TEVATRON HEAVY FLAVOR RESULTS ON B LIFETIMES AND DECAYS AND D ASYMMETRIES

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We review the most recent CDF and DO results related to B lifetimes, decays and D asymmetries. We report on the recent CDF measurement of the properties of several ground state b-baryons, including Ξ_b^-, Ξ_b^0 and Ω_b^-. We also report on the CDF measurements of the B_c^+ cross section performed in the $B_c^+ \to J/\psi\mu^+\nu$ decay mode, and of charm mixing. We present the D0 search for the narrow X(4140) resonance, which supports the evidence of existence of this state, and the D0 searches for direct CP violation in the $B^+ \to J/\psi K^+$, $B^+ \to J/\psi\pi^+$, and in the $D_s^+ \to \phi\pi^+$ decay modes.

1 Introduction

B hadrons are abundantly produced at the Tevatron Collider, and the available energy allows the production of the lighter B mesons as well as the heavier Λ_b, Σ_b, Ξ_b and Ω_b hadrons. The challenge is extracting signals from a level of background which is orders of magnitude higher at production. This is achieved with dedicated detectors and triggers. CDF and D0 have been first class players in the field of heavy flavour physics for 20 years, with more than 150 published papers. These results have been complementary and competitive with B-Factories in terms of precision. The Tevatron experiments leave a rich legacy to LHC and future B-Factories.

2 Measurement of B baryon properties at CDF

The first Ω_b^- observation was made at D0[1] and CDF[2] through the decay chain $\Omega_b^- \to J/\psi\Omega^-$, where $J/\psi \to \mu^+\mu^-$, $\Omega^- \to \Lambda K^-$, and $\Lambda \to p\pi^-$. The Ξ_b^- is reconstructed through the similar decay mode $\Xi_b^- \to J/\psi\Xi^-$, where $J/\psi \to \mu^+\mu^-$, $\Xi^- \to \Lambda\pi^-$, and $\Lambda^- \to p\pi^-$, as a crosscheck. The updated CDF analysis [3] has been performed on 9.6 fb^{-1} of data and selects well-measured $J/\psi \to \mu^+\mu^-$ candidates, where the two-muon invariant mass is required to be compatible with the world-average J/ψ mass. Λ candidates use all opposite charge track pairs with $p_T > 0.4$ GeV/c found in the chamber. The proton (pion) mass is assigned to the track with the higher (lower) momentum. The additional tracks are assigned the pion or kaon mass, and $\Lambda\pi^-$ and ΛK^- combinations are selected if they are consistent with the decay process $\Xi^- \to \Lambda\pi^-$ or $\Omega^- \to \Lambda K^-$. A fit of the charged hyperon candidates simultaneously constrains the appropriate track combinations to the Λ and Ξ^- or Ω^- masses, and provides the best possible estimate of the hyperon momentum and decay position. A significant background reduction is achieved by requiring the charged hyperon candidates to have track measurements in at least one layer of the silicon detector. The shorter lifetime of the Ω^- makes the silicon selection not efficient, if compared to the Ξ^- case. For this reason, silicon detector information on the hyperon track is used when available, but it is not imposed as a requirement for the Ω^- selection. The hyperon

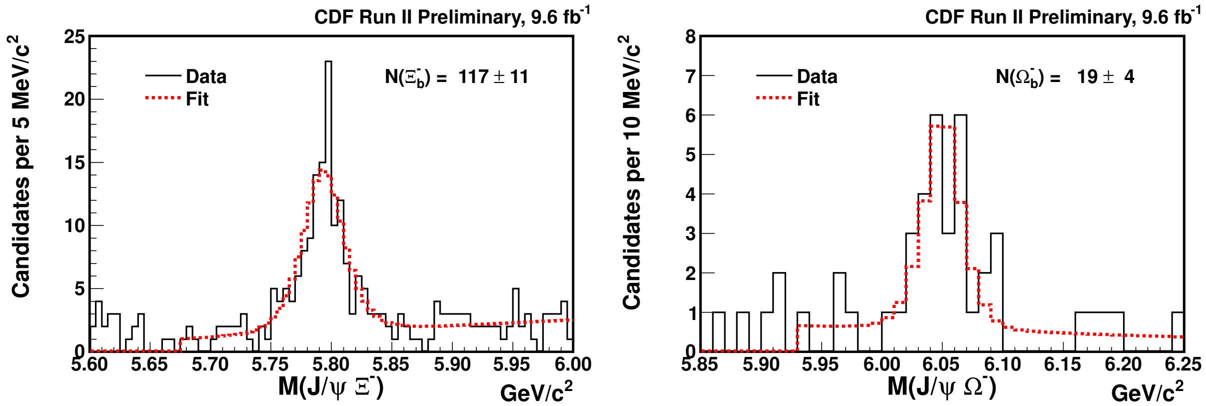

Figure 1 – (Left): The $J/\psi\Xi^-$ and (Right) $J/\psi\Omega^-$ mass distributions used for the CDF b-baryon mass measurements. The probability distributions obtained from the fits are overlaid on the data in dashed red.

candidates are combined with the J/ψ candidates by fitting the five-track state with constraints appropriate for each decay topology. The $\mu^+\mu^-$ mass is constrained to the nominal J/ψ mass, and the hyperon candidate is constrained to originate from the J/ψ decay vertex. The fits that include the charged hyperon constrain the Λ candidate tracks to the nominal Λ mass, and the Ξ^- and Ω^- candidates to the respective nominal masses. b-hadron candidates are required to have $p_T > 6.0$ GeV/c and the hyperon to have $p_T > 2.0$ GeV/c. Figure 1 shows the CDF Ξ_b^- and Ω_b^- mass distributions. CDF measures the Ξ_b^- mass to be 5794.1±2.0(stat)±0.40(syst) MeV/c^2 and the Ω_b^- mass to be 6051.4±4.2(stat)±0.50(syst) MeV/c^2. The systematic errors are due to the uncertainty on the mass scale of the baryons measured with the hyperons in the final state, estimated as the mass difference between the B^0, as measured in the $J/\psi K_s^0$, and the nominal B^0 mass, and rescaled for the different energy measured by the tracking system in the two decay modes. A further systematic is due to the uncertainty on the Ω^- mass. The Ξ_b^- lifetime is measured to be 1.36±0.15(stat)±0.02(syst) ps and the lifetime of the Ω_b^- to be $1.77^{+0.55}_{-0.41}$(stat)±0.02(syst) ps. The systematic errors are due to the treatment of the resolution on the proper decay length in the fit and to the detector mis-alignment.

A second dataset, designed for the collection of heavy flavour decay products through the reconstruction of displaced vertices, is used to provide the first evidence for the process $\Omega_b^- \to \Omega_c^0\pi^-$, with $\Omega_c^0 \to \Omega^-\pi^+$. As a crosscheck of this analysis, also the processes $\Xi_b^- \to \Xi_c^0\pi^+$, with $\Xi_c^0 \to \Xi^-\pi^+$, and $\Xi_b^0 \to \Xi_c^+\pi^-$, with $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ are reconstructed. CDF measures the Ξ_b^0 mass to be 5791.6±5.0(stat)±0.73(syst) MeV/c^2 the Ξ_b^- mass to be 5796.5±4.7(stat)±0.95(syst) MeV/c^2 and the Ω_b^- tmass o be 6040±8(stat)±2(syst) MeV/c^2, compatible with the measurements performed in the J/ψ decay modes.

3 Measurement of the ratio $\frac{\sigma(B_c^+)\times BR(B_c^+\to J/\psi\mu^+\nu)}{\sigma(B^+)\times BR(B^+\to J/\psi K^+)}$ at CDF

The B_c is the bound state of a $\bar{b}$ and c quark. Since the $\bar{b}$ and c quark are much closer in mass than the more commonly studied heavy-light mesons, the B_c is an interesting laboratory for studying QCD. In addition, the B_c total width can have significant contributions from the partial widths of the c-quark decay, the b-quark decay, or annihilation of the b and c quarks to a W boson, in contrast to the light B mesons, where the b quark decay is expected to dominate the width. For this analysis the entire CDF Run II dataset has been used[4]. J/ψ particles are reconstructed through the $\mu^+\mu^-$ decay channel and are matched to a third track associated with the J/ψ vertex. The third track might be the muon in the $B_c^+ \to J/\psi\mu^+X$ decay, or the kaon in the $B^+ \to J/\psi K^+$ decay, or a pion, a kaon or a proton in the misidentified muon background.

There are 1,370 $B_c^+ \to J/\psi\mu^+\nu$ event candidates in the 4-6 GeV/c^2 signal mass window and 14,338 ± 125 events in the $B^+ \to J/\psi K^+$ decay sample. The fit function for the $J/\psi K^+$

Table 1: Summary of the misidentified J/ψ, real J/ψ + one misidentified muon, double fake, and $b\bar{b}$ backgrounds measured in the $B_c^+ \to J/\psi\mu^+\nu$ sample.

	$M \leq 4$ GeV/c^2	$4 \leq M \leq 6$ GeV/c^2	M ≥ 6 GeV/c^2
N($B_c^+ \to J/\psi\mu^+X$), reconstr.	132 $\pm$ 11.5	1370 $\pm$ 37.0	280 $\pm$ 14.4
Backgrounds			
Misidentified J/ψ	11.5 $\pm$ 2.4	96.5 $\pm$ 6.9	25 $\pm$ 3.5
Misidentifed muon	86.7	344.4	32.1
Double fake	-5.1	-19.0	-5.2
$b\bar{b}$	12.4 $\pm$ 2.4	178.6 $\pm$ 12.4	110.4 $\pm$ 10.7
Other decay modes	2.6 $\pm$ 0.1	30.0 $\pm$ 0.2	0
N(B_c^+)	23.9 $\pm$ 12.0	739.5 $\pm$ 39.6	45.7 $\pm$ 18.3

invariant mass distribution consists of a double Gaussian for $B^+ \to J/\psi K^+$ decays, a mass template for the Cabibbo suppressed $B^+ \to J/\psi\pi^+$ contribution, within the mass range 5.28-5.40 GeV/c^2, based on Monte Carlo simulation, and a second order polynomial for the continuum background. The Cabibbo suppressed $B^+ \to J/\psi\pi^+$ contribution is fixed to 3.83 % of the number of $B^+ \to J/\psi K^+$ candidates. The number of B_c^+ signal events is determined by subtracting the background contributions to the sample of B_c^+ candidates.

The main sources of background in the semileptonic B_c^+ sample are misidentified J/ψ, real J/ψ with a misidentified third muon, $b\bar{b}$ background, and contributions from other b decay modes. The number of misidentified J/ψ plus a third muon is estimated using the di-muons from the sidebands of the J/ψ mass distribution. The misidentified muon contribution to the B_c^+ background is calculated using a sample of J/ψ+track candidates, and by determining the kaon, pion, and proton probability to be misidentified as muons. The $b\bar{b}$ background accounts for cases when the J/ψ is produced by a b hadron and the third muon is produced by a $\bar{b}$, or viceversa, in the same event. The $b\bar{b}$ background calculation is based on a PYTHIA Monte Carlo simulation. There is a residual contribution from other B_c^+ decay modes, for example, a B_c^+ might decay into $\psi(2S)\mu^+\nu$, followed by $\psi(2S)$ decay into J/ψ. Another example is a B_c^+ decay into $J/\psi\tau^+\nu$ followed by the τ decay into a muon. The probability that events from these decay sources survive the selection requirements is small, but non-zero. The measured number of B_c^+ candidates is obtained by subtracting the backgrounds from the total number of reconstructed candidates, and is reported in Table 1.

The ratio of the production cross section times branching fraction of the $B_c^+ \to J/\psi\mu^+\nu$ relative to the $B^+ \to J/\psi K^+$ can be written as

$$\frac{\sigma(B_c^+) \times BR(B_c^+ \to J/\psi\mu^+\nu)}{\sigma(B^+) \times BR(B^+ \to J/\psi K^+)} = \frac{N_{B_c^+}}{N_{B^+}} \times \epsilon_{rel} \tag{1}$$

where $N_{B_c^+}$ and N_{B^+} are respectively the number of B_c^+ and B^+ events estimated from data, and ϵ_{rel} is the relative efficiency between the two decay modes, and is estimated from Monte Carlo. The systematic errors are due to the estimates of the background sources and of the relative efficiency. For the relative efficiency, the sources of uncertainty are the uncertainty on the B_c^+ lifetime and production spectrum, on the B^+ production spectrum, and the uncertainties on the detector and trigger simulation. CDF obtains for $p_T \geq 6$ GeV/c and $\mid y \mid \leq 0.6$

$$\frac{\sigma(B_c^+) \times BR(B_c^+ \to J/\psi\mu^+\nu)}{\sigma(B^+) \times BR(B^+ \to J/\psi K^+)} = 0.211 \pm 0.212(stat.)^{+0.021}_{-0.020}(syst.) \tag{2}$$

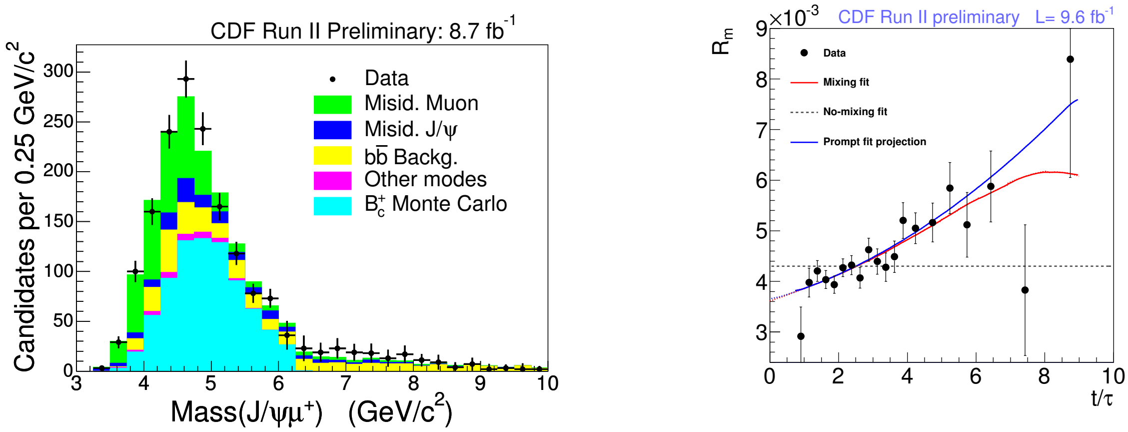

Figure 2 – (Left): Invariant mass distribution of the $B_c^+ \to \mu^+\nu X$ candidate events with the Monte Carlo simulated signal sample and backgrounds superimposed. The backgrounds include the misidentified muon (green), the misidentified J/ψ (dark blue), the $b\bar{b}$ backgrounds (yellow), and the other B_c^+ decay modes (pink). The B_c^+ experimental excess is shown as the B_c^+ Monte Carlo (light blue); (Right): Measured ratio of wrong-sign to right-sign D^* decays as a function of normalised proper decay time for the D^0 mixing measurement. The results of a least-squares fit are shown. A fit assuming no mixing is clearly incompatible with the data.

4 Observation of $D^0 - \overline{D}^0$ mixing at CDF

CDF has measured the time dependence of the ratio of decay rates for the Cabibbo-suppressed $D^0 \to K^+\pi^-$ to the Cabibbo-favored decay $D^0 \to K^-\pi^+$ [5]. The decay $D^0 \to K^+\pi^-$ can arise from mixing of a D^0 state to a $\overline{D}^0$ state, followed by a Cabibbo-favored decay, or from a doubly Cabibbo-suppressed decay of a D^0. The mixing measurement is based on the ratio of $D^0 \to K^+\pi^-$ to $D^0 \to K^-\pi^+$ decay rates. This ratio can be approximated [6 7] as a quadratic function of t/τ, where t is the proper decay time and τ is the mean D^0 lifetime.

$$R(t/\tau) = R_D + \sqrt{R_D}y^{'}(t/\tau) + \frac{x^{'2} + y^{'2}}{4}(t/\tau)^2 \tag{3}$$

A signal of 3.3 $\times 10^4$ $D^{*+} \to \pi^+ D^0$, $D^0 \to K^+\pi^-$ decays is obtained with D^0 proper decay times between 0.75 and 10 mean D^0 lifetimes. The analysis assumes CP conservation and measures the mixing parameters to be $R_D = (3.51 \pm 0.35) \times 10^{-3}$, $y^{'} = (4.3 \pm 4.3) \times 10^{-3}$, and $x^{'2} = (0.08 \pm 0.18) \times 10^{-3}$. This analysis achieves a significance for excluding the no-mixing hypothesis in terms of the equivalent number of Gaussian standard deviations of 6.1σ. For comparison, LHCb achieves a 9.1σ significance in the same decay mode.

5 Search for the X(4140) state in $B^+ \to J/\psi\phi K^+$ decays at D0

The X(4140) state [12] is a narrow resonance in the $J/\psi\phi$ system produced near threshold. The CDF Collaboration reported the first evidence [13] for this state and measured the invariant mass and width, but the comparison with Belle[14], LHCb [15], and CMS[16] is controversial.

Events used in this D0 analysis are collected with single-muon and dimuon triggers. Candidate events are required to include a pair of oppositely charged muons accompanied by three additional charged particles with transverse momenta above 0.7 GeV/c. To form B^+ candidates, muon pairs with an invariant mass consistent with the J/ψ mass are combined with pairs of oppositely charged particles, assigned the kaon mass hypothesis, with an invariant mass consistent with the ϕ mass, and a third track, also assigned the kaon mass hypothesis. To suppress the background, cuts on the B^+ transverse decay length, transverse momentum, and impact parameter, are applied. The estimated $B^+ \to J/\psi\phi K^+$ signal is 215$\pm$ 37 events and is shown in Fig. 3

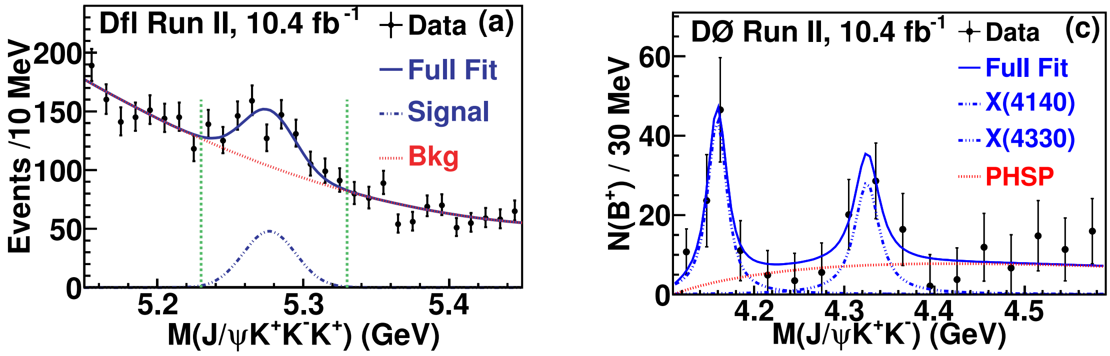

Figure 3 – (Left): $J/\psi K^+K^-K^+$ mass distribution after all selection cuts; (Right): $J/\psi K^+K^-$ mass distributions for candidates in the B^+ and ϕ mass windows.

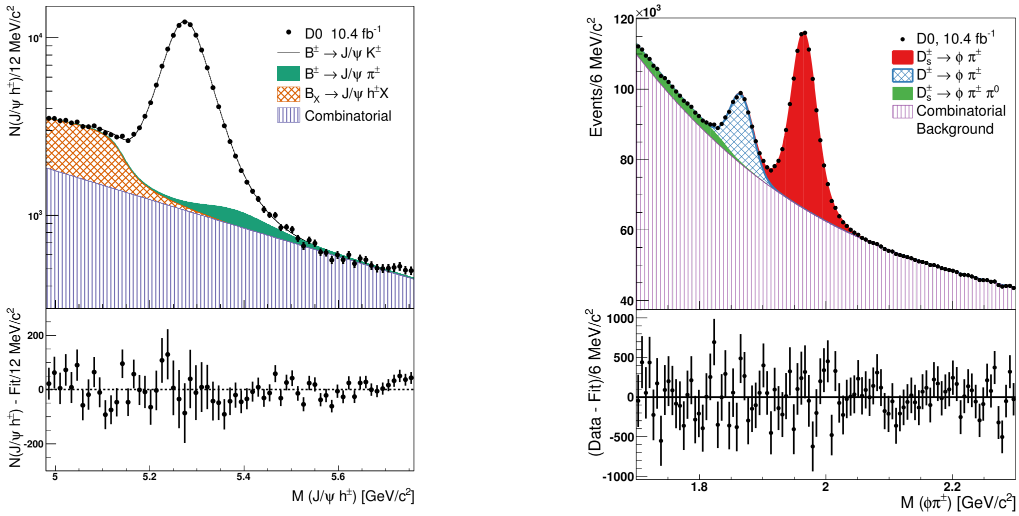

Figure 4 – (Left): Polarity-weighted $J/\psi h^\pm$ invariant mass distribution, where the $h^\pm$ is assigned the charged kaon mass, after all analysis selection cuts. The bottom panel shows the fit residuals; (Right) Polarity-weighted $\phi\pi^+$ invariant mass distribution. The lower mass peak is due to the decay $D^\pm \to \phi\pi^\pm$, while the second peak is due to the $D_s^\pm$ meson decay. The bottom panel shows the fit residuals.

(left). Figure 3 (Right) shows the invariant mass distribution of the $J/\psi\phi$ candidates within the B^+ and ϕ mass windows. The significance of the threshold structure is estimated by performing a binned least-squares fit of the B^+ yield to a sum of a resonance and a phase-space continuum template. A relativistic Breit-Wigner signal shape is assumed, with mass and width allowed to vary, convoluted with the detector resolution of 4 MeV from simulation. The estimated signal is 52±19 events. The statistical significance of the X(4140) is 3.1σ, with a measured mass of 4159.0±4.3(stat)±6.6(syst) MeV/c^2 and a width of 19.9±12.6(stat)$^{+1}_{-9}$(syst) MeV/c^2. The relative branching fraction BR($B^+ \to X(4140)K^+$)/BR($B^+ \to J/\psi\phi K^+$) is measured to be 19±7(stat)±4(syst) % [17].

6 Measurement of the direct CP-violation in $B^\pm \to J/\psi K^\pm$ and $B^\pm \to J/\psi\pi^\pm$ at D0

The standard model predicts that for $b \to sc\bar{c}$ decays, the tree and penguin contributions have the same weak phase, and thus no direct CP violation is expected in the decays of $B^\pm$ mesons to $J/\psi K^\pm$. The measurement of a relatively large asymmetry would indicate the existence of physics beyond the standard model [18]. Since in the transition $b\bar{d}c\bar{c}$, the tree and penguin contributions have different phases, there may be a measurable CP violation in the decay $B^\pm \to J/\psi\pi^\pm$ [19]. The analysis uses the entire Run II dataset of 10.4 fb^{-1} of data, and reconstructs the two decay modes $B^\pm \to J/\psi K^\pm$ and $B^\pm \to J/\psi\pi^\pm$ and measures raw asymmetries by simply measuring the number of B^+ and B^- candidates. The physics CP asymmetry is obtained from the raw CP asymmetry by applying a correction due to the reconstruction asymmetry between positively and negatively charged kaons in the detector. This is measured using a dedicated sample of K^{*0} ($\overline{K}^{*0}$)$\rightarrow K^+\pi^-$ ($K^-\pi^+$), and is found to be (1.046±0.043) %. Other instrumental asymmetries are cancelled by reversing the polarities of the toroidal and solenoidal magnetic fields on average every two weeks, so that the four solenoid-toroid polarity combinations are exposed to approximately the same integrated luminosity. Selection cuts are chosen to minimize the statistical uncertainty of the raw asymmetry in the $B^\pm \rightarrow J/\psi K^\pm$ decay mode. The asymmetries are measured to be $A^{J/\psi K}$ = [0.59 ± 0.36(stat) ± 0.07(syst)] % and $A^{J/\psi\pi}$ = [-4.2 ± 4.4(stat) ± 0.9(syst)] %. The main sources of systematic uncertainty are due to the kaon interaction asymmetry, to tracking, to the choice of the fit function and to the choice of mass range for the fit.

7 Measurement of direct CP-violation in $D_s^\pm \rightarrow \phi\pi^\pm$ at D0

Direct CP violation in the Cabibbo-favored charm decay $D_s^\pm \rightarrow \phi\pi^\pm$ should be non-existent, any effect would indicate physics beyond the standard model. The $D_s^\pm \rightarrow \phi\pi^\pm$, $\phi \rightarrow K^+K^-$ decay is reconstructed in 10.4 fb^{-1} of data. The two particles from ϕ decay are assumed to be kaons and are required to have $p_T \geq 0.7$ GeV/c, opposite charge and a reconstructed invariant mass compatible with the ϕ mass. The third track is assumed to be a charged pion and is combined with the two previous tracks to create a common $D_s^\pm$ decay vertex. Several variables are used to discriminate between signal and the combinatoric background. The resulting $m(K^+K^-\pi^\pm)$ is reported in Figure 4 (right) and is used to measure the number of $D_s^\pm$ candidates and the raw CP asymmetry. The total number of $D_s^\pm$ candidates is 451013±1866. The resulting CP asymmetry, including the corrections due to detector effects and physics effects, is A_{CP} = [-0.38 ± 0.26(stat) ± 0.08(syst)] % [20], currently the most precise measurement, in agreement with the standard model expectation of zero CP violation in this decay.

References

1. V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. 101, 232002 (2008).
2. T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D80, 072003 (2009).
3. T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D89, 072014 (2014).
4. CDF Collaboration Public B Group web page, http://www-cdf.fnal.gov/physics/new/bottom/bottom.html.
5. T. Aaltonen *et al.* (CDF Collaboration), Phys, Rev. Lett. 111, 231802 (2013).
6. G. Blaylock, A. Seiden, and Y. Nir Phys. Lett. B 355, 555 (1995).
7. R. Godang *et al.* (CLEO Collaboration), Phys. Rev. Lett. 84, 5038 (2000).
8. T. Aaltonen *et al.* (CDF Collaboration), Phys, Rev. Lett. 100, 12802 (2008).
9. L. Zhang *et al.* (Belle Collaboration), Phys. Rev. Lett. 96, 151801 (2006).
10. B. Aubert *et al.* (*BABAR* Collaboration), Phys. rev. Lett. 98, 211802 (2007).
11. R. Aaij *et al.* (LHCb Collaboration), Phys, Rev. Lett. 110, 101802 (2013).
12. J. Beringer *et al.* (Particle Data Group), Phys. Rev. D 86, 010001 (2012).
13. T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. 102, 242002 (2009).
14. C. Shen *et al.* (Belle Collaboration), Phys. Rev. Lett. 104, 112004 (2010).
15. R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. D 85, 091103 (2012).
16. S. Chatrchyan *et al.* (CMS Collaboration), arXiv:1309.6920.
17. V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D 89, 012004 (2014).
18. V. Barger, C. W. Chiang, P. Langacker, and H. S. Lee, Phys. Lett. B 598, 218 (2004).
19. I. Dunietz and J. M. Soares, Phys. Rev. D 49, 5904 (1994).
20. V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. 112, 111804 (2014).