B_s Mixing and Lifetime Difference Measurements

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Recent results from the Tevatron have placed important constraints on the B_s mixing and CP violation parameters. CDF has extracted a precise measure of $\Delta M_s = 17.77 \pm 0.10(\mathrm{stat}) \pm 0.07(\mathrm{sys})\mathrm{ps}^{-1}$ from fully and partially reconstructed B_s decays. D0 has measured the lifetime difference in $B_s \rightarrow D_s^{(*)} D_s^{(*)}$ events to be $\Delta\Gamma_{CP} = 0.079^{+0.038}_{-0.035}(\mathrm{stat})^{+0.031}_{-0.030}(\mathrm{sys})$. D0 also performed a time-dependent fit to $B_s \rightarrow J/\psi\phi$ events and extracted constraints on ϕ_s and $\Delta\Gamma_s$. A four-fold ambiguity exists such that the solution $\phi_s = 0.70^{+0.47}_{-0.39}(\mathrm{stat+sys})$ for $\Delta\Gamma_s = +0.13 \pm 0.09(\mathrm{stat+sys})\mathrm{ps}^{-1}$ is the closest to the standard model expectation. This paper summarizes these analyses.

1 Introduction

In the standard model, mass and weak eigenstates of fundamental fermions are related by a matrix of probabilities. For three quark generations, the corresponding CKM matrix encompasses one complex phase which provides for CP violation. One parametrization proposed by Wolfenstein organizes this matrix so that mixing and CP violation are described by two parameters, ρ and η. Neutral mesons provide an ideal laboratory in which to study CP violation because they oscillate continuously between matter and antimatter states. For the B_s system, the specific unitarity triangle constructed in the plane of the Wolfenstein parameters defines a CP phase, ϕ_s. In the absence of new effects, $\phi_s = 4.1 \pm 1.4 \times 10^{-5}$[2].

There are three primary measurements which nail down CP violation in the B_s system. The mass difference between light and heavy states is sensitive to non-standard physics from the presence of additional massive particles in loops. D0 has produced an initial constraint of $17\mathrm{ps}^{-1} < \Delta\mathrm{M_s} < 21\mathrm{ps}^{-1}$ [3] in $B_s \rightarrow D_s l\nu$ decays. The lifetime difference, $\Delta\Gamma_s$, provides another important constraint on the CP violation system. Lastly, ϕ_s is an important additional test of new physics. Fourth generation models can produce a significant enhancement of $\phi_s \sim 0.5 - 0.8$[3].

This paper describes a new precision measurement of ΔM_s, as well as the first constraints on $\Delta\Gamma_s$ and ϕ_s. The measurements are performed by the CDF and D0 experiments at the Fermilab Tevatron. The accelerator has so far delivered about $2.7\mathrm{fb}^{-1}$ of $p\bar{p}$ collisions, of which up to $1.2\mathrm{fb}^{-1}$ are utilized in the analyses described here. The tracking and muon subsystems, and their triggers, are the primary tools used, and are described in detail elsewhere [5]. Data is taken with 2 track or single lepton plus track triggers (CDF), single muon triggers (D0) or dimuon triggers (D0 and CDF). CDF specifically exploits an impact parameter cut on tracks, D0 on the wide acceptance of its muon system.

2 Measuring the Mass Difference, ΔM_s

CDF has performed a measurement of ΔM_s in B_s semileptonic $(D_s l\nu(l \rightarrow e, \mu))$ and hadronic $(D_s\pi, D_s\pi\pi\pi, D_s\rho)$ decays. Flavor is tagged with same-side and opposite-side techniques. The former involves use of a K identification likelihood and particle kinematics

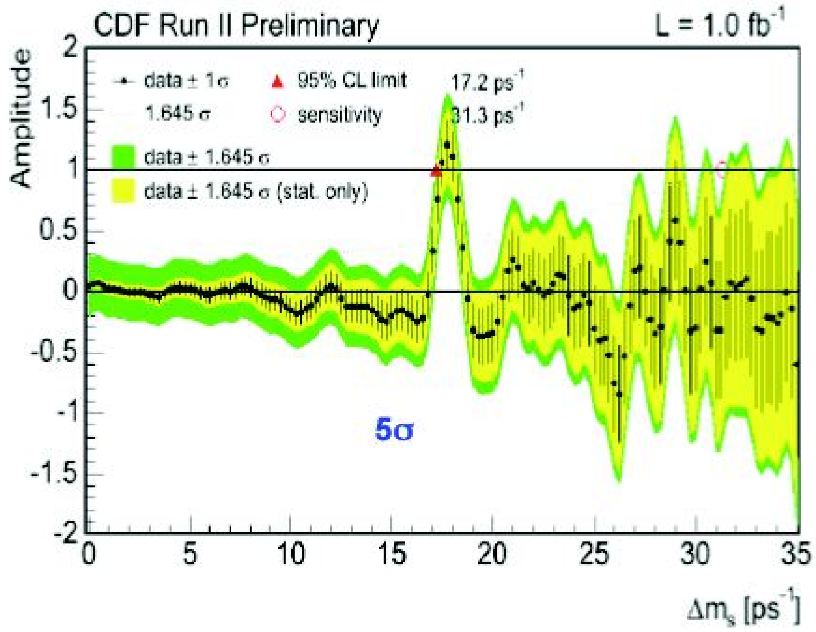

Figure 1: CDF measurement of the probability of B_s oscillations as a function of ΔM_sin ps^{-1}.

via an artificial neural network (ANN). The latter uses lepton, jet and K charge tagging. Events are selected in fully and partially reconstructed hadronic channels, and the more copious partially reconstructed semileptonic events.

The partially reconstructed events give a proper time resolution of 44.6μm. The fully reconstructed sample gives a 25.9μm resolution, which provides excellent ΔM_s sensitivity for values around 20ps^{-1}. The sensitivities are obtained channel by channel and combined in Figure 1. This illustrates essentially the Fourier transform of the proper time distribution. The resultant mass difference is $17.77 \pm 0.1(\text{stat}) \pm 0.07(\text{sys})\text{ps}^{-1}$[6]. This can be related to the ratio of CKM elements by $\frac{\Delta M_s}{\Delta M_d} = \frac{m_{B_s}}{m_{B_d}} \left|\frac{V_{ts}}{V_{td}}\right|^2$ which gives a value of $|V_{td}/V_{ts}| = 0.2006 \pm 0.0070(\text{exp})^{+0.0081}_{-0.0060}(\text{theo})$.

3 Measurement of the Lifetime Difference, $\Delta\Gamma_s$

The value of $\Delta\Gamma_s$ has been extracted by D0 in $B_s \to D_s^{(*)} D_s^{(*)}$ decays. This decay is expected to be 95% CP even[7] although other estimates range as high as 30% for CP odd. The branching ratio for $D_s^{(*)} D_s^{(*)}$ can be related to the lifetime difference by the relation $2BR(B_s \to D_s^{(*)} D_s^{(*)} = \frac{\Delta\Gamma_s}{\Gamma_s}(1 + O(\frac{\Delta\Gamma_s}{\Gamma_s}))$. Signal is identified by correlated production of $D_s \to \phi\mu\nu$ and $D_s \to \phi\pi$. The decay sequence was reconstructed when $\phi \to K^+K^-$. Extra photons from D_s^* decay were ignored. A total of 13.4 events were found in the signal sample. Approximately 2 background events were estimated from data, the primary contribution coming from $B_s \rightarrow D_s\phi\mu\nu$.

In order to reduce systematics, the measurement of the branching ratio is extracted by normalizing the signal sample to a $B_s \rightarrow D_s^{(*)}\mu\nu$ sample. This sample was selected in the same way as the $B_s \rightarrow D_s^{(*)}\phi\mu\nu$ sample. The ratio of branching ratios $R = \frac{BR(B_s\rightarrow D_sD_s)BR(D_s\rightarrow\phi\mu\nu)}{BR(B_s\rightarrow\mu\nu D_s)}$ is calculable if one knows the number of μD_s events, fit from data, and the ratio of efficiencies for $B_s \rightarrow D_s^{(*)}\mu\nu$ and $B_s \rightarrow D_s^{(*)}D_s^{(*)}$, obtained from a full simulation incorporating EVTGEN[8]. The experimental value of $R = 0.015 \pm 0.007$ gives $BR(B_s \rightarrow D_s^{(*)}D_s^{(*)}) = 0.039^{+0.019}_{-0.017}(\text{stat})^{+0.015}_{-0.015}(\text{sys})$, resulting in a measurement of $\Delta\Gamma_s = 0.079^{+0.038}_{-0.035}(\text{stat})^{+0.030}_{-0.031}(\text{sys})$[9]. The constraint is reflected in Figure 2 along with other constraints including $1/\Gamma_s$ from flavor specific channels.

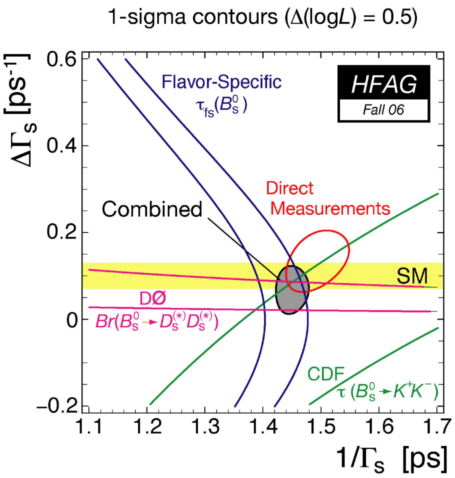

Figure 2: Constraints on $\Delta\Gamma_s$ and $1/\Gamma_s$ from several sources. The D0 measurement of $\Delta\Gamma_s$ from $B_s \rightarrow D_s^{(*)}D_s^{(*)}$decays is shown.

4 Measurement of the CP Violating Phase, ϕ_s

D0 has pursued the extraction of ϕ_s using $B_s \rightarrow J/\psi\phi$ decays. The decay mode includes CP even and CP odd states. These states can be separated because of their different time dependent angular distributions. A large lifetime difference can allow a measurement of ϕ_s. The sample is reconstructed when $J/\psi \rightarrow \mu^+\mu^-$ and $\phi \rightarrow K^+K^-$. The reconstructed mass distribution yields an estimate of 1039 ± 45 signal events.

The time dependent fit is carried out using three angles and the proper decay time. The polar and azimuthal angles, θ and φ respectively, refer to the direction of the μ^+ in the J/ψ rest frame. In the ϕ rest frame, the K^+ has angle Ψ relative to the axis defined to point away from the J/ψ direction. Without constraining $\Delta\Gamma_s$, the fit yields solutions with a four-fold ambiguity. These are given with statistical uncertainties by $\Delta\Gamma_s = 0.17 \pm 0.09(\text{stat})$ ps and $\phi_s = \pm 0.79 \pm 0.56(\text{stat})$, or $\Delta\Gamma_s = -0.17 \pm 0.09(\text{stat})$ ps and $\phi_s = \pm 2.35 \pm 0.56(\text{stat})$ [10]. Additionally, systematic uncertainties of 0.02 ps for $\Delta\Gamma_s$ and $^{+0.14}_{-0.01}$ for ϕ_s were estimated, the latter dominated by background modeling.

These measurements were further constrained using several additional measurements. The world average of the flavor-specific lifetime of B_s mesons, $\tau_{fs} = 1.440 \pm 0.036$ ps[11], constrains the $\Delta\Gamma_s$. The semileptonic charge asymmetry induced by B_s mixing is related to the CP parameters by $A^q_{SL} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$. By combining a previous D0 measurement of this asymmetry in $B_s \rightarrow \mu\nu D_s(D_s \rightarrow \phi\pi)$ decays [13] with a value extracted from the D0 same sign dimuon charge asymmetry[12] and the B-factory value of A^d_{sl}[11], a value of $A^s_{SL} = 0.0001 \pm 0.0090$ was obtained. The CDF ΔM_s measurement gives $\Delta\Gamma_s \tan(\phi_s) = A^s_{SL}\Delta M_s = 0.02 \pm 0.16\text{ps}^{-1}$. D0 refit the $J/\psi\phi$ data using these constraints with the result

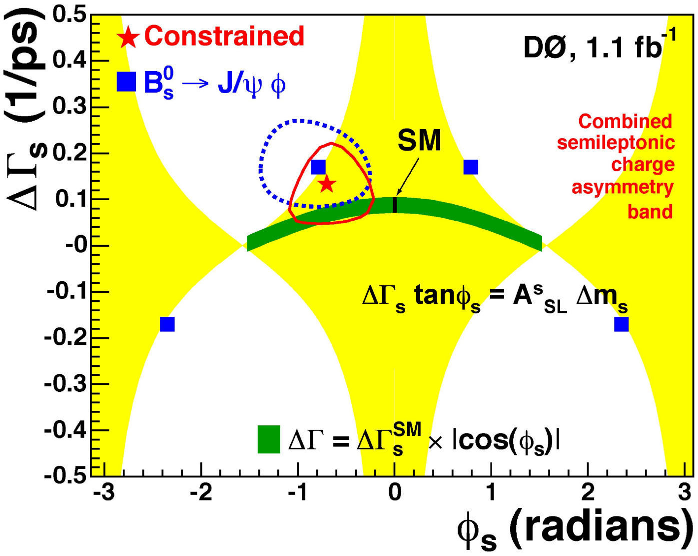

Figure 3: Projected contour limits in $\Delta\Gamma_s$ vs. ϕ_s plane from D0 final analysis of $B_s \to J/\psi\phi$ events. Other measurements of the B_s system were used to further constrain the fit.

shown in Figure 3. The fourfold ambiguity remains, and the value closest to SM expectation is $\Delta\Gamma_s = 0.13 \pm 0.09(\mathrm{stat}+\mathrm{sys})$ ps and $\phi_s = 0.70^{+0.47}_{-0.39}(\mathrm{stat}+\mathrm{sys})$[14].

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