PROCEEDINGS OF SCIENCE

PoS(HEP2005)222

First B_s mixing results at CDF II

Nuno Leonardo [*]
Massachusetts Institute of Technology
77 Mass. Ave., Cambridge, MA 02139, USA
E-mail: `nleonard@mit.edu`

I report the results of the first search for B_s flavor oscillations performed at CDF II. We analyze a dataset of approximately $355\,\mathrm{pb}^{-1}$ from proton–antiproton collisions at $\sqrt{s} = 1.96\,\mathrm{TeV}$ collected in 2002-2004 with the CDF II Detector at the Tevatron Collider. Samples of both fully reconstructed, $B_s \to D_s\pi$, and partially reconstructed, $B_s \to D_s l \nu$, 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 Δm_s is obtained by performing an amplitude scan of the data, from which an exclusion limit

$$\Delta m_s > 7.9\,\mathrm{ps}^{-1} \qquad (95\%\ \mathrm{C.L.})$$

is achieved, with a measured sensitivity of $8.4\,\mathrm{ps}^{-1}$. 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 $\Delta m_s > 8.6\,\mathrm{ps}^{-1}$, with a measured sensitivity of $13.0\,\mathrm{ps}^{-1}$; combination with previously available measurements increases the world exclusion limit from $14.5\,\mathrm{ps}^{-1}$ to $16.6\,\mathrm{ps}^{-1}$ (95% C.L.) [1].

International Europhysics Conference on High Energy Physics
July 21st - 27th 2005
Lisboa, Portugal

---

[*] Representing the CDF Collaboration.

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, Δm_s, given by the mass difference of the heavy and the light B_s mass eigenstates, renders this a challenging measurement; to date only an exclusion limit has been achieved, $\Delta m_s > 14.5$ 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 $120\,\mu\text{m} < d_0 < 1\,\text{mm}$); 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, $B_s \rightarrow D_s l X$, 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

$$\mathscr{P}(t) \sim (1 \pm D S_D A\,cos(\Delta m_s t))\, e^{-\frac{t}{\tau_{B_s}}} \otimes G(t;\sigma_l) \cdot \varepsilon(t). \tag{1}$$

The first term in parenthesis describes the flavor oscillations, while the rest of the expression characterizes the proper time distribution in the absense 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, σ_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, $\varepsilon(t)$, 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: $\int \mathscr{P}(kt)F(k)dk$. The k-factor distributions for the semileptonic modes are characterized by a mean ($\bar{k}$) 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 $\frac{1+D}{2}$. The analysis employs at present a combination of so-called *opposite-side taggers*, which identify the B_s production flavor by tagging the flavor of the accompanying b-hadron which originated from the same $b\bar{b}$ pair, through identification of specific decay products: leptons and jets. The lepton taggers exploit the semileptonic transitions $b \to l^- X$, $\bar{b} \to l^+ X$ $(l = \mu, e)$; the dilution is parameterized in terms of lepton likelihood, and momentum relative to the jet axis, p_T^{rel} (higher dilution expected at higher p_T^{rel} due to softer $b \to c \to l^+$ sequential background). The jet charge taggers use a weighted sum of track charges in opposite-side b-jets; three algorithms are used, which differ on the type of tagging jet found: characterized by an identified secondary vertex; containing displaced tracks; or that with the highest p_T. Taggers are ranked in order of their average expected dilutions; the decision is provided by the highest average dilution tagger which is available for a given event.

The opposite-side taggers are tuned on a large inclusive sample of semileptonic b-decays, obtained with the lepton + SVT trigger mentioned above. The dilution D of each tagger is determined for individual B_s candidates based on the parameterizations achieved therein. In order to take into account sample composition and kinematic differences between that sample and the signal samples, a scale factor S_D for the dilution is allowed for each of the algorithms. The S_D factors are determined, for the semileptonic and hadronic modes, from dilution and mixing fits performed to reconstructed $B_{u,d} \to D^{(*)} l X$ and $B_{u,d} \to J/\psi K^{(*)} / B_{u,d} \to D\pi$ decays, respectively. A tagging method's figure of merit is εD^2, where the efficiency ε is given by the fraction of events which the algorithm tags. The combined calibrated $\varepsilon(DS_D)^2$ for the semileptonic and hadronic modes is $1.43 \pm 0.09\%$ and $1.12 \pm 0.18\%$, respectively.

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 Δm_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 Δm_s value below which all frequencies satisfy this condition. The analysis of the semileptonic modes provides an exclusion limit of $7.7\,\mathrm{ps}^{-1}$, 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 $7.9\,\mathrm{ps}^{-1}$ 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 Δm_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

$$\sigma_A^{-2} \sim \frac{\varepsilon D^2}{2} \frac{S^2}{S+B} \, e^{-\left(\bar{k}^2 \sigma_l^2 + t^2 \sigma_p^2\right) \Delta m_s^2} \tag{2}$$

upon averaging over the B_s proper decay time uncertainties coming from vertex, σ_l, and momentum, $t\,\sigma_p$, resolutions; S and B stand for the number of reconstructed signal and background events

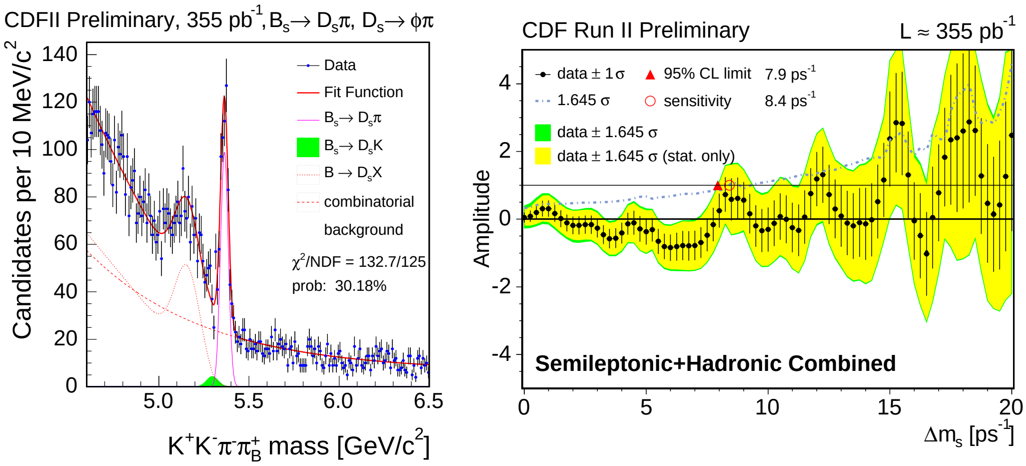

Figure 1: (a) Mass distribution for $B_s \rightarrow D_s(\phi\pi)\pi$ decay (*left*); (b) combined amplitude scan for $B_s \rightarrow D_s l\nu$ and $B_s \rightarrow D_s\pi$ decays (*right*).

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.

I would like to thank the organizing team at LIP for a very enjoyable conference in Lisbon.

References

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

[2] CDF Collaboration, *CDF II Technical Design Report*, FERMILAB-PUB-96/390-E (1996).

[3] S. Eidelman *et al.* [Particle Data Group], *Review of particle physics*, Phys. Lett. B **592**, 1 (2004).

[4] W. Ashmanskas *et al.*, *The CDF Silicon Vertex Trigger*, NIM A **518**, 532 (2004).

[5] H.G. Moser, A. Roussarie, *Mathematical methods for $B^0\overline{B}^0$ oscillation analyses*, NIM A **384** (1997).