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Measurement of upper limits for Upsilon ->gamma+R decays

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We report on a study of exclusive radiative decays $\Upsilon(nS) \to \gamma + \mathcal{R}$ ($n = 1, 2, 3$), with $\mathcal{R}$ a narrow resonant hadronic state decaying into four or more charged particles (plus possible neutrals). Using data collected from the CLEO III detector at the Cornell Electron Storage Ring, we present upper limits of order 10^{-4} for such bottomonium two-body decays as a function of the mass $M_{\mathcal{R}}$ recoiling opposite the photon.

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CLEO recently extracted α_s from a measurement of the direct photon spectra in $\Upsilon(1S, 2S, 3S) \to gg\gamma$ [1]. That extraction was based on a comparison of the $gg\gamma$ width to the dominant three-gluon width of the narrow bottomonium resonances. Since the direct photon is observable above background only for relatively high energies ($E_\gamma \geq E_{\rm beam}/2$), some model dependence is inherent in the determination of the total $gg\gamma$ rate. To extrapolate below $E_{\rm beam}/2$, we rely on theoretical parametrizations of the expected photon energy spectrum in the Υ system [2,3] to obtain the total direct $\Upsilon \to gg\gamma$ decay width relative to the dominant $\Upsilon \to ggg$ width. Given a prescription relating the parton-level rate to α_s, one can then use the total $gg\gamma$ rate to determine α_s. Older estimates of α_s based on inclusive radiative photon production in Υ decay using the Brodsky-Lepage-Mackenzie (BLM) [4] prescription have consistently yielded α_s values smaller than those obtained from different techniques [5]. Recently, it has been realized that color octet contributions, previously ignored in the older BLM calculation, result in estimates of α_s in satisfactory agreement with estimates made at the Z resonance [6], provided one uses an appropriate QCD-inspired model to calculate the expected photon spectrum.

The theoretical calculations are generally done at the parton level, and therefore do not address gluon interactions which may lead to bound states. Such calculations therefore also do not address possible resonant contributions to the photon energy spectrum due to two-body decays, e.g., $\Upsilon \to gg\gamma \to \gamma\mathcal{R}$, with $\mathcal{R}$ some resonant hadronic state. The inability of the current calculations to directly address two-body effects, in part, restricts the applicability of Υ decay models to the region $z_\gamma < 0.92$, with z_γ defined as the scaled photon energy ($\equiv E_\gamma/E_{\rm beam}$). Given that primary scalar glueball candidates are of order 1 GeV in mass, we expect the endpoint region of the photon energy spectrum ($z_\gamma > 0.92$) to be most susceptible to such contamination.

CLEO has recently observed signals in several low-multiplicity modes [7,8] proceeding through $gg\gamma$, as well as two events consistent with the process $\Upsilon(1S) \to \gamma + \eta'$, $\eta' \to \pi^+\pi^-\eta$, $\eta \to \pi^+\pi^-\pi^0$ [9], yielding an upper limit of order 10^{-6}. Previous studies of "bumps" in the inclusive photon spectrum in quarkonium decays have, in fact, been used to set limits on radiative production of exotica, including light Higgs particles [10,11]. Herein, we report on a search for radiative decays of the Υ to resonances $\mathcal{R}$: $\Upsilon(nS) \to \gamma\mathcal{R}$ ($n = 1, 2, 3$). We concern ourselves with high multiplicity (≥ 4 charged tracks) final states, as we employ the same hadronic event selection cuts in this analysis as used in the previous $gg\gamma$ analysis [1].

The analysis, in general terms, proceeds as follows. After selecting a high quality sample of e^+e^- annihilations [1], we construct the inclusive isolated photon spectra in data taken at both on-Υ-resonance and off-Υ-resonance energies (the latter samples are used for systematic checks of the overall procedure). A two-body radiative decay of the Υ will produce a monochromatic photon in the laboratory frame; the energy of the radiated photon E_γ is related to the mass of the recoil hadron $\mathcal{R}$ via $M_{\mathcal{R}} = 2E_{\rm beam}\sqrt{1 - z_\gamma}$. In the case where the intrinsic width of the recoil hadron is much smaller than the experimental photon energy resolution, the measured radiative photon energy should be a Gaussian centered at the energy $z_\gamma E_{\rm beam}$. For a 1 GeV (4.5 GeV) recoil photon, this implies a recoil resonance with width typically narrower than 20 MeV (260 MeV). Not knowing *a priori* the mass of the hadron $\mathcal{R}$, we therefore perform a set of fits of the $\Upsilon(nS)$ photon spectrum to a Gaussian signal, centered at a series of E_γ values, and with resolutions corresponding to the known CLEO III electromagnetic calorimeter resolution ($\sim 2\%$ in the central barrel region of the electromagnetic calorimeter) atop smooth polynomial backgrounds, over the range $0.2 < z_\gamma < 1.0$. We construct 95% confidence level upper limits from these fits by adding $1.645 \times \sigma_A(z_\gamma)$ to the $A(z_\gamma)$ distribution, where $A(z_\gamma)$ is the z_γ-dependent Gaussian fit area and $\sigma_A(z_\gamma)$ is the fit error. In this process, since we are interested in enhancements in the inclusive photon spectrum, all negative areas from the raw fits are set equal to zero, and the corresponding upper limit set to $1.645 \times \sigma_A(z_\gamma)$ at these points. We then recast this upper limit as a function of recoil mass $M_{\mathcal{R}}$, corrected for the efficiency loss due to the fiducial acceptance of the detector and the event and photon-selection cuts that define our data sample. In estimating this correction, we assume $\mathcal{R}$ has spin $= 0$, with a corresponding $1 + \cos^2\theta$ angular distribution for the recoil photon; higher spins will generally give flatter angular distributions and therefore more restrictive upper limits. To be conservative, we derive our z_γ-dependent efficiency correction from that decay mode yielding the worst reconstruction efficiency.

I. EVENT EFFICIENCY CORRECTION

Not knowing *a priori* what the decay mode of our hypothetical resonance $\mathcal{R}$ will be, we have generated Monte Carlo samples corresponding to all kinematically-allowed permutations of $\mathcal{R} \to n_K(K^+K^-)n_\pi(\pi^+\pi^-)n_p(p\bar{p})n_{\pi^0}(\pi^0)$, with $(n_K + n_\pi + n_p) = 2$ or 3. We find that the worst efficiency among the decay modes considered is obtained from $\mathcal{R} \to 2(K^+K^-)\pi^0$, for which the efficiency $\epsilon = 0.48 \pm 0.02$, and select this mode for the purposes of generating upper limits. For invariant masses in our kinematic regime of interest, the efficiency is found to be nearly flat as a function of $M_{\mathcal{R}}$.

II. RESULTS

To convert the efficiency-corrected upper limit contour into an upper limit on the two-body radiative branching ratio $\mathcal{B}(\gamma\mathcal{R})$, we divide the efficiency-corrected upper limit contour by the total calculated number of $\Upsilon(nS)$ decays [1], corresponding to $N_{\text{tot}}(\Upsilon(1S)) = (20.9 \pm 0.2) \times 10^6$, $N_{\text{tot}}(\Upsilon(2S)) = (8.3 \pm 0.1) \times 10^6$, $N_{\text{tot}}(\Upsilon(3S)) = (5.2 \pm 0.1) \times 10^6$, and $N_{\text{tot}}(\Upsilon(4S)) = (6.8 \pm 0.2) \times 10^6$. For completeness, we also include the results for the $\Upsilon(4S)$, for which the decay width is expected to be nearly saturated by $\Upsilon(4S) \to B\bar{B}$ [5]. The resulting on-resonance upper limits $\mathcal{B}(\gamma\mathcal{R})$ are shown in Fig. 1.

Applying our fitting procedure directly to the continuum data we can obtain limits on the cross section for $e^+e^- \to \gamma + \mathcal{R}$ (Fig. 2). It is important to note here that (a) the angular distribution for the continuum initial state radiation processes is considerably more forward peaked than the $1 + \cos^2\theta$ distribution we have assumed for the resonance; we have therefore applied a correction based on the angular distribution appropriate to initial state radiation (ISR), and (b) the quantum numbers of particles produced in association with ISR photons are different than those produced in radiative decays of quarkonium resonances. To set the scale of the continuum cross section sensitivity, the raw ISR cross section for $e^+e^- \to J/\psi + \gamma$ is expected to be $\sim$5 pb in the 10 GeV center-of-mass regime. Taking into account the efficiency of our event selection requirements and the strong forward peaking expected for ISR processes, this corresponds to an expected observed cross section into ≥ 4 charged tracks $\sim 10^{-4}$ nb. This value is below our current statistical sensitivity, and would require an order of magnitude increase in data size in order to be clearly visible.

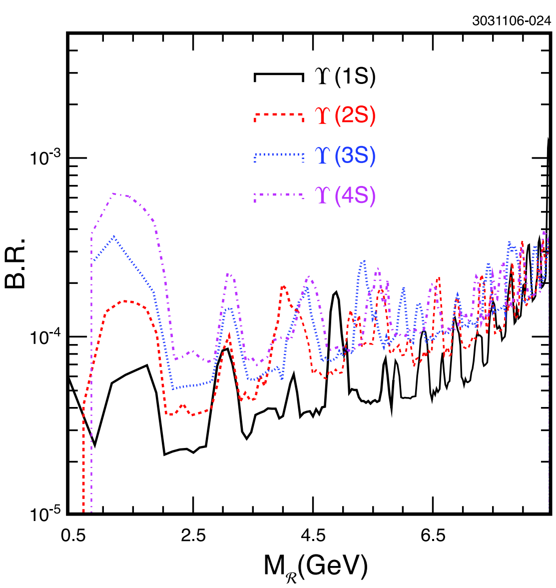

FIG. 1 (color online). The 95% confidence level $M_{\mathcal{R}}$-dependent $\Upsilon(nS) \to \mathcal{B}(\gamma\mathcal{R})$ upper limit contours obtained for $\Upsilon \to \gamma + \mathcal{R}$, $\mathcal{R} \to\geq 4$ charged tracks for the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, and $\Upsilon(4S)$. Limits are obtained by dividing upper limits on yield by reconstruction efficiency and number of resonant events, and also incorporating systematic uncertainties. Limits are of order $\mathcal{B}(\gamma\mathcal{R}) \approx 10^{-4}$.

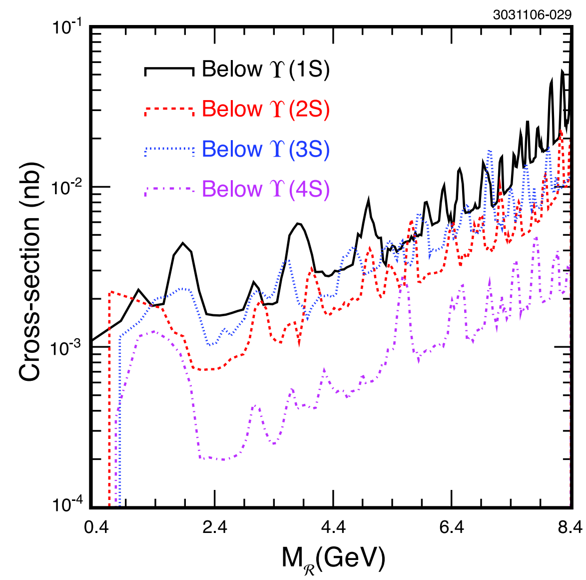

FIG. 2 (color online). The 95% confidence level $M_{\mathcal{R}}$-dependent cross-section upper limit contours obtained for $e^+e^- \to \gamma + \mathcal{R}$, $\mathcal{R} \to\geq 4$ charged tracks for the below $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, and $\Upsilon(4S)$ continua (nb). This plot is obtained by dividing the result of our fitting procedure on the continuum by the off-resonance luminosity. The angular correction here is based on the expected distribution appropriate for continuum initial state radiation. Systematic errors have also been incorporated into these limits.

Given the fact that we have not performed a continuum subtraction of the on-resonance inclusive photon spectrum from Υ decays, it is interesting to compare the structure observed in Fig. 1 with the structure observed when we apply the fitting procedure to continuum data. We observe an apparent correlation between the recoil mass dependent continuum and on-resonance event yields, including an apparent enhancement consistent with charmonium production via radiative return. This indicates that both spectra have large contributions from the initial state radiation (ISR) processes.

III. CROSS-CHECK

A Monte Carlo study has been performed to verify our sensitivity and fitting procedure. Hypothetical $\Upsilon(4S) \to \gamma + \mathcal{R}$, $\mathcal{R} \to \pi^+\pi^-\pi^+\pi^-$ events were embedded into the $\Upsilon(4S)$ inclusive photon spectrum with branching ratios of the order of 10^{-5}, 10^{-4}, 10^{-3}, and 10^{-2} under 10 different $M_{\mathcal{R}}$ hypotheses: $M_{\mathcal{R}} = 0.6$, 1.5, 2.5, 3.5, 4.5, 6.5, 7.5, 8.5, and 9.5 GeV. The resulting 95% confidence level upper limit contours derived from applying our procedure to these spectra are shown in Fig. 3. We reconstruct all signals at our expected sensitivity that are within our accessible recoil mass range.

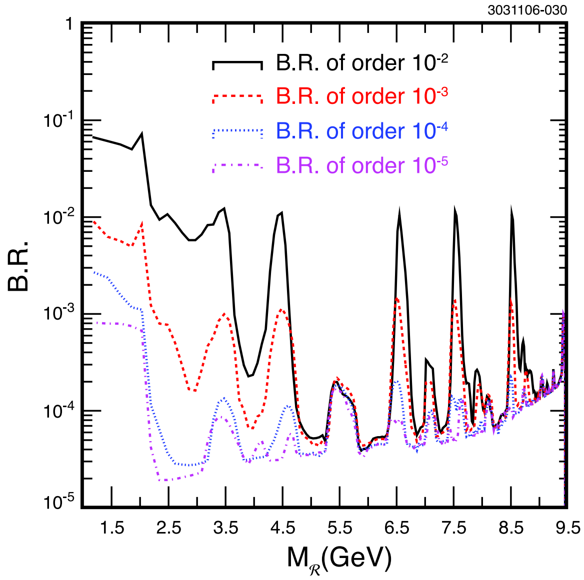

FIG. 3 (color online). The 95% confidence level upper limit contours derived from applying our procedure to fabricated Monte Carlo signal spectra.

IV. SYSTEMATIC ERRORS

We identify systematic errors as follows:

(1) We account for possible systematics in our event and shower reconstruction efficiency by using the lowest-efficiency final state considered, and by assuming $\mathcal{R}$ has spin = 0. The angular distributions for spin = 0, 1, and 2 two-body decays have been calculated, and generally yield flatter distributions for higher spins [7]. We therefore select the production mechanism giving the most conservative upper limit.

(2) We have assessed fitting systematic uncertainties by varying the recoil mass bin width (from 20% to 50% of the resolution σ) and the order of the background polynomial used to parametrize the background (from second order to fifth order). Observing no statistically significant variation between these extremes, we assess no additional systematic error, and use as defaults $\sigma = 5$ bins and a fourth-order background, based on the goodness of the fit of the pull distributions to a unit Gaussian on the continuum.

(3) For continuum measurements, we assess a uniform 1% degradation of the limit due to the luminosity uncertainty as calculated in the previous analysis [1].

(4) For on-resonance measurements, we degrade the limit uniformly by the uncertainty in the calculated number of total resonant events [1].

V. SUMMARY

As shown in Fig. 1, our sensitivity is of the order 10^{-4} across the mass range corresponding to $0.2 < z_\gamma < 1.0$. The most copious two-body radiative Υ decay mode into a resonance ($\mathcal{B}(\Upsilon(1S) \to \gamma f_2(1270)) = (1.00 \pm 0.10) \times 10^{-4}$) results in four charged tracks only 3% of the time [5]. Constraining 1.5 GeV $< M_{\mathcal{R}} <$ 5.0 GeV we set limits of

$$\mathcal{B}(\Upsilon(1S) \to \gamma + \mathcal{R}, \mathcal{R} \to \geq 4 \text{ charged tracks}) < 1.78 \times 10^{-4},$$

$$\mathcal{B}(\Upsilon(2S) \to \gamma + \mathcal{R}, \mathcal{R} \to \geq 4 \text{ charged tracks}) < 1.95 \times 10^{-4},$$

$$\mathcal{B}(\Upsilon(3S) \to \gamma + \mathcal{R}, \mathcal{R} \to \geq 4 \text{ charged tracks}) < 2.20 \times 10^{-4}.$$

We conclude that distortion of the inclusive photon spectrum in our previous extraction of α_s due to the possible contribution of such events is negligible. The possibility of resonances with widths greater than our experimental resolution has yet to be completely addressed. Further work on exclusive multiparticle final states (e.g., $\gamma 2\pi^+ 2\pi^-$, $\gamma 2K^+ 2K^-$, $\gamma K^0 K^0$ and $\gamma K^0 K^\pm \pi^\mp$) would help elucidate the nature of such radiative decays.

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