FERMILAB-CONF-09-012-PPD

Measurement of B_s Oscillations and CP Violation Results from DØ

J. Ellison, for the DØ Collaboration

University of California, Riverside, CA 92521, USA

Abstract

We present a measurement of the $B_s^0 - \bar{B}_s^0$ oscillation frequency, Δm_s, using a combination of semi-leptonic and hadronic B_s decay candidates selected from data collected by the DØ Experiment at the Fermilab Tevatron. We also present several results on CP violation, including an improved measurement of the B_s CP-violating phase from a flavor-tagged analysis of $B_s^0 \to J/\psi + \phi$ decays.

Key words:
PACS:

1. Introduction

Among the primary goals of the Tevatron is the observation of B_s oscillations and the search for CP violation in B-meson decays. In this paper we describe some recent results in these areas. The data used for the results described here are based on approximately $1.2 - 2.8$ fb^{-1} of data collected by the DØ Experiment at the Fermilab Tevatron. The DØ detector consists of a central tracking system surrounded by a uranium liquid-argon calorimeter and an outer muon detection system and is described in [1].

2. Measurement of B_s Oscillations

In this paper we report a preliminary measurement of the $B_s^0 - \bar{B}_s^0$ oscillation frequency Δm_s based on the analysis of five decay channels: (1) $B_s^0 \to D_s^- \mu^+ \nu X, D_s^- \to \phi\pi^-$; (2) $B_s^0 \to D_s^- e + \nu X, D_s^- \to \phi\pi^-$; (3) $B_s^0 \to D_s^- \mu^+ \nu X, D_s^- \to K^{*0} K^-$; (4) $B_s^0 \to D_s^- \mu^+ \nu X, D_s^- \to K_s^0 K^-$; (5) $B_s^0 \to D_s^- \pi^+, D_s \to \phi\pi^-$. The datasets were approximatley 2.4 fb^{-1} for all channels except (4) whihc used a dataset of 1.2 fb^{-1}. DØ has previously reported direct limits on B_s oscillations using 1 fb^{-1} of data in the first decay channel [2].

After selection and reconstruction of the B_s^0 decays, the flavor of the B_s^0 at decay is determined from the charge of the muon, electron, or pion in the final state. The flavor at production is determined using a combined flavor tagger based on opposite-side and same-side tagging [3]. The effectiveness of the tagging algorithm is characterized by the tagging efficiency ϵ and the dilution $\mathcal{D}$ defined by $\mathcal{D} = (N_{RS} - N_{WR})/(N_{RS} + N_{WR})$, where N_{RS} and N_{WR} are the number of right-sign and wrong-sign tags, respectively. The overall effectiveness of the combined tagger, obtained using $B \to \mu\nu D^{*-}$ data and $B_s \to J/\psi\phi$ data and Monte Carlo, is $\epsilon\mathcal{D}^2 = 4.49 \pm 0.88\%$.

The determination of the proper decay length takes into account possible missing momentum, e.g. due to the presence of a neutrino in the semileptonic decay modes. The proper decay length is given by $c\tau_{B_s^0} = x^M K$, where x^M is the measured or visible proper decay length, given by

$$x^M = \left[\frac{\vec{d}_T^{\,B_s^0} \cdot \vec{p}_T^{\,\ell D_s^-}}{(p_T^{\ell D_s^-})^2} \right] cM_{B_s^0} \qquad \text{with} \quad K = \frac{p_T^{\mu D_s^-}}{p_T^{B_s^0}}$$

The K-factor, K, is determined from Monte Carlo.

The measurement of Δm_s is accomplished using an unbinned likelihhod fit to the data. The likelihood function is constructed using the probabilities for mixed and unmixed decays,

$$P_{\text{mix}}(t) = \frac{1}{2}\frac{K}{c\tau_{B_s}} \exp\left(-\frac{Kx}{c\tau_{B_s}}\right)(1 - \mathcal{D}\cos\Delta m_s Kx/c)$$
$$P_{\text{nomix}}(t) = \frac{1}{2}\frac{K}{c\tau_{B_s}} \exp\left(-\frac{Kx}{c\tau_{B_s}}\right)(1 + \mathcal{D}\cos\Delta m_s Kx/c)$$

and accounting for detector resolutions and background contributions. The combined amplitude scan, where the likelihood is modified to include an amplitude term, $\mathcal{L} \propto 1 \pm \mathcal{A}\mathcal{D}\cos(\Delta m_s Kx/c)$, is shown in Fig. 1(a). The likelihood as a function of Δm_s is shown in Fig. 1(b). The measured value of Δm_s is obtained from a fit to the likelihood vs. Δm_s in the region of the minimum shown in Fig. 1(b), and yields $\Delta m_s = 18.53 \pm 0.93(\text{stat.}) \pm 0.30(\text{syst.})\ \text{ps}^{-1}$. The significance of this result is $2.9\ \sigma$.

The Δm_s measurement can be translated into a constraint on $|V_{td}/V_{ts}|$, and we obtain

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2018 \pm 0.005(\text{exp.})\ {}^{+0.0081}_{-0.0060}(\text{theor.})$$

3. Analysis of $B_d^0 \to J/\psi + K^{*0}$ and $B_s^0 \to J/\psi + \phi$ Decays

Before discussing CP Violation in $B_s^0 \to J/\psi + \phi$, we present results of an analysis of $B_d^0 \to J/\psi + K^{*0}$ and $B_s^0 \to J/\psi + \phi$ decays, in which CP violation is neglected. The aim is to measure the parameters which describe the time-dependent angular distributions of these decays where the initial B meson flavor is not determined. The relevant parameters are the linear polarization amplitudes, the strong phases, and the lifetimes. This allows us to obtain the lifetime ratio, and test $SU(3)$ flavor symmetry and factorization. This is achieved by fitting to the mass, lifetime, and angular distributions of the decay products. For details of the analysis see [4].

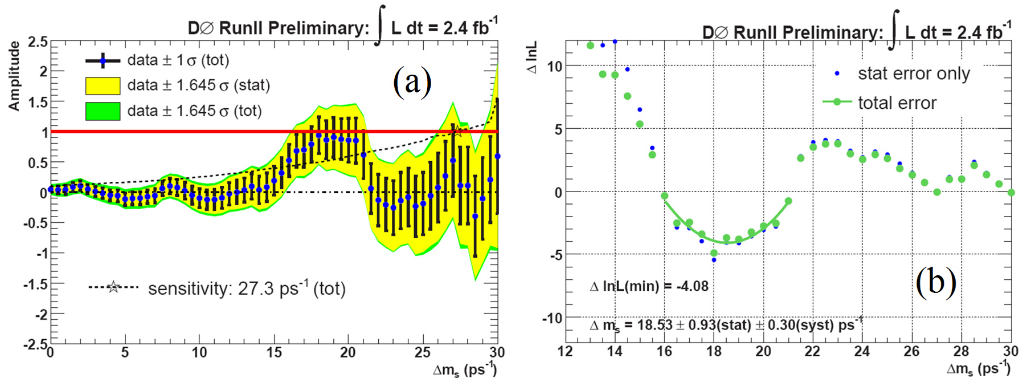

Fig. 1. (a) B_s^0 oscillation amplitude as a function of Δm_s and (b) B_s^0 oscillation likelihood as a function of Δm_s.

The preliminary results are shown in Table 1. The B_d results are competitive and consistent with previous measurements by CDF, BaBar, and Belle. The measurements of the strong phases indicate the presence of final-state interactions for $B_d^0 \to J/\psi + K^{*0}$, since δ_1 is 3.5 σ away from zero. Also, comparison of the polarization amplitudes and strong phases shows no evidence for violation of $SU(3)$ flavor symmetry.

Table 1
Preliminary results for the linear polarization amplitudes, strong phases, lifetime and width difference for $B_d^0 \to J/\psi + K^{*0}$ and $B_s^0 \to J/\psi + \phi$. A_0 and $A_\parallel$ are the linear polarization amplitudes, δ_1, δ_2, and $\delta_\parallel$ are the strong phases, τ is the lifetime, and for the B_s decay, $\Delta\Gamma_s$ is the width difference between the light and heavy mass eigenstates.

Parameter	B_d^0	B_s^0
$\|A_0\|^2$	$0.587 \pm 0.011(\text{stat}) \pm 0.013(\text{syst})$	$0.555 \pm 0.027(\text{stat}) \pm 0.006(\text{syst})$
$\|A_\parallel\|^2$	$0.230 \pm 0.013(\text{stat}) \pm 0.025(\text{syst})$	$0.244 \pm 0.032(\text{stat}) \pm 0.014(\text{syst})$
δ_1 (rad)	$-0.38 \pm 0.06(\text{stat}) \pm 0.09(\text{syst})$	–
δ_2 (rad)	$3.21 \pm 0.06(\text{stat}) \pm 0.06(\text{syst})$	–
$\delta_\parallel$ (rad)	–	$2.72\ ^{+1.12}_{-0.27}(\text{stat}) \pm 0.26(\text{syst})$
τ (ps)	$1.414 \pm 0.018(\text{stat}) \pm 0.034(\text{syst})$	$1.487 \pm 0.060(\text{stat}) \pm 0.028(\text{syst})$
$\Delta\Gamma_s$ (ps^{-1})	–	$0.085\ ^{+0.072}_{-0.078}(\text{stat}) \pm 0.001(\text{syst})$

4. Flavor-Tagged Analysis of $B_s^0 \to J/\psi + \phi$ Decays

The $B_s^0 \to J/\psi\ \phi$ decay involves a final state that is a mixture of CP-even and CP-odd states. In order to separate the CP-even and CP-odd states, we perform a maximum likelihood fit to the mass, lifetime, and time-dependent angular distributions of the $B_s^0 \to J/\psi(\to \mu^+\mu^-)\ \phi(K^+K^-)$ decay. The fit yields the CP-violating phase ϕ_s and the width difference $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$. The decay can be described by three decay angles θ, ϕ, and ψ defined in [5]. We employ initial state flavor tagging which improves the sensitivity to the

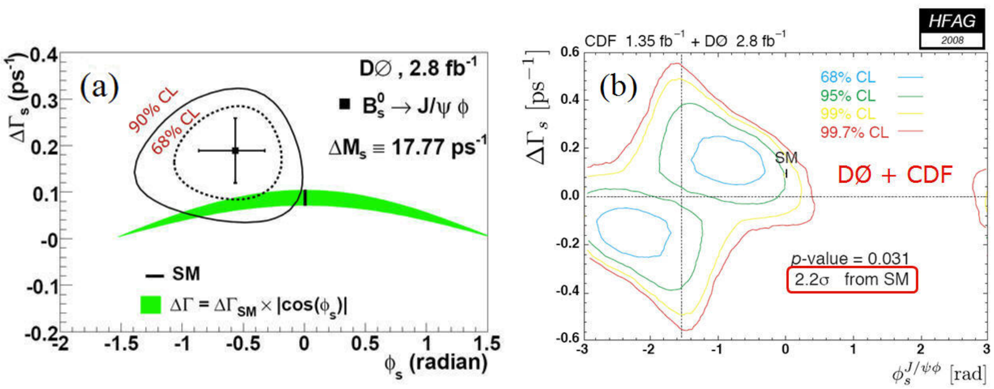

Fig. 2. (a) Results of the fits in the $\phi_s - \Delta\Gamma_s$ plane for the DØ $B_s \to J/\psi\phi$ analysis based on 2.8 fb^{-1} of data. (b) Fit results from the combination of the DØ results with CDF results based on 1.35 fb^{-1} of data.

CP-violating phase and removes a sign ambiguity on ϕ_s for a given $\Delta\Gamma_s$ present in our previous analysis [6]. In the fit, ΔM_s is constrained to its measured value (from CDF) and the strong phases are constrained to values measured for B_d at the B-factories, allowing some degree of violation of SU(3) symmetry. The B_s flavor at production is determined using a combined opposite-side plus sameside tagging algorithm. Confidence level contours in the $\phi_s - \Delta\Gamma_s$ plane are shown in Fig. 2(a).

The fit yields a likelihood maximum at $\phi_s = -0.57^{+0.24}_{-0.30}$ and $\Delta\Gamma_s = 0.19 \pm 0.07$ ps^{-1}, where the errors are statistical only. As a result of the constraints on the strong phases, the second maximum, at $\phi_s = 2.92^{+0.30}_{-0.24}$, $\Delta\Gamma_s = -0.19 \pm 0.07$ ps^{-1}, is disfavored by a likelihood ratio of 1:29.

From the fit results and studies of the systematic errors we obtain the width difference $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H = 0.19 \pm 0.07(\text{stat})\,^{+0.02}_{-0.01}(\text{syst})$ ps^{-1} and the CP-violating phase, $\phi_s = -0.57^{+0.24}_{-0.30}(\text{stat})\,^{+0.07}_{-0.02}(\text{syst})$. The allowed 90% C.L. intervals of $\Delta\Gamma_s$ and ϕ_s are $0.06 < \Delta\Gamma_s < 0.30$ ps^{-1} and $-1.20 < \phi_s < 0.06$, respectively. The probability to obtain a fitted value of ϕ_s lower than -0.57 given SM contributions only is 6.6%, which corresponds to approximately 1.8 σ from the SM prediction.

The results have been combined with CDF results by the Heavy Flavor Averaging Group. The CDF results are based on a data set of 1.35 fb^{-1} and the combination was performed with no constraints on the strong phases. The results are shown in Fig. 2(b). The fit yields two solutions as follows:

$$\phi_s = -2.37^{+0.38}_{-0.27} \text{ rad}, \quad \Delta\Gamma_s = -0.15^{+0.066}_{-0.059} \text{ ps}^{-1}$$
$$\phi_s = -0.75^{+0.27}_{-0.38} \text{ rad}, \quad \Delta\Gamma_s = 0.15^{+0.059}_{-0.066} \text{ ps}^{-1}$$

The p-value assuming only SM contributions is 3.1%, corresponding to 2.2 σ from the SM prediction.

5. Search for Direct CP Violation in $B^{\pm} \to J/\psi\ K^{\pm}(\pi^{\pm})$ Decays

DØ has performed a search for direct CP violation by measurement of the charge asymmetry in $B^{\pm} \to J/\psi\ K^{\pm}(\pi^{\pm})$ decays [7]. The charge asymmetry is defined by

$$A_{CP}(B^{+} \to J/\psi\ K^{+}(\pi^{+})) = \frac{N(B^{-} \to J/\psi\ K^{-}(\pi^{-})) - N(B^{+} \to J/\psi\ K^{+}(\pi^{+}))}{N(B^{-} \to J/\psi\ K^{-}(\pi^{-})) + N(B^{+} \to J/\psi\ K^{+}(\pi^{+}))}$$

Direct CP violation in these decays leads to a non-zero charge asymmetry. In the SM there is a small level of CP violation: $A_{CP}(B^{+} \to J/\psi\ K^{+}) \approx 0.003$ [8] and $A_{CP}(B^{+} \to J/\psi\ \pi^{+}) \approx 0.01$ [9]. New physics may significantly enhance A_{CP}.

After selection of $B^{\pm} \to J/\psi\ K^{\pm}(\pi^{\pm})$ candidates, the invariant mass of the $J/\psi K$ is constructed and fit to the sum of contributions from $B^{\pm} \to J/\psi\ K^{\pm}$, $B^{\pm} \to J/\psi\ \pi^{\pm}$, $B^{\pm} \to J/\psi\ K^{*}$, and combinatorial background. From the fit we find approximately 40,000 $B^{\pm} \to J/\psi\ K^{\pm}$ candidates and about 1,600 $B^{\pm} \to J/\psi\ \pi^{\pm}$ candidates. To extract the charge asymmetry the sample is divided into 8 subsamples according to the solenoid polarity, the sign of the pseudorapidity of the $J/\psi K$ system, and the charge of the K candidate. A χ^2 fit to the number of events in each subsample yields the integrated raw charge asymmetry. This is then corrected for the asymmetry of the kaon interaction rate on nucleons to obtain the final results:

$$A_{CP}(B^{+} \to J/\psi\ K^{+}) = +0.0075 \pm 0.0061(\text{stat.}) \pm 0.0027(\text{syst.})$$
$$A_{CP}(B^{+} \to J/\psi\ \pi^{+}) = -0.09 \pm 0.08(\text{stat.}) \pm 0.03(\text{syst.})$$

The results are consistent with the world average results [10]. The precision for $A_{CP}(B^{+} \to J/\psi\ \pi^{+})$ is comparable with the current world average, while for $A_{CP}(B^{+} \to J/\psi\ K^{+})$ the precision is a significant (factor of 2.5) improvement over the current world average.

6. Search for Direct CP Violation in Semileptonic B_s Decays

In this section we report a new search for CP violation in the decay $B_s^0 \to D_s^- \mu^+ \nu X$, $(D_s^- \to \phi\pi^-,\ \ \phi \to K^+K^-)$ by measurement of the charge asymmetry using a time-dependent analysis with flavor tagging. The technique used is similar to that used in the DØ B_s oscillation analysis (see Section 2). A fit to the invariant $KK\pi$ mass of the selected data is shown in Fig. 3.

The sample is divided into 8 subsamples according to solenoid polarity, the sign of the pseudorapidity of the $D_s\mu$ system, and the muon charge. An unbinned likelihood fit is used to extract the asymmetry. The systematic uncertainties are mainly due to uncertainties in the $c\bar{c}$ contribution, uncertainties in the efficiency vs visible proper decay length, and uncertainties in the $B_s \to D_s^{(*)}\mu\nu$ branching fractions. Accounting for these yields the final result:

$$a_{sl}^{s} = -0.0024 \pm 0.0117(\text{stat.})^{+0.0015}_{-0.0024}(\text{syst.})$$

This result is consistent with the SM prediction and is the most precise measurement to date.

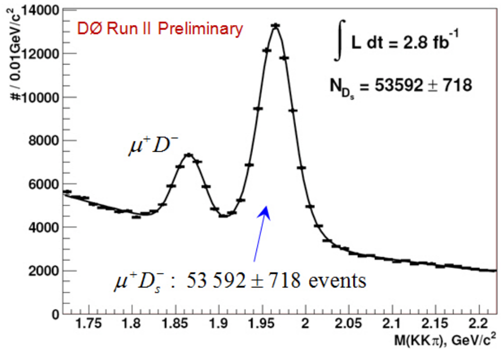

Fig. 3. The $KK\pi$ invariant mass distribution showing the $\mu^+ D^-$ and $\mu^+ D_s^-$ signals together with the fit results.

7. Measurement of $Br(B_s^0 \to D_s^{(*)} D_s^{(*)})$

For the B_s^0 system, the width difference between $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$ is related to the width difference between the CP eigenstates, $\Delta\Gamma_s^{CP} \equiv \Gamma_s^{even} - \Gamma_s^{odd}$, by $\Delta\Gamma_s = \Delta\Gamma_s^{CP} \cos\phi_s$. The quantity $\Delta\Gamma_s^{CP}$ can be estimated from the branching fraction $Br(B_s^0 \to D_s^{(*)} D_s^{(*)})$.

DØ has performed a preliminary measurement of $Br(B_s^0 \to D_s^{(*)} D_s^{(*)})$ based on 2.8 fb^{-1} of data using events which contain decays $D_s^+ \to \phi\pi^+$ and $D_s^- \to \phi\mu^-\nu$ (and their charge conjugates). The signal is extracted from a 2-dimensional likelihood fit to the data in the $m(D_s\phi\pi) - m(\phi\mu)$ plane. The results are [12]:

$$Br(B_s^0 \to D_s^{(*)} D_s^{(*)}) = 0.035 \pm 0.010(\text{stat.}) \pm 0.011(\text{syst.})$$
$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} = 0.072 \pm 0.021(\text{stat.}) \pm 0.022(\text{syst.})$$

Assuming CP violation in the SM is small, the results are in good agreement with the SM prediction.

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