Printed ISSN 1330–0016
Online ISSN 1333–9133
CD ISSN 1333–8390
CODEN FIZBE7

B_s^0 OSCILLATIONS

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Received 23 October 2007; Accepted 20 February 2008
Online 18 June 2008

For a long time, the B_s^0-$\bar{B}_s^0$ system has eluded a complete investigation of its observables. Only recently, the Tevatron experiments have accumulated sizable B_s^0 samples which allow a direct and precise study of the system properties. This contribution reviews the most up-to-date measurements by the CDF and DØ Collaborations of the B_s^0-$\bar{B}_s^0$ system parameters: the mass and decay-width differences, Δm_s and $\Delta\Gamma_s$ between the heavy and light B_s^0 mass eigenstates, the average decay width Γ_s and the CP-violating phase in the mixing ϕ_s.

PACS numbers: 14.40.Nd, 13.25.Hw, 12.15.Ff, 12.15.Hh UDC 539.126

Keywords: Tevatron, CDF, DØ, matter-antimatter oscillations, B_s^0 mixing, decay width difference

1. Introduction

B_s^0 ($\bar{B}_s^0$) mesons are $\bar{b}s$ ($b\bar{s}$) quark bound states, which exhibit particle-antiparticle oscillations due to the flavor-changing weak interactions. The simultaneous time evolution of the B_s^0-$\bar{B}_s^0$ system is conventionally described by a 2×2 effective Hamiltonian $H = M - \mathrm{i}\Gamma/2$, where M and Γ are Hermitian operators, referred to as the mass and the decay matrices, respectively. The off-diagonal elements M_{12} and Γ_{12} of M and Γ are associated with the matter-antimatter transitions. The eigenvectors of H are linear combinations of the B_s^0 flavor eigenstates: $|B_{L,H}\rangle = p|B_s^0\rangle \pm q|\bar{B}_s^0\rangle$. The subscripts L and H stay for "light" and "heavy"; in fact, $|B_L\rangle$ and $|B_H\rangle$ have well-defined masses and decay widths and are characterized by the mass difference $\Delta m_s = M_H - M_L = 2|M_{12}|$ and the decay width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\phi_s$, where ϕ_s is the phase $\arg(-M_{12}/\Gamma_{12})$, which accounts for CP violation in the mixing. The average decay width of the B_s^0 mass eigenstates is defined as $\Gamma_s = 1/\tau_s = (\Gamma_L + \Gamma_H)/2$. In the Standard Model, the B_s^0-$\bar{B}_s^0$ transitions are described at lower order by box diagrams that involve two W bosons and two up-type quarks. Dominant contributions to M_{12} and Γ_{12} are those from diagrams with virtual top quarks in the loop. The theoretical predictions for the B_s^0-$\bar{B}_s^0$ system observables are affected by large uncertainties, of the order of $20-30\%$, due to the non-perturbative calculation of the hadronic matrix elements. Instead, many theoretical uncertainties cancel out in ratios like $\Delta m_s/\Delta m_d = M_{B_s}/M_{B_d}\,\xi^2\,|V_{ts}/V_{td}|^2$, where Δm_d is the mass difference for the B_d^0-$\bar{B}_d^0$ system, M_{Bs} and M_{Bd} are the B_s^0 and B_d^0 masses, V_{ts} and V_{td} are elements of the CKM matrix, and ξ is an $SU(3)$ flavor-symmetry breaking factor obtained from lattice QCD calculations with an uncertainty of a few percents [1].

This contribution will overview the most recent measurements at the Tevatron of the physical parameters associated with the B_s^0-$\bar{B}_s^0$ oscillation phenomenon: Δm_s, Γ_s, $\Delta\Gamma_s$, and ϕ_s.

The Tevatron is a $p\bar{p}$ collider operating at the Fermi National Accelerator Laboratory. Proton and antiproton beams collide at a center of mass energy of 1.96 TeV in two interaction points, where the CDF and DØ detectors are located. To date, the Tevatron has delivered $\sim$3.3 fb^{-1} of data per experiment, $\sim$2.6 fb^{-1} of which are recorded on tape and available for analyses. CDF [2] and DØ [3] are multipurpose central detectors that present similar features: silicon microvertex trackers, a central tracker in a superconducting solenoidal magnetic field, electromagnetic and hadronic calorimeters surrounding the tracking system and muon detectors in the outermost part.

2. Δm_s *measurement*

The mass difference Δm_s between the B_s^0 mass eigenstates is measured directly in a time-dependent analysis. The measurement consists in detecting an oscillatory pattern in the proper time distribution of the B_s^0 mesons, whose frequency is proportional to Δm_s: the probability distribution for a B_s^0, produced at $t_0 = 0$, to decay as a $\bar{B}_s^0(B_s^0)$ at a later time t is given by $P(t) = \Gamma_s \exp(-\Gamma_s t)(1\mp\cos\Delta m_s t)/2$. The average statistical significance of an oscillation signal is usually approximated by the formula $\mathcal{S} = \sqrt{S\varepsilon D^2/2}\,\exp(-(\sigma_t \Delta m_s)^2)\,\sqrt{S/(S+B)}$, which summarizes the crucial elements of the Δm_s measurement: an abundant B_s^0 signal (S) with a good signal to background (B) ratio, the B_s^0 proper time measured with high resolution (σ_t), and a high-efficiency and high-purity identification of B_s^0 flavor at production and decay (*flavor tagging*). εD^2 is a figure of merit that quantifies the performance of a flavor tagging technique: ε is the fraction of signal events with a tag and D is the dilution, defined as twice the purity minus one, which measures the rate of mistags.

The DØ Collaboration analyzed 2.4 fb^{-1} of data, collected with an inclusive single muon and a dimuon trigger. They reconstruct the B_s^0 decays to $\mu^+ D_s^- X$[1], $e^+ D_s^- X$, $\pi^+ D_s^- X$, with $D_s^- \to \phi\pi^-$ and $\phi \to K^+K^-$, and the decay $B_s^0 \to \mu^+ D_s^- X$, with $D_s^- \to K^{*0}(892)K^-$ and $K^{*0} \to K^+\pi^-$. A selection based on a likelihood ratio discriminant yields 64800 candidates. The CDF analysis [4] uses 1 fb^{-1} of data collected with a displaced track trigger. CDF reconstructs the hadronic decays $B_s^0 \to D_s^-\pi^+$ and $D_s^-\pi^-\pi^+\pi^+$, and the semileptonic modes $\mu^+ D_s^- X$ and $e^+ D_s^- X$, where D_s^- decays to $\phi\pi^-$, with $\phi \to K^+K^-$, to $K^{*0}(892)K^-$, with $K^{*0} \to K^+\pi^-$, or to $\pi^-\pi^-\pi^+$. Moreover, CDF uses the hadronic decays $B_s^0 \to D_s^{*-}\pi^+$ with $D_s^{*-} \to D_s^-\gamma/\pi^0$ and $B_s^0 \to D_s^-\rho^+$ with

[1]Charge conjugate decay modes are implied throughout this article.

$\rho^+ \to \pi^+\pi^0$, in which the photon and the neutral pion is missing. An artificial neural network (NN) is used to select 8700 hadronic and 61500 semileptonic candidates.

The proper time of B_s^0 mesons is calculated from the reconstructed distance between the production and decay vertices and the momentum, both measured in the transverse plane: $t = L_T M_{B_s}/P_T$. In the case of partially reconstructed decays, a Monte Carlo correction factor, which accounts for the missing momentum, has to be applied to t. To enhance the resolution on the proper decay time, both experiments exploit a silicon layer close ($\sim$1.5 cm) to the beampipe and utilize an event-by-event σ_t. The average CDF resolution is 87 fs and 150 fs for the fully reconstructed and partially reconstructed decays, respectively. The DØ average resolution is 160 fs.

The B_s^0 flavor at decay time is inferred from the final decay products, i.e. the lepton or pion electric charge, whereas the determination of the production flavor relies on the dedicated *flavor-tagging* techniques. At the Tevatron, b quarks are mainly produced in $b\bar{b}$ pairs; the B_s^0 initial flavor can be determined either from the decay products of the b-hadron originated from the other b quark in the event (opposite-side flavor tags), or from the properties of the particles produced in association with the reconstructed B_s^0 (the same-side flavor tags). The combined tagging power of the CDF opposite-side taggers is $\varepsilon D^2 = 1.8\%$, while the same-side tagger has $\varepsilon D^2 = 3.7\%$ (4.8%) in the hadronic (semileptonic) sample. DØ quotes $\varepsilon D^2 = 2.5\%$ for the opposite-side taggers and 4.5% for a combination of the opposite-side and the same-side taggers.

The amplitude scan technique [5] is used to search for a significant oscillation signal: an unbinned maximum likelihood fit, which combines mass, decay time, decay time resolution, and flavor tagging information, is performed for the oscillation amplitude at different fixed values of Δm_s. The oscillation amplitude is expected to be consistent with 1 at the true oscillation frequency. Fig. 1 (left)

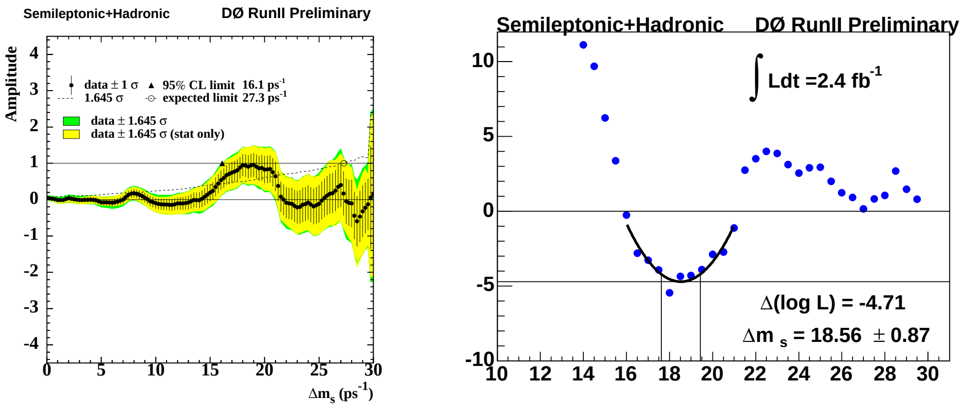

Fig. 1. Combined amplitude scan of the hadronic and semileptonic samples with statistical and systematic uncertainties (left) and global likelihood profile around the minimum (right) of the DØ analysis.

reports the fitted value of the amplitude as a function of Δm_s for the DØ analysis. The scan shows an amplitude consistent with unity at around 18 ps^{-1} with a 3σ statistical significance. A parabolic fit in the minimum region of the likelihood profile, shown in Fig. 1 (right), returns $\Delta m_s = 18.56 \pm 0.87$ ps^{-1}. Figure 2 reports the amplitude scan and the likelihood profile for the CDF analysis. The amplitude is consistent with unity at 17.25 ps^{-1} with a 6σ statistical significance. Fixing the amplitude to 1 and fitting for the oscillation frequency, CDF finds $\Delta m_s = 17.77 \pm 0.12$ ps^{-1}. Inverting the $\Delta m_s/\Delta m_d$ formula and using $M_{Bd}/M_{Bs} = 0.98390$ [6], $\Delta m_d = 0.507 \pm 0.005$ ps^{-1} [7], and $\xi = 1.21^{+0.047}_{-0.035}$ [1], CDF also derives the result $|V_{td}/V_{ts}| = 0.2060^{+0.0081}_{-0.0060}$.

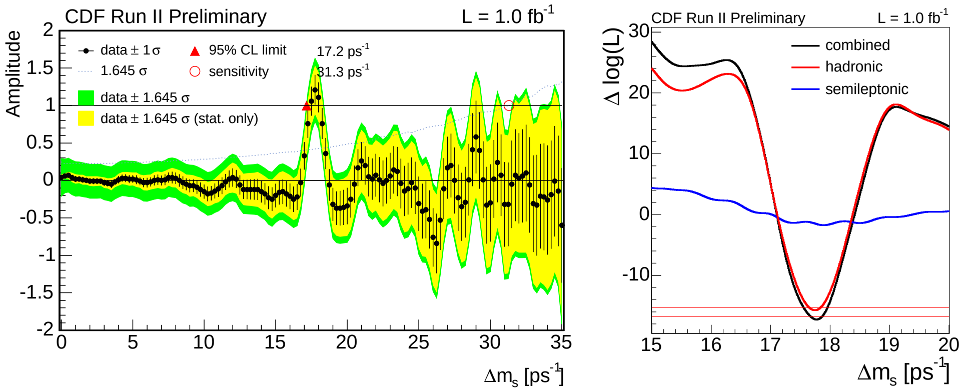

Fig. 2. Combined amplitude scan of the hadronic and semileptonic samples with statistical and systematic uncertainties (left) and global likelihood profile around the minimum (right) of the CDF analysis.

3. Γ_s, $\Delta\Gamma_s$ and ϕ_s measurements

An untagged sample of $B_s^0 \to J/\psi\phi$ candidates represents a powerful tool to measure $\Delta\Gamma_s$, since a time-dependent angular analysis of the decay products allows to disentangle the heavy (B_H) and light (B_L) B_s^0 mass eigenstates. $B_s^0 \to J/\psi\phi$ is a pseudoscalar to vector-vector decay; the final state can either have angular momentum $L = 0, 2$ (CP-even) or $L = 1$ (CP-odd). For negligible CP-violation in the mixing, B_H is CP-odd and B_L is CP-even. Therefore, a time-dependent angular analysis of the J/ψ and ϕ decay products can disentangle the two CP states and, hence, the two B_s^0 mass eigenstates.

Both CDF and DØ use data acquired through a dimuon trigger. The $B_s^0 \to J/\psi\phi$ mode is reconstructed in the final state $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. The CDF measurement uses a 1.7 fb^{-1} dataset; a loose kinematical selection, improved by a further NN selection, yields 2500 candidates. DØ uses 1.1 fb^{-1} of data; a kinematical selection provides 1040 candidates. Figure 3 shows the mass peaks of CDF and DØ signals. The result is obtained by means of an unbinned maximum-likelihood fit of the B_s^0 reconstructed mass, the lifetime, determined in the same way

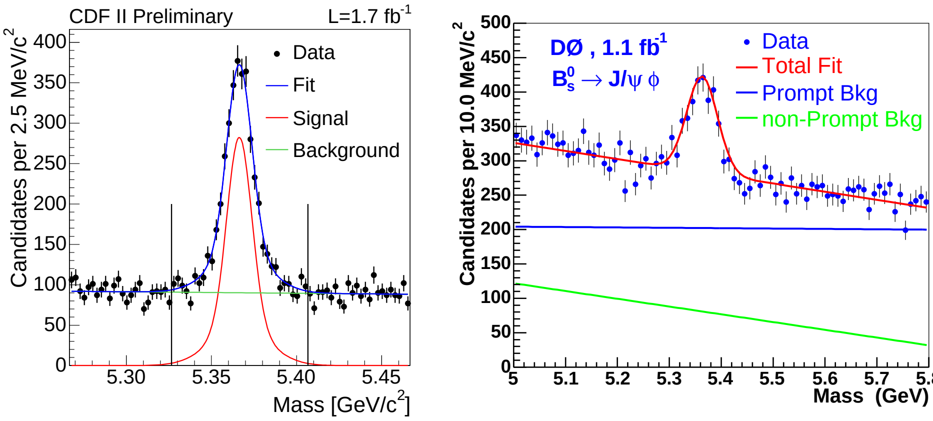

Fig. 3. $B_s^0 \to J/\psi\phi$ reconstructed mass distributions of CDF (left) and DØ (right).

as in the Δm_s analysis, and three angles (the transversity basis), which describe univocally the *CP*-parity of the final state. Under the assumption of no *CP* violation, CDF obtains $\tau_s = 1.52 \pm 0.05$ ps and $\Delta\Gamma_s = 0.076^{+0.059}_{-0.063}$ ps^{-1}, while DØ [8] finds $\tau_s = 1.52^{+0.08}_{-0.09}$ ps and $\Delta\Gamma_s = 0.12^{+0.08}_{-0.10}$ ps^{-1}. Allowing ϕ_s to float in the fit, DØ finds $\Delta\Gamma_s = 0.17 \pm 0.09$ ps^{-1} and $\phi_s = -0.79^{+0.58}_{-0.56}$. CDF does not quote a point estimate for ϕ_s, because they observe a bias towards higher ϕ_s values for low values of $\Delta\Gamma_s$ and ϕ_s. They use a frequentist method, that takes into account the bias, to calculate the 90% and 95% confidence regions in the $\Delta\Gamma_s$-ϕ_s plane, which are shown in Fig. 4 (left).

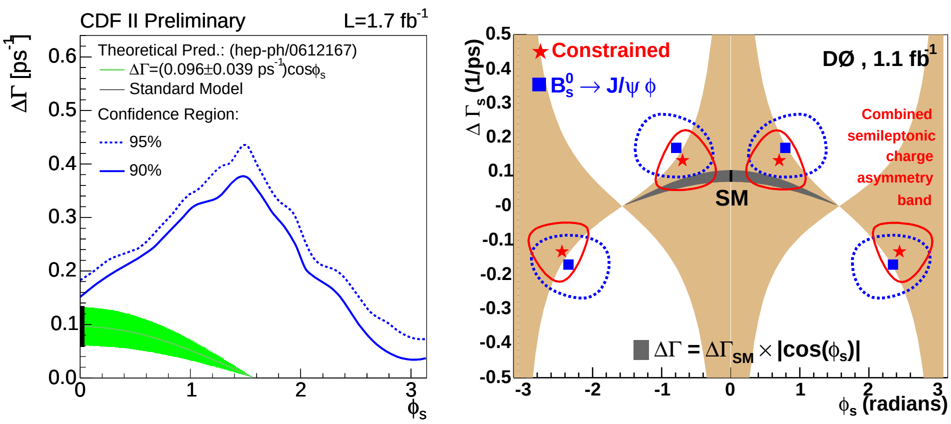

Fig. 4. $\Delta\Gamma_s$-ϕ_s plane with CDF confidence regions (left) and 1σ contours for the four-fold solution of DØ unconstrained, dashed line, and constrained, solid line, fits (right). The light shaded area is the region allowed by the constraint, while the dark shaded band represents the Standard Model expectation.

DØ has recently repeated the fit on the same $B_s^0 \to J/\psi\phi$ sample with two independent constraints on Γ_s, $\Delta\Gamma_s$, and ϕ_s [9]. The first constraint on Γ_s and $\Delta\Gamma_s$

comes from the flavor-specific decay width: $\Gamma_{fs} \simeq \Gamma_s - \Delta\Gamma_s{}^2/(2\Gamma_s)$. The second constraint derives from the B_s^0 semileptonic charge asymmetry (A_{SL}^s), which is related to $\Delta\Gamma_s$, ϕ_s, and Δm_s through $\Delta\Gamma_s \tan\phi_s = A_{SL}^s \Delta m_s$. The world average of the flavor-specific lifetime $1/\Gamma_{fs} = 1.440 \pm 0.036$ ps, the value of Δm_s measured by CDF, and the value $A_{SL}^s = 0.0001 \pm 0.0090$ from the combination of DØ results for the same-sign inclusive dimuon charge asymmetry and the charge asymmetry for the $B_s^0 \to \mu^+\nu D_s^-$ mode are used to extract the constraints. Figure 4 (right) shows the 1σ confidence regions in the $\Delta\Gamma_s$-ϕ_s plane for the four-fold solution of DØ unconstrained and constrained fits. The solution, compatible with the Standard Model expectation, is $\Delta\Gamma_s = 0.13 \pm 0.09$ and $\phi_s = -0.70^{+0.47}_{-0.39}$.

4. Conclusions

Recent measurements by CDF and DØ have started to give unprecedented insights into the nature of the B_s^0-$\bar{B}_s^0$ system. Both collaborations report consistent results on the mass difference Δm_s, the average lifetime τ_s, and the decay width difference $\Delta\Gamma_s$. DØ also quotes a value for the CP-violating phase in the mixing ϕ_s, while CDF sets a confidence region in the $\Delta\Gamma_s$-ϕ_s plane.

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OSCILACIJE B_s^0

Dugo je vremena sustav B_s^0-$\bar{B}_s^0$ bio nedokućiv potpunim istraživanjima svojih fizičkih veličina. Tek su nedavna mjerenja na Tevatronu sakupila poveće uzorke B_s^0 koji omogućuju izravno i točno proučavanje svojstava tog sustava. Ovdje se daje pregled najnovijih mjerenja parametara sustava B_s^0-$\bar{B}_s^0$ koja su obavila suradnje DØ i CDF: razlike masa i širina raspada teškog i lakog svojstvenog stanja B_s^0, Δm_s i $\Delta\Gamma_s$, prosječne širine raspada, Γ_s i faze miješanja koja krši CP, ϕ_s.