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A Search for B_s^0-$\overline{B}_s^0$ Oscillations Using the Semileptonic Decay $B_s^0 \to \phi \ell^+ X \nu$

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Abstract

A search for B_s^0-$\overline{B}_s^0$ oscillations is performed in a sample of B_s^0 semileptonic decays collected using dilepton triggers at the Tevatron Collider during 1992-1995. The B_s^0 is reconstructed using ϕ meson - lepton correlations; its initial production flavor is determined with the second lepton in the event. From a signal of 1068 with a B_s^0 purity of 61%, we obtain a limit on the B_s^0-$\overline{B}_s^0$ oscillation frequency of $\Delta m_s > 5.8$ ps^{-1} at 95% confidence level.

The frequency of oscillatory transitions between B_s^0 and $\overline{B}_s^0$ is proportional to the mass difference Δm_s between the mass eigenstates of the B_s^0-$\overline{B}_s^0$ system. In the Standard Model, Δm_s is related to the CKM matrix element V_{ts} by a second-order weak interaction box diagram involving the top quark. A measurement of Δm_s, together with the B^0-$\overline{B}^0$ oscillation frequency Δm_d, which is a function of V_{td}, could provide a reliable determination of $|V_{ts}/V_{td}|$. Δm_d is well measured [1] but there is no direct measurement of Δm_s yet. A combination of the LEP searches gives a 95% confidence level limit of $\Delta m_s > 9.1$ ps^{-1} [1]. In this letter, we report a limit on Δm_s using decays of $B_s^0 \to \phi \ell^+ X \nu$ with the initial B_s^0 flavor determined by an opposite side lepton. The data used in this analysis were collected with the CDF detector at the Fermilab Tevatron $p\bar{p}$ collider at a center-of-mass energy $\sqrt{s} = 1.8$ TeV during the 1992-1995 collider run and correspond to an integrated luminosity of 110 pb^{-1}. Dilepton triggers [2] were used to select a sample of events with two leptons ($\mu - \mu$ or $\mu - e$).

The reconstruction of B_s^0 signals starts with a $\phi\ell$ pair from the decay $B_s^0 \to D_s^- \ell^+ X \nu \to \phi \ell^+ X \nu$. Throughout this letter, charge conjugate modes are always implied. The $\phi\ell$ pair is required to have an invariant mass in the range $2.0 < m_{\phi\ell} < 5.0$ GeV/c^2 and a combined momentum transverse to the beam line of $p_T(\phi\ell) > 5$ GeV/c. The lepton is required to have a transverse momentum $p_T(\ell) > 2.0$ GeV/c and a $p_T^{rel} > 1.0$ GeV/c, where p_T^{rel} is the component of the lepton momentum transverse to the axis of the B jet reconstructed using a track-based jet clustering algorithm. In the calculation the lepton is taken out of the B jet. The ϕ meson is reconstructed from the decay $\phi \to K^+K^-$, where each kaon track is required to be within a cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} < 1.0$ centered on the lepton direction [3] and to have $p_T > 1.0$ GeV/c. The specific ionization energy loss (dE/dx) measurements for each kaon track is required to be consistent with the expected value. The two kaons are constrained to form the ϕ decay vertex. We require $p_T(\phi) > 2.7$ GeV/c and the ϕ vertex fit confidence level greater than 1%. An extra charged track h^- must accompany the $\phi\ell^+$ pair in a cone of $\Delta R < 1.0$ and is required to satisfy $1.0 < m_{\phi h^-} < 2.0$ GeV/c^2 and $m_{\phi h^- \ell^+} < 5$ GeV/c^2, consistent with the kinematics for the D_s^- and B_s^0 decay modes. If there is more than one h^- candidate, we choose the one with the largest momentum projection onto the direction of the ϕ. The charged track h^- and neutral ϕ are fit to a common D_s^- decay vertex; the fit confidence level is required to be greater than 1%, and the transverse decay length measured from the primary vertex to decay vertex is required to be positive. The run-averaged beam position is used to define the primary vertex in the transverse plane. The D_s^- candidate and lepton track are then fit to a common B_s^0 vertex. The number of $\phi\ell$ pairs passing our cuts is determined from a fit to the K^-K^+ invariant mass distribution with the signal described by a Breit-Wigner function convoluted with a Gaussian resolution function and a polynomial background. The fit is shown in Figure 1 and yields a signal of 1068 ± 70.

Most of the 1068 $\phi\ell$ pairs result from semileptonic decays of B_s^0. The fractions of $\phi\ell$ pairs from $B^0 \to D\ell\nu \to \phi\ell$ and $B^+ \to D\ell\nu \to \phi\ell$ are calculated to be $24.5 \pm 3.3\%$ and $14.5 \pm 2.1\%$ respectively, using their production rates and detection efficiencies. The detection efficiencies [4] are determined from Monte Carlo (MC) calculations. The inclusive ϕ production ratios from charm mesons are calculated following reference [5]. The b-quark fragmentation fractions and $B^0/B^+/B_s^0$ semileptonic decay branching ratios are obtained from the world averages [6] [7]. The contribution from $B^0(B^+) \to DD_s \to \phi\ell$ is estimated to be $5 \pm 1\%$ in a similar way [4] [8] but is treated as an additional error on the sample composition. Pairs from $D(D_s) \to \phi\ell$, $b \to \phi B \to \phi\ell$, $B(B_s^0) \to \phi D(D_s)X \to \phi\ell$, and gluon splitting $g \to b\bar{b}$ with $b \to \phi$ and $\bar{b} \to \ell$, are negligible after invariant mass and momentum cuts. The fraction of $\phi\ell$ pairs from $B_s^0 \to D_s^- \ell^+ \nu$ is thus calculated as $f_{B_s^0} = 61.0^{+4.4}_{-7.0}\%$.

The decay length of the B_s^0 in the transverse plane, L_{xy}, is defined as the transverse distance between the B_s^0 decay vertex and the primary vertex. The decay length is related to the Lorentz-invariant proper decay time t by $t = L_{xy}M/p_T(B_s^0)$, where M is the B_s^0 mass and $p_T(B_s^0)$ is the transverse momentum of B_s^0. Since we do not fully reconstruct the B_s^0 in the semileptonic decay, we use the momentum sum of $p_T(\phi h \ell)$ as an estimate of $p_T(B_s^0)$. A scale factor between $p_T(\phi h \ell)$ and $p_T(B_s^0)$ is obtained from MC simulation. The momentum ratio $K \equiv p_T(\phi h \ell)/p_T(B_s^0)$ has a mean of 0.76 and standard deviation of 0.14.

The flavor of the B_s^0 meson at production is determined by the second lepton, ℓ_{tag}, which is expected to originate from a semileptonic decay of the other b-hadron in the event. We require ℓ_{tag} to be outside a cone of $\Delta R = 2.0$ around the lepton in the $\phi\ell$ pair, and to have $p_T(\ell_{tag}) > 2.0$ GeV/c. The combination of the flavor tagging lepton and the $\phi\ell$ is required to have $m(\ell_{tag}\phi\ell) > 5$ GeV/c^2. We call $\ell^+\ell^+_{tag}$ ($\ell^-\ell^-_{tag}$) a same sign (SS) event and $\ell^+\ell^-_{tag}$ ($\ell^-\ell^+_{tag}$) an opposite sign (OS) event.

The probability for a perfectly flavor tagged B_s^0 to decay at a proper time t as a SS (OS) event, $P^{B_s^0}_{SS(OS)} = \frac{1}{2\tau} exp(-t/\tau)[1 \mp cos(\Delta m_s t)]$, is convoluted with a Gaussian resolution function and a momentum resolution function derived from the K-factor distribution. Mistakes in flavor tagging, due to fake leptons, leptons from sequential decays $b \to c \to \ell$, and b-hadron mixing, are characterized by the mistag rate R_{mistag}, defined as the probability of assigning a wrong correlation. We find $R_{mistag} = 0.24 \pm 0.08$ from an unbinned likelihood fit to the SS (OS) fraction distributions of the $\phi\ell$ data. In the fit, Δm_s is a fixed value in the range of theoretical expectation (> 10 ps^{-1}). The fit of R_{mistag} is found to be independent of the assumed value of Δm_s, since the SS (OS) fraction is insensitive to the fast B_s^0-$\overline{B_s^0}$ oscillations. With R_{mistag}, the probability for a B_s^0 to be a SS (OS) candidate becomes $F_{SS(OS)}^{B_s^0} = (1 - R_{mistag})P_{SS(OS)} + R_{mistag}P_{OS(SS)}$. The analogous functions for B^0 and B^+, $F_{SS(OS)}^{B^0}$ and $F_{SS(OS)}^{B^+}$, are calculated by replacing Δm_s with Δm_d and a zero oscillation frequency, respectively. The combinatorial background fraction for events under the K^+K^- mass peak, f_{bkg}, is estimated from the mass fit. The fraction of same sign events in this background, f_{bkg}^{SS}, is estimated from the same-sign fraction found in the mass sidebands. The lifetime distribution of the background is determined by fitting the mass sideband events to the function F_{bkg}, a sum of a Gaussian distribution centered at zero, symmetric positive and negative exponential tails, and a positive decay exponential that characterizes the heavy flavor component of the background. Finally, the functional forms describing the SS and OS events are $F_{SS} = (1 - f_{bkg})F_{SS}^B + f_{bkg}f_{bkg}^{SS}F_{bkg}$ and $F_{OS} = (1 - f_{bkg})F_{OS}^B + f_{bkg}(1 - f_{bkg}^{SS})F_{bkg}$, where $F_{SS(OS)}^B$ is a weighted sum of $F_{SS(OS)}^{B_s^0}$, $F_{SS(OS)}^{B^0}$ and $F_{SS(OS)}^{B^+}$ using the sample composition fractions of $f_{B_s^0}$, f_{B^0} and f_{B^+}.

The solid line in Figure 2 shows the log-likelihood function $\ln \mathcal{L} = \sum_{i=1}^{N_{OS}} \ln(F_{OS}) + \sum_{i=1}^{N_{SS}} \ln(F_{SS})$ obtained from the $\phi\ell$ data over a range of Δm_s values. Since $\ln \mathcal{L}$ has no statistically significant minimum, we set a lower limit on Δm_s. The lower limit on Δm_s is defined as the highest Δm_s value below which all values of Δm_s are excluded. To set the limit, we use the amplitude fit method [9], in which one looks for peaks in the frequency spectrum rather than for an oscillation in the proper time spectrum. We rewrite the probabilities for a SS(OS) event by adding an extra oscillation amplitude $\mathcal{A}(\Delta m_s)$, $P_{SS(OS)}^{B_s^0} = \frac{1}{2\tau}exp(-t/\tau)[1 \mp \mathcal{A}(\Delta m_s)cos(\Delta m_s t)]$. The procedure is to measure the amplitude $\mathcal{A}(\Delta m_s)$ and its Gaussian error $\sigma_{\mathcal{A}}(\Delta m_s)$ at each assumed Δm_s. If the assumed Δm_s equals the true value, a measurement consistent with $\mathcal{A} = 1$ is expected; otherwise $\mathcal{A} = 0$ is expected. A value of Δm_s can be excluded at 95% confidence level if $\mathcal{A} + \xi\sigma_{\mathcal{A}} < 1$, where $\xi = 1.645$ satisfies $\int_{-\infty}^{\xi} \frac{1}{\sqrt{2\pi}}exp(-\frac{1}{2}x^2)dx = 0.95$. The amplitude values and errors together with the 95% confidence limit contours, $\mathcal{A} + 1.645\sigma_{\mathcal{A}}$, are displayed in Figure 3. The highest

Δm_s value below which all values are excluded with a 95% confidence level is $\Delta m_s > 6.2$ ps^{-1} taking into account only the statistical error.

The systematic error on $\mathcal{A}$, $\sigma_{\mathcal{A}}^{sys}$, is estimated by varying the parameters in the fitting functions using the prescription of reference [9]: $\sigma_{\mathcal{A}}^{sys} = \Delta\mathcal{A} + (1-\mathcal{A})\frac{\Delta\sigma_{\mathcal{A}}}{\sigma_{\mathcal{A}}}$, where $\Delta\mathcal{A}$ and $\Delta\sigma_{\mathcal{A}}$ are changes in the amplitude and its error between the new fit and the fit using nominal parameter values. The B_s^0 fraction $f_{B_s^0}$ and the mistag rate R_{mistag} are each varied by one standard deviation and are the two biggest contributions to the systematic error. The mass difference Δm_d and $B_s^0/B^0/B^+$ lifetimes are varied by their PDG errors [1]. The combinatorial background fraction and shape are varied about their fitted values and parameters by one standard deviation. Uncertainty on the lepton trigger parameterization is estimated using different lepton momentum thresholds in the K-factor calculation. Uncertainties on functional forms of background and resolution functions are estimated using alternative functional forms. The total systematic error is the sum in quadrature of all systematic errors obtained. A limit of $\Delta m_s > 5.8$ ps^{-1} is obtained with systematic errors included.

A likelihood comparison method [9] is employed as a systematic check. The likelihood, $\Delta\mathcal{L}^{\infty}(\Delta m_s) = -2\ln[\mathcal{L}(\Delta m_s)/\mathcal{L}(\infty)]$, is expected to have a Gaussian distribution whose expected value $\Delta\mathcal{L}^{\infty}_{expect}(\Delta m_s)$ and error $\sigma(\Delta\mathcal{L}^{\infty}(\Delta m_s))$ are estimated using MC. Any value of Δm_s is excluded at 95% confidence level if $\Delta\mathcal{L}^{\infty}_{data}(\Delta m_s) > \Delta\mathcal{L}^{\infty}_{expect}(\Delta m_s) + 1.645 \cdot \sigma(\Delta\mathcal{L}^{\infty}(\Delta m_s))$. The obtained limit of $\Delta m_s > 6.0$ ps^{-1}, as shown in Figure 2, is in good agreement with the amplitude result.

In conclusion, using a signal of 1068 $B_s^0 \to \phi\ell^+ X\nu$ decays with a B_s^0 purity of 61% and an opposite side lepton flavor tagging method, we performed a search for B_s^0-$\overline{B}_s^0$ oscillations. We obtain a 95% confidence level limit on the oscillation frequency $\Delta m_s > 6.2$ ps^{-1} with statistical error only and $\Delta m_s > 5.8$ ps^{-1} with statistical and systematic errors combined.

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[3] In CDF the positive z axis lies along the proton direction, r is the radius from this axis, θ is the polar angle, and φ is the azimuthal angle. The pseudo-rapidity is $\eta \equiv -\ln[\tan(\theta/2)]$.

[4] The detection efficiencies are estimated from MC:

$\epsilon(B^0 \to D\ell\nu)/\epsilon(B_s^0 \to \phi\ell) = 0.9602 \pm 0.0041$,

$\epsilon(B^+ \to D\ell\nu)/\epsilon(B_s^0 \to \phi\ell) = 0.5374 \pm 0.0027$,

$\epsilon(B^+ \to DD_s)/\epsilon(B_s^0 \to \phi\ell) = 0.2278 \pm 0.0013$,

$\epsilon(B^0 \to DD_s)/\epsilon(B_s^0 \to \phi\ell) = 0.2291 \pm 0.0014$.

[5] P. Roudeau and A. Stocchi, LAL 93-03, September 1993.

We sum up the measurements from reference [1] using the guidelines from this paper:

$Br(D^0 \to \phi X) = (1.7 \pm 0.3)\%$, $Br(D^+ \to \phi X) = (1.4 \pm 0.2)\%$ and

$Br(D_s \to \phi X) = (5.06 \pm 0.49) \cdot Br(D_s \to \phi\pi)$.

[6] Using LEP average $f(b \to B^0, B^+) = 0.378 \pm 0.022$ and world average $Br(B \to D\ell\nu)$ from [1] together with $Br(D \to \phi)$, we get $f(b \to B^0) \cdot Br(B^0 \to \phi\ell) = (0.649 \pm 0.071) \times 10^{-3}$ and $f(b \to B^+) \cdot Br(B^+ \to \phi\ell) = (0.688 \pm 0.082) \times 10^{-3}$.

[7] D.Buskulic *et al.* (ALEPH Collaboration), Phys. Lett. **B361**, 221 (1995);

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The average is $f(b \to B_s^0) \cdot Br(B_s^0 \to D_s\ell X\nu) \cdot Br(D_s \to \phi\pi) = (3.06 \pm 0.43) \times 10^{-4}$.

[8] T.E.Browder and K.Honscheid, 'B Mesons', UH 511-816-95, March 1995. Using $Br(B \to DD_s)$ from this summary paper we have

$f(b \to B^+) \cdot Br(B^+ \to DD_s \to \phi\ell)/f(b \to B_s^0) \cdot Br(B_s^0 \to \phi\ell) = 0.17 \pm 0.06$ and

$f(b \to B^0) \cdot Br(B^0 \to DD_s \to \phi\ell)/f(b \to B_s^0) \cdot Br(B_s^0 \to \phi\ell) = 0.25 \pm 0.09$.

[9] H.-G.Moser and A.Roussarie, Nucl. Instrum. and Methods. A **384**, 491 (1997).

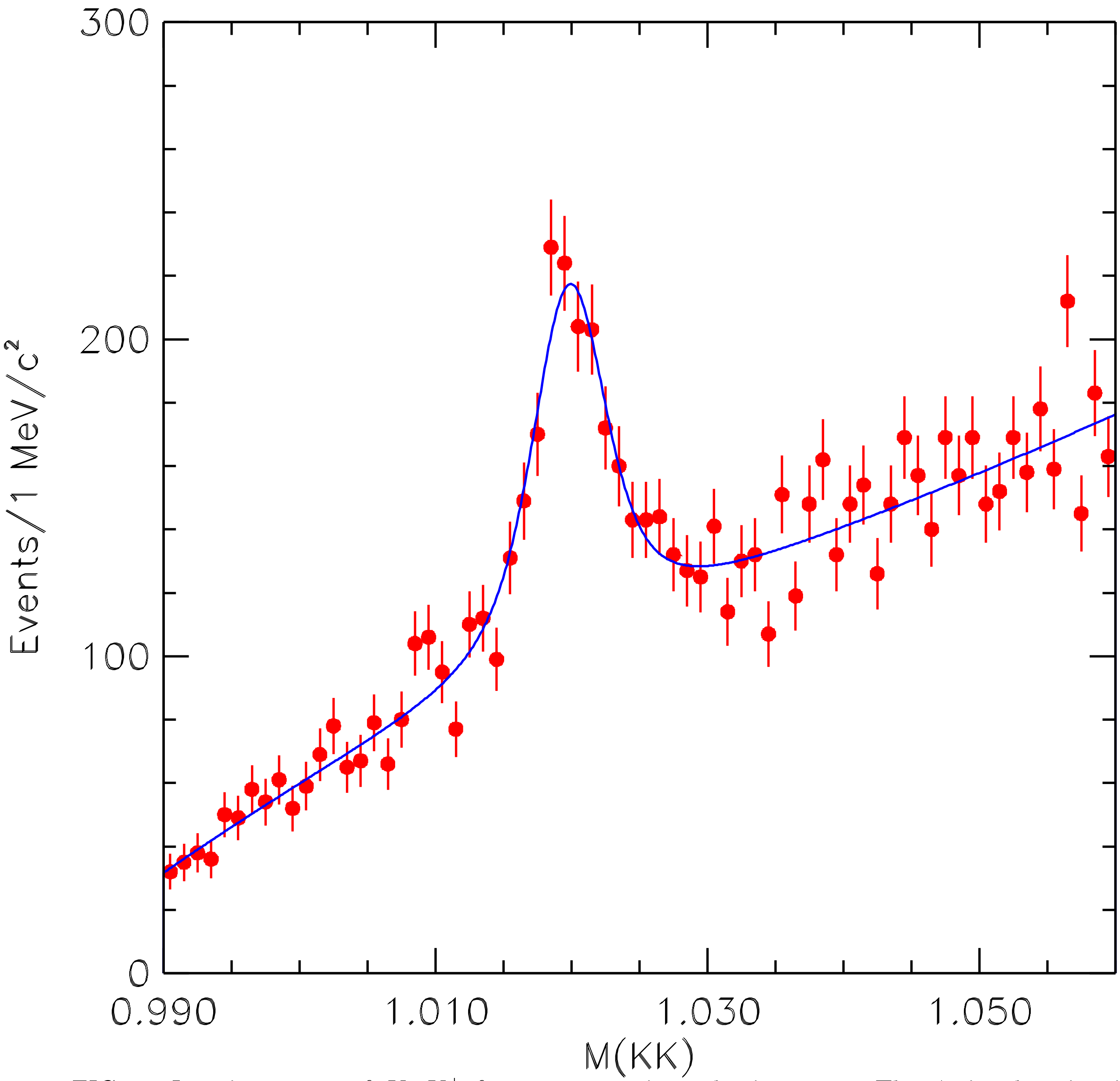

FIG. 1. Invariant mass of K^-K^+ for events passing selection cuts. The ϕ signal region is defined as $(1.0105 - 1.0293)$ GeV/c^2 and the two sideband regions as $(0.9900 - 1.0000)$GeV/c^2 and $(1.0450 - 1.0600)$GeV/c^2.

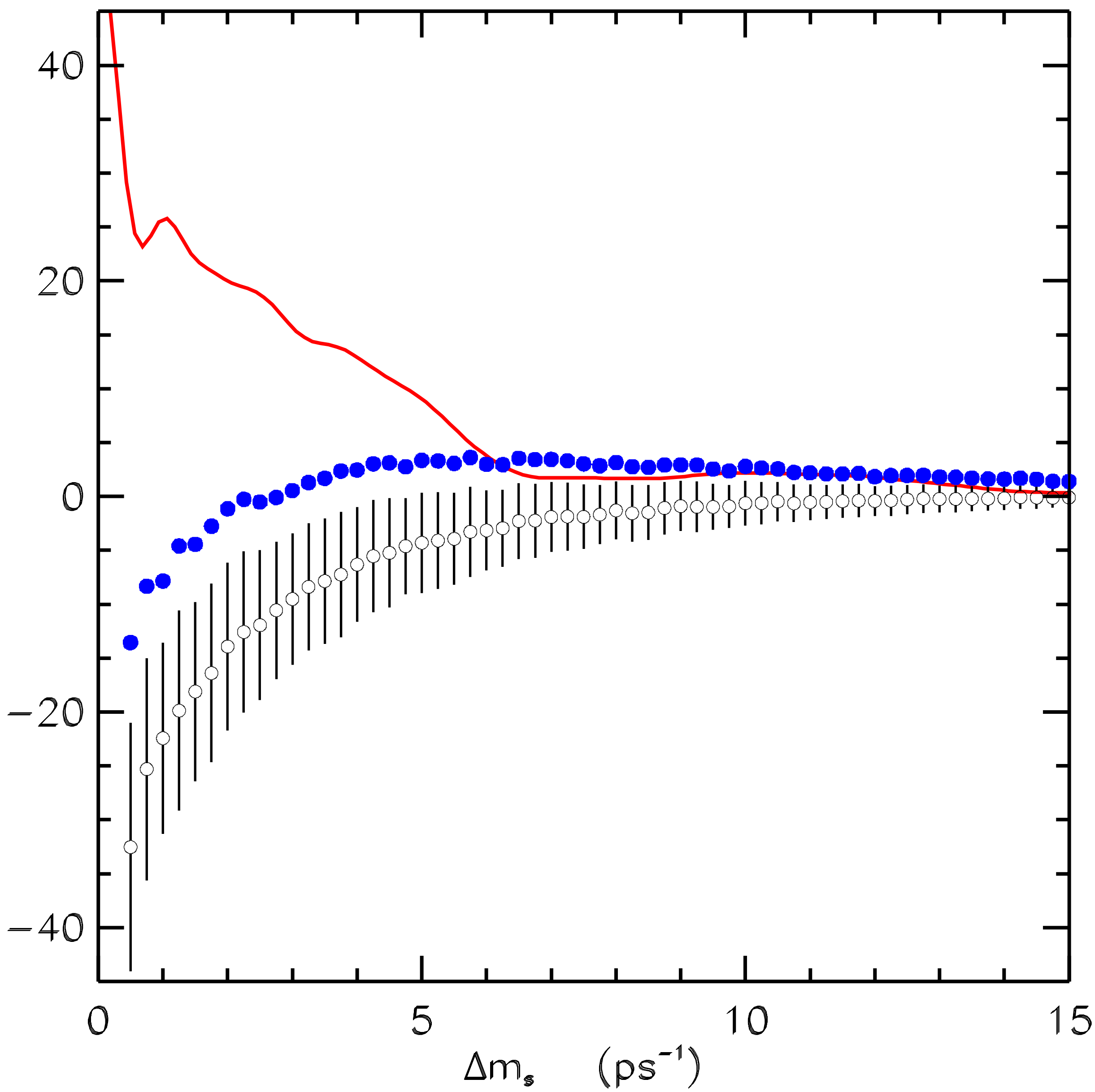

FIG. 2. Distributions of likelihood value $\Delta\mathcal{L}^{\infty}(\Delta m_s)$ relative to infinity ($\Delta m_s = \infty$). The solid line is the likelihood scanning results from the $\phi\ell$ data. The open circles with error bars are the expected values and errors estimated from MC experiments generated with given Δm_s values. The solid dots are the 95% confidence contours calculated by $\Delta\mathcal{L}^{\infty}_{expect}(\Delta m_s) + 1.645 \cdot \sigma(\Delta\mathcal{L}^{\infty}(\Delta m_s))$. Values of Δm_s with $\Delta\mathcal{L}^{\infty}(\Delta m_s)$ above the 95% confidence contours are excluded.

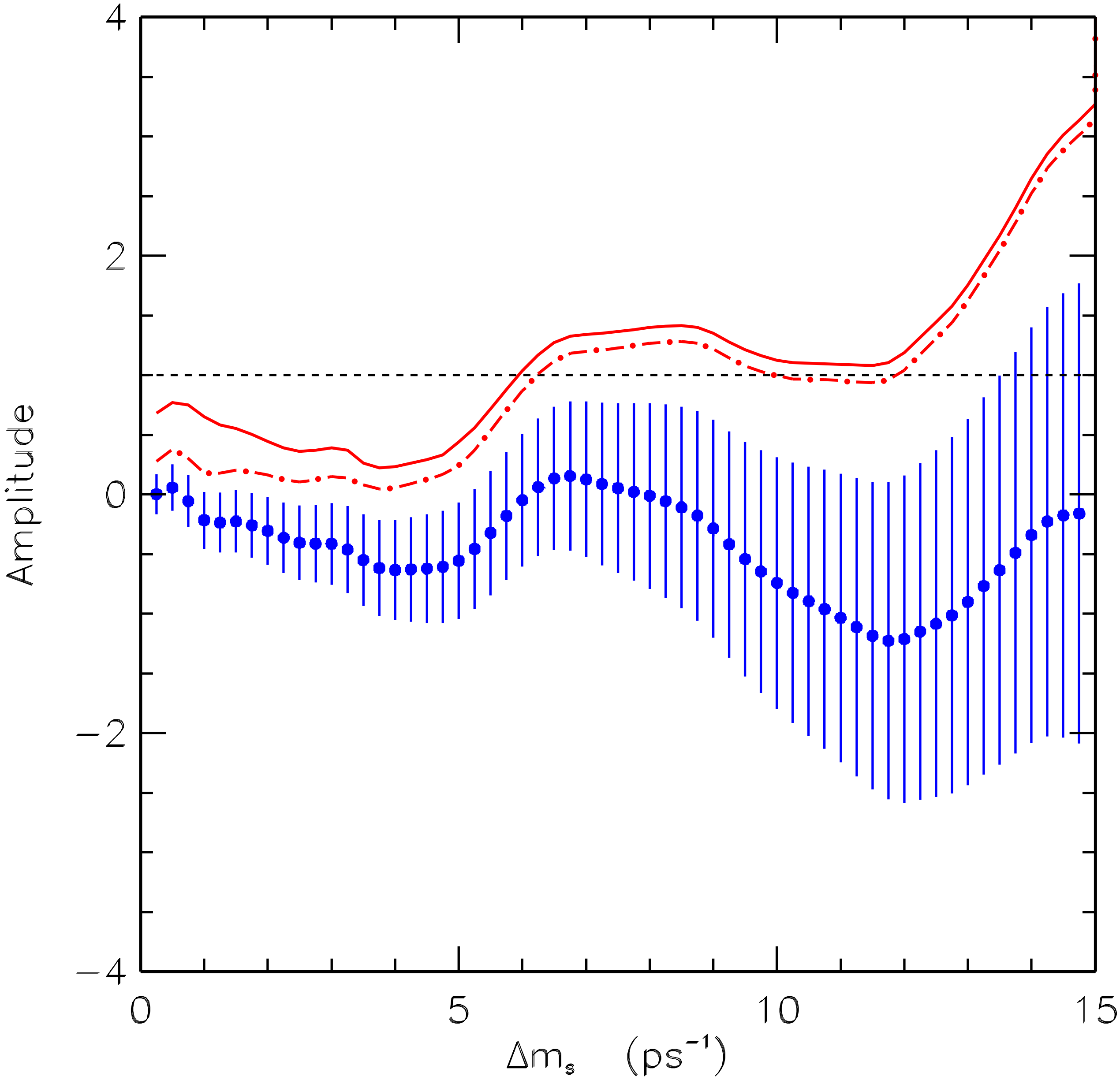

FIG. 3. Measured amplitude as a function of Δm_s. The dots with error bars are the fitted amplitudes and their statistical errors. The dot-dashed line corresponds to $\mathcal{A} + 1.645\sigma_{\mathcal{A}}$ with statistical uncertainties, while the solid line includes the contribution from systematic uncertainties. The values of Δm_s for which the solid line is less than one are excluded at 95% confidence level.