# Extraction of $\alpha_s$ from radiative $\Upsilon(1S)$ decays

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We improve on a recent determination of $\alpha_s$ from $\Gamma(\Upsilon(1S) \to \gamma X)/\Gamma(\Upsilon(1S) \to X)$ with CLEO data by taking into account color octet contributions and avoiding any model dependence in the extraction. We obtain $\alpha_s(M_{\Upsilon(1S)}) = 0.184^{+0.015}_{-0.014}$, which corresponds to $\alpha_s(M_Z) = 0.119^{+0.006}_{-0.005}$.

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## I. INTRODUCTION

In the early days of QCD heavy quarkonium states ($H$), bound states of a heavy quark and a heavy antiquark, provided an ideal probe of the new theory. Among the interesting features, it looked like the strong coupling constant $\alpha_s$ could be neatly extracted from the ratio $\Gamma(H \to \gamma gg)/\Gamma(H \to ggg)$, for which both the wave function at the origin and the relativistic corrections cancel out [1,2].[1] The first measurements of $J/\psi$ inclusive radiative decays by the Mark II collaboration [4] delivered a photon spectrum not compatible with the early QCD predictions. To a lesser extent, this was also the case for bottomonium (see [5] and references therein). With the advent of nonrelativistic QCD (NRQCD) [6,7], it was understood that color octet contributions, which were ignored in the early approaches, become very important in the upper end point region of the spectrum [8]. When the color octet contributions are properly taken into account, a very good description of the photon spectrum can be obtained from QCD, at least for the $\Upsilon(1S)$ state [9]. Color octet contributions also affect the ratio $\Gamma(H \to \gamma gg)/\Gamma(H \to ggg)$ and are parametrically of the same order of the relativistic corrections. They have so far either been ignored [10] or estimated to be small [11] in the available extractions of $\alpha_s$ from this ratio. In this paper we take into account recent determinations of the $\Upsilon(1S)$ color octet matrix elements both on the lattice [12] and in the continuum [13], which indicate that their contribution is actually not small. This, together with the good theoretical description of the photon spectrum [9], allows for a consistent extraction of $\alpha_s(M_{\Upsilon(1S)})$ at NLO in the NRQCD velocity counting. We obtain a precise determination of it from the recent CLEO data [10].

## II. $\alpha_s$ EXTRACTION

The experimental value of $R_\gamma \equiv \Gamma(\Upsilon(1S) \to \gamma X)/\Gamma(\Upsilon(1S) \to X)$, $X$ being hadrons, has been determined most recently in [10].[2] We will use only the value obtained from the Garcia-Soto (GS) parametrization of data [9], which follows from a QCD calculation. This is

$$R_\gamma^{\rm exp} = 0.0245 \pm 0.0001 \pm 0.0013, \qquad (1)$$

where the first error is statistic and the second systematic.

Our starting point is the expression:

$$R_\gamma \equiv \frac{\Gamma(\Upsilon(1S) \to \gamma X)}{\Gamma(\Upsilon(1S) \to X)} = \frac{36}{5}\frac{e_b^2\alpha}{\alpha_s}\frac{N}{D}, \qquad (2)$$

$$N = 1 + C_{gg\gamma}\frac{\alpha_s}{\pi} + C_{\mathcal{P}_1(^3S_1)}\mathcal{R}_{\mathcal{P}_1(^3S_1)} + \frac{\pi}{\alpha_s}C_{\gamma O_8(^1S_0)}\mathcal{R}_{O_8(^1S_0)} + \frac{\pi}{\alpha_s}C_{\gamma O_8(^3P_0)}\mathcal{R}_{O_8(^3P_0)} + \mathcal{O}_N(v^3), \qquad (3)$$

$$D = 1 + C_{ggg}\frac{\alpha_s}{\pi} + C_{\mathcal{P}_1(^3S_1)}\mathcal{R}_{\mathcal{P}_1(^3S_1)} + \frac{\pi}{\alpha_s}C_{O_8(^3S_1)}\mathcal{R}_{O_8(^3S_1)} + \frac{\pi}{\alpha_s}C_{O_8(^1S_0)}\mathcal{R}_{O_8(^1S_0)} + \frac{\pi}{\alpha_s}C_{O_8(^3P_0)}\mathcal{R}_{O_8(^3P_0)} + \mathcal{O}_D(v^3), \qquad (4)$$

where $n_f = 4$ is the number of active flavors, $\alpha$ the fine structure constant, $e_b = -1/3$ the bottom quark electromagnetic charge, $\alpha_s = \alpha_s(M_{\Upsilon(1S)})$ is the strong coupling constant calculated at the $\Upsilon(1S)$ mass, $M_{\Upsilon(1S)} = 9.46$ GeV, $C_{\mathcal{P}_1(^3S_1)} = -(19\pi^2 - 132)/(12\pi^2 - 108)$ [14], $C_{\gamma O_8(^1S_0)} = 27/(4\pi^2 - 36)$ [15], $C_{\gamma O_8(^3P_0)} = 189/(4\pi^2 - 36)$ [15], $C_{O_8(^3S_1)} = 81 n_f/(20\pi^2 - 180)$ [16], $C_{O_8(^1S_0)} = 81/(8\pi^2 - 72)$ [16], $C_{O_8(^3P_0)} = 567/(8\pi^2 - 72)$ [16], $C_{gg\gamma} = -1.71$ (for $n_f = 4$) [17,18], $C_{ggg} = 3.79 \pm 0.54$ (for $n_f = 4$) [7,18], $\mathcal{R}_O = \langle\Upsilon(1S)|O|\Upsilon(1S)\rangle/(m_b^{\Delta d}\langle\Upsilon(1S)|O_1(^3S_1)|\Upsilon(1S)\rangle)$, where $\Delta d$ is the difference in dimension between the operators $O$ and $O_1(^3S_1)$, $m_b$ is the bottom mass, and the $\langle\Upsilon(1S)|O|\Upsilon(1S)\rangle$ are NRQCD decay matrix elements [7]. If we adopt the counting of [7] and $\alpha_s/\pi \sim v^2$, then the expansions (3) and (4) are valid up to order $v^2$. $\mathcal{O}_N(v^3)$ and $\mathcal{O}_D(v^3)$ account for higher-order corrections of order $v^3$. In the following we will assume $v^2 = 0.08$.

[1]See [3] for an update on $\alpha_s$ extractions from heavy quarkonium systems.

[2]$\gamma$ stands for direct photons only and the contributions $\Upsilon(1S) \to \gamma^* \to X$ have been subtracted in the denominator.

 

In order to obtain a sensible extraction, the ratios of NRQCD matrix elements $\mathcal{R}$ must be correctly estimated. $\mathcal{R}_{\mathcal{P}_1(^3S_1)}$ can be related to the binding energy [19,20]. $\mathcal{R}_{O_8(^1S_0)}$ and $\mathcal{R}_{O_8(^3S_1)}$ have been calculated on the lattice [12]. $\mathcal{R}_{O_8(^1S_0)}$ and $\mathcal{R}_{O_8(^3P_0)}$ have been estimated in the continuum [13]. The continuum calculation and one of the lattice calculations of $\mathcal{R}_{O_8(^1S_0)}$ are compatible. We will present two different extractions: C (for continuum) and L (for lattice). Extraction C uses all the weak-coupling expressions available, in the same way they were used for the description of the photon spectrum [9], and the lattice calculation of [12] for $\mathcal{R}_{O_8(^3S_1)}$. Extraction L uses all the lattice calculations available, and NRQCD velocity scaling to estimate $\mathcal{R}_{O_8(^3P_0)}$. In both extractions, we do not expand the $\mathcal{O}(v^2)$ terms in $D$: it turns out that even though they are individually small they add up to give a contribution comparable to one; we will comment on this in Sec. III.

### A. Extraction L (for lattice)

Concerning the ratios $\mathcal{R}_O$, we will take them in the following ranges:

$$0 \le \mathcal{R}_{O_8(^1S_0)} \le 4.8 \times 10^{-3}, \tag{5}$$

$$0 \le \mathcal{R}_{O_8(^3S_1)} \le 1.6 \times 10^{-4}, \tag{6}$$

$$-2.4 \times 10^{-4} \le \mathcal{R}_{O_8(^3P_0)} \le 2.4 \times 10^{-4}, \tag{7}$$

$$-0.16 \le \mathcal{R}_{\mathcal{P}_1(^3S_1)} \le 0. \tag{8}$$

Equations (5) and (6) correspond to the maximum values obtained in the lattice calculations [12] taken with a 100% uncertainty. Equation (7) follows from the naive counting

$$|\mathcal{R}_{O_8(^3P_0)}| = \frac{1}{9}\left|\frac{\langle\eta_b|O_8(^1P_1)|\eta_b\rangle}{m_b^2\langle\Upsilon(1S)|O_1(^3S_1)|\Upsilon(1S)\rangle}\right| \approx \frac{1}{9}\times\frac{v^4}{2N_c}, \tag{9}$$

taken with a 100% uncertainty. The first equality is due to spin symmetry and is valid at leading order in the velocity expansion, in the second one we have evidenced the color factor $1/(2N_c)$ [12] ($N_c = 3$ is the number of colors).

Equation (8) follows from the Gremm-Kapustin relation [19,20] in the weak-coupling regime,

$$\mathcal{R}_{\mathcal{P}_1(^3S_1)} = \frac{E_{\rm bin}}{m_b} \approx -v^2, \tag{10}$$

taken with a 100% uncertainty. $E_{\rm bin}$ stands for the binding energy. The operators $\mathcal{O}_N(v^3)$ and $\mathcal{O}_D(v^3)$ are taken in the range

$$-0.04 \le \mathcal{O}_N(v^3), \mathcal{O}_D(v^3) \le 0.04, \tag{11}$$

which encompasses both $\mathcal{O}(v^3)$ and $\mathcal{O}(\alpha_s^2)$ corrections.

The fine structure constant is taken at the $\Upsilon(1S)$ mass

$$\alpha(M_{\Upsilon(1S)}) = \frac{1}{132}. \tag{12}$$

We evaluate the theoretical side of Eq. (2) as it stands, without further expansions. Taking the central values for $C_{ggg}$ and in Eqs. (5)–(8), (11), and (1), we obtain

$$\alpha_s(M_{\Upsilon(1S)}) = 0.1885. \tag{13}$$

The uncertainty on $\alpha_s$ induced by a given parameter is evaluated by varying it in the range and keeping all other parameters at their central values. We obtain

$$\delta_{C_{ggg}}\alpha_s = 0.0025, \tag{14}$$

$$\delta_{\mathcal{R}_{O_8(^1S_0)}}\alpha_s = 0.0047, \tag{15}$$

$$\delta_{\mathcal{R}_{O_8(^3S_1)}}\alpha_s = 0.0019, \tag{16}$$

$$\delta_{\mathcal{R}_{O_8(^3P_0)}}\alpha_s = 0.0032, \tag{17}$$

$$\delta_{\mathcal{R}_{\mathcal{P}_1(^3S_1)}}\alpha_s = 0.0106, \tag{18}$$

$$\delta_{\mathcal{R}_{\mathcal{O}_N(v^3)}}\alpha_s = 0.0041, \tag{19}$$

$$\delta_{\mathcal{R}_{\mathcal{O}_D(v^3)}}\alpha_s = 0.0031, \tag{20}$$

$$\delta_{R_\gamma^{\rm exp}}\alpha_s = 0.0089. \tag{21}$$

We sum up linearly the errors $\delta_{\mathcal{R}_{O_8(^1S_0)}}$ and $\delta_{\mathcal{R}_{O_8(^3S_1)}}$, which are correlated, and then all the errors quadratically, obtaining

$$\alpha_s(M_{\Upsilon(1S)}) = 0.189 \pm 0.017. \tag{22}$$

The dominant error comes from the uncertainty in $\mathcal{R}_{\mathcal{P}_1(^3S_1)}$. We can reduce this uncertainty, by noticing that for $\mathcal{R}_{\mathcal{P}_1(^3S_1)}$ we have an explicit expression, Eq. (10), that we have only partially exploited. Indeed, in the weak-coupling regime, the exact form of $E_{\rm bin}$ is known. At the order we are interested in, it holds that

$$\frac{E_{\rm bin}}{m_b} = -\frac{(C_F\alpha_s)^2}{4}, \qquad C_F = \frac{4}{3}, \tag{23}$$

where $\alpha_s$ is evaluated at the scale $M_{\Upsilon(1S)}C_F\alpha_s/2$, the typical momentum-transfer scale in a Coulombic bound state. From Eq. (22), we obtain:

$$\alpha_s(M_{\Upsilon(1S)}C_F\alpha_s/2) = 0.311 \pm 0.032, \tag{24}$$

which gives

$$\mathcal{R}_{\mathcal{P}_1(^3S_1)} = \frac{E_{\rm bin}}{m_b} = -(0.043^{+0.009}_{-0.008}). \tag{25}$$

Using this value for $\mathcal{R}_{\mathcal{P}_1(^3S_1)}$ and performing again the above calculation we obtain the new central value

$$\alpha_s(M_{\Upsilon(1S)}) = 0.183, \tag{26}$$

and the new uncertainties

$$\delta_{C_{ggg}}\alpha_s = 0.0026, \tag{27}$$

$$\delta_{\mathcal{R}_{O_8(^1S_0)}}\alpha_s = 0.0040, \tag{28}$$

$$\delta_{\mathcal{R}_{O_8(^3S_1)}}\alpha_s = 0.0026, \tag{29}$$

$$\delta_{\mathcal{R}_{O_8(^3P_0)}}\alpha_s = 0.0027, \tag{30}$$

$$\delta_{\mathcal{R}_{\mathcal{P}_1(^3S_1)}}\alpha_s = 0.0014, \tag{31}$$

$$\delta_{\mathcal{R}_{\mathcal{O}_N(v^3)}}\alpha_s = 0.0044, \tag{32}$$

$$\delta_{\mathcal{R}_{\mathcal{O}_D(v^3)}}\alpha_s = 0.0033, \tag{33}$$

$$\delta_{R_\gamma^{\exp}}\alpha_s = 0.0085. \tag{34}$$

Summing up the errors like before, we obtain as our best estimate

$$\alpha_s(M_{\Upsilon(1S)}) = 0.183 \pm 0.013. \tag{35}$$

This corresponds to a strong coupling constant at the $M_Z$ mass of

$$\alpha_s(M_Z) = 0.119 \pm 0.005. \tag{36}$$

### B. Extraction C (for continuum)

In a weak-coupling analysis, $\langle\Upsilon(1S)|O_1(^3S_1)|\Upsilon(1S)\rangle$ can be calculated in perturbation theory of $\alpha_s(m_b v)$. A NNLO expression is necessary at $\mathcal{O}(v^2)$ [21,22].[3] In order to follow the same procedure as in [9], we multiply the leading order term in the decay widths by the NNLO expression for $\langle\Upsilon(1S)|O_1(^3S_1)|\Upsilon(1S)\rangle$ and the $\alpha_s$ correction to the decay widths by the LO expression for that matrix element. If we factor out the NNLO matrix element, this produces a shift $N \to N + \delta N$ and $D \to D + \delta D$ in (3) and (4):

$$\delta N = C_{gg\gamma}\frac{\alpha_s}{\pi}\delta, \tag{37}$$

$$\delta D = C_{ggg}\frac{\alpha_s}{\pi}\delta, \tag{38}$$

with

$$\delta = \frac{\langle\Upsilon(1S)|O_1(^3S_1)|\Upsilon(1S)\rangle_{\rm LO}}{\langle\Upsilon(1S)|O_1(^3S_1)|\Upsilon(1S)\rangle_{\rm NNLO}} - 1. \tag{39}$$

For the central values of the objects below we take exactly the same ones used in [9], namely

$$\delta = -0.57, \tag{40}$$

$$\mathcal{R}_{\mathcal{P}_1(^3S_1)} = -0.015, \tag{41}$$

$$\mathcal{R}_{O_8(^1S_0)} = 0.0012, \tag{42}$$

$$\mathcal{R}_{O_8(^3P_0)} = 0.0011. \tag{43}$$

For $\mathcal{R}_{O_8(^3S_1)}$, we use the hybrid algorithm output of the lattice calculation [12],[4]

$$\mathcal{R}_{O_8(^3S_1)} = 8 \times 10^{-5}. \tag{44}$$

Using those values, we obtain

$$\alpha_s(M_{\Upsilon(1S)}) = 0.185. \tag{45}$$

In order to associate errors to these central values, we move the values of the objects below in the following ranges:

$$0.18 \le \alpha_s(m_b v) \le 0.38, \tag{46}$$

$$0.32 \le \alpha_s(m_b v^2) \le 1.3, \tag{47}$$

$$0 \le \mathcal{R}_{O_8(^3S_1)} \le 1.6 \times 10^{-4}. \tag{48}$$

The wide variation range of $\alpha_s(m_b v)$ and $\alpha_s(m_b v^2)$ is expected to account for $\mathcal{O}(\Lambda_{\rm QCD})$ uncertainties in the weak-coupling estimates of $O_8(^1S_0)$ and $O_8(^3P_0)$. The upper limit of $O_8(^3S_1)$ corresponds to twice the largest value obtained using the lattice algorithms in [12].

The uncertainty on $\alpha_s$ induced by a given parameter is evaluated by varying it in the range and keeping all other parameters at their central values. We obtain

$$\delta_{C_{ggg}}\alpha_s = 0.0009, \tag{49}$$

$$\delta_{\alpha_s(m_b v)}\alpha_s = {}^{+0.0006}_{-0.0064}, \tag{50}$$

$$\delta_{\alpha_s(m_b v^2)}\alpha_s = {}^{+0.0083}_{-0.0076}, \tag{51}$$

$$\delta_{\mathcal{R}_{O_8(^3S_1)}}\alpha_s = 0.0016, \tag{52}$$

$$\delta_{\mathcal{R}_{\mathcal{O}_N(v^3)}}\alpha_s = {}^{+0.0035}_{-0.0034}, \tag{53}$$

$$\delta_{\mathcal{R}_{\mathcal{O}_D(v^3)}}\alpha_s = {}^{+0.0026}_{-0.0025}, \tag{54}$$

$$\delta_{R_\gamma^{\exp}}\alpha_s = 0.01. \tag{55}$$

We assume these errors to be independent and sum them up

[3]We count $\alpha_s$ at the soft scale as order $v$.

[4]The hybrid algorithm is selected because it compares well with the continuous estimate for $\mathcal{R}_{O_8(^1S_0)}$.

quadratically, obtaining

$$\alpha_s(M_{\Upsilon(1S)}) = 0.185^{+0.014}_{-0.015}. \quad (56)$$

This corresponds to a strong coupling constant at the $M_Z$ mass of

$$\alpha_s(M_Z) = 0.120^{+0.005}_{-0.006}. \quad (57)$$

## III. DISCUSSION

We have presented two extractions of $\alpha_s$ at NLO in the NRQCD velocity counting, the main differences being the values assigned to the NRQCD matrix elements. The two outcomes are very close so we take the average as our final central value. Since the two extractions are not completely independent we take as our error the range of the two determinations. Then our final value is

$$\alpha_s(M_{\Upsilon(1S)}) = 0.184^{+0.015}_{-0.014}, \quad (58)$$

which corresponds to

$$\alpha_s(M_Z) = 0.119^{+0.006}_{-0.005}, \quad (59)$$

which is very close to the central value of the PDG [23] with competitive errors. The key ingredients to get these numbers are the precise CLEO data [10], the use of a QCD calculation (called GS model in [10]) to extrapolate the photon spectrum at low $z$, and accurate estimates of the color octet matrix elements, which have been possible thanks to recent lattice and continuum estimates. Concerning the matrix elements, our results are rather insensitive to the values of $O_8(^1S_0)$ and $O_8(^3P_0)$ [note that the upper limit given in Eq. (7) for $\mathcal{R}_{O_8(^3P_0)}$, based on the scaling (9), is smaller by a factor five than the continuum estimate (43)], but would be sensitive to large values of $O_8(^3S_1)$. However, the lattice values for $O_8(^3S_1)$, which we have used, turn out to be much smaller than what NRQCD velocity scaling rules suggest, and do not have a major impact in our results.

How reliable is our extraction? Our determination is valid at next-to-leading order in $\alpha_s(m_b)$ and in $v^2$. At this order, terms corresponding to new qualitative features appear (radiative, relativistic, octet corrections), each of them of natural size, but whose sum is of order one and hence large. This is not unusual. It is crucial, however, that higher-order corrections, those that we have generically labeled as $\mathcal{O}_N$ and $\mathcal{O}_D$, are small. This is expected because higher-order corrections do not introduce new qualitative features. In Ref. [24], higher-order corrections in the velocity expansion can be found for $\mathcal{O}_D$. These are not the complete set of corrections entering in $\mathcal{O}_D$, since higher-order $\alpha_s$ corrections to the lowest operators are missing. Anyway, using the analogous of Eq. (10) to estimate the matrix elements and taking $E_{\rm bin}/m_b \approx -0.04$, the corrections calculated in [24] amount to about 0.02, which is consistent with the estimate (11). Analogous corrections for $\mathcal{O}_N$ are not known. At present, the main uncertainty in our extraction of $\alpha_s$ comes from the systematic uncertainties in $R_\gamma^{\rm exp}$.

Let us next compare our extraction to two previous related ones [10,11].

Concerning the extraction of the CLEO paper [10], there are two main differences. (i) On the theoretical side an old formula was used there [18], in which the NRQCD color octet operators were ignored. This introduces large theoretical uncertainties. In practice, however, we find that numerically they are not so important for the final result. (ii) For the total radiative width, two numbers are quoted depending on whether the so-called Field model [25] or the GS model, which is in fact a QCD calculation, are used for the extrapolation of the photon spectrum at low $z$. The final number is given as the average of the two procedures. We believe that the use of the Field model, which uses a parton shower Monte Carlo technique to incorporate the effects of gluon radiation by the outgoing gluons in the decay, introduces an unnecessary model dependence that moves the actual central value and artificially increases the errors. Our final results are similar to the ones presented in [10] for the GS model.

Concerning the extraction of [11], which is used by the PDG [23], there are three main differences. (i) On the theoretical side, the color octet NRQCD matrix elements are ignored in $\Gamma(\Upsilon(1S) \to \gamma X)$, whereas we find that they contribute between 30% and 100%.[5] (ii) Older data are used, which are fully consistent with, but not as precise as, the more recent ones, and an older analysis [26], which relies on the Field model for extrapolations to low $z$. (iii) The extraction is actually done from $\Gamma(\Upsilon(1S) \to \gamma X)/\Gamma(\Upsilon(1S) \to l^+l^-)$. We believe, contrary to a statement in [11], that the latter increases rather than decreases the theoretical uncertainties associated to color octet operators. Indeed, whereas the ratio radiative/total has the same color octet operators in the numerator and denominator except for one, the ratio radiative/leptonic (total/leptonic) has two (three) different color octet operators in the numerator and denominator. Furthermore, the leptonic width is known to suffer from large higher-order corrections in $\alpha_s$ (see [27] for a recent discussion), which introduces further uncertainties.

## IV. CONCLUSIONS

We have improved on current determinations of $\alpha_s(M_{\Upsilon(1S)})$ from radiative decays of $\Upsilon(1S)$ by avoiding any model dependence and by taking into account recent estimates of color octet operators. The value we obtain, $\alpha_s(M_Z) = 0.119^{+0.006}_{-0.005}$, is close to the PDG average with competitive errors.

[5]The color octet contributions in $\Gamma(\Upsilon(1S) \to X)$ are estimated to be 9%, whereas ours turns out to be between 50% and 160%.

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