PARTICLE PHYSICS SUMMARY, WHERE ARE WE AND WHERE ARE WE GOING?

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ABSTRACT

The XXVIIth Rencontres de Moriond featured approximately 84 talks on a wide range of topics. I will try to summarize the highlights under the hypothesis that $SU_3 \times SU_2 \times U_1$ is correct to first approximation, concentrating on probes for new physics at various scales.

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2 The Standard Model

I will assume that the standard model is basically correct. The $SU_2 \times U_1$ (electroweak) sector has been stringently tested by QED, neutral and charged current interactions, and the properties of the W and Z. However, it is useful to keep probing to search for TeV-scale perturbations. One missing piece is the top quark mass, m_t, which can be thought of as mainly a nuisance parameter in many of the other tests. There are two untested aspects of the electroweak model. The Higgs sector could well be only a crude approximation. The non-abelian sector is also not directly tested, but indirect evidence suggests that it is probably OK.

The strong interaction theory, QCD, is tested in e^+e^- and hadronic jet production, in deep inelastic scattering, in Υ, decays *etc.*, which probe the perturbative structure.

$\alpha_s(M_Z)$	Source
0.124 ± 0.005	event shapes
0.133 ± 0.012(prelim)	$R_Z = B(Z \to \text{had})/B(Z \to l\bar{l})$
0.113 ± 0.011(prelim)	$R_\tau = B(\tau \to \text{had})/B(\tau \to l)$
0.1155 ± 0.0024	non-LEP

Table 1: Various measurements of $\alpha_s(M_Z)$.

The symmetry properties of the theory are an excellent confirmation. However, there is no smoking gun quantitative test of QCD. Furthermore, QCD tests have always been hindered because there is no viable competing theory. It is useful to keep probing the strong interaction sector of the standard model for a number of reasons.

One motivation is to conclusively establish QCD. There should be future progress from LEP, HERA, and hadron colliders. Another probe involves chiral perturbation theory (ChPT). Ecker [1] emphasized that predictions for rare kaon decays from the chiral anomaly can provide a parameter-free test of the underlying chiral field theories. The non-anomalous ChPT pieces of the decay amplitudes can in principle be separated using detailed decay distributions. Truong [2] emphasized that the ChPT calculations can be improved by a unitarization prescription, which incorporates resonances.

A second motivation is to develop the strong interaction technology needed for interpreting electroweak and collider experiments. Linde [3] reviewed the status of measurements of $\alpha_s(M_Z)$ from LEP; α_s is crucial for QCD tests (*i.e.*, to establish the running), for testing the hypothesis of grand unification, and for the corrections to the hadronic Z width. The results of determinations from event shapes, hadronic Z decays, and hadronic τ decays are shown in Table 1. The most precise value comes from various measurements of the hadronic event topologies. The quoted error of 0.005 is almost all theoretical and is dominated by uncertainties in the scale at which the coupling is evaluated. There was considerable discussion at the meeting as to whether the error is reliable. The true uncertainty may well be larger, at least by a factor of two. The number 0.124 ± 0.005 is actually based on the 1990 LEP data; it involves a new analysis, known as resummed QCD, in which the order α_s^2 terms are combined with next-to-leading logarithm effects in the theoretical expressions. This makes the various determinations more consistent with each other, but the result is 1σ higher than the previous value 0.117 ± 0.007, which was based on the same data. The somewhat higher value based on the width for the Z to decay into hadrons has a larger statistical error but is cleaner theoretically. The value from hadronic τ decays[2] is theoretically more reliable than one might at first guess, as

[2]Dam [4] obtained a somewhat different value 0.119 ± 0.006 from the same data.

was discussed by Pich[5]. The measurement actually determines $\alpha_s(m_\tau)$, which is then extrapolated to M_Z. This also demonstrates the running of α_s. One can average the LEP determinations to yield $\alpha_s(M_Z) = 0.123 \pm 0.004$, but since the most precise determination is theory-dominated one should be careful in using this quantity. The average value obtained from non-LEP experiments shown in Table 1 is somewhat smaller than the new values preferred by the LEP data. The nominal error is much smaller, but it is not clear that scale and theory errors have been fully included.

Another aspect of QCD is developing models for electroweak matrix elements, jet studies, *etc.* The electroweak matrix elements are needed to interpret the results of $B\bar{B}$ oscillation and CP-violation experiments and to extract the CKM matrix. Jet models are needed for the interpretation of almost all new physics (and standard model backgrounds) at colliders. There are various approaches, including, ChPT and beyond [1, 2] and heavy quark symmetry. Boucard [6] reported on lattice calculations, including the new result

$$f_{B_d}\sqrt{B_{B_d}} = 220 \pm 40 \pm (?) MeV \tag{1}$$

on the decay constant of the B_d. The second (unknown) uncertainty is from the use of the quenched approximation. Lattice calculations are a very promising direction, but there are still considerable theoretical uncertainties.

There has been much progress in systematic studies of the c and b spectrum and decays [7]–[15]. It is unlikely that the non-leptonic decays will give indications of new physics, because the theoretical uncertainties are too large. However, such studies are needed for the ultimate test of CKM unitarity, CP violation, *etc.*

Yet another role of strong interaction studies is to develop confidence in calculations of related systems. Of particular importance is the possibility of a strongly-coupled spontaneous symmetry breaking sector of the standard model, the dynamics of which may be related to that of QCD; such physics can be studied at the SSC and LHC [16, 2]. Green [17] discussed a string-inspired model and/or realization of QCD, which is useful as a model, has implications for finite temperature field theories, and may give new insights into the structure of superstring theories.

3 The Great Divide: Out With a Bang or a Whimper

Although the standard model is extremely successful, it has many shortcomings. For example:

- It is very complicated, with 21 free parameters in the minimal version including general relativity.

- It has a complicated gauge structure – the direct product of three gauge groups with three distinct couplings. This suggests the possibility of some sort of grand unification.
- The pattern of fermion masses, mixings, and families is a mystery. Possible solutions involve compositeness or string theories.
- There are naturalness problems associated with the Higgs mass and couplings, suggesting the possibility of supersymmetry or dynamical symmetry breaking.
- The strong CP problem requires a severe fine-tuning in the standard model, suggesting the possibility of a Peccei-Quinn symmetry or spontaneous CP violation.
- There is no basic unification of gravity in the standard model, and it provides no insight into the difficulties of quantum gravity or of the cosmological constant. Spontaneous symmetry breaking induces a vacuum energy (cosmological constant) some 50 orders of magnitude larger than the experimental limit, requiring a fine-tuned cancellation between the induced and primordial cosmological constants. It is not clear whether superstring theories give any help. The subject was reviewed here by Duncan [18].

There are many well-known possibilities for new physics, including compositeness, grand unification, supersymmetry, or superstring theories. It is also possible that there is something completely new and unexpected, though my own suspicion is that that is unlikely at the TeV scale.

Let me describe two generic scenarios for new physics, which I refer to as the great divide, or "out with a bang or a whimper". (Of course, one can have all sorts of hybrid scenarios in between.) The (somewhat discouraging) premise is that progress in particle physics will eventually draw to a close, hopefully on a time scale of more than 40 years, presumably with a bang or a whimper. What I mean by the whimper scenario is the possibility that nature consists of onion-like layers of new physics which manifest themselves as one goes to higher and higher energies. Examples of this are dynamical symmetry breaking and compositeness. The whimper scenario is intrinsically nonperturbative. If this is chosen by nature we may, if we are lucky, unpeel perhaps one more layer at the large hadron colliders, but it is unlikely that we will ever be able to penetrate much beyond that.

The contrasting idea is the bang scenario, *i.e.*, that there is, at least approximately, a desert up to the GUT or Planck scale ($M_P \sim 10^{19} GeV$). Such a scenario is perturbative by nature and is the domain of the elementary Higgs bosons, supersymmetry, grand unification, and superstring theories. If nature choose this course there is some hope of our actually probing all the way to the Planck scale and to the very early Universe. Recent successes of the unification of coupling constants in the supersymmetric extension of the standard model gives some hint that this may be the correct approach.

4 The Great Unknown: Electroweak Symmetry Breaking

In the bang scenario symmetry breaking is assumed to be due to elementary Higgs scalars, which are presumably perturbative and weakly coupled. In the standard model the Higgs boson mass is

$$M_H = \sqrt{2\lambda} v, \tag{2}$$

where $v = 246$ GeV is the weak scale and λ is the quartic Higgs self-interaction. In principle λ could take any value from $0 - \infty$, so there is no real prediction for M_H. However, λ is a running quantity which increases with the scale μ. In order for the theory to make sense λ must remain finite within the domain of validity of the theory. This implies the upper limits

$$M_H \leq \begin{cases} 200\ GeV & , \text{ theory valid to } M_P \\ 600\ GeV & , \text{ theory valid to } 2M_H \end{cases} . \tag{3}$$

These triviality limits can be justified by lattice calculations, independent of perturbation theory.

Another problem with an elementary Higgs field is the quadratic divergence in the Higgs mass. One finds

$$M_H^2 \sim M_H^{0\,2} + O(\Lambda^2), \tag{4}$$

where the first term represents the bare (lowest-order) mass. The second term represents the loop corrections, with Λ the scale of new physics which presumably cuts off the quadratically-divergent integrals. Since M_H must be of the order of the electroweak scale there must be a fine-tuned cancellation between the two terms if $M_H \ll \Lambda$. This suggests one of two possibilities: (a) supersymmetry, in which there are elementary Higgs fields but there are cancellations between fermion and boson contributions to the self-energy, eliminating the quadratic divergence; or (b) dynamical symmetry breaking (DSB), in which there are no elementary scalar fields and loop integrals are cut off at the compositeness scale. There are no realistic models for dynamical symmetry breaking.

The LEP experiments have excluded a light standard model Higgs. The most recent results are

$$M_H > 53.0, \quad 47.0, \quad 52.3, \quad 51.0\, GeV \tag{5}$$

from ALEPH, DELPHI, L3, and OPAL respectively [19]. A naive combining of these results yields a lower limit of 59.2 GeV, but strong caveats against this procedure were given at the meeting because the estimates of backgrounds were based on the limit of $O(50\ GeV)$. Future prospects were reviewed by Janot [20, 21]. The upper limit from LEP 100 should ultimately be $O(60\ GeV)$. Above this the Higgs production process $Z \to Z^* H$ will be hidden by an irreducible four-fermion background in which the Z decays into two fermions, one of which radiates a virtual photon which decays into two more fermions.

At LEP 200 one will have a sensitivity to

$$\begin{array}{lll} 80\ GeV, & \text{for}\ \sqrt{s} = 175\ GeV, & \mathcal{L} = 150\ pb^{-1} \\ 93\ GeV, & \text{for}\ \sqrt{s} = 190\ GeV, & \mathcal{L} = 500\ pb^{-1} \\ 130\ GeV, & \text{for}\ \sqrt{s} = 240\ GeV, & \mathcal{L} = 500\ pb^{-1} \end{array} \tag{6}$$

through the virtual Z decay $Z^* \to ZH$. The various possiblities refer to the fact that the energy and luminosity of LEP 200 have never been well defined. A total energy of 240 GeV is the maximum that is possible, and the lower energies are those that are more frequently discussed. The process $WW \to H$ would dominate at a possible NLC, allowing sensitivity to $M_H = 200\ GeV$ for $\sqrt{s} = 500\ GeV$ and $\mathcal{L} = 10 fb^{-1}$.

Pauss [22] discussed the possibilities of Higgs detection at the hadron colliders LHC and SSC. Gluon-gluon fusion $gg \to H$ should dominate the production for $M_H \leq 700\ GeV$. All of the planned detectors are good for the decay $H \to ZZ \to 4l$, which occurs for $M_H > 2M_Z$. Things are more difficult in the intermediate range below $2M_Z$ but above the LEP range. The decay $H \to 2\gamma$ may be possible to observe, but more study is necessary.

The situation is more complicated in the minimal supersymmetric standard model (MSSM)[3]. One has two Higgs scalars h, H; one pseudo-scalar A; and a pair of charged Higgs scalars $H^{\pm}$. At tree-level one expects $m_h < M_Z$, while H, A, $H^{\pm}$ can be heavier. A number of authors have recently shown that loop corrections may be quite significant if the top quark mass is large, because there are terms quartic in m_t. This was discussed by Brignole [23], who showed that a diagrammatic calculation confirms previous calculations based on the effective potential. A typical result is $m_h \leq 130\ GeV$ for $m_t < 180\ GeV$, $m_{\tilde{q}} < 1\ TeV$. One usually has $M^{\pm}_{H,A,H} \gg m_h$, in which case the h acts like a light standard model Higgs. However, there are some regions of parameter space in which there are relatively light H, A, $H^{\pm}$. Then the signatures at LEP-type energies are more complicated: the decay $Z \to Zh$ has an amplitude proportional to $\sin(\beta - \alpha)$, while

[3]Things are even more complicated in nonminimal models, but there has been relatively little study.

$Z \rightarrow hA$ is proportional to $\cos(\beta - \alpha)$, where $\tan\beta$ is the ratio of vacuum expectation values of the two Higgs doublets in the theory and α is the mixing angle between the two scalars. Current LEP limits exclude light particles in the range $(M_A, m_h) \leq 40\ GeV$ [19].

An NLC with $\sqrt{s} = 500$ and $\mathcal{L} = 10 fb^{-1}$ would be ideally suited for studying the MSSM Higgs sector [20]. It would cover all of the parameter space and would either: (a) find a light standard model-like h; (b) observe the decays $hZ + HA$ or $HZ + hA$; or (c) rule out the MSSM for all acceptable values of m_t, $m_{\tilde{q}}$. LEP 200 with $\sqrt{s} = 190$ could not contribute significantly here, but the higher energy version with $\sqrt{s} = 240$ would cover the part of parameter space corresponding to $m_h < 125\ GeV$. Most but not all of the range for the MSSM would be acccessible at hadron colliders [22]. Small regions of parameter space would not be covered, and there is no claim of a "no lose" theorem.

The limits on charged Higgs particles, such as $t \rightarrow bH^+$at $UA(2)$ [24] and H^+, H^{++} at LEP [19] were reported. At present $M_{H^+} \gtrsim 40\ GeV$.

The whimper scenario is characterized by heavy nonperturbative Higgs fields, technicolor, extended technicolor, composite Higgs bosons, *etc.* One of the best probes is $W_L W_L \rightarrow W_L W_L$ at hadron colliders. For example, there may be bound state vectors or scalars associated with the nonperturbative physics. Veltman [16] discussed the prospects for studying the nature of heavy physics by measuring $W_L W_L \rightarrow W_L W_L$ below the TeV scale and then predicting the results at high energies. Casalbuoni [25] described the consequences of a BESS (Breaking Electroweak Symmetry Strongly) model involving composite gauge bosons and the constraints placed on them by the LEP data. Truong [2] emphasized that one should not trust the predictions of dynamical schemes for the TeV scale unless one can reliably calculate $\pi\pi$ scattering at QCD from first principles, and discussed the importance of including unitarity in the models. Zinn-Justin [26] reviewed aspects of $t\bar{t}$ condensation. He emphasized that the standard model with $M_H \sim 2m_t$ large is mathematically equivalent to a model without an elementary Higgs but with a $t\bar{t}$ condensate. Fritzsch [27] discussed other possibilities associated with a condensate of fourth family fermions in the 1 – 5 TeV range. The mixing of these with the other families leads to interesting effects such as flavor changing neutral currents (FCNC) and violations of $V-A$ and universality, including such rare decays as $t \rightarrow cZ$, $\mu \rightarrow 3e$, $b \rightarrow sg$, and induced right-handed currents such as $t_R \rightarrow b_R$. However, the underlying dynamical mechanisms for generating the mixing and inducing SU_2 breaking are rather vague.

Most of the possibilities for a strongly coupled symmetry-breaking sector are best probed at hadron colliders rather than precision experiments. Maiani [28] described some technically related work on the $m_t \rightarrow \infty$ limit of the standard model.

5 The Scales of New Physics

5.1 The TeV Scale

5.1.1 Supersymmetry

Most of the meeting was devoted to searches for new physics at the TeV scale. One major possibility is supersymmetry. Whether or not there is supersymmetry in nature is, along with the symmetry breaking mechanism, the crucial question as we approach the great divide. As has already been described the SUSY Higgs sector has implications for LEP, a possible NLC, and hadron colliders. Another probe is to look for the superpartners. They have little direct effect on precision observables, except possibly large $m_{\tilde{t}} - m_{\tilde{b}}$ splittings. However, they indirectly affect the possible unification of coupling constants, which is different in supersymmetric models due to the contribution of the superpartners to the running. However, the issue will ultimately be settled by searches for the direct production of the superpartners at the SSC, LHC, and possible e^+e^- colliders.

5.1.2 New Operators, Particles, Interactions, Mixings

Precision experiments are useful for searching for many types of new operators, particles, mixings, and interactions. These by themselves may not solve the problems of the standard model. Rather, they are remnants of new physics that occurs at higher scales. As was emphasized by de Rujula [29], any such new physics should be gauge invariant, or it will undermine the successes of the standard electroweak model.

Such remnants can be searched for directly at hadron colliders, such as the Z' search by CDF [10]. However, much of the effort has been in indirect searches through precision tests – including QED, the weak charged and neutral currents, and the properties of the Z and W – and in astrophysics and cosmology. Treille [30] gave an overview of the precision tests. For example, there is a new QED measurement of the anomalous muon magnetic moment, $g_\mu - 2$, being constructed at Brookhaven; this will improve the present value by a factor of 20, bringing the precision down to the level of the electroweak effects. There is need, however, to have improved measurements of the low energy cross section for $e^+e^- \to$ hadrons to reduce uncertainties from the hadronic component of the vacuum polarization. These are also the major theoretical uncertainty in the $M_Z \leftrightarrow \sin^2\theta_W$ relation.

There are many precise searches for new physics in the weak charged current sector, including β, μ, τ, K, c, and b decays, as well as tests of the CKM matrix and universality. These are especially sensitive to new W_R bosons which couple to right-handed currents, to mixings between exotic and ordinary fermions, and to a possible fourth fermion family. An interesting new result from TRIUMF [31] is

$$R = \frac{B(\pi \rightarrow e\nu + e\nu\gamma)}{B(\pi \rightarrow \mu\nu + \mu\nu\gamma)} = (1.2265 \pm 0.0056) \times 10^{-4}, \tag{7}$$

compared with the previous value of $(1.218 \pm 0.014) \times 10^{-4}$. R probes $e\mu$ universality; one expects $(1.234 \pm 0.001) \times 10^{-4}$ in the standard model, in excellent agreement with (7). From the new TRIUMF result one extracts the ratio

$$f_e/f_\mu = 0.9970 \pm 0.0023 \tag{8}$$

of the effective e and μ interaction strengths, in good agreement with universality. This is sensitive, for example, to certain types of leptoquarks with mass up to 200 TeV, as well as to mixings between ordinary and exotic fermions.

There was considerable discussion of τ physics, including τ physics at LEP [4], a mini-review [5], recent ALEPH results on τ_τ [32], $\tau \rightarrow KX$ at PEP[33], and on the prospects for a τ-charm factory [34]. An important result is that $\tau \rightarrow \nu_\tau +$ hadrons is a clean measurement of $\alpha_s(m_\tau)$ [5] despite the low energy scale. Also, lepton universality is well tested by the LEP experiments: the $Z\tau\tau$, Zee, and $Z\mu\mu$ couplings are all equal within the small uncertainties. The τ polarization has been measured by the LEP experiments, $A_\tau = 0.140 \pm 0.024$ [35], in agreement with the expected 0.136 ± 0.007. There has been a new measurement of the Michel parameters for τ decay at ARGUS [9], yielding

$$\begin{aligned} \tau \rightarrow e\nu_\tau\nu_e \quad &, \quad \rho = 0.78 \pm 0.05 \\ \tau \rightarrow \mu\nu_\tau\nu_\mu \quad &, \quad \rho = 0.72 \pm 0.08. \end{aligned} \tag{9}$$

$V - A$ for $\tau \rightarrow \nu_\tau$ predicts 3/4, while $V + A$ implies 0. Thus (9) establishes that $V - A$ is correct for the τ interactions and that the third lepton family is a left-handed doublet like the other families. These tests would be much more precise at a τ-charm factory.

One still has the limit $m_{\nu_\tau} < 35 MeV$ on the ν_τ mass from ARGUS. However, there is a recent theoretical argument from nucleosynthesis that the range $(few - 25)\ MeV$ for the ν_τ mass is probably excluded [36]; it is therefore important that the laboratory limits be improved to eliminate the small window above 25 MeV.

There have been important new measurements of τ decays from LEP [4]. ALEPH reports higher branching ratios $B(\tau \rightarrow 3\pi\nu,\ \pi 2\pi^0\nu)$ than the world average, and slightly lower 1-prong rates. This appears to eliminate the 1 prong problem, at least as far as the LEP data is concerned. The other famous problem concerning the τ decays is still present. This is the fact that given any two of the three quantities $B(\tau \rightarrow l\nu\bar{\nu})$, τ_τ, and m_τ one can predict the third. For some time there has been an inconsistency, which can be characterized by a somewhat lower effective coupling of the τ to the weak current than expected in the standard model [4]

$$\begin{array}{lll} \text{non}-\text{LEP}: & G_\tau/G_\mu = 0.972 \pm 0.015 \\ \text{LEP} & 0.977 \pm 0.012 \\ \text{combined} & 0.975 \pm 0.010. \end{array} \qquad (10)$$

The new and more precise LEP results still show a discrepancy at 2.5σ. If this holds up it could be an indication that the τ neutrino is a mixture $\nu_\tau = \sin\theta\nu_1 + \cos\theta\nu_2$ of a light component ν_1 and a neutrino ν_2 that is too heavy to be produced in the decay.[4] The anomaly could be accounted for by $\cos\theta \sim 0.975 \pm 0.010$. If the extra neutrino were in a fourth family it would have to be heavier than $M_Z/2$. If it were sterile than it would also affect the invisible width of the Z, leading to an effective number of neutrinos $2 + \cos^4\theta \sim 2.90 \pm 0.05$, which is somewhat low compared to the LEP value [35] $N_\nu = 3.04 \pm 0.04$. However, there is some indication that the problem may be disappearing. The ARGUS group has reported a preliminary value of m_τ some 8 MeV lower than the world average. This is reinforced by preliminary results from Beijing of a lower m_τ mass. If m_τ were lowered by some 11 – 17 MeV the discrepancy would disappear.[5]

5.1.3 The Z-Pole, LEP 100, LEP 200

LEP ran very well in 1991, with an integrated luminosity of 17000 nb^{-1}, twice that of 1990 [39]. They achieved a transverse polarization of around 10%. This should soon allow a determination of the Z mass to $\Delta M_Z \ll 20MeV$ by the method of resonant depolarization. However, some small systematic problems have come up which still have to be worked out. In particular, the alignment of RF cavities leads to a shift $\Delta E_{CM} \sim 16 \pm 4MeV$ of the energies of the OPAL and L3 regions compared to those of ALEPH and DELPHI. An interesting effect is that it is believed that the tidal forces of the moon change the size of the ring by $\Delta r/r \sim 3 \times 10^{-8}$, leading to a shift of $\Delta E_{CM} \sim 8MeV$ in the LEP energy.[6] This will double in the next run due to a reconfiguration of the magnets. These effects can probably be brought under control, but for the time being have delayed a more accurate determination of M_Z.

The electroweak physics program at LEP was reviewed by Nash [35], and the implications of the experiments were described by Altarelli [40]. The hadronic charge asymmetry

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[4]An alternate model for explaining the effects based on universality violation was described by Ma [37].

[5]The Beijing group subsequently announced the preliminary value $m_\tau = 1777 \pm 1\ MeV$ [38], considerably lower than the old average of $1284.1^{+2.7}_{-3.6}\ MeV$. This raises the values of G_τ/G_μ in (10) by 0.010, reducing the discrepancy to 1.5σ.

[6]This is the first experiment in which all four forces play a significant role!

Quantity	1990	1991	standard model
M_Z(GeV)	91.175 ± 0.021	$--$	input
Γ_Z(GeV)	2.487 ± 0.010	2.499 ± 0.0075	$2.494 \pm 0.002 \pm 0.006 \pm [0.006]$
$\Gamma_{l\bar{l}}$(MeV)	83.2 ± 0.4	83.52 ± 0.33	$83.7 \pm 0.1 \pm 0.2$
Γ_{had}(MeV)	1740 ± 9	1742 ± 8	$1743 \pm 2 \pm 4 \pm [6]$
$\Gamma_{b\bar{b}}/\Gamma_{\text{had}}$	0.217 ± 0.010		$0.216 \pm 0 \pm 0.001$
$A_{FB}\,(\mu)$	0.0163 ± 0.0036	0.0176 ± 0.0029	$0.0155 \pm 0.0006 \pm 0.0012$
$A_{\text{pol}}\,(\tau)$	0.134 ± 0.035	0.140 ± 0.024	$0.136 \pm 0.003 \pm 0.006$
$A_{FB}\,(b)$	0.126 ± 0.022	0.094 ± 0.014	$0.092 \pm 0.002 \pm 0.004$
$R = \Gamma_{\text{had}}/\Gamma_{l\bar{l}}$	20.92 ± 0.11	20.86 ± 0.10	$20.82 \pm 0.01 \pm 0.01 \pm [0.07]$
$\sigma_o^h(nb)$	41.36 ± 0.23	41.13 ± 0.20	$41.41 \pm 0.02 \pm 0.02 \pm [0.06]$
N_ν	2.99 ± 0.05	3.04 ± 0.04	3
g_A^2	0.2492 ± 0.0012	0.2500 ± 0.0010	$0.2513 \pm 0.0002 \pm 0.0004$
g_V^2	0.0012 ± 0.0003	0.00131 ± 0.00024	$0.0011 \pm 0.0001 \pm 0.0001$
$\bar{s}_W^2(A_{FB}\,(q))$	0.2310 ± 0.0035	0.2316 ± 0.0032	$0.2325 \pm 0.0004 \pm 0.0007 \pm ?$

Table 2: Electroweak results from LEP.

and the b lifetime and width were discussed in other talks [41, 42, 11]. In the 1989 and 1990 runs the four experiments accumulated a total of 585K hadrons and 63K leptons, while in 1991 the totals were 1114K and 118K. There is still a 20 MeV uncertainty in the LEP energy, which is the dominant uncertainty in ΔM_Z. As discussed above it is hoped[7] that this will soon be reduced to $\ll$ 20 MeV. There is a point-to-point energy uncertainty of 10 MeV, which leads to an uncertainty $\Delta\Gamma_Z \sim 5$ MeV in the Z width. There is an experimental uncertainty in the luminosity $\Delta\mathcal{L}/\mathcal{L}$ of 0.5%, and a common theoretical uncertainty of 0.3%, which leads to systematic effects in σ_0^h, $\Gamma_{l\bar{l}}$, Γ_{had} and Γ_{inv}.

The principle electroweak results from LEP from the 1990 and 1991 runs are shown in Table 2, as well as the predictions of the standard model for the global best fit value $m_t = 151^{+21}_{-23}$ GeV and 50 GeV$< M_H <$ 1000 GeV. The 1991 column includes the earlier data, and many of the results are preliminary. The leptonic width assumes e, μ, τ universality, which is well established by the individual partial widths. The vector coupling g_V^2 is mainly determined from $A_{FB}\,(\mu)$. One notable change from 1990 is that the forward-backward asymmetry into b quarks, $A_{FB}\,(b)$, has decreased somewhat, into excellent agreement with the standard model. The previous high value had pulled up the extracted value of m_t considerably. The quantity $\bar{s}_W^2$ is from the hadronic charge asymmetry. The last column

[7] M_Z is already measured much more precisely than other Z-pole observables, so an improved value is pretty but not urgent.

Data	m_t(GeV)	α_s
LEP [35]	$157^{+25}_{-30}{}^{+17}_{-20}$	$0.142 \pm 0.01 \pm 0.002$
LEP [35]	$168^{+22}_{-26}{}^{+17}_{-20}$	fixed (0.124 ± 0.005)
LEP $+M_W + \nu N$ [35]	$149^{+21}_{-23}{}^{+17}_{-21}$	$0.143 \pm 0.01 \pm 0.002$
LEP $+M_W + \nu N$ [35]	$157^{+20}_{-22}{}^{+18}_{-21}$	fixed $(0.124 \pm 0.005$
All [43]	$151^{+21}_{-23}{}^{+18}_{-14}$	fixed (0.124 ± 0.010)

Table 3: Values of m_t obtained from LEP data and combinations of LEP with other results. The first uncertainty is experimental and the second is from the Higgs mass in the range 50 GeV $-$ 1 TeV. In the first and third rows α_s is fit to the data, and is constrained mainly from the hadronic Z width. The value obtained is slightly higher than that obtained from the event shapes. The other rows use a fixed α_s determined from event shapes.

shows the standard model predictions in terms of M_Z [43]. The first uncertainty is from M_Z and Δr, the second is from m_t and M_H, and the third (in square brackets) is a QCD uncertainty assuming $\alpha_s = 0.124 \pm 0.010$, which is extracted from the LEP event shapes [3] with a larger error quoted to account for theoretical uncertainties. The question mark for $\bar{s}^2_W$ concerns the scheme-dependence of the extracted weak angle. All of the data are in excellent agreement with the predictions of the standard model. The χ^2 obtained when the results of the four experiments for each observable are combined is typically $\chi^2/df \sim 0.25 - 1$, which is low, but not too unreasonable.

From these data one can extract the standard model prediction for the top quark mass. The results are shown in Table 3. The best fit to the data implies $m_t \sim 150$ GeV, though with large uncertainties. It is interesting that CDF and D0 should be able to reach m_t values $O(150)$GeV in the next run [14]. The last row in Table 3 is a global fit to all Z, W, and neutral current data assuming $\alpha_s = 0.124 \pm 0.010$. One also obtains [43]

$$\begin{aligned} \overline{\text{MS}}: &\quad \sin^2\hat{\theta}_W(M_Z) = 0.2325 \pm 0.0007 \\ \text{on}-\text{shell}: &\quad \sin^2\theta_W \equiv 1 - \frac{M_W^2}{M_Z^2} = 0.2257 \pm 0.0026 \end{aligned} \tag{11}$$

for the weak angle in the $\overline{\text{MS}}$ and on-shell schemes. The uncertainties are mainly due to m_t; the $\overline{\text{MS}}$ definition is considerably less sensitive. The m_t value in the last row does not include 2-loop corrections of the form $\alpha\alpha_s m_t^2$. It would increase by some 9 GeV if the perturbative estimate of these terms were included. However, there is theoretical uncertainty in the coefficient. It should be noted that there is no significant sensitivity to the Higgs mass M_H as long as m_t is not known independently.

An interesting development is that the four LEP groups have done a combined study of their results [44]. Their basic inputs are the observables M_Z, Γ_Z, σ_0^h, $\Gamma_{l\bar{l}}$, g_V, and g_A.

They found that one obtains essentially the same result from a joint analysis as from simply averaging the individual experiments (taking common systematic errors properly into account). They also present an average correlation matrix. This joint analysis is very useful, and I would like to encourage that it be continued in the future.

One disturbing aspect of the analysis has been described by Navelet [45]. Navelet and collaborators have reanalyzed the infrared divergences associated with virtual photon exchange between initial and final charged particles. In order to regulate the divergences one can take the external fermions off-shell and give the photon a mass μ. The physical limit involves returning to $p^2 \rightarrow m^2$ and $\mu \rightarrow 0$. Navelet argued that these two limits do not commute, introducing an ambiguity, and that one should take $\mu \rightarrow 0$ first rather than the usual procedure. He then finds that certain α/v terms are absent, changing the formulas for the Z widths by some $O(4\%)$ from the usual formulas. This a substantial correction compared to the experimental uncertainties, and it is crucial that this issue be resolved quickly.

There was considerable discussion of the future LEP program. Treille [30] emphasized that at present the number of events is some $\sim 300K/exp$, allowing a precision of $\Delta \sin^2 \theta_W \sim 0.0013$ from the Z widths and asymmetries, which is much less precise than the value from M_Z. (The comparision of the two is sensitive to now physics.) He advocated the importance of accumulating a few$\times 10^6/exp$ in the future, yielding an uncertainty of 0.00065. Only at that point will the experiments be systematics limited. Mikenberg [15] described the opportunity for a high luminosity LEP (HLEP) in which there would be 36×36 bunches, allowing a luminosity of $(1.5-2) \times 10^{32}\ cm^{-2}s^{-1}$. HLEP could be run at some time after the LEP 200 program. It would allow a precision of $\Delta \sin^2 \theta_W \sim 0.00035$ from $A_{FB}(b)$. It would also be possible to measure $\Gamma_{b\bar{b}}$ to $\sim 1\%$ precision. This would be useful because $\Gamma_{b\bar{b}}$ receives vertex corrections involving the top quark, and would allow a separation of the effects of m_t from other radiative corrections or non-standard Higgs representations which affect the W and Z masses.

Treille [30] described the possibility of measuring the polarization asymmetry, A_{LR}, the "queen of observables", at LEP. A measurement $\Delta A_{LR} \sim 0.3\%$ would allow a precision $\Delta \sin^2 \theta_W \sim 0.0004$. This would be comparable to the value obtained from M_Z and would allow a stringent test of the standard model and search for new physics.

There are a number of practical issues for future LEP 100 running. To exploit the high statistics that will be forthcoming it will be necessary to improve the luminosity measurement to $\Delta\mathcal{L}/\mathcal{L} < 0.1\%$[46, 47]. Work is under way to improve both the luminosity monitors themselves and the theoretical calculations that will be needed to exploit them. More theoretical work is also needed is to build new event generators with two or more hard γ's in the final state, both to compare data with the standard model predictions and to lay the groundwork for searching for new physics in the $\mu\mu(n\gamma)$ and $q\bar{q}\gamma$ channels[48, 49]. As was previously mentioned, there is a theoretical uncertainty

$$\delta\Delta r \sim \frac{\Delta\alpha(M_Z)}{\alpha(M_Z)} \sim 0.0009 \tag{12}$$

from the low-energy hadronic vacuum polarization. This is the major theoretical uncertainty in the relation between M_Z and $\sin^2\theta_W$, and also in $g_\mu - 2$. New high-precision low energy measurements are needed [30].

As precision gets higher it will be necessary to pay more attention to higher-order terms in the electroweak predictions. Closely connected is the proliferation of definitions of values of $\sin^2\theta_W$. I personally get very confused. At present, most of the uncertainty is hidden by the experimental errors, but in the future the issue will be more important. It would be useful if results were always presented in terms of the $\overline{\mathrm{MS}}$ value $\sin^2\hat{\theta}_W$ which is useful for comparison with grand unification. Another scheme, the on-shell $\sin^2\theta_W \equiv 1 - M_W^2/M_Z^2$, is also useful and is easy to translate into the $\overline{\mathrm{MS}}$ scheme. The various effective values that are quoted are difficult to relate to the rest of the world, and more care in stating the definitions and translations is necessary in the future.

Work is also needed is to improve the theoretical error in $\alpha_s(M_Z)$, which has many implications for standard model tests [3]. Finally, some caution is needed in the definitions of M_Z and Γ_Z. The forms generally used now are based on Breit-Wigner formulas, but an alternate definition involves the actual location of the Z pole. The relation between the two is under control but one should be careful.

The LEP 200 machine parameters have never been well-defined. Possibilities for the energy include $\sqrt{s} = 175$, 190, and 240 GeV and suggested luminosities are in the range 125 pb^{-1} to 500 pb^{-1}. It was emphasized by Treille [30] and Janot [20] that the higher energy would be a major advantage for a number of types of physics. LEP 200 should make a precise measurement of the W mass with $\Delta M_W \sim 60$ MeV, and, as has been described, would allow a search for intermediate-mass standard model and supersymmetric Higgs particles.

LEP 200 would also allow a measurement of the γWW and ZWW vertices, which would be useful for the text books. One can, of course, search for anomalous non-abelian vertices. However, de Rujula *et al.*, [29, 50] have argued that most previous estimates of the sensitivity to anomalous couplings were greatly exaggerated because they did not properly taken gauge invariance into account. They argued that any new physics is likely to be electroweak gauge invariant; otherwise, the successes of the standard model would be distroyed. Secondly, they cataloged gauge invariant sets of operators and claimed that the LEP 100 results have already excluded virtually any chance for LEP 200 to observe anomalous vertices. This idea is probably correct and should be taken seriously[8]. However, by utilizing such effects as polarizations LEP 200 may be able to place somewhat better constraints [52] on the anomalous vertices than those assumed in [50].

Kurihara [21] described automated computer calculations of complicated processes such as $e^+e^- \to W^+W^-\nu\bar{\nu}$.

5.1.4 The Weak Neutral Current

The LEP measurements are extremely precise, but they are blind to types of physics which don't directly affect the properties of the Z, such as Z' bosons which do not mix with the ordinary Z or new types of interactions. A number of other types of precision observables are therefore important and will be a useful complement to present and future LEP measurements. Particularly important are M_W, future deep-inelastic neutrino scattering experiments, and atomic parity violation. The W mass will be measured precisely in several types of experiments: LEP 200 is expected to measure to 60 MeV, the hadron colliders CDF and D0 to about 100 MeV, and HERA to about 100 MeV.

Enomoto [53] described the TRISTAN program. He emphasized that the machine is still running and will be for two or three more years. In the past there was a small anomaly in the total hadronic cross section, R_{had}, which was somewhat higher than the standard model predictions. However, new calculations of the radiative corrections have eliminated most of the effect. New measurements of the leptonic cross sections and asymmetries, R_l, and A_l, in excellent agreement with the standard model were also presented.

Cocco [54] described the latest CHARM II results. Previously they concentrated on $\sin^2\theta_W$, which can be cleanly measured from the ratio of neutrino and antineutrino scatterings. They have now extracted the individual $\nu_\mu(\bar{\nu}_\mu)e^-$ elastic scattering cross sections, from which they are able to determine the vector and axial couplings, $g^e_{V,A}$, relevant to the four-fermi neutrino-electron interaction. In the standard model to lowest order these are the same as the vector and axial vector couplings of the Z to the electron, $g_{V,A}$, that are measured at LEP. However, if there is new physics they are not quite the same, so it is important to measure them in both ways. CHARM II obtained

$$\begin{aligned} g^e_V &= -0.025 \pm 0.014 \pm 0.014 \\ g^e_A &= -0.503 \pm 0.007 \pm 0.016, \end{aligned} \tag{13}$$

which are in agreement with the standard model values -0.037 ± 0.001 and 0.506 ± 0.001.

[8]Some aspects of the argument have recently been questioned [51].

Bolton [55] described new measurements of deep inelastic neutrinos scattering by the CCFRW group at Fermilab. They have extracted the on-shell value $\sin^2\theta_W \equiv 1 - \frac{M_W^2}{M_Z^2}$, which is insensitive to m_t for νN scattering. They obtained

$$\text{CCFRW} \quad 0.2242 \pm 0.0042 \pm [0.0047] \tag{14}$$

which is comparable in precision to the CDHS and CHARM measurements

$$\begin{array}{ll} \text{CDHS} & 0.228 \pm 0.005 \pm [0.005] \\ \text{CHARM} & 0.236 \pm 0.005 \pm [0.005]. \end{array} \tag{15}$$

The second uncertainty is theoretical, mainly associated with the c-quark threshold. In the future they expect to improve their experiment significantly. One of their major systematic problems, ν_e contamination of the beam, should be reduced considerably by a new sign-selected quadrupole beam. The uncertainty in the c-quark threshold will be reduced by measuring both ν_μ and $\bar{\nu}_\mu$; appropriate combinations will reduce the sensitivity. They expect to achieve $\Delta \sin^2\theta_W \sim 0.0025$ even without the new Fermilab main injecter, and 0.0015 with it, including all experimental and theoretical uncertainties. There was also a description of a careful study of backgrounds in the CCFRW experiment [56]. This removed essentially all of the anomalous same-sign dimuons which had apparently been present for a long time in many of the neutrino experiments. There no longer seems to be a significant problem.

A number of other future weak neutral current experiments, especially atomic parity violation, were described by Treille [30].

5.1.5 Searches/Parametrizations for New Physics

There are a number of ways to parametrize data to maximize sensitivity to new physics. These are complementary, and each has its advantages.

- One possibility is to study generic models, such as the effects of additional heavy Z' bosons, or the mixing of the ordinary with exotic fermions such as $d_L \leftrightarrow D_L$. The current limits on the Z' in E_6 models are shown in Table 4. Other Z' models were described by Kneur [58] and Casalbuoni [25].

- One can also consider specific models; for example, in which there are Z's, Higgs representations, and exotic fermions with their properties correlated. These are less general in terms of the properties of the Z', for example, but show useful correlations between the effects of the types of new physics.

	Z_χ	Z_ψ	$Z_{\rm LR}$	Z_n
Direct CDF	280	180	240	240
LEP + WNC	320	160	390	180
(mixing arbitrary)				
LEP + WNC	550	160	860	210
(mixing constrained)				

Table 4: Limits on the masses of various Z' bosons which occur in the E_6 model, in GeV. The limits from CDF in the first column are from direct searches [10]. The other rows are indirect limits from precision experiments, with the ZZ' mixing arbitrary or constrained in specific models [57].

- Effective operators are another possibility. In many cases there are too many of these to be useful. However, in the case of showing the constraints of LEP 100 and how they affect new physics at LEP 200 they are extremely useful [29, 50].

- Another possibility are the S, T, U parameters. These apply to all observables, but, by definition, only describe types of new physics which only affect the W and Z self-energies.

- Altarelli [40] described an alternate formalism based on three parameters ϵ_1, ϵ_2, ϵ_3. Theses are defined in terms of the deviations of the three observables M_W/M_Z, $\Gamma_{l\bar{l}}$, and $A_{FB}(l)$ from the standard model predictions. These are more general than S, T, and U in the sense that they can parametrize any type of new physics. However, they have the shortcoming that one cannot extend this parametrization to other observables unless additional assumptions are made.

- Finally, one can define the a$^{\rm th}$ component of the deviation vector [59] $(O_a - O_a^{SM}(M_Z))/\Delta O_a \equiv V_a$, which is the deviation of the a$^{\rm th}$ observable from its standard model prediction normalized by the total (experimental + theoretical) uncertainty in the measurement. The deviation vector would be most useful if deviations are actually seen. Its direction (length) is characteristic of the type (strength) of the new physics.

5.1.6 1 TeV Scale: Astrophysics/Cosmology

Another probe of new physics at the TeV scale involves astrophysics and cosmology. There was an interesting talk by Freeman [60] on Galactic dark matter, which emphasized the observations of the density, evidence for dark matter in the Galaxy, and possible interpretations. The densities, relative to the critical density, of matter on various scales

$\Omega_{\text{visible}} \sim 0.007$	--
$\Omega_{\text{halo}} \sim 0.07$	HI rotation curves
$\Omega_{\text{clusters}} \sim 0.1 - 0.3$	--
$\Omega_{\text{baryon}} \sim 0.02 - 0.1$	nucleosynthesis

Table 5: Values of the density (relative to the critical density) of visible matter, of the matter clustered on the scale of halos and clusters, and the baryon density inferred from nucleosynthesis [60].

are summarized in Table 5. From this we see that baryons in some form could account for the dark matter in halos, *i.e.*, Ω_{halo}, consistent with the normal nucleosynthesis scenario. There are two experiments, the MACHO (Massive Astrophysical Compact Halo Objects) and Saclay experiments, both of which look for gravitational microlensing of distant stars to search for small objects that could comprise baryonic dark matter. They should be able to observe objects in the entire relevant mass range $(10^{-8} - 10^{+2})M_\odot$. If these experiments see no effect one could essentially rule out baryonic dark matter, leaving the possibilities of WIMPS or massive neutrinos.

5.1.7 The TeV Scale: CP Violation

CP violation is strongly suppressed in the standard model and is therefore an excellent place to look for new physics. So far the only indication of CP violation is in the kaon system, in which one observes the two parameters ϵ and ϵ'. ϵ can be generated by $K_1 - K_2$ mixing (indirect CP violation) as well as by direct CP-breaking in the decay amplitudes. ϵ' can be generated only by direct CP breaking. One expects $\epsilon'/\epsilon \neq 0$ in the standard model due to phases in the CKM matrix. The gluon penguin diagrams yield $\epsilon'/\epsilon \sim \text{few} \times 10^{-3}$. However, above $m_t = 100\ GeV$ additional electroweak penguins which can cancel the gluon effects are important, and there are also complications from isospin breaking due to the quark masses $m_d \neq m_u$. All of these effects have theoretical uncertainties, and they can cancel, so the prediction is very uncertain. For large m_t one expects smaller values of $\epsilon'/\epsilon \neq 0$, and it could go through zero, *e.g.*, at 200 GeV.

The experimental situation is equally confused. For years there has been a discrepancy between the Fermilab and CERN experiments. Barker [61] presented a new preliminary value from FNAL E731:

$$Re\frac{\epsilon'}{\epsilon} = [6.0 \pm 5.8 \pm 3.2 \pm 1.8] \times 10^{-4}. \tag{16}$$

The central value is now positive but it is still consistent with zero. Final results from E731 are expected very soon. One anticipates that the final uncertainty will be

$[\pm 5.1 \pm 3.2] \times 10^{-4}$. (The last error in (16) is due to Monte Carlo uncertainties, which should be eliminated in the final value.) The future Fermilab E832 experiment should yield a precision of 10^{-4}. New results from the CERN experiment NA31 (Perdereau [62]) based on 1989 data still indicate a positive and non-zero value:

$$\begin{aligned} 1989 \text{ (preliminary)}: &\quad (2.1 \pm 0.9) \times 10^{-3} \\ 1986-89 \text{ (preliminary)}: &\quad (2.3 \pm 0.7) \times 10^{-3}. \end{aligned} \tag{17}$$

There is a mild discrepancy between the two experiments and until this is resolved it is not clear what is going on. The future CERN experiment NA48 will also have a precision of 10^{-4}. The CPLEAR group [63] will measure to a precision of $(2-3) \times 10^{-3}$, and will also measure a number of other quantities such as CPT phases. By around 1998, the DAΦNE [64] ϕ factory will measure ϵ'/ϵ to a precision of 10^{-4}, and many other CP and CPT observables simultaneously and precisely.

Another way of probing CP breaking in the kaon system is the rare decay $K_L \rightarrow \pi^0 e^+ e^-$ [65]. The dominant decay is via $K_L \rightarrow \pi^0 \gamma^*$, followed by $\gamma^* \rightarrow e^+e^-$, which is CP-violating. One expects a contribution of less than 2×10^{-12} from the indirect $K_1 - K_2$ mixing [66]. The more interesting direct mechanism due to electroweak penguins and WW boxes, *etc.*, is expected to yield a branching ratio around $10^{-11} - 10^{-12}$. There is also a CP-conserving contribution via the two-photon intermediate state $K_L \rightarrow \pi^0 \gamma^* \gamma^*$, $\gamma^* \gamma^* \rightarrow e^+ e^-$, which is strongly suppressed by α. There was considerable theoretical controversy as to whether this would be large enough to be serious. However, measurements by NA31 [67] now indicate that this contribution is less than 4.5×10^{-13} and therefore not a problem. However, there is a very serious background [68] from $K_L \rightarrow e^+ e^- \gamma \gamma_{\text{brems}}$, which yields a contribution of order 7×10^{-11}. The extent to which the signal can be separated from this background depends on the resolution, but it may prove fatal.

A number of rare K decays which are being searched for mainly at Brookhaven and KEK, are listed in Table 6 along with their current limits, their expectations, and why they are interesting.

Other related searches for CP breaking include the electric dipole moments of the neutron and of atoms. Barr [73] described the dipole moments of atoms, which can be generated, amongst other things, by the electron dipole moment d_e and by anomalous eN interactions. These may yield measurable effects in extended models, in which CP violation may be mediated by Higgs exchange. The expectations are much smaller in the CKM model. Eilam [74] discussed the possibility of CP breaking in asymmetric t decays. These are much too small to be observed in the standard model, but could be important if there are some types of exotic new physics.

Mode	Limit/Value 90%	Future	SM	Why Important
$K_L \to \pi^0 e^+ e^-$	$< 5.5 \times 10^{-9}$ [65]	1×10^{-11}[69] [$7 \times 10^{-11} bkg$]	$10^{-11} - 10^{-12}$	direct CP $K_L \to \pi^0\gamma \to \pi^0 e^+ e^-$
$K_L \to e^+ e^- \gamma\gamma_{br}$	$6.6 \pm 3.2 \times 10^{-7}$ [65]		5.8×10^{-7}, $E^* > 5$MeV	bkg to $\pi^0 e^+ e^-$
$K_L \to \pi^0\gamma\gamma$ + Dalitz plot	$1.7 \pm 0.3 \times 10^{-6}$[67]		ChPT 0.7×10^{-6}	CP even $K_L \to \pi^0\gamma\gamma \to \pi^0 e^+ e^-$ $< 4.5 \times 10^{-13}$
$K^+ \to \pi^+ e^+ e^-$ + spectrum	$2.75 \pm 0.26 \times 10^{-7}$[66]			indirect cont to $K_L \to \pi^0 e^+ e^- < 2 \times 10^{-12}$
$K_L \to \pi^0 \nu\bar{\nu}$	$< 2.2 \times 10^{-4}$[61]	10^{-8}	$10^{-10} - 10^{-12}$	CP
$K^+ \to \pi^+ \nu\bar{\nu}$	$< 5 \times 10^{-9}$[70]	2×10^{-10} (AGS booster)	$(1-6) \times 10^{-10}$	V_{td}
$K_L \to e^+ e^- \gamma$	$9.1 \pm 0.6 \times 10^{-6}$ [65]		$9.6 \pm 0.4 \times 10^{-6}$	ChPT
$K_L \to \mu^+\mu^-$	$7.9 \pm 0.6 \pm 0.3 \times 10^{-9}$ [71] $6.96 \pm 0.40 \pm 0.22 \times 10^{-9}$ [72]		$> 6.8 \pm 0.3 \times 10^{-9}$	CPT + Unitarity; m_t (?)
$K_L \to e^+ e^-$	$< 1.6 \times 10^{-10}$ [71] $< 5 \times 10^{-11}$ [72]	8.5×10^{-13}	10^{-12}	
$K_L \to \mu e$	$< 9.4 \times 10^{-11}$ [71] $< 3.3 \times 10^{-11}$[72]	2×10^{-12}	0	FCNC in "non-standard non-standard models"
$K^+ \to \pi^+ \mu^+ e^-$	$< 2.1 \times 10^{-10}$[66]	10^{-12}	0	

Table 6: Some rare decay modes, their current limits or values, standard model expectations, and why they are particulary useful.

5.1.8 CP Violation in the B System

The holy grail of CP breaking is the B system. One expects large effects because of enhanced CP-violating phases and because ordinary B decays are strongly suppressed. The general situation was described by Bigi [75], and other talks dealt with B physics at hadron colliders and the fact that a dedicated experiment at Fermilab would effectively be a B factory [14], the HLEP option [15], CP violation in the B system [76], rare decays [77], and machine possibilities [78] for asymmetric $(e^+e^-)B$ factories.

To observe and interpret CP violation in the B system and thus to stringently test the standard model one needs higher rates for B. The optimal strategy, *i.e.*, to use hadron colliders, HLEP, or an asymmetric B factory, is still not clear. In addition to the machines, there is much background work necessary to develop the theoretical knowledge to interpret the results. Before and during the B factories a full program of studies of B decays will be needed to make reliable phenomenological models.

The B_s mixing is predicted to be nearly maximal in the standard model, which makes it very hard to measure. It is important to verify this. The ratio $|V_{ub}/V_{cb}|$ is important. A new measurement

$$\left|\frac{V_{ub}}{V_{cb}}\right| = (9.4 \pm 1.0 \pm 0.8)\%, \tag{18}$$

which uses the whole spectrum, was reported from ARGUS [12]. The measurements are now very good, but we still need better theoretical models to reduce the theoretical uncertainty in the extraction of $|V_{ub}/V_{cb}|$. We also need better calculations for $B_{d,s} \leftrightarrow \bar{B}_{d,s}$ mixing as well as the value of m_t to extract V_{td} reliably. An alternative and complementary way to extract V_{td} is from the rare decay $K^+ \to \pi^+\nu\bar{\nu}$.

The goal is to construct and overconstrain the unitarity triangle shown in Figure 1. Testing whether the vectors really add up to a triangle probes such new physics as a heavy W_R boson, fourth-family fermions, and new sources of CP violation. The sides of the unitarity triangle are magnitudes of the CKM elements. Two can be constructed from the partial rates for semi-leptonic B decays into c and u quarks, while $|V_{td}|$ can be extracted from $B_d^0 \leftrightarrow \bar{B}_d^0$ or $K^+ \to \pi^+\nu\bar{\nu}$, provided one knows m_t. Bigi [75] emphasized that one of the CP-violating angles, φ_1, can be determined from CP breaking in the kaon system, namely from the ratio $|\epsilon_K|/\Delta m_{B_d}$. Independent measurements of ϕ_1 and the other angles can be obtained from CP asymmetries in the B system, expecially the time-dependent asymmetries

$$A(t) = \frac{\Gamma(B \to f)_t - \Gamma(\bar{B} \to \bar{f})_t}{\Gamma(B \to f)_t + \Gamma(\bar{B} \to \bar{f})_t}. \tag{19}$$

The cleanest determinations theoretically can be made in the case that f is its own CP conjugate, $f = \bar{f}$. Interferences between the phases in the mixing and the decay

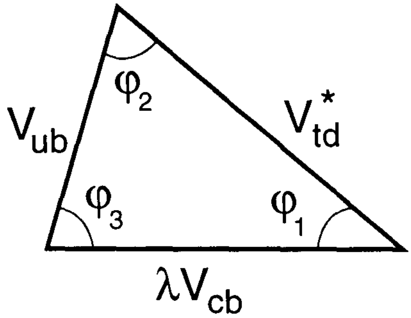


Figure 1: The unitarity triangle. The lengths of the sides are magnitudes of elements of the CKM matrix. The angles are CP-violating phases.

amplitude lead to CP asymmetries if there is only one process contributing to the decay. For example, one measures the three angles of the triangle from the typical decays

$$\begin{aligned} B_d \to \psi K_s &\quad , \quad \sin 2\varphi_1 \\ B_d \to \pi^+\pi^- &\quad , \quad \sin 2\varphi_2 \\ B_s \to K_s\rho_0 &\quad , \quad \sin 2\varphi_3. \end{aligned} \tag{20}$$

The first is very clean. The others suffer from possible penguin pollution: penguin as well as tree diagrams are both present, leading to some theoretical uncertainty.

5.1.9 Weak Scale Baryogenesis

It has long been known that B and L are violated by anomalies in the standard model [79],

$$\partial \cdot J_B = \partial \cdot J_L = -\frac{3g^2}{16\pi^2} TrF\tilde{F}. \tag{21}$$

This can be thought of as tunneling between vacua of different $B + L$ (Figure 2). The anomaly conserves $B - L$. At zero temperature the effect is irrelevant for practical purposes because the tunneling rate is suppressed by the factor $\exp(-4\pi/\alpha_W) \sim 10^{-170}$. However, for temperatures comparable to the electroweak scale, *i.e.*, 1 TeV, there may be unsuppressed thermal fluctuations. A specific solution that describes these transitions is known as the sphaleron. One serious consequence is that any baryon asymmetry of the universe produced earlier, such as in a GUT epoch, would be washed out by the electroweak $B + L$ violation, unless the initial asymmetry had a non-zero $B - L$ or the initial

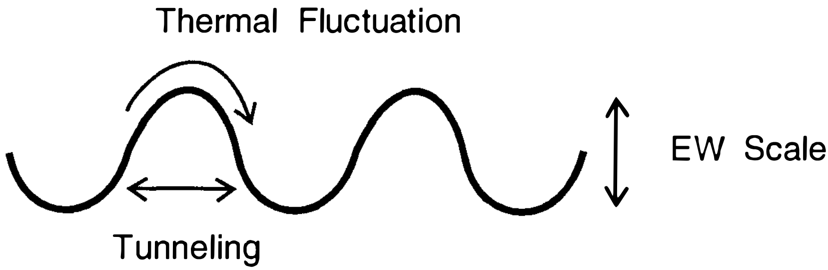


Figure 2: Schematic of baryon number violation in the standard model. The minima correspond to degenerate vacua of different $B+L$. The anomaly describes tunneling between these vacua.

$B+L$ asymmetry was huge, *i.e.,* of $O(1)$ [80]. If the baryon asymmetry was washed out a new asymmetry

$$\frac{n_B - n_{\bar{B}}}{s_\gamma} \sim 10^{-11} \tag{22}$$

must have been created at the time of the electroweak transition. This is possible in principle but difficult in practice. It is hard to achieve sufficient CP violation within the standard model; one must add new physics to enhance the CP breaking. The necessity for being out of equilibrium can be associated with expanding bubbles of true vacuum in a first order phase transition. There a number of possibilities for the mechanism, such as reflection from the wall of the expanding bubble [81].

A related possibility is baryon number violation in high energy hadron collisions, of order $\sqrt{s} \gtrsim 10$ TeV, such as the SSC. It has been speculated that such collisions might produce B-violating transitions. These would manifest themselves not only by the B violation but, more dramatically, by the production of $O(100)W$ and Z particles associated with the fields that characterize the different vacua. The cross section is

$$\sigma_{\text{tot}} \sim \exp\left(\frac{4\pi}{\alpha_W} F(E/E_{\text{crit}})\right), \tag{23}$$

where

$$F(\epsilon) = -1 + \frac{9}{8}\epsilon^{4/3} - \frac{9}{16}\epsilon^2 + \cdots \tag{24}$$

The effect will be strongly suppressed if $F < 0$, and the results are unphysical (nonunitary) for $F > 0$. However, if $F = 0$ there would be huge effects. The calculation of F is extremely difficult because perturbation theory does not hold in the relevant domain; this is an open topic of debate amongst the theorists. This situation was reviewed by Ringwald [82], who expressed the hope that we would have a reliable answer within the next two years. Novikov [83] argued that a previous calculation in a supersymmetric theory is not valid.

5.2 100 TeV: Flavor Changing Neutral Currents

Flavor changing neutral currents (FCNC) in such decays as μ, τ, K, B, $\cdots$ are an important manifestation of physics at the 100 TeV scale. Searches for such decays place stringent constraints on dynamical symmetry breaking, family symmetries, extended Higgs sectors, compositeness, and leptoquarks, all of which are expected to mediate effects. At this meeting Zeller [66] presented results

$$\begin{aligned} K^+ \to \pi^+\mu^+e^- \qquad & B < 2.1 \times 10^{-10} \\ K^+ \to \mu^\pm e^\mp \qquad & B < 3.3 \times 10^{-11} \end{aligned} \tag{25}$$

from the BNL experiments E777 and E791. These are very impressive. However, most types of physics which would lead to these particular decays are already strongly constrained by the $K_L - K_S$ mass difference, and any observable effects would have to be due to "non-standard non-standard" physics. Hou [84] described the possibility of $t \to cH$ or $H \to \bar{t}c$ in models for which there is no natural flavor conservation in the Higgs sector, and Fritzsch [27] emphasized the decay $\mu \to 3e$, which can occur by mixing between right-handed singlets and doublets. In most models the FCNC are largest for the third family.

5.3 10^{2-19} GeV: Neutrino Mass

Many extensions of the standard model predict non-zero neutrino mass at some level. Typically one expects $m_\nu \sim v^2/M \ll v$, where v is the weak scale and M is the scale of new physics. Therefore, small neutrino masses probe large-scale physics; and there are interesting predictions in various models for grand unification [85]. There is some evidence for neutrino masses from Solar neutrinos, atmospheric neutrinos, the possible 17 keV neutrino, and hot dark matter [85, 86, 87].

5.4 $10^{16} - 10^{19}$ GeV: The Ultimate Unification

One of the great dreams is a unification of the fundamental interactions into a simpler structure, perhaps even with gravity. The old fashioned (and perhaps naive) view of grand unification was that the standard model should be embedded in a simple group G at a scale $M_X \sim 10^{14-16}$ GeV. This is sufficiently below the Planck scale, $M_P \simeq 10^{19}$ GeV, that it perhaps makes sense to ignore gravity in this partial unification. In the old-fashioned early days of GUTS, model builders typically invoked very large Higgs representations for whatever purpose they desired. The modern string-inspired view [88] is that there should be a direct unification of all of the forces at the string compactification scale $10^{18} - 10^{19}$ GeV. It is unlikely, through not impossible, that there is an isolated GUT below the 10^{18} GeV scale. Even if one has such a situation, it is unlikely that one would have large Higgs representations. Despite these prejudices, there is experimental evidence, using precise LEP data on the low energy couplings, that the three (properly normalized) gauge couplings α_3, α_2, α_1 meet at a point when extrapolated in the minimal supersymmetric extension of the standard model (MSSM), at a unification scale of around $M_X \sim 2 \times 10^{16}$ GeV. (See Figure 5.4.) This could well be an accident, but could also be a hint that the bang scenario and supersymmetry may be correct. One should not take the details too seriously because of the many theoretical uncertainties, but perhaps some sort of SUSY-unification, with or without strings, is relevant. Another way of seeing this is that one can predict α_s from the observed values of α and $\sin^2\theta_W$:

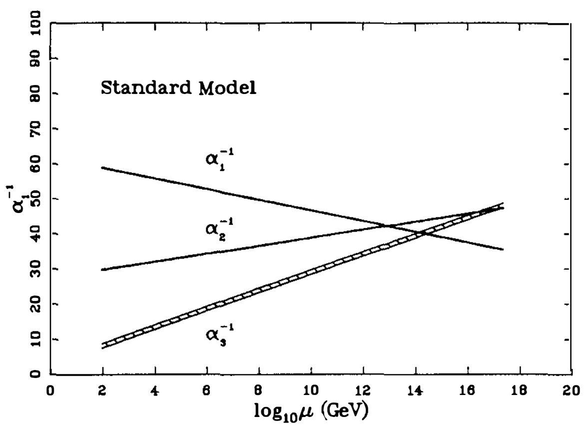
$$\begin{aligned} \text{SM}: &\quad \alpha_s(M_Z) \sim 0.072 \pm 0.001 \pm 0.01 \pm ? \\ \text{MSSM}: &\quad \alpha_s(M_Z) \sim 0.120 \pm 0.003 \pm 0.004 \pm 0.01 \pm ?. \end{aligned} \tag{26}$$

The first uncertainty is from the input parameters. The second in the supersymmetric case is from the masses of the superpartners, and the next is from the splittings of the superheavy particles. The question marks are the possible effects of adding new multiplets that are split into light and heavy sectors. A comparison with the experimental values in Table 1 shows the success of the MSSM.

There are a number of interesting theoretical and experimental implications of unification.

- One is the possible connection with supersting theories.

- Real unified theories that exist as a separate gauge group predict proton decay at some level. Experimentally, the limit on two important modes are $\tau_{e^+\pi^0} > 10^{33}$ yr and $\tau_{\bar{\nu}K^+} > 10^{32}$ yr [86]. The $e^+\pi^0$ decay excludes the ordinary SU_5 model, but is strongly suppressed in the supersymmetric models due to the larger unification scale. In supersymmetric GUTs there is a new mechanism (dimension-five operators) for proton decay. These are generated by the diagrams in Figure 4 and lead mainly to decay modes such as $p \to \bar{\nu}K^+$. Because the basic exchange is a fermion the lifetime is $\tau_p \sim M_{\tilde{H}}^2 \sim M_X^2$, which is much more dangerous than the normal diagrams generated by a boson exchange ($\tau_p \sim M_X^4$). The actual decay rate depends on the details of the spectrum of the superpartners. Nath and Arnowitt [89] have made



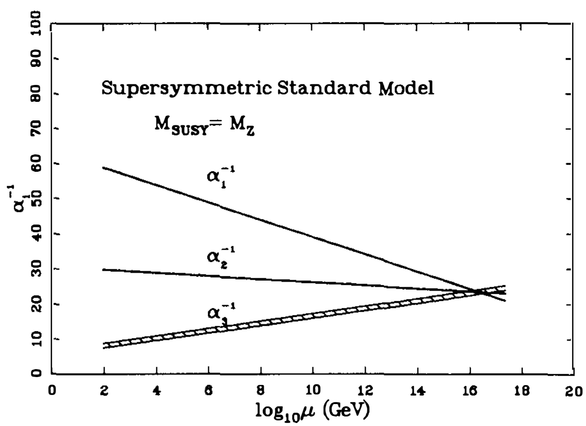


Figure 3:

Extrapolation of the normalized gauge couplings in the standard model and its supersymmetric extension using $\alpha^{-1}(M_Z) = 127.9 \pm 0.2$, $\sin^2 \hat{\theta}_W(M_Z) = 0.2325 \pm 0.0007$, and $\alpha_s(M_Z) = 0.124 \pm 0.010$. Clearly the standard model does not unify into an ordinary GUT, whereas the supersymmetric extension is compatible with grand unification. Ordinary GUTS are also excluded by the non-observation of proton decay, while in SUSY GUTs proton decay via the ordinary $d = 6$ operators is strongly suppressed. However, $d = 5$ operators are still dangerous.

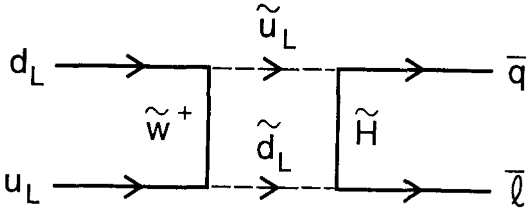


Figure 4: The dimension-five contributions to proton decay. The interaction at the right, mediated by the exchange of superheavy colored Higgsino, must be dressed by the exchange of a wino or other particle to generate an operator involving only quarks and leptons.

a detailed calculation of the spectrum in supergravity models consistent with unification. They find that the no-scale models of supergravity are excluded by proton decay, but generalized models have some allowed regions in parameter space. These regions correspond to $m_{\tilde{g}} < m_{\tilde{q}}$, a light Higgs scalar $m_h < M_Z$, $m_t < 175\ GeV$, and a chargino and two neutralinos with masses $\lesssim 100\ GeV$. Models such as superstring theories or flipped-SU_5 that are not real grand unified theories may not have any proton decay.

Raby [90] described some possibilities for the low energy fermion spectrum in unified theories. There are too many parameters to predict anything from first principles, so additional assumptions are needed. Dimopoulos, Hall, and Raby have revived an old ansatz due to Georgi and Jarlskog for the fermion mass matrices at the high scale, and then run them to low energies. (In the normal grand unified theories the ansatz corresponds to the "bad" GUTs with large Higgs representations and discrete symmetries.) They choose as input parameters the e, μ, τ, u/d, c, and b masses and $|V_{cd}|$, $|V_{cb}|$. As outputs they generate m_d, m_s, $m_t = 180 \pm 10\ GeV$, and $|V_{ub}/V_{cb}| \sim 0.05$. The latter prediction is somewhat low compared to experiment.

- There may also be implications for neutrino masses, and some string-motivated supersymmetric models can generate masses in agreement with what is suggested by the Solar neutrino problem [85].

- There may also be implications for cosmology and the baryon asymmetry of the universe, at least if $B-L$ is violated so as to survive the electroweak phase transition.

There are other special models that lead to other forms of baryon number violation

[91] or neutron oscillations $n \to \bar{n}$ [92]. These are not the canonical grand unified theories and do not have any strong motivations.

6 Conclusion

There is no evidence for any deviation from the standard model. However, its many shortcomings suggest that there must be new physics. The models fall into two broad categories. The whimper models, in which there are many scales of physics, are non-perturbative and include such ideas as dynamical symmetry breaking and compositeness. The other extreme possibility is the bang scenario, which is perturbative and in which there are not many new thresholds between present energies and the Planck scale. This may be associated with elementary Higgs fields, supersymmetry, and grand unification. There is a hint of support for the bang scenario from the unification of coupling constants in the MSSM.

We do not know what is the ultimate source of new physics. There are many complementary probes, all of which are important and should be pursued. These include searches at the large colliders, carrying out the full program of precision experiments, searches for neutrino mass, cosmology and the large-scale structure of the universe, and trying to forge connections with fundamental theories such as superstrings.

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