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Abstract

Previous analyses have yielded lower limits on the mass of a would-be right-handed boson ranging from 150 to 10^9 GeV, depending on the model used or the a priori assumptions made.

In this paper, an essentially model-independent limit on M(W_R) is derived from the \( K_L - K_S \) mass difference. That limit is \( \sim 200 \) GeV.

I. Introduction.

Left-right symmetric models of the weak and electromagnetic interactions based on the gauge group SU(2)_L \times SU(2)_R \times U(1)_{B-L} have 2 charged gauge bosons, \( W_L \) and \( W_R \), with predominantly left- and right-handed couplings. Parity is broken at the mass scale of \( W_R \). Several limits on M(W_R) have been quoted in the literature. 1, 2, 3

Bounds of order 10^9 GeV have been obtained from the constraints of Grand Unification 1: given the experimental value of \( \sin^2 \theta_W \) (obtained from low energy neutral-current data), and the values of \( \alpha_{EM} \) and \( \alpha_3 \) at low energies, and given the constraint on \( M_{\mu\mu} \) from the proton lifetime, the usual pattern of symmetry breaking can only be slightly altered to incorporate an SU(2)_R group; the corresponding energy must be at least 10^9 GeV. But this is merely evidence of the consistency of SU(5) (or of SO(10)), since the value of \( \sin^2 \theta_W \) used as input is obtained from neutral current data in the context of SU(2)_L \times U(1) (i.e. \( M(W_R) = \infty \)).

If the same data is reviewed using both \( \sin^2 \theta_W \) and M(W_R) as parameters from the start, any couple of values ranging from \( .23 \in 190 \) GeV to \( .28 \in 150 \) GeV satisfies the neutral-current data to within 1.5 \( \sigma \), and one can check that a low value of M(W_R) is not ruled out by Grand Unification constraints either 2. However the analysis of neutral-current data depends crucially on the model used; it then becomes very interesting to try and obtain limits on M(W_R) from the charged-current data, which will be much more model-independent.

The often quoted lower bound of 300 GeV is obtained by looking for deviations from a (V-A)(V-A) structure of the Hamiltonian in \( \beta \) decay.

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and $\rho$ decay. A recently proposed experiment suggests an order-of-magnitude improvement in detecting these deviations, thereby pushing up the limit on $M(W_R)$.

These results are based on the tacit assumption that if $W_R$ exists, $\nu_R$ exists too and is massless (or as light as $\nu_L$). On the contrary, all Grand Unification schemes where $\nu_R$ is present tend to give $\nu_R$ a very high mass, thus explaining why $\nu_L$ is much lighter than the associated charged lepton. The mass of the $\nu_R$ may range, according to the model, from the GUM value to $O(10^{-2})x$ the GUM value, to $O(N(W_R))$ in models where chiral symmetry is restored at intermediate energies. In any case, the right-handed $\nu$ is too heavy to be produced in $\beta$ or $\rho$ decay. As Rizzo and Senjanovic pointed out, one can expect, even if the correct theory is left-right symmetric, that:

- purely leptonic processes will reproduce the Weinberg-Salam predictions (up to minute deviations due to the mixing of $\nu_L$ and $\nu_R$);
- semi-leptonic processes may deviate from the Weinberg-Salam predictions if there is mixing between $W_L$ and $W_R$ by an angle $\beta$; such processes will then enable us to measure $\tan \beta$, and not $M(W_R)$ at all.

Places to look for evidence of a right-handed boson are then non-leptonic charged-current processes, where however the analysis may not be so clean in the presence of strong interactions. I want here to have another look at the $K_L - K_S$ mass difference, after the famous prediction by Gaillard and Lee that $m_K < 1.5 \text{ GeV}$.

II. Outline of the calculation.

Gaillard and Lee evaluated an effective Lagrangian for an $s\bar{d} - s\bar{d}$ transition. Having obtained an effective point-like Fermi interaction, they estimated the $K^0 - \bar{K}^0$ transition amplitude by doing all possible Wick contractions of the 4 quark operators contained in $\mathcal{L}_{\text{eff}}$ with the $K^0$ and $\bar{K}^0$ states, and then using PCAC. Their final step was to relate the above amplitude to the $K_L - K_S$ mass difference. They worked in the framework of the Weinberg-Salam model, with 2 quark generations; they used the convenient Feynmann gauge, since diagrams where ghost scalars, present in that gauge, are exchanged give a contribution of order $\left(\frac{m_q}{M_W}\right)^2 \ll 1$ (with respect to the usual box diagram (Fig. 2a).

Therefore they only had to compute the Feynmann diagrams corresponding to the combination of quark helicities of Fig. 1a (all left-handed), that is diagrams of Fig. 2a and 2b. I now want to repeat their approach in the context of a left-right symmetric model proposed by Mohapatra and Senjanovic. I will restrict myself to the case where $W_L$ and $W_R$ do not mix (i.e. they mediate purely left- and right-handed charged weak currents), and to 2 quark generations, and I will afterwards give arguments showing that the result does not change appreciably if there is a slight $W_L - W_R$ mixing, or if there are 3 quark generations.

In a model incorporating right-handed currents, the helicity

*A large $W_L - W_R$ mixing would have been detected in semi-leptonic charged-current experiments, even if $\nu_R$ is heavy.
combinations of Fig. 1(b,c,d) must be considered in addition to Fig. 1a.

The 4-quark operator for each combination is obtained by considering a box diagram of the type drawn in Fig. 2(a,b,c,d), where now the bosons exchanged can be any neutral set of 2 among:

- a left- and a right-handed charged gauge boson $W_L$ and $W_R$;
- 2 neutral gauge bosons $Z_1$ and $Z_2$ (each with left- and right-handed couplings);
- 6 Higgs bosons, 2 charged and 4 neutral, which form an $(SU(2)_L \times SU(2)_R)$ doublet, needed to give masses to the fermions.

All the diagrams corresponding to configuration (1c) can be obtained from the ones corresponding to (1b) by exchanging the 2 outgoing d quarks.

First, the divergent part of the diagrams relevant to each helicity configuration was evaluated (in the physical unitary gauge), to make sure that the computation was being carried out consistently. Then finite amplitudes were obtained for all diagrams in Feynman gauge. Approximations were made with the assumption that all the bosons (including the Higgses) are at least as heavy as $W_L$: all terms of order $\frac{m_{\text{quark}}}{m_{\text{boson}}}$ can then be safely neglected.

A complicated expression is then obtained for $\mathcal{L}_{\text{eff}}$, containing 4 terms $\mathcal{L}_{\text{eff}} a, b, c, d$ for the 4 helicity configurations, $\mathcal{L}_{\text{eff}} a$ being the Gaillard-Lee result, with an extra term from double Higgs exchange.

Even though there are no flavor-changing neutral currents, the neutral Higgses do have non-diagonal couplings, which are needed to generate the Cabibbo angle. A neutral Higgs and a $Z$, or 2 neutral Higgses can thus be exchanged between $K^0$ and $\bar{K}^0$.

The 4-quark operator is of the form $(V-A)(V-A)$ for $\mathcal{L}_{\text{eff}} a$, $(V-A)(V+A)$ for $\mathcal{L}_{\text{eff}} b$ and $\mathcal{L}_{\text{eff}} c$, $(V+A)(V+A)$ for $\mathcal{L}_{\text{eff}} d$. The corresponding $K^0 - \bar{K}^0$ transition amplitude can then be evaluated by making all possible Wick contractions, and using:

- PCAC for $\mathcal{L}_{\text{eff}} a$ and $\mathcal{L}_{\text{eff}} d$:
  $$\langle \bar{K}^0 | \bar{\psi} \gamma^\mu \gamma^\nu \psi | K^0 \rangle = \frac{\alpha}{\sqrt{2}} \langle K^0 | \bar{\psi} \gamma^\mu \gamma^\nu \psi | K^0 \rangle$$

- PCAC and the free Dirac equation for $\mathcal{L}_{\text{eff}} b$ and $\mathcal{L}_{\text{eff}} c$:
  $$\langle \bar{K}^0 | \bar{\psi} \gamma^\mu \gamma^\nu \psi | K^0 \rangle = \alpha \langle K^0 | \bar{\psi} \gamma^\mu \gamma^\nu \psi | K^0 \rangle$$

Care must be taken in $\mathcal{L}_{\text{eff}} b$ and $\mathcal{L}_{\text{eff}} c$, since the corresponding operator is not invariant under a Fierz-transformation, unlike the others; the product of 2 axial-vector terms and the product of 2 pseudo-scalar terms will both contribute.

In the end, it turns out that the major correction to the Gaillard-Lee $K^0 - \bar{K}^0$ amplitude comes from the diagrams of Fig. 3a & 3b. When one decreases the mass of $W_R$ from infinity to a value for which the corrective term is as large as the Gaillard-Lee term, the contribution of all the other diagrams is an order of magnitude below that of diagrams Fig. 3a & 3b.

The amplitude obtained from diagrams 3a & 3b is an expression symmetric in the masses of $W_L$ and $W_R$, but it reaches the same magnitude as the Gaillard-Lee amplitude for a mass of $W_R \sim 200$ GeV, for which the total amplitude can be written in the form:

*In other words, for any mass of $W_R$, the presence of the Higgs sector and of the 2 $Z$'s modifies the Gaillard-Lee result by 10% or less, depending on the Higgs masses.
Even though there is some uncertainty in relating $\mathcal{Z}_{\text{eff}}$ to the $K_L - K_S$ mass difference, as indicated by Gaillard and Lee themselves, and emphasized by numerous papers, it is still true that one cannot add to the original $K^0 - \bar{K}^0$ transition amplitude a piece of equal magnitude (and opposite sign) without upsetting seriously the explanation of the $K_L - K_S$ mass difference. One can therefore set the lower limit:

$$M(W_R) \geq 200 \text{ GeV}.$$
\[ 1 + O \left( \frac{\log M(W_L)/m_e}{\log M(W_L)/m_e} \right) \]

which is \( \sim 1 \) as long as \( m_e \ll M(W_L) \).

In any case, the Feynmann integrals have all been simplified using the fact that \( m_q \ll M(\text{bosons}) \), and the whole computation should be worked out again if the top quark (or any charge +2/3 quark) was close in mass to \( W_L \).

IV. Summary.

The lower limit on the mass of the right-handed boson, \( \sim 200 \) GeV, obtained in this paper by requiring that the explanation of the \( K_L - K_S \) mass difference given by Gaillard and Lee remain valid as to the order of magnitude even if \( W_R \) exists, has been shown to be essentially model-independent, provided that the mass scales of the quarks and the (gauge and Higgs) bosons do not overlap.

It may also be possible to obtain another such lower bound from the analysis of non-leptonic hyperon decays, and this subject is now being investigated.
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Figure Captions

Fig. 1. The 4 helicity combinations contributing to the $K^0 - \bar{K}^0$ transition amplitude. Asymmetric combinations (e.g. 3 left-, 1 right-handed) give a 0 amplitude.

Fig. 2. The 4 possible ways to exchange a neutral pair of bosons. In general, W can be any boson (gauge or Higgs).

Fig. 3. The major correction to the Gaillard-Lee result comes from these diagrams.
Figures

1. \[ \begin{align*}
& s_L \rightarrow d_L \quad s_L \rightarrow d_L \\
& d_L \rightarrow s_L \\
& s_L \rightarrow d_R \quad s_R \rightarrow d_R \\
& d_L \rightarrow s_R \\
\end{align*} \]

2. \[ \begin{align*}
& s \rightarrow w \rightarrow d \quad s \rightarrow w \rightarrow d \\
& d \rightarrow w \rightarrow s \\
& s \rightarrow w \rightarrow w \rightarrow d \\
& d \rightarrow w \rightarrow w \rightarrow s \\
\end{align*} \]

3. \[ \begin{align*}
& s_L \rightarrow w_L \rightarrow d_L \quad s_L \rightarrow w_L \rightarrow d_R \\
& d_R \rightarrow w_R \rightarrow s_R \\
\end{align*} \]
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