

A Search for the Rare Decay $B^0 \rightarrow D_s^+ \rho^-$

The *BABAR* Collaboration

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Abstract

We report on a search for the decay $B^0 \rightarrow D_s^+ \rho^-$ in a sample of 90×10^6 $\Upsilon(4S)$ decays into B meson pairs collected between 1999 and 2001 with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider. No significant excess of signal events above the expected background is observed. We set a 90% C.L. limit on the branching fraction $\mathcal{B}(B^0 \rightarrow D_s^+ \rho^-) < 1.9 \times 10^{-5}$. Assuming a flavor SU(3) symmetry relation between the decays $B^0 \rightarrow D_s^+ \rho^-$ and $B^0 \rightarrow D^+ \rho^-$, we set a limit on the ratio of CKM-suppressed to CKM-favored amplitudes $r(D\rho) < 9.5 \times 10^{-3}$ at 90% C.L. All results are preliminary.

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1 Introduction

The Cabibbo-Kobayashi-Maskawa (CKM) quark flavor-mixing matrix [1] provides an elegant explanation of the origin of CP violation within the Standard Model. CP violation manifests itself as a non-zero area of the unitarity triangle [2]. While it is sufficient to measure one of the angles to demonstrate the existence of CP violation, the unitarity triangle needs to be over-constrained by experimental measurements in order to demonstrate that the CKM mechanism is the correct explanation of this phenomenon. One of the important measurements is constraining the angle $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ of the unitarity triangle. A measurement of $\sin(2\beta + \gamma)$ can be obtained from the study of the time evolution of the $B^0 \rightarrow D^{(*)-}\pi^+$ and $B^0 \rightarrow D^{(*)-}\rho^+$ [4] decays, a large sample of which is already available at the B-factories, and of the corresponding CKM suppressed modes $B^0 \rightarrow D^{(*)+}\pi^-$ and $B^0 \rightarrow D^{(*)+}\rho^-$ [5]. The first measurements of $\sin(2\beta + \gamma)$ using $B^0 \rightarrow D^{(*)\mp}\pi^\pm$ decays have been recently published [6, 7], and a similar analysis using $B^0 \rightarrow D^\mp\rho^\pm$ decays is being reported at this conference [7].

The measurement of $\sin(2\beta + \gamma)$ using $B^0 \rightarrow D^\mp\rho^\pm$ decays requires the knowledge of the ratio of the decay amplitudes, $r(D\rho) = |A(B^0 \rightarrow D^+\rho^-)/A(B^0 \rightarrow D^-\rho^+)|$. Unfortunately, the direct measurement of the branching fraction $\mathcal{B}(B^0 \rightarrow D^+\rho^-)$ is not possible with the currently available data sample due to the presence of the copious background from $\bar{B}^0 \rightarrow D^+\rho^-$. However, assuming SU(3) flavor symmetry, $r(D\rho)$ can be related to the branching fraction of the decay $B^0 \rightarrow D_s^+\rho^-$ [5]:

$$r(D\rho) = (\tan\theta_c) \frac{f_D}{f_{D_s}} \sqrt{\frac{\mathcal{B}(B^0 \rightarrow D_s^+\rho^-)}{\mathcal{B}(B^0 \rightarrow D^-\rho^+)}} \quad (1)$$

where θ_c is the Cabibbo angle, and f_D/f_{D_s} is the ratio of D and D_s meson decay constants [8]. Other SU(3)-breaking effects are typically assumed to be of order 30% [6].

Since $D_s^+\rho^-$ has four different quark flavors in the final state, only a single amplitude contributes to the decay. The presence of the D_s^+ meson makes such decays easy to identify. Fig. 1 shows the dominant Feynman diagrams for the decays $B^0 \rightarrow D^-\rho^+$, $B^0 \rightarrow D^+\rho^-$, and $B^0 \rightarrow D_s^+\rho^-$. Eq. (1) assumes that the color-suppressed direct W -exchange amplitude for $B^0 \rightarrow D^+\rho^-$ is negligibly small, which is supported by the data [9].

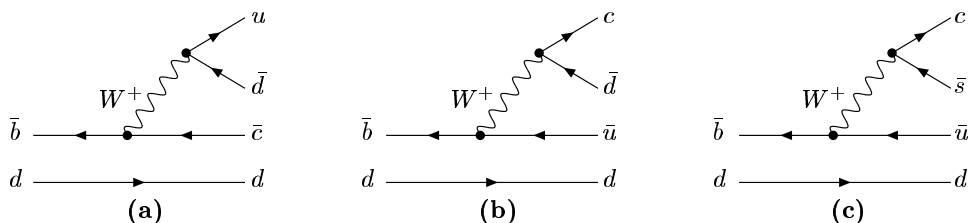


Figure 1: Dominant Feynman diagrams for CKM-favored decay $B^0 \rightarrow D^-\rho^+$ (a), doubly CKM-suppressed decay $B^0 \rightarrow D^+\rho^-$ (b), and the SU(3) flavor symmetry related decay $B^0 \rightarrow D_s^+\rho^-$ (c).

The present limit on the branching fraction $\mathcal{B}(B^0 \rightarrow D_s^+\rho^-)$ is 7×10^{-4} at 90% C.L. [10]. The related decay $B^0 \rightarrow D_s^+\pi^-$ has recently been observed [9].

2 Data Sample, Detector, and Simulation

We use a sample of 90×10^6 $\Upsilon(4S)$ decays into $B\bar{B}$ pairs collected in the years 1999-2002 with the *BABAR* detector at the PEP-II asymmetric-energy B -factory [11]. Since the *BABAR* detector is described in detail elsewhere [12], only the components of the detector crucial to this analysis are summarized below. Charged particle tracking is provided by a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH). For charged-particle identification, ionization energy loss (dE/dx) in the DCH and SVT, and Cherenkov radiation detected in a ring-imaging device (DIRC) are used. Photons and neutral pions are identified and measured using the electromagnetic calorimeter, which comprises 6580 thallium-doped CsI crystals. These systems are mounted inside a 1.5 T solenoidal superconducting magnet. We use the GEANT [13] software to simulate interactions of particles traversing the *BABAR* detector, taking into account the varying detector conditions and beam backgrounds.

3 Analysis

We select events with a minimum of three reconstructed charged tracks and a total measured energy greater than 4.5 GeV, as determined using all charged tracks and neutral clusters with energy above 30 MeV. In order to reject $e^+e^- \rightarrow q\bar{q}$, ($q = u, d, s, c$) continuum background, the ratio of the second and zeroth order Fox-Wolfram moments [14] must be less than 0.5.

The selection criteria are optimized to maximize the ratio of the expected number of signal events over the square-root of the expected number of background events, S/\sqrt{B} . The optimization was performed on large samples of simulated signal and $q\bar{q}$ and $B\bar{B}$ background events.

The D_s^+ mesons are reconstructed in the modes $D_s^+ \rightarrow \phi\pi^+$, $\bar{K}^{*0}K^+$ and $\bar{K}^0(K_s^0)K^+$, with $\phi \rightarrow K^+K^-$, $K_s^0 \rightarrow \pi^+\pi^-$ and $\bar{K}^{*0} \rightarrow K^-\pi^+$. The K_s^0 candidates are reconstructed from two oppositely-charged tracks with an invariant mass $493 < M_{\pi^+\pi^-} < 503$ MeV/ c^2 . All other charged tracks in the B meson decay are required to originate from the e^+e^- interaction point. Depending on the decay mode of the D_s^+ mesons, different selections are used to identify charged kaons. In the $D_s^+ \rightarrow \phi\pi^+$ ($\phi \rightarrow K^+K^-$) decay mode, we identify kaons by applying a pion veto with an efficiency of 95% for kaons and a 20% pion misidentification. In the $D_s^+ \rightarrow \bar{K}^{*0}K^+$ and $D_s^+ \rightarrow \bar{K}^0K^+$ modes, a tight kaon selection with an efficiency of 85% and 5% pion misidentification probability is required for the K^+ candidate from the D_s^+ meson.

The ϕ candidates are reconstructed from two oppositely-charged kaons with an invariant mass $1009 < M_{K^+K^-} < 1031$ MeV/ c^2 . The \bar{K}^{*0} candidates are constructed from the K^- and a π^+ candidates and are required to have an invariant mass in the range $862 < M_{K^-\pi^+} < 922$ MeV/ c^2 .

The polarizations of the \bar{K}^{*0} and ϕ mesons in the D_s^+ decays are also utilized to reject backgrounds through the use of the helicity angles $\theta_H(\bar{K}^{*0})$ and $\theta_H(\phi)$. The helicity angle is defined as the angle between one of the decay products of the \bar{K}^{*0} (or ϕ) and the direction of flight of the meson itself, in the meson rest frame. Background events are distributed uniformly in $\cos\theta_H$ since they originate from random combinations, while signal events are distributed as $\cos^2\theta_H$. Both ϕ and \bar{K}^{*0} candidates are required to have $|\cos\theta_H| > 0.55$. Finally, after constraining the D_s^+ decay products to the same geometric vertex with a probability greater than 10^{-4} , the D_s^+ candidates are required to have an invariant mass within 8 or 9 MeV/ c^2 of the known value [10], depending on the D_s^+ mode.

The neutral pion candidates are reconstructed from a pair of photons with a minimum energy of 30 MeV. The invariant mass of the photon pair is required to be within a window $100 < m_{\gamma\gamma} <$

160 MeV/c². After the mass of the π^0 candidate is constrained to 135 MeV/c², it is combined with a track originating from the interaction point to form ρ^- candidates. The charged tracks are required to pass a loose pion selection. We require that the invariant mass of the two pions forming the ρ^- candidate be within 160 MeV/c² of the known value [10].

We also take advantage of the ρ^- polarization in the $B^0 \rightarrow D_s^+ \rho^-$ decays, requiring that the cosine of the helicity angle $\theta_H(\rho)$ be either larger than 0.3, 0.35, 0.2, or smaller than -0.15 , -0.1 , -0.4 for the $D_s^+ \rightarrow \phi\pi^+$, $D_s^+ \rightarrow \bar{K}^{*0}K^+$, and $D_s^+ \rightarrow \bar{K}^0K^+$ modes, respectively. Signal events are distributed as $\cos^2 \theta_H(\rho)$, modulated by the energy dependence of the π^0 efficiency. The asymmetric selection takes into account the larger probability to find a random combination of charged and neutral pions in the forward direction in $\theta_H(\rho)$, which corresponds to low π^0 energy.

We combine oppositely-charged D_s^\pm and ρ^\mp candidates to form $B^0 \rightarrow D_s^+ \rho^-$ candidates. The mass of D_s^\pm candidates is constrained to the known value [10]. In order to reject events where the D_s^+ comes from a B and the ρ^- from the other B , we require that these two candidates have a vertex fit probability greater than 0.6% of originating from a common vertex.

We suppress combinatorial background from $q\bar{q}$ production using the event topology, computing the angle (θ_T) between the thrust axis of the B meson decay product candidates and the thrust axis of all the other particles in the event. In the center-of-mass frame (CM), $B\bar{B}$ pairs are produced approximately at rest and produce a uniform $\cos \theta_T$ distribution. In contrast, $q\bar{q}$ pairs are produced back-to-back in the CM frame, which results in a $|\cos \theta_T|$ distribution peaking at 1. Depending on the background level of each mode, $|\cos \theta_T|$ is required to be smaller than a value which ranges between 0.6 and 0.85.

We also exploit the characteristic $\sin^2 \theta_B$ angular distribution for $e^+e^- \rightarrow B\bar{B}$ events, where θ_B is the angle between the B candidate flight direction and the direction of the incident electron beam in CM frame. In contrast, the $q\bar{q}$ backgrounds tend to maintain $1 + \cos^2 \theta_B$ distribution characteristic of spin-1/2 particles. We require that $|\cos \theta_B|$ of the B candidate is less than 0.6 for $D_s^+ \rightarrow \phi\pi^+$, 0.8 for $D_s^+ \rightarrow \bar{K}^{*0}K^+$, and 0.7 for $D_s^+ \rightarrow \bar{K}^0K^+$.

We further suppress backgrounds using a Fisher discriminant, \mathcal{F} , constructed from the scalar sum of the CM momenta of all tracks and photons (excluding the B candidate decay products) flowing into 9 concentric cones centered on the thrust axis of the B candidate [15]. The more spherical the event, the lower the value of \mathcal{F} . Figure 2 shows a plot of the Fisher discriminant for signal and continuum background events from Monte Carlo.

We extract the signal using two kinematic variables m_{ES} and ΔE . The first is the beam-energy-substituted mass $m_{\text{ES}} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$, where \sqrt{s} is the total e^+e^- center-of-mass energy, (E_i, \mathbf{p}_i) is the four-momentum of the initial e^+e^- system and \mathbf{p}_B is the B^0 candidate momentum, both measured in the laboratory frame. The second variable is $\Delta E = E_B^* - \sqrt{s}/2$, where E_B^* is the B^0 candidate energy in the CM frame. For signal events, m_{ES} peaks at the B meson mass with a resolution of about 3 MeV/c² and ΔE peaks near zero with a resolution of about 30 MeV, indicating that the candidate system of particles has a total energy consistent with the beam energy in the CM frame. For the purposes of selection optimization, we define the signal region between $5.27 < m_{\text{ES}} < 5.29$ GeV/c² and $|\Delta E| < 45$ MeV. Figure 3 shows the m_{ES} and ΔE distributions for simulated signal events and background from decays $B^0 \rightarrow D_s^{*+} \rho^-$ reconstructed as $B^0 \rightarrow D_s^+ \rho^-$, $D_s^+ \rightarrow \phi\pi^+$.

Approximately 40% of the selected events contained two or more $B^0 \rightarrow D_s^+ \rho^-$ candidates that satisfy the criteria listed above. In such events we select a single B^0 candidate based on: 1) the reconstructed mass of the D_s^+ meson, 2) the reconstructed mass of the π^0 candidate, and 3) the ΔE variable. The choice is made using these variables in a hierarchical manner with the ΔE selection

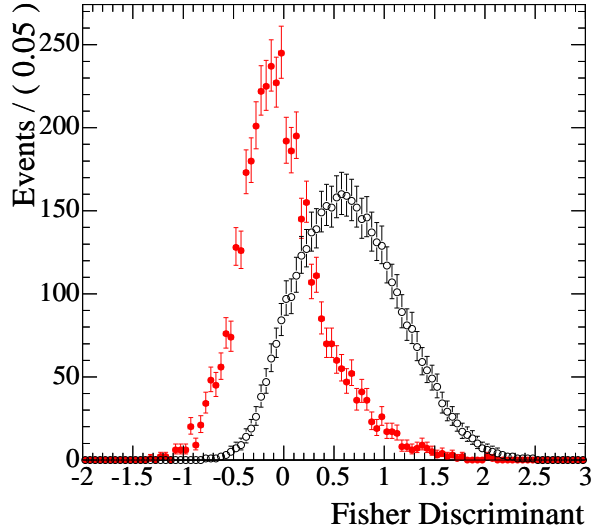


Figure 2: Fisher discriminant for simulated signal (solid red circles) events and continuum background (open black circles) reconstructed as $B^0 \rightarrow D_s^+ \rho^-$, $D_s^+ \rightarrow \phi \pi^+$

applied last, in order to avoid creating a bias in the ΔE distribution of the background events. No significant bias is observed in the large Monte Carlo sample of generic $q\bar{q}$ production events and B^0 and B^\pm decays, excluding $b \rightarrow u\bar{c}s$ transitions.

After the above selection, two main classes of backgrounds remain. First, there is combinatorial background from $q\bar{q}$ production and generic B meson decays. We describe this background by a two-dimensional distribution function of m_{ES} and ΔE . In m_{ES} , this background is described by an ARGUS function, $dN/dx \propto x\sqrt{1-2x^2/s} \exp[-\xi(1-2x^2/s)]$, characterized by the shape parameter ξ [16]. In ΔE , the combinatorial background is well described by a first-order polynomial.

Second, B meson decays with a D_s^+ and a light meson in the final state that correspond to $b \rightarrow u\bar{c}s$ quark transitions produce distributions similar to signal events in m_{ES} , but are typically shifted from zero or broadened in ΔE . These types of background will, hereafter, be referred to as peaking backgrounds. We have found that the largest contributions in the signal region come from decays $B^+ \rightarrow D_s^+ \rho^0$, $B^0 \rightarrow D_s^{*+} \rho^-$, and $B^0 \rightarrow D_s^{*+} \pi^-$. Of these decay modes, only the latter has been previously measured [9]. We determined the m_{ES} and ΔE distributions of these decays, reconstructed as signal $B^0 \rightarrow D_s^+ \rho^-$ chain, from a large Monte Carlo sample, equivalent to several times our data luminosity.

Our kinematic selection suppresses higher resonances such as $\rho(1450)$ and non-resonant $B^0 \rightarrow D_s^+ \pi^- \pi^0$ component, which are found to be negligibly small in $B^0 \rightarrow D^- \pi^+ \pi^0$ decays [7]. We ignore any possible contributions to $D_s^+ \pi^- \pi^0$ final state other than $\rho^- \rightarrow \pi^- \pi^0$.

4 Yield Extraction

Figure 4 shows the distribution of events in the $(m_{\text{ES}}, \Delta E)$ plane for each of the D_s^+ decay modes. In the signal region, we observe 1 event for $D_s^+ \rightarrow \phi \pi^+$, 4 for $D_s^+ \rightarrow \bar{K}^{*0} K^+$, and 2 for $D_s^+ \rightarrow \bar{K}^0 K^+$, with comparable numbers expected from the backgrounds.

To extract the signal yield, we perform an unbinned extended maximum-likelihood fit to the $(m_{\text{ES}}, \Delta E)$ distributions of all three D_s^+ decay modes simultaneously in the ranges $5.2 \leq m_{\text{ES}} \leq$

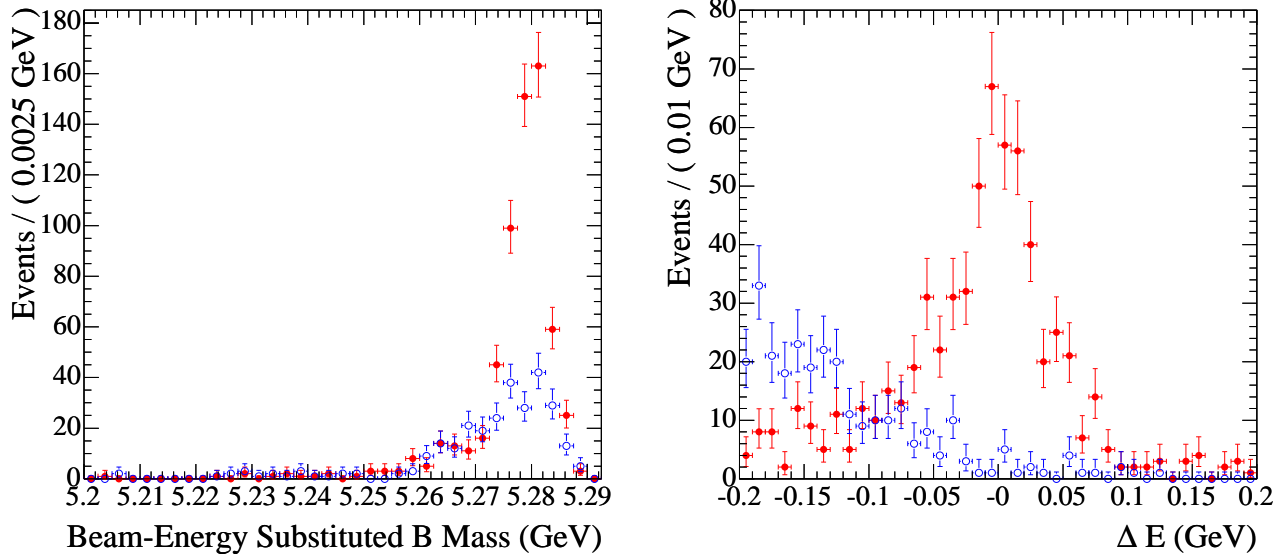


Figure 3: m_{ES} (left) and ΔE (right) distributions for simulated signal (solid red circles) and $B^0 \rightarrow D_s^{*+}\rho^-$ (open blue circles) peaking background events reconstructed as $B^0 \rightarrow D_s^+\rho^-$, $D_s^+ \rightarrow \phi\pi^+$.

5.3 GeV/ c^2 , $-200 \leq \Delta E \leq 200$ MeV. The total number of events in the sample is 163. The likelihood function contains the contributions from the combinatorial backgrounds, signal, and peaking backgrounds. The probability density functions for combinatorial and peaking backgrounds are found to be common to all three D_s^+ modes in Monte Carlo simulation, while the shapes of the signal distributions are determined independently for each D_s^+ decay mode. No significant correlation between m_{ES} and ΔE is observed in Monte Carlo samples, and the likelihoods used in the fit ignore any such correlation.

Eight free parameters constrained by the fit include the shape of the combinatorial background, characterized by the parameter ξ in m_{ES} and the constant term and a linear slope in ΔE , as well as the combinatorial background yields in each D_s^+ mode and the branching fractions of decays $B^0 \rightarrow D_s^+\rho^-$ and $B^0 \rightarrow D_s^{*+}\rho^-$. The signal and peaking background efficiencies are constrained to the values determined by simulation for each D_s^+ decay mode. The branching fraction of $B^+ \rightarrow D_s^+\rho^0$ is constrained to be half of $\mathcal{B}(B^0 \rightarrow D_s^+\rho^-)$ from isospin symmetry, and the branching fraction of $B^0 \rightarrow D_s^{*+}\pi^-$, is fixed in the fit to the value measured by *BABAR* [9]. The uncertainties due to this assumption are included in the systematics. The results of the fit are shown in Fig. 5.

The reconstruction efficiencies, as estimated from the Monte Carlo simulation, and the number of observed events in the signal region are summarized in the top portion of Table 1. The bottom portion of Table 1 summarizes the signal, combinatorial background, and peaking background yields from the fit to data. The central value of the branching fraction returned by the fit is $\mathcal{B}(B^0 \rightarrow D_s^+\rho^-) = [0.2 \pm 0.7(\text{stat.})] \times 10^{-5}$. The log-likelihood of the fit is consistent with Monte Carlo expectations.

5 Systematic Uncertainties

The systematic uncertainties are dominated by the potential contributions from additional peaking backgrounds, such as decays $B^0 \rightarrow D_s^-K^+$, $B^+ \rightarrow D_s^{*+}\rho^0$, $B^0 \rightarrow D_s^-K^{*+}$, $B^0 \rightarrow D_s^+a_1^-$, and

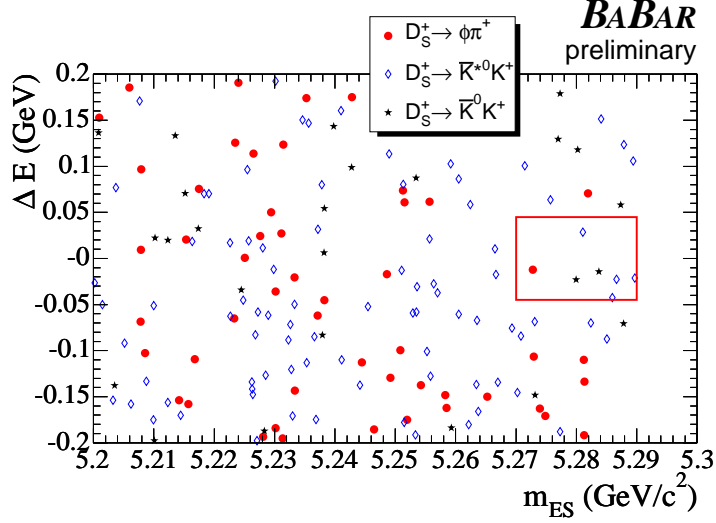


Figure 4: ΔE vs m_{ES} distribution for $B^0 \rightarrow D_s^+ \rho^-$ candidates reconstructed in the sample of $90 \times 10^6 \Upsilon(4S)$ decays in $D_s^+ \rightarrow \phi\pi^+$ (full circles), $D_s^+ \rightarrow \bar{K}^{*0}K^+$ (empty diamonds), and $D_s^+ \rightarrow \bar{K}^0K^+$ (black stars) modes. The box corresponds to the signal region $5.27 < m_{ES} < 5.29 \text{ GeV}/c^2$ and $|\Delta E| < 45 \text{ MeV}$.

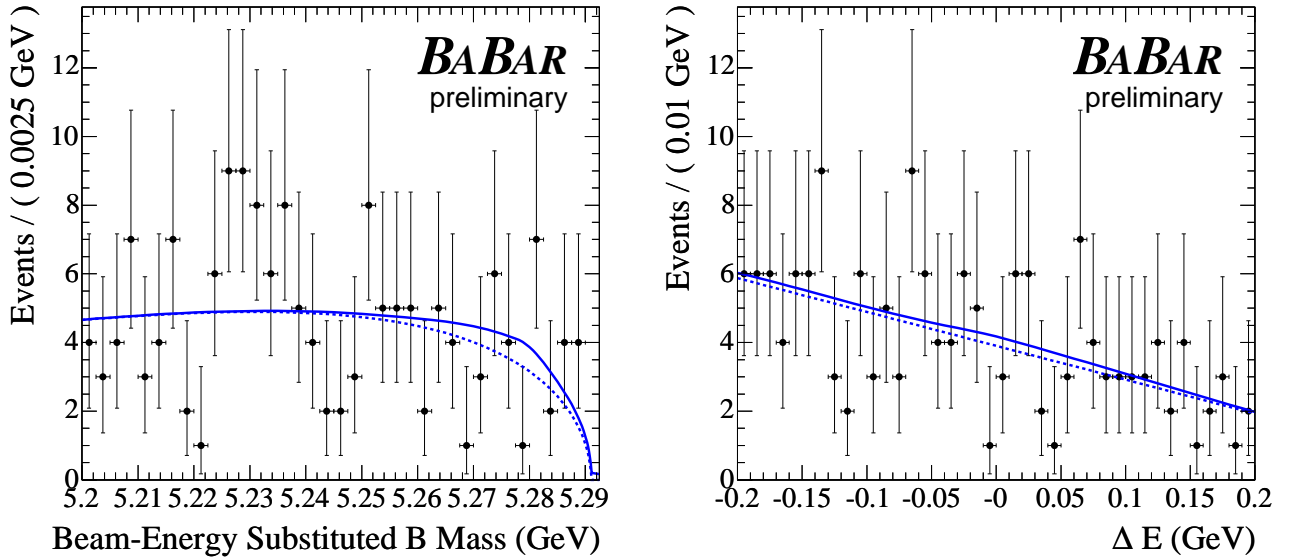


Figure 5: m_{ES} (left) and ΔE (right) distributions for $B^0 \rightarrow D_s^+ \rho^-$ candidates reconstructed in the sample of $90 \times 10^6 \Upsilon(4S)$ decays. The solid curve corresponds to the full probability density function from the combined fit to all D_s^+ decay modes. The dashed line is the contribution from the combinatorial backgrounds.

Table 1: The reconstruction efficiency ε , number of candidates N_{obs} observed in the signal region $5.27 < m_{\text{ES}} < 5.29 \text{ GeV}/c^2$ and $|\Delta E| < 45 \text{ MeV}$, the contributions from the signal mode $B^0 \rightarrow D_s^+ \rho^-$ (N_{sig}), and combinatorial (N_{comb}) and peaking backgrounds from the fit to data.

| | $D_s^+ \rightarrow \phi\pi^+$ | $D_s^+ \rightarrow \bar{K}^{*0}K^+$ | $D_s^+ \rightarrow \bar{K}^0K^+$ | All D_s^+ Modes |
|--------------------------------------|-------------------------------|-------------------------------------|----------------------------------|-------------------|
| ε | 3.4% | 1.4% | 2.1% | |
| N_{obs} | 1 | 4 | 2 | 7 |
| N_{sig} | 0.16 ± 0.60 | 0.06 ± 0.21 | 0.11 ± 0.41 | 0.32 ± 0.75 |
| N_{comb} | 1.64 ± 0.26 | 2.88 ± 0.32 | 0.74 ± 0.18 | 5.27 ± 0.44 |
| $N_{B^0 \rightarrow D_s^{*+}\rho^-}$ | 0.04 ± 0.14 | 0.02 ± 0.07 | 0.03 ± 0.10 | 0.10 ± 0.19 |
| $N_{B^0 \rightarrow D_s^{*+}\pi^-}$ | 0.42 ± 0.29 | 0.15 ± 0.10 | 0.30 ± 0.21 | 0.87 ± 0.37 |
| $N_{B^+ \rightarrow D_s^+\rho^0}$ | 0.01 ± 0.01 | 0.00 ± 0.00 | 0.01 ± 0.01 | 0.02 ± 0.01 |

$B^0 \rightarrow D_s^{*+}a_1^-$. Their contributions are estimated from Monte Carlo. In addition, the branching fraction of $B^0 \rightarrow D_s^{*+}\pi^-$, fixed in the fit, is varied within its experimental uncertainties [9]. Altogether, the uncertainties in the peaking background contributions amount for a $\pm 0.2 \times 10^{-5}$ systematic uncertainty on $\mathcal{B}(B^0 \rightarrow D_s^+\rho^-)$. Other systematic uncertainties include an 11% relative uncertainty in $\mathcal{B}(D_s^+ \rightarrow \phi\pi^+)$ [17], a 9% relative uncertainty in reconstruction efficiency due to Monte Carlo statistics, and uncertainties in charged track reconstruction efficiency, π^0 , K_s^0 , and charged kaon identification.

6 Preliminary Results

Combining all systematic uncertainties, the central value of $B^0 \rightarrow D_s^+\rho^-$ branching fraction is

$$\mathcal{B}(B^0 \rightarrow D_s^+\rho^-) = [0.2 \pm 0.7 \text{ (stat.)} \pm 0.2 \text{ (syst.)}] \times 10^{-5},$$

consistent with zero within the current level of precision. We set a 90% Bayesian confidence limit at

$$\mathcal{B}(B^0 \rightarrow D_s^+\rho^-) < 1.9 \times 10^{-5},$$

assuming a constant prior for $\mathcal{B}(B^0 \rightarrow D_s^+\rho^-) > 0$. The likelihood distribution of $\mathcal{B}(B^0 \rightarrow D_s^+\rho^-)$ and the 90% C.L. limit are shown in Fig. 6.

Using Eq. (1) and the recent lattice QCD value $f_{D_s}/f_D = 1.22 \pm 0.04$ [8], and assuming no additional flavor SU(3) violation, we compute the value and 90% confidence limit on $r(D\rho)$ to be

$$\begin{aligned} r(D\rho) &= 0.003 \pm 0.006 \text{ (stat.)} \pm 0.002 \text{ (syst.)} \\ r(D\rho) &< 9.5 \times 10^{-3} \text{ (at 90\% C.L.)} \end{aligned}$$

The low value of $r(D\rho)$ compared to $r(D^{(*)}\pi)$ determined from $B^0 \rightarrow D_s^{(*)+}\pi^-$ decays [6, 9] is somewhat unexpected. It implies small sensitivity of CP asymmetries in $B^0 \rightarrow D^\mp \rho^\pm$ decays to $\sin(2\beta + \gamma)$, making that measurement significantly more challenging.

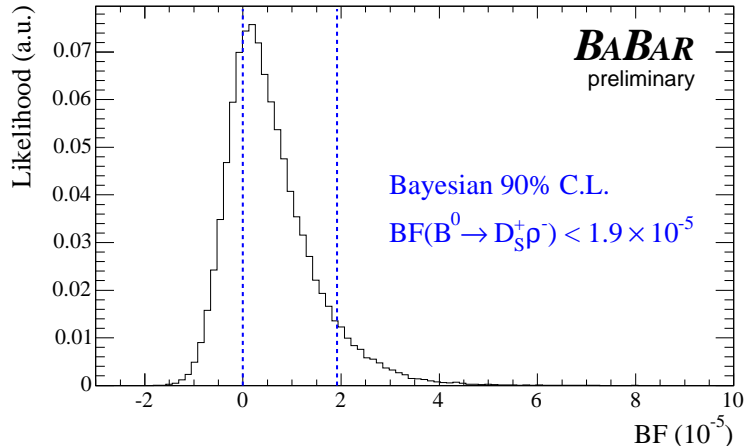


Figure 6: Likelihood distribution for $\mathcal{B}(B^0 \rightarrow D_s^+ \rho^-)$, combining both statistical and systematic uncertainties. The dashed lines show the Bayesian 90% confidence level limit assuming a constant prior for $\mathcal{B}(B^0 \rightarrow D_s^+ \rho^-) > 0$.

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