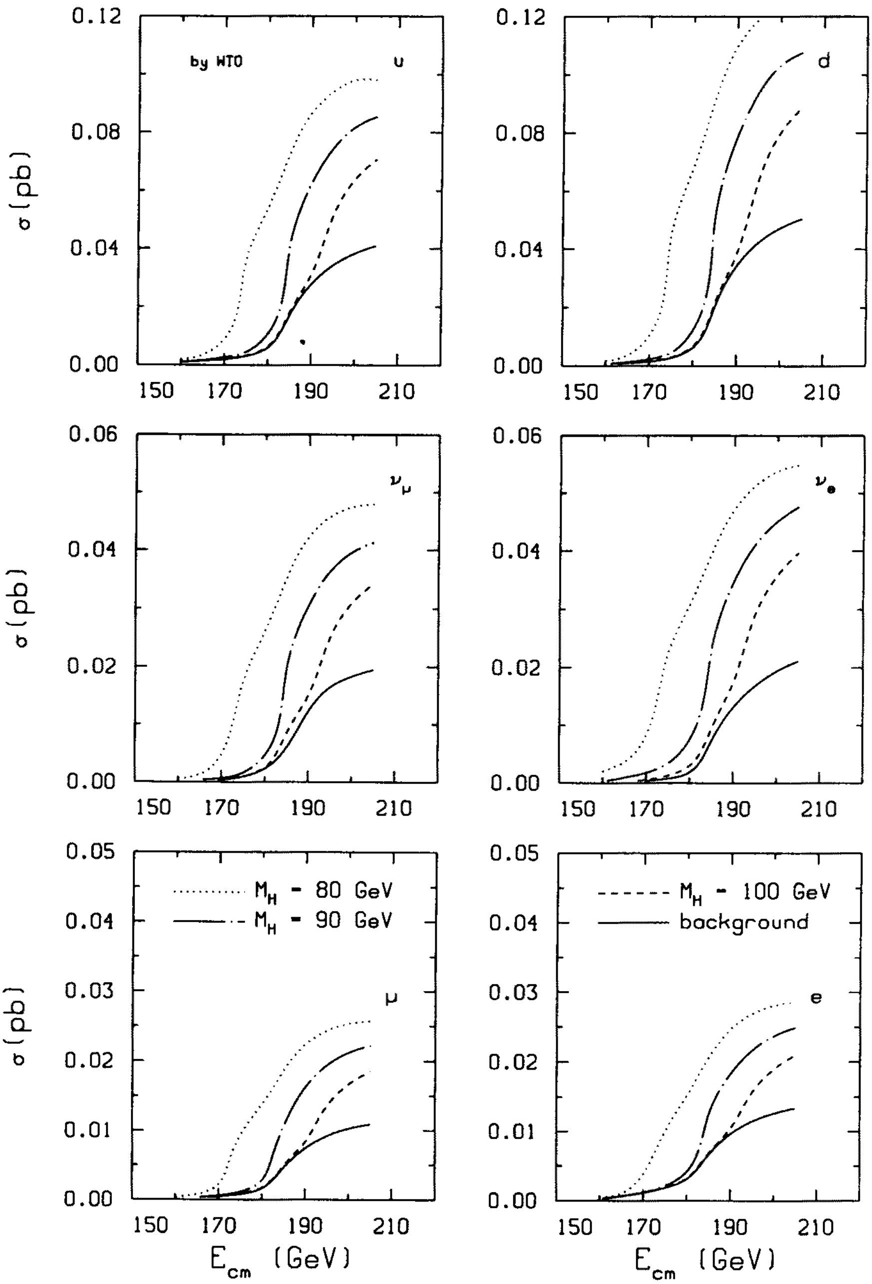

Fig. 1. Cross sections for $e^+e^- \to \bar{b}b\bar{f}f$

3. The visible energy in $\bar{b}b\bar{\nu}\nu$, or in general $E(\bar{b})+E(b)$. The b-quark pairs from the Higgs decay have a sharp peak in the energy distribution due to the small Higgs width.
4. Angular distributions for the b-quark and/or the $\bar{b}$-quark. In particular the $\cos\theta(\bar{b}b)$ distribution of the total 3-momentum $\vec{p}_{\bar{b}b}$. However, in general, the signal angular distributions are very isotropic.

There is not enough space here to discuss all the distributions and for this reason we have limited our presentation to some selected sample where $\sqrt{s} =$ 190 GeV and $M_{\rm H} = 80$ GeV. In Fig. 2 we have shown the $M(\bar{b}b)$ distribution while $E(\bar{b})+E(b)$ is given in Fig. 3. Finally the missing mass recoil is shown in Fig. 4.
The previous examples are meant to show the quality of the results achievable with a dedicated EW calculation its technical precision and the connected theoretical uncertainty. All diagrams have been included and before hadronization this is the status of art.

Our final goal will be to discuss the new frontier: e^+e^- annihilation beyond LEP 2. Among the many facets of the physics at NLC we want to select just one particular issue [6]:

- Any calculation for $e^+e^- \to 4(6)$-fermions is only nominally a tree level approximation because of the presence of charged and neutral, unstable vector bosons. Unstable particles require a special care and their propagators, in some channels, must necessarily include an imaginary part or in other words the corresponding S-matrix elements will show poles shifted into the complex plane (actually on the second Riemann sheet).

  The introduction of a width into the propagators will inevitably result, in some cases, into a breakdown of the relevant Ward identities of the theory with a consequent violation of some well understood cancellation mechanism.

Among the different choices at our disposal we have:

1. Running width for a vector boson (both charged and neutral) in any s-channel,

$$\Delta_V^{-1}(s) = s - M_V^2 + i\,\frac{s}{M_V}\Gamma_V. \tag{9}$$

   as dictated by Dyson re-summation of the self energy diagrams.

2. *Ad hoc* fixed width

$$\Delta_V^{-1}(s) = s - M_V^2 + i\,M_V\Gamma_V. \tag{10}$$

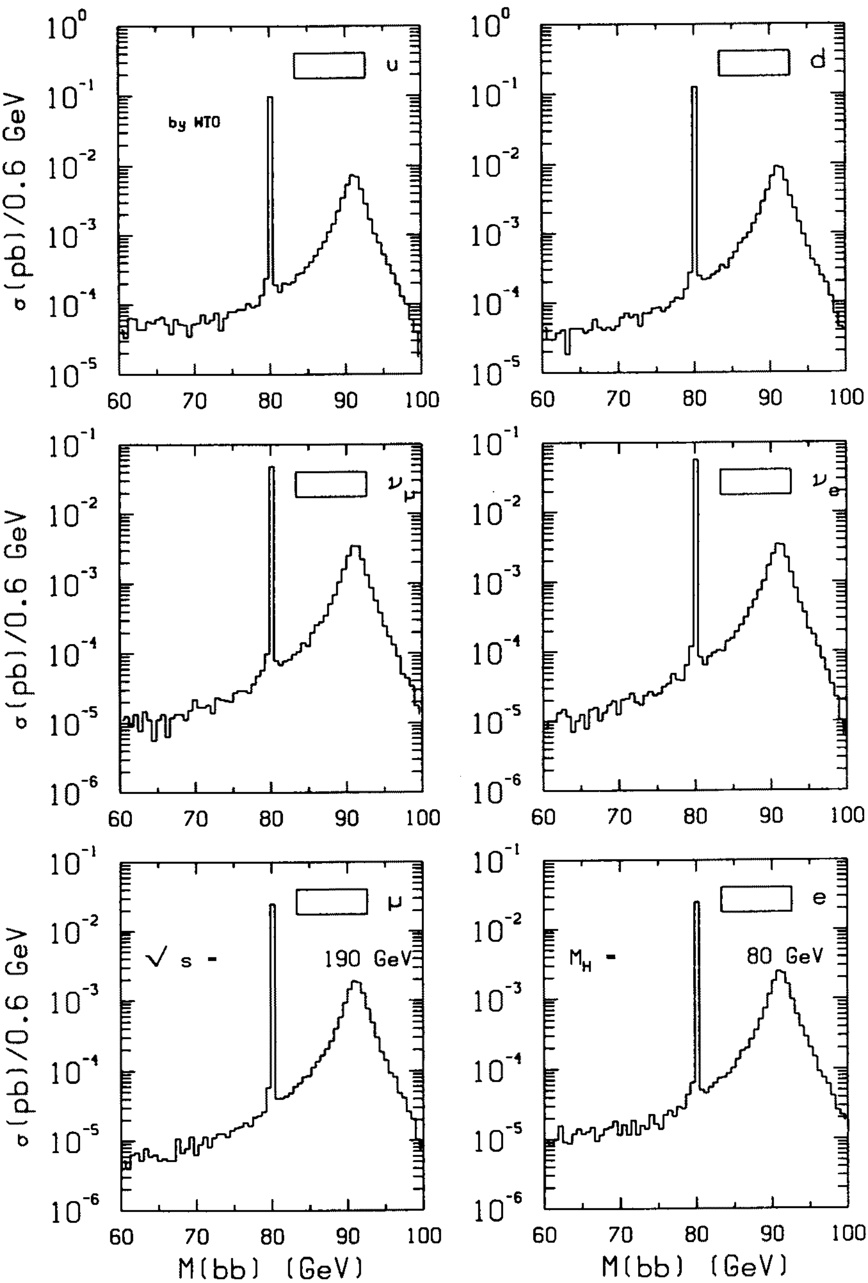

Fig. 2. The $M(\bar{b}b)$ distribution for $e^+e^- \to \bar{b}b\bar{f}f$.

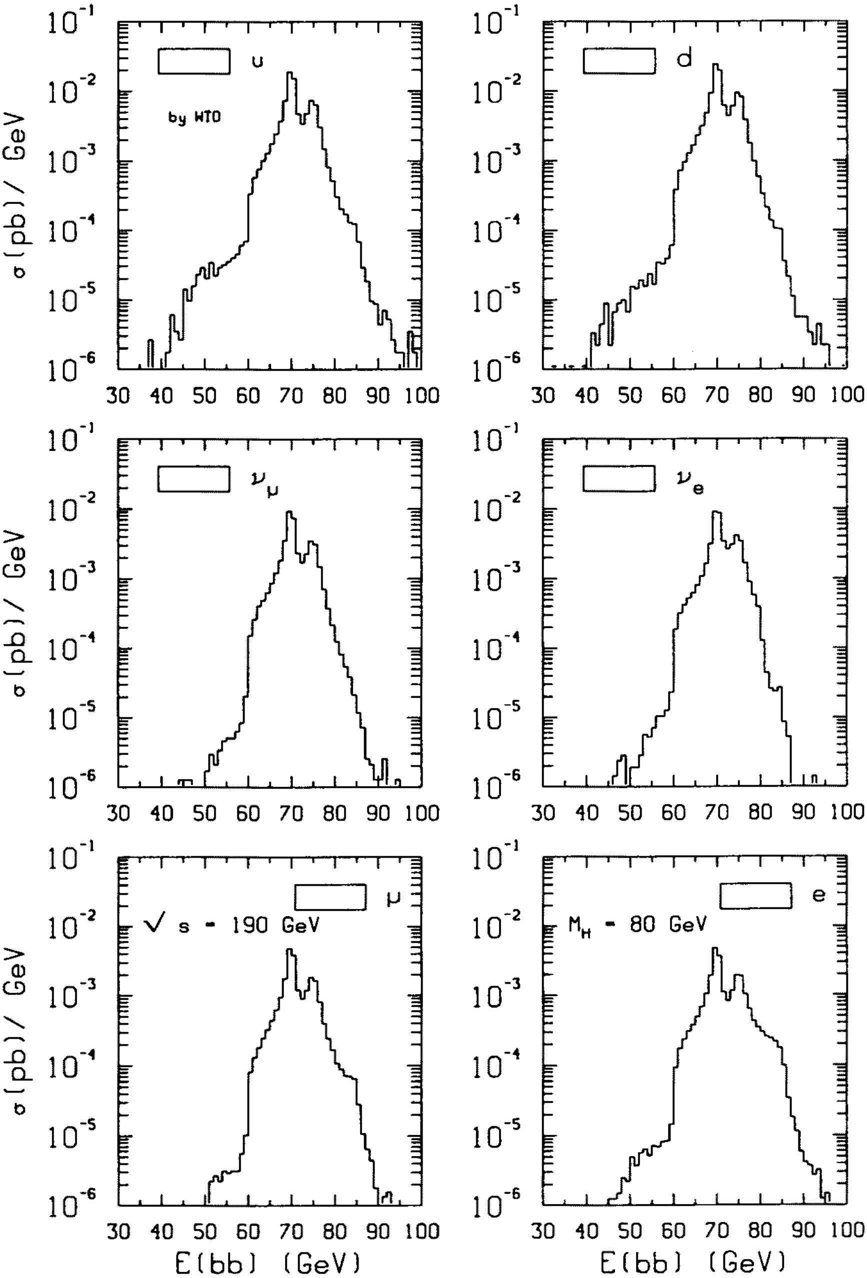

Fig. 3. The $E(\bar{b}) + E(b)$ distribution for $e^+e^- \to \bar{b}b\bar{f}f$

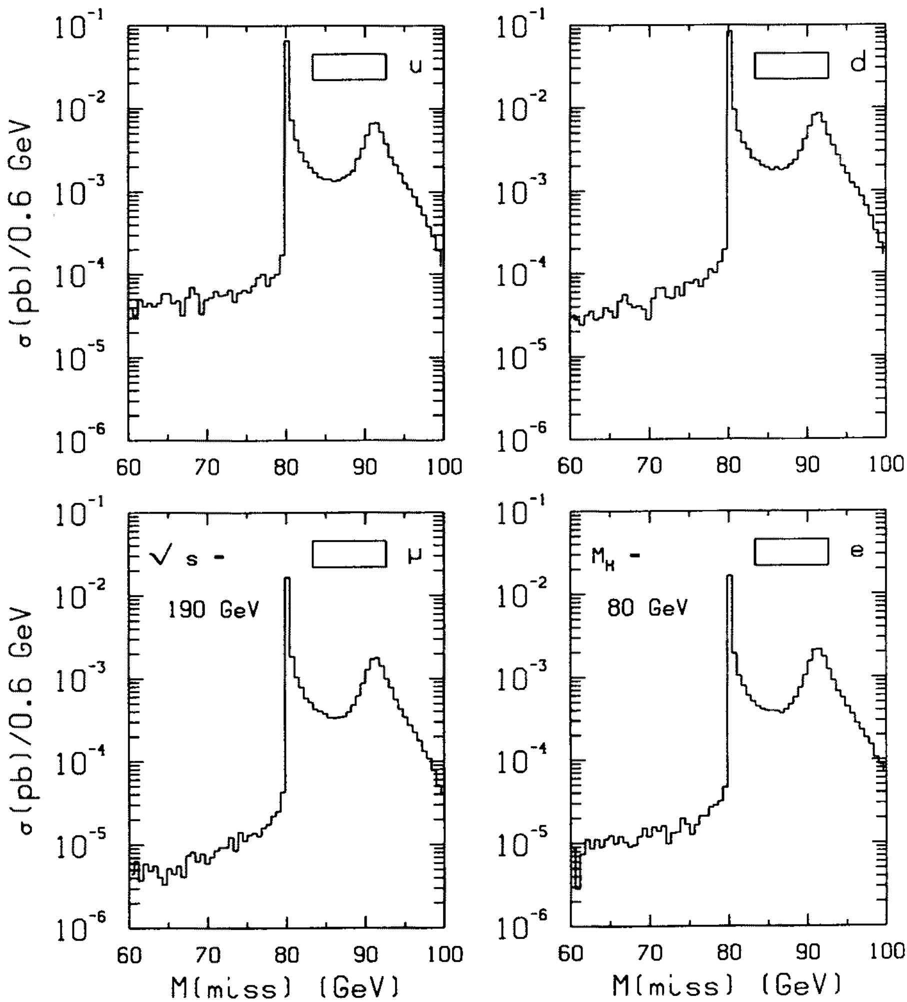

Fig. 4. The $M_{\rm miss}$ distribution for $e^+e^- \to \bar{b}b\bar{f}f$

3. Improved fixed with, as derived by analyzing the solution for the complex pole. Here one uses a fixed complex mass

$$\mu_V^2 = M_V^2 - \Gamma_V^2 - i\, M_V \Gamma_V \left(1 - \frac{\Gamma_V^2}{M_V^2}\right). \tag{11}$$

What are the predictions that we can make for an e^+e^- annihilation into four fermions at large energies? An example for the process $e^+e^- \to d\bar{u}c\bar{s}$

with QED correction (but without beamsthralung) at large energies is shown in Table V

TABLE V

Cross sections for $e^+e^- \to d\bar{u}c\bar{s}$ (No QCD)

$\sqrt{s}$(TeV)	running width	fixed width	improved fixed width
0.5	0.8651(2)	0.8612(5)	0.8614(5)
1	0.3650(1)	0.3505(1)	0.3505(1)
1.5	0.2267(3)	0.1953(3)	0.1957(4)
2	0.1827(7)	0.1279(4)	0.1275(2)

From our calculation one can see that at 2 TeV running versus fixed width (for both W and Z) amounts to quite some difference. The running width prediction is decreasing at a slower rate because a running width is actually spoiling gauge invariance which, in turns, means that the underlying unitarity cancellation at asymptotic energies for $e^+e^- \to W^+W^-$ is not working anymore.

The solution is known by now but let's make a step backward, we have a somehow related problem already at LEP 2. 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. This is already at LEP 2 energies and it has to do with the interaction of W's with photons and with small scattering angle of the electron. The solution is known: one can remain minimalist and include the imaginary parts of all other diagrams, the so called Fermion loop scheme. It goes like this: take $e^+e^- \to e^-\overline{\nu}_e u\overline{d}$ and compute the cross section with $\pi - \theta_{\rm cut} < \theta_e < \theta_{\rm cut}$. We do that for $\sqrt{s} = 175\,$GeV and including QED, but not QCD, and show the results in Table VI. However this is more or less an academical problem, a cut on the electron angle will always be imposed and at, say, 5° any choice is equally good.

TABLE VI

Restoring gauge invariance at LEP 2

$\theta_{\rm cut}$(deg)	running width	FL scheme	fixed width
10°	0.48681(4)	0.48692(4)	0.48674(4)
5°	0.49755(5)	0.49767(4)	0.49748(5)
1°	0.5184(5)	0.5125(4)	0.5123(4)
0.5°	0.546(2)	0.5181(6)	0.5179(5)

At NLC restoring the unitarity cancellation requires more: the full $\mathcal{O}(\alpha)$ fermionic corrections, both real and imaginary must be included. This we call Complete Fermion Loop scheme. All fermionic radiative corrections are organized in terms of:

a The complex poles s_W and s_Z (on the second Riemann sheet) for the W and Z vector boson.

b The running of $\alpha(s)$, the e.m. coupling constant. The running of $g^2(s)$ the SU(2) coupling constant.

c The one loop fermionic vertices.

There is of course a little problem with experimental input data, too many: M_Z, M_W, α, G_F. Thus a consistency condition can be imposed and the only other parameter available should be fixed, the top quark mass. This is, strictly speaking, non completely satisfactory since QCD corrections have not been applied, not even for the self-energies and bosonic corrections cannot be neglected in this matters. Indeed when we include all the available radiative corrections in the on-shell scheme we find the results of Table VII with a quite remarkable agreement with the experimental data.

TABLE VII

Calculated m_t for $\alpha_s(M_Z) = 0.123$ and different Higgs and W masses. The last column is the Fermion Loop prediction.

M_W/M_H (GeV)	60	300	1000	FL
80.10	119.1	137.3	154.2	104.8
80.26	148.1	165.3	181.2	132.2
80.42	174.4	190.7	206.1	157.2

Instead in the Fermion Loop scheme we obtain the results of the last column in Table VII, clearly showing the quality of the approximation.
Once the relevant Ward identities have been proven the corresponding cross sections can be computed, giving a field-theoretically and numerically correct description of e^+e^- annihilation at high energies. While the theoretical bases, including the whole set of Ward identities, compact expressions for the vertices, the full machinery of the running coupling constants is by now fully developed the numerical implementation into a realistic code and its debugging is still not at anchor (the version of WTO showing items a–d is in progress).

The Fermion Loop scheme, being the first self-consistent example of radiative corrections for LEP 2 physics and beyond, will eventually open the road for other (desperately) wanted calculations

- Complete QCD corrections to CC10 processes, $\mathcal{O}(\alpha \times \text{const})$ QED corrections to all LEP 2 processes and full $\mathcal{O}(\alpha)$ EW corrections for LEP 2 processes.

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