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Search for $B \to X_s\phi$ from $b \to s$ gluon transitions.

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Abstract

Using the CLEO II detector, we have searched for evidence of $b \to s$ gluon processes. Such processes can give rise to high momentum ϕ mesons in a range where there is little background from $b \to c$ processes.

Two complementary techniques are used to search for the gluonic penguin processes. Application of the inclusive B-reconstruction technique, which was previously used to obtain a measurement of the inclusive $b \to s\gamma$ rate, yields $\mathcal{B}(B \to X_s\phi) < 1.1 \cdot 10^{-4}$ at the 90 % C.L. for $M_{X_s} < 2$ GeV/c^2. In addition, we have directly examined the continuum-subtracted ϕ momentum spectrum after applying event shape requirements. This method gives $\mathcal{B}(B \to X_s\phi) < 2.2 \times 10^{-4}$ for $2.0 < p_\phi < 2.6$ GeV/c^2 at the 90% confidence level. While the second method suffers from weaker background suppression, it is insensitive

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to the details of the hadronization process associated with production of the high momentum ϕ mesons from $b \to s\bar{s}s$.

I. INTRODUCTION

Experimental evidence for $b \to s$ transitions, which are effective flavor changing neutral currents, was first provided by the CLEO II experiment which observed the exclusive mode $B \to K^*(892)\gamma$. [1] In the Standard Model these decays proceed via the electromagnetic penguin diagram in which a b-quark decays to an s-quark via a loop with a virtual W and an internal t-quark. The photon may be attached to any of the quark lines or to the virtual W. The inclusive rate for these transitions has also been measured by CLEO, $\mathcal{B}(b \to s\gamma) = (2.32 \pm 0.57 \pm 0.35) \times 10^{-4}$ [2].

In the penguin diagram the photon may be replaced by a gluon, giving rise to $b \to sg$ transitions. The inclusive rate for such transitions is expected to be an order of magnitude higher than for electromagnetic penguin transitions. However, most of the final states which can be populated by $b \to sg$ transitions can also be reached by tree diagrams with $b \to uW$, $W \to s\bar{u}$. The decay $B^0 \to K^+\pi^-$ is an example of such a process and some evidence for the existence of it has been found by the CLEO experiment [3]. On the other hand, final states from $b \to sg \to s\bar{s}s$ cannot be reached by tree level processes e.g. $B^0 \to K^0\phi$. Assuming that weak annihilation processes do not play an important role, then the observation of such a process would constitute unambiguous evidence for gluonic penguin transitions. Searches for exclusive rare hadronic decays of B mesons of this type have so far resulted only in upper limits [3]. Examples of these results are given in Table I.

TABLE I. CLEO II Limits on the Branching Fractions for Exclusive Rare Hadronic Decay Modes from Gluonic Penguins.

Mode	Upper Limit
$B^+ \to K^0\pi^+$	$< 4.8 \times 10^{-5}$
$B^0 \to K^0\phi$	$< 8.8 \times 10^{-5}$
$B^+ \to K^+\phi$	$< 1.2 \times 10^{-5}$
$B^0 \to K^{*0}\phi$	$< 4.3 \times 10^{-5}$
$B^+ \to K^{*+}\phi$	$< 7.0 \times 10^{-5}$

In contrast to the case of $b \to s\gamma$, the energy of the gluon from the gluonic penguin is also available in the hadronization process. Many more final states are allowed, and the rate advantage for exclusive modes is lost. The inclusive rate for gluonic penguins will be very difficult to measure because of the absence of a common experimental signature for these decays and because of the backgrounds from the other rare processes mentioned above.

The decay $B \to X_s\phi$, where X_s denotes a particle containing an s quark is the experimental signature of the gluonic penguin, $b \to sg \to s\bar{s}s$. We employ an inclusive measurement of $b \to s\phi$ rather than searching for exclusive signatures of this process. Such an approach has two significant advantages, the inclusive rate may be calculable from first principles and is at least an order of magnitude larger than the rate for any exclusive channel. The experimental signature of these processes is an excess of ϕ mesons with $2.0 < p_\phi < 2.6$ GeV/c^2. This region has little background from ϕ mesons produced by $b \to c$ mechanisms, which produce lower momentum ϕ mesons [7]. The largest difficulty with an inclusive measurement is the large continuum background that must be subtracted or suppressed.

The ϕ meson is formed from the s-quark of the penguin loop and the $\bar{s}$-quark from the gluon splitting, as shown in Fig.1. If the spectator quark is not involved in this process this decay can be treated as the two-body decay of a $b-$quark, $b \to s\phi$. The energy of the ϕ meson is then approximately $m_b/2$. The ϕ meson may play a role analogous to that of the energetic photon in $b \to s\gamma$. Recently, the energy distribution of ϕ mesons from $b \to s\phi$ transitions was calculated by Deshpande, Eilam, He, and Trampetic [5] taking into account spectator quark effects and hard gluon bremsstrahlung as was previously done for $b \to s\gamma$ decays by Ali and Greub [6].

It should be noted that the simple picture described above, which is assumed in the model of Deshpande *et al* [5], in which the formation of the ϕ meson from the penguin diagram is not influenced by the subsequent hadronization of the s-quark and the spectator quark (i.e. factorization hypothesis) may not be valid. Unlike the momentum spectrum of the photon in $b \to s\gamma$, the momentum spectrum for the ϕ meson in $b \to s\phi$ can be modified by the hadronization of the other quarks. For example, a sizeable quasi-three body contribution is observed for both inclusive $B \to X_c D_s$ and $B \to X_s \psi$ decays. The factorization assumption may work better for the case of the $B \to X_s\phi$ meson since the energy release and velocity are larger in this case. In addition, other gluonic penguin diagrams in which a $s - \bar{s}$ quark pair is popped from the vacuum may be more relevant than the diagram shown in Fig. 1.

Because of the uncertainty in the hadronization of $\mathcal{B}(b \to s$ gluon), we separate the experimental task of searching for ϕ's from quasi-two body decays and the theoretical problems of extrapolating from the experimental limit to the total $b \to s\phi$ and $b \to s$ gluon rates.

II. EXPERIMENTAL ANALYSES

In the sections which follow, we describe two techniques used for the search for $B \to X_s\phi$: the B reconstruction analysis and an inclusive ϕ search.

The data samples comprise an integrated luminosity of 2.4 fb^{-1} on the Υ(4S) resonance and 1.2 fb^{-1} off the resonance. This corresponds to approximately 2.6×10^6 produced $B\bar{B}$ pairs.

A. B Reconstruction Analysis

In the B reconstruction analysis, B meson candidates are formed from combinations of a ϕ, a kaon, and additional pions. No attempt is made to identify the various individual decay modes, which in this method, cross feed into each other. Instead, the goal is to find combinations consistent with B decay in order to dramatically suppress the large non-$B\bar{B}$ background.

Hadronic events which are approximately spherical are selected by requiring $R_2 < 0.45$. The quantity R_2 is the ratio of the second to zeroth Fox-Wolfram moments [4].

In each event, the most energetic K^+K^- combination within the mass window $|M_{K^+K^-} - M_\phi| < 20$ MeV/c^2 is then selected. This mass window allows for the ϕ signal region and side-bands. The momentum of the combination must be greater than 1.5 GeV/c^2. The charged tracks which are considered as $K^\pm$ candidates must be well measured, lie in the central part of the detector, and have specific ionization in the drift chamber (dE/dx) consistent with the kaon hypothesis. Information from the time of flight (TOF system) is not required but is used if it is of good quality. The confidence level for the K candidate in the X_s system must be at least 10%. At least one kaon must have good quality TOF information. The confidence level determined from the particle ID systems for the K^+K^- pair must be at least 10%.

The selected K^+K^- pair is combined with an additional kaon (either $K^\pm$ or $K_s \to \pi^+\pi^-$), and with $0 - 4$ pions to form a B-decay candidate. The set of pion candidates may contain at most one π^0.

In the case of multiple combinations in an event which satisfy the B hypothesis, the combination which minimizes a χ^2 is chosen. The χ^2 includes the beam-constrained mass of the combination, the deviation of the measured energy of the combination from the beam energy, the deviations of the specific ionization and the TOF for the charged tracks from the assumed particle hypotheses, and the mass deviations for K_s and π^0 if involved. Finally, a χ^2 which combines the mass and the energy difference terms (denoted χ^2_B) is constructed. This chisquared must be consistent with the B decay hypothesis with a probability greater 5% (i.e. $\chi^2_B < 6.0$).

Since the event is now separated into the signal B (i.e. $B \to X_s\phi$) and the other B, we can determine the thrust axes for each part of the event separately. For continuum background, the axis for the candidate B meson and the axis for the remainder of the event tend to be collinear since fake B candidates are produced by back-to-back jets. For signal events, however, the two axes are uncorrelated since $B\bar{B}$ pairs are produced nearly at rest at the $\Upsilon(4S)$ resonance. We impose the requirement $|\cos\theta_{TT}| < 0.6$ where θ_{TT} is the angle between the two thrust axes. Since the polar angle of B mesons produced from Υ(4S) decay follows a $\sin^2\theta_B$ distribution, we require $|\cos(\theta_B)| < 0.85$, where θ_B is the angle with respect to the beam axis.

Since the boost from the B rest frame to the laboratory frame smears the energy of the ϕ meson but does not modify the effective mass of the X_s system, we cut on M_{X_s} rather than p_ϕ; the B reconstruction analysis is restricted to the region with $M_{X_s} < 2$ GeV/c^2, where backgrounds are small. This region contains about 90% of the total $B \to X_s\phi$ rate according to the recent calculation by Deshpande *et al* ($P_F = 300$ MeV/c^2) [5]. This cut on M_{X_s} corresponds roughly to the requirement $p_\phi > 2.13$ GeV/c^2.

The $M_{K^+K^-}$ invariant mass distributions for the on- and off-resonance data are shown in Fig. 2. For the purpose of an upper limit calculation, we can determine the upper limit on the yield by event counting. For $|M_{K^+K^-} - M_\phi| < 10$ MeV/c^2 we find 21 on-resonance events and 13 off-resonance events. The continuum subtracted yield is -5.8 ± 8.8 events which corresponds to an upper limit of 11.4 events at 90% C.L. We have also fitted the ϕ mass peak in both samples and then computed the upper limit by integrating the resulting likelihood function in the physically allowed region. This gives an upper limit of < 9.5 events (in the $|M_{K^+K^-} - M_\phi| < 10$ MeV/c^2 range). Since the first method gives the more conservative upper limit, it is used for the final result.

From the Monte Carlo simulation we estimate that possible bias in the continuum background subtraction using off-resonance data is 0.4 ± 0.5 events. This correction has been included in the yields given above. To further check the continuum subtraction, some of the cuts are relaxed to increase the amount of continuum in the sample. A clear ϕ signal is then observed in both on-resonance and off-resonance data as shown in Fig. 3. The number of events in the ϕ peak region increases by a factor of 36. After continuum subtraction (including the bias correction) we obtain 19 ± 53 events. This corresponds to a correction of 0.5 ± 1.5 events, after scaling to the nominal cuts by a factor of 1/36. This result confirms, using data, that the continuum background can be properly subtracted using the off-resonance data without introducing a bias.

TABLE II. Efficiency, ϵ, for different MC data sets for events generated with $M_{X_s} < 2.0$ GeV/c^2.

Resonance or Model	ϵ %
K	10.2 ± 0.4
$K^*(892)$	7.3 ± 0.4
$K^*(1270)$	4.4 ± 0.2
$K_1(1400)$	4.7 ± 0.3
$K_1^*(1410)$	5.1 ± 0.3
$K_2^*(1430)$	5.9 ± 0.3
$K_0^*(1430)$	7.3 ± 0.4
$K(1460)$	5.0 ± 0.3
$K^*(1680)$	6.2 ± 0.4
$K_2(1770)$	3.8 ± 0.3
$K_3^*(1780)$	4.9 ± 0.3
$K_4^*(2045)$	3.9 ± 0.3
Average$\pm$RMS	5.7 ± 1.7
Davies *et al.* [8]	5.2 ± 0.1
Deshpande *et al.* [5] $p_F = 300$ MeV/c	5.0 ± 0.2

To estimate the efficiency several complementary approaches were followed. In one approach we assume that X_s is one of the $s\bar{q}$ resonances listed in Table II. A separate Monte Carlo sample is generated for each resonance. We calculate an efficiency averaged over all resonances or use weights predicted by the phenomenological calculations by Davies *et al.* [8] In a complementary approach we use predictions of Deshpande *et al* (with $p_F = 300$ MeV/c^2) for the inclusive E_ϕ spectrum in $B \to X_s \phi$ decays. The recoiling hadronic system, X_s, consisting of a strange and light spectator quarks, $s\bar{q}$, is hadronized by the JETSET 7.3 program, tuned to reproduce the CLEO continuum data. This model necessarily predicts smooth p_ϕ and M_{X_s} spectra averaged over possible resonances and does not contain a contribution from $B \to K\phi$. Since, the efficiency for this mode is significantly larger than for the other modes, we supplemented the inclusive model of Deshpande et al with a 6% contribution from $B \to K\phi$.

We factorize the overall efficiency into the fraction of the inclusive spectrum with M_{X_s} below 2.0 GeV/c^2, and reconstruction efficiency for events in the selected mass range. The latter efficiency for a variety of modes, is given in Table II. The values do not include $\mathcal{B}(\phi \to K^+K^-) = (49.1 \pm 0.9)\%$. The lowest efficiency is predicted by the inclusive model. We use this value, $(5.0 \pm 0.2)\%$, for the upper limit calculation. This accounts for the systematic error due to the multiplicity dependence of the signal efficiency.

There is a 4% error per charged track for tracking, dE/dX and TOF systematics. For K_s (π^0) finding we assign a systematic uncertainty of 8% (5%). There is an additional 7% systematic error for the event selection efficiency. Thus, the total systematic error on the reconstruction efficiency is estimated to be 20%. In the calculation of the upper limit we decrease the efficiency by one standard deviation.

The upper limit for the $\mathcal{B}(B \to X_s\phi)$ within the $M_{X_s} < 2$ GeV/c^2 range is 1.1×10^{-4} at the 90% confidence level.

The extrapolation to the full M_{X_s} range is somewhat model dependent as discussed in the introduction. According to the model of Deshpande, Eilam, He and Trampetic [5] the fraction of the spectrum within our mass cut is 95, 88, 77% for P_F =210, 300, 390 MeV/c^2, respectively. From the fits to the CLEO $B \to Xl\nu$ data, the value $P_F = 270 \pm 40$ MeV/c^2 is obtained. [2] Interpolating the results of the model calculations to $p_F = 270 \pm 40$ MeV/c^2 we estimate that $(90.6^{+3.1}_{-3.8})\%$ of the rate is within our cut. Allowing for the uncertainty in this fraction, we obtain the upper limit $\mathcal{B}(B \to X_s\phi) < 1.3 \times 10^{-4}$ at 90% C.L.

This limit is consistent with the theoretical predictions of Deshpande et al $(0.6-2.0)\times 10^{-4}$ [9] but it excludes most of the upper half of the predicted range.

B. Inclusive Method

A totally inclusive analysis is performed in terms of the scaled momentum

$$x = \frac{p_\phi}{\sqrt{E^2_{beam} - m^2_\phi}}$$

to allow the continuum data taken below $B\bar{B}$ threshold to be scaled and subtracted correctly. The signal region is $0.4 < x < 0.5$ while the range $0.5 < x < 0.9$ is used for a consistency check. After continuum subtraction, no signal should be observed for $x > 0.5$.

Pairs of oppositely charged kaon candidates are combined with the same track quality selection as before. All the available information from both the TOF and dE/dx systems is combined as in the B reconstruction analysis. Each kaon candidate is required to have a probability of being a kaon that is greater than 10%. The pion probability for each candidate should be less than 90%. These particle identification requirements are about 97% efficient for two body $B \to X_s\phi$ exclusive modes. A loose shape cut, $R_2 < 0.5$, reduces continuum background but at the same time avoids the introduction of model dependence.

The resulting K^-K^+ mass spectrum is fitted with a sum of a phase space function $a(M - M_0)^{1/2} + b(M - M_0)^{3/2}$ and a Breit-Wigner convoluted with a Gaussian for the signal as shown in Fig. 4. The Gaussian resolution is fixed from the Monte Carlo simulation to be 1.6 MeV/c^2. We find $N_{excess} = -57 \pm 298$ events or $N_{excess} < 345$ events at the 90% confidence level. A number of variations on the fitting procedure have been tried. These include adding a $(M - M_0)^{5/2}$ term to the fit. This changes the yield to -60 ± 278. Changing the bin size by a factor of two, we find -88 ± 327 events. Excluding the region from $1.07 - 1.1$

GeV/c^2, where the reflection from misidentified $K^{*0} \to K^+\pi^-$ may be present, changes the yield to -42 ± 331 events. Another approach is to fit the yields from the on-resonance and continuum spectra separately. This gives $N_{4s} = 8601 \pm 176$ and $N_{cont} = 4109 \pm 124$ or an excess after continum subtraction of $N_{signal} = -8 \pm 304$ (the region $1.07 < M_{K^+K^-} < 1.1$ GeV/c^2 has been excluded for these fits). All of these are consistent with the primary result, the fit to the continuum-subtracted spectrum. In addition, we find no significant excess or deficit in the control region as shown in Fig. 5, [7].

The detection efficiency is 68% nearly independent of the decay mode,as shown in Table III provided the decay mode produces ϕ mesons in the range $0.4 < x < 0.5$ ($2.0 - 2.5$ GeV/c^2). As in the B reconstruction analysis, to calculate the upper limit we use the detection efficiency determined from the model of Deshpande *et al.* [5]

TABLE III. Detection efficiency, ϵ, for decay modes and hadronization models. The values in parentheses are the efficiencies including the fraction that pass the x_ϕ cut.

Resonance or Model	ϵ %	
$K/K^*(892)$	61 ± 1	
$K^*(1270)$	66 ± 1	
$K_2^*(1430)$	63 ± 1	
$K(1460)$	68 ± 1	
$K_3^*(1780)$	67 ± 1	(60)
$K_4^*(2045)$	70 ± 1	(41)
Davies *et al.* [8]	68 ± 1	
Three-body $B_q \to \phi s\bar{q}$ phase space MC with JETSET hadronization of $s\bar{q}$	74 ± 3	(10)
Deshpande *et al.* [5] $p_F = 300$	68 ± 1	(60)

There is an 8% systematic uncertainty in the yield due to the uncertainties in background parameterization and efficiency. Taking this systematic uncertainty into account, the limit is $\mathcal{B}(B \to X_s\phi) < 2.2 \times 10^{-4}$ at the 90% confidence level for $0.4 < x_\phi < 0.5$. This limit is insensitive to the details of the $b \to s\phi$ hadronization. In the model of Deshpande et al., for $p_F = 270 \pm 40$ MeV/c^2, the interval $0.4 < x_\phi < 0.5$ contains $(96.5^{+1.3}_{-2.1})$% of the total rate. Using this model, a limit on the total rate of $\mathcal{B}(B \to X_s\phi) < 2.3 \times 10^{-4}$ at the 90% C.L. is obtained.

III. CONCLUSIONS

We have searched for quasi-two body $B \to X_s\phi$ decays using a sample of about 2.6×10^6 $B\bar{B}$ pairs collected with the CLEO II detector. These decays are the signature of $b \to sg \to s\bar{s}s$ transitions. The $B \to X_s\phi$ modes can be searched for using two methods. Using the B reconstruction analysis, we find an upper limit of $\mathcal{B}(B \to X_s\phi) < 1.1 \times 10^{-4}$ at the 90% confidence level for $M_{X_s} < 2.0$ GeV/c^2. In the model of Deshpande et al., this corresponds to an upper limit on the total rate of $\mathcal{B}(B \to X_s\phi) < 1.3 \times 10^{-4}$

We have also directly examined the ϕ momentum spectrum in order to reduce the dependence of the limit on details of the $B \to X_s\phi$ hadronization model, we find an upper limit

$\mathcal{B}(B \to X_s\phi) < 2.2 \times 10^{-4}$ at the 90% confidence level for $0.4 < x_\phi < 0.5$. This is consistent with the result of the B reconstruction analysis. In addition, there is no significant excess or deficit in the control region. In the model of Deshpande *et al.*, this method gives a less stringent limit on the total rate of $\mathcal{B}(B \to X_s\phi) < 2.3 \times 10^{-4}$ at the 90% confidence level.

Unfortunately, there is no calculation of the ratio $\mathcal{B}(B \to \phi X_s)/\mathcal{B}(B \to X_s$ gluon) . Thus, at present, more theoretical work is required to rule out possible extensions of the Standard Model involving either supersymmetry or technicolor which have been proposed e.g. by Hou [10] and by A. Kagan [11] with very large $\mathcal{B}(b \to s\ gluon)$. These models do not necessarily modify $\mathcal{B}(b \to s\gamma)$.

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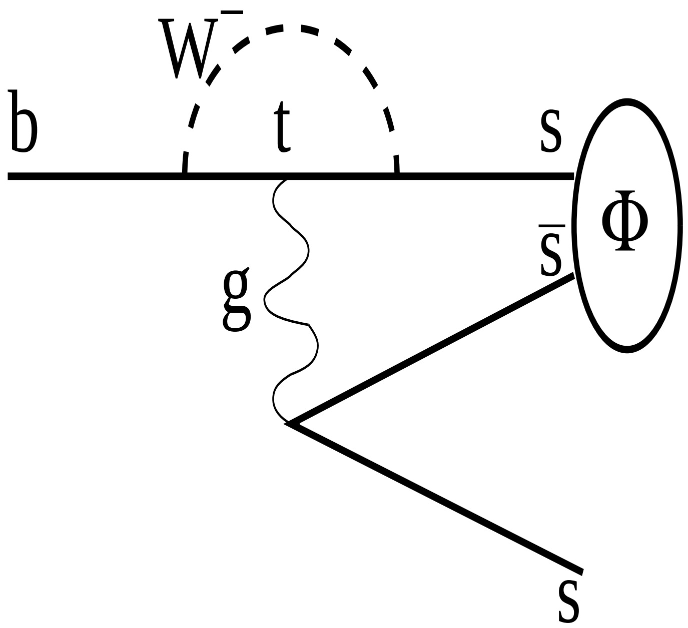

FIG. 1. The gluonic penguin diagram.

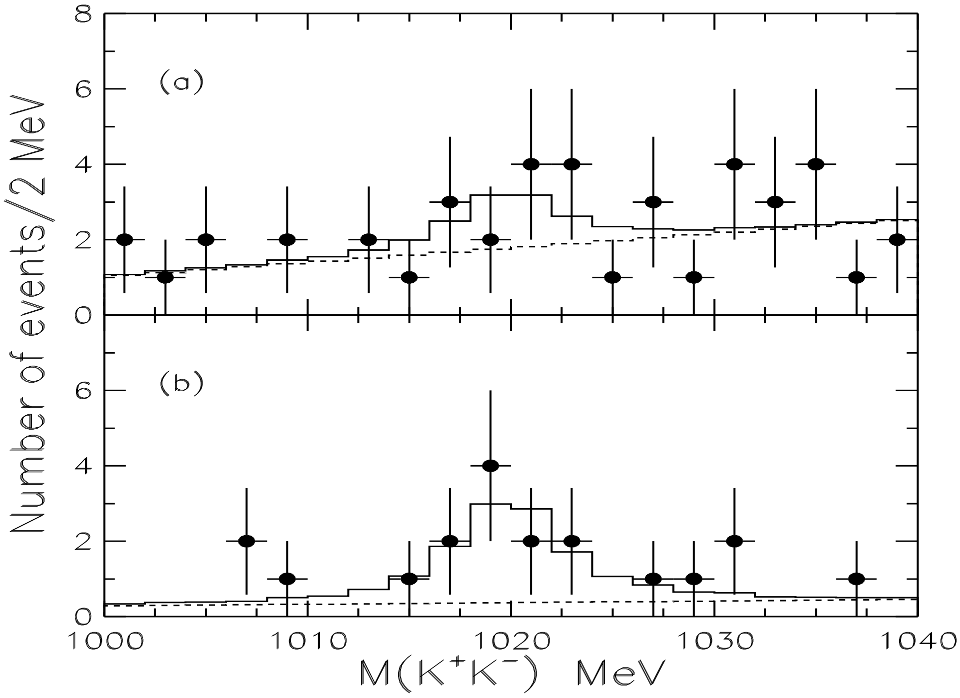

FIG. 2. The K^+K^- invariant mass distributions for (a) On-resonance and (b) off-resonance data. The distributions are fitted with a MC ϕ shape and a linear background.

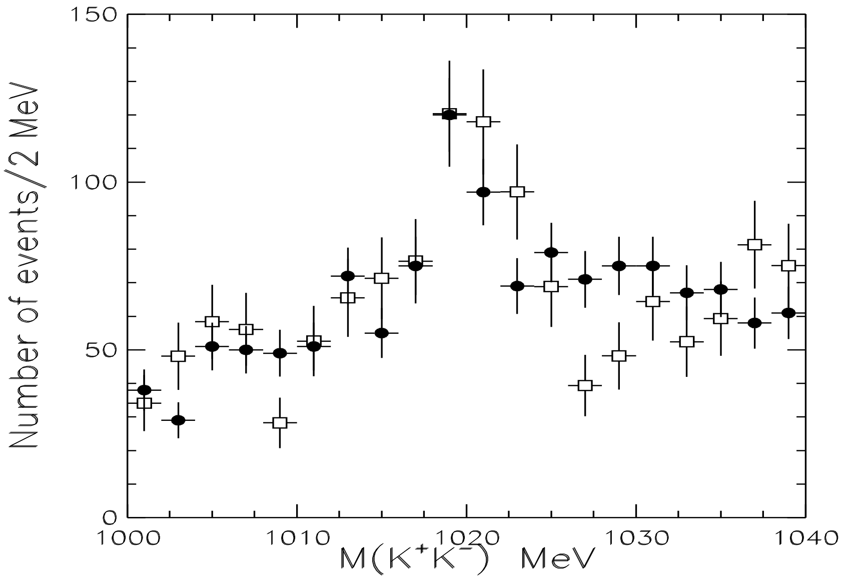

FIG. 3. The distributions of K^+K^- invariant mass for on-resonance data (filled points) and scaled off-resonance data (open squares) after relaxing the continuum suppression cuts.

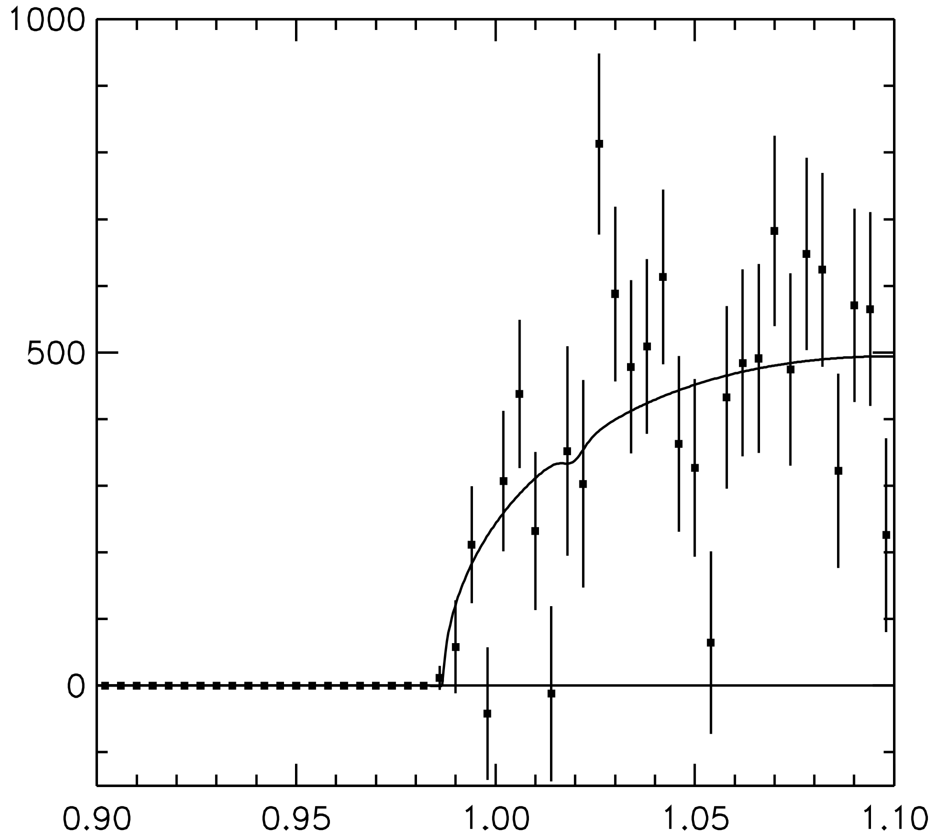

FIG. 4. The continuum subtracted K^+K^- invariant mass spectrum in the $b \to s$ gluon signal region.

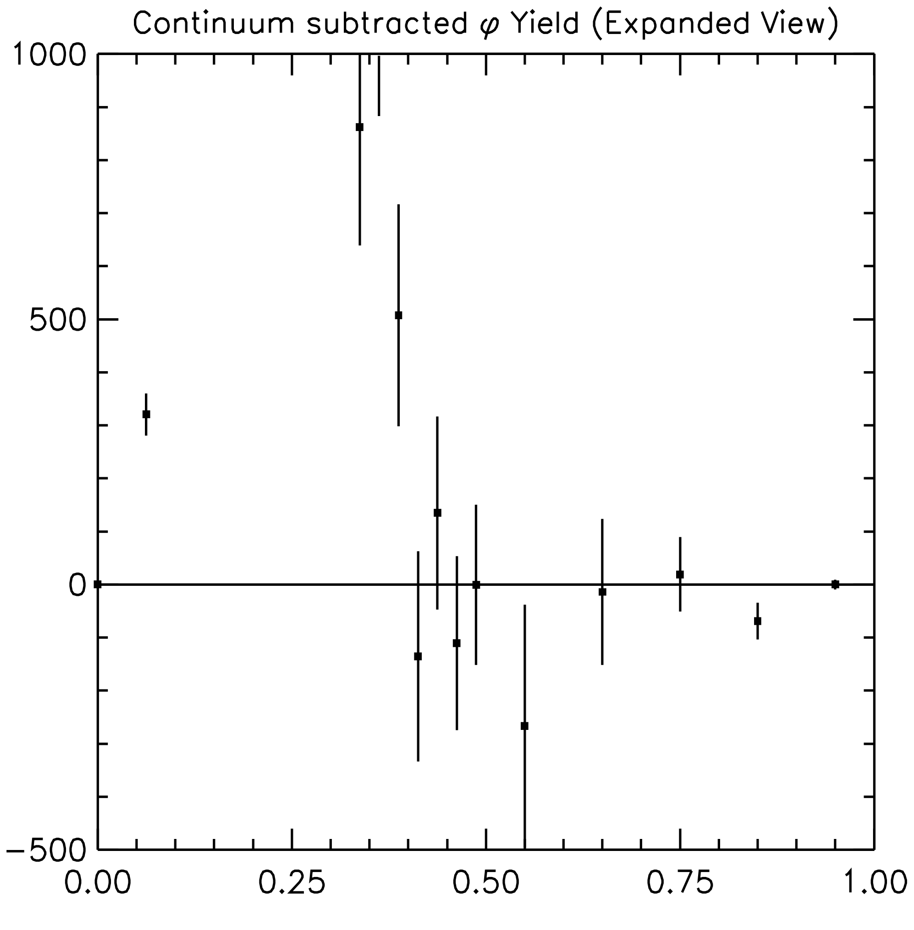

FIG. 5. The continuum subtracted ϕ yield as a function of x. The $b \to s$ gluon signal region are the bins with $0.4 < x < 0.5$. Note the change in bin size for $x > 0.5$.