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B Physics at the Tevatron

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Summary. — The Fermilab Tevatron offers unique opportunities to perform measurements of the heavier b-hadrons that are not accessible at the $\Upsilon(4S)$ resonance. In this summary, we describe most important heavy flavor results from DØ and CDF collaborations and we discuss prospects for future measurements, that could reveal New Physics before the start-up of the Large Hadron Collider (LHC).

PACS 13.20.He – Decays of bottom mesons.
PACS 13.25.Ft – Decays of charmed mesons.
PACS 13.30.Eg – Hadronic decays.

1. – B_s^0 Mixing

In the B_s^0 system, the mass eigenstates B_{sL}^0 and B_{sH}^0 are admixtures of the flavor eigenstates B_s^0 and $\overline{B}_s^0$. This causes oscillations between the B_s^0 and $\overline{B}_s^0$ states with a frequency proportional to the mass difference of the mass eigenstates, $\Delta m_s \equiv m_H - m_L$. In the Standard Model this effect is explained in terms of second-order weak processes involving virtual massive particles that provide a transition amplitude between the B_s^0 and $\overline{B}_s^0$ states. The magnitude of this mixing amplitude is proportional to the oscillation frequency, while its phase, responsible for CP violation in $B_s^0 \to J/\psi\phi$ decays, is $-2\beta_s^{SM} = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$ [1], where V_{ij} are the elements of the CKM quark mixing matrix. The presence of physics beyond the Standard Model could contribute additional processes and modify the magnitude or the phase of the mixing amplitude. The recent precise measurement of the oscillation frequency from CDF $\Delta M_s = 17.77 \pm 0.10$ (*stat.*)± 0.07 (*syst.*) ps^{-1} [2] indicates that contributions of New Physics to the magnitude, if any, are extremely small [3]. Global fits of experimental data tightly constrain the CP phase to small values in the context of the Standard Model, $2\beta_s^{SM} \approx 0.04$ [4]. However, New Physics may contribute significantly larger values [3, 5]. The observed CP phase can be expressed as $2\beta_s = 2\beta_s^{SM} - \phi_s^{NP}$, where ϕ_s^{NP} is due to the additional processes. The decay-width difference between the mass eigenstates, $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$, is also sensitive to the same New Physics phase. If $\phi_s^{NP} \gg 2\beta_s^{SM}$, we expect $\Delta\Gamma_s = 2|\Gamma_{12}|\cos(2\beta_s)$ [5], where $|\Gamma_{12}|$

is the off-diagonal element of the B_s^0-$\overline{B}_s^0$ decay matrix from the Schroedinger equation describing the time evolution of B_s^0 mesons [6].

Recent studies of $B_s^0 \to J/\psi\phi$ decays without identification of the initial flavor of the B_s^0 meson [6, 7] have provided information on $\Delta\Gamma_s$ and have some limited sensitivity to the CP phase.

Assuming CP conservation (a good approximation for the B_s^0 system in the Standard Model) CDF collaboration measured the mean lifetime, $\tau_s = 2/(\Gamma_L + \Gamma_H) = 1.52 \pm 0.04\ (stat.) \pm 0.02\ (syst.)$ ps, and the decay-width difference, $\Delta\Gamma_s = 0.076^{+0.059}_{-0.063}\ (stat.) \pm 0.006\ (syst.)$ ps^{-1} [6], of the light and heavy mass eigenstates, in $B_s^0 \to J/\psi\phi$ decays using 1.7 fb^{-1} of data. The measured value of $\Delta\Gamma_s$ agrees with the expected Standard Model value of 0.096 ps^{-1} [1]. Assuming CP violation, $2\beta_s$ free to vary in the fit, CDF collaboration obtained an agreement at 1.2 Gaussian standard deviations with respect to the SM expectation ($\Delta\Gamma_s \approx 0.1$ ps^{-1} and $2\beta_s \approx 0$).

With a similar analysis, using a data sample corresponding to an integrated luminosity of 1.1 fb^{-1}, DØ collaboration obtained a similar result. They measured $\Delta\Gamma_s = 0.17 \pm 0.09\ (stat.) \pm 0.02\ (syst.)$ ps^{-1} and the CP-violating phase $\phi_s = -2\beta_s = -0.79 \pm 0.56\ (stat.)^{+0.14}_{-0.01}\ (syst.)$ [7]. Under the hypothesis of no CP violation ($\phi_s \equiv 0$), DØ obtained $\tau_s = 1.52 \pm 0.08\ (stat.)^{+0.01}_{-0.03}\ (syst.)$ ps and $\Delta\Gamma_s = 0.12^{+0.08}_{-0.10} \pm 0.02$ ps^{-1} [7].

CDF reported also the first determination of bounds on the *CP*-violation parameter $2\beta_s$ using B_s^0 decays in which the flavor of the bottom meson at production is identified (flavor tagging). Such information is necessary to separate the time evolution of mesons produced as B_s^0 or $\overline{B}_s^0$. By relating this time development with the CP eigenvalue of the final states, which is accessible through the angular distributions of the J/ψ and ϕ mesons, it is possible to obtain direct sensitivity to the CP-violating phase. This CDF result is based on approximately 2000 $B_s^0 \to J/\psi\phi$ decays reconstructed in a 1.35 fb^{-1} data sample. Assuming the Standard Model predictions of $2\beta_s$ and $\Delta\Gamma_s$, the probability of a deviation as large as the level of the observed data is 15%, corresponding to 1.5 Gaussian standard deviations [8]. Treating $\Delta\Gamma_s$ as a nuisance parameter and fitting only for $2\beta_s$, CDF measured that $2\beta_s \in [0.32, 2.82]$ at the 68% confidence level [8].

An alternative way of accessing ϕ_s is through the relation $A^s_{SL} = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s$ where the semileptonic charge asymmetry is defined as [9]: $A^s_{SL} = \frac{N(\bar{B}_s^0 \to \ell^+ X) - N(B_s^0 \to \ell^- X)}{N(\bar{B}_s^0 \to \ell^+ X) + N(B_s^0 \to \ell^- X)}$. DØ collaboration measured A^s_{SL} directly by using all events with at least one muon that were consistent with the sequential decay $B_s^0 \to \mu\nu D_s$ with $D_s \to \phi\pi$ [10]: $A^s_{SL} = +0.0245 \pm 0.0193\ \ (stat.) \pm 0.0035\ \ (syst.)$, and by using the same-sign dimuon charge asymmetry [11] $A^s_{SL} = -0.0064 \pm 0.0101$ [10]. Their combination gives the best estimate of the charge asymmetry in semileptonic B_s^0 decays: $A^s_{SL} = 0.0001 \pm 0.0090$. DØ combined the measurement of the width difference between the light and heavy B_s^0 mass eigenstates and of the CP-violating mixing phase determined from the time-dependent angular distributions in the $B_s^0 \to J/\psi\phi$ decays along with the charge asymmetry in semileptonic decays. With the additional constraint from the world average of the flavor-specific B_s^0 lifetime, DØ obtained $\Delta\Gamma_s = 0.13 \pm 0.09$ ps^{-1} and $\phi_s = -0.70^{+0.47}_{-0.39}$.

In a very recent paper, UTfit collaboration combined all the available experimental information on B_s^0 mixing, including these very recent results from CDF and DØ collaborations [12]. The phase of the B_s^0 mixing amplitude deviates more than 3σ from the Standard Model prediction. While no single measurement has a 3σ significance yet, all the constraints show a remarkable agreement with the combined result. This is a first evidence of physics beyond the Standard Model. This result disfavours New Physics

models with Minimal Flavour Violation with the same significance.

CDF and DØ have analysed only a first part of data ($\approx 1.1 - 1.35$ fb^{-1}). They have on tape already ≈ 3 fb^{-1} and expect to collect a data sample of ≈ 6 fb^{-1} by the year 2010. The prospects for the near future are very interesting, CDF and DØ will probe soon this first evidence of New Physics measuring a more precise CP-violating phase.

2. – D^0 Mixing

In 2007 the first evidence of charm mixing was presented by the B-Factories [13, 14]. CDF also reported recently an evidence of charm mixing in an analysis of 1.5 fb^{-1} of data. Charm mixing is highly suppressed compared with that of the bottom and strange sectors because, since the charm is an up-type quark, top cannot participate in the mixing loop. CDF can exploit its large samples of charm mesons (3.044×10^6 "right-sign" $D^{\star +} \to D^0\pi^+ \to [K^-\pi^+]\pi^+$ and 12.7×10^3 "wrong-sign" $D^{\star +} \to D^0\pi^+ \to [K^+\pi^-]\pi^+$) making an analysis of such small mixing rate variable. The wrong-sign decays are the result of either D^0 mixing or doubly Cabibbo suppressed decays. The ratio of the wrong-sign to right-sign events as a function of D^0 decay time probes the charm sector mixing parameters x' and y': $R(t) = R_D + y'\sqrt{R_D}t + (x'^2 + y'^2)t^2/4$. CDF collaboration measured the time dependence of this ratio in a range of proper decay time between 0.75 and 10 mean D^0 lifetimes, obtaining the mixing parameters to be $R_D = (3.04 \pm 0.55) \times 10^{-3}$, $y' = (8.5 \pm 7.6) \times 10^{-3}$, and $x'^2 = (-0.12 \pm 0.35) \times 10^{-3}$ [15]. CDF also reported Bayesian probability contours in the $x'^2 - y'$ plane finding that the data are inconsistent with the no-mixing hypothesis with a probability equivalent to 3.8 Gaussian standard deviations [15] in agreement with B-Factories results.

The prospects for the future are very promising, CDF will collect ≈ 6 fb^{-1} by the year 2010 and could observe for the first time the D^0 oscillations.

3. – Search for the rare $B^0_{(s)} \to \mu^+\mu^-$ decays

Processes involving flavor-changing neutral currents (FCNCs) provide excellent signatures with which to search for evidence of New Physics since they have small branching fractions in the Standard Model (SM), while New Physics contributions can provide a significant enhancement. The FCNC decays $B^0_s(B^0) \to \mu^+\mu^-$ occur in the SM only through higher order diagrams and are further suppressed by the helicity factor, $(m_\mu/m_B)^2$. The B^0 decay is also suppressed with respect to the B^0_s decay by the ratio of CKM elements, $|V_{td}/V_{ts}|^2$. The SM expectations for these branching fractions are $\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.42 \pm 0.54) \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.00 \pm 0.14) \times 10^{-10}$ [16].

Enhancements to $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ occur in many New Physics models. In general, the search for these rare decays is central to exploring a large class of New Physics models [17, 18, 19, 20, 21].

Both CDF and DØ collaborations have performed a search for $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using 2 fb^{-1} of integrated luminosity. The observed number of B^0_s and B^0 candidates is consistent with background expectations in both experiments. The resulting upper limits on the branching fractions are $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 5.8 \times 10^{-8}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.8 \times 10^{-8}$ at 95% C.L. for CDF [22] and $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 9.3 \times 10^{-8}$ at 95% C.L. for DØ [23].

Tevatron experiments observe no evidence for New Physics and set limits that are the most stringent to date. These limits place further constraints on new-physics models [17,

18, 19, 20, 21], and complement direct searches for New Physics. We expect the analysis sensitivity to continue to improve as we include larger data sets.

4. – Measurements of $B^0_{(s)} \to h^+h^{'-}$ decays

CDF experiment analysed an integrated luminosity of 1 fb^{-1} sample of pairs of oppositely-charged particles and reconstructed a sample of 14500 $B^0_{(s)} \to h^+h^{'-}$ decay modes (where $h = K$ or π) after the off-line confirmation of trigger requirements. In the off-line analysis, the selection cuts was aimed to minimize the expected uncertainty of the physics observables to be measured (through several "pseudo-experiments"). Two different sets of cuts have been used, respectively optimized to measure the CP asymmetry $\mathcal{A}_{\rm CP}(B^0 \to K^+\pi^-)$ and to improve the sensitivity for discovery and limit setting [24] of the not yet observed $B^0_s \to K^-\pi^+$ mode. The resolution in invariant mass and in particle identification (dE/dx) is not sufficient for separating the individual $B^0_{(s)} \to h^+h^{'-}$ decay modes on an event-by-event basis, therefore a maximum likelihood fit was performed. This combines kinematic and particle identification information to statistically determine both the contribution of each mode, and the relative contributions to the CP asymmetries. Significant signals are seen for $B^0 \to \pi^+\pi^-$, $B^0 \to K^+\pi^-$, and $B^0_s \to K^+K^-$ previously observed by CDF [25]. Three new rare modes were observed for the first time $B^0_s \to K^-\pi^+$, $\Lambda^0_b \to p\pi^-$ and $\Lambda^0_b \to pK^-$, with a significance respectively of 8.2σ, 6.0σ and 11.5σ. No evidence was obtained for $B^0_s \to \pi^+\pi^-$or $B^0 \to K^+K^-$ mode.

The branching fraction of the newly observed mode $\mathcal{B}(B^0_s \to K^-\pi^+) = (5.0 \pm 0.75 \pm 1.0) \times 10^{-6}$ [26] is in agreement with the latest theoretical expectation [27], which is lower than the previous predictions [28, 29]. For the first time CDF measured in the B^0_s meson system the direct CP asymmetry $\mathcal{A}_{\rm CP}(B^0_s \to K^-\pi^+) = 0.39 \pm 0.15 \pm 0.08$ [26]. This value favors a large CP violation in B^0_s meson decays, although it is also compatible with zero. In Refs. [30, 31] a robust test of the Standard Model or a probe of New Physics is suggested by comparison of the direct CP asymmetries in $B^0_s \to K^-\pi^+$ and $B^0 \to K^+\pi^-$ decays. Using HFAG input [32] CDF collaboration measured for the first time $\frac{\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(B^0_s \to K^-\pi^+) - \Gamma(\overline{B}^0_s \to K^+\pi^-)} = 0.84 \pm 0.42 \pm 0.15$ [26], in agreement with the Standard Model expectation of unity. The branching fraction $\mathcal{B}(B^0_s \to K^+K^-) = (24.4 \pm 1.4 \pm 4.6) \times 10^{-6}$ [26] is in agreement with the latest theoretical expectation [33, 34] and with the previous CDF measurement [25]. The results for the B^0 are in agreement with world–average values [32]. $\mathcal{A}_{\rm CP}(B^0 \to K^+\pi^-) = -0.086 \pm 0.023 \pm 0.009$ is competitive with the current B-Factories measurements.
CDF collaboration also quoted for the first time $\mathcal{B}(\Lambda^0_b \to p\pi^-) = (3.1 \pm 0.6 \pm 0.7) \times 10^{-6}$ and $\mathcal{B}(\Lambda^0_b \to pK^-) = (5.0 \pm 0.7 \pm 1.0) \times 10^{-6}$ [35] in agreement with theoretical prediction in [36].

With full Run II samples (6 fb^{-1} by year 2010) CDF expects a measurement of $\mathcal{A}_{\rm CP}$ in $B^0 \to K^+\pi^-$ with a statistical plus systematic uncertainty at 1% level; 5-sigma observation of direct $\mathcal{A}_{\rm CP}$ in $B^0_s \to K^-\pi^+$ (or alternatively the possible indication of non-SM sources of CP violation); more precise measurement of $\mathcal{A}_{\rm CP}$ in Λ^0_b charmless decays; and improved limits, or even observation, of annihilation modes $B^0_s \to \pi^+\pi^-$ and $B^0 \to K^+K^-$. In addition to the above, time-dependent measurements will be performed for $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decay [37].

5. – γ from $B \to DK$ decays

The partial widths of $B^- \to D^0 K^-$ modes allow a theoretically-clean extraction of the CKM angle $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ by a variety of methods, depending on the specific D^0 decay channel involved [38, 39, 40, 41, 42]. The precision of current experimental data [32] is still far from theoretical uncertainties and is statistics–limited, so the current limited knowledge of γ can be significantly improved by the addition of further data. All mentioned methods for extracting γ from $B^- \to D^0 K^-$ modes require no tagging or time-dependent measurements, and many of them only involve charged particles in the final state. They are therefore particularly well–suited to analysis in a hadronic collider environment, where the large production can be well exploited.

CDF collaboration reconstructed modes where the D^0 decays in either $K^-\pi^+$ (flavor eigenstate) or $K^-K^+, \pi^-\pi^+$ (CP-even eigenstate), in a sample of about 1 fb^{-1} of CDF data. With a similar analysis of $B^0_{(s)} \to h^+h'^-$ decays CDF measured the direct CP asymmetry [43]: $A_{CP+} = 0.37 \pm 0.14(stat.) \pm 0.04(syst.)$ and the double ratio of the branching fractions: $R_{CP+} = \frac{R_+}{R} = 1.57 \pm 0.24(stat.) \pm 0.12(syst.)$ ([1]) in agreement with previous measurements from other experiments [32]. This is the first measurement of these quantities to be performed at a hadron collider.

For the search of $B^0_s \to D^\mp_s K^\pm$ mode CDF collaboration used an unbinned maximum likelihood fit which combines the kinematic and particle identification information.With a data sample of integrated luminosity of 1.2 fb^{-1} CDF observed for the first time $B^0_s \to D^\mp_s K^\pm$ decays, with a yield of 109 ± 19 events corresponding to a statistical significance of 7.9σ, and measured its branching fraction normalized to $B^0_s \to D^-_s \pi^+$ mode $\frac{\mathcal{B}(B^0_s \to D^\mp_s K^\pm)}{\mathcal{B}(B^0_s \to D^-_s \pi^+)} = 0.107 \pm 0.019\ (stat.)\ \pm 0.007\ (syst.)$ [44]. This is the initial step for a possible time-dependent asymmetry measurement with full Run II statistics.

6. – New states

The latest of several observations of new b bound states (after Λ^0_b, B_c, $\Sigma^\pm_b$, B^*, B^{**0}) is that of the Ξ^-_b baryon in its decay to $J/\psi\Xi^-$ (with $J/\psi \to \mu^+\mu^-$ and $\Xi^- \to \Lambda^0\pi^-$) from the DØ and CDF collaborations [45, 46]. With a data sample of 1.3 fb^{-1} DØ observed for the first time $15 \pm 4.4\ (stat.)\ ^{+1.9}_{-0.4}\ (syst.)$ Ξ^-_b candidates at a mass of $5.774 \pm 0.011\ (stat.) \pm 0.015$ GeV$/c^2$ with a significance of 5.5σ. By normalizing to the decay $\Lambda^0_b \to J/\psi\Lambda^0$, DØ measured the relative rate $\frac{\sigma(\Xi^-_b) \times \mathcal{B}(\Xi^-_b \to J/\psi\Xi^-)}{\sigma(\Lambda^0_b) \times \mathcal{B}(\Lambda^0_b \to J/\psi\Lambda^0)} = 0.28 \pm 0.09\ (stat.)^{+0.09}_{-0.08}\ (syst.)$. CDF collaboration, with 1.9 fb^{-1} of data collected, observed 17.5 ± 4.3 Ξ^-_b candidates at a mass of $5792.9 \pm 2.5\ (stat.) \pm 1.7$ MeV$/c^2$ with a significance of 7.7σ.

Heavy quark states provide an interesting laboratory for testing various approaches to the non-perturbative regime of QCD. The Tevatron experiments have made large effort to improve our knowledge of the b-hadrons.

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