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# Implications of the $\Upsilon$ States*†

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## ABSTRACT

The $\Upsilon$ family of vector mesons is interpreted as a system of $b\bar{b}$ bound states ($b$ = charge $-1/3$ quark). Implications of the new quark for heavy particle spectroscopy, and for the existence of other possible quarks, leptons, and Higgs particles, are discussed.

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## I. INTRODUCTION

The $\Upsilon$ family discovered at Fermilab[1-3] and confirmed at ISR[4] and DORIS[5-6] implies the existence of a fifth quark "b".[7] It has charge $e_Q = -1/3$. It is very likely a color triplet, just like the first four quarks (u, d, s, c). It may have a heavier $e_Q = 2/3$ partner "t", or a charge -1/3 relative "h".

Alternative interpretations of the $\Upsilon$ family are discussed (and found unlikely) in Sec. II. As a corollary, properties of systems containing quarks of other masses, charges, or color representations than b are noted. Some implications of the new quark for heavy particle spectroscopy are mentioned in Sec. III. The possibilities for still heavier quarks, and for searches for other new particles, are greatly enhanced by the discovery of the b (Sec. IV).

## II. THE $\Upsilon$ AS A $b\bar{b}$ STATE

The signal for the $\Upsilon$ as a $\mu^+\mu^-$ resonance in hadronic interactions was very similar to that of $J/\psi$ at a lower mass: a sharp peak above a rapidly falling continuum. The peak is narrow[5,6] and has at least two higher-mass partners.[1,3] All of these properties are similar to the charmonium system ($J/\psi$, $\psi'$, ...)[8,9] and, indeed, the mass splittings in the two families are remarkably similar. A comparison is shown in Table I($\psi$ masses: Ref. 10; $\Upsilon$ splittings: Refs. 3, 6).

The $\psi$ family is a bound system of a charmed quark c and antiquark.[11,12] This idea was generalized to heavier quarks well before the discovery of the $\Upsilon$.[13,14] Thus, the existence of three narrow levels[13] and the value[13,14] $\Gamma(\Upsilon \to e^+e^-) \backsim 1$ KeV (for $\Upsilon = b\bar{b}$, $e_b = -1/3$) were anticipated. The remarkable coincidence of mass splittings (Table I) was somewhat more of a surprise.[13,15] The large $\Upsilon'$-$\Upsilon$ splitting is not a problem for a "standard" $b\bar{b}$ interpretation[16] of the $\Upsilon$ levels. It has, however, led to some interesting alternative proposals.[17-23]

The only nonrelativistic potential for which the level structure is independent of quark mass is $V(r) = C \ln(r/r_0)$.[23] (This potential was first suggested for charmonium[24] because it gives an orderly decrease of leptonic widths of $n\ ^3S_1$ states in accord with experiment.) "Duality" schemes also give equal 2S - 1S splittings for all vector meson states.[25] Now, equal 2S - 1S splittings for two different families arise from a wide variety of potentials. In the Coulomb + linear example, which has some theoretical underpinnings,[12] $M_{\Upsilon'} - M_{\Upsilon} \simeq M_{\psi'} - M_{\psi}$ when one doubles the strength of the Coulomb force[23,26-29] with respect to the value used in Ref. 13. The nonrelativistic prediction[30] for leptonic widths then increases, since the larger Coulomb interaction pulls the wave function toward the origin. Since relativistic corrections tend to reduce leptonic widths,[26,31,32] this is probably acceptable.

Fig. 1 compares level splittings in two extreme examples with equal $\Upsilon' - \Upsilon$ and $\psi' - \psi$ splittings: the logarithmic potential, and a Coulomb + linear potential. The effects of the Coulomb potential are clearly enhanced as the quark mass increases and hence as the shorter-distance part of the potential is probed. Note the similarity of the 3S levels in the two potentials for the $\Upsilon$ family. A sixth quark (Sec. IV), especially if it gives rise to a new vector meson "$\zeta$"[23] heavier than $\Upsilon$, will distinguish between the two.[33] If there really is a short-distance Coulomb interaction between quarks, the $\Upsilon$ family is telling us that it will be easier to see this interaction (that is, lower quark masses will suffice) than originally anticipated.[34]

Let us discuss some of the evidence that $\Upsilon$ really is a $b\bar{b}$ family. Several points are summarized in Table II.

The narrowness of the $\Upsilon$ may be ascribed to the Okubo-Zweig-Iizuka, et al. (OZI)[35] rule. The $\Upsilon$ then must be below some threshold, indicating the need for new heavy objects. The $\Upsilon$ and presumably the $\Upsilon'$, $\Upsilon''$, ... are then viewed as bound states of these objects.

We have assumed $\Upsilon'$ and $\Upsilon$ are related. They may not be.[21] The decay $\Upsilon' \to \Upsilon$ + hadrons, estimated using scaling arguments[15,36] (sec. III) to be $\simeq$ 40% of all $\Upsilon'$ decays, would provide evidence that $\Upsilon$ and $\Upsilon'$ are members of the same family. Radiative decays $\Upsilon' \to \Upsilon\gamma\gamma$ would be still more conclusive, though rarer.[37]

If the $\Upsilon$ is made of spinless bosons,[17] it is not the ground state. It decays rapidly to the ground state and a photon of energy several hundred MeV (also to hadrons), leaving only a fractional-percent branching ratio to lepton pairs. Preliminary indications[3,38] are that $B(\Upsilon \to e^+e^-)$ exceeds a percent, as expected on the "standard" model.[16] We shall thus assume the constituents of $\Upsilon$ are fermions. In this manner the $\Upsilon$ can be a $^3S_1$ state. Its decay to any lower $^1S_0$ state is presumably at least as rare as that of the $\psi$, probably occuring with a rate well below a percent. (See J.D. Jackson, last of Ref. 12.)

Could the fermions in the $\Upsilon$ have spin 3/2? Then $R \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ above flavor threshold ($\simeq$10½ GeV; see Sec. III) should grow rapidly. I shall assume spin 1/2 quarks.

The quarks in the $\Upsilon$ probably have charge -1/3. This was expected on the basis of production estimates,[16] and is much more likely as a result of the measurement (average of values in Ref. 6)

$$\Gamma(\Upsilon \to e^+e^-) = 1.26 \pm 0.21 \text{ keV} \quad . \tag{1}$$

This value is much more compatible with $e_Q = -1/3$ than with $e_Q = 2/3$ in various specific potential models.[16,23,26-29,32,39] The leptonic widths of $\rho$, $\omega$, $\phi$, and $\psi$ obey a nearly universal law[25,40]

$$\Gamma(\mathscr{V} \to e^+e^-)/e_Q^{\,2} = 11.9 \pm 0.8 \text{ keV} \quad , \tag{2}$$

as shown in Fig. 2.[10,41] The $\Upsilon$ is consistent with this behavior for $e_Q = -1/3$, but not for $e_Q = 2/3$.

Since leptonic widths are proportional to the square of the wave function at the origin,[30]

$$\Gamma(\mathscr{V} \to e^+e^-) = \frac{16\pi\alpha^2}{3} N e_Q^{\,2} |\Psi(0)|^2/M_{\mathscr{V}}^{\,2} \quad , \tag{3}$$

(N = dimension of quarks' color representation) and since

$$|\Psi(0)|^2 = \frac{m_Q}{4\pi} \left\langle \frac{dV}{dr} \right\rangle \quad , \tag{4}$$

one can relate leptonic widths in the $\Upsilon$ family to those in the $\psi$ family if one knows how $\langle dV/dr \rangle$ changes with $m_Q$. This has been done for a restricted class of potentials[39]; the result is a set of lower bounds

$$\Gamma(\Upsilon \to e^+e^-) \geq (0.3, 1.2) \text{ keV} \tag{5}$$

$$\Gamma(\Upsilon' \to e^+e^-) \geq (0.17, 0.63) \text{ keV} \tag{6}$$

for $e_Q = (-1/3, 2/3)$, respectively. These are conservative, based on $m_Q/m_c \geq 2.6$. Most potential models have $m_Q/m_c$ lying between 3 and 4, and Grosse and Martin[42] have established $m_Q - m_c \geq 3.29$ GeV for $m_Q/m_c \geq 3$.

While the experimental result (1) does not permit a distinction between $e_Q = -1/3$ and $2/3$, the measurement of $\Gamma(\Upsilon' \to e^+e^-)$[6] is very helpful. This is because $\Upsilon \to e^+e^-$ probes a terra incognita (the deepest part, in fact, yet seen) of the $Q\bar{Q}$ potential, while the physics of the higher-lying $\Upsilon'$ level is restricted to a much greater degree by information from charmonium, and thus is a better indicator of $e_Q$.[43] Since the measured value for $\Gamma(\Upsilon' \to e^+e^-)$ lies below 0.63 keV, $e_Q$ must be -1/3 (see Fig. 3).

Color sextet quarks[44,18-20] raise predicted leptonic widths by 2 (Eq. (3)), but hadronic widths[18] by 49/2! This is because sextet quarks couple copiously to gluons. The predicted branching ratio for $\Upsilon \to e^+e^-$ is far lower for color sextet quarks, as may be seen in Fig. 4. Here we have used[11,12]

$$\Gamma(\mathscr{V} \to 3 \text{ gluons}) = \frac{160}{81}(\pi^2 - 9)\alpha_s^3 \frac{|\Psi(0)|^2}{M_{\mathscr{V}}^2} \times \begin{Bmatrix} 1 \text{ for color 3 quarks} \\ 49/2 \text{ for color 6 quarks} \end{Bmatrix} \quad (7)$$

and extrapolated $\alpha_s$ from the $\psi$ using asymptotic freedom.[45] We have also taken account of $\Upsilon \to \mu^+\mu^-$, $\Upsilon \to \tau^+\tau^-$, and $\Upsilon \to \gamma \to$ hadrons, assuming $R = 4$[5,6] for the last process. With $e_Q = -1/3$, $B(\Upsilon \to e^+e^-)$ is about 0.4% for color sextets, and nearly ten times that value for color triplets.

Color sextet quarks are more strongly bound in QCD; this is one reason they were suggested for the $\Upsilon$ states. The stronger binding spreads apart the 1S and 2S levels.[18-20] It also packs more narrow $^3S_1$ levels below flavor threshold; for color triplet quarks one estimates[46] three or possibly four levels (Sec. III) while one specific sextet model[18] predicts five.

If the jump in R above flavor threshold can be measured precisely enough, and if no other quark or lepton thresholds lie in the same region, both $e_Q$ and N follow:

$$\Delta R = e_Q{}^2 N = \begin{Bmatrix} 1/3 \\ 2/3 \\ 4/3 \\ 8/3 \end{Bmatrix} \qquad \text{for } (e_Q, N) = \begin{Bmatrix} (-1/3, 3) \\ (-1/3, 6) \\ (2/3, 3) \\ (2/3, 6) \end{Bmatrix} .$$

If the $\Upsilon$ were composed of color sextet quarks, these could not be stable when incorporated singly into hadrons. Two experiments[47] indicate the cross section for production of particles of mass $M \simeq M_\Upsilon/2 \simeq 5$ GeV/c$^2$ with lifetimes more than $5 \times 10^{-8}$ sec. is less than 1/10 that of the $\Upsilon$ at 400 GeV/c. To enable sextet quarks to decay, one would have to introduce a new vector boson carrying both color and flavor.

The ratio of $\Upsilon'$ to $\Upsilon$ leptonic widths has been quoted as[6]

$$\frac{\Gamma(\Upsilon' \to e^+e^-)}{\Gamma(\Upsilon \to e^+e^-)} = \begin{Bmatrix} 3.4 \pm 0.9 \text{ (DESY-Heidelberg)} \\ \approx 3 \text{ (DASP II)} \end{Bmatrix} \tag{8}$$

This ratio can be used to extract $|\Psi_{2S}(0)|^2/|\Psi_{1S}(0)|^2$ with the help of (3). Fig. 5 shows the corresponding ratios for $\rho$ and $\rho'$,[48] $J/\psi$ and $\psi'$,[10] and $\Upsilon$ and $\Upsilon'$,[6] along with the predictions for various potentials. A trend toward Coulomb-like behavior is clearly visible as $m_Q$ increases (hence as the quark Compton wavelength decreases, probing shorter distances).

## III. HEAVY PARTICLE SPECTROSCOPY

How good is the nonrelativistic approximation for $Q\bar{Q}$ systems? Fig. 6 gives an example based on the logarithmic potential.[23] The kinetic energy in this potential is a constant $\simeq$ 370 MeV, whatever the quark mass. Relativistic corrections are still appreciable at the $\psi$, but die away rapidly above the $\Upsilon$. Heavy quarks thus could be a boon to nonrelativistic spectroscopy. In particular, the $\Upsilon$ system should allow reliable reconstruction of a $Q\bar{Q}$ potential via inverse methods.[43]

The $\psi'$ [9] was difficult to observe in hadronic interactions, but the $\Upsilon'$ appeared almost directly with the $\Upsilon$. Production ratios at 400 GeV/c are[3]

$$B_{\mu\mu}\frac{d\sigma}{dy}\Big|_{y=0}(\Upsilon : \Upsilon' : \Upsilon'') = 1 : (0.30 \pm 0.03) : (0.155 \pm 0.016) \quad . \tag{9}$$

(These agree with estimates of Ref. 25 and Ellis, et al., Ref. 16). Figs. 4 and 7, the latter incorporating some scaling arguments,[23,36,37,49] show why the $\Upsilon'$ was relatively more prominent than the $\psi'$. The $\Upsilon$ leptonic branching ratio is expected to be about half that of the $\psi$; the leptonic branching ratio of the $\Upsilon'$ could approach nearly double that of the $\psi'$. Moreover, the production ratios of the two states could be more similar for $\Upsilon'$ and $\Upsilon$ than for $\psi'$ and $\psi$. The ratio $m_{\Upsilon'}/m_{\Upsilon}$ is much closer to 1 than $m_{\psi'}/m_{\psi}$ (important if production cross sections behave as a power law), and the higher flavor threshold for the $\Upsilon$ system allows the 2S states of the $\Upsilon'$ family to be fed by a cascade[50,51] from higher quasi-stable C = + states. This is impossible for $\psi'$ production. (The cascade mechanism appears to account for some but certainly not all $\psi$ production.[52])

The successful description[16,25] of the ratio (9) removes one of the major reasons for suggesting that the $\Upsilon'$ and $\Upsilon$ are made of different quarks.[21] In fact, it appears <u>difficult</u> to obtain the $\Upsilon'/\Upsilon$ ratio (9) if both states are $^3S_1$ ground states of two different $Q\bar{Q}$ pairs.

Decays of the $\Upsilon$ will be reviewed elsewhere.[6,53] Expectations for decays of excited $b\bar{b}$ systems have been set forth in Ref. 37. These should be richer than in charmonium because of the higher threshold. One can prove[46] semiclassically for an arbitrary potential that the number $n_{Th}$ of narrow $^3S_1$ $Q\bar{Q}$ levels below flavor threshold is

$$n_{Th} = a(m_Q/m_c)^{1/2} \quad ; \tag{10}$$

with $a \simeq 2$ since charm threshold lies just above the second $^3S_1$ $(c\bar{c})$ level. For $m_b/m_c$ between 3 and 4, $n_{Th} = 3$ or 4, corresponding to $E_{Th} \simeq 10\frac{1}{2}$ GeV (Fig. 1).

New quark flavors may be produced by photons with somewhat greater ease than in hadronic reactions. Estimates still are somewhat model-dependent,[54] but encouraging nonetheless.

## IV. EXPECTATIONS FOR NEW OBJECTS

Even before charm had been confirmed, it was becoming apparent that more than four leptons and the four corresponding quarks <u>had</u> to exist.

1. There was an indication of a new heavy lepton with $M \simeq 1.8$ GeV. $\sigma(e^+e^- \to \text{hadrons})$ was too large above the supposed "charm" threshold to be due to charm alone, and evidence specifically in favor of the lepton came from production of $\mu^\pm e^\mp$ pairs at SPEAR.[55]

2. The new lepton unbalanced the quark-lepton analogy that had been one of the motivations of charm. A popular means of dealing with this situation[7,56] was to introduce a new quark doublet $\begin{pmatrix} t \\ b \end{pmatrix}_L$ to go with $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$. Here $e_t = 2/3$.

3. Models attempting to retain triplets of quarks: (u,d,s); (c,b,h) were proposed.[57] These had extra $e_Q = -1/3$ quarks. Their main justification (in retrospect) seems to have been aesthetic: some of them were based on exceptional groups, which had the property of limited rank and hence limited representation size.

The central question in such models seems not to be whether there is a sixth quark, but what its charge and mass are. A property of both models[56,57] is their tendency to introduce a new charged lepton for every charge -1/3 quark. Hence if a fourth charge -1/3 quark is discovered, the temptation will be great to look for a fourth lepton, and vice versa, regardless of the specific model.

One prediction of the mass of the sixth quark,[58] based on an eight-quark model, fills in a $t\bar{t}$ state just below 30 GeV. Within the confines of six quarks, $m_t$ cannot be predicted, though an estimate of $m_b$ has been made[59] using a highly appealing and economical SU(5) model.[60]

The relative strengths of weak decays of the b quark to u and c can be measured[61]; these constrain models, but don't immediately distinguish between the "quark-doublet" and "quark-triplet" alternatives. The $b \to c$ and $b \to u$ decays could provide a massive weak current, whose importance for particle production of new particles (such as heavy leptons) has been stressed previously.[62]

We conclude by noting that b-quarks and their likely heavier relatives can be copious sources of the long-sought Higgs bosons, both neutral[63,64] and charged.[65,66] For quark masses at the highest PETRA and PEP ranges, the prospects are encouraging if the Higgs bosons are light enough (and if they exist at all!).

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Table I. Comparison of ψ and T Families

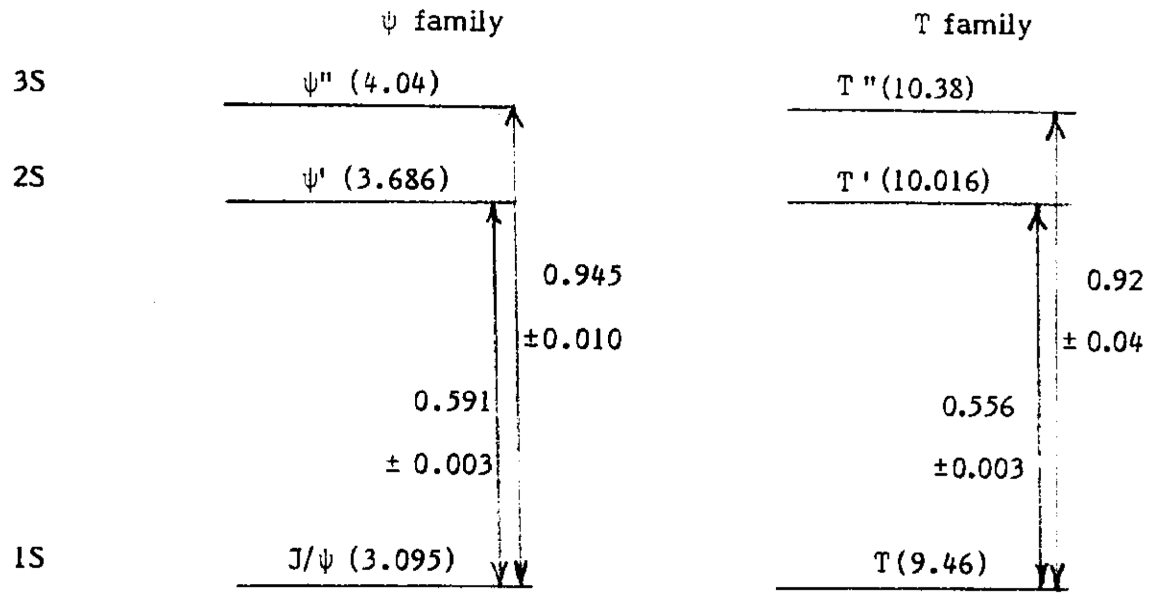



Table II. Evidence that $T = b\bar{b}$

(b = charge -1/3 color triplet quark)

| | | | | |
|---|---|---|---|---|
| Hypothesis | T is a bound state of new objects | New objects are fermions (quarks) | Quarks have $e_Q = -1/3$ | Quarks are color triplets |
| Motivation | Narrow width; (Ref. 35) Similarity of ψ, T families (Table I) | Large (few %) leptonic branching ratio (Refs. 3,38) | $\Gamma(T \to e^+e^-)$ (Refs. 16, 23, 26-29, 32, 39); Universal $\Gamma/e_Q^2$ (Refs. 25, 40, 41, Fig. 2) | Large (few %) leptonic branching ratio (Refs. 3, 37) |
| Further tests | $T' \to T + \ldots$ implies T and T' are related (Rate ests.: Refs. 35, 36) | $\Gamma(T \to 0^+\gamma)$ big; $B(T \to e^+e^-)$ small if T made of bosons (Ref. 17) | If $\Gamma(T' \to e^+e^-)$ < 0.6 keV, $e_Q$ must be -1/3 (Ref. 39) [fulfilled (Ref. 6)] | $B(T \to e^+e^-)$ < ½% for color sextet, $e_Q = -1/3$ (Ref. 18) |

FIGURE CAPTIONS

Fig. 1: Comparison of level splittings in two quarkonium potentials as functions of quark mass $m_Q$. Solid lines: $V(r) = -0.56/r + 0.163\,r$. Dashed lines: $V(r) = 0.733 \ln r$. (Units are in GeV or $\mathrm{GeV}^{-1}$.) [ Note added: the experimental $\psi' - \psi$ and $\Upsilon' - \Upsilon$ splittings can be reproduced with $V(r) = -0.507/r + 0.17\,r$, i.e., with $\alpha_s = 0.38$. ]

Fig. 2: Leptonic widths $\Gamma_{e^+e^-}$ (Refs. 10, 42) normalized by squares of quark charges $e_Q^2$, as functions of vector meson mass $M_{\mathscr{V}}$.

Fig. 3: Lower bounds for leptonic widths of $\Upsilon$ and $\Upsilon'$ (Ref. 39), together with data presented at this conference (Ref. 6). The shaded area represents the range of predictions of twenty potentials reproducing the $\psi$ and $\psi'$ masses and leptonic widths, for $e_Q = -1/3$. Solid and dashed lines correspond to lower bounds for $e_Q = -1/3$ and 2/3, respectively. Eq. (1) and $\Gamma(\Upsilon' \to e^+e^-) = 0.36 \pm 0.09$ keV used.

Fig. 4: Predicted leptonic branching ratios for quarks of various charges (-1/3, 2/3) and colors (3, 6): $B = [\Gamma_h/\Gamma_\ell + 7]^{-1}$, with $\alpha_s$ extrapolated from $\psi$ using asymptotic freedom (Ref. 45).

Fig. 5: Ratios of 2S and 1S squares of wave functions at the origin for various potentials: 2 for oscillator, 1 for linear, $\sim 0.5$ for logarithmic, and 1/8 for Coulomb.

Fig. 6: Magnitude of relativistic corrections as a function of quark mass in a logarithmic potential.

Fig. 7: Branching ratios for $\mathscr{V}' \to e^+e^-$ (left-hand scale; lower $\psi'$ point) and $\mathscr{V}' \to \mathscr{V}$ + hadrons (right-hand scale; upper $\psi'$ point) as functions of quark mass. Color triplet quarks and $\Gamma(\mathscr{V}' \to e^+e^-) = 5e_Q^2$ keV assumed. [ cf. universality in Fig. 2; the coefficient is chosen

to reproduce $\Gamma(\psi' \to e^+e^-)$. ] All $\mathcal{Y}'$ widths proportional to $|\Psi(0)|^2$ scaled accordingly. Radiative $\mathcal{Y}'$ widths scaled via $e_q^{\,2}(M_{\mathcal{Y}'}/M_\psi)^{-1}$ from assumed $\psi'$ value of 60 KeV. (See Refs. 37, 23, 15). Hadronic widths scaled from $\Gamma(\psi' \to \psi + \text{hadrons}) = 124$ keV via $(M_{\mathcal{Y}'}/M_\psi)^{-2}$. (See Ref. 36)

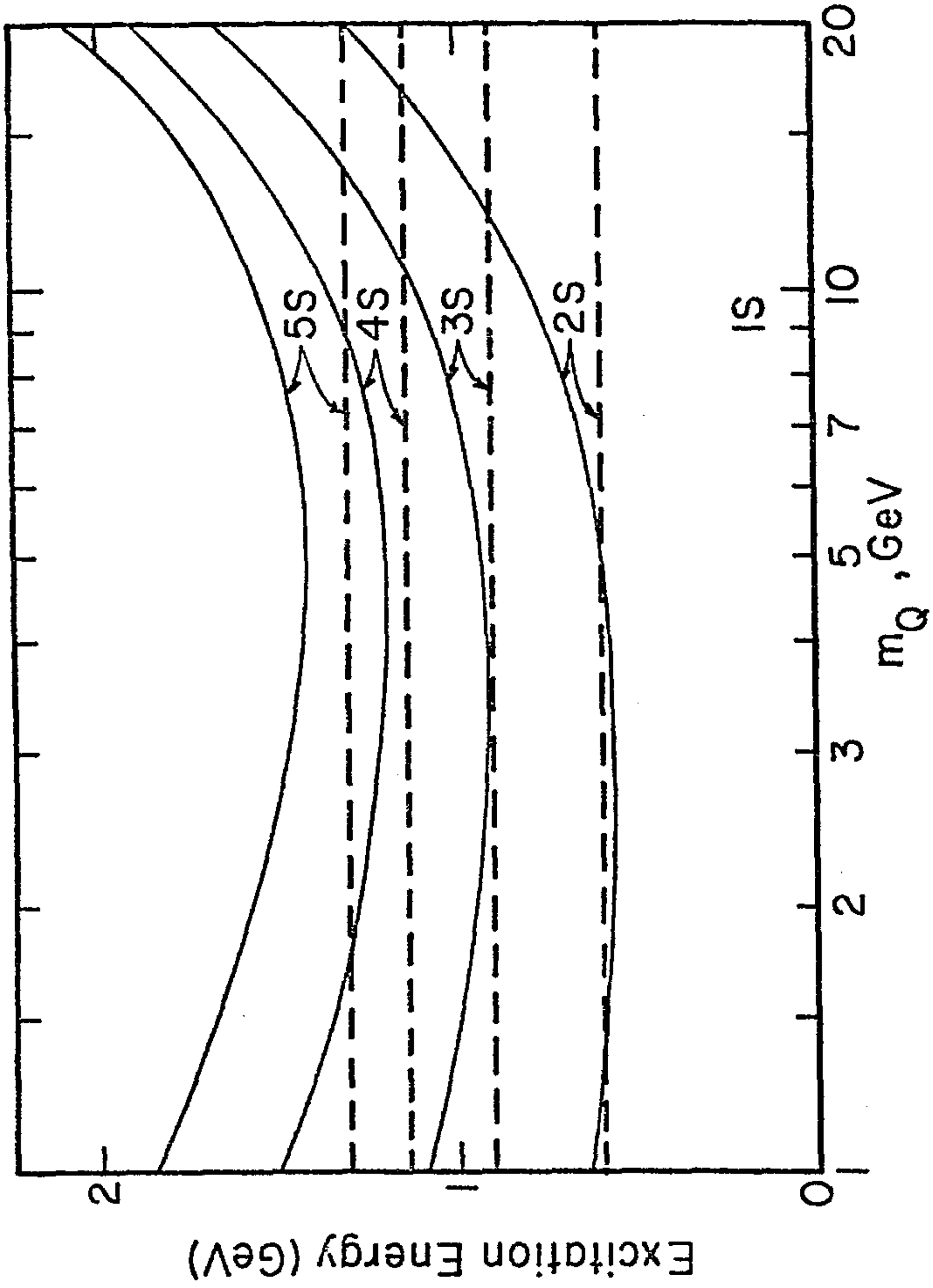



Figure 1

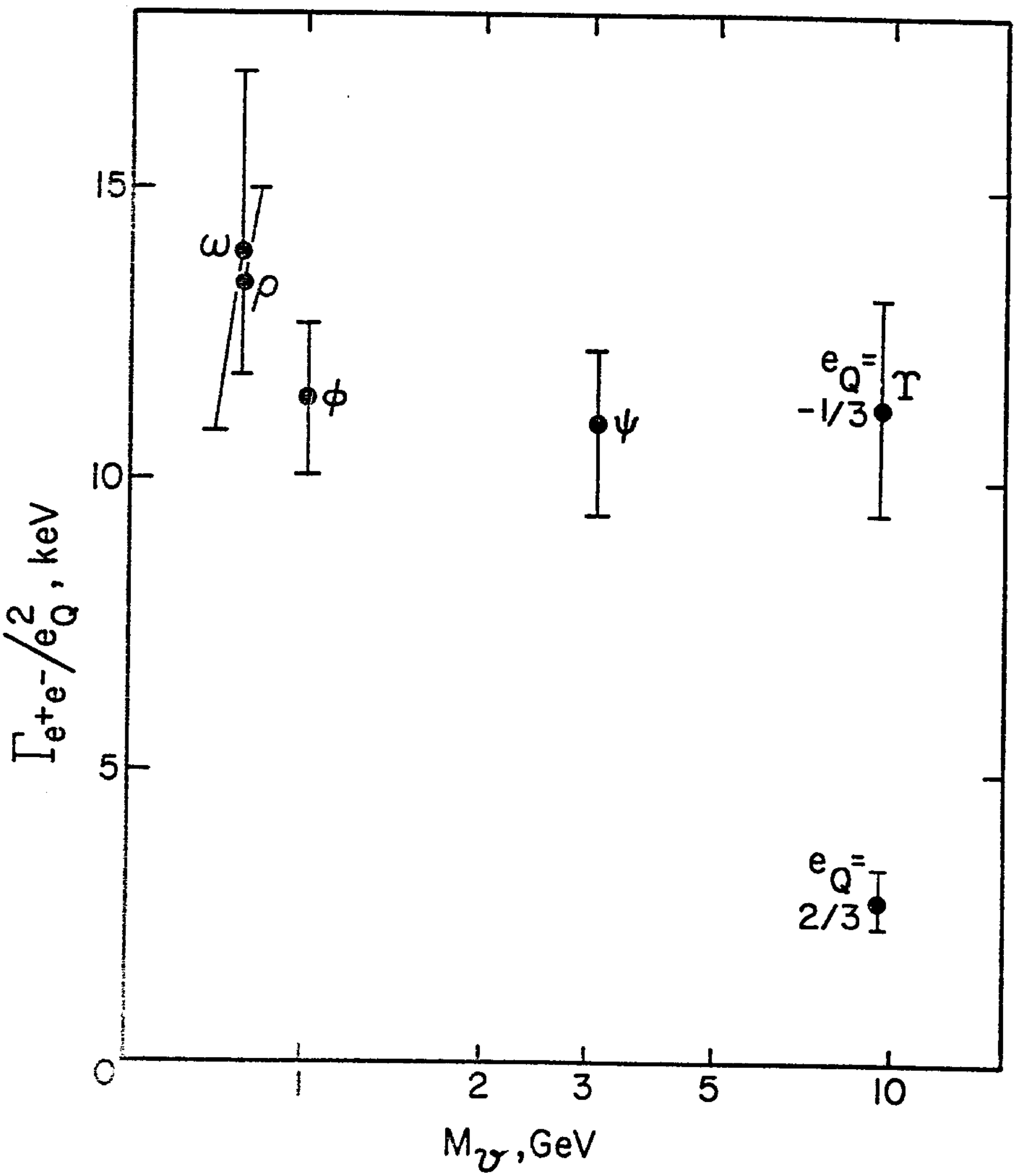



Figure 2

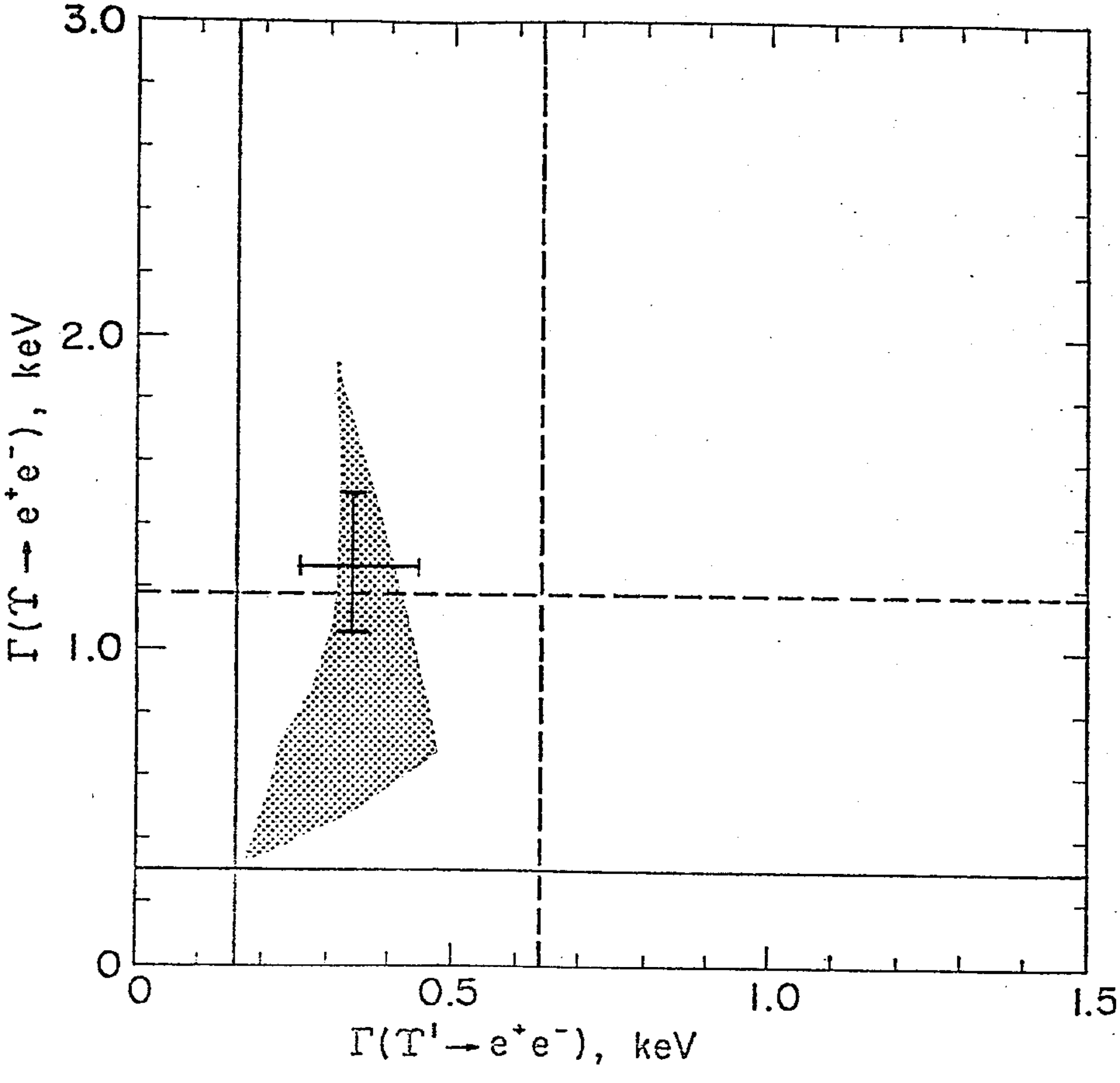



Figure 3

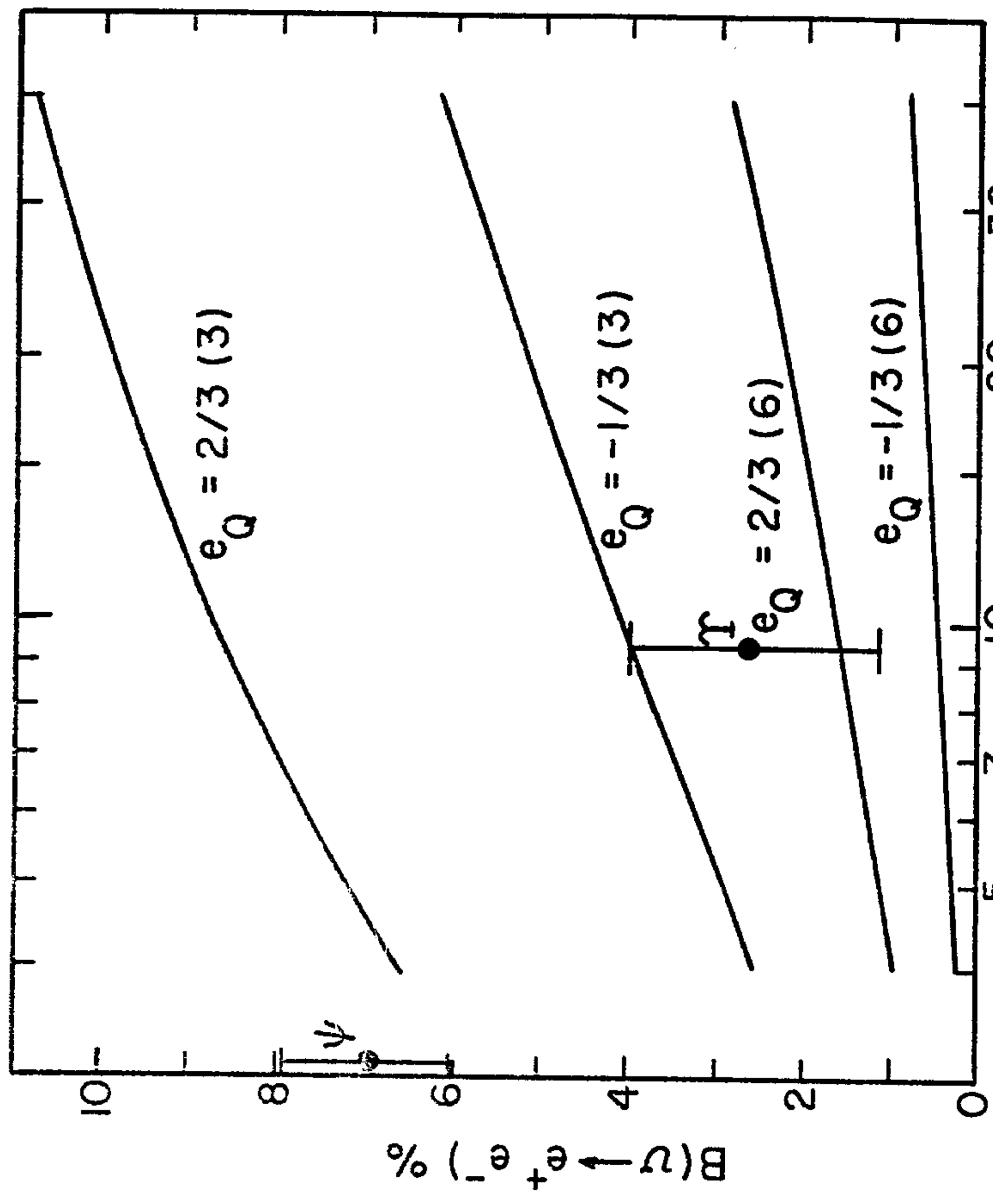
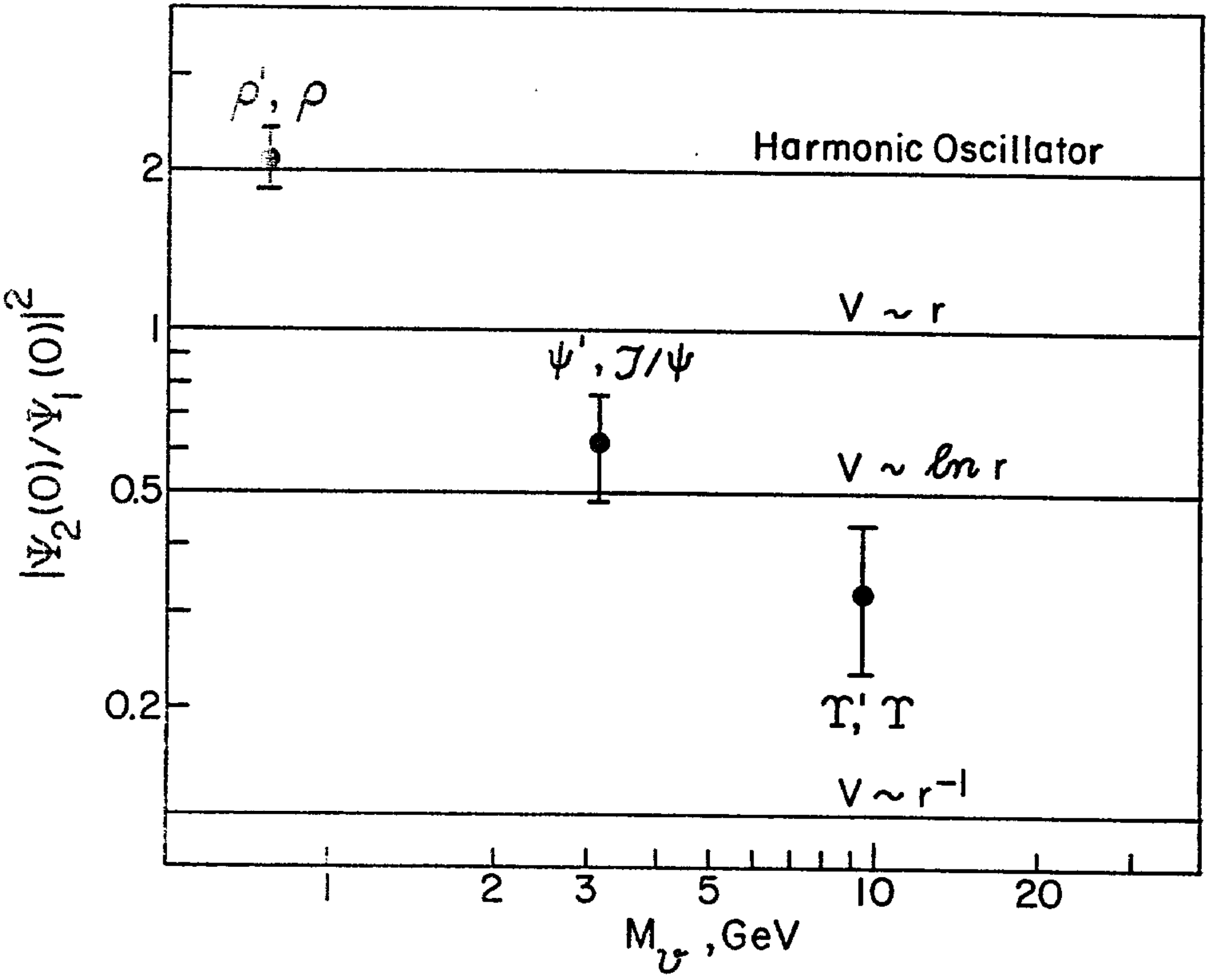



Figure 4



ρ', ρ
Harmonic Oscillator
V ~ r
ψ', J/ψ
V ~ ln r
ϒ', ϒ
V ~ r⁻¹
2
1
0.5
0.2
|Ψ₂(0)/Ψ₁(0)|²
1
2
3
5
10
20
M_V , GeV


Figure 5

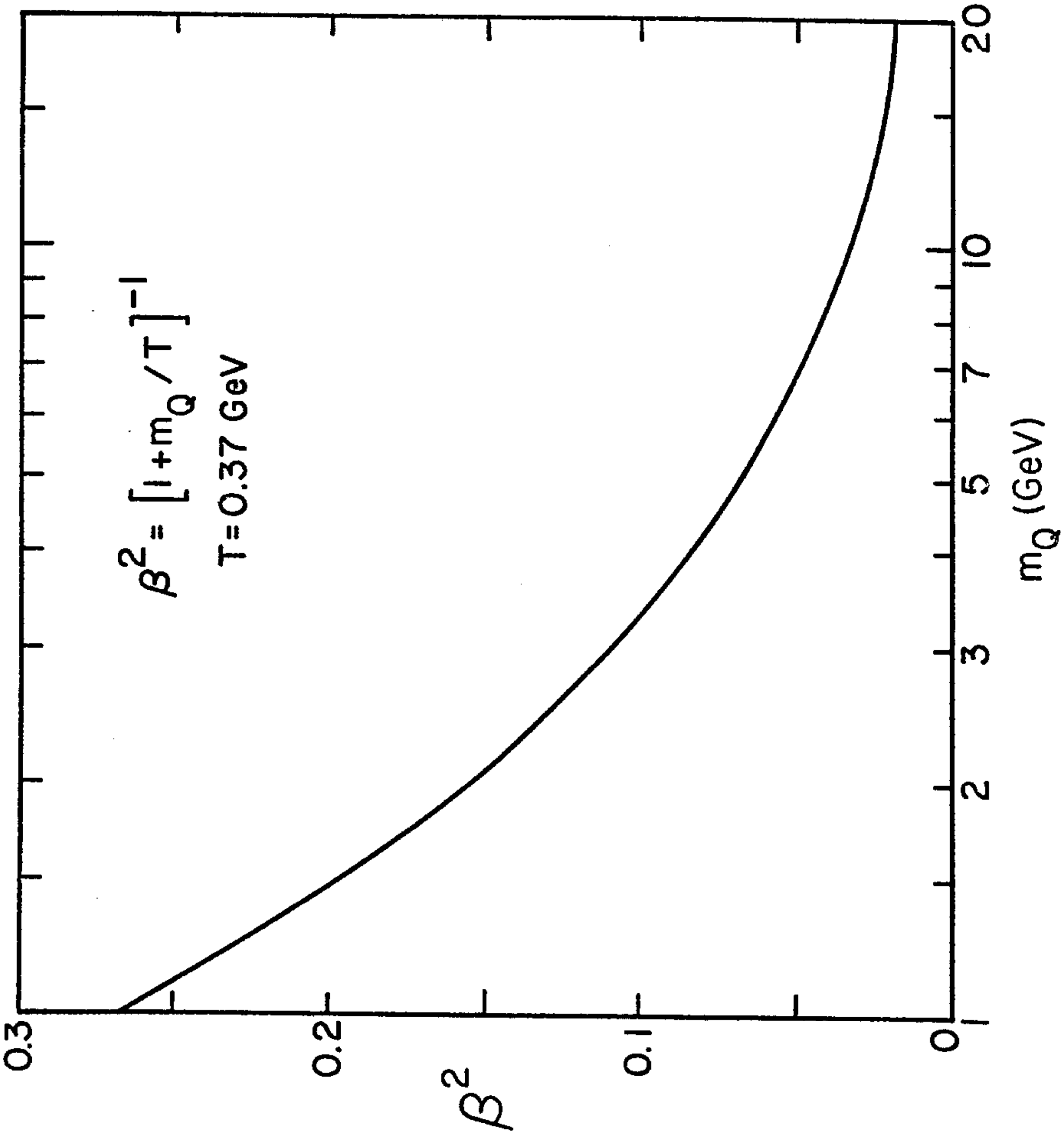



Figure 6

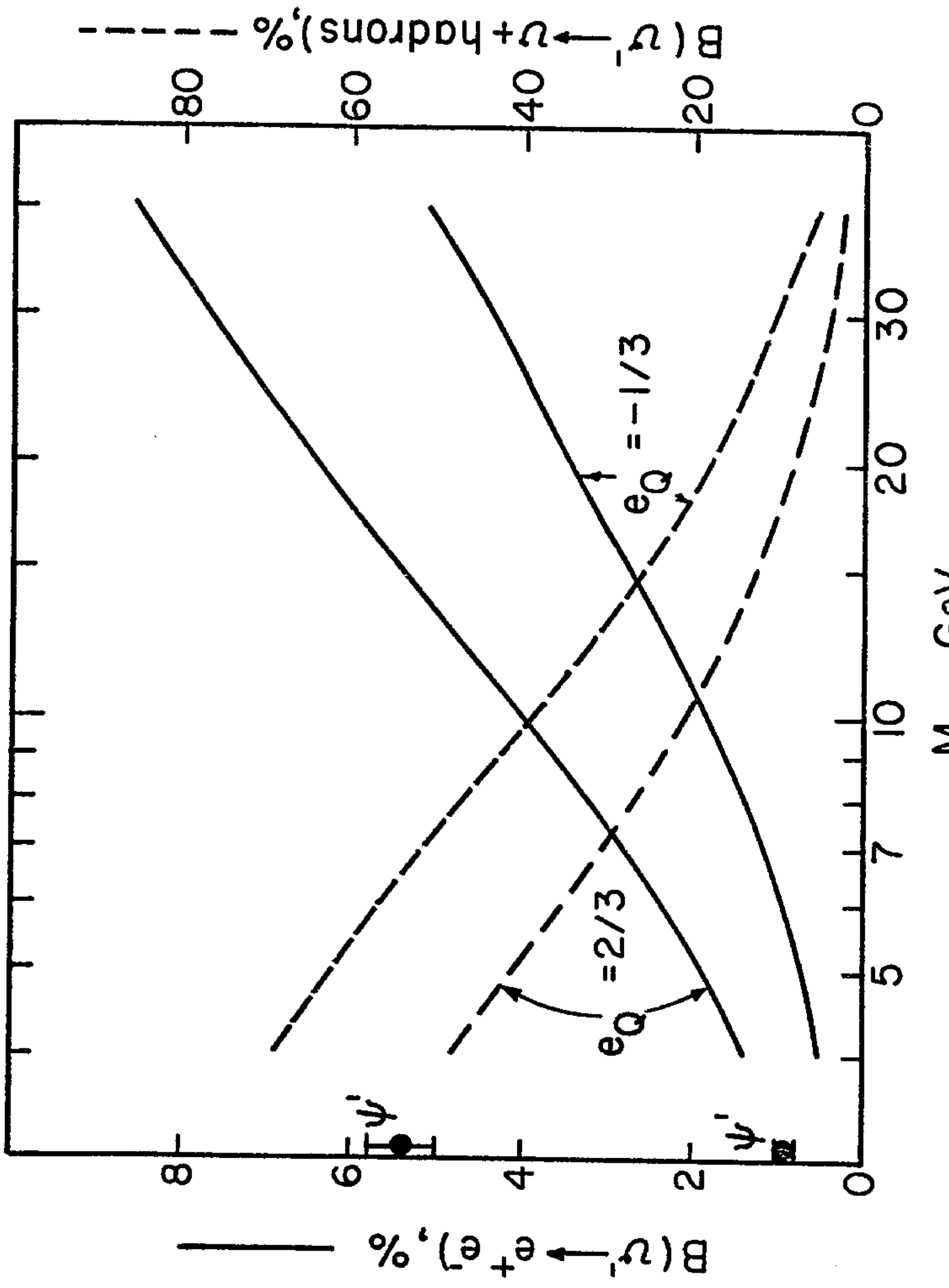



Figure 7

Table III. Properties of vector mesons with established leptonic decays

| Meson | Quark content | $e_Q^2$ | $\Gamma_{e^+e^-}$, keV | $\Gamma/e_Q^2$, keV |
|---|---|---|---|---|
| $\rho(776)$ | $(u\bar{u} - d\bar{d})/\sqrt{2}$ | 1/2 | 6.7 ± 0.8 | 13.4 ± 1.6 |
| $\omega(783)$ | $(u\bar{u} + d\bar{d})/\sqrt{2}$ | 1/18 | 0.77 ± 0.17 | 13.9 ± 3.1 |
| $\phi(1020)$ | $s\bar{s}$ | 1/9 | 1.27 ± 0.07 | 11.4 ± 1.3 |
| $\psi(3097)$ | $c\bar{c}$ | 4/9 | 4.8 ± 0.6 | 10.8 ± 1.4 |
| | Average $\Gamma/e_Q^2$ for $\rho, \omega, \phi, \psi$: | | | 11.86 ± 0.79 |
| $\Upsilon(9460)$ | $b\bar{b}$ | 1/9 | 1.3 ± 0.4 | 11.7 ± 3.6 |
| | $t\bar{t}$ | 4/9 | | 2.9 ± 0.9 |

Table IV. Ratios $\Gamma(3g)/\Gamma(e^+e^-)$ in QCD

| $N_c$ \ $e_Q$ | -1/3 | 2/3 |
|---|---|---|
| 3 | $(5.78\times 10^3)\alpha_s^3$ | $(1.44\times 10^3)\alpha_s^3$ |
| 6 | $(7.07\times 10^4)\alpha_s^3$ | $(1.77\times 10^4)\alpha_s^3$ |