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Absolute Measurement of Hadronic Branching Fractions of the D_s^+ Meson

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Abstract

The branching fractions of $D_s^{\pm}$ meson decays serve to normalize many measurements of processes involving charm quarks. Using 298 pb^{-1} of e^+e^- collisions recorded at a center of mass energy of 4.17 GeV, we determine absolute branching fractions for eight $D_s^{\pm}$ decays with a double tag technique. In particular we determine the branching fraction $\mathcal{B}(D_s^+ \to K^-K^+\pi^+) = (5.50 \pm 0.23 \pm 0.16)\%$, where the uncertainties are statistical and systematic respectively. We also provide partial branching fractions for kinematic subsets of the $K^-K^+\pi^+$ decay mode.

Uncertainties in the decay probabilities (branching fractions) of the D_s^+ meson to various detectable final states significantly impact the precision of a diverse array of measurements, including tests of the Standard Model prediction of the coupling of the Z^0 boson to charm quarks, measurements of B meson properties such as B_s^0 mixing parameters, tests of light quark SU(3) symmetry in the D system, and tests of lattice gauge theory in leptonic D_s^+ decays. Any rate measurement where a D_s^+ meson is an intermediate step in a decay chain demands that the relevant normalizing branching fractions be known precisely to reduce systematic uncertainties. Most D_s^+ branching fractions are presently obtained by combining measurements of ratios with a single absolute branching fraction of one decay mode, thus introducing strong correlations and compounding uncertainties. In this Letter we present the first simultaneous high-statistics determination of multiple D_s^+ absolute branching fractions, using a technique with significantly different systematic uncertainties from previous branching fraction measurements, which results in precision better than current world averages by a factor of two. The eight decays considered in this analysis are $D_s^+ \to K_S^0 K^+$, $K^-K^+\pi^+$, $K^-K^+\pi^+\pi^0$, $K_S^0 K^-\pi^+\pi^+$, $\pi^+\pi^+\pi^-$, $\pi^+\eta$, $\pi^+\eta'$, and $K^+\pi^+\pi^-$. Except where noted, mention of a decay implies the charge conjugate process as well.

The most precise measurements of absolute D_s branching fractions are currently obtained using partial reconstruction techniques to obtain the total number of D_s mesons produced, either from $B \to D^{(*)}D_{s(J)}^{(*)+}$ decays [1, 2] or from $e^+e^- \to D_s^{*\pm}D_{s1}^{\mp}(2536)$ events [3]. References [1] and [2] quote results for the resonant decay $D_s^+ \to \phi\pi^+$, while Ref. [3] measures $\mathcal{B}(D_s^+ \to K^-K^+\pi^+)$.

Here we employ a technique pioneered by the MARK III collaboration for measuring D^0 and D^+ branching fractions [4, 5] and used extensively by CLEO-c, which exploits a feature of near-threshold production of charmed mesons. Below the D_sDK threshold of 4.33 GeV, production of a $D_s^\pm$ meson in a charm- and strangeness-conserving process requires the existence of a $D_s^\mp$ meson elsewhere in the event (possibly with additional photons or pions). Events where at least one D_s candidate is reconstructed ("single tag" or ST events) thus provide a sample with a known number of D_s events. Absolute branching fractions can then be obtained by finding events with two reconstructed D_s candidates ("double tag" or DT events). In this analysis, yields for charge-conjugate ST modes are considered separately, but charge-conjugate branching fractions are assumed to be equal, ignoring the possibility of direct CP violation. There are 16 ST yields, corresponding to two charges for each considered D_s decay, and 64 DT yields, one for each pairing of a D_s^- and a D_s^+ decay.

This analysis uses (298 ± 3) pb^{-1} of data taken at a center of mass energy of 4.17 GeV. At this energy the dominant D_s production mechanism is the process $e^+e^- \to D_s^{*\pm}D_s^\mp$ with a cross-section of ~ 1 nb [6]; the D_s^* then decays to either γD_s or $\pi^0 D_s$ in a $\sim 16:1$ ratio [7]. The very small rate of $e^+e^- \to D_s^+D_s^-$ is not used for this analysis. The transition photon or π^0 is not reconstructed.

To illustrate the method, consider two ST modes, $D_s^+ \to i$ and $D_s^- \to \bar{\jmath}$, and one DT mode $D_s^+ \to i$, $D_s^- \to \bar{\jmath}$. For a given number of produced D_s pairs $N_{D_s^*D_s}$, branching fractions $\mathcal{B}_i$ and $\mathcal{B}_j$, and efficiencies for the ST (ϵ_i and $\epsilon_{\bar{\jmath}}$) and DT ($\epsilon_{i\bar{\jmath}}$) events, we expect to observe the yields

$$
\begin{aligned}
y_i &= N_{D_s^*D_s}\mathcal{B}_i\epsilon_i, \\
y_{\bar{\jmath}} &= N_{D_s^*D_s}\mathcal{B}_j\epsilon_{\bar{\jmath}}, \\
y_{i\bar{\jmath}} &= N_{D_s^*D_s}\mathcal{B}_i\mathcal{B}_j\epsilon_{i\bar{\jmath}},
\end{aligned}
$$

where y_i and $y_{\bar{\jmath}}$ are the ST yields and $y_{i\bar{\jmath}}$ is the DT yield. Using ϵ_i, $\epsilon_{\bar{\jmath}}$, and $\epsilon_{i\bar{\jmath}}$ from Monte Carlo simulations, we can solve for the branching fractions and $N_{D_s^*D_s}$:

$$\mathcal{B}_i = \frac{y_{i\bar{j}}}{y_{\bar{j}}}\frac{\epsilon_{\bar{j}}}{\epsilon_{i\bar{j}}},$$
$$\mathcal{B}_j = \frac{y_{i\bar{j}}}{y_i}\frac{\epsilon_i}{\epsilon_{i\bar{j}}},$$
$$N_{D_s^*D_s} = \frac{y_i y_{\bar{j}}}{y_{i\bar{j}}}\frac{\epsilon_{i\bar{j}}}{\epsilon_i\epsilon_{\bar{j}}}.$$

In practice, to maximize the statistical power of the analysis, the parameters $N_{D_s^*D_s}$ and $\mathcal{B}_i$ are simultaneously optimized using a maximum likelihood fit to the observed yields, where the ST yields use Gaussian likelihood functions and the considerably smaller DT yields use Poisson likelihood functions.

The CLEO-c detector is a modification of the CLEO III detector [8, 9, 10, 11]. The silicon strip vertex detector was replaced by a six layer vertex drift chamber. The charged particle tracking system, consisting of the vertex chamber and a 47-layer central drift chamber, operates in an axial 1 T magnetic field, and provides a momentum resolution $\sigma_p/p \sim 0.6\%$ at $p = 1$ GeV/c for tracks traversing every layer. Photons are detected in an electromagnetic calorimeter consisting of 7784 CsI(Tl) crystals, which achieves an energy resolution $\sigma_E/E \sim 5\%$ at 100 MeV. Two particle identification (PID) systems are used to distinguish charged kaons and pions: the central drift chamber, which provides specific ionization measurements (dE/dx), and, surrounding this chamber, a cylindrical Ring Imaging Cherenkov (RICH) detector. The combined PID system achieves $\pi^{\pm}$ and $K^{\pm}$ identification efficiency exceeding 85% with fake rates less than 5% over the kinematic range of interest [12]. The detector response is modeled with a detailed GEANT-based [13] Monte Carlo simulation, with initial particle trajectories generated by EVTGEN [14] and final state radiation produced by PHOTOS [15]. The initial state radiation spectrum is modeled using cross-sections for $D_s^*D_s$ production at lower energies determined during a CLEO-c scan of this region [6].

Charged tracks are required to be well-reconstructed and, except for K_S^0 daughters, to be consistent with originating at the interaction point. The initial selection requires track momentum > 50 MeV/c. Candidate $K^{\pm}$ and $\pi^{\pm}$ tracks are chosen using dE/dx and RICH information, using the same criteria as the CLEO-c D^0/D^+ absolute branching fraction analysis [12]. Charged kaons must have momentum above 125 MeV/c. Neutral kaon candidates are reconstructed in the $K_S^0 \to \pi^+\pi^-$ decay. The two pions have no PID requirements, and a vertex fit is done to allow for the K_S^0 flight distance. The pion pair is required to have an invariant mass within 6.3 MeV/c^2 of the nominal K_S^0 mass. We form π^0 and η candidates using pairs of isolated electromagnetic showers, keeping combinations within three standard deviations of the nominal masses; for further use a kinematic fit constrains the candidates to the nominal mass. Candidate η' mesons are reconstructed by combining η candidates with $\pi^+\pi^-$ pairs; the pions are subject to the standard pion PID requirements, and the reconstructed η' mass must be within 10 MeV/c^2 of the nominal value.

We identify D_s candidates using their momenta and invariant masses. A candidate may either be the daughter of a D_s^* (an "indirect" D_s) or be produced in the inital $e^+e^- \to D_s^*D_s$ process (a "direct" D_s). Direct D_s candidates have fixed momentum in the center of mass frame because they are produced in a two-body process; indirect D_s candidates have a momentum distribution smeared around this value due to the extra boost of the $D_s^* \to (\gamma, \pi^0)D_s$ decay. We define the recoil mass variable $M_{\rm rec}$ through

$$M_{\rm rec}^2 c^4 \equiv \left(E_0 - \sqrt{\mathbf{p}_{D_s}^2 c^2 + M_{D_s}^2 c^4}\right)^2 - (\mathbf{p}_0 - \mathbf{p}_{D_s})^2 c^2,$$

where $(E_0, \mathbf{p}_0)$ is the center of mass four-vector, $\mathbf{p}_{D_s}$ is the measured D_s momentum, and M_{D_s} is the nominal D_s mass. For direct D_s candidates, $M_{\rm rec}$ peaks at the D_s^* mass of 2.112 GeV$/c^2$; for indirect D_s candidates, $M_{\rm rec}$ spreads roughly ± 60 MeV$/c^2$ around this peak. For DT and most ST candidates, we require $M_{\rm rec} > 2.051$ GeV$/c^2$; for three ST modes ($K^-K^+\pi^+\pi^0$, $\pi^+\pi^+\pi^-$, $K^+\pi^+\pi^-$) tighter mode-dependent selections of $M_{\rm rec} > (2.099, 2.101, 2.099)$ GeV$/c^2$ are applied to reduce background. The $M_{\rm rec}$ requirement eliminates contributions from $e^+e^- \to D_s^+ D_s^-$ events as those occur in a narrow peak at $M_{\rm rec} = M_{D_s}$.

The D_s candidates are subject to mode-dependent vetoes to reduce structure in the background invariant mass spectrum, mostly arising from copiously produced $D^* D^*$ events. In all modes except $K_S^0 K^+$ and $K^-K^+\pi^+$, all neutral and charged pions, including K_S^0 daughters, must have momentum above 100 MeV$/c$ to eliminate the soft pions from D^* decays. Reflections are reduced by vetoing candidates where certain daughter combinations are consistent with the D^0 or D^+ masses (for example, the K^-K^+ pair in a $K^-K^+\pi^+$ candidate must not be consistent with a Cabibbo-suppressed D^0 decay). To remove contamination from K_S^0 decays in the modes $\pi^+\pi^+\pi^-$ and $K^+\pi^+\pi^-$, no $\pi^+\pi^-$ combination may have a mass between 475 and 520 MeV$/c^2$.

For ST yield extraction, every event is allowed to contribute a maximum of one D_s candidate per mode and charge. If there are multiple candidates, the one with $M_{\rm rec}$ closest to $M_{D_s^*}$ is chosen. An unbinned maximum likelihood fit is then performed on the invariant mass spectrum of the candidates in each mode. The expected signal distribution is obtained from Monte Carlo simulations; in fits to data the D_s mass is allowed to float. Backgrounds are modeled with linear functions for all modes except $K^-K^+\pi^+\pi^0$ and $\pi^+\pi^+\pi^-$, where quadratic functions are used. The same background shape is used for both charges in a given mode. The reconstructed candidate masses $M(D_s)$ and ST yield fits are shown in Fig. 1. Efficiencies for ST modes range from 5.3% to 51%.

Double tag yields are extracted by defining a signal region in the two-dimensional plane of the two D_s candidate masses, $M(D_s^+)$ vs. $M(D_s^-)$. Every event is allowed to contribute at most one DT candidate per possible final state; amongst multiple candidates, the combination with average mass $\widehat{M} = (M(D_s^+) + M(D_s^-))/2$ closest to M_{D_s} is chosen. The distribution of $M(D_s^-)$ versus $M(D_s^+)$ for all DT candidates, along with the signal and sideband regions, is shown in Fig. 2. Combinatoric background tends to have structure in $\widehat{M}$ but be flat in the mass difference $\Delta M = M(D_s^+) - M(D_s^-)$. Accordingly both signal and sideband regions require $|\widehat{M} - M_{D_s}| < 12$ MeV$/c^2$. The signal region is $|\Delta M| < 30$ MeV$/c^2$, while the sideband region is $50 < |\Delta M| < 140$ MeV$/c^2$. Efficiencies for DT modes range from 0.3% to 38%.

The D_s decay final states under consideration can often be reached through multiple intermediate resonances; for example, $\phi\pi^+$, $\overline{K}^{*0} K^+$, and $f_0(980)\pi^+$ all contribute to the final state $K^-K^+\pi^+$. The reconstruction efficiency can depend significantly on which resonances are produced. Knowledge of the relative contributions of these intermediate states is incomplete. We compare invariant mass distributions of pairs of D_s daughters in data and Monte Carlo, and use the resulting information on resonant structures to reweight the assumed intermediate state components. The resulting excursions in the efficiency are taken as systematic uncertainties. Where there is a significant component that cannot be explicitly assigned to any intermediate state, we find the worst-case variations between the dominant components. The uncertainties assigned vary from zero for the two-body final states to 6% for $K^-K^+\pi^+\pi^0$ (where there is a large efficiency difference between the $\phi\rho$ and $\overline{K}^{*0} K^{*+}$ intermediate states). We also include uncertainties in the PDG 2007 fit values for

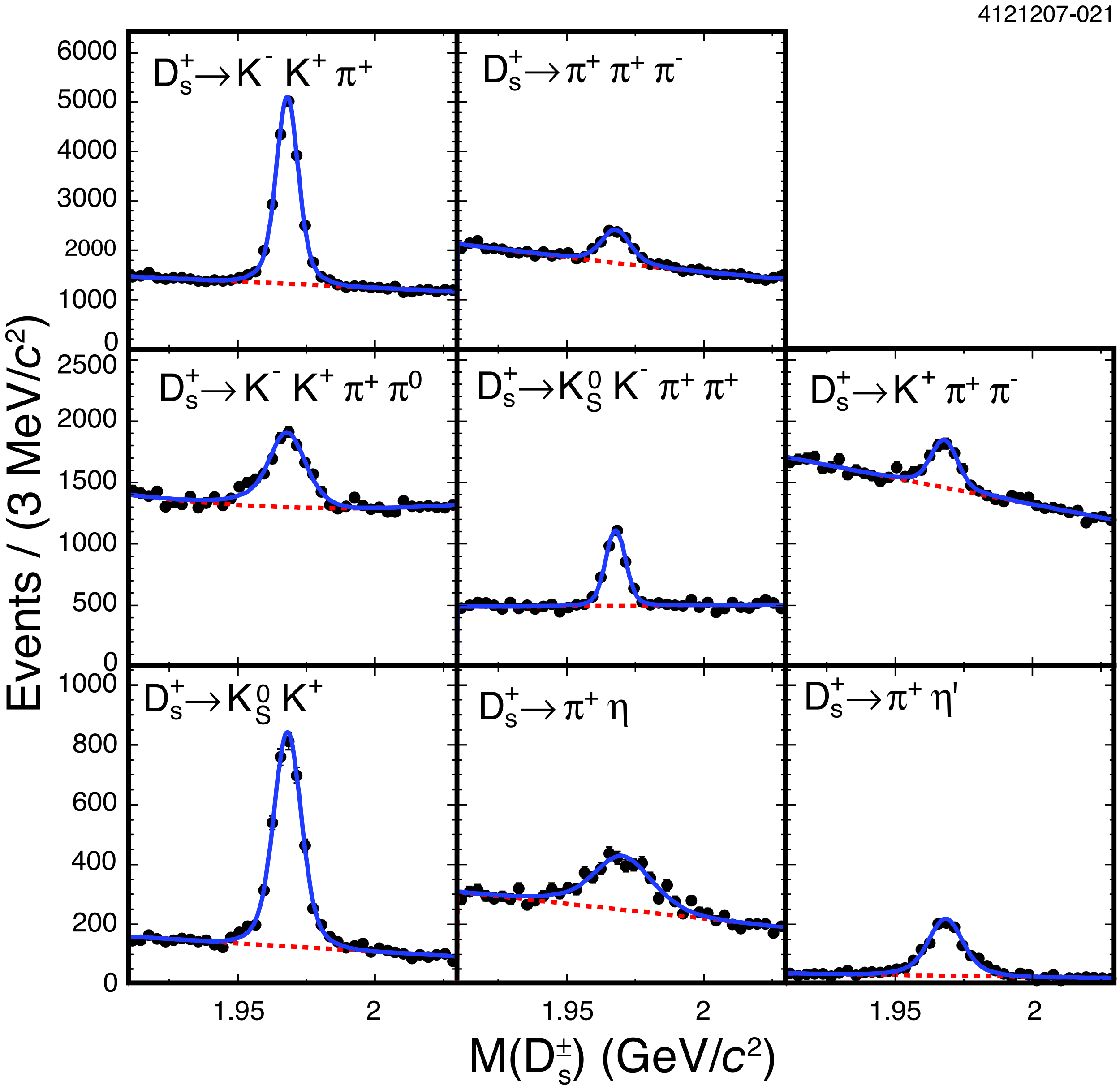

FIG. 1: (Color online) Invariant masses of the $D_s^\pm$ candidates in data in ST modes. Charge-conjugate modes are combined. The fits for yields are shown as the dashed red lines (background component) and solid blue lines (signal plus background). The total ST yield is $(30.9 \pm 0.3) \times 10^3$ events.

$\mathcal{B}(\eta \to \gamma\gamma)$ (0.7%) and $\mathcal{B}(\eta' \to \pi^+\pi^-\eta)$ (3.1%), and correct for the difference between the PDG fit for $\mathcal{B}(K_S^0 \to \pi^+\pi^-)$ and the value used in GEANT.

Systematic uncertainties for the simulation of track, K_S^0, π^0, and η reconstruction and PID efficiencies are determined using partial versus full reconstruction of events in CLEO-c's $\psi(2S)$ and $\psi(3770)$ datasets; the methods are shared with the D^0/D^+ branching fraction analysis [12]. Tracking efficiencies are verified using $\psi(3770) \to D\overline{D}$ events for $\pi^\pm$ and $K^\pm$, and using $\psi(2S) \to \pi^+\pi^- J/\psi$ for $\pi^\pm$. Good agreement is found, and an uncertainty of 0.3% per track is used, correlated among all tracks, with an additional uncertainty of 0.6% per kaon added in quadrature. Systematic effects in the PID efficiency are studied using $\psi(3770) \to D\overline{D}$ events; in general data has slightly

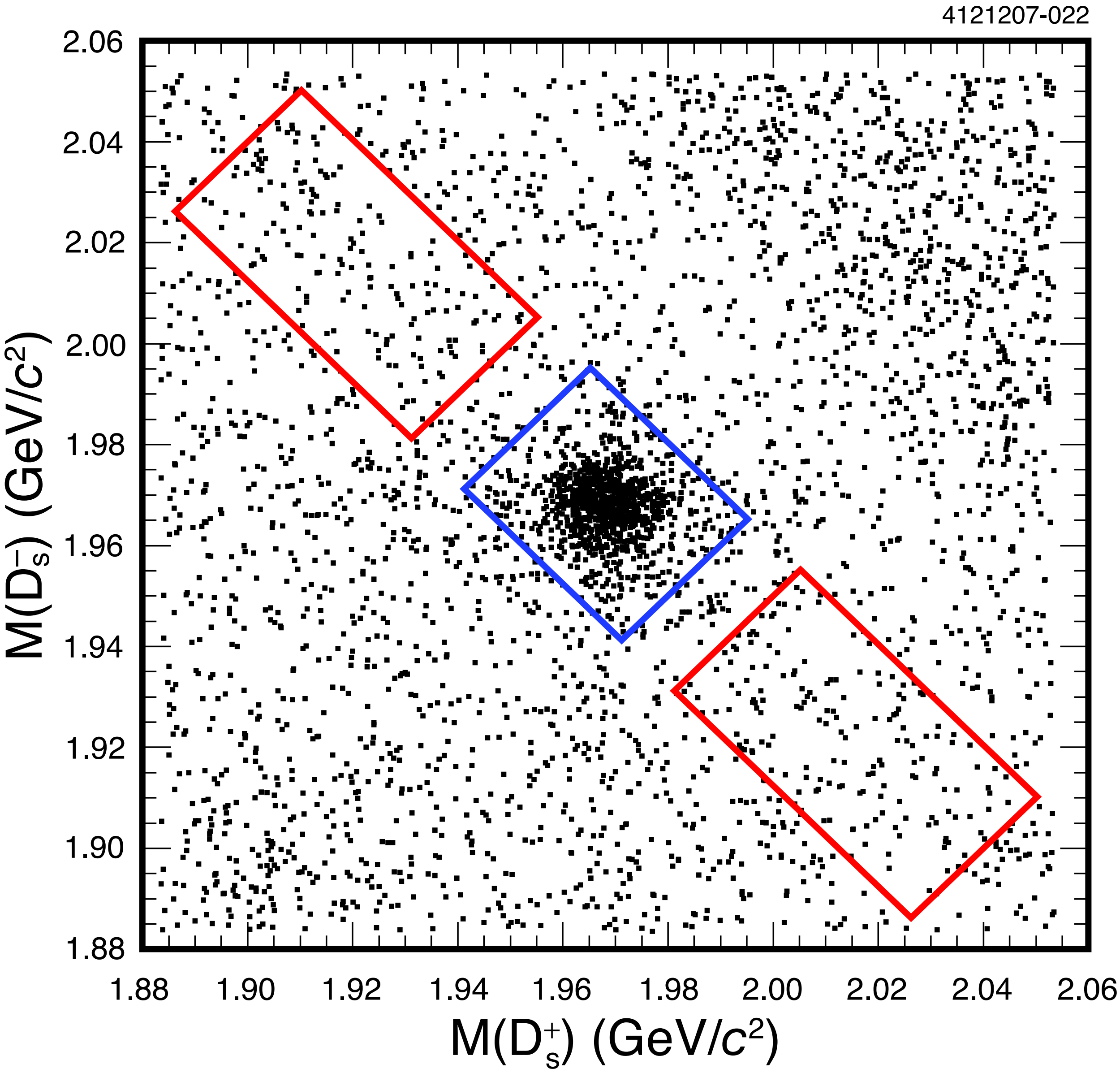

FIG. 2: (Color online) Masses of the D_s^- and D_s^+ candidates for all 64 DT modes in data. The rectangles show the signal region (center) and two sideband regions (diagonally offset). There are 1089 events in the signal region and 339 events in the combined sideband regions.

lower efficiency than the simulations and corrections are applied. Because the corrections are momentum-dependent this is also affected by the uncertainty on the intermediate resonant states. The corrections applied range from $(-0.2 \pm 0.2)\%$ for $\pi^+\eta$ to $(-3.7 \pm 1.4)\%$ for $K^-K^+\pi^+\pi^0$. Neutral kaon efficiencies are verified using $D\overline{D}$ events and the $D_s^+ \to K_S^0 K^+$ mode; a systematic uncertainty of 1.9% per K_S^0 candidate is used. The π^0 efficiency is checked with $\psi(2S) \to \pi^0\pi^0 J/\psi$ decays, and the η efficiency with $\psi(2S) \to \eta J/\psi$ events. In both cases there are discrepancies between data and the simulation, and relative corrections of $(-3.9 \pm 2.0)\%$ per π^0 and $(-5.7 \pm 4.0)\%$ per η are applied.

The nominal signal lineshapes used in the ST yield fits are derived from the simulation, and the backgrounds are either linear or quadratic. We determine systematic uncertainties in the yields

TABLE I: Branching fraction results from this analysis, world average branching fractions from the PDG 2007 fit [7], ratios of branching fractions to $\mathcal{B}(D_s^+ \to K^-K^+\pi^+)$, and charge asymmetries $\mathcal{A}_{CP}$. Uncertainties on CLEO-c measurements are statistical and systematic, respectively.

Mode	This Result $\mathcal{B}$ (%)	PDG 2007 fit $\mathcal{B}$ (%)	$\mathcal{B}/\mathcal{B}(K^-K^+\pi^+)$	$\mathcal{A}_{CP}$ (%)
$K_S^0 K^+$	$1.49 \pm 0.07 \pm 0.05$	2.2 ± 0.4	$0.270 \pm 0.009 \pm 0.008$	$+4.9 \pm 2.1 \pm 0.9$
$K^-K^+\pi^+$	$5.50 \pm 0.23 \pm 0.16$	5.3 ± 0.8	1	$+0.3 \pm 1.1 \pm 0.8$
$K^-K^+\pi^+\pi^0$	$5.65 \pm 0.29 \pm 0.40$	—	$1.03 \pm 0.05 \pm 0.08$	$-5.9 \pm 4.2 \pm 1.2$
$K_S^0 K^-\pi^+\pi^+$	$1.64 \pm 0.10 \pm 0.07$	2.7 ± 0.7	$0.298 \pm 0.014 \pm 0.011$	$-0.7 \pm 3.6 \pm 1.1$
$\pi^+\pi^+\pi^-$	$1.11 \pm 0.07 \pm 0.04$	1.24 ± 0.20	$0.202 \pm 0.011 \pm 0.009$	$+2.0 \pm 4.6 \pm 0.7$
$\pi^+\eta$	$1.58 \pm 0.11 \pm 0.18$	2.16 ± 0.30	$0.288 \pm 0.018 \pm 0.033$	$-8.2 \pm 5.2 \pm 0.8$
$\pi^+\eta'$	$3.77 \pm 0.25 \pm 0.30$	4.8 ± 0.6	$0.69 \pm 0.04 \pm 0.06$	$-5.5 \pm 3.7 \pm 1.2$
$K^+\pi^+\pi^-$	$0.69 \pm 0.05 \pm 0.03$	0.67 ± 0.13	$0.125 \pm 0.009 \pm 0.005$	$+11.2 \pm 7.0 \pm 0.9$

by relaxing each assumption separately: the mass resolution is allowed to vary by an overall scale factor, and the background is parameterized by a second-order polynomial if the nominal fit uses a linear one, or vice versa. The size of the resulting excursions vary from 0.2% ($K^-K^+\pi^+$) to 8.6% ($K^-K^+\pi^+\pi^0$) for background shape and 0.1% ($K_S^0 K^+$) to 10.3% ($\pi^+\eta$) for width.

The efficiency for a reconstructed DT event to lie in the signal region depends on the mass resolutions for both candidates. Errors in modeling the resolution will thus cause errors in the DT efficiency which are correlated with the ST signal lineshape uncertainties. To estimate this effect we use the best fit results from the ST width check to determine the changes expected in the DT efficiency. The difference due to each decay mode is taken as a systematic uncertainty competely correlated with the corresponding ST uncertainty. The range of these effects is 0–8%.

In addition, we consider mode-dependent systematic uncertainties arising from our modeling of average $D_s^*D_s$ event multiplicity and detector noise (0–3%), the final state radiation spectrum generated by PHOTOS (0.2–1.2%), and our simulation of initial state radiation (0–0.8%).

Peaking backgrounds in ST events are found to be negligible compared to the size of the background shape uncertainties. Very small crossfeeds (of order 0.5% or less) are expected between various DT modes and are included in the fit; peaking DT backgrounds from other sources mostly arise from D^*D^* reflections and are again found to be negligible.

We have separate yields and efficiencies for D_s^+ and D_s^- events, so it is possible to compute asymmetries

$$\mathcal{A}_{CP,i} = \frac{y_i/\epsilon_i - y_{\bar{i}}/\epsilon_{\bar{i}}}{y_i/\epsilon_i + y_{\bar{i}}/\epsilon_{\bar{i}}},$$

which are sensitive to direct CP violation in D_s decays (expected to be very small in the Standard Model). Most systematic uncertainties cancel in this ratio; the ones that remain are due to charge dependence in tracking and PID, and the dependence of the ST yields on the signal lineshape and background parametrization.

The obtained branching fractions, branching ratios, and CP asymmetries are shown in Table I. The values we obtain are consistent with the world averages [7] and significantly more precise than any previous absolute measurements of D_s branching fractions. This is also the first result where all eight modes are measured simultaneously; the PDG fit combines many disparate branching ratio results. No significant CP asymmetries are observed. We additionally obtain the number of $D_s^*D_s$ events $N_{D_s^*D_s} = (2.93 \pm 0.14 \pm 0.06) \times 10^5$, which gives $\sigma_{D_s^*D_s}(4.17\ \text{GeV}) = (0.983 \pm 0.046 \pm$

TABLE II: Partial branching fractions $\mathcal{B}_{\Delta M}$ for $K^-K^+\pi^+$ events with K^-K^+ mass within ΔM MeV$/c^2$ of the ϕ mass. Uncertainties are statistical and systematic, respectively.

Value	This Result $\mathcal{B}$ (%)
$\mathcal{B}_5$	$1.69 \pm 0.08 \pm 0.06$
$\mathcal{B}_{10}$	$1.99 \pm 0.10 \pm 0.05$
$\mathcal{B}_{15}$	$2.14 \pm 0.10 \pm 0.05$
$\mathcal{B}_{20}$	$2.24 \pm 0.11 \pm 0.06$

0.021 ± 0.010) nb; in order, the uncertainties are statistical, systematic due to this measurement, and for the cross-section, systematic due to luminosity measurement [12]. The cross-section is consistent with earlier CLEO-c results obtained via a scan of this energy region [6].

In $D_s^+ \to K^-K^+\pi^+$ events, the K^-K^+ mass distribution near the ϕ peak shows the presence of a significant broad scalar component. Depending on the kinematic requirements used to select a ϕ signal, this contribution can vary from less than 5% to over 10% of the observed yield. This variation exceeds the uncertainty in our measurement of the absolute branching fractions. For this reason, we do not quote a branching fraction for the resonant mode $D_s^+ \to \phi\pi^+$. We instead provide partial branching fractions $\mathcal{B}_{\Delta M}$, which are defined as the branching fraction for $K^-K^+\pi^+$ events where the K^-K^+ pair satisfies $|M(K^-K^+) - 1019.5\ \mathrm{MeV}/c^2| < \Delta M$ (MeV$/c^2$); the values obtained are listed in Table II. When fit by a single Gaussian the $M(K^-K^+)$ resolution is 1.1 MeV$/c^2$ in this region. The systematic uncertainties quoted for $\mathcal{B}_{\Delta M}$ include uncertainties due to resolution.

In summary, we have presented the first application of a tagging technique at a center of mass energy of 4.17 GeV to measure eight hadronic D_s^+ branching fractions. We measure eight branching fractions of the D_s^+ meson to hadronic final states, with precisions exceeding world averages. For the key mode $D_s^+ \to K^-K^+\pi^+$, the statistical and systematic uncertainties are comparable. As the experimental meaning of $\mathcal{B}(D_s^+ \to \phi\pi^+)$ is ill-defined at this level of precision, we do not report it. We instead provide partial branching fractions for windows centered on the ϕ mass which do not assume a specific resonant composition of the decay.

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