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Evidence for  $b \rightarrow d \gamma$  transitions from a sum of exclusive final states in the hadronic final state mass range  $1.0 \text{ GeV}/c^2 < M(X_d) < 1.8 \text{ GeV}/c^2$

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**Evidence for  $b \rightarrow d\gamma$  Transitions From a Sum of Exclusive Final States in the Hadronic Final State Mass Range  $1.0 \text{ GeV}/c^2 < M(X_d) < 1.8 \text{ GeV}/c^2$ .**

The *BABAR* Collaboration

December 23, 2013

**Abstract**

We present preliminary results of a search for  $B \rightarrow X_d\gamma$  decays with a hadronic mass  $1.0 \text{ GeV}/c^2 < M(X_d) < 1.8 \text{ GeV}/c^2$ . We consider seven final states with up to four charged pions and one neutral pion or  $\eta$ , which correspond to about 50% of the total  $X_d$  fragmentation in this mass range. Based on a sample of 383 million  $B\bar{B}$  events collected by the BaBar experiment at PEP-II, we measure a partial branching fraction  $\sum_{X_d=1}^7 \mathcal{B}(B \rightarrow X_d\gamma)|_{(1.0 \text{ GeV}/c^2 < M(X_d) < 1.8 \text{ GeV}/c^2)} = (3.1 \pm 0.9_{-0.5}^{+0.6} \pm 0.5) \cdot 10^{-6}$ , where the uncertainties are statistical, systematic and model-dependent respectively.

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# 1 INTRODUCTION

We present an experimental study of the rare decays  $B \rightarrow X_d \gamma$ . Within the standard model of particle physics (SM), these flavor-changing-neutral-current (FCNC)  $b \rightarrow d \gamma$  transitions are forbidden at tree level; the leading-order processes are one-loop electroweak penguin diagrams (see Figure 1), where the top quark is the dominant virtual quark contribution. In the context of theories

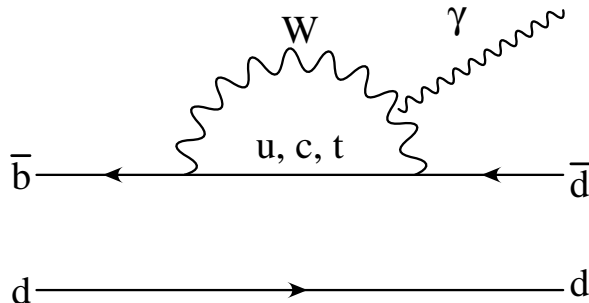


Figure 1: Feynman diagram for a  $\bar{b} \rightarrow \bar{d} \gamma$  transition

beyond the SM, new virtual particles may appear in the loop, which could lead to measurable effects on experimental observables such as branching fractions and  $CP$  asymmetries [1].

Previous measurements of the exclusive decays  $B^+ \rightarrow \rho^+ \gamma$ ,  $B^0 \rightarrow \rho^0 \gamma$ , and  $B^0 \rightarrow \omega \gamma$  by the Belle [2] and *BABAR* [3] experiments found branching fractions of  $\mathcal{O}(10^{-6})$ , in good agreement with SM predictions [5]. In combination with the well-measured  $B \rightarrow K^* \gamma$  branching fractions they also yielded measurements of the ratio of Cabbibo-Kobayashi-Maskawa (CKM) matrix elements  $|V_{td}/V_{ts}|$  which are in good agreement with results independently obtained from the ratio of  $B_d^0$  and  $B_s^0$  mixing frequencies [4].

The experimental and theoretical uncertainties associated with the exclusive measurements are still large and there is a strong motivation to extend the experimental study to additional final states and different regions of the hadronic mass spectrum, with a measurement of the inclusive  $b \rightarrow d \gamma$  transition rate as the ultimate goal. In this note we report the first study of  $b \rightarrow d \gamma$  transitions using a sum of seven exclusive  $X_d \gamma$  final states in the previously unaccessed hadronic mass range  $1.0 \text{ GeV}/c^2 < M(X_d) < 1.8 \text{ GeV}/c^2$ .

## 2 THE *BABAR* DETECTOR

The data used in this analysis were collected with the *BABAR* detector at the PEP-II asymmetric-energy  $e^+ e^-$  storage ring. Charged particle trajectories are measured using a five-layer silicon vertex tracker and a 40-layer drift chamber in a 1.5-T magnetic field. Photons and electrons are detected in a CsI(Tl) crystal electromagnetic calorimeter (EMC) with photon energy resolution  $\sigma_E/E = 0.023(E/\text{GeV})^{-1/4} \oplus 0.019$ . A ring-imaging Cherenkov detector (DIRC) is used for charged-particle identification. In order to identify muons, the magnetic flux return is instrumented with resistive plate chambers and limited streamer tubes. A detailed description of the detector can be found elsewhere [6].

### 3 EVENT RECONSTRUCTION AND SELECTION

We exclusively reconstruct seven  $b \rightarrow d\gamma$  decay modes with up to four charged pions and one neutral pion or eta in the final state:  $B^0 \rightarrow \pi^+\pi^-\gamma$ ,  $B^+ \rightarrow \pi^+\pi^0\gamma$ ,  $B^+ \rightarrow \pi^+\pi^-\pi^+\gamma$ ,  $B^0 \rightarrow \pi^+\pi^-\pi^0\gamma$ ,  $B^0 \rightarrow \pi^+\pi^-\pi^+\pi^-\gamma$ ,  $B^+ \rightarrow \pi^+\pi^-\pi^+\pi^0\gamma$ ,  $B^+ \rightarrow \pi^+\eta\gamma$  [8].

An important source of background is due to continuum events ( $e^+e^- \rightarrow q\bar{q}$ , with  $q = u, d, s, c$ ) that contain a high-energy photon from  $\pi^0$  or  $\eta$  decays or from initial-state radiation. There is also background from combinatorial  $B$  decays. These include  $B \rightarrow X_d\pi^0$  and  $B \rightarrow X_d\eta$  processes that produce a high-energy photon in the  $\pi^0$  or  $\eta$  decay, as well as  $B \rightarrow X_s\gamma$  decays where a  $K^\pm$  is misidentified as a  $\pi^\pm$ . Background suppression cuts have been optimized for maximum statistical sensitivity  $S/\sqrt{(S+B)}$ , where  $S$  and  $B$  are the rates for signal and background events, using Monte Carlo (MC) simulated event samples, and assuming an inclusive  $b \rightarrow d\gamma$  branching fraction of  $1.0 \times 10^{-5}$ . Of particular concern are backgrounds from  $B$  meson decays that resemble the signal.

The photon from the signal  $B$  decay is identified as a localized energy deposit in the calorimeter with energy  $1.15 < E_\gamma^* < 3.5$  GeV in the center-of-mass (CM) frame. The energy deposit must not be associated with any reconstructed charged track, be well isolated from other EMC deposits, and meet a number of additional requirements designed to eliminate background from hadronic showers and small-angle photon pairs. We veto any photons that can form a  $\pi^0$  ( $\eta$ ) candidate by association with another detected photon of energy greater than 30 (250) MeV by requiring that the two-photon invariant mass be outside the range of 105 MeV/ $c^2$ –155 MeV/ $c^2$  (500 MeV/ $c^2$ –590 MeV/ $c^2$ ).

Charged pion candidates are selected from well-reconstructed tracks with a minimum momentum in the laboratory frame of 300 MeV/ $c$ . In order to reduce backgrounds from charged kaons produced in  $b \rightarrow s\gamma$  processes, a  $\pi^\pm$  selection algorithm is applied, combining DIRC information with the energy loss measured in the tracking system. At a typical pion energy of 1 GeV the pion selection efficiency is over 85% and the Kaon mis-identification rate is less than 2%.

$\pi^0$  ( $\eta$ ) candidates are formed from pairs of photons with energies greater than 20 MeV, with an invariant mass  $117 < m_{\gamma\gamma} < 145$  MeV/ $c^2$  ( $470 < m_{\gamma\gamma} < 620$  MeV/ $c^2$ ). We require  $\pi^0$  and  $\eta$  candidates to have a momentum greater than 300 MeV/ $c$ .

The selected  $\pi^\pm$ ,  $\pi^0$ ,  $\eta$ , and high-energy photon candidates are combined to form  $B$  meson candidates consistent with one of the seven signal decays. Here, the charged pions are combined to form a common vertex, where we require the vertex probability be greater than 2%. The mass of the hadronic system is required to be in the range  $1.0 \text{ GeV}/c^2 < M(X_d) < 1.8 \text{ GeV}/c^2$ . We define  $\Delta E \equiv E_B^* - E_{\text{beam}}^*$ , where  $E_B^*$  is the CM energy of the  $B$ -meson candidate and  $E_{\text{beam}}^*$  is the CM beam energy. We also use the beam-energy-substituted mass  $m_{\text{ES}} \equiv \sqrt{E_{\text{beam}}^{*2} - \vec{p}_B^{*2}}$ , where  $\vec{p}_B^*$  is the CM momentum of the  $B$  candidate. Signal events are expected to have a  $\Delta E$  distribution centered at zero with a resolution of about 30 MeV, and an  $m_{\text{ES}}$  distribution centered at the mass of the  $B$  meson,  $m_B$ , with a resolution of 3 MeV/ $c^2$ . We consider candidates in the ranges  $-0.3 \text{ GeV} < \Delta E < 0.2 \text{ GeV}$  and  $m_{\text{ES}} > 5.22 \text{ GeV}/c^2$  to incorporate sidebands that allow the combinatorial background yields to be extracted by a fit to the data.

Contributions from continuum background processes are reduced by considering only events for which the ratio  $R_2$  of second-to-zeroth order Fox-Wolfram moments [7] is less than 0.9. To further discriminate between the jet-like continuum background and the more spherically-symmetric signal events, we compute the angle  $\theta_T$  between the photon and the thrust axis of the rest of the event (ROE) in the CM frame and require  $|\cos(\theta_T)| < 0.8$ . The ROE is defined as all the charged tracks and neutral energy deposits in the calorimeter that are not used to reconstruct the  $B$  candidate.

The quantity  $\cos(\theta_T)$  and twelve other variables that distinguish between signal and continuum events are combined in a neural network (NN):  $R'_2$ , which is  $R_2$  in the frame recoiling against the photon momentum, is used to suppress events with initial-state radiation. We also compute the  $B$ -meson production angle  $\theta_B^*$  with respect to the beam axis in the CM frame, and the Legendre moments  $L_i \equiv \sum_j p_j^* \cdot |\cos \theta_j^*|^i / \sum_j p_j^*$  and  $\tilde{L}_i \equiv \sum_j p_j^* \cdot |\sin \theta_j^*|^i / \sum_j p_j^*$ , where  $p_j^*$  and  $\theta_j^*$  are the momentum and angle with respect to a given axis, respectively, for each particle  $j$  in the ROE. We use  $L_1$  with respect to the ROE thrust axis, as well as  $L_2$ ,  $L_3$ ,  $\tilde{L}_2$ , and  $\tilde{L}_3$  with respect to the high-energy photon direction as NN input. Differences in lepton and kaon production between background and  $B$  decays are exploited by including several flavor-tagging variables described in [10]. We select events for which the NN yields an output value greater than 0.83; this corresponds to signal and continuum background efficiencies of about 50% and 0.5% respectively.

The expected average number of candidates per selected signal event is 1.75. In events with multiple candidates the one with the reconstructed  $\pi^0(\eta)$  mass closest to the nominal [9] is retained. For events containing no  $\pi^0(\eta)$  the candidate with the highest vertex probability is retained.

From simulated signal events with  $1.0 \text{ GeV}/c^2 < M_{X_d} < 1.8 \text{ GeV}/c^2$ , applying all the selection criteria described above, we find an overall signal selection efficiency of 7.5%.

## 4 MAXIMUM LIKELIHOOD FIT

The signal content of the data is determined by means of a two-dimensional unbinned maximum likelihood fit to the  $\Delta E$  and  $m_{\text{ES}}$  distributions. We consider the following contributions: signal, combinatorial backgrounds from continuum and  $B\bar{B}$  background processes,  $B \rightarrow X_d \pi^0/\eta$  decays,  $B \rightarrow X_s \gamma$  decays, and self-crossfeed from mis-reconstructed  $B \rightarrow X_d \gamma$  decays. The likelihood function is defined as

$$\mathcal{L} = \exp \left( - \sum_{i=1}^{N_{\text{hyp}}} n_i \right) \cdot \left[ \prod_{j=1}^{N_{\text{dat}}} \left( \sum_{i=1}^{N_{\text{hyp}}} n_i P_i(\vec{x}_j; \vec{\alpha}_i) \right) \right]. \quad (1)$$

Here,  $n_i$  are the event yields for each of the signal and background hypotheses and  $N_{\text{dat}}$  is the number of events observed in data;  $P_i$  is the probability density function (PDF) for hypothesis  $i$ , which depends on the fit observables  $\vec{x}_j = (\Delta E, m_{\text{ES}})$  and a set of parameters  $\vec{\alpha}_i$ .

The functional form of each PDF is determined from MC simulated events. For the  $B \rightarrow X_d \gamma$  self-crossfeed component we use a binned two-dimensional  $(\Delta E, m_{\text{ES}})$  distribution as the input PDF, while for the other hypotheses we obtain the PDFs from unbinned one-dimensional fits to the  $\Delta E$  and  $m_{\text{ES}}$  distributions respectively. For the signal, the  $m_{\text{ES}}$  spectrum is described by a Crystal Ball function [12], and the  $\Delta E$  distribution is parametrized as an asymmetric, variable-width Gaussian  $f(x) = \exp \left[ -(x - \mu)^2 / (2\sigma_{L,R}^2 + \alpha_{L,R}(x - \mu)^2) \right]$ , where  $\mu$  is the peak position of the distribution,  $\sigma_{L,R}$  are the widths left and right of the peak, and  $\alpha_{L,R}$  are measures of the tails on the left and right sides of the peak. The contributions from  $B \rightarrow X_d \pi^0/\eta$  and  $B \rightarrow X_s \gamma$  decays are both modeled by adding a Gaussian distribution to an ARGUS function [11] for  $m_{\text{ES}}$  and a Gaussian distribution to the second-order polynomial describing the background for  $\Delta E$ . The Gaussian peaks in  $\Delta E$  are displaced by  $\approx 80 \text{ MeV}$  for  $B \rightarrow X_d \pi^0/\eta$  by the missing photon, and by  $\approx 100 \text{ MeV}$  for  $B \rightarrow X_s \gamma$  by the kaon mis-identification. A combined PDF is defined for the remaining  $B$  backgrounds and continuum processes using the sum of a Gaussian and an ARGUS function for  $m_{\text{ES}}$  and a second-order polynomial for  $\Delta E$ . The Gaussian component allows for a small component of  $B$  decays that peaks in  $m_{\text{ES}}$  but not in  $\Delta E$ .

In the likelihood fit the  $m_{\text{ES}}$  ARGUS slope parameter and the  $\Delta E$  polynomial coefficients of the combined background PDF are free parameters, likewise the yields for this background and for the signal. All other fit parameters are fixed to the values obtained from the MC samples.

## 5 VALIDATION OF THE ANALYSIS PROCEDURE

In order to validate the analysis procedure, we embed signal MC events in backgrounds randomly generated from the background PDFs. The embedded events include both the correctly reconstructed and the self-crossfeed signal contributions. For different numbers of embedded signal events we determine the pulls on the yield and the statistical error from the fit. We find a bias in the fitted yield of +24% of the statistical error. We correct the final fit result for this bias and treat it as a systematic error.

To check our analysis on data we select  $B \rightarrow K^*\gamma$  decays, using the  $K^*$  decay modes  $K^{*+} \rightarrow K^+\pi^0$  and  $K^{*0} \rightarrow K^+\pi^-$ . The selection is the same as for the two signal modes  $B^0 \rightarrow \pi^+\pi^-\gamma$  and  $B^+ \rightarrow \pi^+\pi^0\gamma$ , except that the  $\pi^\pm$  identification requirements are replaced with a charged kaon selection, and the mass range is  $0.6 \text{ GeV}/c^2 < M(X_s) < 1.0 \text{ GeV}/c^2$ . In the fit procedure described in the previous section we include a  $B \rightarrow X_s\gamma$  self-crossfeed component and a  $B \rightarrow X_s\pi^0/\eta$  background, but not a  $B \rightarrow X_d\gamma$  misidentification component because this is expected to be negligible.  $B \rightarrow K^*\gamma$  has a large signal yield, so we use this fit to determine the signal shape in data by allowing the means and widths of the signal PDFs to vary. We find  $1680 \pm 51$   $B \rightarrow K^*\gamma$  events in the *BABAR* data, where this error is purely statistical. This is in excellent agreement with the expectation of  $1616 \pm 28$  events based on the previously measured branching fraction of  $\mathcal{B}(B \rightarrow K^*\gamma) = (4.02 \pm 0.33) \times 10^{-5}$  [14].

As a further check on data we perform the signal analysis for the decays  $B^0 \rightarrow \pi^+\pi^-\gamma$ ,  $B^+ \rightarrow \pi^+\pi^0\gamma$ , and  $B^0 \rightarrow \pi^+\pi^-\pi^0\gamma$  in the hadronic mass range  $0.6 \text{ GeV}/c^2 < M(X_d) < 1.0 \text{ GeV}/c^2$ , which contains the  $\rho^0, \rho^\pm$  and  $\omega$  resonances. In this fit we include all the contributions in a similar way to the  $B \rightarrow X_d\gamma$  analysis in the higher mass region, and fix the signal PDF shape to the values obtained from the  $B \rightarrow K^*\gamma$  fit. We obtain a combined  $B \rightarrow (\rho, \omega)\gamma$  signal of  $73 \pm 25$ (stat.) events corresponding to a statistical significance of  $2.9\sigma$ . This is consistent with the  $66 \pm 26$  events expected from the average of previous branching fraction measurements by *BABAR* and Belle of  $\mathcal{B}(B \rightarrow (\rho, \omega)\gamma) = (1.28 \pm 0.21) \times 10^{-6}$  [14]. Note that we do not make use of the resonance mass or the decay helicity angle to discriminate against backgrounds, so we do not expect this measurement to be as precise as the exclusive  $B \rightarrow (\rho, \omega)\gamma$  analyses. Figure 2 shows a comparison of the PDF component shapes (curves) to the data (points).

## 6 RESULTS

Finally we perform the full fit for the sum of all seven decay modes in the hadronic mass range  $1.0 \text{ GeV}/c^2 < M(X_d) < 1.8 \text{ GeV}/c^2$ , again using the signal PDFs from  $B \rightarrow K^*\gamma$ .

Figure 3 shows a comparison of the PDF component shapes (curves) to the data (points). For each plot, a cut is applied to the variable not plotted around the signal peak.

Figure 4 shows a comparison of the PDF shapes (solid curves) to the data using the event-weighting technique described in Ref. [13] to subtract the fitted background. For each plot, we perform a fit excluding the variable being plotted and use the fitted yields and covariance matrix to determine the relative probability that an event is signal or background. The distribution is

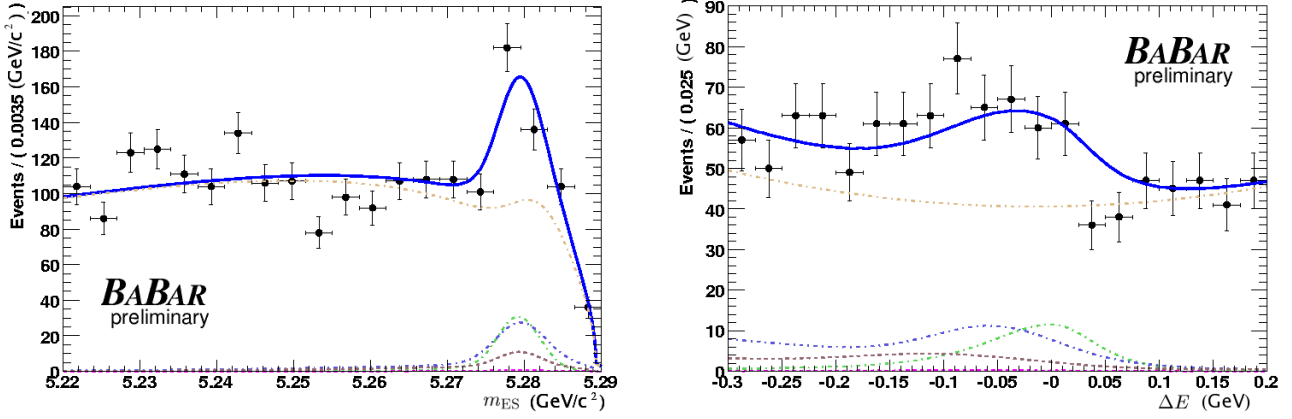


Figure 2: Projections of  $m_{ES}$  with  $-0.1 \text{ GeV} < \Delta E < 0.05 \text{ GeV}$  (left) and  $\Delta E$  with  $5.275 \text{ GeV}/c^2 < m_{ES} < 5.286 \text{ GeV}/c^2$  (right) in the  $B \rightarrow (\rho, \omega)\gamma$  fit to data (points with statistical errors). The curves represent the PDFs used in the fit with the combined PDF in solid blue. The dashed lines represent the individual PDFs with with signal component in green, signal cross-feed in pink,  $b \rightarrow s\gamma$  background in blue,  $B \rightarrow X_d\pi^0/\eta$  background in brown and background in orange.

normalized to the yield for the given component and can be compared directly to the assumed PDF shape. We find good agreement between the data and the PDFs.

We find a signal yield of  $178 \pm 53$  events and a background of  $27670 \pm 173$  events in the full fit. Taking only statistical uncertainties into account, this corresponds to a signal significance of  $3.4\sigma$ . We calculate the partial branching fraction summed over the seven modes in the mass region  $1.0 \text{ GeV}/c^2 < M(X_d) < 1.8 \text{ GeV}/c^2$  using the following formula:

$$\sum_{X_d=1}^7 \mathcal{B}(B \rightarrow X_d\gamma)|_{(1.0 \text{ GeV}/c^2 < M(X_d) < 1.8 \text{ GeV}/c^2)} = \frac{n_{sig}}{2 \epsilon n_{B\bar{B}}}; \quad (2)$$

where  $n_{sig}$  is the number of fitted signal events,  $\epsilon$  is the signal selection efficiency,  $n_{B\bar{B}}$  is the number of  $B\bar{B}$  pairs in the dataset, and the factor 2 is to account for the possibility of either  $B$  decaying into a signal mode. We obtain the following result:

$$\sum_{X_d=1}^7 \mathcal{B}(B \rightarrow X_d\gamma)|_{(1.0 \text{ GeV}/c^2 < M(X_d) < 1.8 \text{ GeV}/c^2)} = [3.1 \pm 0.9(stat.)] \cdot 10^{-6}; \quad (3)$$

The relevant systematic uncertainties are discussed below.

## 7 SYSTEMATIC UNCERTAINTIES

Table 1 gives an overview of the contributions to the systematic uncertainties. These are associated with the signal reconstruction efficiency, the modeling of the signal and  $B\bar{B}$  background PDFs in the likelihood fit, and the modeling of the  $B \rightarrow X_d\gamma$  spectrum and the fragmentation of the  $X_d$  system.

The systematic errors affecting the signal efficiency includes uncertainties on tracking, particle identification,  $\gamma$  and  $\pi^0$  reconstruction, the  $\pi^0/\eta$  veto, and the neural network selection. These

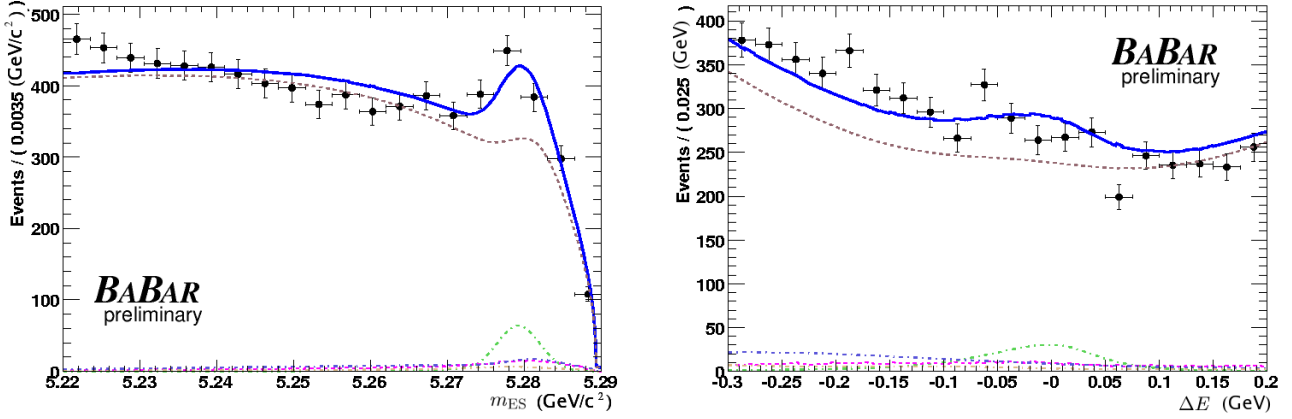


Figure 3: Projections of  $m_{ES}$  with  $-0.1 \text{ GeV} < \Delta E < 0.05 \text{ GeV}$  (left) and  $\Delta E$  with  $5.275 \text{ GeV}/c^2 < m_{ES} < 5.286 \text{ GeV}/c^2$  (right) in the  $b \rightarrow d\gamma$  fit to data. The curves represent the PDFs used in the fit with the combined PDF in solid blue. The dashed lines represent the individual PDFs with with signal component in green, signal cross-feed in pink,  $b \rightarrow s\gamma$  background in blue,  $B \rightarrow X_d\pi^0/\eta$  background in orange and background in brown.

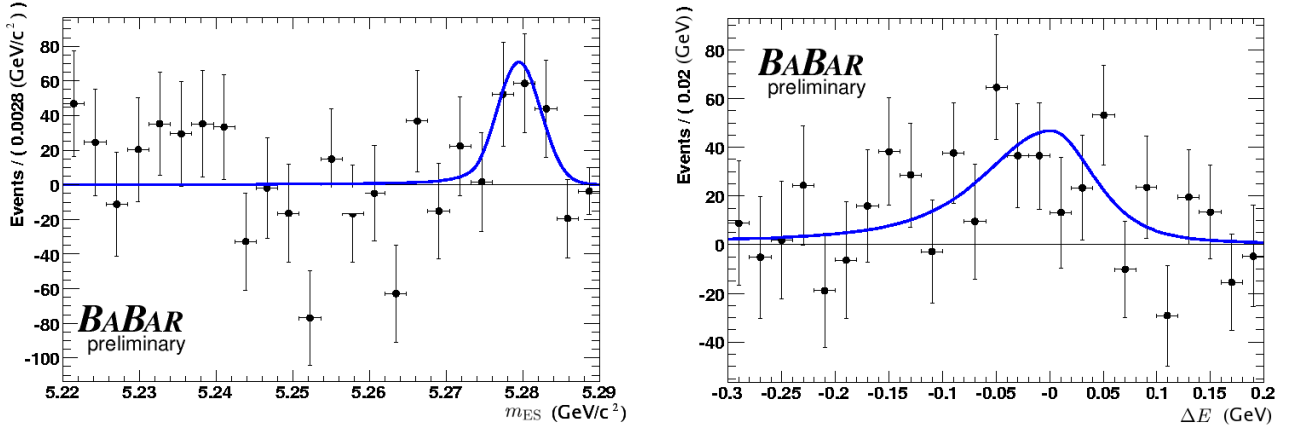


Figure 4: Signal distributions of  $m_{ES}$  (left) and  $\Delta E$  (right) for  $B \rightarrow X_d\gamma$  in the range  $1.0 \text{ GeV}/c^2 < M(X_d) < 1.8 \text{ GeV}/c^2$  with the background subtraction as described in the text. The curves represent the PDFs used in the fit, normalized to the fitted yield.

uncertainties are evaluated using independent data and MC-simulated event samples. They give a combined systematic error of 6.5% when added in quadrature.

To estimate the uncertainties related to the signal and background yields we vary the parameters of the PDFs that are fixed in the fit. For the signal PDF the means and widths are varied within the range allowed by the fit to the  $B \rightarrow K^*\gamma$  data. Other fixed PDF parameters are fluctuated within their statistical errors. The combination gives errors of  $\pm 13\%$  on the signal yield.

All relative and absolute normalizations of background components that are fixed in the fit are also varied. The absolute normalizations of the  $B \rightarrow X_d\gamma$  cross feed,  $B \rightarrow X_s\gamma$ , and  $B \rightarrow X_d\pi^0/\eta$

Table 1: Fractional systematic errors of the measured branching fraction.

Source	Relative uncertainty (%)
Tracking efficiency	1.7
Charged-particle identification	2.0
Photon selection	2.5
$\pi^0$ and $\eta$ reconstruction	1.7
$\pi^0$ and $\eta$ veto	1.0
NN efficiency	5.0
PDF shapes	13.0
$B$ background normalization	+10.5 -3.0
Fit bias	7.1
$B$ counting	1.1
Combined	+19.3 -16.5
Signal model	3.4
$X_d$ fragmentation model	13.6
Combined	14.7

components are changed by  $\pm 50\%$ ,  $\pm 20\%$ , and  $\pm 100\%$  respectively; and the relative contribution of the remaining  $B$  decays to the combined background component is varied by  $\pm 20\%$ . The full size of the bias on the signal yield observed in MC experiments (see Section 5), is taken as a systematic uncertainty of the fit procedure.

There is a small 1.1% uncertainty on the overall normalization associated with the the total number of  $B\bar{B}$  pairs in the underlying data sample.

The impact of the assumed  $X_d$  spectrum on the efficiency is studied by using two different sets of values for the kinetic parameters of the Kagan-Neubert model [15]  $(m_b, \mu_\pi^2) = (4.65, -0.50)$  and  $(4.80, -0.35)$ . These are consistent with fits of  $B \rightarrow X_s \gamma$  data [16]. The default fragmentation model for the  $X_d$  is JETSET [17], known not to give a good description of the distribution of final states in  $B \rightarrow X_s \gamma$  [18]. To estimate the uncertainty associated with the fragmentation model, we re-weight the relative contributions of the seven signal modes according to results obtained in [18] for the corresponding  $B \rightarrow X_s \gamma$  decays, and take the resulting change in the signal yield as a systematic error. Combining these two uncertainties, we assign a systematic error of 14.7/the modeling of the signal.

## 8 SUMMARY

In this paper we have demonstrated the feasibility of measuring  $B \rightarrow X_d \gamma$  decays with a semi-inclusive technique using a sum of seven exclusive final state in the mass range  $1.0 \text{ GeV}/c^2 < M(X_d) < 1.8 \text{ GeV}/c^2$  and presented the first evidence for  $b \rightarrow d \gamma$  transitions in this mass range. We find  $178 \pm 53$  signal events.

We measure a partial branching fraction  $\sum_{X_d=1}^7 \mathcal{B}(B \rightarrow X_d \gamma)|_{(1.0 \text{ GeV}/c^2 < M(X_d) < 1.8 \text{ GeV}/c^2)} =$

$(3.1 \pm 0.9_{-0.5}^{+0.6} \pm 0.5) \cdot 10^{-6}$ , where the uncertainties are statistical, systematic and model respectively. Including statistical and systematic uncertainties only, this corresponds to a signal significance of  $3.1\sigma$ .

## 9 OUTLOOK

In the future, the inclusive  $b \rightarrow d\gamma$  transition rate can be measured. This will require further study to:

- Extend the current measurement to the mass region  $0.6 \text{ GeV}/c^2 < M(X_d) < 1.0 \text{ GeV}/c^2$ , which has been used as a control sample in this analysis with only three decay modes reconstructed. We can measure the seven decay modes over both ranges.
- Correct for the part of the  $X_d$  fragmentation that is not reconstructed by the seven decay modes. Based on MC simulation and the JETSET model we expect the measured seven modes to account for about 50% of the the hadronic mass region  $1.0 \text{ GeV}/c^2 < M(X_d) < 1.8 \text{ GeV}/c^2$ .
- Extrapolate to the full mass region. Assuming the shape of the hadronic mass spectrum is the same for  $b \rightarrow d\gamma$  as for  $b \rightarrow s\gamma$  decays [18], the mass region  $0.6 \text{ GeV}/c^2 - 1.8 \text{ GeV}/c^2$  comprises roughly 60% of the spectrum.

Further, the extraction of the ratio  $|V_{td}/V_{ts}|$  can be performed by comparing the branching fractions for  $b \rightarrow d\gamma$  and  $b \rightarrow s\gamma$  over the experimentally accessible final states and hadronic mass range. By measuring this ratio over a larger hadronic mass range, and with a larger set of final states it should be possible to reduce the theoretical uncertainties compared to the ratio of  $B \rightarrow \rho\gamma$  and  $B \rightarrow K^*\gamma$  decays.

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