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FIFTH QUARK AND DIMUON PRODUCTION BY NEUTRINOS*

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ABSTRACT

It is shown that the recent experimental data on dimuon production by neutrinos and antineutrinos, even with currently available statistics and uncertainties, set a severe upper bound on the semileptonic decay branching ratio of a fifth quark, if any. With this semileptonic branching ratio, production of the b quark is suspicious theoretically.

The energy dependence of the cross section ratio of ν- and $\bar{\nu}$-induced reactions and the high y anomaly in $\bar{\nu}$ reaction seem to suggest a heavy quark of a new flavor at effective mass ~ 5 GeV which couples with the leptonic current in right-handed helicity. Another information currently available on such a heavy quark is dimuon production by ν and $\bar{\nu}$. After weak interaction properties of the charmed hadrons are established in e^+e^- annihilation, it is now

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obvious that the dimuon production is due largely to production of the charmed quark and its subsequent semileptonic decay. However, evidence for a fifth quark is rather weak in dimuon production.

The recent experimental results obtained by Caltech-Fermilab group [1] allow us to extract several quantitative and semiquantitative informations on a fifth quark, if any, which are much needed in theory and experiment. Being fully aware of the fact that these data may still be subject to errors due to uncertainties in background subtraction, we have drawn the following conclusion:

(1) The semileptonic branching ratio of the charmed quark (more precisely, stable charmed hadrons averaged over) is determined to be

$$B_c \equiv \Gamma(c \to s_C + \mu^+ + \nu)/\Gamma(c \to \text{all}) = (12.0 \pm 2.4)\% , \tag{1}$$

where the error is statistical only.

(2) Within one standard deviation or so, the charmed quark can explain all of the dimuon production in $\bar{\nu}$ reaction (and, of course, in ν reaction). The fifth quark of the properties as normally postulated can be accommodated if one wishes, but its semileptonic branching ratio times Cabbibo-like angle θ' is bounded as

$$\left\{\Gamma(b \to X + \mu^- + \bar{\nu})/\Gamma(b \to \text{all})\right\} \cos\theta' = (1.5 {}^{+1.9}_{-1.5})\% . \tag{2}$$

These results are derived by assuming exact scaling in parton model. After a brief account of our analysis is given below, we shall discuss on its implications in search for hadrons of this new flavor in e^+e^- annihilation at PETRA/PEP and then look for any possibility to accommodate such a small semileptonic branching ratio in the standard picture of weak interactions. The asymptotic freedom correction will be discussed.

We write the relevant part of weak interactions as

$$L = \sqrt{\tfrac{1}{2}}\ G\ j_\alpha^+ J^\alpha + \text{H.c.}, \qquad (3)$$

where $j_\alpha = \bar{\mu}\gamma_\alpha(1-\gamma_5)\nu$ and

$$J^\alpha = \bar{d}_C\gamma^\alpha(1-\gamma_5)u + \bar{s}_C\gamma^\alpha(1-\gamma_5)c + \bar{b}\,\gamma^\alpha(1+\gamma_5)u\cos\theta' .$$

We work in the scaling parton model where quark masses are introduced in the standard manner ($m_{u,d}$ = 350 MeV, m_s = 500 MeV, m_c = 2 GeV, and m_b = 5 GeV). Because kinematical cuts are made for muons in the data, we have to specify a dynamical mechanism after production to compare theory with experiment. Heavy quarks (c and b), after production through weak currents, slow down by picking up one or two light quarks (u, d, and s) to form physical hadrons, cascade down to states (H) stable against strong and electromagnetic decays, and finally decay semileptonically. (See Fig. 1 for notations.) The energy distribution of H, unlike that of light hadrons fragmented from light quarks, probably peaks toward the high $\bar{x}$ ($= E_H/E_{c,b}$) end since energetic heavy quarks lose little momenta in picking up light quarks and in fragmenting light hadrons. We thus make the simple approximation that heavy quarks do not slow down at all between production and weak decay. For the energy distribution of semileptonic charmed hadron decays, the Ke coincidence experiment at DESY [2] suggests $\ell d\Gamma/d^3\ell \sim \exp(-\ell/a)$ with a = 300 MeV for c and $a = (m_b/m_c) \times$ 300 MeV for b in the rest frame of the decaying hadron H. We have calculated momentum distributions of dimuon on

these assumptions to confirm that the theoretical distributions fit quite nicely experiment [3]. A fragmentation function localized at small $\bar{x}$, similar to that of light particles, leads to a momentum distribution where wrong sign muons are much too soft [4]. All of the following results have turned out to be insensitive to the scale-up factor, m_b/m_c as well as to a possible slow-down factor of a heavy quark.

In the model described above, we obtain the dimuon production cross section through a heavy quark of mass M produced from a light quark as

$$\sigma_{\mu\mu} = 2(G^2/\pi)m_N\,E\,B\int dy\int dx\int (d\Gamma/d^3\ell)d^3\ell/\Gamma \times \left\{\begin{matrix} 1 - M^2/2m_N xE \\ (1-y)(1-y+M^2/2m_N xE) \end{matrix}\right\} xf(x)\,, \qquad (4)$$

where B is the semileptonic decay branching ratio of a heavy quark and one of the two entries should be chosen in the curly bracket according to helicities of quarks and neutrinos. The boundaries of the integrals are set as follows:

$$(\ell\cdot p')\in\left[\text{Max}\left\{m_\mu M,\ (xm_N + Ey - |\underset{\sim}{q}|)\ell\right\},\ \text{Min}\left\{\tfrac{1}{2}M^2,\ (xm_N + Ey + |\underset{\sim}{q}|)\ell\right\}\right],$$

$$\ell\in\left[\text{Max}\left\{E''_{\min},\ \tfrac{1}{2}M(xm_N + Ey - |\underset{\sim}{q}|)\right\},\ \tfrac{1}{2}M(xm_N + Ey + |\underset{\sim}{q}|)\right],$$

(Equation 5 continued)

$$x \in \left[M^2/2m_N Ey,\ \ \mathrm{Min}\left\{ 1,\ \ (M^2/2m_N Ey)(1 + \theta_{max}^2\ E^2(1 - y)/M^2) \right\} \right] ,$$

$$y \in \left[M^2/2m_N E,\ \ 1 \right], \tag{5}$$

where θ_{max} is the maximum deflection angle of right sign muons, E''_{min} is the minimum energy of wrong sign muons, and p' is the heavy quark momentum. For the light quark distribution $xf(x)$, we choose the fit given in [5]. We have tried two other fits [6,7], but all the numbers to be given below do not vary by more than 10% with different choices of $xf(x)$.

The Caltech-Fermilab data are presented in two sets with different cuts in the minimum energy for wrong sign muons. The data with $E''_{min} = 4$ GeV are cleaner because of less contamination due to π and K decays, though a little more liable to uncertainties due to hadron penetration. We have succeeded in fitting perfectly the dimuon production by ν of $E''_{min} = 4$ GeV by choosing the semileptonic branching ratio as

$$B_c \equiv \Gamma(c \to s_C + \mu^+ + \nu)/\Gamma(c \to \mathrm{all}) = (12.0 \pm 2.4)\% , \tag{6}$$

where the error is statisticaly only. (See Fig. 2(a).) This value for B_c is in a good agreement with what we can deduce from the Ke coincidence experiment [2]. Using $B_c = 0.12$, we can fit reasonably well the less cleaner set of data of $E''_{min} = 2.4$ GeV though the data points tend to fall above the theoretical curve roughly by one standard deviation. (See Fig. 2(b).) These successful fits, not only in magnitude, but also in energy dependence, lead us to believe that

in spite of the warning given in [1], systematic errors due to hadron penetration at large energies are rather small in these data.

To fit dimuon production in $\bar{\nu}$ reactions, we must know the normalization of single-muon production by $\bar{\nu}$, since the measurement was made in the ratio $\sigma_{\mu\mu}/\sigma_\mu$. To be consistent, we have used the total cross section measurement by the Caltech-Fermilab group [8]. The energy dependence is parametrized for our purpose as $\sigma_\mu^{(\bar{\nu})}/\sigma_\mu^{(\nu)} = 0.38 + 0.22\ (E - 10)/100$ which goes up linearly to 0.80 at $E = 200$ GeV. With this parametrization and $B_c = 0.12$ as determined above, we have plotted the dimuon production by $\bar{\nu}$ which originates from $\bar{c}$ production (solid curves in Fig. 2(c) and (d)). Except that theory overestimates in the region of $E < 80$ GeV for the data of $E_{min} = 4$ GeV, the $\bar{c}$ contribution alone can explain the data of $E''_{min} = 4$ GeV and 2.4 GeV within one large standard deviation. With the semileptonic branching ratio times $\cos\theta'$ chosen as

$$B_b \cos\theta' = 1.5\% , \tag{7}$$

we can have $(\sigma_{\mu\mu}/\sigma_\mu)$ raised up to broken curves in Fig. 2(c) and (d). Since $\cos\theta'$ must be close to unity to explain the observed $\sigma_\mu^{(\bar{\nu})}/\sigma_\mu^{(\nu)}$ ratio [8] and $\langle y \rangle$ in the scaling model, we obtain

$$B_b = (1.5\ {}^{+1.9}_{-1.5})\% , \tag{8}$$

where the errors are statistical only. We are fully aware of the fact that the data particularly at higher energies may involve large uncertainties due to hadron penetration correction. However, hadron penetration correction can not raise the $\bar{\nu}$ data alone, leaving the ν data as they are, which is needed to increase $B_b \cos\theta'$. Though it is a little overstretching, considering the quality of the data, to take 1.5% seriously, we believe that the upper bound 3.4% contains something worth discussing.

Let us first examine implications of (8) in e^+e^- annihilation. If the Okubo-Iizuka-Zweig rule works, we expect to see narrow $^3S_1$ states of $(b\bar{b})$. But, it is probably impossible to find flavored states such as $(b\bar{u})$ and $(b\bar{d})$: Production of $b\bar{b}$ pairs is 1/3R of the total in contrast to 4/3R for $c\bar{c}$ pairs, the main non-leptonic decay modes of b do not contain any conspicuous signature such as K mesons, and the semileptonic branching is now deduced to be less than 1/4 of that for c. The situation will be worsened by the low counting rate of σ_{tot} which decreases like 1/s.

Let us explore a theoretical side. In order for the semi-leptonic branching to be so small, the nonleptonic decays of b must be enhanced enormously. After fifteen years of work, theorists have come to the understanding that nonleptonic enhancement is due partly to short distance effects, as calculated in the renormalization group method, and partly to long distance effects such as tadpole mechanism, duality enhancement, adjoint representation enhancement, and so forth. For the short distance enhancement, an estimate has been made for c to show that there is only a small enhancement because of the large mass [9]. For the b quark being even heavier than c, there is practically no enhancement at short distances. All of the long distance enhancement are based explicitly or implicitly on existence of low lying mesonic states having relevant flavors. The mesonic states of the b flavor are too heavy to enhance nonleptonic decay modes at long distances. Though the nonleptonic enhancement

mechanisms have not yet been completely understood quantitatively, every argument on enhancement indicates that the semileptonic branching ratio of b should be equal to or larger than that of c. Note that B_b determined in (8) includes effectively the muons due to the cascade decay process

$$b \to u + \bar{s}_C + c, \quad c \to s_C + \mu^+ + \nu . \qquad (9)$$

If the nonleptonic decay rates are comparable for $b \to u + s_C + \bar{c}$ and $b \to u + d_C + \bar{u}$, this cascade process alone would give ~ 6% for B_b, well beyond the limit deduced above.

One way to avoid a large semileptonic branching is to introduce an additional weak interaction of b that dominates over the weak decays obeying universality. However, such an interaction can not be accommodated easily in gauge models except that introducing light Higgs particles might work. An alternative may be to expect that $\cos\theta'$ is not as large as unity. Though $\cos\theta' \simeq 1$ gives the best fit to the single-muon production data in the exact scaling model, $\cos\theta'$ may be smaller if the asymptotic freedom corrections are significant. If we make such a correction following [10], for instance, $\cos\theta'$ is lowered to 0.6 ~ 0.7. This would boost B_b by ~50%, yet far below what we would normally expect for B_b. Such a correction should be subjected to more careful examinations numerically [11]. But, if one brings B_b up to the level of B_c ($\simeq$ 12%) somehow by a different method of asymptotic correction, there would be no need to introduce the b quark at all.

In conclusion, the dimuon production data of Caltech-Fermilab, even with currently available accuracy present a strong case against fifth-quark production. In order to accommodate such production, we must abandon completely our accumulated knowledge of nonleptonic decay enhancement, or else allow such a quark to decay through weak interactions dominant over ordinary W-exchange processes.

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FIGURE CAPTIONS

Fig. 1. Schematic picture of dimuon production.

Fig. 2. Ratios of dimuon vs. single muon productions by neutrinos ((a) and (b)) and by antineutrinos ((c) and (d)). Solid curves are the c quark contributions and broken curves are possible contributions of the b quark. The estimated background have been subtracted from the data given in [1].

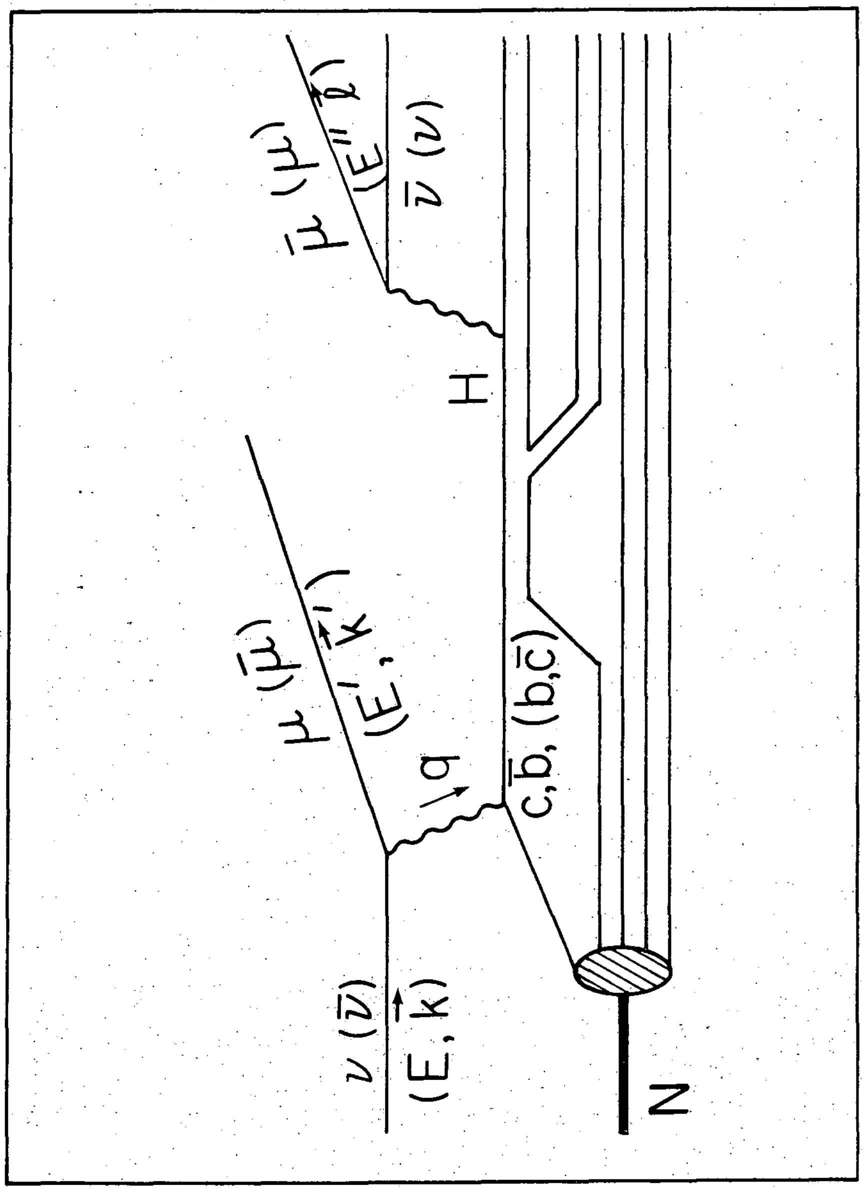

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Fig. 1

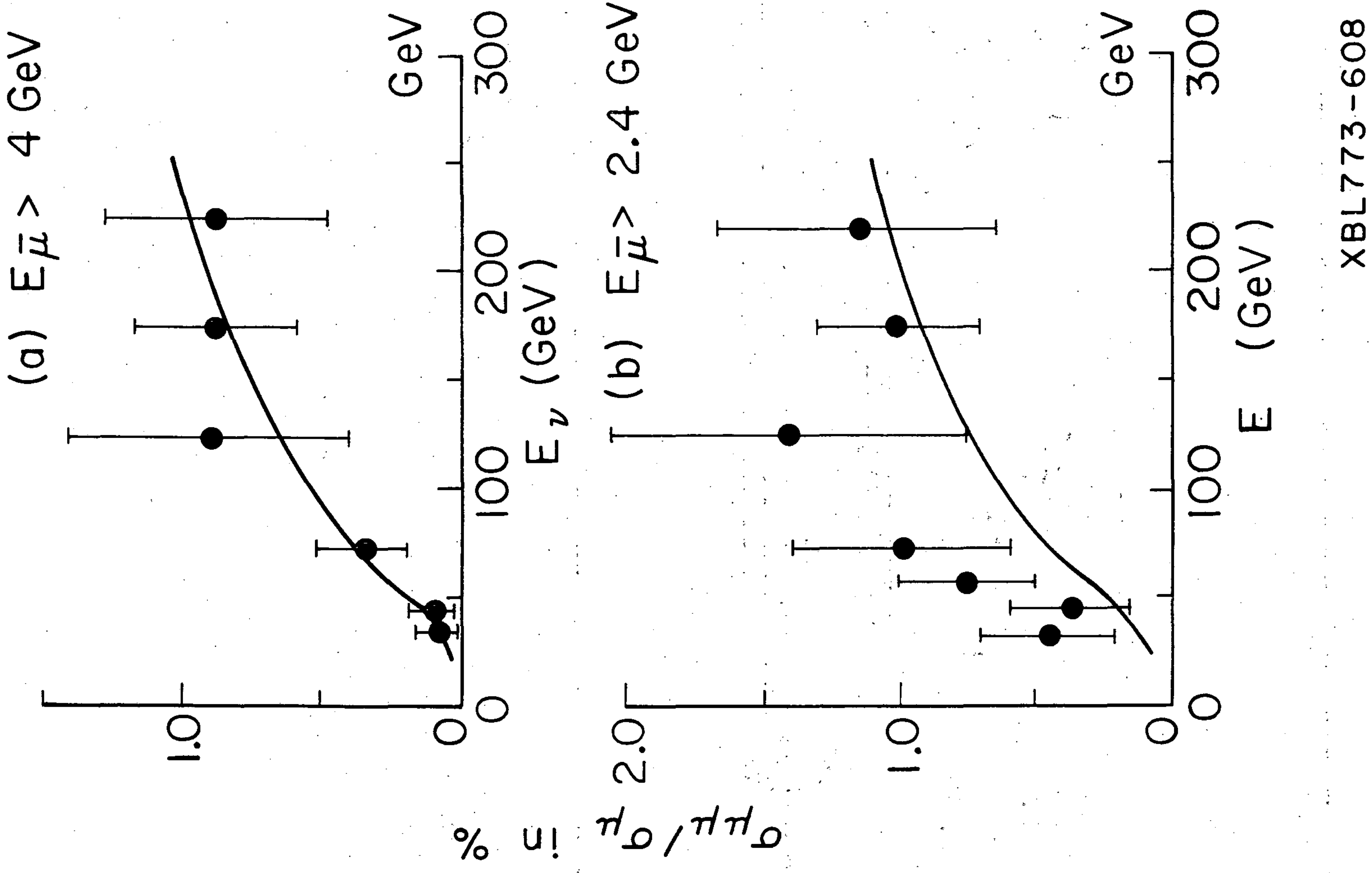
(a) E$_{\bar{\mu}}$ > 4 GeV
(b) E$_{\bar{\mu}}$ > 2.4 GeV
$\sigma_{\mu\mu}/\sigma_{\mu}$ in %
E$_{\nu}$ (GeV)
E (GeV)
GeV
0
100
200
300
1.0
2.0
XBL773-608

Fig. 2 (a + b)

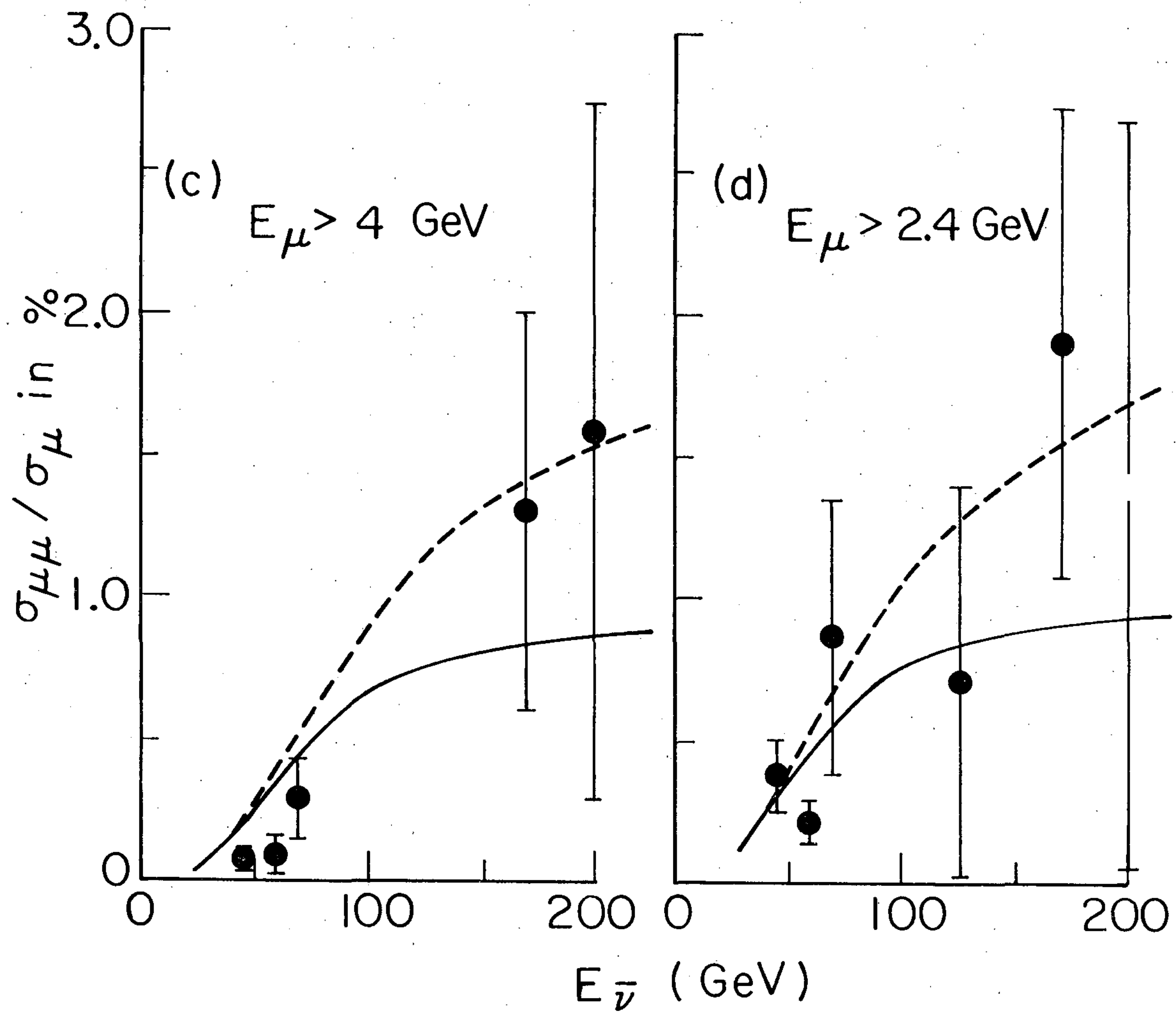

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Fig. 2 (c + d)

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