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## Direct measurement of $B(D_s^+ \rightarrow \phi X^+)$

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The absolute inclusive branching fraction of  $D_s^+ \rightarrow \phi X^+$  has been measured from data collected by the BES detector at a center-of-mass energy of 4.03 GeV, corresponding to an integrated luminosity of 22.3 pb<sup>-1</sup>. At this energy, direct pair production  $e^+e^- \rightarrow D_s^+D_s^-$  has been observed. We have selected  $D_s$  candidate events by reconstructing five hadronic decay modes  $D_s^+ \rightarrow \phi\pi^+$ ,  $\bar{K}^0K^+$ ,  $\bar{K}^0K^+$ ,  $f_0\pi^+$  and  $K^0K^-\pi^+\pi^+$  and have searched for inclusive  $\phi$ 's in the recoiling  $D_s^-$ . We observed three recoiling  $\phi$ 's in the  $166.4 \pm 31.8 D_s$  candidate events, which leads to the absolute branching fraction  $B(D_s^+ \rightarrow \phi X^+) = (17.8_{-7.2}^{+15.1} \text{ }_{-6.3}^{+0.6})\%$  and  $B(D_s^+ \rightarrow \phi\pi^+) = (3.6_{-1.6}^{+3.1} \text{ }_{-1.3}^{+0.4})\%$ . [S0556-2821(97)02423-5]

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The main experimental difficulties in charmed particle decays are the problems of overall normalization and the precise determination of charm branching fractions. Previously, we have reported the absolute model-independent branching ratio of  $D_s^+ \rightarrow \phi\pi^+$  [1]. Here we consider the absolute branching fraction of  $D_s^+ \rightarrow$  inclusive  $\phi$ , which contributes toward our understanding of the overall  $D_s$  branching fraction scale. Moreover the absolute inclusive branching fraction of  $D_s^+ \rightarrow \phi X^+$  [2] is used in  $B_s^0\bar{B}_s^0$  oscillation [3] and  $B_s$

mixing [4] measurements at the CERN  $e^+e^-$  LEP and Collider Detector at Fermilab (CDF).

In this paper, we report a direct and model independent measurement of the  $D_s$  inclusive  $\phi$  branching fraction using the BES detector at the Beijing Electron Positron Collider (BEPC). The data were obtained using the BES detector, and correspond to a total integrated luminosity of 22.3 pb<sup>-1</sup> as determined by large angle Bhabha scattering events at a center-of-mass energy of 4.03 GeV. This is just above  $e^+e^- \rightarrow D_s^+D_s^-$  threshold.

The BES detector is a conventional cylindrical detector, which is described in detail in Ref. [5]. A four-layer central drift chamber (CDC) surrounding the beampipe provides

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trigger information. Outside the CDC, a forty-layer main drift chamber (MDC) provides tracking and energy loss ( $dE/dx$ ) information on charged tracks over  $\sim 85\%$  of the total solid angle. The momentum resolution is  $\sigma_p/p = 0.017\sqrt{1+p^2}$  ( $p$  in GeV/ $c$ ), and the energy loss ( $dE/dx$ ) resolution is  $\sim 11\%$  for hadron tracks and  $\sim 8.5\%$  for Bhabha electrons. Scintillation counters that surround the MDC provide time-of-flight (TOF) measurements with resolutions of  $\sim 450$  ps for hadrons and  $\sim 330$  ps for Bhabha events. Outside the TOF system, a 12-radiation-length, lead-gas barrel shower counter (BSC), operating in limited streamer mode, measures the energies of electrons and photons over  $\sim 80\%$  of the total solid angle. Surrounding the BSC, a solenoidal magnet provides a 0.4 T magnetic field in the central tracking region of the detector. Three double-layer muon counters (MUC) instrument the magnet flux return and serve to identify muons of momentum greater than 0.5 GeV/ $c$ . They cover  $\sim 68\%$  of the total solid angle with longitudinal (transverse) spatial resolution of 5 cm (3 cm).

In this experiment, the  $D_s$  signal has been detected via five hadronic decay modes:  $D_s^+ \rightarrow \phi\pi^+$ ,  $\bar{K}^{0*}K^+$ ,  $\bar{K}^0K^+$ ,  $f_0\pi^+$  or  $K^0K^-\pi^+\pi^+$ . The subresonances are detected by the decays  $\phi \rightarrow K^+K^-$ ,  $\bar{K}^{0*} \rightarrow K^-\pi^+$ ,  $\bar{K}^0 \rightarrow K_S^0 \rightarrow \pi^+\pi^-$ , and  $f_0 \rightarrow \pi^+\pi^-$ . Each candidate was formed using well-reconstructed tracks. Each track's closest approach to the origin was required to be smaller than 1.2 cm in the  $xy$  plane and 15 cm in the  $z$  direction. For the  $f_0\pi$  mode, the vertexing requirements were tightened to 0.65 cm in the  $xy$  plane and 9 cm in the  $z$  direction due to larger backgrounds. Vertexing requirements were not applied to candidate pions from  $K_S^0$  decay. The proper decay time of  $K_S^0$  candidates was required to be between 0.01 and 0.33 ns. Additionally in the  $K^0K^-\pi^+\pi^+$  mode, the  $K_S^0$  vertex was required to have the difference between the  $z$  coordinates of the two tracks to be within 4 cm, and the  $xy$  alignment of the parent momentum with the line from the interaction point to the  $K_S^0$  vertex was required to have a confidence level  $> 5\%$ . A fiducial requirement,  $|\cos\theta| < 0.85$  was used for charged tracks. Both TOF and  $dE/dx$  systems were used to reduce background from random combinations of different particles. Time-of-flight and  $dE/dx$  information associated with each track was required to be consistent with the assigned mass interpretation with a confidence level  $> 1\%$ . Kaon candidates were required to have  $\chi^2(K) < \chi^2(\pi)$ . Pion candidates were required to have  $\chi^2(\pi) < \chi^2(K)$  and additionally  $\chi^2(\pi) < \chi^2(e)$  for  $f_0\pi^+$  candidates. Candidates for  $\phi$ ,  $\bar{K}^{0*}$ ,  $\bar{K}^0$ , and  $f_0$  were required to be within 18, 60, 20, and 30 MeV/ $c^2$ , respectively, of the nominal mass.

Additional background rejection was obtained with helicity angle cuts for the  $\phi$  and  $\bar{K}^{0*}$ . We required  $|\cos\theta_K| > 0.25$  in the  $\phi$  rest frame for the  $\phi\pi$  mode and  $|\cos\theta_K| > 0.4$  in the  $\bar{K}^{0*}$  rest frame for the  $\bar{K}^{0*}K$  mode.

The production of  $D_s$  has a  $\sin^2\theta$  distribution with respect to the beam direction. In single tag modes with large backgrounds, the signal-to-noise ratio can be improved by only using tags with small values of  $\cos\theta$ . We required  $|\cos\theta_{D_s}| < 0.7$  for the  $\bar{K}^{0*}K^+$  mode, and  $|\cos\theta_{D_s}| < 0.85$  for both the  $f_0\pi^+$  and the  $\bar{K}^0K^+$  modes.

Candidates satisfying these criteria were subjected to a one-constraint (1C) kinematic fit to the beam energy. Those having a fit confidence level  $> 1\%$  for  $\phi\pi^+$ ,  $\bar{K}^{0*}K^+$  and  $\bar{K}^0K^+$ ,  $> 5\%$  for  $K^0K^-\pi^+\pi^+$ , and  $> 10\%$  for  $f_0\pi^+$  were retained. The unbinned maximum likelihood fit to each single tag plot [Figs. 1(a)–1(e)] gave the number of single tag events ( $N_{\text{snl}}^i$ ), and fitting to Fig. 1(f) gave a total of  $166.4 \pm 31.8 D_s$  single tags above background.

Double tagged  $D_s$  events were obtained by reconstructing a  $\phi \rightarrow K^+K^-$  recoiling against one of the five  $D_s$  single tag modes. Recoiling  $\phi$ 's were selected with the same track and particle identification requirements described earlier for the  $\phi\pi$  single tag mode.  $\phi$  candidates were required to be within 18 MeV/ $c^2$  of the  $\phi$  mass (3 times the resolution for the reconstructed  $\phi$  mass). A total of 3 double tag events (Fig. 2) were found, and the characteristics of these events are summarized in Table I.

A direct measurement of  $B_{\phi X}$  is obtained from the number of single tag events ( $N_{\text{snl}}$ ), the number of double tag events ( $N_{\text{dbl}}$ ), and the inclusive  $\phi$  efficiency ( $\epsilon_{\text{dbl}}$ ) as follows:

$$B_{\phi X} = \frac{N_{\text{dbl}}}{N_{\text{snl}} \times \epsilon_{\text{dbl}} \times B(\phi \rightarrow K^+K^-)}. \quad (1)$$

The inclusive  $\phi$  double tag efficiency,  $\epsilon_{\text{dbl}}$ , was determined using Monte Carlo simulation for each of the five modes (Table II).

A  $D_s$  tag side band method was used to estimate the background in the double tag sample. As consistency checks three different methods were used in the background estimation: recoil  $\phi$  side band method, tag subresonance side band method, and Monte Carlo background studies.

The  $D_s$  tag side band regions (Fig. 2) were defined from 1.79–1.957 GeV/ $c^2$  and from 1.981–2.105 GeV/ $c^2$ . One  $\phi$  was found recoiling from a sideband of the  $\bar{K}^{0*}K^+$  tag. No background event was detected in the  $\phi\pi^+$  side band region. For both  $\phi\pi^+$  and  $\bar{K}^{0*}K^+$  channels, we have normalized the tag side bands by the ratio of single tag events in the signal and side band regions. Poisson errors for a single event in the  $\bar{K}^{0*}K^+$  side band region implies an estimated background of  $0.13_{-0.04}^{+0.30}$ . In order to express the uncertainty of the  $\phi\pi$  mode background, we have used the 84.1 % confidence level upper limit for zero events giving  $0.0_{-0.0}^{+0.26}$ .

There is no background event from the the recoil  $\phi$  mass side band (Fig. 2) method.

All analyses were repeated using the side bands of the tag subresonances, 0.965–1.001 and 1.037–1.073 GeV/ $c^2$  for  $\phi$ , 0.712–0.832 and 0.952–1.072 GeV/ $c^2$  for  $\bar{K}^{0*}$ , 0.4376–0.4776 and 0.5176–0.5576 GeV/ $c^2$  for  $\bar{K}^0$ , 0.89–0.95 and 1.01–1.07 GeV/ $c^2$  for  $f_0$ . No event passed the selection criteria, leading to an estimate of zero background events in our double tag sample.

Finally, large Monte Carlo samples of  $D^{*+}D^-$ ,  $D^{*0}D^0$ ,  $D^{*+}D^{*-}$ , and  $D^{*0}D^{*0}$  were used to estimate backgrounds from these sources. These samples correspond to 6.4, 5.9, 5.3 and 5.0 times the real data sample respectively. All Monte Carlo background events in the double tag signal region were rejected.

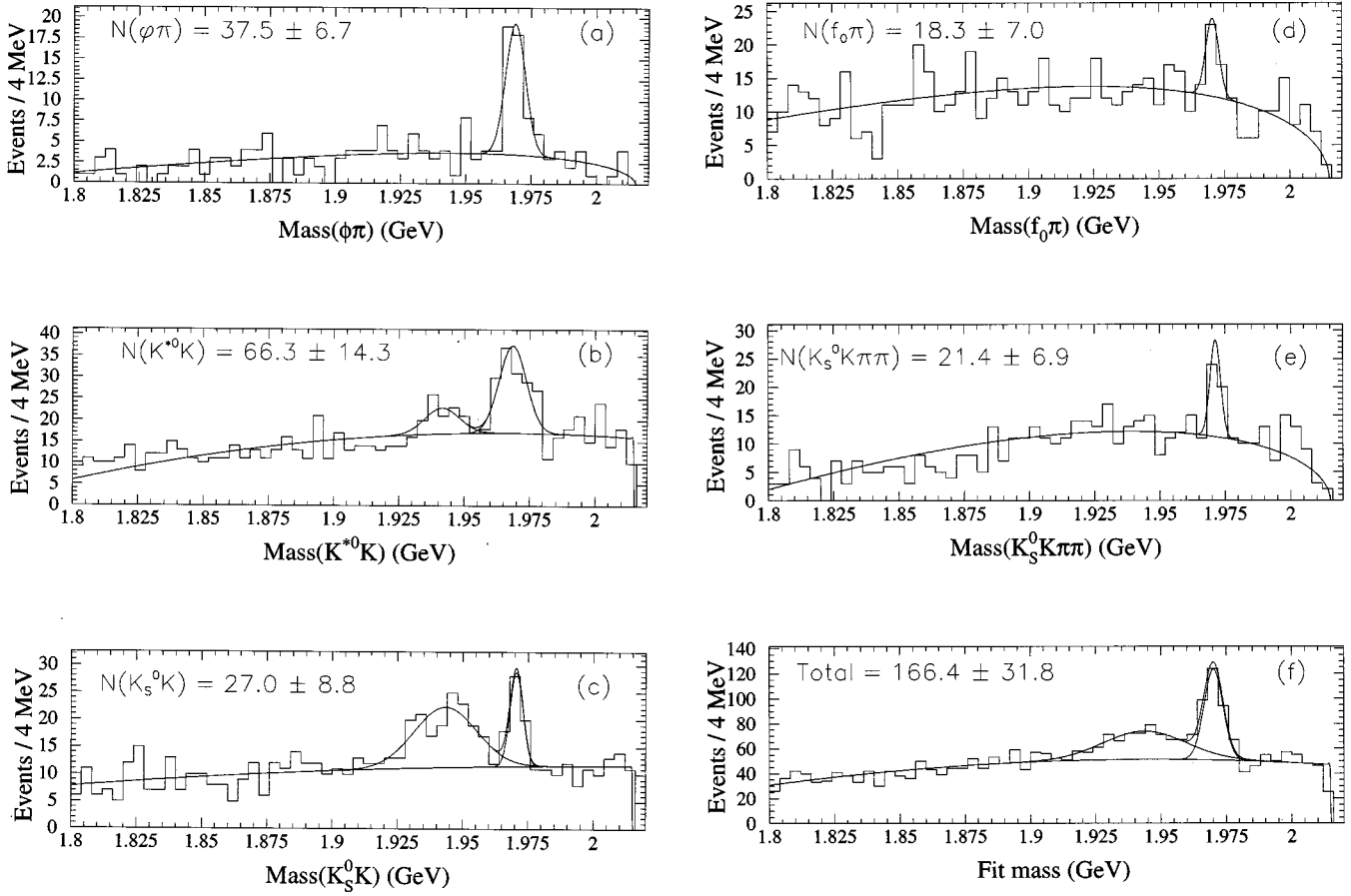


FIG. 1. Kinematically fit mass of  $D_s$  candidates. The curves are the result of unbinned fits to the data.

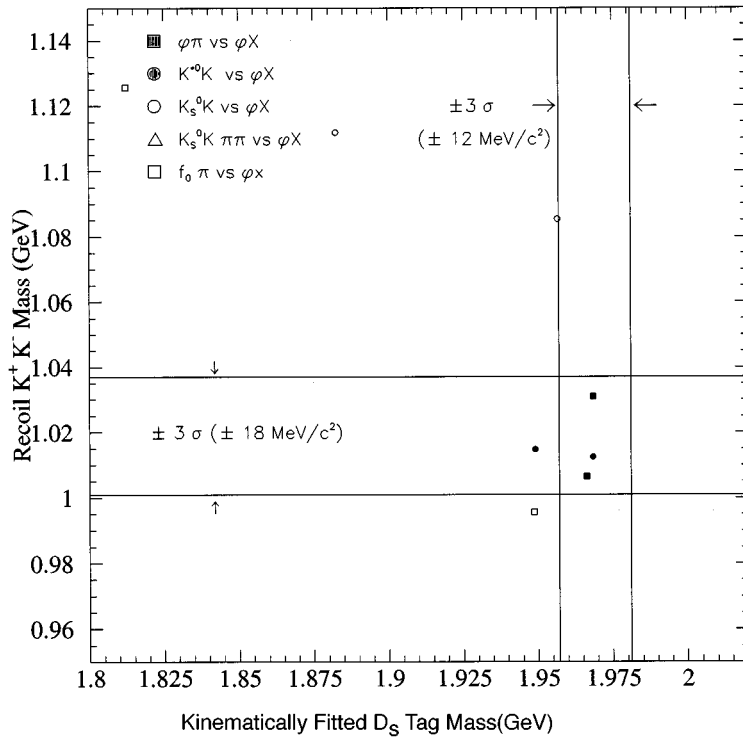


FIG. 2. Double tag candidates.

TABLE I. Properties of the double tag candidates.

Event	1	2	3
Tagging $D_s$ Decay	$\phi\pi^+$	$\phi\pi^+$	$\bar{K}^0 K^+$
Subsystem mass (GeV/ $c^2$ )	1.0090	1.0229	0.8345
$D_s$ invariant mass (GeV/ $c^2$ )	1.9723	1.9694	1.9678
1C $D_s$ fitmass (GeV/ $c^2$ )	1.9662	1.9686	1.9684
Recoiled $\phi$ mass (GeV/ $c^2$ )	1.0068	1.0306	1.0125
Number of visible charged tracks	6	5	6
Number of isolated showers	5	3	1

Since there are no signal events in the  $\bar{K}^0 K^+$ ,  $f_0 \pi^+$ , and  $K^0 K^- \pi^+ \pi^+$  modes, the background estimates do not affect the shape of the likelihood function.

Combining all four different methods gives estimated backgrounds of  $0.0_{-0.0}^{+0.26}$  events for the  $\phi\pi^+$  mode and  $0.13_{-0.04}^{+0.30}$  events for the  $\bar{K}^0 K^+$  mode. The background uncertainties contribute  $_{-35.0\%}^{+1.0\%} \times B_{\phi X}$  to the systematic error for the branching fraction  $B_{\phi X}$ .

The value of  $B_{\phi X}$  is obtained using a maximum likelihood method. The likelihood function,

$$L^i(B_{\phi X}, N_{\text{sngl}}^i; \epsilon_{\text{dbl}}^i, N_{\text{dbl}}^i, N_{\text{bg}}^i),$$

is constructed from Eq. (1) using a Poisson distribution to describe the number of double tag events and a Gaussian distribution to describe the single tag sample:

$$L(B_{\phi X}) = \prod_i L_{\text{mar}}^i(B_{\phi X}), \quad (2)$$

where  $i$  refers to the single tag mode. The marginalized likelihood function for each of the five different  $D_s$  modes is obtained by integrating out the single tag uncertainty:

$$L_{\text{mar}}^i(B_{\phi X}) = \int d\tilde{N}_{\text{sngl}}^i L^i(B_{\phi X}, \tilde{N}_{\text{sngl}}^i) \exp\left[-\frac{1}{2}\left(\frac{N_{\text{sngl}}^i - \tilde{N}_{\text{sngl}}^i}{\delta N_{\text{sngl}}^i}\right)^2\right] \times \frac{1}{\sqrt{2\pi} \delta N_{\text{sngl}}^i}.$$

The likelihood function  $L^i$  is given by

$$L^i = \frac{A_i^{N_{\text{dbl}}^i}}{N_{\text{dbl}}^i!} e^{-A_i},$$

TABLE II. Result of the measurement.

Decay mode	$N_{\text{sngl}}^i$	$N_{\text{dbl}}^i$	$\epsilon_{\text{dbl}}^i$	$N_{\text{bg}}^i$
$\phi\pi^+$	$37.5 \pm 6.7$	2	$0.202 \pm 0.004$	$0.0_{-0.0}^{+0.26}$
$\bar{K}^0 K^+$	$66.3 \pm 14.3$	1	$0.200 \pm 0.005$	$0.13_{-0.04}^{+0.30}$
$\bar{K}^0 K^+$	$27.0 \pm 8.8$	0	$0.190 \pm 0.004$	N/A
$f_0 \pi^+$	$18.3 \pm 7.0$	0	$0.180 \pm 0.005$	N/A
$K^0 K^- \pi^+ \pi^+$	$21.4 \pm 6.9$	0	$0.181 \pm 0.007$	N/A

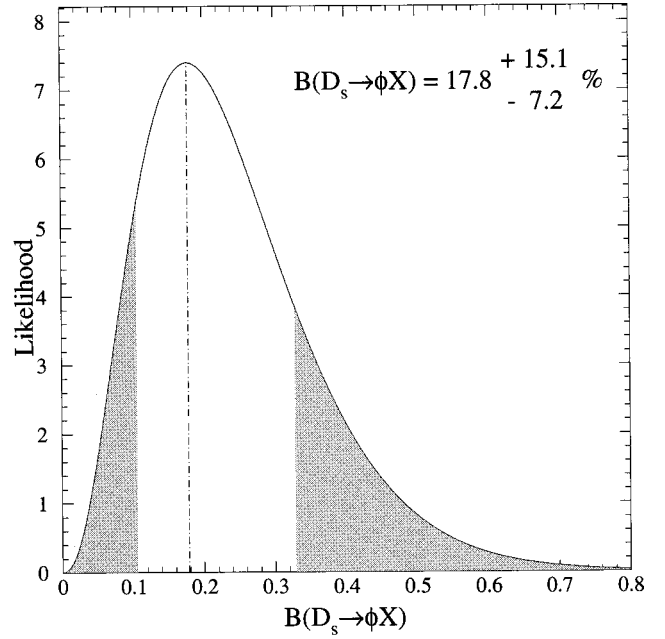


FIG. 3. The variation of the normalized likelihood function with respect to  $B_{\phi X}$ ; the unshaded area under the curve denotes the 68% confidence interval.

where

$$A_i \equiv B_{\phi X} N_{\text{sngl}}^i \epsilon_{\text{dbl}}^i B(\phi \rightarrow K^+ K^-) + N_{\text{bg}}^i.$$

The value of the likelihood function,  $L(B_{\phi X})$ , is shown in Fig. 3. The maximum likelihood solution is  $B_{\phi X} = (17.8_{-7.2}^{+15.1})\%$ , where the statistical errors are obtained by integrating the function; the area under the curve between the peak value and  $-1\sigma$  ( $+1\sigma$ ) corresponds to 68% of the total area below (above) the peak position.

Several systematic uncertainties affect this measurement. The inclusive  $\phi$  efficiency,  $\epsilon_{\text{dbl}}$ , introduces a systematic error for  $B_{\phi X}$  of  $2.4\% \times B_{\phi X}$ . The choice of a background functional form and fit interval for the single tag sample introduces a  $2.0\% \times B_{\phi X}$  uncertainty. Finally, the double tag background estimate is responsible for a  $_{-35.0\%}^{+1.0\%} \times B_{\phi X}$  uncertainty. After combining the systematic errors in quadrature, the final result for  $B_{\phi X}$  is

TABLE III. Inclusive  $\phi$  decay modes of  $D_s$  (PDG 1996).

Decay mode	Branching fraction (%)	$\Gamma_i / \Gamma_{\phi\pi}$
$D_s^+ \rightarrow \phi e^+ \nu$	$1.9 \pm 0.5$	$0.54 \pm 0.05$
$D_s^+ \rightarrow \phi \mu^+ \nu$	$1.9 \pm 0.5$	$0.54 \pm 0.05$
$D_s^+ \rightarrow \phi \pi^+$	$3.6 \pm 0.9$	1.00
$D_s^+ \rightarrow \phi \pi^+ \pi^0$	$9 \pm 5$	$2.4 \pm 1.0 \pm 0.5$
$D_s^+ \rightarrow \phi \pi^+ \pi^+ \pi^-$	$1.8 \pm 0.6$	$0.51 \pm 0.12$
$D_s^+ \rightarrow \phi K^+$	$< 0.05$	$< 0.071$
Total	$18.2 \pm 5.2$	$5.0 \pm 1.0 \pm 0.5$

$$B_{\phi X} = (17.8^{+15.1}_{-7.2} \text{ }^{+0.6}_{-6.3}) \% .$$

This is a direct measurement of the  $D_s$  inclusive  $\phi$  branching fraction that is model-independent. The present world average value from indirect or model-dependent procedures is  $B_{\phi X} = (18.2 \pm 5.2) \%$  (Table III).

LEP experiments [3] and CDF [4] have used a theoretically inspired method to estimate  $B_{\phi X}$  from  $B_{\phi\pi}$ . The theoretical  $D_s^+$  branching fractions are evaluated from the BSW model [6], giving  $B(D_s^+ \rightarrow \phi X^+) = (4.84 \pm 0.51) b_s$  [7], where  $b_s$  is the measured branching fraction of  $D_s^+ \rightarrow \phi\pi^+$ . Using the Particle Data Group (PDG) (1996) [8] value yields  $B_{\phi X} = (17.4 \pm 4.7) \%$ .

A measurement of  $B_{\phi\pi}$  can be obtained from  $B_{\phi X}$  using the sum of exclusive measurements shown in the Table III under the assumption that no significant decays of the  $D_s$  to

$\phi$  remain unmeasured. Scaling  $B_{\phi X}$  by the sum of the world average values of  $\Gamma_i / \Gamma_{\phi\pi}$  gives  $B_{\phi\pi} = (3.6^{+3.1+0.4}_{-1.6-1.3}) \%$ . This value is consistent with the previous BES result  $B_{\phi\pi} = (3.9^{+5.1+1.8}_{-1.9-1.1}) \%$  [1].

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