THEORETICAL SUMMARY:
1999 Electroweak Session of the Rencontres de Moriond

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The following aspects of the electroweak interactions are discussed, based on presentations here: the status of the Standard Model, CP violation, neutrino masses and oscillations, supersymmetry and models in extra dimensions, and future projects. Particular emphasis is laid on the tests of CP and CPT by KTeV and CPLEAR, on the problems of degenerate neutrinos, on supersymmetric dark matter, on future long-baseline neutrino beams, and on muon storage rings that may be used as neutrino factories.

1 Status of the Standard Model

The Standard Model is the rock on which all our knowledge of particle physics rests. Novel phenomena such as neutrino masses, that cannot be accommodated within it, are not thought to contradict it, but rather to take us beyond the Standard Model. In the first section of this Summary, I review the status of the electroweak sector of the Standard Model, that is the most precisely (and successfully) tested. Then I review some of the accelerating progress in flavour physics and CP violation, where exciting new developments were reported at this meeting and more are expected soon. Next I discuss in some detail the growing evidence for neutrino oscillations, which would take us beyond the Standard Model into a new world of lepton flavour physics. This is followed by a review of new developments in supersymmetry and further beyond the Standard Model, in particular the possibility that there may be one or more extra dimensions appearing at some large distance scale. Finally, I review how our theoretical questions may be answered by future projects such as LEP 2000, Run II of the Fermilab Tevatron, long-baseline neutrino experiments, the LHC, a linear e^+e^- collider, a neutrino factory and muon colliders.

As we heard at this meeting [1], (almost) everything in the garden is lovely, as far as precision tests of the Standard Model are concerned. Previous discrepancies are gradually eroding:

for example, the discrepancy between the LEP and SLC values of $\sin^2\theta_W$ is now only about 1 1/2 standard deviations [2], the b-quark coupling A_b is less than 1 standard deviation from the Standard Model, and even the famous R_b deviates by only about 1 1/4 standard deviations. The biggest high-energy problem seems to be in the forward-backward asymmetry for b quarks A^b_{FB}, at a level of about two standard deviations, but at least one fluctuation at this level could be expected in the high-energy data set.

One of the most significant potential problems may be in atomic-physics parity violation. The latest determination of the neutral weak charge in cesium yields $Q_W = -72.06(28)(34)$, to be compared with the Standard Model prediction $Q_W = -73.20(13)$ [3]. As pointed out by the authors, this discrepancy is not compatible with a vacuum-polarization S contribution in a "model-independent" parametrization [4].

We heard at this meeting of significant progress in measuring M_W in $p\bar{p}$ collisions: 80.448 ± 0.062 GeV [5] as well as at LEP: 80.350 ± 0.056 GeV [6]. So far, there are contradictory indications on the importance of hadronization effects in $W^+W^- \rightarrow q\bar{q}q\bar{q}$ final states [7]. For example, DELPHI reports possible hints of colour reconnection effects in the spectra of low-momentum particles and also an indication of Bose-Einstein correlations between particles from the $W^\pm$, whereas ALEPH sees neither of these effects. It is in any case clear that the effects are not as large as in the model [8], which has not been tuned to match Z^0 decays, and hence cannot be used to estimate systematic errors in the M_W measurement: see also [9]. However, putting together the LEP measurements reported here there *is* a difference of 152 ± 74 MeV between the measurements of M_W in $q\bar{q}q\bar{q}$ and $q\bar{q}\ell\nu$ final states [1], rather larger than the hadronization error usually quoted. It remains to be seen whether this discrepancy will turn out to be significant. The current world average of direct measurements:

$$M_W = 80.394 \pm 0.042 \text{ GeV} \tag{1}$$

has a reduced error that begins to challenge that on the indirect prediction $M_W = 80.364 \pm 0.029$ GeV within the Standard Model, and leaves little room for New Physics, such as that suggested in some supersymmetric scenarios.

As seen in Fig. 1, the current indirect prediction for the Higgs-Boson mass is [1,2]:

$$m_H = 76^{+79}_{-67} \text{ GeV} \tag{2}$$

with a 95% confidence-level upper limit of 235 GeV, if a conservative error ±0.00090 on $\alpha_{em}(M_Z)$ is adopted. On the other hand, if a more aggressive error ± 0.00036 is adopted, as suggested on the basis of hadronic τ decays and QCD theory [11], one finds:

$$m_H = 93^{+63}_{-54} \text{ GeV} \tag{3}$$

So near, and yet so far? Within the uncertainties (2,3), there are significant prospects for finding the Higgs boson at LEP during the next couple of years, or it may be found during Run II at the Tevatron [12], or one may have to wait for several years of LHC running before it is detected.

In my view, it is a real tragedy that no money can apparently be found to run the SLC during the year 2000, just when the accelerator has been operating at higher luminosity than ever, and the SLD detector is poised to make the most precise measurement of $\sin^2\theta_W$ via A_{LR}, as well as contribute important new information on the b-quark couplings [2]. These measurements would, in particular, contribute significantly to reducing the present uncertainty in the prediction of M_H, which is one of the main uncertainties in the LHC enterprise. It seems strange that the equivalent of a small fraction of the investment in the LHC cannot be found to sharpen this prediction.

An important contribution to reducing the uncertainty in M_H is made by those who measure $R \equiv \sigma(e^+e^- \rightarrow \text{hadrons}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-)$ at intermediate energies [13], which affects the effective value of α_{em} to be used in analyzing LEP and SLC measurements via vacuum-polarization

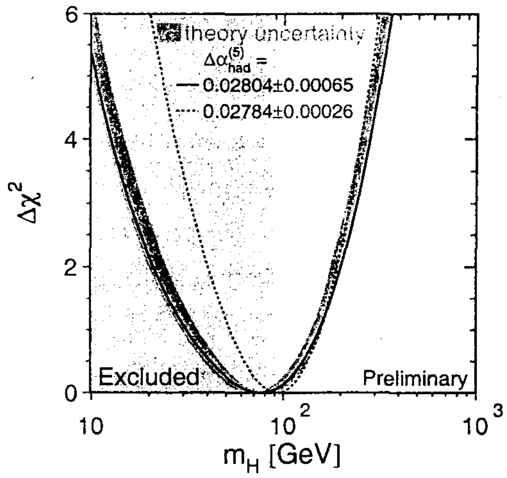

Figure 1: *The latest result[1,2] of fitting precision electroweak data to obtain an indirect estimate of the mass of the Higgs boson. The most likely value is very close to the present lower limit from direct searches at LEP[10].*

diagrams. Uncertainties in R also make significant contributions to the theoretical error of $\pm$ 0.66 ppm in $(g-2)_\mu$, which is large compared to the objective of the new BNL experiment: $\pm$ 0.35 ppm[14]. These considerations motivate the important experimental campaigns in Beijing and Novosibirsk to remeasure R at center-of-mass energies below 5 GeV[13].

Up to what scale can the Standard Model remain valid? If M_H is too large, the Standard Model couplings blow up below the Planck mass M_P, and if it is too small, the effective potential of the Standard Model is not stable against the development of a vacuum-expectation value below M_P[15]. The range preferred by precision electroweak measurements (2), (3) is still compatible with the Standard Model remaining valid up to M_P, but may be hinting that New Physics will appear before then. Some possibilities are discussed in later sections of this talk.

2 Flavour and CP

Until this meeting, all the confirmed CP-violating effects could be explained in terms of superweak CP violation in the $K^0\bar{K}^0$ mass matrix[16]:

$$\mathrm{Im} M_{\Delta s=2} \neq 0 \rightarrow \epsilon \qquad (4)$$

However, we are now sure that there is also CP violation in the $K^0 \rightarrow 2\pi$ decay amplitudes[17]:

$$\epsilon'/\epsilon = (28.0 \pm 4.1) \times 10^4 \qquad (5)$$

In the Standard Model with six quarks[18], in which there is a CP-violating phase in the $W^\pm$ couplings, a non-zero value was to be expected[19]. If there is only one Higgs doublet, there is no other CP violation in the Standard Model[19]. However, there are additional CP-violating phases in extensions of the Standard Model, such as the Minimal Supersymmetric Extension of the Standard Model (MSSM), which may contain arbitrary phases in the soft supersymmetry breaking mass terms [20]:

$$m_{12}^{*2} A_f \mu, \quad m_{12}^{*2} M_a \mu \tag{6}$$

Phenomenologically, the most important may be those associated with the third generation. There are even more possibilities in general two-Higgs doublet models [21].

Confirmation of direct CP violation in the $K^0 \bar{K}^0$ system has come twenty-three years after it was first calculated [19]. When we first calculated it, using what we subsequently baptized penguin diagrams [22], we estimated

$$|\frac{\epsilon'}{\epsilon}| \lesssim \frac{1}{450} \tag{7}$$

which is compatible with the value found by NA31 [23] and now confirmed by KTeV (5) [17]. This is, of course, pure coincidence, since there have been many conceptual advances and calculational improvements since our first calculation: see, e.g., [24,25]. The best available recent estimate is [26]:

$$\mathrm{Re}(\frac{\epsilon'}{\epsilon}) = \mathrm{Im}\lambda_t \left\{ -1.35 + \left(\frac{150 \text{ MeV}}{m_s(m_c)}\right)^2 \times [1.1 R_{SD} B_6^{(1/2)} + (1.0 - 0.67 R_{SD}) B_8^{(3/2)}] \right\} \tag{8}$$

where $\mathrm{Im}\lambda_t$ is a Kobayashi-Maskawa factor that is expected to lie between 1.0 and 1.7×10^{-4}, R_{SD} is a short-distance factor that is expected to lie between 7.5 and 8.5, and $B_6^{(1/2)}, B_8^{(3/2)}$ are hadronic matrix elements that are estimated to lie in the ranges

$$0.8 \lesssim B_6^{(1/2)} \lesssim 1.3 , \quad 0.6 \lesssim B_8^{(3/2)} \lesssim 1.0 \tag{9}$$

It is possible to fit [26] the NA31/KTeV experimental value of ϵ'/ϵ if one pulls on all these factors, in particular with a relatively small strange-quark mass:

$$m_s(m_c) \lesssim \text{ MeV} \leftrightarrow m_s(2 \text{ GeV}) \lesssim 110 \text{ MeV} \tag{10}$$

This is compatible with other estimates of m_s, including those from the lattice [27] and a recent determination from $\tau \to (K n \pi)\nu$ decays [28]:

$$m_c(m_\tau) = 176^{+46}_{-57} \text{ MeV} \tag{11}$$

We may therefore conclude that the NA31/KTeV measurement [23,17] of ϵ'/ϵ *does not require physics beyond the Standard Model.* On the other hand, there is room for a supersymmetric contribution [29], e.g., via an enhanced $Z\bar{d}s$ vertex [30], which could enhance significantly the rates for some rare $K^{0,\pm}$ decays:

$$\begin{aligned} B(K_L^0 \to \pi^0 \nu \bar{\nu}) &\sim 3 \times 10^{-11} \to 27 \times 10^{-10} \\ B(K_L^0 \to \pi^0 e^+ e^-)_{direct} &\sim 5 \times 10^{-12} \to 43 \times 10^{-11} \\ B(K^+ \to \pi^+ \nu \bar{\nu}) &\sim 8 \times 10^{-11} \to 8 \times 10^{-10} \end{aligned} \tag{12}$$

putting them within reach of forthcoming experiments.

We can expect in the near future a new measurement of ϵ'/ϵ from the NA48 experiment [31], as well as further data from KTeV and subsequently from the KLOE experiment at DAϕNE, perhaps closing an exciting chapter in K physics. What are the next important steps in K decays? The most interesting decay modes may be those mentioned above: $K_L \to \pi^0 \bar{\nu} \nu$ violates CP and could occur at a rate much larger than that predicted by the Standard Model [19], $K^+ \to \pi^+ \bar{\nu} \nu$ could provide a good measurement of the Cabibbo-Kobayashi-Maskawa mixing angles, and $K_L^0 \to \pi^0 e^+ e^-$ may be dominated by direct CP violation. It is surely worth pursuing these decays in parallel with the large investment currently being made in B physics, via HERA-B, CLEO, BaBar, BELLE, CDF, D0, BTeV and LHCb. There are interesting prospects for rare

K decay experiments at FNAL, BNL, KEK and CERN. Can the world community agree on at least one next-generation rare K decay experiment?

There was active discussion here of T and CPT violation. The discovery of CP violation in the $K^0\bar{K}^0$ mass matrix in 1964 meant that either CPT or T should be violated, or both. Since CPT violation is not permitted by quantum field theory, it is generally expected to be absent. However, the possibility of CPT violation has been raised in the context of quantum gravity[32], and it is good that experiments continue to search for it. It is known that $K_L^0 \to 2\pi$ decay is not due to CPT violation, and therefore one expects that the observed CP violation should be accompanied by T violation at the same rate, but this was not observed directly until recently. The CPLEAR collaboration reported here[33] a measurement of the asymmetry

$$\frac{P_{K\to\bar{K}}B(K \to \pi^- e^+ \nu) - P_{\bar{K}\to K}B(\bar{K} \to \pi^+ e^- \bar{\nu})}{P_{K\to\bar{K}}B(K \to \pi^- e^+ \nu) + P_{\bar{K}\to K}B(\bar{K} \to \pi^+ e^- \bar{\nu})} \tag{13}$$

This is a direct probe of reciprocity and hence T violation if $B(K \to \pi^- e^+ \nu) = B(\bar{K} \to \pi^+ e^- \bar{\nu})$, which has indeed been checked by independent CPLEAR measurements[34]. Thus the CPLEAR collaboration has indeed observed T violation[35,36]. The KTeV collaboration reported here a beautiful measurement of a T-odd asymmetry in $K_L^0 \to \pi^+\pi^- e^+ e^-$ [37]: since this is not a direct test of reciprocity, this could be due to either T violation or CPT violation or both[35], at least until more experimental information is available.

Another exciting development at this meeting was the report of a two-standard-deviation CP-violating asymmetry in $B^0 \to J/\psi K_S^0$ [38]. In the absence of other information, this could in principle be due to a superweak effect, so we need another decay mode such as $B^0 \to \pi^+\pi^-$ to confirm its interpretation. However, we cannot avoid noticing that its sign and large magnitude agree with the predictions of the Kobayashi-Maskawa model[18], as seen in Fig. 2: in particular, the sign of ϵ_K agrees with the apparent sign of $\sin 2\beta$. It is encouraging that the values of the Cabibbo-Kobayashi-Maskawa parameters extracted from the data are consistent with naïve model predictions[39]:

$$\begin{aligned} \frac{\lambda}{c}\sqrt{(1-\bar{\rho})^2+\bar{\eta}^2} &= \left|\frac{V_{td}}{V_{ts}}\right| = \sqrt{\frac{m_d}{m_s}} \\ \frac{\lambda}{c}\sqrt{\bar{\rho}^2+\bar{\eta}^2} &= \left|\frac{V_{ub}}{V_{cb}}\right| = \sqrt{\frac{m_u}{m_c}} \end{aligned} \tag{14}$$

where $c \equiv \sqrt{1-\lambda^2}$. These model predictions and global Cabibbo-Kobayashi-Maskawa fits[40] agree in predicting that the $B_s^0 - \bar{B}_s^0$ mixing parameter Δm_s should be observable "soon". Indeed, both SLD[41] and the LEP collaborations[42] reported here not only interesting lower limits on Δm_s, but also enticing hints that it may lie just around the corner.

3 Neutrino Masses

These are known to be much smaller than those of the corresponding charged leptons:

$$\begin{aligned} m_{\nu_e} &\lesssim 2.5 \text{ eV} &\ll m_e &\sim 1/2 \text{ MeV} \\ m_{\nu_\mu} &\lesssim 160 \text{ keV} &\ll m_\mu &\sim 100 \text{ MeV} \\ m_{\nu_\tau} &\lesssim 15 \text{ keV} &\ll m_\tau &\sim 1.78 \text{ MeV} \end{aligned} \tag{15}$$

so one might be tempted to suspect that they vanish. However, we have learnt that particles have zero mass (e.g., the photon and gluon) only if they are associated with an exact gauge symmetry (e.g., the U(1) of QED and the SU(3) of QCD) and a corresponding conserved charge (e.g., Q_{em} and colour). There is no candidate gauge symmetry available to conserve lepton number L, and GUTs generically predict non-zero neutrino masses.

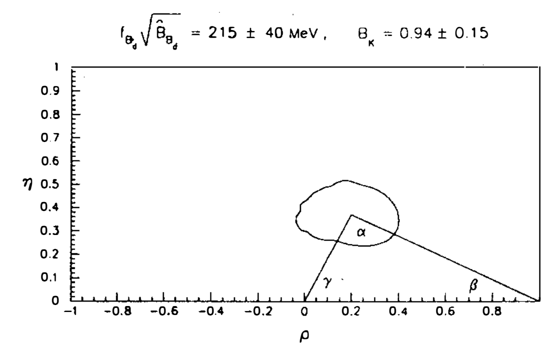

Figure 2: *A recent global fit to data on charged-current interactions and ϵ_K [40], which suggests a value of sin2β within the range reported by CDF [38].*

It is possible for these to appear even if there are no new particles beyond the Standard Model, e.g., via a non-renormalizable interaction [43] of the form

$$\frac{(\nu_L H)\,(\nu_L H)}{M} \tag{16}$$

but the most plausible hypothesis is that M represents the mass scale of some new renormalizable gauge theory, such as the GUT mass scale. Interactions of the form (16) arise from the exchange of massive singlet fermions (often called "right-handed neutrinos" ν_R), and most models of neutrino masses are based on the see-saw form of mass matrix that mixes then with conventional left-handed neutrinos [44]:

$$(\nu_L\ ,\ \nu_R)\ \begin{pmatrix} 0 & m \\ m & M \end{pmatrix}\ \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \tag{17}$$

where the off-diagonal "Dirac" elements m are generally comparable to conventional quark and lepton masses whereas $M \gg m_W$, leading to light neutrino masses $m_\nu \sim m^2/M$. As an example of possible orders of magnitude, with $m \simeq 10$ GeV and $M \simeq 10^{13}$ GeV one finds $m_\nu \sim 10^{-2}$ eV.

Within this general framework, many models are possible. Could there be other light neutrinos? Neutrino counting at LEP [1] tells us that these could only be sterile ν_s. But then what forbids a large gauge-invariant mass term $M_s(\nu_s\nu_s)$ with $M_s \gg M_W$? In my view, this is a major objection to models with light sterile neutrinos and/or right-handed neutrinos. On the basis of (17), most theorists expect the light neutrinos to be predominantly left-handed and to have effective Majorana masses $m_{eff}(\nu_L\nu_L)$. It often used to be thought that neutrino mixing would be small, by analogy with the small quark mixing angles. However, now it is widely recognized that this need not be the case [45]. For one thing, the Dirac masses might not be directly related to conventional quark or lepton masses, and, for another, the heavy Majorana mass M has no good reason to be diagonal in a basis aligned closely with the light charged-lepton flavours [46].

It is widely thought that oscillations between neutrinos with different masses may explain the anomalies seen in solar and atmospheric neutrinos. In the solar case, the Standard Solar Model is nicely consistent with the powerful constraints of helioseismology, and models with large mixing of solar material also seem to be disfavoured [47], so it seems that neutrino physics must be the culprit for the persistent solar-neutrino deficit. In the case of atmospheric neutrinos, it has been shown that neutrino decays and modifications of special and general relativity do not fit the data well [48].

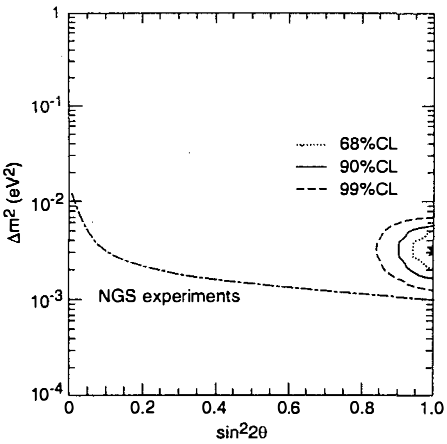

Figure 3: *The range of parameters for $\nu_\mu - \nu_\tau$ oscillations preferred by the Super-Kamiokande data at the indicated levels of confidence*[51]*, compared with the estimated sensitivity to τ appearance of either the OPERA or the ICARUS experiment in the CERN-Gran Sasso long-baseline beam.*

Among the indications of neutrino oscillations, the evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations presented by LSND [49] has not been confirmed by KARMEN [50], though it is not excluded, either. The MiniBooNE experiment at FNAL should confirm or refute this signal, as well as the MINOS long-baseline experiment discussed later.

As we heard at this meeting [51], the range of Δm^2 favoured by the Super-Kamiokande atmospheric-neutrino data [52] has recently been elevated, as seen in Fig. 3. This is a result of higher statistics for contained events, an improved Monte Carlo including a more complete treatment of the Earth's magnetic field (that is validated by its agreement with the observed East-West effect [53]), and combining the contained events with data on up-going muons. The Super-Kamiokande evidence is supported by data from MACRO [54] and Soudan II [55]. It remains important to reduce the systematic uncertainties in the interpretation of the data [56]. This will require, e.g., more precise measurements of the primary cosmic-ray spectrum. New data tend to favour lower fluxes than used in some Monte Carlos: the AMS space experiment may be able to help here. Better measurements of the differential cross-sections $d^2\sigma^{\pi,K}/dx_{\|}dp_{\perp}$ for secondary-particle production are also needed: here is a possible role for a new experiment at the CERN PS accelerator. Also needed is a fully three-dimensional cosmic-ray Monte Carlo: there are hints that this might further elevate the preferred range of Δm^2. Measurements of cosmic-ray secondaries on balloon flights [57] could be helpful in constraining and validating such Monte Carlos. It should also not be forgotten that aspects of the interpretation depend on low-energy ν cross-section measurements [58], both total and exclusive: here the close-up detectors in the K2K and NuMI beam lines will play useful roles, as might measurements by CHORUS and/or NOMAD.

In the case of solar neutrinos, there are three regions of neutrino-mixing parameters that are compatible with the rates observed in the different experiments [60]: Kamiokande and Super-Kamiokande at high energies, Homestake that is also sensitive to Be neutrinos, and SAGE and GALLEX that are also sensitive to pp neutrinos. The favoured parameter regions are the small-angle Mikheyev-Smirnov-Wolfenstein [59] (MSW) (SMA) solution with $\Delta m^2 \sim 10^{-5}$ eV^2 and $\sin^2 2\theta \sim 10^{-2}$ to 10^{-3}, the large-angle MSW (LMA) solution with $\Delta m^2 \sim 10^{-4}$ to 10^{-5} eV^2 and $\sin^2 2\theta \sim 1$, and the vacuum-oscillation (VO) solution with $\Delta m^2 \sim 10^{-10}$ eV^2

and $\sin^2 2\theta \sim 1$.

In the case of atmospheric neutrinos [60], the possibility of large $\nu_\mu \rightarrow \nu_e$ oscillations is excluded by Chooz [61] [a] as well as by Super-Kamiokande itself. However, $\nu_\mu \rightarrow \nu_e$ oscillations could still be present at a subdominant level, and exploring this possibility is a key task for future experiments. The dominant ν_μ oscillations may be into either ν_τ or a sterile neutrino ν_s. One way to distinguish these possibilities may be via π^0 production by atmospheric neutrinos[60]: they can be produced by ν_τ interactions, but not by ν_s. Another signature is in the zenith-angle distribution of upward-going muons [51]. In both cases, Super-Kamiokande data may be starting to favour $\nu_\mu \rightarrow \nu_\tau$ oscillations. A key test will be the neutral- to charged-current ratio in long-baseline experiments. However, for me the crucial experiment is to observe τ production by either atmospheric or long-baseline neutrinos, as discussed later.

In the case of solar neutrinos, three measurements may soon be able to discriminate between the proposed SMA, LMA and VO solutions [60]. Super-Kamiokande reports a distortion of the recoil e energy spectrum [51], in good agreement with that expected in the VO solution. The SMA solution generally predicts a smaller distortion (and the LMA solution an even smaller distortion). However, this difficulty may be overcome if the high-energy hep neutrino production cross-section, which is difficult to calculate reliably, is (much) larger than the value assumed in Standard Solar Model calculations [63]. Both the SMA and LMA solutions tend to predict some day-night difference, but not the VO solution. The present Super-Kamiokande data constrain the possible magnitude of this day-night effect, thereby constraining the SMA and LMA parameter regions. If any day-night effect were to be seen, its dependence on the solar nadir angle could in principle discriminate further between different parameter choices [64]. Some seasonal variation is predicted in all models, because of the trivial geometric effect due to the eccentricity of the Earth's orbit. However, a larger seasonal variation is predicted in VO solutions, and this might be further enhanced at high energies.

Oscillation experiments can determine differences in neutrino masses squared, but not the absolute values of their masses. Astrophysical and cosmological data already exclude $m_\nu \gtrsim 3$ eV[65], and future data may be sensitive to $m_\nu \gtrsim 0.3$ eV [66] [b]. Below this range, neutrinos would not constitute a significant fraction of the astrophysical dark matter, though masses in the range $\gtrsim 0.03$ eV favoured by atmospheric-neutrino data would have some cosmological implications [66].

Are there any experimental or theoretical reasons why the three flavours of neutrinos should not all be almost degenerate with $\bar{m} \gtrsim 2$ eV ? There is a strong constraint from the absence of neutrinoless double-β decay [69]:

$$< m_\nu > \simeq \bar{m} \times \left| c_2^2 \, c_3^2 \, e^{i\phi} + s_2^2 \, c_3^2 \, e^{i\phi'} + s_3^2 \, e^{2i\phi''} \right| \lesssim 0.2 \text{ eV} \tag{18}$$

Here $\nu_\mu \rightarrow \nu_e$ oscillations suggest that the last term in (18) may be neglected, in which case the first two terms would need to cancel at the 90 % level. Thus $\phi' \simeq \phi + \pi$ and

$$c_2^2 - s_2^2 = \cos 2\theta_2 \lesssim 0.1 \tag{19}$$

implying that $\sin^2 2\theta_2 \gtrsim 0.99$. This certainly excludes the SMA solution, and very likely LMA solutions, but not VO solutions. However, in the latter case, the neutrino mass degeneracy would need to be accurate to one part in 10^{10} ! The neutrino-mass degeneracy would be broken by non-universal loop corrections: we find [70] that these are much larger than would be allowed in the VO solution, that in the MSSM they have the wrong sign for the LMA solution, and that in one favoured neutrino-mass texture they produce unacceptable patterns of mixing angles. We conclude that degenerate neutrinos are distinctly problematic [71].

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[a] More data are on their way from the Palo Verde experiment [62].

[b] Negative results of searches, using the CERN beam, for oscillations involving neutrinos with masses of interest to cosmology were also reported here [67,68].

Some cute neutrino calculations were reported here. One was of the related processes $\bar{\nu}\nu \to \gamma\gamma\gamma$, $\gamma\gamma \to \gamma\gamma\gamma$ and $\gamma\gamma \to \bar{\nu}\nu\gamma$ [72]. These turn out to have cross-sections 9 to 13 orders of magnitude larger than the corresponding 2-→ 2 processes $\bar{\nu}\nu \to \gamma\gamma$, $\gamma\nu \to \gamma\nu$ and $\gamma\gamma \to \bar{\nu}\nu$! A full Standard Model calculation agrees with an effective Lagrangian result at low energies $E \ll m_e$. One of the consequences is that the neutrino mean free path in a supernova becomes smaller than the core radius, with potentially important consequences for supernova simulation codes, that are now being revised to incorporate these effects. The effects of multibody neutrino exchange in neutron stars was also discussed[73]. A first estimate had overestimated its importance by 63 orders of magnitude! The new calculations indicate that a neutrino condensate forms in a neutron star, changing its mass by about 30 kg out of 10^{30} kg. By comparison, two-body neutrino effects change the mass by about 10^{14} kg.

4 Supersymmetry and Further Beyond

The phenomenological motivation for supersymmetry is very simple, namely to stabilize the gauge hierarchy. The theory of supersymmetry is not too complicated either, since all the sparticle couplings are related to the gauge and Yukawa couplings of the Standard Model. However, more complications arise when one considers the soft supersymmetry breaking needed to elevate sparticle masses. These are usually parametrized as

$$(m_0^2)_i^j \, \phi^i \, \phi_j \; , \quad M_a \tilde{V}_a \tilde{V}_a \; , \quad A^{ijk} \lambda^{ijk} \phi_i \, \phi_j \, \phi_k \; , \quad B^{ij} \, \mu^{ij} \, \phi_i \, \phi_j \tag{20}$$

which are usually quoted as leading to 105 free parameters in the MSSM. These are often simplified by imposing universality at some input GUT or string scale:

$$M_a = m_{1/2} \; , \quad (m_0^2)_i^j = m_0^2 \, \delta_i^j \; , \quad A^{ijk} = A \; , \quad B^{ij} = B \tag{21}$$

before renormalization. Universality for the gaugino masses M_a may be more plausible than that for the scalar masses, which is particularly questionable for Higgs scalar masses.

However, one should also bear in mind the possible appearance of other supersymmetry-breaking parameters[74] corresponding to interactions of the form

$$\phi^i \, \phi_j \, \phi_k \; , \quad \varphi_i \, \varphi_j \tag{22}$$

which should be considered equally soft if they do not generate quadratic quantum divergences. Important questions to understand include whether string/M theory can generate terms like (22), and what might be their implications for phenomenology, particularly in the $\tilde{t}, \tilde{b}$ and Higgs sectors. When considering the phenomenology of the MSSM, it is important to include the constraint of correct electroweak symmetry breaking (as characterized by m_Z and $\tan\beta$) after renormalization, and also to check that there is no lower-energy charge- and/or colour-breaking vacuum. These issues, together with the implementation of experimental constraints on m_h, m_A and sparticle masses, are discussed in more detail later.

The phenomenological signatures of supersymmetry to be sought by experiments vary in different theoretical scenarios. One basic issue is whether R parity is conserved or not. In the latter case, one should look for sparticle decays into quarks and/or leptons, providing the opportunity of looking for bumps in the invariant masses of leptons and/or jets [75]. On the other hand, if R parity is conserved, the lightest supersymmetric particle (LSP) is stable, and hence expected to be present in the Universe as a relic from the Big Bang. Upper limits on the relative abundances of anomalous heavy isotopes of many elements conflict with calculations of the relic abundance, suggesting that any such relic cannot bind to conventional matter, and hence should not have electric charge or strong interactions[76]. Thus the LSP is expected to be a neutral weakly-interacting particle such as the lightest neutralino χ. This leads to the "classic" missing-energy signature of supersymmetry. On the other hand, if the lightest neutralino is not the LSP, one expects χ decays to provide characteristic signatures, e.g., $\chi \to \gamma \tilde{G}$ if the gravitino $\tilde{G}$ is the LSP. This is the generic prediction of models in which supersymmetry breaking is communicated to the observable sector by a messenger gauge-interaction sector [77].

Such gauge-mediated models have recently attracted interest for two reasons. One is theoretical: they provide a natural explanation why supersymmetry-breaking scalar masses should be generation-independent [77]. The second is experimental: they might explain the $\bar{p}p \to e^+e^-\gamma\gamma \not{E}_T + X$ event seen by CDF [78]. However, popular supersymmetric interpretations of this event have now been almost excluded by searches at LEP as well as the Tevatron itself[79,80]. Indeed, since the lightest neutralino is directly detectable in gauge-mediated and R-breaking models, unlike the standard R-conserving model with a neutralino LSP, the experimental constraints on MSSM parameter space are generally stronger in these alternative scenarios. In the following, we concentrate on the "conservative" R-conserving neutralino LSP scenario.

Important constraints on the MSSM parameter space are provided not only by direct searches for unstable sparticles such as sleptons and charginos, but also by unsuccessful searches for the Higgs bosons of the MSSM. These are sensitive to other sparticle masses via loop corrections, so lower limits on Higgs masses may be interpreted as lower limits on the universal soft supersymmetry-breaking masses, particularly if the input Higgs scalar masses are also universal. Requiring the relic χ density to be in the range allowed by astrophysics and cosmology: $0.1 \le \Omega_\chi h^2 \le 0.3$ (where $\Omega_\chi \equiv \rho_\chi/\rho_c$, with ρ_c the critical density and h the Hubble constant in units of 100 km s^{-1} Mpc^{-1}) further constrains the MSSM parameter space. In a combined analysis a couple of years ago[81], it was found that $m_\chi \ge 40$ GeV, to be compared with a lower limit of 20 GeV from LEP searches for charginos and neutralinos alone.

One might begin to wonder whether the constraints on the parameter space of the MSSM are still compatible with the phenomenological motivation of avoiding the need to fine-tune parameters in order to maintain the gauge hierarchy. A first attempt to capture the idea of fine tuning was the "price" [82]

$$\Delta \equiv \max_i \Delta_i \ : \ \Delta_i \equiv \frac{\partial \ln m_Z^2}{\partial \ln \ a_i} \tag{23}$$

where the a_i are input MSSM parameters. The LEP data impose the price $\Delta \ge 13$ [83]. Is this a lot or a little? There is no objective reply, and the price may be reduced significantly by postulating some theoretical correlations between the MSSM parameters. Alternatively, it was proposed here[84] that one evaluate the percentage of the *a priori* MSSM parameter space that is still permitted by the experimental constraints. By one estimate, the residual conditional probability P (LEP|susy)$\simeq$ 5 %. However, what one really wants to know [84] is the opposite conditional probability

$$P(\text{susy}|\text{LEP}) = \frac{P(\text{susy}) \times 5\%}{1 - 95\% \times P(\text{susy})} \tag{24}$$

which depends on the *a priori* probability assignment P(susy). Clearly the estimate P(LEP|susy) $\simeq$ 5 % depends on the choice of measure in the MSSM parameter space made in specifying (susy). If you are totally convinced by the original choice made: P(susy) = 1, then (24) tells you that you still believe it: P(susy|LEP) = 1! On the other hand, if you disbelieved it *a priori*: P(susy) = 0, then (24) tells you that you still disbelieve it! It seems to me that one needs some external rationale to determine the measure in MSSM parameter space and the corresponding P(susy). Fine tuning in the sense (23) is one proposal, but there may be better ones.

The new LEP constraints on MSSM particle masses were reviewed here[85]. Among the most important ones is

$$m_{\chi^\pm} > 95 \text{ to } 90 \text{ GeV} \tag{25}$$

except in the deep Higgsino region. Combining with other searches, including associated neutralino production $e^+e^- \to \chi\chi'$, one now finds

$$m_\chi > 32 \text{ GeV} \tag{26}$$

for all m_0 and $\tan\beta$. If $\tilde{t} \to c\chi$ decays dominate and $m_{\tilde{t}} - m_\chi \leq 10$ GeV, one has

$$m_{\tilde{t}} > 87 \text{ GeV} \tag{27}$$

In addition

$$m_{\tilde{\ell}} > 88 \text{ GeV} \tag{28}$$

for $m_{\tilde{\ell}} - m_\chi \gtrsim 5$ GeV, with somewhat weaker limits for $m_{\tilde{\mu}}$ and $m_{\tilde{\tau}}$. In addition to sparticle limits, very important constraints on the MSSM parameter space come from the Higgs limit [10]: the best limit from an individual LEP experiment is

$$m_H > 95.2 \text{ GeV} \tag{29}$$

and the joint sensitivity is to $m_H \lesssim 98$ GeV. A few candidate events have been reported [10], but there is no significant signal yet.

One may analyze the constraints these limits impose jointly in the space of MSSM parameters. I should like to underline the importance of including radiative corrections to the relations between these parameters and physical sparticle masses [86]. These are included routinely for Higgs masses, but not for chargino and neutralino masses, whereas these are also significant. In particular, the change in sensitivity in the (μ, M_2) plane when these radiative corrections are included is comparable to the change in physics reach between one year's run of LEP and the next, as the beam in energy is increased, so these should not be neglected in a complete analysis of LEP data [86].

Fig. 4 shows the impacts of various LEP constraints in the $(m_{1/2}, m_0)$ plane[87], including also the requirement that the electroweak vacuum be stable against transitions to vacua that violate charge and/or colour conservation (CCB) [88]. These are weakest for $A \simeq -m_{1/2}$ as plotted in Fig. 4, but even so they indicate a preference for

$$110 \text{ GeV} \lesssim m_{1/2} \lesssim 400 \text{ GeV}, \quad 80 \text{ GeV} \lesssim m_0 \lesssim 170 \text{ GeV} \tag{30}$$

when combined with the cosmological relic density limit. However, it is not clear whether vacuum stability is an absolute necessity. It might be sufficient if the early Universe evolved into our vacuum, and if this is metastable with a lifetime $\gtrsim 10^{10}$ years.

The cosmological domains in Fig. 4 include the effects of coannihilation between the neutralino LSP and the next-to-lightest supersymmetric particle (NLSP), which can be important if their mass difference $\Delta m \lesssim \mathcal{O}(m_\chi/10)$ [89]. In the region of Fig. 4, the NLSP is the $\tilde{\tau}_R$, and coannihilations with the $\tilde{\mu}_R$ and $\tilde{e}_R$ are also significant, particularly because the $\chi\chi$ annihilations are suppressed in the non-relativistic limit. The coannihilations suppress the relic density for large $m_{1/2}$, so that the LSP may be substantially heavier than was previously thought. Combining all the new LEP constraints [87], we may estimate that

$$m_\chi \gtrsim 50 \text{ GeV}, \quad \tan\beta \gtrsim 1.8 \tag{31}$$

and

$$m_\chi \lesssim 600 \text{ GeV} \tag{32}$$

when coannihilations are taken into account.

The lower limit (31) is tantalizingly close to the report from the DAMA collaboration [90], in which they fail to exclude the presence of an annual modulation of a recoil signal, which could

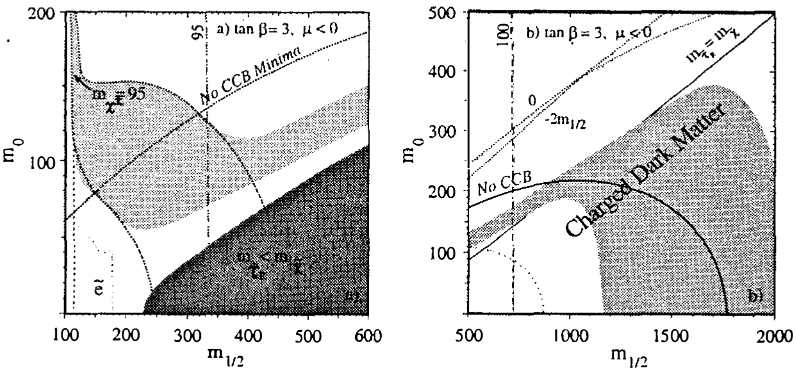

Figure 4: *Experimental, theoretical and cosmological constraints in the* $(m_{1/2}, m_0)$ *plane, for* $tan\beta = 3, \mu < 0$, *indicating the physics reach of LEP for* $\tilde{e}, \chi^{\pm}$ *and Higgs searches* [87]. *The light shaded region is that where* $0.1 < \Omega_\chi h^2 < 0.3$ *after including coannihilation effects* [89], *and the region plagued by charge and colour-breaking (CCB) minima is also delineated. Panel (a) is extended in panel (b) to larger values of* $m_{1/2}$, *showing how the upper limit* $m_\chi < 600$ *GeV may be reached.*

correspond to $m_\chi \sim 60$ GeV with large errors. Not only is the indicated mass compatible with the experimental limit (31), but also the corresponding cross section is compatible with some theoretical models, particularly if the MSSM Higgs is light[91]. However, care should be exercised in interpreting the possible annual modulation: we shall need to see data over a complete annual cycle and be reassured that any modulation could not be due to some non-fundamental seasonal effect.

There was considerable discussion here of possible phenomenological signatures of large extra space dimensions[92]. In "classical" perturbative string theory, the gauge and gravitational interactions are unified at an energy $E = m_s$ where they become equal:

$$\frac{e^2}{r} = \frac{E^2}{m_P^2} \frac{1}{r} \tag{33}$$

corresponding to a string scale $m_S = \mathcal{O}(\sqrt{\alpha}) m_P \simeq 10^{18}$ GeV, at which six extra dimensions appear. This is modified in "post-classical" M theory, where one can enforce $m_s \simeq m_{GUT} \simeq 10^{16}$ GeV as indicated by LEP, by postulating an extra dimension with characteristic size $R \gg m_{GUT}^{-1}$ [93]. Above this scale, the Newton potential is modified:

$$\frac{E^2}{m_P^2} \frac{1}{r} \to \frac{E^3}{\tilde{m}_P^3} \frac{1}{r} \tag{34}$$

whereas the gauge interactions do not feel the extra dimension. The resulting picture of space time resembles a pair of capacitor plates. There are two infinitely large four-dimensional plates separated by a distance $R \gg m_{GUT}^{-1}$, and each "point" in this picture can in fact be resolved into six compactified dimensions at energies $E \gtrsim m_{GUT}$.

In the new "deconstructionist" approach[94,95], one asks the natural and important question: how large could the extra dimension(s) be? In particular, could the scale of gravity be as low as 1 TeV, in which case the hierarchy problem is entirely reformulated. If n extra dimensions appear at a scale R so that the Newton potential $\propto 1/r^{1+n}$ at shorter distances, one has

$$m_P^2 = m_s^{n+2} R^n \tag{35}$$

and if $m_s \simeq 1$ TeV by construction, $R \simeq 10^{13}$ m (1 mm) (10 fm) for $n = 1(2)(6)$. The Newton $1/r$ law has been checked down to $r \gtrsim 1$ cm, so one needs $n \gtrsim 2$ in (35): near-future experiments may be able to probe down to $r \simeq 10\mu m$. Some of the most important constraints on such theories come from astrophysics and cosmology [96], including graviton emission from supernovae, the cosmic microwave background, Big Bang nucleosynthesis and inflation, which appear to indicate that m_s may need to be considerably larger than 1 TeV.

There has been some discussion whether gauge interactions might also "feel" (some of) the bulk dimensions appearing at distances $\lesssim R$ [97]. This is not the case in "canonical" string or M theory, and is actually impossible in the standard formulation of five-dimensional supergravity [98]. It may be possible to mimic the very successful GUT prediction for $\sin^2\theta_W$ in such a scenario [97], but I need reassurance how naturally and precisely this may work. Among the signatures for such higher-dimensional theories discussed here [94] are missing-energy events: $e^+e^- \to \gamma +$ (gravitons), $gg \to g +$ (gravitons), and angular distortions in $e^+e^- \to \mu^+\mu^-$ due to higher-dimensional graviton exchange. The latter has been used to show that $m_s \gtrsim 0.6$ TeV for $n = 2$ on the basis of LEP data [99]. Among the many issues being studied in such models are flavour-changing processes, baryon stability and neutrino masses.

An interesting theoretical question for such models is whether supersymmetry is still necessary. Not for solving the hierarchy problem in the traditional way, but string theory still (apparently) requires supersymmetry for its consistency, so it should still appear around m_s($\sim$ 1 TeV?). The traditional hierarchy problem is now repackaged as the question why R is so large. Since the fixing of the compactification radius and related moduli are not understood in conventional string theory, though, do we have any good reason to think that R could not be large?

5 Future Projects

There were many discussions here of the future prospects in electroweak projects, of which I give here a few highlights. Over the next two years, 1999 and 2000, LEP should finally reach its design energy of 200 GeV in the centre of mass, perhaps even a bit more. Clearly this provides further opportunities to search for supersymmetric particles, etc., but the most exciting prospects may be those for the Higgs boson search. We see in Fig. 1 that the highest probability density for its mass is the range just at the present direct search limit, and within the reach $m_H \lesssim 110$ GeV of LEP 200+ϵ. This is, moreover, the most likely range in the MSSM [100].

If LEP does not find the Higgs, it may be found at the Fermilab Tevatron collider during one of its future runs, starting in 2000. The Tevatron collider may also be able to find, or at least exclude, MSSM Higgs bosons over a considerable range of parameter space [101]. The reach in the space of MSSM soft supersymmetry breaking parameters will also be extended at the Tevatron collider [102]. Overall, there is significant chance that the Tevatron collider will be able to steal some of the LHC's supersymmetric thunder.

Turning now to neutrino physics, there is an extensive programme of work for long-baseline experiments [103]. Accelerators produce intense beams with controlled energy spectra, fluxes and flavours of neutrinos, that can be monitored and adjusted. These may be needed to convince sceptics of the reality of neutrino oscillations, and in order to make precision measurements. Among the key measurements to make are those of ν_μ disappearance and the neutral- to charged-current ratio, involving the comparison of rates in near and far detectors, as planned for the K2K [104] and MINOS [105] experiments. Another key measurement is that of ν_e appearance, which is not expected to be the dominant mode of oscillation, but might be present below the 10 % level.

In my view, the key experiment to pin down the interpretation of the atmospheric neutrino data will be the search for τ appearance subsequent to $\nu_\mu \to \nu_\tau$ oscillations. This is the favoured interpretation of the current data, but on the basis of indirect arguments. I believe there is no substitute for direct observation of τ production in a long-baseline experiment. The interpretation would be unambiguous, since the accelerator and other backgrounds are negligible. Only in this way could alternative interpretations such as ν_μ oscillations into sterile neutrinos be definitively rejected. Remember Jimmy Hoffa, and the basic legal principle "if you have not seen the body, you have not proven there was a murder". Remember also the gluon: there were many indirect and theoretical arguments that it should exist, and that it should have unit spin, but everybody remembers the direct observation of gluon jets in the reaction $e^+e^- \rightarrow \bar{q}qg$ [106] as the "discovery of the gluon" [107].

Three long-baseline neutrino oscillation projects have been approved so far [103]. Two are in Japan: KamLAND, which sets out to detect ν_e from power reactors and should be able to confirm or refute the LMA solution to the solar neutrino problem, and K2K, which is a ν_μ disappearance experiment using a KEK beam that can probe aboout a half of the region in $(\sin^2 2\theta, \Delta m^2)$ favoured by Super-Kamiokande. KamLAND should start taking data in 2001, and K2K has already started. The only approved project with a beam energy high enough to detect ν_τ via τ production is NuMI. The MINOS detector (to start data-taking in 2002, with the detector to be completed in 2003) should be able to cover all the Super-Kamiokande region with a ν_μ disappearance measurement, but has a limited ability to detect τ leptons. A proposal has now been made to add to MINOS a τ detection module based on emulsion tracking, which could be completed in 2004.

In Europe, CERN and the Gran Sasso laboratory are proposing a slightly higher energy beam optimized for τ production, that could be ready in 2005 [108]. It would make optimized use of the CERN infrastructure, including one of the lines transferring protons to the LHC, and benefit from the fact that the Gran Sasso experimental halls were, from the beginning, oriented so as to profit maximally from a CERN neutrino beam. Experimental concepts now being developed [109] should be able comfortably to detect τ leptons over all the parameter range allowed by Super-Kamiokande, as seen in Fig. 3.

The LHC physics programme was not much discussed at this meeting. Paramount is the search for the "holy Higgs". This has been well studied in the Standard Model, and extensive studies have been made in the MSSM [110], but the latter has not been completely explored. LEP studies have revealed the possibility of a reduction in the $h \rightarrow \bar{b}b$ decay mode that usually dominates. The possibilities of interference effects in $\sigma(gg \rightarrow h)$ and $\Gamma(h \rightarrow \gamma\gamma)$ merit further work, and this is one area where more dialogue between theorists and experimentalists preparing LHC detectors would be useful. Moriond could play a useful role in this regard, particularly in encouraging and motivating the young people who will do most of the work. The success of the LHC will require a big, coherent effort from all sectors of the community.

Also important at the LHC will be the search for supersymmetric particles. Here the production cross sections are well understood, and potentially complicated decay chains such as $\tilde{g} \rightarrow \tilde{b}\bar{b}$, $\tilde{b} \rightarrow \chi_2 b, \chi_2 \rightarrow \chi\ell^+\ell^-$ have been explored. The LHC will be able to explore $m_{\tilde{g},\tilde{q}} \lesssim$ 2 TeV and $m_{\tilde{\ell}} \lesssim$ 400 GeV, and could make some detailed studies of sparticle spectroscopy [111]. It used to be thought that the entire region of MSSM parameter space favoured by cosmology could be covered comfortably by the LHC, several times over [112]. However, the coannihilation effects [89,87] mentioned earlier stretch the cosmologically favoured region up to larger $m_{1/2}$ as seen in Fig. 4, close to the LHC reach, so this issue needs to be reviewed.

Beyond the LHC, the physics programme for a linear e^+e^- collider is currently being extensively studied, particularly the relative advantage of high luminosities, e.g., with TESLA [113]. One example is the study of Standard Model Higgs decays: if the Higgs boson has a mass in the range favoured by precision electroweak measurements, its $\bar{b}b, \bar{c}c, gg$ and $\tau^+\tau^-$ branching ratios could be measured accurately. However, the total Higgs decay width could not be measured without implementing the $\gamma\gamma$ collider option, which is not currently part of the TESLA baseline.

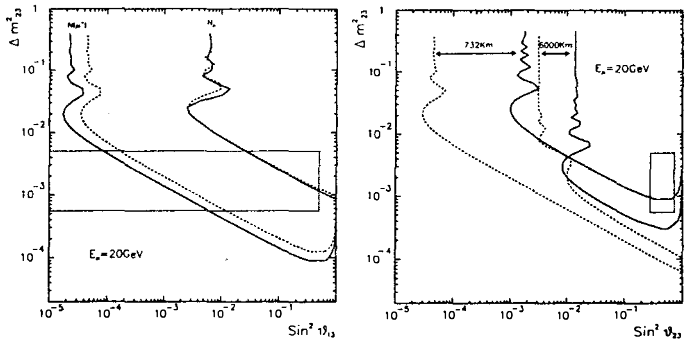

Figure 5: *The sensitivities of long-baseline neutrino experiments using beams from a muon storage ring used as a neutrino factory* [116]*: (a) to search for mixing between the first- and third-generation neutrinos via appearance (left lines) and disappearance (right lines) for $\theta_{23} = 45^o$ (solid lines) and 30^o (dashed lines), assuming a baseline of 732 km, and (b) to search for mixing between the second- and third-generation neutrinos via appearance (dashed lines) and disappearance (solid lines), assuming the indicated beam lengths. The boxes represent current indications and limits.*

I close by mentioning the most futuristic project idea discussed here: muon storage rings. These could be developed in a three-step scenario [114], starting with a neutrino factory [115] using the known fluxes, flavours, charges and spectra from muon decay - the "ultimate weapon" for ν oscillation studies [116], continuing with one or more $\mu^+\mu^-$ colllider Higgs factories suitable for measuring the total decay width(s), reducing the allowed phase space of the MSSM and perhaps providing a new window on CP violation – the "ultimate weapon" for Higgs studies [117], and a high-energy $\mu^+\mu^-$ collider, whose maximum energy is currently limited by the potential neutrino-induced radiation hazard [114].

Very many basic technical issues need to be resolved before the feasibility of such storage rings and colliders can be judged, but their physics is very enticing. In the presence of three different masses, neutrinos would have three real mixing angles and three phases (though two of the latter cannot be measured at energies $E \gg m_\nu$). Thus there is a programme of work as rich as that for the B factories now coming on line [116]. As discussed here [116] and reflected in Fig. 5, the following are the sensitivities of appearance and disappearance experiments as functions of the beam length and energy:

$$\begin{aligned} \Delta m^2_{ij} \ &: \ E_\mu^{-1/2} \ , \ \ L^{-1/2}\, E_\mu^{1/4} \\ \sin^2\theta_{ij} \ &: \ LE_\mu^{-3/2} \ , \ \ L^{1/2}\, E_\mu^{-3/4} \end{aligned} \qquad (36)$$

These dependences imply that very-long-baseline experiments ($L \gtrsim 3000$ km) are not necessarily the best. As shown here, long-baseline experiments have very interesting physics reaches for oscillation parameters in a three-generation analysis. In addition, there is a chance of observing CP-violating effects, particularly with a very long baseline [116].

A first Higgs factory with $E_{cm} \sim 110$ GeV could measure the mass of the Higgs with a precision of 0.1 MeV [114,117]. In the MSSM, a second Higgs factory with $E_{cm} \sim m_{H,A}$ could measure their masses with a precision of 10 MeV and their (relatively large) widths with a precision of 50 MeV. The twin peaks may also offer prospects for observing CP-violating observables. Such $\mu^+\mu^-$ colliders offer precision tests of the MSSM [114,117].

Table 1: *Accessibilities of various possible new physics phenomena with the LHC, a 4-TeV e^+e^- collider and a 4-TeV $\mu^+\mu^-$ collider. The crosses X denote inaccessible features of models, the symbols Y denote accessible features. We indicate by F (E) the topics where flavour non-universality (energy resolution) is a particular advantage for a $\mu^+\mu^-$ collider, and by γ (P) topics where $\gamma\gamma$ collisions (polarization) confer advantage on an e^+e^- collider.*

Physics topic	LHC	e^+e^-	$\mu^+\mu^-$
Supersymmetry			
Heavy Higgses H, A	X ?	?: γ	Y: F,E
Sfermions	$\tilde{q}$	$\tilde{\ell}$	$\tilde{\ell}$: F
Charginos	X ?	Y: P	Y: F,E
R violation	$\tilde{q}$ decays	λ_{1ij}	λ_{2ij}:F,E
SUSY breaking	some	more	detail: F E
Strong Higgs sector			
Continuum	$\leq$ 1.5 TeV	$\leq$ 2 TeV	$\leq$ 2 TeV
Resonances	scalar, vector	vector, scalar	vector (E), scalar (F)
Extra dimensions			
Missing energy	large E_T	Y	Y: E?
Resonances	q^*, g^*	γ^*, Z^*, e^*	γ^*, Z^*, μ^*: E

Finally, the Table summarizes some of the comparative physics strengths of the LHC and high-energy e^+e^- and $\mu^+\mu^-$ colliders [114]. Each has unique advantages (e.g., flavour non-universality and energy resolution in the case of a $\mu^+\mu^-$ collider), and a key role to play in the future elucidation of electroweak physics. The LHC is already on the way, and we hope that a first-generation e^+e^- linear collider can follow it. In the mean time, let us work to make $\mu^+\mu^-$ colliders realistic options for the more distant future.

References

1. LEP Electroweak Working Group, CERN preprint EP/99-15; updates may be found at `http://www.cern.ch/LEPEWWG/Welcome.html`.
2. N. de Groot, SLD collaboration, talk at this meeting.
3. S.C. Bennett and C.E. Wieman, Phys. Rev. Lett. **82**, 2484 (1999).
4. See also: R. Casalbuoni, S. De Curtis, D. Dominici and R. Gatto, hep-ph/9905568.
5. M. Lancaster, talk at this meeting; for other Tevatron measurements, see N. Graf, talk at this meeting.
6. I. Riu, talk at this meeting.
7. M. Hapke, talk at this meeting.
8. J. Ellis and K. Geiger, Phys. Lett. **B404**, 230 (1997).
9. K. Geiger, J. Ellis, U. Heinz and U. Wiedemann, hep-ph/9811270.
10. M. Felcini, talk at this meeting.
11. M. Davier and A. Hoecker, Phys. Lett. **B419**, 419 (1998).
12. J. Lykken, opening talk at this meeting, see also: `http://www.fnal.gov/pub/hep_descript.html`.
13. X.-R. Qi, talk at this meeting.
14. E. Perazzi, talk at this meeting; D. Urner, talk at this meeting.
15. T. Hambye and K. Riesselmann, hep-ph/9708416.
16. L. Wolfenstein Phys. Rev. Lett. **13**, 562 (1964).
17. E. Blucher, KTeV Collaboration, talk at this meeting; see also: A. Alavi-Harati et al.,

KTeV Collaboration, hep-ex/9905060.
18. M. Kobayashi and K. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
19. J. Ellis, M.K. Gaillard and D.V. Nanopoulos, Nucl. Phys. **B109**, 213 (1976).
20. C.E.M. Wagner, talk at this meeting; see also: A. Pilaftsis and C.E.M. Wagner, hep-ph/9902371.
21. J. Kalinowski, talk at this meeting; see also: B. Grzadkowski, J.F. Gunion and J. Kalinowski, hep-ph/9902308.
22. J. Ellis, M.K. Gaillard, D.V. Nanopoulos and S. Rudaz, Phys. Lett. **B131**, 285 (1977).
23. G.D. Barr et al., NA31 Collaboration, Phys. Lett. **B317**, 233 (1993).
24. F. Gilman and M. Wise, Phys. Lett. **B83**, 83 (1979).
25. J.M. Flynn and L. Randall, Phys. Lett. **B224**, 221 (1989).
26. Y. Keum, U. Nierste and A.I. Sanda, hep-ph/9903230; S. Bosch, A.J. Buras, M. Gorbahn, S. Jager, M. Jamin, M.E. Lautenbacher and L. Silvestrini, hep-ph/9904408.
27. L. Lellouch, talk at this meeting.
28. H. Videau, talk at this meeting.
29. A. Masiero and H. Murayama, hep-ph/9903363; K.S. Babu, B. Dutta and R.N. Mohapatra, hep-ph/9905464.
30. L. Silvestrini, talk at this meeting, hep-ph/9906202.
31. I. Mikulec, NA48 Collaboration, talk at this meeting.
32. J. Ellis, J.S. Hagelin, D.V. Nanopoulos and M. Srednicki, Nucl. Phys. **B241**, 381 (1984); J. Ellis, J.L. Lopez, N.E. Mavromatos and D.V. Nanopoulos, Phys. Rev. **D53**, 3846 (1996); R. Adler *et al.*, CPLEAR Collaboration, Phys. Lett. **B364**, 239 (1995).
33. A. Angelopoulos *et al.*, CPLEAR Collaboration, Phys. Lett. **B444**, 43 (1998).
34. A. Filipcic, CPLEAR Collaboration, talk at this meeting;
35. J. Ellis and N.E. Mavromatos, hep-ph/9903386.
36. S. Lola, talk at this meeting; see also: L. Alvarez-Gaumé, C. Kounnas, S. Lola and P. Pavlopoulos, hep-ph/9812326 and hep-ph/9903458.
37. T. Yamanaki, KTeV Collaboration, talk at this meeting; see also: `http://www.fnal.gov/pub/hep_descript.html`.
38. M. Schmidt, CDF Collaboration, talk at this meeting; see also: CDF Collaboration, CDF/PUB/BOTTOM/CDF/4855 (1999).
39. A. Romanino, talk at this meeting; see also: R. Barbieri, L.J. Hall and A. Romanino, hep-ph/9812384.
40. A. Ali and D. London, hep-ph/9903535.
41. T. Moore, SLD Collaboration, talk at this meeting.
42. D. Bloch, talk at this meeting.
43. R. Barbieri, J. Ellis and M.K. Gaillard, Phys. Lett. **90B**, 249 (1980).
44. M. Gell-Mann, P. Ramond and R. Slansky, Proceedings of the Stony Brook Supergravity Workshop, New York, 1979, eds. P. Van Nieuwenhuizen and D. Freedman (North-Holland, Amsterdam); T. Yanagida, Proceedings of the Workshop on Unified Theories and Baryon Number in the Universe, Tsukuba, Japan 1979, eds. A. Sawada and A. Sugamoto, KEK Report No. 79-18.
45. B. Allanach, talk at this meeting; see also: B. Allanach, Phys. Lett. **B450**, 182 (1999).
46. For one particular take on this, see: J. Ellis, G. Leontaris, S. Lola and D.V. Nanopoulos, hep-ph/9808251; for a recent review, see: G. Altarelli and F. Feruglio, hep-ph/9905536.
47. W. Haxton, Prog. Part. Nucl. Phys. **40**, 101 (1998).
48. G.L. Fogli, E. Lisi, A. Marrone and G. Scioscia, Phys. Rev. **D59**, 117303 (1999) and hep-ph/9904248; see also: S. Pakvasa, hep-ph/9905426.
49. G. Mills, LSND Collaboration, talk at this meeting.
50. T. Jannakos, KARMEN Collaboration, talk at this meeting.

51. D. Casper, Super-Kamiokande Collaboration, talk at this meeting; see also: K. Scholberg, hep-ex/9905016.
52. Y. Fukuda et al., Super-Kamiokande collaboration, Phys. Rev. Lett. **81**, 1562 (1998).
53. T. Futagami et al., Super-Kamiokande Collaboration, astro-ph/9901139.
54. D. Michael, MACRO Collaboration, talk at this meeting; see also: R. Ronga, MACRO Collaboration, hep-ex/9905025; A. Surdo, MACRO Collaboration, hep-ex/9905028.
55. W.W.M. Allison et al., Soudan II Collaboration, Phys. Lett. **B449**, 137 (1999).
56. P. Lipari, hep-ph/9905506.
57. R. Bellotti et al., hep-ex/9905012.
58. J. Marteau, talk at this meeting.
59. L. Wolfenstein, Phys. Rev. **D17**, 2369 (1978); S.P. Mikheev and A.Y. Smirnov, Sov. J. Nucl. Phys. **B42**, 913 (1985) and Nuov. Cim. **9C**, 17 (1986).
60. A.Y. Smirnov, talk at this meeting.
61. D. Nicolo, Chooz Collaboration, talk at this meeting.
62. Y. Wang, Palo Verde Collaboration, talk at this meeting.
63. J. N. Bahcall and P.I. Krastev, Phys. Lett. **B436**, 243 (1998).
64. J.N. Bahcall, P.I. Krastev and A.Y. Smirnov, hep-ph/9905220 and references therein.
65. R.A.C. Croft, W. Hu and R. Davé, astro-ph/9903335 and references therein.
66. W. Hu, D.J. Eisenstein and M. Tegmark, Phys. Rev. Lett. **80**, 5255 (1998).
67. M. Messina, CHORUS Collaboration, talk at this meeting.
68. P. Salvatore, NOMAD Collaboration, talk at this meeting.
69. L. Baudis et al., hep-ex/9902014.
70. J. Ellis and S. Lola, hep-ph/9904279.
71. For another viewpoint, see: J.A. Casas, J.R. Espinosa, A. Ibarra and I. Navarro, hep-ph/9904395 and hep-ph/9905381.
72. J. Matias, talk at this meeting, hep-ph/9905380; see also: A. Abada, J. Matias and R. Pittau, Phys. Rev. **D59**, 013008 (1999), Nucl. Phys. **B543**, 255 (1999) and hep-ph/9809418.
73. M. Tytgat, talk at this meeting; see also: K. Kiers and M. Tytgat, hep-ph/9905532.
74. I. Jack and D.R.T. Jones, hep-ph/9903365.
75. Y. Arnoud, talk at this meeting.
76. J. Ellis, J.S. Hagelin, D.V. Nanopoulos, K. Olive and M. Srednicki, Nucl. Phys. **B238**, 453 (1984).
77. G.F. Giudice and R. Rattazzi, hep-ph/9801271.
78. F. Abe et al., CDF Collaboration, Phys. Rev. Lett. **81** (1998) 1791 and Phys. Rev. **D59**, 092002 (1999).
79. M. Antonelli, talk at this meeting;
80. A. Numerotski, talk at this meeting; other Tevatron limits were reported here by D. Claes, talk at this meeting.
81. J. Ellis, T. Falk, K.A. Olive and M. Schmitt, Phys. Lett. **B388**, 97 (1996) and **B413**, 355 (1997).
82. J. Ellis, K. Enqvist, D.V. Nanopoulos and F. Zwirner, Mod. Phys. Lett. **A1**, 57 (1986); R. Barbieri and G.F. Giudice, Nucl. Phys. **B306**, 63 (1988).
83. P.H. Chankowski, J. Ellis and S. Pokorski, Phys. Lett. **B423**, 327 (1998); R. Barbieri and A. Strumia, Phys. Lett. **B433**, 63 (1998); P.H. Chankowski, J. Ellis, M. Olechowski and S. Pokorski, Nucl. Phys. **B544**, 39 (1999).
84. A. Strumia, talk at this meeting, hep-ph/9904247.
85. R. McPherson, talk at this meeting.
86. J. Ellis, T. Falk, G. Ganis, K.A. Olive and M. Schmitt, Phys. Rev. **D58**, 095002 (1998).
87. J. Ellis, T. Falk, K.A. Olive and M. Srednicki, hep-ph/9905481.

88. S. Abel and T. Falk, Phys. Lett. **B444**, 427 (1998).
89. J. Ellis, T. Falk and K.A. Olive, Phys. Lett. **B444**, 367 (1998).
90. R. Bernabei et al., DAMA Collaboration, Phys. Lett. **B450**, 448 (1999).
91. A. Bottino, F. Donato, N. Fornengo and S. Scopel, Phys. rev. **D59**, 095003, 095004 (1999).
92. J. Lykken, talk at this meeting.
93. P. Horava and E. Witten, Nucl. Phys. **B460**, 506 (1996); E. Witten, Nucl. Phys. **B471**, 135 (1996); P. Horava and E. Witten, Nucl. Phys. **B475**, 94 (1996).
94. G. Dvali, talk at this meeting.
95. A. Donini, talk at this meeting.
96. N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Rev. **D59**, 086004 (1999); S. Cullen and M. Perelstein, hep-ph/9903422; L.J. Hall and D. Smith, hep-ph/9904267; V. Barger, T. Han, C. Kao and R.-J. Zhang, hep-ph/9905474.
97. K. Dienes, E. Dudas and T. Gherghetta, Phys. Lett. **B436**, 55 (1998) and Nucl. Phys. **B537**, 47 (1999).
98. G. Sierra, Phys. Lett. **154B**, 379 (1985); M. Gunaydin, G. Sierra and P.K. Townsend, Nucl. Phys. **B355**, 573 (1985); I. Antoniadis, S. Ferrara and T. Taylor, Nucl. Phys. **B460**, 489 (1996); A. Lukas, B.A. Ovrut, K.S. Stelle and D. Waldram, Phys. Rev. **D59**, 086001 (1999) and hep-th/9806051; J. Ellis, Z. Lalak, S. Pokorski and W. Pokorski, Nucl. Phys. **B540**, 149 (1999); J. Ellis, Z. Lalak and W. Pokorski, hep-th/9811133.
99. P.J. Holt, talk at this meeting.
100. M. Carena, M. Quiros and C.E.M. Wagner, Nucl. Phys. **B461**, 407 (1996); H.E. Haber, R. Hempfling and A.H. Hoang, Zeit. für Phys. **C75**, 539 (1997).
101. M. Carena, talk at this meeting; see also: M. Carena, S. Mrenna and C.E.M. Wagner, hep-ph/9808312.
102. V. Barger and C. Kao, hep-ph/9811489.
103. M. Campanelli, talk at this meeting; see also: hep-ex/9905035.
104. Y. Oyama, K2K Collaboration, hep-ex/9803014.
105. E. Ables et al., MINOS Collaboration, Fermilab proposal P-875.
106. J. Ellis, M.K. Gaillard and G.G. Ross, Nucl. Phys. **B111**, 253 (1976).
107. R. Brandelik et al., TASSO Collaboration, Phys. Lett. **86B**, 243 (1979).
108. G. Acquistapace et al., *The CERN neutrino beam to Gran Sasso (NGS): Conceptual technical design*, CERN-98-02 (1998).
109. A. Rubbia, et al., ICARUS Collaboration, *A search program of explicit neutrino oscillations with the ICARUS detector at long distances*, CERN-SPSLC-96-58 (1996); K. Kodama et al., *The OPERA tau neutrino appearance experiment in the CERN-Gran Sasso neutrino beam*, CERN-SPSC-98-25 (1998); M. Doucet, J. Panman and P. Zucchelli, hep-ex/9905029.
110. E. Richter-Was, D. Froidevaux, F. Gianotti, L. Poggioli, D. Cavalli and S. Resconi, Int. J. Mod. Phys. **A13**, 1371 (1998).
111. I. Hinchliffe, F.E. Paige, M.D. Shapiro, J. Soderqvist and W. Yao, Phys. Rev. **D55**, 5520 (1997).
112. S. Abdullin and F. Charles, Nucl. Phys. **B547**, 60 (1999).
113. D. Schulte, talk at this meeting.
114. *Prospective Study of Muon Storage Rings at CERN*, eds. B. Autin, A. Blondel and J. Ellis, CERN-99-02 (1999).
115. F. Dydak, talk at this meeting.
116. B. Gavela, talk at this meeting; see also: A. De Rujula, B. Gavela and P. Hernandez, Nucl. Phys. **B547**, 21 (1999); M. Campanelli, A. Bueno and A. Rubbia, hep-ph/9905240.
117. P. Janot, talk at this meeting.