THRESHOLDS IN PARTICLE PHYSICS

M. Veltman
Institute for Theoretical Physics
University of Utrecht
The Netherlands

Experimentally, particle physics is more or less known to about 18 GeV, the present limit on the mass of the top quark. Theoretically everything seems well described by the standard model of strong, e.m. and weak interactions [1].

However, the standard model is unlikely to be true indefinitely, as a function of energy, since it does not include the theory of gravitation. Thus there is a limit, 10^{19} GeV, where the model is incomplete. This aside from the fact that there are other unsatisfactory features such as the large number of free parameters; also we really do not understand the remarkable family structure, nor do we know why nature has chosen the groups SU_3, SU_2 and U_1. We may put things as follows. There is a cut-off Λ above which the present structure either disappears or is amended, and we would like to explore the various possibilities concerning the magnitude of Λ.

To be strict, the present experimental situation is in fact well described by the four-fermion theory plus electromagnetism. No one has as yet found any evidence for vector bosons. The starting point of any investigation must therefore necessarily be the four-fermion theory. Several authors [2] have investigated the limit of validity of this model, and very recently Abbott and Fahri [3], and Fritzsch and Mandelbaum [4] have proposed more or less explicit models.

There are basically two ways in which the four-fermion theory may break down at higher energies. First, it may indeed be that vector bosons exist, and that indeed the standard model, or something similar, is true. The authors mentioned have derived upper bounds on the W-masses for this case. Basically there are two inputs to this problem: (i) the strength and structure of the neutral currents, and (ii) the maximally allowed magnitude of the radiative corrections. The limits for the vector boson masses come out to be of order 150 GeV and 250 GeV.

Secondly, it may turn out that the basic fermions, quarks and leptons, are composite, and that this structure shows up at about 300

GeV. Let us explore this possibility.

One of the first arguments concerning this possibility relates to the family problem. We now believe in three, possibly four, but no more families with the structure and mass pattern as the observed ones. It seems therefore that this family structure stops well before 200 GeV. It is then quite natural to believe that quarks and leptons are composites, with an "ionization" energy of the order of 300 GeV [5], which is incidentally the "Fermi length".

Toying with this idea one very soon arrives at the following basic structure. Assume the existence of one basic family, made up from a high and a low quark, and a lepton with its neutrino. Furthermore there is a scalar particle. The families are obtained by binding the basic family with one, two or three scalars.

The model of Fritzsch and Mandelbaum assumes the existence of a quark-like coloured doublet, except that the charges are ±1/2, and two scalars, behaving like a 3 and a $\bar{3}$ with respect to color and charges -1/6 and +1/2. Some new hypercolor force binds scalars and fermions to give rise to a family; other families are supposed to be excitations involving some extra bosonic object. The binding force is due to a new type of confining interactions called hypercolor. The extra bosonic object is identified with some hypercolor gluon. The usual vector bosons of weak interactions are more like resonances, comparable to the well-known ρ of strong interactions.

The model of Abbott and Fahri uses for the basic fermions precisely a family structure as indicated above. The scalar is called H and has much in common with the Higgs of the standard model. The families are bound states of the left-handed basic fermions and one H; additional families require other scalars. 't Hooft's [6] work on anomalies is quoted to explain the correct number of nearly mass zero fermions. The confining force is precisely the usual $SU(2)_L$; thus in this theory the usual vector bosons are massless. Masses arise through Yukawa couplings.

It is an advantage of these schemes that no spontaneous symmetry breakdown is needed, i.e. no vacuum expectation values and cosmological constants. As such they are very attractive. In these schemes the usual vector bosons become wide resonances supposedly located at about 100 GeV.

At this moment the lack of knowledge of physics around 100 GeV makes the models somewhat arbitrary. It is not very clear if they are in trouble with respect to the radiative corrections generated. After all, the confining interactions are strong, and in the first instance one would expect radiative corrections of order one. This could upset for instance CVC, i.e. the close experimental agreement between the vector coupling constants of μ-decay and β-decay, taking into account the radiative corrections as computed by Sirlin [7] in the standard model.

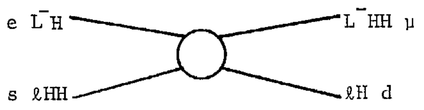
Experiment will tell us rather soon if something of this type is true. If indeed leptons and quarks are confined objects with a structure of the order of 300 GeV, and if there is a confining strong interaction, then at energies of this order of magnitude all these particles start behaving like hadrons involved in some strong interaction. Massive production of muons and electrons is then to be expected. Probably this would become visible in the $p\bar{p}$ experiments of the near future.

The main difficulty with these models is in fact the absence of neutral, strangeness changing currents, i.e. the GIM mechanism. Consider the very first model cited. In this model we would have:

electron	L^-H
muon	L^-HH
down quark	ℓH
strange quark	ℓHH

The following process would be possible:

$$e^- + s \rightarrow \mu^- + d$$



This is a simple exchange process. It would give rise to the decay K → πμe. No particular kinematics seems to inhibit this possibility. The presently known limits on this decay suggest that the structure must be smaller than 300 GeV, presumably of the order of a few TeV.

Recently the connection between infrared and ultraviolet theories has been elaborated [8]. The main conclusions are:

(i) If the distance between the infrared and ultraviolet is sufficiently large then the infra-red theory must be renormalizable.

(ii) If symmetry persists over some range then the symmetry must be valid indefinitely.

These "theorems" apply if we assume that the next threshold is higher than 300 GeV, say 1000 GeV or higher. Let us first consider the case that the next threshold is at 1000 GeV. Then we must assume that the standard model, including vector-boson masses of about 90 GeV is valid to 1000 GeV. Above this threshold the particle spectrum may or may not change, i.e. quarks and leptons may or may not be composite. If quarks and leptons are composite then the same difficulty as mentioned before (unwanted currents) applies. More modest, one may assume that only the Higgs (and the longitudinal vector bosons) are composite. Due to the insensitivity of weak interactions to the Higgs system (the screening theorem) this possibility will be very difficult to exclude for a long time to come.

The forces necessary to obtain bound states are commonly called technicolor. These theories have been discussed very extensively in recent times, and we will not consider them here [9]. There is however one aspect that needs consideration, and that is naturalness.

In the standard model there is precisely one quadratic divergence, and if the standard model is an effective theory with a cut-off then the magnitude of this divergence is of the order of the cut-off energy Λ squared. Now this divergence is part of the vector boson mass which is of the order of 100 GeV. Assuming naturalness this states that $\alpha\Lambda^2$ is of the order of $(100\ \text{GeV})^2$, which gives the usual technicolor value Λ 1000 GeV. If indeed technicolor starts at 1000 GeV then this is just fine.

However, if there is no technicolor at 1000 GeV then we have here a problem with respect to naturalness. The only solution at this time seems to be that things are arranged in such a way that the coefficient of the quadratic divergence is zero [8]. This coefficient is zero if:

$$\sum_{\text{fermions}} \frac{m_f^2}{M^2} = \frac{3}{2} + \frac{3}{4}\frac{M_o^2}{M^2} + \frac{3}{4}\frac{m_H^2}{M^2} .$$

Can this equality be true? Now, first of all, the masses appearing in this equation (the fermion masses m_f, the Higgs mass m_H and the charged and neutral vector boson masses M and M_o) are the masses in the bare Lagrangian. The observed masses differ by radiative corrections, involving $\ell n(\Lambda/M)$. They have not yet been computed.

Aside from this it seems that some heavy fermions are needed. For instance, fitting the top mass to this equation, assuming a relatively light Higgs gives $m_t \sim 69$ GeV. This may be too high. The point is that in the present model the top quark mass influences K-decay and the K_L-K_s mass difference. This constrains the mixing angles, and a limit on the top quark mass can be obtained. Recently such a reasoning and calculation has been done by A. Buras [10], and he quotes the value 26±7 GeV.

If this is true then probably a fourth generation is necessary to keep the W-mass down to 100 GeV.

A number of questions concerning the existence of further generations and Higgs masses may be resolved if both the neutral vector boson mass as well as the weak mixing angle are measured accurately. Precision of the order of 0.3% is perhaps possible with the SLAC collider and/or CERN's LEP. This precision is just enough to limit the Higgs mass to below 1000 GeV. Also, every very heavy generation contributes about 100 MeV to M_o; thus the sensitivity is to three generations. The feature that the radiative corrections to the W masses remain finite even if the fermion masses become very large is a very exciting aspect of these radiative corrections. Everything should be done to measure at least two quantities to the highest possible precision. One is for sure: M_o will be measured up to 0.1%.

In this way we may expect that within the next decade at least certain things will become clear. The $\Lambda = 300$ GeV models will be confirmed or ruled out; the naturalness of the standard model will be better understood in case of a Λ far above 300 GeV.

Let us now consider the case for which Λ is really very high, say 10^{17}GeV. If that is so then SU_5 unification will be reached before Λ is visible. How could this situation be understood?

Actually, one may make a very amusing observation. In the SU_5 theory there are two Higgs sectors, being the 100 GeV and the 10^{15} GeV systems. There are now two quadratic divergencies, namely one associated with each Higgs system. It is now conceivable that due to a vanishing coefficient for the low Higgs system there is really only one quadratic divergence, namely for the other Higgs sector. But this is fine, perhaps that is the reason that the X and Y vector boson and that Higgs system are so heavy!

In this way we arrive at the following point of view. There is a super symmetric theory valid above 10^{17} GeV. A renormalizable zero-mass subset of the SU_5 type is part of that theory. Subsequently there is some small breaking of the theory giving rise to masses of the order of

100 GeV; next quadratic divergencies lift the X, Y bosons etc. to 10^{15} GeV. It seems an entirely natural situation.

There is of course in the scheme a very big problem as to the details of the theory between 10^{15} and 10^{19} GeV, as well as the origin of the 100 GeV mass scale. No one has come up with any ideas on that so far.

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