Branching fractions of $B^0_{(s)} \to h^+ h'^-$ modes at CDF

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I report the analysis of $B^0_{(s)} \to h^+ h'^-$ decays (where h and h' denote K or π), in 180 pb^{-1} of proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV, with the CDF II detector at the Tevatron Collider. A $B^0_{(s)} \to h^+ h'^-$ signal was reconstructed at a hadron collider for the first time, in the sample collected by the dedicated trigger on long-lived decays. With about 900 signal events, we observed the new mode $B^0_s \to K^+ K^-$, and we measured its branching fraction relative to the $B^0 \to K^+ \pi^-$ mode:

$$\frac{f_s}{f_d} \cdot \frac{\mathscr{B}(B^0_s \to K^+ K^-)}{\mathscr{B}(B^0 \to K^+ \pi^-)} = 0.46 \pm 0.08 \ (stat.) \pm 0.07 \ (syst.);$$

we also measured the CP-violating decay-rate asymmetry for the $B^0 \to K^+ \pi^-$ mode:

$$A_{\text{CP}}(B^0 \to K^+ \pi^-) = \frac{N(\bar{B}^0 \to K^- \pi^+) - N(B^0 \to K^+ \pi^-)}{N(\bar{B}^0 \to K^- \pi^+) + N(B^0 \to K^+ \pi^-)} = -0.013 \pm 0.078 \ (stat.) \pm 0.012 \ (syst.).$$

Since we did not find evidence for rarer modes, we set the following 90% C.L. upper limits on the decay rates:

$$\frac{f_s}{f_d} \cdot \frac{\mathscr{B}(B^0_s \to K^- \pi^+)}{\mathscr{B}(B^0 \to K^+ \pi^-)} < 0.08 \quad \text{and} \quad \frac{\mathscr{B}(B^0_s \to \pi^+ \pi^-)}{\mathscr{B}(B^0_s \to K^+ K^-)} < 0.05$$

that are greatly improved with respect to current world averages.

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1. Introduction

Today, the *b*-sector of flavor dynamics is being widely investigated in searching for anomalous CP-violation effects. Direct measurements of the quark-mixing parameters from *b*-hadrons are compared with indirect results from global fits, related to other sectors, to look for deviations from the Standard Model predictions. This approach may not be straightforward, since the interpretation of *b*-physics results is often affected by large uncertainties coming from non-perturbative QCD effects: hence the need to simplify the problem by invoking symmetries under which the unknowns (partially) cancel. In this respect, the joint study of two-body decays of B^0 and B^0_s mesons into light, charged, pseudo-scalar mesons (K^+K^-, $\pi^+\pi^-$ and $K^+\pi^-$)[1] plays a key role, since these modes are related by subgroups of SU(3) symmetry [1]. CDF at the Fermilab Tevatron $p\bar{p}$ collider is the first and only experiment that has simultaneous access to B^0 and $B^0_s \to h^+h'^-$ decays. The CDF II detector is a multipurpose magnetic spectrometer, surrounded by $\sim 4\pi$ calorimetry and muon chambers. Its components relevant for this analysis are the tracking system, composed by a silicon micro-vertex and an outer drift chamber, and the trigger; for further detector details, see [2].

2. Trigger and dataset

The study of $B^0_{(s)} \to h^+h'^-$ decays at a hadron collider is challenging, since one searches for generic final states in huge QCD backgrounds; high (~ 50/event) track-multiplicities and tiny signal-to-noise ratios at production, $(\sigma_{b\bar{b}}/\sigma_{p\bar{p}}) \cdot \mathscr{B} \sim 10^{-9}$, make crucial the role of the trigger. The Silicon Vertex Trigger (SVT) [3] exploits the ~ 1.5 ps lifetime of *b*-hadrons, which, combined with their boost, results in decay vertices separated by hundreds of microns from the $p\bar{p}$ vertices. At the level-2 of the trigger, with 25 μs latency, the SVT finds silicon tracks in the plane transverse to the beam, and identifies displaced tracks with offline-quality resolution[2] on their impact parameters[3].

We analyzed a ≈ 180 pb^{-1} sample of pairs of oppositely-charged tracks with $p_T > 2$ GeV/*c*, $p_T(1) + p_T(2) > 5.5$ GeV/*c*, and a transverse opening-angle $20° < \Delta\phi < 135°$. We required each track to have an impact parameter $100\ \mu$m $< d_0 < 1$ mm. The *B* meson candidate was required to have an impact parameter $d_0(B) < 140\ \mu$m and a transverse decay-length $L_{xy}(B) > 200\ \mu$m.

3. Signal extraction

In the offline analysis, an unbiased procedure of optimization provided a tightened selection on track-pairs fit to a common vertex. We found the optimal cuts by maximizing the quantity $S/\sqrt{S+B}$. For each set of cuts, *S* was the signal yield expected from Monte Carlo simulation, and *B* were the background events found in the sidebands of the $\pi\pi$-mass distribution in data. Offline, we cut also on the *B* meson *isolation*: $I(B) = p_T(B)/[p_T(B) + \sum_i p_T(i)]$, in which the sum runs over every other track within a cone of radius 1 in the $\eta - \phi$ space around the *B* meson flight-direction. This rejected 75% of background while keeping 80% of signal. The resulting $\pi\pi$-mass distribution (Fig. 1, (a)) shows a clean signal, estimated by a Gaussian (signal) plus exponential (background) fit to contain 893 ± 47 events, with standard deviation $\sigma = 38 \pm 2$ MeV/c^2 and SNR≈ 1.7 at peak.

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[1]Unless otherwise stated, CP-conjugated modes are implied, and all branching fractions indicate CP-averages.

[2]The SVT resolution combined with the beam-width determines the total resolution $\sigma_{SVT} \oplus \sigma_{beam} \simeq 47\ \mu$m.

[3]The i. p. (d_0) is the distance between the track's momentum and the $p\bar{p}$ vertex in the plane transverse to the beam.
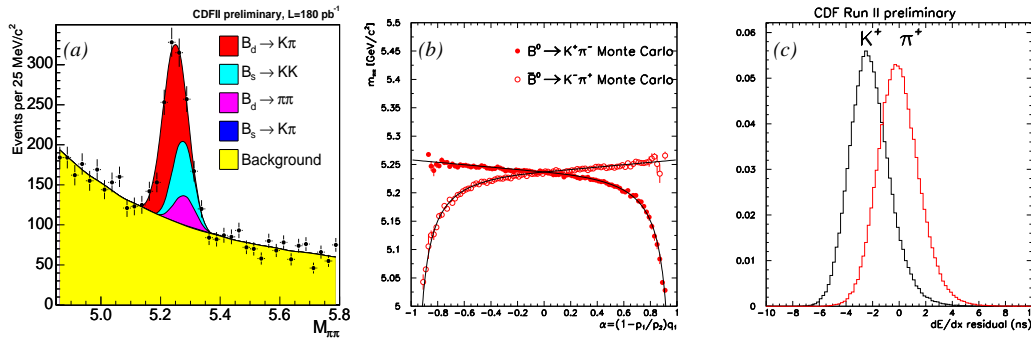
Figure 1: *(a)*, $\pi\pi$-mass distribution after the optimized cuts; *(b)*, $<m_{\pi\pi}>$ *versus* α distribution for $B^0 \to K^+\pi^-$ Monte Carlo events with the analytic function overlaid; *(c)*, dE/dx residual for K^+ and π^+.

4. Peak composition

Despite the excellent CDF II mass resolution[4], the expected contributions to the signal ($B^0 \to K^+\pi^-$ and $\pi^+\pi^-$, $B^0_s \to K^+K^-$ and $K^-\pi^+$) overlap into an unresolved peak, preventing an event-by-event separation. We achieved a statistical separation instead, with an unbinned Likelihood fit that used PID information, provided by the dE/dx in the drift chamber, and kinematics.

We exploited the kinematic differences among modes by using an approximate relation between any two invariant masses (M_{m_1,m_2} and $M_{m'_1,m'_2}$) obtained with two arbitrary mass-assignments to the tracks (m_1, m_2 and m'_1 m'_2). If $m_{1,2} \ll p_{1,2}$ we have $M^2_{m_1,m_2} \approx M^2_{m'_1,m'_2} + (1 + p_1/p_2) \cdot (m_2^2 - m_2'^2) + (1 + p_2/p_1) \cdot (m_1^2 - m_1'^2)$, where the kinematic information is contained in just two observables, a single candidate invariant-mass and the ratio of momenta. The plot (b) in Fig. 1 shows the averaged $\pi\pi$-mass *versus* the signed momentum-imbalance, $\alpha = (1 - p_1/p_2)q_1$, for $B^0 \to K^+\pi^-$ Monte Carlo events. The momentum (charge) p_1 (q_1) refers to the softer track; by combining kinematics and charge, we therefore separated also $B^0_{(s)}$ from $\bar{B}^0_{(s)}$ mesons in $K\pi$ modes.

We equalized the dE/dx over the tracking volume and time using $\sim$300,000 $D^{*+} \to D^0\pi^+ \to [K^-\pi^+]\pi^+$ decays, where D^0 daughters were identified by the strong D^{*+} decay[5] [4]. In >95% pure K and π samples, we obtained 1.4σ of K/π separation (Fig. 1, (c)). We measured, and included in the fit, a 11% residual track-to-track correlation due to common-mode dE/dx fluctuations.

5. Fit and efficiency corrections

The fit used five observables: the $\pi\pi$-mass $m_{\pi\pi}$, the signed momentum-imbalance α, the scalar sum of track's momenta, and the dE/dx of both tracks. The Likelihood for the single event i was: $\mathcal{L}^i = (1 - b)\sum_{j=mode} f_j \mathcal{L}^{kin}_j \mathcal{L}^{PID}_j + b \mathcal{L}^{kin}_{bck} \mathcal{L}^{PID}_{bck}$ where j runs over the signal modes, and the output parameters f_j (b) are the fractions of each mode (background). We obtained the kinematic shape for signal ($\mathcal{L}^{kin}_j$) partly from the formula of Sec. 4 and partly from Monte Carlo. We fit the kinematic shape for background ($\mathcal{L}^{kin}_{bck}$) in sideband events of Fig. 1, (a). We obtained the dE/dx shapes for signal ($\mathcal{L}^{PID}_j$) and background ($\mathcal{L}^{PID}_{bck}$) in pure K and π from D^0 decays (Fig. 1, (c)).

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[4]See some observed mass widths: $\sigma(J/\psi \to \mu^+\mu^-) \simeq 14$ MeV/c^2, $\sigma(D^0 \to K^+\pi^-) \simeq 10$ MeV/c^2.

[5]We neglected the $\sim 0.4\%$ contamination from doubly Cabibbo-suppressed $D^0 \to K^+\pi^-$ decays.

The fit found three contributions to the peak: 121 ± 27 $B^0 \to \pi^+\pi^-$, 542 ± 30 $B^0 \to K^+\pi^-$, and 236 ± 32 $B^0_s \to K^+K^-$ decays. This is the first observation of the $B^0_s \to K^+K^-$ mode.

We converted the fit results into ratios of branching fractions by correcting for the differences in efficiencies between modes. We obtained part of the corrections from simulation (geometric acceptances, interaction and decay-in-flight probability of K *vs.* π, interaction probability of K^+ *vs.* K^-), and part from samples of real data (dE/dx-dependent trigger efficiency and efficiency of the isolation cut). The resulting total corrections varied between modes by less than 12%.

6. Results

We observed the new decay $B^0_s \to K^+K^-$. The measurement[6] $(f_s/f_d) \cdot \mathscr{B}(B^0_s \to K^+K^-)/\mathscr{B}(B^0 \to K^+\pi^-) = 0.46 \pm 0.08 \pm 0.07$[7] agrees with QCD-factorization predictions [5], and it may probe the size of U-spin violation, possibly favoring the large SU(3)-breaking predicted by QCD sum-rules [6]. For comparison with theory [7], we also quote $(f_d/f_s) \cdot \mathscr{B}(B^0 \to \pi^+\pi^-)/\mathscr{B}(B^0_s \to K^+K^-) = 0.45 \pm 0.13 \pm 0.06$. We found no evidence of rarer $B^0_s \to h^+h'^-$ modes, and we set 90% C.L. upper limits [8] on their decay rates. These limits, $(f_s/f_d) \cdot \mathscr{B}(B^0_s \to K^-\pi^+)/\mathscr{B}(B^0 \to K^+\pi^-) < 0.08$ and $\mathscr{B}(B^0_s \to \pi^+\pi^-)/\mathscr{B}(B^0_s \to K^+K^-) < 0.05$, are greatly improved over current world averages.

In the B^0 sector, we measured the direct CP-asymmetry of $B^0 \to K^+\pi^-$ decay-rates: $A_{\text{CP}} = -0.013 \pm 0.078 \pm 0.012$, in agreement with the results from the *B*-factories. With significantly more data already collected, the CDF measurement will soon be competitive with their results. We also quote $\mathscr{B}(B^0 \to \pi^+\pi^-)/\mathscr{B}(B^0 \to K^+\pi^-) = 0.21 \pm 0.05 \pm 0.03$, used as a check of the validity of the whole analysis. We found no evidence of rarer $B^0 \to h^+h'^-$ modes, and we set the following 90% C.L. upper limit [8] on the relative decay rate: $\mathscr{B}(B^0 \to K^+K^-)/\mathscr{B}(B^0 \to K^+\pi^-) < 0.10$.

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[6] In all results, the first error is statistical, the second systematic. $f_{d(s)}$ are the production fractions for $B^0_{(s)}$ mesons.

[7] This result assumes the $B^0_s \to K^+K^-$ dominated by the short-lived component, $\Gamma_d = \Gamma_s$ and $\Delta\Gamma_s/\Gamma_s = 0.12 \pm 0.06$.