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First ADS analysis of $B^- \to D^0 K^-$ decays in hadron collisions

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Measurements of branching fractions and CP-asymmetries of $B^- \to D^0 K^-$ modes allow a theoretically-clean extraction of the CKM angle γ. The method proposed by Atwood, Dunietz and Soni (ADS) makes use of a decay chain where color and Cabibbo suppression interfere, which produces large CP-violating asymmetries. The CDF experiment reports the first measurement at a hadron collider of branching fractions and CP-asymmetries of suppressed $B^- \to D^0 h^-$ signals, where h is π or K. Using 5.0 fb^{-1} of data we found a combined significance exceeding 5σ and we determined the ADS parameters with accuracy comparable with B-factories.

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PoS(BEAUTY 2011)019

1. Introduction

The measurement of the CKM matrix elements plays a central role both to test the Standard Model consistency and to probe New Physics scenarios. The complex phase of the CKM matrix leads to *CP* violation in weak processes. Observables are written in terms of the angles α, β and γ of the "Unitarity Triangle", obtained from the unitarity condition of the CKM matrix [1]. While the resolutions on α and β reached a good level of precision, the measurement of $\gamma = arg(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb})$ is still limited by the smallness of the branching ratios involved in the processes and its uncertainty varies between 11 and 25 degrees, depending on the method used to combine the experimental results [2, 3, 4].

Among the various methods for the γ measurement, those which make use of the tree-level dominated $B^- \to DK^-$ decays (where D labels either D^0 or $\overline{D}^0$ mesons) have the smallest theoretical uncertanties [6, 7, 8]. In fact γ appears as the relative weak phase between two amplitudes, the favored $b \to c\bar{u}s$ of the $B^- \to D^0K^-$ (whose amplitude is proportional to $V_{cb}V_{us}$) and the color-suppressed $b \to u\bar{c}s$ of the $B^- \to \overline{D}^0K^-$ (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 a measurable *CP*-violating effect.

According to the final state of the *D*, we have the following methods *GLW (Gronau-London-Wyler) method* [6, 9], 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* [7, 10], which uses the doubly Cabibbo suppressed mode $D^0 \to K^+\pi^-$ and *GGSZ (or Dalitz) method* [8, 10], 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 exploited. The use of a specialized trigger based on online detection of a secondary vertex (SVT trigger [11]) allows the selection of pure *B* meson samples.

We will describe in more details the ADS and GLW methods, for which CDF reports the first results in hadron collisions.

2. The Atwood-Dunietz-Soni method

In the ADS method [7, 10] the interference between these two decay channels is studied: $B^- \to D^0K^-$ (*color favored*), with $D^0 \to K^+\pi^-$ (*doubly Cabibbo suppressed*) and $B^- \to \overline{D}^0K^-$ (*color suppressed*), with $\overline{D}^0 \to K^+\pi^-$ (*Cabibbo favored*). Since D^0 and $\overline{D}^0$ are indistinguishable, the final state $[K^+\pi^-]_DK^-$ is reconstructed and the direct *CP* asymmetry can be measured. For simplicity we will call "suppressed" (*sup*) this final state. The interfering amplitudes are of the same order of magnitude, so large asymmetry effects are expected.

The direct CP asymmetry

$$A_{ADS} = \frac{\mathscr{B}(B^- \to [K^+\pi^-]_DK^-) - \mathscr{B}(B^+ \to [K^-\pi^+]_DK^+)}{\mathscr{B}(B^- \to [K^+\pi^-]_DK^-) + \mathscr{B}(B^+ \to [K^-\pi^+]_DK^+)}$$

can be written in terms of the decay amplitudes and phases $A_{ADS} = \dfrac{2r_B r_D \sin\gamma \sin(\delta_B + \delta_D)}{r_D^2 + r_B^2 + 2r_D r_B \cos\gamma \cos(\delta_B + \delta_D)}$, 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 suppressed and favored (*fav*) events, the latter coming from the decay channel $B^- \to D^0 K^-$ (*color favored*), with $D^0 \to K^-\pi^+$ (*Cabibbo favored*): $R_{ADS} = r_D^2 + r_B^2 + 2r_D r_B \cos\gamma \cos(\delta_B + \delta_D)$

$$R_{ADS} = \frac{\mathscr{B}(B^- \to [K^+\pi^-]_D K^-) + \mathscr{B}(B^+ \to [K^-\pi^+]_D K^+)}{\mathscr{B}(B^- \to [K^-\pi^+]_D K^-) + \mathscr{B}(B^+ \to [K^+\pi^-]_D K^+)}.$$

We can measure the corresponding quantities, A_{ADS} and R_{ADS}, also for the $B^- \to D\pi^-$ mode, for which sizeable asymmetries may be found [2].

The invariant mass distributions of the favored and suppressed modes, using a sample of 5 fb^{-1} of data, with a nominal pion mass assignment to the track from the B meson decay, are reported in Fig. 1.

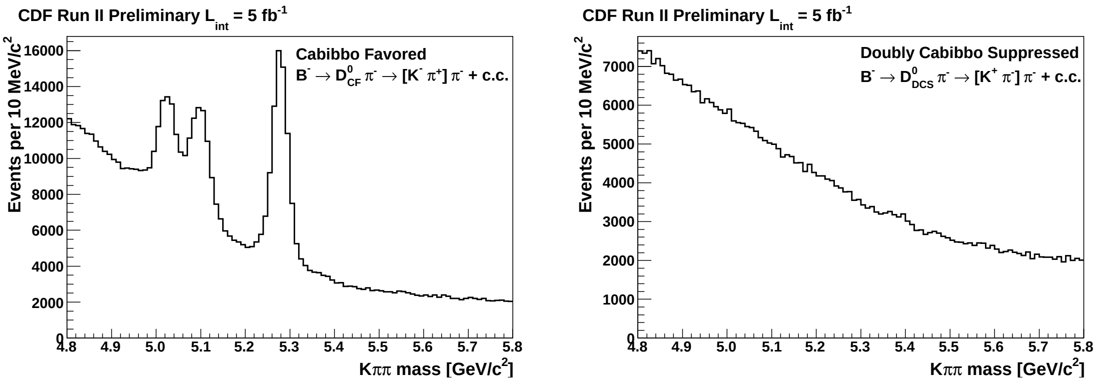

Figure 1: Invariant mass distributions of $B^- \to Dh^-$ (h is π or K) candidates for each reconstructed decay mode, favored on the left and suppressed on the right.

A $B^- \to D\pi^-$ favored signal is visible at the correct mass of about 5.279 GeV$/c^2$. Events from $B^- \to DK^-$ decays are expected to cluster in smaller and wider peaks, located about 50 MeV$/c^2$ below the $B^- \to D\pi^-$ peak. The $B^- \to D\pi^-$ and $B^- \to DK^-$ suppressed signals appear to be buried in the combinatorial background. Suppression of the combinatorial background is obtained through a cut optimization focused on finding a signal of the $B^- \to D_{sup}\pi^-$ mode. Since the $B^- \to D_{fav}\pi^-$ mode has the same topology of the suppressed one, but more statistics, we did the optimization using signal (S) and background (B) directly from favored data, choosing a set of cuts which maximize the figure of merit $S/(1.5 + \sqrt{B})$ [12].

Several variables have been chosen to select signal from background [13], the most important being the *offline cut on the three-dimensional vertex quality* χ^2_{3D}, which exploits the 3D silicon-tracking to resolve multiple vertices along the beam direction and to reject fake tracks, and the *B isolation*. Another important cut is also the *decay length of the D with respect to the B*, which allows rejection of most of the $B^- \to hhh$ backgrounds, where h is either the charged π or K. All variables and threshold values applied are described in [13]. The resulting invariant mass distributions of favored and suppressed modes are reported in Fig. 2 where the combinatorial background is almost reduced in the B^- mass region, allowing a signal to be seen.

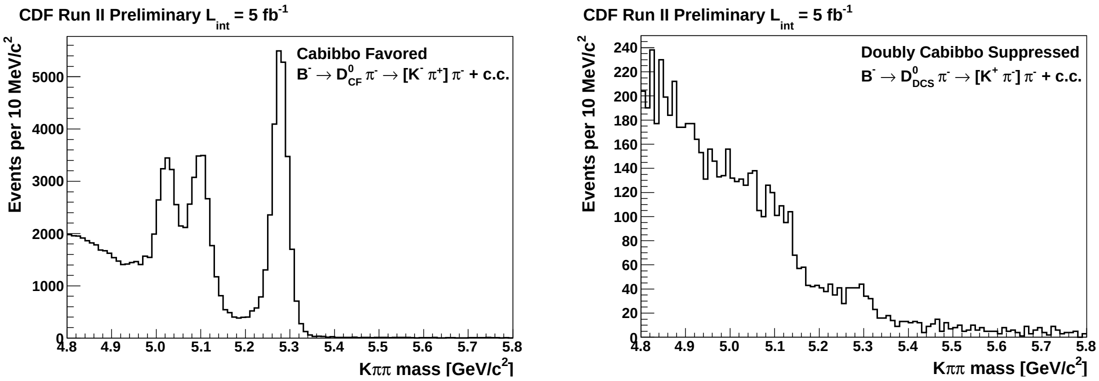

Figure 2: Invariant mass distributions of $B^- \to Dh^-$ candidates for each reconstructed decay mode, favored on the left and suppressed on the right, after the cuts optimization.

An unbinned likelihood fit, exploiting mass and particle identification information is performed [13] on both favored and suppressed samples, to separate the $B^- \to DK^-$ contributions from the $B^- \to D\pi^-$ signals and the combinatorial and physics backgrounds. The particle identification information is provided by the specific ionization (dE/dx) of the CDF drift chamber which allows a π/K separation of about 1.5σ. The dominant physics backgrounds for the suppressed mode are the inclusive $B^- \to D^0\pi^-$, with $D^0 \to X$ (where X are modes other than $K\pi$); $B^- \to D^0K^-$, with $D^0 \to X$; $B^- \to D^{0*}\pi^-$, with $D^{0*} \to D^0\pi^0/\gamma$; $B^- \to K^-\pi^+\pi^-$ and $B^0 \to D_0^{*-}e^+\nu_e$.

Projections of the fit in the suppressed invariant mass distributions, separated in charge, are shown in Fig. 3. We obtained 34 ± 14 $B^- \to D_{sup}K^-$ and 73 ± 16 $B^- \to D_{sup}\pi^-$ signal events,

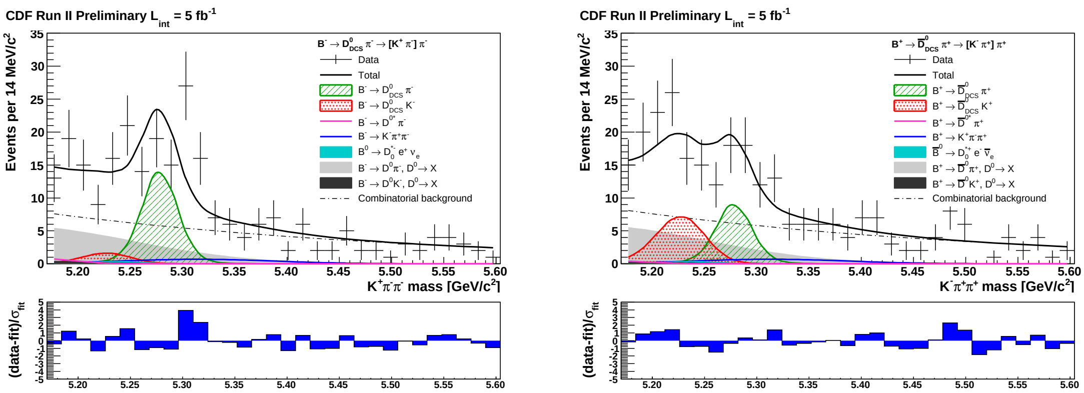

Figure 3: Invariant mass distributions of $B^- \to D_{sup}h^-$ candidates for negative (top) and positive (bottom) charges. The projections of the likelihood fit are overlaid.

with a combined significance greater than 5σ. Since K^+ and K^- have a different probability of interaction in the detector, we evaluated the efficiency using a simulation sample and we corrected the fit results for this value.

The final results for the asymmetries are:

$$A_{ADS}(K) \; = \; -0.63 \pm 0.40(\text{stat}) \pm 0.23(\text{syst})$$

$$A_{ADS}(\pi) \;=\; 0.22 \pm 0.18(\text{stat}) \pm 0.06(\text{syst})$$

and for the ratios of suppressed to favor modes:

$$\begin{aligned} R_{ADS}(K) &= [22.5 \pm 8.4(\text{stat}) \pm 7.9(\text{syst})] \times 10^{-3} \\ R_{ADS}(\pi) &= [4.1 \pm 0.8(\text{stat}) \pm 0.4(\text{syst})] \times 10^{-3}. \end{aligned}$$

These quantities are measured for the first time in hadron collisions and the results are in agreement with existing measurements performed at the Υ(4S) resonance [2, 4].

3. Gronau-London-Wyler method

In the GLW method [6, 9] the CP asymmetry of $B^- \to D_{CP\pm}K^-$ is studied, where D is D^0 or $\overline{D}^0$ and $CP\pm$ are the CP even and odd eigenstates of the D: $D_{CP^+} \to K^+K^-, \pi^+\pi^-$ and $D_{CP-} \to K_s^0\pi^0, K_s^0\phi, K_s^0\omega$.

We can define four observables:

$$\begin{aligned} A_{CP\pm} &= \frac{\mathscr{B}(B^- \to D_{CP\pm}K^-) - \mathscr{B}(B^+ \to D_{CP\pm}K^+)}{\mathscr{B}(B^- \to D_{CP\pm}K^-) + \mathscr{B}(B^+ \to D_{CP\pm}K^+)} \\ R_{CP\pm} &= 2 \cdot \frac{\mathscr{B}(B^- \to D_{CP\pm}K^-) + \mathscr{B}(B^+ \to D_{CP\pm}K^+)}{\mathscr{B}(B^- \to D_{fav}K^-) + \mathscr{B}(B^+ \to \overline{D}_{fav}K^+)} \end{aligned}$$

The relations with the amplitude ratios and phases are: $A_{CP\pm} = 2r_B \sin\delta_B \sin\gamma / R_{CP\pm}$ and $R_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\gamma$. Three of them are independent observables since $A_{CP+}R_{CP+} = -A_{CP-}R_{CP-}$. 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 fb^{-1} of data [14]. The mass distributions obtained for the two modes of interest ($D \to K^+K^-$ and $\pi^+\pi^-$) are reported in Fig. 4, where a clear $B^- \to D\pi^-$ signal can be seen in each plot.

The dominant backgrounds are the combinatorial background and the mis-reconstructed physics background such as $B^- \to D^{0*}\pi^-$ decay. In the $D^0 \to K^+K^-$ final state also the non-resonant $B^- \to K^-K^+K^-$ decay appears, as determined by a study on CDF simulation [15]. From an unbinned maximum likelihood fit, exploiting kinematic and particle identification information, we obtained about 90 $B^- \to D_{CP+}K^-$ events and we measured the double ratio of CP-even to flavor eigenstate branching fractions and the direct CP asymmetry:

$$\begin{aligned} R_{CP+} &= 1.30 \pm 0.24(\text{stat}) \pm 0.12(\text{syst}) \\ A_{CP+} &= 0.39 \pm 0.17(\text{stat}) \pm 0.04(\text{syst}). \end{aligned}$$

These results are in agreement with previous measurements from Υ(4S) decays [2, 4].

4. Conclusions

The CDF experiment is pursuing a global program to measure the γ angle from tree-dominated processes. The published measurement using the GLW method and the preliminary result using the

PoS(BEAUTY 2011)019

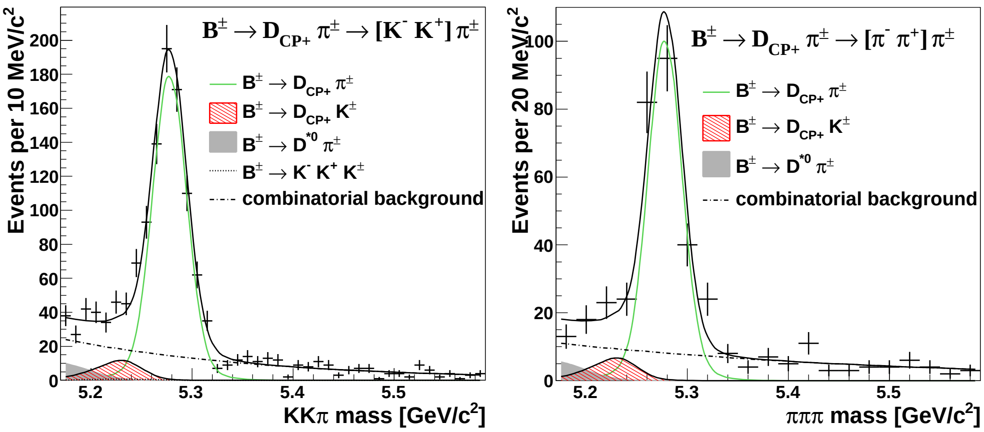

Figure 4: Invariant mass distributions of $B^- \to D_{CP}h^-$ candidates for each reconstructed decay mode, Cabibbo-suppressed K^+K^- on the left and Cabibbo-suppressed $\pi^+\pi^-$ on the right. The projections of the likelihood fit are overlaid for each mode.

ADS method show competitive results with previous measurements performed at *B*-factories and demonstrate the feasibility of these kinds of measurements also in a hadron collider environment.

We expect to increase the data-set available by the end of the year 2011 and obtain interesting and more competitive results in the near future.

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