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CURRENT ISSUES IN THE PHENOMENOLOGY OF PARTICLE PHYSICS

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ABSTRACT

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Invited plenary talk presented at the
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Current Issues in the Phenomenology of Particle Physics[a]

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Abstract

The present status of the Standard Model and its experimental tests are reviewed, including indications on the likely mass of the Higgs boson. Also discussed are the motivations for supersymmetry and grand unification, searches for sparticles at LEP, neutrino oscillations, and the prospects for physics at the LHC.

1 Introduction to the Standard Model and its Deficiencies

The building blocks of the Standard Model[1] of particle physics are listed in Table 1. The fundamental electromagnetic, weak, strong and gravitational forces are carried by the photon γ, the $W^{\pm}$ and Z^0, the gluon and (we firmly believe) the graviton, respectively. Of these, the γ, gluon and graviton are thought to be massless, whilst the $W^{\pm}$ and the Z^0 are as heavy as medium-sized nuclei: 80.356 ± 0.125 and 91.1863 ± 0.0020 GeV, respectively[2], leading to the very short $\simeq 10^{-16}$ cm range of the weak forces, as opposed to the very large and probably infinite ranges of the electromagnetic forces. One of the greatest issues in particle physics - which will be discussed extensively in this talk - is to understand why the $W^{\pm}$ and Z^0 intermediate bosons behave so differently from their peers, although their basic properties, such as spins and couplings to matter particles, seem so similar.

The fundamental particles of matter, the quarks and leptons, are also listed in Table 1, together with the information we currently possess concerning their masses. As we shall discuss in more detail later on, experiments at LEP have told us that there can be no more than three light neutrino species[2], and hence presumably no more than three charged leptons and three corresponding pairs of quarks. Thus, the discovery last year of the top quark t[3] would appear to complete the Mendeleev table of elementary particles. A basic issue is to

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[a] Invited plenary talk presented at the Inaugural Conference of the Asia-Pacific Center for Theoretical Physics, Seoul, Korea, June 1996.

Table 1: Particles in the Standard Model

Gauge Boson	Mass	Range of Force
Photon (γ)	0	$> 10^{21}$ cm
$W^{\pm}$	80.356(125) GeV	$\sim 10^{-16}$ cm
Z^0	91.1863(20) GeV	$\sim 10^{-16}$ cm
gluon (g)	0	$\sim 10^{-13}$ cm

Lepton	Mass	Quark	Mass
$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix}$	1/2 MeV < 1 eV	$\begin{pmatrix} u \\ d \end{pmatrix}$	~ 5 MeV ~ 8 MeV
$\begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix}$	105 MeV < 0.2 MeV	$\begin{pmatrix} c \\ s \end{pmatrix}$	1.5 GeV ~ 100 MeV
$\begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$	1.78 GeV < 23 MeV	$\begin{pmatrix} t \\ b \end{pmatrix}$	172 ± 6 MeV 5 GeV ?

understand the number and variety of types of fundamental matter particle, as well as the range of their masses. As you see from Table 1, currently we only have upper limits on the neutrino masses[4]. Another of the major current issues in particle physics to be discussed later is whether they are strictly zero, as suggested by the Standard Model, or are non-zero as suggested by most attempts to grand unify the strong, weak and electromagnetic interactions.

Experiments at LEP and elsewhere have by now tested the Standard Model, as summarized in Table 1, down to levels from 1% to 1 per mille. Althought there have been a few 'anomalies' to be discussed in more detail later, there are no confirmed accelerator data that disagree with the Standard Model. Nevertheless, particle theorists are convinced that it is incomplete, for reasons that we now review briefly. First of all, the Standard Model contains at least 19 parameters: 3 gauge couplings $g_{1,2,3}$ for the $U(1), SU(2)$ (electroweak) and $SU(3)$ (strong) factors in the Standard Model gauge group, and 1 CP-violating vacuum phase angle θ_3 for the strong interactions; 6 quark masses, 3 lepton masses and 4 parameters to describe the couplings of the $W^{\pm}$ to quarks; and the masses of the $W^{\pm}$ and the Higgs Boson H (of which more later). The issues motivating theoretical attempts understand these many parameters by going beyond the Standard Model can be collected into the following 3 categories.

The Issue of Unification: Can the disparate fundamental forces listed in Table 1 be regarded as different aspects of a single Grand Unified Theory (GUT)? This could have observable implications for proton decay as well as neutrino masses, and predicting testable relations between the Standard Model gauge couplings g_i and between quark and lepton masses.

The Issue of Flavour: Why are there so many different types of quarks and leptons, and what explains their mixing and CP violation? Some suggest that this might reflect a new level of compositeness within the matter particles, a speculation revived recently in connection with data from the Fermilab $\bar{p}p$ collider[6].

The Issue of Mass: What is the origin of the particle masses? Is it the Higgs Boson postulated in the Standard Model? If so, why are the masses of the Standard Model particles so much smaller than the Planck Mass $M_P \simeq 10^{19}$ GeV[5], which is the only candidate we have for a fundamental mass scale in physics? Is this hierarchy of masses protected by supersymmetry?

All of these issues should be resolved within the **Theory of Everything** (TOE), which should also include gravity and reconcile it with quantum mechanics, explain the origin of space and time and why there are just 4 large dimensions, etc.. The only candidate we have is superstring theory, which is discussed here by Gross[7]. My rôle at this meeting is to address the previous issues, which we start by examining the bedrock of the Standard Model.

2 Testing the Standard Model at LEP and Elsewhere

Experiments to test the Standard Model have been carried out over a large range of energies and distance scales, from measurements of parity violation in atoms at effective momentum transfers $Q^2 \simeq 10^{-10}$ GeV^2, through experiments scattering leptons (e, μ, ν) on fixed nucleon targets at $Q^2 \simeq 1$ to 100 GeV^2, to e^+e^-, $\bar{p}p$ and ep collider experiments at $Q^2 \simeq 10^4$ GeV^2. Of these, the most precise so far have been those carried out in e^+e^- annihilation into Z^0 particles at LEP (at CERN) and the SLC (at SLAC). In particular, the largest accelerator in the world is LEP with a circumference of $\simeq 27$ km (more on this later), whose energy has recently been upgraded from $\simeq 90$ GeV around the Z^0 peak, first to 130/140 GeV at the end of 1995 (called LEP 1.5), then to 161 GeV in mid-1996 (called LEP 2W), and to 172 GeV in late 1996.

Annihilation through the Z^0 produces what is perhaps the most perfect Breit-Wigner peak ever seen. The basic measurements made at the Z^0 peak include the following[8]. The **Total Hadronic Production Cross Section** is given at the classical level by

$$\sigma_h^0 = \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_h}{\Gamma_Z^2} \tag{1}$$

where $\Gamma_{e,h}$ are the widths for Z^0 decays into e^+e^- and hadrons, respectively, and

$$\Gamma_Z = \Gamma_e + \Gamma_\mu + \Gamma_\tau + N_\nu \Gamma_\tau + \Gamma_h \tag{2}$$

is the **Total Decay Rate** of the Z^0. Quantum (radiative) corrections reduce the total cross section (1) by tens of %, but are now calculated with precisions at the per mille level[8]. Other important measurements are those of the **Leptonic Partial Decay Rates** $\Gamma_\ell = \Gamma_{e,\mu,\tau}$, which are equal in the Standard Model, via the ratios

$$R_\ell = \frac{\Gamma_h}{\Gamma_\ell} \tag{3}$$

A measurement that has ignited considerable interest during the past year has been that of the **Partial Decay Rate for Z^0 decay into $\bar{b}b$**, parametrized by

$$R_b = \frac{\Gamma_b}{\Gamma_h} \tag{4}$$

A comparison of the measurements of all the visible Z^0 decays with that of Γ_Z (2) via (1) enables the **Invisible Z^0 Decay Width**

$$\Gamma_{inv} = N_\nu \Gamma_\nu \tag{5}$$

to be measured, and hence, since Γ_ν can be calculated very precisely in the Standard Model, the number of equivalent light neutrino species N_ν.

In addition to these cross-section measurements, there are also precision determinations of the **Forward-Backward Asymmetries**

$$A_{FB} = \frac{\int_0^1 d(\cos\theta) \frac{d\sigma}{\cos\theta} - \int_{-1}^0 d(\cos\theta) \frac{d\sigma}{\cos\theta}}{\sigma} \tag{6}$$

for the various flavours of leptons and quarks, where θ is the polar angle relative to the incoming e^- beam, as well as the **Final-State τ Polarization**. It is also possible to measure the **Polarized-Beam Asymmetry** A_{LR}, defined as the difference in cross sectioxns for left- and right-polarized e^- beams:

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \tag{7}$$

if one has longitudinally-polarized beams, as at the SLC [9]. LEP only has transversely-polarized beams, which are useful in their own way, as we shall see shortly.

The current set of precision high-energy electroweak measurements at LEP, the SLC and the Fermilab $\bar{p}p$ collider is shown in Table 2, and I shall now comment on some of the most interesting items on the list [2]. Most basic of all is the measurement of the Z^0 mass from LEP. This requires very precise calibration of the LEP beam energy, which is provided by resonant destruction of the transverse beam polarization. In order to obtain the stated precision, which is comparable to the accuracy with which the Fermi weak coupling is measured in μ decay, a myriad of delicate effects such as the temperature and humidity of the LEP tunnel must be taken into account. Effects have also been seen which are due to the tides, which expand and contract the rock in which LEP is embedded, altering the circumference of the machine [10]. Because of the RF tuning of LEP, these alterations cause the orbits of the beams to move relative to the LEP magnets, which in turn alters the beam energies by several MeV, as seen in Fig. 1(a). There are other effects that can alter the circumference of LEP, and hence the beam energy. One is whether it has been raining: if the water table in the Jura mountains rises, the absorbent rock expands, as seen in Fig. 1(b). Another is the water level in Lake Geneva: each Spring, lake water is let out to make room for molten snow from the Alps. When the weight of the lake water is removed, the rock rises and expands with a time delay of about 100 days, as seen in Fig. 1(c) [11]. All of these variations have been taken into account in the calculation of M_Z shown in Table 2.

Another effect first surfaced as variations in the LEP energy during fills, which diminished during the night [12]. These were eventually traced to nearby electric trains: see the passage of a TGV in Fig. 1(d). The explanation is that some of the return current passes through the Earth, and in particular through LEP (which is a relatively good conductor). Since the LEP beam energy shifted during the course of each fill, and since the beam was calibrated at the ends of the fills, there was a systematic correction to the beam energy and hence M_Z of a few MeV, which has now been taken into account in the value quoted in Table 2 [2].

Table 2: High-Energy Precision Electroweak Data Set

M_Z	91.1863 (20)	GeV	A^b_{FB}	0.0979 (23)
Γ_Z	2.4946 (27)	GeV	A^c_{FB}	0.0733 (49)
σ^0_n	41.508 (56)	nb	$\sin^2\theta_{eff}(Q_{FB})$	0.2320 (10)
R_L	20.778 (29)		M_W	80.356 (125)
A^L_{FB}	0.0174 (10)		$\sin^2\theta_W(A_{LR})$	0.23061 (47)
A_τ	0.1401 (67)		R_b (SLC)	0.2149 (38)
A_e	0.1382 (76)		A_b (SLC)	0.863 (49)
R_b	0.2179 (12)		A_c (SLC)	0.625 (84)
R_c	0.1715 (56)			

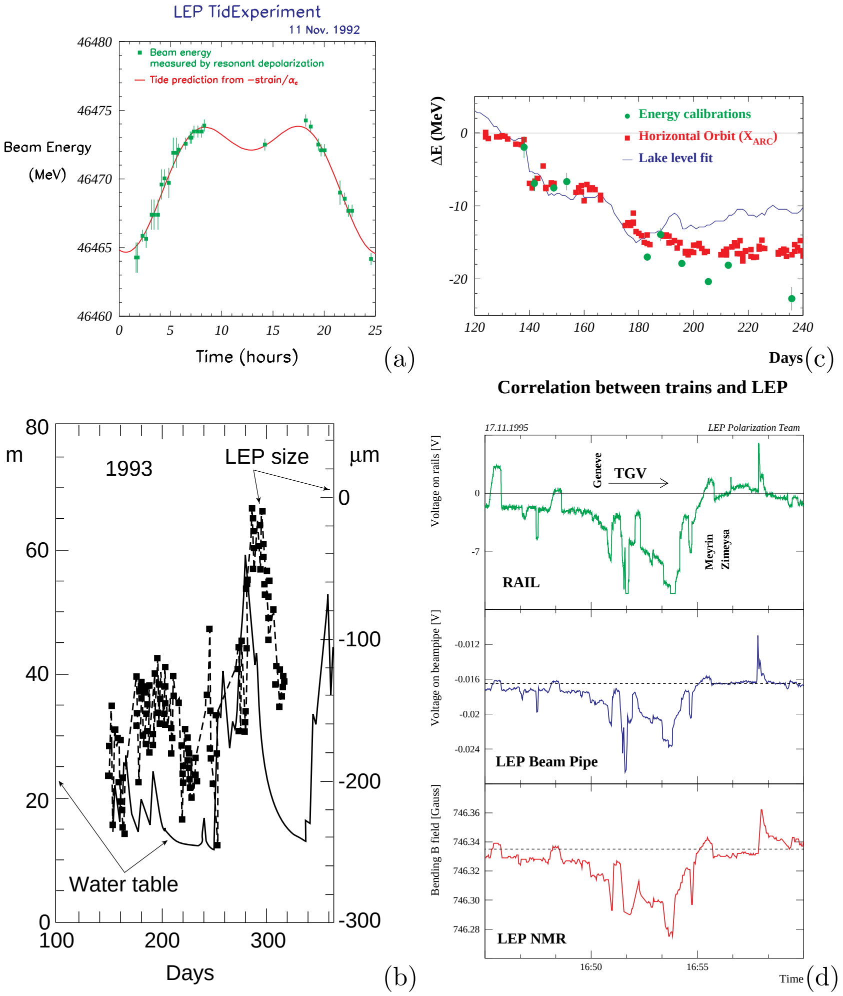

Figure 1: Sensitivity of the LEP beam energy to (a) tides [10]: the solid lines are due to a tidal model, (b) the water table in the Jura mountains and (c) the level of Lake Geneva [11], and (d) the "TGV effect" on the LEP beam energy [12].

Turning now to some of the other measurements in Table 2, the relative beam energy calibrations are also important for the determination of Γ_Z, but the TGV effect is not so important, since it tends to move all the beam energies by similar amounts. Last year, measurements of R_b and R_c appeared to come into significant disagreement with the Standard Model predictions, but this anomaly now seem to have evaporated, as we discuss in section 5. In the previous year, there had been some concern about the compatibility of the LEP and SLC measurements of the electroweak mixing angle $\sin^2\theta_W$, but this no longer seems to be a significant discrepancy [2,9]. Finally, note the accuracy with which the effective number of light ν species has now been measured [2]:

$$N_\nu \, = \, 2.989 \pm 0.012 \tag{8}$$

I had always hoped N_ν would turn out to be non-integer, say π or, even better, e, but this was not to be. Even so, the measurement (8) is a useful constraint on supersymmetric extensions of the Standard Model, as we discuss later.

What use are the precise numbers in Table 2? One answer is provided by their sensitivity to the masses of unseen particles, via quantum (radiative) corrections. For example, at one loop:

$$M_W^2 \sin^2\theta_W = M_Z^2 \cos^2\theta_W \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r) \tag{9}$$

and the correction Δr is sensitive to the masses of the top quark and the Higgs boson. In the case of the top, the sensitivity is quadratic [13]:

$$\Delta r \, \simeq \, \frac{3G_\mu}{8\pi^2\sqrt{2}} m_t^2 \tag{10}$$

for $m_t >> m_b$. This sensitivity enables precision data to be used to a theoretical prediction for m_t. In the case of the Higgs boson, the sensitivity is unfortunately only logarithmic at the one-loop level [14]:

$$\Delta r \, \simeq \, \frac{\sqrt{2}G_\mu}{16\pi^2} M_W^2 [\frac{11}{3} \ln(\frac{M_H^2}{M_W^2}) + \ldots] \tag{11}$$

making the use of precision data to predict M_H much more delicate.

If just one quantum correction is determined, e.g., Δr from measurements of $M_{W,Z}$ (9), a trade-off between the values of m_t and M_H is possible, but these can both be determined if enough quantum corrections are pinned down [15].

Our latest prediction of m_t, based on a χ^2 analysis of the available precision electroweak data shown is [15]

$$m_t \; = \; 157^{+16}_{-12}\,\mathrm{GeV} \tag{12}$$

including the error associated with leaving M_H a free parameter. This prediction of m_t is compatible with the latest Fermilab measurement [16]:

$$m_t \; = \; 175 \pm 6\,\mathrm{GeV} \tag{13}$$

The consistency between (12) and (13) is a non-trivial check of the Standard Model at the quantum level. The agreement between (12) and (13) also means that they can legitimately be combined to yield [15]

$$m_t \; = \; 172 \pm 6\,\mathrm{GeV} \tag{14}$$

which is the current best estimate of m_t within the Standard Model.

3 The Origin of Mass

Let us now address in more detail the central issue of the origin of mass: How come the $W^{\pm}$ and Z^0 are massive, whereas the γ and gluon are massless? The core of this problem lies in the fact that a massless spin-1 particle has only two polarization states with helicities ± 1, whereas a massive spin-1 particle has three polarization states: $1, 0-1$. The suggestion is that the primordially massless $W^{\pm}$ and Z^0 combine with extra spin-0 particles which provides their third polarization states, enabling them to become massive. As we shall discuss in more detail shortly, realistic electroweak models require there to exist at least one physical scalar, in addition to the spin-0 degrees of freedom 'eaten' by the massive $W^{\pm}$ and Z^0. there is no direct experimental evidence for such a Higgs boson, and searches at LEP have established the lower limit

$$M_H \; \geq \; 66\,\mathrm{GeV} \tag{15}$$

There are, however, theoretical arguments based on unitarity, which suggest that [17]

$$M_H \; \leq \; 1\,\mathrm{TeV} \tag{16}$$

and hence that the Higgs boson may lie within the reach of the next generation of accelerators, such as the LHC discussed in section 7.

At a more theoretical level, the problem of mass can be seen as requiring a 'breakdown' of the electroweak gauge symmetry. To avoid non-renormalizability problems in higher-order calculations, this 'breakdown' should only be spontaneous, i.e., it should be due to the condensation in the electroweak vacuum of some field X with non-zero electroweak isospin:

$$M_{W,Z} \neq 0 \;\; <=> \; < 0|X_{I,I_3}|0 > \neq 0 \tag{17}$$

The numerical values of the $W^{\pm}$ and Z^0 masses indicate a particular ratio

$$\rho \, = \, \frac{M_W^2}{M_Z^2 \cos^2\theta_W} \simeq 1 \tag{18}$$

which corresponds to the simplest choice $I = 1/2$ [18]. This is what is required also to give masses to the quarks and leptons, and was the choice of Weinberg and Salam when they originally wrote down the Standard Model [1].

The next Big Question is whether this field X sitting in the vacuum is elementary (as Weinberg and Salam postulated) or composite. The latter possibility may be appealing to many of you from a condensed-matter background, who are familiar with the role of Cooper pairs in superconductivity and pairing in superfluid ^{3}He, and could also be reminiscent of quark condensation in QCD: $< 0|\bar{q}q|0 > \neq 0$. Composite Higgs models have included $\bar{t}t$ condensate models [19] - but these initially wanted $m_t > 200$ GeV, and are now looking for epicycles - and so-called technicolour models [20], which postulate new fermions bound by new interactions that become strong on an energy scale around 1 TeV. At least the simplest versions of such models seem to be disfavoured by a χ^2 analysis of the precision electroweak measurements [21], as seen in Fig. 2, and variations in these models are now also being explored.

In the absence so far of a credible composite alternative, we are led to examine more closely the elementary possibility. If there is just a single $I = 1/2$ Higgs doublet, consisting of two complex fields, the three degrees of freedom eaten by the $W^{\pm}$ and Z^0 leave behind a single physical higgs boson to be detected. A χ^2 analysis of precision electroweak data within the minimal Standard Model with just this one physical elementary Higgs boson leads to the estimate [15], see also [2]:

$$M_H \, = \, 145\,^{+164}_{-77}\,\text{GeV} \tag{19}$$

Figure 3 displays $\Delta\chi^2 = 1, 4$ contours in the M_H, m_t plane, for a fit [15] to the precision electroweak data which includes the direct CDF and D0 measurements of m_t. These results are quite consistent with the idea of a weakly-coupled elementary Higgs boson within reach of planned accelerators.

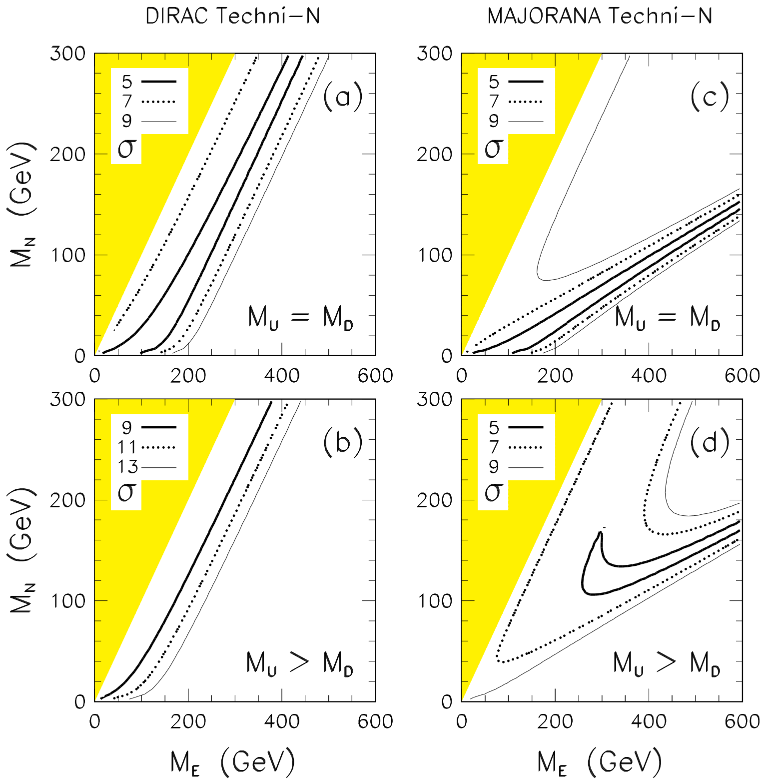

Figure 2: Contours [21] of $\sigma \equiv \sqrt{\Delta\chi^2}$ for one-generation models with either Dirac technineutrinos (a), (b) or a Majorana technineutrino (c), (d). Note that $\sigma \gtrsim 4.3$ in all of the TC parameter space, to be compared with $\sigma = 2.6$ in the SM at the reference point ($m_t =$ 170 GeV, $M_H = M_Z$). In the case of techniquark mass degeneracy ($M_U = M_D$), however, the Dirac model becomes highly disfavoured. In all cases, $\xi = 1/2$ is assumed.

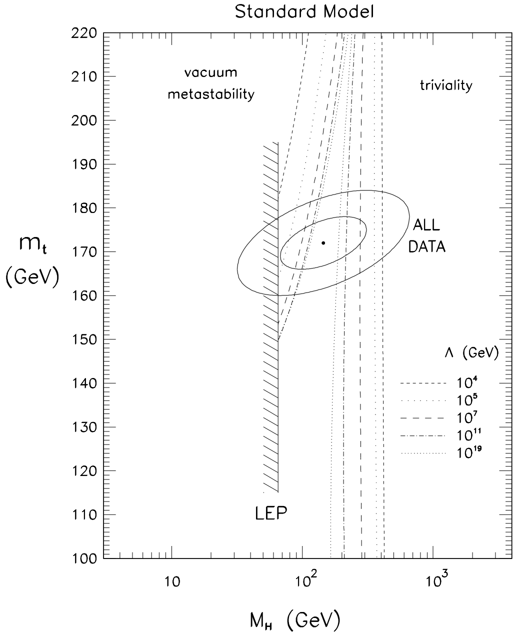

Figure 3: Indirect bounds [15] on (M_H, m_t) and one-sided experimental and theoretical limits in the Standard Model. The solid ellipses represent the 1-σ and 2-σ contours from the best-fit Gaussian distribution obtained by analysing all electroweak precision data, including the measurement of m_t at CDF and D0. The hatched line is the LEP lower bound on M_H . The other curves represent the lower and upper limits on M_H from vacuum metastability and triviality respectively, as functions of the scale of new physics Λ.

4 Motivations for Supersymmetry

There are, however, theoretical problems with such a simple possibility, associated with the gross disparities in the known mass scales in physics. The only candidate we have for a fundamental mass scale is the Planck mass, related to Newton's constant: $M_P = 1/\sqrt{G_N}$. Why is $M_W \ll M_P$? This is commonly known as the Hierarchy Problem[5], which can be rephrased as: why is $G_F \gg G_N$? Some atomic and condensed-matter physicists may consider this question remote from their concerns, but it is equivalent to the question: why is the Coulomb potential in an atom so much smaller than the Newtonian potential, i.e., why is $e^2 \gg G_N m^2$, where m is a typical particle mass?

These questions are particularly worrying for models with an elementary Higgs boson, because its mass is subject to large quantum corrections, meaning that the small physical value (16) can be obtained only at the expense of extreme fine tuning. One usually prefers that quantum corrections to a measurable quantity not be much larger than its physical value, since otherwise its value would seem unnatural[5]. An example of a physical quantity with naturally small quantum corrections is a fermion mass:

$$\delta m_f \simeq (\frac{\alpha}{\pi}) m_f \ln(\frac{\Lambda}{m_f}) \tag{20}$$

which is not much greater than m_f for any plausible value of the cutoff $\Lambda \leq M_P$.

The same cannot be said for quantum corrections to the mass of an elementary Higgs boson, which are quadratically divergent:

$$\delta M_H^2 \simeq g_{f,W,H}^2 \int^{\Lambda} \frac{d^4k}{(2\pi)^4} \frac{1}{k^4} \simeq (\frac{\alpha}{\pi}) \Lambda^2 >> M_H^2 \tag{21}$$

If one inserts a guess for the cutoff $\Lambda \simeq M_P$ or M_{GUT} up to which the Standard Model may be valid, one gets a correction which is many orders of magnitude greater than the possible physical value of M_H.

This unpleasant conclusion can be avoided by observing that the fermion and boson loops have opposite signs:

$$\delta M_{W,H}^2 \simeq -(\frac{g_F^2}{4\pi^2})(\Lambda^2 + M_F^2) + (\frac{g_B^2}{4\pi^2})(\Lambda^2 + M_B^2) \tag{22}$$

The leading quadratic divergences will therefore cancel if there are equal numbers of bosons and fermions: $N_B = N_F$, and if their couplings are identical:

$g_B = g_F$. These are the conditions that a field theory manifest supersymmetry[22]. After the cancellation which it enforces, the remainder

$$\delta M_{W,H}^2 \simeq (\frac{\alpha}{\pi})|M_B^2 - M_F^2| \tag{23}$$

will be small, rendering the hierarchy natural, if

$$|M_B^2 - M_F^2| \,\leq\, 1\,\mathrm{TeV}^2 \tag{24}$$

It is this squared-mass difference that should be interpreted as the cut off Λ^2 at which new physics modifies the Standard Model. Although there are other arguments for supersymmetry[b], such as its intrinsic beauty and its necessity for the consistency of string theory, this is the only argument to indicate that supersymmetry should appear at an accessible mass scale. It should be emphasized that this argument is, nevertheless, qualitative and a matter of taste: even an unnatural theory may be renormalizable. Mathematically, all one needs for renormalizability is that all Λ cutoff dependence can be absorbed by a finite set of bare parameters: *a priori* there is no need for the bare parameters and the quantum corrections to be comparable, as is implied by the naturalness argument. The latter is a physical argument motivated by the absence of fine tuning, not a precise mathematical requirement.

The first question you might ask is whether any of the known fermions (quarks, leptons) could be the supersymmetric partners of any of the known bosons ($\gamma, W^\pm, Z^0$, Higgs, gluon). The answer is no[24], because the fermions and bosons have different internal quantum numbers, and hence different couplings. For example, quarks are in triplets **3** of colour, whereas the the known bosons are singlets or octets **8** of colour, and leptons are the only particles that carry lepton number L. One is therefore led to introduce supersymmetric partners for all the known particles, as shown in Table 3. Supersymmetry is not economical in particles, though it is economical in principle!

Sparticle searches at accelerators have so far been unsuccessful: the latest limits on squark and gluino production in $\bar{p}p$ collisions[25] indicate that

$$m_{\tilde{q},\tilde{g}} \,>\, 200\ \mathrm{GeV} \tag{25}$$

and LEP limits on slepton production[26] indicate that

$$m_{\tilde{\ell}} > 70\,\mathrm{GeV} \tag{26}$$

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[b] In particular, safeguarding the hierarchy in some GUTs benefits from the absence[23] of certain logarithmic divergences in supersymmetric theories.

Table 3: Particles and Sparticles

Name		Spin	Sname		Spin
quark	q	1/2	squark	$\tilde{q}$	0
lepton	ℓ	1/2	slepton	$\tilde{\ell}$	0
photon	γ	1	photino	$\tilde{\gamma}$	1/2
	Z^0	1	zino	$\tilde{Z}$	1/2
	$W^{\pm}$	1	wino	$\tilde{W}^{\pm}$	1/2
gluon	g	1	gluino	$\tilde{g}$	1/2
Higgs	$H^{0,\pm}$	0	higgsino	$\tilde{H}^{0,\pm}$	1/2
graviton	G	2	gravitino	$\tilde{G}$	3/2

The $\tilde{W}^{\pm}$ and $\tilde{H}^{\pm}$ mix to yield two mass eigenstates called charginos, and the $\tilde{\gamma}$, $\tilde{Z}$ and $\tilde{H}^0$ mix to yield four mass eigenstates called neutralinos.

Although disappointing, these limits do not yet bite far into the expected mass range (24). Completing these searches will be the task of future accelerators, such as the LHC discussed in section 7.

Of particular interest is the lightest supersymmetric particle (LSP), denoted by χ, which is expected to be stable in many models, and is therefore a good candidate for the Cold Dark Matter (CDM) believed to constitute most of the matter in the Universe. Fig. 4(a) shows the experimental lower limit on its mass,

$$m_\chi \geq 12.8\,\mathrm{GeV} \tag{27}$$

obtained by the ALEPH collaboration[27] by combining searches at LEP 1 and 1.5, and assuming large slepton masses. As discussed in [28], this and other loopholes in the ALEPH analysis that may be filled by additional theoretical and cosmological inputs, and, as also seen in Fig. 4(a), the bound (27) may be strengthened[c] to

$$m_\chi \geq 21.4\,\mathrm{GeV} \tag{28}$$

As can be seen in Fig. 4(b), in many models the LSP χ has a relic cosmological density in the range of interest for cosmological CDM[30], and there are reasonable prospects that it could be detected either directly or indirectly[31].

In view of all the experimental disappointments to date, are there any experimental reasons for believing in supersymmetry? In my view, there are two encouraging tentative indications. One is the apparent lightness (19) of the Higgs boson favoured by the precision electroweak data[15] (see also[2]). The mass of the lightest Higgs boson in the minimal supersymmetric extension of the Standard Model can be calculated[32], and it comes out below 130 GeV or so, in high consistency with (19). The second tentative indication is furnished by the consistency of LEP and other measurements of the Standard Model gauge coupling strengths $\alpha_{1,2,3}$ with the prediction of a minimal supersymmetric GUT[33]. As seen in the left-hand part of Fig. 5, GUTs both with and without supersymmetry are in good qualitative agreement with the measurements. However, when we blow up the vertical scale, as shown in the other two parts of Fig. 5, we see that the non-supersymmetric GUT prediction disagrees with the data, whereas the minimal supersymmetric GUT is very close. Plausible variations in the supersymmetric GUT model-building can bring the prediction into perfect agreement with the data[34].

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[c] Preliminary LEP 2W data also enable the limit (27) be strengthened to about 20 GeV without additional assumptions[29].

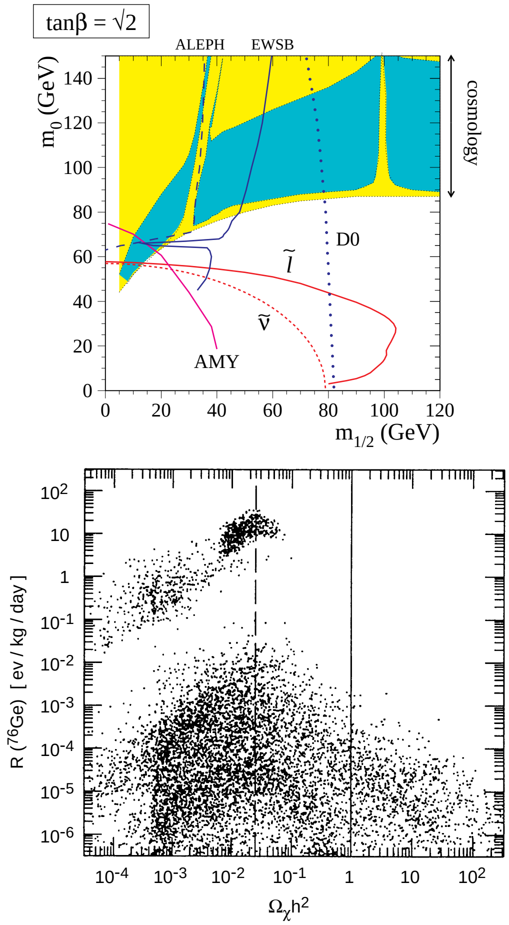

Figure 4: (a): The domain of the $(m_{1/2}, m_0)$ plane for $\mu < 0$ and tan$\beta = \sqrt{2}$ that is excluded by ALEPH chargino and neutralino searches [27] (long-dashed line), by the Z^0 limit on $m_{\tilde{\nu}}$ (short-dashed line), by the LEP limits on slepton production (solid line), by single-photon measurements (grey line), and by the D0 limit on the gluino mass (dotted line) [28]. The region of the plane in which $0.1 < \Omega_\chi h^2 < 0.3$ for some experimentally-allowed value of $\mu < 0$ is light-shaded, whilst the dark-shaded region is for μ determined by dynamical EWSB. The constraint derived from the ALEPH searches [27] when dynamical EWSB is imposed is also shown as a solid line [28].

(b): Relic density of supersymmetric particles, calculated in a sampling of different models [31], together with the estimated scattering rate on ^{76}Ge.

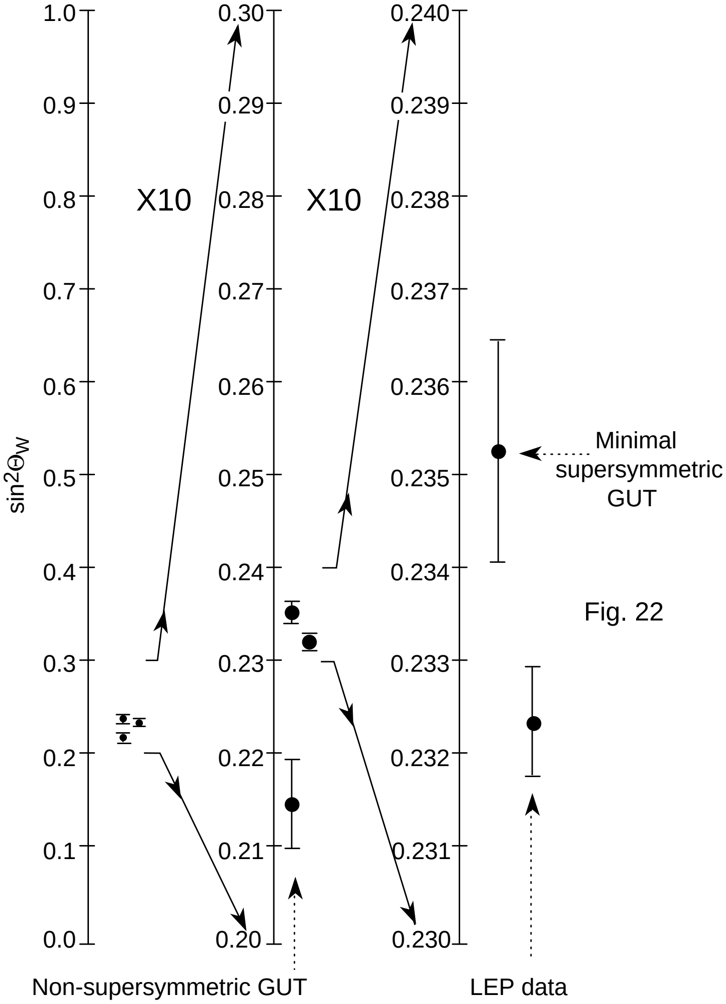

Figure 5: Gee-whizz plot showing how well GUT predictions of $\sin^2\theta_W$ agree with the experimental data.

5 Experimental Anomalies?

Several possible experimental anomalies have been under active discussion during the past few months, and here are updates and opinions on two of them.

R_b/R_c **'Crisis' at LEP**: This is the disagreement between the Standard Model prediction for these two Z^0 decay branching ratios (4) mentioned previously, which was simmering at the $2-\sigma$ level until a new round of preliminary measurements announced in 1995 escalated the apparent discrepancies to 3.7σ for R_b and 2.5σ for R_c [35]. It should be remembered that these are among the most difficult and complex LEP measurements, with large systematic errors associated with the modelling of complicated hadronic final states. One suggestion was that some misunderstanding of these problems might responsible for the apparent anomalies. Alternatively, it was suggested that the discrepancies might be due to some new physics beyond the Standard Model, such as supersymmetry [36] or a new Z' boson [37].

We studied [38] the former possibility, constraining possible supersymmetric models using all the available phenomenological limits on their parameters, including those from unsuccessful sparticle searches at LEP and Fermilab, the experimental lower limit on the mass of the lightest supersymmetric Higgs boson, and the measured rate of $b \to s\gamma$ decay. Particularly important was the lower limit on the chargino mass from LEP 1.5. Out of over $450,000$ parameter choices with $\tan\beta < 5$ and sparticle mass parameters below 250 GeV, we found none that yielded a contribution to R_b greater than 0.0017, which was too small to make a significant contribution to the resolution of the R_b discrepancy. We concluded that "... it may be necessary to review carefully the calculation and simulation of the Standard Model contributions to R_b ..." [38].

Considerable new effort has now been put into the simulation of $Z^0 \to \bar{b}b$ and $\bar{c}c$ decays, and several significant new measurements of R_b have been announced in the Summer of 1996, notably by the ALEPH, DELPHI and SLD collaborations [39]. None of the new measurements disagrees significantly with the Standard Model. There is still some question how to combine these new results with the previous ones, but it seems that the R_b/R_c anomaly is on the way to resolution within the Standard Model [2].

High-E_T jet spectrum: this excited considerable attention in January 1996, when the CDF collaboration revealed their spectrum of high-E_T jets at the Fermilab $\bar{p}p$ collider, which exhibited for $E_T > 200$ GeV an apparent excess above Standard Model calculations made with the distributions of partons inside protons proposed previously [6]. A possible explanation within the Standard Model was that of modifying these model parton distributions [40],[41], which cannot be calculated accurately from first principles. Possible explanations beyond the Standard Model included the suggestion that the parton distributions should not be altered, but that the strong coupling α_s might decrease more slowly than expected in standard QCD, because of the appearance of new strongly-interacting degrees of freedom such as squarks and gluinos [42]. Another suggestion was to keep the usual parton distributions and leave QCD unscathed, but postulate an extra interaction between quarks, due to the exchange of a new electroweak boson Z', which might also resolve the R_b/R_c 'crisis' mentioned above [37]. Finally, the most radical interpretation was that mentioned by the CDF collaboration[6], namely that quarks might be composite objects.

We analyzed in detail [43] the possible effects of a sparticle threshold on the jet spectrum, via their quantum corrections to parton-parton scattering cross sections. The maximum effect that we found was just a few % in a narrow region around the sparticle threshold, as seen in Fig. 6, and we found that previous calculations [42] far above and below threshold were unreliable guides.

Meanwhile, uncertainties in the parton distributions have been studied carefully by two groups: one concluded that modifications in the distributions of quarks inside protons could not explain away the CDF anomaly [40], whereas the other group found that it could be removed by possible modifications in the gluon distribution [41]. This group also found that the CDF and D0 large-E_T date could be reconciled once the different angular acceptances of the two experiments were taken into account, as seen in Fig. 7. It seems, therefore, that this anomaly has also found an interpretation within the Standard Model.

6 Grand Unified Theories

We have already seen how the measurements of the different gauge couplings from LEP and elsewhere are qualitatively consistent with the predictions of GUTs, particularly those with supersymmetry [33]. This is fine, but what one would really like to see is some evidence for one of the novel phenomena predicted by GUTs, such as proton decay or neutrino masses.

The start-up of the Superkamiokande detector will enable existing lower limits on the proton lifetime to be improved by an order of magnitude or

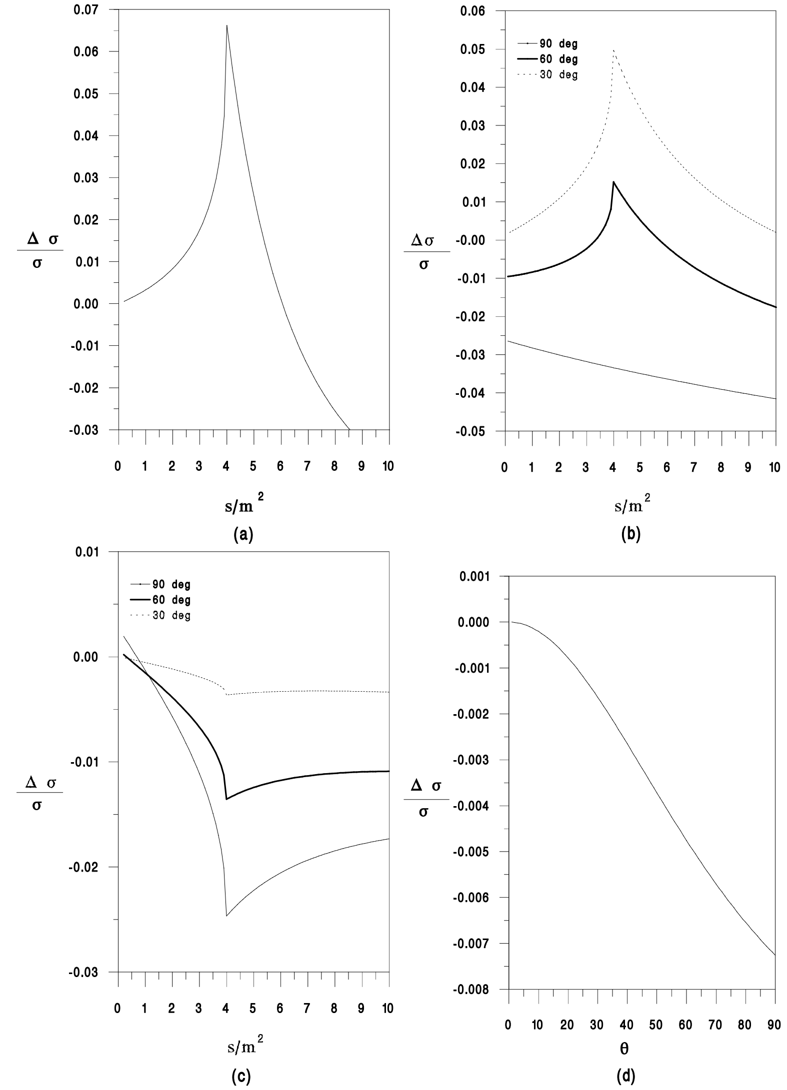

Figure 6: One-loop virtual-sparticle corrections [43] in the threshold region of the subprocess centre-of-mass energy squared s to the processes (a) $q_j\bar{q}_j \to q_k\bar{q}_k$, (b) $q\bar{q} \to gg$ for three different subprocess centre-of-mass scattering angles, (c) $qg \to qg$ also for three different values of scattering angle, and (d) $q_jq_k \to q_jq_k$, against the centre-of-mass subprocess scattering angle, θ, for $s = 10m^2$. All corrections are evaluated using $\alpha_s = 0.11$.

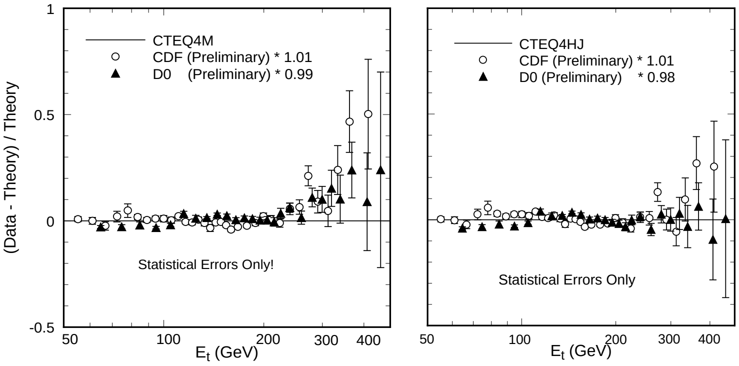

Figure 7: Large-E_T jet data from CDF and D0 are compared with QCD predictions based on recent parton distributions [41].

more [44]. There is no guarantee that this will be sufficient, but at least different GUT models such as minimal supersymmetric $SU(5)$, missing-partner $SU(5)$ models and flipped $SU(5)$ make characteristic predictions for the favoured decay modes [45]. Thus, if proton decay is seen, models will be distinguishable.

The available upper limits on neutrino masses are shown in Table 1: these are so far below the masses of the corresponding charged leptons that one might wonder whether they might vanish entirely. However, theoretically there is no good reason, such as an exact gauge symmetry, why neutrino masses should be strictly zero. Indeed, the consensus among GUT models is that neutrinos should have masses, though the precise form of their mass matrix is very model-dependent. One favoured possibility is the see-saw mass matrix [46]:

$$(\nu_L, \bar{\nu}_R) \begin{pmatrix} \sim 0 & \sim m_q \\ \sim m_q & \sim M_{GUT} \end{pmatrix} \begin{pmatrix} \nu_L \\ \bar{\nu}_R \end{pmatrix} \tag{29}$$

where $\nu_{L,R}$ denote the usual electroweak doublet left- and singlet right-handed neutrinos, respectively. Diagonalizing (29) leads to very light (very nearly) left-handed neutrinos with masses:

$$m_{\nu_i} \simeq \frac{m_{q_i}^2}{M_{GUT}} \gg m_{q,\ell} \tag{30}$$

By analogy with the Cabibbo-Kobayashi-Maskawa mixing of the $W^\pm$ couplings to the quarks, one also expects mixing between the different neutrino species, which leads in general to neutrino oscillations.

Neutrino oscillations rank among the possible interpretations of three anomalous phenomena in neutrino experiments. Foremost among these is the **Solar Neutrino Deficit** now seen in five experiments [47]. These results cannot be explained away by *ad hoc* modifications of the Standard Solar Model, e.g., by simply postulating a reduction in the central temperature of the Sun, without running into trouble with (for example) helioseismological observations [48]. On the other hand, there are three candidate neutrino-oscillation interpretations: in terms of matter-enhanced Mikheyev-Smirnov-Wolfenstein [49] oscillations with a small mixing angle θ:

$$\Delta m_\nu^2 \simeq 10^{-5}\mathrm{eV}^2,\ \sin^2 2\theta \simeq 10^{-2}, \tag{31}$$

or with a large mixing angle:

$$\Delta m_\nu^2 \simeq 10^{-5}\mathrm{eV}^2,\ \sin^2 2\theta \simeq 1, \tag{32}$$

or non-enhanced oscillations *in vacuo*:

$$\Delta m_\nu^2 \simeq 10^{-10}\mathrm{eV}^2,\ \sin^2 2\theta \simeq 1. \tag{33}$$

These different interpretations may be distinguished by new experiments now starting to take data and in preparation, notably the Superkamiokande, SNO and Borexino experiments [50].

Of the three interpretations presented above, (31) seems the most plausible from the point of view of the see-saw mechanism (29), with

$$m_{\nu_e} << m_{\nu_\mu} \simeq 3 \times 10^{-3}\mathrm{eV} \tag{34}$$

Furthermore, if one scales (34) up to the ν_τ mass as in (30), this interpretation carries with it the intriguing speculation that

$$m_{\nu_\tau} \simeq (\frac{m_t^2}{m_c^2}) \times m_{\nu_\mu} \simeq (1-10)\mathrm{eV} \tag{35}$$

in which case the ν_τ could provide the Hot Dark Matter of interest to cosmologists [51]. If m_{ν_τ} is in the range (35), $\nu_\mu - \nu_\tau$ oscillations might be within reach of accelerator neutrino experiments. Two suitable experiments are now taking data at CERN [52], and another is planned at Fermilab [53].

An **Atmospheric Neutrino Deficit** in the ratio of ν_μ- to ν_e-induced events has been reported by some underground detectors, notably the Kamiokande and IMB experiments [54]. However, this has not been confirmed by other experiments using different techniques, and requires further confirmation.

Also in need of confirmation is the suggestion of $\nu_\mu \to \nu_e$ oscillations by the **LSND Experiment**[55], which may be forthcoming from the KARMEN experiment[56] at the Rutherford-Appleton Laboratory.

7 LHC

Some of the best prospects for addressing key current issues in the phenomenology of particle physics will be provided by the LHC accelerator, which has been approved for construction at CERN. This is planned to collide protons at a centre-of-mass energy of 14 TeV with a luminosity of 10^{34} cm^{-2}s^{-1}, and lead ions at 1.2 PeVin the centre of mass with a luminosity of 10^{27} cm^{-2}s^{-1}. The *pp* option is primarily intended to address the Issue of Mass, by producing and detecting the Higgs boson and supersymmetric particles, if they exist, whereas the lead-lead option is aimed at the production and detection of the quark-gluon plasma.

As seen in Fig. 8, it is believed that experiments at the LHC can detect the Higgs boson of the Standard Model if it weighs above 90 GeV, thus dovetailing nicely with LEP 2. The $H \to \gamma\gamma$ decay mode should be detectable if 90GeV $< M_H <$ 150 GeV, and Higgs decay into two real or virtual Z or W bosons if 120GeV $< M_H <$ 1 TeV. As seen in Fig. 9, the Higgs bosons of the minimal supersymmetric extension of the Standard Model should be detectable over essentially all of the model's parameter space[57].

Intense efforts are now underway to evaluate precisely the ability of the LHC experiments to detect the strongly-interacting squarks and gluinos. Some recent results[58] are displayed in Fig. 10: the missing-energy signature for sparticle decay stands out above the total standard Model background and possible detector effects. Preliminary studies indicate that experiments at the LHC can detect squarks and gluinos weighing up to $1-2$ TeV[59], covering the entire range (24) suggested by the naturalness of the mass hierarchy. It also seems that the LHC may be able to provide us with some precision measurements of sparticle masses[58]

8 Beyond the Standard Model?

We have seen in previous sections that there are good theoretical reasons to expect new physics beyond the Standard Model, and that there are some ten-

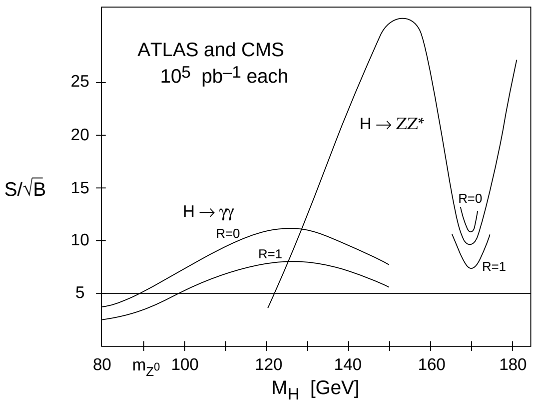

Figure 8: The expected significance for a Standard Model Higgs boson in the ATLAS and CMS experiments at the LHC [59]. The higher-mass range is also accessible up to about 1 TeV.

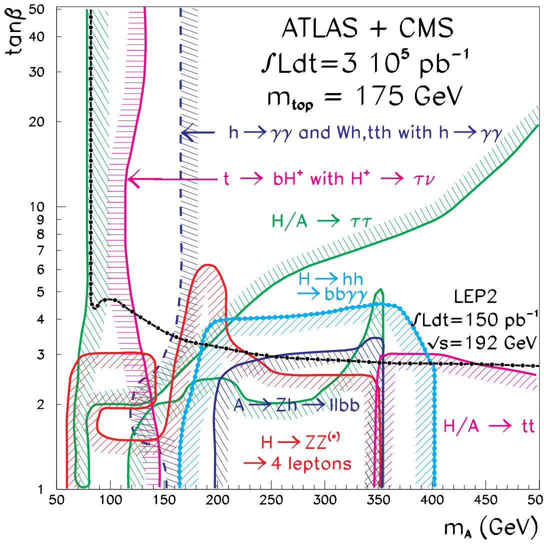

Figure 9: Capability of LHC experiments to explore the MSSM Higgs sector [57]. The regions with shaded edges can be explored with the channels indicated. Also shown is the region accessible to LEP2. Between LHC and LEP2, essentially the entire plane is covered.

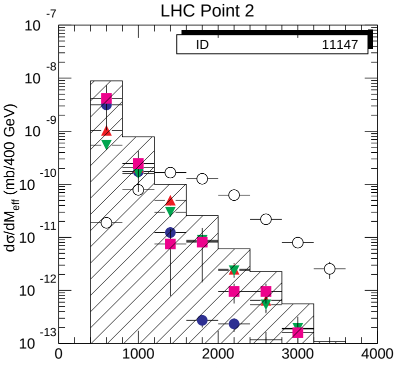

Figure 10: Comparison of calculated missing-energy signature due to $\tilde{q}, \tilde{g}$ production at the LHC with Standard Model and detector backgrounds [58], in a model with dynamical EWSB and $m_0 = 400$ GeV, $m_{1/2} = 400$ GeV, $\tan\beta = 10$ and $\mu > 0$.

tative experimental indications that may point towards the way to go. I attach particular significance to the indications from precision electroweak measurements at LEP and elsewhere that the Higgs boson may be relatively light as suggested by supersymmetric models, the agreement between the measurements of gauge couplings and the predictions of simple supersymmetric GUTs, and the apparent solar neutrino deficit. In my view, these are pointers towards supersymmetry and GUTs.

We are fortunate that experiments now starting to take data should be able to explore broad domains of parameter space. Specifically, I have in mind the CHORUS and NOMAD neutrino oscillation experiments at CERN [52], LEP 2, and the Superkamiokande underground detector [44]. Beyond these, we have in prospect many further neutrino oscillation experiments and the LHC to spearhead our search for new physics. Ever since the establishment of the Standard Model, we have been waiting in vain for physics beyond the Standard Model to appear. Will our luck soon improve?

1. S.L. Glashow, *Nucl.Phys.* **22** (1961) 579;
   S. Weinberg, *Phys.Rev.Lett.* **19** (1977) 1264;
   A. Salam, Proc. 8th Nobel Symposium, Stockholm 1968, ed. N. Svartholm (Almqvist and Wiksells, Stockholm, 1968) p. 367.
2. A. Blondel, Plenary talk at the *International Conference on High Energy Physics*, Warsaw, 1996, reporting the analysis of the LEP Electroweak Working Group and the SLD Heavy Flavor Group,

CERN Report No. LEPEWWG/96-02, available at the URL: http://www.cern.ch/LEPEWWG.

3. CDF Collaboration, F. Abe et al., *Phys.Rev.Lett.* **74** (1995) 2676;
   D0 Collaboration, S. Abachi et al., *Phys.Rev.Lett.* **74** (1995) 2632.
4. Particle Data Group, R. M. Barnett et al., *Phys.Rev.* **D54** (1996) 1.
5. L. Maiani, Proc. Summer School on Particle Physics, Gif-sur-Yvette, 1979 (IN2P3, Paris, 1980), p. 3;
   G 't Hooft, in *Recent Developments in Field Theories*, eds. G. 't Hooft et al. (Plenum Press, New York, 1980);
   E. Witten, *Nucl.Phys.* **B188** (1981) 513;
   R.K. Kaul, *Phys.Lett.* **109B** (1982) 19.
6. CDF collaboration, *Phys.Rev.Lett.* **77** (1996) 2852.
7. D. Gross, talk at this meeting.
8. *Reports of the Working Group on Precision Calculations for the Z resonance*, eds. D. Bardin, W. Hollik and G. Passarino, CERN Preprint TH/95-03 (1995).
9. SLD collaboration, K. Abe et al., SLAC reprint PUB-7069, hep-ex/9609019, and references therein.
10. L. Arnaudon et al., *Z.Phys.* **C66** (1995) 45.
11. J. Wenninger, CERN Preprint SL/TN Note 95-21(OP) (1995).
12. G. Wilkinson, talk at the *International Conference on High Energy Physics*, Warsaw, 1996.
13. M. Veltman, *Nucl.Phys.* **123** (1977) 89;
    M.S. Chanowitz, M. Furman and I. Hinchliffe, *Phys.Lett.* **78B** (1978) 285.
14. M. Veltman, *Acta Phys.Pol.* **8** (1977) 475.
15. J. Ellis, G.L. Fogli and E. Lisi, CERN Preprint TH/96-216 (1996), hep-ph/9608329, to appear in *Phys. Lett.* **B**.
16. D. Gerdes, hep-ex/9609013.
17. C. Vayonakis, *Lett. Nuov. Cim.* **17** (1976) 383 and Athens University Preprint (1978);
    B.W. Lee, C. Quigg and H.B. Thacker, *Phys.Rev.* **D16** (1977) 1519.
18. D.A. Ross and M. Veltman, *Nucl.Phys.* **B95** (1975) 135.
19. Y. Nambu, in *Proc. XI Int. Symp. on Elementary Particle Physics*, eds. Z.Ajduk, S. Pokorski and A. Trautman (World Scientific, Singapore, 1989);
    A. Miranski, M. Tanabashi and K. Yamauraki, *Mod.Phys.Lett.* **A4** (1989) 1043 and *Phys.Lett.* **B221** (1989) 177;
    W.A. Bardeen, C.T. Hill and M. Lindner, *Phys.Rev.* **D41** (1990) 1647.
20. For a review, see:

E. Farhi and L. Susskind, *Physics Reports* **74C** (1981) 277.

21. J. Ellis, G.L. Fogli and E. Lisi, *Phys.Lett.* **B343** (1995) 282.
22. Y.A. Gol'fand and E.P. Likhtman - *Pis'ma Zh.E.T.F.* **13** (1971) 323;
    D. Volkov and V.P. Akulov, *Phys.Lett.* **46B** (1973) 109;
    J. Wess and B. Zumino, *Nucl.Phys.* **B70** (1974) 39;
    For a review, see P. Fayet and S. Ferrara, *Physics Reports* **32C** (1977) 249.
23. J. Wess and B. Zumino, *Phys.Lett.* **49B** (1974) 52;
    J. Iliopoulos and B. Zumino, *Nucl.Phys.* **B76** (1974) 310;
    S. Ferrara, J. Iliopoulos and B. Zumino, *Nucl.Phys.* **B77** (1974) 413.
24. P. Fayet, in *Unification of the Fundamental Particle Interactions*, eds. S. Ferrara, J. Ellis and P. Van Nieuwenhuizen (Plenum Press, New York, 1980), p. 587.
25. D0 Collaboration, S. Abachi et al., *Search for Squarks and Gluinos in $p\bar{p}$ Collisions at the D0 Detector*, contributed paper No 434 to the Int. Europhys. Conf. on High Energy Physics, Brussels, 1995.
26. W. de Boer (DELPHI), R. Miquel (ALEPH), M. Pohl (L3) and N. Watson (OPAL), Joint Particle Physics Seminar and Open Session of the LEP experiments committee, CERN, October 8th, 1996.
27. ALEPH collaboration, D. Buskulic et al., CERN-PPE/96-83 (submitted to Zeitschrift für Physik).
28. J. Ellis, T. Falk, K.A. Olive and M. Schmitt, CERN Preprint TH/96-102, hep-ph/9606292, to be published in *Phys.Lett.* **B**.
29. J. Ellis, T. Falk, K.A. Olive and M. Schmitt, CERN Preprint TH/96-284, hep-ph/9610410.
30. J. Ellis, J.S. Hagelin, D.V. Nanopoulos, K.A. Olive and M.Srednicki, *Nucl.Phys.* **B238** (1984) 453.
31. For a review, see: G. Jungman, M. Kamionkowski and K. Griest, *Phys. Rep.* **267** (1996) 195.
32. Y. Okada, M. Yamaguchi and T. Yanagida, *Progr.Theor.Phys.* **85** (1991) 1;
    J. Ellis, G. Ridolfi and F. Zwirner, *Phys.Lett.* **B257** (1991) 83, *Phys.Lett.* **B262** (1991) 477;
    H.E. Haber and R. Hempfling, *Phys.Rev.Lett.* **66** (1991) 1815;
    R. Barbieri, M. Frigeni and F. Caravaglios, *Phys.Lett.* **B258** (1991) 167;
    Y. Okada, M. Yamaguchi and T. Yanagida, *Phys.Lett.* **B262** (1991) 54.
33. S. Dimopoulos, S. Raby and F. Wilczek, *Phys.Rev.* **D24** (1981) 1681;
    W.J. Marciano and G. Senjanovic, *Phys.Rev.* **D25** (1982) 3092;
    L.E. Ibàñez and G.G. Ross, *Phys.Lett.* **105B** (1982) 439;
    M.B. Einhorn and D.R.T. Jones, *Nucl.Phys.* **B196** (1982) 475;

J. Ellis, S. Kelley and D.V. Nanopoulos, *Phys.Lett.* **B249** (1990) 441 and **B260** (1991) 131;
P. Langacker and M. Luo, *Phys.Rev.* **D44** (1991) 817;
U. Amaldi, W. de Boer and H. Furstenau, *Phys.Lett.* **B260** (1991) 447;
F. Anselmo, L. Cifarelli, A. Peterman and A. Zichichi, *Nuovo Cimento* **104A** (1991) 1817.

34. J. Ellis, Rapporteur Talk at the *International Symposium on Lepton and Photon Interactions at High Energies*, Beijing 1995, CERN Preprint TH/95-316, hep-ph/9512335.
35. LEP Electroweak Working Group, The LEP Collaboration ALEPH, DELPHI, L3 and OPAL, and the LEP Electroweak Working Group, CERN Report No. LEPEWWG/95-01;
P. Renton, rapporteur talk at *Int. Symp. on Lepton and Photon Interactions at High Energies*, Beijing 1995, Oxford Preprint OUNP-95-20 (1995).
36. A. Djouadi et al., *Nucl.Phys.* **B349** (1991) 48;
M. Boulware and D. Finell, *Phys.Rev.* **D44** (1991) 2054;
G. Altarelli, R. Barbieri and F. Caravaglios, *Phys.Lett.* **B314** (1993) 357;
D. Garcia and J. Sola, *Phys.Lett.* **B357** (1995) 349;
X. Wang, J. Lopez and D.V. Nanopoulos, *Phys.Rev.* **D52** (1995) 4116;
M. Shifman, *Mod.Phys.Lett.* **A10** (1995) 605;
G.L. Kane, R.G. Stuart and J.D. Wells, Univ. Michigan Preprint UM-TH-95-16, hep-ph/9505207;
J. Erler and P. Langacker, *Phys.Rev.* **D52** (1995) 441;
P.H. Chankowski and S. Pokorski, Warsaw University Preprint IFT-UW-95/5.
37. G. Altarelli, N. Di Bartolomeo, F. Feruglio, R. Gatto and M. L. Mangano, *Phys.Lett.* **B375** (1996) 292;
P. Chiappetta, J. Layssac, F.M. Renard and C. Verzegnassi, *Phys.Rev.* **D54** (1996) 789.
38. J. Ellis, J. Lopez and D.V. Nanopoulos, *Phys.Lett.* **B372** (1996) 95.
39. ALEPH Collaboration, Contributed paper PA10-015;
SLD Collaboration, Contributed paper PA10-023;
DELPHI Collaboration, Contributed paper PA01-061;
International Conference on High Energy Physics, Warsaw, 1996.
40. E.W.N. Glover, A.D. Martin, R.G. Roberts and W.J. Stirling, *Phys.Lett.* **B381** (1996) 353.
41. H.L. Lai, J. Huston, S. Kuhlmann, F. Olness, J. Owens, D. Soper, W.K. Tung and H. Weerts, Michigan State University Preprint

MSUHEP-60426, hep-ph/9606399.

42. V. Barger, M.S. Berger and R.J.N. Phillips, *Phys.Lett.* **B382** (1996) 178;
P. Kraus and F. Wilczek, *Phys.Lett.* **B382** (1996) 262.
43. J. Ellis and D.A. Ross, *Phys.Lett.* **B383** (1996) 187.
44. Superkamiokande Collaboration, Y. Totsuka, ICC report 227-90-20 (1990).
45. B.A. Campbell, J. Ellis and D.V. Nanopoulos, *Phys.Lett.* **141B** (1994) 229.
46. T. Yanagida, *Proc. Workshop on the Unified Theory and the Baryon Number in the Universe* (KEK, Japan, 1979);
R. Slansky, Talk at *Sanibel Symposium*, Caltech Preprint CALT-68-709 (1979).
47. B.T. Cleveland et al., *Nucl. Phys. Proc. Supp.* **B38** (1995) 47;
R. Davis, *Prog.Part.Nucl.Phys.* **32** (1994) 13;
Kamiokande Collaboration, Y. Suzuki, *Nucl. Phys. Proc. Suppl.* **B38** (1994) 54;
SAGE Collaboration, J.N. Abdurashitov et al., *Phys.Lett.* **B328** (1994) 234;
GALLEX Collaboration, P. Anselmann et al., *Phys.Lett.* **B327** (1994) 377 and **B342** (1995) 440.
48. J. Christensen-Dalsgaard, *Nucl.Phys.* **B** (Proc. Suppl.) **48** (1996).
49. L. Wolfenstein, *Phys.Rev.* **D17** (1978) 2369;
S.P. Mikheyev and A.Yu. Smirnov, *Yad. Fiz.* **42** (1985) 1441.
50. SNO Collaboration, G.T. Ewan et al., Sudbury Neutrino Observatory proposal SNO-87-12 (1987);
BOREXINO Collaboration, C. Arpesella et al., BOREXINO proposal (University of Milano, Milano, 1992).
51. R.K. Schaefer and Q. Shafi, *Nature* **359** (1992) 119;
M. Davis, F.J. Summers and D. Schlegel, *Nature* **359** (1992) 393;
A.N. Taylor and M. Rowan-Robinson *Nature* **359** (1992) 396.
52. CHORUS Collaboration, M. de Jong et al., CERN Preprints PPE/90-42 (1990) and 93-13 (1993);
NOMAD Collaboration, L. Di Lella, *Nucl.Phys. Proc. Supp.* **B31** (1993) 319.
53. COSMOS Collaboration, P803 proposal to Fermilab (1993).
54. Kamiokande Collaboration, K.S. Hirata et al., *Phys.Lett.* **B205** (1988) 416 and **B280** (1992) 146.
55. C. Athanassopoulos et al., Los Alamos Preprints LA-UR-96-1326, nucl-ex/9605001 and LA-UR-96-1582, nucl-ex/9605003.
56. B. Zeitnitz et al., *Prog. Nucl. Part. Phys.* **32** (1994) 351, and references

therein.

57. E. Richter-Was, D. Froidevaux, F. Gianotti, L. Poggioli, D. Cavalli and S. Resconi, CERN Preprint TH/96-111 (1996).
58. F. Paige, BNL Preprint, hep-ph/9609373.
59. ATLAS Collaboration Technical Proposal, CERN/LHCC 94-93 (1994); CMS Collaboration Technical Proposal, CERN/LHCC 94-38 (1994).