Search for $B_s^0 - \bar{B}_s^0$

F. Abe  
*National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan*

Kenneth A. Bloom  
*University of Nebraska-Lincoln, kbloom2@unl.edu*

Collider Detector at Fermilab Collaboration

Follow this and additional works at: https://digitalcommons.unl.edu/physicsbloom

Part of the Physics Commons

Abe, F.; Bloom, Kenneth A.; and Collaboration, Collider Detector at Fermilab, "Search for $B_s^0 - \bar{B}_s^0$" (1999). *Kenneth Bloom Publications.* 125.  
https://digitalcommons.unl.edu/physicsbloom/125

This Article is brought to you for free and open access by the Research Papers in Physics and Astronomy at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Kenneth Bloom Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.
Search for $B_s^0 - B_s^0$ Oscillations Using the Semileptonic Decay $B_s^0 \to \phi \ell^+ \nu$
A search for $B^0_s$-$\bar{B}^0_s$ oscillations is performed in a sample of $B^0_s$ semileptonic decays collected using dilepton triggers at the Tevatron Collider during 1992–1995. The $B^0_s$ is reconstructed using $\phi$ meson-lepton correlations; its initial production flavor is determined with the second lepton in the event. From a signal of 1068 with a $B^0_s$ purity of 61%, we obtain a limit on the $B^0_s$-$\bar{B}^0_s$ oscillation frequency of $D_{ms}$.

\[ D_{ms} = 5.8 \pm 1 \text{ ps}^{-2} \] at 95% confidence level. [S0031-9007(99)09005-5]

PACS numbers: 14.40.Nd, 13.20.He

A search for $B^0_s$-$\bar{B}^0_s$ oscillations is performed in a sample of $B^0_s$ semileptonic decays collected using dilepton triggers at the Tevatron Collider during 1992–1995. The $B^0_s$ is reconstructed using $\phi$ meson-lepton correlations; its initial production flavor is determined with the second lepton in the event. From a signal of 1068 with a $B^0_s$ purity of 61%, we obtain a limit on the $B^0_s$-$\bar{B}^0_s$ oscillation frequency of $\Delta m_s > 5.8 \text{ ps}^{-1}$ at 95% confidence level. [S0031-9007(99)09005-5]

PACS numbers: 14.40.Nd, 13.20.He

The frequency of oscillatory transitions between $B^0_s$ and $\bar{B}^0_s$ is proportional to the mass difference $\Delta m_s$ between the mass eigenstates of the $B^0_s$-$\bar{B}^0_s$ system. In the standard model, $\Delta m_s$ is related to the Cabibbo-Kobayashi-Maskawa matrix element $V_{ts}$ by a second-order weak interaction box diagram involving the top quark.
quark. A measurement of $\Delta m_s$, together with the $B^0\bar{B}^0$ oscillation frequency $\Delta m_d$, which is a function of $V_{td}$, could provide a reliable determination of $|V_{td}/V_{td}|$. $\Delta m_d$ is well measured [1], but there is no direct measurement of $\Delta m_s$ yet. A combination of the CERN Large Electron-Positron Collider (LEP) searches gives a 95% confidence level limit of $\Delta m_s > 9.1 \text{ ps}^{-1}$ [1]. In this Letter, we report a limit on $\Delta m_s$, using decays of $B^0 \rightarrow \phi \ell^+\ell^-\nu \nu$ with the initial $B^0$ 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 $\sqrt{s} = 1.8 \text{ TeV}$ during the 1992–1995 collider run and correspond to an integrated luminosity of $110 \text{ pb}^{-1}$. Dilepton triggers [2] were used to select a sample of events with two leptons ($\mu$-$\mu$ or $\mu$-$e$).

The reconstruction of $B^0$ signals starts with a $\phi \ell$ pair from the decay $B^0 \rightarrow D^-_s \ell^+X\nu \rightarrow \phi \ell^+X\nu$. Throughout this Letter, charge conjugate modes are always implied. The $\phi \ell$ pair is required to have an invariant mass in the range $2.0 < m_{\phi \ell} < 5.0 \text{ GeV}/c^2$ and a combined momentum transverse to the beam line of $p_T(\phi \ell) > 5 \text{ GeV}/c$. The lepton is required to have a transverse momentum $p_T(\ell) > 2.0 \text{ GeV}/c$ and a $p_T^{rel} > 1.0 \text{ GeV}/c$, 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 $\phi$ meson is reconstructed from the decay $\phi \rightarrow K^+K^-$, where each kaon track is required to be within a cone of $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 1.0$ centered on the lepton direction [3] and to have $p_T > 1.0 \text{ GeV}/c$. The specific ionization energy loss ($dE/dx$) measurements for each kaon are required to be consistent with the expected value. The two kaons are constrained to form the $\phi$ decay vertex. We require $p_T(\phi) > 2.7 \text{ GeV}/c$ and the $\phi$ 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 $1.0 < m_{h^-\ell} < 2.0 \text{ GeV}/c^2$ and $m_{\phi h^-\ell} < 5 \text{ GeV}/c^2$, consistent with the kinematics for the $D^-_s$ and $B^0$ decay modes. If there is more than one $h^-$ candidate, we choose the one with the largest momentum projection onto the direction of the $\phi$. The charged track $h^-$ and neutral $\phi$ 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 the 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 $B^0$ 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 Fig. 1 and yields a signal of $1068 \pm 70$.

![FIG. 1. Invariant mass of $K^- K^+$ for events passing selection cuts. The $\phi$ signal region is defined as $1.0105 - 1.0293 \text{ GeV}/c^2$ and the two sideband regions as $0.9900 - 1.0000 \text{ GeV}/c^2$ and $1.0450 - 1.0600 \text{ GeV}/c^2$.](image-url)
The flavor of the $B^0$ meson at production is determined by the second lepton, $\ell_{tag}$, which is expected to originate from a semileptonic decay of the other $b$ hadron in the event. We require $\ell_{tag}$ 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 $B^0$ to decay at a proper time $t$ as a SS (OS) event, $P_{SS(0)}^{B^0} = \frac{1}{2 \tau} \exp(-t/\tau)[1 \mp \cos(\Delta m_s t)]$, 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 $b \rightarrow c \rightarrow \ell$, 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, $\Delta m_s$ 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 $\Delta m_s$, since the SS (OS) fraction is insensitive to the fast $B^0 \rightarrow B^0$ oscillations. With $R_{mistag}$, the probability for a $B^0$ to be a SS (OS) candidate becomes $F_{SS(0)}^{B^0} = (1 - R_{mistag})P_{SS(0)}^{B^0} + R_{mistag}P_{OS(0)}^{B^0}$. The analogous functions for $B^+$ and $B^*$, $F_{SS(0)}^{B^+}$ and $F_{SS(0)}^{B^*}$, are calculated by replacing $\Delta m_t$ with $\Delta m_d$ and a zero oscillation frequency, respectively. The combinatorial background fraction of events under the $K^+K^-$ mass peak, $f_{bg \ell}$, is estimated from the mass fit. The fraction of same sign events in this background, $f_{bg \ell}$, 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 $F_{bg \ell}$, 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 $F_{SS} = (1 - f_{bg \ell})F_{SS}^{B^0} + f_{bg \ell}F_{SS}^{B^0}$ and $F_{OS} = (1 - f_{bg \ell})F_{OS}^{B^0} + f_{bg \ell}(1 - f_{BG \ell})F_{bg \ell}$, where $F_{SS(0)}^{B^0}$ is a weighted sum of $F_{SS(0)}^{B^0}$, $F_{SS(0)}^{B^0}$, and $F_{SS(0)}^{B^0}$ using the sample composition fractions of $f_{B^0}$, $f_{B^0}$, and $f_{B^0}$.

The solid line in Fig. 2 shows the log-likelihood function $-\ln L = -\sum_{i=1}^{N_{SS}} \ln(F_{SS}) - \sum_{i=1}^{N_{OS}} \ln(F_{OS})$ obtained from the $\phi$ data over a range of $\Delta m_s$ values. Since $-\ln L$ has no statistically significant minimum, we set a lower limit on $\Delta m_s$. The lower limit on $\Delta m_s$ is defined as the highest $\Delta m_s$ value below which all values of $\Delta m_s$ are excluded. To set the limit, we use the amplitude fit method [1], in which one looks for a peak 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 $A(\Delta m_t)$, $P_{SS(0)}^{B^0} = \frac{1}{2 \tau} \exp(-t/\tau)[1 \mp A(\Delta m_t) \cos(\Delta m_t t)]$. The procedure is to measure the amplitude $A(\Delta m_t)$ and its Gaussian error $\sigma_A(\Delta m_t)$ at each assumed $\Delta m_t$. If the assumed $\Delta m_t$ equals the true value, a measurement consistent with $A = 1$ is expected; otherwise $A = 0$ is expected. A value of $\Delta m_t$ can be excluded at 95% confidence level if $A + \xi \sigma_A < 1$, where $\xi = 1.645$ satisfies $\int_{-\infty}^{\infty} (1/\sqrt{2 \pi}) \exp(-1/2 x^2) dx = 0.95$. The amplitude values and errors together with the 95% confidence limit contours, $A + 1.645 \sigma_A$, are displayed in Fig. 3. The highest $\Delta m_t$ value below which all values are excluded with a 95% confidence level is $\Delta m_t > 6.2$ ps$^{-1}$ taking into account only the statistical error.

The systematic error on $A$, $\sigma_A$, is estimated by varying the parameters in the fitting functions using the prescription of Ref. [9]: $\sigma_A = \Delta A + (1 - A) \Delta \sigma_A$, where $\Delta A$ and $\Delta \sigma_A$ are changes in the amplitude and its error between the new fit and the fit using nominal parameter values. The $B^0$ fraction $f_{B^0}$ 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 $\Delta m_d$ and the $B^0$, $B^+$, and $B^*$ lifetimes are varied by their Particle Data Group 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 parametrization 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 statistical 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 $\Delta \mathcal{L}_\text{exp}(\Delta m_s)$ and error $\sigma(\Delta \mathcal{L}^\infty(\Delta m_s))$ are estimated using MC.

Any value of $\Delta m_s$ is excluded at 95% confidence level if $\Delta \mathcal{L}_\text{data}(\Delta m_s) > \Delta \mathcal{L}_\text{exp}(\Delta m_s) + 1.645\sigma(\Delta \mathcal{L}^\infty(\Delta m_s))$. The obtained limit of $\Delta m_s > 6.0$ ps$^{-1}$, as shown in Fig. 2, is in good agreement with the amplitude result.

In conclusion, using a signal of 1068 $B^0 \to \phi \ell^+ \nu$ decays with a $B^0$ purity of 61% and an opposite side lepton flavor tagging method, we performed a search for $B_s^0 \bar{B}_s^0$ 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.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions.

This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Science and Culture of Japan; the National Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; and the Bundesministerium fuer Bildung und Forschung, Germany.

![FIG. 3. Measured amplitude as a function of $\Delta m_s$. 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 uncertainty, while the solid line includes the contribution from systematic uncertainties. The values of $\Delta m_s$ for which the solid line is less than 1 are excluded at 95% confidence level.](image-url)