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CP violation in $B \to DK$ decays at CDF

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Summary. — Measurements of branching fractions and CP asymmetries of $B^- \to D^0K^-$ modes allow to extract the CKM angle γ in a theoretically clean way. CDF recently performed, for the first time at a hadron collider, these measurements with the Cabibbo-suppressed $B^- \to [\pi\pi, KK]_D K^-$ mode and the doubly Cabibbo-suppressed $B^- \to [K^+\pi^-]_D K^-$ mode, obtaining competitive results with other experiments.

PACS 13.25.Hw – Decays of bottom mesons.
PACS 11.30.Er – Charge conjugation, parity, time reversal, and other discrete symmetries.
PACS 14.40.Nd – Bottom mesons ($|B| > 0$).

1. – Introduction

The CKM angle $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ is nowadays the least well-known angle of the CKM triangle [1]. Improving the experimental resolution on this angle is one of the challenging issue in B-physics. In fact, with the current statistical error on γ, several theoretical possibilities are allowed, either confirmations of the Standard Model predictions or New Physics scenarios [2, 3].

The cleanest way to extract γ makes use of tree level $B \to DK$ decays, for which very small theoretical uncertanties are predicted [4-6]. γ appears as the relative weak phase between two amplitudes, the favored $b \to c\bar{u}s$ transition of the $B^- \to D^0K^-$ and the color-suppressed $b \to u\bar{c}s$ transition of the $B^- \to \overline{D}^0K^-$. The interference between D^0 and $\overline{D}^0$, decaying into the same finale state, leads to measurable CP violation effects, from which γ can be extracted.

There are several methods to extract γ depending on D^0 modes used:

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– *GLW (Gronau-London-Wyler) method* [4, 7], which uses CP eigenstates of D^0, as $D^0_{CP+} \to K^+K^-$, $\pi^+\pi^-$ and $D^0_{CP-} \to K^0_s\pi^0$, $K^0_s\phi$, $K^0_s\omega$.

– *ADS (Atwood-Dunietz,-Soni) method* [5, 8], which uses the doubly Cabibbo-suppressed mode $D^0_{DCS} \to K^+\pi^-$.

– *GGSZ (or Dalitz) method* [6, 8], which uses three-body decays of D^0, as $D^0 \to K^0_s\pi^+\pi^-$.

All mentioned methods 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 hadron collider environment, where the large production of B mesons can be well exploited.

We will describe in more details the ADS and GLW methods, for which the CDF experiment performed the measurement for the first time at a hadron collider.

2. – CDF II detector and trigger

The CDF II detector [9] is a magnetic spectrometer surrounded by calorimeters and muon detectors. It provides a determination of the decay point of particles with $15\,\mu$m resolution in the transverse plane using six layers of double-sided silicon microstrip sensors at radii between 2.5 and 22 cm from the beam. A 96-layer drift chamber extending radially from 40 to 140 cm from the beam provides excellent momentum resolution, yielding approximately $8\,\text{MeV}/c^2$ mass resolution for two-body charm decays. A tree-level trigger system [10] selects events enriched in decays of long-lived particles by exploiting the presence of displaced tracks in the event and measuring their impact parameter with offline-like $30\,\mu$m resolution. The trigger requires the presence of two charged particles with transverse momenta greater than $2\,\text{GeV}/c$, impact parameters greater than $100\,\mu$m and basic cuts on azimuthal separation and scalar sum of momenta.

3. – The Atwood-Dunietz-Soni method

The ADS method [5, 8] takes into account the following decay channels:

$B^- \to D^0 K^-$	with	$D^0 \to K^+\pi^-$
color favored,		*doubly Cabibbo suppressed*
$B^- \to \overline{D}^0 K^-$	with	$\overline{D}^0 \to K^+\pi^-$
color suppressed,		*Cabibbo favored*

Since D^0 and $\overline{D}^0$ are undistinguishable, the interference between the two decaying amplitudes is measured and the final state $[K^+\pi^-]_D K^-$ is reconstructed. We expect to see large asymmetry effects, since the interfering amplitudes are of the same order of magnitude. For simplicity we will call "DCS" the final state $[K^+\pi^-]_D K^-$ and we will use the label $B \to D^0_{DCS}K$ to identify it.

We can measure the direct CP asymmetry:

$$A_{ADS} = \frac{\mathcal{BR}(B^- \to [K^+\pi^-]_D K^-) - \mathcal{BR}(B^+ \to [K^-\pi^+]_D K^+)}{\mathcal{BR}(B^- \to [K^+\pi^-]_D K^-) + \mathcal{BR}(B^+ \to [K^-\pi^+]_D K^+)}\,.$$

Written in terms of the decay amplitudes and phases:

$$A_{ADS} = \frac{2r_B r_D \sin\gamma \sin(\delta_B + \delta_D)}{r_D^2 + r_B^2 + 2r_D r_B \cos\gamma \cos(\delta_B + \delta_D)}\,,$$

where $r_B = |A(b \to u)/A(b \to c)|$, $\delta_B = arg[A(b \to u)/A(b \to c)]$ and r_D and δ_D are the corresponding amplitude ratio and strong phase difference of the D meson.

The denominator corresponds to another physical observable, the ratio between the DCS events and the Cabibbo-favored ("CF") events:

$$\begin{aligned} R_{ADS} &= r_D^2 + r_B^2 + 2r_D r_B \cos\gamma \cos(\delta_B + \delta_D) = \\ &= \frac{\mathcal{BR}(B^- \to [K^+\pi^-]_D K^-) + \mathcal{BR}(B^+ \to [K^-\pi^+]_D K^+)}{\mathcal{BR}(B^- \to [K^-\pi^+]_D K^-) + \mathcal{BR}(B^+ \to [K^+\pi^-]_D K^+)}\,, \end{aligned}$$

where CF events come from the following decay channel:

$$\begin{array}{ccc} B^- \to D^0 K^- & \text{with} & D^0 \to K^-\pi^+ \\ \textit{color favored}, & & \textit{Cabibbo favored} \end{array}$$

As for the DCS label, we will use the label CF to identify the final state $[K^-\pi^+]_D K^-$ and the decay $B \to D^0_{CF} K$.

We can measure the corresponding quantities, A_{ADS} and R_{ADS}, also for the $B^- \to D^0\pi^-$ mode, for which sizeable asymmetries may be found [1].

The invariant-mass distributions of CF and DCS modes, using a data sample of 5 fb^{-1} of data, with a nominal pion mass assignment to the track from B, are reported in fig. 1. An obvious $B \to D^0\pi$ CF signal is visible at the correct mass of about 5.279 GeV/c^2. Events from $B \to D^0 K$ decays are expected to form a much smaller and wider peak, located about 50 MeV/c^2 below the $B \to D^0\pi$ peak.

The $B \to D^0\pi$ and $B \to D^0 K$ DCS signals instead appear to be buried in the combinatorial background. For this reason an important issue of this analysis is the suppression of the combinatorial background, obtained through a cuts optimization focused on finding a signal of the $B \to D_{DCS}\pi$ mode. Since the $B \to D_{CF}\pi$ mode has the same topology of the DCS one, but more statistic, we did the optimization using the signal (S) and the background (B) directly from CF data, choosing a set of cuts which maximize the figure of merit $S/(1.5 + \sqrt{B})$ [11].

The *offline cut on the tridimensional vertex quality* χ^2_{3D} and the B *isolation* are powerful handles among the variables used in the optimization. The first exploit the 3D silicon-tracking to resolve multiple vertices along the beam direction and to reject fake tracks. It allows a background reduction by a factor of two and has small inefficiency on signal (less than 10%). The B isolation corresponds to the fraction of momentum carried by the B meson, which is usually greater than the momentum carried by lighter mesons. Another important cut is on the *decay lenght of the* D^0 *with respect to the* B, which allows to reject most of the $B \to hhh$ backgrounds, where h is either π or K. All variables and threshold values applied are described in [12].

The resulting invariant-mass distributions of CF and DCS modes are reported in fig. 2 where the combinatorial background is almost reduced to zero and an excess of events is now visible in the correct DCS signal mass window.

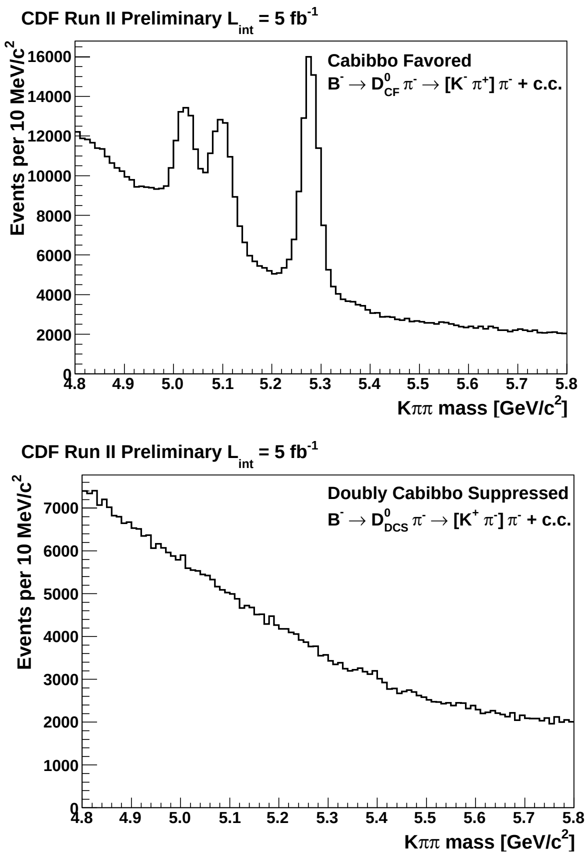

Fig. 1. – Invariant-mass distributions of $B \to D^0 h$ candidates for each reconstructed decay mode, Cabibbo favored on the top and doubly Cabibbo suppressed on the bottom. The pion mass is assigned to the track from the B decay.

An unbinned maximum-likelihood fit has been performed to separate the $B \to DK$ contributions from the $B \to D\pi$ signals and the combinatorial and physics backgrounds. Preliminary results can be found in [12].

4. – Gronau-London-Wiler method

In the GLW method [4, 7] the CP asymmetry of $B \to D^0_{CP\pm}K$ is studied, where $CP\pm$ are the CP even and odd eigenstates of the D^0, as $D^0_{CP+} \to K^+K^-$, $\pi^+\pi^-$ and $D^0_{CP-} \to K^0_s\pi^0$, $K^0_s\phi$, $K^0_s\omega$.

We can define four observables:

$$A_{CP\pm} = \frac{\mathcal{BR}(B^- \to D^0_{CP\pm}K^-) - \mathcal{BR}(B^+ \to D^0_{CP\pm}K^+)}{\mathcal{BR}(B^- \to D^0_{CP\pm}K^-) + \mathcal{BR}(B^+ \to D^0_{CP\pm}K^+)}$$

$$R_{CP\pm} = 2 \cdot \frac{\mathcal{BR}(B^- \to D^0_{CP\pm}K^-) + \mathcal{BR}(B^+ \to D^0_{CP\pm}K^+)}{\mathcal{BR}(B^- \to D^0_{CF}K^-) + \mathcal{BR}(B^+ \to \overline{D}^0_{CF}K^+)},$$

of which only three are independent (since $A_{CP+}R_{CP+} = -A_{CP-}R_{CP-}$).

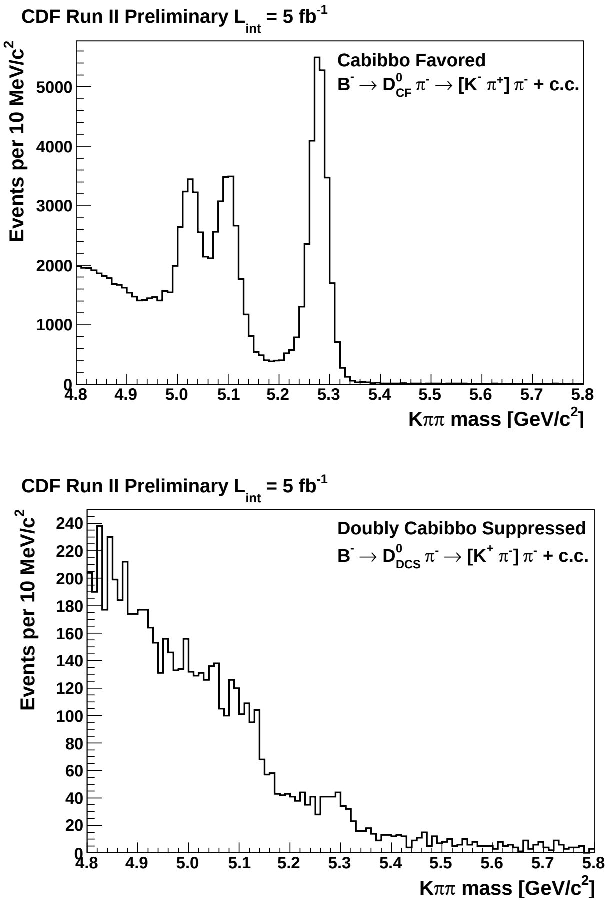

Fig. 2. – Invariant-mass distributions of $B \to D^0 h$ candidates for each reconstructed decay mode, Cabibbo favored on the top and doubly Cabibbo suppressed on the bottom, after the cuts optimization. The pion mass is assigned to the track from the B decay.

The relations with the amplitude ratios and phases are:

$$A_{CP\pm} = 2r_B \sin\delta_B \sin\gamma / R_{CP\pm},$$
$$R_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\gamma.$$

The GLW method is a very clean method, in fact for three independent observables we have three unknowns. Unfortunately the sensitivity to γ is proportional to r_B, so we expect to see small asymmetries.

CDF performed the first measurement of branching fraction and CP asymmetry of the $CP+$ modes at a hadron collider, using $1\,\text{fb}^{-1}$ of data [13].

The distributions obtained for the three modes of interest ($D^0 \to K\pi$, KK and $\pi\pi$) are reported in fig. 3; a clear $B \to D\pi$ signal can be seen in each plot.

The dominant backgrounds are combinatorial background and mis-reconstructed physics background such as $B^- \to D^{0*}\pi^-$ decay. In the $D^0 \to KK$ final state also

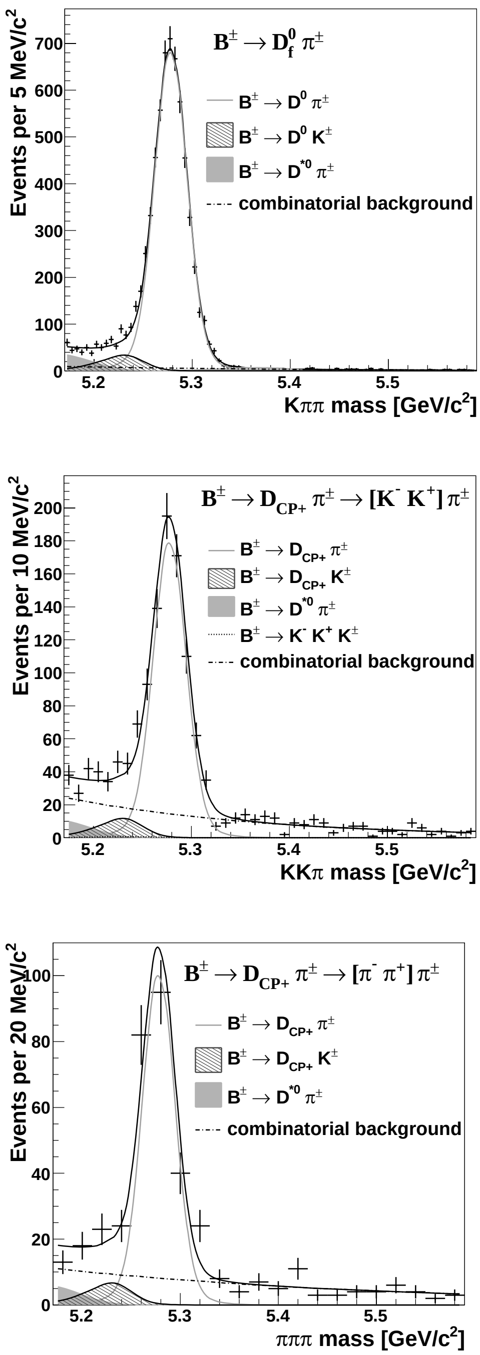

Fig. 3. – Invariant-mass distributions of $B \to D^0 h$ candidates for each reconstructed decay mode, Cabibbo favored on the top, Cabibbo-suppressed KK in the middle and Cabibbo-suppressed $\pi\pi$ on the bottom. The pion mass is assigned to the track from the B decay. The projections of the likelihood fit are overlaid for each mode.

the non resonant $B \to KKK$ decay appears, as determined by a study on CDF simulation [14].

An unbinned maximum-likelihood fit, exploiting kinematic and particle identification information provided by the $\mathrm{d}E/\mathrm{d}x$, is performed to statistically separate the $B \to D^0K$ contributions from the $B \to D^0\pi$ signals and from the combinatorial and physics backgrounds.

We obtained about 90 $B \to D^0_{CP+}K$ events and we measured the double ratio of CP-even to flavor eigenstate branching fractions

$$R_{CP+} = 1.30 \pm 0.24(\mathrm{stat}) \pm 0.12(\mathrm{syst})$$

and the direct CP asymmetry

$$A_{CP+} = 0.39 \pm 0.17(\mathrm{stat}) \pm 0.04(\mathrm{syst})$$

These results are in agreement with previous measurements from $\Upsilon(4S)$ decays [1].

5. – Conclusions

The CDF experiment has a global program to measure the γ angle from tree-dominated processes. The published result using the GLW method and the preliminary result using the ADS method show competitive results with previous measurements performed at B-factories. With these results the feasibility of these kinds of measurements also at a hadron collider has been demonstrated.

We expect to double the data-set available by the end of the next year and to obtain interesting and more competitive results in the near future.

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