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CP violation in the B mesons at hadron colliders

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Summary. — CP violation measurements are a good way to test the validity of the Standard Model where CP violation phenomena are described by the CKM mechanism. A selection of recent measurements of CP violating observables in the decays of beauty hadrons performed at the hadronic colliders is presented.

PACS 11.30.Er – CP invariance.
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1. – Introduction

By measuring CP asymmetries in different processes, it is possible to set constraints on the CKM angles and to uncover possible contributions of new physics beyond the Standard Model. An interesting place to look for CP violation is the b hadron system. Precise and independent measurements which complement and improve the ones performed at the b-factories can be performed at hadronic colliders. In particular the two main hadronic colliders which are actively contributing to the experimental foundation of B meson physics are the Tevatron at Fermilab and the Large Hadron Collider (LHC) at CERN. The Tevatron, which has been shut down at the end of 2011, was a $p\bar{p}$ collider at an energy of $\sqrt{s} = 2\,\text{TeV}$ producing about $100\,\text{kHz}$ of $b\bar{b}$ pairs. The two experiments installed at Tevatron, CDF [1] and D0 [2], have been the first performing CP violation measurements in an hadronic environment. The Large Hadron Collider is currently the largest source of b-hadron ever built producing $3 \times 10^{11}\, b\bar{b}$ pairs per nominal year ($10^7\,\text{s}$) at an energy of $\sqrt{s} = 7\,\text{TeV}$ which are studied by the LHCb experiment [3].

2. – Charmless two-body decays

The study of charmless two-body decays is of fundamental importance since they are potentially sensitive to new physics beyond the Standard Model. The measurements of the direct CP violating asymmetries in $B^0 \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$ have been performed by the LHCb [4] and CDF [5] experiments. The LHCb analysis uses two different sets of criteria optimised for B^0 and B^0_s. The invariant mass distributions of

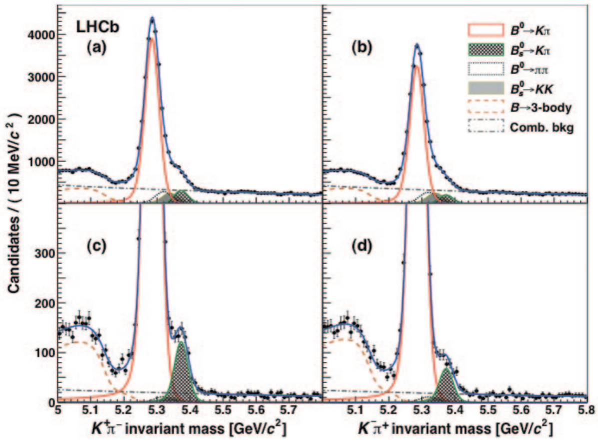

Fig. 1. – Invariant mass spectra of B^0 optimised selection candidates (top) and of B_s^0 (bottom).

the selected candidates are shown in fig. 1 where non-zero raw asymmetries are clearly visible. Instrumental asymmetries and production asymmetries have been estimated using control samples and corrected for. Using $1\,\text{fb}^{-1}$ of data LHCb measured

$$A_{CP}(B^0 \to K\pi) = -0.080 \pm 0.007(\text{stat}) \pm 0.003(\text{syst}), \tag{1}$$
$$A_{CP}(B_s^0 \to \pi K) = 0.27 \pm 0.04(\text{stat}) \pm 0.01(\text{syst}), \tag{2}$$

which with a significance of 6.5σ is the first observation of CP violation in the B_s^0 system.

CDF has also performed CP asymmetry measurement in the same channels using data corresponding to an integrated luminosity of $9.3\,\text{fb}^{-1}$. Since the initial $p\bar{p}$ state is symmetric, no production asymmetry has to be taken into account. Detector effects are corrected using charm control samples. CDF has obtained

$$A_{CP}(B^0 \to K\pi) = -0.083 \pm 0.013(\text{stat}) \pm 0.003(\text{syst}), \tag{3}$$
$$A_{CP}(B_s^0 \to \pi K) = 0.22 \pm 0.07(\text{stat}) \pm 0.02(\text{syst}). \tag{4}$$

The values obtained by CDF and LHCb are compatible. Moreover CDF has performed the measurement of CP asymmetries of b barions [5] $A_{CP}(\Lambda_b \to p\pi) = 0.07 \pm 0.07(\text{stat}) \pm 0.03(\text{syst})$ and $A_{CP}(\Lambda_b \to pK) = -0.09 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})$.

3. – Charmless three-body decays

Three-body charmless decays are of great interest since they offer the possibility to study CP violation in the interference patterns between two body resonances in the Dalitz plot. LHCb has performed a preliminary measurement of $B^+ \to K^+\pi^+\pi^-$, $B^+ \to K^+K^+K^-$, $B^+ \to K^+K^-\pi^+$ and $B^+ \to \pi^+\pi^-\pi^+$ using a sample of data corresponding to $1.0\,\text{fb}^{-1}$. All the considered three-body charmless decays are selected using a common kinematic selection. PID information is then used to separate final state particles. Raw asymmetries are corrected for production and detection asymmetries using $B^+ \to J/\psi K^+$ decays and samples of D^0 and D^{0*} as control channels. LHCb has measured [6, 7]

$$A_{CP}(KKK) = -0.046 \pm 0.009(\text{stat}) \pm 0.005(\text{syst}) \pm 0.007(J/\psi K) \quad [3.7\sigma], \tag{5}$$

$$A_{CP}(K\pi\pi) = 0.034 \pm 0.009(\text{stat}) \pm 0.004(\text{syst}) \pm 0.007(J/\psi K) \quad [2.8\sigma], \tag{6}$$

$$A_{CP}(\pi\pi\pi) = 0.120 \pm 0.020(\text{stat}) \pm 0.019(\text{syst}) \pm 0.007(J/\psi K) \quad [4.2\sigma], \tag{7}$$

$$A_{CP}(KK\pi) = -0.153 \pm 0.046(\text{stat}) \pm 0.019(\text{syst}) \pm 0.007(J/\psi K) \quad [3.0\sigma]. \tag{8}$$

The $A_{CP}(KKK)$ is the first evidence of an inclusive CP violation in charmless three-body decays. Distributions of CP asymmetries in the Dalitz plot have also been measured.

4. – Measurement of the Unitarity Triangle angle γ

The CKM angle $\gamma = \arg(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb})$ is the least well known parameter angle of the Unitarity Triangle. Several established methods to measure γ in tree decays exploit the $B^+ \to D^{(*)}K^{(*)+}$ decays. They are based on the interference between the $b \to u$ and $b \to c$ tree amplitudes, which arises when the neutral D meson is reconstructed in a final state accessible to both D^0 and $\bar{D}^0$ decays. The interference between the amplitudes results in observables which depend on their relative weak phase. At LHCb different analysis with different final states have been performed and in particular $D^0 \to \pi\pi/KK$ GLW and $D^0 \to K\pi$ ADS [8], $D^0 \to K3\pi$ ADS [9] and $D^0 \to K^0_s hh$ GGSZ [10]. The combination of all the $B^+ \to DK^+$ decay channels gives a value of $\gamma = (71.1^{+16.1}_{-15.2})^\circ$ [11].

5. – Semileptonic asymmetry

Studies of neutral B meson oscillations, whereby a neutral meson changes into its own antiparticle via a box-diagram-mediated weak interaction provide a sensitive probe for CPV processes. The semileptonic mixing asymmetry, defined as

$$a^q_{sl} = \frac{\bar{B}^0_q \to \mu^+ X - B^0_q \to \mu^- X}{\bar{B}^0_q \to \mu^+ X + B^0_q \to \mu^- X} = \frac{\Delta\Gamma_q}{\Delta M_q \tan(\phi_q)}$$

allows the effects of any CP-violating processes to be directly observed in terms of the resulting asymmetry of the decay products and it is related to the properties of the corresponding B meson system, namely the mass difference ΔM_q, the decay-width difference $\Delta\Gamma_q$, and the CP-violating phase ϕ_q. In the Standard Model, the semileptonic asymmetries in the $B^0\bar{B}^0$ and $B^0_s\bar{B}^0_s$ are predicted to be very small [12]. The experimental precision achieved so far on those asymmetries currently prevents any chance to directly measure them. Hence, the measurement of any significant deviation from zero will be an unambiguous signal of new physics. D0 has performed the measurement of a^d_{sl} using two separate decay channels $B^0 \to \mu^+\nu D^- X$ and $B^0 \to \mu^+\nu D^{*-} X$ and for a^s_{sl} $B^0 \to \mu^+\nu D^-_s X$ decay channel [13, 14]. LHCb has reported a preliminary measurement of a^s_{sl} using the same decay as D0 [15]. The D0 measured values are

$$a^s_{sl} = [-1.12 \pm 0.74(\text{stat}) \pm 0.17(\text{syst})]\%, \qquad a^d_{sl} = [0.68 \pm 0.45(\text{stat}) \pm 0.14(\text{syst})]\%. \tag{9}$$

Using $1\,\text{fb}^{-1}$ of data at an energy of $\sqrt{s} = 7\,\text{TeV}$, LHCb has measured

$$a^s_{sl} = [-0.24 \pm 0.54(\text{stat}) \pm 0.33(\text{syst})]\%. \tag{10}$$

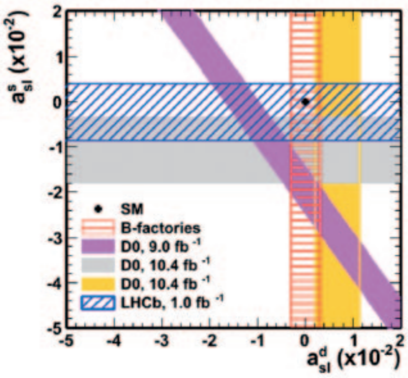

Fig. 2. – LHCb and D0 measured values of a^d_{sl} and a^s_{sl}. The $A_{\mu\mu}$ measured value is also reported. The Standard Model expected value is indicated with a black dot.

The two values agree and are also in good agreement with the Standard Model prediction. The D0 Collaboration, however, also reported a measurement of the asymmetry in the rate of like-sign muon pairs [16], $A_{\mu\mu} \sim 0.6 \cdot a^d_{sl} + 0.4 \cdot a^s_{sl}$, which yielded an anomalously large value (see fig. 2).

6. – Measurement of ϕ_s

The CP violating phase in B^0_s mixing, ϕ_s, appears in the interference between a direct decay to a final state and the decay to the same final state after an oscillation. The SM predicts a value of $\phi_s^{SM} = 0.036 \pm 0.002\,\mathrm{rad}$ [17]. The precise measurement of ϕ_s is interesting because new physics processes could modify its value if new particles were to contribute to the B^0_s-$\bar{B}^0_s$ box diagrams. CDF [18], D0 [19], ATLAS [20] and LHCb [21] have performed a measurement of ϕ_s where the most precise measurement is the one obtained by LHCb using both the $B^0_s \to J/\psi\phi$ and $B^0_s \to J/\psi\pi^-\pi^+$ channels. The fundamental ingredients to perform the time-dependent asymmetry measurement are an excellent time resolution in order to resolve the fast B^0_s-$\bar{B}^0_s$ oscillations and an efficient flavour tagging algorithm. The $B^0_s \to J/\psi\phi$ decay has the advantage to be experimentally clean exploiting the outstanding tracking and vertexing performances, that allow to reconstruct a narrow ϕ resonance peak and a pure and efficient B_s candidates selection. The disadvantage is that the final state is a mixture of CP odd and even components which have to be disentangled using an angular analysis. The $B^0_s \to J/\psi\pi^-\pi^+$ is instead dominated by the f_0 resonance, has a smaller branching fraction and the final state is a pure CP odd state [22] so no angular analysis is required. The combined fit gives

$$\phi_s = 0.01 \pm 0.07(\mathrm{stat}) \pm 0.01(\mathrm{syst})\ \mathrm{rad}, \tag{11}$$

$$\Gamma_s = 0.661 \pm 0.004(\mathrm{stat}) \pm 0.006(\mathrm{syst})\ \mathrm{ps}^{-1}, \tag{12}$$

$$\Delta\Gamma_s = 0.106 \pm 0.011(\mathrm{stat}) \pm 0.007(\mathrm{syst})\ \mathrm{ps}^{-1}, \tag{13}$$

which are the most precise values of ϕ_s, Γ_s and $\Delta\Gamma_s$ and they are consistent with the SM prediction.

7. – $B_s \to \phi\phi$

The first measurement of the CP-violating phase, ϕ_s in the $B_s^0 \to \phi\phi$ penguin decay has been performed at LHCb using $1\,\text{fb}^{-1}$ of data at an energy of $\sqrt{s} = 7\,\text{TeV}$ [23]. In the SM, ϕ_s is expected to be close to zero due to a cancellation of the phases arising from B_s^0-$\bar{B}_s^0$ oscillations and decay. A time dependent tagged angular analysis similar to the $B_s^0 \to J/\psi K^+K^-$ has been performed fitting the three helicity angles and decay time. A coverage of 68% C.L. gives $[-2.46, -0.76]$ rad. The precision of the ϕ_s measurement is dominated by the statistical uncertainty.

8. – Conclusions

Tevatron experiments have opened the way to the B meson study at hadronic colliders and have produced many interesting and precise measurements. The LHCb experiment is currently producing many first and world's best CP asymmetry measurements in many different B decays using only data collected in 2011 which corresponds to $1\,\text{fb}^{-1}$. In 2012 LHCb has collected $\sim 2\,\text{fb}^{-1}$ at an energy of $\sqrt{s} = 8\,\text{TeV}$ which have still to be analysed. New and updated results are expected soon.

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