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B physics at the Tevatron

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Summary. — The CDF and DØ experiments at the Tevatron $p\bar{p}$ collider established that extensive and detailed exploration of the b-quark dynamics is possible in hadron collisions, with results competitive and supplementary to those from e^+e^- colliders. This provides a rich, and highly rewarding program that is currently reaching full maturity. I report a few recent world-leading results on rare decays, CP-violation in B_s^0 mixing, $b \to s$ penguin decays, and charm physics.

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

1. – Introduction

Precise results from the successful B factory experiments disfavor large contributions from non-standard model (SM) physics in tree-dominated bottom meson decays. Agreement with the SM within theory uncertainties is also manifest in higher-order processes, such as K^0-$\bar{K}^0$ or B^0-$\bar{B}^0$ flavor mixing. The emerging picture confirms the Cabibbo-Kobayashi-Maskawa (CKM) framework as the leading pattern of flavor dynamics. Non-SM contributions, if any, are small corrections, or appear well beyond the TeV scale (and the LHC reach), or have an unnatural, highly fine-tuned flavor structure that escaped all experimental tests to date. The last chances to avoid such a disappointing impasse include the extensive study of the physics of the bottom-strange mesons, still fairly unexplored, along with a few rare B^0 decays, not fully probed at the B factories because of limited event statistics.

CDF and DØ experiments at the Tevatron are currently leading the exploration of this physics, owing to CP-symmetric initial states in $\sqrt{s} = 1.96\,\text{TeV}$ $p\bar{p}$ collisions, large event samples collected by well-understood detectors, and mature analysis techniques. CDF and DØ have currently collected more than $8\,\text{fb}^{-1}$ of physics-quality data. The sample size will reach $10\,\text{fb}^{-1}$ in October 2011.

In the following I report some recent, world-leading results, selected among those more sensitive to the presence of non-SM particles or couplings. Branching fractions indicate CP-averages, charge-conjugate decays are implied everywhere.

2. – Rare $B \to \mu^+\mu^-$ and $B \to h\mu^+\mu^-$ decays

Decays mediated by flavor changing neutral currents, such as $B^0_{(s)} \to \mu^+\mu^-$ or $B \to h\mu^+\mu^-$ are highly suppressed in the SM because they occur only through higher-order loop diagrams. Their phenomenology provide enhanced sensitivity to a broad class of non-SM contributions.

The $B^0_{(s)} \to \mu^+\mu^-$ rate is proportional to the CKM matrix element $|V_{td}|^2(|V_{ts}|^2)$, and is further suppressed by helicity factors. The SM expectations for these branching fractions are $\mathcal{O}(10^{-9})$, ten times smaller than the current experimental sensitivity. An observation of these decays at the Tevatron would unambiguously indicate physics beyond the SM. On the other hand, improved exclusion-limits strongly constrain the available space of parameters of several models of supersymmetry (SUSY). The latest CDF search for $B^0_{(s)} \to \mu^+\mu^-$ decays uses $3.7\,\text{fb}^{-1}$. The resulting 90 (95)% CL upper limits are $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 3.6(4.3) \times 10^{-8}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) < 6.0(7.6) \times 10^{-9}$ [1]. These results are the most stringent currently available and reduce significantly the allowed parameter space for a broad range of SUSY models. An update of this analysis with approximately double-sized sample will further improve them soon. The CDF expected 95% CL upper limit is $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 2 \times 10^{-8}$ [2], on a data sample corresponding to approximatively $7\,\text{fb}^{-1}$. DØ performed a similar analysis using a data sample of about $6.1\,\text{fb}^{-1}$. The resulting 90 (95)% CL upper limit is $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 4.2(5.1) \times 10^{-8}$ [3].

CDF also updated the analysis of $B^0 \to K^*(892)^0\mu^+\mu^-$, $B^+ \to K^+\mu^+\mu^-$, and $B^0_s \to \phi\mu^+\mu^-$ decays to $4.4\,\text{fb}^{-1}$ of data [4]. These are suppressed in the SM ($\mathcal{B} \approx 10^{-6}$), with amplitudes dominated by penguin and box $b \to s$ transitions. Despite the presence of final-state hadrons, accurate predictions greatly sensitive to non-SM contributions are possible for relative quantities based on angular-distributions of final state particles [5]. Prominent signals of 120 ± 16 $B^+ \to K^+\mu^+\mu^-$ and 101 ± 12 $B^0 \to K^{*0}\mu^+\mu^-$ events are observed. The absolute branching fractions, measured using the resonant decays as a reference, are $[0.38 \pm 0.05\ (\text{stat.}) \pm 0.03\ (\text{syst.})] \times 10^{-6}$ and $[1.06 \pm 0.14\ (\text{stat.}) \pm 0.09\ (\text{syst.})] \times 10^{-6}$, respectively, consistent and competitive with previous determinations [6]. In addition, 27 ± 6 $B^0_s \to \phi\mu^+\mu^-$ events are reconstructed, corresponding to the first observation of this decay, with a significance in excess of 6σ. The branching ratio, $[1.44 \pm 0.33\ (\text{stat.}) \pm 0.46\ (\text{syst.})] \times 10^{-5}$, is consistent with theoretical prediction, and corresponds to the rarest B^0_s decay ever observed to date.

3. – Measurement of the B^0_s mixing phase

Non-SM contributions have not yet been excluded in B^0_s-$\overline{B}^0_s$ mixing. Their magnitude is constrained to be small by the precise determination of the frequency [7]. However, knowledge of only the frequency leaves possible non-SM contributions to the unconstrained (CP-violating) mixing phase. The time evolution of flavor-tagged $B^0_s \to J/\psi\phi$ decays allows a determination of this phase largely free from theoretical uncertainties. These decays probe the phase-difference between the mixing and the $\bar{b} \to \bar{c}c\bar{s}$ quark-level transition, $\beta_s = \beta_s^{\text{SM}} + \beta_s^{\text{NP}}$, which equals $\beta_s^{\text{SM}} = \arg(-V_{ts}V^*_{tb}/V_{cs}V^*_{cb}) \approx 0.02$ in the SM and is extremely sensitive to non-SM physics in the mixing. A non-SM contribution (β_s^{NP}) would also enter $\phi_s = \phi_s^{\text{SM}} - 2\beta_s^{\text{NP}}$, which is the phase difference between direct decay and decay via mixing into final states common to B^0_s and $\overline{B}^0_s$, and is also tiny in the SM: $\phi_s^{\text{SM}} = \arg(-M_{12}/\Gamma_{12}) \approx 0.004$. Because the SM values for β_s and ϕ_s cannot be resolved with the precision of current experiments, the following approximation is used:

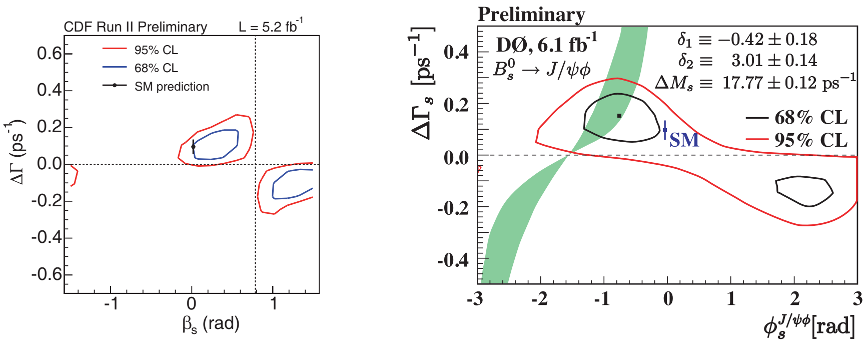

Fig. 1. – Confidence region in the $(\beta_s, \Delta\Gamma)$-plane for CDF (left panel), in the $(\phi_s, \Delta\Gamma)$-plane for DØ (right panel).

$\phi_s \approx -2\beta_s^{\mathrm{NP}} \approx -2\beta_s$, which holds in case of sizable non-SM contributions. Note that the phase ϕ_s also modifies the decay-width difference between light and heavy states, $\Delta\Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos(\phi_s)$, which enters in the $B_s^0 \to J/\psi\phi$ amplitude and equals $\Delta\Gamma^{\mathrm{SM}} \approx 2|\Gamma_{12}| = 0.086 \pm 0.025\,\mathrm{ps}^{-1}$ in the SM [8].

CDF and DØ updated the measurement of the time-evolution of flavor-tagged $B_s^0 \to J/\psi\phi$ decays respectively to a sample of $5.2\,\mathrm{fb}^{-1}$ and $6.1\,\mathrm{fb}^{-1}$ [9,10]. With phase floating the resulting allowed regions in the $(\beta_s, \Delta\Gamma_s)$-plane are shown in fig. 1. They are greatly reduced with respect to the previous measurements [11]. CDF is fairly consistent with the SM, at 0.8σ level with no external constraints. DØ reports a similar result, but using external inputs for strong phases $\delta_1 = -0.42 \pm 0.18$ and $\delta_2 = 3.01 \pm 0.14$ [6] and $\Delta M_s = 17.77 \pm 0.12\,\mathrm{ps}^{-1}$ [7].

The decay $B_s^0 \to J/\psi\phi$ has a mixture of the CP-even and -odd components in the final state and an angular analysis is needed to separate them. A sufficiently copious $B_s^0 \to J/\psi f_0(980)$ signal with $f_0(980) \to \pi^+\pi^-$, and tagged B_s^0 production flavor can be used to measure β_s without the need of an angular analysis as $J/\psi f_0(980)$ is a pure CP-odd final state. Further interest in the decay $B_s^0 \to J/\psi f_0(980)$ arises from the fact that it could contribute to an S-wave component in the $B_s^0 \to J/\psi K^+K^-$ decay if $f_0(980)$ decays to K^+K^-. CDF recently confirmed the observation of the $B_s^0 \to J/\psi f_0(980)$ decay from the LHCb and Belle experiments [12]. At present the observed signal is the world's largest and the measurement of the ratio of branching fractions between $B_s^0 \to J/\psi f_0(980)$ and $B_s^0 \to J/\psi\phi$ decays 0.257 ± 0.020 (stat.) $\pm\, 0.014$ (syst.) [13] is the the most precise. Using the world average $B_s^0 \to J/\psi\phi$ branching fraction [6] this can be converted into the product of branching fractions of $\mathcal{B}(B_s^0 \to J/\psi f_0(980))\mathcal{B}(f^0(980) \to \pi^+\pi^-) = (1.63 \pm 0.12 \pm 0.09 \pm 0.50) \times 10^{-4}$ [13] where the first uncertainty is statistical, the second is systematic and the third one is due to the uncertainty on branching fraction of normalization channels. The measurement presented here agrees well with the previous measurements of this quantity. CDF reports also the first determination of the lifetime of this decay mode $\tau = 1.70^{+0.12}_{-0.11}$ (stat.) $\pm\, 0.03$ (syst.) [13].

An alternative way of accessing ϕ_s is through the measurement of the asymmetry A_{sl}^b defined as $A_{sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$, where N_b^{++} and N_b^{--} represent the number of events containing two b hadrons decaying semileptonically and producing two positive or two negative muons, respectively. Measurements of A_{sl}^b or ϕ_q that differ significantly from the SM expectations would indicate the presence of new physics.

DØ analysed a data sample corresponding to an integrated luminosity of 6.1 fb^{-1} and measured the like-sign dimuon charge asymmetry of semileptonic b-hadron decays: $A^b_{sl} = -0.00957 \pm 0.00251$ (stat.) $\pm$ 0.00146 (syst.) [14], which is in disagreement with the prediction of the standard model by 3.2 standard deviations, as reported in fig. 1 by the band, which is a 68% CL contour.

4. – γ from $B \to DK$ decays

Conventionally, CP-violating observables are written in terms of the angles α, β and γ of the "Unitarity Triangle", obtained from one of the unitarity conditions of the CKM matrix. While the resolution on α and β reached a good level of precision, the measurement of γ is still limited by the smallness of the branching ratios involved in the processes. Among the various methods for the γ measurement, those which make use of the tree-level $B^- \to D^0 K^-$ decays have the smallest theoretical uncertainties [15-17]. In fact γ appears as the relative weak phase between two amplitudes, the favored $b \to c\bar{u}s$ transition of the $B^- \to D^0 K^-$, whose amplitude is proportional to $V_{cb}V_{us}$, and the color-suppressed $b \to u\bar{c}s$ transition of the $B^- \to \overline{D}^0 K^-$, whose amplitude is proportional to $V_{ub}V_{cs}$. The interference between D^0 and $\overline{D}^0$, decaying into the same final state, leads to measurable CP-violating effects, from which γ can be extracted. The effects can be also enhanced choosing the interfering amplitudes of the same order of magnitude. All methods require no tagging or time-dependent measurements, and many of them only involve charged particles in the final state. CDF reports the first results in hadron collisions for the ADS [15] and GLW [16] methods.

In a data sample of about 5 fb^{-1} CDF measures the following asymmetries: $A_{\text{ADS}}(K) = -0.63 \pm 0.40$ (stat.) ± 0.23 (syst.) and $A_{\text{ADS}}(\pi) = 0.22 \pm 0.18$ (stat.) ± 0.06 (syst.) [18]. For the ratios of doubly Cabibbo suppressed mode to flavor eigenstate CDF finds $R_{\text{ADS}}(K) = [22.5 \pm 8.4\text{ (stat.)} \pm 7.9\text{ (syst.)}] \cdot 10^{-3}$ and $R_{\text{ADS}}(\pi) = [4.1 \pm 0.8\text{ (stat.)} \pm 0.4\text{ (syst.)}] \cdot 10^{-3}$ [18]. These quantities are measured for the first time in hadron collisions. The results are in agreement with existing measurements performed at $\Upsilon(4S)$ resonance [19]. The results on GLW method from CDF can be found in ref. [20].

5. – Charm physics

While investigations of the K and B systems have and will continue to play a role in the understanding of flavor physics and CP violation, the D mesons sector have yet probed with a sufficient precision to explore the range of SM predictions. Since charm quark is the only up-type charged quark accessible to experiment though the D mesons, it provides the unique opportunity to probe flavor physics in this sector that is complementary to the one of down-type quarks. Examples of clean channels sensitive to possible sources of CP violation in the charm system are the singly-Cabibbo suppressed transitions such as $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$. Contributions to these decays from "penguin" amplitudes are negligible in the SM, thus the presence of new exotic particles may enhance the size of CP violation with respect to the SM expectation. Any asymmetry significantly larger than a few times 0.1% may unambiguously indicate NP contributions.

CDF recently measured the time-integrated CP asymmetry in the $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays using 5.94 fb^{-1} of data collected by the displaced track trigger. The final results, which are the most precise up to date, are $A_{CP}(D^0 \to \pi^+\pi^-) = [+0.22 \pm 0.24\text{ (stat.)} \pm 0.11\text{ (syst.)}]\%$ and $A_{CP}(D^0 \to K^+K^-) = [-0.24 \pm 0.22$ (stat.) $\pm$

0.10 (syst.)]% [21]. They are consistent with CP conservation and also with the SM predictions. As expressed by eq. (3) of ref. [21] the $A_{CP}(D^0 \to h^+h^-)$ measurement describes a straight line in the plane $(A_{CP}^{\text{ind}}, A_{CP}^{\text{dir}})$ with angular coefficient given by $\langle t \rangle/\tau$, t being the measured proper decay time of the D^0 candidates and τ the lifetime of the D^0 meson. Because of a threshold on the impact parameter of tracks, imposed at trigger level, the CDF sample of $D^0 \to \pi^+\pi^-$ ($D^0 \to K^+K^-$) decays is enriched in higher-valued proper decay time candidates with a mean value of $2.40(2.65) \pm 0.03$ (stat. + syst.) times the D^0 lifetime, as measured from a fit to the proper time distribution. Due to their unbiased acceptance in charm decay time, B factories samples have instead $\langle t \rangle \approx \tau$. Hence, the combination of the three measurements allow to constrain independently both A_{CP}^{dir} and A_{CP}^{ind} [21].

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