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Measurement of Inclusive Production of η, η' and ϕ Mesons in D^0, D^+ and D_s^+ Decays

G. S. Huang,[1] D. H. Miller,[1] V. Pavlunin,[1] B. Sanghi,[1] I. P. J. Shipsey,[1] B. Xin,[1] G. S. Adams,[2] M. Anderson,[2] J. P. Cummings,[2] I. Danko,[2] J. Napolitano,[2] Q. He,[3] J. Insler,[3] H. Muramatsu,[3] C. S. Park,[3] E. H. Thorndike,[3] F. Yang,[3] T. E. Coan,[4] Y. S. Gao,[4] M. Artuso,[5] S. Blusk,[5] J. Butt,[5] J. Li,[5] N. Menaa,[5] R. Mountain,[5] S. Nisar,[5] K. Randrianarivony,[5] R. Sia,[5] T. Skwarnicki,[5] S. Stone,[5] J. C. Wang,[5] K. Zhang,[5] S. E. Csorna,[6] G. Bonvicini,[7] D. Cinabro,[7] M. Dubrovin,[7] A. Lincoln,[7] D. M. Asner,[8] K. W. Edwards,[8] R. A. Briere,[9] J. Chen,[9] T. Ferguson,[9] G. Tatishvili,[9] H. Vogel,[9] M. E. Watkins,[9] J. L. Rosner,[10] N. E. Adam,[11] J. P. Alexander,[11] K. Berkelman,[11] D. G. Cassel,[11] J. E. Duboscq,[11] K. M. Ecklund,[11] R. Ehrlich,[11] L. Fields,[11] R. S. Galik,[11] L. Gibbons,[11] R. Gray,[11] S. W. Gray,[11] D. L. Hartill,[11] B. K. Heltsley,[11] D. Hertz,[11] C. D. Jones,[11] J. Kandaswamy,[11] D. L. Kreinick,[11] V. E. Kuznetsov,[11] H. Mahlke-Krüger,[11] P. U. E. Onyisi,[11] J. R. Patterson,[11] D. Peterson,[11] J. Pivarski,[11] D. Riley,[11] A. Ryd,[11] A. J. Sadoff,[11] H. Schwarthoff,[11] X. Shi,[11] S. Stroiney,[11] W. M. Sun,[11] T. Wilksen,[11] M. Weinberger,[11] S. B. Athar,[12] R. Patel,[12] V. Potlia,[12] J. Yelton,[12] P. Rubin,[13] C. Cawlfield,[14] B. I. Eisenstein,[14] I. Karliner,[14] D. Kim,[14] N. Lowrey,[14] P. Naik,[14] C. Sedlack,[14] M. Selen,[14] E. J. White,[14] J. Wiss,[14] R. E. Mitchell,[15] M. R. Shepherd,[15] D. Besson,[16] T. K. Pedlar,[17] D. Cronin-Hennessy,[18] K. Y. Gao,[18] J. Hietala,[18] Y. Kubota,[18] T. Klein,[18] B. W. Lang,[18] R. Poling,[18] A. W. Scott,[18] A. Smith,[18] P. Zweber,[18] S. Dobbs,[19] Z. Metreveli,[19] K. K. Seth,[19] A. Tomaradze,[19] J. Ernst,[20] H. Severini,[21] S. A. Dytman,[22] W. Love,[22] V. Savinov,[22] O. Aquines,[23] Z. Li,[23] A. Lopez,[23] S. Mehrabyan,[23] H. Mendez,[23] and J. Ramirez[23]

(CLEO Collaboration)

[1]Purdue University, West Lafayette, Indiana 47907
[2]Rensselaer Polytechnic Institute, Troy, New York 12180
[3]University of Rochester, Rochester, New York 14627
[4]Southern Methodist University, Dallas, Texas 75275
[5]Syracuse University, Syracuse, New York 13244
[6]Vanderbilt University, Nashville, Tennessee 37235
[7]Wayne State University, Detroit, Michigan 48202
[8]Carleton University, Ottawa, Ontario, Canada K1S 5B6
[9]Carnegie Mellon University, Pittsburgh, Pennsylvania 15213
[10]Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637
[11]Cornell University, Ithaca, New York 14853
[12]University of Florida, Gainesville, Florida 32611
[13]George Mason University, Fairfax, Virginia 22030
[14]University of Illinois, Urbana-Champaign, Illinois 61801
[15]Indiana University, Bloomington, Indiana 47405
[16]University of Kansas, Lawrence, Kansas 66045

[17] *Luther College, Decorah, Iowa 52101*
[18] *University of Minnesota, Minneapolis, Minnesota 55455*
[19] *Northwestern University, Evanston, Illinois 60208*
[20] *State University of New York at Albany, Albany, New York 12222*
[21] *University of Oklahoma, Norman, Oklahoma 73019*
[22] *University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[23] *University of Puerto Rico, Mayaguez, Puerto Rico 00681*
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Abstract

We measure the inclusive branching fractions of charm mesons into three mesons with large $s\bar{s}$ content, namely the η, η' and ϕ. Data were accumulated with the CLEO-c detector. For D^0 and D^+ rates, we use 281 pb^{-1} taken on the $\psi(3770)$ resonance, and for D_s^+ rates, we use 195 pb^{-1} taken at 4170 MeV. We find that the production rates of these particles are larger in D_s^+ decays than in D^0 and D^+ decays. The ϕ rate, in particular, is 15 times greater. These branching fractions can be used to measure B_s yields either at the $\Upsilon(5S)$ resonance or at hadron colliders.

I. INTRODUCTION

Inclusive decay rates of charm mesons into mesons with large $s\overline{s}$ inherent quark content, the η, η' and ϕ mesons, are important for studies of both charm and b decays. Non-strange D mesons are generally expected not to decay into such objects, while the D_s^+ is likely to have both s and $\overline{s}$ quarks present after the primary $c \to sW^+$ transition, resulting in many more such particles. This is particularly useful in distinguishing between B and B_s mesons as the B decays into D's with a large rate of $\sim$90%, while the decays into D_s^+ are at the $\sim$10% level. We expect that the reverse is true for B_s mesons. Knowledge of the charm yields into these mesons would allow alternative analyses of B_s rates at the $\Upsilon(5S)$ or at hadron colliders [1].

In this analysis we use 281 pb^{-1} integrated luminosity of CLEO-c data produced in e^+e^- collisions and recorded at the peak of the ψ'' resonance (3.770 GeV) to study the η, η' and ϕ yields in D^0 and D^+ decays. Production in D_s^+ decays is studied at 4170 MeV, where the cross-section for $D_s^{*\pm}D_s^{\mp}$ is $\sim$1 nb [2].

The CLEO-c detector is equipped to measure the momenta and directions of charged particles, identify charged hadrons, detect photons, and determine with good precision their directions and energies. It has been described in more detail previously [3–5].

II. SELECTION OF D^0, D^- AND D_s^- TAGGING MODES

Fully reconstructed charged or neutral D meson candidates are selected from the data at 3.770 GeV, where pairs of $D^0\overline{D}^0$ or D^+D^- mesons are produced. The decay modes used are listed in Table I. In general, in this paper, D refers to either a D^0 or D^+ meson and its anti-particle, and D_s refers to D_s^+ meson and its anti-particle. (Also, mention of a flavor specific state also implies use of the charge-conjugate state.)

Mode	Signal	Background
$K^+\pi^-\pi^-$	77387 ± 281	1868
$K^+\pi^-\pi^-\pi^0$	24850 ± 214	12825
$K_s\pi^-$	11162 ± 136	514
$K_s\pi^-\pi^-\pi^+$	18176 ± 255	8976
$K_s\pi^-\pi^0$	20244 ± 170	5223
Sum D^-	151819 ± 487	29406
$K^+\pi^-$	49418 ± 246	630
$K^+\pi^-\pi^0$	101960 ± 476	18307
$K^+\pi^-\pi^+\pi^-$	76178 ± 306	6421
Sum $\overline{D}^0$	227556 ± 617	25357

TABLE I: Tagging modes and numbers of signal and background events determined from the fits to the D^- and $\overline{D}^0$ beam constrained mass distributions, after making the mode-dependant $m_{\rm BC}$ cuts. The error on the summed signal yield is obtained by adding the errors on the individual yields in quadrature.

At 4.170 GeV [2] we produce $D_s^+ D_s^-$ pairs, with one of the D_s being, most of the time, the daughter of a D_s^* decay. Fully reconstructed D_s^+ candidates are selected in the decay modes listed in Table II. D mesons at this energy are a source of background, they are mostly produced in $D^* \overline{D}^*$ final states, with a cross-section of ∼5 nb, and $D^* \overline{D} + D \overline{D}^*$ final states, with a cross-section of ∼2 nb. $D\overline{D}$ is a relatively small, ∼0.2 nb. There also appears to be $D\overline{D}$ production with extra pions.

Mode	Signal	Background
$K^+K^-\pi^-$	8446 ± 160	6793
K_sK^- $(K_s \to \pi^+\pi^-)$	1852 ± 62	1022
$\eta\pi^-$	1101 ± 80	2803
$\eta'\pi^-$	786 ± 37	242
$\phi\rho^-$	1140 ± 59	1515
$K^{*+}(890)K^{*0}(890)$	1197 ± 81	2599
Sum	14522 ± 218	15328

TABLE II: Tagging modes and number of signal and background events determined from the fits shown in Fig. 4, after making the mode dependant invariant mass cuts. The error on the summed signal yield is obtained by adding the errors on the individual yields in quadrature.

We fully reconstruct one of the D mesons at 3.770 GeV or one of the D_s mesons at 4.170 GeV to form a specific tag, and then look for cases where the particle produced in association with our tag has a decay of either $\eta \to \gamma\gamma$, $\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$, or $\phi \to K^+K^-$.

All acceptable track candidates must have a helical trajectory that approaches the event origin within a distance of 5 mm in the azimuthal projection and 5 cm in the polar view, where the azimuthal projection is in the bend view of the solenoidal magnet. Each track must possess at least 50% of the hits expected to be on a track, and it must be within the fiducial volume of the drift chambers, $|\cos\theta| < 0.93$, where θ is the polar angle with respect to the beam direction.

We reconstruct π^0's by first selecting photon candidates from energy deposits in the crystals that are not matched to charged tracks and that have deposition patterns consistent with that expected for electromagnetic showers. Pairs of photon candidates are kinematically fit to the known π^0 mass [6]. We require the pull, the difference between the reconstructed and known π^0 mass normalized by its uncertainty, to be less than three for acceptable π^0 candidates.

K_S candidates are formed from a pair of charged pions that are constrained to come from a single vertex. We also require that the invariant mass of the two pions be within 4.5 times the width of the K_S mass peak, which has an r.m.s. width of 4 MeV.

We use both charged particle ionization loss in the drift chamber (dE/dx) and Ring-Imaging Cherenkov (RICH) information to identify kaons and pions used to fully reconstruct D and D_s mesons. The RICH is used for momenta above 0.7 GeV/c. The angle of detected Cherenkov photons that were radiated by a particular charged track are translated into an overall likelihood denoted by $\mathcal{L}_i$ for each particle hypothesis. To differentiate between pion and kaon candidates, we require the difference $-2\log(\mathcal{L}_\pi) + 2\log(\mathcal{L}_K)$ to be less than zero. To utilize the dE/dx information, we calculate σ_π as the difference between the expected ionization loss for a pion and the measured loss divided by the measurement error. Similarly, σ_K is defined using the expected ionization for a kaon.

We use both the RICH and dE/dx information for D and D_s meson tag candidate tracks in the following manner: (a) If neither the RICH nor dE/dx information is available, then the track is accepted as both a pion and a kaon candidate. (b) If dE/dx is available and RICH is not then we insist that pion candidates have $PID_{dE} \equiv \sigma_\pi^2 - \sigma_K^2 < 0$, and kaon candidates have $PID_{dE} > 0$. (c) If RICH information is available and dE/dx is not available, then we require that $PID_{RICH} \equiv -2\log(\mathcal{L}_\pi) + 2\log(\mathcal{L}_K) < 0$ for pions and $PID_{RICH} > 0$ for kaons. (d) If both dE/dx and RICH information are available, we require that $(PID_{dE} + PID_{RICH}) < 0$ for pions and $(PID_{dE} + PID_{RICH}) > 0$ for kaons.

A. Reconstruction of $\overline{D}^0$ and D^- Tagging Modes

Tagging modes for D^0 and D^+ decays are reconstructed as described previously [7]. Briefly, at the $\psi(3770)$ D meson final states are reconstructed by first evaluating the difference, ΔE, between the energy of the decay products and the beam energy. We fit the ΔE spectrum with a double Gaussian to represent the signal, and a polynomial representing the background. We require the absolute value of this difference to contain 98.8% of the signal events, *i. e.* to be within $\sim$2.5 times the r.m.s width of the peak value. For final states consisting entirely of tracks, the ΔE resolution is ~ 7 MeV. A π^0 in the final state degrades this resolution by roughly a factor of two. Candidates with ΔE consistent with zero are selected, and then the D beam-constrained mass is evaluated,

$$m_{\rm BC} = \sqrt{E_{\rm beam}^2 - (\sum_i \overrightarrow{p}_i)^2}, \tag{1}$$

where i runs over all the final state particles.

The $m_{\rm BC}$ distributions for all $\overline{D}^0$ and D^- tagging modes are shown in Figs. 1 and 2. Table I lists the numbers of signal and background events within the signal region defined as containing 98.8% of the signal events with $m_{\rm BC}$ below the peak and 95.5% of the signal events above the peak; the interval varies from mode to mode. The numbers of tagged events are determined from fits of the $m_{\rm BC}$ distributions to a signal function plus a background shape. The signal is described by a Crystal Ball Line shape [9, 10]. For the background, we fit with a shape function analogous to one first used by the ARGUS collaboration [8], which has approximately the correct threshold behavior at large $m_{\rm BC}$, except for the $\overline{D}^0 \to K^-\pi^+$ and $\overline{D^0} \to K^-\pi^+\pi^0$ modes where we use a fourth order polynomial. For each tagging mode, the background function is first fit to a $m_{\rm BC}$ distribution that lies within an interval from 5 to 7.5 r.m.s. widths away from the peak of the ΔE distribution. We fix the shape parameters from these fits and then use these functions for background distributions in the signal fits, allowing the normalization to float.

We find $151819 \pm 487 \pm 759$ D^- and $227556 \pm 617 \pm 1138$ $\overline{D}^0$ signal events that we use for further analysis. The systematic uncertainty on this number is estimated to be $\pm 0.5\%$ by varying the fitting functions.

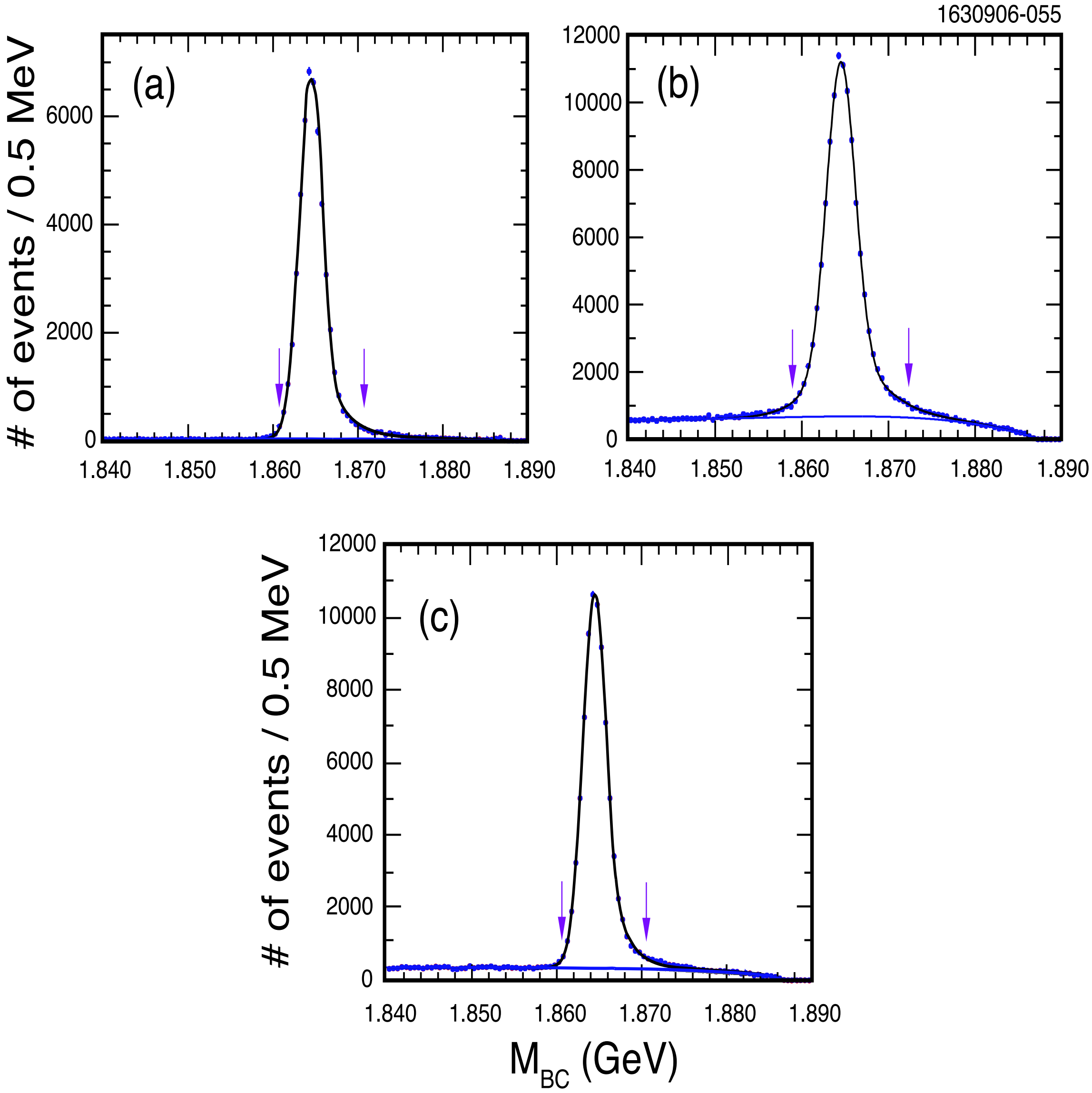

FIG. 1: Beam-constrained mass distributions for fully reconstructed $\overline{D}^0$ decay candidates in the final states: (a) $K^+\pi^-$, (b) $K^+\pi^-\pi^0$, and (c) $K^+\pi^-\pi^-\pi^+$. The distributions are fit to a Crystal Ball Line shape for the signal. For the background, we either use a fourth order polynomial (in (a) and (b)) or an ARGUS shape (in (c)). Both background shapes are obtained from the ΔE sidebands. The regions between the arrows are selected for further analysis.

B. Reconstruction of D_s^- Tagging Modes

At 4170 MeV the presence of the γ from $D_s^{*-} \to \gamma D_s^-$ causes us to adopt a different procedure. If we ignore the photon and reconstruct the $m_{\rm BC}$ distribution, we obtain the distribution from Monte Carlo shown in Fig. 3. The narrow peak occurs when the reconstructed D_s does not come from the D_s^* decay. Thus, the method of applying narrow cuts on $m_{\rm BC}$ and ΔE, used so successfully on the $\psi(3770)$, no longer works.

Instead, we insist that the D_s^- candidate has momenta which satisfies the requirement

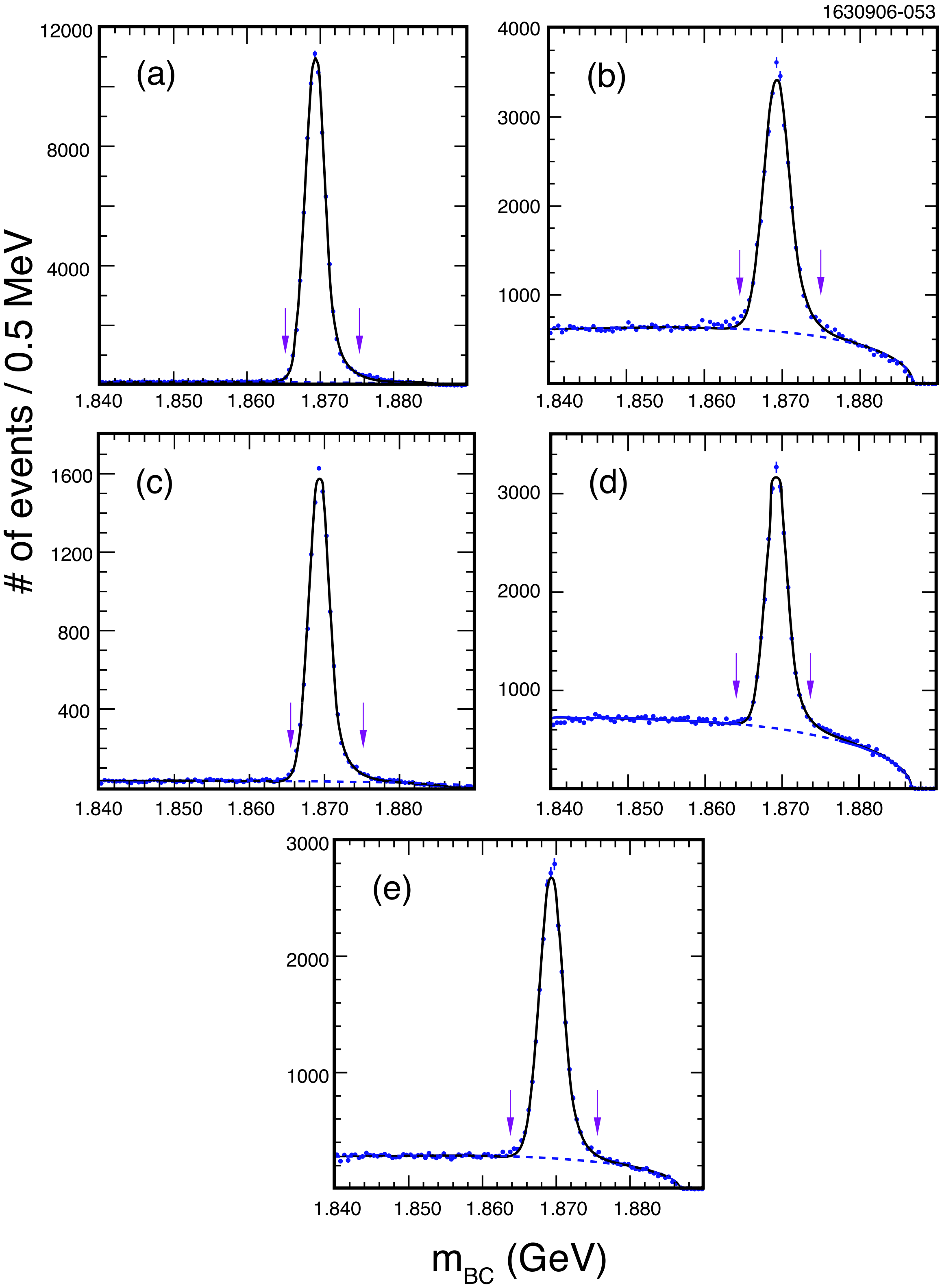

FIG. 2: Beam-constrained mass distributions for fully reconstructed D^- decay candidates in the final states: (a) $K^+\pi^-\pi^-$, (b) $K^+\pi^-\pi^-\pi^0$, (c) $K_s\pi^-$, (d) $K_s\pi^-\pi^+\pi^-$, and (e) $K_s\pi^-\pi^0$. The distributions are fit to a Crystal Ball Line shape for the signal and an ARGUS shape obtained from the ΔE sidebands for the background. The regions between the arrows is selected for further analysis.

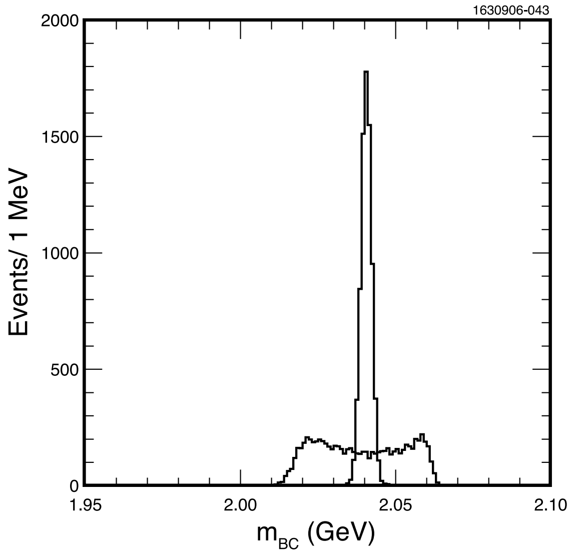

FIG. 3: The beam constrained mass $m_{\rm BC}$ from Monte Carlo simulation of $e^+e^- \to D_s^+D_s^{*-}$, $D_s^{*-} \to \gamma D_s^-$, $D_s^{\pm} \to \phi\pi^{\pm}$ at 4170 MeV. The narrow peak is from the D_s^+ and the wider one from the D_s^-. (The distributions are not centered at the D_s^+ or D_s^{*+} masses, because the reconstructed particles are assumed to have the energy of the beam.)

$2.015 < m_{\rm BC} < 2.067$ GeV. This requirement allows for the fact that the D_s^- could have been produced directly or as a result of a D_s^{*-} decay to either γD_s^-, or $\pi^0 D_s^-$ decay with a small $\sim 5.8\%$ branching fraction [6]. We then reconstruct the invariant mass of the D_s candidates. The invariant mass distributions of the tagging modes we considered in this analysis are shown in Fig. 4; they are listed in Table II, where we also give the number of signal and background events. Here we use only the secondary decays $K^{*0}(890) \to K^+\pi^-$, $K^{*+}(890) \to K_s\pi^+$, $\rho^- \to \pi^-\pi^0$, $\eta \to \gamma\gamma$ and $\eta' \to \pi^+\pi^-\eta$. (More specifically, when appropriate, we require the $K\pi$ invariant mass to be within ± 100 MeV of the K^* mass, the $\pi^-\pi^0$ mass to be within ± 100 MeV of the ρ^- mass, the $\gamma\gamma$ invariant mass minus the η mass divided by its error to be less than 3, and the invariant mass of the $\gamma\gamma\pi^+\pi^-$ minus the $\gamma\gamma$ mass, for $\gamma\gamma$ combinations consistent with the η hypothesis, to be within ± 10 MeV of the known $\eta' - \eta$ mass difference.)

The D_s^- signal regions are defined as containing 98.8% of the signal events within an invariant mass window symmetric about the D_s^- mass peak. The intervals vary from mode to mode. To find the numbers of signal tag events, the invariant mass distributions are fit to a sum of two Gaussian signal functions with the means constrained to be the same and the r.m.s. widths allowed to float. The background function is a second or third order Chebychev polynomial.

We have $14522 \pm 218 \pm 145$ D_s^- signal events that we use for further analysis. The systematic uncertainty is estimated to be $\pm 1.0\%$ by varying the signal and background fitting functions.

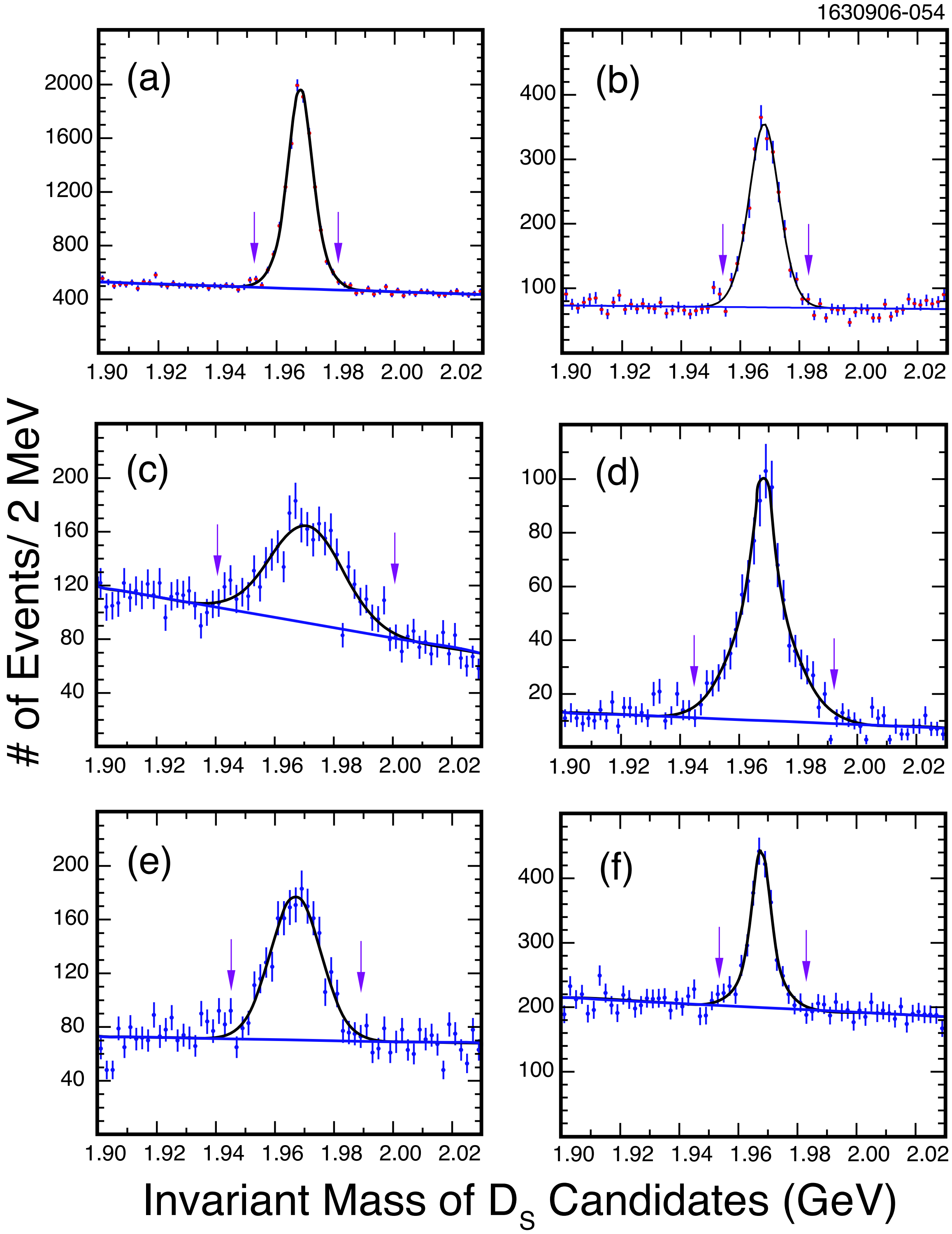

FIG. 4: Invariant mass distributions for fully reconstructed D_s^- decay candidates in the final states: (a) $K^+K^-\pi^-$, (b) K_sK^-, (c) $\eta\pi^-$, (d) $\eta'\pi^-$, (e) $\phi\rho^-$, and (f) $K^{*0}K^{*+}$. The distributions are fit to double Gaussian signal shapes and Chebychev polynomial backgrounds. The regions between the arrows is selected for further analysis.

III. η, η' AND ϕ SELECTION

For the η we use the $\gamma\gamma$ final state, which has a measured branching fraction of $(39.43 \pm 0.26)\%$. To detect η' we use the $\pi^+\pi^-\eta$ final state, which has a branching fraction of $(44.3 \pm 1.5)\%$, with the η subsequently decaying into $\gamma\gamma$. For the ϕ we use the K^+K^- final state with a rate of $(49.1 \pm 0.6)\%$ [6].

The track selection and particle identification requirements for the signal side are identical to those for the tag side, except for momenta less than 0.2 GeV/c, where we loosen the dE/dx consistency requirement to 4 σ_K. This is the case for both D and D_s meson tags.

We accept photons only in the best-resolution region of the detector, $|\cos\theta| < 0.8$, where θ is the angle of the photon with respect to the beam direction. Photon candidates must not be matched to charged tracks, must have a reconstructed energy greater than 30 MeV and have a spatial distribution in the crystals consistent with that of an electromagnetic shower.

Candidates for η' mesons are selected by combining η candidates within 3 r.m.s. widths of the η mass, with a π^+ and a π^-. The mass difference between $\eta\pi^+\pi^-$ and η is then examined. Both pions forming η' and kaons forming ϕ candidates are required to pass the track selection and particle identification requirements. The signal yield is then extracted from fits to the η, $\eta' - \eta$, and ϕ mass distributions.

IV. RECONSTRUCTION EFFICIENCIES

The reconstruction efficiencies for η, η' and ϕ in our tag samples of D and D_s events are shown in Fig. 5. They are determined from a Monte Carlo simulation of the detector [11]. There is no observable difference in the efficiencies for D^0 and D^+ decays. In the case of the D_s, the reconstruction efficiency, especially for the ϕ, is lower in the highest momentum bin, due to the different angular distributions of these particles, caused by the different production angles with respect to the beam of charmed mesons from $D\overline{D}$ production compared with $D_s^*\overline{D}_s$ production. In other words, the kaons on average are produced closer to the beam axis in $D_s^*\overline{D}_s$ events than in $D\overline{D}$ events.

The η efficiency falls slowly below 300 MeV/c, and then levels out. Since our aim here is to measure the inclusive branching fractions, we break the η sample into two parts, one below 300 MeV/c and the other above. For the η', the efficiency is constant with momentum, so we do not separate the data into momentum intervals. The ϕ efficiency, on the other hand, changes drastically with momentum and therefore we use several momentum regions. The increase in the ϕ efficiency is easily explained by the fact that as the ϕ becomes more energetic it is less likely to produce a kaon of $p < 0.2$ GeV/c, which would cause the event to be rejected.

The simulated ϕ efficiency could be inaccurate if the ϕ polarization were not correct; this could occur because of a poor choice of the mixture of final states. The data and Monte Carlo, however, show the same polarization. (The observed polarization is almost independent of momentum in both data and Monte Carlo.)

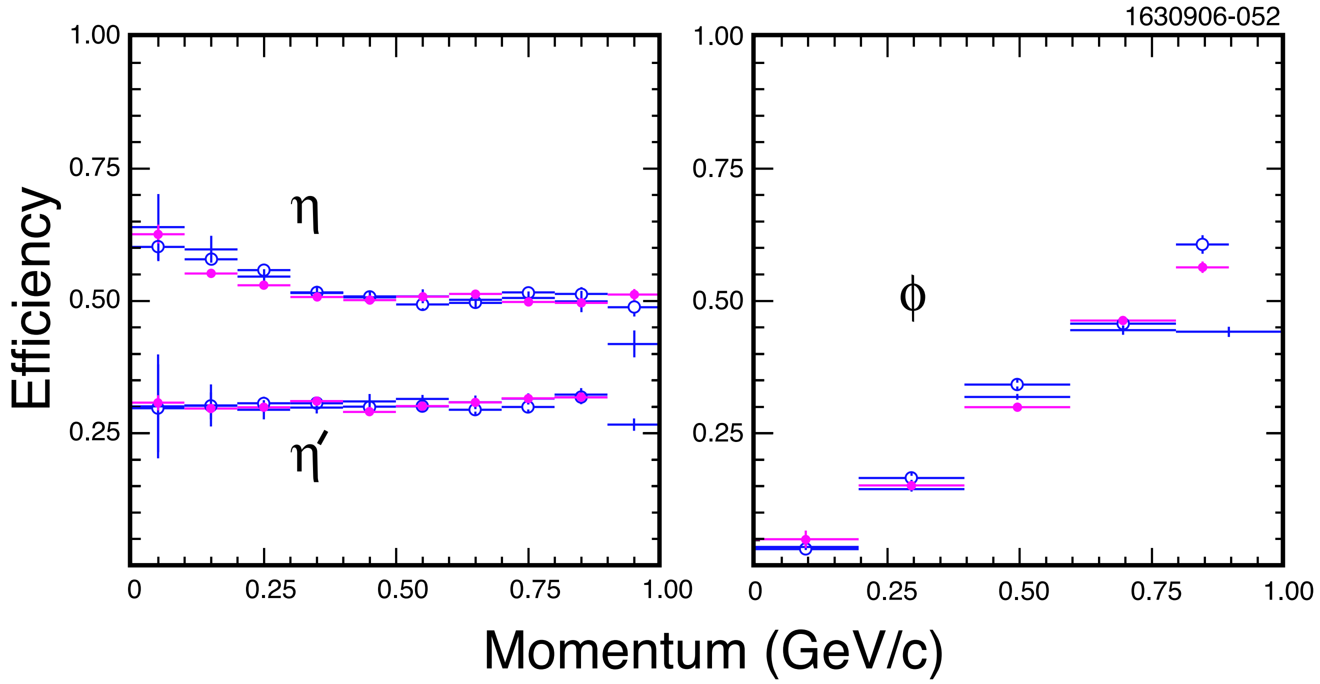

FIG. 5: Reconstruction efficiencies for: $\eta \to \gamma\gamma$, $\eta' \to \eta\pi^+\pi^-$, and $\phi \to K^+K^-$. The filled circles indicate $D^0\overline{D}^0$ events, the open circles D^+D^- events, and the crosses $D_s^*\overline{D}_s$ events. The efficiencies do not include branching ratios.

V. SIGNAL YIELDS AND BRANCHING FRACTIONS

The signal yields in this analysis are evaluated by taking the difference between the η, η' and ϕ yields opposite selected tags and the yields in samples that estimate the background under the tag peaks. Our procedure is somewhat different for D and D_s decays. In the D case, we evaluate the background yields using events in the low and high sidebands of the ΔE distribution from 5σ to 7.5σ away from the peak. These sidebands are normalized to have the same number of events as the backgrounds under the ΔE peaks. In the D_s case we select sidebands in the same interval relative to the peak as for the D but in invariant mass rather than in ΔE.

A. Inclusive η Yields

In Fig. 6 we show the two-photon invariant mass in our two momentum intervals for both signal and sideband regions for D tags; Fig. 7 shows the corresponding distributions for D_s tags.

The η signal and background yields are determined by fits to a Crystal Ball function, to account for the peak and the low mass tail, and a background polynomial. For the signal D^0 region, the four fit parameters describing the Crystal Ball line shape, three for shape and one for the mean are allowed to float. These parameters are then fixed and used for the D^0 sideband regions and the D^+ and D_s^+ signal and sideband regions, since some of these have relatively small yields. Table III lists the yields, the efficiencies, and the branching

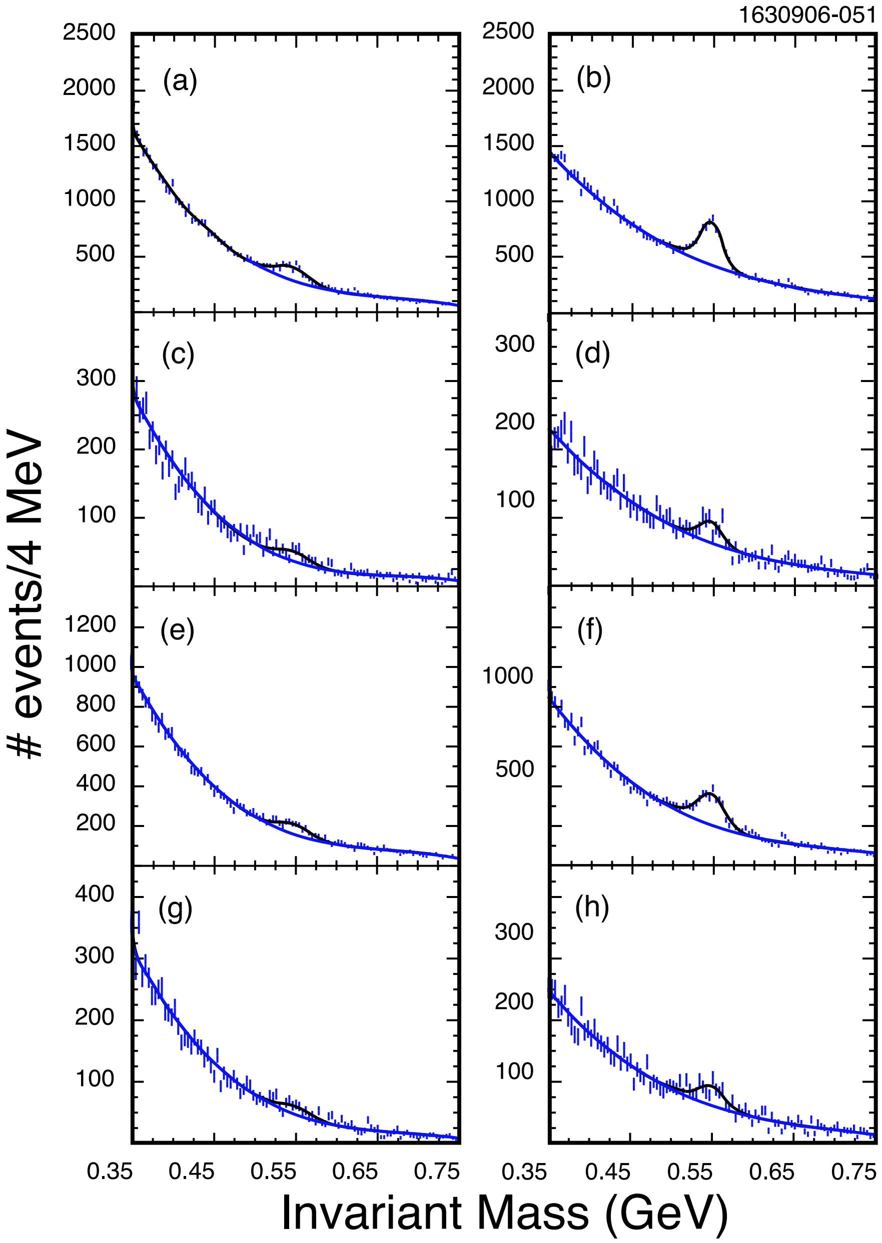

FIG. 6: Invariant mass of the $\eta \to \gamma\gamma$ candidates from D^0 decay: (a) signal region events with the momentum of η, $|p_\eta|$, less than 0.3 GeV/c, (b) signal region events with $0.3 < |p_\eta| < 1.0$ GeV/c, (c) sideband events with $|p_\eta| < 0.3$ GeV/c, (d) sideband events with $0.3 < |p_\eta| < 1.0$ GeV/c. Candidates from D^+ decay are shown in (e)-(h), with corresponding descriptions.

fractions for the two momentum intervals. (Yields in the highest momentum bin include a small number of events that slightly exceed 1 GeV/c.)

The systematic uncertainties arise from several sources. For the η we estimate a detection efficiency error of $\pm 2\%$ per photon[1] for a total of $\pm 4\%$. We also include an error due to fitting

[1] This is determined from a study of pions in $\psi(2S) \to J/\psi \pi^0 \pi^0$ transitions [12].

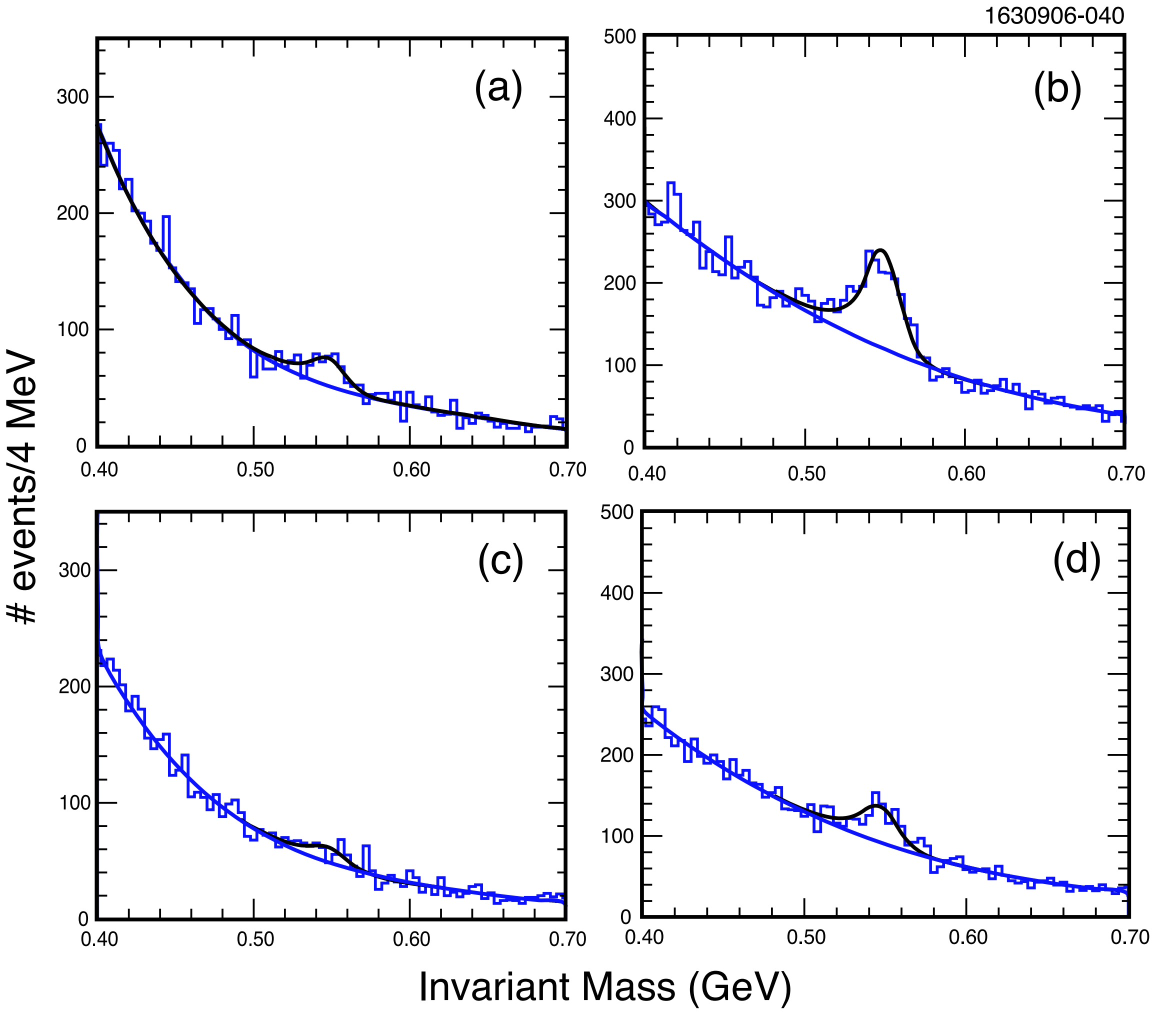

FIG. 7: Invariant mass of the $\eta \to \gamma\gamma$ candidates from D_s^+ decay: (a) signal region events with the momentum of η, $|p_\eta|$, less than 0.3 GeV/c, (b) signal region events with $0.3 < |p_\eta| < 1.0$ GeV/c, (c) sideband events with $|p_\eta| < 0.3$ GeV/c, (d) sideband events with $0.3 < |p_\eta| < 1.0$ GeV/c.

the Monte Carlo samples. In addition, there is an uncertainty caused by using the efficiency in only two momentum intervals, due to possible variations in these intervals, amounting to 3%. This error is estimated by considering the effects of different parent momentum distributions. The uncertainties on the tag yields are derived by varying the fitting functions. We also have significant contributions from uncertainties on the signal and background fitting function, determined by varying the functions. All the systematic error contributions are listed in Table IV. For the η' and ϕ modes we also list the estimated uncertainties for finding the charged tracks and identifying their species. These differ somewhat between the η' and ϕ because of the different track momenta involved. For the ϕ mode we include another additional error source due the lack of efficiency in the first momentum bin that we will discuss in more detail subsequently.

For the η rates we find

$$\mathcal{B}(D^0 \to \eta X) = (9.5 \pm 0.4 \pm 0.8)\% \tag{2}$$

Tag	$\lvert p_\eta \rvert$ (GeV/c)	$N_\eta^{\rm sig}$	$N_\eta^{\rm bkg}$	N_η	ϵ^i	$\mathcal{B}^i(D \to \eta X)$ (%)
D^0	0.0-0.3	1454 ± 133	176 ± 33	1278 ± 137	57	2.5 ± 0.3
	0.3-1.0	3427 ± 137	242 ± 36	3185 ± 141	50	7.0 ± 0.3
Sum		4880 ± 191	418 ± 49	4463 ± 197	–	9.5 ± 0.4
D^+	0.0-0.3	608 ± 65	153 ± 35	455 ± 74	58	1.3 ± 0.2
	0.3-1.0	1811 ± 115	294 ± 39	1517 ± 121	51	5.0 ± 0.4
Sum		2419 ± 132	448 ± 332	1972 ± 142	–	6.3 ± 0.5
D_s^+	0.0-0.3	230 ± 38	152 ± 36	78 ± 53	55	2.5 ± 1.7
	0.3-1.0	963 ± 56	367 ± 48	596 ± 74	50	21.0 ± 2.6
Sum		1193 ± 68	519 ± 60	674 ± 91	–	23.5 ± 3.1

TABLE III: η signal yields ($N_\eta^{\rm sig}$), background yields ($N_\eta^{\rm bkg}$) and background-subtracted yields (N_η) as a function of momentum. Also listed are the η reconstruction efficiencies (ϵ^i) in percent, and the partial branching fractions versus momentum. (Yields in the highest momentum bin include a small number of events that slightly exceed 1 GeV/c.)

Systematic uncertainties	η(%)	η'(%)	ϕ(%)
Photon reconstruction	4.0	4.0	-
Charged track finding	-	1.4	5.0
Particle identification	-	2.0	2.0
Monte Carlo fitting	2.0	1.0	1.0
Average efficiency	3.0	3.2	-
Number of tags (D^0 & D^+)	0.5	0.5	0.5
Number of tags (D_s^+)	1.0	1.0	1.0
Signal & Background Fitting	6.5	5.3	2.1
Estimate of 1st p bin (D^0 & D^+)	-	-	2.0
Estimate of 1st p bin (D_s^+)	-	-	3.1
Total (D^0 & D^+)	8.5	8.6	6.3
Total (D_s^+)	8.5	8.6	6.8

TABLE IV: Systematic uncertainties ($\pm$) on the inclusive η, η' and ϕ branching ratios.

$$\begin{aligned} \mathcal{B}(D^+ \to \eta X) &= (6.3 \pm 0.5 \pm 0.5)\% \\ \mathcal{B}(D_s^+ \to \eta X) &= (23.5 \pm 3.1 \pm 2.0)\%. \end{aligned}$$

Note that these rates naturally include cascade decays from $\eta' \to \eta X$.

B. Inclusive η' Yields

We first reconstruct $\gamma\gamma$ invariant mass as shown above. Then we use $\gamma\gamma$ mass combinations within $\pm 3\sigma$ of the η mass as η candidates, where σ is the r.m.s. width of the mass peak. In

Figs. 8 and 9 we show the $\eta\pi^+\pi^-$ - η mass difference for D and D_s tags from both signal and sideband regions. To determine the yields in this case we fit to a Gaussian signal function and a background polynomial. The signal shapes and means are allowed to float for the signal distributions and fixed to the values obtained there in the corresponding sideband regions.

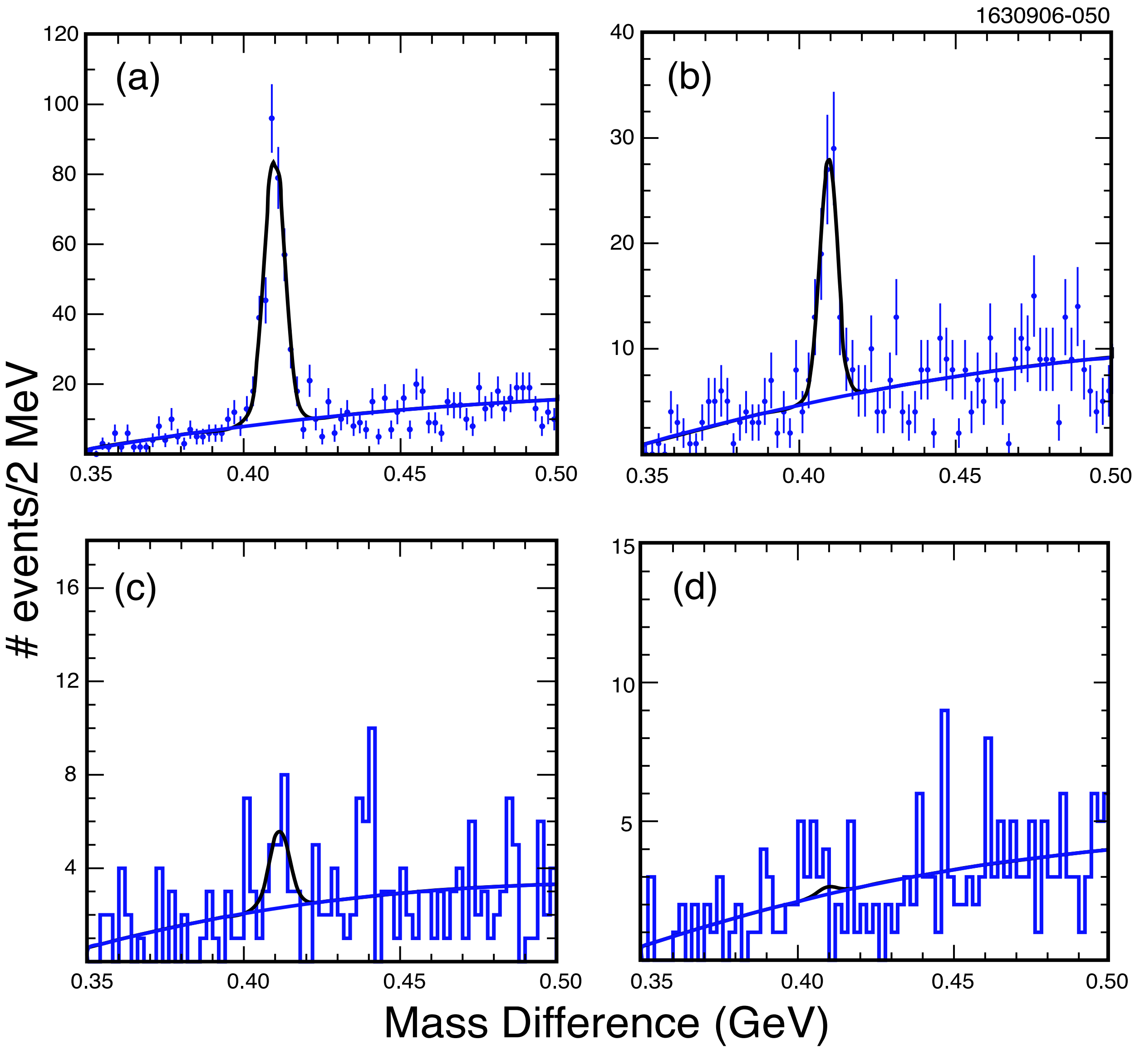

FIG. 8: Difference in the invariant mass of $\eta' \to \eta\pi^+\pi^-$ and η ($\eta \to \gamma\gamma$) candidates from: (a) D^0 signal region events (b) D^+ signal region events (c) D^0 sideband events, and (d) D^+ sideband events. The fits are described in the text.

The signal, background, and background-subtracted yields, the detection efficiency and the branching fraction are given in Table V. The systematic error sources are listed in

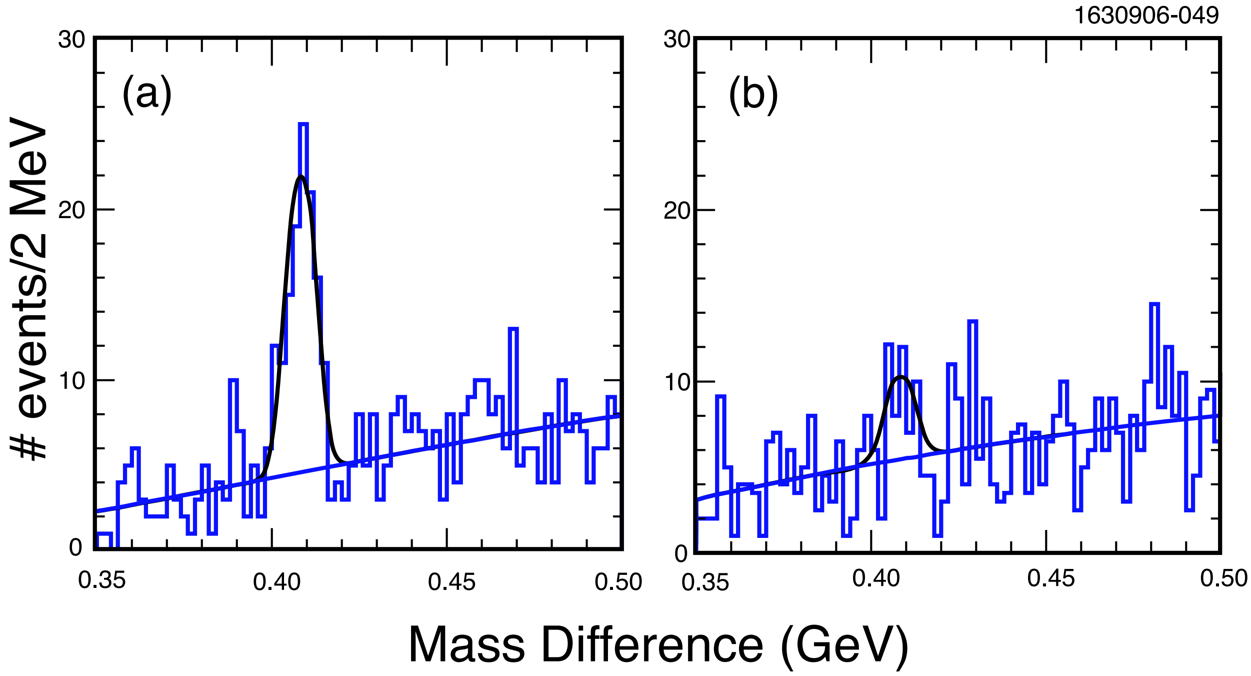

FIG. 9: $\eta\pi^+\pi^-$ - η mass difference from $D_s^+ D_s^-$ signal events (a) and sideband events (b). The fits are described in the text.

Table IV. For the charged tracks we estimate a systematic error of $\pm 0.7\%$ for track finding[2] and $\pm 1\%$ for particle identification.

Tag	$N_{\eta'}^{\rm sig}$	$N_{\eta'}^{\rm bkg}$	$N_{\eta'}$	ϵ^i	$\mathcal{B}(D_{(s)} \to \eta' X)(\%)$
D^0	313 ± 20	14 ± 5	299 ± 21	30	$2.48 \pm 0.17 \pm 0.21$
D^+	83 ± 12	1^{+4}_{-1}	82 ± 13	30	$1.04 \pm 0.16 \pm 0.09$
D_s^+	91 ± 12	23 ± 8	68 ± 15	31	$8.7 \pm 1.9 \pm 0.8$

TABLE V: η' signal yields ($N_{\eta'}^{\rm sig}$), background yields ($N_{\eta'}^{\rm bkg}$) and background-subtracted yields ($N_{\eta'}$), the η' reconstruction efficiencies (ϵ^i), and the branching fractions.

C. Inclusive ϕ Yields

In Figs. 10-15 we show the K^+K^- invariant mass for the signal region in five different momentum intervals from both signal and sideband regions for D^0, D^+ and D_s^+ tags respectively. The signals are fit with a sum of two Gaussian shapes and the background is fit to a polynomial. The signal shapes are fixed to the values obtained by Monte Carlo simulation, while the mean is allowed to float. The signal, background, and background-subtracted

[2] This is determined from a study of pions in $\psi(2S) \to J/\psi\pi^+\pi^-$ transitions [12] but increased to account for the contribution from low momentum tracks.

$\lvert p_\phi \rvert$ (GeV/c)	$N_\phi^{\rm sig}$	$N_\phi^{\rm bkg}$	N_ϕ	ϵ^i (%)	$\mathcal{B}^i(D_{(s)} \to \phi X)$(%)
$D^0 \to \phi X$					
0.0 - 0.2	1.0 ± 1.0	1.0 ± 1.0	0.0 ± 1.4	5.2	0.0 ± 0.0
0.2 - 0.4	25.5 ± 7.9	2.0 ± 1.4	23.5 ± 8.0	15.3	0.14 ± 0.05
0.4 - 0.6	171.9 ± 18.1	3.2 ± 2.8	168.7 ± 18.3	30.2	0.50 ± 0.05
0.6 - 0.8	209.7 ± 17.6	11.3 ± 3.8	198.4 ± 18.0	46.5	0.38 ± 0.03
0.8 - 0.9	8.7 ± 3.5	1.0 ± 1.0	7.7 ± 3.7	56.6	0.012 ± 0.006
Sum	416.7 ± 26.7	18.5 ± 5.1	398.2 ± 27.2	–	1.03 ± 0.08
$D^+ \to \phi X$					
0.0 - 0.2	3.0 ± 1.7	1.0 ± 1.0	2.0 ± 2.0	3.3	0.08 ± 0.08
0.2 - 0.4	49.9 ± 8.6	7.7 ± 3.3	42.2 ± 9.2	16.8	0.34 ± 0.07
0.4 - 0.6	90.2 ± 11.8	12.1 ± 4.2	78.2 ± 12.5	34.4	0.30 ± 0.05
0.6 - 0.8	127.6 ± 14.0	7.6 ± 3.0	119.9 ± 14.4	45.9	0.35 ± 0.04
0.8 - 0.9	6.8 ± 3.1	1.0 ± 1.0	5.8 ± 3.3	60.9	0.013 ± 0.002
Sum	277.4 ± 20.6	29.4 ± 6.3	248.0 ± 21.3	–	1.08 ± 0.12
$D_s^+ \to \phi X$					
0.0 - 0.2	1.4 ± 1.6	1.2 ± 1.4	0.1 ± 2.1	3.7	0.1 ± 0.8
0.2 - 0.4	49.0 ± 7.4	8.3 ± 3.5	40.7 ± 8.2	14.6	3.9 ± 0.8
0.4 - 0.6	144.4 ± 12.9	28.4 ± 6.2	116.1 ± 14.3	32.1	5.1 ± 0.6
0.6 - 0.8	155.6 ± 13.1	20.3 ± 5.1	135.3 ± 14.1	44.7	4.2 ± 0.5
>0.8	82.1 ± 9.1	6.3 ± 3.0	75.8 ± 9.6	44.4	2.4 ± 0.3
Total	432.5 ± 21.9	64.5 ± 9.4	368.0 ± 23.8	–	15.7 ± 1.4

TABLE VI: Measured ϕ signal yields ($N_\phi^{\rm sig}$), background yields ($N_\phi^{\rm bkg}$) and background-subtracted yields (N_ϕ) versus momentum from D and D_s decays. Also listed are the ϕ reconstruction efficiencies (ϵ^i), and the partial branching fractions vs momentum. (Note that measurements in the lowest momentum interval will be replaced by a model dependent estimate.)

yields, the detection efficiency and the branching fraction in each momentum interval are given in Table VI. For D^0 and D^+ there are no events above 0.9 GeV/c, while for the D_s^+ there are a small number of events above 1.0 GeV/c.

Although the measured yields in the lowest momentum bin, $0< p <0.2$ GeV/c, are quite small, so are the efficiencies. To take into account possible incorrect efficiency estimates in this difficult kinematic region we make an independent estimate of the rate by using the Monte Carlo predicted fraction of the ϕ yield. We then take a conservative 100% error on these estimates. The fractions are 2.0%, 2.0% and 3.1%, for D^0, D^+ and D_s^+, respectively. These correspond to partial branching fractions of (0.02±0.02)%, (0.02±0.02)%, and (0.5±0.5)%, respectively. Using these more reliable estimates for the rates in the first bin, we show the efficiency corrected momentum distributions in Fig. 16. The inclusive branching ratios are

$$\begin{aligned} \mathcal{B}(D^0 \to \phi X) &= (1.05 \pm 0.08 \pm 0.07)\% \\ \mathcal{B}(D^+ \to \phi X) &= (1.03 \pm 0.10 \pm 0.07)\% \\ \mathcal{B}(D_s^+ \to \phi X) &= (16.1 \pm 1.2 \pm 1.1)\% \ . \end{aligned} \quad (3)$$

The systematic uncertainties are listed in Table IV. Due to the difficulty in tracking slow charged kaons, we use an increased systemic error of ±2.5% per track in evaluating the efficiency error from track finding. The error due to particle identification remains at ±1%.

VI. CONCLUSIONS

Our results of the inclusive η, η' and ϕ production rates from D^0, D^+ and D_s^+ decays are summarized in Table VII. Of the 9 measured rates in this paper, 8 are first measurements and the other one, $D^0 \to \phi X$, improves the accuracy from 50% to 10%. We are consistent with previous upper limits [6] in the three cases where they exist.

Mode	D^0(%)		D^+(%)		D_s^+(%)	
	Our result	PDG	Our result	PDG	Our result	PDG
$\eta\ X$	9.5±0.4±0.8	<13	6.3±0.5±0.5	<13	23.5±3.1 ± 2.0	-
$\eta'\ X$	2.48±0.17±0.21	-	1.04±0.16±0.09	-	8.7±1.9 ± 0.8	-
$\phi\ X$	1.05±0.08±0.07	1.7±0.8	1.03±0.10±0.07	<1.8	16.1±1.2 ± 1.1	-

TABLE VII: Summary of inclusive branching ratio results.

These particles all have significant components of $s\bar{s}$. Our results show that η' and ϕ are relatively rare in D^0 and D^+ decay while the η which has a lower mass and a significant light quark component, is produced at a significantly higher rate. The η, η' and ϕ are all produced at higher rates in D_s decays than the corresponding rates from D decays. The ratio of rates is given in Table VIII. The ϕ yield is 15 times higher in D_s^+ decays than in D decays.

Ratio	η	η'	ϕ
D_s^+/D^0	$2.47 \pm 0.34 \pm 0.18$	$3.51 \pm 0.80 \pm 0.27$	$15.3 \pm 1.6 \pm 0.8$
D_s^+/D^+	$3.73 \pm 0.57 \pm 0.27$	$8.37 \pm 2.23 \pm 0.64$	$15.6 \pm 1.9 \pm 0.8$

TABLE VIII: Ratios of D_s^+ to D yields. Common systematic errors have been eliminated.

The large asymmetry in the yields of these particles between D_s and the lighter D mesons will permit further studies of B_s decays at the $\Upsilon(5S)$, and will be most useful for separating B_s from B decays at hadron colliders.

VII. ACKNOWLEDGMENTS

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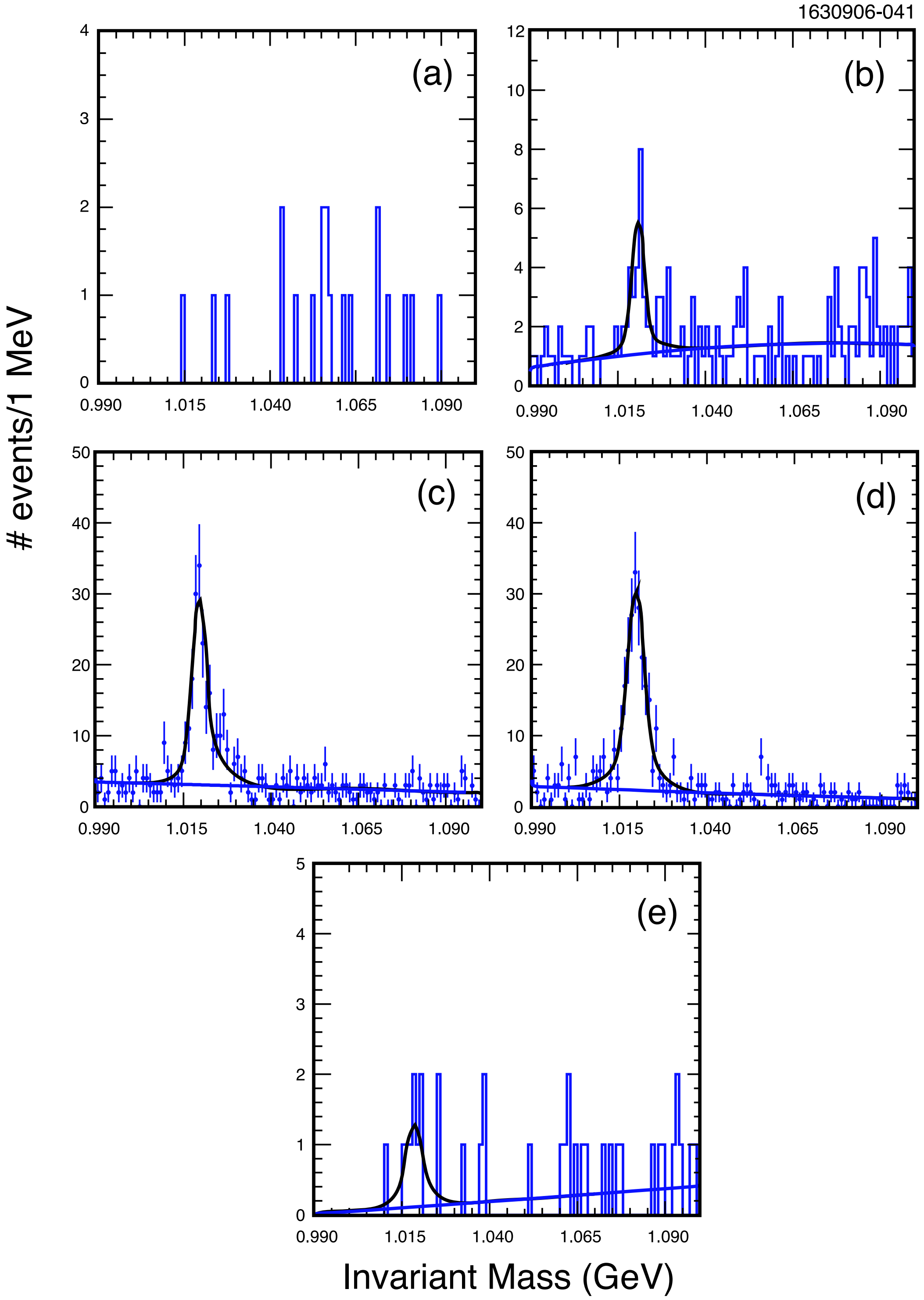

FIG. 10: Invariant mass of $\phi \to K^+K^-$ candidates from $D^0\overline{D}^0$ signal events in five different momentum intervals: (a) $0 < |p_\phi| < 0.2$ GeV/c, (b) $0.2 < |p_\phi| < 0.4$ GeV/c, (c) $0.4 < |p_\phi| < 0.6$ GeV/c, (d) $0.6 < |p_\phi| < 0.8$ GeV/c, (e) $0.8 < |p_\phi| < 0.9$ GeV/c. The fits are described in the text.

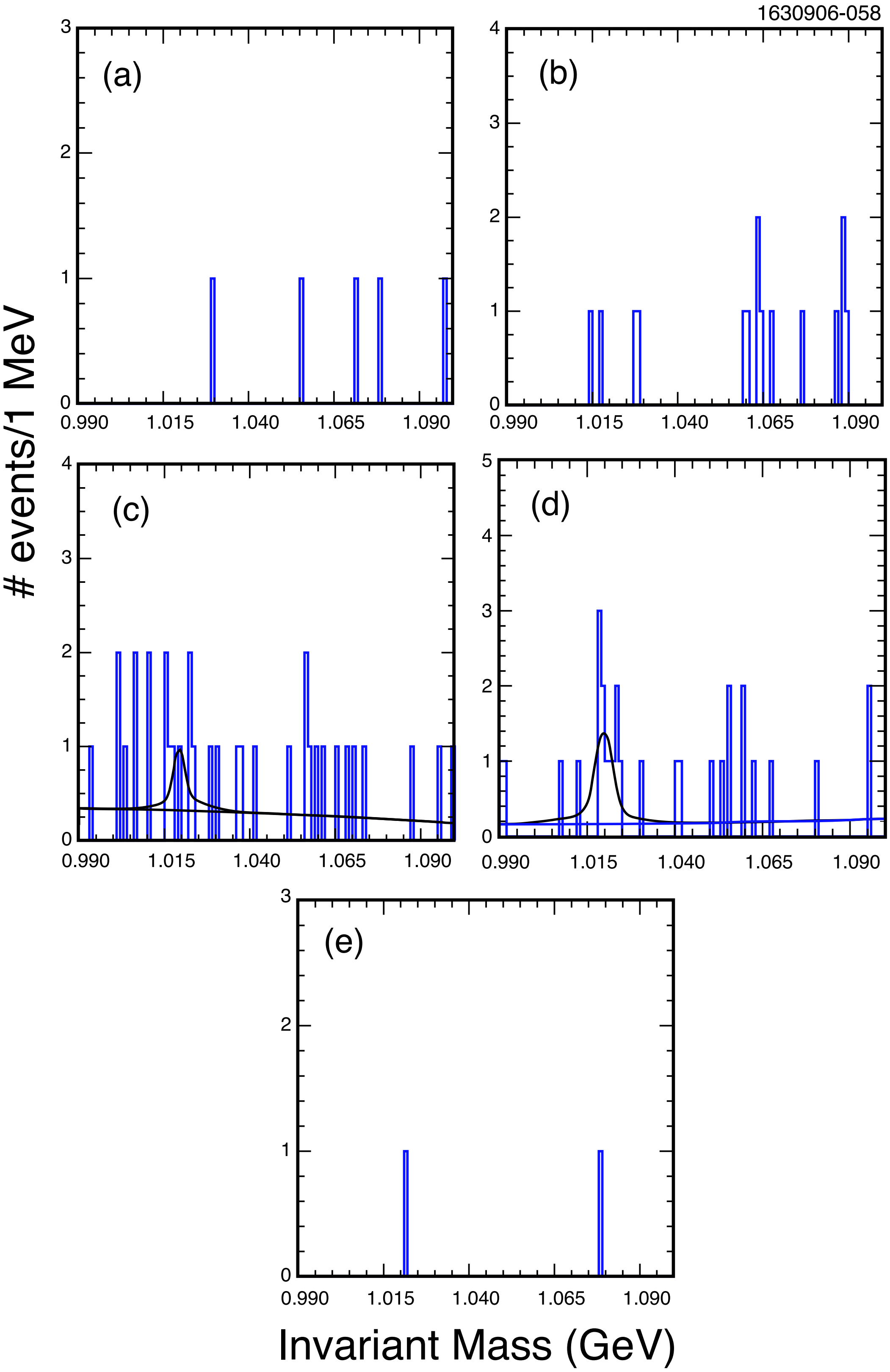

FIG. 11: Invariant mass of $\phi \to K^+K^-$ candidates from $D^0\overline{D}^0$ background events in five different momentum intervals: (a) $0 < |p_\phi| < 0.2$ GeV/c, (b) $0.2 < |p_\phi| < 0.4$ GeV/c, (c) $0.4 < |p_\phi| < 0.6$ GeV/c, (d) $0.6 < |p_\phi| < 0.8$ GeV/c, (e) $0.8 < |p_\phi| < 0.9$ GeV/c. The fits are described in the text.

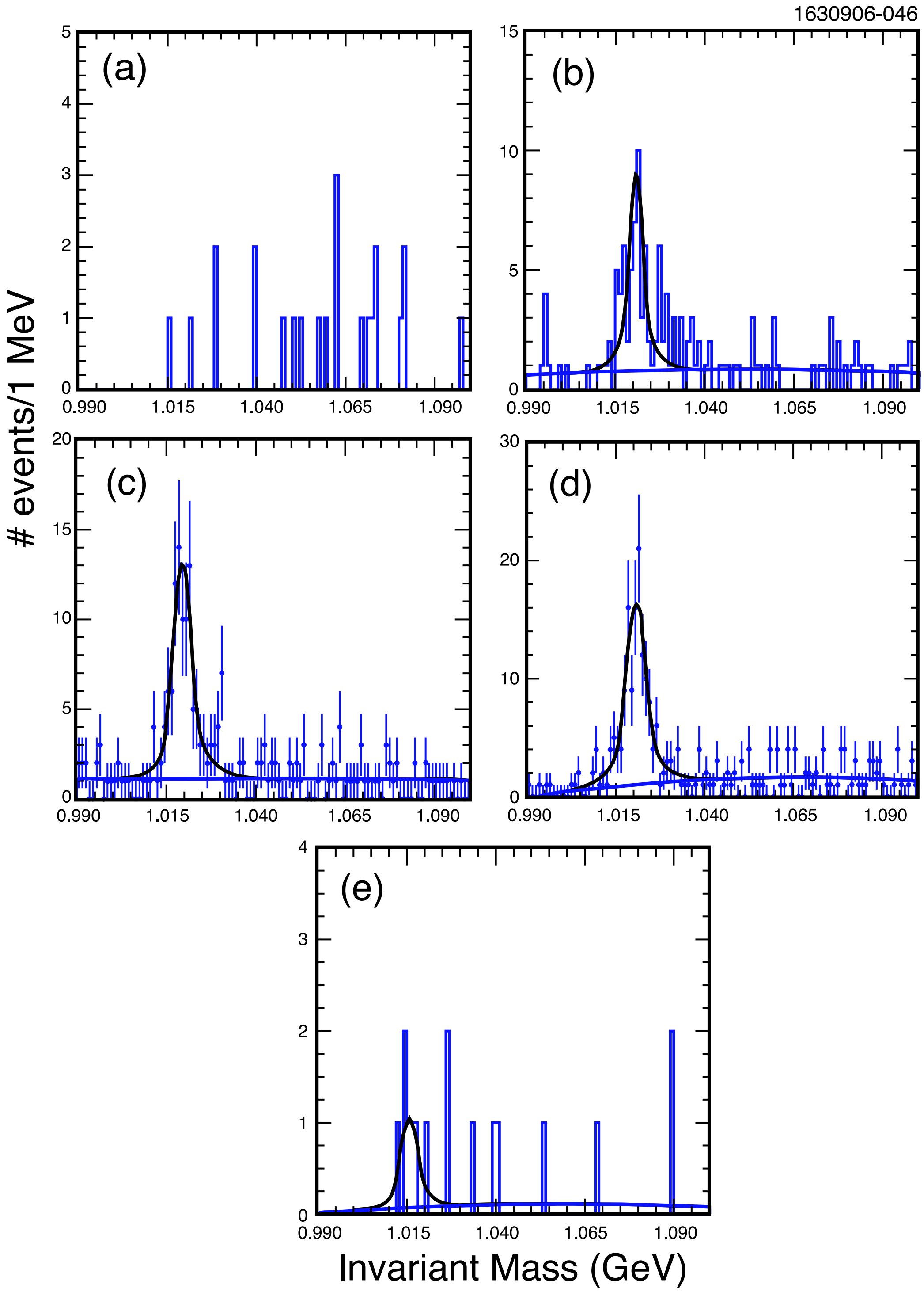

FIG. 12: Invariant mass of $\phi \to K^+K^-$ candidates from D^+D^- signal events in five different momentum intervals: (a) $0 < |p_\phi| < 0.2$ GeV/c, (b) $0.2 < |p_\phi| < 0.4$ GeV/c, (c) $0.4 < |p_\phi| < 0.6$ GeV/c, (d) $0.6 < |p_\phi| < 0.8$ GeV/c, (e) $0.8 < |p_\phi| < 0.9$ GeV/c. The fits are described in the text.

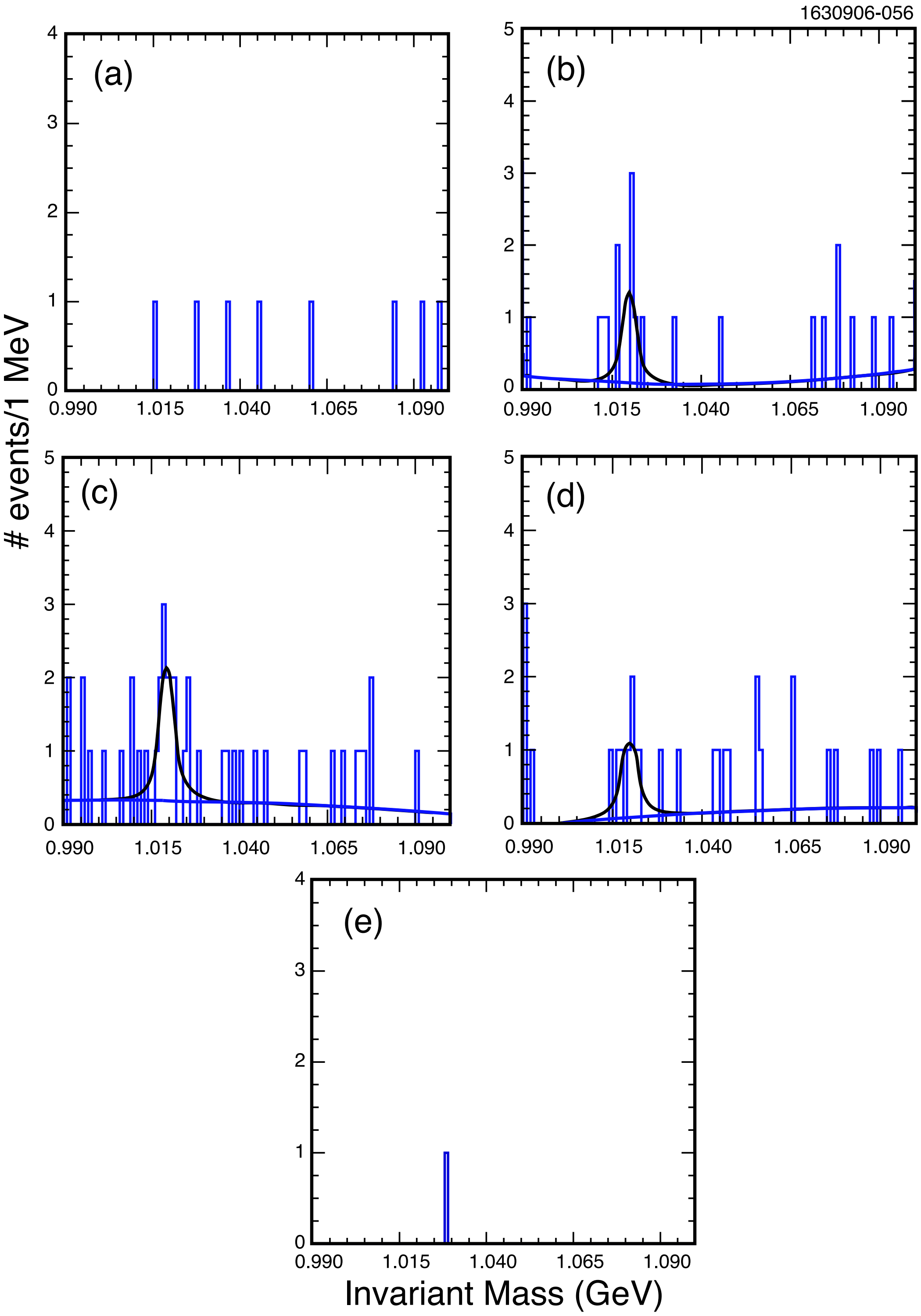

FIG. 13: Invariant mass of $\phi \to K^+K^-$ candidates from D^+D^- background events in five different momentum intervals: (a) $0 < |p_\phi| < 0.2$ GeV/c, (b) $0.2 < |p_\phi| < 0.4$ GeV/c, (c) $0.4 < |p_\phi| < 0.6$ GeV/c, (d) $0.6 < |p_\phi| < 0.8$ GeV/c, (e) $0.8 < |p_\phi| < 0.9$ GeV/c. The fits are described in the text.

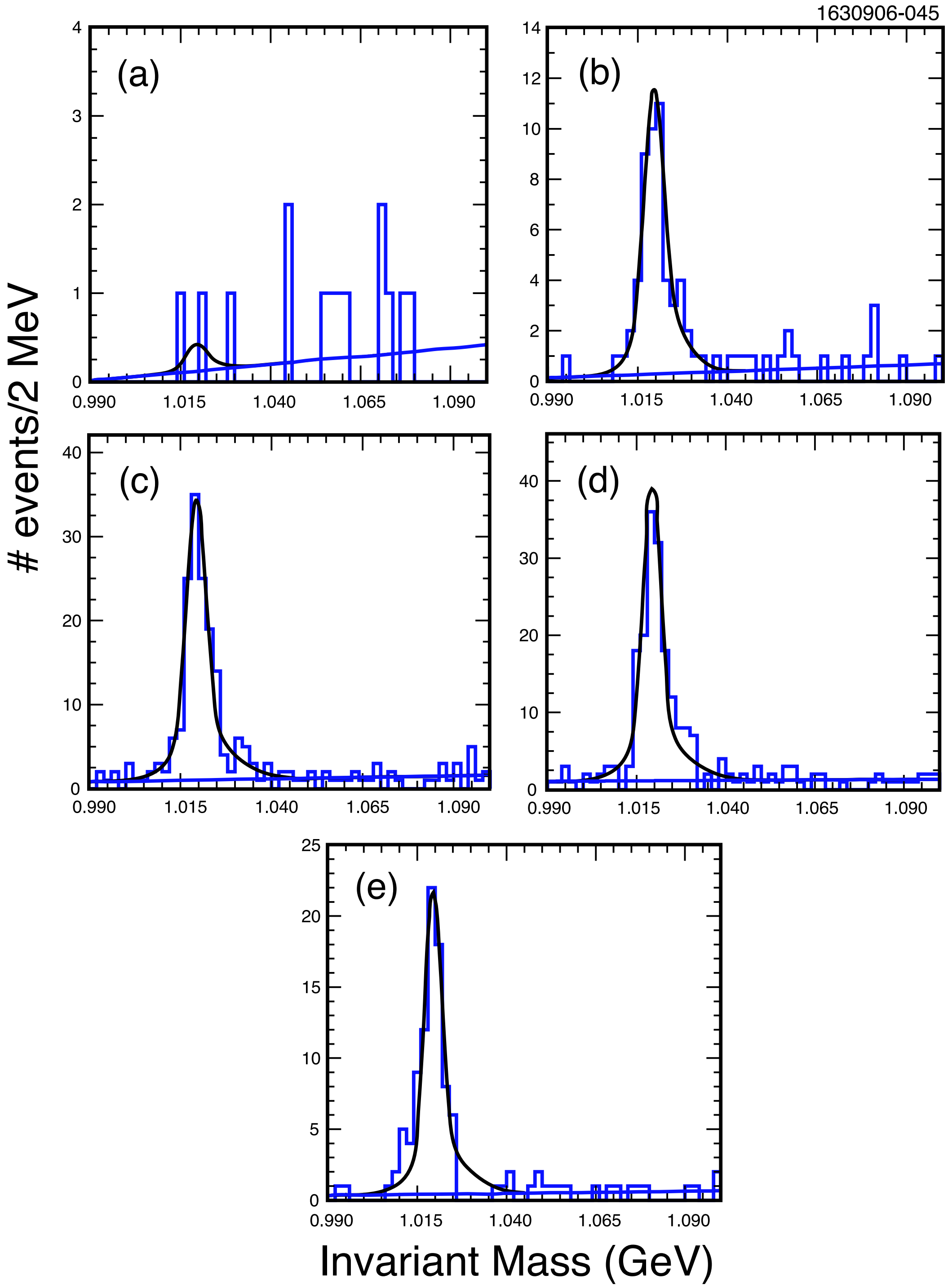

FIG. 14: Invariant mass of $\phi \to K^+K^-$ candidates from $D_s^+ D_s^-$ signal events in five different momentum intervals: (a) $0 < |p_\phi| < 0.2$ GeV/c, (b) $0.2 < |p_\phi| < 0.4$ GeV/c, (c) $0.4 < |p_\phi| < 0.6$ GeV/c, (d) $0.6 < |p_\phi| < 0.8$ GeV/c, (e) $|p_\phi| > 0.8$ GeV/c. The fits are described in the text.

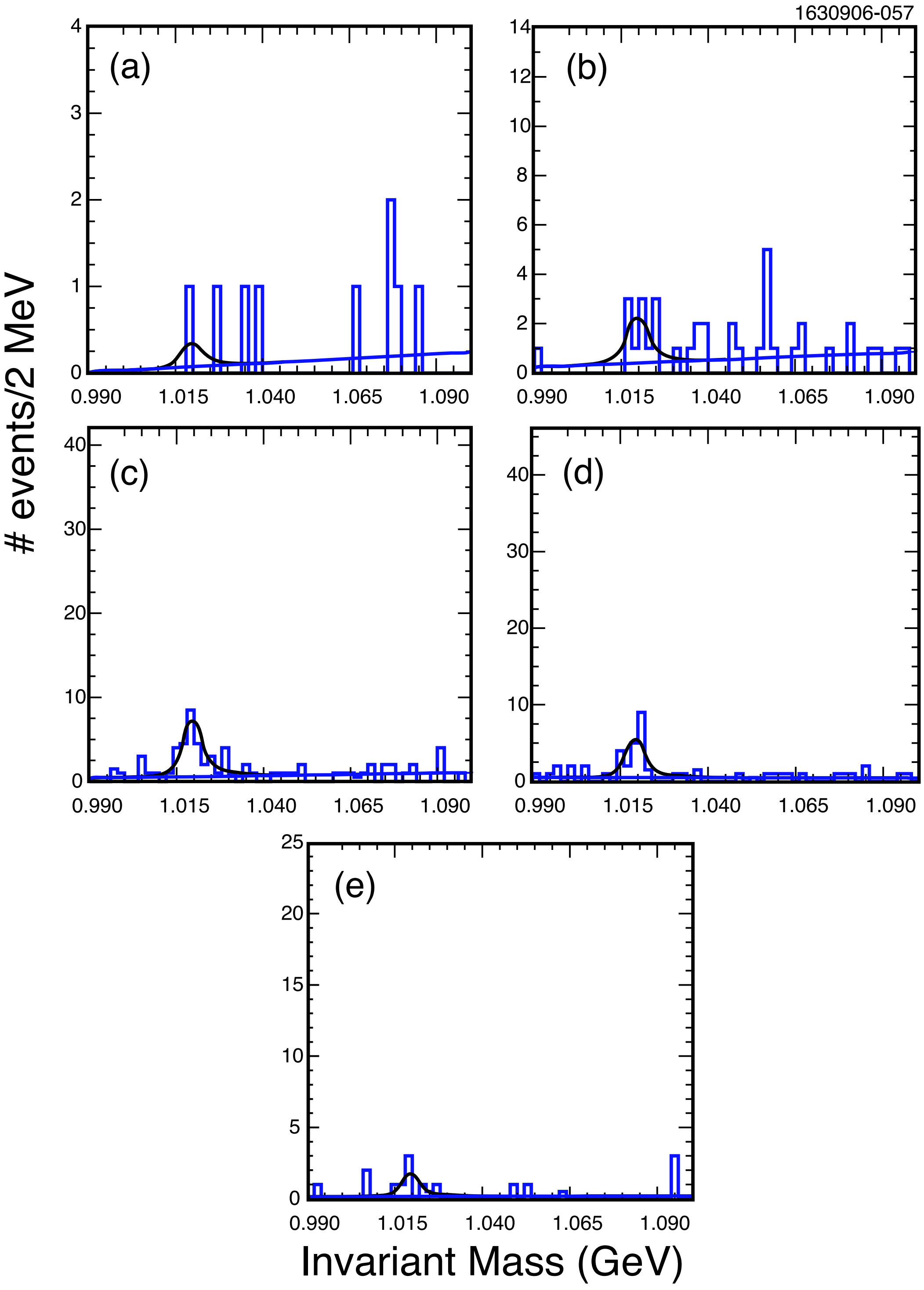

FIG. 15: Invariant mass of $\phi \to K^+K^-$ candidates from $D_s^+D_s^-$ background events in five different momentum intervals: (a) $0 < |p_\phi| < 0.2$ GeV/c, (b) $0.2 < |p_\phi| < 0.4$ GeV/c, (c) $0.4 < |p_\phi| < 0.6$ GeV/c, (d) $0.6 < |p_\phi| < 0.8$ GeV/c, (e) $0.8 < |p_\phi|$ GeV/c. The fits are described in the text.

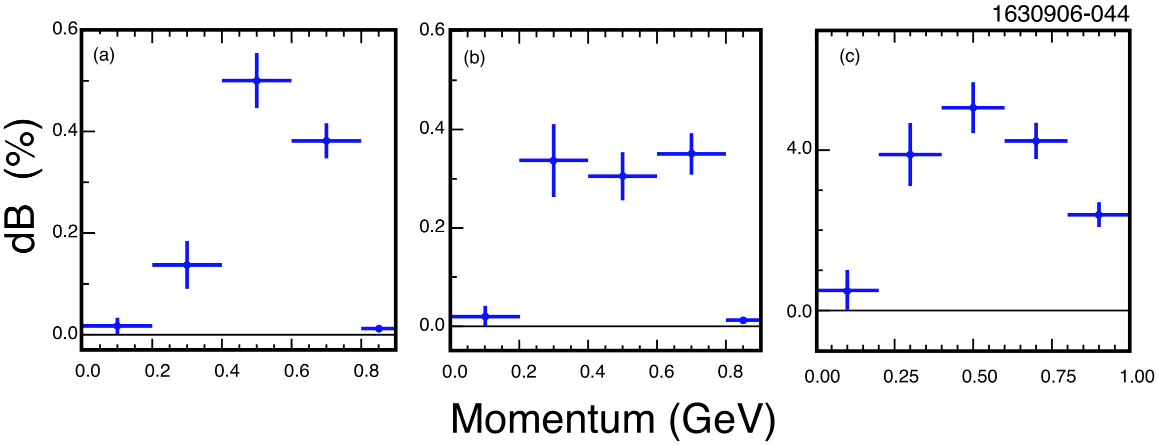

FIG. 16: The branching fraction in % in each 200 MeV interval of momentum for ϕ mesons from (a) D^0 decays, (b) D^+ decays and (c) D_s^+ decays.