UNIVERSITÀ DEGLI STUDI DI PAVIA

SCIENTIFICA ACTA

QUADERNI DEL DOTTORATO

VOLUME III ANNO III NUMERO 3

5 DICEMBRE 1988

ISTITUTO NAZIONALE DI FISICA NUCLEARE

CENTRO STAMPA - DIPARTIMENTI FISICI
via Bassi, 6 27100 Pavia

L. Maiani

Department of Physics, University of Rome "La Sapienza"
P.le A.Moro 2 - 00185 Rome
INFN - Sezione di Roma, Italy

FLAVOUR PHYSICS

1. INTRODUCTION

Flavour physics was opened by the discovery of the muon, and by the celebrated Rabi sentence: "who ordered that?". Indeed, the replication of quark and lepton generations is one of the most fascinating misteries of modern physics. We do not understand it any better now than fourthy years ago.

Progress in physics comes more often from asking "how" rather than "why". Seen from this side, the existence of heavy copies of the first generation of quark and leptons has been a real God blessing, and it has provided crucial clues to the understanding of fundamental interactions. Three examples will suffice.

i) The muon and strange particle β-decays have been crucial to establish the universality of the weak interactions, a concept that eventually led to the unified gauge theory of today.

ii) The strange particle mass spectrum has given a solid basis to the very notion of quark.

iii) The narrow width of the J/ψ has given the final support to the notion of asymptotic freedom in strong interactions.

Flavour physics of today is interesting and vital as it was in the past, as I will try to indicate in this talk and, I am sure this Workshop will demonstrate.

2. QUARK MODEL AND NON-LEPTONIC WEAK INTERACTIONS

Seen in retrospective, it is impressive how well the naive, non-relativistic quark model reproduces the spectrum of s-wave baryon and meson states.

In the exact isospin limit there are in all 16 independent masses, and 6 independent parameters: two symmetric masses, M_{0B} and M_{0M}, the strange and up constituent mass, m_s and m_u, and the strenghts of the spin-spin hyperfine interaction, a_M and a_B:

$$H_{spin-spin} = \sum_{i=j} \frac{a_{M,B}}{m_i m_j} \vec{S}_i \vec{S}_j \tag{2.1}$$

This leads to the 10 mass relations reported in Table 1. The failure of the last two relations is well understood in QCD, in term of the anomaly of the axial U(1) current. Otherwise, the relations are extremely successful. Note further that the sign of a_M (a_B) agrees with that of the one-gluon exchange for color singlet $\bar{q}q$ states (or antitriplet qq states).

A remarkable failure of the naive quark model occurs for non-leptonic weak decays, notably in $\Delta S=1$ strange particle decays. The $\Delta S=1$ and $\Delta S=0$ weak currents carry $I=1/2$ and $I=1$ respectively, so one would expect a similar mixture of $\Delta I=1/2$ and $\Delta I=3/2$ in the current - current product and, consequently, approximately equal rates for $K^+ \to \pi^+ \pi^0$ ($\Delta I=3/2$) and $K_S \to \pi^+\pi^-$ ($\Delta I=1/2$ and 3/2). As is well known, the experimental amplitudes are in the ratio of about 20:1 in favour of $\Delta I=1/2$. This is perhaps the only known case where the naive quark model prediction is far away from the experimental number.

In QCD, some part of the enhancement[1] comes from the virtual gluon exchange at short distances, which favours the $\Delta I=1/2$ over the $\Delta I=3/2$ effective hamiltonian by a factor of about 2-3. The rest is supposed to arise from gluonic corrections with virtual momenta between say the K-mass and the charmed particle mass. New terms in the effective hamiltonian, arising from "penguin" diagrams, have been

Table 1

Mass relations for the $J^P=1/2^+$, $3/2^+$ baryons and $J^P=0^-$, 1^- mesons in the non-relativistic quark model. Masses are given in MeV. Note the failure of the last two relations, which can be understood in terms of the U(1) anomaly and η-η' mixing.

Relations	l.h.s.	r.h.s.	Observations
$\frac{1}{4}(\Sigma+3\Lambda)=\frac{1}{2}(\Xi+P)$	1134	1126	SU(3) - relation
$Y^* - \Delta = \Xi^* - Y^*$	152	150	(Okubo-Gell Mann)
$Y^* - \Delta = \Omega - \Xi^*$	152	140	
$\Xi - \Sigma = \Xi^* - Y^*$	123	150	universality of m_s-m_u
$\Lambda - P = \frac{3}{4}(K^*-\rho)+\frac{1}{4}(K-\pi)$	178	178	
$\frac{2(\Delta-P)+3(\Lambda-\Sigma)}{2(\Delta-P)}=\frac{K^*-K}{\rho-\pi}$	0.62	0.63	hyperfine interaction $\alpha\ (m_i m_j)^{-1}$
$\rho = \omega$	773	783	φ is pure $s\bar{s}$ state
$K^*=\frac{1}{2}(\rho+\varphi)$	892	896	
$\pi = \eta$	140	549	broken by U(1) anomaly and η-η' mixing
$\frac{\pi+3\eta}{4} = K$	447	495	

claimed[2] to give the correct order of magnitude effect, but the situation is still unclear, particularly since penguin dominance would naturally lead to a large value for the CP-violating parameter ϵ'/ϵ, in contrast (?) with the rather tight experimental upper bounds. Extensive calculations in lattice QCD are being performed[3] to see if the large distance enhancement is indeed reproduced. Time will tell.

The situation is a little better with charmed particle non-leptonic decays. This subject will be discussed at the Workshop by Stech and coworkers, so I will limit myself to a few comments.

i) The inclusive non-leptonic rates are more or less reproduced by the QCD corrected effective hamiltonian. The lifetime ratio:

$$\frac{\tau(D^+)}{\tau(D^o)} \approx 2.5 \qquad (2.2)$$

and the corresponding semileptonic branching ratios may well be explained by a combination of the negative interference[4], which reduces the D^+ non leptonic rate, and by the soft-gluon emission,[5] which gives non-spectator contributions to the D^o rate.

ii) Exclusive D-decays are in a more confused situation. The pattern predicted by the naive quark model, using the QCD corrected coefficients of the effective hamiltonian,[6] does not agree with data. Good agreement is obtained if one keeps the operator structure of H_{eff}, but leaves the coefficients as free parameters.[7] The meaning of this result is unclear, at least to me. There have been attempts[8] to relate the structure of the coefficients which fit the data to the expansion in 1/N (N being the number of colours). Although interesting, I do not think a sound and convincing explanation has been found yet.

3. THE PSEUDOSCALAR MESON-AXIAL CURRENT COUPLING

For any (charged) pseudoscalar meson $M=\bar{Q}q$ one can define a coupling f_M according to:

$$< 0 \mid (\bar{q}\, \gamma_\mu\, \gamma_5\, Q) \mid M(p) > = p_\mu\, f_M \tag{3.1}$$

For quark masses which are vanishing or very small with respect to Λ_{QCD} (as is the case for the up and down and, to a lesser extent, for the strange quark) f_M is the order parameter of the spontaneous breaking of the symmetry generated by the corresponding axial charge.

Although dynamically non trivial, the couplings f_M are sufficiently simple quantities so that we may be able to compute them from first-principles. Thus, the experimental determination of f_M for all stable pseudoscalar mesons would be very useful (other, more practical reasons will appear in the next Section). Of course, f_M and f_K have been determined since long. Otherwise, we have a recently determined[9] bound on f_D:

$$f_D < 340 \text{ MeV} \tag{3.2}$$

from the non-observation of $D \rightarrow \mu\nu$.

Theoretical estimates of f_D and f_B have been obtained with the QCD-sum rule method by two different groups:

$$\left.\begin{array}{l} f_D = 170 \div 220 \text{ MeV} \\ f_B = 100 \div 130 \text{ MeV} \end{array}\right\} \text{ref.(10)}$$

$$f_B = 190 \pm 30 \text{ MeV} \qquad \} \text{ ref(11)} \tag{3.4}$$

I will discuss in Sect.5 the most recent lattice QCD calculations.

The non-relativistic quark model gives

$$f_M^2 = 12 \frac{|\psi(o)|^2}{M}$$

and, at the same time, it predicts the JP = 1^-, 0^- meson splitting to be:

$$\Delta M = \frac{32\pi}{9} \alpha_s \frac{|\psi(o)|^2}{M m}$$

One expects the wave function at the origin to be quite independent from the heavy quark mass M, at least for large values of M. This has the consequence that[12]:

$$2M \,.\, \Delta M \sim M^2(1^-) - M^2(0^+) \;\alpha\; |\psi(o)|^2 \qquad (3.5)$$

should be independent from M, as observed. The difference in mass-squared is about 0.55 GeV^2 for strange, charmed, and beauty mesons. Furthermore:

$$f_M \;\alpha\; \frac{1}{\sqrt{M}} \qquad (3.6)$$

Using the bound eq.(3.2), one obtains:

$$f_B \sim f_D \sqrt{\frac{M_D}{M_B}} < 200 \text{ MeV} \qquad (3.7)$$

On the other hand, if the $(M)^{-1/2}$ behaviour starts to apply already at the Kaon mass, one obtains:

$$f_B \sim f_K \sqrt{\frac{M_K}{M_B}} \sim 52\ \text{MeV} \qquad (3.8)$$

which gives, most likely, the absolute lower bound to f_B.

4. B-$\bar{B}$ MIXING

Perhaps, the most exciting recent development in flavour physics is the observation of the mixing between neutral B and $\bar{B}$ mesons. The first positive indication has been obtained by the UA1 collaboration[12], from the production of equal sign dimuons in p-$\bar{p}$ collisions. Even more remarkable is the result of the ARGUS collaboration[14], who observes a non-negligible mixing between the <u>non-strange</u> B_d-$\bar{B}_d$ states, giving rise to equal sign dileptons from the Y(4S) decay:

$$r_d = \frac{N(e^-e^-) + N(e^+e^+)}{N(e^+e^-)} \Big|_{Y(4S)} = 0.2 \pm 0.1 \qquad (4.1)$$

Upper bounds to the equal sign dileptons from B-$\bar{B}$ decay in e^+e^- collisions have been given by the CLEO and MARK II collaborations.

The large effect in eq.(4.1) came rather unexpected. Taken at face value, it can be explained by the standard (three generation) model, if the t-quark mass is rather large: lower bounds from 50 GeV to 100 GeV have been given in the phenomenological analysis of ref.(15).
At the same time, one predicts uniquely a maximal mixing in the strange system B_s-$\bar{B}_s$ (r_s>0.90).

To appreciate better how significant is the lower bound to the t-quark mass, it is useful to give some details about the theoretical calculation of r_d.

Keeping into account the fact that the B_d-$\bar{B}_d$ pair is produced from a $J^P=1^-$ state, one can relate directly r_d to the mass-difference and lifetimes of the long and short states, B_L and B_S, according to:

$$r_d = \frac{(\Delta M)^2}{2\Gamma^2 + (\Delta M)^2 - (\frac{\Delta\Gamma}{2})^2} \approx \frac{(\Delta M)^2}{2\Gamma^2 + (\Delta M)^2} \tag{4.2}$$

$$\Delta M = |M_L - M_S| \sim 2\,|M(B_o \to \bar{B}_o)| \tag{4.3}$$

$$\Gamma = \frac{1}{2}(\Gamma_L + \Gamma_S) \tag{4.4}$$

The approximate equalites in eq.(4.2) and (4.3) follow from the neglect of lifetime-differences, which is quite justified for B-mesons; $M(B_0 \to \bar{B}_0)$ is the off-diagonal matrix element of the hamiltonian, in the B_0-$\bar{B}_0$ basis.

$M(B_0 \to \bar{B}_0)$ is computed from the familiar box diagram. After integration over the internal lines, the calculation is reduced to that of the matrix element of an effective, $\Delta B=2$, hamiltonian of the form:

$$H_{eff} = \frac{G^2}{16\pi^2} (U_{tb} U_{td}^*)^2 \, m_t^2 \, f(\frac{m_t^2}{M_w^2}) \, (1+\text{QCD-corrections})$$

$$x \;\; \bar{d}\gamma_\mu (1-\gamma_5) b \;\; \bar{d}\gamma^\mu (1-\gamma_5) b \tag{4.5}$$

$$M(B_o \to \bar{B}_o) = \langle \bar{B}_o | H_{eff} | B_o \rangle$$

with f(x) a well determined function[16] (f(o)=1) and with calculable, but not very important, QCD corrections. U_{tb} and U_{td} are the usual K-M weak mixing coefficients and we have approximated $m_c \approx m_u \approx 0$. Note that internal momenta in the box diagram have an infrared cut-off of the order of $M_B >> \Lambda_{QCD}$, so that the use of perturbative QCD to derive H_{eff} seems to be well justified here, in contrast to the K_o-$\bar{K}_o$ case. Real uncertainties arise in the evaluation of the matrix element. First, one uses the so-called vacuum saturation approximation, whereby:

$$<\bar{B}_o|(\bar{d}\gamma_\mu(1-\gamma_5)b)^2|B_o> = \frac{4}{3} f_B^2 M_B \tag{4.6}$$

This introduces another unknown, f_B, which is next taken from the estimates illustrated in the previous Section.

We know that $|U_{tb}| \sim 1$ to a very good approximation. If we knew $|U_{td}|$ exactly, we would get from eqs.(4.5) and (4.6) a prediction for the t-quark mass (although dependent from the assumed value of f_B).Since we have only bounds for U_{td}, we can derive only bounds for m_t (always f_B dependent). Writing[12]:

$$|U_{td}| \approx \theta_c \gamma (1 - \frac{\beta}{\gamma\theta_c} e^{i\delta}) \tag{4.7}$$

with θ_c the Cabibbo angle, δ the CP-violating phase, we have[17]:

$$\gamma \approx |U_{cb}| \approx 0.06 \tag{4.8}$$

$$\beta \approx |U_{ub}| < 1.0 \times 10^{-2} \tag{4.9}$$

The situation is illustrated in Fig.1, where lines of constant r_d=0.2 (0.1) are drawn in the β-$\cos\delta$ plane, and labeled by the corresponding value of m_t (f_B=150 MeV or 110 MeV is assumed). The lower bound to m_t is(f):

(f) Notice that $\beta < 1.0 \times 10^{-2}$ corresponds to $\frac{\Gamma(b \to u)}{\Gamma(b \to c)} < 0.08$.

$m_t < 55$ GeV (r_d=0.1, f_B=150 MeV, β<1.0x10)$^{-2}$

$m_t <$ 70 GeV (r_d=0.2, f_B=150 MeV, β<1.0x10)$^{-2}$ (4.10)

These number agree with those given in ref.(15), given the slightly different choice of the parameters,:

$m_t \leq 50$ GeV ($r_d = 0.09$, f_B = 160 MeV; $\beta \leq 1.0 \times 10^{-2}$)

$m_t \leq 100$ GeV (r_d=0.2, f_B= 110 MeV; $\beta \leq 1.0 \times 10^{-2}$) (4.11)

From the r.h.s. of Fig.1 one could also read an upper bound to m_t. Howevere, from the present limitation on β one can obtain an almost vanishing $|U_{td}|$, so that this limit is not very significant, and it is definitely larger than the limits derived from the close equality of the ρ-parameter and of M_W, M_Z and $\sin^2\theta_W$ to the lowest order values in the standard model, which give by tipically: $m_t < 250$ GeV (see Sect.7).

The discussion goes essentially unchanged for B_S-$\bar{B}_S$ mixing, with the substitution: $U_{td} \rightarrow U_{ts}$. Since $|U_{ts}/U_{td}|^2 \sim (\theta_c)^{-2} \sim 16$, the conclusion that $r_S \sim 1$ follows uniquely.

A fourth generation could change the relative size of r_S versus r_d. Supersymmetric particles could also affect somehow[18] the theoretical value of ΔM. The overall conclusion is that B-$\bar{B}$ mixing is a real window on high-energy physics, which is a quite interesting argument in favour of high-luminosity B-factories. Machines of this type are also needed to determine r_S, which is a crucial test of the standard theory. On the other hand, the prospects to observe CP-violating asymmetry in semileptonic B_d and $\bar{B}_d$ decays are rather remote[19], at least in the standard theory.

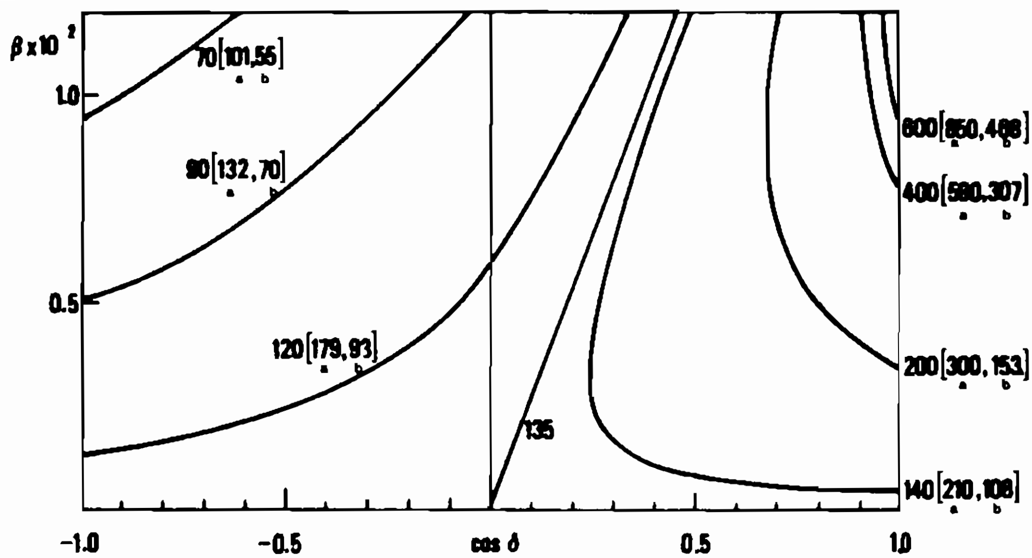


FIGURE 1

Lines of constant r_d=0.2 in the cosδ-β plane, for various values of m_t, calculated for f_B=150 MeV. For each curve, we give in parenthesis the value of m_t which corresponds to the same r_d but f_B=110 MeV (labeled (a)) or to r_d=0.11 and f_B=150 MeV (labeled (b)). I thank A. Pugliese for providing the calculation.

5. MORE ABOUT B-PHYSICS

Besides B-$\bar{B}$ mixing, there are several important issues which can be clarified with a deeper study of b-decays.

i- *b → u transitions* The study of these transitions is needed to determine the mixing coefficient U_{ub}, a crucial parameter of the Standard Model. The present upper bounds to the ratio:

$$R = \frac{|U_{ub}|}{|U_{cb}|}$$

are obtained from the study of the end-point of the electron spectrum in the semileptonic inclusive decay: $B \rightarrow e + \nu +$ anything. The earlier theoretical analysis[20] based on the parton model with QCD corrections has been criticized on various grounds.[21] However, in the end, the other methods give results which are not widely different from the simple parton model approach, and the present conclusion is that[22]:

$$R < 0.25 \div 0.20 \quad (5.1)$$

I do not think that, at present, one can really justify any of the theoretical proposals over the others. A real improvement of the situation may be obtained from the study of the exclusive semileptonic decays, such as

$$B \rightarrow e + \nu + \rho\ (\pi) \quad (5.2)$$

or from the leptonic mode

$$B \rightarrow \mu + \nu\ (\tau + \nu) \quad (5.3)$$

In both cases, a theoretical input is needed: the vector form factor for (5.2) and f_B for (5.3). Both should be given in a reliable way by the next generation lattice QCD calculations, so that efforts to detect experimentally the transitions (5.2) and (5.3) are welcome.

ii. *CP violation in B decays.* The observation of any such effect would be a first class result and a beatiful test of the present ideas about CP-violation. Extensive theoretical studies[23] indicate that $10^7 \div 10^8$ B-decays are needed to obtain the required sensitivity level. Is this experimentally feasible?

iii. *b→u non leptonics*The non-leptonic transition:

B → uncharmed states

is induced by an effective hamiltonian which is obtained from the ΔS=1 hamiltonian with the exchange s→b, and, analogously, has both ΔI=1/2 and ΔI=3/2 terms. The difference is that the relevant momentum scale is considerably higher, and one should be closer to the short distance renormalization effect, namely A(ΔI ~ 1/2) ≈ (2÷3) A(ΔI=3/2) (see Sect.2). Experimental results on this point would be quite illuminating.

iv. *Rare b decays*. These are a good signature for the physics beyond the Standard Model. A recent interesting development is the observation[24] that the decay:

$$b \to s + \gamma \qquad (5.4)$$

i.e.:

$$B \to K^* + \gamma,\ K^* \pi + \gamma,\ \ldots.$$

may be quite sensitive to the presence of supersymmetric particles, and provide limits which are quite competitive with those arising from high-energy experiments.

6. FLAVOUR ON THE LATTICE

Lattice QCD is[25], at present, the only way we can explore the predictions of QCD in the fully non-perturbative domain. The available computing power introduces drastic limitations, however, whose impact on the precision of the predictions is very difficult to assess.

i. The lattice spacing, a, and the lattice size, L, of today calculations, performed typically with CRAY supercomputers, are of the order of 0.1 Fermi and 1÷2 Fermi respectively. This makes lattice artifact effects (of the order of $a\Lambda_{QCD} \approx 0.1$) and volume effects reasonable but not negligible. Furthermore, the size of L limits the smallness of quark mass we can introduce. In practice, we have to work with quark mass of the order of 100 MeV and extrapolate to zero to get to the chiral limit.

ii. Fermion loops are suppressed completely (quenched approximation).

In spite of these limitations, the extensive calculations[26,27] performed till now have met with a considerable success. Let me mention just two cases.

The hadron spectrum of non-strange and strange particles is qualitatively reproduced (once quark masses are fixed from the ps-meson masses and the lattice spacing is calibrated, e.g. from the ρ-mass). The proton to ρ mass ratio is still too large, but this could be due easily to the errors introduced by the limitations (i) and (ii). Calculations of f_π[27] show clearly the sign of the spontaneous breaking of the chiral symmetry ($f_\pi \neq 0$ when $m_\pi = 0$) and the size of f_π is close to the experimental value.

Besides the traditional spectroscopy, I think there are further interesting problems which can be studied in lattice QCD.

a) The value of f_M, Sect.2, for large values of the quark mass. We have already preliminary results for f_D, on a lattice of dimensions $16^3 \times 48$, at $\beta=6.2$. We find[28]:

$$f_D = 180 \pm 30 \text{ MeV} \tag{6.1}$$

which compares well with the QCD sum rule value. A systematic study of the dependence of f_M from the heavy meson mass, to compare with the scaling law eq.(3.6) would be interesting, and it would allow to extrapolate to f_B which, as discussed in Sects. 4 and 5, is an extremely interesting quantity. Extrapolating with the square-root law, eq.(3.6), we find:

$$f_B \approx 110 \text{ MeV} \tag{6.2}$$

b) The computation of the matrix elements of four fermion operators are relevant to the study of $\Delta S=1$ non leptonic amplitudes. Furthermore, it allows to test the validity of the vacuum saturation hypothesis, eq.(4.6), for light and heavy systems. Defining:

$$<\bar{M}_o| (\bar{q}\gamma_\mu (1-\gamma_5) Q)^2 |M_o> \equiv B \frac{4}{3} f_M^2 M \qquad (6.3)$$

we have found[29] B ~ 1 for the K_0-$\bar{K}_0$ system. Preliminary results for the D_0 case also indicate a value close to unity[28]. Again a study of the mass-dependence could allow to extrapolate to the B-meson, and confront a reliable theoretical calculation to the experimental results on B-$\bar{B}$ mixing.

c) The study of the moments of deep-inelastic structure functions, which has been just started with encouraging results[30].

d) Finally, coming back to spectroscopy, a study of the $J^P=1/2^-$ baryons mass-spectrum could be very interesting. These states appear together with the $J^P=1/2^+$ baryons in the correlation functions of baryon sources. Unlike the $J^P=1/2^-$ case, the non-relativistic quark model has few predictions to make (too many parameters describe the P-wave mass-spectrum) and it would be illuminating to compare the lattice results with the already abundant but essentially neglected, experimental information.[31]

7. NEW FLAVOURS AT HIGH ENERGY

Besides the t-quark, the search of new lepton and quark families is an obvious target of the present and future high energy machines. The idea of supersymmetry provides us with a new possibility: flavour associated with elementary scalar particles, the supersymmetric partners of the old (and new) fermions. The discovery potential for quark, leptons and supersymmetric scalars of the next generation accelerators (SSC, LHC and the high energy linear e^+e^- collider, CLIC) has been widely studied[32]. Generally speaking, we may hope to extend our knowledge well above the weak scale,

$$\Lambda_F = 250 \text{ GeV} \approx G_F^{-1/2} \tag{7.1}$$

up to mass-values of the order of 1TeV.

To this, I would like to add a few comments.

i. *Fermion flavours*. All known quark and leptons receive their mass from the breaking of $SU(2)_L \times U(1)$. Therefore we expect masses and mass-differences of possible new multiplets to be at most of order Λ_F. This goes well with the present limits obtained from ρ, the ratio of neutral to charged current neutrino cross-sections, and from the W and Z mass, which make it unlikely the existence of new lefthanded doublets with a mass splitting much larger than 200 GeV (a recent analysis[33] gives a limit to m_t-m_b of 180 GeV, which can be immediately applied to a new chiral multiplet with $\Delta m \approx m$).

Although there is no theory of neutrino masses, we can guess, on the basis of past experience, that light neutrinos are associated with new chiral families. In this case, neutrino counting from the Z_0 width is a powerful and complementary tool to determine the number of fermion flavours in Nature. At present, with $p\bar{p}$ colliders, we can determine the ratio $\Gamma(Z)\backslash\Gamma(W)$ which depends from the number of neutrinos, assuming that neutrinos are the only members of the new families to participate to the real decay, and from the t-quark mass. Taking the upper bound to this ratio from the combined data of UA1 and UA2 (95% confidence limit) one obtains that[34]:

-$N\nu = 3$ is allowed for all values of m_t

-$N\nu = 4$ is allowed for $m_t < 70$ GeV (7.2)

-$N_\nu = 5$ is allowed for $m_t < 60$ GeV

Note how close the upper bounds to m_t for $N_\nu = 4,5$ are to the lower bounds from B-$\bar{B}$ mixing, Sect.4. I will come back to this point shortly.

ii *Scalar flavours* The first supersymmetric models[35] were based on the idea that supersymmetry is broken by the same mechanism that breaks $SU(2)_L \times U(1)$. Thus squark and sleptons were expected to lie in the same mass range as, say, the t-quark. This kind of models has *failed* to produce a consistent picture of particle masses. Present supersymmetric models[36] are based rather on the idea that supersymmetry is explicitely broken, at low energy, and introduce a new mass scale, independent from Λ_F, and associated with the gravitino mass, $m_{3/2}$. There is, however, a further concept wich forbids $m_{3/2}$ to be arbitrarily large. Supersymmetric particles are supposed to cancel the quadratic divergences that appear in the Higgs potential at the one loop-level. If this has to happen in a "natural" way, sparticle masses, and therefore $m_{3/2}$, cannot be too large:

$$m_{3/2} < (\alpha \, \Lambda_F)^{-1/2} \approx 0(1 \text{ TeV}) \tag{7.3}$$

(a quantitave analysis of the consequences of the "naturalness" hypothesis for the sparticle mass spectrum has been recently carried out in ref.(37)). In view of eq.(7.3), it appears that the next generation accelerators are well-placed to look for squarks and sleptons, although still higher energies may be required to kill supersymmetric models of this kind.

iii. *An intriguing scenario.* At the classical level, a gauge theory contains no restriction on the number of families. Including quantum corrections, one finds that asymptotic freedom in the non-abelian sector is lost when the number of matter particles increases beyond a certain point (e.g. 16 flavours are needed to lose asymptotic freedom in QCD). Is this a useful hint? Yes, if we believe that the Standard Theory has to merge into a more unified structure, e.g. with gravity, at a large mass-scale, Λ. If this is the case, and the number of flavour were too small, colour and weak SU(2) forces would be asymptotically free and would play no role at Λ, a quite unlikely situation. On the contrary, with N too large, the gauge couplings would enter into a strong regime at $\Lambda_c << \Lambda$, which is again at odds with the idea of unification at Λ. The ideal solution is that all gauge interactions become strong at Λ, which requires a definite number of matter multiplets, typically very close to the value which makes the one-loop β - function to vanish. These ideas have been first applied to the standard theory in ref.(38), where N=8 families was found to be required, a most likely excluded possibility. The introduction of supersymmetry improves considerably the situation, and leads to predict N=5 families[(39)]. In the most recent analysis[(40)], the supersymmetry breaking scale, $m_{3/2}$, was also left as free parameter. A good fit to the low-energy gauge couplings is obtained, with:

$$\begin{aligned} &N=5 \;\; \text{generations} \\ &m_{3/2} < 2 \div 3 \text{ TeV} \end{aligned} \tag{7.4}$$

and with the upper bounds to the heaviest lepton and quark mass:

$$\begin{aligned} &m_L < 170 \text{ GeV} \\ &m_Q < 200 \text{ GeV} \end{aligned} \tag{7.5}$$

It is quite satisfactory that the bound (7.4) agrees so well with the "naturalness" value, eq.(7.3). What is intriguing is that if we combine the result (7.4) with the neutrino number estimated from $\Gamma(Z) / \Gamma(W)$, see (7.2) and with the lower bound to m_Z from B-$\overline{B}$ mixing, one is led to the striking result:

$$m_t \approx 50 \text{ GeV}$$

a prediction we should be able to test quite soon.

8. CONCLUSIONS

Flavour physics has been strange, charming and beautiful in the past. We hope it will become truthful soon. Search for new generations and sparticles, but also for the rare decays of B's may provide useful hints about its main mistery: who ordered that?

Note added

After the Workshop, the result of a new experiment has appeared, indicating a non vanishing and positive value for ϵ'/ϵ [41]. Although errors are still large, this most interesting result seems to be consistent with the Standard Theory for a rather large t-quark mass, reinforcing the conclusions drawn from B-$\bar{B}$ mixing.

REFERENCES

1] M.K.Gaillard and B.W.Lee, Phys.Rev.Lett. 33 (1974) 108; G.Altarelli and L.Maiani, Phys.Lett. 52B (1974) 351.

2] M.A.Shifman, A.I.Vainshtein and V.J.Zakharov, Nucl.Phys. B120 (1977) 316; Sov.Phys. JETP 45 (1977) 670.

3] M.B.Gavela, L.Maiani, G.Martinelli, O.Pène, S.Petrarca, Workshop "Theorie des Champs sur Reseau" Seillac, France, 1987;
C.Bernard, T.Draper, G.Hockney, A.Soni, same Proceedings.

4] B.Guberina, S.Nussinov, R.D.Peccei, R.Rückl, Phys.Letters 98B (1979) 111.

5] M.Bander, D.Silvermann, A.Soni, Phys.Rev.Letters 44 (1980) 7, 962 (E). See also L.L.Chau, Phys.Rep. 95 (1983) 1.

6] N.Cabibbo, L.Maiani, Phys.Letters 73B (1978) 418; D.Fakirov, B.Stech, Nucl.Phys. B133 (1978) 315.

7] M.Wirbel, B.Stech, M.Bauer, Z.Phys. C29 (1985) 637. B.Stech, this Workshop.

8] W.A.Bardeen, A.J.Buras, J.-M.Gérard, Phys.Letters 180B (1986) 133; Nucl.Phys. B293 (1987) 787; Phys.Letters 192B (1987) 138.

9] R.H.Schindler et al. (Mark III Collab.), Proc. of the XXIII Int. Conference on High Energy Physics, Berkeley, 1986.

10] E.V.Shuryak, Nucl.Phys. B198 (1982) 83;
V.L.Chernyak et al., Sov.J.Nucl.Phys. 38 (1983) 773;
T.M.Aliev et al., Sov.J.Nucl.Phys. 38 (1983) 936.

11] L.J.Reinders, H.Rubinstein and S.Yazaki, Physics Reports 127 (1985) 1. See also S.Narison, CERN preprint TH. 4746 (1987); C.A.Dominguez and N.Paver, DESY Report 87-060 (1987).

12] L.Maiani in Proc. of the XXI Int. Conf. on High Energy Physics, Paris, 1986.
M.Frank, P.O'Donnell, Phys.Letters 359B (1985) 174.

13] C.Albajar et al. (UA1 Collab.), Phys.Letters 186B (1987) 247.

14] H.Albrecht et al. (ARGUS Collab.), DESY-87-029 (1987).

15] J.Ellis, J.S.Hagelin, S.Rudaz, CERN-TH. 4679/87, MIU-THP-87/011, UMN-TH-602/87. In the meanwhile many other papers have appeared on this subject, see e.g. G.Altarelli in Proc. of the Int. Europhysics Conf. Uppsala, 1987 and references therein.

16] T.Inami, C.S.Lium, Progr. Theor. Phys. 65 (1981) 297; Erratum 65 (1981) 1772.

17] See e.g. K.Kleinknecht, B.Renk, Z.Phys. C34 (1987) 209.

18] G.Altarelli, P.Franzini, CERN-TH 4745/87.

19] E.Franco, M.Lusignoli, A.Pugliese, Nucl.Physics B194 (1982) 403; P.Franzini, CERN-TH 4846/87.

20] G.Altarelli, N.Cabibbo, G.Corbò, L.Maiani, G.Martinelli, Nucl. Physics B208 (1982) 365.

21] S.-H.H.Tye and G.Trahern, CLEO Collaboration, Internal Note CBX-85-45; B.Grinstein, M.Wise and N.Isgur, Phys.Rev.Lett. 56 (1986) 298; L.Angelini, L.Nitti, M.Pellicoro and G.Preparata, Phys. Letters 172 (1986) 447.
M.Gilchriese in Proceedings of the XXIII International Conference on High Energy Physics, Berkeley, USA, 1986.

22] See e.g. the analysis presented at this Workshop the Crystal-Ball Collaboration

23] See e.g. I.I.Bigi, A.I.Sanda, Nucl.Phys. B281 (1987) 41; J.F.Donoghue, B.Holstein, G.Valencia, Int. Journal of Mod. Phys. A2 (1987) 319.

24] S.Bertolini, F.Borzumati, A.Masiero, preprint CMU-HEP 86-19, NYU/TR12/86.

25] K.G.Wilson, Phys.Rev. D10 (1974) 2445 and in "New Phenomena in Subnuclear Physics" edited by A.Zichichi (Plenum, New York, 1977).

26] See e.g. P.Hasenfratz, Proc. of the XXIII Int. Conf. on High Energy Physics, Berkeley, 1986.

27] L.Maiani, G.Martinelli, Phys.Letters 178B (1986) 265.
W.Hamber, Proc. of the Irvine Conf. on Non Perturbative Methods in Field Theory, Jan. 1987.

28] M.B.Gavela et al., quoted in ref.(3) and in preparation.

29] O.Pène, Proc. of the Int. Europhysics Conf., Uppsala, 1987.

30] G.Martinelli, C.T.Sachrajda, Phys.Letters B196 (1987) 184.

31] Reviews of Particle Properties. Particle Data Group, 1987.

32] See e.g. the Proceedings of the Workshop on Physics at Future Accelerators. La Thuile (Val d'Aosta) and CERN. Jan. 1987.

33] U.Amaldi et al., Phys.Rev. D36 (1987) 1385.

34] See e.g. the talk by G.Altarelli, quoted in ref.(15), and references therein.

35] See e.g. P.Fayet, S.Ferrara, Phys.Reports 32C (1977) 249.

36] E.Cremmer, S.Ferrara, L.Girardello and A.van Proyen, Phys.Lett. 116B (1982) 231 and Nucl.Phys. B212 (1982) 413;
J.Bagger and E.Witten, Phys.Lett. 115B (1982) 202.
R.Barbieri, S.Ferrara and C.Savoy, Phys.Lett. 119B (1982) 343.
R.Arnowitt, A.Chamseddine and P.Nath, Phys.Rev.Lett. 49 (1982) 970;
L.Ibanez, Phys.Lett. 118 (1982) 73;
H.Nilles, M.Srednicki and D.Wyler, Phys.Lett. 120B (1983) 346;
L.Hall, J.Lykken and S.Weinberg, Phys.Rev. D27 (1983) 2359;
J.Ellis, J.S.Hagelin, D.Nanopoulos and K.Tamvakis, Phys.Lett. 125B (1983) 27.

37] R.Barbieri, G.F.Del Giudice, CERN-TH. 4825/87.

38] L.Maiani, G.Parisi and R.Petronzio, Nucl.Phys. B136 (1978) 115.

39] N.Cabibbo and G.R.Farrar, Phys.Lett. 110B (1982) 107.

40] L.Maiani, R.Petronzio, Phys.Lett. B176 (1986) 120. A similar analysis for N=2 supersymmetry has been done by J.P.Derendinger and M.Roncadelli (unpublished).

41] I.Mannelli, Proc. of the 1987 Int. Symposium on Lepton and Photon Interaction at High Energies. Hamburg, 1987.

Pierre Darriulat

CERN, Geneva, Switzerland

THE STANDARD ELECTROWEAK MODEL: PRESENT EXPERIMENTAL STATUS

1. FERMION MASSES AND MIXING : THE QUARK SECTOR.

At last year Berkeley Conference, Marciano [1] reviewed our knowledge of the Cabibbo-Kobayashi-Maskawa mixing matrix for three fermion families. His evaluation of the absolute values of the matrix elements is repeated below :

	d	s	b
u	0.9747 ± 0.0010	0.220 ± 0.002	< 0.009
c	0.207 ± 0.024	0.95 ± 0.14	$0.043^{+0.006}_{-0.008}$
t	< 0.14	< 0.53	< 0.999

A major contribution to the field is the definite observation by the Argus Collaboration [2] of $B_d^0\ \bar{B}_d^0$ mixing. This observation, in agreement with previous limits, implies important constraints on the mixing matrix. Its restriction to the $B_d^0\ \bar{B}_d^0$ channel (the $B_s^0\ \bar{B}_s^0$ channel is not yet open at the Doris energy of the Argus experiment) makes it particularly interesting, $B_d^0\ \bar{B}_d^0$ mixing being expected to be much smaller than $B_s^0\ \bar{B}_s^0$ mixing. As a result, the early evidence for $B^0\bar{B}^0$ mixing announced by UA1 [3] without the ability to discriminate between the two channels has become of lesser consequence. A detailed account of these results was presented by K. Schubert at the 1987 Uppsala Conference [4]. As a simple amateur, I shall therefore be satisfied with a qualitative approach and restrict my presentation to the most salient features. The Wolfenstein parametrization [5] of the mixing matrix is well suited to such an approach. The mixing matrix takes the form

$$U = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3\rho^* \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4),$$

where $\lambda \simeq \sin\theta_c \simeq 0.22$ (θ_c is the Cabibbo angle) and $A \simeq 1.0 \pm 0.2$. All CP violation is in $\mathrm{Im}(\rho)$ with this choice of phase (ρ is the only complex parameter), namely in $\mathrm{Im}(U_{bu})$ and in $\mathrm{Im}(U_{td})$, making it explicit that there would be no CP violation if there were only two fermion families. More precisely, all CP violating observables are proportional [6] to the quantity $J = A^2 \lambda^6 \mathrm{Im}(\rho)$.

The formalism used in the description of $B_0\,\bar{B}_0$ mixing largely inherits from that formerly developed for $K_0\,\bar{K}_0$ mixing, of which I consider appropriate to briefly remind the reader.

The mass matrix of the neutral kaon system takes the form

$$M = \begin{pmatrix} M_1 & im' \\ -im' & M_2 \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_1 & 0 \\ 0 & \Gamma_2 \end{pmatrix}$$

where a non-zero value of m′ is a direct revelator of CP violation. The relation $|\epsilon| = 1/\sqrt{2}\, m'/\Delta m$ relates m′ to ϵ, the complex parameter which contains the quasi-totality of our experimental knowledge of CP violation and which is obtained from the amplitude ratios

$$\eta_{+-} = K_L \rightarrow \pi^+\pi^-/K_s \rightarrow \pi^+\pi^- \simeq \epsilon + \epsilon'$$

and

$$\eta_{00} = K_L \rightarrow \pi^0\pi^0/K_s \rightarrow \pi^0\pi^0 \simeq \epsilon - 2\epsilon'.$$

The parameter ϵ is accurately measured

$$|\epsilon| = (2.27 \pm 0.02)\ 10^{-3}$$
$$\mathrm{Arg}\,(\epsilon) = (44.6 \pm 1.2)^0$$

and, in particular, the agreement between the latter and the quantity $\tan^{-1}(2\,\Delta m/\Gamma s)$ provides a very powerful test of CPT invariance :

$$|m(K_0) - m(\bar{K}_0)| < 10^{-18}\, m(K_0).$$

The ϵ' parameter is a revelator of CP violation in the decay amplitudes. Its absolute value is measured much smaller than that of ϵ. The most accurate measurement is from the NA31 Collaboration [7], $|\epsilon'/\epsilon| = (3.5 \pm 0.7 \pm 0.4 \pm 1.2)\ 10^{-3}$.

Calculations involving K_0-$\bar{K}_0$ transitions are based on diagrams of the "box" type, Figures 1a,b, and of the "penguin" type, Figure 1c. In addition to these so-called "short-range" contributions there exist also "long-range" contributions with intermediate states containing light mesons, Figures 1d,e. In general, such calculations suffer significant uncertainties, in particular in the long-range case. A quantity such as Δm (characteristic of $K_0\,\bar{K}_0$ mixing) takes the form (box contribution)

$$\propto G_F{}^2\, m_k\, f_k{}^2\, B(K)\, \Sigma\, |U_{si}\, U^*_{di}||U_{sj}\, U^*_{dj}|\, \eta_{ij}\, f(m_i, m_j).$$

Here G_F is the Fermi constant, m_k is the kaon mass and f_K the decay constant. The so-called "box parameter" B(K) accounts for higher order corrections, usual estimates are between 0.3 and 1.0. The sum extends over the 3 × 3 possible pairs of mediating quarks, each being weighted by a QCD correction factor η (usually close to unity) and a mass-dependent term f. The latter is approximately proportional to $m_i{}^2$ for $m_i \ll m_W$, implying dominance of massive mediating quarks. The leading terms in the λ-expansions of the matrix elements qualitatively govern the overall behaviour. For example, from

$$U_{su} U_{ud}{}^* \propto \lambda + \ldots$$
$$U_{sc}\, U_{cd}{}^* \propto \lambda + \ldots$$
$$U_{st}\, U_{td}{}^* \propto A^2 \lambda^5 (1 - \rho) + \ldots$$

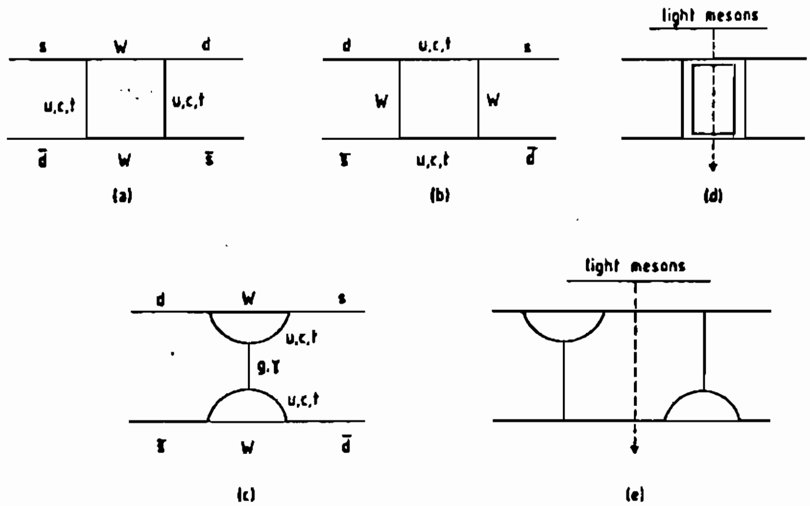


Figure 1. K_0-$\bar{K}_0$ mixing contributions.

we see that Δm is of order λ^2 and dominated by u,c mediation while m′, which must contain $U_{st}\, U_{td}^*$ in order to violate CP, is of order $A^2 \lambda^4$ Im(ρ). Consequently $|\epsilon|$ is of order λ^4, which explains its small value, and the CP violating phase, Arg(ρ), is not much constrained. The measured value of $|\epsilon|$ implies a correlation between Im(ρ) and the top quark mass, a small value of Im(ρ) requiring a large top quark mass.

The calculation of ϵ', dominated by Penguin-type contributions, gives typical values of $|\epsilon'/\epsilon|$ between 10^{-3} and 7 10^{-3}. It has become a challenge for experimentalists to evidence a non-zero value of $|\epsilon'/\epsilon|$. The motivation is to exclude models of the superweak type, for which $\epsilon' = 0$. It must however be recognized that such models have become of lesser interest. Our present understanding of the Standard Model favours $\epsilon' \neq 0$ but $|\epsilon'/\epsilon|$ is not a very sensitive revelator of deviations expected from fashionable extensions beyond the Standard Model.

The above formalism, developed for the $K_0\bar{K}_0$ case, applies as well to the $D_0\bar{D}_0$ and $B_0\ \bar{B}_0$ cases. The leading terms in the λ expansion of the relevant matrix elements are listed below :

B_d^0	$U_{bc}U_{cd}^* \propto A\lambda^3$	$U_{bu}U_{ud}^* \propto A\lambda^3\rho$	$U_{bt}\, U_{td}^* \propto A\lambda^3(1-\rho)$
B_s^0	$U_{bc}U_{cs}^* \propto A\lambda^2$	$U_{bu}U_{us}^* \propto A\lambda^4\rho$	$U_{bt}\, U_{ts}^* \propto A\lambda^2$
D^0	$U_{cd}U_{du}^* \propto \lambda$	$U_{cs}U_{su}^* \propto \lambda$	$U_{cb}\, U_{bu}^* \propto A^2\lambda^5\rho$

from which we infer the qualitative behaviour of Δm, m′ and ϵ, and the dominant pairs of mediating quarks, in each of the three cases :

	Δm	m′	ϵ
B_d^0	λ^6(tt)	λ^6(tt)	1
B_s^0	λ^4(tt)	λ^6(tu)	λ^2
D^0	λ^2(ss)	λ^6(bs)	λ^4

In the D^0 case the most massive mediating quark contributing to mixing is the strange quark, and dispersive (long range) contributions dominate. The expected Δm value is very small.

In the B^0 case we note that $\Delta m(B_s^0)/\Delta m(B_d^0) \propto \lambda^{-2}$ is large, illustrating the earlier statement that more mixing is expected for $B_s^0\ \bar{B}_s^0$ than for $B_d^0\ \bar{B}_d^0$. However, the reverse is true for CP violation with $\epsilon(B_s^0)/\epsilon(B_d^0) \propto \lambda^2$: more CP violation is expected for $B_d^0\ \bar{B}_d^0$ than for $B_s^0\ \bar{B}_s^0$.

At variance with the K^0 $\bar{K}_0$ system, the neutral B and D mesons have many possible decay modes, resulting in $\Gamma_s \simeq \Gamma_L$. The calculation of the box parameters is believed to be more reliable for heavier quarks and we expect $B(B_s) \simeq B(B_d) \simeq 1$. In fact a lattice calculation of box parameters was presented recently with the result [8]

$$B(K) = 0.50 \qquad B(D) = 1.0$$

The Argus result is on the charge asymmetry of $B_d{}^0$ semileptonic decays [2]

$$r_D \equiv \frac{\Gamma(B_D \to \ell^+ x)}{\Gamma(B_D \to \ell^- x)} = \frac{(\Delta m)^2}{2\Gamma^2 + (\Delta m)^2} = 0.21 \pm 0.08,$$

implying $\Delta m/\Gamma = 0.73 \pm 0.18$.
From the relation [9]

$$\frac{\Delta m}{\Gamma} \approx 0.15 \left(\frac{\tau_B \; |U_{td}|^2}{3.3 \; 10^{-16}\,s} \right) \left(\frac{B(B) \; f_B{}^2}{140 \text{ MeV}} \right) \left(\frac{m_t}{40 \text{ GeV}} \right)^2$$

we see that the measured excess (0.73 ± 0.18 compared to 0.15) requires that at least one of the brackets in the r.h.s. exceed unity. The constraints on the mixing matrix are conveniently summarised in Figure 2 where the approximate relation

$$U_{td} + U_{bu}{}^* = \lambda \, U_{bc}$$

has been used. A natural way to reconcile all measurements is to accept a top quark mass in excess of 40 GeV, resulting in large expected values for $\Delta m/\Gamma$ ($B_d{}^0$) and $|\varepsilon|$ (K^0). Numerous quantitative analyses [9] are available in the literature, all concluding that a top mass in excess of 50 GeV is favoured. They mostly differ from the confidence placed in the uncertain ingredients entering the calculation and from possible prejudices against a large top quark mass. With these qualifications in mind we may retain that the Argus result is perfectly consistent with the Standard Model with three fermion families as long as the top quark has a mass of the order of 100 GeV, a top quark mass lower than 50 GeV being most likely excluded.

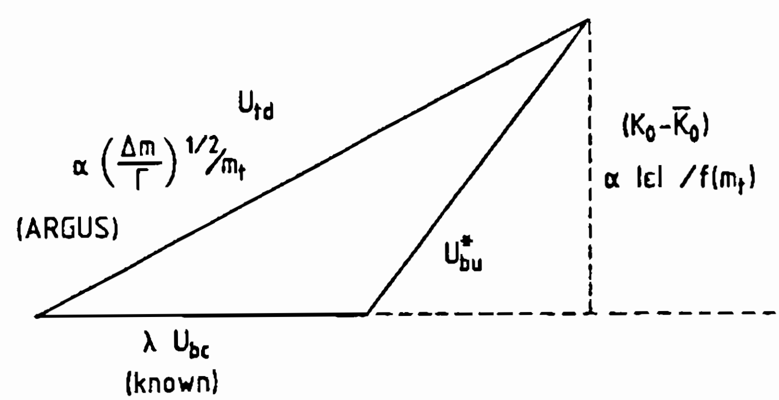


Figure 2. Constraints on m_t from the mixing matrix.

From the Argus measurement of r_d we expect $r_s \geq 0.8$, nearly maximal mixing in the $B_s^0\ \bar{B}_s^0$ channel, in agreement with UA1 data [3].

The remarkable progress in our knowledge of the mixing matrix in the quark sector enables us to name a number of interesting measurements to farther challenge the validity of the Standard Model : a direct measurement of U_{ub} from the observation of charmless decays of B mesons [10], a search for the $\pi^{\pm}\ \nu\bar{\nu}$ decay mode of $K^{\pm}$ which is now expected to occur at the level of (1 to 8) 10^{-10} [11] and, most important, the quest for evidences of CP violation effects in systems other than $K_0\ \bar{K}_0$, a topic likely to require the construction of new dedicated facilities providing adequate rates of $B_0\ \bar{B}_0$ pairs (the $\Lambda\bar{\Lambda}$ system is another possible candidate).

2. FERMION MASSES AND MIXING : THE LEPTON SECTOR.

Contrasting with the quark sector, the lepton sector is characterized by two distinct features : vanishing neutrino masses and lepton flavour conservation. The topic was recently reviewed by H.J. Gerber [12] : I shall once more be satisfied with a very brief review of the most salient features.

The most stringent limits on lepton flavour conservation are from three ingenious high statistics muon experiments : the Crystal Box [13] at Los Alamos, with $B(\mu \rightarrow e\gamma) < 4.9\ 10^{-11}$ and $B(\mu \rightarrow e\gamma\gamma) < 7.2\ 10^{-11}$, SINDRUM [14] at SIN, with $B(\mu \rightarrow 3e) < 1.1\ 10^{-12}$, and the TRIUMF TPC [15], with $\Gamma(\mu\ \mathrm{Ti} \rightarrow e\mathrm{Ti})/\Gamma(\mu\ \mathrm{Ti} \rightarrow \nu...) < 2\ 10^{-11}$. Improvements of the order of two orders of magnitude on these limits are expected from the MEGA and SINDRUM II experiments in the early nineties. A new limit obtained by the ARGUS Collaboration [16] complements these measurements in the τ sector. They find $B(\tau \rightarrow 3$ charged leptons$) < 3.8\ 10^{-5}$, a result used by Harari and Nir [17] to argue, assuming the validity of the see-saw mechanism, that the mass of possible unstable neutrinos should not exceed 65 eV (cosmological bounds exclusively apply to stable neutrinos). In general, the Argus result, though less spectacular than the limits obtained for muon decays, may be more powerful at constraining possible lepton-flavour violating interactions (an effect of the larger masses involved in the decay).

Several direct measurements of neutrino masses were reported recently, always in the form of upper limits. Tritium β decay [18] has been the subject of thorough investigations following the claim of the Moscow group for a non-zero $\bar{\nu}_e$ mass : $17 < m(\bar{\nu}_e) < 40$ eV. This result, obtained using tritized valine molecules, is not confirmed by any of the three high accuracy experiments who have reported new limits : the Zürich group using tritium absorbed in thin carbon layers reports $m(\bar{\nu}_e) < 18$ eV, the INS Tokyo group using arachidic acid reports $m(\bar{\nu}_e) < 32$ eV and the Los Alamos group, using molecular tritium reports $m(\bar{\nu}_e) < 27$ eV. An unexpected and highly welcome limit, $m(\bar{\nu}_e) < 20$ eV, is obtained using the time of flight of the few neutrinos detected from the implosion of the SN 1987 A Supernova [19]. More stringent but less reliable limits may be obtained by making additional hypotheses on the Supernova model.

While the best limit on $m(\nu_\mu)$ remains that obtained from $\pi \rightarrow \mu\nu$ decays [20], $m(\nu_\mu) < 250$ keV, a new limit on $m(\nu_\tau)$ was reported by the Argus Collaboration [21] from a study of $\tau \rightarrow 5\pi^{\pm}(\pi^0)\nu$ decays. They find $m(\nu_\tau) < 50$ MeV, thereby improving on former limits by the HRS and CLEO Collaborations (76 and 85 MeV respectively).

Concerning searches for neutrino oscillations the situation is essentially unchanged with respect to last year [22]. The only reactor experiment to have claimed a signal [23] is presently being significantly upgraded in order to obtain better control over systematic effects. Last year highlight was the suggestion that the defect of solar neutrinos reported by the Homestake Mine experiment [24] could result from the Mikheyer - Smirnov - Wolfenstein mechanism [25] according to which the absence of free muons in solar matter (and the resulting difference between ν_e and ν_μ interactions inside the sun) provides a regeneration mechanism in resonance with normal ν_μ-ν_e oscillations in the region $m^2(\nu_\mu) - m^2(\nu_e) \sim 10^{-4}(\mathrm{eV})^2$. This conjecture gave much incentive to the new low threshold solar neutrino experiments presently under construction [26]. Under this heading I also mention an interesting comment [27] that regeneration in the earth may be expected to cause differences between day and night (and therefore Summer and Winter) detection rates.

I close the present section with a few comments concerning double beta decay. On the front of neutrinoless double beta decay the situation is essentially the same as last year [28], the best limit from Germanium experiments being that of the Oroville Dam detector, $T_{1/2} > 8\ 10^{23}$ years. From this result an upper limit $m(\nu_e) < 19$ eV can be inferred for the (Majorana) electron neutrino (better limits can be obtained under more restrictive assumptions). It is on the front of double beta decay with Majoron emission [29] that new events have occured : in January 1987 the Homestake experiment (Pacific Northwest Laboratory and University of South Carolina) announced its observation at the level of $T_{1/2} = 6\ 10^{20}$ years. This result has since been contradicted [30] by the St Gothard (Caltech, SIN, Neuchâtel) and Oroville (Santa Barbara, LBL) experiments as well as by the Selenium TPC experiment (Irvine), however with some model dependence. We shall await results from the large TPC xenon experiments (Caltech, Milan) presently in preparation to consider the issue to be resolved but, meanwhile, it would be premature to consider the Standard Model as endangered on this front.

3. THE CHARGED CURRENT (V-A AND UNIVERSALITY).

Most of the new experimental results on charged weak currents concern τ decays. New measurements of the τ lifetime are now available [31]. The 1987 average, 0.307 ± 0.009 ps is slightly lower than before. Data are from ARGUS (0.309 ± 0.012 ± 0.012 ps), CLEO (0.325 ± 0.014 ± 0.018 ps), MAC (0.309 ± 0.019 ps) and HRS (0.302 ± 0.015 ± 0.008 ps). The Standard Model predicts the $\tau \to e\nu\nu$ partial width to be $(1.595\ \text{ps})^{-1}$. Using the new lifetime measurement we infer for the $\tau \to e\nu\nu$ branching fraction the value (19.2 ± 0.6)% while the measured value is only (17.9 ± 0.4)%, nearly two standard deviations lower. A new measurement of the Michel parameter [32] was presented by the MAC Collaboration, resulting in a world average value (including former DELCO and CLEO measurements) $\rho = 0.73 \pm 0.07$, still allowing for 40% V + A admixture at 95% confidence level.

The technique of using tagged τ-pairs has been extensively used to better understand the various decay modes [33,34] and measure their branching fractions with increased reliability. However some deficit [12] is still present, at the ≃ 6% level, for one prong final states. The first observation of $\tau \to \pi\nu\pi^0\pi^0$ decays was reported by the Crystal Ball Collaboration with a branching fraction of (6.6 ± 0.7 ± 1.7)%, consistent with the $\pi^+\pi^-\pi^\pm\nu$ decay channel. Measurements of the branching fractions in the $\pi\nu$ and $K\nu$ channels, by the HRS Collaboration, can be compared to predictions obtained from the $\pi \to \mu\nu$ and $K \to \mu\nu$ partial widths with the results :

$BR(\tau \to \pi\nu) = (10.9 \pm 0.6)\%$ measured, $(11.7 \pm 0.4)\%$ predicted,
$BR(\tau \to K\nu) = (0.67 \pm 0.17)\%$ measured, $(0.76 \pm 0.02)\%$ predicted.

Finally, the apparent evidence for second class currents reported last year by the HRS Collaboration who measured $BR(\tau \to \nu\pi\eta) = 5 \pm 1\%$ is now superseded by new more reliable measurements in which the η signal is searched for in both the 3π and $\gamma\gamma$ decay modes. The absence of signal is clearly demonstrated by several experiments, the best limits being obtained by the ARGUS Collaboration, $BR(\tau \to \nu\pi\eta) < 1.3\%$, and by the Crystal Ball Collaboration (who, however, had indications for a signal a year ago).

The main contributions outside the τ sector are a comprehensive analysis of muon decays using the accurate experimental results obtained in the recent years [12] and an update of W decay measurements by the UA1 and UA2 Collaborations. The latter reports the observation of $W \to q\bar{q}$ decays [35], the former provides improved evidence for the universality of W decays into each of the three leptonic modes by measuring [36] $\Gamma(W \to \mu\nu)/\Gamma(W \to e\nu) = 1.00 \pm 0.15 \pm 0.08$ and $\Gamma(W \to \tau\nu)/\Gamma(W \to e\nu) = 0.99 \pm 0.20 \pm 0.10$. Both experiments are presently upgrading their detectors in preparation for the higher $Sp\bar{p}S$ luminosity which should be available by the end of the present year.

Finally, F. Sciulli [37] reported that an anomalous excess of same sign dimuons previously observed in neutrino-nucleus interactions has disappeared : the measured rates (CCFR) are now smaller than in earlier reports and the theoretical prediction (from charmed sources) has significantly increased.

4. THE ELECTROWEAK NEUTRAL CURRENT.

In the neutral current sector there are essentially two standard model parameters : the weak angle describing the mixing between the neutral partner of $W^{\pm}$ and the SU(1) boson (to obtain the Z^0 and photon) and the ρ parameter relating neutral and charged current couplings. In practice several definitions are possible depending upon the separation between tree level and higher order (radiative) corrections. Thorough discussions of this subject are available in the literature, including detailed studies of the sensitivity of radiative corrections to various processes [38]. It has now become customary to use a scheme [39] in which the weak angle is defined from the relation

$$\sin^2\theta_W = 1 - (m_W/m_Z)^2$$

in which case a same radiative correction Δr enters the expressions of the $W^{\pm}$ and Z masses :

$$m_W^2 = A^2/(1 - \Delta r)\sin^2\theta_W,$$
$$m_Z^2 = A^2/(1 - \Delta r)\sin^2\theta_W\cos^2\theta_W,$$

where $A = (\pi\alpha/\sqrt{2}\,G_F)^{1/2} = 37.2810 \pm 0.0003$ GeV. In the above formulation the ρ parameter, defined as $\rho = m_W^2/m_Z^2\cos^2\theta_W$, is taken to be unity. This minimal form of the Standard Model could become inappropriate if there existed Higgs multiplets with isospin larger than 1/2, in which case ρ would deviate from 1. Final results from UA1 and UA2 in the $W \to e\nu$ and $Z \to ee$ channels are now available, in excellent agreement with the Standard Model [40]. They are summarized below :

	UA2	UA1
m(W)	$80.2 \pm 0.6 \pm 1.4$ GeV	$82.7 \pm 1.0 \pm 2.7$ GeV
m(Z)	$91.5 \pm 1.2 \pm 1.7$ GeV	$93.1 \pm 1.0 \pm 3.1$ GeV
Γ_z (90% CL)	< 5.6 GeV	< 5.2 GeV
Δm (Z-W)	$11.3 \pm 1.3 \pm 0.9$ GeV	$10.4 \pm 1.4 \pm 0.8$ GeV
Γ_z/Γ_w	$0.82^{+0.19}_{-0.14} \pm 0.06$	$1.04^{+0.19}_{-0.14} \pm 0.06$
(90% CL)	$< 1.09 \pm 0.07$	$< 1.31 \pm 0.07$

I defer the analysis of these data in terms of Standard Model parameters to the end of the present Section. Additional results from the UA1 Collaboration concern μ-e universality in Z decays, with a measurement of $\Gamma(Z \to \mu\mu)/\Gamma(Z \to ee) = 0.91 \pm 0.29 \pm 0.06$, and a measurement of the weak angle from the shape of the $Z \to ee$ angular distribution, $\sin^2\theta_W = 0.18 \pm 0.04$.

In the above table the measurements associated with the W and Z widths, Γ_W and Γ_Z, deserve some comments. The direct measurement of Γ_Z, listed on the third line, is obtained by unfolding the experimental resolution from the observed e^+e^- mass distribution. This experimental resolution is not only as large as the width to be measured but varies from event to event in a way which is difficult to accurately monitor, thereby seriously limiting the accuracy attainable in the direct measurement of Γ_Z. The ratio Γ_Z/Γ_W listed at the bottom of the table is obtained from a completely different method. It uses the relation

$$\frac{\Gamma_Z}{\Gamma_W} \quad \frac{\sigma(p\bar{p} \rightarrow W(\rightarrow e\nu) + ...)}{\sigma(p\bar{p} \rightarrow Z(\rightarrow ee) + ...)} \quad \frac{\sigma_Z}{\sigma_W} \quad \frac{\Gamma(Z \rightarrow ee)}{\Gamma(W \rightarrow e\nu)}$$

The first term on the r.h.s. is measured with uncertainties related to differences between the $W \rightarrow e\nu$ and $Z \rightarrow ee$ values of the acceptance, efficiency and background contaminations. It is unaffected by effects contributing equally to each of the two channels, such as an uncertainty on the measurement of the integrated luminosity. The second term is calculated from perturbative QCD and takes values between 0.285 and 0.325 depending upon the exact ratio between the d and u valence distributions [41]. The third term is predicted by the Standard Model and depends on the number of lepton families and on the value of the top mass which governs the rate of $W \rightarrow t\bar{b}$ decays. The product of the second and third terms is almost independent from $\sin^2\theta_W$: within the allowed range it does not vary by more than a percent. The results [42] are summarized in Figure 3. They provide a stringent limit, $\Delta N < 2.5$ at 90% CL, on the number of additional lepton families having a charged member too massive to contribute to W decays and a neutrino light enough to contribute to Z decays. For such measurements to provide useful information on the value of the top mass, the uncertainty on Γ_Z/Γ_W would need to be much smaller than the predicted swing between extreme values of m_t, $\Delta(\Gamma_Z/\Gamma_W) \simeq 0.2$. This being unfortunately not the case, no reliable information on m_t can be deduced from these data [43].

The neutral electroweak current is also probed by several low energy experiments, the most significant contributions being from neutrino reactions and from γ-Z interference measurements. Neutrino interactions were reviewed by H. Wachsmuth [44]. The CHARM 2 experiment on neutrino-electron scattering is presently collecting data and is expected to reach an accuracy on $\sin^2\theta_W$ similar to that obtained from neutral current measurements on isoscalar targets. While the interaction rate is much lower, and background contamination consequently larger, no hadronic correction is required in the analysis. Forward-backward charge asymmetries and cross-section ratios in $ee \rightarrow \mu\mu$ and $ee \rightarrow \tau\tau$ annihilation processes have been measured at PEP and PETRA below the Z pole. These γ-Z interference results are summarized in Figure 4 and were reviewed by T. Greenshaw [45]. Cross-section ratios do not significantly deviate from their QED values because $\sin^2\theta_W$ is nearly 1/4, the value for which no deviation should be observed. Forward-backward asymmetries are proportional to $s/(m_Z^2 \sin^2\theta_W)$ in the $s \ll m_Z^2$ region probed by present experiments. A strong correlation results between the measured values of m_Z and $\sin^2\theta_W$. There is no more indication for the slight inconsistency between μ and τ data which was formerly reported.

A thorough analysis of all experiments contributing to the neutral current sector was recently carried out by U. Amaldi and collaborators [46]. I borrow from their work the remaining of this section. Measurements of the weak angle in the minimal model ($\rho = 1$) and with ρ free are summarized in the table below.

Reaction	$\sin^2\theta_W(\rho=1)$	$\sin^2\theta_W$	ρ
$\nu_\mu A \rightarrow \mu A$	0.233±0.003±0.005	0.232±0.014±0.008	0.999±0.013±0.008
$\nu_\mu p \rightarrow \nu_\mu p$	0.210±0.033	0.205±0.041	0.98±0.06±0.05
$\nu_\mu e \rightarrow \nu_\mu e$	0.233±0.018±0.002	0.221±0.021±0.003	0.976±0.036±0.002
W/Z	0.228±0.007±0.002	0.228±0.008±0.003	1.015±0.026±0.004
Parity violation in atoms	0.209±0.018±0.014		
Polarized e on deuterium	0.221±0.015±0.013		
μC D.I.S.	0.25±0.08		
All	0.230±0.005	0.229±0.006	0.998±0.009

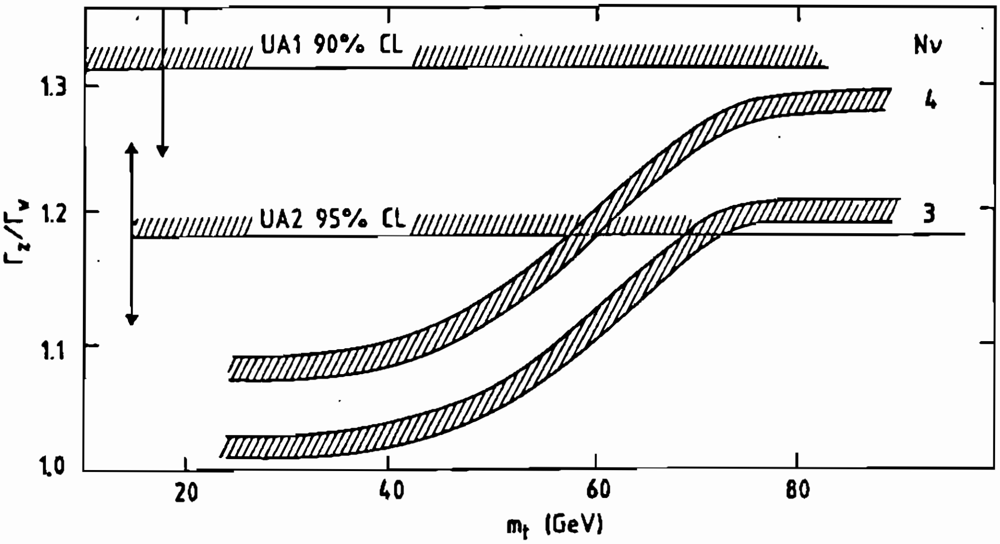


Figure 3. Limits on Γ_z/Γ_w from the UA1 and UA2 experiments and related constraints on the number of families as a function of m_t.

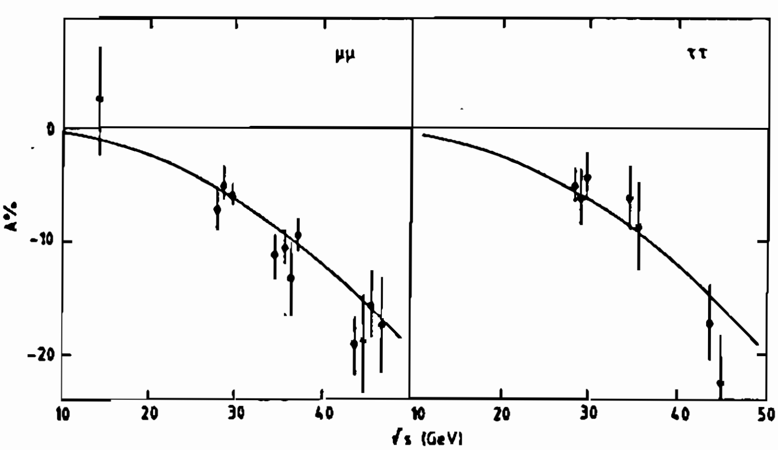


Figure 4. Asymmetries in ee → μμ and ee → ττ from PEP and PETRA data. Data points with error bars in excess of 5% are ignored.

The analysis assumes top and Higgs masses of 45 and 100 GeV respectively. The second error, when shown, corresponds to the effect of increasing m_t to 100 GeV and m_H to 1000 GeV. An overall excellent agreement with the minimal Standard Model is obtained, with the result $\sin^2\theta_W = 0.230 \pm 0.005$. Figure 5 illustrates the most salient features. The overall situation is dominated by two sets of experimental results : the measurements of m_W and m_Z by UA1 and UA2 and of the neutral to charged current ratio in neutrino interactions on isoscalar targets [44]. The radiative corrections entering these two measurements are dominated by different contributions and their difference, 0.112 ± 0.037, is measured with sufficient accuracy to place a significant limit on the top mass, $m_t < 180$ GeV at 90% CL. The sensitivity to the Higgs mass (Figure 6) is however too small to allow for any significant limit to be obtained.

5. TWO MISSING LINKS : THE TOP QUARK AND THE HIGGS BOSON.

A most important event was the recent withdrawal by UA1 of their earlier indication for a top quark with a mass between 30 and 50 GeV [47]. The data, based on a total integrated luminosity of $110\ nb^{-1}$, were from a search for $W \to t\bar{b}$ decays in $\bar{p}p$ collisions, the top quark subsequently decaying into $be\nu$. The background and the claimed signal were unfortunately similar in shape (Figure 7a) and it is now proven that the background was simply underestimated. The new UA1 data are for an integrated luminosity of $700\ nb^{-1}$ and include events having a muon in the final state as well as events with an electron. Both the $W \to t\bar{b}$ and the QCD $t\bar{t}$ productions are taken into account. The data are accounted for by various backgrounds (mostly $b\bar{b}g$ and $c\bar{c}g$) and are used by UA1 to place a limit on the top production cross-section. Two essential ingredients of their analysis are the availability of a reliable calculation of the top production cross-section for a given value of m_t and a good understanding of the detection efficiency of low transverse momentum leptons. The former (Figure 7b) is addressed by UA1 with much care and, under rather pessimistic hypotheses, they infer an upper limit $m_t \geq 44$ GeV to 95% CL. New experiments using ACOL and TEV1 will provide firmer ground to the UA1 conclusion and hopefully find evidence for a top signal (which is expected to be within ACOL reach if $m_t \leq m_{W,Z}$ and within TEV1 reach if $m_t \leq 120$ GeV, with $t \to Wb$ giving a beautiful signature). The UA1 limit supersedes not only the PETRA limit (which is, however, more foolproof) but also limits expected from e^+e^- machines in the near future (TRISTAN, SLC, LEP1). Within the framework of the Standard Model with three families we mentioned earlier a $\simeq 50$ GeV lower limit from the quark mixing matrix and a $\simeq 180$ GeV upper limit from electroweak radiative corrections. Even if a fourth family is not excluded neither by the UA measurement of Γ_Z/Γ_W nor by the Petra search for $ee \to \gamma\nu\bar{\nu}$ events ($N_\nu < 4.9$ to 90% CL), there are now strong indications that the top mass is large, typically between 50 and 200 GeV. We should stop using the traditional default value $m_t \simeq 40$ GeV in our calculations and rather assume $m_t \simeq 100$ GeV. In this context one may note that if the scaling law [48] $m_t/m_c + m_b/m_s + m_\tau/m_\mu$ implies $m_t \simeq 30$ GeV another scaling law, $m_t/m_c + m_c/m_u$ and $m_b/m_s + m_s/m_d$ would imply $m_t > 150$ GeV.

There are unfortunately much less handles to grab information on the Higgs mass than there are for the top mass. The subject was discussed by Maiani at the Bari Conference two years ago [49] and our understanding has not made spectacular progress since then. There had been some hope to place a significant limit on m_H from the measurement by the CUSB-II Collaboration of the ratio $\Gamma(\Upsilon \to \gamma H)/\Gamma(\Upsilon \to \mu\mu)$. However, once QCD corrections are correctly taken into account, this turns out to have insufficient sensitivity. A new lower limit was presented by the CLEO Collaboration [50] in a search for $B^0 \to H^0 K + ...$ decays from which they infer $m_H > 3.6$ GeV if m_t exceeds 43 GeV, by now a reasonable assumption. The argument is similar to that previously used in $K^+ \to \pi^+ + H$ decays to place a 325 MeV lower limit on m_H [49]. It implies however good confidence on the calculation of the ratio $\Gamma(B \to HK + ...)/\Gamma(B \to H + ...)$ which is presently lacking. A mean to check on this point would be to measure ratios such as $\Gamma(B \to \psi K)/\Gamma(B \to \psi x)$ or $\Gamma(B \to DK)/\Gamma(B \to Dx)$ which should provide reliable tests of the validity of the model [51].

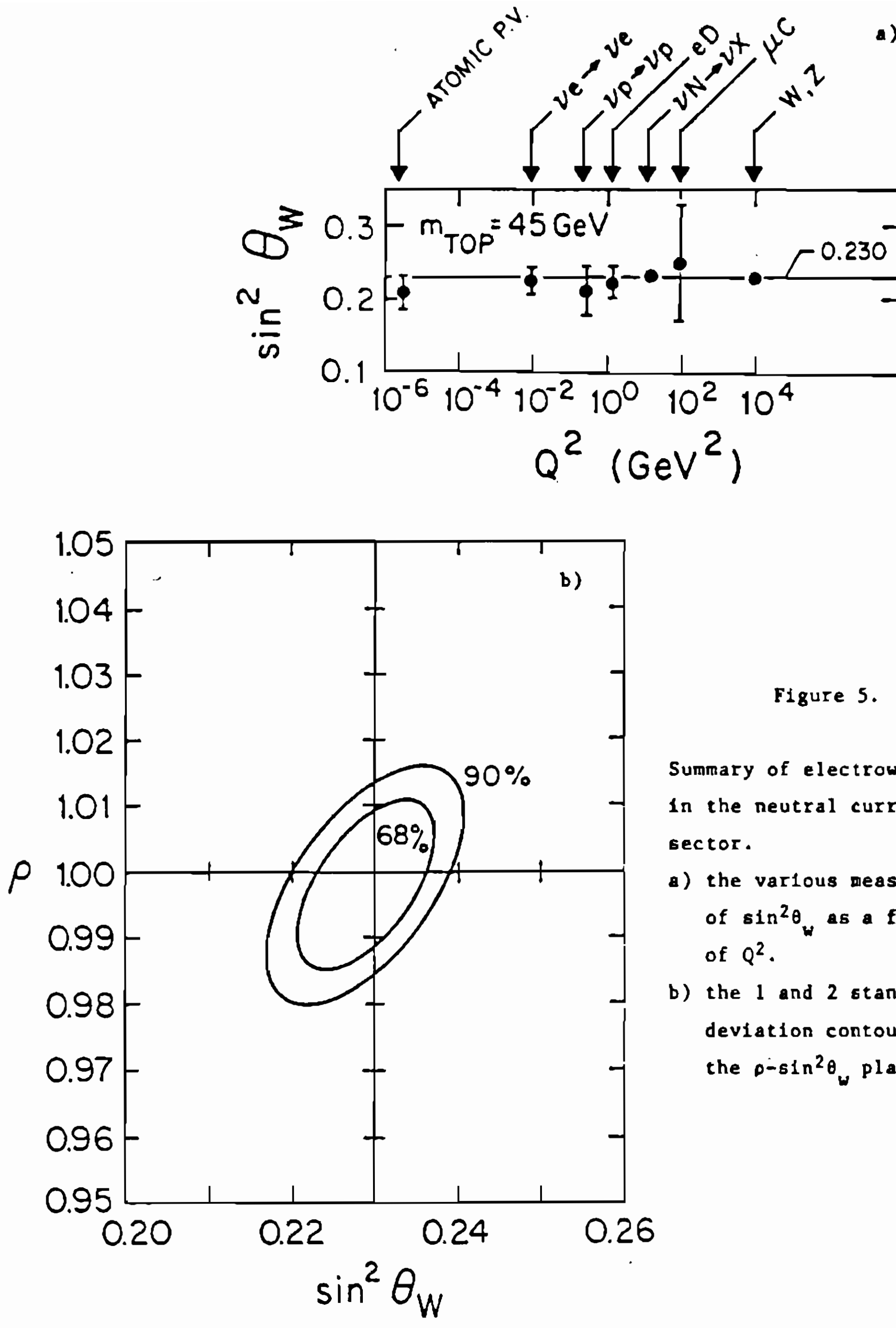


Figure 5.

Summary of electroweak data in the neutral current sector.

a) the various measurements of $\sin^2\theta_w$ as a funtion of Q^2.

b) the 1 and 2 standard deviation contours in the ρ-$\sin^2\theta_w$ plane.

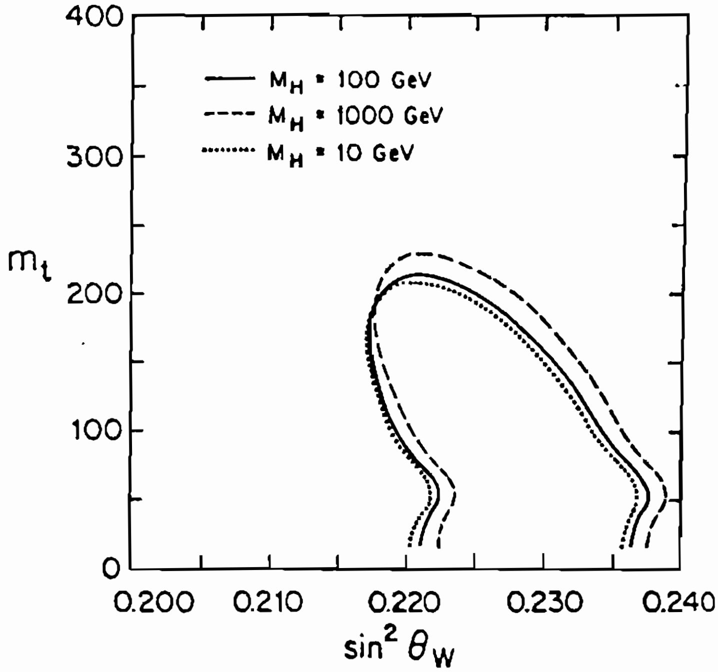
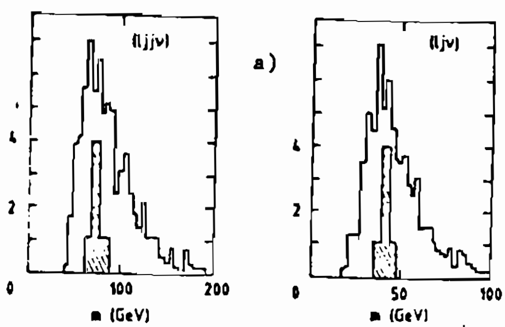


Figure 6.

Constraints on m_t from electroweak radiative corrections in the neutral current sector for various values of the Higgs mass.



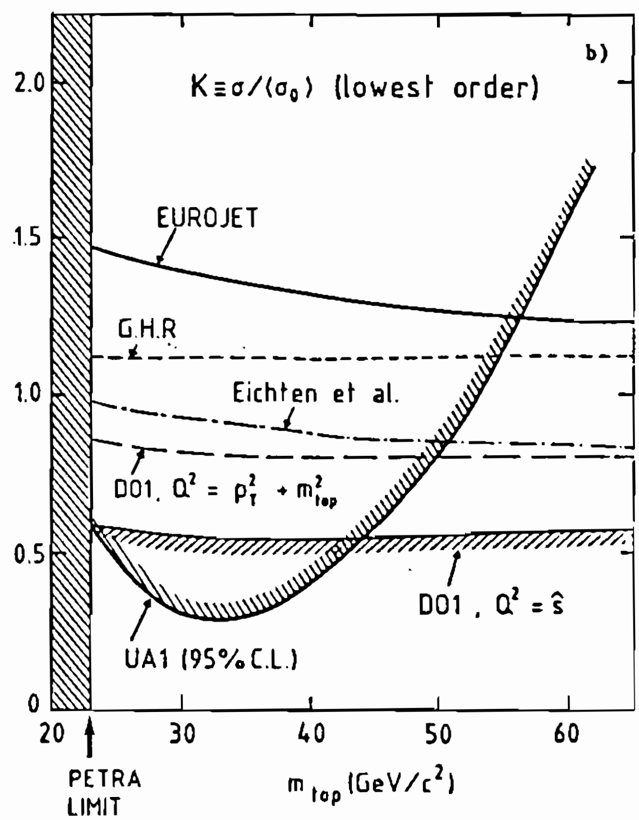


Figure 7.

UA1 data on m_t

a) Old data on the ($t \to b e\nu$) $\bar{b}$ mass and on the $be\nu$ mass (cross-hatched) with the corresponding backgrounds.

b) New data on the measured ratio to the tree level calculation of $W \to t\bar{b}$ and $\bar{p}p \to t\bar{t}$.

6. CONCLUSIONS

The Standard Model is healthier than it ever was, we were unable to name a single observation which could seriously endanger its validity. Our knowledge of its parameters has significantly progressed, in particular in the sectors of quark mixing and electroweak neutral currents.

We haven't yet seen any sign of the top quark and there are by now serious indications that its mass is likely to be significantly larger than formerly anticipated, somewhere between 50 and 200 GeV. Collider experiments at CERN and Fermilab have good chances to find it in the coming two years.

New tools are becoming available which will enable us to continue testing the Standard Model more thoroughly than in the past. Tristan and TEVI have already started operation, SLC is being commissioned, they will soon be followed by LEP and HERA : we shall be well equipped in the years to come for new unexpected discoveries or at least for higher precision measurements which could reveal deviations from the Standard Model predictions and thereby provide clues towards a better understanding of the many questions which the Standard Model leaves unanswered. In particular the Higgs territory remains virgin and it may well be that its exploration will require the availability of still higher energy accelerators, such as LHC and SSC, to the construction of which we must devote our efforts.

REFERENCES

1. W.J. Marciano, Proceedings of the 1986 Berkeley Conference, p.815.

2. H. Schröder, contribution to the 1987 Uppsala Conference;
   See also A. Seiden, contribution to the 1987 Uppsala Conference.

3. C. Albajar et al., UA1 Collaboration, CERN-EP/86-208 and 209.

4. K. Schubert, contribution to the 1987 Uppsala Conference;
   See also contributions by R. Ammar and T. Bowcock to the Uppsala Conference.

5. L. Wolfenstein, Ann. Rev. Nucl. Part. Sci 36 (1986) 137 and references therein.

6. C. Jarlskog, Phys. Rev. Lett. 55 (1985) 1039;
   O.W. Greenberg, Phys. Rev. D32 (1985) 1841 ;
   D.D. Wu, Phys. Rev. D33 (1986) 860.

7. P. Debu, contribution to the 1987 Uppsala Conference;
   R. Bernstein et al., Phys. Rev. Lett. 54 (1985) 163 ;
   J.K. Black et al., Phys. Rev. Lett. 54 (1985) 1628.

8. O. Pene et al., contribution to the 1987 Uppsala Conference.

9. G. Altarelli and P.J. Franzini, CERN-TH 4745/87;
   See also J. Ellis et al., CERN-TH 4679/87, V. Barger et al., MAD/PH/341, A. Datta et al., D0-TH 87/9, E.A. Paschos, D0-TH 87/8, J. Maalampi and M. Roos, HU-TFT-87/12, Xias Gang He and S. Pakvasa, UH-619-87, J.R. Cudell et al., MAD/PH/353, L.L. Chau and W.Y. Keung, UCD 87-02.

10. The observation of charmless B decays was reported by the Argus Collaboration at the 1987 Hamburg Conference.
    See also L.L. Chau and H.Y. Cheng, UCD-86-34 and 35.

11. J. Ellis et al., CERN-TH 4679/87;
    T. Inami and C.S. Lim, Prog. Theo. Phys. 65 (1981) 297.

12. H.J. Gerber, lepton properties, contribution to the 1987 Uppsala Conference;
    See also contributions by R. von Dincklage, W. Bertl, contribution to the 1987 Uppsala Conference. A review on muon decay is to be found in W. Fetscher et al., Phys. Lett. B173 (1986) 102.

13. R.D. Bolton et al., Phys. Rev. Lett. 56 (1986) 2461 and 57 (1986) 3241.

14. W. Bertl, contribution to the 1987 Uppsala Conference and Nucl. Phys. A434 (1985) 409.

15. S. Ahmad et al., Phys. Rev. Lett. 59 (1987) 970;
    D.A. Bryman et al., Nucl. Phys. A434 (1985) 409.

16. H. Albrecht et al., Phys. Lett. B185 (1987) 228.

17. H. Harari and Y. Nir, Phys. lett. B188 (1987) 163.

18. E. Holzschuh, contribution to the 1987 Uppsala Conference;
    M. Fritschi et al., Phys. Lett. B173 (1986) 484 ;

S. Boris et al., Phys. Rev. Lett. 58 (1987) 2019 ;
H. Kawakami et al., Phys. Lett. B187 (1987) 198 ;
J.F. Wilkerson et al., Phys. Rev. Lett. 58 (1987) 2023.

19. M. Ross, contribution to the 1987 Uppsala Conference; see also E.W. Kolb, A.J. Stebbins and M.S. Turner, FERMILAB - Pub - 87/74-A;
See also J.A. Lowan and W.W. Repko, contribution to the 1987 Ippsala Conference;
J. Ellis and K.A. Olive, CERN-TH 4701/87 and UMN-TH-605/87 ;
A. De Rujula, CERN-TH 4702/87.

20. R. Abela et al., Phys. Lett. 146B (1984) 431;
See also H.J. Gerber, Ref. 12.

21. H. Kolanoski, contribution to the 1987 Uppsala Conference;
For previous results see S. Csoma et al., Phys. Rev. D35 (1987) 2747.

22. See V. Blobel, contribution to the 1987 Uppsala Conference and H.J. Gerber, Ref. 12.

23. J.F. Cavaignac et al., Phys. Lett. 148B (1984) 387.

24. J.K. Rowley et al., Solar neutrinos and neutrino astronomy, Homestake 1984, AIP Conf. Proc. No. 126, p.1.

25. L. Wolfenstein, Phys. Rev. D17 (1978) 2369;
S.P. Mikheyer and A. Iou. Smirnov, Nuovo Cimento 9C (1986) 17 Sov. J. Nucl. Phys. 42(1985) 913;
See also J.M. Losecco et al., Phys. Lett. B188 (1987) 305.

26. See contributions by G. Giacomelli, B. Barish and O. Cremonesi to the Uppsala Conference (session P16).

27. M. Cribier et al., Phys. Lett. B188 (1987) 168.

28. See P. Fisher, contribution to the 1987 Uppsala Conference;
See also B. Kayser, Proc. 1986 Berkeley Conference, page 945 and D. Caldwell, Proc. 1986 Berkeley Conference, page 951;
W.C. Haxton and G.J. Stephenson, Prog. Part. Nuc. Phys. 12 (1984) 409;
T. Tomoda et al., Nucl. Phys. A452 (1986) 591 ;
K. Grotz and H.V. Klapdor, Phys. Lett. 157B (1985) 242.

29. R. Peccei, contribution to the 1987 Uppsala Conference.

30. P. Fisher, contribution to the 1987 Uppsala Conference, and references therein;
See also the review by B. Degrange, contribution to the 1987 Uppsala Conference.

31. See R.S. Galik, Session P09, contribution to the 1987 Uppsala conference;
and H. Kolanoski, Session P15, contribution to the 1987 Uppsala Conference.

32. K. Mursula and F. Scheck, Nucl. Phys. B253 (1985) 189.

33. T. Skwarnicki, Session P09, contribution to the 1987 Uppsala Conference.

34. A. Pich, Session P09, contribution to the 1987 Uppsala Conference.

35. R. Ansari et al., Phys. Lett. 186B (1987) 452.

36. C. Albajar et al., Phys. Lett. 185B (1987) 233.

37. F. Sciulli, contribution to the 1987 Uppsala Conference.

38. D.A. Ross and M. Veltman, Nucl. Phys. B95 (1975) 135;
Pham Quang Hung and J.J. Sakurai, Nucl. Phys. B143 (1978) 81 ;
M. Veltman, Nucl. Phys. B123 (1977) 89 ;
M. Veltman, Phys. Lett. 91B (1980) 95 ;
Z. Hioki, Nucl. Phys. B229 (1983) 284 ;
F. Antonelli et al., Phys. Lett. 91B (1980) 90.

39. W.J. Marciano, Phys. Rev. D20 (1979) 274;
A. Sirlin, Phys. Rev. D22 (1980) 971 ;
W.J. Marciano and A. Sirlin, Phys. Rev. D29 (1984) 945 ; D22 (1980) 2695.

40. R. Ansari et al., Phys. Lett. B186 (1987) 440;
E. Locci, CERN-EP/87-154, 26 August 1987.

41. F. Halzen and K. Mursula, Phys. Rev. Lett. 51 (1983) 857;
G. Altarelli et al., Nucl. Phys. B246 (1984) 12 and Z. Phys. C27 (1985) 617;
J. Kuhn et al., Nucl. Phys. B272 (1986) 560 ;
A.D. Martin, R.G. Roberts and W.J. Stirling, contribution to the 1987 Uppsala Conference.

42. R. Ansari et al., Phys. Lett. 186B (1987) 440, and 194B (1987) 158;
C. Albajar et al., CERN-EP/87-149.

43. F. Halzen et al., MAD/PH/342, May 1987.

44. H. Wachsmuth, contribution to the 1987 Uppsala Conference;
CDHS, H. Abramowicz et al., Z. Phys. C28 (1985) 51 and Phys. Rev. Lett. 57 (1986) 298;
CHARM, J.V. Allaby et al., Phys. Lett. 177B (1986) 446 ;
FMMF, D. Bogert et al., Phys. Rev. Lett. 55 (1985) 1969 ;
CCFRR, P.G. Reutens et al., Phys. Lett. 152B (1985) 404 ;
See also the contribution by V. Blobel to the Uppsala Conference.

45. T. Greenshaw, session P01, contribution to the 1987 Uppsala Conference.

46. U. Amaldi et al., A comprehensive analysis of data pertaining to the weak neutral current and the intermediate vector boson masses, UPR-0331T;
See also G. Costa et al., Neutral currents within and beyond the standard model, CERN-TH 4675/87, MAD/TH/87-07, LBL 23271.

47. G. Arnison et al., Phys. Lett. 147B (1984) 493;
The new UA1 results presented at the Uppsala Conference are from CERN-EP/87-163, 8 September 1987.

48. S. Pakvasa and H. Sugawara, Phys. Lett. 82B (1979) 105 and X-G. He and S. Pakvasa, Ref. 9, op. cit.

49. L. Maiani, Proc. 1985 Bari Conference, p.641;
R.S. Willey and H.L. Yu, Phys. Rev. D26 (1982) 3287.

50. P. Avery et al., Search for the neutral Higgs in B-meson decay, CLNS87/June 1987.

51. I am grateful to J. Ellis for having brought my attention on this point.

Table 1

Mass relations for the $J^P=1/2^+$, $3/2^+$ baryons and $J^P=0^-$, 1^- mesons in the non-relativistic quark model. Masses are given in MeV. Note the failure of the last two relations, which can be understood in terms of the U(1) anomaly and η-η' mixing.

Relations	l.h.s.	r.h.s.	Observations
$\frac{1}{4}(\Sigma+3\Lambda)=\frac{1}{2}(\Xi+P)$	1134	1126	SU(3) - relation
$Y^* - \Delta = \Xi^* - Y^*$	152	150	(Okubo-Gell Mann)
$Y^* - \Delta = \Omega - \Xi^*$	152	140	
$\Xi - \Sigma = \Xi^* - Y^*$	123	150	universality of m_s-m_u
$\Lambda - P = \frac{3}{4}(K^*-\rho)+\frac{1}{4}(K-\pi)$	178	178	
$\frac{2(\Delta-P)+3(\Lambda-\Sigma)}{2(\Delta-P)} = \frac{K^*-K}{\rho-\pi}$	0.62	0.63	hyperfine interaction $\alpha\ (m_i-m_j)^{-1}$
$\rho = \omega$	773	783	φ is pure ss state
$K^* = \frac{1}{2}(\rho+\varphi)$	892	896	
$\pi = \eta$	140	549	broken by U(1) anomaly and η-η'
$\frac{\pi+3\eta}{4} = K$	447	495	mixing

Martin M. Block

Department of Physics and Astronomy
Northwestern University
Evaston, IL, 60201

WHY BE EVEN-HANDED?

Today, November 29, 1985, is my sixtieth birthday. On this occasion, on the one hand, I feel old enough, and perhaps wise enough, to reflect on the important and revolutionary steps taken in particle physics during my scientific lifetime. On the other hand, I feel young enough to still by thrilled and excited to have been a part of this fascinating era. Perhaps in the above statement, one should read "mature" for "old" and "open minded" for "young". I will talk today on the guiding principle that the concept of symmetry has been to physics, and in particular, how we have to examine critically our hypotheses about how nature evolves.

It has long been a tenet of physics that the world is simple, and is indeed elegant in its simplicity. Classical physics was long guided by symmetry principles. In my opinion, the most beautiful exploration classically for the conservation of linear momentum in isolated systems is the invariance of the Hamiltonian under a translation of coordinates, while the conservation of angular momentum, correspondingly, is due to the invariance of the Hamiltonian to a rotation of the coordinate system in which the observer makes his measurements. That the world (nature) should be independent of the rotations and translations that we make seems almost self-evident. However, we should not forget that the experimental verification for these conservation laws was found long before we found their interpretation through spatial symmetries. In spite of the fact that they make a beautiful and self-contained picture, they <u>required</u> experimental confirmation.

When quantum mechanics was developed, the theory of unitary transformations immediately told usthat quantum-mechanical momenta and angular momenta were similarly conserved, if the quantum mechanical Hamiltonian was invariant under translations and rotations, just as in the classical case, and just as we expected from the correspondence principle. We really did no experiments to test these ideas they were taken for granted, or were regarded as self-evident (and correctly so). Pauli even invoked these idea -early on to make the then radical postulate of the existence of a neutrino (that you couldn't feel, weigh or see) to explain the missing momentum and energy in β-decay.

The one additional symmetry of space, the invariance of the Hamiltonian under <u>inversion</u> of coordinates, i.e., the invariance of the Hamiltonian under the transformation $\mathbf{r} \rightarrow -\mathbf{r}$ (where $\mathbf{r}$ is the position vector), has an important quantum-mechanical consequence, the conservation of the quantum number called parity. Another way of stating this symmetry is to say that the Hamiltonian is invariant under a reflection in a mirror. Unlike the cases of conservation of linear and angular momentum, this quantum number has <u>no</u> classical analogue, since the concept of parity includes <u>intrinsic</u> parity, the behavior of the particle's intrinsic wave function under coordinate inversion.

Thus, in 1956, when particle physicists were trying to understand the so-called τ–θ puzzle, it was clearly assumed by physicists that all interactions of elementary particles satisfied the three symmetry properties of invariance under rotations, translations, and inversions of coordinates. In simple language, space was isotropic, with no preferred points, directions or handedness. You could not distinguish one point on a straight line from another, you could not distinguish one point on a circle from another, and you could not distinguish a right-handed screw from a left-handed one.

What was there that caused us therefore to challenge the world that we had been so confortable with all of those years? After all, Maxwell's equations were patently invariant under inversions, so electromagnetism was clearly parity conserving. Perhaps by critically examining these events again, we can learn how physics advances. At the very least, we can try to recapture some of the excitement that goes with the human spirit when great discoveries and intellectual revolutions are formenting.

So I turn to the time of the Rochester meeting of the Spring of 1956, in April. Particle physics for the past few years had been excited about the concept of associated production of V-particles, which later became explained by Gell-Mann and Nishijima as the conservation of the then new quantum number, strangeness. The scheme was simple and elegant and suddenly explained a vast wealth of experimental data. In that era, it was popular to name the particles after their decay modes. In particular, the "particles"

$$\tau^+ \rightarrow \pi^+ + \pi^+ + \pi^-$$

and

$$\tau^- \rightarrow \pi^- + \pi^- + \pi^+,$$

and the "particles"

$$\theta^+ \rightarrow \pi^+ + \pi^o$$

and

$$\theta^- \rightarrow \pi^- + \pi^o,$$

as well as

$$\theta^o \rightarrow \pi^o + \pi^o \ ,$$

had been discovered and studied extensively.

The experimental situation was as follows:

1) Both the τ and the θ masses, within rather small errors, were equal.

2) At all production angles or momenta, in any production reaction, the ratio of τ to θ was the same constant value. In other words, no matter where you looked, the ratio of τ to θ was the same.

3) The lifetime of both the τ and the θ were the same, within experimental errors.

4) Conservation of angular momentum required the θ^o, since it decayed into two identical pions, to have angular momentum J=0, 2, 4 etc., since the wave function for two identical bosons must be summetric under particle exchange, and pions have spin zero.

5) Examination of the Dalitz-Fabri plot for the decay of the 3-body τ yielded a distribution compatible with phase space, indicating that the matrix element corresponded to l=0 and L=0, where l is the relative angular momentum between the like-charged pions and L is the angular momentum between the center-of-mass of this pair with the unlike-charged pion. Since pions have spin zero, this immediately tells us that the τ and the θ can have the <u>same</u> spin, J=0, since the τ spin is given by J= L+ l. Thus, the simplest possibility of nature, that they both have spin zero, is realized.

From reasons (1) to (5) above, if this were all that we knew, we would immediately conclude that the τ and the θ were one and the same particle, and that would be the end of the story. However, we have not yet discussed the <u>intrinsic</u> parity of the τ and the θ, which must also be the same if they are to be the same particle. Thus, we now examine point (6).

6) Since the θ decays into two identical pseudoscalar pions [the parity of the pion having been found by studying the absorption of slow negative pions in the reaction $\pi^- + d \rightarrow n + n$], the intrinsic parity of the q meson will be

$$P_\theta = (-1)^l \times \ [(-1) \times (-1)] = (-1)^l,$$

where l (=J) is 0,2,4, etc. Thus, the parity of the θ meson is +l, and it is compatible with the J^P (spin-parity) assignment 0^+. On the other hand, the parity of the τ, a 3-body decay, is given by

$$P_\tau = (-1)^l \times (-1)^L \times [\,(-1) \times (-1) \times (-1)\,] = -\,(-1)^{l+L}.$$

For l and L both equal to zero, we find $P_\tau = -1$, and τ has the assignment 0^-. Thus, the intrinsic parities of τ and θ are different, and they can't be the same particle, since they have different quantum numbers.

This, in brief, is the famous τ–θ puzzle. Why are there such similarities between the τ and the θ particles, such as points (1)-(5), yet nature eventually contrives (point 6) to make them different?

During 1955 and 1956, Lee and Yang, along with Gell-Mann, had tried to reconcile the above facts by the introduction of what were called "parity doublets". In essence, they suggested that the puzzle be solved by the introduction of a new strong interaction symmetry, used only for strange particles, in which each strange particle had its own doublet particle, identical in all respects except that its parity was opposite to its partner's parity, i.e., there existed Λ,Λ',Σ,Σ',K,K', etc. However, for this argument to be viable, in addition to a new strong interaction symmetry that acted only for strange particles (and there wasn't a shred of evidence for the doubling of the hyperons), a second "miracle" had to take place they had to have the same lifetimes. Other suggestions which had been made, of a less radical nature, were being ruled out by more and more accurate experimental data that were rapidly being collected from all over the world. Thus, points (1)-(6) above summarized the experimental situation as of the Spring of 1956. The τ–θ puzzle was indeed to be heartily debated and discussed at the 1956 Rochester Conference.

I now depart from the impersonal to give a very personal account of that meeting, which has indeed made a major impact on my way of looking at physics, as well as on my life in general. I was a young experimentalist, at Duke University, during this era. This was the first major international meeting that I was to attend, and I was very excited. By pure chance (and to this day I reflect how lucky I was), I was assigned to room with Richard Feynman, whom I had not personally met before. The first evening that I met him, just before we were ready to go to bed, I suggested to Feynman that the τ and the θ are really the same particle, and that parity was not conserved in the weak interactions. Feynman was ready to tell me how dumb I was and go to bed, when he thought for a moment. It turned out that we discussed the subject until the small hours of the morning, in a most exciting and stimulating way, as only Feynman can provide.

I take the liberty now of directly quoting Feynman from his recent book, *"Surely You're Joking, Mr. Feynman": I was sharing a room with a guy named Martin Block, an experimenter. And one evening he said to me, "Why are you guys so insistent on this parity rule? Maybe* *the τ and θ are the same particle. What would be the consequences if the parity rule were wrong?"*

I thought a minute and said, "It would mean that nature's laws are different for the right hand and the left hand, that there's a way to define the right hand by physical phenomena. I don't know that that's so terrible, though there must be some bad consequences of that, but I don't know. Why don't you ask the experts?"

He said, "No, they won't listen to me. You ask."

So, at the meeting, when we were discussing the τ–θ puzzle, Oppenheimer said, "We need to hear some new, wilder ideas about this problem."

So I got up and said, "I'm asking this question for Martin Block: What would be the consequences if the parity rule was wrong?"

Murray Gell-Mann often teased me about this, saying that I didn't have the nerve to ask the question for myself. But that's not the reason. I thought that it might very well be an important idea.

Lee, of Lee and Yang, answered something complicated, and, as usual I didn't understand very well. At the end of the meeting, Block asked me what he said, and I said that I didn't know, but as far as I could tell, it was still open-there was a possibility. I didn't think it was likely, but I thought it was possible.

Murray told me later, when he gave some talks in Russia, that he used the idea of parity law violation as an example of what ridiculous and crazy ideas people were considering, in order to straighten out the τ–θ puzzle.

Feynman's recollections above are only slightly flawed in that it was C.N. Yang who gave the response to my question, and not T.D. Lee. It was on Saturday morning, on the last day of the Conference, while the ideas then current (parity doublets, etc.), were being discussed when Feynman asked his question "for the experts". I now quote directly from the Proceeding of the 1956 Rochester Conference: Pursuing the open mind approach, *Feynman broght up a question of Block's: Could it be that the θ and τ are different parity states of the same particle which has no definite parity, i.e., that parity is not conserved. That is, does nature have a way of defining right of (sic) left-handedness uniquely? Yang stated that he and Lee looked into this matter without arriving at any definite conclusions.*

In reality, Yang's response was much more complicated and negative at that time. The Proceedings came out after their famous paper on parity non-conservation in the weak interactions, and had been thoroughly edited.

At the end of this Saturday morning session, which closed the meeting, I went out to the airport to take a plane for Newark, New Jersey, in order to visit my mother over the weekend, before returning to Durham, North Carolina. It was snowing heavily in Rochester, N.Y. that day-a wild spring storm. All planes were delayed for many hours. I had lunch with T.D. Lee and Sir Rudolph Peierls, who were fellow passengers headed for Newark on my flight. T.D. proceeded to tell me how silly was my idea about parity non-conservation in the weak interactions. He asserted that he and Yang had shown that parity certainly was conserved, and that I just didn't understand any quantum mechanics (the latter was unfortunately probably a correct statement). He proceeded to give me elegant lectures in quantum mechanics, as seen by Professor Lee. After many hours of waiting (and accompanying lectures), the snow was sufficently cleared from the runway for our departure. T.D. sat next to me on the airplane, continuing the discourse. The ride was really a very bumpy one, and the plane was tossing badly. While lecturing me on parity conservation, Lee, a very poor air traveler, got very ill all over my only clean shirt. It is an experience indelibly impressed upon me mind I wound up visiting my mother somewhat disheveled. Lee doesn't recall the incident and/or discussions at all.

Of course, shortly after this episode, particle physics (indeed, all physics), suffered rapid and permanent major changes. The beautiful paper of Lee and Yang on parity non-conservation came out that fall, followed shortly thereafter by the work of Madame Wu and Ambler et al. of the National Bureau of Standards, which showed conclusively, from polarized Co^{60} β-decay, that parity was not conserved in β-decay, as well as in kaon decay (the $\tau-\theta$ dichotomy). Shortly thereafter, the experiments of Lederman and Garwin, as well as that of Telegdi, illustrated that the $\pi-\mu$ system also has parity violation, and, Gell-Mann's beautiful paper on the V-A interaction and conserved vector currents. Thus, in one brief period of about 11/2 years, particle physics, in terms of weak interactions, was rewritten and understood from new perspectives in a radically different way. Indeed, the lesson of the necessity for experimental verification of symmetry principles was not lost on the community, culminating in the early 1960's in the work of Fitch and Cronin on the discovery of the violation of charge conjugation and time reversal invariance.

I return here to summarize the brilliant contribution o science made by Lee and Yang. It was been remarked by many that science is not the making of a sage observation (which may or may not be true-indeed, it is irrelevant) to explain ad hoc a phenomenon-rather, real science is the art of making predictions about as yet unobserved phenomena. My observation about the $\tau-\theta$ problem perhaps was seminal. But the suggestion of Lee and Yang to look for the experimentally observable quantity,

$$\sigma_\Lambda \cdot p_\pi \times p_\Lambda,$$

for the reaction

$$\pi^- + p \rightarrow \Lambda^o + K^o,$$

is parity conserving and furnishes us with a Λ polarization axis, normal to the production plane, for subsequent analysis of the parity non-conserving term

$$\sigma_\Lambda \cdot \mathbf{p}_\pi,$$

where, in the above parity violating term, the momentum $\mathbf{p}_\pi$ is the momentum of the decay pion from $\Lambda \rightarrow \pi^- + p$. Indeed, the analysis of this experiment was carried out in Italy by Professor Steinberger, in collaboration with the University of Bologna in 1957, using a bubble chamber.

In conclusion, what we learn from my rambling tale is that you should not trust any theory or idea that hasn't been experimentally tested. You can not in physics ever use the excuse, *It's the only wheel in town,* the gamble on a crooked roulette wheel! The parity revolution of particle physics indeed marked a turning point in our intellectual approach, leaving its mark on all of physics. Physicists became more critical, and in the process, we became aware that nature is richer than our expectations.