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Measurement of the $B^0\bar{B}^0$ Oscillation Frequency in p$\bar{\text{p}}$ Collisions Using π - B Meson Charge-Flavor Correlations at $\sqrt{s}$ = 1.8 TeV/c^2

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Distribution

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We present a measurement of the mass difference between the two B^0 mass eigenstates, Δm_d, using a flavor tagging method based on correlations of B meson flavor with the charge of other particles produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV/c^2. Such correlations are expected to arise from b quark hadronization and from B^{**} decays. B mesons are partially reconstructed using the semileptonic decays $B^0 \to \ell^+ D^{(*)-} X$ and $B^+ \to \ell^+ \bar{D}^0 X$. We obtain $\Delta m_d = 0.471^{+0.078}_{-0.068}(\text{stat}) \pm 0.034(\text{syst})\ \hbar\ \text{ps}^{-1}$, and measure the efficiency and purity of this flavor tagging method for both charged and neutral B mesons.

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The mass difference between the two B^0 mass eigenstates, Δm_d, is sensitive to the magnitude of the element V_{td} of the Cabbibo-Kobayashi-Maskawa matrix [1]. In this paper we determine Δm_d by measuring the frequency of $B^0\bar{B}^0$ flavor oscillations using partially reconstructed semileptonic decays of the B meson to $\ell D^{(*)} X$. The data used in this analysis were collected with the Collider Detector at Fermilab (CDF), at the Tevatron $p\bar{p}$ Collider at $\sqrt{s} = 1.8$ TeV, and correspond to an integrated luminosity of ~ 110 pb^{-1}.

For a sample of initially pure B^0 mesons (at $t = 0$), the numbers of B^0 (N_+) and $\bar{B}^0$

(N_-) mesons at proper time t are given by

$$N_\pm(t) = N_+(0)\frac{e^{-t/\tau}}{2}(1 \pm \cos \Delta m_d t), \quad (1)$$

where τ is the lifetime of the B^0 meson. To extract Δm_d the proper time of the B decay is required, as well as the flavor of the B meson at the time of its decay and production.

While the B flavor at decay is determined by its decay products, *e.g.* from the lepton charge in the $B \to \ell D^{(*)} X$ decays considered here, the determination of the initial B flavor is experimentally challenging. Most techniques rely on identifying the flavor from the other b hadron in the event (*e.g.*, using the lepton charge from the semileptonic decay of this other hadron) [2], and are thus referred to as Opposite Side Tagging (OST).

It has been suggested [3] that the electric charge of particles produced near a B meson could also be used to determine its flavor, providing a basis for Same Side Tagging (SST). For example, if a $\bar{b}$ quark combines with a u quark to form a B^+ meson [4], the remaining $\bar{u}$ quark may combine with a d quark to form a π^-. Similarly, if a $\bar{b}$ quark hadronizes to form a B^0 meson, the associated pion would be a π^+. Another source of correlated pions are decays of the orbitally excited ($L = 1$) B mesons (B^{**}) [5], *i.e.* $B^{**0} \to B^{(*)+}\pi^-$ or $B^{**+} \to B^{(*)0}\pi^+$. In a hadron collider experiment with central rapidity coverage such as CDF, SST methods are attractive since they are expected to have significantly higher efficiency than the OST methods.

In this paper we extract Δm_d by applying an SST method to a sample of events containing a lepton and a reconstructed D meson from B decay. To determine the initial flavor of the B meson, we select one charged track that we will generically refer to as a "pion", and use its charge as a tag. We do not attempt to distinguish the hadronization pions from those originating from B^{**} decays. The lepton charge tags the B-flavor at decay time. We classify the $B - \pi$ combinations as right-sign (RS: $B^+\pi^-$ and $B^0\pi^+$) or wrong-sign (WS: $B^+\pi^+$ and $B^0\pi^-$). We form the asymmetry in the RS and WS combinations, $\mathcal{A}(ct) \equiv (N_{RS}(ct) - N_{WS}(ct))/(N_{RS}(ct) + N_{WS}(ct))$, as a function of the proper decay length ct. For B^+ mesons, we expect an asymmetry independent of ct: $\mathcal{A}^+(ct) = \text{constant} \equiv \mathcal{D}_+$.

The quantity $\mathcal{D}_+$ is called the dilution and it is a direct measure of the SST purity, *i.e.* $(1+\mathcal{D})/2$ is the fraction of correctly tagged events. Due to $B^0\bar{B}^0$ mixing, $\mathcal{A}(ct)$ for the neutral B mesons will vary as a function of the proper decay length ct. From eq. (1) and the definition of the B^0 asymmetry, it follows that the latter is expected to oscillate as $\mathcal{A}^0(ct) = \mathcal{D}_0 \cdot \cos(\Delta m_d t)$. Mistags, *i.e.* incorrect flavor determinations, result in a decrease of the oscillation amplitude by the B^0 dilution factor $\mathcal{D}_0$. We measure the asymmetry as a function of the proper decay length ct (we denote it by $\mathcal{A}^{(m)}$), for both B^+ and B^0 mesons, and fit them with their expected time dependence, obtaining Δm_d, $\mathcal{D}_0$ and $\mathcal{D}_+$. The two dilutions are not necessarily the same [6].

The CDF detector is discussed in detail elsewhere [7], and only the features most relevant to this analysis are described here. For the tracking of charged particles, two devices inside a 1.4 T solenoid are used: the central tracking chamber (CTC) and the silicon vertex detector (SVX). The combined CTC+SVX tracking system covers the pseudorapidity interval $|\eta| < 1.1$ [8], and gives a resolution on the transverse momentum, p_{T}, of $\delta(p_{\mathrm{T}})/p_{\mathrm{T}} = ((0.0066)^2 + (0.0009 p_{\mathrm{T}})^2)^{1/2}$ and a resolution on the track impact parameter [9] of about $(13+40/p_{\mathrm{T}})$ μm, where p_{T} is in GeV/c. Electromagnetic (CEM) and hadronic (CHA) calorimeters are located outside the solenoid and are surrounded by the central muon chambers (CMU) followed by the central upgrade muon chambers (CMP).

The data were recorded using an inclusive lepton (e and μ) trigger. The E_T threshold for the single electron trigger was 8 GeV, where $E_T \equiv E\sin\theta$, E is the energy measured in the CEM, and θ is the polar angle with respect to the beam. The single muon trigger required a charged track with $p_{\mathrm{T}} > 7.5$ GeV/c in the CTC with matched track segments in both the CMU and CMP systems. Details of the identification of electrons and muons are described in references [10] and [11].

We use the decay chains $B^0 \to \nu\ell^+ D^{(*)-}$, with $D^- \to K^+\pi^-\pi^-$, or $D^{*-} \to \bar{D}^0\pi^-_*$, followed by $\bar{D}^0$ decaying to $K^+\pi^-$, $K^+\pi^-\pi^+\pi^-$, or $K^+\pi^-\pi^0$ (by π^-_* we denote the low-momentum (soft) pion from the D^{*-} decay). We use $B^+ \to \nu\ell^+\bar{D}^0$, with $\bar{D}^0 \to K^+\pi^-$, where the $\bar{D}^0$ is required not to form a D^{*-} candidate with another π candidate in the event. We reconstruct the D meson candidates using tracks in a cone of unit radius in $\eta - \phi$ [8] space around the lepton [12]. All tracks are required to have included hits from the SVX. The decay products from the D mesons are required to be significantly displaced from the interaction point (primary vertex) of the event. The mass distributions of the four modes with fully reconstructed D mesons are shown in Fig. 1a, b and c, while the distribution of $\Delta m = m(K\pi\pi_*) - m(K\pi)$ for the decay mode with $D^{*-} \to \bar{D}^0\pi_*^-$, followed by $\bar{D}^0 \to K^+\pi^-\pi^0$ (the π^0 is not reconstructed) is displayed in Fig. 1d. The lack of any charm signal in the "wrong" lepton-kaon correlation (ℓ^+K^-) sample (dashed histograms) indicates that each $\ell D^{(*)}$ pair actually comes from the decay of a single B meson.

To select the SST pion, we consider all tracks that are within the η-ϕ cone of radius 0.7 centered around the direction of the B meson, approximated by $\vec{p}(\ell)+\vec{p}(D)$. SST candidate tracks should originate from the B production point (the primary vertex of the event), and are therefore required to satisfy $d_0/\sigma_{d_0} < 3$ [9]. String fragmentation models [13] indicate that particles produced in the b-quark hadronization chain have low momenta transverse to the direction of the b-quark momentum. We thus select as the tag the track that has the minimum component of momentum orthogonal to the momentum sum of the track and the B meson, $p_{\rm t}^{\rm rel}$. We define the tagging efficiency, ϵ, as the fraction of B candidates with at least one track satisfying the above requirements. We measure $\epsilon \approx 70\%$, independent of the decay mode used.

For each of the five decay signatures, we subdivide the candidates into six bins in proper decay length, ct. The measurement of ct begins with finding the D decay vertex. The D candidate momentum is intersected with the lepton momentum (and the momentum of π_* from the D^*, if present) to form the B decay vertex. The transverse distance between the primary vertex and the B vertex, projected along the B-momentum vector, is defined as $L_{\rm xy}^B$. We estimate $p_{\rm T}^B$ from the p_T of the visible decay products, $p_{\rm T}^{\ell D} = |\vec{p}_{\rm T}(\ell)+\vec{p}_{\rm T}(D^{(*)})|$, and the mean of the distribution of the momentum ratio $\mathcal{K} \equiv \langle p_{\rm T}^{\ell D}/p_{\rm T}^B\rangle$ obtained from a Monte Carlo simulation [14]. The $p_{\rm T}^{\ell D}/p_{\rm T}^B$ distribution has a mean of $\sim 85\%$ and RMS of $\sim 12\%$.

The proper decay length of the B meson is then given by $ct = L_{xy}^{B}(m_B/p_{\rm T}^{\ell D})\mathcal{K}$ [15].

We measure the asymmetry $\mathcal{A}^{(m)}(ct)$, in each ct bin by simultaneously fitting the mass distributions for candidates tagged with a RS or WS pion. The measured asymmetries are shown in Fig. 2. If the $\ell^+\bar{D}^0$ and $\ell^+D^{(*)-}$ signatures were pure signals of B^+ and B^0 decays, we could simply extract Δm_d using the time-dependence of $\mathcal{A}^0(ct)$. However, the signatures are admixtures of B^+ and B^0 decays, and thus $\mathcal{A}^{(m)}(ct)$ is a linear combination of the true asymmetries $\mathcal{A}^0(ct)$ and $\mathcal{A}^+(ct)$. To extract Δm_d, $\mathcal{D}_0$ and $\mathcal{D}_+$, it is necessary to determine the *sample composition* of each $\ell^+D^{(*)}X$ signature, by which we mean the fractions of the $\ell^+D^{(*)}$ candidates originating from the decays of the B^0 and B^+ meson. Because a B^+ is associated with a π^-, whereas an unmixed B^0 is associated with a π^+, the observed asymmetries are reduced by cross-contamination. We determine the degree of this cross-contamination in the five signatures and then simultaneously fit the observed asymmetries to disentangle the true asymmetries $\mathcal{A}_0$ and $\mathcal{A}_+$.

Cross-contamination can arise if the soft pion π_*^- from the D^{*-} decay is not identified – the decay sequence $B^0 \to \nu\ell^+D^{*-}$ will be reconstructed as $\ell^+\bar{D}^0$, that is, as a B^+ candidate. We quantify this effect by the efficiency for reconstructing the soft pion, $\epsilon(\pi_*)$. Another source of cross-contamination arises from semileptonic B decays involving P-wave D^{**} resonances as well as non-resonant $D^{(*)}\pi$ pairs, which cannot be easily recognized and removed from the sample. For example, the decay sequence $B^0 \to \nu\ell^+D^{**-}$, followed by $D^{**-} \to \bar{D}^0\pi_{**}^-$ (where by π_{**} we denote the pion originating fromD^{**} decay) will be reconstructed as $\ell^+\bar{D}^0$, because of the missed π_{**}^-; again, a B^0 decay is misclassified as a B^+ candidate. We quantify this effect by the parameter f^{**}, which is the ratio of the branching fraction $\mathcal{B}(B \to \nu\ell D^{**})$ to the inclusive semileptonic B branching fraction, $\mathcal{B}(B \to \ell\nu X)$. We use $f^{**} = 0.36 \pm 0.12$ [16]. The fractions of B^+ and B^0 decays in each decay signature are also affected by the relative abundance of the four possible spin-parity D^{**} states, some of which decay only to $D^*\pi$ and others to $D\pi$. We define $P_V = \mathcal{B}(B \to D^{**} \to D^*\pi)/\left[\mathcal{B}(B \to D^{**} \to D^*\pi) + \mathcal{B}(B \to D^{**} \to D\pi)\right]$, which we leave as a free parameter in our fit. The sample composition also depends on f

and f^*, the ratios of the branching fractions $B \to \nu\ell D$ and $B \to \nu\ell D^*$ to the inclusive semileptonic B branching fraction. We define $R_f \equiv f^*/f = 2.5 \pm 0.6$ [17], and assume $f + f^* + f^{**} = 1$. The lifetime ratio τ_{B^+}/τ_{B^0} is another sample composition parameter: $\tau_{B^+} \neq \tau_{B^0}$ implies $\mathcal{B}(B^+ \to \ell^+\nu X) \neq \mathcal{B}(B^0 \to \ell^+\nu X)$, as well as a ct-dependent sample composition. We use $\tau_{B^+}/\tau_{B^0} = 1.02 \pm 0.05$ [17].

The tagging is further complicated when a $\pi^{\pm}_{**}$ from D^{**} decay is present. The $\pi^{\pm}_{**}$ may be incorrectly selected as the SST pion, always resulting in a RS correlation. The requirement $d_0/\sigma_{d_0} < 3$ reduces this effect: the π_{**} originates from the B meson *decay* point, whereas the appropriate tagging track originates from the B meson *production* point. The contamination of the tagging pions from $\pi^{\pm}_{**}$ will decrease with increasing ct. It is quantified by the parameter ξ, defined as a probability of selecting the π_{**} as a tag in a tagged event where a $\pi^{\pm}_{**}$ was produced. We use a Monte Carlo simulation [18] of B decays to determine the dependence of ξ on the proper decay time. Over our range of ct, an good parameterization is the sum of a Gaussian centered at zero and a constant ($\xi_{MC}(ct) = 0.22\exp(-0.5(ct/0.04)^2) + 0.04$). We allow for a normalization scale factor, ξ_{norm}, between the Monte Carlo simulation and data, $\xi(ct) = \xi_{norm} \cdot \xi_{MC}(ct)$, which is needed if the Monte Carlo simulation does not fully reproduce the kinematic distributions of the SST candidate tracks, thus affecting the normalization of ξ.

The parameter ξ_{norm} is determined from the fraction of the tagged events in which the π_{**} was selected as the tag, R^{**}. The measured value of R^{**}, $R^{**(m)}$ is derived using the impact parameter, d_B, of the SST pion with respect to the B decay point, and the uncertainty on this quantity, σ_{d_B}. In this study, the $d_0/\sigma_0 < 3$ requirement was released to increase the statistics. Pions from D^{**} decays should have low values of d_B/σ_{d_B}, whereas pions from the primary vertex should be more evenly distributed in d_B/σ_{d_B}. We fit the RS distribution of d_B/σ_{d_B} with the sum of the scaled WS distribution and a Gaussian of unit width centered at zero. The area of this Gaussian yields the total number of SST pions originating from D^{**} decays. R^{**} is a product of $\xi_{norm} \cdot \xi_{MC}$ and a known function of other sample composition parameters (f^{**}, $P_V \ldots$). Combining R^{**} and the measured $R^{**(m)}$ allows one to extract

ξ_{norm} ($\xi_{norm} = 0.8 \pm 0.2$ in the final result).

The mass difference Δm_d, and the dilutions $\mathcal{D}_0$ and $\mathcal{D}_+$ are determined from the measured asymmetries $\mathcal{A}^{(m)}$, by the following χ^2 function,

$$\chi^2 = \sum_{k,ct} \left(\frac{\mathcal{A}_k^{(m)}(ct) - \bar{\mathcal{A}}_k(ct)}{\sigma_k^{\mathcal{A}}(ct)} \right)^2 + \sum_j \left(\frac{F_j^{(m)} - \bar{F}_j}{\sigma_j^F} \right)^2$$

where k is the index that runs over the five decay modes, and ct symbolizes the summation over the proper time bins for all data points. The first term in the χ^2 corresponds to the asymmetry measurement, whereas the second term constrains the functions $\bar{F}_j(f^{**}, P_V, R_f, \epsilon(\pi_*) \ldots)$ of quantities F_j, which are functions of the fit parameters. $F_j^{(m)} \pm \sigma_j^F$ is a measurement of F_j. Examples of F_j are the parameters f^{**}, R_f and τ_{B^+}/τ_{B^0}, as well as more complicated functions like R^{**} (that constrains ξ_{norm} and P_V). The prediction for the measured asymmetry, $\bar{\mathcal{A}}_k(ct)$, is a linear combination of the true asymmetries $\mathcal{A}^0(ct)$ and $\mathcal{A}^+(ct)$ in the amounts governed by the sample composition. For example, for any of the four B^0 signatures,

$$\bar{\mathcal{A}}_k = \alpha_k^0 \mathcal{A}^0 + \alpha_k^+(-\mathcal{A}^+) + \alpha_k^{**}(+1) \tag{2}$$

where all information about the sample composition is contained in the coefficients $\alpha_k^{0,+} \equiv \alpha_k^{0,+}(ct, f^{**}, P_V, R_f, \epsilon(\pi_*) \ldots)$ [15]. The second term in (2) describes the cross-contamination occurring with the minus sign due to the opposite definition of RS and WS for B^+, while the third term describes the effect of selecting the $\pi_{**}^{\pm}$ as a tag (and is proportional to $\xi(ct)$). In the fit, f^{**}, R_f and τ_{B^+}/τ_{B^0} float within their measurement uncertainties, while P_V, ξ_{norm} and $\epsilon(\pi_*)$ are constrained indirectly through functions like R^{**}.

The result of the fit, overlaid onto the measured asymmetries, is displayed in Fig. 2. The oscillation in the neutral B signatures is clearly present, giving $\Delta m_d = 0.471\, \hbar$ ps^{-1}. The sample composition parameters f^{**}, R_f and τ_{B^+}/τ_{B^0} are floating in the fit, and the reported errors on Δm_d, $\mathcal{D}_0$ or $\mathcal{D}_+$, are the sum in quadrature of the statistical error and the systematic uncertainty contributed by the sample composition. In the fit where f^{**}, R_f and τ_{B^+}/τ_{B^0} are fixed, the errors are only statistical, allowing us to separate the correlated systematic uncertainties due to the sample composition. The uncorrelated systematic uncertainties, which are much smaller than those from the sample composition, are due to uncertainties in the Monte Carlo simulation as well as the presence of physics background processes that can mimic the $\ell^+ D^{(*)} X$ signatures. The breakdown of the systematic uncertainties is given in table I. The final result for the mixing frequency is $\Delta m_d = 0.471^{+0.078}_{-0.068}(\mathrm{stat}) \pm 0.034(\mathrm{syst})\ \hbar\ \mathrm{ps}^{-1}$. We also obtain the following values for the neutral and charged meson tagging dilutions: $\mathcal{D}_0 = 0.18 \pm 0.03(\mathrm{stat}) \pm 0.02(\mathrm{syst})$ and $\mathcal{D}_+ = 0.27 \pm 0.03(\mathrm{stat}) \pm 0.02(\mathrm{syst})$. The fit indicates that $\sim 82\%$ of the $\ell^+ \bar{D}^0 X$ signature comes from B^+ decays, while $\sim 80\%$ of the $\ell^+ D^- X$ and $\sim 95\%$ of the $\ell^+ D^{*-} X$ originate from B^0. The B^0 component of the $\ell^+ \bar{D}^0 X$ signature can be seen as a small anti-oscillation in fig. 2, top.

In conclusion, we have applied a Same Side Tagging technique to samples of $B^0 \to \ell^+ D^{(*)-} X$ and $B^+ \to \ell^+ \bar{D}^0 X$ decays in $p\bar{p}$ collisions. The measurement of the asymmetry between tag-charge and B-flavor as a function of proper time for neutral B mesons results in the observation of a time-dependent oscillation $B^0 \leftrightarrow \bar{B}^0$, with the oscillation frequency $\Delta m_d = 0.471^{+0.078}_{-0.068}(\mathrm{stat}) \pm 0.034(\mathrm{syst})\ \hbar\ \mathrm{ps}^{-1}$. This establishes the effectiveness of the Same Side Tagging for the first time in hadronic collisions.

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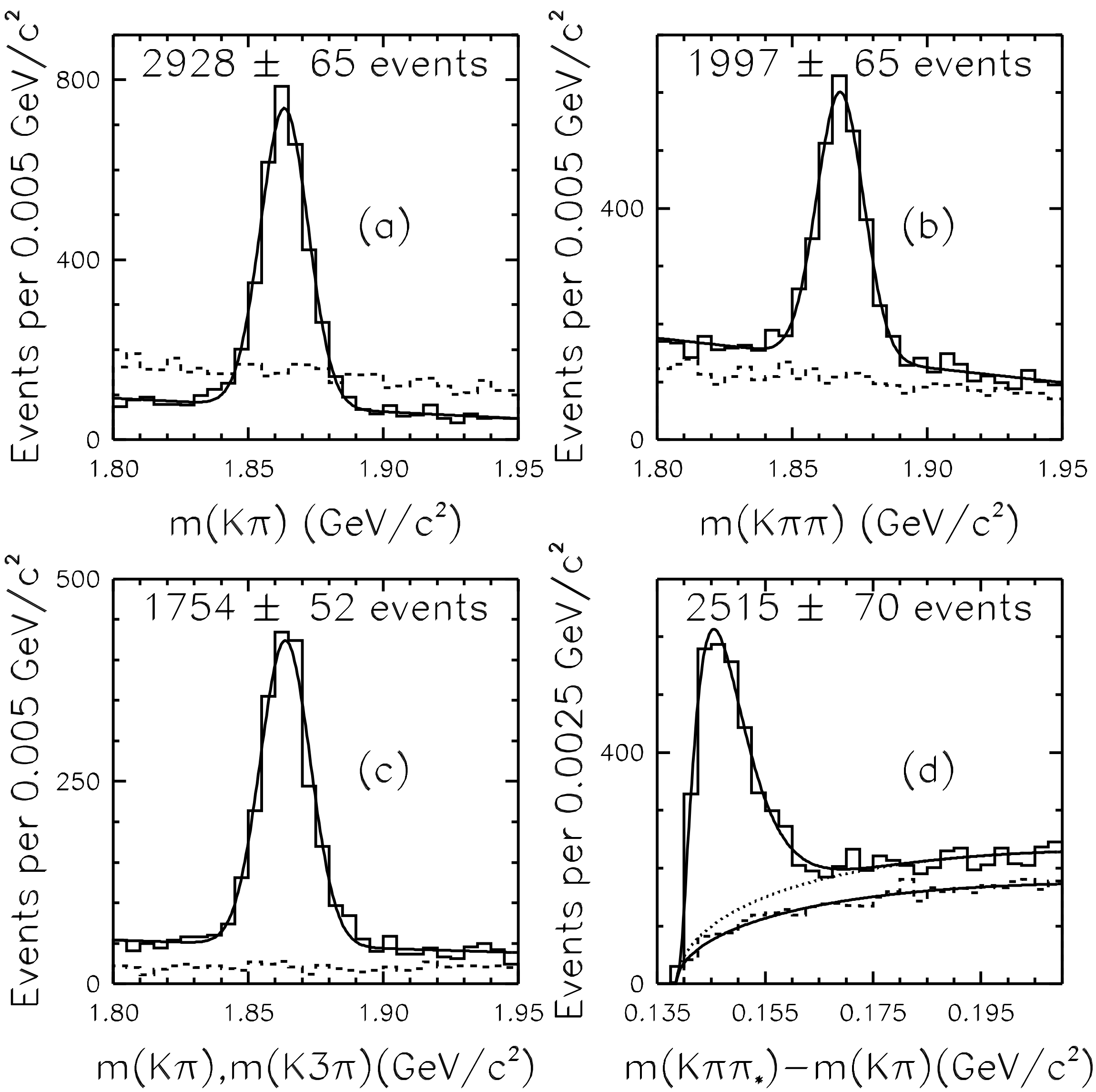
Source	$\sigma(\mathcal{D}_+)$	$\sigma(\mathcal{D}_0)$	$\sigma(\Delta m_d)(\hbar\ \mathrm{ps}^{-1})$
Composition	${}^{+0.0216}_{-0.0131}$	${}^{+0.0225}_{-0.0131}$	${}^{+0.0295}_{-0.0310}$
Other sources	± 0.0068	± 0.0074	± 0.0146
Total	${}^{+0.0226}_{-0.0147}$	${}^{+0.0237}_{-0.0150}$	${}^{+0.0329}_{-0.0343}$

TABLE I. The breakdown of the systematic uncertainties.



2928 ± 65 events
(a)
Events per 0.005 GeV/c²
m(Kπ) (GeV/c²)
1997 ± 65 events
(b)
Events per 0.005 GeV/c²
m(Kππ) (GeV/c²)
1754 ± 52 events
(c)
Events per 0.005 GeV/c²
m(Kπ),m(K3π)(GeV/c²)
2515 ± 70 events
(d)
Events per 0.0025 GeV/c²
m(Kππ*)−m(Kπ)(GeV/c²)

FIG. 1. Invariant mass distributions of the five $B \to \ell^+ D^{(*)} X$ signatures used in the analysis. The solid histograms correspond to the "right" lepton-kaon charge correlation ($\ell^+ K^+$), and the dashed histograms the "wrong" one ($\ell^+ K^-$). The solid lines are the fits to the $\ell^+ K^+$ distributions, and the resulting number of B candidates is given on each figure. (a) $K^+\pi^-$ mass in $\ell^+ \bar{D}^0 X$ ($\bar{D}^0 \to K^+\pi^-$). (b) $K^+\pi^-\pi^-$ mass in $\ell^+ D^- X$ ($D^- \to K^+\pi^-\pi^-$). (c) $\bar{D}^0$ candidate mass in $\ell^+ D^{*-} X$ ($D^{*-} \to \bar{D}^0 \pi^-_*$, $\bar{D}^0 \to K^+\pi^-$ and $\bar{D}^0 \to K^+\pi^-\pi^+\pi^-$). (d) $K^+\pi^-\pi^-_* - K^+\pi^-$ mass difference in $\ell^+ D^{(*)-} X$ ($D^{*-} \to \bar{D}^0 \pi^-_*$, $\bar{D}^0 \to K^+\pi^-\pi^0$). The $\ell^+ K^+$ background shape (dotted line) was determined from the fit (lower solid curve) of the $\ell^+ K^-$ distribution.

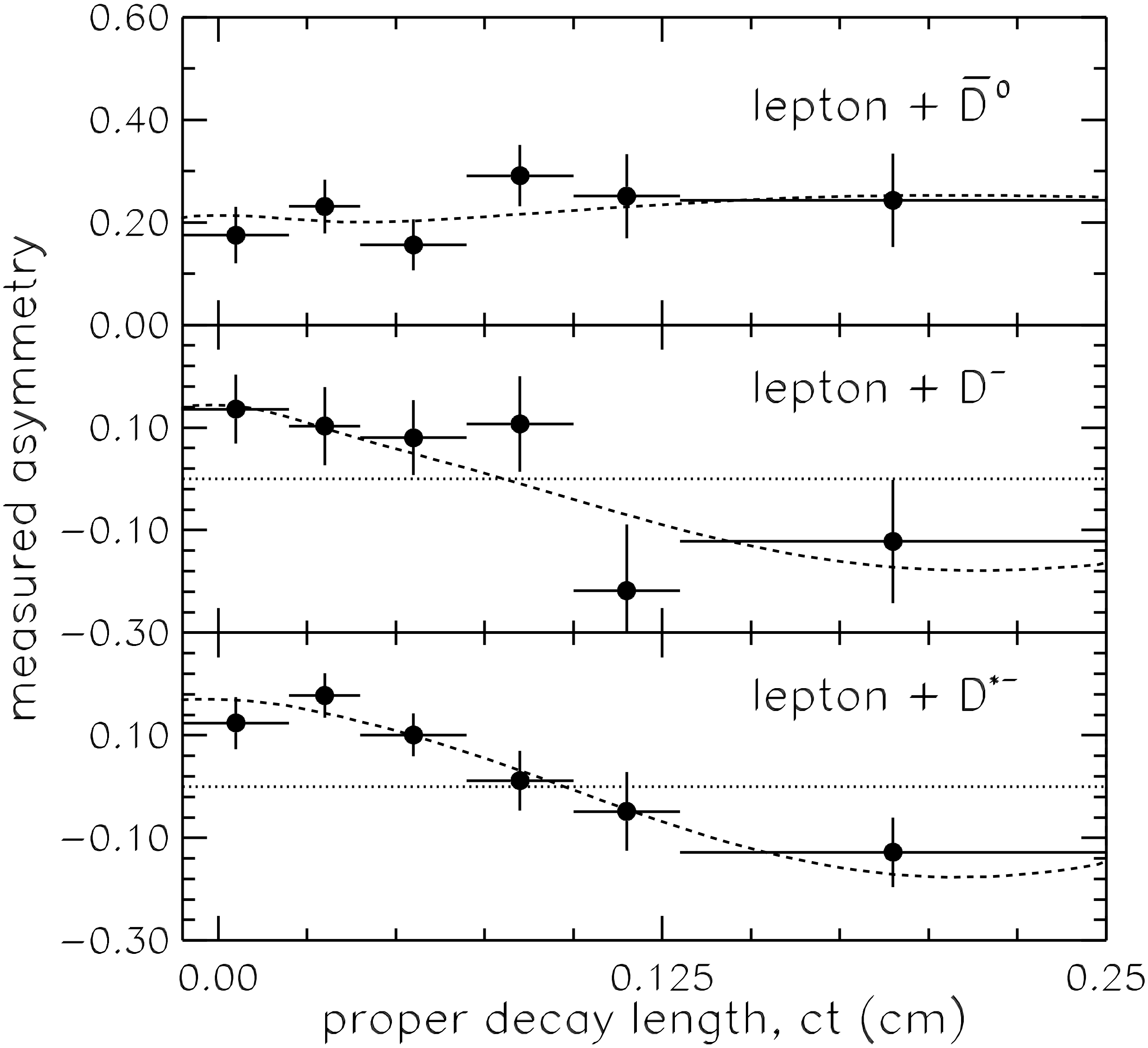


FIG. 2. Measured asymmetries as a function of the proper decay length, ct, for the decay signatures: $\ell^+\bar{D}^0$ (dominated by B^+), ℓ^+D^- and the sum of all three ℓ^+D^{*-} (dominated by B^0). We fit the three ℓ^+D^{*-} signature separately, but combine them for display purposes. The dashed line is the result of the fit.