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SYMMETRY VIOLATIONS IN WEAK INTERACTIONS AND IMPLICATIONS FOR NEW FORCES

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Abstract: Weak interactions violate symmetries which are satisfied by the other interactions: Parity, CP (Time-reversal), Flavor symmetry (conservation of particle type); other symmetries are however conserved. The broken gauge theory description explains some of these facts which could only be phenomenologically parametrized in the old four-Fermi theory; furthermore it furnishes a renormalizable theory. However, the breaking of the gauge symmetry is not understood; a phenomenological model for it implies scalars, in particular a new particle (Higgs boson) whose properties are briefly described.

Attempts to treat all interactions in a symmetric fashion, to understand the origin of flavor, to cure difficulties with the scalars lead to further interactions. These new interactions may break (or explain) symmetries of the weak interactions, much in the same way weak interactions violate symmetries of the other interactions or the GSW model explains symmetries of the four-Fermi theory. Parametrizing the new effects in an effective low energy description we show that low energy experiments impose severe restrictions on new forces and imply that the symmetries of the weak interactions are likely to be broken only by extremely weak (high energy) effects; the characteristic scale being $\sim 10^6$ GeV. This implies that the symmetries of the weak interactions are already built in into any further theory of particle interactions.

1. Introduction and the old theory

Weak interactions (β decay and similar processes involving the other elementary particles) are often associated with symmetry violations. 1956/57 parity violation was discovered[1),2)] after it was observed that the charged Kaon could decay in two ways

$$K^+ \to \pi^+ \pi^0$$
$$K^+ \to \pi^+ \pi^+ \pi^- \ . \qquad (1)$$

Since the parity of π is -1, Bose statistic and angular momentum imply that the parity of $\pi^+ \pi^0$ is positive, that of the three π's negative.

Then, CP violation was discovered (1964) by observing that the same neutral K^0 state could decay into two and three pions, whose CP properties are opposite. Whereas parity violation was large, $|\mathrm{Ampl.}_{\mathrm{Par.viol}} / \mathrm{Ampl.}_{\mathrm{Par.cons}}| \approx 1$, CP violation is small and characterized by $\sim 10^{-3}$.

Parity violation can be conveniently summarized by looking at the helicities of the particles, the projection of spin onto the momentum, $h = \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|}$. Under parity, $h \to -h$. Thus, in a parity conserving theory, both helicities interact in the same way. In the weak interactions only one helicity is active (the left); weak interactions thus violate parity maximally. CP violation could (and can) not be parametrized in this striking way.

New symmetries (or conservation laws) appeared with the discovery of new particles, since weak interactions affect all known particles, except gluons (this is why the weak interactions are strongly related to number and structure of fundamental particles). It became possible to associate with each new particle a quantum number ("charge") and test whether it is violated. At this time there are six [4)] leptons (e,μ,τ with charge $-1, \nu_e, \nu_\mu, \nu_\tau$, neutral) and six quark flavors (d,s,b with charge $-\frac{1}{3}$, u,c (t) with charge $\frac{2}{3}$). Correspondingly, there are three lepton numbers, six quark flavor charges; total lepton number (the sum of all lepton numbers) etc. Weak interactions conserve all lepton numbers (no decay $\mu \to e\gamma$ etc.) but violate the quark flavors in a certain way: $s \to u + e + \bar{\nu}_e$ is possible, $s \to d + e : \bar{e}$ is not. ("There are no flavor changing neutral currents"), but total quark (baryon) number is conserved. There also exists a symmetry between leptonic and baryonic weak processes: The coupling strengths c_k, c_n, c_μ, c_τ in the processes $K \to \pi e\nu$, $n \to pe\nu$, $\mu \to \nu e\nu$, $\tau \to \nu\mu\nu$ satisfy the relations

$$c_k^2 + c_n^2 = c_\mu^2 \qquad c_\mu^2 = c_\tau^2 \quad \text{etc.} \tag{2}$$

(Cabibbo universality)[5].

The first description of weak interactions was in form of a phenomenological four-Fermi interaction [6]. It allowed only for a phenomenological parametrization of the observed violations; on the other hand, relations such as (2) could not be explained; however a lot of theoretical work (CVC, PCAC) paved the road to a further understanding.

Finally, we mention that the four-Fermi theory is not renormalizable and violates unitarity at higher energies [7].

2. The Glashow-Salam-Weinberg model [8]

The GSW model for the weak interactions is based on a non-abelian generalization of the gauge theory of QED (a generalization of the U(1) local symmetry $\psi \to e^{i\alpha(x)}\psi$, $A_\mu \to A_\mu + i\partial_\mu\alpha(x)$ to the group SU(2) x U(1). For a successful model, one needed 4 photon-like exchange particles, one identified with the photon, the other three forming a charged pair ($W^\pm$) and a neutral one (Z). Gauge invariance is spontaneously broken and the W and Z are massive. This new picture explains many of the previously mentioned properties of the weak interactions:

(i) Maximal parity violation is a consequence of gauge invariance. In the GSW model (one pair of W) parity violation is maximal or zero. If parity was conserved one could introduce gauge invariant mass terms and there would be no symmetry (chiral symmetry) in the gauge group which prevented very heavy quarks. The point is that a gauge group fixes not just interactions, but also the chiral transformation properties of the fermions.

We mention that this parity non-invariant (chiral) structure has severe implications on attempts to understand the particles as originating from a multi (>4) dimensional space[9)], a generalization of the Kaluza-Klein idea[10)].

(ii) The observed universality (equality of quark and lepton couplings) follows from gauge invariance.

(iii) Total baryon and lepton numbers are naturally conserved.

(iv) The theory is renormalizable[11)] (there are for instance no Adler-Bell-Jackiw anomalies[12)]), leading to a unitary theory in each order of perturbation theory.

(v) There are no flavor changing neutral currents.

(vi) Flavor violations in charged current interactions are well described; for instance the neutral Kaon mass difference[13)].

(vii) The mass of neutrinos is zero (but there is no must to have this) and individual lepton charges are conserved.

Some of the questions, however, remain:

(i) CP violation must still be parametrized in a phenomenological way. Within the usual GSW model there is only one possibility, one phase in the charged currents involving the heavier quarks[14)]. Given all information at the present time, it is on the verge of inconsistency. One finds ($\eta^{ij} = \frac{A(K_L \to \pi^i \pi^j)}{A(K_S \to \pi^i \pi^j)}$)

$$\frac{\varepsilon'}{\varepsilon} \approx \frac{n^{+-} - \eta^{oo}}{2\eta^{+-} + \eta^{oo}} = \begin{cases} 0.0017 \pm 0.008 \\ -0.0046 \pm 0.008 \end{cases} \text{exp.} \qquad (3)^{15)}$$

$$\frac{\varepsilon'}{\varepsilon} \gtrsim 0.002 - 0.009 \qquad \text{theoret.} (4)^{16)}$$

The theoretical value is rather uncertain, but the next experiments might be capable to exclude it. Inconsistency of (3) and (4) may require new fields and interactions. On the other hand, the bound on the electric dipole moment, $d_n \lesssim 10^{-25}$ ecm.[17] is consistent with above model of CP-violation which yields $d_n \simeq 10^{31}$ ecm. [18] .

ii) It is not possible to have baryon/lepton number violations or small neutrino masses. Certain experiments indicated $m_\nu \neq 0$ ($m_\nu < 40$ eV)[19] and neutrino oscillations; however they are still plagued by uncertainities and disputed. On the other hand, within the framework of the big bang cosmology we must have a baryon number violating interaction, if the initial stage of the universe had net baryon number equal to zero.

iii) There is no understanding of the flavors (mass ratios of quarks and leptons, nunbers of them etc.); all such quantities are just parameters.

3. New Problems

The "breaking"[20] of the gauge symmetry SU(2) x U(1) is, so far, described phenomenologically by a Ginzburg-Landau type complex scalar field ϕ, an SU(2) doublet, with self-interaction

$$V = -\mathcal{L}_p = -m^2|\phi|^2 + \frac{\lambda}{2}|\phi|^4 \; . \tag{5}$$

In the ground state, $\langle|\phi|^2\rangle = m^2/\lambda = \frac{\sqrt{2}}{4} G_F \simeq (175 \text{ GeV})^2$. ("Gap"). The W and Z fields get massive, with

$$m_Z^2 = m_W^2/\cos^2\theta_W \qquad m_W^2 = \frac{e^2}{2\cdot\sin^2\theta_W} \langle|\phi|^2\rangle$$

where $\sin^2\theta_W$ is a measurable quantity, about 0.2. The mass is responsible for the short range of the weak force - e.g. their weakness at low energies.

There is, in addition, a physical scalar, the Higgs field ϕ_o (21). It has not been observed so far. Its mass is given by $8\lambda v^2$ and is a free parameter[22].

Theoretical arguments limit the mass: A lower bound is obtained by requiring the ground state $<|\phi^2|> \neq 0$ to be stable against one-loop radiative corrections. The result is[23]

$$m_H \gtrsim 7 \text{ GeV} . \tag{6}$$

An upper bound follows from requiring λ to be small enough to allow perturbation theory: (unitarity)[24]

$$m_H \lesssim 1500 \text{ GeV} \tag{7}$$

Experimental constraints (radiative corrections) only give[25]

$$m_H \lesssim 10 \text{ TeV} \tag{8}$$

The complete, non perturbative treatment of the ϕ^4 theory indicates deviations from the simple picture[26]. Without new interaction at larger energies, (5) probably describes a non-interacting field (there is only the $\lambda = 0$ infrared fixed point corresponding to $m_H = 0$. Couplings to the gauge fields change the fixed point structure. Following results have been obtained

$$\left.\begin{array}{l}\text{One-loop fixed points}^{27)}\\ \text{with U(1) gauge coupling}\end{array}\right\} m_H \lesssim 130 \text{ GeV } (\simeq 1.6\ M_W)$$

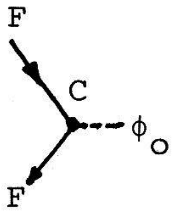
$$\left.\begin{array}{l}\text{Lattice Monte Carlo}^{28)}\\ \text{SU(2) groups}\end{array}\right\} m_H \simeq 500 \text{ GeV}$$

This subject is of great interest at the moment.

A further difficulty of scalar systems are that there seems to be no understanding why m^2 is so small compared to a typical cutoff at $10^{15} - 10^{19}$ GeV (quadratic divergences). This has led to considering supersymmetry in the context of particle physics[29].

There have been attempts to find a microscopic theory for the order parameter ϕ in terms of a composite field (BCS): Technicolor[30] or Composite Higgs[31]. However, they lead to flavor changing neutral currents. (This problem comes up because of the aforementioned chiral structure of the fermions. Because of it, a mass for them implies $SU(2) \times U(1)$ symmetry breaking and requires scalars coupled to fermions.) In any case, all these theories predict new (inclusive scalar) particles which should be observed.

The couplings of the Higgs particle ϕ_o to other particles are proportional to their mass, and thus small for the easily produced lighter species. For instance



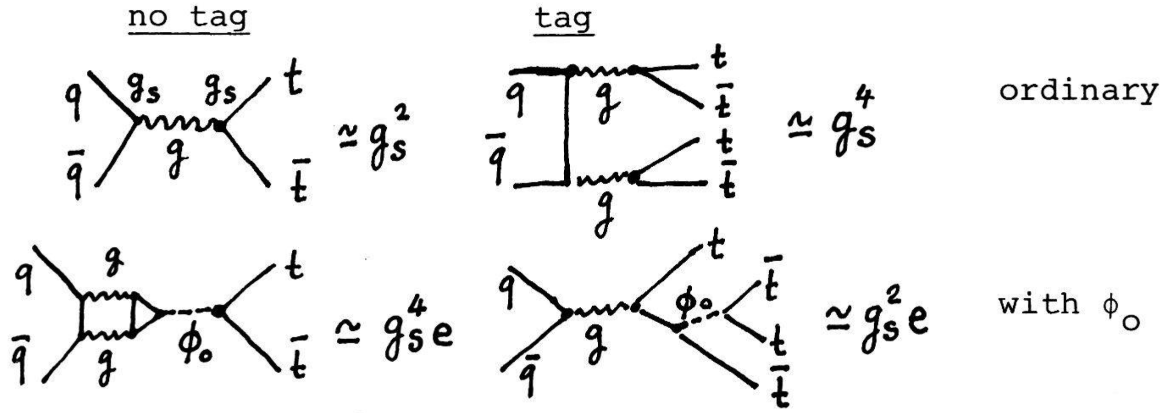
$$C \cong \sqrt{G_F}\, m_F \simeq 10^{-3} \cdot g \qquad (9)$$

(for a muon)

where g is the coupling to a W-boson. Only if a particle is heavy, mass $\gtrsim M_W$, the couplings can be compared to weak interactions. Heavy particles, if coupled to light ones can however enlarge the Higgs couplings to the lighter particles through loop (intermediate) effects[32].

ϕ_o will be hard to observe. Only if $m_H \lesssim 0.8\, m_Z$ it can be found at the next machine, LEP (assuming the top quark mass is $\lesssim m_Z/2$). Otherwise, new accelerators must search for it. Also there, discovery is difficult, because of background problems. Since a Higgs particle decays with a typical lifetime of $\simeq 10^{-20}$ sec, one must look for its decay products; but they can generally be produced by the ordinary particles. A possibility is to "tag" them, by looking for a ϕ_o produced along with a tag, like a W boson or a $t\bar{t}$ quark pair.

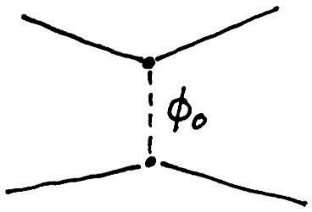
Example: Higgs decaying into $t\bar{t}$, with a tag = $t\bar{t}$ [33)]



We see that since $e^2 \simeq g_s \equiv g_{strong}$, the tagged processes are comparable, whereas the others are not.

Very heavy ϕ_o ($m \gtrsim 700$ GeV) have a width which compares to their mass; they are difficult to see as a resonance.

The ϕ_o exchange gives deviations from ordinary weak interactions. From (9) we see that these processes are suppressed by $\sim 10^{-6}$. This precision can only be reached at very low energies, for $m_{\phi_o} \lesssim 20$ MeV in muonic atoms (SIN measurement[34)]) or for $m_\phi \lesssim m_K - m_\pi \simeq 350$ MeV from K-decays since measurable rare branching ratios are $\simeq 10^{-6} - 10^{-9}$. Typical accuracies for $m_{\phi_o} \simeq m_W$ are, however, $\sim 10^{-2}$.



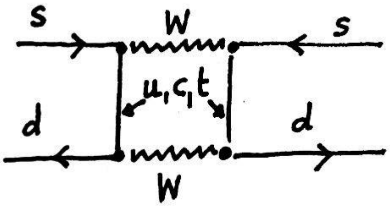
It goes without saying that identifying ϕ_o (or other particles) is of extreme importance to understand the gauge symmetry breaking; much theoretical work is needed to interpret possible experiments.

4. Tests of the theory (outside scalars)

In view of the following, I would like to briefly comment on the tests of the broken gauge theory without large accelerators.

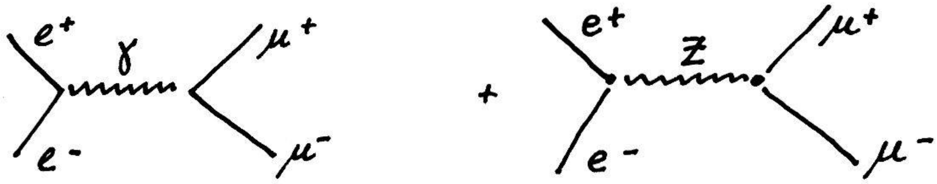
a) Low energy precision tests. Lacking a high energy accelerator to produce directly the heavy particles, their effects on intermediate on low energy observables can be calculated. The prime example is the mass difference of the two neutral Kaons

$\Delta m_K \approx$



calculated from the box diagram above [35]. The calculation fits the small number, $\Delta m_K \simeq 10^{-12}$ MeV very well. Unfortunately, the precision of the calculation is limited by strong interaction effects which are hard to evaluate.

b) "Medium" Energy. Even without the $p\bar{p}$ colliders it is possible to test the properties of intermediate W, Z. As example, take e^+e^- annihilation into $\mu^+\mu^-$; two graphs contribute:



Z has two pieces, vectorial and axial couplings. The "asymmetry" A measures the interference of the γ-coupling and the axial Z coupling. One obtains [36]

$$A \simeq \frac{\text{const} \cdot E^2 \cdot m_Z^2}{(m_Z^2 - E^2)} \tag{10}$$

at a C.O.M. energy E. With a four-Fermi interaction, A grows like E^2, otherwise differently. The results are:

	A_{exp}	A_{th}
E = 30	- 6.4	- 6.3
34	- 10.8	- 9.5
40	- 13.2	- 13.6

(11)

yielding

$$(60 < m_Z < 130) \text{ GeV !}$$

within the errors.

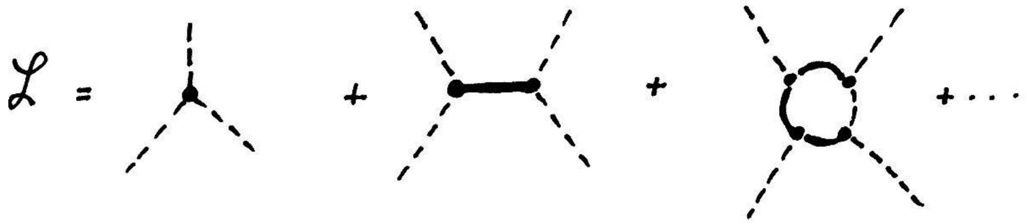
5. New interactions

The broken gauge theory answers several questions left open in the four-Fermi theory. There remain some phenomenological issues (CP-violation; theories of baryon number violation, lepton number violation (including neutrino masses)) but there are new questions which could not be asked before: More technical problems include the breaking of SU(2) x U(1), the theory of scalar particles. These are hoped to be resolved by using new symmetries and interactions (for instance supersymmetry (superstrings)$^{37)}$. But there are more visible issues which have been raised, and influence above questions:

- Symmetric treatment of strong, weak and electromagnetic interactions (Grand Unified theories)$^{38)}$
- Restoration of parity invariance at high energies (left-right symmetric theories)$^{39)}$
- Origin of the quark and lepton flavors from a composite picture$^{40)}$ of the fermions.

All these questions result in new interaction, some of which give rise to violations of the weak interaction symmetries. There are new particles associated with them, many with large masses, larger than can be reached in accelerators. We must therefore find a framework to study them in low energy experiments (see section 4).

A systematic way to classify phenomenologically new effects is in terms of a low energy effective Lagrangian$^{41)}$. If one assumes that the new particles are heavy, they cannot appear as external fields, but only as intermediate states. We have then,



(12)

where – – – – – denote light* and ———— the heavy fields. If the intermediate fields have a mass Λ (we take all masses equal for simplicity) we can write

$$\mathcal{L} = \mathcal{L}_o + \frac{1}{\Lambda}\mathcal{L}_1 : \frac{1}{\Lambda^2}\mathcal{L}_2 + \ldots \tag{13}$$

where $\mathcal{L}_o$ is the tree-level Lagrangian[42)] . Assuming the "low energy" theory of the fields to be SU(3)xSU(2)xU(1) invariant, the $\mathcal{L}_i$ can be constructed. (This is like making the four Fermi theory from an intermediate vector boson theory and requiring charge invariance, color invariance (but note that the exchanged particles can have charge). If the $\mathcal{L}_i$ give rise to new effects, which can be measured (or bound) we can estimate Λ , and thus the scale of the new physics.

This approach has been used to classify lepton/baryon number violating effects (see below)[41)]; recently an extensive construction of $\mathcal{L}_2$ and its consequences has been given[43)].

In the following I want to discuss the implications of such an analysis.

The only term in $\mathcal{L}_1$ is of the form

$$\mathcal{L}_1 = \text{leptons}^2 \cdot \phi^2 \ . \tag{14}$$

It gives rise to a Majorana-Mass for the neutrino, of order

$$m_\nu^M \simeq \frac{<|\phi^2|>}{\Lambda} \ . \tag{15}$$

Such a mass gives rise to neutrinoless double β decay, for example to $^{76}\text{Ge}\rightarrow{}^{76}\text{Se} + 2e$. The bound on m_ν calculated from the absence of this process is

$$m_\nu^M \lesssim 5\ \text{eV}\ (\sim 10^{-5}\ m_e)^{44)} \tag{16}$$

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[*] light means here all fields in the SU(3)xSU(2)xU(1) theory.

which yields

$$\Lambda > 10^{13}\ \text{GeV}\ . \tag{17}$$

This result indicates that any lepton number violation of this type cannot occur in the "next coming" interaction.

$\mathcal{L}_2$ contains some 100 terms. The most dramatic ones are

$$\mathcal{L}_{\Delta B_2} = (\text{Quark})^3(\text{Lepton}) \tag{18}$$

which cause proton decay. The bound $\tau_p > 10^{32}y$ 45) yields

$$\Lambda > 10^{16}\ \text{GeV}\ . \tag{19}$$

The grand unified theories38) do indeed predict these operators, along with a prediction46)

$$\tau_p \lesssim 10^{31}y \tag{20}$$

in the simplest case. More complicated models do accomodate the measured bound on τ_p marginally, but have other problems. It is at the moment not clear whether grand unification can work below the Planck mass.

Of somewhat more immediate interest are processes which are not so highly suppressed.

If quarks and leptons are composite, or if there exist symmetries between the various flavors, there are most certainly flavor changing interactions. (For example, if quarks/leptons are build like ordinary hadrons, we expect analogs to $\Sigma^o \rightarrow \Lambda\gamma$ etc). Now $\mathcal{L}_o$ is automatically flavor conserving in neutral processes. However $\mathcal{L}_2$ in general leads to flavor changing processes. Two examples are

$$\frac{1}{\Lambda^2_{\mu e\gamma}}\ \mathcal{L}_{\mu e\gamma} = \frac{\bar{\mu}\ \sigma_{\mu\nu} e\ ^{u\nu}\ \phi}{\Lambda^2_{\mu e\gamma}}\ \varepsilon \tag{21}$$

$$\frac{1}{\Lambda^2_{\mu eee}}\ \mathcal{L}_{\mu eee} = \frac{(\bar{u}\ \gamma_\mu e)(\bar{e}\ \gamma_\mu e)}{\Lambda^2_{\mu eee}} \tag{22}$$

which give rise to $\mu \to e\gamma / \to eee$. Using the bounds[47)] on these lepton number violating processes, one gets

$$\begin{aligned} \Lambda_{\mu e\gamma} &> 10^4\ \text{TeV}\ (\varepsilon = 1) \\ &> 250\ \text{TeV}\ (\varepsilon = m_\mu/\langle|\phi|\rangle) \\ \Lambda_{\mu eee} &> 150\ \text{TeV}. \end{aligned} \tag{23}$$

In this way one can go through a variety of processes, the values of the bound on Λ range typically between 40 ∿ 1000 TeV.

Clearly, flavor symmetry cannot be violated by the "next" physics.

Assuming next that there are only interactions which conserve flavor the same way $\mathcal{L}_o$ does, we must look at other deviations from the standard ($\mathcal{L}_o$) results stemming from $\mathcal{L}_2$. One finds:

scalar couplings in μ-decay

$$\Lambda > 650\ \text{GeV}\ . \tag{24}$$

Cabibbo Universality

$$\Lambda > 5\ \text{TeV}\ . \tag{25}$$

magnetic moments of e, μ

$$\Lambda > 40\ \text{TeV}\ (\gtrsim 1\ \text{TeV if}\ \varepsilon = \frac{m_\mu}{V}) \tag{26}$$

(see Eq. (21)) .

Finally, one particular operator is ($G_{\mu\nu}$ is the gluon field strength)

$$\frac{1}{\Lambda^2_{CP}} \mathcal{L}_{CP} = \frac{1}{\Lambda^2_{CP}} G_{\mu\nu} G_{\alpha\beta} \phi^2 \quad \varepsilon^{\mu\nu\alpha\beta} \tag{27}$$

Bounds on the electric dipole moment of the neutron$^{17)}$ yield

$$\Lambda_{CP} > 10^5 \text{ TeV} . \tag{28}$$

If we have a definite model for a new interaction, we can give even more precise values. An example are models, where parity conservation is restored at higher energies, by introducing a new W-boson W_R . From the standard calculation, one gets^{48}, with a few assumptions,

$$m_{W_R} > 1.6 \quad \text{TeV}$$

if flavor violation in the new interactions parallels that of $\mathcal{L}_o$ (instead of just $m_{W_R} \gtrsim 650$ GeV (see eq. (24)).

Similarly one can set bounds on supersymmetric particles, which, however, are less constraining than those of collider experiments.

The above analysis showed that flavor violations are associated with very high energies. One can then ask how a theory must be built in order that it conserves flavor and the bounds do not apply.

An example is furnished by the operators

$$\frac{1}{\Lambda^2} \mathcal{L}_M = \frac{1}{\Lambda^2} (\bar{d}_{L_i} \gamma_\mu \delta_\nu \bar{d}_{L_j} + \bar{u}_{L_i} \gamma_\mu \delta_\nu u_{L_j}) F^{\mu\nu} G_{ij} \tag{29}$$

where d_{L_i}, u_{L_i} are the lefthanded "weak" eigenstates for $-\frac{1}{3}$ and $\frac{2}{3}$ charged states. When they are replaced by physical states, e.g. $d_{L_i} = (KM)_{ij}\, d^P_{L_j}$, $u_{L_i} = u^P_{L_j}$ (KM is the Kobayashi-Maskawa matrix14), $d^P_{L_i}$, $u^P_{L_i}$ the physical states) then the couplings of d^P_i and u^P_i to $F^{\mu\nu}$ are

$$(KM^{+}G\ KM)_{ij} \text{ and } G_{ij} \ . \tag{30}$$

These matrices are only simultaneously diagonal if $G = \mathbb{1}$ ($KM \neq \mathbb{1}$). If we extend this reasoning to the new, heavy particles, we see that their coupling to fermions is (in flavor space) proportional to $\mathbb{1}$, exactly like an ordinary Z or γ.

These results make it plausible that new interactions must satisfy the same (flavor-charge mainly) symmetries if they should be within reach of further accelerators. They show that low energy experiments are indeed a very strong tool in shaping our ideas about further developments.

New interactions are more likely to be of the canonical GUT or supersymmetry structure than of a "composite" type (unless a clever mechanism for suppression of unwanted effects is found! But then we must deal with their effects such as the proton life-time or neutrino masses. They lead to less well tested (or testable) properties of the weak interactions, such as new, weakly coupled particles (supersymmetric partners etc.).

This would imply, however, that the explanation of the quark/lepton masses lies at much higher energies, possibly through geometric properties of some fictitious spaces.

Still an open question is CP violation.

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