Search for $b \to u$ transitions in $B^0 \to D^0 K^{*0}$ decays

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We present a study of the decays $B^0 \to D^0 K^{*0}$ and $B^0 \to \overline{D}^0 K^{*0}$ with $K^{*0} \to K^{+} \pi^{-}$. The $D^0$ and the $\overline{D}^0$ mesons are reconstructed in the final states $f = K^{+} \pi^{-}$, $K^{+} \pi^{-} \pi^{0}$, $K^{+} \pi^{-} \pi^{+} \pi^{-}$ and their charge conjugates. Using a sample of 465 million $BB$ pairs collected with the BABAR detector at the PEP-II asymmetric-energy $e^+e^-$ collider at SLAC, we measure the ratio $R_{ADS} \equiv [\Gamma(B^0 \to f)|\Gamma(\overline{D}^0 \to f)]$ for the three final states. We do not find significant evidence for a signal and set the following limits at 95% probability: $R_{ADS}(K^{+} \pi^{-}) < 0.244$, $R_{ADS}(K^{+} \pi^{-} \pi^{0}) < 0.181$ and $R_{ADS}(K^{+} \pi^{-} \pi^{+} \pi^{-}) < 0.391$. From the combination of these three results, we find that the ratio $r_S$ between the $b \to u$ and the $b \to c$ amplitudes lies in the range $[0.07, 0.41]$ at 95% probability.

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Various methods have been proposed to determine the Unitarity Triangle angle $\gamma$ [1–3] of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [4] using $B^- \to D^{(*)0}K^{(*)-}$ decays, where the symbol $D^{(*)0}$ indicates either a $D^{(*)0}$ or a $D_s^{(*)0}$ meson. A $B^-$ meson can decay into a $D^{(*)0}K^{(*)-}$ final state via a $b \to c$ or a $b \to u$ process. CP violation may occur due to interference between the amplitudes when the $D^{(*)0}$ and $\bar{D}^{(*)0}$ decay to the same final state. These processes are thus sensitive to $\gamma = \arg\{-V_{cb}^*V_{ub}/V_{cb}V_{ub}\}$. The sensitivity to $\gamma$ is proportional to the ratio between the $b \to u$ and $b \to c$ transition amplitudes ($r_B$), which depends on the $B$ decay channel and needs to be determined experimentally.

In this paper we consider an alternative approach, based on neutral $B$ mesons, which is similar to the ADS method [2] originally proposed for charged $B^- \to \bar{D}^{(*)0}K^{(*)-}$ decays. We consider the decay channel $B^0 \to \bar{D}^{0}K^{*0}$ with $K^{*0} \to K^+\pi^-$ (charge conjugate processes are assumed throughout the paper and $K^{*0}$ refers to the $K^*(892)^0$). This final state can be reached through $b \to c$ and $b \to u$ processes as shown in Fig. 1. The flavor of $b$ meson is identified by the charge of the kaon produced in the $K^{*0}$ decay. The neutral $D$ mesons are reconstructed in three final states, $f = K^+\pi^-, K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-$. We search for $B^0 \to [f]_{D}[K^{(*)-}]_{K^{*0}}$ events, where the CKM-favored $B^0 \to \bar{D}^{0}K^{*0}$ decay, followed by the doubly Cabibbo-suppressed $\bar{D}^{0}K^{*0}$ decay, interferes with the CKM-suppressed $B^0 \to \bar{D}^{0}K^{*0}$ decay, followed by the Cabibbo-favored $D^{(*)0} \to \bar{f}$ decay. These are called “opposite-sign” events because the two kaons in the final state have opposite charges. We also reconstruct a larger sample of “same-sign” events, which

\[ R_{ADS} \equiv \frac{\Gamma(B^0 \to [f]_{D}[K^{(*)-}]_{K^{*0}})}{\Gamma(B^0 \to [f]_{D}[K^{(*)-}]_{K^{*0}})} \]
\[ A_{ADS} \equiv \frac{\Gamma(B^0 \to [f]_{D}[K^{(*)-}]_{K^{*0}}) - \Gamma(B^0 \to [f]_{D}[K^{(*)-}]_{K^{*0}})}{\Gamma(B^0 \to [f]_{D}[K^{(*)-}]_{K^{*0}}) + \Gamma(B^0 \to [f]_{D}[K^{(*)-}]_{K^{*0}})} \]

where $R_{ADS}$ is the ratio between opposite- and same-sign events.

The $K^{*0}$ resonance has a natural width (50 MeV/$c^2$) that is larger than the experimental resolution. This introduces a phase difference between the various amplitudes. We therefore introduce effective variables $r_S$, $k$, and $\delta_S$ [5], obtained by integrating over the region of the $B^0 \to \bar{D}^{0}K^+\pi^-$ Dalitz plot dominated by the $K^{*0}$ resonance, defined as follows:

\[ r_S^2 \equiv \frac{\Gamma(B^0 \to D^{0}K^+\pi^-)}{\Gamma(B^0 \to D^{0}K^+\pi^-)} = \int dp A_S^2(p) \]
\[ k e^{i\delta_S} \equiv \frac{\int dp A_c(p)A_u(p) e^{i\delta(p)}}{\int dp A_c^2(p) \int dp A_u^2(p)} \]

From their definition, $0 \leq k \leq 1$ and $\delta_S \in [0, 2\pi]$. The amplitudes for the $b \to c$ and $b \to u$ transitions, $A_c(p)$ and $A_u(p)$, are real and positive and $\delta(p)$ is the relative strong phase. The variable $p$ indicates the position in the $D^0K^+\pi^-$ Dalitz plot. The parameter $k$ accounts for contributions, in the $K^{*0}$ mass region, of higher-mass resonances. In the case of a two-body $B$ decay, $r_S$ and $\delta_S$ become $r_B = A_u/A_c$ and $\delta_S$ (the strong phase difference between $A_u$ and $A_c$) with $k = 1$. As shown in [6], the distribution of $k$ can be obtained by simulation studies based on realistic models for the different resonance contributions to the decays of neutral $B$ mesons into $D^0K^+\pi^\pm$ final states. When considering the region in the $B^0 \to \bar{D}^{0}K^+\pi^-$ Dalitz plane where the invariant mass of the kaon and the pion is within 48 MeV/$c^2$ of the nominal $K^{*0}$ mass [7], the distribution of $k$ is narrow, and is centered at 0.95 with a root-mean-square width of 0.03.

Because of CKM factors and the fact that both diagrams in Fig. 1 are color-suppressed, the average amplitude ratio $r_S$ in $B^0 \to \bar{D}^{0}K^{*0}$ is expected to be of order 0.3, larger than the analogous ratio for the charged $B^- \to D^{0(*)}K^{(*)-}$ decays, which is of order 0.1 [8, 9]. This implies better sensitivity to $\gamma$ for the same number of events, an expectation that applies to all $B^0 \to \bar{D}^{0(*)}K^{(*)0}$ decays, and that motivates the use of neutral $B$ meson decays to determine $\gamma$. Currently, the experimental knowledge of $r_S$ [6, 10] is $r_S < 0.54$ at 95% probability.

The ratios $R_{ADS}$ and $A_{ADS}$ are related to $r_S$, $\gamma$, $k$ and

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\( \delta_S \) through the following relations:

\[
R_{ADS} = r_D^2 + r_0^2 + 2kK_D r_D \sin \gamma \cos(\delta_S + \delta_D),
\]

\[
A_{ADS} = 2kK_D r_D \sin \gamma \sin(\delta_S + \delta_D)/R_{ADS},
\]

where

\[
r_D^2 = \frac{\Gamma(D^0 \to f)}{\Gamma(D^0 \to f)} = \frac{\int dm A_{DCS}^2(m)}{\int dm A_{CF}^2(m)},
\]

\[
k_{DE} e^{i\delta_D} = \frac{\int dm A_{CF}(m)A_{DCS}(m)e^{i\delta(m)}}{\sqrt{\int dm A_{CF}^2(m) \int dm A_{DCS}^2(m)}},
\]

with \( 0 \leq k_D \leq 1, \delta_D \in [0, 2\pi], A_{CF}^2(m) \) and \( A_{DCS}^2(m) \) the magnitudes of the Cabibbo-favored and the doubly-
Cabibbo-suppressed amplitudes, \( \delta(m) \) the relative strong
phase, and the variable \( m \) the position in the \( D \) Dalitz
plot. In the case of a two-body \( D \) decay, \( k_D = 1 \), \( r_D \)
the ratio between the doubly-Cabibbo-suppressed and
the Cabibbo-favored decay amplitudes and \( \delta_D \) is the
relative strong phase.

Determining \( r_S, \gamma \) and \( \delta_S \) from the measurements of
\( R_{ADS} \) and \( A_{ADS} \), with the factor \( k \) fixed, requires knowl-
edge of the parameters \( k_D, r_D, \delta_D \), which depend on
the specific neutral \( D \) meson final states. The ratios \( r_D \)
the three \( D \) decay modes have been measured [7], as
has the strong phase \( \delta_D \) for the \( K^0 \) mode [11]. In addi-
tional, experimental information is available on \( k_D \) and \( \delta_D \)
for the \( K^+ \pi^0 \) and \( K^0 \pi^0 \) modes [12]. The smallness of
the \( r_D \) ratios implies good sensitivity to \( r_S \) from a mea-
surement of \( R_{ADS} \). For the same reason, and since, with
the present statistics, the asymmetries \( A_{ADS} \) cannot be
extracted from data, the sensitivity to \( \gamma \) is reduced.
The aim of this analysis is therefore the measurement of \( r_S \).
In the future, good knowledge of all the \( r_D, k_D \) and \( \delta_D \)
parameters, and a precise measurement of the \( R_{ADS} \) ra-
tios for the three channels, will allow \( \gamma \) and \( \delta_S \) to be
determined from this method as well.

The results presented here are obtained with 423 \( \text{fb}^{-1} \)
of data collected at the \( \Upsilon(4S) \) resonance with the \( \text{BaBar} \) detector at the PEP-II \( e^+e^- \) collider at SLAC [13],
corresponding to 465 million \( B\overline{B} \) events. An additional
“off-resonance” data sample of 41.3 \( \text{fb}^{-1} \), collected at
a center-of-mass (CM) energy 40 \( \text{MeV} \) below the \( \Upsilon(4S) \)
resonance, is used to study backgrounds from continuum
events, \( e^+e^- \rightarrow q\overline{q} \) \((q = u,d,s,\text{or }c)\). The \( \text{BaBar} \) detec-
tor is described elsewhere [14].

The event selection is based on studies of off-resonance
data and Monte Carlo (MC) simulations of continuum
and \( e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B} \) events. All the selection crite-
ria are optimised by maximising the function \( S/\sqrt{S+B} \)
on opposite-sign events, where \( S \) and \( B \) are the expected
numbers of opposite-sign signal and background events,
respectively.

The neutral \( D \) mesons are reconstructed from a
charged kaon and one or three charged pions and
in the \( K^+\pi^0 \) mode, a neutral pion. The \( \pi^0 \) can-
didates are reconstructed from pairs of photon candidates,
each with energy greater than 70\( \text{MeV} \), total energy
greater than 200\( \text{MeV} \) and invariant mass in the interval
[118, 145]\( \text{MeV}/c^2 \). The \( \pi^0 \) candidate’s mass is subse-
quently constrained to its nominal value [7].

The invariant mass of the particles used to reconstruct
the \( D \) is required to lie within 14\( \text{MeV}/c^2 \) (\( \sim 1.9\sigma \)),
20\( \text{MeV}/c^2 \) (\( \sim 1.5\sigma \)) and 9\( \text{MeV}/c^2 \) (\( \sim 1.6\sigma \)) of
the nominal \( D^0 \) mass, for the \( K\pi, K\pi\pi \) and \( K\pi\pi\pi \) modes,
respectively. For the \( K\pi\pi\pi \) mode we also require that
the tracks originate from a single vertex with a probability
greater than 0.1%.

The tracks used to reconstruct the \( K^{*0} \) are con-
strained to originate from a common vertex and their
invariant mass is required to lie within 48 \( \text{MeV}/c^2 \) of
the nominal \( K^{*0} \) mass [7]. We define \( \theta_H \) as the angle between
the direction of flight of the \( K \) and \( B \) in the \( K^{*0} \) rest frame.
The distribution of \( \cos \theta_H \) is proportional to \( \cos^2 \theta_H \)
for signal events and is expected to be flat for background
events. We require \(|\cos \theta_H| > 0.3 \). The charged kaons
used to reconstruct the \( D^0 \) and \( K^{*0} \) mesons are re-
cquired to satisfy kaon identification criteria, based on
Cherenkov angle and \( dE/dz \) measurements and are typ-
ically 85% efficient, depending on momentum and polar
angle. Misidentification rates are at the 2% level.

The \( B^0 \) candidates are reconstructed by combining a
\( D^0 \) and \( K^{*0} \) candidate, constraining them to originate
from a common vertex with a probability greater than
0.1%. In forming the \( B \), the \( D \) mass is constrained to its
nominal value [7]. The distribution of the cosine of the
\( B \) polar angle with respect to the beam axis in the \( e^+e^- \) CM
frame \( \cos \theta_B \) is expected to be proportional to \( 1 - \cos^2 \theta_B \).
We require \(|\cos \theta_B| < 0.9 \). We measure two almost
independent kinematic variables: the beam-energy substi-
tuted mass \( m_{ES} \equiv \sqrt{(E_B^2/2 + p_B^2)^2/E_B^2 - p_B^2} \),
and the energy difference \( \Delta E \equiv E_B - E_0/2 \), where \( E \)
and \( p \) are energy and momentum, the subscripts \( B \) and 0 refer
to the candidate \( B \) and \( e^+e^- \) system, respectively, and
the asterisk denotes the \( e^+e^- \) CM frame. The distribu-
tions of \( m_{ES} \) and \( \Delta E \) peak at the \( B \) mass and zero,
respectively, for correctly reconstructed \( B \) mesons. The \( B \)
candidates are required to have \( \Delta E \) in the range \([-16, 16] \)
\( \text{MeV} \) (\( \sim 1.3\sigma \)), \([-20, 20] \) \( \text{MeV} \) (\( \sim 1.5\sigma \))
and \([-19, 19] \) \( \text{MeV} \) (\( \sim 1.4\sigma \)) for the \( K\pi, K\pi\pi \)
and \( K\pi\pi\pi \) modes, respectively. Finally we consider events with \( m_{ES} \) in the
range \([5.20, 5.29] \) \( \text{GeV}/c^2 \).

We examine background \( B \) decays that have the same
final state reconstructed particles as the signal decay to
identify modes with peaking structure in \( m_{ES} \) or \( \Delta E \)
that can potentially mimic signal events. We iden-
tify three such “peaking background” modes in the
opposite-sign sample: \( B^0 \rightarrow D^- K^{*0} K^- \pi^+ \) (for \( K\pi \)), \( B^0 \rightarrow D^- [K^{*0} K^-] \rho^0 [\pi^+ \pi^0] \) (for \( K\pi\pi \)) and \( B^0 \rightarrow D^- [K^{*0} K^-] a_1^0 [\pi^+ \pi^0 \pi^-] \) (for \( K\pi\pi\pi \)). To reduce their
contribution we veto all candidates for which the invariant
mass of the \( K^{*0} \) and the \( K^- \) from the \( D^0 \) lies within
6 \( \text{MeV}/c^2 \) of the nominal \( D^- \) mass.

After imposing the vetoes, the contributions of the
peaking backgrounds to the \( K\pi, K\pi\pi \) and \( K\pi\pi\pi \) sam-
ple are predicted to be less than 0.07, 0.05 and 0.12.
events, respectively, at 95% probability. Other possible sources of peaking background are \( B^0 \to D^0 \rho^0 \) and \( B^0 \to D^* \to [D^0 \pi^-] \pi^+ \), which contribute to the three decay modes in both the same- and opposite-sign samples. These events could be reconstructed as signal, due to misidentification of a \( \pi \) as a \( K \). We impose additional restrictions on the identification criteria of charged kaons from \( K^\pm \) decays to reduce the contribution of these backgrounds to a negligible level. Charmless \( B^0 \) decays, like \( B^0 \to K^{*0} K \pi \), can also contribute. The number of expected charmless background events, evaluated with data from the \( D^0 \) mass sidebands, is \( N_{\text{peak}} = 0.5 \pm 0.5 \) (0.1 ± 1.2) in the same (opposite) sign samples.

In case of multiple \( D \) candidate (less than 1% of events), we choose the one with reconstructed \( D^0 \) mass closest to the nominal mass \([7]\). In the case of two \( B \) candidates reconstructed from the same \( D^0 \), we choose the candidate with the largest value of \( |\cos \theta_H| \).

The overall reconstruction efficiencies for signal events are \((13.2 \pm 0.1)\%\), \((5.2 \pm 0.1)\%\) and \((6.5 \pm 0.1)\%\) for the \( K\pi, K\pi\pi^0 \) and \( K\pi\pi\pi \) modes, respectively.

After applying the selection criteria described above, the remaining background is composed of continuum events and combinatorial \( B\bar{B} \) events. To discriminate against the continuum background events (the dominant background component), which, in contrast to \( B\bar{B} \) events, have a jet-like shape, we use a Fisher discriminant \( F \) \([15]\). The discriminant \( F \) is a linear combination of four variables calculated in the CM frame. The first discriminant variable is the cosine of the angle between the \( B \) thrust axis and the thrust axis of the rest of the event. The second and third variables are \( L_0 = \sum_i p_i \) and \( L_2 = \sum_i p_i |\cos \theta_i|^2 \), where the index \( i \) runs over all the reconstructed tracks and energy deposits in the calorimeter not associated with a track, the tracks and energy deposits used to reconstruct the \( B \) are excluded, \( p_i \) is the momentum, and \( \theta_i \) is the angle with respect to the thrust axis of the \( B \) candidate. The fourth variable is \( |\Delta t| \), the absolute value of the measured proper time interval between the \( B \) and \( \bar{B} \) decays, calculated from the measured separation between the decay points of the \( B \) and \( \bar{B} \) along the beam direction.

The coefficients of \( F \), chosen to maximize the separation between signal and continuum background, are determined using samples of simulated signal and continuum events and validated using off-resonance data.

The signal and background yields are extracted, separately for each channel, by maximizing the extended likelihood \( L = (e^{-N})/(N!) \cdot N^{N_0} \cdot \prod_{j=1}^N f(x_j \mid \theta, N') \). Here \( x_j = \{m_{\text{ES}}, F\}, \theta \) is a set of parameters, \( N \) is the number of events in the selected sample and \( N' \) is the expectation value for the total number of events. The term \( f(x \mid \theta, N') \) is defined as:

\[
 f(x \mid \theta, N') = \frac{R_{\text{ADS}} N_{\text{DK}}\cdot f_{\text{SIG}}(x \mid \theta_{\text{SIG}})}{1 + R_{\text{ADS}} f_{\text{SIG}}(x \mid \theta_{\text{SIG}}) + N_{\text{DK}}\cdot f_{\text{SIG}}(x \mid \theta_{\text{SIG}}) + N_{\text{bkg}}\cdot f_{\text{SIG}}(x \mid \theta_{\text{SIG}})}
\]

where \( N_{\text{DK}}\cdot \) is the total number of signal events, \( R_{\text{ADS}} \) is the ratio between opposite- and same-sign signal events, and \( "\text{bkg}" \) refers to continuum or \( B\bar{B} \) background, and \( N_{\text{SIG}}^{\text{cont}}, N_{\text{SIG}}^{\text{cont}} \cdot N_{\text{SIG}}^{\text{cont}}, N_{\text{SIG}}^{\text{cont}} \cdot N_{\text{SIG}}^{\text{cont}} \) are the number of same- and opposite-sign events for continuum and \( B\bar{B} \) backgrounds. The probability density functions (PDFs) \( f \) are derived from MC and are defined as the product of one-dimensional distributions of \( m_{\text{ES}} \) and \( F \). The \( m_{\text{ES}} \) distributions are modeled with a Gaussian for signal, and threshold functions with different parameters for the continuum and \( B\bar{B} \) backgrounds. The threshold function is expressed as follows:

\[
 A(x) = x \sqrt{1 - \left(\frac{x}{x_0}\right)^2} \cdot e^{(1 - (\frac{x}{x_0})^2)},
\]

where \( x_0 \) represents the maximum allowed value for the variable \( x \) described by \( A(x) \) and \( c \) accounts for the shape of the distribution. The \( F \) distributions are modeled with Gaussians.

The fit to data extracts \( N_{\text{DK}}\cdot, R_{\text{ADS}} \) and the background yields \( (N_{\text{SIG}}^{\text{cont}}, N_{\text{SIG}}^{\text{cont}} \cdot N_{\text{SIG}}^{\text{cont}} \cdot N_{\text{SIG}}^{\text{cont}} \cdot N_{\text{SIG}}^{\text{cont}}) \). We allow the mean of the signal \( m_{\text{ES}} \) PDF and parameters of the continuum \( m_{\text{ES}} \) PDF’s to float.

The fitting procedure is validated using ensembles of simulated events. A large number of pseudo-experiments is generated with probability density functions and parameters as obtained from the fit to the data. The fitting procedure is then performed on these samples. We find no bias on the number of fitted events for any of the components.

The results for \( N_{\text{DK}}\cdot, R_{\text{ADS}} \) and the background yields are summarized in Table I. The total number of opposite-sign signal events in the three channels is \( N_{\text{SIG}}^{\text{cont}} = 24.4^{+15.7}_{-10.5} \) (statistical uncertainty only). Projections of the fit onto the variable \( m_{\text{ES}} \) are shown.
in Fig. 2 for the opposite- and same-sign samples. To enhance the visibility of the signal, events are required to satisfy $F > 0.5$ for $K\pi$, $F > 0.7$ for $K\pi\pi^0$, and $F > 1$ for $K\pi\pi\pi$. These requirements have an efficiency of about 67%, 67% and 50% for signal and 9%, 5% and 3% for continuum background.

The systematic uncertainties on $R_{ADS}$ are summarized in Table II. To evaluate the contributions related to the $m_{DS}$ and $F$ PDFs, we repeat the fit by varying all the PDF parameters that are fixed in the final fit within their statistical errors, as obtained from the parametrization on simulated events. To evaluate the uncertainty arising from the assumption of negligible peaking background contributions, we repeat the fit by varying the number of these events within their statistical errors. In this evaluation, we consider all the possible sources of such backgrounds, coming from charmed B decays and from B decays with a $D$ meson in the final state, as discussed above. For the multi-body $D$ decays, the selection efficiency on same- and opposite-sign events has been confirmed to be the same, regardless of the difference in the Dalitz structure, within a relative error of 3%. Finally, a systematic uncertainty associated with cross feed between same- and opposite-sign events is evaluated from MC studies to be $(3.5 \pm 0.5)\%$, $(4.6 \pm 0.6)\%$ and $(1.9 \pm 0.4)\%$ for the $K\pi$, $K\pi\pi^0$ and $K\pi\pi\pi$ modes, respectively. The total systematic uncertainties are defined by adding the individual terms in quadrature.

**TABLE II: Systematic uncertainties $\Delta R_{ADS}$, in units of $[10^{-2}]$, for $R_{ADS}^{K\pi}$, $R_{ADS}^{K\pi\pi^0}$ and $R_{ADS}^{K\pi\pi\pi}$.

<table>
<thead>
<tr>
<th>Source</th>
<th>$K\pi$</th>
<th>$K\pi\pi^0$</th>
<th>$K\pi\pi\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sig. PDF</td>
<td>0.19</td>
<td>0.11</td>
<td>0.82</td>
</tr>
<tr>
<td>Cont. PDF</td>
<td>0.32</td>
<td>0.02</td>
<td>0.29</td>
</tr>
<tr>
<td>$BB$ PDF</td>
<td>0.57</td>
<td>0.16</td>
<td>1.48</td>
</tr>
<tr>
<td>Peaking bgk</td>
<td>1.70</td>
<td>0.87</td>
<td>1.40</td>
</tr>
<tr>
<td>$\epsilon_{CF/\epsilon_{DCS}}$</td>
<td>-0.17</td>
<td>0.17</td>
<td>0.39</td>
</tr>
<tr>
<td>cross-feed</td>
<td>0.04</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1.8</td>
<td>0.91</td>
<td>2.2</td>
</tr>
</tbody>
</table>

The final likelihood $\mathcal{L}(R_{ADS})$ for each decay mode is obtained by convolving the likelihood returned by the fit with a Gaussian whose width equals the systematic uncertainty. Figure 3 shows $\mathcal{L}(R_{ADS})$ for all three channels, where we exclude the unphysical region $R_{ADS} < 0$. The integral of the likelihood corresponding to $R_{ADS} < 0$ is 9.5% for $K\pi$, 15.8% for $K\pi\pi^0$ and 5.5% for $K\pi\pi\pi$. The significance of observing a signal is evaluated in each channel using the ratio $\log(\mathcal{L}_{\text{max}}/\mathcal{L}_0)$, where $\mathcal{L}_{\text{max}}$ and $\mathcal{L}_0$ are the maximum likelihood values obtained from the nominal fit and from a fit in which the signal component is fixed to zero, respectively. We observe a ratio $R_{ADS}$ different from zero with a significance of 1.1, 1.7 and 1.4 standard deviations for the $K\pi$, $K\pi\pi^0$ and $K\pi\pi\pi$ modes, respectively. Since the measurements for the $R_{ADS}$ ratios are not statistically significant, we calculate 95% probability limits by integrating the likelihoods, starting from $R_{ADS} = 0$. We obtain $R_{ADS}(K\pi) < 0.244$, $R_{ADS}(K\pi\pi^0) < 0.181$ and $R_{ADS}(K\pi\pi\pi) < 0.391$ at 95% probability. The overall significance of observing an $R_{ADS}$ signal, evaluated from the combination of the three measurements, is 2.5 standard deviations.

Following a Bayesian approach, the measurements of the $R_{ADS}$ ratios are translated into a likelihood for $r_S$. A large number of simulated experiments for the parameters on which $R_{ADS}$ depends (see Eq. 5) are performed. For each experiment, the values of $R_{ADS}(K\pi)$, $R_{ADS}(K\pi\pi^0)$ and $R_{ADS}(K\pi\pi\pi)$ are obtained and a weight $\mathcal{L}(R_{ADS}(K\pi))\mathcal{L}(R_{ADS}(K\pi\pi^0))\mathcal{L}(R_{ADS}(K\pi\pi\pi))$ is computed. In the extraction procedure to determine $r_S$, we use the experimental distributions for the $r_D$ ratios, $\delta_D(K\pi)$, $k_D(K\pi\pi^0)$, $k_D(K\pi\pi\pi)$ and $\delta_D(K\pi\pi\pi)$ [7, 11, 12]. All the remaining phases are extracted from a flat distribution in the range $[0, 2\pi]$, $r_S$ is extracted from a flat distribution in the range $[0, 1]$ and $k$ is extracted from a Gaussian distribution with mean 0.95 and standard deviation 0.03. We obtain the likelihood $\mathcal{L}(r_S)$ shown in Fig. 4. The most probable value is $r_S = 0.26$ and we obtain, by integrating the likelihood, the following 68% and 95% probability regions:

$$r_S \in [0.18, 0.34] \text{ @ 68% probability},$$
$$r_S \in [0.07, 0.41] \text{ @ 95% probability}.$$ 

Given the functional dependence of $R_{ADS}$ on $r_S$ ($R_{ADS} \sim r_S^2$), the likelihoods corresponding to $R_{ADS} < 0$ have no effective role in the extraction of $r_S$. The dependence of the $r_S$ likelihood shown in Fig. 4 on the choice of the prior distributions in the extraction procedure has been studied. While the 68% and 95% probability regions are quite stable, the likelihood shows a dependence on the choice of the prior distribution for values of $r_S$ close to zero. For this reason, the region near zero should not be used to evaluate the significance. The significance to observe $r_S$ different from zero corresponds to the significance for $R_{ADS}$, and is evaluated from the combined fit to be 2.5 standard deviations. The result obtained for $r_S$ with the procedure described above is consistent with the result found from a direct fit to data assuming the simplified expression $R_{ADS} = r_S^2$.

In summary, we have presented a search for $b \rightarrow u$ transitions in $B^0 \rightarrow D^{0*}K^{*0}$ decays, analysed through an ADS method. We see indications of a signal at the level of 2.5 standard deviations including systematic uncertainties. The most probable value for $r_S$ extracted from this result is $r_S = 0.26$, where the 68% and 95% probability regions are indicated above. This result is in agreement with the phenomenological expectations from Ref. [16], and shows that the use of these decays and related ones [6] for the determination of $\gamma$ is interesting in present and future facilities.

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on
excluding unphysical values. The dark and light shaded zones represent the 68% and 95% probability regions, respectively.

FIG. 2: Projections of the fit onto the variable $m_{ES}$ after a cut on $F$ is applied (>$0.5$ for $K\pi$, $>0.7$ for $K\pi\pi^0$ and $>1$ for $K\pi\pi\pi$), to enhance the signal. The plots are shown for $K\pi$ (left), $K\pi\pi^0$ (middle) and $K\pi\pi\pi$ (right), same-sign (top) and opposite-sign (bottom) events. The points with error bars are data. The dashed, dotted and dash-dotted lines represent the signal, continuum background and $BB$ background contributions, respectively. The solid line represents the sum of all the contributions.

FIG. 3: Likelihood function for $R_{ADS}(K\pi)$ (left), $R_{ADS}(K\pi\pi^0)$ (middle) and $R_{ADS}(K\pi\pi\pi)$ (right), for $R_{ADS} \geq 0$, thus excluding unphysical values. The dark and light shaded zones represent the 68% and 95% probability regions, respectively.

FIG. 4: Likelihood function for $r_S$ from the combination of the measurements of $R_{ADS}$ obtained in the three $D$ decay channels. The dark and light shaded zones represent the 68% and 95% probability regions, respectively.

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