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PERTURBATIVE QCD PHENOMENOLOGY WITH MASSIVE GLUONS

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ABSTRACT

Two independent perturbative QCD analyses sensitive to the gluon mass are presented. The first, based on measurements of $R_{e^+e^-}$, Γ_h^Z and $\alpha_s(0)$ with standard current quark masses gives : $m_g = 1.5 \pm^{1.2}_{0.6}$ GeV. The second, a fit to the direct photon spectrum in $\Upsilon(1S)$ radiative decays finds : $m_g = 1.17 \pm 0.08$ (stat) $\pm$ 0.11 (theory) GeV. The weighted mean of six independent determinations gives $\alpha_s(0) = 0.290 \pm 0.015$ and the prediction :

$$\tilde{\alpha}_s^{(2)}(M_Z^2) = 0.128 \pm 0.005.$$

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Two independent perturbative QCD analyses sensitive to the gluon mass are presented. The first, based on measurements of $R_{e^+e^-}$, Γ_h^Z and $\alpha_s(0)$ with standard current quark masses gives : $m_g = 1.5 \pm {}^{1.2}_{0.6}$ GeV. The second, a fit to the direct photon spectrum in $\Upsilon(1S)$ radiative decays finds : $m_g = 1.17 \pm 0.08$ (stat) $\pm$ 0.11 (theory) GeV. The weighted mean of six independent determinations gives $\alpha_s(0) = 0.290 \pm 0.023$ and the prediction :

$$\tilde{\alpha}_s^{(2)}(M_Z^2) = 0.128 \pm 0.005.$$

1. Introduction

This letter describes two independent perturbative QCD analyses of experimental data which lead to consistent determinations of the mass of the gluon. These are :

i) A combined analysis using measurements of : a) the couplant $\tilde{\alpha}_s^{(2)}$ occuring in the Perturbation Expansions (PE) for $R_{e^+e^-}$ or Γ_h^Z and b) : the On-Shell QCD couplant ($a_s \equiv \alpha_s(0)/\pi$), together with : c) well known estimates of the quark masses.

ii) A fit to recent high precision data by the ARGUS [1] and CRYSTAL BALL [2] Collaborations on the photon spectrum in the process $\Upsilon(1S) \to \gamma + X$.

Method (i) is described in detail elsewhere [3]; here only the salient points of the analysis and the results are recalled. The On-Shell ($\overline{OS}$) renormalisation scheme used here, where the basic parameters are a_s and the quark and gluon masses, rather than the conventional Λ parameter is introduced in Ref. [4]. After describing (i) and (ii) in the following two Sections, Section 4 considers the effect of massive gluons in the decay $J/\Psi \to \gamma + X$. Section 5 presents a weighted average of the "strong fine structure constant" $\alpha_s(o)$ based on six independent and consistent experimental determinations. In Section 6 some other theoretical and phenomenological consequences of the existence of massive gluons are briefly mentioned.

2. Determination of m_g from $\tilde{a}_s^{(2)}(M_Z^2)$, a_s and the Quark Masses

The quantity :

$$R^{\gamma}_{e^+e^-} = \frac{\sigma_{TOT}\ (e^+e^- \to \gamma^* \to \text{hadrons})}{\sigma_{TOT}\ (e^+e^- \to \gamma^* \to \mu^+\mu^-)} \tag{1}$$

may, in perturbative QCD, be expressed as a PE in the couplant $\tilde{a}_s$ [5,6,7] :

$$R^{\gamma}_{e^+e^-}(s) = N_c \sum_q e_q^2\ [1 + r_1^{\gamma}\tilde{a}(s) + r_2^{\gamma}[\tilde{a}(s)]^2 + \ldots] \tag{2}$$

where $N_c = 3$ is the number of colours, e_q = the quark electric charge in units of e, the charge of the electron, and $\sqrt{s}$ is the total C.M. energy. The coefficients r_1^{γ}, r_2^{γ}, ... are free of logarithms containing s. Similarly the quantity $R^Z_{e^+e^-} = \Gamma^Z_h/\Gamma^Z_\ell$ has a PE with different coefficients r_1^Z, r_2^Z, ... [8,9]. A combined fit of the PE for $R^{\gamma}_{e^+e^-}$, $R^Z_{e^+e^-}$ up to $O(\tilde{\alpha}_s^3)$ to the 1991 world data was performed in Ref. [10] with the result :

$$\tilde{a}_s^{(2)}(M_Z^2) = 0.0442 \pm 0.0038 \tag{3}$$

The superscript (2) here indicates that the couplant is evaluated to two-loop or-

der. In the $\overline{OS}$ scheme one has [3,4] :

$$\tilde{a}_s^{(2)}(s) = \frac{a_s}{1 + \frac{a_s}{6}\left[(33 + \frac{153}{2}a_s)\ln\frac{\sqrt{s}}{m_g} - (10 + \frac{95}{2}a_s)\ln\frac{\sqrt{s}}{\bar{m}}\right]} \tag{4}$$

where $\bar{m} \equiv (m_u m_d m_s m_c m_b)^{1/5}$

and m_g is the gluon mass. It is convenient in phenomenological analyses to introduce the $\overline{OS}$ mass scale parameter m_0 given by the expression :

$$m_0 = \exp\left[\frac{\left(33 + \frac{153}{2}a_s\right)\ln m_g - \left(10 + \frac{95}{2}a_s\right)\ln\bar{m}}{(23 + 29a_s)}\right] \tag{5}$$

so that :

$$\tilde{a}_s^{(2)}(s) = \frac{a_s}{1 + a_s\,[A + a_s B]\ln\left(\frac{s}{m_0^2}\right)} \tag{6}$$

where $A \equiv (33 - 2n_f)/12$, $B = (153 - 19n_f)/24$.

n_f is the number of quark flavours with mass $\ll \sqrt{s}$ ($n_f = 5$ in Eqns (4), (5)):

For given values of s, $\tilde{a}_s^{(2)}(s)$ (6) is a quadratic equation in a_s. Taking $\tilde{a}_s^{(2)}(M_Z^2)$ from (3) this equation has a real solution for a_s provided that :

$$m_0 \geq 2.26 \pm {}^{0.96}_{0.79} \text{ GeV} \tag{7}$$

If current quark masses are assumed [11] :

$$m_u,\ m_d,\ m_s,\ m_c,\ m_b = 5.6,\ 9.9,\ 199,\ 1350,\ 5000 \text{ MeV} \tag{8}$$

Eqn (5) may be solved for m_g to give the limit :

$$m_g \geq 0.73 \pm 0.16 \text{ GeV (current quarks)} \tag{9}$$

For constituent masses :

$$m_u,\ m_d,\ m_s,\ m_c,\ m_b = 350,\ 350,\ 500,\ 1500,\ 5000 \text{ MeV} \tag{10}$$

one obtains the limit :

$$m_g \geq 1.51 \pm 0.16 \text{ GeV (constituent quarks)} \tag{11}$$

The lower limits (9), (11) on m_g are independent of the value of a_s. A better estimate of m_0 (and hence, via Eqn (5), m_g) is obtained by using the experimental value of a_s in (6) and solving for m_0. Five different experimental determinations (see TABLE II of Ref. [3] and the entries I – V of TABLE II below) are consistent with the value :

$$a_s = 0.096 \pm 0.016 \tag{12a}$$

or

$$\alpha_s(0) = 0.30 \pm 0.05 \tag{12b}$$

A discussion of these a_s determinations may be found in Ref. [3]. Using (3) and (12a) and solving (6) for m_0 gives :

$$m_0 = 5.7 \pm {}^{1.6}_{1.7} \text{ GeV} \tag{13}$$

or, using (5)

$$m_g = 1.5 \pm {}^{1.2}_{0.6} \; [2.7 \pm {}^{2.1}_{1.0}] \text{ GeV} \tag{14}$$

for current [constituent] quarks.

Although (14) indicates that m_g is $< 3\sigma$ above zero, Eqn (14) and the non zero measured value of $\tilde{a}_s^{(2)}$ at various values of $\sqrt{s}$ excludes the possibility $m_g = 0$. See Ref. [3] for further discussion of this important point.

3. Determination of m_g from the Direct Photon Spectrum in the Decay $\Upsilon(1S) \to \gamma + X$

In the lowest order of QCD perturbation theory, direct photon production is described by the process $\Upsilon(1S) \to \gamma gg$[12] and for massless gluons the photon energy spectrum is the same as in orthopositronium decay [13] :

$$\frac{1}{\Gamma}\frac{d\Gamma}{dz\,dx_1} = \frac{1}{(\pi^2 - 9)}\left[\left(\frac{1 - x_1}{x_2 z}\right)^2 + \left(\frac{1 - x_2}{x_1 z}\right)^2 + \left(\frac{1 - z}{x_1 x_2}\right)^2\right] \tag{15}$$

where x_1, x_2, z are defined as :

$$x_i = 2E_i/W, \qquad i = 1,2; \qquad z = 2E_\gamma/W$$

$E_{1,2}$ are the gluon energies, E_γ the photon energy and W the mass (9.46 GeV) of the $\Upsilon(1S)$ state. Energy conservation gives the condition :

$$x_1 + x_2 + z = 2$$

so that only two independent variables (say x_1, z as in (15)) completely define the kinematical configuration. It is shown in Ref. [14] that the photon spectrum given by integrating (15) over x_1 is very close to a pure phase space distribution given by an uniformly populated triangular Dalitz plot in the variables x_1, z. In the case that gluons have a definite mass m_g the kinematically allowed region is restricted by the conditions :

$$0 \le z \le 1 - 4\,(m_g/W)^2 \tag{16a}$$

$$x_1^{MIN} \le x_1 \le x_1^{MAX} \tag{16b}$$

where :

$$x_1^{\substack{MAX\\MIN}} = 1 - \frac{z}{2}\left[1 \mp \sqrt{1 - \frac{4m_g^2}{W^2(1-z)}}\right] \tag{17}$$

The inclusive photon spectrum for the massive gluon case may now be estimated by integrating (15) over x_1 subject to the kinematical constraints (16). The approximation made here is that for massive gluons, as for the massless case, the photon spectrum is phase space dominated. Also longitudinal gluon contributions which may be important when the gluons are soft are not taken into account. The result is :

$$\frac{1}{\Gamma}\frac{d\Gamma}{dz} = f(x_1^{MAX}) - f(x_1^{MIN}) \tag{18a}$$

where :

$$f(x) = \frac{2x}{z^2} + (1-z)\left\{(1-z)\left[\frac{1}{z^2} + \frac{1}{\alpha^2}\right]\left[\frac{1}{(\alpha - x)} - \frac{1}{x}\right]\right.$$

$$\left. + 2\left[\frac{1}{z^2} - \frac{(1-z)}{\alpha^3}\right]\ln\left(\frac{\alpha - x}{x}\right)\right\} \tag{18b}$$

and $\alpha \equiv 2 - z$.

For the massless gluon case Higher Order (HO) corrections to the spectrum (18) have been calculated by Photiadis [15] leading to a multiplicative correction function F(z). In this calculation leading logarithms in 1 − z are summed to all orders in α_s. In the absence of a similar calculation for massive gluons an estimate of the HO corrections is made here by using the function F(z′) where $z' = z/z_{MAX}$ and z_{MAX} is the maximum kinematically allowed value of z, given by Eqn (16a).

After introducing a gaussian energy smearing consistent with the resolution of the different experiments :

ARGUS : $$\sigma_{E_\gamma}/E_\gamma = \sqrt{0.0518 + 0.00423/E_\gamma(\mathrm{GeV})} \tag{19}$$

CRYSTAL BALL : $$\sigma_{E_\gamma}/E_\gamma = 0.027\ E_\gamma(\mathrm{GeV})^{-1/4} \tag{20}$$

Eqn (18) has been fitted to the published data of Ref. [1,2] either without the correction factor F(z′) (LO Lowest Order) or including F(z′) (HO). The results of these fits are compared to the experimental data in Fig. 1 and are presented in TABLE I. The CRYSTAL BALL results given by two different background subtraction procedures (I and II corresponding to Figs 4, 5 respectively of Ref. [2]) are given in TABLE I, but only that yielding the most accurate value of m_g (II) is shown in Fig. 2. This data set is also the one used in the weighed average quoted in TABLE I.

In all cases the quality of the fit is improved by including the HO correction, markedly so in the case of the CRYSTAL BALL II spectrum. This is understandable since the very good resolution of the CRYSTAL BALL detector makes it specially sensitive to the spectrum shape in the critical region near z = 1. Inclusion of the HO correction reduces the weighted average fitted value of m_g from 1.28 ± 0.07 GeV to 1.17 ± 0.08 GeV. In view of the approximate treatment of the HO QCD corrections given by F(z′) a conservative "theoretical systematic " error

corresponding to the difference between the HO and LO fit results is assigned in addition to the purely statistical errors quoted in TABLE I. The final result for the gluon mass is then :

$$m_g = 1.17 \pm 0.08(\text{stat}) \pm 0.11(\text{theory}) \text{ GeV} \tag{21}$$

For the calculations using m_g described in Section 5 below the two errors quoted in (21) are added in quadrature.

The value of m_g in (21) is in very good agreement with the "current quark" value of the analysis of Ref. [3] presented in Section 2 above. It is however still consistent at a level of $< 2\sigma$ with the "constituent quark" value of Ref. [3]. As discussed in Section 5 below however, the rather precise value of m_g in (21) when used in (4) to predict the value of a_s, given the experimental value of $\tilde{a}_s^{(2)}(M_Z^2)$ enables the "constituent quark" hypothesis for the quark masses to be rejected.

Excellent fits to the data of Ref. [1,2] have been obtained using a Monte Carlo parton shower model to describe higher order QCD corrections [14]. In this model the gluons are assigned an initial "effective mass" whose mean value is $\simeq 1.6$ GeV, comparable to the value of m_g given in (21). In Fig. 2 different theoretical predictions for the photon spectrum $(1/\Gamma)(d\Gamma/dz)$ are shown. These include the spectra given by Eqn (18) for $m_g = 0$ and the best fit value 1.17 GeV both with and without the HO correction factor $F(z')$, as well as the prediction of the parton shower model of Ref. [14].

It is not possible to discriminate between the parton shower model and the hypothesis of a fixed gluon mass using the $\Upsilon(1S)$ data since both models give equally good fits to the data. The predictions of the two models are however very different for the decay $J/\Psi \to \gamma + X$ as is described in the following Section.

4. Predictions for $J/\Psi \to \gamma + X$

With a gluon mass of 1.17 GeV the available energy for on-shell gluon production in the decay $J/\Psi \to \gamma gg$ is only 760 MeV and $z_{MAX} = 0.43$. Higher photon

energies require virtual gluon emission with rate suppression due to propagator factors. The scaled photon energy spectrum in J/Ψ decays is then expected to be much softer than in Υ decays. The experimental data of the MARK II Collaboration [16] (Fig. 3) show that this is indeed the case. The solid curve is a fit to the LO QCD prediction of Eqn (18) taking into account gaussian smearing by the resolution function of the MARK II detector [16].

$$\text{MARK II}: \qquad \sigma_{E_\gamma}/E\gamma = 0.12/\sqrt{E_\gamma(\text{GeV})} \tag{22}$$

This fit (also reported in TABLE I) is a very good representation of the experimental data ($P\chi^2 = 0.8$) but the value obtained for m_g of 0.66 ± 0.01 GeV is quite inconsistent with that obtained from Υ decays. This is to be expected since the off-shell gluons in the final state γgg in J/Ψ decays are forced by kinematics to have an effective mass much less than that in Υ decays where, except for $z \geq 0.94$, On-Shell gluons are kinematically allowed. That the fit of Eqn (18) to the J/Ψ data is very good one should, in the light of this argument be considered as an accident rather than of physical significance. This simple representation of the data is however useful for possible future comparisons with QCD calculations taking explicitly into account the gluon virtualities. The massive gluon hypothesis to explain the soft photon spectrum in J/Ψ decays was first suggested by Parisi and Petronzio [17], who estimated the gluon mass to be 0.8 GeV. Their comparison with the experimental data did not however take into account the experimental resolution function (22).

If gluons indeed have a mass ~ 1.2 GeV the non-abelian branching process $g \to gg$ which has a threshold of ~ 2.4 GeV will be strongly suppressed relative to $g \to q\bar{q}$ in all decays of the J/Ψ, in spite of colour factors favouring the former process. This gives a natural explanation of the MARK II result that the mean multiplicity both of unidentified charged hadrons and K_s is the same in the hadronic final state X in the decay $J/\Psi \to \gamma + X$ as in continuum e^+e^- annihilation at the same average CM energy [16].

The prediction of the parton shower model of Ref. [14] including the experimental resolution function (21) is shown as the dotted curve in Fig. 4. The unsmeared spectrum is actually the same as that shown in Fig. 2, which corresponds to $\Upsilon(1S)$ decays. However, as described in Ref. [14] the shape of the spectrum in the scaled variable z is almost independent of W. The parton shower model prediction is clearly inconsistent with the experimental data, which have a markedly softer spectrum. In the case of Υ decays the average mass assigned to gluons that initiate the parton shower is 1.6 GeV, close to the fitted values of the fixed gluon mass presented in TABLE I. For J/Ψ decay the mean initial mass, which is roughly proportional to W is only 0.5 GeV, so that phase space suppression of the photon spectrum occurs only for $z > 0.90$ and the predicted spectrum is too hard to explain the experimental data.

5. Phenomenology of the Strong Fine Structure Constant $\alpha_s(0)$

Seven independent determinations of the On-Shell strong coupling constant $\alpha_s(0)$ are presented in Fig. 5 and TABLE 2. I – V are taken form Ref. [3] which should be consulted for further details.

The entries VI and VII are new estimates based on Eqn (4), using the fitted value of m_g from $\Upsilon(1S) \to \gamma X$ decays from Section 3 and $\tilde{a}_s^{(2)}(M_Z^2)$ from Eqn (3). If the quark masses are assumed to be known Eqn (4) may be solved for $a_s \equiv \alpha_s(0)/\pi$. The values thus obtained for $\alpha_s(0)$ on the assumption of current [constituent] quark masses as given in Eqn (7) [(8)] are reported as the entries VI, [VII] of Fig. 5 and TABLE 2. Only the value corresponding to the current quark mass hypothesis gives a value of $\alpha_s(0)$ consistent with the other determinations I – VI. The weighted average of I – V is : $\alpha_s(0) = 0.287 \pm 0.024$ to be compared with :

$$\alpha_s(0) = 0.36 \pm {}^{0.11}_{0.09} \text{ (current quarks)} \tag{23a}$$

$$\alpha_s(0) \geq 0.48 \text{ (95 \% CL) (constituent quarks)} \tag{23b}$$

the constituent quark hypothesis for the quark masses in Eqn (4) is therefore

ruled out at a level of $\geq 8\sigma$.

The weighted average value of $\alpha_s(0)$ given by the determinations I – VI is :

$$\alpha_s(0) = 0.291 \pm 0.023 \text{ (weighted mean)} \tag{24}$$

The consistency of the six independent determinations with the value (24) is very good ($\chi^2 = 3.59$ for 5 D.F., or $P\chi^2 = 0.60$). This value is completely consistent with the value in Eqn (12) used in Ref. [3] for the gluon mass estimates of Eqn (4).

Comparing (24) with the value of the running coupling constant at the Z mass scale [10]† :

$$\hat{\alpha}_s^{(2)}(M_Z^2) = 0.139 \pm 0.012 \tag{25}$$

a "running" of the coupling constant of 52 % is seen between scales of ~ 1 – 2 GeV and the Z mass, a 6σ effect. Using (8), (21) and (24) in Eqn (5) the $\overline{OS}$ scheme mass parameter is determined to be

$$m_0 = 3.71 \pm 0.69 \text{ GeV} \tag{26}$$

The error quoted in (26) is dominated by that in m_g. An independent determination of $\alpha_s^{(2)}(M_Z^2)$ is now possible using $a_s = \alpha_s(0)/\pi$, where $\alpha_s(0)$ is taken from (24) and m_0 from (26). Eqn (6) then gives the prediction ($\tilde{\alpha}_s^{(2)} \equiv \pi\, \tilde{a}_s^{(2)}$) :

$$\tilde{\alpha}_s^{(2)}(M_Z^2) = 0.128 \pm 0.005 \tag{27}$$

This is somewhat lower than, but consistent with, the experimental value quoted in (25). The error or $\tilde{\alpha}_s^{(2)}(M_Z^2)$ in (27) which is dominated by that on m_0 (and hence on m_g) is remarkably small ≈ 4 %. It is then clearly of interest to improve the error on the experimental value $\hat{\alpha}_s^{(2)}(M_Z^2)$. New high statistics LEP data is expected

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† Following Ref [10] the superscript ^ on $\alpha_s^{(2)}$ indicates that it is evaluated only from measurements of $R^{\gamma}_{e^+e^-}$ and $R^{Z}_{e^+e^-}$ (or Γ^Z_h).

to provide a measurement of $R^Z_{e^+e^-}$ sufficiently accurate to reduce the error on $\hat{\alpha}_s^{(2)}(M_Z^2)$ by at least a factor of two [10]. A test of the consistency of perturbative QCD at the few % level, free of hadronisation and renormalisation scale uncertainties, will then be possible by comparing $\hat{\alpha}_s^{(2)}(M_Z^2)$ with $\tilde{\alpha}_s^{(2)}(M_Z^2)$ as given in (27).

6. Summary, Survey and Outlook

The main results of the analysis presented here are the values of the parameters of the $\overline{OS}$ scheme : m_g, m_0, $\alpha_s(0)$ to be found in Eqns (21; (26), (24) respectively, as well as the predicted value of $\tilde{\alpha}_s^{(2)}(M_Z^2)$ in Eqn (27). A consistent phenomenology requires that "current" masses be assigned to the quarks, and as the quark and gluon masses appear on an equal footing in the $\overline{OS}$ scheme formulae the quoted value of m_g should also, in some sense, be interpreted as a "current" mass. The parton shower model of R.D. Field [14] which successfully describes the $\Upsilon(1S)$ radiative decay, does not describe the corresponding decay of the J/Ψ. This is understandable if gluons have a fixed mass of ~ 1.2 GeV.

The idea of introducing massive gluons into QCD phenomenology, resulting in the "freezing" of the running coupling constant at scales at the order of and below the gluon mass is due to Parisi and Petronzio [17]†. They introduced the massive gluon hypothesis to explain the observed behaviour of the proton form factor and small angle proton-proton elastic scattering as well as the low value of α_s determined from J/Ψ decays. Their suggested values of $\alpha_s(0)$ and m_g were 0.35 and 0.8 GeV. A brief list of some other applications of massive gluons to QCD phenomenology follows :

a) Landshoff and Nachtman [23] have introduced a non-perturbative contribution to the gluon propagator at long distances in order to reconcile QCD with the success of the additive quark rule and the description

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†I became aware of the work of these authors only after completing the papers cited in Ref. [3] and [4].

of elastic scattering by Regge pole and pomeron exchange. In QCD the leading contribution to the pomeron is two gluon exchange, which is required to have a range considerably less than the typical hadronic dimension of 1 fermi. Several authors have presented solutions of the Dyson–Schwinger equation in which the running of α_s is "frozen" at low scales [24, 25, 26]. The "constituent" quark mass corresponding to this non-perturbative modification of the gluon propagator is ~ 1 GeV.

b) The recent, final, high statistics data from the MARK III Collaboration [27] has shown evidence for appreciable production (~ 0.1 % branching ratio) of axial vector mesons in radiative J/Ψ decays : $J/\Psi \to \gamma a$. The lowest order QCD diagram requires that mesons with spin parity 1^+ couple to two spin one gluons. By Yang's theorem [28] this coupling is forbidden for massless gluons.

c) The MARK II results show no convincing evidence [27] for glueball production in the "gluon-rich" channel X in the decays $J/\Psi \to \gamma X$. If gluons have a mass of ~ 1.2 GeV gluonium states may be much higher in mass than hitherto supposed, and so may be kinematically forbidden in J/Ψ decays.

d) Gluons of mass ~ 1.2 GeV impose a threshold of ≃ 2.4 GeV on the non-abelian splitting process $g \to gg$. This will result in the "quenching" of soft gluon production at scales below a few GeV. As discussed in Section 4 above this effect may already have been observed in J/Ψ decays.

e) Considerable evidence has accumulated in recent years for the existence of short range diquark correlations in nucleon structure [29]. Such correlations would be a natural consequence of a finite range colour magnetic interaction [30]. Exchange of a gluon with a mass of ~ 1.2 GeV provides a simple mechanism for such a short range force.

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TABLE I

Gluon mass (m_g) values obtained from fits to the photon spectrum in the decays $\Upsilon(1S) \to \gamma x$, $J/\Psi \to \gamma x$

EXPERIMENT	REF.	m_g (GeV)	χ^2_{MIN}	D.F.	P_{χ^2} (%)	FIT TYPE
ARGUS **T(1S)**	[1]	1.34 ± 0.094 1.21 ± 0.10	19 14.7	18 18	47 62	LO HO
CRYSTAL BALL I* **T(1S)**	[2]	$1.15^{+0.16}_{-0.18}$ $1.03^{+0.16}_{-0.20}$	18 18	12 12	10 23	LO HO
CRYSTAL BALL II* **T(1S)**	[2]	$1.20^{+0.12}_{-0.10}$ $1.10^{+0.12}_{-0.13}$	24 18	13 13	3 16	LO HO
MARK II J/Ψ	[16]	$0.66^{+0.07}_{-0.08}$	18.3	26	85	LO

T(1S) LO weighted average m_g (ARGUS and CRYSTAL BALL II) = 1.28 ± 0.07 GeV

T(1S) HO weighted average m_g (ARGUS and CRYSTAL BALL II) = 1.17 ± 0.08 GeV

* CRYSTAL BALL I, II are photon spectra given in Fig. 4, 5 respectively of Ref. [2]

TABLE II

Experimental values of the strong fine structure constant $\alpha_s(0)$

Entry	Method	$\alpha_s(0)$	References
I	e^+e^- jet fractions	0.27 ± 0.04	[4, 18]
II	High p_T γ and π^0 production	$0.31 \begin{smallmatrix} +0.11 \\ -0.05 \end{smallmatrix}$	[4, 19]
III	Baryon colour and hyperfine splittings	0.28 ± 0.05†	[20]
IV	$R_\tau^{exp,B}$	0.35 ± 0.05	[21, 22]
V	$R_\tau^{exp,\Gamma}$	0.21 ± 0.07	[22]
VI	Eqn (4) using m_g from $\Upsilon(1S)$ decays, $\tilde{a}_s^{(2)}(M_Z^2)$ and current quark masses	$0.36 \begin{smallmatrix} +0.11 \\ -0.09 \end{smallmatrix}$	This work
VII	As VII but with constituent quark masses	≥ 0.48 (95 % C.L.)	This work
VIII	Weighted mean of I – VI	0.291 ± 0.023	This work

† This is the author's estimate. No error is quoted in Ref. [20].

Figure Captions

1) Inclusive photon spectra for the process $\Upsilon(1S) \rightarrow \gamma+X$ as measured by: a) ARGUS [1], b) CRYSTAL BALL [2]. The curves are best fits to the data treating the gluon mass m_g as a free parameter. The fitted curves take into account the experimental resolution functions by a gaussian smearing procedure. The dashed curves use the theoretical spectrum (18) whereas the solid curves include a multiplicative correction factor $F(z')$ to (18) from Ref. [15] that takes into account higher order QCD corrections. The fitted values of m_g may be found in TABLE I.

2) Theoretical predictions for the inclusive photon spectrum in $\Upsilon(1S)$ decays. Broad dashed curve : lowest order QCD prediction with massless gluons. Solid curve : QCD prediction for massless gluons with higher order corrections from Ref. [15] included. Fine dashed curve : Eqn (18) with $m_g = 1.17$ GeV. Dot-dashed curve : Eqn (18) with $m_g = 1.17$ GeV including the higher order correction factor $F(z')$ from Ref. [15]. Dotted curve : prediction of the parton shower model of Ref. [14].

3) Inclusive photon spectrum in $J/\Psi \rightarrow \gamma+X$ decay, as measured by the MARK II Collaboration [16]. Solid curve : best fit (after correction for resolution smearing) to Eqn (18) [$m_g = 0.66$ GeV]. Dotted curve : the prediction of Ref. [14] (see text).

4) Different determinations of the strong fine structure constant $\alpha_s(0)$. See TABLE II and the text for details.

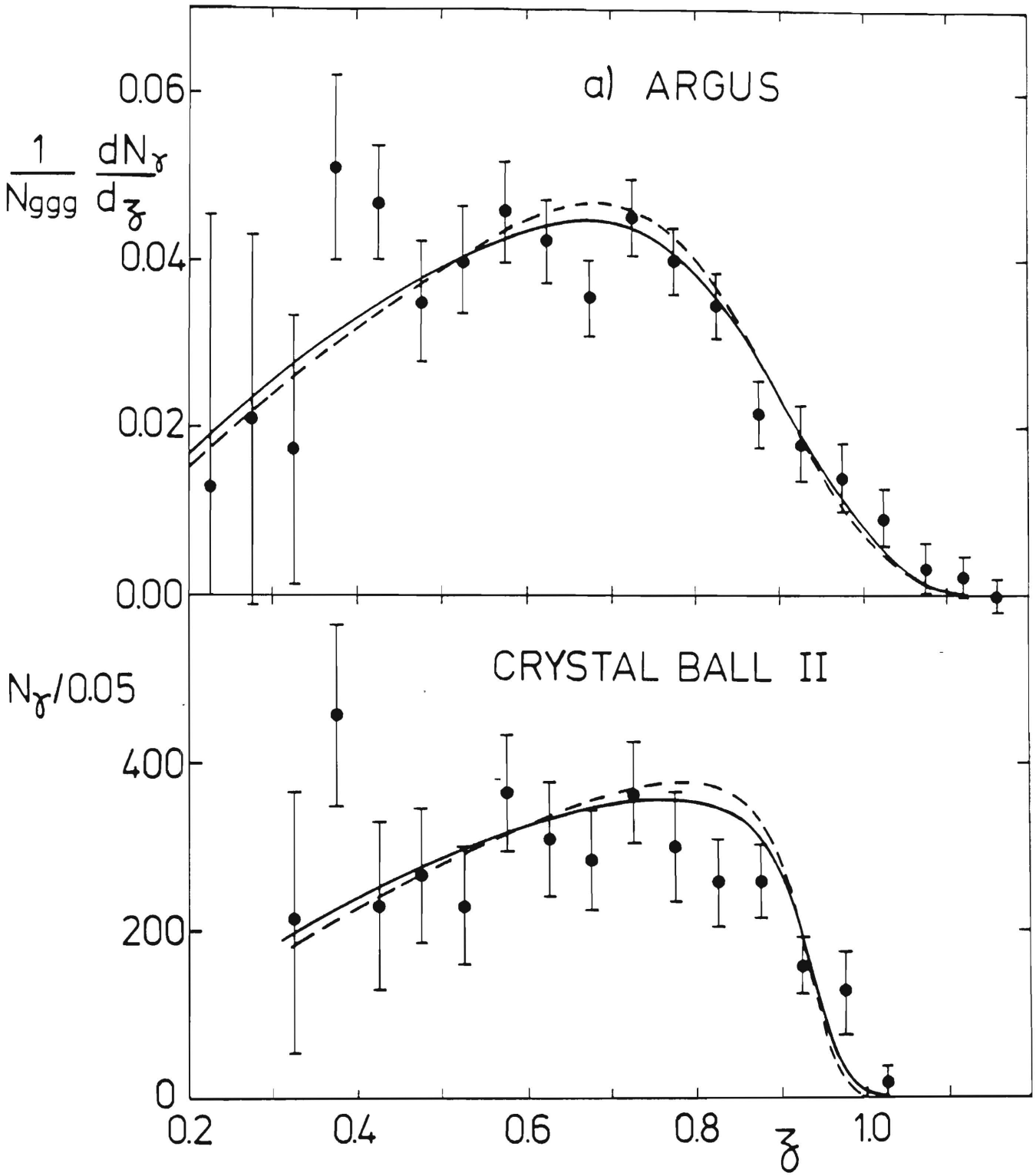
a) ARGUS
$\frac{1}{N_{ggg}} \frac{dN_\gamma}{dz}$
0.06
0.04
0.02
0.00
CRYSTAL BALL II
$N_\gamma/0.05$
400
200
0
0.2
0.4
0.6
0.8
1.0
z

Figure 1

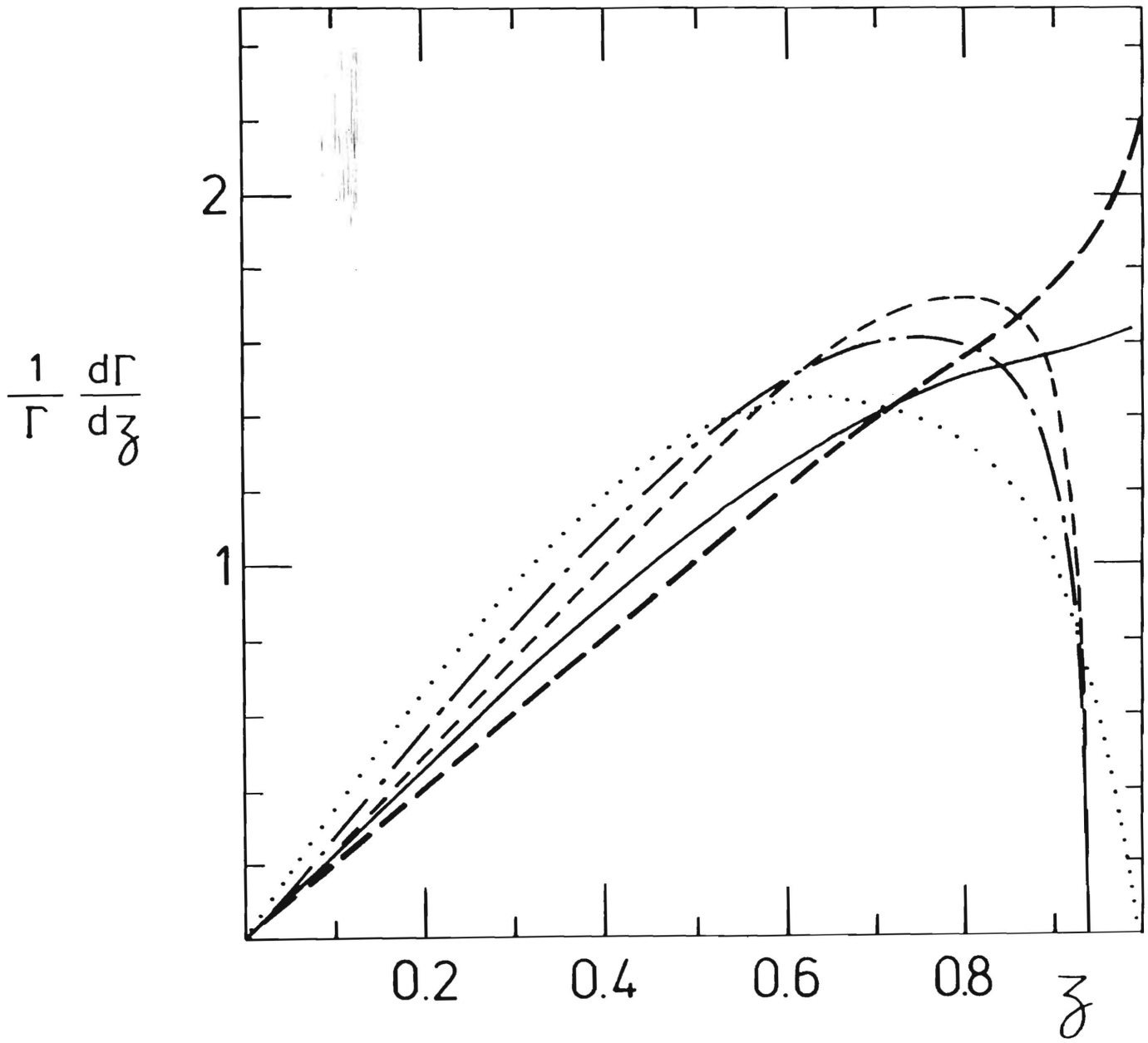

Figure 2

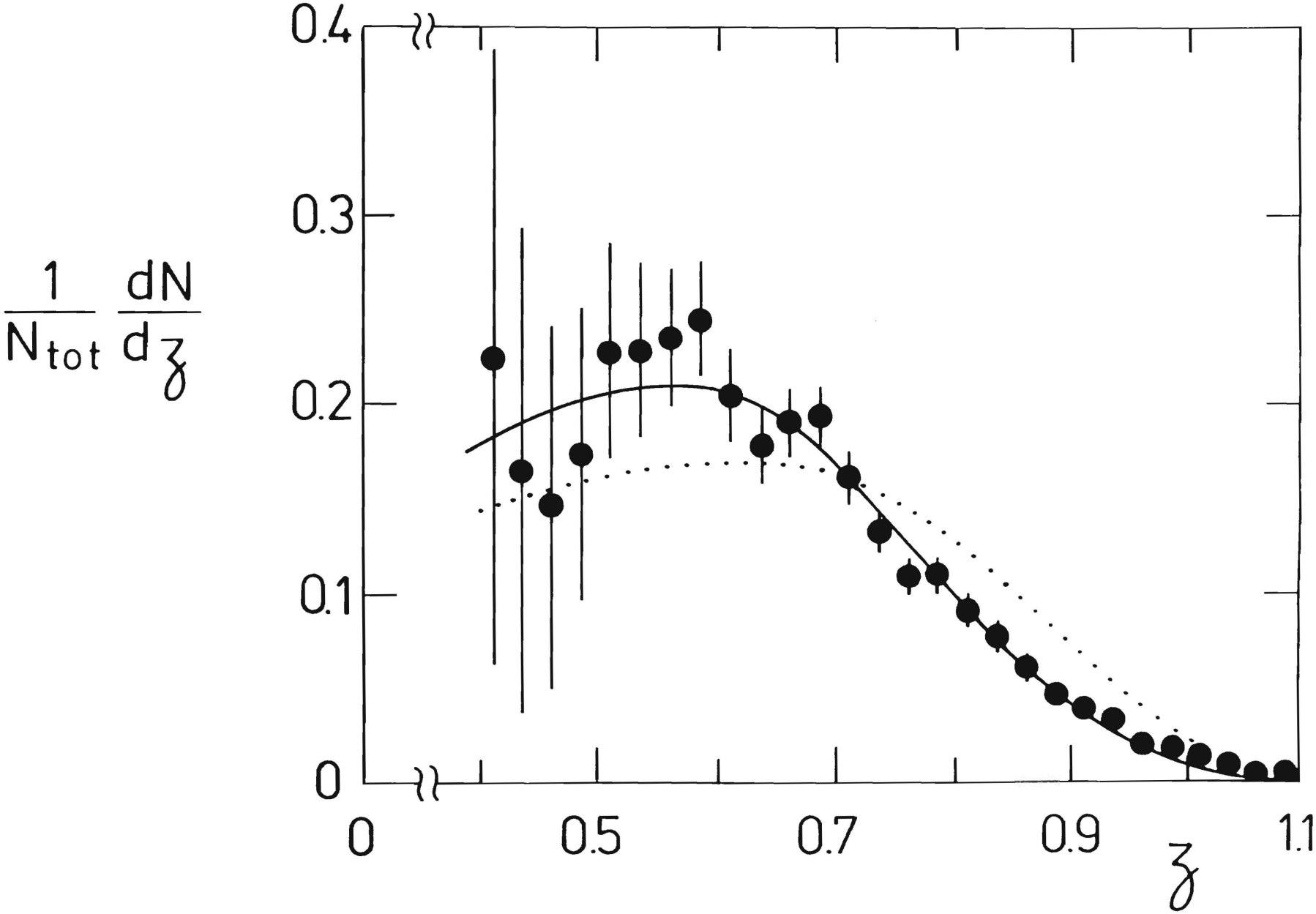

Figure 3

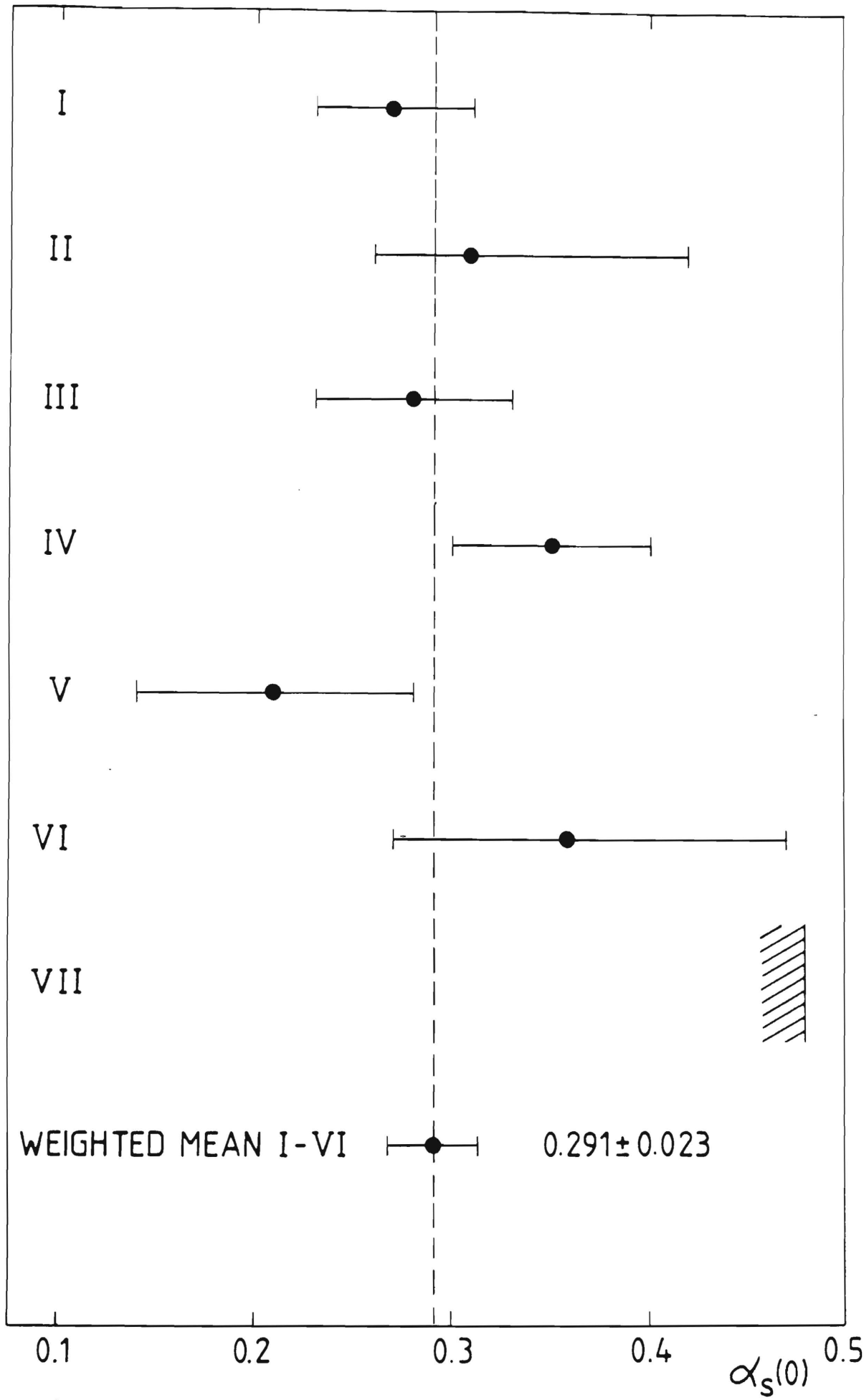
I
II
III
IV
V
VI
VII
WEIGHTED MEAN I-VI
0.291± 0.023
0.1
0.2
0.3
0.4
0.5
$\alpha_s(0)$

Figure 4