Tevatron Results on the Discovery of $\Sigma_b^{(*)}$, B_s Oscillations and the Measurement of Δm_s, the Lifetime Difference $\Delta\Gamma_s$ and the CP-violating phase ϕ_s.

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I discuss results from the Tevatron experiments on mixing and CP-violation in B_s mesons, including the observation of B_s oscillations and the first precision measurement of the mixing frequency, as well as a measurement of the lifetime difference $\Delta\Gamma_s$ and the first measurement of the CP-violating phase ϕ_s. I also briefly report on the observation of four new bottom baryons at CDF.

1 Introduction

The Tevatron $p\bar{p}$ collider at Fermilab, operating at a center of mass energy of $\sqrt{s} = 1.96$ TeV, is a unique place to study the properties of B baryons and the heavy B mesons: the B_s, B_c and their excited states. By now, the two experiments, D0 and CDF have collected an integrated luminosity of ~ 2.5 fb^{-1} each, of which the analyses discussed here use between 1.0 and 1.3 fb^{-1}.

The hadronic environment makes triggering an important prerequisite for B physics. D0 collects events containing B mesons by triggering on muons produced in semi-leptonic decays. The excellent muon coverage allows the collection of large samples of semileptonically decaying B mesons, which drive the D0 analyses discussed here. In addition to leptonic triggers, CDF exploits triggers which find tracks that are displaced from the primary $p\bar{p}$ interaction point. These triggers give unique access to hadronic B-decays, which are of prime importance in both the CDF B_s oscillation and the $\Sigma_b^{(*)}$ analyses.

2 Observation of $\Sigma_b^{(*)}$ at CDF

CDF has observed four new bottom baryons, $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$, decaying into $\Lambda_b^0\pi^{\pm}$, where $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and $\Lambda_c^+ \to p^+K^-\pi^+$ (charge conjugation is implied). So far, only the lightest b baryon, the Λ_b (udb) had been observed. The $\Sigma_b^{+(-)}$ has quark content buu (bdd) and $J^P = \frac{1}{2}$, whereas

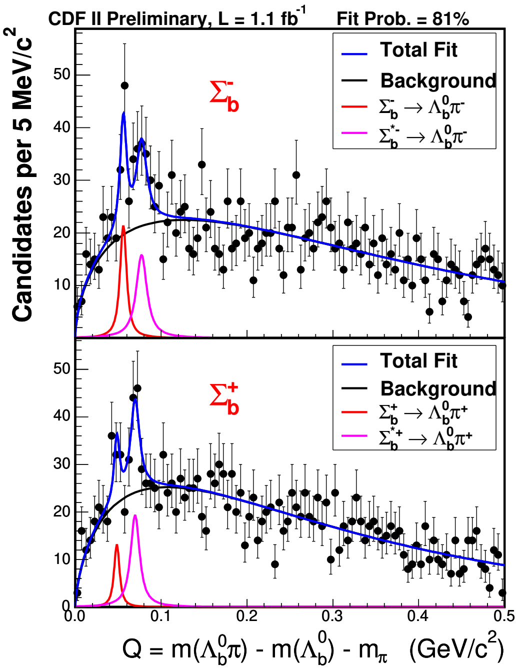

Figure 1: Distribution of the mass difference Q for $\Lambda_b^0\pi^-$ (top) and $\Lambda_b^0\pi^+$ (bottom) combinations. The unbinned maximum likelihood fit and the fitted contributions of Σ_b and Σ_b^* are also shown.

the excited states $\Sigma_b^{*\pm}$ have $J^P = \frac{3}{2}$. Observation of these states, and the measurement of their mass splittings, provides a test of QCD, which is predictive in this case because of the large mass of the b quark, through e.g. heavy quark effective theory. Figure 1 shows the distribution of the mass difference $Q = m(\Lambda_b^0\pi) - m(\Lambda_b^0) - m_\pi$. The four new states are clearly visible as excesses over the background. The significance of this signal has been determined to exceed 5.2σ. A more detailed description of this analysis can be found in J. Pursley's contribution to these proceedings and in [1].

3 Lifetime difference and CP-violation in the B_s system.

The phenomenology of mixing between B_s and $\bar{B}_s$ mesons is characterized by the mass difference between the mass eigenstates of the system Δm_s, which is equal to the $B_s - \bar{B}_s$ oscillation frequency, the difference in lifetime $\Delta\Gamma_s$ of the mass eigenstates, and the CP-violating phase ϕ_s. The phase ϕ_s is predicted to be small in the Standard Model (SM) but new physics could introduce (large) CP-violation in the B_s system. Observation of a sizable value of ϕ_s would therefore be an definite sign of physics beyond the standard model. The lifetime difference $\Delta\Gamma_s$ is related to ϕ_s: $\Delta\Gamma_s = \Delta\Gamma_s^{\rm SM} \times [\cos(\phi_s^{SM} + \phi_s^{NP})]$. The SM prediction is $\Delta\Gamma_s^{\rm SM} = 0.096 \pm 0.039$ [2], but a large CP violating phase would lower this value, making the measurement of $\Delta\Gamma_s$ another important probe for new physics.

3.1 Charge Asymmetry measurements

CP-violation in B_s mixing could give rise to a charge asymmetry in (semileptonically) decaying B_s mesons:

$$A_{SL}^s = \tan(\phi_s)\frac{\Delta\Gamma_s}{\Delta m_s}. \tag{1}$$

D0 obtains a first handle on the on the change asymmetry in B_s decays from a measurement of the same-sign dimuon charge asymmetry:

$$A_{SL}^{\mu u} = \frac{N(bb \to \mu^+\mu^+) - N(bb \to \mu^-\mu^-)}{N(bb \to \mu^+\mu^+) + N(bb \to \mu^-\mu^-)}. \tag{2}$$

Here, one of the muon tags the initial flavor of the B meson, while the other μ reveals the flavor at decay. A net positive (negative) asymmetry would imply that the $B^0 \to \bar{B}^0$ transition (yielding $\mu^+\mu^+$) occurs more (less) often than the charge conjugate process: a clear violation of CP. Using a sample of $\sim 310,000$ dimuon pairs, D0 obtains: $A_{SL}^{\mu\mu} = -0.0092 \pm 0.0044(\mathrm{stat}) \pm 0.0032(\mathrm{syst})$[3]. This asymmetry has contributions from both neutral B mesons: B_d and B_s. Using world average values for B_d and B_s production fractions and the B_d^0 charge asymmetry measurements from the B-factories, the charge asymmetry in B_s mixing is extracted [6] as:

$$A_{SL}^{\mu\mu,B_s} = -0.0064 \pm 0.0101(\mathrm{stat} + \mathrm{syst}). \tag{3}$$

In another measurement[4], D0 have directly measured the untagged charge asymmetry in a sample of reconstructed B_s decays into μD_s, with $D_s \to \phi\pi$ and $\phi \to K^+K^-$. Assuming equal cross-sections for the production of B_s and $\bar{B}_s$, they find:

$$A_{SL}^{\mu D_s} = \frac{N(\mu^+ D_s^-) - N(\mu^- D_s^+)}{N(\mu^+ D_s^-) + N(\mu^- D_s^+)} = 0.0245 \pm 0.00193(\mathrm{stat}) \pm 0.0035(\mathrm{syst}). \tag{4}$$

In both asymmetry measurements, certain sources of systematic uncertainty are reduced by regular flipping of the magnetic fields in D0. The remaining systematic uncertainties in the two measurements are dominated by different effects and the overlap between the two samples is only $\sim 10\%$. The combination of the two results is straightforward and yields the best estimate of the charge asymmetry in semileptonic B_s decays:

$$A_{SL}^{s} = -0.0001 \pm 0.0090(\mathrm{stat} + \mathrm{syst}), \tag{5}$$

which is consistent with zero and with the SM prediction.

3.2 Lifetime difference of CP-violating phase.

The decay $B_s \to J/\psi\phi$, proceeding through the $b \to c\bar{c}s$ transition, gives rise to both CP-even and CP-odd final states, which can be separated in a simultaneous analysis of the time evolution and the distributions of three decay angles that convey the CP information.

D0 have performed this measurement using a sample containing $\sim 23,000$ untagged signal events [5]. Assuming no large CP-violation, as predicted by the SM, the mass eigenstates and the CP eigenstates coincide. Under this assumption, the fit yields:

$$\Delta\Gamma_s = \Delta\Gamma_{CP} = 0.12^{+0.08}_{-0.10} \pm 0.02(\mathrm{syst})\ \mathrm{ps}^{-1}, \tag{6}$$

in accordance with the SM prediction, with an older measurement from CDF [7], and with the value of $\Delta\Gamma_s$ obtained from the branching ratio $B_s \to D_s^{(*)} D_s^{(*)}$ [8].

In a more general fit to same data, ϕ_s is treated as a free parameter, allowing for possible CP-violation through contributions from new physics. In this case, the result is (up to a 4-fold ambiguity):

$$\Delta\Gamma_s = 0.17 \pm 0.09\mathrm{stat} \pm 0.02(\mathrm{syst})\ \mathrm{ps}^{-1}, \tag{7}$$

$$\phi_s = -0.79 \pm 0.56(\mathrm{stat})^{+0.14}_{-0.01}(\mathrm{syst}), \tag{8}$$

which constitutes the first direct measurement of the mixing phase.

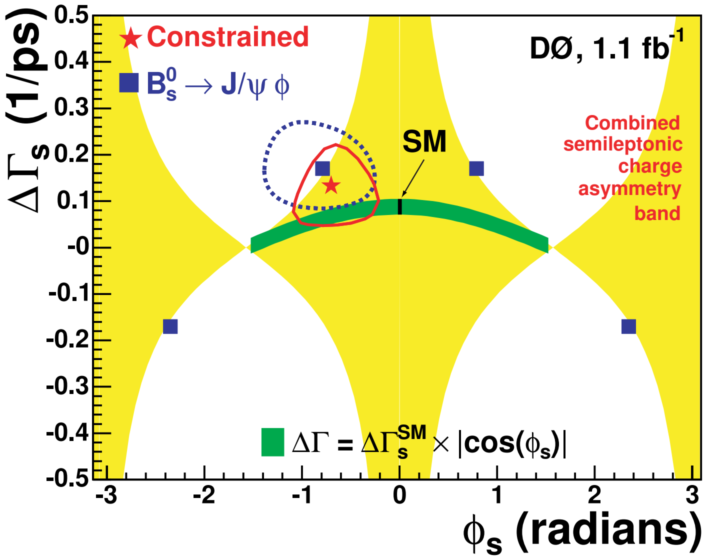

Figure 2: The ϕ_s vs $\Delta\Gamma_s$ plane, showing the four degenerate best fit values for the unconstrained fit to the $B_s \rightarrow J/\psi\phi$ data and the $\Delta \ln(\mathcal{L})$ error ellipse (blue, dashed) for one of the SM-like solutions. The combined semileptonic charge asymmetry band (yellow) shows the constraint from Eq. 1. The red star and error contour indicate the result with the constraint from the semileptonic charge asymmetry measurements and from the world average flavor specific lifetime. A band representing the relation $\Delta\Gamma_s = \Delta\Gamma_s^{SM} \times |\cos\phi_s|$ for SM allowed range of $\Delta\Gamma_s$ is shown in green.

3.3 Combination

Since Δm_s has been measured precisely (see next section), Eq. (1) can be used to constrain the measurement of $\Delta\Gamma_s$ and ϕ_s by using the charge asymmetry measurements.

Further constraints are provided by measurements of the B_s lifetime using flavor-specific decays, which are measured by fitting a single lifetime, $1/\Gamma_{\rm fs}$, to the decays. In case there are two components to the lifetime distribution (non-zero $\Delta\Gamma_s$), the fitted value of the flavor specific lifetime deviates form the average lifetime, $1/\bar{\Gamma}_s$ like $\Gamma_{\rm fs} = \bar{\Gamma}_s - (\Delta\Gamma_s)^2/2\bar{\Gamma}_s + \mathcal{O}(\Delta\Gamma_s)^3/\bar{\Gamma}_s^2$ [9]. The world average flavor specific lifetime [10] is thus used to further constrain the measurement of $\Delta\Gamma_s$ and ϕ_s.

Figure 2 shows the constrained and unconstrained results. The combined measurement yields $\Delta\Gamma_s = 0.13 \pm 0.09\ \mathrm{ps}^{-1}$, which is in good agreement with the SM prediction, and $\phi_s = -0.70^{+0.47}_{-0.39}$, which is consistent at the 1.8σ level with the SM prediction, $|\phi_{\rm SM}| = (4.2 \pm 1.4) \times 10^{-3}$.

4 B_s oscillations

Resolving the rapid oscillations between B_s and $\bar{B}_s$ and making a precise measurement of the oscillation frequency Δm_s have been important goals of the experiments at the Tevatron and elsewhere.

At Moriond 2006, D0 presented the first double sized bound on Δm_s, based on a sample of 27,000 $B_s \rightarrow \mu\nu_\mu D_s$ decays, with $D_s \rightarrow \phi\pi$. Since then, the analyses has been improved by including $D_s \rightarrow K^*K$ and $D_s \rightarrow K_sK$ and $B_s \rightarrow e\nu_e D_s$, with $D_s \rightarrow \phi\pi$, bringing the total signal yield to 42,000 semileptonically decaying B_s events.

CDF have used a sample of $\sim 62,000$ $B_s \rightarrow \mu\nu_\mu D_s$ and $e\nu_e D_s$ decays, collected using both leptonic and displaced track triggers. The latter also give access to a sample of 5600 fully reconstructed hadronic decays, $B_s \rightarrow D_s\pi$ and $B_s \rightarrow D_s\pi\pi\pi$, with $D_s \rightarrow \phi\pi$, K^*K or $\pi\pi\pi$. Another 3100 signal events are obtained in the channel $B_s \rightarrow D_s^*\pi$ and $B_s \rightarrow D_s\rho$, with

$D_s \to \phi\pi$. In these modes a low momentum π^0 or γ escapes detection.

4.1 Lifetime resolution

In order to resolve the rapid oscillations, an accurate determination of the decay time of the Bs mesons is crucial. The experiments use their silicon trackers to accurately determine the flight distance in the transverse plain L_T. The decay time is $t = L_T \times m_b / cP_T$, where m_b is the B_s mass and p_T is the transverse momentum of the B_s.

The semileptonic events, have an intrinsic p_T uncertainty due to the unobserved momentum of the neutrino. This translates in an uncertainty on the decay time, which is detrimental to the sensitivity for rapid oscillations (large Δm_s). For this reason, CDF's hadronic events are particularly valuable. Despite the relatively low number of events, they dominate in the signal. The average decay time resolution is about 87 (150) fs for CDF's hadronic (semileptonic) events and 160 fs in the D0 analysis. This should be compared to the B_s oscillation period of about 300 fs ($\Delta m_s = 18$ ps^{-1}).

4.2 Initial flavor tagging

While the flavor at decay is unambiguously identified from the decay products, the oscillation measurement also requires knowledge of the flavor at production. Opposite Side Taggers (OST) infer the B_s production flavor from the decay products of the other B hadron that results from the initially produced $b\bar{b}$ pair. Various OSTs measure the charge of leptons from semileptonically decaying B hadrons, of kaons resulting from the $b \to c \to s$ decay chain, or of the jet produced by the B hadron decay. CDF combines these OSTs using a neural network, while D0 uses a combination of jet charge and lepton tags.

In addition, CDF has developed a Same Side Kaon Tagger (SSKT). The idea behind this tagger is that an $s\bar{s}$ quark pair must be created in the hadronization of a b quark into a B_s. The remaining s quark will combine with a light quark into a kaon. The charge of the kaon identifies the production flavor of the B_s. CDF uses its Time-of-flight detector, a measurement of dE/dx in the central tracker, and kinematic variables to identify kaons in a cone around the B_s.

The performance of the flavor taggers is quantified by the efficiency ϵ and the dilution D , which is related to the wrong-tag probability w, $D \equiv 1 - 2w$. The effectiveness, ϵD^2 of the OSTs used in D0 and CDF is 2.5% and 1.8% respectively. CDF's SSKT has $\epsilon D^2 = 3.5\%$(hadronic) and 4.8%(semileptonic) and thus contributes most to the sensitivity of the CDF analysis.

4.3 Results

The most recent D0 amplitude scan is shown in Figure 3(left). The amplitude is consistent with unity around $\Delta m_s = 18$ ps^{-1}. A 90% C.L. double sided confidence bound is obtained: $17 < \Delta m_s < 21$ ps^{-1}. The probability for a random fluctuation to produce such a signal is about 8%, as estimated from Monte Carlo.

After having published a first result [11], CDF have upgraded their 1 fb^{-1} analysis [12]. The main improvements are the application neural networks for the signal selection and in the flavor taggers, and the inclusion of the partially reconstructed hadronic decays. The amplitude scan is shown in Figure 3(right). At its highest point, the amplitude is consistent with one and clearly incompatible with zero. The significance has been estimated from the data by randomizing the tagger decisions to create pseudo-experiments devoid of an oscillation signal. 28 out of 3.5×10^8 trials were more signal-like than the main result, giving the signal a significance of 5.4 σ. This signal allows for a precise measurement of Δm_s:

$$\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst}) \quad \text{ps}^{-1}, \tag{9}$$

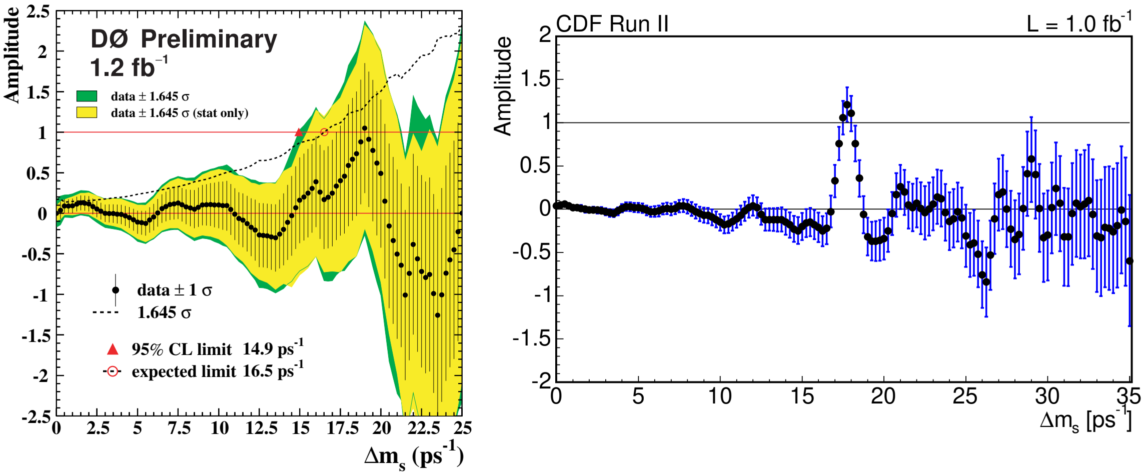

Figure 3: Amplitude scans for the B_s mixing results from D0 (left) and CDF (right). Around CDF's central value ($\Delta m_s = 17.77$), the mixing amplitude measured by both experiments is consistent with unity.

which is in good agreement with the SM expectation. This result has been used to determine the ratio of CKM matrix elements

$$\frac{|V_{td}|}{|V_{ts}|} = 0.2060 \pm 0.0007(\text{stat})^{+0.0081}_{-0.0060}(\text{theo} + \Delta m_d). \tag{10}$$

5 Conclusions

The Tevatron experiments are combing the B_s system for new physics. Both have seen $B_s\bar{B}_s$ oscillations and CDF has measured the mixing frequency with $\sim 1\%$ accuracy, using a signal with $> 5\sigma$ significance. The experiments have started to look for CP-violation in B_s mixing. D0 has made charge asymmetry measurements and performed the angular analysis of $B_s \to J/\psi\phi$ decays, resulting in the first precision measurement of $\Delta\Gamma_s$ and the first determination of the CP-violating phase ϕ_s. While based on only $\sim 50\%$ of the data currently on tape, these measurements already put powerful constraints on models of new physics (see the contribution of P. Ball to this conference). Significant improvements will be made as the Tevatron keeps producing data. In particular, the taggers developed for the B_s oscillation analysis will be used to perform a tagged measurement in $B_s \to J/\psi\phi$, improving the sensitivity to $\Delta\Gamma_s$ and ϕ.

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