First $B_s$ mixing results at CDF II

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I report the results of the first search for $B_s$ flavor oscillations performed at CDF II. We analyze a dataset of approximately 355 pb$^{-1}$ from proton–antiproton collisions at $\sqrt{s} = 1.96$ TeV collected in 2002-2004 with the CDF II Detector at the Tevatron Collider. Samples of both fully reconstructed, $B_s \rightarrow D_s\pi$, and partially reconstructed, $B_s \rightarrow D_s\nu$, decays are employed. A combination of tagging algorithms is used to determine the flavor of the $B_s$ mesons at production time. We fit the data using an unbinned likelihood technique which combines mass, proper decay time, and flavor tagging information of the $B_s$ candidates. Information about the oscillation frequency of the system $\Delta m_s$ is obtained by performing an amplitude scan of the data, from which an exclusion limit

$$\Delta m_s > 7.9 \text{ ps}^{-1} \quad (95\% \text{ C.L.})$$

is achieved, with a measured sensitivity of 8.4 ps$^{-1}$. Improvements currently under development, together with the increasing data samples, are expected to enhance the sensitivity beyond the Standard Model favored region before the end of Run II.

Since the time the conference took place, part of the here mentioned improvements to the analysis have been incorporated, which result in the following updates: combined exclusion limit of $\Delta m_s > 8.6 \text{ ps}^{-1}$, with a measured sensitivity of 13.0 ps$^{-1}$; combination with previously available measurements increases the world exclusion limit from 14.5 ps$^{-1}$ to 16.6 ps$^{-1}$ (95% C.L.) [1].

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The observation of flavor oscillations in the $B_s$ system constitutes a flagship measurement of the Run II CDF [2] physics program. It would result in stringent constraints to the CKM description of the Standard Model flavor sector. The expected large oscillation frequency, $\Delta m_{s}$, given by the mass difference of the heavy and the light $B$ mass eigenstates, renders this a challenging measurement; to date only an exclusion limit has been achieved, $\Delta m_{s} > 14.5 \text{ ps}^{-1}$ (95\% C.L.) [3].

At present, large amounts of $B_s$ mesons are produced only at the $p\bar{p}$ ($\sqrt{s}=1.96$ TeV) Tevatron Collider at Fermilab, providing the CDF and the DØ experiments with unique data samples to exploit the $B_s$ system, as well as other heavy and excited $b$-hadrons. In collecting these samples, the trigger systems play crucial roles. At CDF, the Silicon Vertex Tracker (SVT) [4] enables, for the first time at a hadron collider, triggering on $B$-decay vertices. The data samples used in this analysis are collected using two trigger strategies: (i) require a lepton with high transverse momentum ($p_{T} > 4$ GeV) associated with a displaced SVT-trigger track (impact parameter $120 \mu m < d_{0} < 1 \text{ mm}$); or (ii) require two displaced SVT-trigger tracks forming a displaced vertex (transverse decay-length $L_{xy} > 200 \mu m$).

The $B_s$ candidates are reconstructed from the above trigger samples in two classes of final states: partially-reconstructed semileptonic modes, $B_s \rightarrow D_{s}\ell X$, and fully-reconstructed hadronic modes, $B_s \rightarrow D_{s}\pi$, respectively. In both cases, the $D_s$ meson is reconstructed in the following channels: $D_s \rightarrow \phi (K^{+}K^{-})\pi$, $D_s \rightarrow K^{*}(K^{+}\pi^{-})K$, and $D_s \rightarrow \pi\pi\pi$. Figure (1-a) shows the invariant mass distribution for the $B_s \rightarrow D_s(\phi\pi)\pi$ channel. We reconstruct about 900 hadronic and 7700 semileptonic signal $B_s$ decays, with a signal-to-noise ratio $S/B$ of approximately 1.7 and 1.9, respectively.

The analysis of the data is performed using an unbinned likelihood fit and techniques that have been developed in order to maximize the statistical power of the data samples. For each candidate, the input to the fit includes: mass, proper decay time, and flavor tagging information about the $B_s$ candidates. The likelihood model for the observed proper decay time, $t = L_{xy}M_{B_s}/p_{T}$ ($M_{B_s}$ being the nominal $B_s$ meson mass), of the signal component is given by

$$P(t) \sim (1 \pm DS_{D}A\cos(\Delta m_{s}t))e^{-t/\langle \sigma_{l} \rangle} \otimes G(t; \sigma_{f}) \cdot \epsilon(t).$$

The first term in parenthesis describes the flavor oscillations, while the rest of the expression characterizes the proper time distribution in the absence of flavor tagging information.

The description of the observed proper decay time includes the smearing effect caused by the detector vertex resolution, through a Gaussian resolution function. The average resolution, $\sigma_{l}$, is about 115 fs and 170 fs for the hadronic and semileptonic modes, respectively. The trigger requirements and analysis selection criteria impose additional sculpting of the $t$ distribution, which is described by a function, $\epsilon(t)$, derived from Monte Carlo simulation of each decay.

In the case of the partially reconstructed modes the momentum of the candidate is underestimated. This underestimate is corrected via an average $k$-factor distribution, $F(k)$, obtained from Monte Carlo simulation, resulting in an additional smearing of $t$: $\int P(kt)F(k)dk$. The $k$-factor distributions for the semileptonic modes are characterized by a mean ($\langle k \rangle$) and an r.m.s. of about 0.83 and 0.12, respectively.

The decision of whether or not a $B_s$ candidate has mixed (shown by the signs ‘−’ and ‘+’, respectively, in the expression above) is made by the flavor tagging algorithms. The dilution, $D$, is related to the probability that the tag is correct, given by $1 + D$. The analysis employs at present a
The analysis of $B_s$ oscillations is performed using the amplitude method [5]. A fit to the amplitude parameter $A$ appearing in equation (1) is performed at each value of the mixing frequency being probed. The amplitude $A$ is expected to be unit for the true value of $\Delta m_s$, and zero otherwise. A 95% C.L. exclusion is thus achieved at a frequency value for which the amplitude and its uncertainty satisfy the condition: $A + 1.645 \cdot \sigma_A < 1$; the exclusion limit is defined as the $\Delta m_s$ value below which all frequencies satisfy this condition. The analysis of the semileptonic modes provides an exclusion limit of 7.7 ps$^{-1}$, while no significant limit is achieved with the hadronic modes alone. Figure (1-b) shows the combined amplitude scan for the hadronic and semileptonic modes; an exclusion limit of 7.9 ps$^{-1}$ is achieved. The combination of the present CDF measurement with previously available results [3] does not modify the existing limit.

The precision on the amplitude measurement at each probed value of $\Delta m_s$ determines the sensitivity of the sample, which is defined as the largest frequency value for which $1.645 \cdot \sigma_A < 1$ holds. The analysis is currently statistics dominated, with overall systematic contributions to the amplitude uncertainties which are considerably smaller, as shown in figure (1-b). The measured sensitivities for the hadronic, semileptonic, and combined analyses are 0.4, 7.4, and 8.4 ps$^{-1}$, respectively. From the combined scan with previous [3] measurements, the average sensitivity increases from 18.2 to 18.6 ps$^{-1}$.

The measured amplitude statistical uncertainty is described [5] to good approximation using

$$\sigma_A^{-2} \sim \frac{\varepsilon D^2}{2} \frac{S^2}{S+B} e^{-(\Delta m_s^2 t^2 + \Delta m_s^2 \rho^2)}$$

upon averaging over the $B_s$ proper decay time uncertainties coming from vertex, $\sigma_t$, and momentum, $t \sigma_p$, resolutions; $S$ and $B$ stand for the number of reconstructed signal and background events.
in the signal fitting region. For the fully reconstructed modes, the momentum resolution is negligible \((k \equiv 1)\); for the semileptonic modes it is determined from the \(k\)-factor distribution \(F(k)\), and characterized on average by \(\sigma_p \sim 0.15\). This results in an expected increase of the measured amplitude uncertainty in semileptonic relative to hadronic modes, which is observed in data, most importantly in the region of largest probed frequencies of the scan.

Equation (2) can be used to quantify the effect of expected improvements, by re-scaling the measured amplitude uncertainties. Besides the increasing size of our datasets, various additional improvements to the analysis are being pursued. The inclusion of the same-side tagging technique, which is based on flavor-charge correlations between the \(B_s\) meson and particles produced in fragmentation, is expected to increase a few times the tagging power. A more accurate determination of the transverse decay-length will reduce the amplitude uncertainties especially for larger probed frequency values. Other improvements include a more thorough extraction of \(B_s\) signals from existing trigger samples, and possibly optimized trigger strategies.

To conclude, CDF has performed its first search for \(B_s\) oscillations in Run II, which involved the implementation, testing, and application of the developed analysis techniques to our data samples. Quantification of improvements being pursued demonstrates that significant increases in sensitivity will be achieved in a short term, and that either the exclusion or an observation in the Standard Model favored region is within reach at Run II.

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**References**

[1] Details can be found at: http://www-cdf.fnal.gov/physics/new/bottom


