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The magnitude of the gluon condensate from vector mesons consisting of light quarks.

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THE MAGNITUDE OF THE GLUON CONDENSATE FROM VECTOR MESONS CONSISTING OF LIGHT QUARKS: Preprint ITEP 20-95/

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The analysis of the families of ρ, ω, φ-mesons gives the value of the gluon condensate $\langle 0 \mid \frac{\alpha}{\pi} G^2 \mid 0 \rangle = 0.061 \pm 0.019 GeV^4$ in agreement with the magnitude of the gluon condensate obtained by the author from the families of J/ψ and Υ-mesons. The following items have been obtained as by-product:
1) more precise value of the electronic width of ρ-meson $\Gamma_\rho^{ee} = 6.72 \pm 10$kev (from π-mesons formfactor);
2) the electronic widths of $\rho(1450)$ meson equal to $\Gamma_\rho^{ee} = 2.51 \pm 0.12$kev, of $\omega(1420)$ meson equal to $\Gamma_{\omega'}^{ee} = 0.27 \pm 0.04$kev and $\varphi(1680)$ meson equal to $\Gamma_\varphi^{ee} = 0.87 \pm 0.10$kev;
3) mass of φ'' meson equal to $M_{\varphi''} = 2.00 \pm 0.06$GeV.

Fig. - 1, ref. - 32.

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1. Introduction.

The gluon condensate $\langle(\alpha_s/\pi)G^2\rangle$ is one of the fundamental characteristics of QCD vacuum. Shifman, Vainshtein and Zakharov (S.V.Z.)showed that the magnitude of the gluon condensate is nonzero and obtained for it the value

$$\langle(\alpha_s/\pi)G^2\rangle_{\rm SVZ} = 0.012{\rm GeV}^4 \tag{1}$$

Since then a large number of papers [2-12] have given various gluon condensate values which often significantly differ from the value (1).

The analysis made for the families of J/ψ and Υ mesons in Ref.[13] gives for the gluon condensate the value

$$0.05 \leq \langle(\alpha_s/\pi)G^2\rangle \leq 0.1{\rm GeV}^4 \tag{2}$$

strongly differing from the value (1). Ref.[14] deals with the problem of which value of the gluon condensate is correct. It was shown that the model used in Ref.[1] to describe the experimental function $R_c(s)$ as a sum of δ–functions due to resonances of J/ψ family and the plateau strongly contradicts to the Wilson operator expansion (O.E.) in terms due to the gluon condensate.

In Refs.[13,15] the QCD model with an infiite number of vector mesons was suggested. This model allowed one to satisfy all the O.E. requirements at the gluon condensate value (2). The QCD model with an infinite number of vector mesons was then used to derive hadronic contributions to the value of the electromagnetic coupling constant $\alpha(q^2)$ at $q^2 = m_z^2$ [16] and to the anomalous magnetic moment of muon [17] with a per cent accuracy.

The goal of this paper is to determine the value of the gluon condensate from the analysis of the ρ, ω, φ–meson families. We used the same method as in the analysis of the J/ψ and Υ-families [13,14].

2. The magnitude of the gluon condensate from the ρ–meson family.

The polarization operator Π^{ρ} associated with the light-quark current

$$j_{\mu}^{I=1}(x) = \frac{1}{2}\,[\bar{u}(x)\gamma_{\mu}u(x) - \bar{d}(x)\gamma_{\mu}d(x)\,] \tag{3}$$

is

$$i\int d^4x e^{iqx}\langle 0 \mid T\{\, j_{\mu}^{I=1}(x),\ j_{\nu}^{I=1}(0)\,\} \mid 0\rangle = (q_{\mu}q_{\nu} - q^2 g_{\mu\nu})\Pi^{(\rho)}(Q^2) \tag{4}$$

where $Q^2 = -q^2$

The dispersion relation for $\Pi^{(\rho)}(Q^2)$ is

$$\Pi^{(\rho)}(Q^2) = \frac{1}{12\pi^2}\int\limits_{4m_{\pi}^2}^{\infty}\frac{R^{I=1}(s)}{s+Q^2}ds \tag{5}$$

The dispersion relation (5) is written without subtractions since, as will be shown below, the divergent part in $\Pi^{(\rho)}$ is canceled. In the approximation of an infinite number of narrow resonances with the masses M_k and electronic widths Γ_k^{ee} the function $R^{I=1}(s)$ has the form:

$$R^{I=1}(s) = \frac{9\pi}{\alpha^2}\sum_{k=0}^{\infty}\Gamma_k^{ee}M_k\delta(s - M_k^2) \tag{6}$$

$\alpha = 1/137$. The electronic width Γ_k^{ee} is connected with the derivative of the mass M_k with respect to number k by the formula [13,14]:

$$\Gamma_k^{ee} = \frac{2\alpha^2}{9\pi}\,R_{PT}^{I=1}(s_k)M_k^{(1)} \tag{7}$$

The function $R_{PT}^{I=1}$ includes all corrections in α_s in perturbation theory (PT). In Eq.(7) and in the following formulae we use the notations

$$M_k^{(l)} = d^lM_k/dk^l, \qquad s_k = M_k^2, \qquad s_k^{(l)} = d^ls_k/dk^l \tag{8}$$

We substitute into Eq.(5) the function (6) and make use of Eq.(7) and of the Euler-Maclaurin formula [18] and obtain

$$\Pi^{(\rho)}(Q^2) = \frac{1}{12\pi^2}\sum_{k=0}^{\infty}\frac{R_{PT}^{I=1}(s_k)s^{(1)}}{s_k+Q^2} = \frac{1}{12\pi^2}\left\{\int\limits_{(m_u+m_d)^2}^{\infty}\frac{R_{PT}^{I=1}(s)ds}{s+Q^2} - \right.$$

$$- \int\limits_{(m_u+m_d)^2}^{s_1} \frac{R_{PT}^{I=1}(s)ds}{s+Q^2} + \frac{R_{TB}^{I=1}(s_0)s_0^{(1)}}{s_0+Q^2} + \tag{9}$$

$$+\frac{1}{2}\,\frac{R_{PT}^{I=1}(s_1)s_1^{(1)}}{s_1+Q^2} - \frac{1}{12}\left[\frac{R_{PT}^{I=1}(s_1)s_1^{(1)}}{s_1+Q^2}\right]^{(1)}\Bigg\}$$

In Eq.(9) we replace summation by integration starting from $k=1$ and discard all terms not written out.

In the given case the O.E. makes it possible to write the formula of $\Pi^{(\rho)}$ in the form

$$\Pi^{(\rho)}(Q^2) = \int\limits_{(m_u+m_d)^2}^{\infty} \frac{R_{PT}^{I=1}(s)ds}{s+Q^2} + C_2/Q^2 + C_4/Q^4 \tag{10}$$

where

$$C_2 = 0$$

$$C_4 = \frac{1}{24}\,\langle 0 \mid \frac{\alpha_s}{\pi}G^2 \mid 0\rangle + \frac{1}{2}(m_u\langle 0 \mid \bar{u}u \mid 0\rangle + m_d\langle 0 \mid \bar{d}d \mid 0\rangle) \tag{11}$$

For large values of Q^2, Eqs. (9) and (10) should coincide; therefore we expand Eq.(9) in $1/Q^2$ and equate terms of the same order $1/Q^2$ in Eqs.(9) and (10). In the coefficient C_4 corrections in α_s are not taken into account and consequently, we can make replacement $R_{PT}^{I=1}(s) \to R_{PT}^{I=1}(s)\,|_{\alpha_s=1} = \frac{3}{2}$. Neglecting the masses of u and d–quarks we obtain

$$\langle 0 \mid (\alpha_s/\pi)G^2 \mid 0\rangle = \frac{3}{\pi^2}\,\{-s_0s_0^{(1)} - \frac{1}{2}s_1s_1^{(1)} + \frac{1}{2}s_1^2 + \frac{1}{12}(s_1s_1^{(2)} + s_1^{(1)^2})\} \tag{12}$$

For the function $R_{PT}^{I=1}(s)$ we use here the formula [19,20]

$$R_{PT}^{I=1}(s) = 3Q_{I=1}^2\left[1 + \frac{\alpha_s(s)}{\pi} + r_1\left(\frac{\alpha_s(s)}{\pi}\right)^2 + r_2\left(\frac{\alpha_s(s)}{\pi}\right)^3\right] + 0(\alpha_s^4) \tag{13}$$

where $Q_{I=1}^2 = \frac{1}{2}$, $r_1 = 1.9857 - 0.1153f$, $r_2 = -6.6368 - 1.2001f - 0.0052f^2 - 1.2395\,\frac{(\sum_f Q_f)^2}{3\sum_f Q_f^2}$, $f = 3$. Similar equations are valid for $R_{PT}^{I=0}(Q_{I=0}^2 = 1/18,\ \omega$–family) and R_{PT}^{φ} ($Q_s^2 = 1/9,\ \varphi$–family).

For $\alpha_s(s)$ we used formulae Ref.[21], described the evolution of $\alpha_s(s)$ taking into account effects of flavor thresholds and new results $\alpha_s(M_z^2) = 0.125 \pm 0.005$ [22].

Within the framework of modified minimal subtraction $\overline{MS}$ scheme [23–25] we obtained $\Lambda^{(5)}_{\overline{MS}} = 310 \pm 8$Mev, $\Lambda^{(4)}_{\overline{MS}} = 420 \pm 9$Mev, $\Lambda^{(5)}_{\overline{Ms}} = 460 \pm 9$Mev. The function $R_{PT}(s)$ is presented in Fig.1.

The curve $R_{PT}(s)$ breaks down at $s < 1\text{Gev}^2$. We continue on smoothly the curve $R_{PT}(s)$ at $s < 1\text{Gev}^2$ (dashed line). The function $R_{PT}(s)$ can be written in a more convenient form

$$R^{PT}(s) \equiv 2\left(1 + \frac{\alpha^{\text{eff}}(s)}{\pi}\right) \tag{14}$$

We will use dashed curve to evaluate $\alpha_s^{\text{eff}}(s)$ at $s < 1\text{Gev}^2$. For example, $\alpha_s^{\text{eff}}(m_\rho^2) = 0.59$

There is a great cancellation in Eqs.(12) and for this reason we have to know $s_0^{(1)}$ and $s_1^{(1)}$ with a sufficient accuracy. At present there are 3 mesons from the ρ–family with the masses $M_0 = 0.7699 \pm 0.0008$Gev, $M_1 = 1.465 \pm 0.025$Gev, $M_2 = 1.70 \pm 0.02$Gev and the electronic width of ρ–meson is $\Gamma_0^{ee} = 6.77 \pm 0.32$ [26]. To precise Γ_0^{ee} we will use the results of the work [27]. The experiments on the measurement of the pion electromagnetic formfactor (ff) in the time–like and space like region were analysed in Ref.[27] using the ff model with correct analytical properties and asymptotics predicted by QCD. Although the ff model used in [27] is far from the model of this work but since ff [27] describes the experiments very well and has correct analytical properties, the value of Γ_0^{ee} following from [27] is most likely valid. The value of Γ_0^{ee} is not presented in [27] but only the value of the residue $g_\rho m_\rho^2 = 0.676 \pm 0.003\text{Gev}^2$. It follows from this value $g_\rho m_\rho^2$ [28]

$$\Gamma_0^{ee} = 6.72 \pm 0.10\text{keV} \tag{15}$$

In the following we will use the value (15) for Γ_0^{ee}. The value $s_0^{(1)}$ follows from Eqs.(7,8,14)

$$s_0^{(1)} = 1.538 \pm 0.023\text{Gev}^2 \tag{16}$$

The value $s_1^{(1)}$ can be obtained from the trivial formula

$$s_1^{(1)} = \frac{s_2 - s_1}{2} - \frac{1}{6} s_1^{(3)} \tag{17}$$

The estimate of $s_1^{(3)}$ follows from the assumption $\mid s_1^{(3)} \mid \simeq \mid s_1^{(2)} \mid$ and the formula $s_1^{(2)} \approx s_2 + s_0 - 2s_1 = -0.81 \pm 0.16\text{Gev}^2$. Note that $\mid s_1^{(2)} \mid < s_1^{(1)} \mid$ (Eq.(18)). The last term $s_1^{(3)}/6$ of formula (15) is added to the error of the first term $(s_2 - s_1)/2$. We obtain

$$s_1^{(1)} = 1.15 \pm 0.14\text{Gev}^2 \tag{18}$$

and the magnitude of the gluon condensate following from the analysis of ρ–meson family

$$\langle 0 \mid \frac{\alpha_s}{\pi} G^2 \mid 0 \rangle = 0.061 \pm 0.019\text{Gev}^4 \text{ [1]} \tag{19}$$

The electronic width Γ_1^{ee} can be obtained from the formulae (7,8,18).

$$\Gamma_1^{ee} = 2.51 \pm 0.12\text{keV} \tag{20}$$

The value $\alpha_s^{\text{eff}}(s_1) = 0.41$ was used to obtain (20). The results (20) can be compared with the value $\Gamma_1^{ee} = 2.5 \pm 0.9\text{keV}$ obtained in [30] from the analysis of experiments $e^+e^- \to hadrons$.

3. The magnitude of the gluon condensate from the ω–mesons family.

The polarization operator associated with the light–quark vector current

$$J_\mu^{I=0}(x) = \frac{1}{6} \{\bar{u}(x)\gamma_\mu u(x) + \bar{d}(x)\gamma_\mu d(x)\} \tag{21}$$

is

$$i \int d^4x e^{iqx} \langle 0 \mid T\{j_\mu^{I=0}(x) j_\nu^{I=0}(0)\} \mid 0 \rangle = (q_\mu q_\nu - q^2 g_{\mu\nu}) \Pi^\omega(Q^2) \tag{22}$$

All the previous formulas remain unchanged with the one exception the factor 1/9 in the right–hand side of the Eq.(7). There are 3 ω–resonances: the ω–meson with the mass $M_0 = 0.78194 \pm 0.00012\text{Gev}$, the electronic width $\Gamma_0^{ee} = 0.60 \pm 0.02\text{kev}$, the ω'–meson with the mass $M_1 = 1.419 \pm$

[1]Notice that the experimental data of $R^{I=0}$ changed significantly from the time of the publication of Ref.[3]. For example the electronic width of the ρ–meson changed from $\Gamma_0^{ee} = 5,78\text{keV}$ to the value (15). The estimate shows that the value (15) contradicts the magnitude of the gluon condensate (1).

0.031Gev and the ω''–meson with the mass $M_2 = 1.662 \pm 0.013$Gev [26]. For the ω-family we obtain

$$s_0^{(1)} = 1.258 \pm 0.042\text{GeV}^2 \tag{23}$$

$$s_1^{(1)} = 1.075 \pm 0.140\text{GeV}^2 \tag{24}$$

$$\Gamma_1^{ee} = 0.27 \pm 0.04\text{keV} \tag{25}$$

$$\langle 0 \mid \frac{\alpha_s}{\pi} G^2 \mid 0 \rangle = -0.051 \pm 0.028\text{GeV}^4 \tag{26}$$

The magnitude of the gluon condensate obtained from the different processes must be equal. That is the contradiction between the results (19) and (26). Taking into account the $\rho - \omega$ mixing we can resolve this contradiction.

3.1 The $\rho - \omega$ mixing and the resolution of the contradiction.

Eqs. (21,22) are written for vector mesons with $I = 0$. Real ω-meson has an admixture of the state with $I = 1$. This is evident from the decay $\Gamma(\omega \to 2\pi) = 0.186 \pm 0.025$Mev. In addition $(\Gamma_\rho^{ee}/\Gamma_\omega^{ee})_{Exp} = 11.28 \pm 0.06$ instead of 9.

The real state of the ω–meson is

$$\mid \omega \rangle = \mid \omega_0 \rangle + \lambda \mid \rho \rangle \tag{27}$$

Where $\mid \omega_0 \rangle$ is the state with $I = 0$. The parameter λ can be found by formula

$$\lambda^2 = \frac{\Gamma(\omega \to 2\pi)}{\Gamma(\rho \to 2\pi)} = (1.35 \pm 0.18) \cdot 10^{-3} \tag{28}$$

$$\mid \lambda \mid = 0.037 \pm 0.002$$

From $\langle e^+e^- \mid \rho \rangle = 3 \langle e^+e^- \mid \omega_0 \rangle$ it follows $\Gamma_\omega^{ee} = (1 + 6\lambda)\Gamma_{\omega_0}^{ee}$ and

$$\Gamma_{\omega_0}^{ee} = \frac{\Gamma_\omega^{ee}}{1 + 6\lambda} = \frac{1}{9}\Gamma_\rho^{ee} = 0.747 \pm 0.011\text{keV} \tag{29}$$

The parameter λ must be real in the approximation of narrow resonances and from (29) it follows that $\lambda = -0.033 \pm 0.005$ and $s_0^{(1)} = 1.565 \pm 0.023 GeV^2$.

The magnitude of the gluon condensate is equal to

$$\langle 0 \mid \frac{\alpha_s}{\pi} G^2 \mid 0 \rangle = 0.080 \pm 0.024 \mathrm{GeV}^4 \tag{30}$$

in a good agreement with the magnitude of the gluon condensate from the analysis of families $\rho, J/\psi, \Upsilon$.

4. The magnitude of gluon condensate from the φ- meson family

The polarization operator associated with the strange quark vector current has the form

$$i \int d^4x e^{iqx} \langle 0 \mid T\{j_\mu^\varphi(x) j_\nu^\varphi(0)\} \mid 0 \rangle = (q_\mu q_\nu - q^2 g_{\mu\nu}) \Pi^\varphi(Q^2) \tag{31}$$

where

$$j_\mu^\varphi(x) = -\frac{1}{3} \bar{s}(x) \gamma_\mu s(x) \tag{32}$$

All the previous formulae remain unchanged with one exception: the factor 2/9 in the right-hand side of Eq.(7). The mass of s-quark should be taken into account. The formula for the gluon condensate has the form:

$$\langle 0 \mid \frac{\alpha_s}{\pi} G^2 \mid 0 \rangle = -24 m_s \langle 0 \mid \bar{s} s \mid 0 \rangle + \frac{3}{\pi^2} \{ (s_2 - s_0) s_0^{(1)} + \\ + (s_2 - s_1) s_1^{(1)} - \frac{1}{2} s_2^2 + 4 m_s^2 s_2 - \frac{1}{2} (4 m_s^2)^2 \} \tag{33}$$

There are 2 φ- mesons, the φ-meson with the mass $M_0 = 1.019413 \pm 0.000008 GeV$, the electronic width $\Gamma_0^{ee} = 1.37 \pm 0.05 keV$ [26] and the φ' - meson with the mass $M_1 = 1.7 \pm 0.02 GeV$, the electronic width $\Gamma_e^{ee} = 0.7 \pm 0.175 keV$ [30]

From the formula

$$\Gamma_k^{ee} = \frac{2}{9} \frac{\alpha^2}{3\pi} \left(1 + \alpha_s^{\mathrm{eff}}(M_k)\right) M_k^{(1)} \tag{34}$$

and the values $\alpha_s^{\mathrm{eff}}(M_0) = 0.42$, $\alpha_s^{\mathrm{eff}}(M_1) = 0.39$ we get $s_0^{(1)} = 1.96 \pm 0.07 GeV^2$ and $s_1^{(1)} = 1.68 \pm 0.42 GeV^2$. The values m_s and $m_s \langle \bar{s} s \rangle$ are taken from [31]

$$m_s = 0.11 \pm 0.01 GeV \tag{35}$$
$$m_s \langle \bar{s} s \rangle = -(0.20 \pm 0.01) 10^{-2} GeV^4$$

The magnitude of the gluon condensate is

$$\langle 0 \mid \frac{\alpha_s}{\pi} Q^2 \mid 0 \rangle = -0.005 \pm 0.062 GeV^4 \tag{36}$$

Another magnitude of the gluon condensate we get using only Particle Data [26] with the mass of the φ'- meson $M_1 = 1.68 \pm 0.05 GeV$ and the formulae

$$\Gamma_0^{ee}(\varphi) = \frac{2}{9}\Gamma_0^{ee}(\rho) = 1.493 \pm 0.022 keV \tag{37}$$

$$\Gamma_1^{ee}(\varphi) = \frac{2}{9}\Gamma_1^{ee}(\rho) = 0.558 \pm 0.027 keV \tag{38}$$

The magnitude of the gluon condensate from (37–38) is

$$\langle 0 \mid \frac{\alpha_s}{\pi} G^2 \mid 0 \rangle = 0.08 \pm 0.04 \mathrm{GeV}^4 \tag{39}$$

It is clear from the Eqs.(36,39) that the analysis of φ-family gives no way to obtain a more precise magnitude of the gluon condensate in comparison with Eq.(19).

5. Some consequences for vector mesons consisting of light quarks.

The method developed in this work allows us to calculate electronic widths of vector mesons if masses of neighbouring mesons are known. The electronic widths of ρ' and ω'–mesons were calculated with this method.

The formula for the electronic width of the k–th vector meson is

$$\Gamma_k^{ee}(a) = \frac{\alpha^2}{3\pi} Q_a^2 \, R^{PT}(M_k) \, \frac{M_{k+1}^2 - M_{k-1}^2}{2M_k} \tag{40}$$

For the ρ–family $Q_a^2 = \frac{1}{2}$, for the ω–family $Q_a^2 = \frac{1}{18}$ and for the φ–family $Q_a^2 = \frac{1}{9}$.

As an example let us calculate the mass of nondiscovered the φ''–meson and improve the accuracy of the electronic width of the φ'–meson. Let us make the replacement of the summation by an integration starting from $k = 2$. Instead of Eq.(33) we obtain

$$\langle 0 \mid \frac{\alpha_s}{\pi} G^2 \mid 0 \rangle = -24 m_s \langle 0 \mid \bar{s}s \mid 0 \rangle + \frac{3}{\pi^2}\{(s_1 - s_0)s_0^{(1)} - \frac{1}{2}s_1^2 + \\ + \frac{1}{12}s_1^{(1)^2} + 4m_s^2 s_1 - \frac{1}{2}(4m_s^2)^2\} \tag{41}$$

The term $\frac{1}{12}s_2^{(1)}$ is small and has been discarded. Let us write eq.(41) in form

$$(s_2 - s_0^{(1)} - s_1^{(1)} - 4m_s^2)^2 \equiv x = \bar{x} + \Delta x \tag{42}$$

where

$$\bar{x} = (\overline{s_0^{(1)}} + \overline{s_1^{(1)}} - \overline{4m_s^2})^2 - 2(\overline{s_0}\,\overline{s_0^{(1)}} + \overline{s_1}\,\overline{s_1^{(1)}}) - \overline{(4m_s^2)^2} - \\ - 16\pi^2 m_s \overline{\langle \bar{s}s \rangle} - \frac{2\pi^2}{3}\overline{\langle 0 \mid \frac{\alpha_s}{\pi}G^2 \mid 0 \rangle} \tag{43}$$

is the average value of x and

$$\Delta x = 2(\overline{s_0^{(1)}} + \overline{s_1^{(1)}} - \overline{s_0} - \overline{4m_s^2})\Delta s_0^{(1)} + 2(\overline{s_0^{(1)}} + \overline{s_1^{(1)}} - \overline{s_1} - \overline{4m_s^2})\Delta s_1^{(1)} - \\ - \overline{2s_1^{(1)}}\Delta s_1 - 16\pi^2\Delta(m\langle \bar{s}s \rangle) - \frac{2\pi^2}{3}\Delta\langle 0 \mid \frac{\alpha_s}{\pi}G^2 \mid 0 \rangle \tag{44}$$

is an error in the value x. The substitution of $s_0^{(1)}$ and $s_1^{(1)}$ and $\langle 0 \mid \frac{\alpha_s}{\pi}G^2 \mid 0 \rangle$ (19) gives $\bar{x} = -1.02\text{Gev}^4$. But the value x must be positive. After summing the first, the third, the fourth and the fifth terms we obtain the estimate

$$\Delta x = \pm 1.44\Delta s_1^{(1)} \pm 0.44 \tag{45}$$

The use of the inequality $\bar{x} + \Delta x \geq 0$ gives an approximate estimate $s_1^{(1)} = 2.10 \pm 0.24\text{Gev}^2$ and the value of the mass of the φ''–meson

$$M_2 = 2.00 \pm 0.06\text{GeV} \tag{46}$$

The more refined value of the electronic width of φ'–meson is

$$\Gamma_1^{ee} = 0.87 \pm 0.10\text{keV} \tag{47}$$

The more refined value of the electronic widths of $\rho, \omega, \rho', \omega', \varphi'$ - mesons makes possible a more precise prediction of the hadronic contributions to the value of the electromagnetic coupling constant $\alpha(q^2)$ at $q^2 = M_z^2$ equal to $\delta\alpha_{hadr} = 0.02780(6)$ and to the anomalous magnetic moment of the muon equal to $a_\mu^{tot}(hadr) = 666(7) \cdot 10^{-10}$ [32].

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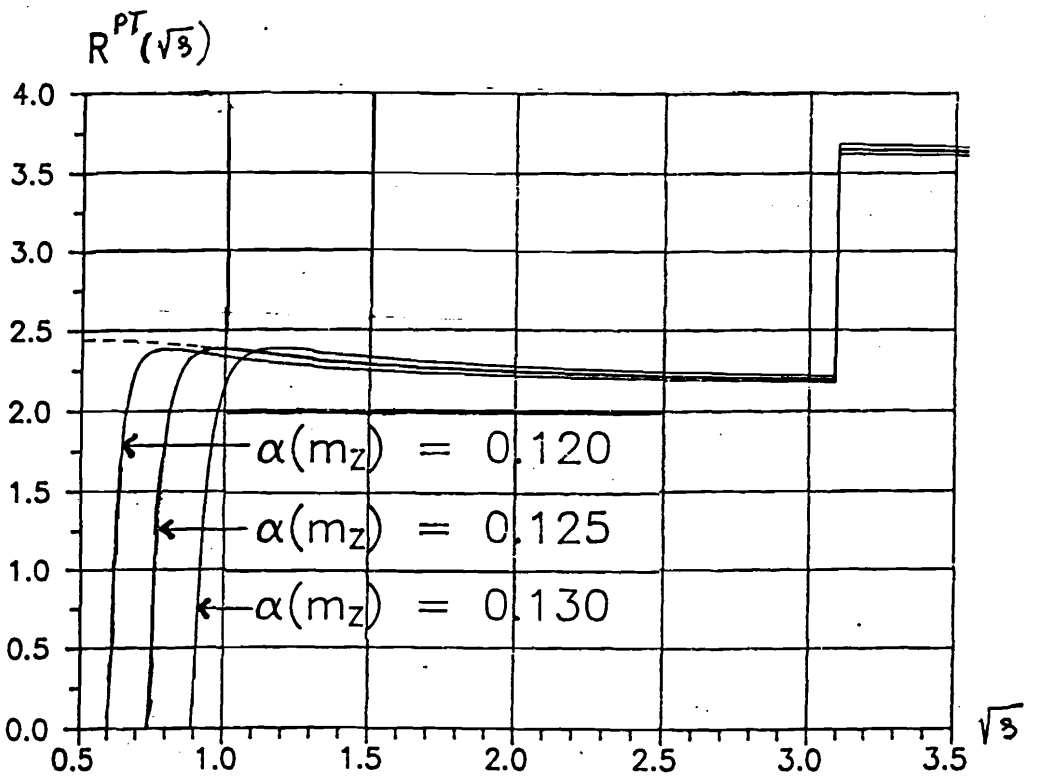
$R^{PT}(\sqrt{s})$
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
$\sqrt{s}$
$\alpha(m_Z) = 0.120$
$\alpha(m_Z) = 0.125$
$\alpha(m_Z) = 0.130$

Fig. 1

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