Possible indication of a light gluino

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The quarkonia data on α_3 taken at face value, although consistent among themselves at the 10% level, are inconsistent with the current picture of minimal supersymmetric grand unification. They become consistent if the gluino octet lies below half the Z mass and are also consistent with jet measurements of α_3 in the Z region if the gluino lies below the Υ region.

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I. INTRODUCTION

Renewed attention to the supersymmetric grand unification scenario has been generated in the past year by the observation that the new measurements of the standard model couplings at the CERN e^+e^- collider LEP, although inconsistent by themselves with grand unification, were consistent with unification if there was approximate supersymmetry above the TeV energy scale [1]. Alternative ways of reconciling the LEP data with unification have also been proposed [2] with the common feature of new particle content at 1 TeV or above.

The LEP measurements of the strong coupling constant $\alpha_3(M_Z)$, however, are inconsistent with the simplest reading of the quarkonium data: namely,

$$\alpha_3(M_Z)=0.108\pm0.005 \quad \text{(DELPHI data quoted in Ref. [1])}\,, \tag{1.1}$$

$$\alpha_3(M_Z)=0.113\pm0.003 \quad \text{(world average [3])}\,, \tag{1.2}$$

$$\alpha_3(M_Z)=0.094\pm0.001 \quad \text{(quarkonia)}\,. \tag{1.3}$$

For completeness we include here the world average data for the other couplings,

$$\alpha_{\rm em}(M_Z)^{-1}=127.9\pm0.2\,, \tag{1.4}$$

$$\sin^2\theta_{\overline{\rm MS}}=0.2333\pm0.0008 \quad \text{(world average [4])}\,, \tag{1.5}$$

as well as the values from Ref. [1]:

$$\alpha_{\rm em}(M_Z)^{-1}=128.8, \quad \sin^2\theta_{\overline{\rm MS}}=0.2336\pm0.0018\,, \tag{1.6}$$

where $\overline{\rm MS}$ denotes the modified minimal subtraction scheme. From there the U(1) and SU(2) coupling constants are obtained by

$$\alpha_1=\tfrac{5}{3}\alpha_{\rm em}/\cos^2\theta_{\overline{\rm MS}}\,,$$

$$\alpha_2=\alpha_{\rm em}/\sin^2\theta_{\overline{\rm MS}}\,.$$

The quarkonia data leading to Eq. (1.3) are analyzed in Sec. II. The results are in agreement with earlier analyses except where new data have made the results more precise. Equation (1.3) is obtained assuming the standard model running as shown in Fig. 1 with standard particle content up to the Z. Thus there is a broad disagreement between the LEP and world average values (1.1) and (1.2) and those coming from quarkonia taken at face value. It is extremely unlikely that this disagreement is due to statistical fluctuations. The quarkonia data, however, might be subject to relativistic corrections to the bound state decay, and the jet data, as is well known, receive important corrections due to hadronization which can only be treated at present in phenomenological models. There-

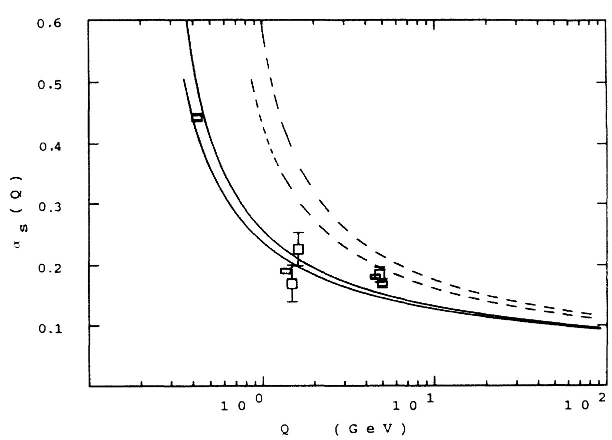

FIG. 1. Best fit to the quarkonia data assuming standard model running of the coupling constant with standard particle content. Also shown (dashed) is the running from the world average values of $\alpha_3(M_Z)$.

fore the disagreement between the LEP data and the quarkonia data is not as bothersome as the fact that the quarkonia value of Eq. (1.3) is inconsistent with the current picture of a supersymmetric (SUSY) grand unification with a SUSY threshold in the region from 100 GeV to 10 TeV. As discussed in Sec. III, unification with this value of $\alpha_3(M_Z)$ would require a SUSY scale thousands of times higher than theoretically desirable and would be in violation of proton decay constraints.

The majority opinion among those familiar with the discrepancy and perhaps the most likely resolution is the following point of view: *The quarkonia data do not provide a reliable measure of the strong coupling constant at the Z due to as yet uncalculable higher-order or nonperturbative QCD corrections or to relativistic corrections to the bound state.*

In the current work we consider the case for an alternative point of view. In Sec. II we note the following.

(a) The quarkonia data taken by themselves are consistent with the predicted running of the strong coupling constant at the 10% level. It would be remarkable if currently uncalculated effects so accurately mimicked perturbative QCD.

(b) If one tries to parametrize the nonperturbative or relativistic corrections to reconcile the J/ψ and Υ data with higher values of the coupling constant [5] the corrections are such as to make lower energy states more narrow. This is counterintuitive since the lowest energy and the most relativistic states (e.g., ρ and ω) are very broad and the narrowness of the heavy quarkonia is in the usual view attributed to perturbative QCD.

(c) Such parametrizations are unable to account for the three-gluon (i.e., nonstrange) decays of the ϕ which are (see Sec. II) nevertheless consistent with pure perturbative QCD and the rest of the quarkonia data if the strong coupling constant is small. The possibility of explaining the narrowness of the ϕ (Zweig rule) was one of the early motivations of QCD. With the standard picture and a coupling as large as given in Eq. (1.1) or (1.2) the narrowness of the ϕ remains a total mystery.

The purpose of the current work is to point out that the discrepancy can be adequately resolved if the gluino octet lies at low energy. This is discussed in Sec. III. Other resolutions in addition to the presently incalculable ones discussed above and the light gluino option are presumably also possible. The extent to which a light gluino is consistent with other data is also reviewed in Sec. III.

The possibility of a light gluino was reconsidered recently [6] relative to the SUSY unification hypothesis and the Υ data. The conclusion of that work was that a light gluino was disfavored by the data. The difference in our conclusions is due mostly to the fact that in Ref. [6] the lighter quarkonia states were not considered and perhaps also (slightly) due to certain approximations made in Ref. [6] in the renormalization group extrapolation. However, we find that even the Υ data, in the absence of a light gluino, imply a SUSY scale near 5 TeV, uncomfortably far from the weak scale and possibly out of easy range of the Superconducting Super Collider (SSC). If we had a well-founded calculable theory of nonperturbative effects supporting the majority opinion above, the motivation for the current paper would disappear. At this point, however, we would like to remain open to discussions such as those here which seek a resolution at the level of perturbative field theory.

II. GLUONIC DECAYS OF S-WAVE QUARKONIA AS A MEASURE OF α_3

The nonelectromagnetic decays of quarkonia states into dissimilar quarks is a measure of the strong coupling constant α_3 that is insensitive to hadronization effects. Instead there are in principle corrections due to bound state effects. The primary nonperturbative parameter, the bound state wave function at the origin, cancels out if we consider the ratio of the gluonic decays to the electromagnetic lepton pair decay mode. Further corrections become negligible for a sufficiently heavy quark mass. In the following we pursue the tentative hypothesis that these corrections are small even for the ϕ meson to the extent that the data are consistent with perturbative QCD alone. As we will see there is some scatter in the resulting values of α_3 at the 5% to 10% level which could be attributed to such corrections. The quarkonia data are now sufficiently precise to warrant the following careful treatment which we believe is more detailed and comprehensive than previous analyses. In addition we use the latest data on branching ratios from the Particle Data Group [7] which in some cases is significantly more precise than the currently published analysis.

Through second order in QCD the ratio of three-gluon decays of the vector quarkonia to the lepton pair decay is given by

$$R \equiv \frac{\Gamma(GGG)}{\Gamma(l^+l^-)} = r_0\alpha_3(\mu_S)^3[1+r_1(\mu_S)\alpha_3(\mu_S)/\pi+\cdots] , \tag{2.1}$$

where

$$r_0=\frac{10}{81}\frac{\pi^2-9}{\pi e_q^2}\alpha_{\rm em}^{-2} \tag{2.2}$$

and

$$r_1(\mu_S)=-14+(33-2n_f)[1.16+\ln(2\mu_S/M_V)]/2 . \tag{2.3}$$

Here M_V is the mass of the vector quarkonium, n_f is the number of quark flavors of mass less than $M_V/2$, and e_q is the quark charge. μ_S is an arbitrary scale in the full theory but can be prudently chosen to minimize higher-order corrections. In this spirit, as is customary [8] we choose μ_S so that $r_1(\mu_S)$ vanishes:

$$\mu_S=\tfrac{1}{2}M_V e^{28/(33-2n_f)}e^{-1.16} . \tag{2.4}$$

μ_S is slightly below half the quarkonium mass. Then (2.1) becomes

$$\alpha_3(\mu_S)=(R/r_0)^{1/3} . \tag{2.5}$$

In (2.2) we also evaluate the inverse fine structure constant at μ_S. Then $\alpha_{\rm em}^{-1}(\mu_S)$ varies from 135.8 for ϕ decay to 133.8 for Υ decay. The effect is to raise the measured value of α_3 in Υ decay by 1.6% with a lesser correction in ϕ decay.

We assume standard lepton universality; i.e., we take all the leptonic quarkonia decays to be related by phase space. In the denominator of (2.1), therefore, we use the most accurately measured leptonic decay Γ_l. This is the μ pair decay for the Υ resonances and the e pair for the lighter quarkonia. In terms of this favored decay rate the total leptonic decay rate is then

$$\Gamma_L=\Gamma_l r_L \ , \tag{2.6}$$

where the phase space factor is

$$r_L=\left[\sum_l (1-4m_1^2/M_V^2)^{3/2}\right]\Big/(1-4m_l^2/M_V^2)^{3/2} \ . \tag{2.7}$$

The three-gluon decay is the total decay rate minus the leptonic decay rate of (2.6) and minus the following additional corrections.

(1) "Cascade decays" Γ_C. These are all the final states which involve quarks of the same species as the decaying quarkonium. They are primarily cascade decays such as $\psi'\to\psi\pi\pi$. However, we also include here radiative decays into final states of similar quarks, such as $\Upsilon'\to\gamma+P$ wave bottomonium states, and $\psi\to\eta_c\gamma$. These decays are conveniently written as a fraction of the total decay rate:

$$\Gamma_C=r_C\Gamma_T \ . \tag{2.8}$$

(2) Radiative decays $\Gamma_{\gamma GG}$. These are all the decays into gamma + hadrons of dissimilar quarks. These decays can also be used as a measure of α_3 and, where data are available, give results which are consistent with those obtained here but with much larger errors. Our approach is an iterative one using the theoretical value for these decays based on the value of α_3 coming from the three-gluon decays. We assign a 20% uncertainty to these radiative decays which still gives only a small part of the resulting uncertainty in α_3:

$$\Gamma_{\gamma GG}=r_\gamma\Gamma_l \ . \tag{2.9}$$

The theoretical value for r_γ is

$$r_\gamma=\frac{8}{9}\,\frac{\pi^2-9}{\pi}\,\frac{\alpha_3^2}{\alpha_{\rm em}}(1+3.7\pm0.4\alpha_3/\pi+\cdots) \ . \tag{2.10}$$

(3) Virtual photon mediated decays Γ_{γ^*}. These are the decays into hadrons through an intermediate virtual photon:

$$\Gamma_{\gamma^*}=r_{\gamma^*}\Gamma_l \ . \tag{2.11}$$

r_{γ^*} is equal to the e^*e^-R parameter.

Thus

$$\Gamma_{GGG}=\Gamma_T-\Gamma_C-\Gamma_{\gamma GG}-\Gamma_{\gamma^*}-\Gamma_L \ . \tag{2.12}$$

Dividing by Γ_l we have, for (2.1),

$$R=(1-r_C)/B_l-r_\gamma-r_{\gamma^*}-r_l \ , \tag{2.13}$$

where B_l is the branching ratio into the most accurately known lepton pair. The current values are tabulated in Table I. We thus have six independent measurements of α_3 at various scales from the three-gluon decays of vector quarkonia. To these we can add the information from the two-gluon decay of $\eta_c(2980)$:

$$R\equiv\frac{\Gamma(\eta_c\to GG)}{\Gamma(J/\psi\to l^+l^-)}=\frac{2\alpha_3(\mu_S)^2M_\psi^2[1+10.2\alpha_3(\mu_S)/\pi]}{3e_q^2\alpha_{\rm em}^2M_{\eta_c}^2[1-16\alpha_3/(3\pi)]} \ . \tag{2.14}$$

We adopt a scale $M_{\eta_c}/2$ in this case which then falls in the same energy region as the scale for the vector charmonia. In Table II we list the seven R ratios together with their individual scales μ_S and the resulting values of $\alpha_3(\mu_S)$. All data are taken from the 1992 Particle Data Group [7]. Each measurement is then extrapolated to the Z mass (91.17 GeV) using the renormalization group equations to provide seven measurements of $\alpha_3(M_Z)$. In this extrapolation we assume the standard particle content (SPC), take full account of threshold effects, and include off-diagonal effects through two-loop order. Inclusion of threshold effects reduces the value of $\alpha_3(M_Z)$ by about 1%. In addition for the strong coupling constant we include the three-loop term [9] which reduces the value of $\alpha_3(M_Z)$ by 0.2%:

$$\left[\frac{d\alpha_3^{-1}}{dt}\right]_{3\ \rm loop}=(2857/2-5033n_f/18+325n_f^2/54)\alpha_3^2/(4\pi)^3 \ . \tag{2.15}$$

TABLE I. Current data on branching ratios of vector quarkonia from the 1992 compilation of the Particle Data Group.

	$\phi(1019)$	$\psi(3097)$	$\psi(3686)$	$\Upsilon(9460)$	$\Upsilon(10020)$	$\Upsilon(10350)$
B_l	$3.09\pm0.07\times10^{-4}$	$(6.3\pm0.2)\%$	$(0.88\pm0.13)\%$	$(2.49\pm0.07)\%$	$(1.31\pm0.21)\%$	$(1.81\pm0.17)\%$
$1-r_C$	0.152 ± 0.006	0.987 ± 0.004	0.206 ± 0.040	0.995 ± 0.001	0.55 ± 0.02	0.662 ± 0.019
r_γ	9.5 ± 1.9	1.3 ± 0.3	1.9 ± 0.4	1.2 ± 0.2	1.3 ± 0.3	1.1 ± 0.2
r_{γ^*}	1.7 ± 0.2	2.7 ± 0.3	3.3 ± 0.7	3.3 ± 0.7	3.3 ± 0.7	3.3 ± 0.7
r_l	1.94	1.99	2.00	2.79	2.82	2.85
R	492 ± 22	9.71 ± 0.66	16.2 ± 5.8	32.7 ± 1.3	34.6 ± 6.9	27.2 ± 3.3

TABLE II. Values of α_3 from gluonic decays assuming relativistic and binding corrections are negligible. The values at the quark scale, μ_S, are extrapolated to the Z scale assuming either standard particle content (SPC) (no new particles below $M_Z/2$) or a 4 GeV light gluino (LG).

	R	μ_S (GeV)	$\alpha_3(\mu_S)$	$\alpha_3(M_Z)$ SPC	$\alpha_3(M_Z)$ LG
$\phi(1019)$	492 ± 22	0.42	0.443 ± 0.007	0.0938 ± 0.0002	0.1029 ± 0.0003
$\psi(3097)$	9.7 ± 0.7	1.37	0.191 ± 0.004	0.0894 ± 0.0009	0.0975 ± 0.0011
$\psi(3686)$	16.2 ± 5.8	1.62	0.226 ± 0.027	0.0982 ± 0.0048	0.1084 ± 0.0059
$\Upsilon(9460)$	32.7 ± 1.3	4.54	0.181 ± 0.002	0.1043 ± 0.0008	0.1159 ± 0.0010
$\Upsilon(10020)$	34.6 ± 6.9	4.81	0.185 ± 0.012	0.1062 ± 0.0039	0.1184 ± 0.0050
$\Upsilon(10350)$	27.2 ± 3.3	4.97	0.170 ± 0.007	0.1020 ± 0.0024	0.1131 ± 0.0030
$\eta_c(2980)$	1922 ± 680	1.49	0.170 ± 0.030	0.0851 ± 0.0074	0.0924 ± 0.0088

Equation (1.3) is obtained by the weighted average of the resulting values at M_Z treated following the practice of the Particle Data Group. From Table II or from Fig. 1 it is clear that there are isolated deviations from the weighted average at the 10% level. Presumably the binding corrections must provide for at least this great a correction to the perturbative treatment. We find it, however, remarkable that to this precision the quarkonia data, including that of the ϕ, agree among themselves with standard model perturbation theory. If the fit of Fig. 1 is indeed significant, perturbative QCD provides a striking quantitative understanding of the Zweig rule.

The extrapolation of Fig. 1 requires standard particle content up to half the Z mass. If, however, the gluino octet lies below this scale the falloff of α_3 is somewhat slowed. In the last column of Table II we give the extrapolation to M_Z assuming a 4 GeV light gluino (LG). The resulting value of the strong coupling constant at the Z mass is then

$$\alpha_3(M_Z)=0.1036\pm0.0016 \quad \text{(quarkonia assuming 4 GeV gluino)} . \tag{2.16}$$

This value is consistent with at least some of the jet measurements at the Z [e.g., Eq. (1.1)] and would imply (see Fig. 4 in Sec. III) a SUSY threshold for the sfermions between 500 GeV and 1.5 TeV well within reach of the SSC and very close to the weak scale, as is desired theoretically. A gluino octet of this mass would not affect the analysis of the data in Table I. However, it is also of interest to consider even lighter gluinos. In this case the decay of the Υ resonances into final states containing gluinos will be allowed thus reducing the value of α_3 required to fit the Υ decay rates. It is clear from Table II that a 10% reduction of the value of α_3 in Υ decay would greatly improve the quality of the overall fit to the quarkonia data.

III. SUSY UNIFICATION AND THE LIGHT GLUINO SCENARIO

In Sec. II we have argued for the consideration of the quarkonia data in the determination of the strong coupling constant. The resulting value of $\alpha_3(M_Z)$ [Eq. (1.3)] is, however, in serious disagreement with the jet measurements at LEP [Eqs. (1.1) and (1.2)] [3,10]. We now turn to a comparison of the effect of the quarkonia data on the SUSY unification scenario.

In the standard model the low values of the coupling constant implied by the quarkonia data would lead to a value of the grand unified theory (GUT) scale M_G, too low to be consistent with proton decay in the unification scenario [11]. In a recent article [12] we have noted that the renormalization group (RG) equations in the presence of a SUSY threshold can be integrated analytically to an adequate approximation including average second order effects.

One begins from the standard model running of the three couplings

$$\frac{d\alpha_i^{-1}(t)}{dt}=-b_i-b_{ij}\alpha_j(t)/(4\pi)-\cdots \tag{3.1}$$

and in the SUSY region

$$\frac{d\alpha_i^{-1}(t)}{dt}=-b_i^s-b_{ij}^s\alpha_j(t)/(4\pi)-\cdots . \tag{3.2}$$

A sum over repeated indices is implied except where noted in the following. Here t is the logarithmic energy scale $t=\ln(q)$ and the coefficients b_i,b_{ij} and b_i^s,b_{ij}^s are the usual functions of the standard model and SUSY particle content, respectively, quoted for example in Refs. [1] and [2] above. Assuming a grand unification and neglecting for the moment the second order terms in (3.1) and (3.2), it was shown in Ref. [12] that the required SUSY scale M_S is related to the three couplings at the Z by

$$\ln(M_S/M_Z)=\mathbb{R}_{2j}^{-1}\alpha_j^{-1}(M_Z) , \tag{3.3a}$$

$$\ln(M_G/M_Z)=\mathbb{R}_{3j}^{-1}\alpha_j^{-1}(M_Z) , \tag{3.3b}$$

where

$$\mathbb{R}_{2j}^{-1}=\sum_i \epsilon_{jki}b_k^s/\det\mathbb{R} , \tag{3.3c}$$

$$\mathbb{R}_{3j}^{-1}=\sum_i \epsilon_{jki}(b_k^s-b_k)/\det\mathbb{R} , \tag{3.3d}$$

$$\det\mathbb{R}=\sum_i \epsilon_{jki}b_jb_k^s . \tag{3.3e}$$

Because of the slow change of the α_i, the second order effects can be approximated by the replacements $b_i \to b_i + \delta b_i$ and $b_i^s \to b_i^s + \delta b_i^s$ where, from Eqs. (3.1) and (3.2),

$$\delta b_i = b_{ij}\bar{\alpha}_j/(4\pi), \quad \delta b_i^s = b_{ij}^s \bar{\alpha}_j/(4\pi) \tag{3.4}$$

with $\bar{\alpha}_j$ being some average values of the three couplings. The exact results of the numerical integration of (3.1) and (3.2) can be obtained analytically to better than an order of magnitude in M_S by the simple "eyeball" choices quoted in Ref. [12]: $\bar{\alpha}_i = (0.02, 0.04, 0.06)$. As can be seen by integrating (3.1) and (3.2) iteratively, above the SUSY threshold the corrections vanish to even better accuracy if one chooses (no sum on j)

$$\bar{\alpha}_j = \frac{\ln[1 + b_j^s \alpha_j(M_G)\ln(M_G/M_S)]}{b_j^s \ln(M_G/M_S)} \approx \alpha_j(M_G) \ . \tag{3.5}$$

If we take $\bar{\alpha}_j = (0.035, 0.035, 0.035)$, Eq. (3.3a) becomes

$$\ln(M_S/M_Z) = 3.33\alpha_1^{-1}(M_Z) - 7.86\alpha_2^{-1}(M_Z) + 4.53\alpha_3^{-1}(M_Z) \ . \tag{3.6}$$

The coefficients in (3.6) differ by less than 3% from those of Ref. [12] so the choice of $\bar{\alpha}_i$ is not critical. Nevertheless the better accuracy of (3.6) can be checked by inserting the values of the three couplings given in Ref. [1] and comparing the resulting value of M_S (1.3 TeV) with their numerical result $M_S \approx 1$ TeV. The exact numerical extrapolation with $M_S = 1.3$, including threshold effects and three-loop effects in the strong coupling constant, is shown in Fig. 2. This analytic treatment is useful to give one an immediate feeling for the effect of small changes in the low energy couplings or in the RG coefficients b_i, etc. Its validity, however, is only justified *a posteriori* by the extreme linearity of the $\alpha_i^{-1}(t)$ in the renormalization group running and is always checked in the current work by an exact numerical integration. From (3.6) one can see that SUSY unification with standard particle content and a single low SUSY scale implies the constraint

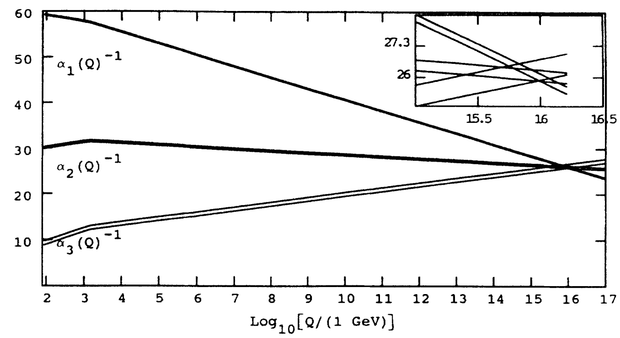

FIG. 2. SUSY unification using the couplings given in Ref. [1] and the value of the SUSY threshold given by the analytic treatment of Ref. [12].

$$M_Z/2 < M_S < 10 \text{ TeV} \Longrightarrow 0.102 < \alpha_3(M_Z) < 0.123 \ . \tag{3.7}$$

That is, requiring a single SUSY scale between $M_Z/2$ and 10 TeV implies an upper and lower limit on $\alpha_3(M_Z)$. Equation (3.7) is in agreement with the LEP values of α_3 [(1.1) and (1.2)] and in sharp disagreement with the quarkonia value (1.3). In addition by the same techniques the GUT scale would be

$$\ln(M_G/M_Z) = 0.105\alpha_1^{-1}(M_Z) + 1.29\alpha_2^{-1}(M_Z) - 1.40\alpha_3^{-1}(M_Z) \ . \tag{3.8}$$

The central quarkonia value of Eq. (1.3) would give a unification scale in the 10^{14} GeV range inconsistent with present experiments on proton decay. These results could be taken to support the majority opinion discussed in the Introduction. However, in view of the arguments of Sec. II in favor of the quarkonia data we note that the situation can be greatly ameliorated if one allows for the possibility of a light gluino octet.

If there is a gluino octet and (possibly) a photino at or below half the Z mass but the remaining superparticles are very heavy with some average mass M_S, the only change in the renormalization group coefficients through second order is a small modification of b_3 and b_{33}:

$$b_i = \frac{1}{2\pi}\begin{bmatrix} 4N_{\text{fam}}/3 + N_{\text{Higgs}}/10 \\ -22/3 + 4N_{\text{fam}}/3 + N_{\text{Higgs}}/6 \\ -11 + 4N_{\text{fam}}/3 \end{bmatrix} \to \frac{1}{2\pi}\begin{bmatrix} 4N_{\text{fam}}/3 + N_{\text{Higgs}}/10 \\ -22/3 + 4N_{\text{fam}}/3 + N_{\text{Higgs}}/6 \\ -11 + 4N_{\text{fam}}/3 + 2 \end{bmatrix} , \tag{3.9}$$

$$b_{33} = \frac{1}{2\pi}(-102 + 76N_{\text{fam}}/3) \to \frac{1}{2\pi}(-102 + 76N_{\text{fam}}/3 + 48) \ . \tag{3.10}$$

Contributions of the gluinos or photinos to the other b_{ij} are damped by heavy slepton or squark masses and are therefore negligible. Above M_S the full SUSY spectrum is active as before so the b_i^s and b_{ij}^s do not change. In the presence of the light gluino Eqs. (3.6) and (3.8) become

$$\ln(M_S/M_Z) = 1.36\alpha_1^{-1}(M_Z) - 3.21\alpha_2^{-1}(M_Z) + 1.85\alpha_3^{-1}(M_Z) \ , \tag{3.11a}$$

$$\ln(M_G/M_Z) = 0.72\alpha_1^{-1}(M_Z) - 0.14\alpha_2^{-1}(M_Z) - 0.57\alpha_3^{-1}(M_Z) \ . \tag{3.11b}$$

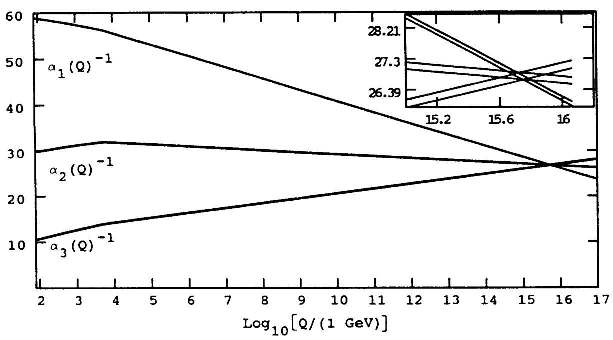

FIG. 3. SUSY unification using the world average value of $\sin^2\theta_w$ assuming a gluino mass of $M_Z/2$ and the quarkonia value, Eq. (1.3), for $\alpha_3(M_Z)$. The exact numerical integration shown here agrees well with the analytic estimate $M_S = 4.6$ TeV discussed in the text.

The constraint (3.11a) with a light SUSY scale now gives the result

$$M_Z/2 < M_S < 10 \text{ TeV} + \text{light gluino}$$
$$\Longrightarrow 0.092 < \alpha_3(M_Z) < 0.122 \ . \quad (3.12)$$

If the gluino lies at or above half the Z mass, the extrapolation of α_3 from the quarkonium region to M_Z leading to Eq. (1.3) is still correct and the resulting value [Eq. (1.3)] is consistent with SUSY unification with $M_S = 4.6$ TeV. Said in another way, a gluino at half the Z mass together with SUSY unification with $M_S = 4.6$ TeV implies $\alpha_3(M_Z)$ roughly equal to the quarkonia value of Eq. (1.3). The exact numerical integration of this solution is portrayed in Fig. 3. It would imply that the quoted world average value (1.2) is too high by 17%. Since α_1 and α_2 are known to within small errors with (essentially) no nonperturbative uncertainties, Eqs. (3.6) and (3.11a) give us a relation between $\alpha_3(M_Z)$ and M_S with and without light gluinos. These graphs are shown in Fig. 4.

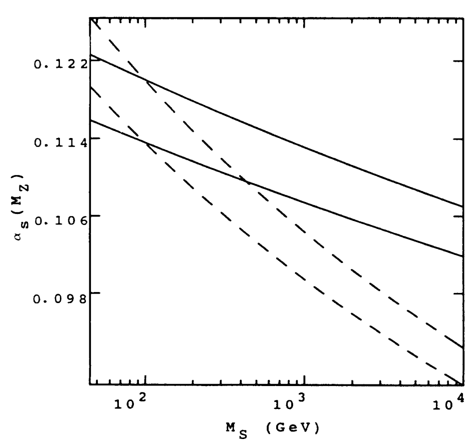

FIG. 4. The allowed bands of $\alpha_3(M_Z)$ vs the SUSY threshold M_S assuming the world average value of $\sin^2\theta_w$. The solid curves correspond to the assumption that all SUSY partners are at the SUSY scale M_S while the dashed curves assume that the gluino and (possibly) the photino lie below $M_Z/2$.

If, however, the gluino mass is even lighter than $M_Z/2$, the falloff of α_3 from the quarkonium region is slowed down by the change (3.9) and (3.10) in the renormalization group coefficients thus providing better agreement with the LEP values. This allows us perhaps to seek a best fit to the gluino mass requiring consistency with the quarkonia data and the LEP data together. In Fig. 5 we show the running of α_3 from the quarkonium region assuming a gluino mass of 4 GeV (large enough that the analysis of the quarkonia data will not be significantly changed by decays into gluinos. The resulting value at the Z is

$$\alpha_3(M_Z) = 0.1036 \pm 0.0016$$
$$\text{(quarkonia data with 4 GeV gluino)} \ . \quad (3.13)$$

This value is fully consistent with the LEP value given in Eq. (1.1) as well as with SUSY grand unification. It is also not far from the world average values of Eq. (1.2) and could possibly come into total agreement if those values were reanalyzed allowing for light gluinos in Z decay. As can be seen from Fig. 4, Eq. (3.13) would predict a threshold for the remaining SUSY particles between 300 GeV and 2 TeV well within reach of the SSC.

It is also possible that the gluino mass is below 4 GeV. A detailed analysis of this possibility including effects on the quarkonia measurements is underway in collaboration with others [13]. The first effect is that the value of α_3 in the Υ region will decrease due to decays of the Υ (and possibly other quarkonia) into gluino-containing final states. As can be seen from Fig. 1 or Fig. 5, there is some indication that the Υ values are slightly high compared to the prediction from the lower quarkonia. Apart from this effect it is qualitatively clear that a lower gluino mass will raise the value of $\alpha_3(M_Z)$ obtained by extrapolating from the quarkonia region and (from Fig. 4) lower the value of the SUSY threshold M_S. Conversely, a light gluino will lower the α_3 value resulting from the analysis of LEP data especially if M_S falls below M_Z allowing decays of the Z into squark+antiquark+gluino. If the

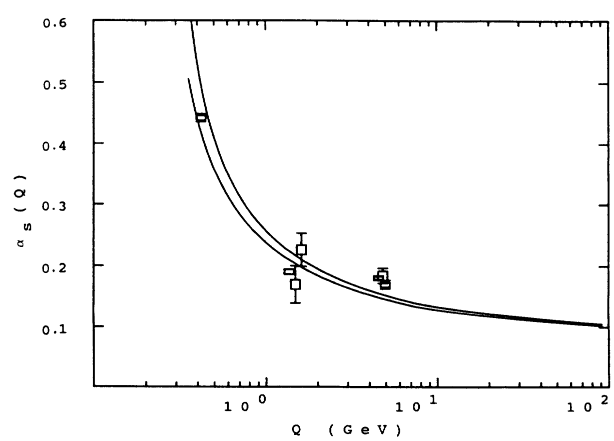

FIG. 5. Best fit to the quarkonia data assuming standard model running of the coupling constant with a 4 GeV gluino mass.

resolution we suggest is correct, a best fit to all the current quarkonia and LEP data taken together could lead to a relatively precise prediction for the gluino mass and SUSY scale.

Since the values of $\alpha_3(M_Z)$ from quarkonia measurements with or without the presence of a light gluino are in disagreement with some of the disparate jet measurements it is important to keep in mind the difficulty of interpreting these measurements. One may also note that the lower values of α_3 favored by the quarkonia data do agree with some of the jet measurements that are interpretable without obvious need for nonperturbative hadronization corrections. Examples of such measurements are the energy-dependent average values of the jet mass difference and the energy-energy correlation asymmetry. In Fig. 6 we compare these data [14] with the running of the coupling constant assuming a 4 GeV gluino. The data are not accurate enough to distinguish between the curves of Figs. 1 and 5 nor to rule out the effect of an even lighter mass gluino.

Lest the case for a light gluino presented here be overstated we should note that there is a possible discrepancy between the quarkonia values of α_3 and the value from τ decay. The existence or nonexistence of a discrepancy depends on the resolution of the well-known τ decay puzzle [15]. One way of stating the puzzle is to note that there are two ways of defining the R_τ parameter [16] which governs the value of α_3 from the hadronic decays of the τ:

$$R_\tau = \frac{1}{B_e} - 1 - \frac{B_\mu}{B_e} = 3.60 \pm 0.08 \ , \tag{3.14a}$$

or

$$\begin{aligned} R_\tau &= (\tau_\tau \Gamma_e^{\text{th}})^{-1} - 1 - \frac{B_\mu}{B_e} \\ &= \frac{\tau_\mu}{\tau_\tau}\left[\frac{M_\mu}{M_\tau}\right]^5 - 1.973 = 3.28 \pm 0.10 \ . \end{aligned} \tag{3.14b}$$

Here, B_e, B_μ, and τ_τ represent the experimental values of the electronic branching ratio, muonic branching ratio, and lifetime of the tau, respectively, and τ_μ is the muon lifetime. Γ_e^{th} represents the theoretical value of the electronic partial decay rate of the τ which depends only on lepton universality (which is well established to the accuracy needed here) and the electronic decay rate of the muon. Γ_e^{th} should be as reliable as any prediction of the standard model so the difference between (3.14a) and (3.14b) implies that either the experimental value of the τ lifetime or the experimental value of its electronic branching ratio is in error by several standard deviations. In perturbative QCD,

$$\begin{aligned} R_\tau = 3.058[1.001 + \alpha_3/\pi + 5.202(\alpha_3/\pi)^2 \\ + 26.37(\alpha_3/\pi)^3 + \cdots] \ . \end{aligned} \tag{3.15}$$

The nonperturbative corrections to the expression in parentheses here have been estimated to be less than 1% [17]. The value of R_τ given in (3.14a) yields a measure of $\alpha_3(M_\tau)$ that is in agreement [16,18] with the renormalization group and the LEP values of $\alpha_3(M_Z)$ without light gluinos and disagrees with the value of $\alpha_3(M_\tau)$ from quarkonia by several standard deviations. On the other hand R_τ as given in (3.14b) is in agreement with the value of $\alpha_3(M_\tau)$ suggested by the quarkonium analysis (see Table II or Fig. 5). If the current experimental value of the τ electronic branching ratio is confirmed and the lifetime measurement is in error, the τ data would be in conflict with the suggestion here of a light gluino. On the other hand, if the τ lifetime measurement is confirmed and the electronic branching ratio is found to be in error, the τ data would lend further support to the suggestion of a light gluino.

A few comments are in order on the question of the consistency of a light gluino with other empirical constraints. It is our feeling that the effects of color confinement and uncertainties due to hadronization of gluinos severely weaken the interpretation of experimental limits on gluino masses.

We will consider first some model-dependent lower limits on $M_{\tilde{G}}$. The effect of a light gluino on hadron collider experiments has been discussed by several authors [19]. The often quoted Collider Detector at Fermilab (CDF) and UA2 limit [20] $M_{\tilde{G}} > 73$ GeV involves the assumption that a heavy gluino decays into an energetic photino which will carry away significant amounts of missing energy. Such limits are somewhat fragmentation model dependent but we do not have to consider them in detail here since these limits allow a light gluino window of less than half the Z mass as is of interest in the current context.

A possible light gluino "window" in the region from zero mass to a few GeV has been discussed by many authors including in the present context Ref. [6] mentioned in Sec. I. We assume that the photino exists with a mass below that of the lightest gluino bound state since otherwise the gluino states would be stable (assuming R-parity invariance). Possible weak decays into sneutrinos are ruled out by the LEP limits on sneutrino masses. We would expect that bound states involving gluinos would

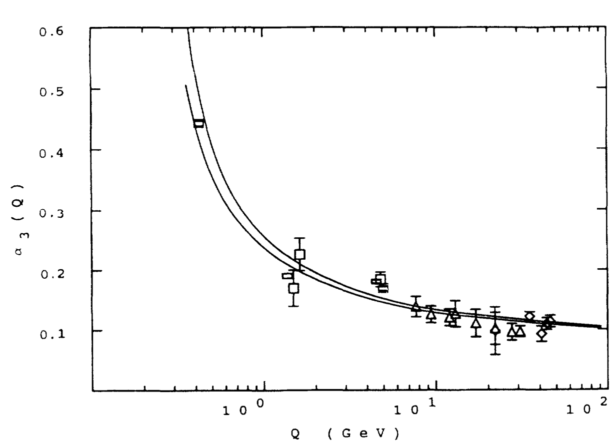

FIG. 6. The renormalizatoin group curve of Fig. 5 compared to jet data from Ref. [14] (PLUTO data: triangles; JADE data: diamonds).

be as difficult, or somewhat more difficult, to detect than the corresponding bound states of gluons which are expected to exist in the 1.5 to 2.5 GeV energy region. Therefore taking into account uncertainties due to confinement effects, it is not clear to us that any unavoidable limits exclude a gluino in the region from zero to 50 GeV, especially if the squark masses are in the multihundred GeV range. Zero mass gluinos, although stable as free particles, would be expected to hadronize into gluino-gluino (gluino-ball) resonances or into gluino-gluon states. The former type of states would be indistinguishable in their decay modes from that of ordinary glueballs. The latter states would decay into multipion states plus a (possibly soft) photino. Such resonances, although narrow, would appear as broad enhancements in the multipion mass due to the missing photino energy. Some of the relevant published constraints are the following.

(1) The beam dump experiment [21]: This experiment disfavors gluinos of less than 1 GeV mass if the squark masses are less than 220 GeV. Assumptions in this analysis are that the decay of the gluino is calculable as the decay of a free gluino into $q\bar{q}\tilde{\gamma}$. Although such calculations are thought to be reliable for heavy particles, it is not clear whether a light confined gluino will have the same lifetime nor how a different lifetime or photino spectrum would affect the beam dump constraints. Furthermore, the constraints from the beam dump experiment require the gluino regeneration in the beam dump detector to be calculable ignoring gluino hadronization effects. This is likely to be unreliable for gluino energies below or near the lightest gluino bound state energy.

(2) Quarkonia decays [22,23]: If the squark mass is sufficiently large, decays of ${}^3S_1$ quarkonia into gluinos are dominated by intermediate gluons and are suppressed by one factor of α_3 relative to the dominant three-gluon decays. Reference [22] calculates these corrections as a function of the gluino/quark mass ratio. Their result is not exact for small gluino masses due to an infrared divergence which is not treated in their work. Nevertheless the result suggests a 20–30 % increase in the total decay rate due to approximately massless gluinos. This would cause the effective value of α_3 analyzed without considering such modes to be too high by some 7–10 %. Reducing the value of α_3 by such an amount would clearly improve the agreement of the Υ data with that coming from lower quarkonia as can be deduced from Figs. 1 and 5. Such an improvement might require that the gluino mass not be negligible compared to the charm-quark mass so that the value of α_3 in the charm region would not be similarly reduced. Reference [23] proposes a limit on gluino mass from the absence of a monoenergetic photon in Υ decay coming from the two-body final state photon + gluinoball. This decay is suppressed by the fine structure constant and by the heavy mass of an intermediate squark. In addition the decay rate would be proportional to the gluinoball wave function at the origin which is difficult to estimate. A search for such decays would also be difficult to distinguish from the decay into photon plus ordinary glueball for which there are some candidates. In conclusion, we suspect that current observations of quarkonia decay do not put any restrictive limits on the mass of the gluino, assuming the mass of the squark is sufficiently heavy. This question is further investigated in Ref. [13].

IV. CONCLUSION

We have argued in this paper that the data on α_3 from quarkonia decays including those of the ϕ meson are consistent among themselves with perturbative QCD at the 10% level and deserve some consideration as measurements of the fundamental coupling. If, by hypothesis, we adopt the quarkonia measurements of α_3 and postulate a grand unification consistent with proton decay experiments and some low energy threshold (below 10 TeV) for new physics then the decrease of α_3 at higher energies must be slowed down by one or more new particles with strong interactions but no electroweak charge. A prime candidate for such a new particle is the gluino predicted by supersymmetry. Our results are that a gluino of not more than 50 GeV would make the quarkonia measurements consistent with the GUT hypothesis as stated above. Furthermore, the quarkonia measurements become consistent with the current interpretation of the jet measurements of α_3 in the LEP region if the gluino is below the Υ region. We have pointed out indications in the relative observed strength of the strong coupling constant in the Υ and J/ψ regions favoring a very light gluino. Apart from these possible hints which are obviously not yet statistically compelling, we are not aware of any positive indications of the existence of SUSY particles in current particle physics data.

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