The Standard Model and Beyond–LEP/SLC/Tevatron and the LHC

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The current status of the standard model of particle physics is described, in particular the recent progress made in its consolidation at LEP, SLC and the Tevatron. With the advent of the LHC, at CERN, science stands poised for a generational leap in the understanding of the universe at both the sub-nuclear and the cosmological level. Thus the LHC will act both as an ultra powerful microscope and telescope simultaneously, recreating conditions as they existed soon after the ig ang. Speculations about the supersymmetric nature of dark matter would be confronted with direct experiment. Perhaps the most exciting and uni ue feature of the LHC is the opportunity it will provide to directly study interactions at the tera energy scale. Something has to give at this scale, some new phenomena have to be lurking in the shadows. The presence or absence of the Higgs and S S will both be momentous discoveries. Of course one hopes for the totally unexpected which would be the real icing on the cake.

1. Introduction

The Standard Model (SM) of particle physics is one of the most developed and tested theories in the history of science, and attempts to describe the universe at the most fundamental level, both at the consituent level and in terms of the forces between them. While both theoretical developments as well as experimental observations accumulated over a period of time, the advent of the SM as we know it today may be dated from the late 1960s.

The coherent unification of electromagnetism with the theory of weak interactions, now known as electroweak (EW) theory by Salam [1] and Weinberg [2], may be considered to be the turning point. Soon thereafter its renormalisability was proven by 't Hooft and it became an established theory. The 1970s also saw the advent of quantum chromodynamics (QCD) as the theory of strong interactions, with an octet of gluons mediating the strong force between quarks and binding the nucleons.

The work of Kobayashi and Maskawa arguing for minimum of three doublets of constituent particles (quarks and leptons) in order to account for CP violation set the stage for later discoveries which completely vindicated this line of work.

The parallel string of experimental discoveries more than kept pace with the theoretical developments. The prediction of the EW theory that there must be a neutral current, Z^0, in addition to the well known charged current ($W^\pm$) was confirmed in a bubble chamber experiment at CERN, setting the seal on the veracity of the EW theory. This was followed by the discovery of the fourth quark, called charm in 1974, thus completing two doublets of quarks. The third charged lepton, the τ was discovered soon after thus necessitating the existence of 3 lepton doublets. This was followed up with the discovery of the fifth quark, the bottom in 1977 at Fermilab and the gluon in $e^+e^- \to 3$ jets interactions at PETRA. The discovery of directly produced $W^\pm$ and Z^0 in the early 1980s at the CERN $p\overline{p}$ collider crowned the success of the EW theory. The final icing on the cake was the discovery of the top quark at Fermilab in 1994/95, which completed the experimental observation of all the 3 doublets of quarks and leptons as well as the force particles, the gluon and the W and Z, and the photon of course had been known for a long time.

The Z^0 factories SLC at Stanford and LEP at CERN have played a crucial role in experimental consolidation of the SM. In particular LEP, with its large Z^0 statistics set new standards for the precision determination of its properties. After its energy was raised above the W-pair production threshold it allowed a precision measurement of the W properties too, and finally raising its energy to the highest possible, around 209 GeV, allowed a direct search for the Higgs boson upto hitherto unexplored mass limts. While the SLC did not compare well with LEP in terms of statistics it had the great advantage of having polarised beams which enhances the sensitivity of the data to EW mixing. Thus the determination of the EW angle from the SLC is the single most precise value of this quantity.

In this article the experimental results will be reviewed in the chronological order, from LEP100 and SLC, then the discovery of the top quark, followed by results from LEP200. After that a brief description of what one expects from the Large Hadron Collider (LHC) will be given, with emphasis on a few most salient topics.

2. SLC and LEP100

While the Z^0 and $W^\pm$ were discovered at the CERN $p\bar{p}$ collider it was clear that the number of events that could be studied would always remain small and in order to make detailed studies of the production and decay of these particles one would need Z^0 and $W^\pm$ "factories". LEP was designed as a 27 km circular e^+e^- collider with initial energy around the Z^0 mass, with a later energy upgrade to become a $W^\pm$ factory with CM energy above the W^+W^- threshold. The SLC was the world's first e^+e^- Single-pass Linear Collider with CM energy focussed on the Z^0, but with an added advantage of polarised beams, which strongly helps in the study of certain EW quantities.

A detailed account of the work carried out at LEP100 and SLC is given in a review by the LEP/SLC groups [3] and in the W and Z sections of the review of particle properties [4].

The location of the LEP storage ring and the placement of the four experiments is shown in Fig. 1 and the layout of the SLC is shown in Fig. 2.

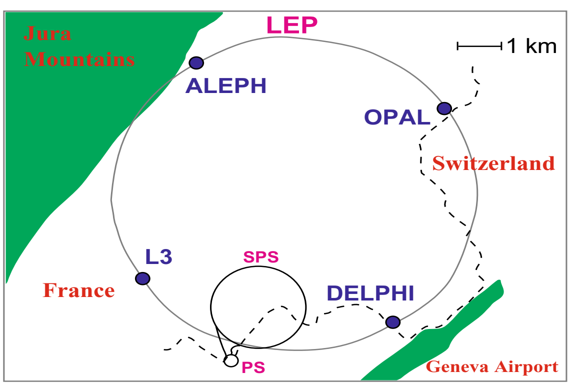

Figure 1. The LEP storage ring and location of the four experiments, ALEPH, DELPHI, L3 and OPAL

The main physics process studied at LEP and SLC is the production of a fermion anti-fermion pair, $e^+e^- \to f\bar{f}$ where f maybe one of the leptons or a quark, as shown in Fig. 3. All quark anti-quark pairs, except $t\bar{t}$ can be produced at these energies, the top quark being heavier than kinematically allowed. The study of heavy (bottom) quark production leads to indirect information about vertex corrections involving heavier particles as depicted in Fig. 4.

The main topics studied at LEP100 and SLC are the production and decay properties of the Z^0. As one scans

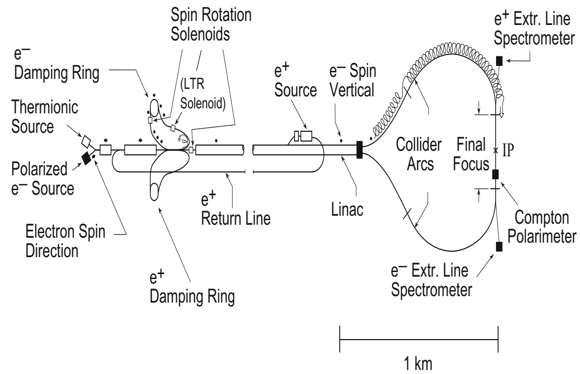

Figure 2. The layout of the SLC at Stanford. There was only a single experiment at the intersection point of the beams

the CM energy range from a few GeV below the Z^0 mass to above it, the cross section traces out the "lineshape" of the Z. The variation of the hadronic cross section in e^+e^- interactions from low to the highest energies is shown in Fig. 5. Differentiating between "forward" and "backward" cross sections (where "forward" means the fermion follows the direction of the electron) one can determine the asymmetry in the production process. A measurement of the lineshape allows one to determine the Z^0 mass, total width and its partial decay widths into various channels. The asymmetry measurements allow one to separately determine the vector and axial-vector couplings of the Z^0 to leptons and quarks and test the predictions of the EW theory in detail. At LEP one has also made a measurement of the τ-polarisation and used it to obtain additional information on τ-asymmetry parameter.

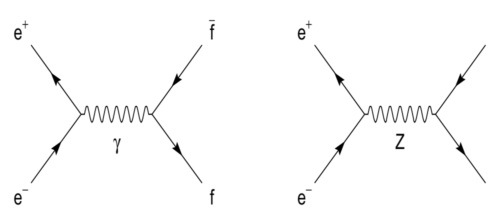

Figure 3. The lowest order s-channel Feynman diagrams

2.1. Z^0 Lineshape and Asymmetry Studies

While the SLC ran at a single energy very near the Z^0

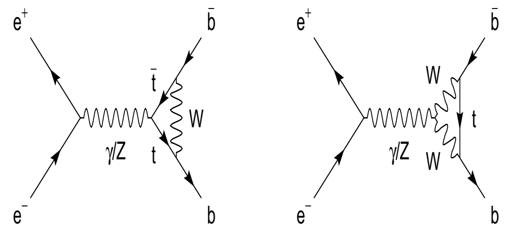

Figure 4. Vertex corrections in the process $e^+e^- \to b\overline{b}$

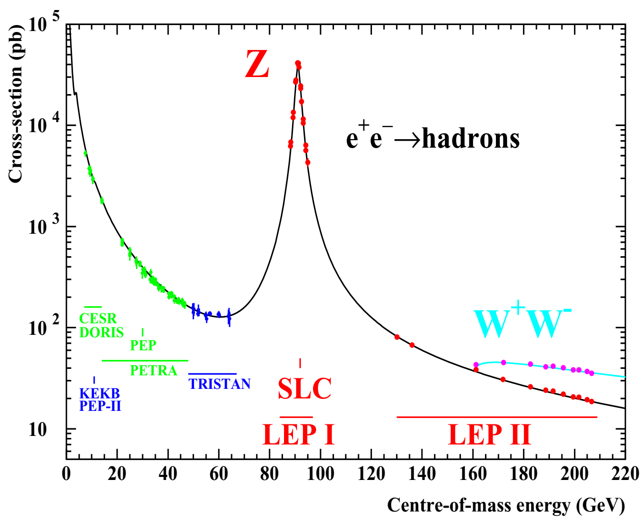

Figure 5. Hadronic cross section vs energy in e^+e^- interactions

pole, LEP ran at various energies at one GeV intervals within ±3 GeV around the pole and scanned the lineshape of the Z^0.

The shape of the cross-section variation around the Z^0 peak can be described by a Breit-Wigner *ansatz* with an energy-dependent total width [5–7]. The three main properties of this distribution, viz. the position of the peak, the width of the distribution and the height of the peak, determine respectively the values of M_Z, Γ_Z and $\Gamma(e^+e^-) \times \Gamma(f\overline{f})$, where $\Gamma(e^+e^-)$ and $\Gamma(f\overline{f})$ are the electron and fermion partial widths of the Z. The quantitative determination of these parameters is done by writing analytic expressions for these cross sections in terms of the parameters and fitting the calculated cross sections to the measured ones by varying these parameters, taking properly into account all the errors. Single-photon exchange (σ^0_γ) and γ-Z interference ($\sigma^0_{\gamma Z}$) are included, and the large (∼25 %) initial-state radiation (ISR) effects are taken into account by convoluting the analytic expressions over a 'Radiator Function' [5–9,26] $H(s,s')$. Thus for the process $e^+e^- \to f\overline{f}$:

$$\sigma_f(s) = \int H(s,s')\ \sigma^0_f(s')\ ds' \tag{1}$$

$$\sigma^0_f(s) = \sigma^0_Z + \sigma^0_\gamma + \sigma^0_{\gamma Z} \tag{2}$$

$$\sigma^0_Z = \frac{12\pi}{M^2_Z}\ \frac{\Gamma(e^+e^-)\Gamma(f\overline{f})}{\Gamma^2_Z}\ \frac{s\ \Gamma^2_Z}{(s-M^2_Z)^2\ +\ s^2\Gamma^2_Z/M^2_Z} \tag{3}$$

$$\sigma^0_\gamma = \frac{4\pi\alpha^2(s)}{3s}\ Q^2_f N^f_c \tag{4}$$

$$\sigma^0_{\gamma Z} = -\frac{2\sqrt{2}\alpha(s)}{3}\ (Q_f G_F N^f_c \mathcal{G}^e_V \mathcal{G}^f_V) \times\frac{(s-M^2_Z)M^2_Z}{(s-M^2_Z)^2 + s^2\Gamma^2_Z/M^2_Z}\ , \tag{5}$$

where Q_f is the charge of the fermion, $N^f_c = 3$ for quarks and 1 for leptons and $\mathcal{G}^f_V$ is the vector coupling of the Z to the fermion-antifermion pair $f\overline{f}$.

Since $\sigma^0_{\gamma Z}$ is expected to be much less than σ^0_Z, the LEP collaborations have generally calculated the interference term in the framework of the SM. This fixing of $\sigma^0_{\gamma Z}$ leads to a tighter constraint on M_Z and consequently a smaller error on its fitted value. It is possible to relax this constraint and carry out the fit within the S-matrix framework.

The QED radiative corrections have been explicitly taken into account by convoluting over the ISR and allowing the electromagnetic coupling constant to run [10]: $\alpha(s) = \alpha/(1-\Delta\alpha)$. Weak radiative corrections that depend upon the assumptions of the EW theory and on the values of $M_{\rm top}$ and $M_{\rm Higgs}$ are accounted for by absorbing them into the couplings, which are then called the *effective* couplings $\mathcal{G}_V$ and $\mathcal{G}_A$.

$\mathcal{G}_V$ and $\mathcal{G}_A$ are complex numbers with small imaginary parts. As experimental data does not allow simultaneous extraction of both real and imaginary parts of the effective couplings, the convention $g^f_A = {\rm Re}(\mathcal{G}^f_A)$ and $g^f_V = {\rm Re}(\mathcal{G}^f_V)$ is used and the imaginary parts are added in the fitting code [8].

Defining

$$A_f = 2\frac{g^f_V \cdot g^f_A}{(g^f_V)^2 + (g^f_A)^2} \tag{6}$$

the lowest-order expressions for the various lepton-related asymmetries on the Z pole are [11–13] $A^{(0,\ell)}_{FB} = (3/4)A_e A_f$, $P(\tau) = -A_\tau$, $P(\tau)^{fb} = -(3/4)A_e$, $A_{LR} = A_e$. The full analysis takes into account the energy dependence of the asymmetries. Experimentally A_{LR} is defined as $(\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$ where $\sigma_{L(R)}$ are the $e^+e^- \to Z$ production cross sections with left- (right)-handed electrons.

The definition of the partial decay width of the Z to $f\overline{f}$ includes the effects of QED and QCD final state corrections as well as the contribution due to the imaginary parts of the couplings:

$$\Gamma(f\overline{f}) = \frac{G_F M_Z^3}{6\sqrt{2}\pi} N_c^f (\left|\mathcal{G}_A^f\right|^2 R_A^f + \left|\mathcal{G}_V^f\right|^2 R_V^f) + \Delta_{ew/\mathrm{QCD}} \quad (7)$$

where R_V^f and R_A^f are radiator factors to account for final state QED and QCD corrections as well as effects due to non-zero fermion masses and $\Delta_{ew/\mathrm{QCD}}$ represents the non-factorisable EW/QCD corrections.

The $\mathbf{e^+e^-}$ final state

Unlike other final states, this state has contributions from $t-$channel and $s - t$ interference and these amplitudes are not amenable to fast calculation. Thus the non-s channel part of this cross section is calculated using the SM programmes ALIBABA [14] and TOPAZ0 [15], for a given M_{top} and M_{Higgs}, and added to the $s-$channel cross section as for other channels. The theoretical uncertainties and the uncertainties due to errors on top and Higgs masses are folded into the error calculation.

Errors dur to uncetainty in beam energy [16–21]

Systematic errors on beam energy may be due to the absolute energy scale, energy-point to energy-point errors due to non-linear response of magnets or higher order effects relating the dipole field and beam energy, and energy reproducibility errors due to uncertainties in temperatures, tidal effects, RF status, etc. A detailed model was developed which took into account these factors, including leakage currents produced by trains running nearby, the earth-tide effects due to the sun and the moon. A covariance matrix for energy errors for LEP running between 1993 and 1995 was provided by the LEP Energy Working Group [16].

The choice of fit parameters

The parameter set $M_Z, \Gamma_Z, \sigma^\circ_{\mathrm{hadron}}, R(\mathrm{lepton}), A_{FB}^{(0,\ell)}$, where $R(\mathrm{lepton}) = \Gamma(\mathrm{hadrons})/\Gamma(\mathrm{lepton})$, $\sigma^0_{\mathrm{hadron}} = 12\pi\Gamma(e^+e^-)\Gamma(\mathrm{hadrons})/M_Z^2\Gamma_Z^2$ was chosen by the LEP collaborations for fitting the data. The main advantage is that these parameters form the least correlated set of parameters thus making it easier to combine the data from the four experiments.

Thus one starts with the general fit in which lepton universality is not assumed and there are three R(lepton) and $A_{FB}^{(0,\ell)}$ parameters, making a total of nine. Having ascertained the validity of lepton universality a five parameter fit is carried out.

Combining results of LEP and SLC collaborations

With the huge amount of statistics collected by each of the LEP experiments the main errors are due to systematics, many of which are common to the different experiments. The experimental systematic errors common among LEP experiments are due to the LEP energy calibration uncertainties. Other systematic errors that are common to LEP and SLC experiments are due to theoretical uncertainties, in the luminosity determination using small angle Bhabha scattering, estimating non-s channel contribution to large angle Bhabha scattering, calculation of QED radiative effects and parametrisation of the cross section in terms of the parameter set used.

All the theory related systematic errors utilise SM programmes which need some basic inputs and all LEP collaborations used identical values for these: $M_Z =$ 91.187 GeV, the Fermi constant $G_F = (1.16637 \pm 0.00001) \times 10^{-5}$ [22], $\alpha^{(5)}(M_Z) = 1/128.877 \pm 0.090$ [23], $\alpha_s(M_Z) = 0.119$ [24], $M_{top} = 174.3 \pm 5.1$ GeV [24] and $M_{Higgs} = 150$ GeV.

Methodology and results of LEP combination

Each LEP experiment provided the results from a nine-parameter fit result using the variables: $M_Z, \Gamma_Z, \sigma^\circ_{\mathrm{hadron}}, R(\mathrm{e}), R(\mu), R(\tau), A_{FB}^{(0,e)}, A_{FB}^{(0,\mu)}, A_{FB}^{(0,\tau)}$, together with the full 9×9 covariance. A grand covariance matrix, V, was constructed using the four covariance matrices as its diagonal components and filling the remaining off-diagonal elements with common systematic errors. A combined 9-parameter set was the obtained by minimising $\chi^2 = \Delta^T V^{-1} \Delta$, where Δ is the vector of residuals of the combined parameter set to the results of individual experiments.

After verifying that the fit parameters for the three leptons are compatible, each LEP experiment assumed lepton universality and obtained a 5-parameter fit and the corresponding error matrix. These were then combined as described above to obtain the LEP combined 5-parameter values.

Results of the fits as described above are given in Table 1.

Some important physics related quantities can be derived using the above fitted values. These are the Z

Parameter	Fit not assuming lepton universality	Fit assuming lepton universality	Derived not assuming lepton universality	Derived assuming lepton universality
M_Z(GeV)	91.1876 ± 0.0021	91.1875 ± 0.0021		
Γ_Z(GeV)	2.4952 ± 0.0023	2.4952 ± 0.0023		
σ^0_{had}(nb)	41.541 ± 0.037	41.540 ± 0.037		
R_e	20.804 ± 0.050			
R_μ	20.785 ± 0.033			
R_τ	20.764 ± 0.045			
R_ℓ		20.767 ± 0.025		
Γ_e(MeV)			83.92 ± 0.12	
Γ_μ(MeV)			83.99 ± 0.18	
Γ_τ(MeV)			84.08 ± 0.22	
Γ_ℓ(MeV)				83.985 ± 0.086
Γ_{had}(MeV)				1744.4 ± 2.0
Γ_{inv}(MeV)				499.0 ± 1.5
N_ν(light)				2.9840 ± 0.0082
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025			
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013			
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017			
$A_{FB}^{(0,\ell)}$		0.0171 ± 0.0010		

Table 1. Model independent combined LEP fit results.

decay width into invisible particles and, from this the number of light neutrino species into which the Z can decay. As there is one neutrino species per generation, this also indicates strongly that the total number of matter species may be limited to three, unless additional neutrinos have a mass far heavier than the known neutrinos.

Study of τ-polarisation in Z $\rightarrow \tau^+\tau^-$ at LEP and the availability of beam polarisation at the SLC enables one to obtain very accurate information on the asymmetry parameters of Z decays into various modes and helps one to fix the value of the effective mixing angle $\sin^2\theta_{\rm eff}^{\rm lept}$. Figure 6 summarises these measurements and also depicts the variation of $\sin^2\theta_{\rm eff}^{\rm lept}$ with the Higgs mass. One can notice the inconsistency between the measurement from SLC and from the b-asymmetry measurement at LEP.

2.2. Z^0 Decays to Heavy Flavours (b- and c-quarks)

The LEP experiments have measured the ratios of partial widths $R_b = \Gamma(Z \rightarrow b\bar{b})/\Gamma(Z \rightarrow \text{hadrons})$ and $R_c = \Gamma(Z \rightarrow c\bar{c})/\Gamma(Z \rightarrow \text{hadrons})$ and the forward-backward (charge) asymmetries $A_{FB}^{b\bar{b}}$ and $A_{FB}^{c\bar{c}}$. The SLD experiment at SLC has measured the ratios R_c and R_b and, utilising the polarisation of the electron beam was able to obtain the final state coupling parameters A_b and A_c from a measurement of the left-right forward-backward asymmetry of $b-$ and $c-$quarks. The high precision measurement of R_c at SLD was made possible owing to the small beam size and very stable beam spot at SLC, coupled with a highly precise CCD pixel detector. Several of the analyses have also determined other quantities, in particular the semileptonic branching ratios, $B(b \rightarrow \ell^-)$, $B(b \rightarrow c \rightarrow \ell^+)$ and $B(c \rightarrow \ell^+)$, the average time-integrated $B^0\overline{B}^0$ mixing parameter $\overline{\chi}$ and the probabilities for a c–quark to fragment into a D^+, a D_s, a D^{*+} or a charmed baryon. All these quantities are correlated with the EW parameters, and since the mixture of b hadrons is different from the one at the $\Upsilon(4S)$, their values might differ from those measured at the $\Upsilon(4S)$.

The LEP Electroweak Heavy Flavour Working Group has developed [25] a procedure for combining the measurements taking into account known sources of correlation. The combining procedure determines fourteen parameters: the six parameters of interest in the EW sector R_b, R_c, $A_{FB}^{b\bar{b}}$, $A_{FB}^{c\bar{c}}$, A_b and A_c and, in addition $B(b \rightarrow \ell^-)$, $B(b \rightarrow c \rightarrow \ell^+)$, $B(c \rightarrow \ell^+)$, $\overline{\chi}$, $f(D^+)$, $f(D_s)$, $f(c_{\rm baryon})$ and $P(c \rightarrow D^{*+}) \times B(D^{*+} \rightarrow \pi^+ D^0)$ to take into account their correlations with the EW parameters. Before the fit both the peak and off-peak asymmetries are translated to the common energy

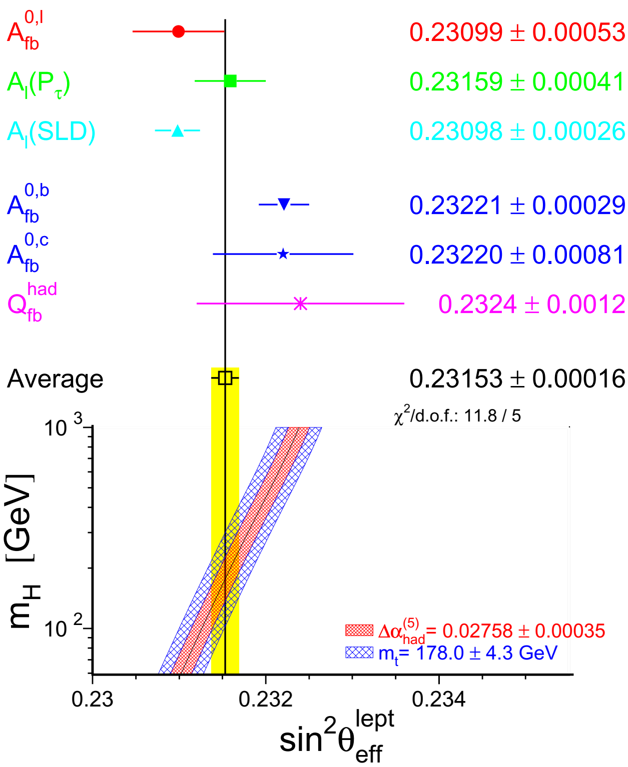

Figure 6. $\sin^2\theta_{\rm eff}^{\rm lept}$ derived from various asymmetry measurements at the Z-pole

$\sqrt{s} = 91.26$ GeV using the predicted energy dependence from ZFITTER [26].

The results are given in Table 2.

2.3. Search for Higgs at LEP

A systematic search for the SM and non-SM Higgs bosons has been made at LEP. The main production mechanism for the SM Higgs is the Higgs-strahlung process:

$$e^+e^- \to Z^\star \to HZ$$

and all the possible detectable decay modes of H and Z have been used in the search. While some initial hints of a Higgs signal with mass around 115 GeV was seen, in the final combined paper by the LEP collaborations, a 95% lower limit on the mass is given [27]: 114.4 GeV. The reconstructed Higgs mass with loose and tight cuts is shown in Fig. 7 and the likelihood function for observing a Higgs is shown in Fig. 8.

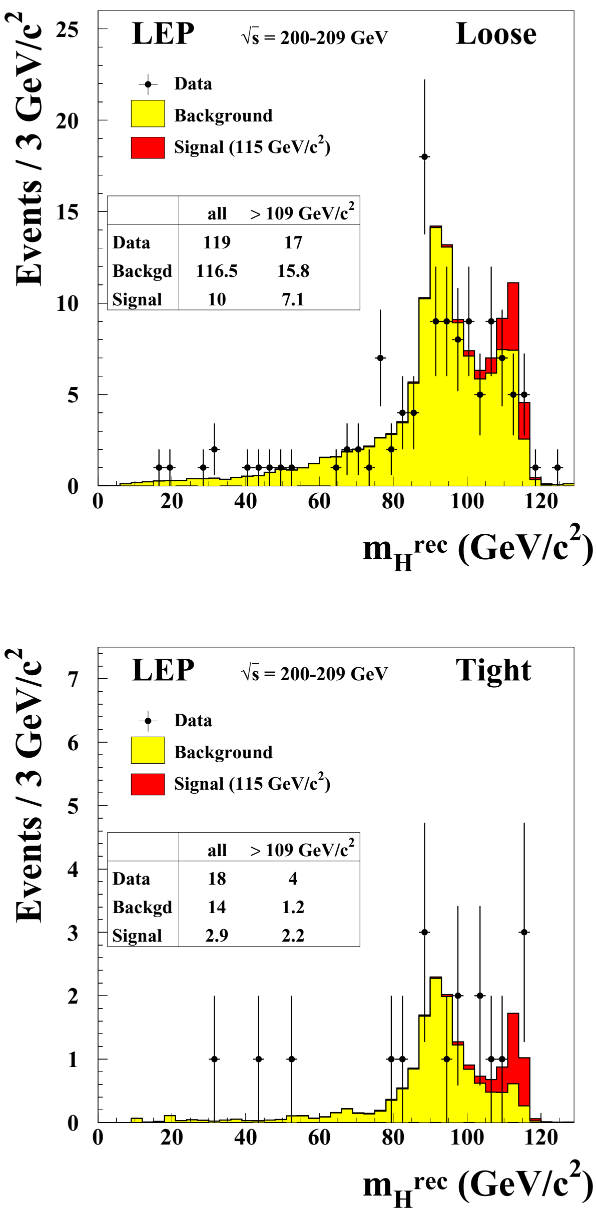

Figure 7. Reconstruted Higgs mass using loose and tight cuts (all LEP)

3. Discovery of Top Quark at Fermilab

The CDF [28] and D0 [29] collaborations discovered the top quark in the mid-1990s. The initial studies were made in RUN I, with a centre-of-mass energy of 1.8 TeV and subsequent RUN II studies are at 1.96 TeV. The production cross section at 1.96 TeV is around 7 pb, with almost 85% contribution due to the quark-

$R_b^0 = 0.21629 \pm 0.00066$	$R_c^0 = 0.1721 \pm 0.0030$
$A_{FB}^{0,b} = 0.0992 \pm 0.0016$	$A_{FB}^{0,c} = 0.0707 \pm 0.0035$
$A_b = 0.923 \pm 0.020$	$A_c = 0.670 \pm 0.027$
$B(b \to \ell^-) = 0.1071 \pm 0.0022$	$\mathrm{B}(b \to c \to \ell^+) = 0.0801 \pm 0.0018$
$B(c \to \ell^+) = 0.0969 \pm 0.0031$	$\overline{\chi} = 0.1250 \pm 0.0039$
$f(D^+) = 0.235 \pm 0.016$	$f(D_s) = 0.126 \pm 0.026$
$f(c_{\mathrm{baryon}}) = 0.093 \pm 0.022$	$P(c \to D^{*+}) \times \mathrm{B}(D^{*+} \to \pi^+ D^0) = 0.1622 \pm 0.0048$

Table 2. Results from global fit to measurements on Z decays to b- and c-quarks.

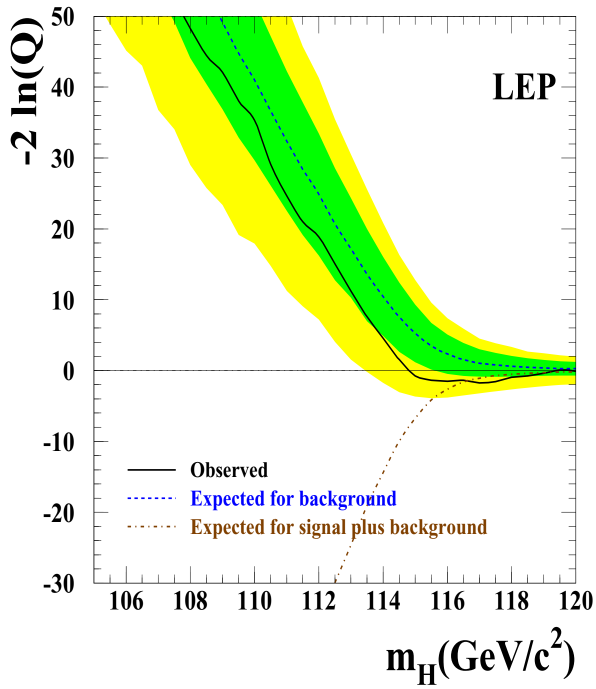

Figure 8. Log likelihood function as a function of Higgs mass

antiquark annihilation. The dominant decay mode of the top quark is t → bW. Thus the decay signatures of $t\bar{t}$ production are the presence of b-quarks and high p_T leptons if the Ws decay leptonically. The all hadronic final state is more problematic to identify above background and analyse. The latest results on the $t\bar{t}$ production cross section in RUN II [30] are $\sigma(p\overline{p} \to t\overline{t}) = 7.0 \pm 0.3(stat) \pm 0.4(syst) \pm 0.4(lumi)$ pb for CDF and $\sigma(p\overline{p} \to t\overline{t}) = 7.8 \pm 0.5(stat) \pm 0.6(syst) \pm 0.5(lumi)$ pb for D0; and the Tevatron combined top mass value is $172.4 \pm 0.7 \pm 1.0$ GeV.

4. Standard Model Fit to all Electroweak Data

With only the Higgs boson as the missing piece of the SM predictions, it is obvious to attempt to predict its mass by fitting all data within the SM framework, having it as one of the free parameters. The data used in the fit is shown in Fig. 9 and the χ^2 variation as a function of the Higgs mass is shown in Fig. 10.

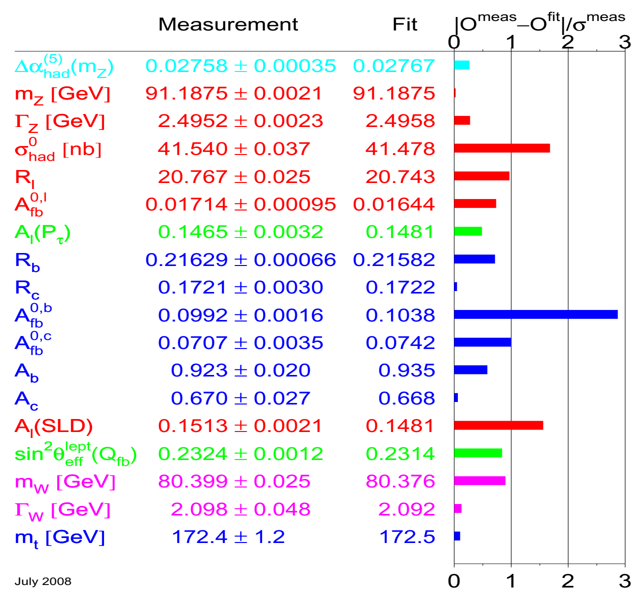

Figure 9. Electroweak data used in the SM fit

5. Enter the LHC Programme

The world stands today on the verge of a new era of scientific discovery. The brand new atom smasher under construction at the European Laboratory of Particle Physics (CERN) located a few kilometres out-

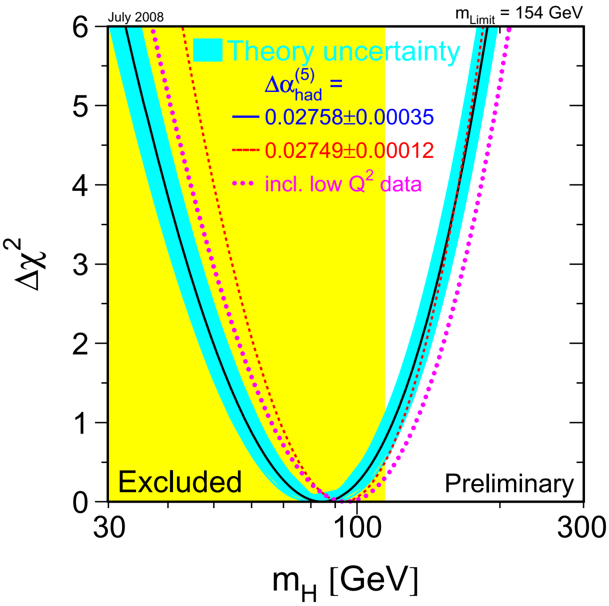

Figure 10. Electroweak data used in the SM fit

side Geneva, Switzerland, will begin operation in 2009. Conceptualised around a quarter century back, approved for construction in the mid-1990s and now almost a decade in the making, this technological marvel of a machine which accelerates counter rotating beams of protons in two steel pipes 27 km in circumference is ready to operate. It will become the highest energy particle accelerator in the world with 7 times as much energy compared to the existing accelerator, Tevatron, at Fermilab, USA.

Its scientific goals are truly stupendous, ranging from understanding the microcosm of the sub-nuclear world to attempting to answer the question what was the universe like at the very beginning of time, a few moments after the Big Bang. Is the universe really filled with an all pervading Higgs field, as postulated by theorists, or is there some other explanation for the origin of mass itself? Does dark matter, which constitutes 25% of the universe, really consist of the so-called supersymmetric (SUSY) particles which form an integral part of the modern so-called theory of everything that scientists are working overtime on? These questions relating to the nature of the universe are some of the most fundamental questions that have been asked by humankind ever since men started to wonder about the world around them. And the new atom smasher called the LHC has the capability of answering them. Science will not be the same after a few years, whether the answers to the above questions are in the affirmative or not, in which case there will be a paradigm shift in theory itself.

There are four experimental collaborations in the LHC programme: two large experiments, ATLAS and CMS, which are geared more towards proton-proton collisions; ALICE which is meant to study heavy ion collisions; and LHCb which will mainly study b-quark production and decay. India is participating in CMS and ALICE experiments and in this article Indian participation in CMS will be discussed briefly.

5.1. The CMS Detector and Indian Contributions

A view of the CMS detector is shown in Fig. 11.

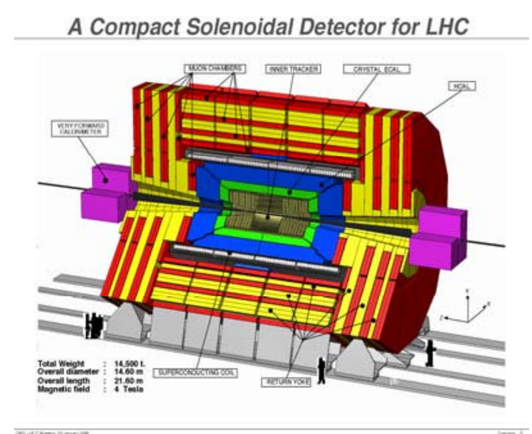

Figure 11. CMS detector

It is a typical high energy physics detector, cylinderical in geometry, surrounding the beam pipe at the intersection region. Closest to the beam pipe there is a silicon pixel vertex detector followed by an all-silicon microstrip tracker. Next is the electromagnetic calorimeter consisting of lead-tungstate crystals. This calorimeter will provide an excellent electromagnetic energy resolution that could be critical in the detection and mass measurement of a low mass Higgs as indicated by fit to the EW data within the SM framework. Next is the hadron calorimeter whose active elements are plastic scintillator tiles and the absorber is brass. All these detectors are surrounded by a 4 tesla superconducting solenoidal magnet that will enable precise momenta of charged particles as well as sweep away the very low momentum uninteresting debris and thus reduce background. Just outside the magnet is the outer hadron calorimeter (HO), consisting of layers of plastic scintillator, to measure the remnant hadronic energy after the particles have passed through the magnet coil that acts as another layer of absorber. Indian groups were responsible for the R&D and fabrication of this detector. The outermost layers are four muon detection layers with drift tubes as the detector elements. A similar layering of detectors is present in the forward-backward directions, with an additional element: the silicon pre-shower detector whose active elements are silicon microstrip detectors. This detector is necessary to distinguish between a γ and a π^0, in order to effectively identify the Higgs $\rightarrow \gamma\gamma$ decay mode, which will be the only way to detect a light Higgs. Indian groups have participated in providing 25% of the detectors for this. The fabrication took place in BEL, Bangalore. The placement of the HO and silicon pre-shower detector within the CMS detector is shown in Figs. 12 and 13.

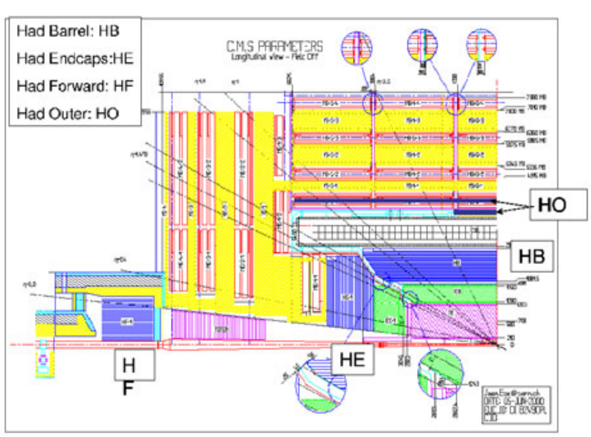

Figure 12. Quarter longitudinal view of the CMS detector showing HO placement

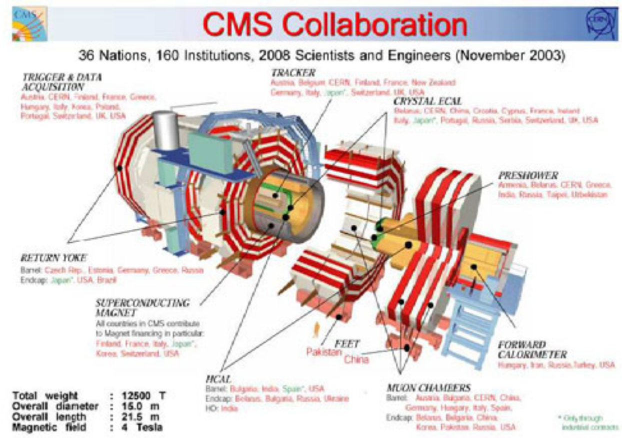

Figure 13. Opened out view of the CMS detector, showing placement of the silicon pre-shower detector

The HO detector has been fully installed and commissioned within the overall CMS detector and the silicon PSD will be installed during the 2008–09 shut down, both as per CMS schedule.

Peta-bytes of data per year will start flowing once the LHC starts operation. In order to reconstruct raw data in the form of pp interactions, called events, to generate simulated events, and to allow teams spread worldwide to analyse this data to extract physics, the only possible scenario was to go in for GRID technology. This is the child of the worldwide-web which was invented at CERN for making available high energy data to various geographically separated laboratories. The GRID does one better: with the help of suitable middleware it enables relatively cheap computer farms located worldwide to act as a coherent computing engine. Such a tier-2 centre is now becoming operational at TIFR, being connected to CERN by a 1 Gbps link.

Indian scientists in CMS have been very actively preparing for physics analyses using simulated data, working out and fine tuning algorithms which would sift the wheat from the chaff in real data. A number of studies have been carried out for detection of different types of Higgs, of SUSY, studying the W and Z, etc. Thus Indian groups are well prepared for extracting exciting science when real data becomes available.

5.2. Physics at the LHC

While there have been accelerators before, it is for the first time in history that the TeV energy scale will become available for systematic scientfic exploration. One will get definitive answers to the most pressing questions of the day: experimental evidence on the EW symmetry breaking via search for the Higgs and on the existence of supersymmetric particles, which form an essential building block of the most ambitious theories of everything or supergravity theories. This would also throw light on the nature of dark matter; if SUSY is discovered in its popular (R-parity conserving) form, then the lightest SUSY particle could account for the dark matter.

Apart from the above two critical issues, detailed studies of the top quark would become possible, and also of the b-quark, decays of which may still bring surprise discoveries. The programme of colliding heavy ions (Pb on Pb) would extend that energy reach far beyond what is available today at RHIC and again could be decisive in confirming the existence of quark-gluon plasma and studying its properties.

Finally the most exciting new physics would probably come in the form of totally unexpected discoveries upon breaching the tera-energy scale.

As there are only theories and models about physics beyond the SM at these energy scales, below we will only mention two topics: how the SM Higgs would be discovered and how the first evidence of SUSY could be detected.

5.3. The Standard Model Higgs at the LHC

As mentioned earlier, indirect experimental evidence points strongly to a Higgs of relatively low mass, < 154 GeV at 95% confidence level. And LEP has excluded a mass < 114.4 GeV. Moreover, within the minimal SUSY extension of the SM (MSSM) the lightest neutral Higgs must be low mass, less than around 140–150 GeV. At such low mass the only decay mode that will be detectable above QCD background is the $H \to \gamma\gamma$ mode. Thus a lot of effort has gone into improving the electromagnetic energy resolution of the detectors; in particular CMS went in for lead tungstate crystals for this purpose. For an assumed Higgs mass of 130 GeV, the effective mass distribution of two photons in the CMS detector is shown in Fig. 14 for an integrated luminosity of 100 fb^{-1}.

On the other hand, if the Higgs is heavier than 180 GeV it can decay into a ZZ pair, whose leptonic decay modes provide a gold plated signature for detecting Higgs. Upto about 400 GeV Higgs mass an integrated luminosity of 20 fb^{-1} is sufficient to discover and measure the Higgs mass. Beyond that around 100 fb^{-1} would be required. This is shown in Fig. 15.

While the discovery of a neutral Higgs would establish its existence, it would take some while to make detailed studies to determine if its a SM or beyond SM Higgs (in MSSM there are three neutral Higgs). Discovery of a charged Higgs (as in MSSM) would clearly indicate the presence of physics beyond the SM.

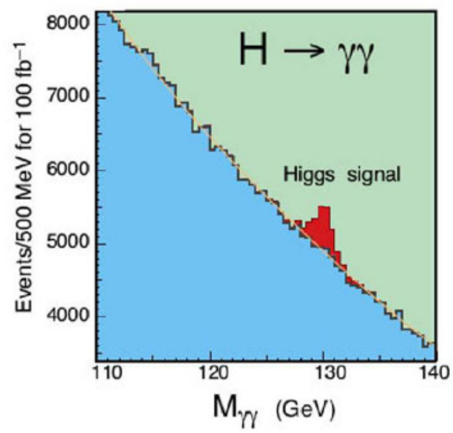

Figure 14. Higgs $\to \gamma\gamma$ reconstruction in CMS. Higgs mass = 130 GeV

5.4. SUSY at the LHC

One of the continuing themes in science has been the quest for unification. Electricity and magnetism unified into the electromagnetic theory of Maxwell. Then the unification of this with weak interaction theory to give us the EW theory. A further unification of EW with the theory of strong interactions, QCD is accommodated within the supersymmetric framework. The two become unified at around 10^{15} GeV mass scale. Within this framework each known particle has a supersymmetric partner with the spin differing by half unit. Thus the normal fermions have scalar superpartners and the normal bosons have spin half superpartners. The spectrum is shown in Fig. 16.

Under the popular assumption of R-parity conservation s-particles would be produced in pairs and at the end of the decay chain the lightest s-particle would escape undetected. As the masses of these particles would be at least a few hundred GeV the typical signature of such an event would be large amount of missing energy. A typical decay chain is as shown in Fig. 17.

Leptons being easy to identify and measure, decay chains involving leptons is a clean way of identifying s-particle producing events. A characteristic signature is a sharp drop in the effective mass of the dilepton pair called the dilepton edge. The mass of the s-particle can be inferred from this. An example is shown in Fig. 18.

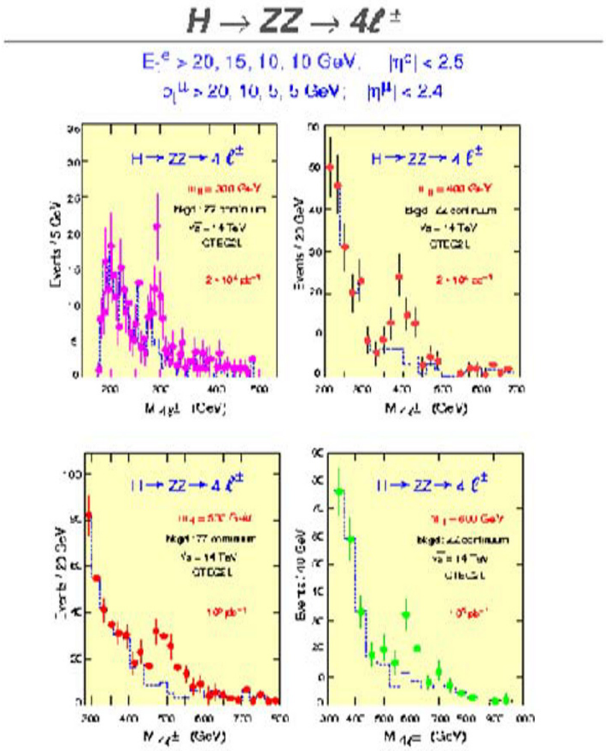

Figure 15. Higgs $\rightarrow ZZ \rightarrow \ell eptons$ reconstruction in CMS

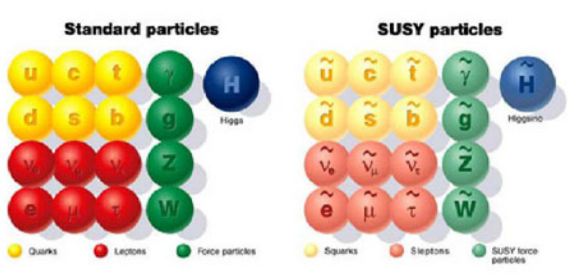

Figure 16. SUSY spectrum

Successive application of this method can allow one to reconstruct the masses of the particles.

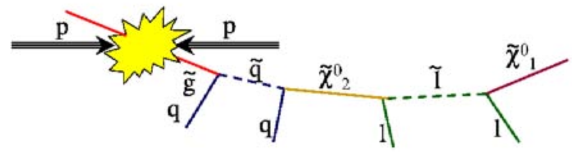

Figure 17. SUSY decay chain

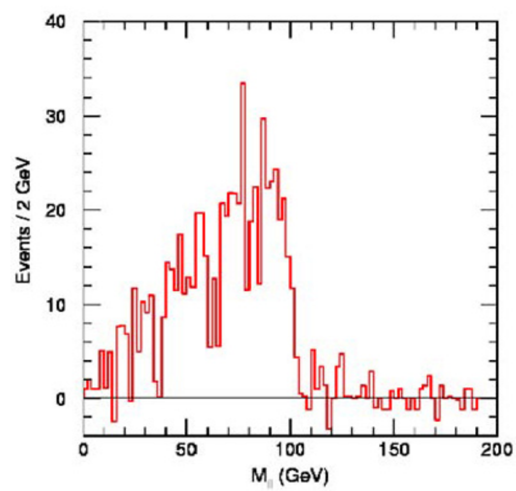

Figure 18. SUSY discovery by leading di-lepton leading edge

6. Summary

The scientific world is at a major junction in history. With the turning on of the LHC in 2009 many outstanding questions about the universe would become addressable, among them the origin of mass and the nature of dark matter. One looks forward to many years of exciting discoveries.

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