M. I. Vysotskii, A. D. Dolgov, and Ya B. Zel'dovich. Cosmological limitations on the mass of neutral leptons. In connection with the discovery of the charged lepton, it is shown that cosmological considerations limit the mass

M. A. Shifman. Charmonium and asymptotic freedom. We are witnessing the development of a new hadron theory. Dubbed quantum chromodynamics, this is a renormalizable theory of the Yang-Mills type, in which the interaction is realized by an octet of massless vector gluons connected with the color degrees of freedom of the quarks. A unique property of quantum chromodynamics is a logarithmic decrease of the coupling constant  $\alpha_s$  over small distances<sup>(1)</sup>

$$\alpha_s(r) \sim \frac{1}{\ln(r_0/r)} \tag{1}$$

The unlimited growth of the constant at large distances gives grounds for hoping that all the objects with nonzero color charge (quarks, diquarks, gluons, etc.) have infinite mass, so that the physical sector of the theory covers only colorless states. It must be emphasized that despite the noticeable progress, color confinement has not yet been proved, and no quantitative approach to the problem of large distances has been developed in chromodynamics (as already mentioned in Polyakov's paper).

Whereas the theoreticians' attack on this flank of the theory is still tactical, strong positions have been won on another flank, in the region of short distances. The logarithmic exclusion of the interaction (1), dubbed asymptotic freedom, has explained qualitatively a large number of phenomena connected with deep-inelastic processes.<sup>[21]</sup> A large number of quantitative corollaries was obtained after the discovery of the  $\Psi$  family of particles. Being made up of heavy charmed quarks  $c\bar{c}$ , these particles (now usually designated by the term "charmonium") annihilate into ordinary hadrons over distances on the order of the Compton wavelength of the c-quark. At these distances, the effective coupling constant is already small,<sup>[3]</sup>

$$\alpha_s(m_c) \approx 0.2, \tag{2}$$

and the well-developed formalism of perturbation theory can already be used. For a long time, the rich possibilities connected with this circumstance could not be realized fully, since it was impossible to "get rid" of the effects of the relatively large distances inevitably encountered in charmonium, since the radius of the latter is quite large  $\sim 1-0.5$  GeV. A solution of the problem was proposed in<sup>[4-6]</sup>, where a new dispersion approach to charmonium was developed. Using the dispersion method, it is possible to calculate, solely from "first" (asymptotic freedom, unitarity, and analyticity), the

## of the corresponding neutrino to a value less than 30 eV.

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Communication published in Pis'ma v Zh. Eksp. Teor. Fiz. 26, 200 (1977) [JETP Lett. 26, 188 (1977)].

leptonic widths of all the charmonium levels without exception. In conjunction with the Appelquist-Politzer prescription, <sup>(31</sup> this predicts also the hadronic widths. None of the results contradict the presently available experimental data.

We shall illustrate the method using the calculation of the  $\psi \rightarrow e^+e^-$  decay width as an example. We begin with an examination of the production of a pair of charmed particles in electron-positron annihilation at  $s \sim 0$ , where  $\sqrt{s}$  is the total  $e^+e^-$  energy in the c.m.s. It is obvious that such a process cannot be real, in view of the energy-momentum conservation, but can only be virtual. According to the uncertainty principle, charmed particles are produced within a time  $\tau \sim 1/2m_c$ and diverge to a distance  $\stackrel{<}{\sim} c\tau$ . We find ourselves thus in the region of asymptotic freedom. Bearing estimate (2) on mind, we can state that the contribution of the "charming" to the amplitude of the elastic  $e^+e^-$  scattering at s is given, at any rate accurate to 20%, by the bare quark loop (Fig. 1), while inclusion of one gluon (Fig. 2) improves the accuracy to  $\sim 4\%$ . Diagrams 1 and 2 can be easily calculated.

On the other hand, the same amplitude can be expressed, by virtue of unitarity and analyticity, in terms of the dispersion integral of the cross section for the production of real mesons, both with latent charm of  $\psi$ ,  $\psi'$ , and of the pairs  $D\overline{D}$ ,  $F\overline{F}$ , etc. We get thus a set of relations of the type

$$\int \frac{ds}{s^n} \sigma \left( e^+ e^- \longrightarrow \text{charm} \right) = 4\pi^2 Q_c^2 \alpha^2 \frac{A_n}{(4m_c^2)^n} \qquad (n = 1, 2, \ldots),$$
(3)

where  $Q_c = 2/3$  is the charge of the *c*-quark,  $\alpha = 1/137$ ,  $A_n$  are dimensionless constants known in the forms of series in  $\alpha_s(m_c)$ , and the mass  $m_c$  of the *c*-quark is the only fit parameter of the theory. With increasing *n*, the accuracy of the calculation of the constants  $A_n$  by perturbation theory becomes worse, inasmuch as at sufficiently large *n* the relations (3) should be violated. Direct calculations, however, show that, say at n=3 or 4, the relation (3) are still accurate within several per cent, but on the other hand the contribution of the region  $s > 4m_D^2$  is already small, less than several per cent. At these values of *n*, the left-hand side of (3) is saturated mainly by the contribution of the  $\psi$  meson. Eliminating  $m_{c}$ , we find<sup>[4]</sup>

$$\Gamma(\psi \to e^*e^-) = \frac{\alpha^2}{\pi} \cdot \frac{2^{11} \cdot 11^3}{3^7 \cdot 5^4 \cdot 7} \ m_{\psi} = 5 \ \text{keV} \ .$$
(4)

Let us recall that the experimental width of the  $\psi$ 



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