A Measurement of the Branching Fraction for the Inclusive $B \rightarrow X_s \gamma$ Decays with the Belle Detector

The Belle Collaboration

K. Abe$^{10}$, K. Abe$^{37}$, I. Adachi$^{10}$, Byoung Sup Ahn$^{15}$, H. Aihara$^{38}$, M. Akatsu$^{20}$, G. Alimonti$^9$, K. Aoki$^{10}$, K. Asai$^{21}$, Y. Asano$^{43}$, T. Aso$^{42}$, V. Aulchenko$^2$, T. Aushhev$^{13}$, A. M. Bakich$^{34}$, E. Banas$^{16}$, W. Bartel$^{10,6}$, S. Behari$^{20}$, P. K. Behera$^{44}$, D. Beiline$^2$, A. Bondar$^2$, A. Bozek$^{16}$, T. E. Browder$^9$, B. C. K. Casey$^9$, P. Chang$^{24}$, Y. Chao$^{24}$, B. G. Cheon$^{33}$, S.-K. Choi$^8$, Y. Choi$^{33}$, Y. Doi$^{10}$, J. Dragic$^{18}$, A. Drutskoy$^{13}$, S. Eidelman$^2$, Y. Enari$^{20}$, R. Enomoto$^{10,11}$, F. Fang$^9$, H. Fujii$^{10}$, C. Fukunaga$^{40}$, M. Fukushima$^{11}$, A. Garmash$^{2,10}$, A. Gordon$^{18}$, K. Gotow$^{45}$, H. Guler$^9$, R. Guo$^{22}$, J. Haba$^{10}$, H. Hamasaki$^{10}$, K. Hanagaki$^{30}$, F. Handa$^{37}$, K. Hara$^{28}$, T. Hara$^{28}$, T. Haruyama$^{10}$, N. C. Hastings$^{18}$, K. Hayashi$^{10}$, H. Hayashii$^{21}$, M. Hazumi$^{28}$, E. M. Heenan$^{18}$, Y. Higasino$^{20}$, I. Higuchi$^{37}$, T. Higuchi$^{38}$, H. Hirano$^{41}$, T. Hojo$^{28}$, Y. Hoshi$^{36}$, W.-S. Hou$^{24}$, S.-C. Hsu$^{24}$, H.-C. Huang$^{24}$, S. Ichizawa$^{39}$, Y. Igarashi$^{10}$, T. Iijima$^{10}$, H. Ikeda$^{10}$, K. Ikeda$^{21}$, K. Inami$^{20}$, A. Ishikawa$^{20}$, H. Ishino$^{39}$, R. Itoh$^{10}$, G. Iwai$^{26}$, H. Iwasaki$^{10}$, Y. Iwasaki$^{10}$, D. J. Jackson$^{28}$, P. Jalocha$^{16}$, H. K. Jang$^{32}$, M. Jones$^9$, R. Kagan$^{13}$, H. Kakuno$^{39}$, J. Kaneko$^{39}$, J. H. Kang$^{46}$, J. S. Kang$^{15}$, P. Kapusta$^{16}$, N. Katayama$^{10}$, H. Kawai$^3$, N. Kawamura$^1$, T. Kawasaki$^{26}$, H. Kichimi$^{10}$, D. W. Kim$^{33}$, Heejong Kim$^{46}$, H. J. Kim$^{46}$, Hyunwoo Kim$^{15}$, S. K. Kim$^{32}$, K. Kinoshita$^5$, K. Korotushenko$^{30}$, P. Krokovny$^2$, R. Kulasiri$^5$, S. Kumar$^{29}$, T. Kuniya$^{31}$, E. Kurihara$^3$, A. Kuzmin$^2$, Y.-J. Kwon$^{46}$, J. S. Lange$^7$, M. H. Lee$^{10}$, S. H. Lee$^{32}$, H.B. Li$^{12}$, D. Liventsev$^{13}$, R.-S. Lu$^{24}$, A. Manabe$^{10}$, T. Matsubara$^{38}$, S. Matsui$^{20}$, S. Matsumoto$^4$, T. Matsumoto$^{20}$, Y. Mikami$^{37}$,
K. Misono\textsuperscript{20}, K. Miyabayashi\textsuperscript{21}, H. Miyake\textsuperscript{28}, H. Miyata\textsuperscript{26}, L. C. Moffitt\textsuperscript{18},
G. R. Moloney\textsuperscript{18}, G. F. Moorhead\textsuperscript{18}, S. Mori\textsuperscript{43}, A. Murakami\textsuperscript{31},
T. Nagamine\textsuperscript{37}, Y. Nagasaka\textsuperscript{19}, Y. Nagashima\textsuperscript{28}, T. Nakadaira\textsuperscript{38},
E. Nakano\textsuperscript{27}, M. Nakao\textsuperscript{10}, J. W. Nam\textsuperscript{33}, S. Narita\textsuperscript{37}, Z. Natkaniec\textsuperscript{16},
K. Neichi\textsuperscript{36}, S. Nishida\textsuperscript{17}, O. Nitoh\textsuperscript{41}, S. Noguchi\textsuperscript{21}, T. Nozaki\textsuperscript{10}, S. Ogawa\textsuperscript{35},
T. Ohshima\textsuperscript{20}, Y. Ohshima\textsuperscript{39}, T. Okabe\textsuperscript{20}, T. Okazaki\textsuperscript{21}, S. Okuno\textsuperscript{14},
S. L. Olsen\textsuperscript{9}, W. Ostrowicz\textsuperscript{16}, H. Ozaki\textsuperscript{10}, H. Palka\textsuperscript{16}, C. S. Park\textsuperscript{32},
C. W. Park\textsuperscript{15}, H. Park\textsuperscript{15}, L. S. Peak\textsuperscript{34}, M. Peters\textsuperscript{9}, L. E. Piilonen\textsuperscript{45},
E. Prebys\textsuperscript{30}, J. L. Rodriguez\textsuperscript{9}, N. Root\textsuperscript{2}, M. Rozanska\textsuperscript{16}, K. Rybicki\textsuperscript{16},
J. Ryuko\textsuperscript{28}, H. Sagawa\textsuperscript{10}, Y. Sakai\textsuperscript{10}, S. Schrenk\textsuperscript{45}, S. Semenov\textsuperscript{13}, K. Senyo\textsuperscript{20}, M. E. Sevior\textsuperscript{18},
H. Shibuya\textsuperscript{35}, B. Shwartz\textsuperscript{2}, V. Sidorov\textsuperscript{2}, J.B. Singh\textsuperscript{29}, S. Stanič\textsuperscript{43}, A. Sugii\textsuperscript{20},
A. Sugiyama\textsuperscript{26}, K. Sumisawa\textsuperscript{28}, T. Sumiyoshi\textsuperscript{10}, K. Suzuki\textsuperscript{3}, S. Suzuki\textsuperscript{20},
S. Y. Suzuki\textsuperscript{10}, S. K. Swain\textsuperscript{9}, H. Tajima\textsuperscript{38}, T. Takahashi\textsuperscript{27}, F. Takasaki\textsuperscript{10},
M. Takita\textsuperscript{28}, K. Tamai\textsuperscript{10}, N. Tamura\textsuperscript{26}, J. Tanaka\textsuperscript{38}, M. Tanaka\textsuperscript{10},
Y. Tanaka\textsuperscript{19}, G. N. Taylor\textsuperscript{18}, Y. Teramoto\textsuperscript{27}, M. Tomoto\textsuperscript{20}, T. Tomura\textsuperscript{38},
S. N. Tovey\textsuperscript{18}, K. Trabelsi\textsuperscript{9}, T. Tsuboyama\textsuperscript{10}, Y. Tsujita\textsuperscript{43}, T. Tsukamoto\textsuperscript{10},
S. Uehara\textsuperscript{10}, K. Ueno\textsuperscript{24}, N. Ujiie\textsuperscript{10}, Y. Unno\textsuperscript{3}, S. Uno\textsuperscript{10}, Y. Ushiroda\textsuperscript{17},
Y. Usov\textsuperscript{2}, S. E. Vahsen\textsuperscript{30}, G. Varner\textsuperscript{9}, K. E. Varvell\textsuperscript{34}, C. C. Wang\textsuperscript{24},
C. H. Wang\textsuperscript{23}, M.-Z. Wang\textsuperscript{24}, T.J. Wang\textsuperscript{12,f}, Y. Watanabe\textsuperscript{39}, E. Won\textsuperscript{32},
B. D. Yabsley\textsuperscript{10}, Y. Yamada\textsuperscript{10}, M. Yamaga\textsuperscript{37}, A. Yamaguchi\textsuperscript{37},
H. Yamamoto\textsuperscript{9}, H. Yamaoka\textsuperscript{10}, Y. Yamaoka\textsuperscript{10}, Y. Yamashita\textsuperscript{25},
M. Yamauchi\textsuperscript{10}, S. Yanaka\textsuperscript{39}, M. Yokoyama\textsuperscript{38}, K. Yoshida\textsuperscript{20}, Y. Yusa\textsuperscript{37},
H. Yuta\textsuperscript{1}, C.C. Zhang\textsuperscript{12}, J. Zhang\textsuperscript{43}, Y. Zheng\textsuperscript{9}, V. Zhilich\textsuperscript{2}, and D. Žontar\textsuperscript{43}

\textsuperscript{1}Aomori University, Aomori
\textsuperscript{2}Budker Institute of Nuclear Physics, Novosibirsk
\textsuperscript{3}Chiba University, Chiba
\textsuperscript{4}Chuo University, Tokyo
\textsuperscript{5}University of Cincinnati, Cincinnati, OH
\textsuperscript{6}Deutsches Elektronen–Synchrotron, Hamburg
\textsuperscript{7}University of Frankfurt, Frankfurt
\textsuperscript{8}Gyeongsang National University, Chinju
\textsuperscript{9}University of Hawaii, Honolulu HI
\textsuperscript{10}High Energy Accelerator Research Organization (KEK), Tsukuba
\textsuperscript{11}Institute for Cosmic Ray Research, University of Tokyo, Tokyo
\textsuperscript{12}Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
\textsuperscript{13}Institute for Theoretical and Experimental Physics, Moscow
\textsuperscript{14}Kanagawa University, Yokohama
\textsuperscript{15}Korea University, Seoul
Abstract

We have measured the branching fraction of the inclusive radiative $B$ meson decay $B \to X_s \gamma$ to be

$$Br(B \to X_s \gamma) = (3.36 \pm 0.53 \text{(stat)} \pm 0.42 \text{(sys)}^{+0.50}_{-0.54} \text{(th)}) \times 10^{-4}.$$ 

The result is based on a sample of $6.07 \times 10^6 \bar{B}B$ events collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric $e^+e^-$ storage ring.

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In the framework of the Standard Model (SM), the inclusive decay $B \to X_s \gamma$, where $X_s$ is a hadronic recoil system containing an $s$ quark, proceeds primarily through the electroweak penguin diagrams of the radiative $b \to s \gamma$ transition. These diagrams are of interest because they have loops where non-SM particles, such as charged Higgs bosons or SUSY particles, can contribute and potentially produce deviations from SM expectations. An SM branching fraction calculation for $B \to X_s \gamma$ that includes next-to-leading order QCD corrections has an expected precision of 10% [1]. Experimental measurements of the branching fraction at this level of precision are useful for identifying or limiting non-SM theories [2].

A semi-inclusive analysis is used to reconstruct the $B \to X_s \gamma$ decay from a primary photon, a kaon and multiple pions. The monochromatic photon energy from the two-body decay $b \to s \gamma$ is smeared by gluon emission, the Fermi motion of the $b$ quark inside the $B$ meson, and the $B$ meson momentum in the $\Upsilon(4S)$ center-of-mass (CM) frame.

The $B \to X_s \gamma$ decay is studied with the Belle detector at the KEKB asymmetric $e^+e^-$ storage ring [3]. The dataset consists of a sample of $6.07 \times 10^6$ $B\bar{B}$ events corresponding to an integrated luminosity of 5.8 fb$^{-1}$ taken at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV), and an off-resonance background sample of 0.6 fb$^{-1}$ taken 60 MeV below $\Upsilon(4S)$. The beam energies at the $\Upsilon(4S)$ resonance are 3.5 GeV for positrons and 8.0 GeV for electrons. Quantities used in this analysis are defined in the CM frame, in which the beam energy $E_{\text{beam}}$ is defined as $\sqrt{s}/2$. Inclusion of charge conjugated modes are implied throughout the text.

A full description of the Belle detector is given in [4]; here we briefly describe the components relevant for this analysis. Charged tracks are reconstructed inside a 1.5 T magnetic field induced by a superconducting solenoid magnet, by means of a 50 layer central drift chamber (CDC) that covers the laboratory polar angle $17^\circ < \theta_{\text{lab}} < 150^\circ$. Tracks are fitted through the CDC and a three layer double sided silicon vertex detector (SVD), with a transverse momentum resolution of $(\sigma_{p_t}/p_t)^2 = (0.0019p_t)^2 + (0.0034)^2$ $(p_t$ in GeV/c). For particle identification, we combine information from three detectors. The high momentum range, typically from 1 to 3.5 GeV/c, is covered by a silica aerogel Cherenkov counter (ACC) system, providing threshold-type kaon-to-pion separation. The momentum range below 1.5 GeV/c is covered by a time-of-flight (TOF) counter system, and the very low and high momentum ranges are accessible with $dE/dx$ information from the CDC. Photons are detected by an electromagnetic calorimeter (ECL) located between the particle identification devices and the solenoid coil. The entire tracking acceptance is covered with 8736 CsI(Tl) crystals that are typically $5.5 \times 5.5$ cm$^2$ in cross-section at the front surface and 16.2 $X_0$ in depth. The photon energy resolution is $(\sigma_E/E)^2 = 0.013^2 + (0.0007/E)^2 + (0.008/E^{1/4})^2$ ($E$ in GeV), which is better
than 2% for the primary photons used in this analysis. The Belle detector is modelled with the GEANT program [5] to simulate the detector response. Both the data and the Monte Carlo (MC) events [6] are reconstructed with the same program.

Hadronic events are selected with an efficiency of 99% for $B\bar{B}$ final states. Events with at least three tracks from the interaction region and visible energy greater than $0.2\sqrt{s}$ are selected. The QED and $\tau^+\tau^-$ events that remain are removed using ECL information and event topology [7].

Photon candidates are selected from ECL clusters of $5 \times 5$ crystals. Each photon candidate is required to have a laboratory energy greater than 20 MeV with no associated charged track, and shower shape consistent with an electromagnetic shower. We accept events in which the most energetic photon is in the barrel region ($33^\circ < \theta_{lab} < 132^\circ$). In order to reject $\pi^0$ and $\eta$ mesons, we combine this primary photon candidate with any other photon (for $\eta$ we only use photons with $E_\gamma > 200$ MeV) and reject the event if the invariant mass of the two photons is within \( \pm 18 \text{ MeV}/c^2 \) of $M_{\pi^0}$ or $\pm 32 \text{ MeV}/c^2$ of $M_\eta$.

We reconstruct the recoil system $X_s$ in 16 different final states of one charged kaon or $K^0_S$ plus one to four pions which may include one $\pi^0$. We combine the primary photon with every $X_s$ combination and calculate the opening angle $\theta_{Xs\gamma}$ between $\vec{p}_\gamma$ and $\vec{p}_{X_s}$, the energy difference $\Delta E = E_\gamma + E_{X_s} - E_{\text{beam}}$ and the beam constrained mass $M_{bc} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_\gamma + \vec{p}_{X_s}|^2}$. Then, we require $\theta_{Xs\gamma} > 167^\circ$, $M_{bc} > 5.2 \text{ GeV}/c^2$ and $-0.15 < \Delta E/\text{GeV} < 0.1$.

Charged kaon candidates are selected using a kaon-to-pion likelihood ratio. For every charged track, likelihoods from ACC, TOF and $dE/dx$ are calculated for pion and kaon hypotheses. A combined likelihood is constructed for each hypothesis, and a tight cut is applied on the likelihood ratio. Kaons are identified with a typical efficiency of 65% with 2% pion fake rate. All charged tracks that are not identified as kaons are considered to be pions.

The neutral kaon candidates are reconstructed in the $K^0_S \rightarrow \pi^+\pi^-$ mode from two oppositely charged tracks. The $K^0_S$ momentum is recalculated with a vertex constrained fit. The candidates are then required to have an invariant mass within $\pm 8 \text{ MeV}/c^2$ ($\sim 2\sigma$) of $M_{K^0}$ and a vertex that is displaced from the interaction point in a direction consistent with the $K^0_S$ momentum. The $K^0_S$ reconstruction efficiency is $65 \pm 4\%$.

The $\pi^0 \rightarrow \gamma\gamma$ candidates are reconstructed from two photons that have an invariant mass within $\pm 16 \text{ MeV}/c^2$ ($\sim 3\sigma$) of $M_{\pi^0}$. Then, the $\pi^0$ momentum is recalculated with a mass constrained fit. The $\pi^0$ reconstruction efficiency is
When multiple candidates are found in an event, the best candidate is selected as follows: If there is at least one charged kaon or pion that forms the $X_s$ vertex with the constraint from the run-by-run determined profile of the $B$ meson decay vertices [8], the candidate with the largest vertex confidence level is chosen. The candidate with the largest $\theta_{Xs\gamma}$ is chosen in the following cases: (1) there is no charged kaon or pion to form the vertex; (2) there remains an ambiguity whether to add a $\pi^0$; or (3) there are several $\pi^0$ and $K^0_S$ candidates to choose from. After selecting the best candidate, we require $M_{Xs} < 2.05 \text{ GeV}/c^2$.

The largest background source is from continuum $q\bar{q}$ production where the photon originates from initial state radiation or from high momentum neutral hadron decays such as $\pi^0 \to \gamma\gamma$ with one undetected photon. In order to reduce and estimate the contribution of the $q\bar{q}$ background, we introduce a new variable that exploits the topological difference between the jet-like $q\bar{q}$ events and the spherical $B\bar{B}$ events. We define the following variables in the $B$ meson rest frame,

$$R_l = \frac{\sum_i |p_i| |p_{\gamma}| P_l(\cos \theta_{ij})}{\sum_i |p_i| |p_{\gamma}|}, \quad r_l = \frac{\sum_{i,j} |p_i| |p_j| P_l(\cos \theta_{ij})}{\sum_{i,j} |p_i| |p_j|},$$

where $P_l$ is a Legendre polynomial of order $l$, and $i, j$ run over all the photons and charged tracks that are not used to form the $B$ candidate. Then, we combine six of them into a Fisher discriminant

$$F = \sum_{l=2,4} \alpha_l R_l + \sum_{l=1,2,3,4} \beta_l r_l,$$

where the six coefficients $\alpha_l$ and $\beta_l$ are optimized to maximize the discrimination between signal and background as shown in Fig. 1. The terms $R_1$ and $R_3$ are excluded from the Fisher discriminant, because either of these terms is found to have a correlation with $M_{bc}$. We call $F$ the Super Fox-Wolfram (SFW) variable, since the terms are combined in such a way as to enhance the discriminating power of the original Fox-Wolfram moments [9]. We select events with $F > 0.1$, which is a compromise between the statistical significance of the signal and the size of the systematic error due to background subtraction. In order to estimate the $q\bar{q}$ background contribution, we use the SFW sideband region of $F < -1.5$, where the signal fraction is only $(0.7 \pm 0.2)\%$. This translates into a contribution of $0.7 \pm 0.2$ events in the signal region.

In addition to the $q\bar{q}$ background, there is a contribution from $b\to c$ decays, in which $B\to D^{(*)}\rho$ modes are dominant. This background, which does not
contribute to the SFW sideband, is estimated by MC to be $9.1 \pm 1.8$ events and is subtracted from the data sample.

The signal yield is obtained from the $M_{bc}$ distribution (Fig. 2). In Fig. 3 we show that the ratio between the number of events in the signal region and in the sideband of the SFW variable is independent of the beam constrained mass $M_{bc}$ according to a MC calculation assuming continuum $q\bar{q}$ production. This observation is consistent with the background estimated using the off-resonance data. Thus, the SFW sideband data can be used to model the background shape of the $M_{bc}$ spectrum in the absence of a substantial sample of off-resonance data. We fit the $M_{bc}$ distribution with a background shape taken from the SFW sideband data and a signal shape obtained from MC simulation.

We observe 222 events in the signal region $M_{bc} > 5.27$ GeV/$c^2$, of which $115.5 \pm 7.7$ is the estimated background contribution, and is consistent with the MC expectation. An excess of $106.5 \pm 16.8$ events is clearly seen in the $M_{bc}$ distribution shown in Fig. 2 at the $B$ meson mass with a mass resolution of 4.4 MeV/$c^2$ and a signal-to-background ratio of 0.9.

To obtain the background subtracted recoil mass spectrum shown in Fig. 4, we use the shape of the $M_{X_s}$ spectrum determined from MC, whose contribution is normalized to the estimated background of the $M_{bc}$ distribution. We adopt this method because the ratio between the number of signal events and SFW sideband events has a finite slope as a function of $M_{X_s}$, especially in the region $M_{X_s} > 2.05$ GeV, and thus the SFW sideband does not properly represent the background sample for the $M_{X_s}$ spectrum [10]. Nevertheless, the slope in the $M_{X_s} < 2.05$ GeV region is small and compatible with a flat distribution within the statistical fluctuation, and the background subtraction method using the SFW sideband sample leads to consistent results for the $M_{X_s}$ spectrum and the $B \to X_s \gamma$ branching fraction.

The signal MC sample is generated as a mixture of the exclusive $B \to K^*(892)\gamma$ mode and an inclusive $B \to X_s \gamma$ contribution for $M_{X_s} > 1.15$ GeV/$c^2$ in order to separate the $K^*(892)$ signal from higher resonances starting with $K_1(1270)$. The recoil system $X_s$ is modelled as an equal mixture of $\bar{s}d$ and $\bar{s}u$ states [6]. To simulate the inclusive $M_{X_s}$ spectrum, we adopt the model by Kagan and Neubert [11] with the $b$ quark pole mass parameter $m_b = 4.75$ GeV/$c^2$.

The fraction of $K^*(892)\gamma$ decays in the $B \to X_s \gamma$ transition, $r_{K^*\gamma}$, is determined from the $M_{X_s}$ spectrum with a consideration of the migration effects on the reconstructed $M_{X_s}$ due to incorrect particle assignments to the $X_s$ final state. The $M_{X_s}$ spectrum is divided into two regions: the $K^*(892)$ region below 1.15 GeV/$c^2$ and the continuum region between 1.15 GeV/$c^2$ and 2.05 GeV/$c^2$. The MC sample is analyzed to determine the number of events
migrating between the regions. The MC results are used to unfold the migration effects and to generate a set with an improved value, \( r_{K^*\gamma} = (11.3 \pm 3.5)\% \). Using the new MC sample, the procedures of \( M_{bc} \) fitting, \( M_{X_s} \) background subtraction, and \( r_{K^*\gamma} \) unfolding are iterated. It is checked that \( r_{K^*\gamma} \) is stable under the iteration. The size of the migration effects and the value of \( r_{K^*\gamma} \) depend on the assumed \( m_b \) value: for \( m_b = 4.75 \text{ GeV}/c^2 \), 77\% of the events reconstructed below 2.05 GeV/c\(^2\) are genuine and 23\% are from the region above 2.05 GeV/c\(^2\). We note that due to a non-negligible amount of migration between the regions below and above 2.05 GeV/c\(^2\), this boundary does not correspond to a sharp value in \( M_{X_s} \) or \( E_\gamma \).

According to the authors of ref. [11], the \( K^*(892) \) contribution can be approximated by integrating the \( M_{X_s} \) spectrum up to a threshold mass above the \( K^*(892) \) mass, though their model does not explicitly take resonance contributions into account. This integral is sensitive to the parameter \( m_b \). To match the measured \( K^*(892) \) fraction we varied \( m_b \) and the threshold mass and observed that \( m_b \geq 4.9 \text{ GeV}/c^2 \) is disfavored. We use \( m_b = (4.75 \pm 0.10) \text{ GeV}/c^2 \) as the parameter region to test the model dependence of the branching fraction measurement [12]. We assume a somewhat larger error on \( m_b \) than that used for the semileptonic \( B \) meson decays in the combined LEP, SLD and CDF evaluation [13] based on the recent theoretical work of [14], in which \( m_b(1 \text{ GeV}) = (4.58 \pm 0.06) \text{ GeV}/c^2 \) is quoted. We note that the corresponding pole mass is \( m_b \approx 4.70 \text{ GeV}/c^2 \). Other theoretical input parameters have little impact on the shape of the \( M_{X_s} \) spectrum.

The event selection efficiency is determined from a MC sample that is calibrated with high statistics control data samples for all final state particles. The reconstruction efficiency for the primary photon is obtained using photons with energies between 2 and 3 GeV from the processes \( e^+e^-\rightarrow e^+e^-\gamma \) and \( \eta\rightarrow\gamma\gamma \). The charged tracking efficiency for momenta relevant to this analysis is obtained by comparing the high momentum \( \eta \) yields for the \( \eta\rightarrow\pi^+\pi^-\pi^0 \) and \( \eta\rightarrow\gamma\gamma \) decay modes. The kaon selection efficiency is determined from a sample of \( \phi\rightarrow K^+K^- \) and \( D_s\rightarrow\phi\pi \) decays. The pion rejection efficiency is also determined from the \( \eta\rightarrow\pi^+\pi^-\pi^0 \) sample. The \( K_S^0 \) and \( \pi^0 \) efficiencies are tested with a sample of \( K^*(892) \) decays into \( K^+\pi^-, K^+\pi^0, K_S^0\pi^+ \) and \( K_S^0\pi^0 \). Combining all 16 different channels, the selection efficiency becomes \( (12.8 \pm 1.3)\% \). The \( M_{X_s}, \text{SFW} \) and \( M_{bc} \) cuts reduce the efficiency by \( (57 \pm 2)\% \), \( (50 \pm 3)\% \) and \( (70 \pm 1)\% \), respectively. The SFW cut and the \( \pi^0/\eta \) veto efficiencies are measured by applying the cuts on a sample of exclusively reconstructed \( B^-\rightarrow D^0\pi^- \), \( D^0\rightarrow K^-\pi^+ \) decays, in which the first pion is assumed to be massless in order to mimic the primary photon for the cuts. The size of the systematic error from the efficiency determination is dominated by the statistical error of the control sample. The final event reconstruction efficiency is \( (2.58 \pm 0.29)\% \).
The total systematic error is quoted as a quadratic sum of the systematic errors on the efficiency, the best candidate selection procedure, signal MC statistics, SFW sideband uniformity and the number of $B\bar{B}$ events. The sensitivity of the cuts to the experimental error on the beam constrained mass $M_{bc}$ is tested by changing the MC resolution function, and the effect is found to be negligible. The efficiency errors on the 16 different final states are calculated individually and are then combined. The best candidate selection is tested with a $B^+\rightarrow D^0\pi^-$ sample, which is analyzed using the inclusive reconstruction method of this analysis. The effect of the SFW sideband uniformity is tested by adding a slope to the background distribution within the tolerance level of Fig. 3. The contributions to the systematic error on the branching fraction are given in Table 1.

The fitted signal yield is extrapolated over the entire $M_{Xs}$ region using the model of ref. [11] with $m_b = 4.75$ GeV/$c^2$ and corrected for the final states that are not reconstructed. The analysis is repeated for $m_b = 4.65$ GeV/$c^2$ and 4.85 GeV/$c^2$ to test the model uncertainty. The signal efficiency is found to be 15% lower and 16% higher, respectively. This error and the error of $r_{K^*\gamma}$, which typically corresponds to 5.0% in the branching fraction calculation, are combined into the theoretical model error.

Finally, we obtain the branching fraction of $B\rightarrow X_s\gamma$,

$$Br(B\rightarrow X_s\gamma) = (3.36 \pm 0.53\,(stat) \pm 0.42\,(sys)^{+0.50}_{-0.54}(th)) \times 10^{-4}$$

where the first error is statistical, the second is systematic and the third is the theoretical model error. Using the values of the measured $B\rightarrow X_s\gamma$ branching fraction and the fraction of the $K^*(892)\gamma$, we find the $B \rightarrow K^*(892)\gamma$ branching fraction to be $(3.8 \pm 0.9) \times 10^{-5}$ (statistical error only), which is consistent with the $B \rightarrow K^*(892)\gamma$ branching fraction measurements from CLEO [15] and a separate Belle analysis [16]. In Fig. 5 we show the measured photon spectrum in which the background is subtracted and the efficiency loss due to the cut on $M_{Xs}$ is corrected by using MC input. This spectrum may be compared with model calculations.

To summarize, we have measured the inclusive branching fraction of $B\rightarrow X_s\gamma$ decay with the Belle detector. The result is consistent with the SM prediction of $Br(B\rightarrow X_s\gamma) = (3.28 \pm 0.33) \times 10^{-4}$ [1]. The result is also consistent with previous measurements by the CLEO [17] and ALEPH [18] experiments.

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Table 1
The contributions to the systematic error on the branching fraction.

| Contribution                                      | Error |
|---------------------------------------------------|-------|
| Photon reconstruction                             | ±5.3% |
| Charged track reconstruction                       | ±4.7% |
| Charged kaon selection                             | ±1.8% |
| Charged pion selection                             | ±1.1% |
| $K^0_S$ reconstruction                             | ±1.2% |
| $\pi^0$ reconstruction                             | ±3.1% |
| SFW efficiency and $\pi^0/\eta$ veto              | ±6.8% |
| Best candidate selection                           | ±2.4% |
| SFW sideband uniformity                            | ±4.7% |
| Signal MC statistics                               | ±3.0% |
| Number of $B\bar{B}$ events                        | ±2.3% |
| **Total systematic error**                         | ±12.4%|

Fig. 1. The distribution of the SFW variable described in the text. The off-resonance background background data (solid circles) and the $qq$ MC expectation (open histogram) are compared with the signal distribution of $B\to D\pi$ data (open circles) and signal MC (hatched histogram).
Fig. 2. The beam constrained mass ($M_{bc}$) distribution (a) compared with the total background $q\bar{q}$ and $b\rightarrow c$ (open histogram); (b) after background subtraction compared with the signal MC expectation (hatched histogram).

Fig. 3. The ratio of the background events in the SFW signal region to the sideband region as a function of $M_{bc}$ from the $q\bar{q}$ MC (solid circles) and off-resonance data (open circles).
Fig. 4. The recoil mass ($M_{X_s}$) distribution after background subtraction compared with the signal MC expectation (hatched histogram).

Fig. 5. The photon energy spectrum, background subtracted and corrected for the cut-off on $M_{X_s}$. The data points are compared with signal MC expectations for three different values of $m_b$. 