Electroweak physics at colliders

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Abstract

We review the status of the Electroweak Standard Model after a decade of accurate measurements at LEP and SLC. Possible ways to improve the present situation in the future are presented. The fundamental problem of electroweak symmetry breaking is emphasized, and we discuss how present and future machines can contribute to its understanding.

1 INTRODUCTION

In the first part of the lectures I will recall briefly what a test of the Standard Model (SM) consists of and summarize the main features and virtues of the colliders which contributed most.

The problem of the entries of the SM will be adressed next. What do we need, what do we have presently and where could the progress come from?

A selection of a few important electroweak observables will be reviewed, insisting on the key experimental aspects of their determination. We

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will then ask ourselves how one can improve such measurements in the future.

The second half of the lectures will be devoted to electroweak symmetry breaking (EWSB). The possible scenarios will be briefly described. We will then proceed in the following order: what do we learn presently from LEP200? What will we learn from the next round, at the Tevatron first, then at LHC. Finally what can one envisage for the farther future, either to perform metrology on already observed phenomena, or to explore the outmost energy frontier. Here again we will insist on the key experimental points, and on the main sectors of R/D needed to build and exploit such demanding machines.

2 Basics

All of you know the table of the elementary constituants of matter. While the first days at this School were devoted to the colour sector, we will now turn to the weak isospin sector. In weak isospin space, the fermions live different lifes depending on their chirality: the left-handed (LH) as doublets, the RH as singlets. It is therefore not surprising that the spin will be at the heart of the SM and that we will frequently refer to polarization.

While the zoo of fermions keeps its mysteries, the principle of their interactions is simple: they interact by exchanging a boson. The electroweak sector involves a triplet of W and a singlet B. The universal couplings are g and g', respectively. The charged W perform rotations in the weak isospace. A last complication is that the W^0 and B^0 get mixed to give the physical Z^0 and photon, by the weak mixing angle θ_w. The huge difference between the massless photon and the heavy Z^0, which otherwise are close relatives, is a manifestation of EWSB.

The traditionnal way to envisage EWSB is through the Higgs mechanism. A naive way is to introduce it in analogy with supraconductivity. In QED, for an electron wave-function, does one have the freedom to choose the phase arbitrarily at each point of space-time? Yes, provided one introduces the photon in the game. The result is QED. In weak isospace does one have the freedom to rotate arbitrarily at each point of space time? Yes, provided one introduces the weak bosons.

However something external may refuse that freedom. In a supraconductor the field of Cooper pairs, macroscopic overlapping objects which act coherently as bosons can do, locks the phase. The freedom is lost and the photon, by interacting with the field of the Cooper pairs, gets a mass. This mass is the inverse of the penetration depth of an external magnetic field in the supraconductor: m $\sim 1/\lambda \sim \sqrt{d}$, where d is the density of the Cooper pairs.

The idea of the Higgs mechanism is the same: considering now weak isospace, one invents a field, without caring about its source, which imposes an orientation in that space. The freedom to rotate arbitrarily is lost and W and Z get a mass. $M_W = g \times v/2$, very reminiscent of the preceding formula. Here v is the Higgs field vacuum expectation value (vev).

You all know the limit of such an analogy. However it has the merit to recall us that, while EWSB can result from a field whose quantum is an elementary object, a possibility we must fully explore in priority, it may also result from the effect of composite objects. Another interesting analogy is the spontaneous breaking of flavour chiral symmetry by quark condensates in QCD.

Since we will be concerned a lot by Z physics, let me briefly recall the expression of the neutral current coupling in terms of electric charge and weak isospin:

$$v_f = I_3^f - 2\ Q_f\ \sin^2\theta_w$$
$$a_f = I_3^f$$

Here a stands for L−R and v for L+R. For neutrinos one finds that the R coupling vanishes. Choosing $\sin^2\theta_w$=0.23, the L coupling of a down quark is −0.423 while its R coupling is +0.077, a big asymmetry indeed, Let us also define the flavour dependent asymmetry parameter $A^f = 2\ a_f\ v_f\ /\ (a_f^2 + v_f^2)$.

The reader will find in [1] the formulae for the differential cross-section for $e^+\ e^- \rightarrow f\ \bar{f}$ at the Z^0, for any possible state of polarization of the beams. It is quite easy to get from these the expression of any Z observable, in terms of the neutral current couplings.

These are however tree level expressions and we need to go to the loop level. A complete description of the procedure can be found in [1]. Here we will take the fast way and simply substitute in the expression of the neutral weak current the couplings a and v by effective ones, g_a and g_v:

$$\begin{aligned} J_\mu^{NC} &= (\sqrt{2}\ G_\mu\ M_Z^2\ \rho_f)^{1/2}\ [(I_3^f - 2\ Q_f\ s_w^2\ \kappa_f)\ \gamma_\mu - I_3^f\ \gamma_\mu\ \gamma_5\ ] \\ &= (\sqrt{2}\ G_\mu\ M_Z^2)^{1/2}\ [g_v^f\ \gamma_\mu - g_a^f\ \gamma_\mu\ \gamma_5\ ] \end{aligned}$$

s_w^2 is a short-hand notation for $\sin^2\theta_w$.

ρ_f and κ_f are flavour dependent correction factors which appear at the loop level and are absorbed in the definition of the effective couplings.

Similarly, instead of the tree level weak mixing angle θ_w, we will use an effective one, incorporating the κ factor of the equation above. More precisely, since this is flavour dependent, we will choose the leptonic one, $\sin^2\theta_{eff}^{lep}$, which is the one given directly by Z^0 leptonic widths and asymmetries under the assumption of universality.

The gauge couplings, g and g', and the Higgs vacuum expectation value, v, are the three basic entries of the SM. Actually, to these somewhat abstract quantities, one substitutes three well measured experimental ones. We will choose here: $\alpha(M_Z)$, the fine structure constant evolved to the Z scale, G_μ, also called G_F, the muon or Fermi constant, and the newly promoted M_Z. At tree level they are sufficient to compute all observables. At loop level, quark masses, especially the top mass, intervene in the expressions of the observables, as well as the Higgs mass. The strong coupling α_s also plays a role for hadronic observables. Obviously possible new physics can enter the game, at loop and even at tree level. So the principle of SM testing of an observable consists in feeding these entries into the appropriate theoretical expression, incorporating the required level of electroweak radiative corrections. A numerical value is predicted and compared to the experimental value, itself corrected for "trivial" effects, like QED radiation. For details see [2].

3 Existing colliders

The Tevatron has been described by J.Womersley. I just recall that in the past run I they have accumulated .1 fb^{-1} of data per experiment. Run

II, in 2001-2003, will get ~ 2 fb^{-1}. With further improvements, one could have registered ~ 15 fb^{-1} by 2007.

It is the right year to pay tribute to the prematurely stopped SLC. About half a million of Z have been registered, which may sound a modest number: however the longitudinal polarization of the electron beam was reaching 77 %, through the use of a strained GaAs photocathode hit by a circularly polarized laser beam [3]. The physics output was magnified by this high level of polarization, and its accurate knowledge, as we will see.

LEP has accumulated 17 million Z^0 between 1989 and 1996, but with unpolarized beams. Since then LEP has gradually increased its beam energy, up to 104 GeV. The decisive factor there was the good behaviour of its park of 285 Cu-Nb supraconducting RF cavities, which, designed for 6 MV/m, have been pushed to 7.5 MV/m.

Actually LEP could achieve some level of transverse polarization and this turned out to be crucial for the accurate determination of its beam energy, key to the Z and W mass measurements. In the LEP machine, transverse polarization of the beams builds up naturally, due to a spin asymmetry of synchrotron emission. One has however to speed up the process and to fight against depolarizing phenomena. Once polarization is built, one can measure the beam energy with an exquisite accuracy by a technique of resonant depolarization [4].

One could have rotated P_T into longitudinal polarization and used it for physics. Due to other priorities this was not done. However in these studies a clever scheme was invented [5] and, as we will see later, it may be a key for the future of accurate measurements.

Another important technique is laser backward Compton scattering on electron beams. This was used at LEP to detect and measure P_T, at SLC to measure P_L. It may be the right way to obtain also positron polarization at future Linear Colliders. Finally it allows to envisage a gamma$-$gamma collider option of these LC. This is kinematically a quite interesting process and I advise you to give a look to it.

4 The main entries of the SM

One should first realize that among the three entries chosen, the fine structure constant, which has to be evaluated at the Z^0 mass scale, is the main problem: few years ago its uncertainty was estimated to be ∼700 part per million (ppm). On the other hand the Fermi constant and the Z^0 mass are known to 9 and 23 ppm, respectively.

About G_μ, because of the accuracy already achieved, I will not tell much. It is derived from the measurement of the muon lifetime, presently known to 40 picosecond. Some experiments, including the FAST project at PSI [6], foresee to decrease this uncertainty to ∼2 ps.

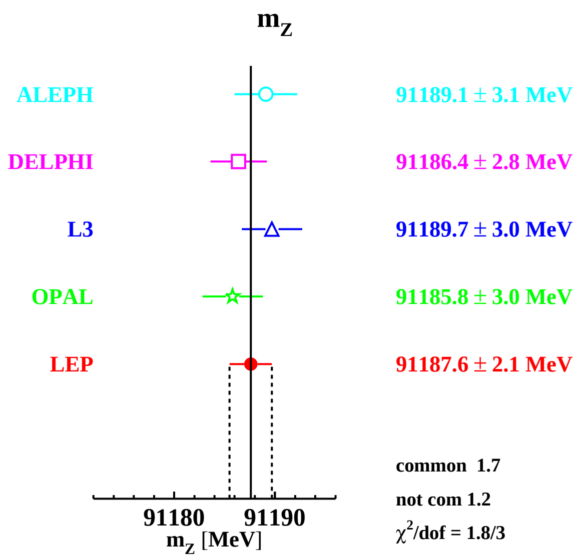

Figure 1: The Z mass measurement.

The Z mass measurement (Figure 1) at LEP was a modern epic [7]. It consists in measuring the central value of the Z pseudo Breit−Wigner resonance curve. One needs both a precise definition of the mass and an elaborate treatment of radiative corrections which strongly distort the resonance curve. Then the measurement amounts to get a most accurate value of the beam energy. This was obtained from resonant depolarization measurements, and a modelling of all effects taking place in between these measurements. When reaching the last decimal, several kinds of effects had to be understood. One should remember that in LEP, due to an extreme accuracy in the RF frequency measurement, a change of ∼0.3 mm of the 27 km central orbit can be detected. Because LEP is a strong focusing machine, this small change translates into a relatively large shift in momentum (the "momentum compaction factor", expressing the inverse of this relationship, is $\sim 2\ 10^{-4}$). So any cause of distortion of the orbit may have an effect. The terrestrial tides were such a source, on a daily basis. The change in the weight of Lake of Geneva, depending on the water level, was another one on a seasonal basis. A last effect to be corrected for was the change of magnetization of LEP magnets induced by electric "courants vagabonds" when a TGV is passing by.

Let us come now to the main issue which concerns α. The extreme precision of measurement of the fine structure constant at the static limit is of no use for electroweak tests: one needs to know its evolution up to the weak scale due to the effect of loops in the photon propagator. A precise value is needed as shown by Figure 2[8]. The effect of leptons is calculable. The role of the top is negligible because of its decoupling. The problem comes from the light quarks and the unsufficient knowledge of their masses. A subtracted dispersion relation and the optical theorem allow to relate their effect to the knowledge of R(s), the ratio of hadronic production to the point−like cross section in low energy e^+-e^- collisions. At large s one can use a perturbative expansion, but at low s one is bound to use data.

Since the evaluations performed in 1995, two new facts have occured: first, new data came from VEPP in Novosibirsk, from low energy to 1.4 GeV, and from BES in Beijing[9] who recently released the results for 85 points taken between 2 and 5 GeV (Figure 3). Second, new analyses relying somewhat more on theory appeared [10, 11]. Recent analyses [12, 8] discuss the validity of such approaches and incorporate VEPP and part of BES results. A reduction of the uncertainty on $\alpha(M_Z)^{-1}$ seems to be agreed upon. One will see later the effect of this improvement on the indirect Higgs mass determination. We will also see that, to take full benefit of future potential accurate measurements at a LC, one will have to measure the hadronic cross−section to an accuracy of 1% from threshold to the Υ region.

Besides the three main entries, one needs also, at loop level, the value of the mass of the top. Before 1994 this mass was actually derived indirectly from LEP accurate measurements on the Z^0 (Figure 4 from [13]).

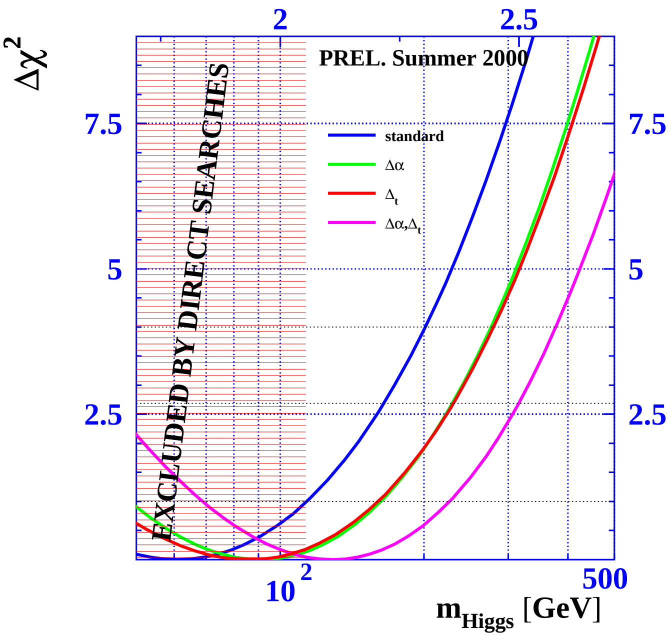

Figure 2: The potential impact of a change in $\alpha(M_Z)$ and m_{top} by one sigma on the indirect Higgs mass determination.

After the Tevatron discovery of the top one got the possibility to input it from outside.

The present uncertainty on the top mass from the direct measurement is ±5.1 GeV. It is $+13,-10$ GeV from the indirect one, resulting from accurate measurements at lower energy. There are clear motivations to improve this accuracy:

1/ the precision tests of the SM need it.
Here one should remember that:
$\Delta m_W/\Delta m_t = 0.006$ (this means that 5 GeV on Δm_t imply 30 MeV on Δm_W).
and $\Delta \sin^2\theta_{eff}/\Delta m_t = 0.00003$/GeV.

2/ in Supersymmetry, the upper limit on the lighest Higgs boson mass changes with m_t according to $\Delta m_h/\Delta m_t \sim 1$.

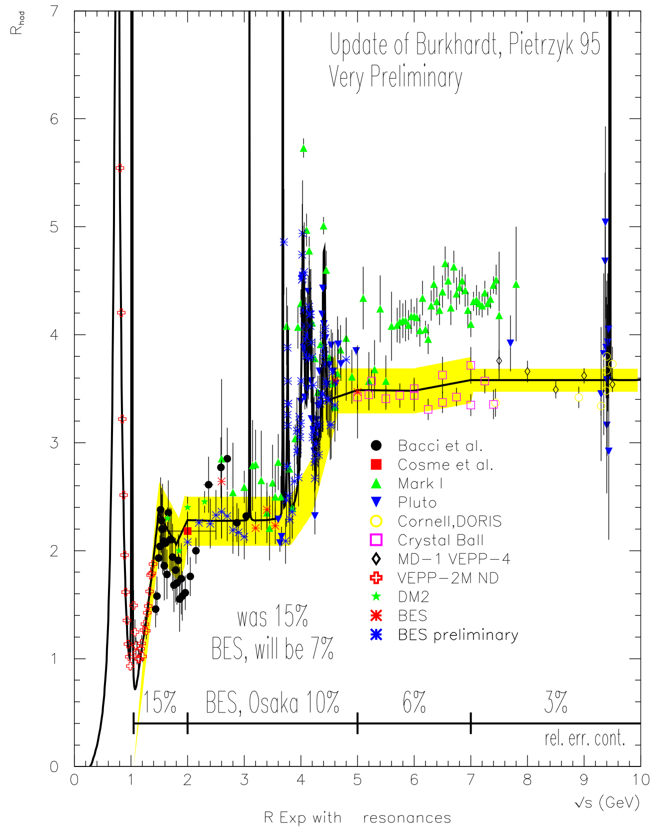

Figure 3: The present status of low energy measurements of the e^+ e^- hadronic cross-section.

3/ a future theory of flavour, still to come, may require the best possible accuracy on m_t.

The Tevatron Run II will give $\Delta m_t \sim 2.5$ GeV. The LHC will improve it to $\sim$1.5 GeV, while a LC will reach $\sim$0.15 GeV. We will see that this last value is needed to match the potential reach of a LC Z^0 factory on $\sin^2\theta_{eff}$.

5 A few outstanding LEP/SLC electroweak observables

We now describe a short selection of important observables. We recall that the comparison of the values of $\sin^2\theta_{eff}$ extracted from different ob-

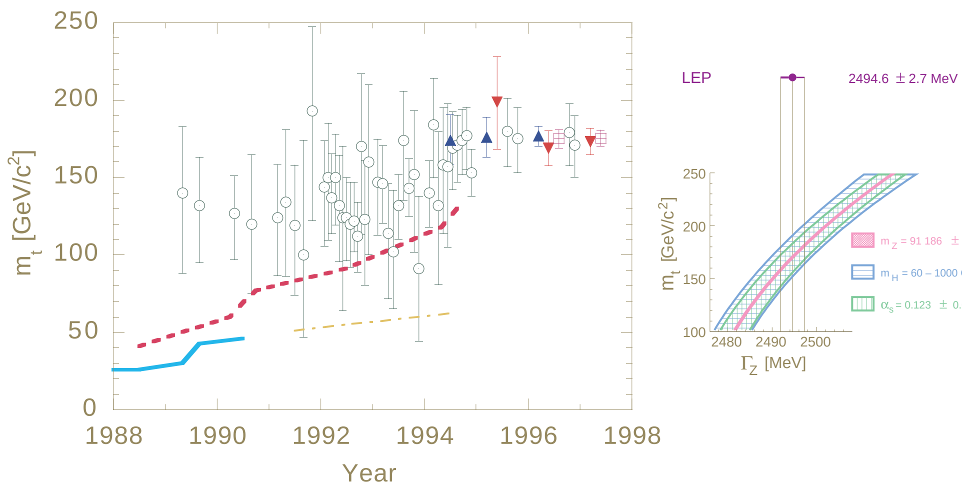

Figure 4: Evolution of our knowledge of the top mass along the years: indirect (open circles) and direct (triangles) determinations.

servables is a good test of the coherence of the results, while their accuracy measures the quality of the observable. The numerical results come from [14, 15]

This quality can be visualized from Figure 5: a good observable is one which is well measured experimentally (narrow vertical band), well predicted theoretically (narrow oblique band, which means a small dependence on the uncertainties of the entries) and has a strong dependence on the Higgs mass, whose indirect determination is our main goal (this implies that the band is far from vertical). Another way is to look at Figure 6 and Figure 7 [16]. They show, in the plane of the variables S and T of [17] (related to the variables ϵ_3 and ϵ_1 of [18]), the situation before (big ellipsa) and after LEP/SLC (small dot of Figure 6, magnified in Figure 7). One sees that the most useful informations come from $\sin^2\theta_{eff}$, itself derived from various Z pole measurements (Figure 8), from the Z width and the W mass.

Figure 9, Figure 10 and Figure 11 illustrate the accuracy obtained on the Z width (one per mille), on the universality of the leptonic widths, on the hadronic to leptonic ratio, a key variable for the measurement of the strong coupling. Figure 12 summarizes all the results which have been presented to Osaka conference. An interesting quantity derived from the line shape is the number of neutrino species, obtained from the Z invisible width:

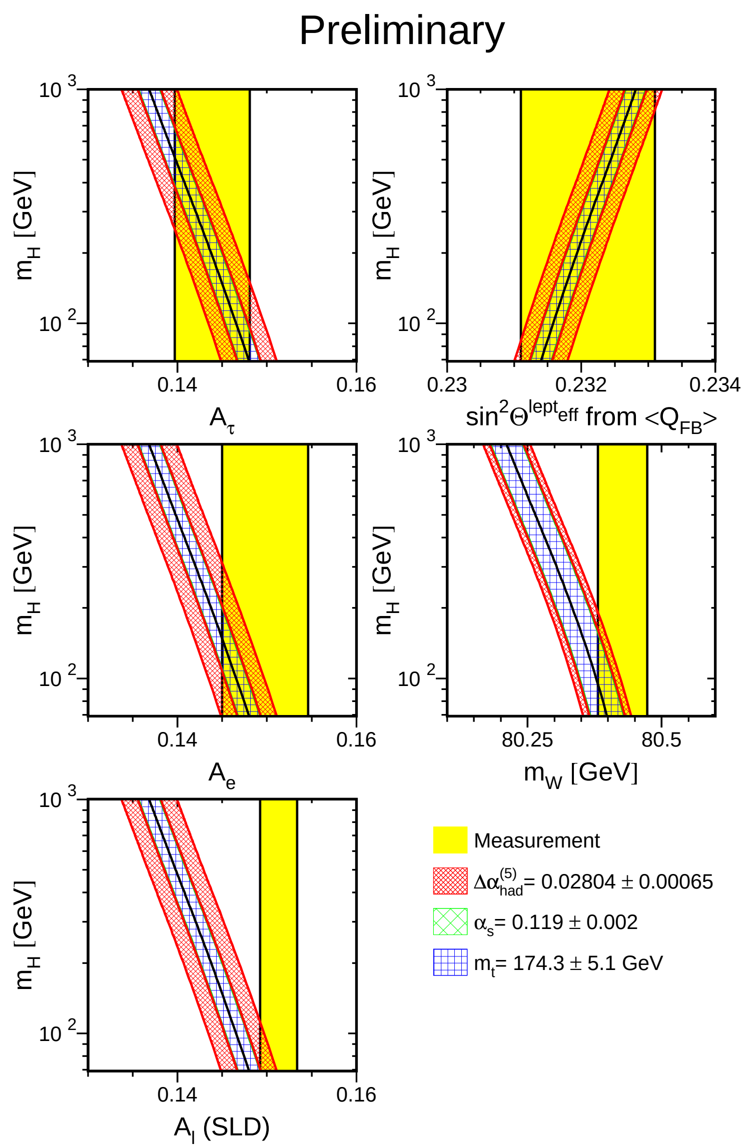

Figure 5: Sensitivity of different observables to the Higgs mass.

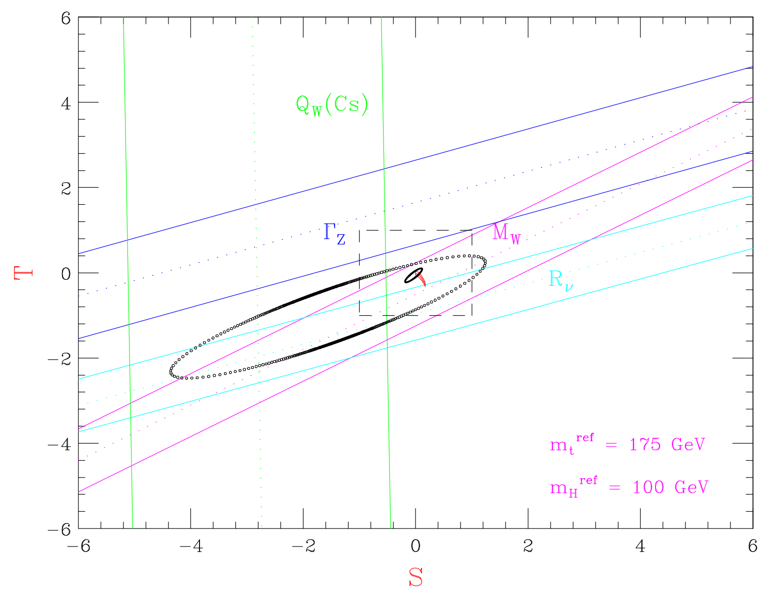

Figure 6: The impact of LEP/SLC: before and after.

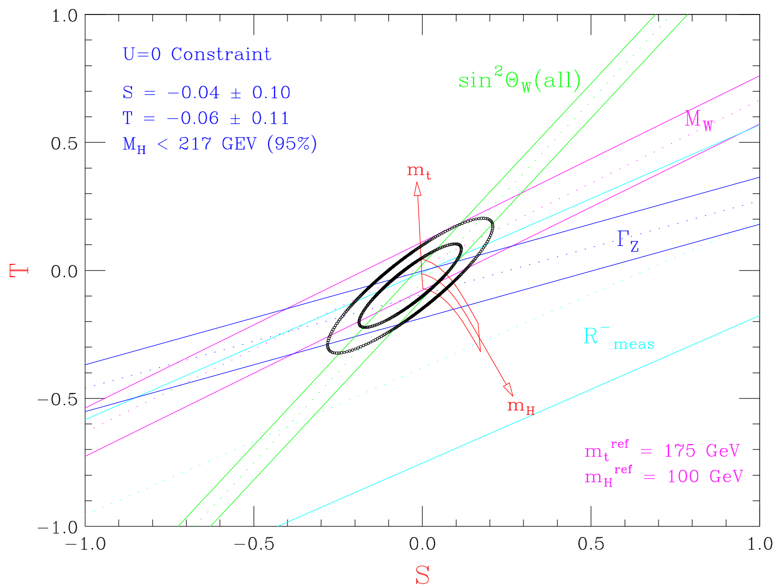

Figure 7: Contribution of various observables to the overall information in the S−T plane.

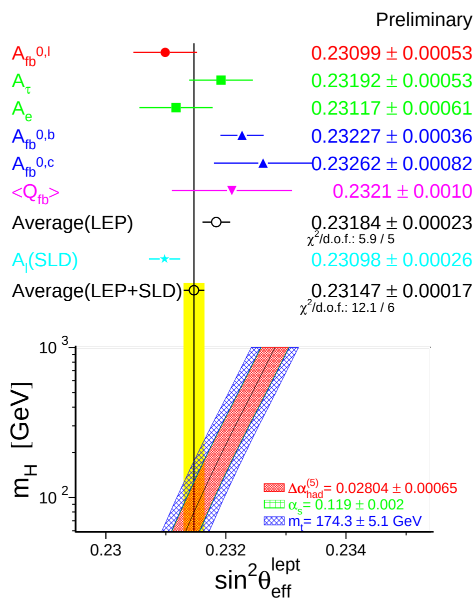

Figure 8: All $\sin^2\theta$ measurements.

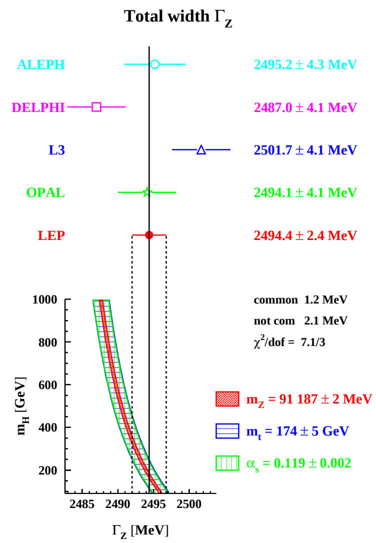

Figure 9: The Z width measurement.

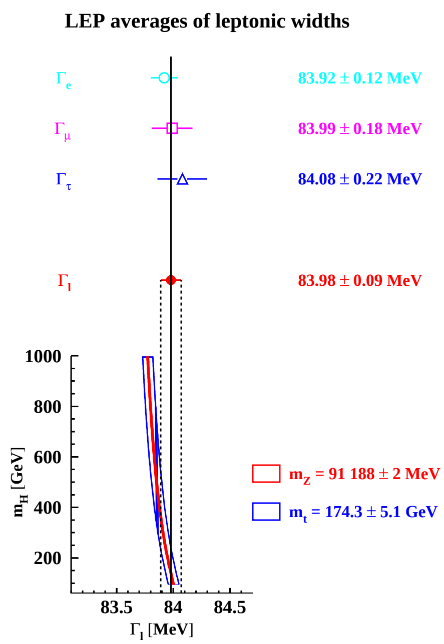

Figure 10: The Z leptonic width measurements.

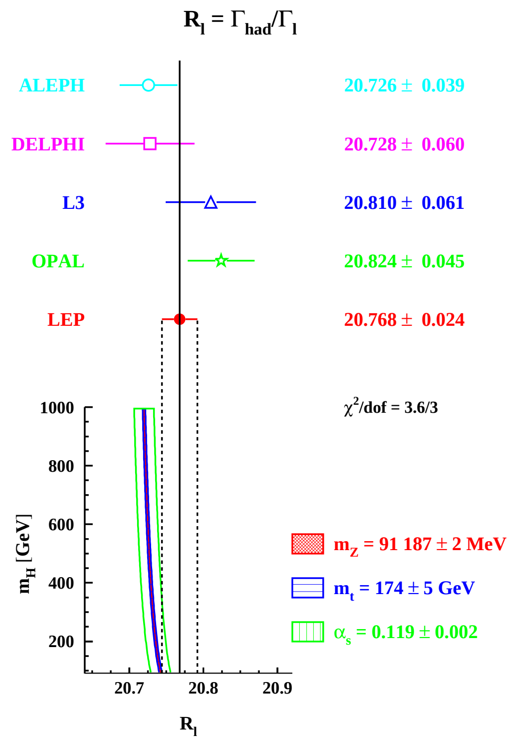

Figure 11: The Z R_l measurement.

$$\Gamma_{inv}/\Gamma_l = (\Gamma_Z - \Gamma_{had} - \Gamma_l)/\Gamma_l.$$

One finds $N_\nu = 2.9835 \pm 0.0083$. This downward pull compared to 3 is due to the upward pull of Γ_{had}. For speculations on its possible signification see [19].

Moving now to the asymmetries measured on the Z, one can gauge the quality of each one by examining four criteria: available statistics, mastery of theory (in particular of radiative corrections), systematics of the measurement and sensitivity to $\sin^2\theta_{eff}$.

A single one merits three stars in all respects: the polarized A_{LR} asymmetry which requires the polarization of one beam:

$$A_{LR} = (\sigma_L - \sigma_R)/(\sigma_L + \sigma_R) \times 1/P_e,$$

where P_e is the beam polarization.

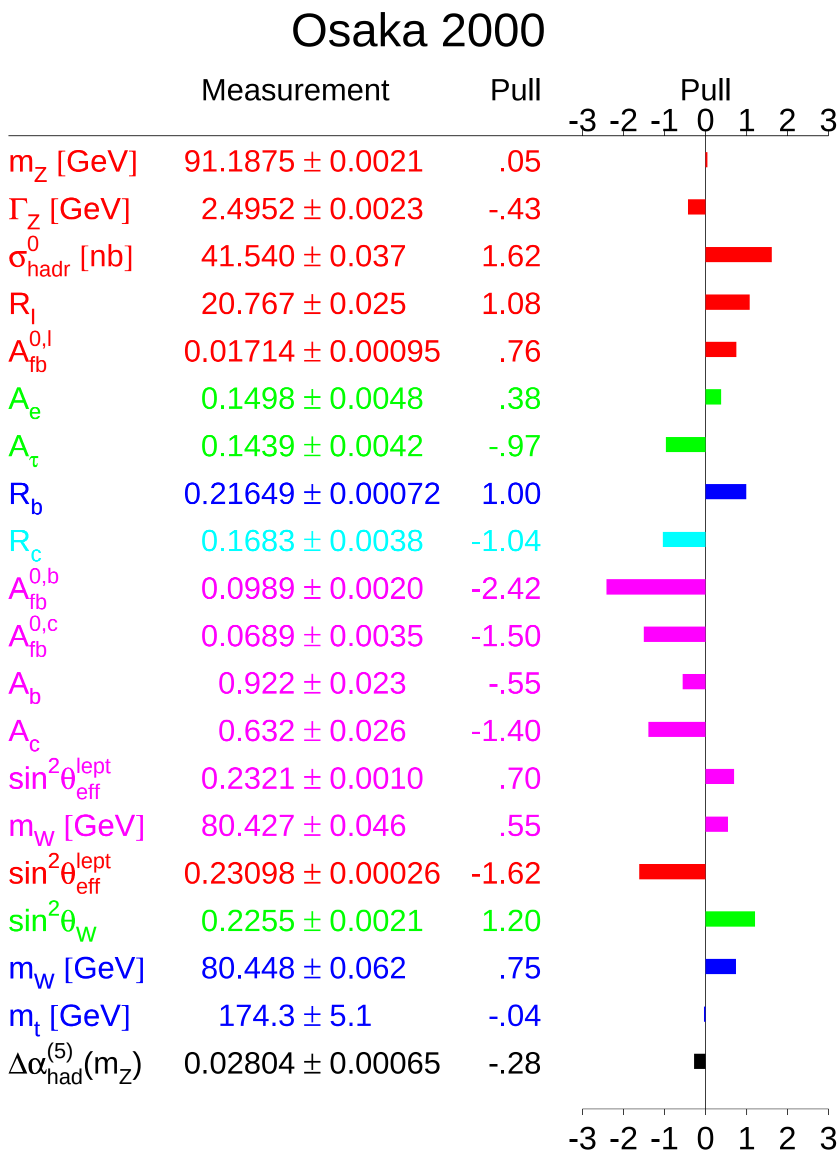

Figure 12: Pulls of all electroweak measurements.

Under the assumption of universality, this is equivalent to A_l. Only tiny correcting terms, due to photon exchange and its interference and well under control, have to be considered. All other effects practically cancel. This observable is a unique laboratory for the non-QED part of electroweak theory.

The experimental measurement (SLD [15]), which is a priori a mere counting experiment, actually needs great care [20].

$$A_{LR} = A_m/\bar{P}_e + 1/\bar{P}_e \,[f_b(A_m - A_b) - A_{lum} + A_m^2\, A_{pol} \\ - E_{cm}\, A_E\, \sigma'(E_{CM})/\sigma(E_{CM}) - A_\epsilon + \bar{P}_e\, P_\rho]$$

A_m is the measurement: $(N_L - N_R)/(N_L + N_R)$. $\bar{P}_e$ is the mean value of the polarization, corrected for small changes between the point where it is measured and the interaction point. f_b is the residual background fraction. A_i are various possible residual asymmetries between the two polarizations, concerning background, luminosity, level of polarization, CM energy, detector acceptance and efficiency. P_ρ is a potential spurious amount of polarization of the positrons, which should be unpolarized: it was directly measured and found to be -0.02 ± 0.07 %.

The dominant systematics came from the polarization measurement (0.40% relative uncertainty), more precisely from the uncertainty on the analysing power of their calorimetry detecting the recoiling particles in backward Compton scattering of a laser on the electron beam. The next uncertainty in magnitude was due to the electroweak interference correction caused by the uncertainty on the SLC energy scale, in spite of the fact that the LEP M_Z value was used to calibrate it. In total, they measure the asymmetry to 0.64 % relative uncertainty. This resulted in the most precise single measurement of $\sin^2\theta_{eff}$.

At SLAC the electron beam polarization was flipped at each bunch by reversing the circularity of the laser impinging on the AsGa photocathode, and the positron beam was unpolarized. There were two types of crossings giving respectively (A_{LR} is σ_L/σ_U)

$$\sigma_1 = \sigma_U - P\sigma_L$$
$$\sigma_2 = \sigma_U + P\sigma_L$$

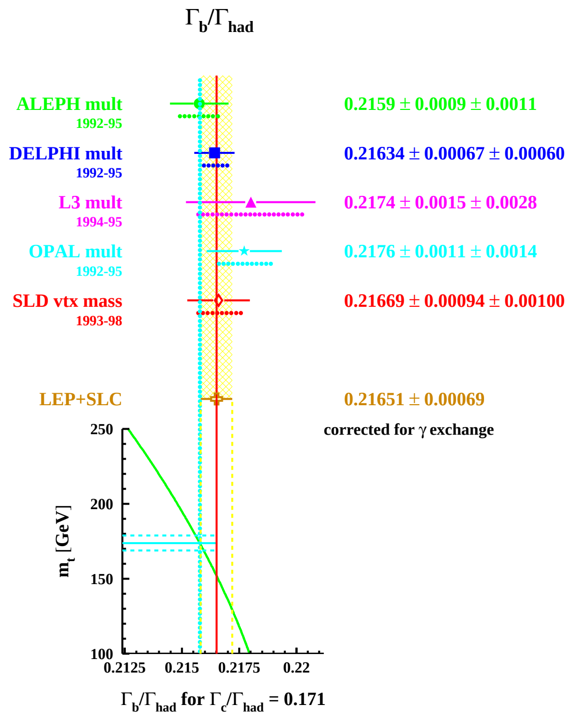

Figure 13: All R_b measurements.

So the polarization has to be measured externally. On the contrary, in a machine where the two beams are longitudinally polarized, as LEP would have been if the polarization program had come to reality, and where one acts on the polarization of individual bunches, one can get four types of crossings: two of them are equivalent to the SLC scheme and give A_{LR}, and two others, with both bunches unpolarized and both bunches polarized, respectively, provide the value of the polarization by Z counting: in first approximation, the polarization measurement is thus a matter of statistics. This ingenious scheme may be the key of future improvements in electroweak measurements at LC.

In our Michelin guide of asymmetries the next in quality are front−back (FB) asymmetries involving heavy quarks, especially beauty. Any electroweak measurement involving beauty is potentially rewarding because of its belonging to the third family. The measurement of R_b, the relative width of hadronic decay into the b flavour, was another adventure at LEP. Finally, this observable agrees with the SM (Figure 13), one sigma above the expec-

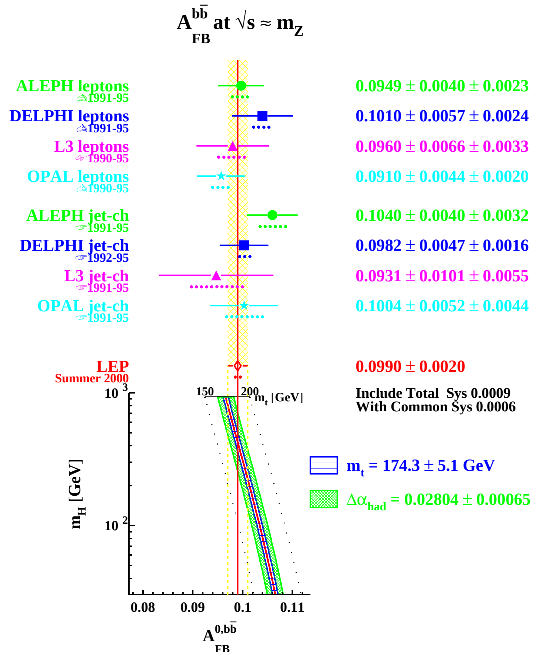

Figure 14: All measurements of LEP A^b_{FB}.

tation. The statistical and the systematic uncertainties are about the same. I will not say more on it.

Let us come back to asymmetries. LEP has measured FB asymmetries A^f_{FB} (Figure 14 for beauty, note that the uncertainty is dominated by statistics), providing the product $A^e A^f$, while SLD, exploiting again the polarization, could measure the FB polarized asymmetries $\tilde{A}^f_{FB}$, which give $P_e A^f$. This corresponds to a large gain in statistics in favour of $\tilde{A}^f_{FB}$: $(P_e/A^e)^2$. The results can be summarized by Figure 15 in which the vertical band is A^l from SLD and LEP, the horizontal one is A^b from SLD and the oblique is $A^e A^b$ from LEP. One sees that the set of measurements is not in good agreement with the SM. $\sin^2\theta_{eff}$ extracted from A^b_{FB} is ∼3 sigma away from the given by A_{LR}.

One attitude is to stress this discrepancy between the leptonic sector and the hadronic sector, which indeed, when they are treated separately, give quite different predictions for the Higgs mass. Pushing to an extreme, one could defend that the former, combined to the present direct limit on the Higgs mass, excludes the SM at 95% CL, while the latter favours a rather heavy Higgs. I refer you to [21] for speculations on what this could mean

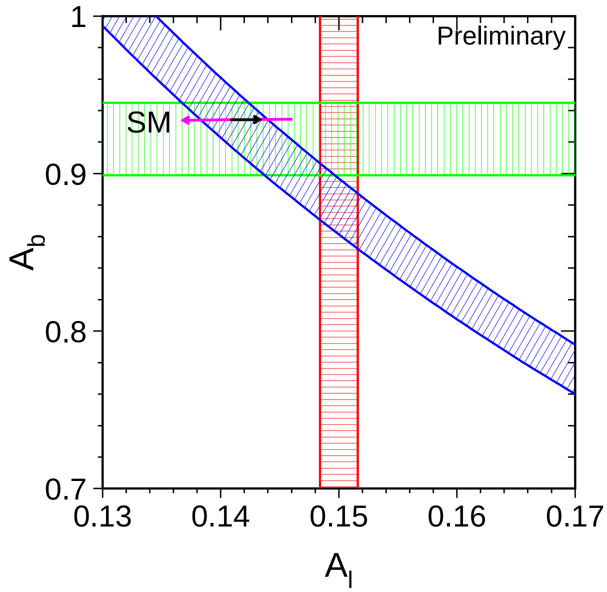

Figure 15: World results on A^b versus A^l.

physically.

One can also consider that this discrepancy is a normal accident, among so many measurements, and one produces the usual χ^2 curve favouring, in a strict SM interpretation, a light Higgs boson (Figure 16), lighter than ∼200 GeV at 95 % CL.

I will not go further in the detail of these measurements involving heavy quarks. The messages are that they are quite rewarding and that, experimentally, they rest on two key elements: the quality of the microvertexing, providing b and c tagging, and the amount of statistics accumulated, which also governs the amount of systematics, because one usually measures the latter from the data.

Microvertexing is performed at LEP with silicon microstrip detectors (2 or 3 layers of detectors, part of it double-sided, with a resolution of ∼10 microns). At SLD, 3D CCD-based pixel vertex detectors were used. The small and stable beam spot of SLC, as well as the smaller distance of approach (2.5 cm against 6 cm for LEP), were strong advantages for SLD

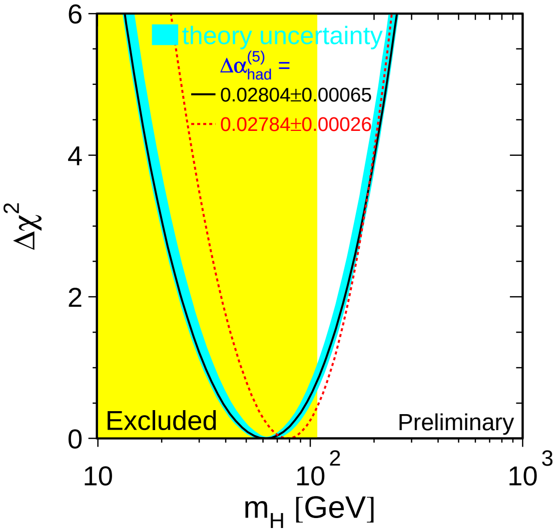

Figure 16: Prediction of the Higgs mass from all electroweak measurements.

(Figure 17). Needless to say, a high quality microvertexing is crucial for future programs: pixel detectors, giving 3D information, should be preferred. Due to the luminosities considered and to the related backgrounds, these detectors will have to be radiation-hard, a problem which was basically inexistent at LEP.

The last measurement contributing (slightly up to now) to the overall electroweak information is the W mass. Figure 18 summarizes it. One sees that the direct and indirect determinations are in fair agreement. LEP may finally reach an accuracy of ∼30 MeV. The Tevatron in Run II may get to ±25 MeV, LHC to ±15 MeV. HERA, from the propagators, confirms the value of the mass, but with 4 to 5 GeV uncertainty.

One can summarize the situation for instance by Figure 19 [22], in the epsilon plane, and by the Higgs mass prediction, about which one has to remember the caveat quoted previously, which can be visualised in Figure 20. Figure 21 [8] shows the change in the χ^2 curve when one takes into account BESS results.

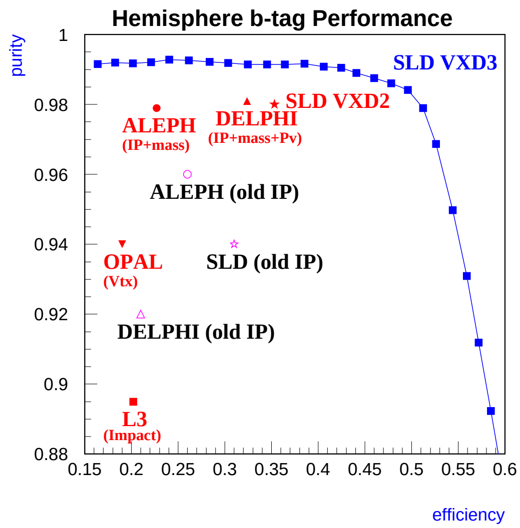

Figure 17: B-tag performances of the various experiments.

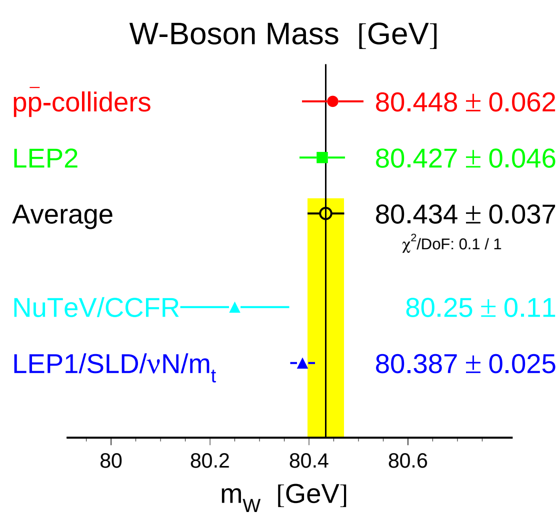

Figure 18: All measurements of the W mass.

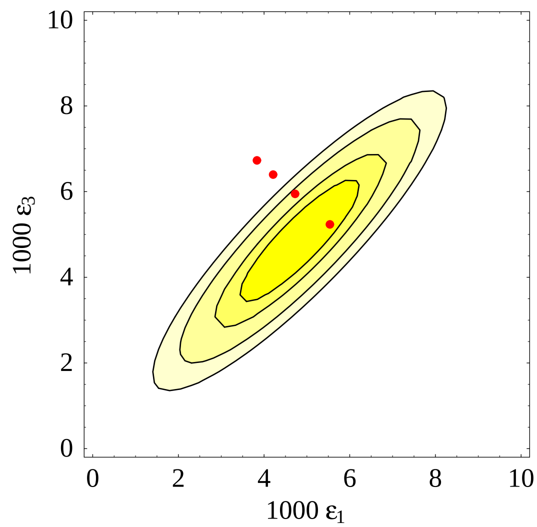

Figure 19: The status of accurate measurements in the epsilon plane.

6 How can one do better?

The idea would be to exploit a Z factory, with more luminosity than LEP, and the tools needed to make a breakthrough in the systematics as well.

A circular machine like LEP could in principle raise its luminosity by going to a large number of bunches: but this scheme is rapidly cumbersome because one must avoid bunch crossings outside of the experiments, and the most radical solution would be to have two rings. The Blondel scheme could then be used, but one has also to manage to rotate the polarization from transverse to longitudinal. See [23] for details.

It is thus admitted that such a machine should actually be one step of a Linear Collider, on the way to higher energies. This is now considered under the name of GigaZ option [24, 25]. With L=5 10^{33} cm$^{-2}s^{-1}$ one would get 10^9 hadronic Z in few months. Prospective studies are made assuming an electron polarization of 80 %, a positron polarization of 60 %: these numbers give an effective polarization $(P^+ + P^-)/(1 + P^+ P^-)$ of 95%. To measure the beam energy one uses a spectrometer, calibrated to the Z mass.

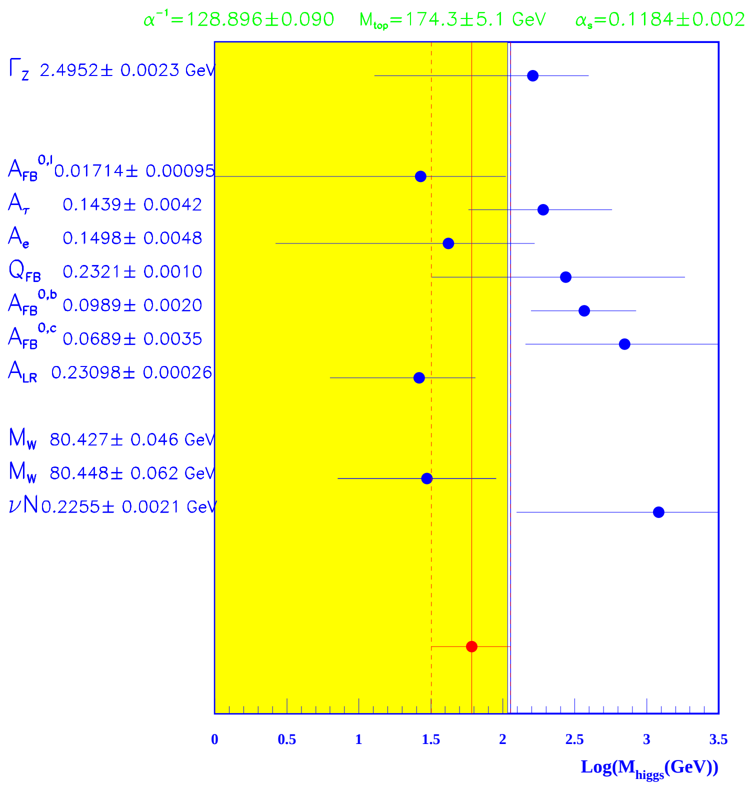

Figure 20: The dispersion of the predicted Higgs mass from the various observables.

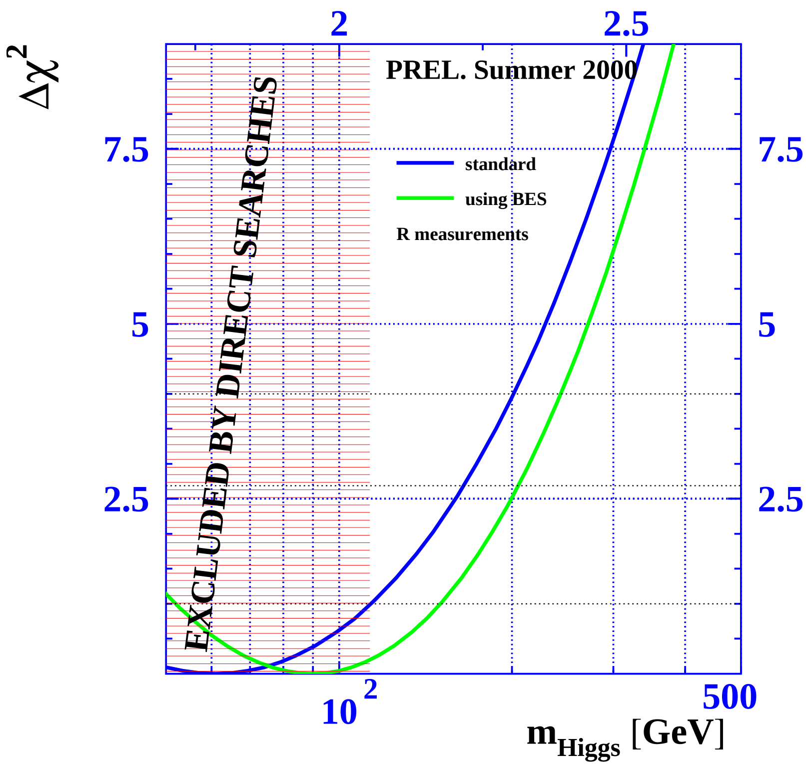

Figure 21: The effect of the inclusion of Bess results.

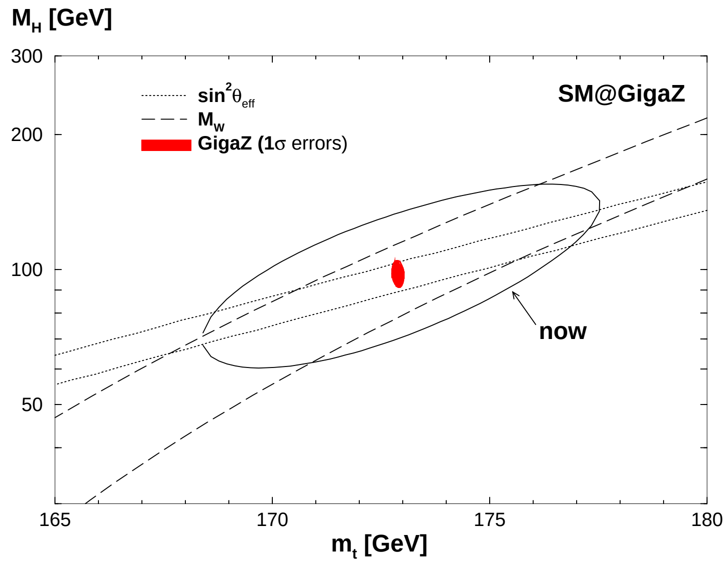

Figure 22: Prediction for M_H from a GigaZ.

Detailed studies from [24] show the following:

1/ While N_ν, the number of neutrinos, cannot be improved, one would gain a factor two in the accuracy on α_s (reaching ± 0.0016) and a factor ~ 8 on $\Delta\rho$ (reaching ± 0.0005).

2/ one could gain a factor ~ 5 on the accuracy on R_b. The measurement could be performed with an efficiency of ~ 30 % and a purity of ~ 98 %. The increased statistics would allow to have a much better knowledge of ingredients required by the measurement, like gluon splitting, etc..

3/ By implementing a extension of the Blondel scheme, one could reach an accuracy of 10^{-4} on A_{LR}, which means 0.000013 on $\sin^2\theta_{eff}$. However, to exploit it, one would need to know the top mass to ~ 200 MeV and have measured the $e^+ - e^-$ hadronic cross section to ~ 1 % up to the Υ region. Then one would predict the Higgs mass with an accuracy of 5 % (Figure 22).

The overall improvement is shown by Figure 23, in the plane A^b versus A^l.

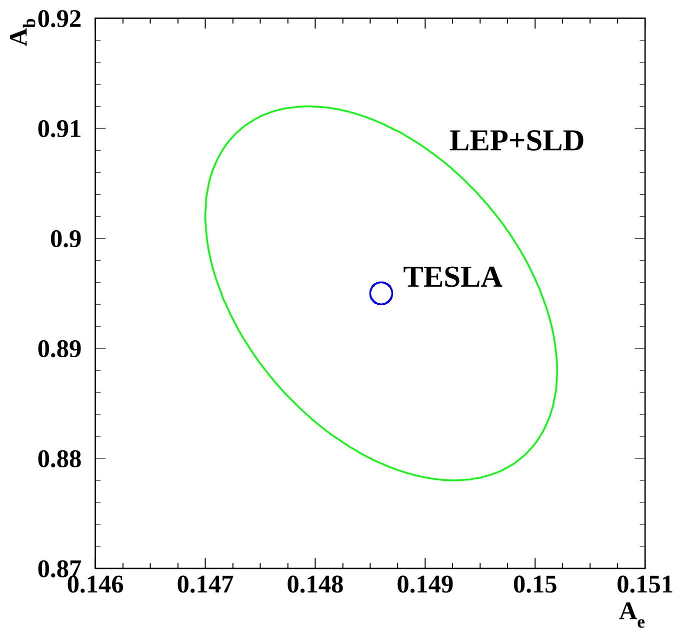

Figure 23: What a GigaZ can bring in the A^b versus A^l plane.

All that assumes however that the positron beam is polarized. The reader will find in [26] a review of the potential methods which could provide such a polarization:

1/ use of an helical undulator (150 GeV e^- in a 150 m long undulator); the circularly polarized photons are directed to a thin conversion target.

2/ Compton backscatter of circularly polarized photons by unpolarized HE electrons; the gamma are then directed to a thin conversion target.

3/ modification of the conventional scheme where one uses highly polarized incident electrons: then the HE end of the gamma spectrum and of the resulting e^+ is polarized.

4/ direct polarization of an unpolarized e^+ beam by Compton scattering; this could be combined with laser cooling in a storage or damping ring.

As an exemple of the power of such accurate measurements, we can quote [27] : in case of a conspiracy between new physics (here a new 5 TeV quark, changing the variable T) and a relatively heavy Higgs boson (here 500 GeV), which overall mimics the light Higgs situation, an increase of accuracy in the S−T plane allows to decipher the problem and resolve the new physics.

7 Electroweak symmetry breaking

The second part of the note will be devoted to the crucial problem of EWSB.

We have seen in the first part that the SM is numerically in agreement with the data to the per mille level or better. These accurate data also predict a light Higgs boson, lighter than $\sim$200 GeV at 95 % CL. A clear question is whether this is the truth or the result of a conspiration. Furthermore there are many reasons, that I will not repeat here, which push to go beyond the SM.

To do so, the two classical avenues are to add either new forces and/or constituents, like in Technicolor, or to add more symmetry, like in Supersymmetry (SUSY). The former breaks EWS by condensates of new fermions and does not contain elementary Higgs scalars. A priori it is not favoured by accurate measurements, but we will come back to that point. The latter, on the contrary, justifies the existence of elementary scalars and predicts sharply a feature of the Higgs sector: the existence of one light boson at least. It also predicts a spectrum of superpartners, however less accurately as far as masses are concerned. It agrees with present data as perfectly as the SM does.

A third avenue appeared more recently [28]: the possible existence of extra−dimensions at energy scales much lower than expected, may be down to the TeV scale. I will not discuss here the "bien−fondé" of such assumptions, but it is certainly interesting and motivating to study whether they have testable consequences.

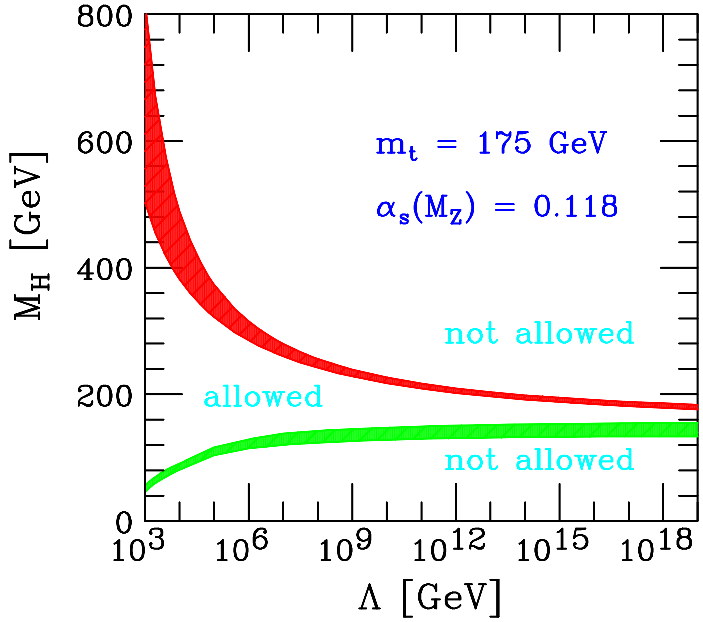

Figure 24: The limits on the SM higgs mass.

It is worthwhile to repeat that, whatever be the fashionable theories, the first duty of an experimentalist is to keep his eyes wide open and to explore systematically all accessible channels.

The reader is certainly familiar with the SM Higgs digest, summarized by Figure 24 [29]. The main message for phenomenology is that the Higgs boson is coupled to the heaviest kinematically accessible objects.

In SUSY there is a dramatic difference: the self-coupling, which was unknown in the SM, is now related to g and g' and perfectly known. At tree level the Higgs sector is described by two parameters: tgβ, the ratio of the vev of the two Higgs doublets, and one mass, for instance the mass of the pseudoscalar boson, m_A. The tree level prediction of a boson h^0 lighter than M_Z is violated by radiative corrections involving the top as dominant effect. But since one knows semi−accurately the top mass, the bulk of the correction is known as well. The exact upper limit of the h^0 mass depends on tgβ and on the details of the stop sector: in the MSSM, it is known since ∼5 years to be ∼130 GeV, in the most unfavourable case (Figure 25 from [30]). If m_A is large, say larger than ∼100 GeV, h^0 is SM−like. If m_A is very large, one can conceive a limiting case, the "heavy MSSM", where, apart from h^0,

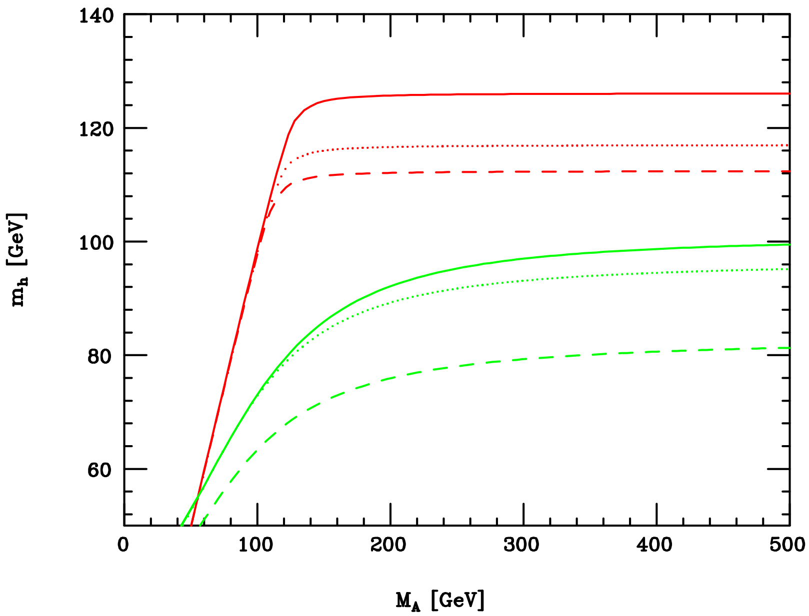

Figure 25: The upper limit on the MSSM h^0. The three lower curves are for small tgβ, the three upper for large tgβ. In each family the three curves, from bottom to top, correspond to an increasing mixing in the stop sector.

all other bosons, degenerate with A^0, and the superpartners are heavy.

The problem of phases of the MSSM parameters, ignored for many years, was recently studied [31, 32]. Although it may have influences on the phenomenology, the consequences should be minor: this is for instance the case at an electron machine if one has enough CM energy to "catch" the next−to−lightest boson when the lightest one falls in a domain of the parameters where it has a low detectability. By leaving the MSSM and for instance by adding singlets to the Higgs sector, one can raise somewhat the upper bound quoted in the MSSM frame, but not beyond ∼180 GeV.

If on the contrary one chooses the composite way, the most general possibility, derived from the Goldstone Boson Equivalence Theorem [33], is to consider new strong interactions between the Intermediate Vector Bosons, more exactly between their longitudinal components. To reveal it one can study the production of vector boson pairs, in e^+-e^- or $q-\bar{q}$ scattering: this is the high energy analogue of the study of the time−like pion form factor. Another way is to study boson−boson scattering, where the bosons are emitted from incident $e^\pm$ or quarks: this is the HE analogue of pion−pion scattering. Such interactions may be resonant or not. In the non−resonant case, one is still guided by Low Energy Theorems (LET), as in the pion−pion case.

Technicolor [34] is probably the most studied theory of dynamical EWSB. It stems from the QCD analogy of spontaneous chiral flavour symmetry breaking by quark condensates: these also break electroweak symmetry, but the Z mass is predicted to be 60 MeV! The idea is to emulate this mechanism at a much higher scale: one assumes a new asymptotically free gauge interaction called Technicolor, with a gauge group G_{TC}, and a coupling α_{TC}, which becomes strong at a few hundred GeV. N_D is the number of doublets of L and R Technifermions. Their condensates form, and break the chiral flavour symmetry, giving masses to the Z and the W.

However the quarks and leptons are still massless. One has to go to Extended Technicolor (ETC): quarks, leptons and TF are put into the same representation of a new gauge group, with Λ_{ETC} much larger than Λ_{TC}.

ETC has still problems with the rate of flavour changing neutral currents and its confrontation to the accurate measurements. The reason is that it is just a scaled-up version of QCD: asymptotic freedom sets in too fast.

One has therefore to invent "Walking Technicolor" (WTC), a version of the theory in which the evolution of couplings is very slow. The problems with accurate measurements disappear because in WTC one cannot compute the observables reliably! This is not a strong point of the theory, but it saves it temporarily.

Practically, the search for Technicolor is quite analogous to Higgs search. One looks for Techni-vector mesons (ρ_T, ω_T) produced in e^+-e^- or $q-\bar{q}$ collisions. A Technirho can decay into Technipion pairs, W_L-Technipion or W_L pairs. A neutral Technipion (π_T^0) decays into $b-\bar{b}$, a charged one into $b-\bar{c}$.

Here the message to the experimentalists is that they should explore all accessible channels, optimize the heavy flavour tagging devices and procedures, in particular with the aim of separating b from c. Furthermore one should watch in priority the V_L component of vector bosons and, when possible, enhance its contribution by appropriate projections.

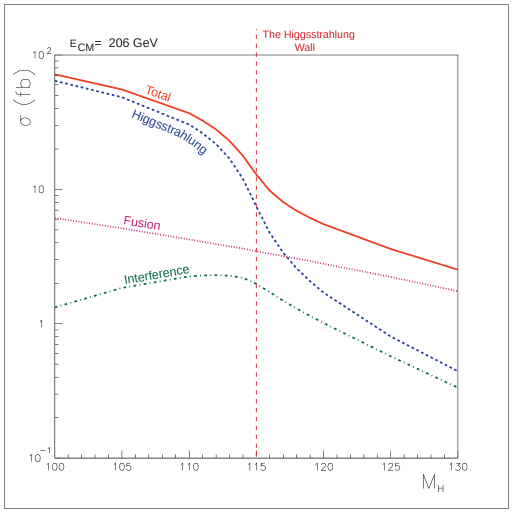

Figure 26: The various components of the H ν ν channel near the "kinematical limit"(from E.Gross et al).

8 Searches at LEP

The Higgs boson searches at LEP have been described in such detail [35] that I will only summarize the situation. A SM or SM-like boson, like h^0 under the conditions given above, is produced in association with a Z by the Higgsstrahlung (HS) process. The HS hits a kinematical barrier when sqrt(s) equals M_Z + M_H: tails beyond this barrier reflect the tail of the Z Breit-Wigner. At and beyond the kinenatic limit, the fusion process and its interference with HS can be used in the H $\nu\nu$ channel (Figure 26 [36]) but the cross-section is tiny. So LEP is a threshold machine and must be run at the highest possible energy to maximize the chances of discovery: such an exploitation pushes up the kinematic limit, allows the Higgs production cross-section to approach it maximal value, and in case of a possible signal, gives a chance to raise the energy in order to check its reality.

Unfortunately LEP has now reached its maximum energy, ∼206 GeV allowed by its 285 SC RF cavities, already run beyond their design accelerating voltage. One could have gone ∼15 GeV higher in CM energy by filling the equipped zones with cavities, reaching an amount of ∼380 of them overall, but this option has not been retained.

Given the three generic channels of Z decay, the Higgs boson is searched for in all hadronic mode (4 or 5 jets, two from beauty), missing energy mode (the Z into neutrinos) and dilepton−dijet (the jets being b-jets from the Higgs boson).

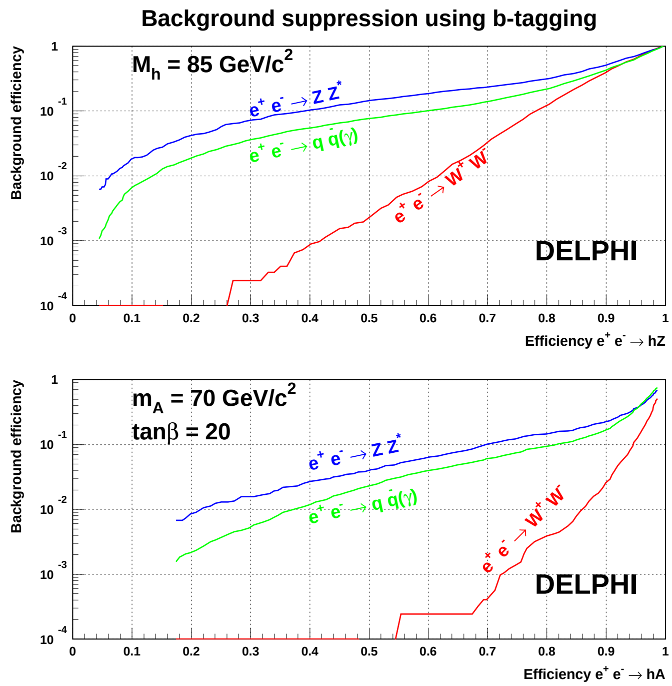

Figure 27: The rejection due to b-tag at LEP2 .

The last one is the cleanest, but has the smallest branching ratio.

The missing energy channel uses rescaling of the missing mass to the Z mass. A perverse background is due to double radiative return to the Z in a quasi-symmetric way. This produces a Z roughly at rest and the procedure of rescaling boosts its mass to a value close to the kinematic limit. The main weapon against this is a cut in acoplanarity, because such a Z, with both photons in the beam pipe, is roughly coplanar. For a high mass Higgs, one can also require that the measured hadronic mass is neatly above what one expects for a Z. With few other precautions this channel can be made rather background free for a high mass search.

The four jet channels is more difficult. WW, ZZ and QCD all contribute to the background, up to the highest masses that even WW and ZZ can populate through mis-pairing of jets. A very strong rejection of WW is obtained through b-tagging (Figure 27), the limit coming from our unability to distinguish totally c from b jets, and from some tiny content of beauty in WW events.

Figure 28 shows the evolution of the background in 4-jet with the severity of the cuts, hence for a decreasing efficiency to the signal. As ex-

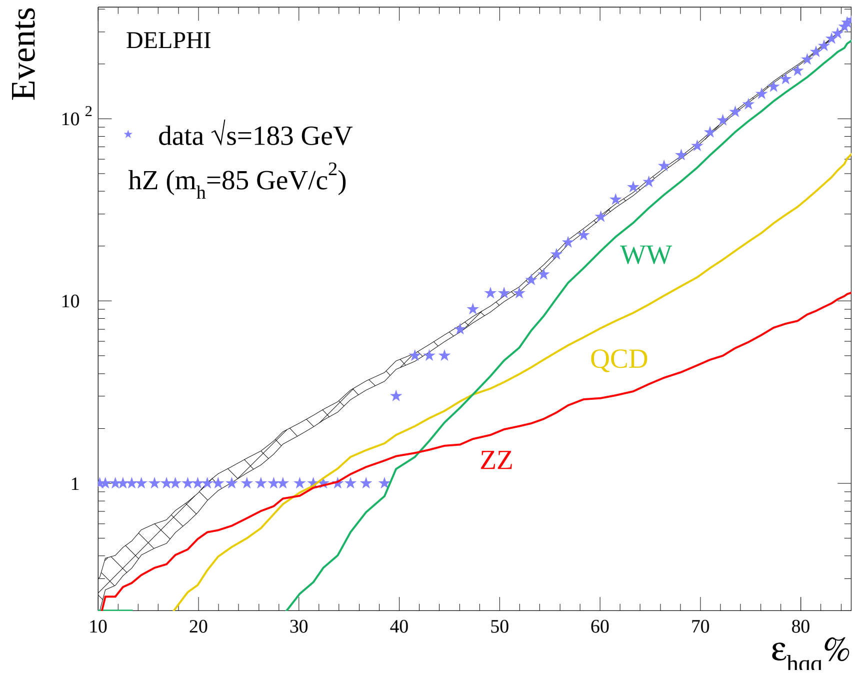

Figure 28: The evolution of the data and of various backgrounds when the severity of the cuts is increased.

pected, the ZZ background is the most resistant, in particular because 44 % of ZZ have one $b\bar{b}$ at least and 74% have $b\bar{b}$ or $c\bar{c}$. Besides the resolution of the mass determination procedure, tails towards high masses are due to mis-pairings of jets and to initial state radiation: the latter, being generally unnoticed, leads to rescale to an energy higher than the one at which the ZZ event occured, and thus to inflate masses. If the ISR photon is detected and incorporated to the final state, one similarly gets masses higher than one should.

The traditional statement is that " all these effects are present in the simulation": indeed a tremendous effort has been put into the understanding and modelling of these various effects. But when one deals with the few last events, after having achieved rejection factors of up to a few hundred, one may fear that reality and simulation have gone apart, especially close to the kinematic limit.

Having excluded lower masses, up to 112.3 GeV, LEP search is now focusing on the highest accessible one, at the kinematical limit of the Higgsstrahlung, namely ∼114/115 GeV for a CM energy of ∼206 GeV. For a

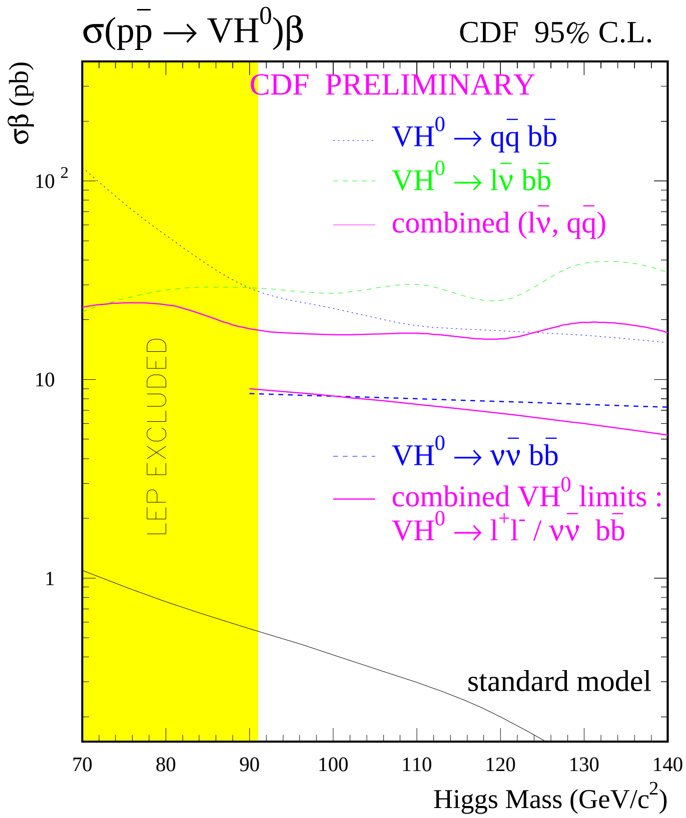

Figure 29: Limits on the SM Higgs from CDF Run I.

mass of 115 GeV the total Higgs cross-section is ∼50 fb only, compared to 1 picobarn for ZZ. Some all-hadronic events, appearing at such masses, have generated a lot of turmoil. Being for the moment unable to conclude on their real significance, since raising the energy is impossible, I can only refer you to your daily newspaper for more details.

Among all searches for non-conventional Higgs bosons [37], let us quote the invisible one. There may be several reasons why it could be so. The boson could decay into neutralinos, although this is almost excluded for the MSSM with universality. One may also invoke TeV gravity, Higgs decay into majorons [38] or the SM with a singlet. For LEP, detecting such a boson is not much of a problem. The main background is ZZ, with one Z decaying in neutrinos, and the possibility to reduce it through b-tagging is lost. ADLO limit is presently 113.7 GeV.

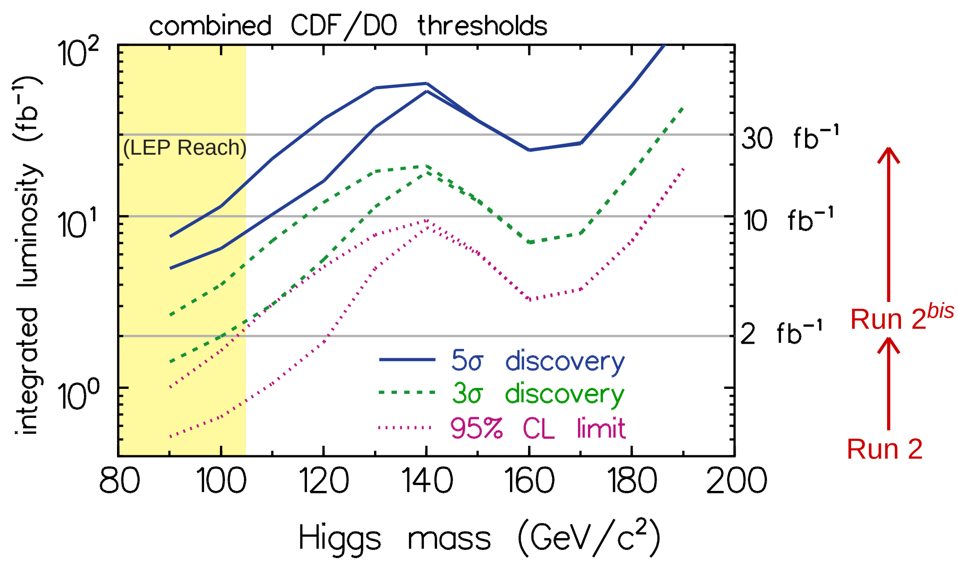

Figure 30: The expected reach of the Tevatron in Higgs search.

9 EWSB at the Tevatron

At the Tevatron the dominant production mode of the Higgs boson is through gluon-gluon fusion. However this is not exploitable because of the rate of background, and one has to use the smaller production rate of the boson in association with a W or a Z, due to quark−antiquark scattering.

For a low mass boson, below 130 GeV, beauty is still the dominant decay and the modes looked for are those of LEP, plus l ν b $\bar{\text{b}}$. Obviously proton and antiproton remnants are also present in the final state. Above 130 GeV, simpler modes like l^+ l^- ν ν, or 3 leptons + ν, coming from H decay into W W^*, will be searched for.

From Run I, combined limits have been produced which, per experiment, are typically 30 times above the SM expectation (for M_H = 120 GeV) (Figure 29). One must therefore gain a large cumulative factor in the effective integrated luminosity, of the order of ∼900. The gain expected in

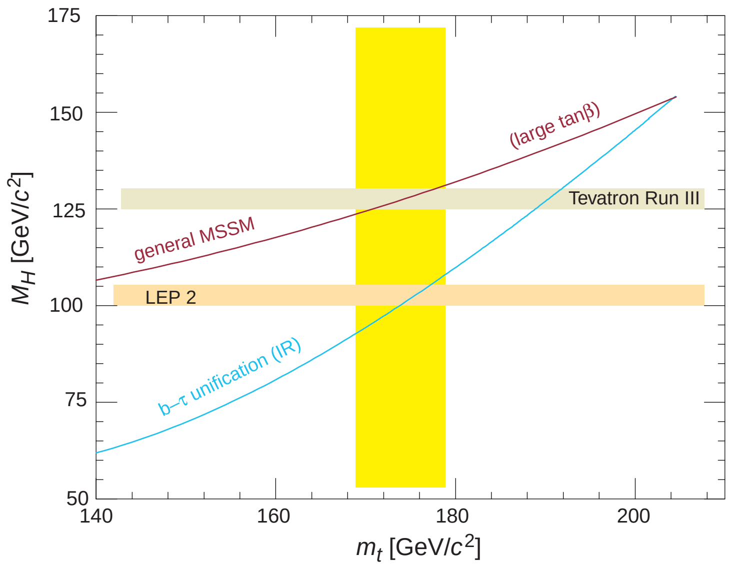

Figure 31: Summary of the situation at the end of LEP for the MSSM h^0 search. The exact values of the bounds have to be adjusted.

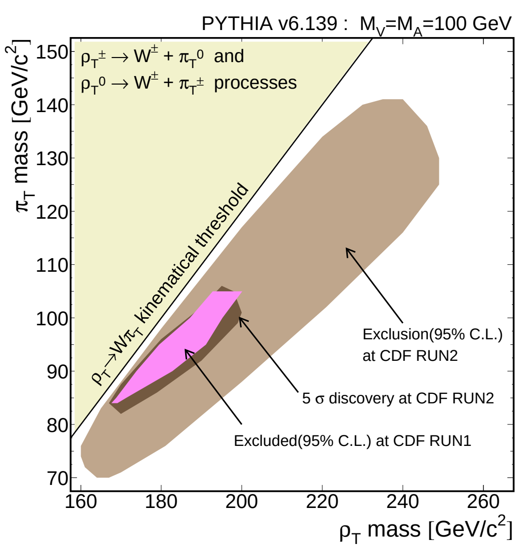

Figure 32: The reach of Run II of Tevatron in the TC plane.

Run II from increasing the luminosity, combining the two experiments, increasing their geometrical acceptance as well as their b-tagging and trigger efficiencies, improving the di-jet mass resolution and refining the analyses is indeed quite impressive, of the order of 600 [39]. If this is achieved, the 95 % CL sensitivity to the Higgs would be 115 GeV. With 15 fb^{-1}, by 2007, a 5 sigma discovery is possible for the same mass. Needless to say, this will not be an easy task, but it may be feasible.

Figure 30 and Figure 31 summarize the expected reach of the Tevatron. One should add that in SUSY some coverage of the parameter space at large tgβ will be ensured through the study of the 4 b-jet channel.

Run II will also improve the coverage in the search for Technicolor [40]. Figure 32 from CDF gives the exclusion and discovery domains in the π_T versus ρ_T plane. D0 proposes a search for ρ_T and ω_T into e^+ e^-, superimposed to the expected Drell-Yan spectrum.

It is clear that for EWSB study at the Tevatron the best preparation, besides the detector improvements, consists in front line QCD studies, refining the cross-section estimates as well as several key distributions. This has been thoroughly described by J.Womersley.

10 EWSB at LHC

Here again the literature is abundant [41]. In brief, the discovery potential of LHC is wide, but, except for very simple channels, experimentation will be difficult. LHC will collide 7 TeV protons, providing parton collisions in the TeV CM region. The interesting cross-sections scaling as $1/E^2$, one will need 100 times more luminosity that at LEP. To achieve that, proton bunches will encounter every 25 ns (nearly 1000 times more frequent than LEP bunches do). Per crossing $\sim$20 interactions will occur, giving overall 10^9 interactions per second (at LEP1 one had 1 Z^0 every 3 seconds and, with Bhabhas, this represented a large fraction of the total rate).

Of this billion of interactions, the trigger has to keep about 100/sec: so a hard selection has to be performed in several steps. At LEP the trigger was at the 1 Hz level. The rate of events will require to fragment the detectors in a very large number of channels ($\sim$100 millions overall), to keep the occupancy at an acceptable level (at the percent level or less). The average LHC event size will be 1 MByte, ten times a Z event at LEP, and the data production will represent $\sim$1 TByte per day, the equivalent of several years of LEP. Finally, due to the high rate of hadronic interactions, the irradiation of the central parts of the detector will reach $\sim$10 Mrad in the LHC lifetime, a problem which was practically absent at LEP.

One will thus have to implement at LHC a large number of forefront technologies: a study of their evolution with time shows that the LHC requirements in the key sectors of computing will hopefully be satisfied at the horizon 2005, thanks to the steady progress of the performances observed and still expected in these sectors. This challenging situation makes already LHC a very interesting project [42].

The LHC program opens the possibility to make a decisive step in our understanding of EWSB, by producing Higgs bosons, as well as superpartners, if any, or indicating what alternative has been chosen.

The SM Higgs boson is dominantly produced by gluon-gluon interaction, but also in association with vector bosons. The decay modes exploited are, for a light object, still beauty-antibeauty, but also the small (BR$\sim 10^{-3}$) mode gamma-gamma, a loop process. At higher masses the WW and ZZ modes always dominate the t-$\bar{\text{t}}$ mode. Very elaborate studies, well documented, have shown that, with $\sim$30 fb^{-1}, one gets a significant signal over the full range of mass (Figure 33 [43]). The only relatively recent fact was to realize the importance of the H to WW channel, where both W decay leptonically: exploiting angular distributions, one can enhance the S/B and provide a very significant signature in the important mass domain around 170 GeV [44].

With more luminosity, say 300 fb^{-1} per experiment, one can start to give measurements of the SM Higgs mass ($\sim$0.1 %) and of the Higgs width (better than 10 %, for masses above 250 GeV) [45].

A complete coverage of the MSSM tgβ - M$_A$ plot can be achieved for a similar luminosity, by combining a large set of measurements (Figure 34).

LEP, if it had been pushed a bit higher, would have also provided a sustantial coverage (Figure 35). Given what will be achieved with the present LEP energy, there will exist some regions in the MSSM plane (say $M_A \sim$300 GeV, tg$\beta \sim$10) where a single object (here the h^0) will ever be observed. However, except in a scenario like the Heavy MSSM, the LHC should also see some of the superpartners.

If Nature has chosen the composite way, the LHC offers also the possibility to study vector boson scattering. The difficulty will depend on its behaviour, resonant or not. At LHC, one will have to use the gold-plated signature of VB leptonic decays, decreasing thus the available statistics. In a previous session of this School, Chanowitz [46] has given rates for various scenarii. Taking for instance a ρ_T of 2.52 Tev, he predicts, for 100 fb^{-1} and after the cuts required:

for WW	15.9 signal/5.8 background
for WZ	5.8 signal/3.4 background

The rates, for such an example, are clearly not overwhelming and it is likely that LHC will then only give a hint of what is going on.

11 EWSB at Linear Colliders

As you know, two kinds of LC are presently considered [47], on different time-scales: a ∼500 GeV version, which may be extendable to the TeV region, and CLIC which is considered as a genuine multi-TeV collider (3 TeV CM energy). In the former version, one can contrast the supraconducting design of Tesla to the warm versions of JLC and ILC. The beam time structures are quite different, although all of these machines will collide of the order of 10000 bunches per second with $\sim 10^{10}$ particles per bunch. All of them have to to realize collisions of bunches whose vertical size is one to a few nanometers. Among other key points, one can say that:

1/ Tesla depends much on the performances of the SC RF cavities, working at 1.3 GigaHz, so smaller than LEP ones. Accelerating fields of ∼25 MV/m have been achieved.

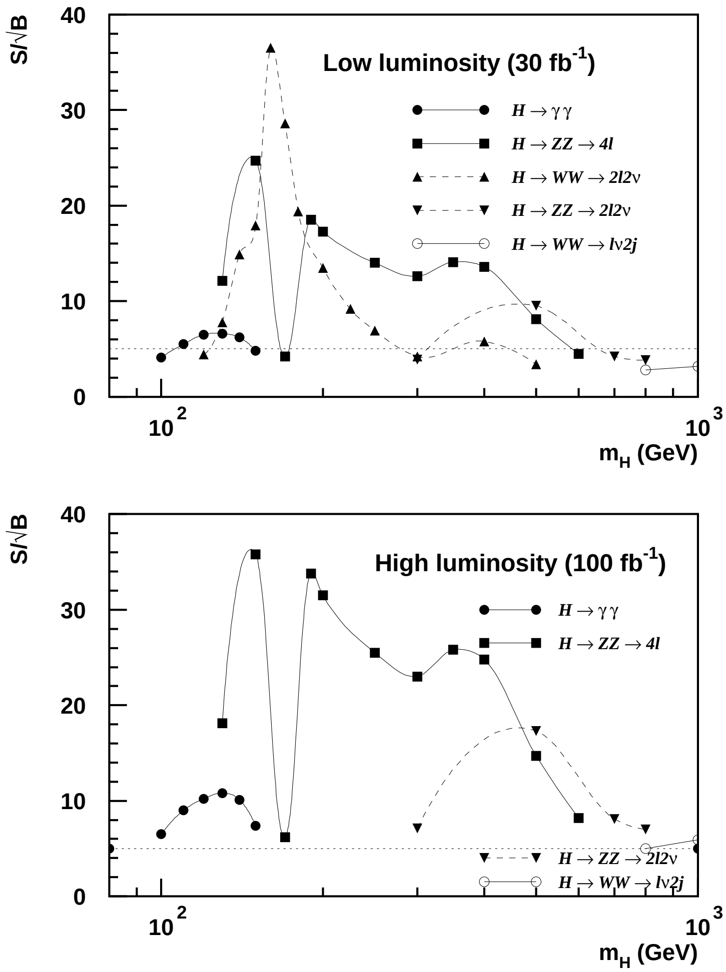

Figure 33: The significance of Higgs searches at LHC in CMS.

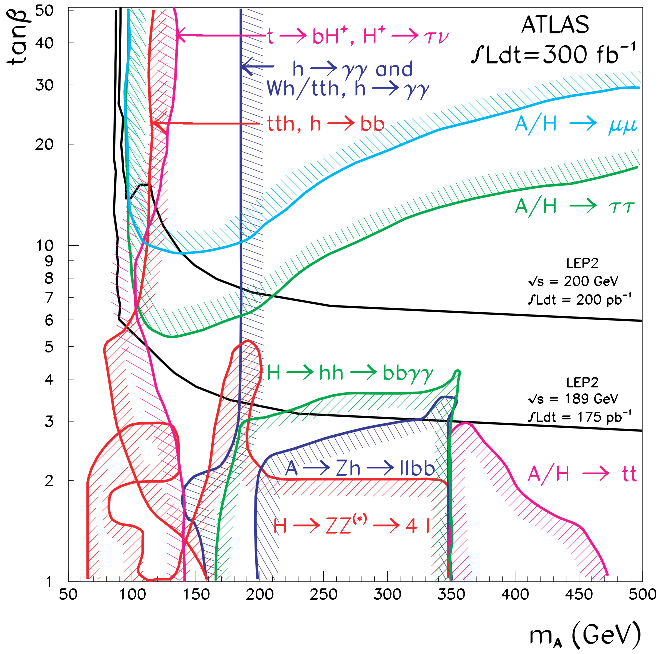

Figure 34: The coverage of the MSSM plane by the explorations of various final states at LHC.

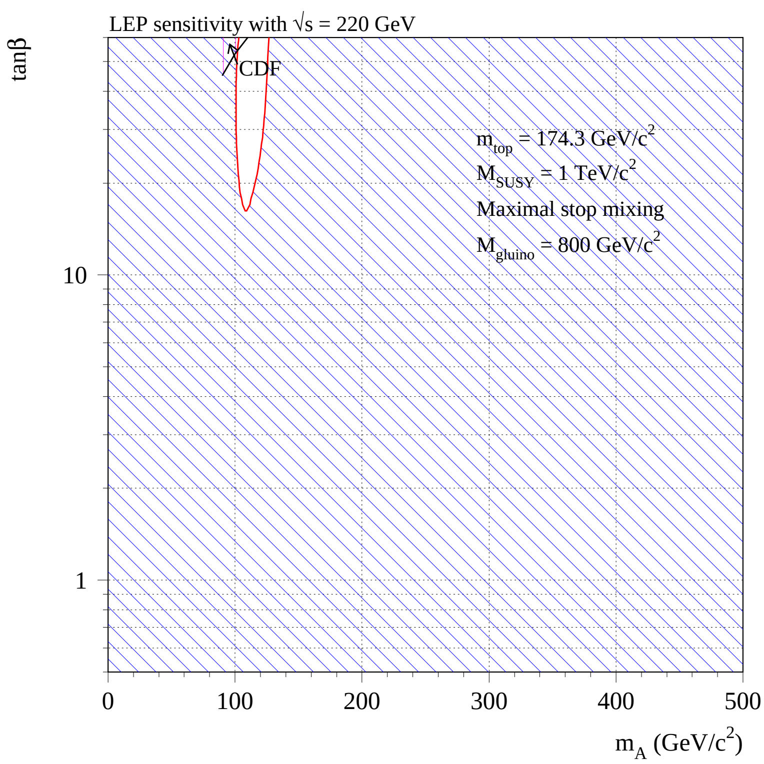

Figure 35: The coverage of the same plane by a would−be 220 GeV LEP, from P.Janot.

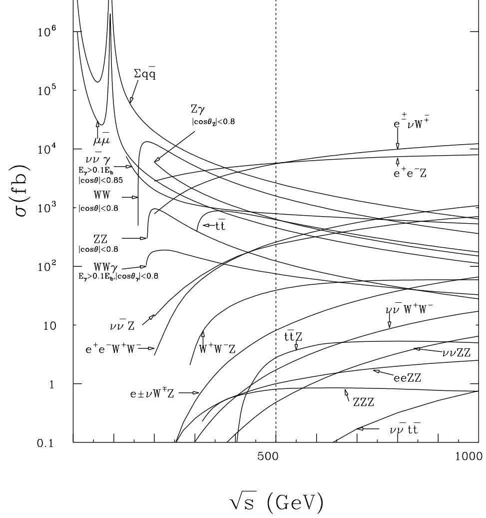

Figure 36: Scenery at a LC.

2/ The JLC and ILC depend much on the performances of their numerous (several thousands) klystrons which must reach 50 to 75 MW for a couple of microseconds. The use of periodic permanent magnet focusing, instead of a solenoid, is an example of ongoing development on these klystrons.

3/ CLIC has to go on demonstrating the validity of the principle and the performances of two-beam acceleration, which is likely to be the road towards multi-TeV collisions. A third test facility, CTF3, is on the way.

As described in detail by [47], all versions have vigorous programs of R/D going on, with very encouraging results.

Figure 36 shows the scenery at a LC. At a few hundred GeV, one recognizes well the LEP200 situation, with some increase of the role played by the rising fusion processes. But the difference will get larger and larger with energy and the CLIC scenery may be very new compared to what we know. Let us note that, for a Higgs boson of ∼100 GeV, the fusion process takes over the Higgsstrahlung at E_{CM} ∼500 GeV.

A first merit of a LC would be to provide the top mass with great accuracy, ∼150 MeV, from a threshold scan. Figure 37 [48] gives the luminosity needed to discover a SM-like Higgs boson and Figure 38 shows how it would appear. However the main role of a LC should be, once the boson has been discovered, to provide some accurate measurements of its properties. Figure 39 [49] gives the accuracy with which one can obtain the Higgs branching ratios, with 500 fb^{-1}. The main systematic errors come from our limited knowledge of basic quantities like the b and c running masses or α_S.

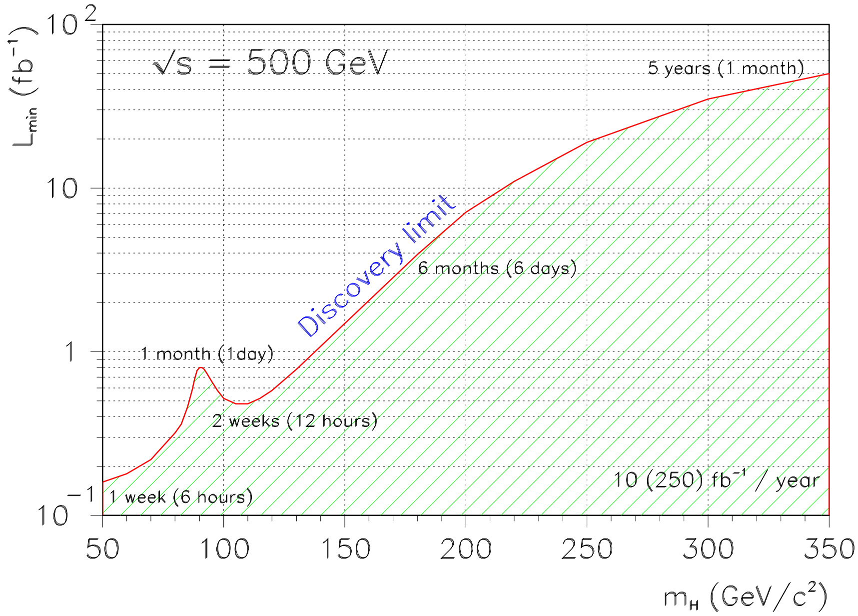

Figure 37: Luminosity needed to discover a SM-like Higgs at a LC.

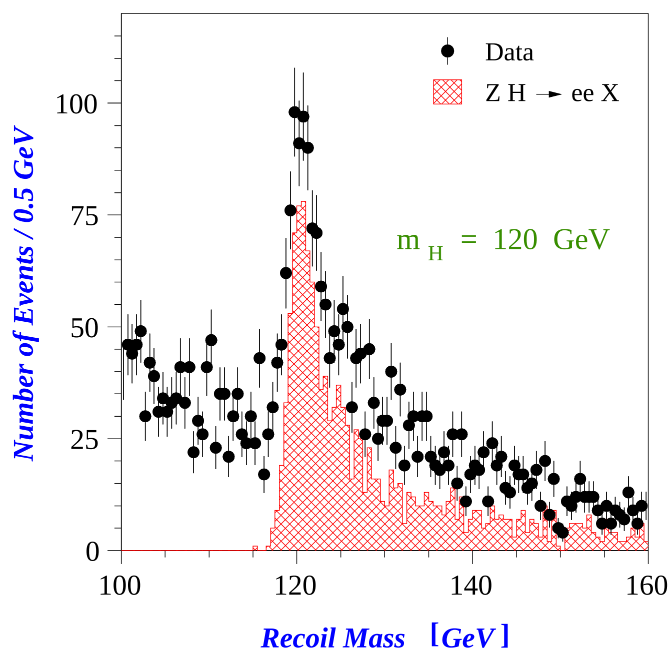

Figure 38: How this boson would appear.

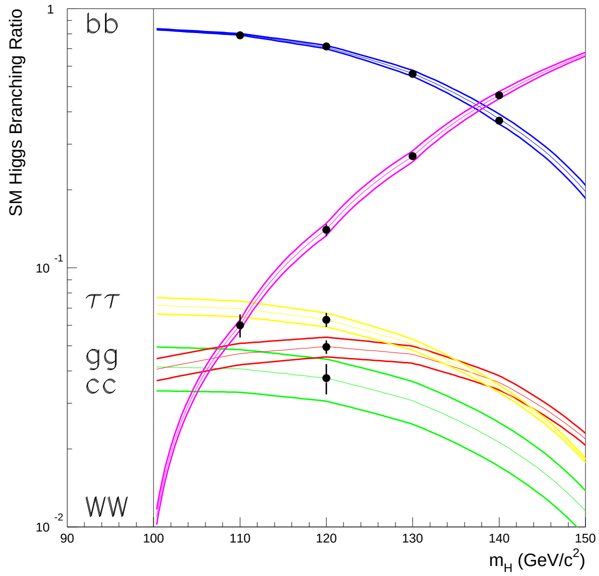

Figure 39: Measurement of the Higgs branching ratios at a LC.

Several papers [50, 51, 52, 27] have discussed recently the possibility, already mentioned, of conspirations, in which some new effects beyond the SM mimic the effect of a light Higgs boson, while in reality the boson is heavier or composite: in the scenarii considered up to now, one always find, given the constraints of the accurate measurements, that a boson should nevertheless exist below ∼500 GeV: the consensus is that a ILC is thus likely to be sufficient to disclose any of these possibilities [53].

In case of light Supersymmetry it has also been shown that a LC is likely to be a splendid machine for discovery and measurement [54].

However, in the case of a dynamical symmetry breaking and if Nature is unkind to us and does not provide light conspicuous resonances, the situation may be more difficult: Figure 40, referring to vector boson scattering, Figure 42 and Figure 41, referring to W pair production, show the clear advantage of higher energies [54].

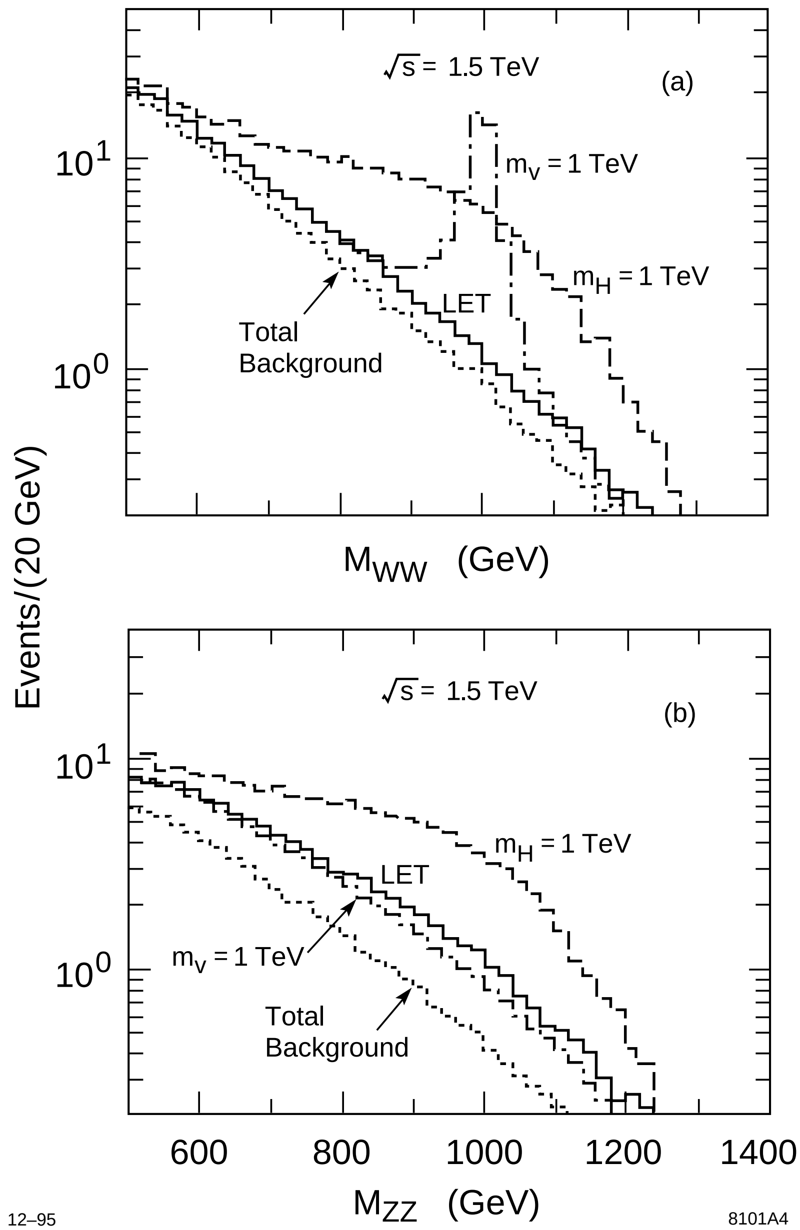

Figure 40: The rate of events at a 1.5 TeV LC in WW and ZZ scattering, for 200 fb^{-1}: the scenarii are the LET, SM and Chirally-coupled vector models.

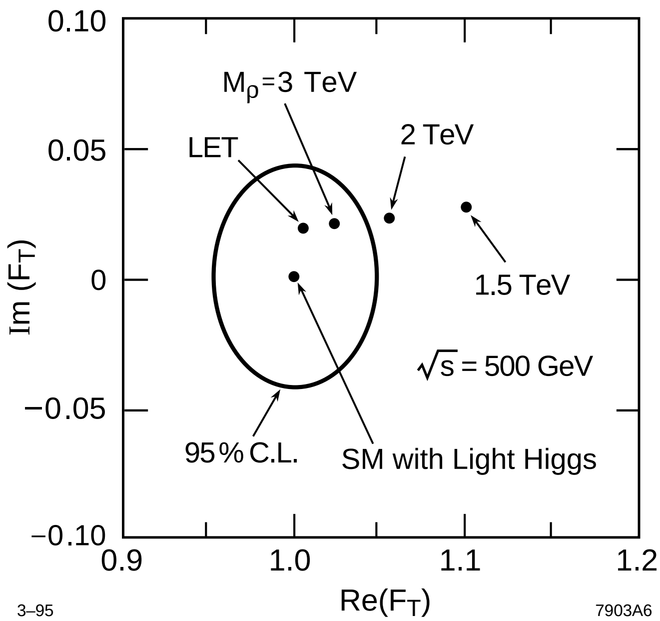

Figure 41: Separability of the LET scenario and various Technirho hypotheses from the SM at a 0.5 TeV LC. F_T is the technipion form factor. The contour around the point SM with light Higgs is at 95% confidence level.

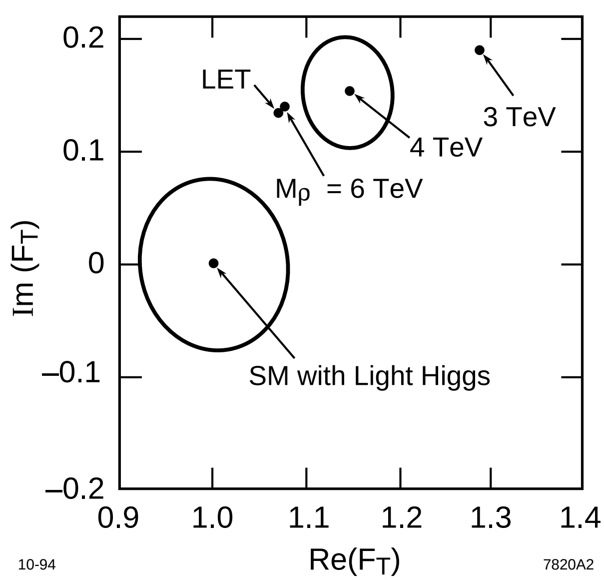

Figure 42: Separability of the LET scenario and various Technirho hypotheses from the SM at a 1.5 TeV LC.

12 Muon colliders

The potential advantages of muons are that:

1/ they don't radiate "externally" (the internal radiation, logarithmic in mass, is however not so different from electrons).

2/ they live relatively long, $\sim$2 microsecond, which allows them to make $\sim$300 B_{tesla} turns in a collider.

3/ they are coupled $(200)^2$ more to the Higgs boson than electrons. One can then produce it in the s-channel. Naturally the Higgsstrahlung process is present as well.

One can conceive a large span of colliders [55, 47], from a light Higgs factory (E_{CM} $\sim$115 GeV) to a really multiTeV machine (we will consider 4 TeV of E_{CM}). The luminosity has to scale as E^2. We will assume it to be $L\sim10^{34}$ E^2_{CM}, with E in TeV. This represents 100 E^2_{CM} fb^{-1} per "year". Another very interesting feature of such machines are their resolution in energy: 0.1 % is a standard feature, but, at the expense of luminosity, one can hope to reach 0.003% if needed.

The road to a Muon Collider requires an enormous amount of R/D in several sectors, in particular the capture and cooling of the muons (MUCOOL program at Fermilab), and one is far from a proven design. The proton source is another concern, and a substantial step compared to existing machines has to be made to reach for instance the 16 GeV with 4 MW on target required by one of the schemes. The size of the complex, if one folds it on itself, is not too unreasonable (Figure 43).

I will very briefly describe two extreme aspects of what MC could bring [56, 57, 48].

At low energy, sitting on the pre-discovered Higgs boson and using the high resolution mode (Figure 44), one can provide a scan of the Higgs line-shape and get its parameters with an extreme accuracy: $\pm$0.1 MeV on its mass, $\pm$0.5 MeV on its width. One can also resolve the h^0 and A^0 bosons,

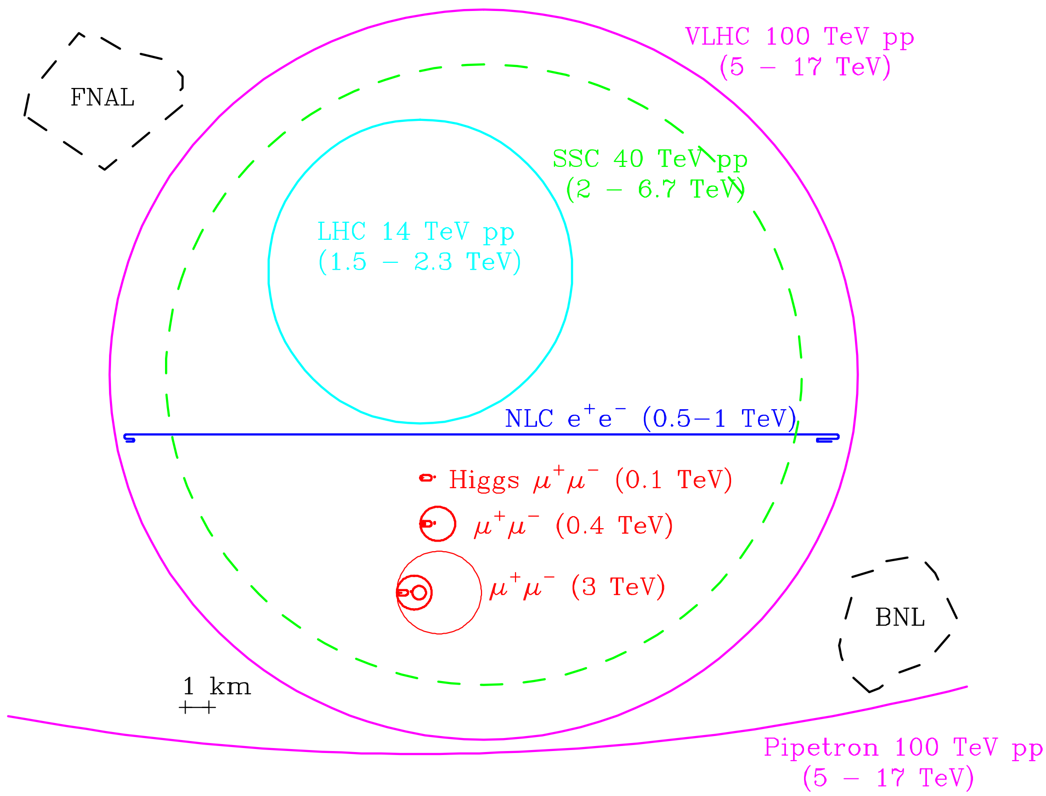

Figure 43: The size of possible Muon Colliders, compared to other machines.

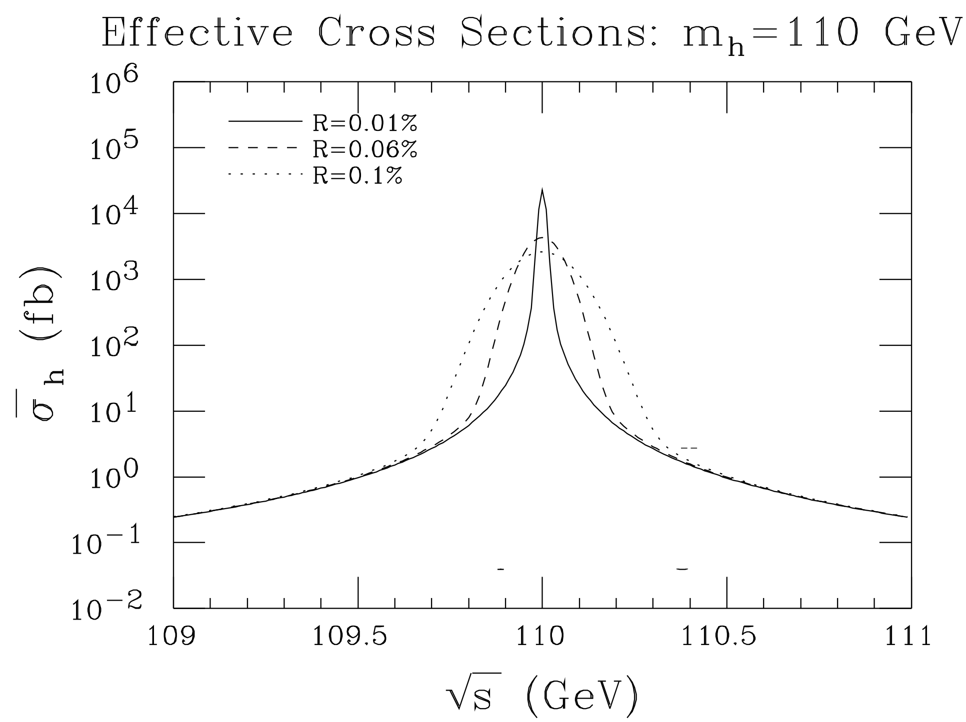

Figure 44: Effective cross-section for a Higgs boson of 110 GeV, depending on the energy resolution of the machine.

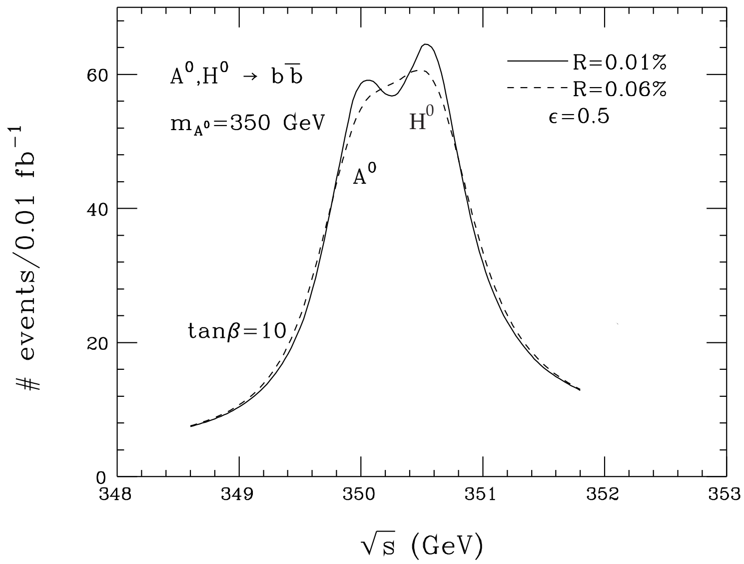

Figure 45: Profile of the nearly degenarate h^0 and A^0 bosons at a muon collider.

nearly degenerate (Figure 45) [56].

At the other extreme, a VHE muon collider may turn out to be the right machine, with CLIC, to make quantitative studies of V_L V_L scattering at TeV energies, if needed. This is shown in Figure 46 and Figure 47 [57]. If integrated luminosities of ~1000 fb^{-1} can be envisaged, the accumulated statistics should be sufficient to distinguish even "nasty" scenarii from the background. One should not forget however that such spectra are still a bit academic: they imply that one can separate W and Z hadronic decays which is not a proven issue. If for instance one has to impose one leptonic decay among the two bosons, the statistics will suffer.

13 EWSB: summary

For the SM-like Higgs we saw that, if it is not discovered at LEP200 nor at the Tevatron, it will be at LHC, with ~10 to 30 fb^{-1} depending of the mass. With 100 fb^{-1} one can envisage at LHC some measurements of

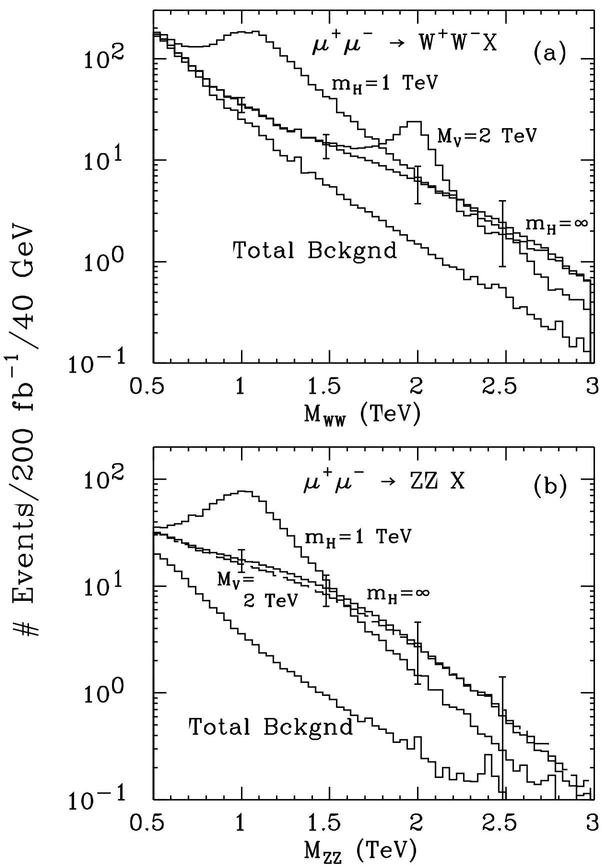

Figure 46: The WW and ZZ mass spectra at a Muon Collider, for three scenarii: Higgs of 1 TeV, Higgs of infinite mass, vector resonance of mass=2 TeV and width=0.2 TeV, compared to the total background. The CM energy is 4 TeV and the luminosity 200 fb^{-1}.

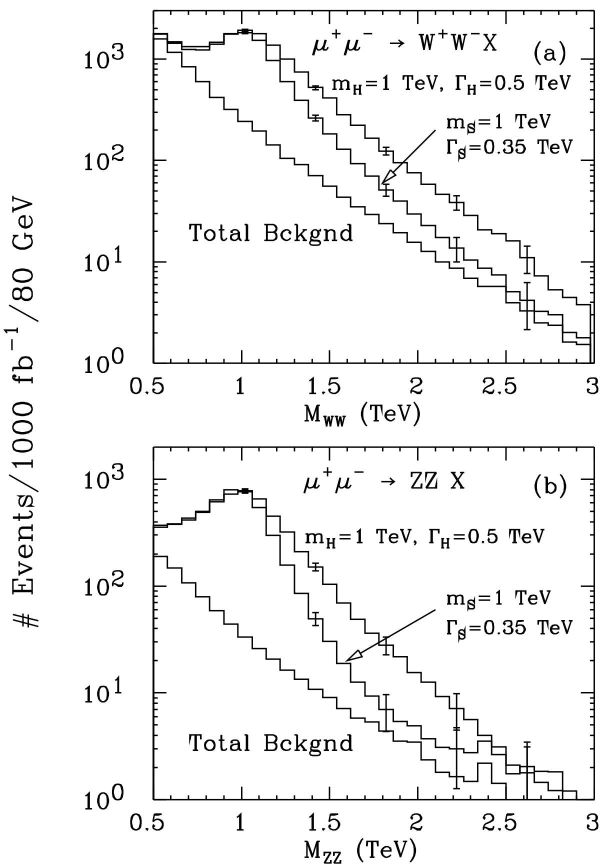

Figure 47: Same as preceeding figure for the SM Higgs of mass=1 TeV, width=0.5 TeV, and the scalar model with M_S=1 TeV, Γ_S=0.35 TeV. Results are for E_{CM}=4 TeV and L=1000fb^{-1}.

its mass, its width and, at $\sim$10 %, of its production times decay rate into gamma-gamma and ZZ.

A 500 GeV a LC can discover it, if this has not been done previously, up to 350 GeV. With 500 fb^{-1}, it can provide: its mass to 0.05 %, its spin and parity, the Higgsstrahlung cross-section, therefore the ZZH coupling, to a couple of %. Most of its decay fractions will be measured with good statistical precision: the dominant systematics will come from the uncertainty on b and c running masses and from α_S. Its total decay width can be estimated from its branching ratio into WW and the knowledge of the WWH coupling (from ZZH), with a $\sim$6 % uncertainty.

Later a $\mu - \mu$ collider could measure the Higgs boson line shape. With 1000 pb^{-1} per year, for a 110 GeV boson, it would give the mass to $\pm$0.1 MeV, the width to $\pm$0.5 MeV, the cross-section to $\pm$5 %, without the systematic errors quoted previously.

For the MSSM we saw that LHC with 300 fb^{-1} will cover the whole parameter plane, as would do a $e^+ e^-$ machine slightly above LEP energy. H and A bosons can only be discovered in parts of the parameter space.

A LC and a $\mu - \mu$ collider can then provide the needed precision studies.

For V_L V_L strong scattering, the possibilities depend much on the scenario. LHC or a 500 GeV LC may observe it, or have a hint of what goes on. But it is not unlikely that the right machine to perform quantitative work on such a scenario has to be a multiTeV lepton collider, CLIC or a $\mu - \mu$ collider.

Let us hope that Nature will not leave us waiting for so long, that the indirect indications of a light Higgs are correct and that such an object will soon reveal itself.

It would be fun as well if speculations about nearby extra-dimensions turn out to be true and offer us in the future spectra like those of Figure 48 [58, 59] and Figure 49 [60]!... It will be up to you to tell.

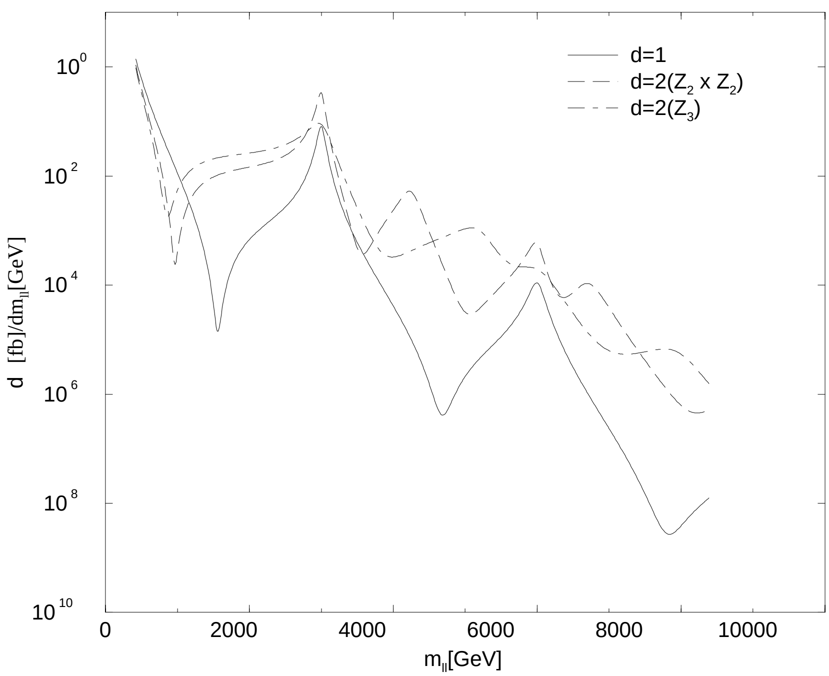

Figure 48: Dilepton mass spectra expected at LHC due to Kaluza-Klein recurrences of the photon and Z^0, for 1/R=3 TeV.

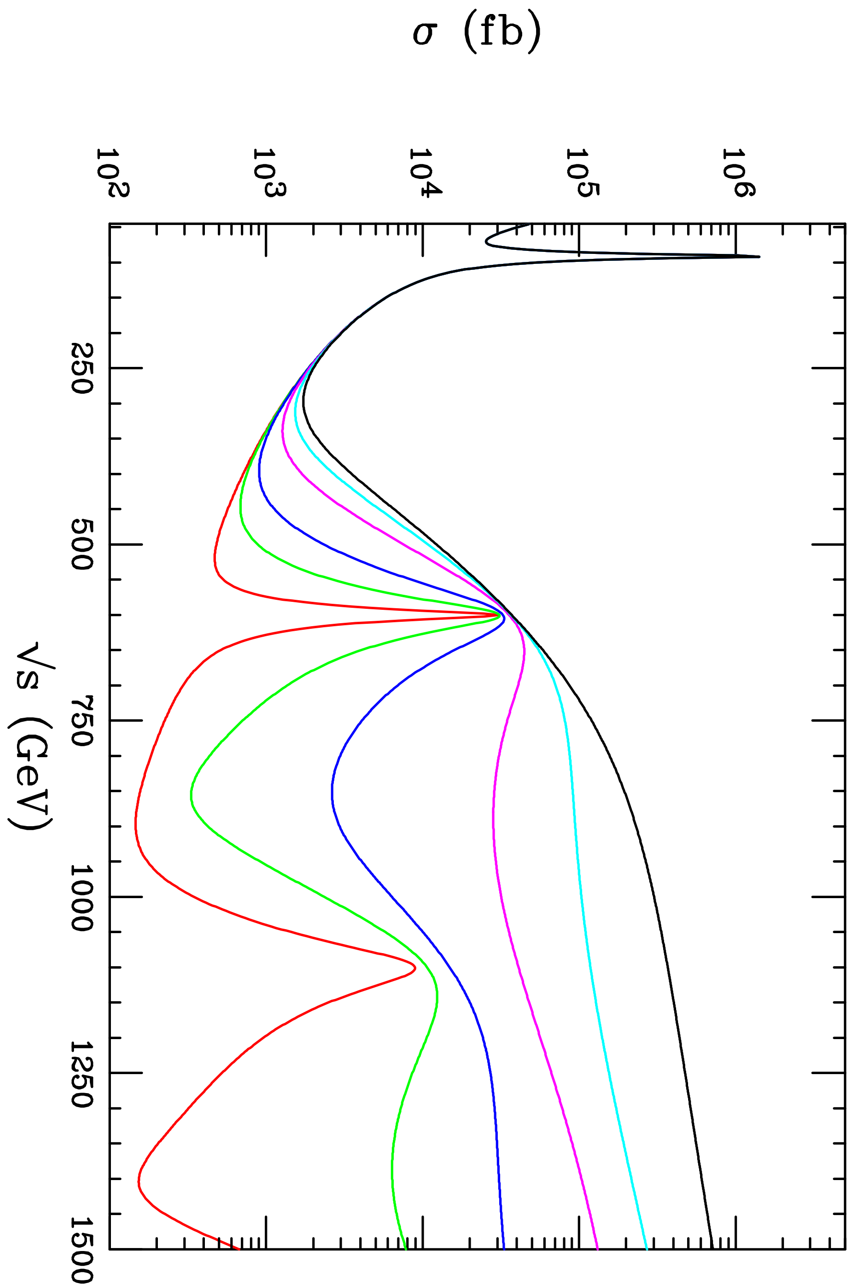

Figure 49: The cross-section for $e^+ e^-$ to $\mu^+\mu^-$ including the exchange of a tower of KK gravitons, taking the mass of the first mode to be 600 GeV.

14 Acknowledgments

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