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Measurement of the average ϕ multiplicity in B meson decay

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We present a measurement of the average multiplicity of ϕ mesons in B^0 , \bar{B}^0 , and B^\pm meson decays. Using 17.6 fb^{-1} of data taken at the $\Upsilon(4S)$ resonance by the BABAR detector at the PEP-II e^+e^- storage ring at the Stanford Linear Accelerator Center, we reconstruct ϕ mesons in the K^+K^- decay mode and measure $\mathcal{B}(B \rightarrow \phi X) = (3.41 \pm 0.06 \pm 0.12)\%$. This is significantly more precise than any previous measurement.

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I. INTRODUCTION

The large data sample collected by the BABAR detector provides an excellent opportunity for a significant improve-

ment to the existing measurements of the average ϕ multiplicity in B meson decay at the $\Upsilon(4S)$ resonance. This quantity, which is conventionally denoted $\mathcal{B}(B \rightarrow \phi X)$, was previously measured by CLEO as $(2.3 \pm 0.6 \pm 0.5)\%$ [1] and by ARGUS as $(3.90 \pm 0.30 \pm 0.35)\%$ [2]. These two measurements disagree at the 1.8σ level, leading to a large error on the Particle Data Group average $(3.5 \pm 0.7)\%$ [3]. The OPAL Collaboration has measured the average multiplicity $\mathcal{B}(b \rightarrow \phi X) = (2.82 \pm 0.13 \pm 0.19)\%$ [4] at the Z^0 pole. This latter measurement is sensitive to b -hadron decays that are not accessible at $\Upsilon(4S)$ experiments, including b baryons

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¶Deceased.

and, in particular, the B_s^0 meson.

An improved measurement of $\mathcal{B}(B \rightarrow \phi X)$ can lead to improved measurements of the B_s^0 oscillation frequency. The primary decay modes of the B_s^0 meson contain D_s^+ mesons, which often (18% [5]) produce a ϕ meson in their decays. Because of this high rate, B_s^0 decays into ϕ mesons are a prime decay chain for B_s^0 oscillation searches. An important input to such searches is the knowledge of the background arising from nonstrange B meson decays into ϕ mesons.

Given the large size of the *BABAR* data sample, this measurement is limited by systematic errors. As a result, this analysis is designed to minimize these systematic errors. Minimal selection criteria are applied, and efficiencies and backgrounds are evaluated directly from data where possible. The measurement is performed in ϕ -momentum intervals to minimize the systematic effects that may be introduced by differences between the ϕ momentum spectrum in data and simulation.

II. THE *BABAR* DETECTOR AND DATA SAMPLES

The data used in this analysis were collected by the *BABAR* detector at the SLAC PEP-II storage ring. We use 17.6 fb^{-1} of data taken at the $Y(4S)$ resonance (on-resonance) and 4.1 fb^{-1} of data taken at a center-of-mass energy 20 MeV below the $B\bar{B}$ threshold (off resonance). The latter sample is used for the subtraction of the non- $B\bar{B}$ component (continuum) in the on-resonance data. These data samples were taken between January and May 2002. Additional data, consisting of 3.5 fb^{-1} of on-resonance data and 1 fb^{-1} of off-resonance data taken under different running conditions, are used for verification of the result.

A detailed description of the *BABAR* detector is presented in Ref. [6]. The components of the detector most relevant to this analysis are described here. Charged-particle tracks are reconstructed with a five-layer, double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) with a helium-based gas mixture, placed in a 1.5-T solenoidal field produced by a superconducting magnet. The resolution on p_T , the charged-track momentum transverse to the beam direction, is approximately $(\delta p_T/p_T)^2 = [0.0013 (\text{GeV}/c)^{-1} p_T]^2 + (0.0045)^2$. Charged particles are identified from the ionization energy loss (dE/dx) measured in the DCH and SVT, and the Cherenkov radiation detected in a ring-imaging Cherenkov device. The efficiency for identifying true kaons exceeds 80% over most of the momentum range of interest, while the probability for a pion to be misidentified as a kaon is less than 3%.

We use Monte Carlo samples of $Y(4S) \rightarrow B^0 \bar{B}^0$ and $B^+ B^-$ decays, corresponding to twice the expected number of B mesons in the data sample, to study our selection efficiency. The B -meson decays are simulated according to previously measured branching fractions which account for approximately 60% of all B decays. The remaining 40% are modeled by JETSET [7], while preventing any enhancement of the first 60%. The detector response in these samples is simulated with the GEANT4 program [8] and cross-checked with control samples in the data.

III. EVENT AND CANDIDATE SELECTION

Events are selected if at least three tracks are found and the measured total energy is at least 4.5 GeV . In order to suppress continuum background, events are rejected if the ratio of the second-to-zeroth order Fox Wolfram moments [9] (R_2) is higher than 0.25. This requirement rejects 62% of the off-resonance data, while retaining 78% of the simulated $B \rightarrow \phi X$ events.

The selection of $\phi \rightarrow K^+ K^-$ candidates requires two oppositely charged tracks that satisfy $0.1 < p_T < 10 \text{ GeV}/c$, have at least 12 hits in the DCH, are consistent with originating from the primary interaction point, and satisfy kaon identification criteria based on dE/dx measurements and Cherenkov radiation. Tracks are assigned a kaon mass hypothesis and neutral two-track combinations are formed. Candidates are selected if their invariant mass is in the range $1.004 < m_{KK} < 1.036 \text{ GeV}/c^2$. This mass window is equivalent to about 4.5 standard deviations on either side of the nominal ϕ mass, where the rms spread in the m_{KK} distribution is due to both the natural ϕ width and the detector resolution. This relatively large acceptance is chosen to reduce the effect of a possible mass resolution difference between data and the Monte Carlo sample, at the expense of signal-to-background significance.

A total of 471, 941 (34, 900) ϕ candidates survive these selection criteria in the on (off) resonance sample.

IV. BACKGROUND ESTIMATION

Two sources of background to the $B \rightarrow \phi X$ signal are considered: random combinations of tracks that pass the selection (combinatorial background) and true ϕ mesons that do not originate from $B\bar{B}$ events (continuum background). Because the reconstruction efficiency depends on the momentum of the ϕ , these backgrounds are subtracted separately in 16 bins of ϕ momentum.

We first remove the continuum background from our signal by subtracting the m_{KK} distribution obtained in the off-resonance sample from that in the on-resonance sample, scaled by the ratio of the luminosities of the two samples. This scale factor is calculated by comparing the number of $e^+ e^- \rightarrow \mu^+ \mu^-$ events in the two samples, correctly accounting for the different continuum cross sections at the two running energies. The center-of-mass momenta of ϕ candidates in the off-resonance data are scaled by the ratio of on-/off-resonance beam energies to account for the slightly different momentum spectrum of the continuum component in the on-resonance sample. This procedure explicitly accounts for all backgrounds from physics processes other than $Y(4S)$ production as their cross sections are almost identical at the two energies; it also accounts for beam-related backgrounds, as the running conditions were very similar.

We next subtract the combinatorial background to extract the number of ϕ mesons. This background is estimated by fitting the mass distribution in sideband regions well away from both the signal and the KK threshold. The ranges

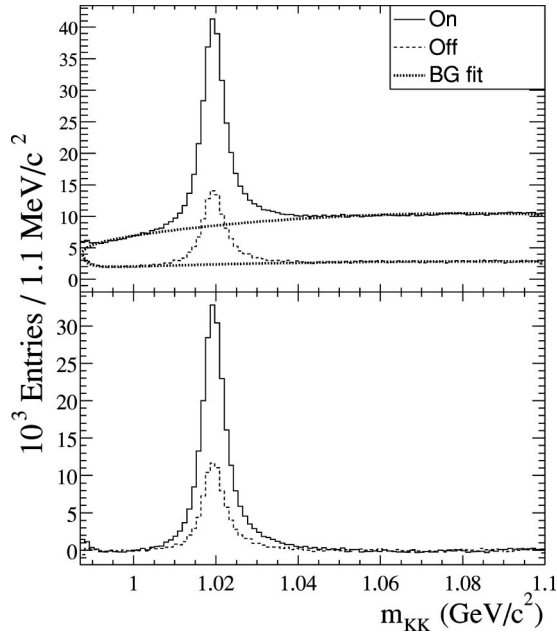


FIG. 1. Top: Invariant mass distributions of candidates passing all selection requirements except that for the mass. The solid histogram shows candidates in the on-resonance data sample, while the dashed histogram shows the off-resonance sample, scaled to the luminosity of the on-resonance data. The fitted combinatorial background is overlaid on both histograms as a dotted curve. Bottom: Resulting signal after combinatorial background subtraction. Again, the solid histogram represents on-resonance candidates, and the dashed histogram represents the luminosity-scaled off-resonance candidates. Note that the vertical scale is displaced from zero. The bump visible in the lowest bins of these plots is a threshold effect, which is well understood, and the fit range was chosen so that this does not contribute to the measurement.

$0.989 < m_{KK} < 1.002 \text{ GeV}/c^2$ and $1.04 < m_{KK} < 1.1 \text{ GeV}/c^2$ were chosen and the function $(m_{KK} - 2m_K)^a \cdot (b + c \cdot m_{KK} + d \cdot m_{KK}^2 + e \cdot m_{KK}^3)$ was used. This function provides a good description of the phase space in the vicinity of a threshold; a fit to the combinatoric m_{KK} spectrum (removing true ϕ mesons) in the Monte Carlo sample gives $\chi^2 = 104$ for 95 degrees of freedom.

Figure 1 shows the m_{KK} distributions of the on-resonance and luminosity-scaled off-resonance data samples for all ϕ momentum bins combined; the fitted combinatorial background shapes are overlaid. The on (off) resonance fit has $\chi^2 = 86$ (75) for 61 degrees of freedom. With estimates of the combinatorial background shape, the signal is extracted by subtracting the background. The resulting signals are shown in the lower part of Fig. 1. In the on-resonance sample, we observe $(2.349 \pm 0.007) \times 10^5$ ϕ candidates, and the corresponding number in the off-resonance sample is $(1.95 \pm 0.02) \times 10^4$. These plots and numbers are representative only; they are not used in the signal extraction.

Erroneous estimation of the signal in data and simulation could arise from a number of sources. The phase-space function may be unable to describe the background shape correctly (see the Monte Carlo fit above). There may be ϕ mesons with a reconstructed mass in the sideband regions,

which would affect the background estimation and therefore the signal yield. The Monte Carlo sample may not correctly model the signal line shape (in particular, the fraction of ϕ mesons outside the signal mass region), leading to a systematic uncertainty on the efficiency. We consider each of these sources below.

We vary the fitting procedure in a number of ways in order to test the robustness of our background estimation. We replace the third order polynomial in the above function with both a second order polynomial in m_{KK} and an exponential term $\exp(b \cdot m_{KK})$. These changes result in a 0.15% and 0.65% change in the number of ϕ candidates, respectively.

To account for the possibility that the reconstructed ϕ mass extends into the sideband regions, we vary the upper bound of the region excluded from the fit, raising it from 1.04 to 1.06 GeV/c^2 (while keeping the signal region as defined above). The largest difference in the number of ϕ mesons in the signal region in the above variations is 2.4%.

Finally, we look at the fraction of candidates, after background subtraction, outside the signal mass region. We count the number of candidates in the range $1.036 < m_{KK} < 1.05 \text{ GeV}/c^2$ and calculate the ratio of this number to the number of candidates in the signal region. This ratio is found to be 2.4% in data and 2.6% in the Monte Carlo sample. This yields a difference of 0.2% on the number of ϕ candidates between the data and the Monte Carlo sample.

We take the largest difference in all the above tests (2.4%) to be the systematic uncertainty associated with the combinatorial background subtraction and signal selection.

V. SELECTION EFFICIENCY

The kaon identification efficiency is extracted from data to avoid the systematic errors associated with Monte Carlo-based determinations. To do this, ϕ candidates are constructed from two-track combinations with at least one track passing the kaon identification criteria. This is done for positive and negative tracks separately to account for a possible asymmetry. Three subsamples of the data are defined: K^+K^- , where both tracks have passed the kaon identification requirements, and $K^\pm T^\mp$, where only one track is required to pass the kaon selection. The same off-resonance subtraction and R_2 requirement is made in defining these samples as for the standard selection. The kaon identification efficiency is then given by the ratio of the number of ϕ mesons reconstructed in the K^+K^- sample to the number in the $K^\pm T^\mp$ samples: $\epsilon_{K^\pm} = N_{\phi_{KK}} / N_{\phi_{K^\mp T^\pm}}$. Figure 2 shows the invariant mass distribution of the K^+K^- , K^+T^- , and K^-T^+ samples over the entire momentum region.

Studies of data and Monte Carlo samples show that the kaon identification efficiency is not constant throughout the momentum range of our ϕ sample, but can be described by one constant efficiency values below $p_\phi = 1.2 \text{ GeV}/c$ and another above this value. This step in efficiency is caused by the transition from dE/dx -based particle identification at low momenta to Cherenkov-angle-based particle identification at higher momenta. Since our analysis was performed in ϕ momentum bins, such behavior may introduce a bias in the re-

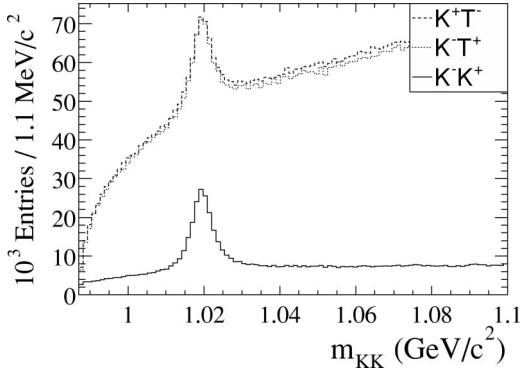


FIG. 2. Mass distribution of the K^+K^- , K^+T^- , and K^-T^+ samples. All selection criteria were applied in the K^+K^- sample but one track is not required to pass the kaon selection in the $K^\pm T^\mp$ samples.

sult if the kaon selection efficiency is taken as a constant value over the entire range. We therefore extract the kaon selection efficiency separately above and below this momentum. We measure $\varepsilon_{K^+} = (98.6 \pm 1.2)\%$ and $\varepsilon_{K^-} = (98.7 \pm 1.2)\%$ for $p_\phi < 1.2$ GeV/ c , and $\varepsilon_{K^+} = (79.0 \pm 1.8)\%$ and $\varepsilon_{K^-} = (79.7 \pm 1.9)\%$ for $p_\phi > 1.2$ GeV/ c .

The remaining efficiency to be estimated is ε_{2T} , that of finding two charged tracks that originate from a ϕ meson, satisfy the R_2 requirement, and have an invariant mass in the signal region (with no kaon identification requirement). This efficiency is estimated from the Monte Carlo. Since the efficiency to reconstruct a ϕ depends on the ϕ momentum, differences between the momentum spectrum in data and the generated spectrum in the Monte Carlo sample must be considered. Therefore, the analysis was carried out separately in 16 bins of ϕ momentum. The bins are chosen to have equal (with the exception of the lowest momentum range) numbers of reconstructed ϕ mesons in the Monte Carlo sample. Figure 3 shows the efficiency ε_{2T} as a function of the ϕ momentum.

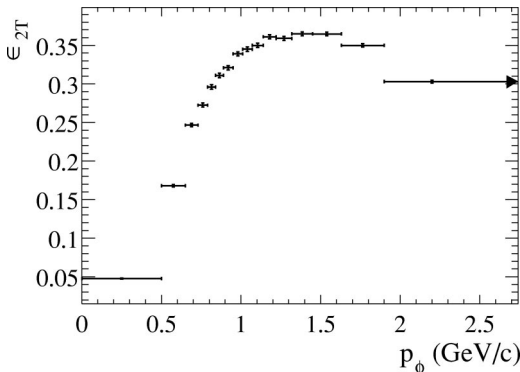


FIG. 3. Efficiency (ε_{2T}) as a function of ϕ momentum. The highest bin includes all entries above 1.9 GeV/ c . Errors shown are statistical only.

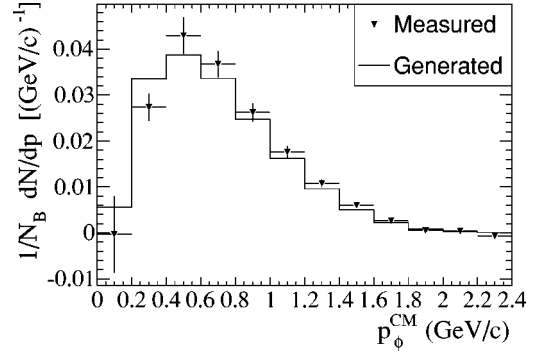


FIG. 4. Center-of-mass ϕ momentum spectra of the measured and Monte Carlo generated samples. The measured spectrum shows statistical and systematic errors combined, and the generated spectrum is normalized to the measured multiplicity. The lowest momentum bin has a negative central value due to the large continuum component but is consistent with positive values due to the large error.

VI. RESULTS

The average multiplicity is calculated with the formula

$$\mathcal{B}(B \rightarrow \phi X) = \frac{1}{2N_{BB}\mathcal{B}(\phi \rightarrow K^+K^-)} \sum_{i=1}^{16} \frac{N_{B,i}^\phi}{\varepsilon_i}, \quad (1)$$

where $N_{B,i}^\phi$ is the number of ϕ mesons in momentum bin i found in the data and assumed to come from B mesons. This number is obtained by performing the background fit to the on-resonance data samples after subtracting the off-resonance data samples, scaled to the on-resonance luminosity. The efficiency $\varepsilon = \varepsilon_{2T}\varepsilon_{K^+}\varepsilon_{K^-}$ is the product of the reconstruction efficiency and the kaon identification efficiencies for each track. The quantity N_{BB} is the number of $B\bar{B}$ events in the data sample, which is measured to be $N_{BB} = (18.7 \pm 0.2) \times 10^6$ using a technique described elsewhere [10].

Since the analysis was performed in ϕ momentum bins, the efficiency in each bin has very little dependence on the modeling of the ϕ spectrum, except for the lowest-momentum bin, which includes the tracking detection limit. We therefore sum the yield in the highest 15 bins and extrapolate the result based on the simulated spectrum, so that the sum in Eq. (1) is replaced by

$$\sum_{i=1}^{16} \frac{N_{B,i}^\phi}{\varepsilon_i} \Rightarrow \sum_{i=2}^{16} \frac{N_{B,i}^\phi}{\varepsilon_i} \times \frac{\sum_{i=1}^{16} N_{MC,i}^\phi}{\sum_{i=2}^{16} N_{MC,i}^\phi}. \quad (2)$$

Here, $N_{MC,i}^\phi$ is the number of ϕ mesons in the Monte Carlo sample in momentum bin i .

Using $\mathcal{B}(\phi \rightarrow K^+K^-) = 0.492 \pm 0.006$ [3], we obtain $\mathcal{B}(B \rightarrow \phi X) = (3.41 \pm 0.06)\%$, where the error is statistical only. Figure 4 shows the measured and simulated ϕ momentum spectra in the $Y(4S)$ center-of-mass frame. We note that the Monte Carlo sample predicts the observed ϕ momentum spectrum reasonably well.

TABLE I. Relative systematic uncertainties.

Source	$\Delta\mathcal{B}/\mathcal{B}(\%)$
Combinatorial BG fitting	2.4
On/off scale factor	0.1
$\mathcal{B}(\phi \rightarrow K^+ K^-)$	1.2
N_{BB}	1.1
ε_{2T} (total)	1.9
R_2	0.5
Monte Carlo statistics	0.3
Monte Carlo ϕ modeling	0.7
Tracking efficiency	1.6
Total	3.4

VII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties are associated with all of the variables in Eq. (1). Table I lists the various systematic uncertainties, which are described in detail below.

Two sources contribute to the uncertainty on N_{Bi}^ϕ , the number of ϕ mesons from $B\bar{B}$ events. One is the fitting procedure error which is described in Sec. IV and was taken to be 2.4%. The other is the error on the scaling factor (on/off resonance) which contributes 0.1% relative uncertainty on the measured average multiplicity.

The uncertainty on $\mathcal{B}(\phi \rightarrow K^+ K^-)$ introduces a relative error of 1.2%, while that on N_{BB} contributes 1.1% relative uncertainty on the average multiplicity.

Systematic errors on ε_{K^\pm} are considered by varying the fits on the $K^\pm T^\mp$ samples in the same way as the signal fits are varied in Sec. IV. Taking into account the correlation between the systematic uncertainties on the different samples, we find this error to be smaller than the error on the $K^+ K^-$ sample alone, and we retain the larger error as the systematic associated with the fitting procedure.

As ε_{2T} is obtained from Monte Carlo, differences between data and Monte Carlo give rise to systematic uncertainties. Several components contribute to this systematic uncertainty:

There is a systematic uncertainty related to the extrapolation of the 15-bin yield to the full result because of our limited knowledge of the ϕ spectrum in B decays. Since only about 60% of B meson decays are well understood (see Sec. II), mismodeling of the remaining 40% can affect the result. To account for this model dependence, we study two Monte Carlo subsamples representing extreme cases to make up the entire remaining 40%. The first subsample contains a B meson undergoing a two-body decay to a charm meson, with the charm meson undergoing a two-body decay to a ϕ . In the second subsample, the B meson undergoes a multibody (greater than two) decay and the subsequent charm meson undergoes a multibody decay into a final state that contains a ϕ meson. These two cases yield very different kinematic distributions for the ϕ meson. We measure the fraction of candidates in the lowest bin in each sample. We take the largest difference between these samples and the primary result as a systematic uncertainty. It is found to be 0.7%. The effect of ϕ polarization was similarly studied and found to

have a negligible impact on the result.

To establish the contribution to the systematic uncertainty from the simulation of R_2 , the number of ϕ mesons from $B\bar{B}$ events is estimated again without the R_2 requirement, and the same procedure is applied to the Monte Carlo sample. The fraction of ϕ mesons from B decays with $R_2 < 0.25$ in data is $(78.18 \pm 0.80)\%$ while this fraction in Monte Carlo is $(78.00 \pm 0.09)\%$, in agreement within statistical errors. We also investigate the two decay models mentioned above for their effect on the R_2 selection. We find that the largest difference between the models and our Monte Carlo distribution is 0.5%, and we take this difference as a systematic uncertainty.

An additional test is performed by examining different continuum-suppression variables. We study the angle between the ϕ direction in the center-of-mass frame and the thrust axis of the event, where the thrust was calculated both including and excluding the ϕ candidate. These two variables are each used in place of R_2 in order to suppress continuum events. We place appropriate criteria on these variables to maintain similar efficiency to that of R_2 in our analysis. We then measure the efficiency of these requirements in data and the Monte Carlo sample. The ratio of efficiencies between data and the Monte Carlo sample is found to be 0.982 ± 0.015 for the first variable (with the ϕ) and 1.007 ± 0.015 for the other.

Tracking performance is studied using control samples in data, and the track-finding efficiency is found to be accurate to within 0.8% per track. We therefore assign a 1.6% systematic uncertainty due to tracking efficiency.

Finally, the statistical uncertainty on ε_{2T} contributes a 0.3% systematic uncertainty.

The use of one single kaon selection efficiency for all ϕ momenta was compared to the use of separate values above and below $p_\phi = 1.2$ GeV/ c . The observed difference in the average multiplicity was 0.9%. This is below the statistical error on the kaon identification efficiencies, hence no additional error was assigned to this source. The statistical error on the kaon selection efficiencies is treated as part of the statistical error in this analysis as it is obtained from the same data set as our signal and scales appropriately.

The above sources of systematic uncertainty are added in quadrature and yield a relative uncertainty on the average multiplicity of 3.4%.

This analysis is repeated by replacing the 16 p_ϕ bins with six bins of θ_ϕ , the polar angle of the ϕ candidate with respect to the beam axis. As the total number of events is exactly the same as in the analysis described above, this is not an independent measurement, and can only serve to validate the fitting procedure. The combinatorial background in these bins is significantly different in shape to that used in the primary analysis. The total yield of ϕ mesons from B decays is found to differ by 0.88% from the yield in the primary analysis—well within the assigned uncertainty for this source.

We also repeat the analysis using a different data set. We use a smaller data set from the year 2000 in which the detector was operating under different conditions. This analysis

yields $\mathcal{B}(B \rightarrow \phi X) = (3.34 \pm 0.07)\%$ where the error is statistical only, entirely consistent with our primary result.

VIII. CONCLUSION

By selecting two identified oppositely charged kaons from a sample of $Y(4S)$ data and subtracting the combinatorial and continuum background, we measure the average multiplicity of ϕ mesons in B meson decays. Our measurement of $\mathcal{B}(B \rightarrow \phi X) = (3.41 \pm 0.06 \pm 0.12)\%$ is consistent with both previous measurements at the 1.5σ level, although it is significantly more precise.

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