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ТЯЖЕЛЫЕ МЕЗОНЫ В БУТСТРАПНОЙ КВАРКОВОЙ МОДЕЛИ

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Аннотация

В рамках подхода, развитого в [1,2] для легких кварков, вычислены амплитуды рассеяния тяжелых кварков $q\bar{Q} \to q\bar{Q}$, $Q\bar{Q} \to Q\bar{Q}$ ($q=u,d,s$; $Q=c,b,t$). Получены массы низших мультиплетов c,b-мезонов с квантовыми числами J^{PC}; 0^{-+}, 1^{--}, 0^{++}, которые находятся в удовлетворительном согласии с имеющимися экспериментальными данными. Предсказываются массы новых тяжелых частиц, содержащих t-кварки.

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Abstract

In the frame of an approach developed for light quarks [1,2] the scattering amplitudes of heavy quarks $q\bar{Q}$ -> $q\bar{Q}$, $Q\bar{Q}$ -> $Q\bar{Q}$ ($q=u,d,s$; $Q=c,b,t$) are calculated. The obtained mass values of the lowest c,b-mesons ($J^P=0^-,1^-,0^+$) are in a good agreement with the experimental ones. The masses of the new heavy particles with the t-quark are predicted.

1. INTRODUCTION

The spectrum of the charm and beauty mesons is the subject of many theoretical papers which are based upon different approaches. As a rule the calculations are performed in the framework of potential models [3-18]. The potential approach has such advantages as simplicity and clarity and it allows one to calculate the energy levels, the radiation transition widths and the annihilation decay widths. Therefore we actually can get information about wave function of the system in a broad interval of distances, that is important for understanding the quark interaction dynamics. But the serious problem is how to make the QCD-grounded explanation of the potential approach.

The QCD sum rule method is successfully applied for the study of charmonium. Since the sum rule method is described in detail in refs. [19-21] we will not discuss it here but only put an attention to the distinctions which are typical for heavy bottomonium. The contribution of Y-mesons and ground states from other channels dominates only for the momenta M_n with $n \geqslant 0$, so as the relative difference of the resonance masses is small enough. (For the charmonium the J/ψ-resonance practically saturates the momenta even for $n \geqslant 4$). For $n \geqslant 20$ the expressions for the momenta [22] originally obtained for the charmonium cannot be used directly [23], because the parameter describing the perturbative QCD contribution is not α_s but $\alpha_s n^{1/2}$. The momentum M_n depends on the relative velocity of quarks $V \sim n^{-1/2}$. The perturbative theory for the Coulomb-type interaction uses the parameter α_s/v, which is proportional to $\alpha_s n^{1/2}$ for M_n. If we calculate the leading terms $n \sim V^{-2}$, one can deal with the nonrelativistic method using the Coulomb-like Green function of the Schrodinger equation.

The principal difficulty of the sum rule method used for bottomonium is to take into account the relativistic corrections, i.e. the next term in the expansion in n^{-1}. Therefore it is necessary to calculate all the terms of the type of $(\alpha_s n^{1/2})^k n^{-1}$ which are equivalent to $\alpha_s^2(\alpha_s n^{1/2})^k$ (since $\alpha_s n^{1/2} \sim 1$) and contain the radiation corrections of the order of α_s^2 together with the relativistic effects described by the Breit-Fermi Hamiltonian. Calculation of such a type is absent up to now.

This problem appears, for instance, in the calculating [24] of masses 1p- and 1s - bottomonium levels. The disagreement between experimental value and the nonrelativistic calculation is of the order of the splitting of the ^3P_J-level, which owes just to the relativistic correction.

It is worth mentioning a model, which is connected with Regge theory, topological expansion and the idea of the gluon "tube" in vacuum [25,26]. One of the predictions of this model is the splitting of the 1s- and 1p-levels of the beauty mesons. For instance, the differences between meson masses with $J^P=0^+$ and 0^- is about 400 MeV. This value agrees with the potential model prediction, while the QCD sum rule provides us with the one about 800 MeV (Table 1). If the QCD sum rule predictions are true, the interaction of the light valence quark with the quark vacuum condensate has to depend on the parameters of the second quark in the meson. Therefore in the Qq-systems (Q - heavy quark) the assumption of the constituent quark model about the flavor-independent quark interaction with the gluon is not valid and some items of the quark model should be revised.

In Section 2 we discuss the scheme of the quark-quark amplitude calculations of the bootstrap quark model. Section 3 is devoted to the description of the way to include heavy quarks into the bootstrap procedure. In Section 4 the results of the calculation are presented. In conclusion we discuss the status of the considered model.

2.CALCULATION SCHEME OF THE QUARK-QUARK AMPLITUDES

In refs. [27,28] the bootstrap quark model is used for the construction of the scattering amplitude of the light dressed one-flavour quark. Iteration bootstrap procedure for the quark-quark and quark-antiquark amplitudes has been performed with the initial four-fermion interaction as an input:

$$g_v(\bar{q}\gamma_\mu\bar{\lambda}q)(\bar{q}\gamma_\mu\bar{\lambda}q), \qquad (1)$$

where λ are the Gell-Mann matrices. The point-like structure of this interaction is based upon an idea of the small gluon interaction range. On the other hand, the choosing interaction in the eq.(1) is supported by the success of the De Rujula-Georgi- Glashow quark model [3], where only short-range part of the Breit potential connected with the gluon exchange is responsible for the mass splitting in the hadron multiplets.

The scheme of the iteration bootstrap procedure suggested in refs. [27,28] is as follows. Partial amplitudes are calculated through the dispersion N/D-method. The interaction (1) is the N-function in the zero approximation. Regularization of the dispersion integral for the D-functions (or Chew-Mandelstam functions [29]) is performed through the cut-off procedure. Cut-off parameter is chosen to be the same for all states. Zero-approximation amplitude (fig. 1d) can be drawn as the sum of diagrams shown in figs.1 a,b,c,etc. The amplitude of the first approximation (fig. 1h) is obtained with N/D-method when the zero-approximation amplitude is taken as the N-function. The first approximation amplitude is the sum of diagrams shown in figs.1 e,f,g, etc. The use of the first approximation amplitude as an "interaction force" (for N-function) provides us with the second approximation, and so on.

In refs. [1,2] the scattering amplitude of the three-flavour (u,d,s) quarks is considered: the poles of this amplitude define the mass spectrum of light quarks. The mass of the dressed u,d-quarks is of the order of 300-400 MeV, the strange quark mass is about 150-200 MeV heavier. Constituent quarks are colour triplet and quark amplitudes obey the global colour symmetry.

Together with the gluon interaction we included the four-fermion interaction induced by instantons [30-34]. This interaction should be also short-range one, if the radius of the effective gluon interaction is small. This type of interaction in the iteration bootstrap calculations is needed to obtain the small pion mass and the large value of the η-η' mass splitting. The iteration procedure converges rather rapidly due to $1/N_c$-expansion [35,36]. In ref. [2] it was suggested (for the calculation of the light meson mass), that the contribution of the axial interaction to the pseudoscalar sector is compensated by p-wave blocks (state $J^P=1^+$) in the iteration bootstrap procedure. Here we take into account the contribution of the axial interaction for multiplet states $J^P=0^-$, that practically does not change the spectrum of the light mesons, but is important for the description of the heavy mesons.

In Table 2 the calculated masses of the light mesons are shown. For the 0^+ multiplet the discrepancy between the calculated and observed mass values is greater than for the other channels. It is possible that for the scalar mesons this is due to the admixture of the glueball states [37] or the $qq\bar{q}\bar{q}$-states [38], which are not taken into account in our study. Generally speaking, it should be noted that the determination of the resonance parameters with masses $m \geqslant 1$ GeV can be only qualitative because of the relatively small value of the cut-off parameter (for the nonstrange quarks Λ = 1.5-2.2 GeV^2).

In all versions of our calculation there exists a bound state in the gluon channel with the mass of the order of 0.67 GeV. Its quark wave function is $1/\sqrt{3}(1.06\ (u\bar{u}+d\bar{d}) + 0.87s\bar{s})$, hence, with a good accuracy it is a singlet of the flavour $SU(3)_f$-group. This bound state can be identified as a constituent gluon.

3. AMPLITUDE OF THE QUARK-QUARK TRANSITIONS WITH HEAVY QUARKS

In the present paper the spectrum of low-lying mesons $Q\bar{Q}.q\bar{Q}$ with light q=u,d,s and heavy Q=c,b,t quarks is considered. The heavy quark interaction is provided by the N-function, corresponding to the exchange of the light white and colour mesons. The main role in creating the heavy meson spectrum is played by forces connected with the exchange massive gluon. It is necessary to take into consideration the renormalization of the Chew-Mandelstam function for the light quarks, which is defined by the rescattering of heavy quarks Q (fig. 2 a,b). In fig. 2b one link of the chain of the light quark, which includes the heavy quark loop is shown. Owing to the point-like character of the heavy quark interaction their contribution gives rise to the numerical renormalization of the Chew-Mandelstam function only. Therefore, the introduced interaction vertex function of heavy quark should be effectively taken into account in this renormalization procedure. Heavy quark interaction parameter α_{Qq},α_Q and the cut-off parameter of the Chew-Mandelstam function Λ_{Qq},Λ_Q are given by the experimental magnitudes for the mass of mesons of $Q\bar{Q},Q\bar{q}$. The heavy quark mass m_Q is an additional parameter which permits us to optimize the spectrum of heavy mesons.

The main result of this section is the construction of the amplitude of the heavy quark interaction. We introduce the auxiliary amplitude a_{ijkl} corresponding to the diagram of fig.3a. The notating i,j,k,l define various flavours. The simplest interaction in this diagrams is the two-loop one (fig. 3b). If k=l, we must take into account one-loop interaction a_{ijl}(fig.3c).

Summing up the diagrams, we obtain for the amplitude a_{ijkl} the following systems of equation:

$$a_{ijk\ell} = \sum_{m} a_{ijmk} B_{mk\ell} + B_{ij\ell}\delta_{k\ell} \qquad (2)$$

Here the Chew-Mandelstam function B_{ijk} is introduced

$$B_{ijk} = \int \frac{ds'}{\pi} \frac{\sqrt{N_{ij}N_{jk}}}{s'-s} \rho_j(s') \tag{3}$$

Further we also use the truncated Chew-Mandelstam function:

$$B_{ij} = \int \frac{ds'}{\pi} \frac{\sqrt{N_{ij}}}{s'-s} \rho_j(s') \tag{4}$$

$$B_{j} = \int \frac{ds'}{\pi} \frac{1}{s'-s} \rho_j(s') \tag{5}$$

Here ρ_j is the phase space.

Solving the equation system (2) we obtain the auxiliary amplitude a_{ijkl} and the quark scattering amplitude, which has two fixed vertices:

$$A_{il} = \sum_{jk} a_{ijkl} \sqrt{N_{ij}N_{kl}} \tag{6}$$

Using the eqs. (2)-(6) we obtain the interaction amplitude of light quark i(i=u,d,s) with the heavy quark Q(Q=c,b,t) in the following form:

$$A_{iQ} = \sum_{jkl} a_{ijkl} \sqrt{N_{ij}} B_{kl} \alpha_{Ql} + \sum_{j} \sqrt{N_{ij}} B_{ij} \alpha_{jQ} + \alpha_{iQ} \tag{7}$$

where α_{qQ} is the interaction constant of the light quark with the heavy one. The heavy quark interaction amplitude is described in the form

$$A_Q = \sum_{ijkl} a_{ijkl} B_{ij} B_{kl} \alpha_{jQ} \alpha_{lQ} + \sum_{ij} B_{ij} B_{ji} \alpha_{iQ} \alpha_{jQ} + \sum_{i} B_i \alpha_{iQ}^2 + \alpha_Q \tag{8}$$

where α_Q is the interaction constant of the heavy quarks.

4. CALCULATION RESULTS

In this paper the masses of the mesons ($J^{PC}=0^{++},1^{--}$) with c- and b-quarks were obtained. To calculate meson masses we used three parameters α_Q, α_{Qq}, Λ_Q: α_Q - characterizes the interaction of heavy quarks, α_{Qi} is that for the interaction of light and heavy quarks and Λ is cut-off parameter for the scattering amplitude of heavy quarks. The cut-off parameter for scattering amplitude of heavy and light quarks was calculated as:

$$\Lambda_{Qq} = 1/4\ (\sqrt{\Lambda_Q} + \sqrt{\Lambda_q})^2. \qquad (9)$$

The values of the Λ_q and the light-quark masses ($m_{u,d}$ 0.385 GeV, $m_s = 0.510$ GeV) were taken from ref. [2]. Parameters α_Q, α_{Q1}, Λ_Q have been determined for c-quark using experimental data on D, D^*, J/ψ meson masses and for b-quark using B, B^*, Υ ones. Masses of the heavy quarks are the model parameters as well, they have been determined in order to obtain the best description of masses η_c (for c-quark) and B_s (for B-quark). Calculation results are shown in Table 3. 4 for the meson mass spectrum. When we consider parameters α and Λ as functions of the sum of quark masses squared $\alpha = f_\alpha\ (m_a + m_b)^2)$ and $\Lambda = f_\Lambda((m_a + m_b)^2)$, we can see that their behavior is rather smooth. And they can be approximated as follows

$$\alpha(x) = 2.3\ \left(\frac{1}{\ln(1+x)} + \frac{3060}{x^2 + 1330}\right)$$

$$\Lambda(x) = 4 + \frac{8.187}{x + 0.0271} \qquad (10)$$

Here the asymptotic quark interaction $\alpha(x)$ is chosen in the form const./ln(1+x).

In the framework of this approximation we obtained the interaction constant α_{bo} and cut-off parameter for the scattering amplitude of this quarks. The masses of mesons with c- and b-quarks are presented in Table 4. Using approximation (10) we calculate meson masses with the t-quark dependent on the t-quark mass /39-45/.

Binding energy of these mesons as a function of the t-quark mass in the range $70 \leq m_t \leq 150$ GeV is given in Table 5.

5. CONCLUSION

In the paper the bootstrap quark model which describes rather well the spectroscopy of the light mesons (Table 2.) is used for the study of the heavy $\tilde{q}Q,\bar{Q}Q$-systems. The obtained masses of the S-wave states with the open c,b-flavour and lowest heavy quarkonium ones are in a good agreement with experimental data (Tables 3,4).

From Table 1 one can see the qualitative agreement of the change of the ^1S and ^1P-levels splitting Δ with the increase of the mass of the light component of the mesons in the bootstrap quark model and in the model [17,18]. In the Isgur nonrelativistic quark model [13] and in the model of the gluon "tube" in the QCD vacuum [26] the value Δ does not change. In the QCD-sum rule model [21] for the mesons containing b-quarks the sudden increase of the value Δ compared with the c-meson family occurred. The experimental data, which can give choice between the various models are absent now.

The approximating curve of the interaction constant shows that the region of the asymptotic freedom begins only from t-quark masses.

In our model we have obtained for t-quark only toponium bound states and the states of $t\bar{b}$-type (Table 5). To obtain the bound states of t-quark with more light quarks (u,d,s,c) the long-range force component must be taken into account.

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Table 1
S,P-wave mass difference for heavy mesons
($\Delta = M(J^P\!=\!0^+) - M(J^P\!=\!0^-)$)

	/13/	/17/	/18/	/21/	/26/	/*/	Exp /46/
$u\bar{c}$	0.520	0.304	0.399	0.410	0.510	0.252	
$s\bar{c}$	0.500	0.331	0.382		0.510	0.290	
$c\bar{c}$	0.470	0.399	0.404	0.415		0.498	0.435
$u\bar{b}$	0.490	0.246	0.359	0.820	0.400	0.216	
$s\bar{b}$	0.490	0.268	0.355	0.870	0.380	0.277	
$c\bar{b}$	0.500	0.404	0.406		0.390	0.650	
$b\bar{b}$	0.450	0.522	0.458	0.400		0.731	

/*/ - our results

Table 2

Masses of the light mesons containing light quarks q=(u,d,s). The model parameters are $\Lambda_q=17.3$, gluon exchange constant $g_v=0.226$, the interaction induced by instantons constant $q_I=-0.081$, the constant of the white isosinglet meson interaction $\beta=0.55$.

The quark masses $m_u=0.385$ GeV, $m_s=0.501$ GeV.

$m(0^-)$ (GeV)	$m(1^-)$ (GeV)	$m(0^+)$ (GeV)
π 0.14 (0.14)	ρ 0.77 (0.77)	δ 0.98 (0.98)
K 0.50 (0.50)	K^* 0.89 (0.89)	æ 1.35 (0.88)
η 0.55 (0.48)	ω 0.78 (0.77)	S^* 0.98 (0.87)
η' 0.96 (0.96)	φ 1.02 (1.00)	ε 1.30 (1.16)

The experimental data are given in the brackets.

Table 3

The lowest states of the charmonium and states with open charm masses. The model parameters: the cut-off parameter Λ_c=5.94, the constants of the c-quark interaction α_{qc}=6.56, α_c=5.41, c-quark mass m_c=1.645 GeV.

	$m(0^-)$ (GeV)	$m(1^-)$ (GeV)	$m(0^+)$ (GeV)
$u\bar{c}$ $d\bar{c}$	D 1.867 (1.867)	D^* 2.010 (2.010)	2.119 (—)
$s\bar{c}$	D_s 2.010 (1.971)	D_s^* 2.120 (2.113)	2.300 (—)
$c\bar{c}$	η_c 2.955 (2.980)	J/Ψ 3.097 (3.097)	χ_0 3.453 (3.415)

The experimental data are given in the brackets.

Table 4

The lowest states of the bottomonium and states with open bottom masses. The model parameters: the cut-off parameter Λ_b=4.91, the constants of the b-quark interaction α_{qb}=4.08, α_b=1.12, b-quark mass m_b=4.940 GeV.

	$m(0^-)$ (GeV)	$m(1^-)$ (GeV)	$m(0^+)$ (GeV)
$u\bar{b}$ $d\bar{b}$	B 5.270 (5.270)	B^* 5.320 (5.320)	5.486 (—)
$s\bar{b}$	B_s 5.375 (5.340)	B_s^* 5.425 (5.390)	5.625 (—)
$c\bar{b}$	6.085 (—)	6.320 (—)	6.735 (—)
$b\bar{b}$	9.340 (—)	Υ 9.460 (9.460)	10.070 (—)

The experimental data are given in the brackets.

Table 5

The dependence of the t-mesons bound energy ($J^P=0^-$, 1^-) on the t-quark mass.

m_t (GeV)	$\varepsilon_{t\bar{t}}$ (0^-) (GeV)	$\varepsilon_{t\bar{t}}$ (1^-) (GeV)	$\varepsilon_{t\bar{b}}$ (0^-) (GeV)	$\varepsilon_{t\bar{b}}$ (1^-) (GeV)
70	[illegible].00	5.91	0.09	0.01
80	7.23	7.15	0.08	0.01
90	8.53	8.45	0.08	0.01
100	9.88	9.80	0.08	0.
110	11.3	11.[illegible]	0.08	0.
120	12.7	12.6	0.08	0.
130	14.2	14.1	0.08	0.
140	15.7	15.6	0.08	0.
150	17.3	17.2	0.08	0.

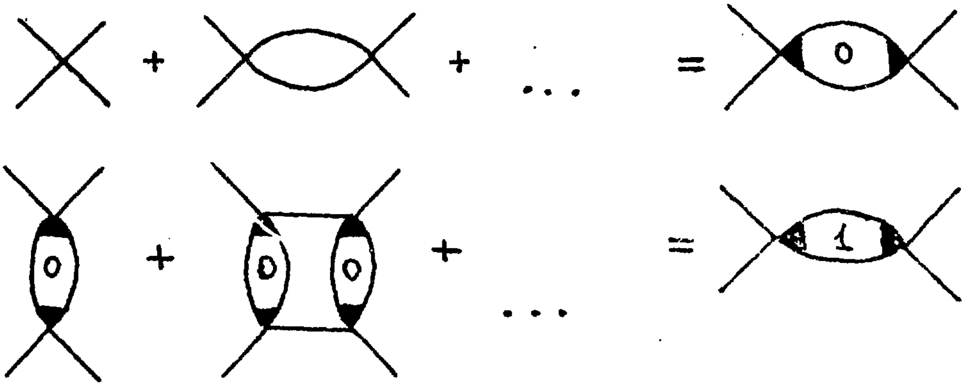

Fig.1. Diagrams corresponding to the iteration procedure.

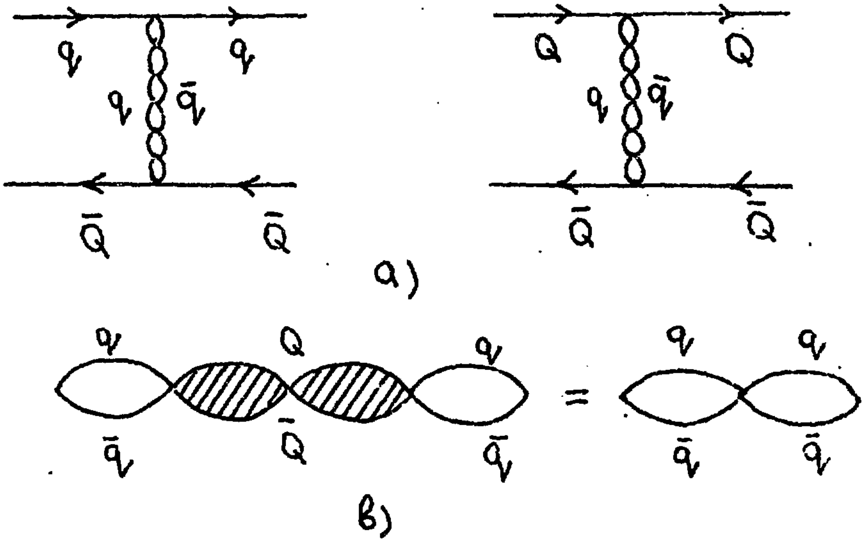

Fig.2. a) Diagrams for the heavy quark amplitudes Q is heavy quark, q is light one;
b) renormalization of the vertices for the interaction of light quarks due to the contribution of heavy quarks

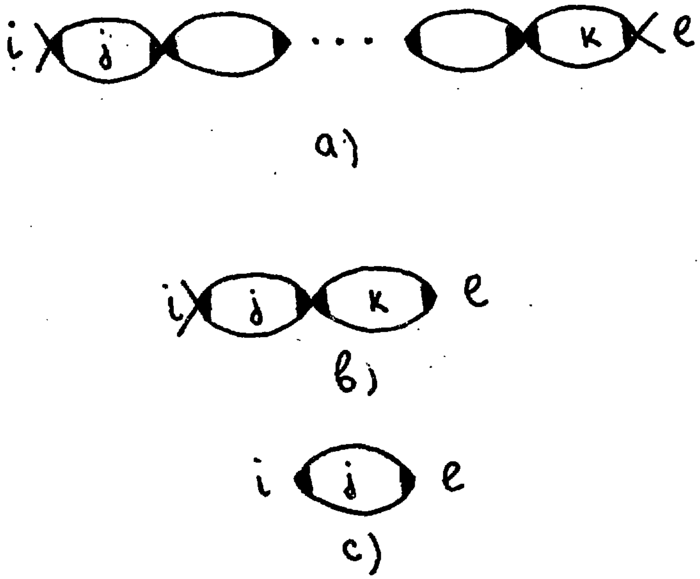

Fig.3. a) Definition of auxiliary amplitudes a_{ijkl};
b) two-loop amplitude a_{ijkl};
c) one-loop amplitude a_{ijkl} at $l=k$.

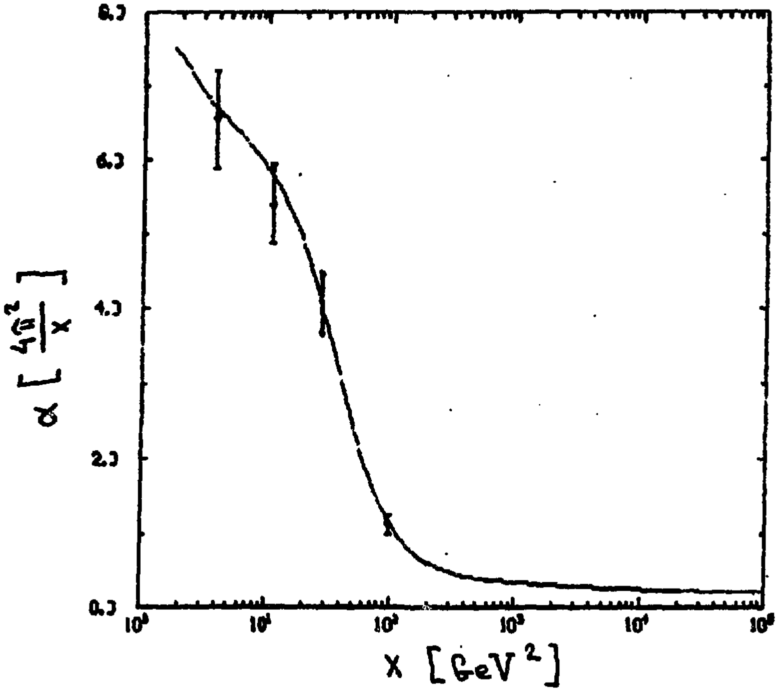

Fig.4. a) Dependence of the vertex function α on the mass of heavy mesons:

$$\alpha = 2.3\left(\frac{1}{\ln(1+x)} + \frac{3060}{x^2 + 1330}\right),\ x = (m_a + m_b)^2,\ m_a,\ m_b \text{ are}$$

the quark masses;

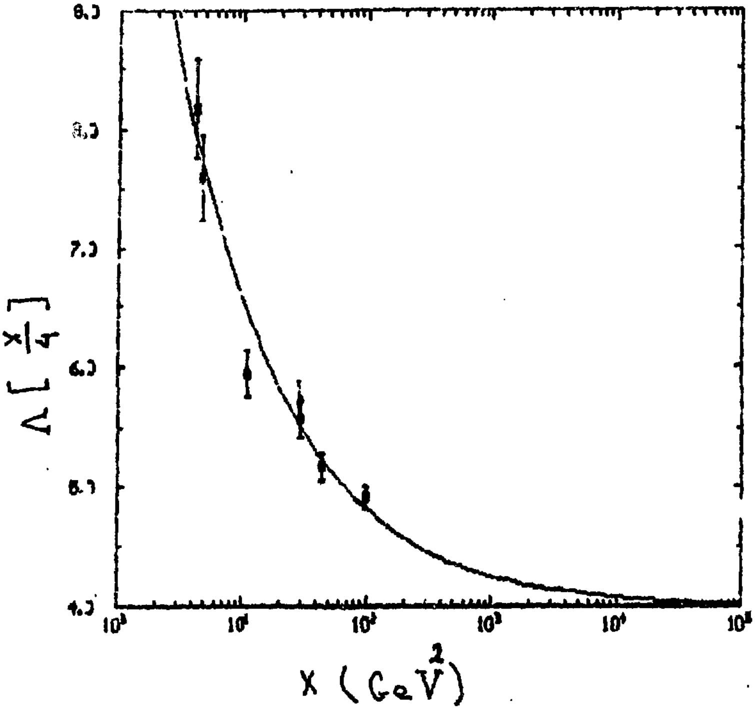

Fig.4. b) dependence of the cut-off parameter Λ on the mass of heavy mesons:

$$\Lambda = 4 + \frac{8.187}{x + 0.0271}, \qquad x = (m_a + m_b)^2.$$

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