CLEO CONF 98-17
ICHEP98 1011

Improved Measurement of $\mathcal{B}(b \to s\gamma)$

CLEO Collaboration

(July 21, 1998)

Abstract

We have measured the inclusive $b \to s\gamma$ branching fraction to be (3.15 $\pm$ 0.35 $\pm$ 0.32 $\pm$ 0.26) $\times 10^{-4}$, where the first error is statistical, the second is systematic, and the third is from the model dependence of the signal. For the restricted photon energy range $E_\gamma > 2.1$ GeV, the branching fraction is (2.97 $\pm$ 0.33 $\pm$ 0.30 $\pm$ 0.21) $\times 10^{-4}$.

S. Glenn,[1] Y. Kwon,[1,*] A.L. Lyon,[1] S. Roberts,[1] E. H. Thorndike,[1] C. P. Jessop,[2] K. Lingel,[2] H. Marsiske,[2] M. L. Perl,[2] V. Savinov,[2] D. Ugolini,[2] X. Zhou,[2] T. E. Coan,[3] V. Fadeyev,[3] I. Korolkov,[3] Y. Maravin,[3] I. Narsky,[3] R. Stroynowski,[3] J. Ye,[3] T. Wlodek,[3] M. Artuso,[4] E. Dambasuren,[4] S. Kopp,[4] G. C. Moneti,[4] R. Mountain,[4] S. Schuh,[4] T. Skwarnicki,[4] S. Stone,[4] A. Titov,[4] G. Viehhauser,[4] J.C. Wang,[4] J. Bartelt,[5] S. E. Csorna,[5] K. W. McLean,[5] S. Marka,[5] Z. Xu,[5] R. Godang,[6] K. Kinoshita,[6] I. C. Lai,[6] P. Pomianowski,[6] S. Schrenk,[6] G. Bonvicini,[7] D. Cinabro,[7] R. Greene,[7] L. P. Perera,[7] G. J. Zhou,[7] S. Chan,[8] G. Eigen,[8] E. Lipeles,[8] J. S. Miller,[8] M. Schmidtler,[8] A. Shapiro,[8] W. M. Sun,[8] J. Urheim,[8] A. J. Weinstein,[8] F. Würthwein,[8] D. E. Jaffe,[9] G. Masek,[9] H. P. Paar,[9] E. M. Potter,[9] S. Prell,[9] V. Sharma,[9] D. M. Asner,[10] J. Gronberg,[10] T. S. Hill,[10] D. J. Lange,[10] R. J. Morrison,[10] H. N. Nelson,[10] T. K. Nelson,[10] D. Roberts,[10] B. H. Behrens,[11] W. T. Ford,[11] A. Gritsan,[11] H. Krieg,[11] J. Roy,[11] J. G. Smith,[11] J. P. Alexander,[12] R. Baker,[12] C. Bebek,[12] B. E. Berger,[12] K. Berkelman,[12] V. Boisvert,[12] D. G. Cassel,[12] D. S. Crowcroft,[12] M. Dickson,[12] S. von Dombrowski,[12] P. S. Drell,[12] K. M. Ecklund,[12] R. Ehrlich,[12] A. D. Foland,[12] P. Gaidarev,[12] R. S. Galik,[12] L. Gibbons,[12] B. Gittelman,[12] S. W. Gray,[12] D. L. Hartill,[12] B. K. Heltsley,[12] P. I. Hopman,[12] J. Kandaswamy,[12] D. L. Kreinick,[12] T. Lee,[12] Y. Liu,[12] N. B. Mistry,[12] C. R. Ng,[12] E. Nordberg,[12] M. Ogg,[12,†] J. R. Patterson,[12] D. Peterson,[12] D. Riley,[12] A. Soffer,[12] B. Valant-Spaight,[12] A. Warburton,[12] C. Ward,[12] M. Athanas,[13] P. Avery,[13] C. D. Jones,[13] M. Lohner,[13] C. Prescott,[13] A. I. Rubiera,[13] J. Yelton,[13] J. Zheng,[13] G. Brandenburg,[14] R. A. Briere,[14] A. Ershov,[14] Y. S. Gao,[14] D. Y.-J. Kim,[14] R. Wilson,[14] H. Yamamoto,[14] T. E. Browder,[15] Y. Li,[15] J. L. Rodriguez,[15] S. K. Sahu,[15] T. Bergfeld,[16] B. I. Eisenstein,[16] J. Ernst,[16] G. E. Gladding,[16] G. D. Gollin,[16] R. M. Hans,[16] E. Johnson,[16] I. Karliner,[16] M. A. Marsh,[16] M. Palmer,[16] M. Selen,[16] J. J. Thaler,[16] K. W. Edwards,[17] A. Bellerive,[18] R. Janicek,[18] P. M. Patel,[18] A. J. Sadoff,[19] R. Ammar,[20] P. Baringer,[20] A. Bean,[20] D. Besson,[20] D. Coppage,[20] C. Darling,[20] R. Davis,[20] S. Kotov,[20] I. Kravchenko,[20] N. Kwak,[20] L. Zhou,[20] S. Anderson,[21] Y. Kubota,[21] S. J. Lee,[21] R. Mahapatra,[21] J. J. O'Neill,[21] R. Poling,[21] T. Riehle,[21] A. Smith,[21] M. S. Alam,[22] S. B. Athar,[22] Z. Ling,[22] A. H. Mahmood,[22] S. Timm,[22] F. Wappler,[22] A. Anastassov,[23] J. E. Duboscq,[23] K. K. Gan,[23] T. Hart,[23] K. Honscheid,[23] H. Kagan,[23] R. Kass,[23] J. Lee,[23] H. Schwarthoff,[23] A. Wolf,[23] M. M. Zoeller,[23] S. J. Richichi,[24] H. Severini,[24] P. Skubic,[24] A. Undrus,[24] M. Bishai,[25] S. Chen,[25] J. Fast,[25] J. W. Hinson,[25] N. Menon,[25] D. H. Miller,[25] E. I. Shibata,[25] and I. P. J. Shipsey[25]

[1]University of Rochester, Rochester, New York 14627
[2]Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
[3]Southern Methodist University, Dallas, Texas 75275
[4]Syracuse University, Syracuse, New York 13244
[5]Vanderbilt University, Nashville, Tennessee 37235
[6]Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

[*]Permanent address: Yonsei University, Seoul 120-749, Korea.

[†]Permanent address: University of Texas, Austin TX 78712.

[7]Wayne State University, Detroit, Michigan 48202
[8]California Institute of Technology, Pasadena, California 91125
[9]University of California, San Diego, La Jolla, California 92093
[10]University of California, Santa Barbara, California 93106
[11]University of Colorado, Boulder, Colorado 80309-0390
[12]Cornell University, Ithaca, New York 14853
[13]University of Florida, Gainesville, Florida 32611
[14]Harvard University, Cambridge, Massachusetts 02138
[15]University of Hawaii at Manoa, Honolulu, Hawaii 96822
[16]University of Illinois, Urbana-Champaign, Illinois 61801
[17]Carleton University, Ottawa, Ontario, Canada K1S 5B6
and the Institute of Particle Physics, Canada
[18]McGill University, Montréal, Québec, Canada H3A 2T8
and the Institute of Particle Physics, Canada
[19]Ithaca College, Ithaca, New York 14850
[20]University of Kansas, Lawrence, Kansas 66045
[21]University of Minnesota, Minneapolis, Minnesota 55455
[22]State University of New York at Albany, Albany, New York 12222
[23]Ohio State University, Columbus, Ohio 43210
[24]University of Oklahoma, Norman, Oklahoma 73019
[25]Purdue University, West Lafayette, Indiana 47907

I. INTRODUCTION

CLEO has previously reported [1] observation of the inclusive radiative penguin decay $b \to s\gamma$, obtaining a measurement of the branching fraction of $(2.32 \pm 0.57 \pm 0.35) \times 10^{-4}$. That result stimulated much theoretical activity [2], which explored the limitations on physics beyond the Standard Model placed by the measured branching fraction. Also, since our 1995 measurement, the theoretical calculations of the Standard Model rate have improved with full next-to-leading-log calculations [3]; they predict a branching fraction of (3.28 ± 0.33) $\times 10^{-4}$. Here we report an improved measurement of the $b \to s\gamma$ branching fraction, using 60% additional data and improved analysis techniques.

II. METHOD

The data were taken with the CLEO detector at the Cornell Electron Storage Ring (CESR), and consist of 3.13 fb^{-1} on the Υ(4S) resonance and 1.60 fb^{-1} at a center-of-mass energy 60 MeV below the resonance. The on-resonance sample contains 3.3 million $B\bar{B}$ events and 10 million continuum events. The CLEO detector [5] measures charged particles over 95% of 4π steradians with a system of cylindrical drift chambers. Its barrel and endcap CsI electromagnetic calorimeters cover 98% of 4π. The energy resolution for photons near 2.5 GeV in the central angular region ($|\cos\theta_\gamma| < 0.7$) is 2%.

Our signature for $b \to s\gamma$ is a photon from B-meson decay with energy between 2.1 and 2.7 GeV (as compared with 2.2 – 2.7 GeV in the earlier analysis). The Fermi motion of the b quark in a B meson and the momentum of the B meson in the lab result in this Doppler-broadened photon line. Spectator model calculations [6] indicate that 85-94% of the signal lies in this range. Backgrounds from other B-decay processes are small and calculable. There are very large backgrounds from the continuum, both from the initial-state-radiation (ISR) process $e^+e^- \to q\bar{q}\gamma$, and from the continuum reaction $e^+e^- \to q\bar{q}$, with the high energy photon arising from the hadronic debris (π^0, η, $\omega \to \pi^0\gamma$, *etc.*). We suppress the continuum with the same two approaches used previously, but combine them in a more effective way. We subtract what remains of the continuum background using off-resonance data.

We select events that pass general hadronic event selection criteria [7]. We further require that the event contain a high energy calorimeter cluster with $|\cos\theta_\gamma| < 0.7$ and unmatched to a charged particle track. The vast majority of photons, both from continuum and $B\bar{B}$ events, are π^0 and η decay products. We discard those high energy clusters which, when paired with another γ in the event, have a $\gamma\gamma$ mass consistent with a π^0 or η. Finally, we require that the lateral energy distribution of the cluster be consistent with that of a single isolated photon, thus suppressing random overlaps, single-cluster π^0's, and non-photon clusters.

The first approach [7] for suppressing continuum background uses eight carefully chosen event-shape variables: R_2, $S_\perp$, R_2', $\cos\theta'$ as defined in Ref. [4], and the energies in 20° and 30° cones, parallel and antiparallel to the high energy photon direction. While no individual variable has strong discriminating power, each possesses some. Consequently we combine the eight variables into a single variable r which tends towards $+1$ for $b \to s\gamma$ and tends towards -1 for ISR and $q\bar{q}$. A neural network is used for this task.

In the second approach for suppressing the continuum, we search each event for combinations of particles that reconstruct to a $B \to X_s\gamma$ decay. For X_s we use: $K^0_s \to \pi^+\pi^-$ or a charged track with dE/dx consistent with a kaon; and 1–4 π's, of which at most one may be a π^0. There are reconstruction ambiguities and cross-feed between decay modes, but these are not important because this method is used only to suppress background and *not* for a mode-by-mode B-reconstruction analysis. In each event, we pick the combination that minimizes an overall χ^2, which includes χ^2_B (see below), together with contributions from dE/dx and K^0_s and π^0 mass deviations, where relevant. We calculate the momentum P_B, the energy E_B, and the beam-constrained mass $M_B = \sqrt{E^2_{\rm beam} - P^2_B}$ of the combination, and also $\cos\theta_{tt}$, where θ_{tt} is the angle between the thrust axis of the candidate B and the thrust axis of the rest of the event. We discriminate between signal and background using $|\cos\theta_{tt}|$ and χ^2_B, where

$$\chi^2_B = \left(\frac{M_B - 5.279}{\sigma_M}\right)^2 + \left(\frac{E_B - E_{\rm beam}}{\sigma_E}\right)^2. \quad (1)$$

For events containing a plausible reconstructed $B \to X_s\gamma$ (taken as $\chi^2_B < 20$), we have three quantities which help discriminate between $b \to s\gamma$ signal and continuum background, namely r, $|\cos\theta_{tt}|$ and χ^2_B. We combine those 3 variables into a single variable r_c, again using a neural network. For events containing no plausible reconstructed $B \to X_s\gamma$ ($\chi^2_B > 20$, or no candidate at all), we use r alone to discriminate between signal and background. Distributions in r_c for events with a reconstructed $B \to X_s\gamma$, and in r for events without a reconstructed $B \to X_s\gamma$, are shown in Figs. 1a and 2a, respectively, for Monte Carlo samples of $b \to s\gamma$ signal and continuum background.

We weight each event according to its value of r_c (or r), with a weight given by

$$w_i = s_i/[s_i + (1+\alpha)b_i],$$

where s_i is the expected [8] signal yield in the r_c (or r) bin i, b_i is the expected continuum background yield in that bin, and α is the luminosity scale factor between on-resonance and off-resonance data samples. These weights are shown as a function of r_c (r) in Fig. 1b (Fig. 2b). For the case where backgrounds other than from the continuum are negligible (a reasonable approximation in this case), this weighting gives the smallest statistical error on the background-subtracted yield.

Of course, the weights that give minimum statistical error are defined only to within an arbitrary multiplicative scale factor. With the definition chosen, the weight approaches 1.0 as the continuum background becomes very small.

There are backgrounds from B decay processes other than $b \to s\gamma$, in particular from $b \to cW^-$ and $b \to uW^-$. As a first approximation, we take these from MC. We then correct for any difference between the π^0 momentum spectra from data and MC, and similarly for the η momentum spectra. These spectra are obtained by treating the π^0 or η as if it were a photon, performing the same analysis as for photons, weighting with w_i. This procedure corrects for any flaws in the event generators for $b \to cW^-$ and $b \to uW^-$, and for any omissions (*e.g.*, $b \to sg$). Thus we rely on MC only for the π^0 and η veto efficiencies, and for those small B-decay backgrounds with photons *not* originating from π^0 or η.

III. YIELDS

Weighted yields are shown in Table 1, for the signal E_γ interval (2.1 – 2.7 GeV), and for two intervals below and one interval above the signal interval. The first and second errors shown on the background-subtracted weighted yields are statistical and systematic, respectively. The systematic error is a quadratic sum of 20% of the total corrected $B\bar{B}$ background estimate, to allow for uncertainties in π^0 and η veto efficiencies, and $\pm 1\%$ of scaled off-resonance, to allow for uncertainties in that subtraction.

The weighted yields are plotted against photon energy in Fig. 3. Fig 3a shows all the backgrounds, while Fig. 3b shows the background-subtracted weighted yield, the putative signal. The spectrum expected for $b \to s\gamma$, as given by a spectator model calculation, is also shown. The measured spectrum is perhaps somewhat softer than the spectator model expectations.

IV. EFFICIENCY

From a typical sample of Monte Carlo $b \to s\gamma$ signal events, approximately 50% pass all cuts including the 2.1 – 2.7 GeV photon energy cut. Of these, 40% additionally have $\chi_B^2 < 20$. But because we are weighting our candidate events, these efficiencies are *not* what we need for determining branching fractions. Instead we need a *weighted efficiency*. That is, for a Monte Carlo signal sample, we sum the weights of the events passing all cuts, and divide by the number of events in the sample. We denote this weighted efficiency ϵ_w. Because weights lie between 1.0 and 0.0, with our chosen normalization, and are typically $\sim$0.1, the weighted efficiency ϵ_w is much smaller than the unweighted event efficiencies quoted above.

To model the decay $b \to s\gamma$, i.e., $B \to X_s\gamma$, we use the spectator model of Ali and Greub [6], which includes gluon bremsstrahlung and higher-order radiative effects. In the Ali-Greub model, we vary the Fermi-momentum parameter P_F and spectator-quark mass simultaneously so that the b-quark average mass $\langle m_b \rangle$ is constant at 4.88 ± 0.10 GeV, a value suggested by recent theoretical work [9]. We take $P_F = 250 \pm 50$ MeV$/c$. For hadronization of $s\bar{q}$ into X_s, we have compared two approaches. In the first, we have taken several K^* resonances and combined them in proportions to approximate the X_s mass distribution given by the Ali-Greub model. In the second, we have let JETSET hadronize the $s\bar{q}$, again giving the Ali-Greub X_s mass distribution.

We find

$$\epsilon_w = (4.43 \pm 0.29 \pm 0.22 \pm 0.03 \pm 0.31) \times 10^{-2},$$

where the first uncertainty is due to spectator model inputs, the second is due to recoil system hadronization (half the difference of our two approaches), the third is due to the uncertainty in the production ratio of B^+B^- to $B^0\bar{B}^0$, and the last to detector modeling.

The weighted efficiency just quoted, when combined with the weighted yield, gives the branching fraction for $b \to s\gamma$ for photons over the full energy range according to the Ali-Greub model. We also wish to give a branching fraction for a restricted energy range, $E_\gamma > 2.1$ GeV. For this, we need a weighted efficiency obtained with a denominator being the number of Monte Carlo events with E_γ generated above 2.1 GeV. For that we obtain

$$\epsilon_{w,2.1} = (4.70 \pm 0.23 \pm 0.23 \pm 0.04 \pm 0.33) \times 10^{-2},$$

where the uncertainties have the same meaning as for ϵ_w above. Although we do not rely on the spectator model to extrapolate the branching ratio to the phase space below 2.1 GeV, the hadronization of decays above 2.1 GeV depends on the shape of the spectrum in that region. Thus, systematic uncertainties associated with spectator model inputs are reduced relative to the full branching ratio but are not entirely eliminated.

V. BRANCHING FRACTIONS

Combining the background-subtracted weighted yield from Table 1 with the weighted efficiency given in the previous section, we obtain a branching fraction

$$\mathcal{B}(b \to s\gamma) = (3.15 \pm 0.35 \pm 0.32 \pm 0.26) \times 10^{-4},$$

where the errors are statistical, systematic, and for model dependence, respectively.

Conservatively allowing for the systematic error, we find $\mathcal{B}(b \to s\gamma) < 4.5 \times 10^{-4}$, $\mathcal{B}(b \to s\gamma) > 2.0 \times 10^{-4}$, each limit at 95% CL.

To allow use with theoretical descriptions of the photon energy spectrum other than the Ali-Greub model, we also quote a branching fraction for photons into the energy range above 2.1 GeV, finding

$$\mathcal{B}_{2.1}(b \to s\gamma) = (2.97 \pm 0.33 \pm 0.30 \pm 0.21) \times 10^{-4},$$

where the errors have the same meaning as above. Note that by taking the branching fraction for the restricted E_γ range, one lowers the model dependence by 14% of itself.

The branching fractions just obtained are in good agreement with theoretical calculations based on the Standard Model. They are in reasonable agreement with our earlier measurement, and supplant it. The large yield in the 2.1–2.2 GeV region is the main reason for the increased central value of this measurement relative to the previous one. The statistical error is about 60% of that quoted previously.

In summary, the inclusive branching ratio for $b \to s\gamma$ has been determined using using 60% additional data and improved analysis techniques relative to our previous measurement. Our measurement is in good agreement with Standard Model predictions, and places constraints on other models.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. We thank A. Ali and C. Greub for performing spectator model calculations for us. J. Hewett and T. Rizzo have helped us understand the implications of $b \to s\gamma$ for non-standard models. This work was supported by the National Science Foundation, the U.S. Department of Energy, Research Corporation, the Natural Sciences and Engineering Research Council of Canada, the A.P. Sloan Foundation, the Swiss National Science Foundation, and the Alexander von Humboldt Stiftung.

REFERENCES

[1] M.S. Alam *et al.* (CLEO), Phys. Rev. Lett. **74**, 2885 (1995).

[2] See, for example, F. Borzumati and C. Greub, hep-ph/9802391; W. de Boer *et al.*, hep-ph/9805378; H. Baer *et al.*, Phys.Rev. D **58** 15007 (1998). For a review of implications of $b \to s\gamma$ for non-standard models, see J. Hewett, SLAC-PUB-6521 (1994).

[3] K. Chetyrkin *et al.*, Phys. Lett. B **400**, 206 (1997); Phys. Lett. B **425**, 414 (1998); A. Kagan and M. Neubert hep-ph/9805303 (submitted to Eur.Phys.J.) and references therin.

[4] R. Ammar *et al.* (CLEO), Phys. Rev. Lett. **71**, 674 (1993).

[5] Y. Kubota *et al.* (CLEO), Nucl. Instrum. Meth. A **320**, 66 (1992).

[6] A. Ali and C. Greub, Phys. Lett. B **259**, 182 (1991).

[7] J.A. Ernst, Ph.D. thesis, Univ. of Rochester (1995).

[8] For purposes of determining weights, we assume $\mathcal{B}(b \to s\gamma) = 3.0 \times 10^{-4}$ and $\sigma(\text{continuum}) = 3.3$ nb.

[9] M. Voloshin and Y. Zaitsev, Sov. Phys. Usp. **30**, 553 (1987); C. Davies *et al.*, Phys. Rev. Lett. **73**, 2654 (1994).

Source	$1.7 \leq E_\gamma < 1.9$ GeV	$1.9 \leq E_\gamma < 2.1$ GeV	$2.1 \leq E_\gamma < 2.7$ GeV	$2.7 \leq E_\gamma < 2.9$ GeV
On-resonance	323.37 ± 5.31	269.47 ± 7.41	500.52 ± 7.41	86.65 ± 2.10
Scaled Off-resonance	231.11 ± 5.37	193.48 ± 7.00	382.25 ± 7.00	83.39 ± 2.57
$B\bar{B}$ Background	77.54	53.40	20.60	0.09
π^0 Correction	1.81 ± 0.86	0.19 ± 0.55	1.91 ± 0.55	0.00 ± 0.00
η correction	4.37 ± 1.57	4.14 ± 1.06	3.55 ± 1.06	0.02 ± 0.05
Net Yield	$8.54 \pm 7.76 \pm 16.90$	$18.27 \pm 7.70 \pm 11.71$	$92.21 \pm 10.26 \pm 6.46$	$3.15 \pm 3.32 \pm 0.83$

TABLE I. Weighted yields for photon energy bins.

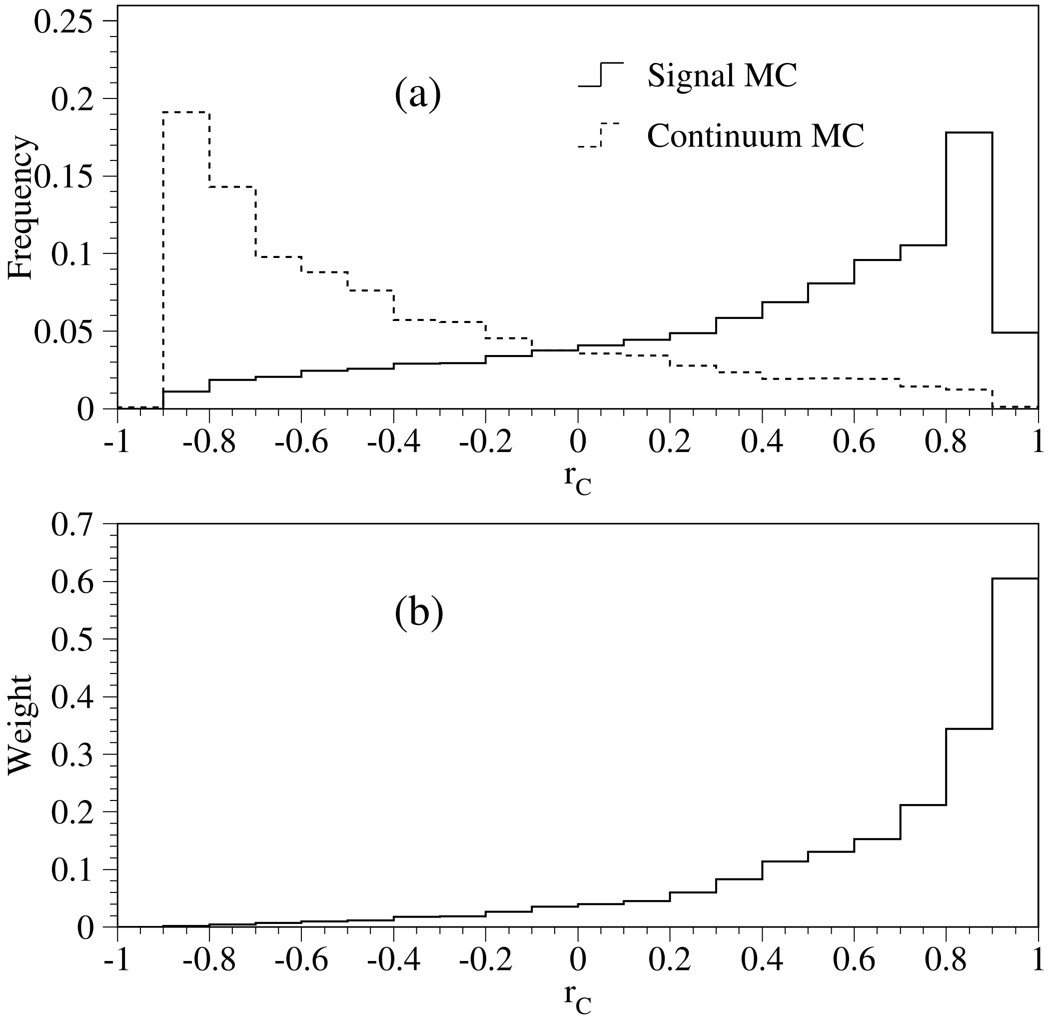

FIG. 1. (a) Distributions in the neural net variable r_c, for Monte Carlo samples of $b \to s\gamma$ signal (solid histogram) and continuum background (dashed histogram) for events with $\chi^2_B < 20$. (b) Event weighting function.

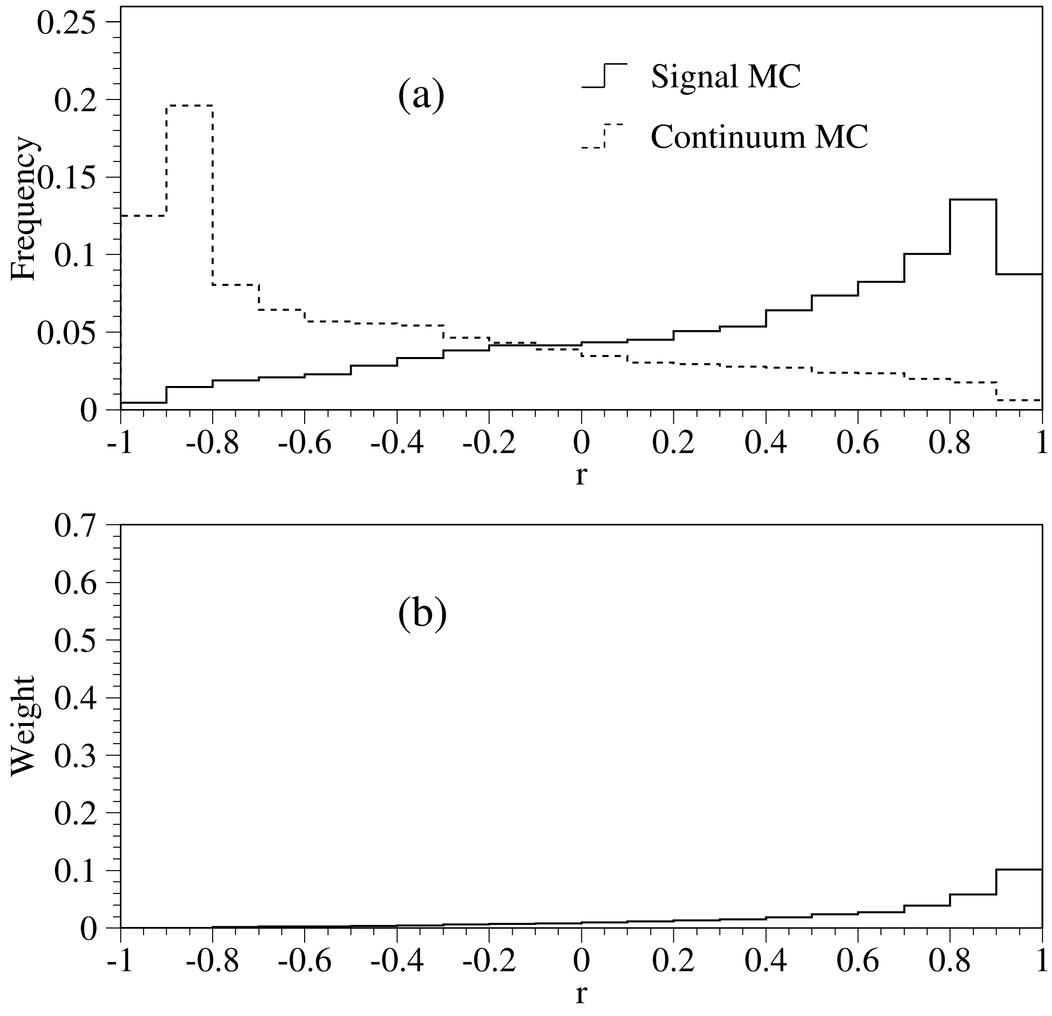

FIG. 2. (a) Distributions in the neural net variable r, for Monte Carlo samples of $b \to s\gamma$ signal (solid histogram) and continuum background (dashed histogram) for events with $\chi^2_B > 20$ or no reconstructed B. (b) Event weighting function.

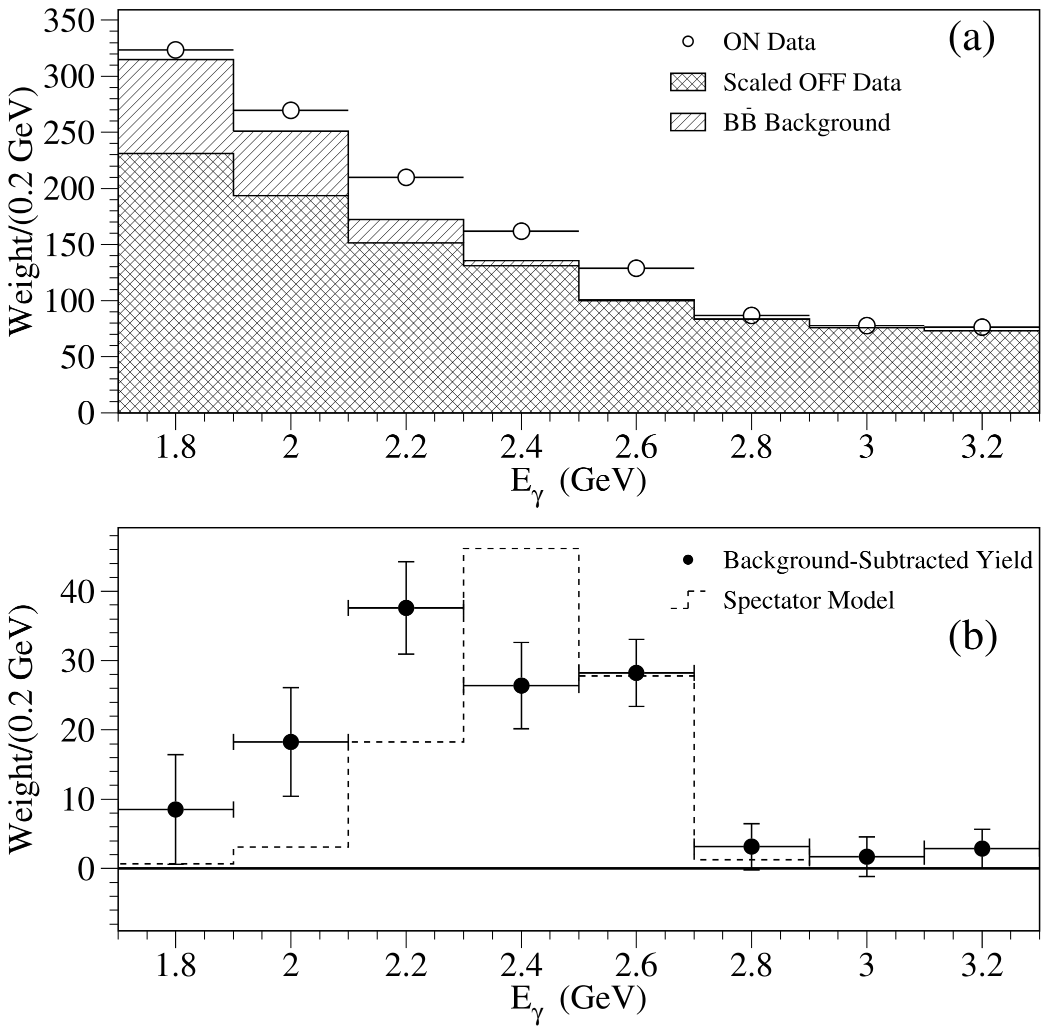

FIG. 3. Photon energy spectra. (a) On-resonance (points), scaled off-resonance (double-hatched), and background from $B\bar{B}$ (single-hatched). (b) Background-subtracted data (points) and Monte Carlo prediction for the shape of the $b \to s\gamma$ signal (dashed curve) for $\langle m_b \rangle = 4.88$ GeV and $P_F = 250$ MeV$/c$[6]. Error bars indicate statistical uncertainties only.