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Improved Measurement of $\Gamma(D_s^+ \to \mu^+\nu)/\Gamma(D_s^+ \to \phi\pi^+)$

D. Gibaut,[1] K. Kinoshita,[1] P. Pomianowski,[1] B. Barish,[2] M. Chadha,[2] S. Chan,[2] D.F. Cowen,[2] G. Eigen,[2] J.S. Miller,[2] C. O'Grady,[2] J. Urheim,[2] A.J. Weinstein,[2] F. Würthwein,[2] D.M. Asner,[3] M. Athanas,[3] D.W. Bliss,[3] W.S. Brower,[3] G. Masek,[3] H.P. Paar,[3] J. Gronberg,[4] C.M. Korte,[4] R. Kutschke,[4] S. Menary,[4] R.J. Morrison,[4] S. Nakanishi,[4] H.N. Nelson,[4] T.K. Nelson,[4] C. Qiao,[4] J.D. Richman,[4] D. Roberts,[4] A. Ryd,[4] H. Tajima,[4] M.S. Witherell,[4] R. Balest,[5] K. Cho,[5] W.T. Ford,[5] M. Lohner,[5] H. Park,[5] P. Rankin,[5] J.G. Smith,[5] J.P. Alexander,[6] C. Bebek,[6] B.E. Berger,[6] K. Berkelman,[6] K. Bloom,[6] T.E. Browder,[6*] D.G. Cassel,[6] H.A. Cho,[6] D.M. Coffman,[6] D.S. Crowcroft,[6] M. Dickson,[6] P.S. Drell,[6] D.J. Dumas,[6] R. Ehrlich,[6] R. Elia,[6] P. Gaidarev,[6] M. Garcia-Sciveres,[6] B. Gittelman,[6] S.W. Gray,[6] D.L. Hartill,[6] B.K. Heltsley,[6] S. Henderson,[6] C.D. Jones,[6] S.L. Jones,[6] J. Kandaswamy,[6] N. Katayama,[6] P.C. Kim,[6] D.L. Kreinick,[6] T. Lee,[6] Y. Liu,[6] G.S. Ludwig,[6] J. Masui,[6] J. Mevissen,[6] N.B. Mistry,[6] C.R. Ng,[6] E. Nordberg,[6] J.R. Patterson,[6] D. Peterson,[6] D. Riley,[6] A. Soffer,[6] P. Avery,[7] A. Freyberger,[7] K. Lingel,[7] C. Prescott,[7] J. Rodriguez,[7] S. Yang,[7] J. Yelton,[7] G. Brandenburg,[8] D. Cinabro,[8] T. Liu,[8] M. Saulnier,[8] R. Wilson,[8] H. Yamamoto,[8] T. Bergfeld,[9] B.I. Eisenstein,[9] J. Ernst,[9] G.E. Gladding,[9] G.D. Gollin,[9] M. Palmer,[9] M. Selen,[9] J.J. Thaler,[9] K.W. Edwards,[10] K.W. McLean,[10] M. Ogg,[10] A. Bellerive,[11] D.I. Britton,[11] E.R.F. Hyatt,[11] R. Janicek,[11] D.B. MacFarlane,[11] P.M. Patel,[11] B. Spaan,[11] A.J. Sadoff,[12] R. Ammar,[13] P. Baringer,[13] A. Bean,[13] D. Besson,[13] D. Coppage,[13] N. Copty,[13] R. Davis,[13] N. Hancock,[13] S. Kotov,[13] I. Kravchenko,[13] N. Kwak,[13] Y. Kubota,[14] M. Lattery,[14] M. Momayezi,[14] J.K. Nelson,[14] S. Patton,[14] R. Poling,[14] V. Savinov,[14] S. Schrenk,[14] R. Wang,[14] M.S. Alam,[15] I.J. Kim,[15] Z. Ling,[15] A.H. Mahmood,[15] J.J. O'Neill,[15] H. Severini,[15] C.R. Sun,[15] F. Wappler,[15] G. Crawford,[16] R. Fulton,[16] D. Fujino,[16] K.K. Gan,[16] K. Honscheid,[16] H. Kagan,[16] R. Kass,[16] J. Lee,[16] M. Sung,[16] C. White,[16] A. Wolf,[16] M.M. Zoeller,[16] X. Fu,[17] B. Nemati,[17] W.R. Ross,[17] P. Skubic,[17] M. Wood,[17] M. Bishai,[18] J. Fast,[18] E. Gerndt,[18] J.W. Hinson,[18] T. Miao,[18] D.H. Miller,[18] M. Modesitt,[18] E.I. Shibata,[18] I.P.J. Shipsey,[18] P.N. Wang,[18] L. Gibbons,[19] S.D. Johnson,[19] Y. Kwon,[19] S. Roberts,[19] E.H. Thorndike,[19] T.E. Coan,[20] J. Dominick,[20] V. Fadeyev,[20] I. Korolkov,[20] M. Lambrecht,[20] S. Sanghera,[20] V. Shelkov,[20] T. Skwarnicki,[20] R. Stroynowski,[20] I. Volobouev,[20] G. Wei,[20] M. Artuso,[21] M. Gao,[21] M. Goldberg,[21] D. He,[21] N. Horwitz,[21] S. Kopp,[21] G.C. Moneti,[21] R. Mountain,[21] F. Muheim,[21] Y. Mukhin,[21] S. Playfer,[21] S. Stone,[21] X. Xing,[21] J. Bartelt,[22] S.E. Csorna,[22] V. Jain,[22] and S. Marka[22]

(CLEO Collaboration)

[1] *Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24061*
[2] *California Institute of Technology, Pasadena, California 91125*
[3] *University of California, San Diego, La Jolla, California 92093*
[4] *University of California, Santa Barbara, California 93106*
[5] *University of Colorado, Boulder, Colorado 80309-0390*
[6] *Cornell University, Ithaca, New York 14853*
[7] *University of Florida, Gainesville, Florida 32611*
[8] *Harvard University, Cambridge, Massachusetts 02138*
[9] *University of Illinois, Champaign-Urbana, Illinois, 61801*
[10] *Carleton University, Ottawa, Ontario K1S 5B6 and the Institute of Particle Physics, Canada*
[11] *McGill University, Montréal, Québec H3A 2T8 and the Institute of Particle Physics, Canada*
[12] *Ithaca College, Ithaca, New York 14850*
[13] *University of Kansas, Lawrence, Kansas 66045*
[14] *University of Minnesota, Minneapolis, Minnesota 55455*
[15] *State University of New York at Albany, Albany, New York 12222*
[16] *Ohio State University, Columbus, Ohio, 43210*
[17] *University of Oklahoma, Norman, Oklahoma 73019*
[18] *Purdue University, West Lafayette, Indiana 47907*
[19] *University of Rochester, Rochester, New York 14627*
[20] *Southern Methodist University, Dallas, Texas 75275*
[21] *Syracuse University, Syracuse, New York 13244*
[22] *Vanderbilt University, Nashville, Tennessee 37235*

Abstract

We have significantly improved the previous CLEO measurement of f_{Ds}. Our value derives from the measurement $\Gamma(D_s^+ \to \mu^+\nu)/\Gamma(D_s^+ \to \phi\pi^+) = 0.184 \pm 0.038 \pm 0.038$. Using $\mathcal{B}(D_s^+ \to \phi\pi^+) = (3.5 \pm 0.4)\%$, we extract $f_{D_s} = (284 \pm 30 \pm 30 \pm 16)$ MeV. We compare this result with various model calculations.

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*Permanent address: University of Hawaii at Manoa

I. INTRODUCTION

Purely Leptonic decays of heavy mesons provide direct access to meson decay constants, which connect measured quantities, eg. $B\bar{B}$ mixing ratio, to CKM matrix elements.

Currently, it is not possible to determine f_B experimentally from leptonic B decays, so theoretical calculations of f_B must be used. Measurements of of the Cabibbo favored pseudoscalar decay constants such as f_{Ds} could check these calculations and will help discriminate among different models. The decay rate for D_s^+ is given by [1]

$$\Gamma(D_s^+ \to l^+\nu) = \frac{1}{8\pi} G_F^2 f_{D_s}^2 m_l^2 M_{D_s} \left(1 - \frac{m_l^2}{M_{D_s}^2}\right)^2 |V_{cs}|^2 \quad , \tag{1}$$

where M_{D_s} is the D_s mass, m_l is the mass of the final state lepton, V_{cs} is a CKM matrix element equal to 0.974 [2], and G_F is the Fermi coupling constant. Various theorical predictions of f_{Ds} range from 200 MeV to 350 MeV.

Due to helicity suppression, the electron mode $D_s^+ \to e\nu$ has a very small rate. The relative widths are $10 : 1 : 2 \times 10^{-5}$ for the $\tau^+\nu$, $\mu^+\nu$ and $e^+\nu$ final states, respectively. Unfortunately the biggest mode, $\tau^+\nu$, has at least two neutrinos in the final state and is difficult to detect.

In a previous publication [3], CLEO reported the measurement of $f_{D_s} = (344 \pm 37 \pm 52 \pm 42)$ MeV, using the decay chain $D_s^{*+} \to \gamma D_s^+$, $D_s^+ \to \mu^+\nu$. Two other groups have also claimed the observation of $D_s^+ \to \mu^+\nu$. WA75 reported f_{Ds} is $(232 \pm 45 \pm 20 \pm 48)$ MeV using muons from D_s^+ leptonic decays seen in emulsions [4], and a value of $(430^{+150}_{-130} \pm 40)$ MeV was measured at the D_s^+ production threshold by BES [5].

In this paper we present an improved CLEO analysis. This analysis uses a sample of about 3.2 million $e^+e^- \to c\bar{c}$ events collected with the CLEO II detector [6] at CESR. The integrated luminosity is 3.06 fb^{-1} at the $\Upsilon(4S)$ resonance or at energies just below. This paper supercedes our previous analysis result based on a subset of current data of 2.13 fb^{-1}. The improvements in this analysis include both more data and better measurements of the lepton fakes.

II. ANALYSIS METHOD

A. Overview

This analysis is based on our previous one, which should be consulted for a detailed decription of the technique [3]. Here we give a brief overview of the method.

We search for the decay chain of $D_s^{*+} \to \gamma D_s^+$, $D_s^+ \to \mu^+\nu$. The photon and the muon from the $D_s^+ \to \mu^+\nu$ decay are measured directly whereas the neutrino is indirectly detected by the missing momentum and energy using the near-hermeticity of the CLEO II detector. Using the missing momentum as the neutrino momentum, we look for a signal in the mass difference

$$\Delta M = M(\gamma\mu\nu) - M(\mu\nu) \tag{2}$$

so that the relatively large errors from missing momentum calculation will mostly cancel. Two data samples of similar topology, $D^{*+} \to \pi^+ D^0$ and $D^{*0} \to \gamma D^0$ where $D^0 \to K^-\pi^+$, are used to study the ΔM signal and background shapes and to evaluate the effectiveness of our Monte Carlo efficency simulation. We treat these fully reconstructed data samples as $D_s^+ \to \mu^+\nu$ decays by removing the measurements of the fast π^+ from both the tracking chambers and the calorimeter to simulate the ν, and by "identifying" the K^- as a muon.

B. Background

There are various kinds of backgrounds. The real physics backgrounds, such as semileptonic decays, are almost identical in muon and electron final states because of lepton universality. For the leptonic D_s^+ decay, however, the electronic width is negligible in comparison to the muonic width. Thus, performing the identical analysis, except for selecting electrons rather than muons, gives us a quantitative measurement of the physical background level. $D_s^+ \to \mu^+\nu$ and $D^+ \to \mu^+\nu$ are the only physics processes which produce significantly more primary muons than electrons with momenta above 2 GeV/c in continuum e^+e^- annihilations in the $\Upsilon(4S)$ energy region. $D^+ \to \mu^+\nu$ decay is suppressed by the CKM angle (Eq. 1), and by the $D^{*+} \to \gamma D^+$ branching ratio which is small, $< 4\%$ at 90% confidence level [7].

The next source of background results from hadrons faking muons. Since muons are more difficult to identify than electrons, we need to consider the excess fakes in the muon sample relative to the electron sample. To determine this hadron fake background contribution, we multiply the ΔM distribution of all tracks, except identified leptons, by an effective hadron-to-lepton fake rate difference, measured with tagged hadron data samples. We consider kaon and pion decays in flight as fake leptons. The detailed analysis of this effective fake rate is described in section III.

After removing the above two components, any remaining background results from combinatorial background of random photons and real $D_s^+ \to \mu^+\nu$ and $D^+ \to \mu^+\nu$ events. This background is simulated using the fully reconstructed $D^{*+} \to \pi^+ D^0$ data sample.

C. Event Selection and Background Suppression

Most of the leptons from B meson decays are removed by requiring a minimum lepton momentum of 2.4 GeV/c, which is 33% efficient for $D_s^+ \to \mu^+\nu$. Leptons from $\tau^+\tau^-$ pairs, and other QED processes with low multiplicity, are suppressed by requiring that either the event has at least five well reconstructed charged tracks, or at least three charged tracks accompanied by at least six neutral energy clusters. To suppress background caused by particles which escape detection at large $\cos\theta$, where θ is the angle of the momentum with respect to the beam axis, we require that the angle between the missing momentum of the event and the beam axis, θ_{miss}, does not point along the beam direction, $|\cos\theta_miss| < 0.9$.

Muons are required to penetrate at least seven interaction lengths of iron, and to have $|\cos\theta| < 0.85$. The muon identification efficiency, measured with $e^+e^- \to \mu^+\mu^-\gamma$ events, is $(85\pm2)\%$. Electrons must have an energy deposit in the electromagnetic calorimeter close to the fitted track momentum, and a dE/dx measurement in the main drift chamber consistent with that expected for electrons. The electron identification efficiency for $|\cos\theta| < 0.85$, $(87\pm4)\%$, is found by embedding tracks from radiative Bhabha events into hadronic events.

A Monte Carlo study shows that the main background contributions from real leptons in the ΔM distribution are semileptonic D decays, mostly $D \to K/\pi l\nu$ and $D_s \to \eta l\nu$. The relative identification-efficiency ratio is corrected for differences in electron and muon radiation in the detector material (outer bremsstrahlung) (+5%), the different probabilities that a photon is emitted in the decay (inner bremsstrahlung) (+2.7% for $D^+ \to K^0 l^+\nu$), and the differences in muon and electron phase space (-1.7% for $D^+ \to K^0 l^+\nu$). Therefore, we use a correction factor of 1.04 ± 0.03 to multiply the electron sample to account for the physics backgrounds and identification efficiency difference.

Photons must be in the angular region $|\cos\theta| < 0.71$. We require a minimum energy of 150 MeV, which is 78% efficient for $D_s^{*+} \to \gamma D_s^+$ decay, to eliminate backgrounds caused by the large number of low energy photons. Combinations of two photons which have invariant masses within two standard deviations ($\sigma \sim 5$ MeV) of the π^0 mass are eliminated. We also insist that in the rest frame of the D_s^{*+} candidate, the cosine of the angle between the photon and the D_s^{*+} direction in the lab be larger than -0.7. A small residual $b \to ul\nu$ background is suppressed by insisting that the thrust axis lines up with the D_s^{*+} candidate momentum such that the cosine of the angle between them is greater than 0.975.

D. Signal Shape and Efficiency

Using our $D^{*+} \to \pi^+ D^0$ sample which has high statistics and negligible background, we calibrate the D meson invariant mass, $M(\mu\nu) = M(Kp_{miss})$, by eliminating the π^+ from the $D^0 \to K^-\pi^+$ decay to simulate the neutrino. We divide the event into two hemispheres using the thrust axis of the event. The missing momentum $\overrightarrow{p}_{miss}$ and energy E_{miss} are calculated using only energy and momentum measurements $(E_i, \overrightarrow{p}_i)$ in the hemisphere which contains the lepton (kaon). The energy sum is computed assuming all tracks are pions, unless they are positively identified as kaons, or protons by dE/dx measurement in the drift chamber. We define missing momentum and energy as

$$\begin{aligned} \overrightarrow{p}_{miss} &= \overrightarrow{p}_{thrust} - \sum \overrightarrow{p}_i \\ E_{miss} &= E_{beam} - \sum E_i \quad . \end{aligned} \tag{3}$$

where the direction of $\overrightarrow{p}_{thrust}$ is given by the thrust axis. The magnitude is $p^2_{thrust} = E^2_{beam} - m^2_{jet}$, where E_{beam} is the beam energy and m_{jet} is the average jet mass measured to be 3.2 GeV. A D_s^+ candidate is selected by requiring 1.6 GeV $< M(\mu\nu) <$ 2.6 GeV. The missing mass squared must be consistent with a neutrino, $|E^2_{miss} - p^2_{miss}| < 2$ GeV^2. We find a factor of two increase in efficiency and background by using only one hemisphere to determine the missing momentum relative to using the whole event. We also require $p_{miss} > 0.9$ GeV/c to suppress the fake lepton background.

The mass difference distribution ΔM (Eq. 2) is simulated by our $D^{*0} \to \gamma D^0$, $D^0 \to K^-\pi^+$ sample. In the fully reconstructed mass difference $\delta M = M(\gamma K\pi) - M(K\pi)$ distribution there is a substantial signal but also significant background, so a δM sideband subtraction is performed. After applying the additional background suppression cuts, described above, we obtain the mass difference distribution $\Delta M = M(\gamma K p_{miss}) - M(K p_{miss})$

shown in Fig. 1(a). There is a clear signal peak associated with the photon and it is fitted to an asymmetric Gaussian with low side and high side σ's of 18 MeV and 27 MeV, respectively. The small flat component results from replacing the correct photon with another photon.

The efficiency for an event to appear in the peak is $\epsilon_\nu = (25\pm3)\%$. The overall detection efficiency for $D_s^{*+} \to D_s^+\gamma$, $D_s^+ \to \mu^+\nu$ is $\epsilon = (2.6 \pm 0.2)\%$ using Monte Carlo simulation. To evaluate the effectiveness of the Monte Carlo calculation, we compared our $D^{*+} \to \pi^+ D^0$, $D^0 \to K^-\pi^+$ Monte Carlo and data sample for the missing momentum calculations. We find the efficiencies of the missing momentum reconstruction agree well between data and Monte Carlo. Since in both cases we have the information of the rejected pion, we can also compare the missing momentum calculation error distribution between the two cases. They also agree well. The error in the efficiency largely reflects the statistics of our D^{*+} sample.

Random photons also give contributions to the ΔM distribution. First, there are direct $D_s^+ \to \mu^+\nu$ decays which pair with a random photon to form a D_s^{*+} candidate. Secondly, there are D_s^{*+} events where the correct photon is replaced by another photon. These two contributions are fixed relative to the direct $D_s^{*+} \to \gamma D_s^+, D_s^+ \to \mu\nu$ signal using our measurement of D_s^{*+}/D_s^+ production ratio above 2.4 GeV of 1.03 ± 0.20. Thirdly, there is a small contribution from $D^+ \to \mu^+\nu$ decays combined with a random photon. The shape in ΔM of these contributions is modeled using the $D^{*+} \to \pi^+ D^0$ event sample, by combining the $M(Kp_{miss})$ candidates with random photons in the same event and shown in Fig. 1(b). Overlaid is a fit to the functional form $\sqrt{x - x_0}e^{-a(x-x_0)}$ which is used to parameterize the random photon component. The distributions in Fig. 1(a) and Fig. 1(b) are summed using appropriate weights to produce an expected signal shape.

III. FAKE BACKGROUND CALCULATION

A. Method and Channels

Even after strict lepton identification requirements have been applied, significant numbers of hadron fakes still enter our signal region because of the abundance of hard hadron tracks. To properly account for the hadron fake background, we need to precisely measure the effective excess muon/electron fake rate to derive the correct background level. The D^* decays provide us with well-tagged kaon and pion samples. In our previous publication, the uncertainty in the fake rate value dominated the systematic errors. One major improvement of the current analysis is the better determination of this effective fake rates for muons and electrons from much larger tagged data samples by using new data and adding more channels.

In this analysis, in addition to the decay chain $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$, we also include the $D^{*+} \to D^0\pi^+ \to (K^-\rho^+)\pi^+$, and $D^{*0} \to D^0\pi^0 \to (K^-\pi^+)\pi^0$ to get as many events as possible. $K_S \to \pi^+\pi^-$ samples are also used to determine the pion fake rate and are combined with the D^* results to get better statistics. Over 10,000 events are collected with either a π or K with momentum greater than 2.4 GeV from the above channels.

B. Fake Rates from D^* and K_s sample study

Fig. 2 summarizes the fake signals and the fitting curves using $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$ sample. The $M(\pi K\pi) - M(K\pi)$ mass difference is shown after a cut on $K\pi$ mass constraint with D^0 mass. The number of events is determined by a fit with double gaussian for signal and half-integer power polynomials for background. Both fitting functions are derived from the mass difference distribution without lepton identification suppression. The extracted fake rates (before decay in flight correction) are listed in Table I. The same reconstructing and fitting methods are used to collect $D^0 \to K^-\rho^+$, and $D^{*0} \to D^0\pi^0$ where D^0 goes to $K^-\pi^+$ sample. All the fake rate numbers are also summarized in Table I as well as the number of hadrons in each sample and the weighted averages of the fake rates.

TABLE I. Fake Rates for P > 2.4 GeV/c

Data Samples	# of K	# of π	Fake Rates (%) K/μ	K/e	π/μ	π/e
$D^{*+}(D^0 \to K^-\pi^+)$	5709	4471	0.97±0.15	0.03±0.09	0.63±0.17	0.40±0.12
$D^{*+}(D^0 \to K^-\rho^+)$	1368	682	1.23±0.33	0.22±0.20	0.30±0.40	0.15±0.21
$D^{*0}(D^0 \to K^-\pi^+)$	3174	2048	1.07±0.21	0.17±0.10	0.84±0.35	0.60±0.31
$K_S \to \pi^+\pi^-$	-	3527	-	-	0.74±0.15	0.37±0.10
Total/Average	10449	10728	1.03±0.11	0.11± 0.06	0.68±0.10	0.37±0.07

C. Decay in flight correction

The contributions to the lepton fake rates from kaon and pion decays in flight are not necessarily included in the above procedure because particles decaying close to the production point may not appear in the D^0 mass peak. To account for this effect, we used a Monte Carlo study of 200,000 $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$ events. After muon identification cuts are applied, the D^{*+} mass difference plot has a peak region used to derive the fake signal and a tail away from the peak, which is due to events in which the kaon decays. We extract a correction factor to the fake rate of 1.18±0.06 by computing the ratio of the tail area to the peak area. We find no events out of the D^* mass difference peak in which the pion has decayed. This is because of the long lifetime for the pion and because of the fact that the muon momentum is very close to that of the parent pion.

IV. RESULTS

The ΔM distributions for the muon and electron data and the calculated effective excess of muon fakes over electron fakes are given in Fig. 3(a). The histogram shows a likelihood fit to the muon spectrum from the sum of three contributions: the signal distribution evaluated from the D^{*0} and D^{*+} samples (Fig. 1), the scaled electrons, and the excess of muon over electron fakes. Here, the size of the electron and fake contributions are fixed and only the signal normalization is allowed to vary. We find 47±10 events in the peak which are attributed to the process $D_s^{*+} \to \gamma D_s^+$, $D_s^+ \to \mu^+\nu$, and 50±12 events in the flat part of the distribution corresponding to $D_s^+ \to \mu^+\nu$ or $D^+ \to \mu^+\nu$ events coupled with a random photon. The contribution of a real $D^+ \to \mu^+\nu$ decay with random photons is larger since the $D^{*+} \to \gamma D^+$ branching ratio does not enter in. It is estimated to be about (18±8)% relative to the total $D_s^+ \to \mu^+\nu$ plus random photon contribution.

To explicitly display the signal, we show, in Fig. 3(b), the ΔM distribution after the electrons and the fakes are subtracted. The curve is a fit of the data to the signal shape calculated from the D^{*0} and D^{*+} samples.

Using the likelihood fit result of 47±10 events, we extract a width for $D_s^+ \to \mu^+\nu$ by normalizing to the the efficiency corrected number of fully reconstructed $D_s^{*+} \to \gamma D_s^+$, $D_s^+ \to \phi\pi^+$ events, 9740±620±580. The efficiency for reconstructing the $\phi\pi^+$ decay is obtained from Monte Carlo. We find

$$\frac{\Gamma(D_s^+ \to \mu^+\nu)}{\Gamma(D_s^+ \to \phi\pi^+)} = 0.184 \pm 0.038 \pm 0.038 \quad , \tag{4}$$

where the first error is statistical error on the measured numbers of $\mu^+\nu$ and $\phi\pi^+$ events. The second error is the total systematic error of 21%, which is summarized in Table II.

TABLE II. Systematic Errors on Width Ratio

Source of Error	Value	Size of error (%)
Muon fake rate	(0.73±0.07)%	12
Electron fake rate	(0.25±0.04)%	8
μ/e normalization	1.04±0.03	9
Detection efficiency	(2.6±0.2)%	7
D_s^{*+}/D_s^+ production ratio	1.03±0.2	11
$\phi\pi^+$ normalization	9740±620±580	6
Total systematic error		21

The errors that arise from the relative muon/electron normalization (9%), the muon fake rate (12%), the electron fake rate (8%), and the D_s^{*+}/D_s^+ production ratio (11%), are estimated by fitting the data with each parameter changed by $\pm$ 1σ. The systematic error due to the detection efficiency is dominated by the statistics of our D^{*+} sample. A systematic error of ±6% for the detection efficiency of the normalization mode $\phi\pi^+$ is included.

V. CONCLUSIONS

We have improved our previous measurement of the ratio of decay widths

$$\Gamma(D_s^+ \to \mu^+\nu)/\Gamma(D_s^+ \to \phi\pi^+) = 0.184 \pm 0.038 \pm 0.038 \quad . \tag{5}$$

Using the PDG average value $\mathcal{B}(D_s^+ \to \phi\pi^+)$ of (3.5±0.4)%, and $\tau_{D_s} = (4.67 \pm 0.17) \times 10^{-13} s$, we find

$$f_{D_s} = (284 \pm 30 \pm 30 \pm 16) \text{ MeV} \tag{6}$$

The first two errors are the statistical and systematic errors resulting from our relative width ratio measurement, and the third error reflects the uncertainty in the absolute $D_s^+ \to \phi\pi^+$

branching ratio. This result supercedes our previous one, using a data sample that includes the one used in the previous analysis. The reduction in the central value is primarily due to the better measurement of the lepton fake rates.

For comparison, we list the published results from other experiments and the old CLEO result in Table III. We also include the corrected values of f_{D_s} according to the new PDG D_s decay branching fractions. For the old CLEO result, we also correct it with the new fake rate value determined in this analysis.

TABLE III. Current Experimental Results of f_{D_s} Measurements

Collaboration	Observed Events	Published f_{D_s} value (MeV)	Corrected f_{D_s} value (MeV)
WA75 [4]	6	$232 \pm 45 \pm 20 \pm 48$	$238 \pm 47 \pm 21 \pm 43$
CLEO (old)	39±8	$344 \pm 37 \pm 52 \pm 42$	$278 \pm 35 \pm 30 \pm 16$
BES	3	$430^{+150}_{-130} \pm 40$	Same

Theoretical predictions of f_{D_s} have been made using many methods. Recent lattice gauge calculations [8] from MILC collaboration give 225 to 275 MeV with different parameters, while potential model values [9] range from 210 to 356 MeV. QCD sum rule estimates [10] are between 200 and 290 MeV. Predictions for f_{D_s} have also been made by combining theory with experimental input. Assuming factorization for $B \to D^* D_s^-$ decays combined with measured branching ratios, values of f_{D_s} range from 230 to 280 MeV with an error of about 50 MeV [11].

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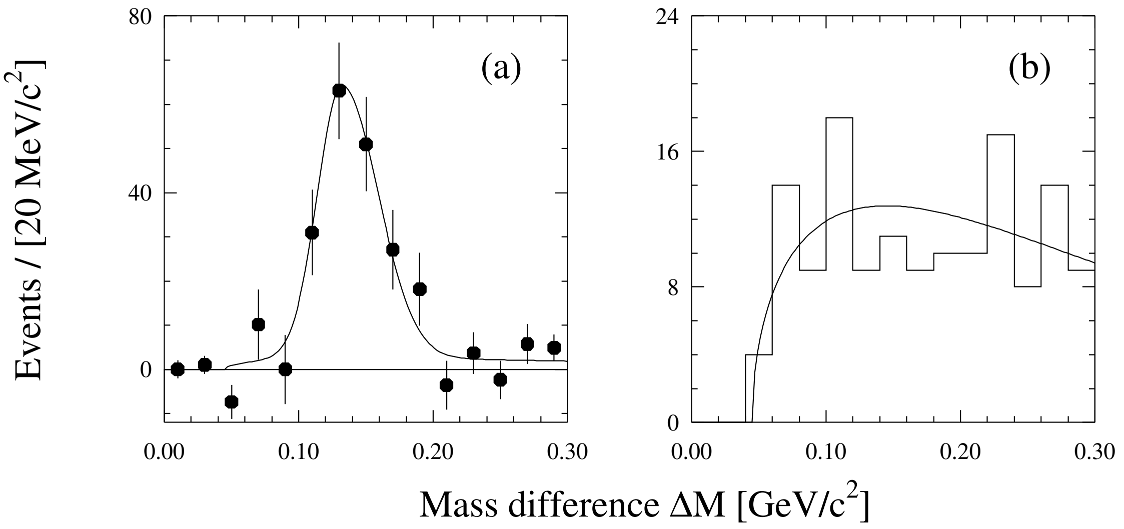

FIG. 1. The ΔM mass difference distributions for the missing momentum analysis for (a) the $D^{*0} \to \gamma D^0$, $D^0 \to K^- \pi^+$ event sample and (b), the $D^{*+} \to \pi^+ D^0$, $D^0 \to K^- \pi^+$ event sample, combined with random photons. The fits are described in the text.

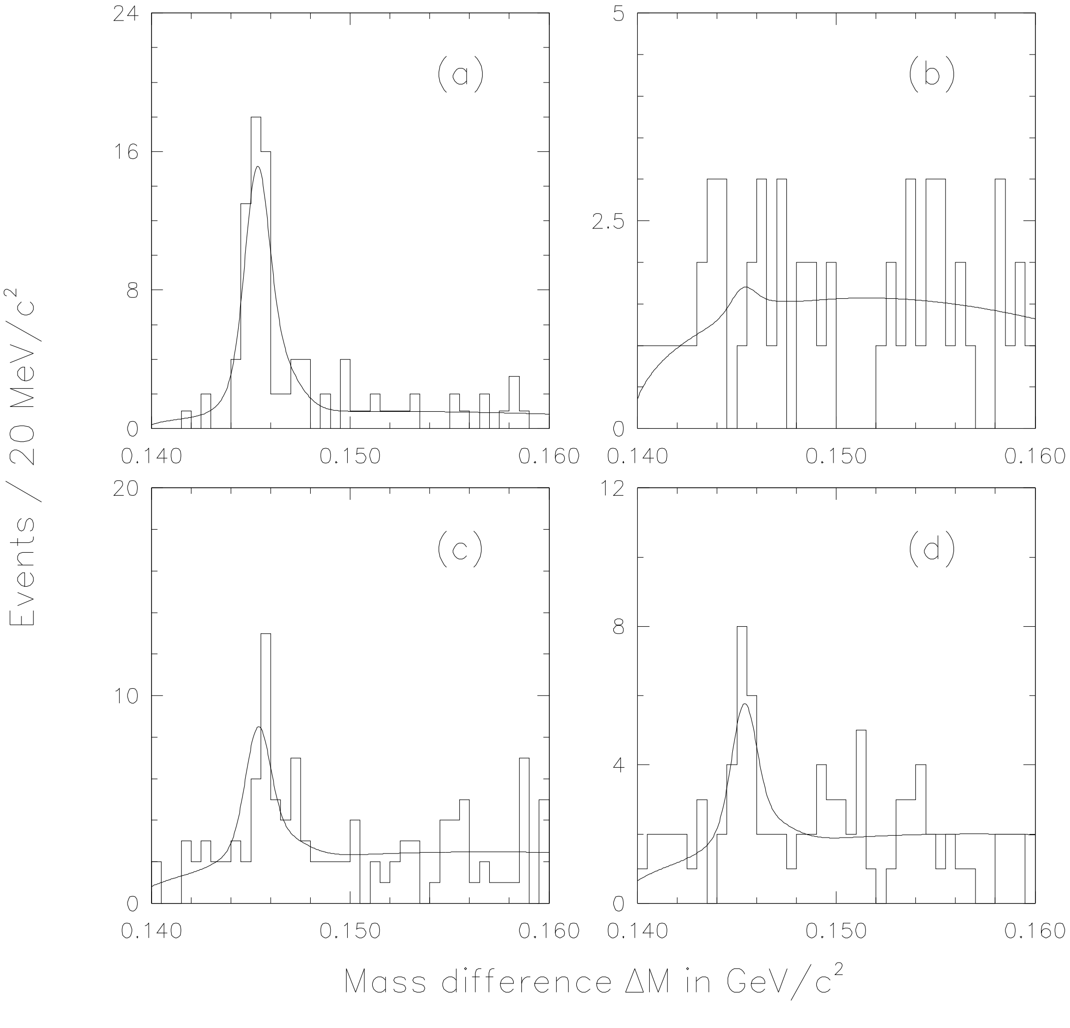

FIG. 2. $M(\pi K\pi) - M(K\pi)$ mass difference after lepton identification requirement for (a) kaon as muon, (b) kaon as electron, (c) pion as muon, (d) pion as electron.

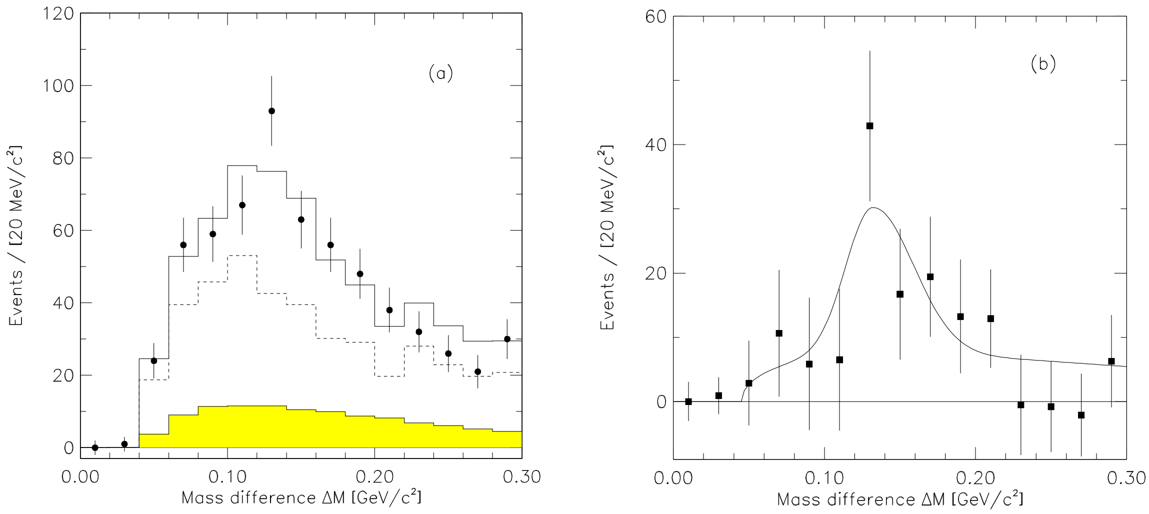

FIG. 3. a) The ΔM mass difference distribution for D_s^{*+} candidates for both, the muon data (solid points), the electron data (dashed histogram) and excess muon fakes over electron fakes (shaded). The histogram is the result of the likelihood fit described in the text. b) The ΔM mass difference distribution for D_s^{*+} candidates with electrons and excess muon fakes subtracted. The curve is a fit to the signal shape described in the text.