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LIMITS ON THE STRENGTH OF A LEFT-RIGHT SYMMETRIC ELECTROWEAK INTERACTION

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ABSTRACT

We have investigated the constraints imposed on left-right symmetric theories of weak and electromagnetic interactions by the K_L-K_S mass difference, including the additional restrictions on the top quark mass and mixing angles coming from the $K_L \to \mu^+\mu^-$ decay rate, and emphasizing the sensitivity of the results to various model-dependent assumptions. In the manifest left-right-symmetric electroweak theory it was found that values for the mass m_R of the charged, right-handed boson W_R as low as 220 GeV/c^2, the original estimate of Bég, Budny, Mohapatra and Sirlin, cannot be rigorously ruled out by existing data. However, for a large class of plausible models the lower bound on the mass of W_R was found to be considerably higher, but still within the range that experiments now in progress will be able to explore. The lower bound on m_R was also found to be quite sensitive to the value assumed for the top quark mass and to the model dependent values of the hadronic matrix elements of the quark operators, as well as to certain model-dependent assumptions regarding the dispersive part of the $K_L \to \mu^+\mu^-$amplitude. We present the lower bound on m_R for a wide range of the relevant parameters, which includes two specific models: the MIT Bag Model and the vacuum insertion approximation.

One possible extension of the highly successful standard theory[1] of weak and electromagnetic interactions of three generations of quarks and leptons is the left-right symmetric model[2] based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. This model has the standard theory as a low energy limit and bounds can be placed on the minimum energy range at which deviations from the standard theory resulting from the right-handed V+A weak interaction are allowed by present data. Bég, et al.[3] concluded some time ago, from an analysis of all the low energy charged current data, that the mass m_R of a right-handed intermediate boson W_R was bounded below by

$$m_R \gtrsim 2.76\, m_L \simeq 220 \text{ GeV}/c^2 \ . \tag{1}$$

where $m_L \simeq 80$ GeV/c^2 is the mass of the left-handed intermediate boson W_L.

In a more recent paper Beall, et al.,[4] found the K_L-K_S mass difference Δm leads to a much stronger constraint,

$$m_R \gtrsim \sqrt{430}\, m_L \simeq 1.6 \text{ TeV}/c^2 \quad , \tag{2}$$

for the "manifest" left-right symmetric model, under certain, not unreasonable, assumptions. The present generation of experiments[5] in progress are expected to be sensitive to right-handed weak interactions with mass scales below about 500 to 600 GeV/c^2, which is considerably above the lower limit found by Bég, et. al.,[3] but far below the more recent lower bound of Beall, et al.[4].

We have therefore investigated the lower bound on m_R imposed by the K_L-K_S mass difference Δm, including the additional constraint coming from the branching ratio for the rare decay $K_L \rightarrow \mu^+\mu^-$ and we have explored the sensitivity of the numerical results to the various assumptions involved in the analysis. Furthermore, in our analysis all the Kobayaski-Maskawa[6] mixing parameters were allowed to vary over the full range by the present data.

We have found that right-handed intermediate boson masses even as low as 220 GeV/c^2 cannot be excluded at present without introducing theoretical assumptions that are open to question. Specifically, the lower bound on m_R was found to be quite sensitive to the mass m_t assumed for the predicted top quark, there being no stronger constraints than originally given by Bég, et al.[3] if $m \gtrsim 45$ to 50 GeV/c^2. And for smaller values of m_t the bound on m_R depends very much on the model used to calculate the $K^\circ - \overline{K}^\circ$ matrix elements of the $\Delta S = 2$ quark current operators, particularly the ratio of matrix elements of the right-handed to left-handed contributions to Δm. For example, the lower bound on m_R obtained in the context of MIT Bag Model turned out to be significantly different from the resulting bound using the vacuum insertion approximation for the $\Delta S = 2$ matrix element. We shall therefore present our numerical results below for a wide range of the relevant parameters, allowing the lower bound on m_R to be extracted graphically for various values of the top quark mass and different models for the $\Delta S = 2$ matrix elements. When the top quark mass is known, provided it is not too large, the lower bound on m_R can be substantially strengthend.

In the following we first discuss the rather important implications of the $K_L \rightarrow \pi^+\pi^-$ branching ratio, which we then include analysis of the constraint on m_R due to the $K_L - K_S$ mass difference. Numerical results are then presented and discussed, emphasizing their relevance for experiments now in progress.

In the context of the standard six-quark model the short distance contribution to the $K_L \to \mu^+\mu^-$ amplitude, in the unitary guage, is given by the diagrams shown in Fig. 1. This short-distance contribution to $K_L \to \mu^+\mu^-$is bounded by the dispersive part of the amplitude, which in turn can be bounded in terms of the two-photon contributions to the absorptive part of the amplitude and the measured $K_L \to \mu^+\mu^-$ and $K_L \to \gamma\gamma$ decay rates.[7] One finds that

$$\left|\sum_{i=u,c,t} \mathrm{Re}A_i \; G(x_i)\eta_i\right| \leq K \tag{3}$$

where the $A_i = V_{di} V_{si}^*$ are products of standard Kobayashi-Maskawa (K-M) matrix elements. In their original work Shrock and Voloshin[7] estimated the dispersive part of the $K_L \to \mu^+\mu^-$ amplitude of the two-photon intermediate state to be unimportant and found the constant K in Eq. (3) to be $K = 1.96 \times 10^{-3}$. More recently Barger, Long, Ma and Pramudita[8] have concluded that, while the two-photon intermediate state indeed dominates the absorptive part of the $K_L \to \mu^+\mu^-$ amplitude, the dispersive part cannot be neglected. Including the two-photon contribution to the dispersive part in the analysis, they find the data do not rule out bound K values for the bound K in Eq. (3) as large as 7.34×10^{-3}. In our numerical calculations below we shall consider a wide range of values K.

The functions $G(x_i)$, with $x_i = m_i^2/m_L^2$, contains the dependence on the charge 2/3 quark masses. Specifically, for arbitary quark masses,[9]

$$G(x) = \frac{3}{4}\left(\frac{x}{1-x}\right)^2 \ln x + \frac{x}{4} + \frac{3}{4}\frac{x}{1-x} \tag{4}$$

while

$$A_u = c_1 s_1 c_3 \tag{5}$$

$$A_c = -s_1 c_2 (c_1 c_2 c_3 + s_2 s_3 e^{i\delta})^* \tag{6}$$

and

$$A_t = -s_1 s_2 (c_1 s_2 c_3 - c_2 s_3 e^{i\delta})^* \tag{7}$$

where $s_i = \sin\theta_i$ and $c_i = \cos\theta_i$, as usual. (Note, that by unitarity of the K-M matrix $A_u + A_c + A_t = 0$, which will be of considerable practical usefulness in the computations below.)

The factors η_i represent multiplicative QCD corrections, which are unity in the free quark-proton model. Numerically, the contributions of the u and c quarks in Eq. (3) are negligible compared to the right-hand side and we shall ignore them. And the contributions to the $K_L \to \mu^+\mu^-$ decay rate involving V + A interactions in the $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$ model are also negligible since these right-handed interactions are supressed by at least one factor of $\beta = (m_L/m_R)^2$ relative to the V-A interactions; and β is already known to be small ($\beta \lesssim 0.13$) from previous work.[3]

Consequently, the net effect of the $K_L \to \mu^+\mu^-$ decay rate is to limit the range of the combination of K-M parameters A_t as a function of the top quark mass, and Eq. (3) becomes simply

$$|\mathrm{Re}A_t| \leq K / G(x_t)\eta_t \tag{8}$$

This restriction plays a very important role in determining the lower bound on m_R due to Δm.

Following the original work of Gaillard and Lee,[10] we shall assume the K_L - K_S mass diffeence is given by the short-distance contributions of the box diagrams shown in Fig. 2. For the standard model one finds[11]

$$\Delta m_{LL} = \frac{G_F^2}{8\pi^2} m_L^2 \; \mathrm{Re}[F(x_i,\theta_i)M_{LL}] \tag{9}$$

where $F(x_i,\theta_i)$ depends upon quark masses ($x_i = m_i^2/m_L^2$) and the parameters θ_i and

$$M_{LL} = \langle \bar{K}^\circ[\bar{s}\gamma_\mu(1-\gamma_5)d]^2|K^\circ\rangle. \tag{10}$$

Allowing for multiplicative QCD correction parameters η_{ij}, which are unity in the free quark-proton model, we have[11]

$$F(x_i,\theta_i) = \sum_{j,k=c,t} A_j A_k B(x_j,x_k)\eta_{jk} \tag{11}$$

where for i = j

$$B(x_i,x_i) = x_i[\tfrac{1}{4} + \tfrac{9}{4}(1 - x_i)^{-1} - \tfrac{3}{2}(1 - x_i)^{-2}]$$

$$- \frac{3}{2}[x_i/(1 - x_i)]^3 \ln x_i \tag{12}$$

and for $i \neq j$

$$B(x_i,x_j) = x_i x_j\{(x_j-x_i)^{-1}[\tfrac{1}{4} + \tfrac{3}{2}(1-x_j)^{-1} - \tfrac{3}{4}(1-x_j)^{-2}]\ln x_j$$

$$+ i \leftrightarrow j - \tfrac{3}{4}[(1-x_i)(1-x_j)]^{-1}\} \tag{13}$$

The contributions involving the up quark have been included in Eqs. (11)-(13) using unitarity of the K-M matrix and taking $m_u = 0$, a good approximation.

Since β is small it is sufficient to consider only the contributions to Δm of the V+A interaction coming from the box diagrams shown in Figure 2 in which there is one W_R and one W_L. In the approximation that $1 \gg x_t \gg x_c \simeq 0$ one finds for $\beta \ll 1$ that

$$\Delta m_{LR} = \beta \frac{G_F^2}{\pi^2} m_L^2 \mathrm{Re}[H(x_i,\theta_i) M_{LR}] \tag{14}$$

where

$$H(x_i,\theta_i) = A_c^2 x_c (\ln X_c + 1)\eta_{cc} + A_t^2 x_t [1-x_t]^{-1} (\ln x_t + 1)\eta_{tt}$$

$$+ 2A_c A_t \sqrt{x_c x_t}\, [1-x_t]^{-1} \ln X_t\, \eta_{ct} \tag{15}$$

and

$$M_{LR} = \langle \bar{K}^\circ | \bar{s}\gamma^\mu (1-\gamma_5) d\, \bar{d}\, \gamma_\mu (1+\gamma_5) s | K^\circ \rangle \tag{16}$$

In Eqs. (14) and (15) we have assumed "manifest" left-right-symmetry in which the quark mass matrix is hermitian and can be diagonalized by the single unitary K-M matrix V; i.e., $V^L = V^R$. Moreover, we have assumed the multiplicative QCD correction factors are also left-right symmetric, a point we shall return to below.

Combining both contributions, the K_L-K_S mass difference is then

$$\frac{\Delta m}{m} = \frac{G_F^2}{6\pi^2} m_L^2 F_K^2 (M_{LL}/M_{LL}^{VAC}) \mathrm{Re}[F(x_i,\theta_i) + 8\,\rho\beta \frac{M_{LR}^{VAC}}{M_{LL}^{VAC}} H(x_i,\theta_i)] \tag{17}$$

For convenience, we have normalized the matrix elements M_{LL} and M_{LR} to their values in the vacuum insertion approximation:

$$M_{LL}^{VAC} = \frac{8}{3} F_K^2 m^2/(2m), \tag{18}$$

and

$$(M_{LR}/M_{LL})_{VAC} = \frac{3}{4}[m^2/(m_d+m_s)^2 + \frac{1}{6}]e^{i\phi} \tag{19}$$

Here, $F_K \simeq 1.23\ m_\pi$ and m are the kaon decay constant and mass while $m_d \simeq 7$ MeV/c^2 and $m_s \simeq 150$ MeV/c^2 are quark masses and[4] $|(M_{LR}/M_{LL})_{VAC}| \simeq 7.7$. We have allowed for an arbitrary value of the additional physically observable CP nonconserving phase ϕ in Eq. (19), which is possible in the left-right-symmetric model, and we have chosen ϕ to be the relative phase between s_L and s_R, the left and right-handed strange quarks.[12] And we also have parameterized most of the model-dependence in Eq. (17) by introducing in

$$\rho = (M_{LR}/M_{LL})/(M_{LR}/M_{LL})_{VAC} \tag{20}$$

Numerically we determined the lower bound on m_R resulting from the constraint imposed by the K_L-K_S mass difference [Eq. (17)] and the $K_L \to \mu^+\mu^-$ decay rate [Eq. (8)] for a wide range of values of the top quark mass m_t, the model dependent matrix elements M_{LL} and M_{LR} and the bound K in Eq. (8). For simplicity we neglected any QCD corrections ($\eta_i = \eta_{ij} = 1$) and also ignored small CP nonconserving effects, considering only $\delta = 0$ or π in the numerical computations. However, all other K-M parameters were allowed to vary over the entire range consistent with the measurements[13] $|\cos\theta_1| = 0.9737 \pm 0.0025$, $|\sin\theta_1\cos\theta_3| = 0.219 \pm 0.011$ and $|\sin\theta_1\sin\theta_3| = 0.06 \pm 0.06$. These data imply that $|A_u| = 0.213 \pm 0.012$ and unitarity of the K-M matrix requires that

$$A_c = -(A_u + A_t) \tag{21}$$

while the $K \to \mu^+ \mu^-$ decay rate restricts $|A_t|$ for a given value of m_t as indicated above in Eq. (8). In addition, these data[13] also require $|\sin\theta| < 0.5$, which bounds A_t even more strongly than Eq. (8) for small [3] values of m_t in the case $A_t > 0$.

The lower bound on m_R was found to be very sensitive to the value of the top quark mass and the numerical value of the bound K in Eq. (8), as might be expected; but, in addition, the results were found to also depend quite significantly on the model used to evaluate the $\Delta S = 2$ matrix elements M_{LL} and M_{LR}, the critical parameter being ρ, their ratio. For illustrative purposes we show in Fig. 3 the lower bound on m_R as a function of m_t assuming the largest value for the bound in Eq. (8) $K = 7.34 \times 10^{-3}$, for two typical models: the vacuum insertion approximation ($\rho = 1$) and the MIT Bag Model ($\rho = 1.667$). It is clear from Fig. 3 that, independent of the model for the matrix elements, if m_t is larger than about 45 to 50 GeV/c^2, there is no better lower bound on m_R than Bég, et al.[3] found in their analysis of all the low energy charged current data some time ago. However, if m_t is smaller than about 45 GeV/ c^2 a considerally stronger bound does result from imposing the constraints due to the K_L-K_S mass difference and the $K_L \to \mu^+\mu^-$ decay rate and this improved lower bound on m_R is rahter model-dependent, being larger for models in which ρ is larger.

The critical dependence on the value of M_t of the lower bound on m_R can be qualitatively understood essentially as follows: Even though the K-M martrix elements coupling the top quark to the down and strange quarks are rather small, the very large mass of the top quark tends to compensate[14], making the top quark contribution to Δm comparable to the contribution of the lighter up and charm quarks. For small m_t, i.e.; below the "knee" in Fig. 3, the lower bound on m_R occurs for $A_t < 0$, while at larger values of m_t the bound occurs when $A_t > 0$. In both cases $|A_t|$ is bounded by the constraint due to the $K_L \rightarrow \mu^+\mu^-$ decay rate [Eq. (8)]. The "knee" in the curves shown in Fig. 3, corresponds to the point where the lower bound on m_R changes from occuring at the <u>most negative</u> to the <u>most positive</u> value of A_t allowed by the $K_L \rightarrow \mu^+\mu^-$ decay rate. And this changeover reflects the fact that for small m_t the large <u>positive</u> values of A_t allowed by Eq. (8) are forbidden by the constraint $|\sin\theta_3| < 0.5$, which follows from the measured K-M matrix elements, independent of the $K_L \rightarrow \mu^+\mu^-$ decay rate; cf., Eqs. (5)-(7) above. As m_t increases the cancelations among the various contributions become more significant due to the increasing relative importance of the diagrams in Fig. 2 with one top quark and one charm or up quark. [Recall that the minimum value of m_R occurs in the regime when A_t, while small, is <u>positive</u> and $A_c \simeq -A_u = -0.213 \pm 0.012$; cf., Eq. (17).]

The lower bound on m_R is also rather sensitive to the model chosen for evaluating the $\Delta S=2$ matrix elements M_{LL} and M_{LR}, primarily through their ratio ρ since $\Delta m/m$ is so very small. In Figs. 4 and 5 we have illustrated this point for some representative values of m_t. Using the vacuum insertion approximation for M_{LL}, Eq. (18), we shown in Fig. 4 the dependence of $[m_R]_{MIN}$ on the ration $\rho = (M_{LR}/M_{LL})/M_{LR}/M_{LL})_{VAC}$ for corresponding lower bound on m_R obtained using the MIT BAG Model for

M_{LL} $[(M_{LL})_{BAG} = 0.42\ (M_{LL})_{VAC}]$.[15] The dramatic decrease in the lower limit on m_R as m_t becomes large is evident in these figures, as it was in Fig. 3, which emphasizes that this is a typical feature of any plausible model. The increase of $[m_R]_{MIN}$ as ρ increases simply reflects the fact that the larger left-right matrix element M_{LR} must be compensated by a larger W_R mass in the propagator occurring in the denominator of the diagram; cf., Fig. 2. And it is easy to understand that ρ is larger for the MIT BAG Model than for the vacuum insertion approximation since the V+A interaction, which becomes S-P after Fierz rearrangement, is more spread out in space and therefore makes possible a larger contribution to the integration over the extended size of the bag.

Since there are a number of other models for evaluating the matrix elements M_{LL} and M_{LR} we emphasize that Figures 3, 4 and 5 can be used to estimate the resulting lower bound on m_R by interpolation; and if one considers $\phi \neq 0$, simply replace ρ by Reρ.

It should be noted that in our numerical computations we have used the free quark-parton model for which the multiplicative QCD correction factors η_i and η_{ij} are all unity. To explore the sensitivity of our results to these corrections we have taken the QCD correction factors for the pure V-A interaction matrix element M_{LL}, calculated by Gilman and Wise[16], and assumed the unknown corrections to M_{LR} to be the same. Our numerical results for $[m_R]_{MIN}$ increases somewhat (~ 10%) under this ad hoc assumption, but not enough to significantly effect our conclusions which are illustrated in Fig. (3) -(5). And we must emphasize that in obtaining the results shown in these figures we have assumed that both β and X_t are small, so the bounds shown cannot confidently be extrapolated beyond this regime. We have also neglected possible mixing between W_L and W_R, which has been shown to be small[3]; and the contributions of unphysical scalars in the diagrams shown in Fig. 2, which are suppressed by mass-dependent couplings, are unimportant for our considerations.

The suggestion of Barger, et al.[8] that the two-photon contribution to the <u>dispersive</u> part of the $K_L \to \mu^+\mu^-$ amplitude is more important than previously estimated by Shrock and Voloshin[7] is more significant for our results. In our numerical computations illustrated in Figs. (3)-(5) we allowed for the largest possible contributions of the top quark in Figs. (1) and (2) consistent with all the analysis of the present data, choosing $K = 7.34 \times 10^{-3}$, since we sought the <u>smallest</u> lower bound on m_R. We have explored the sensitivity of the resulting $[m_R]_{MIN}$ to the value to the value of K, as well as the value of m_t, in the context of both the vacuum insertion approximation and the MIT Bag Model for the ΔS=2 matrix elements. In Figs. 6 and 7 we show the three-dimensional surface representing the lower bound $[m_R]_{MIN}$ as a function of both m_t and K for the interesting ranges of these parameters. Clearly, as K is decreased $[m_R]_{MIN}$ increases rapidly.

We note that our results are in substantial agreement with the recent work of Donoghue and Holstein[17] based on an analysis of $\Delta S = 1$ matrix elements. Nor do we disagree with the results calculated by Trampetic[18] for the matrix elements M_{LL} and M_{LR}, where our work overlaps; although the lack of physical significance of the sign of the integral for M_{LL} in the MIT BAG Model pertaining to Δm has been misunderstood. Since only certain values of the relevant parameters were considered in this paper, the lower bound on m_R was not obtained. And we note that a related calculation by de Forcrand[19] seems to agree with our conclusions regarding the bound found by Beall, et al.[4]; but we do not understand why, since the effects of the top quark were ignored, while we found them essential to our results.

To summarize we have shown that the $K_L \to \mu^+\mu^-$ decay rate plays an important role in establishing the lower bound on m_R imposed by the K_L $-K_S$ mass difference. Moreover, the results are quite sensitive to several theoretical assumptions and present experimental information is not sufficient to rigorously rule out a right-hand boson W_R as light as 220 GeV/c^2, the original bound of Bég, et al[3]. However, we emphasize that this approach is potentially very useful; the lower bound m_R would be quite substantially strengthened if the top quark were found to below about 40 GeV/c^2. Clearly, the present round of experiments designed to explore the mass range up to about 500 -600 GeV/c^2 will very important.

Addendum: The preliminary result $m_R > 450$ GeV/c^2, assuming no W_L-W_R mixing, has recently been reported by the Berkeley/LBL/ Northwestern/ TRIUMF collaboration[20].

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REFERENCES

1. S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in Elementary Particle Theory, edited by N. Svartholm (Almgvist and Wiksell, Stockholm, 1968); P. 367; S. Glashow, Nucl. Phys. 22, 579 (1961); S. L. Glashow, J. Ilopoulos and L. Maiani, Phys. Rev. D2, 1285 (1970).
2. J. Pati and A. Salam, Phys. Rev. Lett. 31, 661 (1973); R. Mohapatra and J. Pati, Phys. Rev. D11, 566 (1975); R. Mohapatra, Phys. Rev. D12, 566 (1975);
3. M. Bég, R. Budny, R. Mohapatra and A. Sirlin, Phys. Rev. Lett. 38, 1252 (1977). See also M. Bég and A. Sirlin, Physics Reports (to be published).
4. G. Beall, M. Bander and A. Soni, Phys. Rev. Lett. 48, 848 (1982).
5. M. Strovink, Workshop on Weak Interactions and Grand Unification, Blacksburg, Virginia, Dec. 3-6, 1980; LBL Preprint, LBL-12275.
6. M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973). We shall follow the standard conventions adopted by M. Aguilar-Benitez et al. (Particle Data Group), Phys. Lett. 111B (1982).
7. M. Voloshin and E. Shabalin, Pis'ma Zh. Eksp. Theor. Fiz. 23, 123 (1976). [JEPT Lett. 23, 107 (1976)]; R.E. Shrock and M.B. Voloshin, Phys. Lett. 87B, 375 (1979).
8. V. Barger, W. Long, E. Ma and A. Pramudita, Phys. Rev. D 25, 1860 (1982).
9. E. Ma and A. Pramudita, Phys. Rev. D22, 214 (1980); T. Inami and C. Lim, Prog. Theor. Phys. 65, 297 (1981) ; A. Buras, Phys. Rev. Lett 46, 1354 (1981) and R. E. Shrock, unpublished.
10. M.K. Gaillard and B.W. Lee, Phys. Rev. D10, 897 (1974).
11. T. Inami and C. Lim, ref. 9; A. Buras, ref. 9; R. Shrock, ref. 9.

12. We are grateful to H. Harrari for discussions of the importance of this phase ϕ. In our numerical calculations below we shall take ρ real by putting $\phi = 0$, for convenience. The results for $\phi \neq 0$ can be obtained by simply replacing ρ by Re ρ.

13. M. Aguilar-Benitez, et al. (Particle Data Group) ref. 6.

14. The possibility of such cancellations was indeed noted in ref. 4 (footnote 9), but thought to be unlikely.

15. R. E. Shrock and S.B. Treiman, Phys. Rev. D19, 2148 (1978)

16. H. J. Gilman and M. B. Wise, Phys. Lett. 83B, 83 (1979);

17. J. Donoghe and B. Holstein, Phys. Lett. 113B, 382 (1982).

18. J. Trampetic, Preprint MPI-PAE/PTH 43/82 (unpublished).

19. P. de Forcrand, LBL preprint LBL-13594.

20. B. Gobbi, Talk presented at XVIIIth Recontre de Moriond, 13-19 March, 1983. See also, J. Carr, et al., Phys. Rev. Lett. (to be published).

FIGURE CAPTIONS

Fig. 1: One-loop diagrams contributing to the short-distance part of the $K_L \to \mu^+\mu^-$ amplitude, in the unitary gauge.

Fig. 2: The annihilation box diagram contributing to the short-distance part of the $K_L - K_S$ mass difference. The scattering box diagram is obtained by crossing.

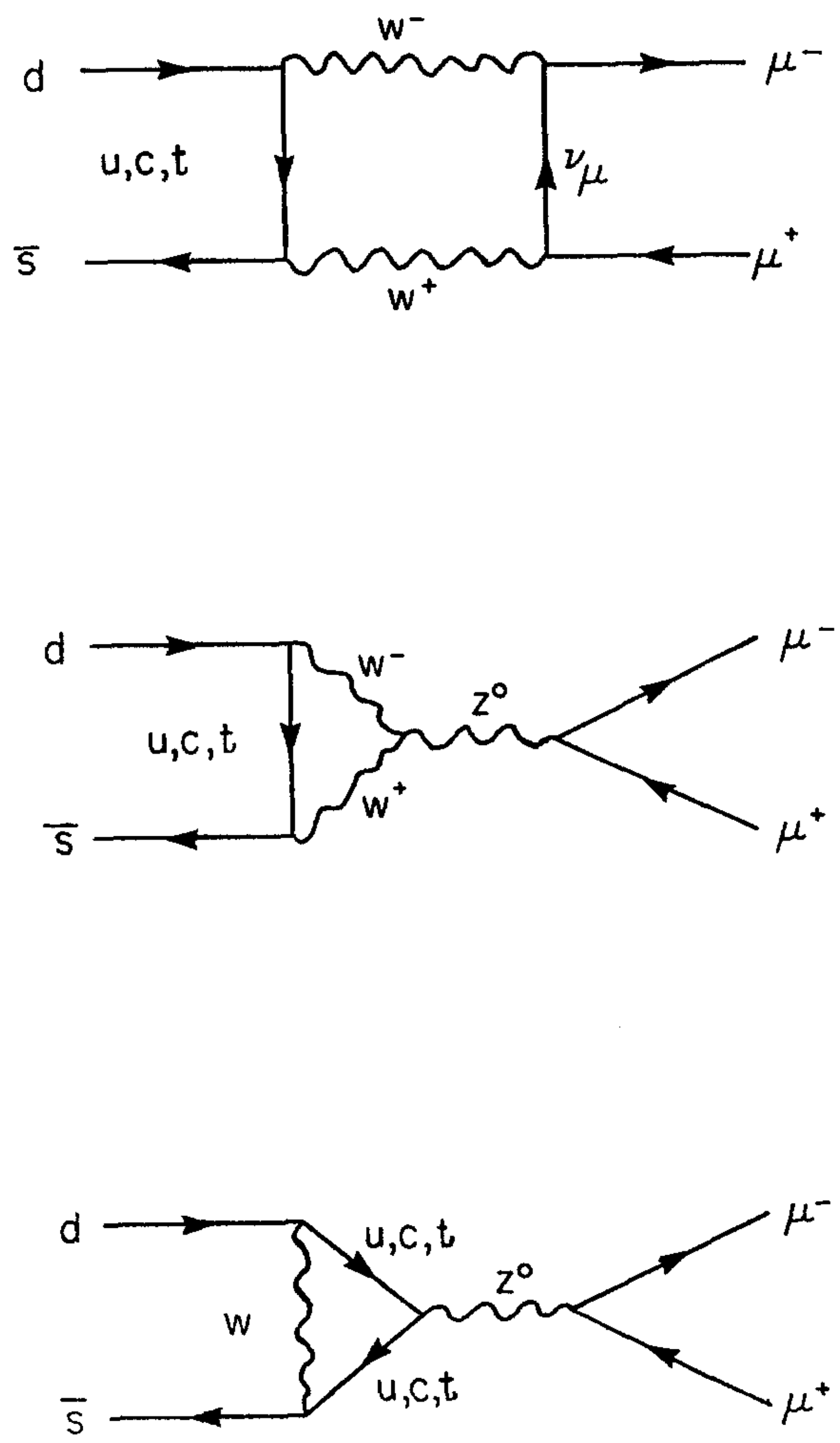
Fig. 3: Lower bound on the mass m_R of the right-handed weak boson W_R as function of the mass m_t of the predicted top quark assuming $K = 7.34 \times 10^{-3}$. The bounds are shown for two typical models for the $\Delta S = 2$ matrix elements: MIT Bag Model ($\rho = 1.667$) and the vacuum insertion model ($\rho = 1.0$). Also shown is the lower bound $m_R > 220$ GeV/c^2 of ref 3.

Fig. 4: Lower bound on the mass m_R of the right-handed weak boson W_R as a function of $\rho = (M_{LR}/M_{LL})/(M_{LR}/M_{LL})_{VAC}$ for several values of the top quark mass m_t in GeV/c^2 assuming $K = 7.34 \times 10^{-3}$ and the vacuum insertion approximation for M_{LL} [Eq. (18)]. Note that $\rho_{VAC} = 1.0$ while $\rho_{BAG} = 1.667$.

Fig. 5: Lower bound on the mass m_R of the right-handed weak boson W_R as a function of $\rho = (M_{LR}/M_{LL}/(M_{LR}/M_{LL})_{VAC}$ for several values of the top quark mass m_t in GeV/c^2 assuming $K = 7.34 \times 10^{-3}$ the MIT BAG Model for M_{LL} $[(M_{LL})_{BAG} = 0.42\ (M_{LL})_{VAC}]$. Note that $\rho_{VAC} = 1.0$ while $\rho_{BAG} = 1.667$.

Fig. 6: Lower bound $[m_R]_{MIN}$ as a function of both m_t and K assuming the vacuum insertion approximation for M_{LL} and M_{LR}.

Fig. 7: Lower bound $[m_R]_{MIN}$ as a function of both m_t and K assuming the MIT Bag Model for M_{LL} and M_{LR}.


d
u,c,t
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W$^-$
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ν_μ
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μ^+
d
u,c,t
$\bar{s}$
W$^-$
W$^+$
Z°
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W
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u,c,t
Z°
μ^-
μ^+

Fig. 1

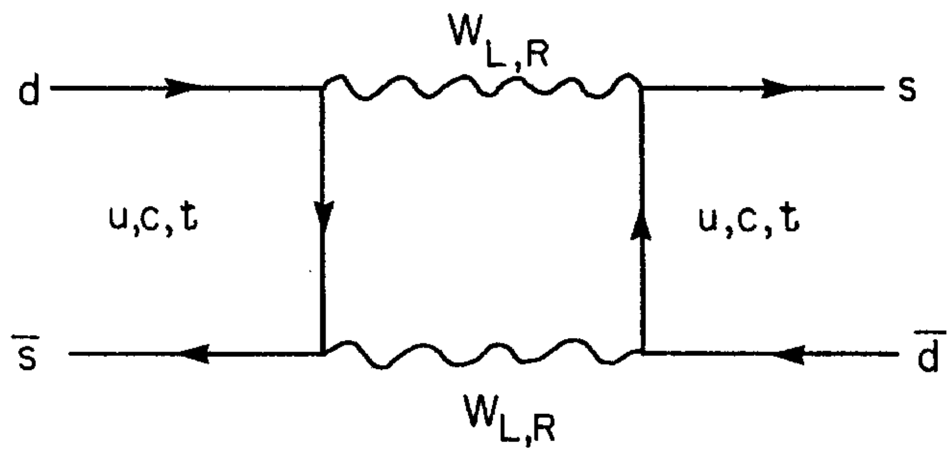
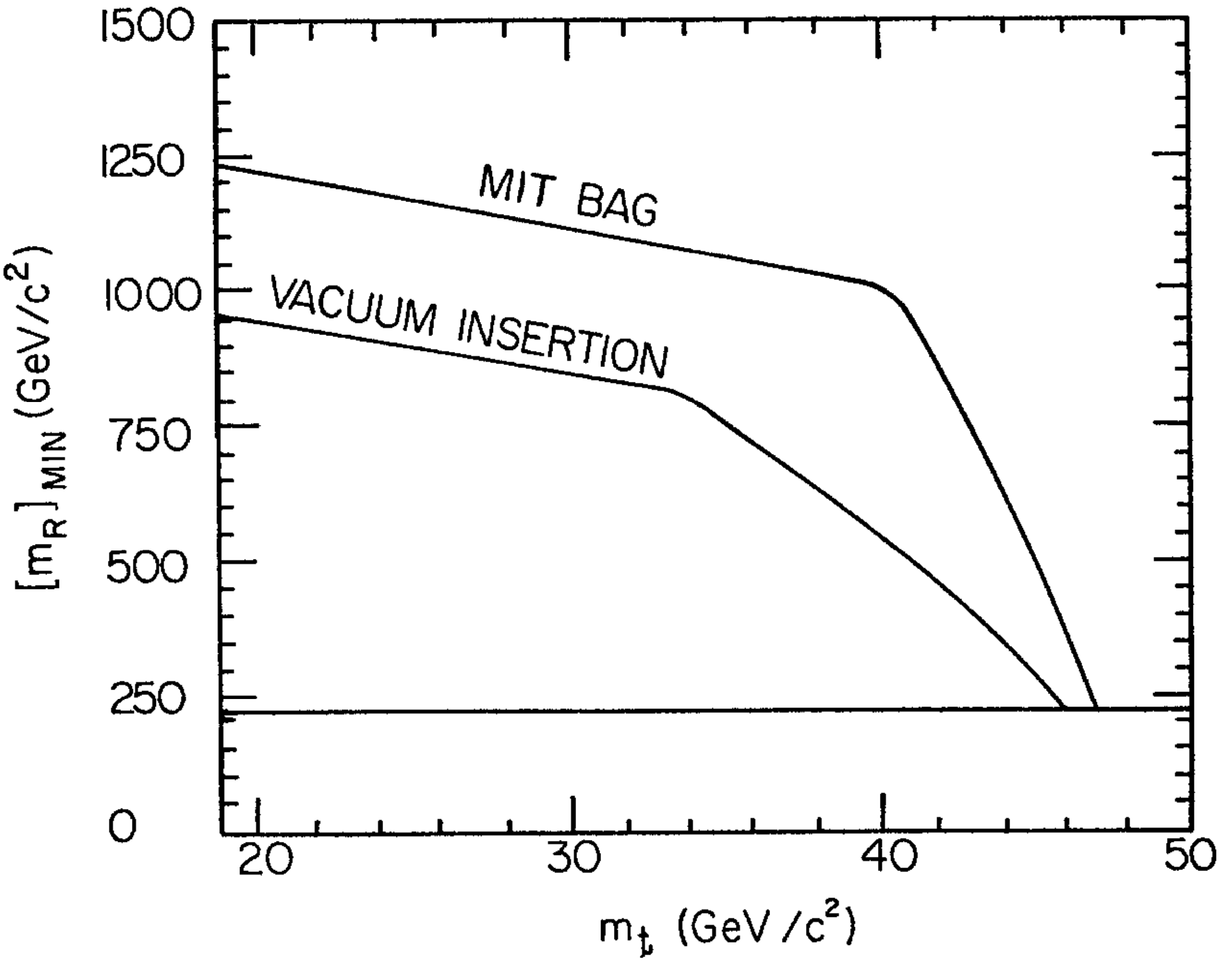


Fig. 2



1500
1250
1000
750
500
250
0
MIT BAG
VACUUM INSERTION
$[m_R]_{MIN}$ (GeV/c^2)
20
30
40
50
m_t (GeV/c^2)

Fig. 3

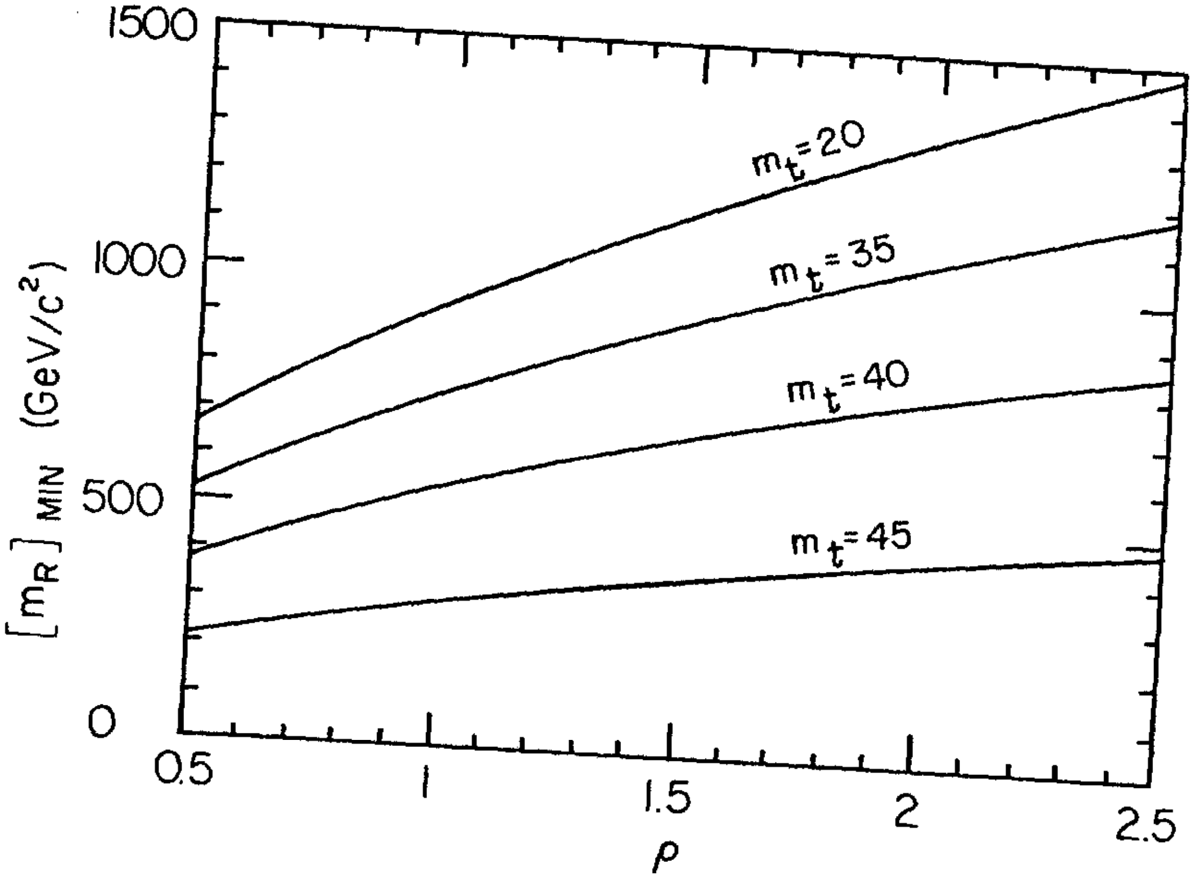


Fig. 4

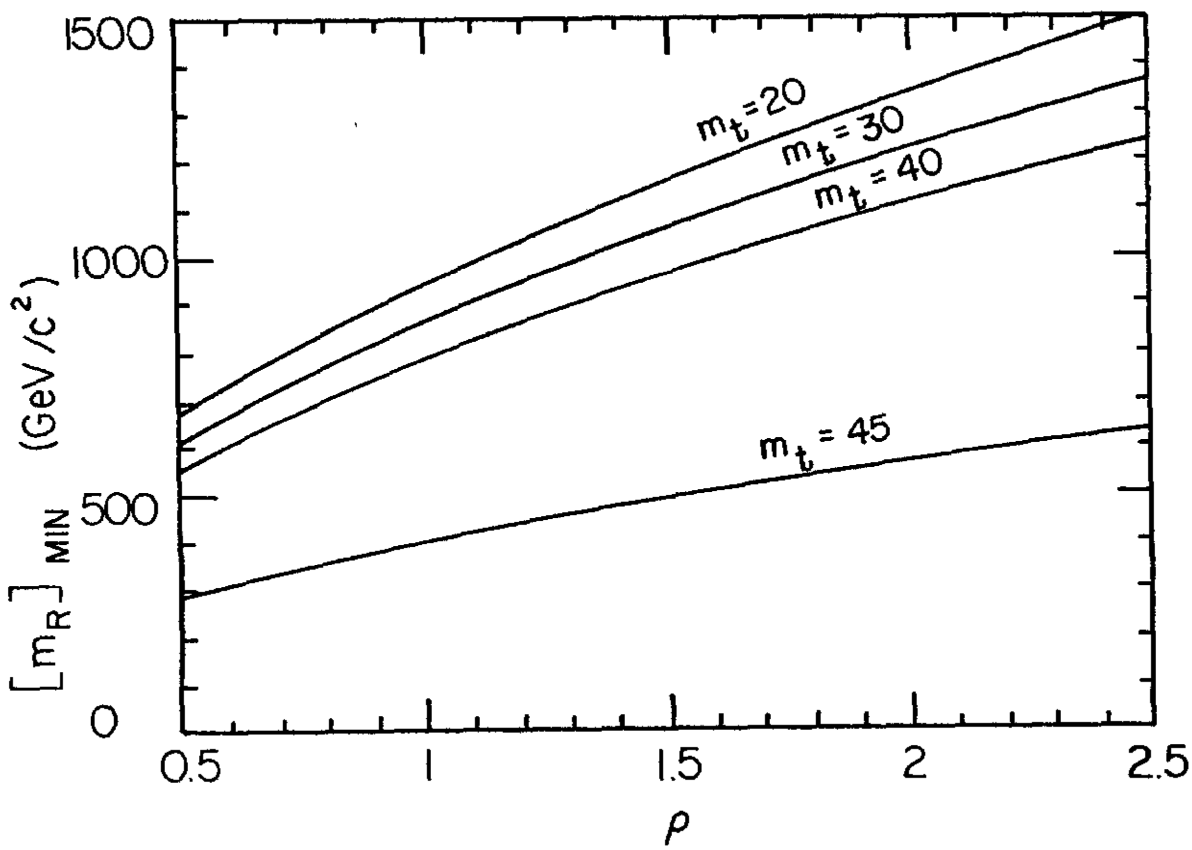


Fig. 5

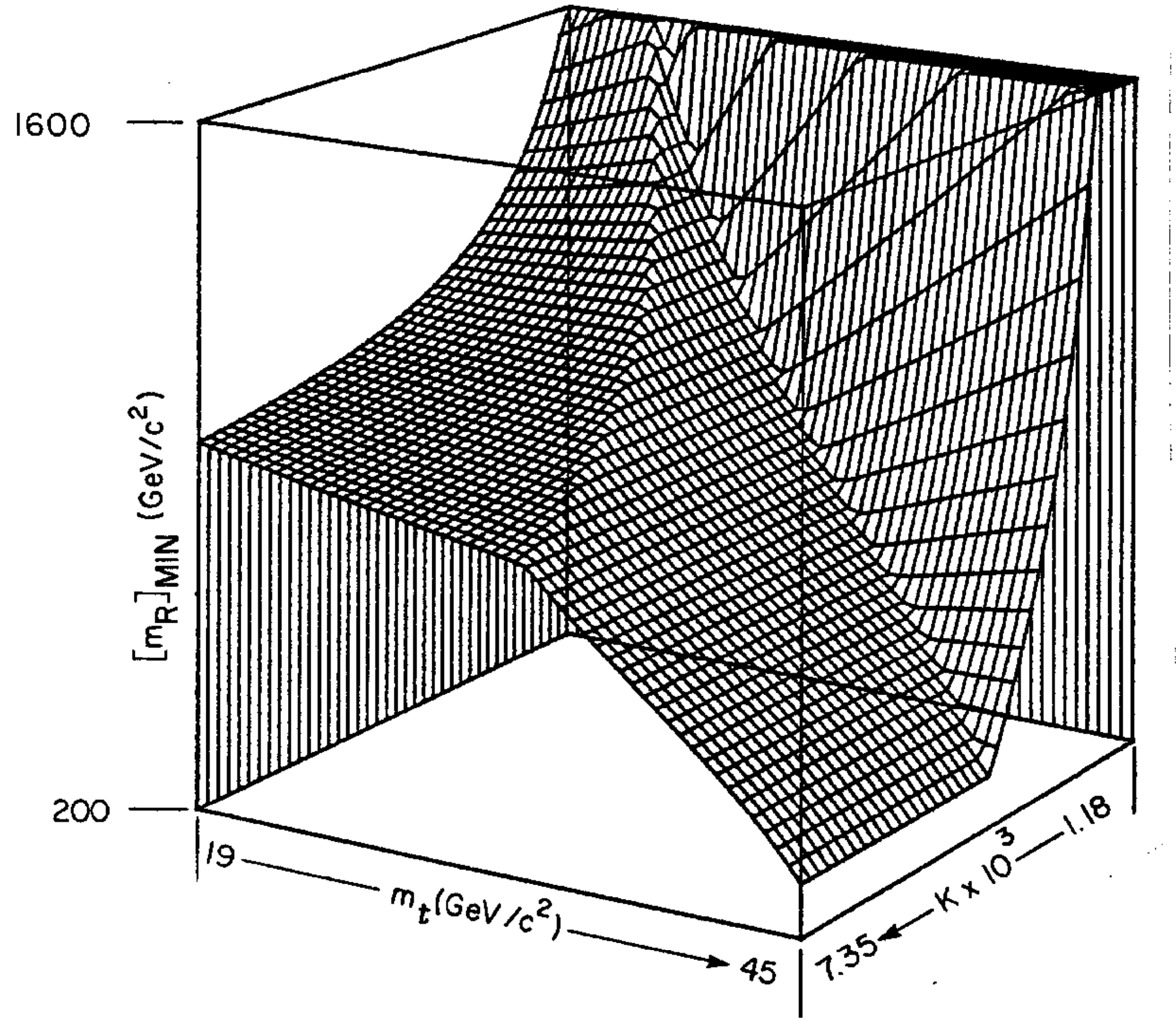


Fig. 6

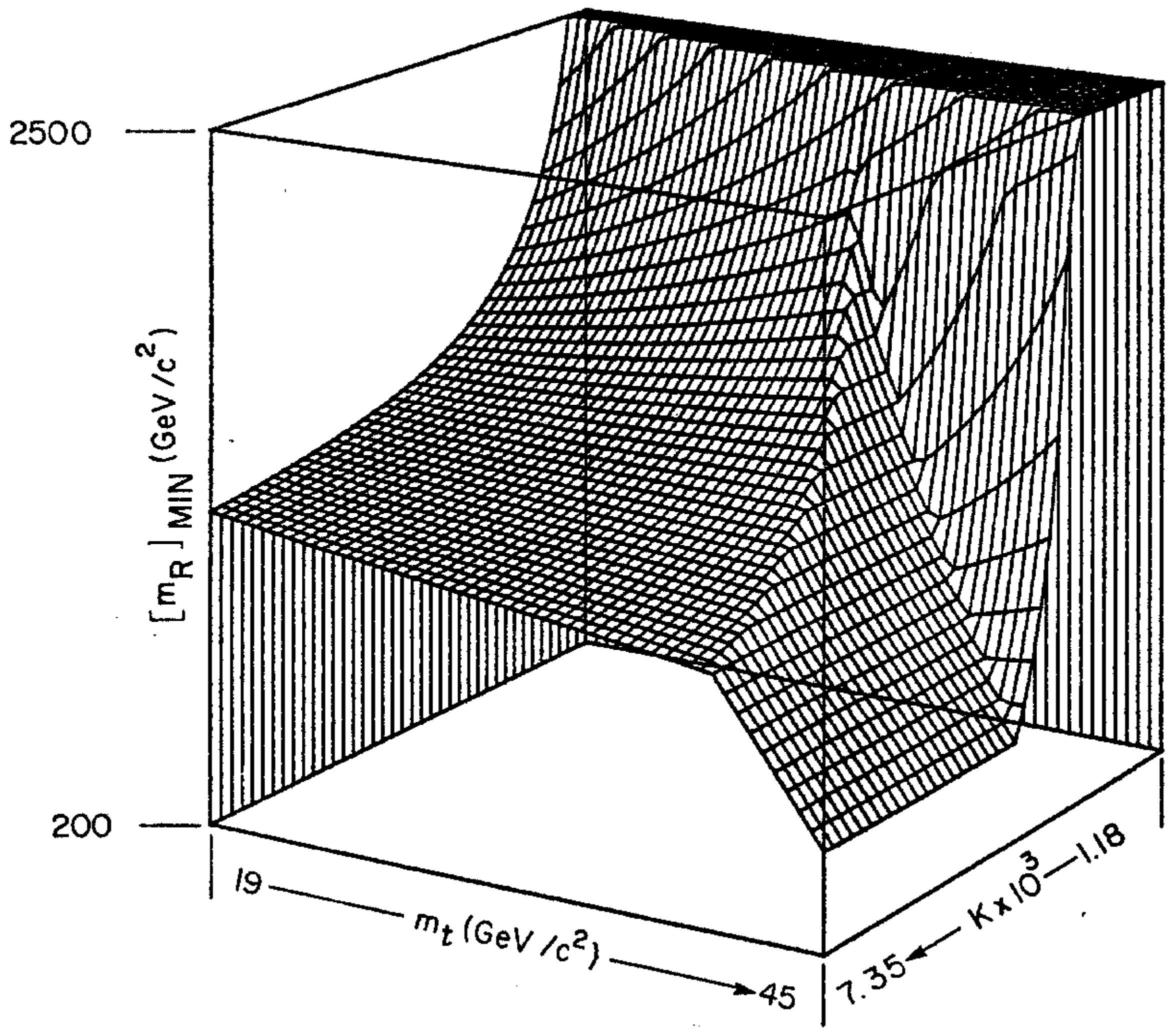


Fig. 7