Eur. Phys. J. C 47, 39–44 (2006)
Digital Object Identifier (DOI) 10.1140/epjc/s2006-02563-1

THE EUROPEAN
PHYSICAL JOURNAL C

Search for $D^+ \to \phi l^+ \nu$ and measurement of the branching fraction for $D^+ \to \phi\pi^+$

The BES Collaboration

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Received: 17 December 2005 / Revised version: 7 April 2006 /
Published online: 15 May 2006 –

Abstract. Using a data sample of integrated luminosity of about 33 pb^{-1} collected around 3.773 GeV with the BESII detector at the BEPC collider, the semileptonic decays $D^+ \to \phi e^+ \nu_e$, $D^+ \to \phi \mu^+ \nu_\mu$ and the hadronic decay $D^+ \to \phi\pi^+$ are studied. The upper limits of the branching fractions are set to be $BF(D^+ \to \phi e^+ \nu_e) < 2.01\%$ and $BF(D^+ \to \phi \mu^+ \nu_\mu) < 2.04\%$ at the 90% confidence level. The ratio of the branching fractions for $D^+ \to \phi\pi^+$ relative to $D^+ \to K^-\pi^+\pi^+$ is measured to be $0.057 \pm 0.011 \pm 0.003$. In addition, the branching fraction for $D^+ \to \phi\pi^+$ is obtained to be $(5.2 \pm 1.0 \pm 0.4) \times 10^{-3}$.

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1 Introduction

Searching for new modes in charm decays is of great interest. It not only investigates possible decay mechanism and finds its contribution to the total decay width, but is also useful to simulate accurately cascade decays of bottom mesons and to eliminate backgrounds of charm modes in studying bottom decays.

In this paper, the semileptonic and hadronic D decays in which the final state particles contain a ϕ meson are studied. Whenever a specific state or decay mode is mentioned in this work, the charge-conjugate state or decay mode is always implied.

2 BESII detector

The BESII detector upgraded from the BES [1] is a large solid-angle magnetic spectrometer described in detail elsewhere [2]. A 12–layer vertex chamber (VC) surrounding the beryllium beam pipe provides the trigger and coordinate informations. A forty-layer main drift chamber (MDC), located outside the VC, yields precise measurements of charged particle trajectories with a solid angle coverage of 85% of 4π; it also provides ionization energy loss ($\mathrm{d}E/\mathrm{d}x$) measurements used for particle identification. Momentum resolution of $1.78\%\sqrt{1+p^2}$ (p in GeV/c) and $\mathrm{d}E/\mathrm{d}x$ resolution of 8.5% for Bhabha scattering are obtained for data taken at $\sqrt{s}=3.773$ GeV. An array of 48 scintillation counters surrounding the MDC measures the time of flight (TOF) of charged particles with a resolution of about 180 ps for electrons. Outside the TOF is a 12 radiation length barrel shower counter (BSC) comprised of gas tubes interleaved with lead sheets. The BSC measures the energies of electrons and photons over 80% of the total solid angle with an energy resolution of $\sigma_{\mathrm{E}}/E = 0.22/\sqrt{E}$ (E in GeV) and spatial resolution of $\sigma_\phi = 7.9$ mrad and $\sigma_{\mathrm{Z}} = 2.3$ cm for electrons. A solenoidal magnet outside the BSC provides a 0.4 T magnetic field in the central tracking region of the detector. The magnet flux return is instrumented with three double layers of counters, that are used to identify muons with momentum greater than 500 MeV/c and cover 68% of the total solid angle.

3 Data analysis

The data used for this analysis were collected around the center-of-mass energy of 3.773 GeV with the BESII detector operated at the Beijing Electron Positron Collider (BEPC). The total integrated luminosity of the data set is about 33 pb^{-1}. At the center-of-mass energy 3.773 GeV, the $\psi(3770)$ resonance is produced in electron-positron (e^+e^-) annihilation. The $\psi(3770)$ decays predominately into $D\bar{D}$ pairs. If one $\bar{D}$ meson is fully reconstructed, the D meson must exist in the system recoiling against the fully reconstructed $\bar{D}$ meson (called singly tagged $\bar{D}$). Using the singly tagged D^- sample, the semileptonic decays $D^+ \to \phi e^+ \nu_{\mathrm{e}}$ and $D^+ \to \phi\mu^+\nu_\mu$ are searched in the recoiling system. The hadronic candidates $D^+ \to \phi\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ are reconstructed directly from the data sample of 33 pb^{-1}.

3.1 Event selection

Events which contain at least three charged tracks with good helix fits are selected. To ensure good momentum resolution and reliable charged particle identification, every charged track is required to satisfy $|cos\theta| < 0.85$, where θ is the polar angle. All tracks, save those from K^0_{S} decays, must originate from the interaction region by requiring that the closest approach of a charged track is less than 2.0 cm in the xy plane and 20 cm in the z direction. Pions and kaons are identified by means of the combined particle confidence level which is calculated with information from the $\mathrm{d}E/\mathrm{d}x$ and TOF measurements [3, 4]. Pion identification requires a consistency with the pion hypothesis at a confidence level (CL_π) greater than 0.1%. In order to reduce misidentification, a kaon candidate is required to have a larger confidence level (CL_{K}) for a kaon hypothesis than that for a pion hypothesis. For electron or muon identification, the combined particle confidence level (CL_{e} or CL_μ), calculated for the e or μ hypothesis using the $\mathrm{d}E/\mathrm{d}x$, TOF and BSC measurements, is required to be greater than 0.1%.

The π^0 is reconstructed in the decay of $\pi^0 \to \gamma\gamma$. To select good photons from the π^0 decay, the energy deposited in the BSC is required to be greater than 0.07 GeV, and the electromagnetic shower is required to start in the first 5 readout layers. In order to reduce backgrounds, the angle between the photon and the nearest charged track is required to be greater than 22°, and the angle between the cluster development direction and the photon emission direction to be less than 37° [3, 4].

3.2 Singly tagged D^- sample

The singly tagged D^- sample used in the analysis was selected previously [3–6]. The singly tagged D^- mesons were reconstructed in the nine hadronic modes of $D^- \to K^+\pi^-\pi^-$, $K^0_{\mathrm{S}}\pi^-$, $K^0_{\mathrm{S}}K^-$, $K^-K^+\pi^-$, $K^0_{\mathrm{S}}\pi^-\pi^-\pi^+$, $K^0_{\mathrm{S}}\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^-\pi^+$ and $\pi^-\pi^-\pi^+$. The distributions of the fitted invariant masses of the $mKn\pi$ ($m=0,1,2; n=1,2,3,4$) combinations are shown in Fig. 1. The number of the singly tagged D^- mesons is $5321 \pm 149 \pm 160$ [5, 6], where the first error is statistical and the second systematic.

3.3 Candidates for $D^+ \to \phi e^+ \nu_{\mathrm{e}}$ and $D^+ \to \phi\mu^+\nu_\mu$

Candidates for $D^+ \to \phi e^+ \nu_{\mathrm{e}}$ and $D^+ \to \phi\mu^+\nu_\mu$ are selected from the surviving tracks in the system recoiling against

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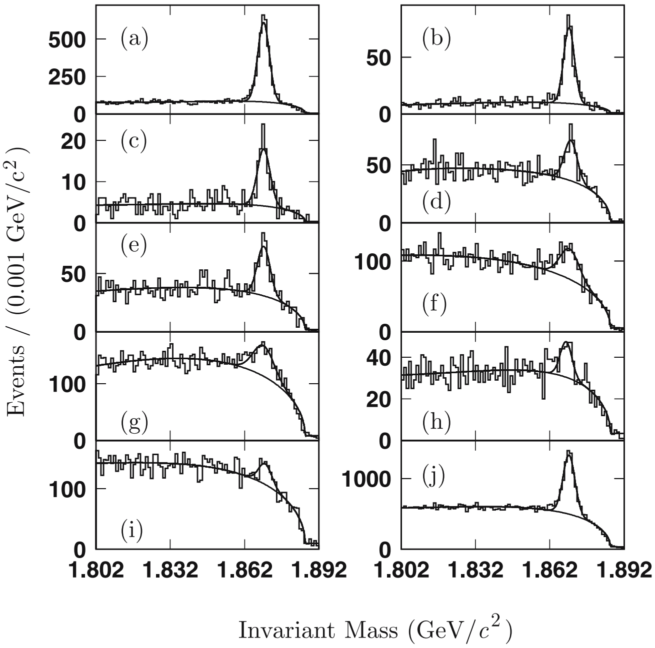

Fig. 1. The distributions of the fitted invariant masses of **a** $K^+\pi^-\pi^-$, **b** $K^0_S\pi^-$, **c** $K^0_S K^-$, **d** $K^+K^-\pi^-$, **e** $K^0_S\pi^-\pi^-\pi^+$, **f** $K^0_S\pi^-\pi^0$, **g** $K^+\pi^-\pi^-\pi^0$, **h** $K^+\pi^+\pi^-\pi^-\pi^-$, **i** $\pi^-\pi^-\pi^+$ combinations; **j** is the fitted masses of the $mKn\pi$ combinations for the nine modes combined together

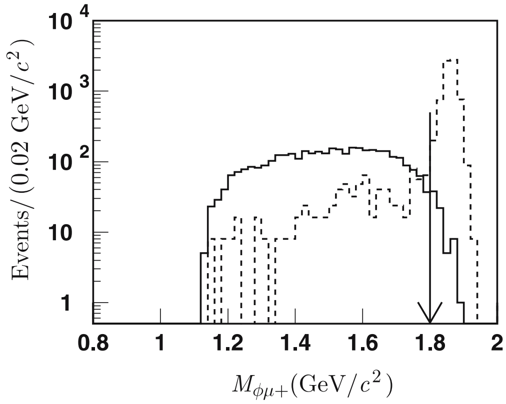

Fig. 2. The distributions of the invariant masses of $\phi\mu^+$ (*solid*) and $\phi\pi^+$ (*dashed*) for $D^+ \to \phi\mu^+\nu_\mu$ and $D^+ \to \phi\pi^+$ from Monte Carlo events

the tagged D^-. To select these candidates, it is required that there are three charged tracks, one of which is identified as an electron or a muon with the charge opposite to the charge of the tagged D^- meson, the other two are identified as a K^+ and a K^- mesons. The ϕ meson is selected by requiring that the difference between the invariant mass of K^+K^- and the nominal ϕ mass should be less than $20\,\mathrm{MeV/c^2}$.

In the semileptonic decays, one neutrino is undetected. A kinematic quantity $U_{\mathrm{miss}} \equiv E_{\mathrm{miss}} - p_{\mathrm{miss}}$ is used to obtain the information of the missing neutrino, where E_{miss} and p_{miss} are the total energy and the total momentum of all missing particles respectively. Monte Carlo study shows that the background modes for $D^+ \to \phi e^+(\mu^+)\nu_{\mathrm{e}(\mu)}$ come primarily from $D^+ \to \phi\mu^+(e^+)\nu_{\mu(\mathrm{e})}$, $D^+ \to \phi\pi^+\pi^0$ and $D^+ \to \phi\pi^+$. The requirement $|U_{\mathrm{miss}}| < 3\sigma_{\mathrm{U_{miss}}}$ is imposed to reduce these backgrounds, where $\sigma_{\mathrm{U_{miss}}}$ is the standard deviation of the U_{miss} distribution obtained from Monte Carlo simulation. In Fig. 2, the solid and dashed histograms show respectively the distributions of the invariant masses of $\phi\mu^+$ and $\phi\pi^+$ for $D^+ \to \phi\mu^+\nu_\mu$ and $D^+ \to \phi\pi^+$ from Monte Carlo events. The candidate mode $D^+ \to \phi\mu^+\nu_\mu$ has a potential hadronic background of $D^+ \to \phi\pi^+$ due to the misidentification of a charged pion as a muon. These backgrounds can be suppressed by requiring the invariant masses of the $\phi\mu^+$ combinations to be less than $1.8\,\mathrm{GeV/c^2}$. Similarly the invariant masses of the ϕe^+ combinations are also required to be less than $1.8\,\mathrm{GeV/c^2}$ in order to remove the $D^+ \to \phi\pi^+$ background for the $D^+ \to \phi e^+\nu_{\mathrm{e}}$ decay. To suppress backgrounds from decays with neutral pion, for example $D^+ \to \phi\pi^+\pi^0$, the number of the isolated photons is required to equal two if the singly tagged D^- mode contains a π^0 meson, otherwise zero. The events with isolated photons those energies are larger than 0.1 GeV excluded in the tagged D^- are not kept. Figure 3 and Fig. 4 show respectively the scatter plots of the invariant masses of the K^+K^- combination versus the $mKn\pi$ combination for $D^+ \to \phi e^+\nu_{\mathrm{e}}$ and $D^+ \to \phi\mu^+\nu_\mu$ before and after applying both U_{miss} and $M_{\phi l^+}$ cuts. No event for the $D^+ \to \phi e^+\nu_{\mathrm{e}}$ and $D^+ \to \phi\mu^+\nu_\mu$ decays satisfies the selection criteria.

3.4 Candidates for $D^+ \to \phi\pi^+$ and $D^+ \to K^-\pi^+\pi^+$

The candidate for $D^+ \to \phi\pi^+$ is reconstructed from $D^+ \to K^+K^-\pi^+$. The distribution of the fitted invariant mass of the $K^+K^-\pi^+$ combination is shown in Fig. 1d. As mentioned in previous subsection, the ϕ meson is selected though its decay to K^+K^-. Figure 5a shows the fitted invariant mass spectrum of the K^+K^- pairs from the D^+

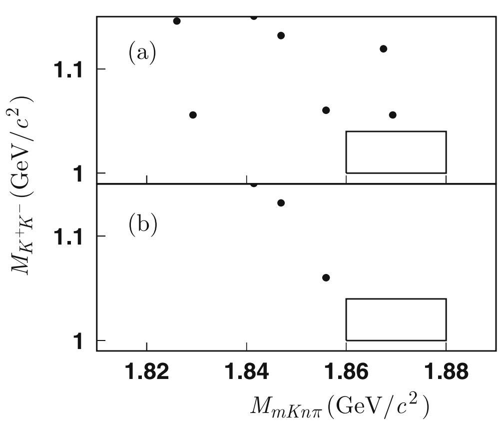

Fig. 3. Scatter plot of the K^+K^- invariant masses versus the $mKn\pi$ invariant masses for the $D^+ \to \phi e^+\nu_{\mathrm{e}}$ candidates: **a** before and **b** after applying both U_{miss} and $M_{\phi\mathrm{e}^+}$ cuts, where the rectangle represents the combined signal region of ϕ and D^+

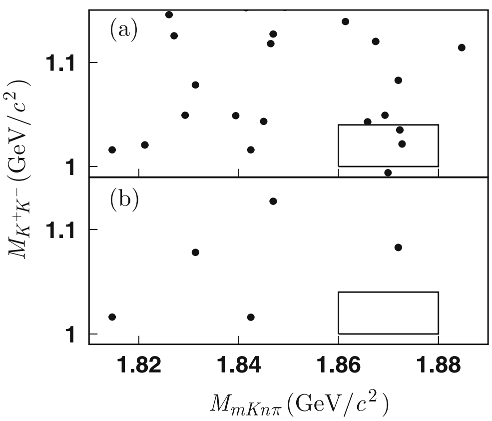

Fig. 4. Scatter plot of the K^+K^- invariant masses versus the $mKn\pi$ invariant masses for the $D^+ \to \phi\mu^+\nu_\mu$ candidates: **a** before and **b** after applying both $U_{\rm miss}$ and $M_{\phi\mu^+}$ cuts, where the rectangle represents the combined signal region of ϕ and D^+

signal region for the $D^+ \to K^+K^-\pi^+$ candidate events. Fitting the mass spectrum with a Gaussian function convoluted Breit–Wigner gives 64.3 ± 10.3 ϕ signal events. To select the decay $D^+ \to \phi\pi^+$, we require the invariant mass of the K^+K^- combination to be within $20\,\rm MeV/c^2$ of the nominal ϕ mass, and the invariant mass distribution of $K^+K^-\pi^+$ combination is shown in Fig. 5b, a clear signal of the decay $D^+ \to \phi\pi^+$ is observed. Fitting the mass spectrum of the $K^+K^-\pi^+$ combination with a Gaussian function as the signal and a special function [3, 4] for the background yields 55.6 ± 8.6 signal events, where the mass resolution is fixed at $0.0022\,\rm GeV/c^2$ determined from the Monte Carlo simulation. There may be the K^+K^- combinatorial background in the observed $\phi\pi^+$ events. The background events are estimated to be 6.1 ± 2.5 by the ϕ sideband $|M_{\rm K^+K^-} - 1.10| < 0.05\,\rm GeV/c^2$. For the $D^+ \to K^-\pi^+\pi^+$ candidates, the fitted invariant mass spectrum is shown in Fig. 1a, and 3153.8 ± 69.2 events are yielded from the fit.

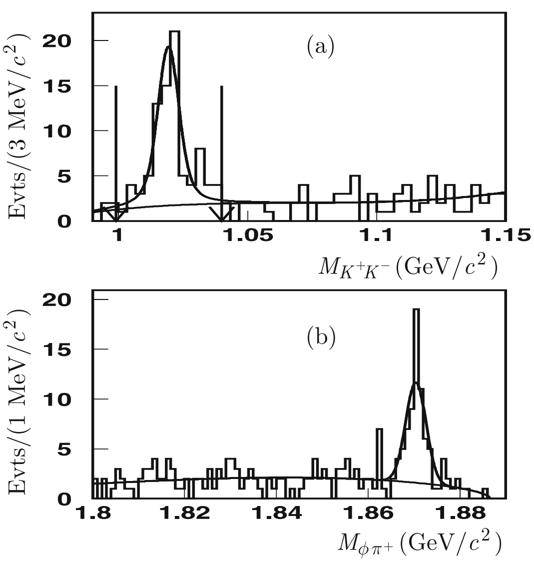

Fig. 5. The distributions of the fitted invariant masses of **a** K^+K^- combination in the D^+ signal region, **b** $K^+K^-\pi^+$ combination in the ϕ signal region

In the fitted yields, there are still some background contaminations which shape a peak under the D^+ peak. These backgrounds are estimated by analyzing the Monte Carlo sample which is about 14 times larger than the data. The Monte Carlo events are generated as $e^+e^- \to D\overline{D}$, and both D and $\overline{D}$ mesons decay to all possible modes according to the decay modes and the branching fractions quoted from PDG [7] excluding decay modes under study. The number of events satisfying the selection criteria is then normalized to the data. For the $D^+ \to \phi\pi^+$ decay, the dominant background modes are $D^+ \to \phi\mu^+\nu_\mu$, $D^+ \to \phi e^+\nu_{\rm e}$ and $D^+ \to \phi\pi^+\pi^0$, and the number of the background events is 3.6 ± 1.1. For the $D^+ \to K^-\pi^+\pi^+$ decay, the number of the background events is 35.2 ± 4.2, After subtracting the numbers of the background events, 45.9 ± 9.0 and 3118.6 ± 69.3 signal events for the $D^+ \to \phi\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ decays are remained.

4 Results

4.1 Monte Carlo efficiency

The reconstruction efficiencies of the semileptonic decays $D^+ \to \phi e^+\nu_{\rm e}$, $D^+ \to \phi\mu^+\nu_\mu$ and the hadronic decays $D^+ \to \phi\pi^+$, $D^+ \to K^-\pi^+\pi^+$ are estimated by Monte Carlo simulation with the GEANT3 based Monte Carlo simulation package [8]. A detailed Monte Carlo study shows that the efficiencies are $\epsilon_{\phi e^+\nu_{\rm e}} = (2.46 \pm 0.03)\%$, $\epsilon_{\phi\mu^+\nu_\mu} = (2.43 \pm 0.03)\%$, $\epsilon_{\phi\pi^+} = (6.47 \pm 0.05)\%$ and $\epsilon_{\rm K^-\pi^+\pi^+} = (24.99 \pm 0.13)\%$.

4.2 Branching fraction

A D^+ signal is observed neither in the $D^+ \to \phi e^+\nu_{\rm e}$ decay nor in the $D^+ \to \phi\mu^+\nu_\mu$ decay. The upper limit of the branching fraction can be calculated using

$$BF < \frac{N_{\rm sg}}{\epsilon N_{\rm tag}^{\rm D^-}(1-\delta)}\,, \tag{1}$$

where $N_{\rm sg}$ is the upper limit of the signal yield given with the Feldman–Cousins prescription [9], which is 2.44 for zero observed event in the absence of background for the confidence level of 90%, ϵ is the detection efficiency, $N_{\rm tag}^{\rm D^-}$ is the number of the singly tagged D^- mesons and δ is the systematic error. The upper limits of the branching fractions are summarized in the second column of Table 1. Comparisons with those obtained by MARKIII [10] and BESI [11] experiments are also listed in the third and fourth columns of Table 1. The systematic error, δ, includes the uncertainties from particle identification (1.4% for $D^+ \to \phi e^+\nu_{\rm e}$, 1.6% for $D^+ \to \phi\mu^+\nu_\mu$), tracking efficiency (2.0% per track), photon reconstruction (2.0%), $U_{\rm miss}$ selection (0.6%), the number of the singly tagged D^- mesons (3.0%) and Monte Carlo statistics (1.2%). These

Table 1. Upper limits for the branching fractions (%) are given at the 90% confidence level

Mode	BESII	MARKIII	BESI
$D^+ \to \phi e^+ \nu_e$	< 2.01	< 2.09	1.38
$D^+ \to \phi \mu^+ \nu_\mu$	< 2.04	< 3.72	–

uncertainties are added in quadrature to obtain the total systematic errors to be 7.3% for $D^+ \to \phi e^+ \nu_e$ and 7.4% for $D^+ \to \phi \mu^+ \nu_\mu$. The ratio of the branching fractions for $D^+ \to \phi\pi^+$ relative to $D^+ \to K^-\pi^+\pi^+$ can be obtained by

$$\frac{BF(D^+ \to \phi\pi^+)}{BF(D^+ \to K^-\pi^+\pi^+)} = \frac{N_{\phi\pi^+}}{N_{K^-\pi^+\pi^+}} \frac{\epsilon_{K^-\pi^+\pi^+}}{\epsilon_{\phi\pi^+}}, \qquad (2)$$

where $N_{\phi\pi^+}$, $N_{K^-\pi^+\pi^+}$ are the numbers of the signal events, and $\epsilon_{\phi\pi^+}$, $\epsilon_{K^-\pi^+\pi^+}$ are the detection efficiencies for the tagging and normalizing modes. Inserting these numbers into (2), the relative branching fraction is obtained to be $0.057 \pm 0.011 \pm 0.003$, where the first error is statistical, and the second systematic. By normalizing $D^+ \to \phi\pi^+$ to $D^+ \to K^-\pi^+\pi^+$, the systematic uncertainty from tracking efficiency can be canceled. The residual error, including both contributions of the tagging and normalizing modes, arises from uncertainties in particle identification (0.5% for uncanceled kaon track in $D^+ \to \phi\pi^+$, 0.5% for uncanceled pion track in $D^+ \to K^-\pi^+\pi^+$),the number of the singly tagged D^+ meson (3.7% for $D^+ \to \phi\pi^+$, 3.3% for $D^+ \to K^-\pi^+\pi^+$), background uncertainty (1.4% for $D^+ \to \phi\pi^+$, 0.2% for $D^+ \to K^-\pi^+\pi^+$) and Monte Carlo statistics (0.8% for $D^+ \to \phi\pi^+$, 0.5% for $D^+ \to K^-\pi^+\pi^+$). These uncertainties are added in quadrature to obtain the total systematic error to be 5.3%. The relative branching fraction is compared with other measurements in Table 2. In addition, the branching fraction for $D^+ \to \phi\pi^+$ is obtained to be

$$BF(D^+ \to \phi\pi^+) = (5.2 \pm 1.0 \pm 0.4) \times 10^{-3} \qquad (3)$$

by using the branching fraction of the $D^+ \to K^-\pi^+\pi^+$ decay quoted from PDG [7], where the first error is statistical and the second systematic. The systematic error of the branching fraction for $D^+ \to \phi\pi^+$ includes the systematic error of the ratio $BF(D^+ \to \phi\pi^+)/BF(D^+ \to K^-\pi^+\pi^+)$ (5.3%) and the uncertainty of the branching fraction for $D^+ \to K^-\pi^+\pi^+$ (6.5%). The total systematic error is obtained to be 8.4% by adding these uncorrelated errors in quadrature.

Table 2. Ratio of partial widths $\frac{\Gamma(D^+ \to \phi\pi^+)}{\Gamma(D^+ \to K^-\pi^+\pi^+)}$ and comparison with other experiments (Evts stands for $D^+ \to \phi\pi^+$)

Reference	$\frac{\Gamma(D^+ \to \phi\pi^+)}{\Gamma(D^+ \to K^-\pi^+\pi^+)}$	Evts
BESII(this work)	$0.057 \pm 0.011 \pm 0.003$	46
E687 [12]	$0.058 \pm 0.006 \pm 0.006$	–
WA82 [13]	$0.062 \pm 0.017 \pm 0.006$	19
CLEO [14]	$0.077 \pm 0.011 \pm 0.005$	128
NA14 [15]	$0.098 \pm 0.032 \pm 0.014$	12
E691 [16]	$0.071 \pm 0.008 \pm 0.007$	84
MARKIII [17]	$0.084 \pm 0.021 \pm 0.011$	21

5 Summary

Using a data sample of integrated luminosity of 33 pb^{-1} collected around 3.773 GeV with the BESII detector at the BEPC, the semileptonic decays $D^+ \to \phi e^+ \nu_e$, $D^+ \to \phi \mu^+ \nu_\mu$ and the hadronic decay $D^+ \to \phi\pi^+$ are studied. The upper limits of the branching fractions are set to be $BF(D^+ \to \phi e^+ \nu_e) < 2.01\%$ and $BF(D^+ \to \phi \mu^+ \nu_\mu) < 2.04\%$ at the 90% confidence level. The ratio of the branching fractions for $D^+ \to \phi\pi^+$ relative to $D^+ \to K^-\pi^+\pi^+$ is measured to be $0.057 \pm 0.011 \pm 0.003$. In addition, the branching fraction for $D^+ \to \phi\pi^+$ is obtained to be $(5.2 \pm 1.0 \pm 0.4) \times 10^{-3}$.

Acknowledgements. The BES collaboration thanks the staff of BEPC for their hard efforts. This work is supported in part by the National Natural Science Foundation of China under contracts Nos. 10 491 300, 10 225 524, 10 225 525, 10 425 523, the Chinese Academy of Sciences under contract No. KJ 95T-03, the 100 Talents Program of CAS under Contract Nos. U-11, U-24, U-25, the Knowledge Innovation Project of CAS under Contract Nos. U-602, U-34 (IHEP), the National Natural Science Foundation of China under Contract No. 10 225 522 (Tsinghua University).

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