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

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The absolute inclusive branching fraction of $D_s^+ \to \phi X^+$ 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^{-1}. At this energy, direct pair production $e^+e^- \to D_s^+ D_s^-$ has been observed. We have selected D_s candidate events by reconstructing five hadronic decay modes $D_s^+ \to \phi\pi^+$, $\overline{K^0}{}^* K^+$, $\overline{K^0} K^+$, $f_0\pi^+$ and $K^0 K^- \pi^+ \pi^+$ and have searched for inclusive ϕ's in the recoiling D_s^-. We observed three recoiling ϕ's in the 166.4 $\pm$ 31.8 D_s candidate events, which leads to the absolute branching fraction $B(D_s^+ \to \phi X^+) = (17.8^{+15.1}_{-7.2}{}^{+0.6}_{-6.3})$ % and $B(D_s^+ \to \phi\pi^+) = (3.6^{+3.1}_{-1.6}{}^{+0.4}_{-1.3})$ %. [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 $D_s^+ \to \phi\pi^+$ [1]. Here we consider the absolute branching fraction of $D_s^+ \to$ inclusive ϕ, which contributes toward our understanding of the overall D_s branching fraction scale. Moreover the absolute inclusive branching fraction of $D_s^+ \to \phi X^+$ [2] is used in $B_s^0 \overline{B_s^0}$ 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 ϕ 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^{-1} as determined by large angle Bhabha scattering events at a center-of-mass energy of 4.03 GeV. This is just above $e^+e^- \to D_s^+ D_s^-$ 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: $D_s^+\to\phi\pi^+$, $\overline{K^0}{}^*K^+$, $\overline{K^0}K^+$, $f_0\pi^+$ or $K^0K^-\pi^+\pi^+$. The subresonances are detected by the decays $\phi\to K^+K^-$, $\overline{K^0}{}^*\to K^-\pi^+$, $\overline{K^0}\to K_S^0\to\pi^+\pi^-$, and $f_0\to\pi^+\pi^-$. 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 ϕ, $\overline{K^0}{}^*$, $\overline{K^0}$, 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 ϕ and $\overline{K^0}{}^*$. We required $|\cos\theta_K|>0.25$ in the ϕ rest frame for the $\phi\pi$ mode and $|\cos\theta_K|>0.4$ in the $\overline{K^0}{}^*$ rest frame for the $\overline{K^0}{}^*K$ 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 $\overline{K^0}{}^*K^+$ mode, and $|\cos\theta_{D_s}|<0.85$ for both the $f_0\pi^+$ and the $\overline{K^0}K^+$ 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 $\phi\pi^+$, $\overline{K^0}{}^*K^+$ and $\overline{K^0}K^+$, >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 ($N^i_{\rm sngl}$), 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 $\phi\to K^+K^-$ recoiling against one of the five D_s single tag modes. Recoiling ϕ's were selected with the same track and particle identification requirements described earlier for the $\phi\pi$ single tag mode. ϕ candidates were required to be within 18 MeV/c^2 of the ϕ mass (3 times the resolution for the reconstructed ϕ 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 ($N_{\rm sngl}$), the number of double tag events ($N_{\rm dbl}$), and the inclusive ϕ efficiency ($\epsilon_{\rm dbl}$) as follows:

$$B_{\phi X}=\frac{N_{\rm dbl}}{N_{\rm sngl}\times\epsilon_{\rm dbl}\times B(\phi\to K^+K^-)}. \tag{1}$$

The inclusive ϕ double tag efficiency, $\epsilon_{\rm dbl}$, 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 ϕ 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 ϕ was found recoiling from a sideband of the $\overline{K^0}{}^*K^+$ tag. No background event was detected in the $\phi\pi^+$ side band region. For both $\phi\pi^+$ and $\overline{K^0}{}^*K^+$ 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 $\overline{K^0}{}^*K^+$ side band region implies an estimated background of $0.13^{+0.30}_{-0.04}$. 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 $0.0^{+0.26}_{-0.0}$.

There is no background event from the the recoil ϕ 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 ϕ, 0.712–0.832 and 0.952–1.072 GeV/c^2 for $\overline{K^{*0}}$, 0.4376–0.4776 and 0.5176–0.5576 GeV/c^2 for $\overline{K^0}$, 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.

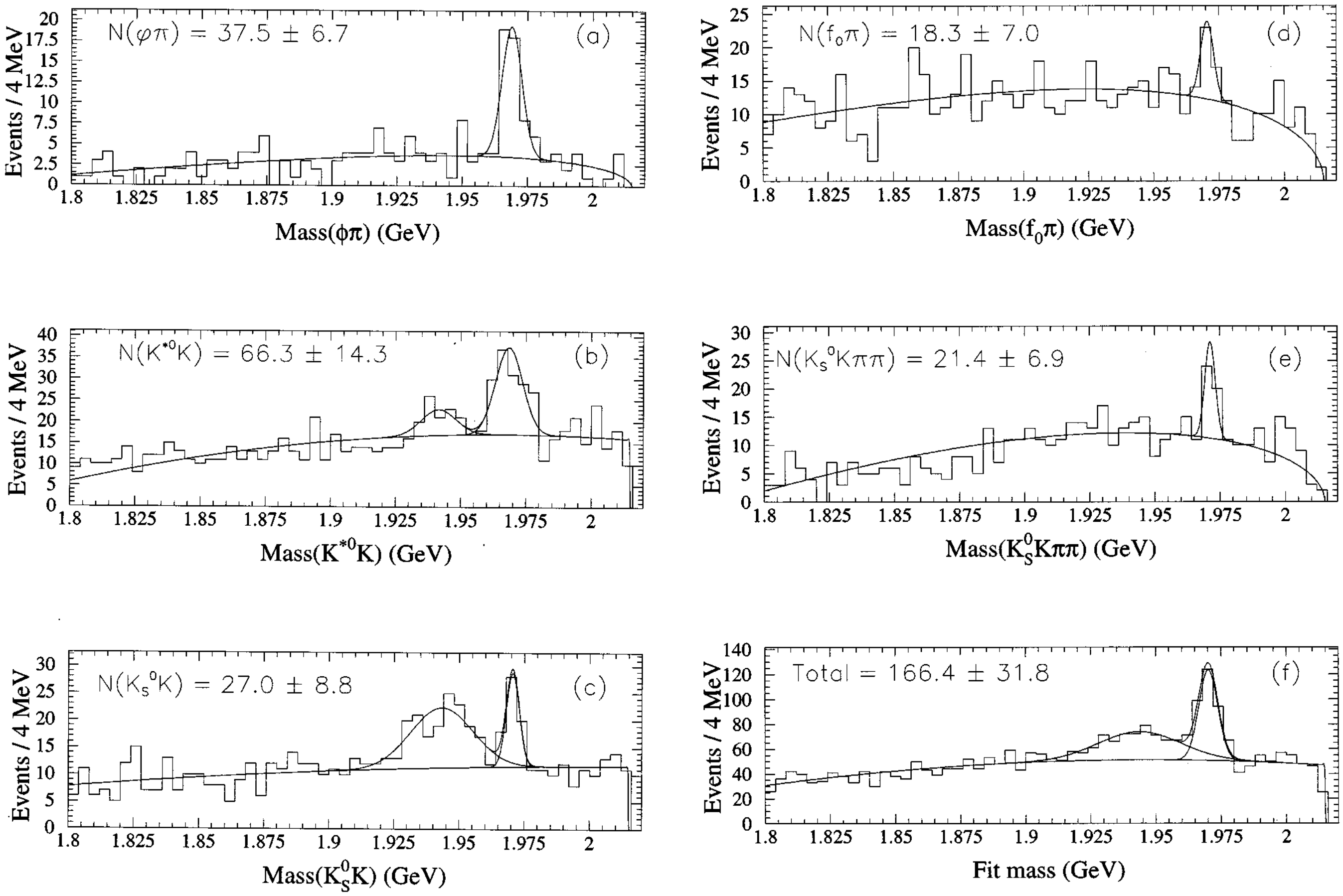

FIG. 1. Kinematically fit mass of D_s candidates. The curves are the result of unbinned fits to the data.

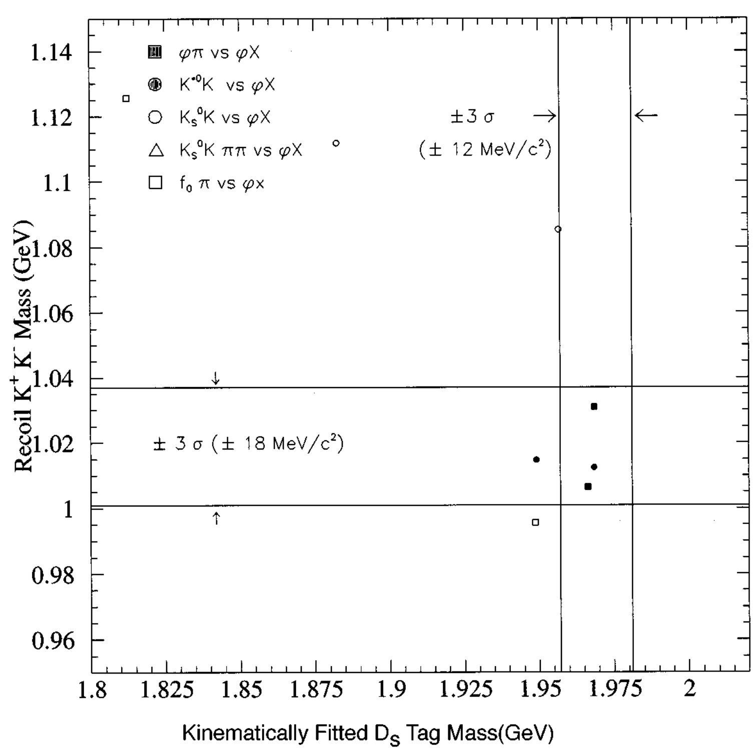

FIG. 2. Double tag candidates.

TABLE I. Properties of the double tag candidates.

Event	1	2	3
Tagging D_s Decay	$\phi\pi^+$	$\phi\pi^+$	$\overline{K^0}{}^*K^+$
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 ϕ 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 $\overline{K^0}K^+$, $f_0\pi^+$, and $K^0K^-\pi^+\pi^+$ modes, the background estimates do not affect the shape of the likelihood function.

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

$$L^i(B_{\phi X}, N^i_{\rm sngl}; \epsilon^i_{\rm dbl}, N^i_{\rm dbl}, N^i_{\rm bg}),$$

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:

$$L(B_{\phi X}) = \prod_i L^i_{\rm mar}(B_{\phi X}), \tag{2}$$

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:

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

The likelihood function L^i is given by

$$L^i = \frac{A_i^{N^i_{\rm dbl}}}{N^i_{\rm dbl}!} e^{-A_i},$$

where

$$A_i \equiv B_{\phi X} N^i_{\rm sngl} \epsilon^i_{\rm dbl} B(\phi \to K^+K^-) + N^i_{bg}.$$

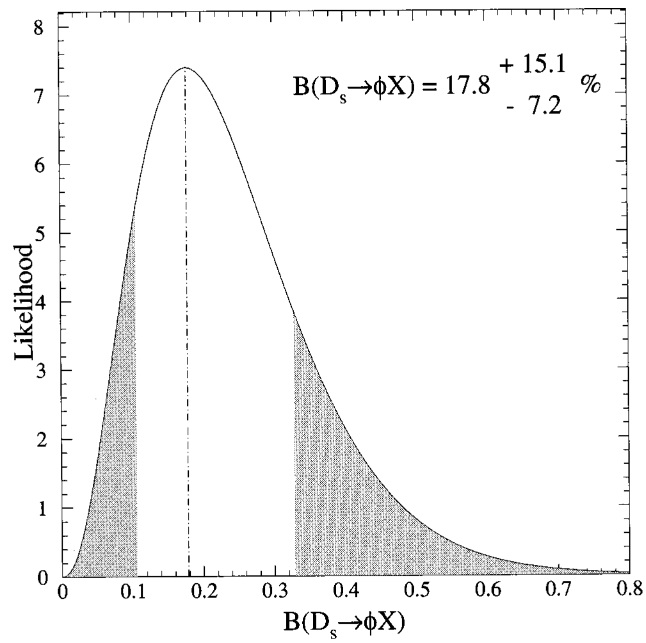

FIG. 3. The variation of the normalized likelihood function with respect to $B_{\phi X}$; the unshaded area under the curve denotes the 68% confidence interval.

The value of the likelihood function, $L(B_{\phi X})$, is shown in Fig. 3. The maximum likelihood solution is $B_{\phi X} = (17.8^{+15.1}_{-7.2})\%$, 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 ϕ efficiency, $\epsilon_{\rm dbl}$, 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 $^{+1.0}_{-35.0}\% \times B_{\phi X}$ uncertainty. After combining the systematic errors in quadrature, the final result for $B_{\phi X}$ is

TABLE II. Result of the measurement.

Decay mode	$N^i_{\rm sngl}$	$N^i_{\rm dbl}$	$\epsilon^i_{\rm dbl}$	N^i_{bg}
$\phi\pi^+$	37.5 ± 6.7	2	0.202 ± 0.004	$0.0^{+0.26}_{-0.0}$
$\overline{K^0}{}^*K^+$	66.3 ± 14.3	1	0.200 ± 0.005	$0.13^{+0.30}_{-0.04}$
$\overline{K^0}K^+$	27.0 ± 8.8	0	0.190 ± 0.004	N/A
$f_0\pi^+$	18.3 ± 7.0	0	0.180 ± 0.005	N/A
$K^0K^-\pi^+\pi^+$	21.4 ± 6.9	0	0.181 ± 0.007	N/A

TABLE III. Inclusive ϕ decay modes of D_s (PDG 1996).

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

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

This is a direct measurement of the D_s inclusive ϕ branching fraction that is model-independent. The present world average value from indirect or model-dependent procedures is $B_{\phi X}=(18.2\pm5.2)$ % (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 $B(D_s^+\to\phi X^+)$ = (4.84 ± 0.51) b_s [7], where b_s is the measured branching fraction of $D_s^+\to\phi\pi^+$. Using the Particle Data Group (PDG) (1996) [8] value yields $B_{\phi X}=(17.4\pm4.7)\%$.

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 ϕ remain unmeasured. Scaling $B_{\phi X}$ by the sum of the world average values of Γ_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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