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Search for  $B^- \to D_S^{(*)-} \phi$ 

The BABAR Collaboration

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#### Abstract

We report on searches for  $B^- \to D_S^- \phi$  and  $B^- \to D_S^{*-} \phi$ . In the context of the Standard Model the branching fractions for these decays are expected to be highly suppressed, since they proceed through annhibition of the *b* and  $\bar{u}$  quarks in the  $B^-$  meson. Our results are based on 234 million  $\Upsilon(42) \to B\overline{B}$  decays collected with the BABAR detector at SLAC. We find no evidence for these decays, and we set 90% confidence level upper limits on the branching fractions

> $\mathcal{B}(B^- \to D_S^- \phi) < 1.8 \times 10^{-6}$  $\mathcal{B}(B^- \to D_S^{*-} \phi) < 1.1 \times 10^{-5}.$

These results are consistent with Standard Model expectations.

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# 1 Introduction

In the Standard Model (SM), the decay  $B^- \to D_S^{(*)-}\phi$  occurs through annhibition of the two quarks in the *B*-meson into a virtual *W*, see Figure 1. No annhibition-type *B* decays have ever been observed to date. The current 90% C.L. upper limits on  $B^- \to D_S^-\phi$  and  $B^- \to D_S^{*-}\phi$  are  $3.2 \times 10^{-4}$  and  $4 \times 10^{-4}$ , respectively [1].



Figure 1: Feynman diagram for  $B^- \to D_S^{(*)-} \phi$ .

In the SM, annhibition diagrams are highly suppressed. Calculations of the  $B^- \to D_S^- \phi$  branching fraction give predictions of  $3 \times 10^{-7}$  using a perturbative QCD approach [2], or  $7 \times 10^{-7}$  using QCD-improved factorization [3].

Since the current experimental limits are about three orders of magnitude higher than the SM expectations, searches for  $B^- \to D_S^{(*)-}\phi$  could be sensitive to new physics contributions. For example, in Reference [3] the branching fraction of  $B^- \to D_S^-\phi$  is estimated to be  $8 \times 10^{-6}$  in a two Higgs doublet model and  $3 \times 10^{-4}$  in the minimal supersymmetric model with *R*-parity violation.

# 2 The BABAR detector and dataset

Our results are based on  $234 \times 10^6 \ \Upsilon(4S) \to B\overline{B}$  decays, corresponding to an integrated luminosity of 212 fb<sup>-1</sup>, collected between 1999 and 2004 with the *BABAR* detector [4] at the PEP-II *B* Factory at SLAC [5]. A 12 fb<sup>-1</sup> off-resonance data sample, with a center of mass (CM) energy 40 MeV below the  $\Upsilon(4S)$  resonance peak, is used to study continuum events,  $e^+e^- \to q\bar{q}$  (q = u, d, s, or *c*). The number of *B*-mesons in our data sample is two orders of magnitudes larger than in the previously published search for  $B^- \to D_S^{(*)-} \phi$  [1].

## 3 Analysis method

We search for the decay  $B^- \to D_S^{(*)-} \phi$  in the following modes:  $D_S^{*-} \to D_S^- \gamma$ ,  $D_S^- \to \phi \pi^-$ ,  $K_S K^-$ , and  $K^{*0}K^-$ ,  $\phi \to K^+K^-$ ,  $K_S \to \pi^+\pi^-$ , and  $K^{*0} \to K^+\pi^-$  (charged conjugate decay modes are implied throughout this article). We denote the  $\phi$  from  $B^- \to D_S^{(*)-} \phi$  decay as the "bachelor  $\phi$ ", in order to distinguish it from the  $\phi$  in the  $D_S^- \to \phi \pi^-$  decay. All kaon candidate tracks in the reconstructed decay chains must satisfy a set of loose kaon identification criteria based on the response of the internally-reflecting ring-imaging Cherenkov radiation detector and the ionization measurements in the Drift Chamber and the Silicon Vertex Tracker. The kaon selection efficiency is a function of momentum and polar angle, and is typically 95%. These requirements provide a rejection factor of order 10 against pion backgrounds. No particle identification requirements are imposed on pion candidate tracks.

We select  $\phi$ ,  $K_S$ , and  $K^{*0}$  candidates from pairs of oppositely-charged tracks with invariant masses consistent with the parent particle decay hypothesis and consistent with originating from a common vertex. The invariant mass requirements are  $\pm 10 \text{ MeV}$  ( $\sim 2.4\Gamma$ ) for the  $\phi$ ,  $\pm 9 \text{ MeV}$  ( $\sim 3\sigma$ ) for the  $K_S$ , and  $\pm 75 \text{ MeV}$  ( $\sim 1.5\Gamma$ ) for the  $K^{*0}$ . We then form  $D_S^-$  candidates in the three modes listed above by combining  $\phi$ ,  $K_S$ , or  $K^{*0}$  candidates with an additional track. The invariant mass of the  $D_S^-$  candidate must be within 15 MeV ( $\sim 3\sigma$ ) of the known  $D_S^-$  mass. In the  $D_S^- \to \phi\pi^-$  and  $D_S^- \to K^{*0}K^-$  modes, all three charged tracks are required to originate from a common vertex. In the  $D_S^- \to K_S K^-$  mode, the  $K_S$  and  $D_S^-$  vertices are required to be separated by at least 3 mm. This last requirement is very effective in rejecting combinatorial background and is 94% efficient for signal. We select  $D_S^{*-}$  candidates from  $D_S^-$  and photon candidates. The photon candidates are constructed from calorimeter clusters with lateral profiles consistent with photon showers and with energy above 60 MeV in the laboratory frame. We require that the mass difference  $\Delta M$  between the  $D_S^{*-}$  and  $D_S$  candidates be between 130 and 156 MeV. The  $\Delta M$  resolution is about 5 MeV.

At each stage in the reconstruction chain, the measurement of the momentum vector of an intermediate particle is improved by refitting the momenta of the decay products with kinematical constraints. These constraints are based on the known mass of the intermediate particle and on the fact that the decay products must originate from a common point in space.

Finally, we select  $B^-$  candidates by combining  $D_S^{(*)-}$  and bachelor  $\phi$  candidates. A  $B^-$  candidate is characterized kinematically by the energy-substituted mass  $m_{\rm ES} \equiv \sqrt{(\frac{1}{2}s + \vec{p}_0 \cdot \vec{p}_B)^2 / E_0^2 - p_B^2}$ and energy difference  $\Delta E \equiv E_B^* - \frac{1}{2}\sqrt{s}$ , where E and p are energy and momentum, the asterisk denotes the CM frame, the subscripts 0 and B refer to the initial  $\Upsilon(4S)$  and B candidate, respectively, and s is the square of the CM energy. In the CM frame,  $m_{\rm ES}$  reduces to  $m_{\rm ES} = \sqrt{\frac{s}{4} - p_B^{*2}}$ . For signal events we expect  $m_{\rm ES} \sim M_B$ , the known  $B^-$  mass, and  $\Delta E \sim 0$ . The resolutions on  $m_{\rm ES}$  and  $\Delta E$  are approximately 2.6 MeV and 10 MeV, respectively.

If there is more than one  $B^-$  candidate in an event, we retain the best candidate based on a  $\chi^2$  algorithm that uses the measured values, known values, and resolutions for the  $D_S^-$  mass, the bachelor  $\phi$  mass, and, where applicable,  $\Delta M$ .

Studies of simulated events and off-resonance data indicate that most of the backgrounds to the  $B^- \to D_S^{(*)-} \phi$  signal are from continuum events. To reduce these backgrounds we make two additional requirements. First, we require  $|\cos \theta_T| < 0.9$ , where  $\theta_T$  is the angle between the thrust axes of the  $B^-$  candidate and the rest of the tracks and neutral clusters in the event, calculated in the CM frame. The distribution of  $|\cos \theta_T|$  is essentially uniform for signal events and strongly peaked near one for continuum events. Second, for each event we define a relative likelihood for signal and background based on a number of kinematical quantities. The relative likelihood is defined as the ratio of the likelihoods for signal and background. The signal (background) likelihood is defined as the product of the probability density functions, PDFs, for the various kinematical quantities in signal (background) events.

The kinematical quantities used in the likelihood are reconstructed masses, decay angles, and a Fisher discriminant designed to distinguish between continuum and  $B\overline{B}$  events. All PDFs are

chosen based on studies of Monte Carlo and off-resonance data.

The masses used in the likelihoods are those of the  $D_S^-$ , the  $\phi$  in the  $D_S^- \to \phi \pi^-$ , the  $K^{*0}$  in  $D_S^- \to K^{*0}K^-$ , and  $\Delta M$  in  $D_S^{*-} \to D_S\gamma$ . The signal PDFs for the mass variables are the sum of two Gaussian distributions for  $D_S$  and  $\Delta M$ , a Breit Wigner distribution for the  $K^{*0}$ , and a Voigtian distribution for the  $\phi$  from  $D_S$  decay. The background PDFs are constant functions. Note that the mass of the bachelor  $\phi$  and the mass of the  $K_S$  in  $D_S^- \to K_S K^-$  are not used in the definition of the likelihoods. This is because studies of background event samples suggest that background events contain mostly real bachelor  $\phi$  and real  $K_S$  mesons.

The decay angles used in the likelihood are those in the  $K^{*0} \to K^+\pi^-$  and in the  $\phi \to K^+K^$ decay, both for bachelor  $\phi$  and the  $\phi$  from  $D_S^- \to \phi\pi^-$  decay. The signal PDFs for these quantities are set by angular momentum conservation to be proportional to  $\cos^2 \theta$ , where  $\theta$  is the decay angle for the process. The one exception is the decay angle distribution of the bachelor  $\phi$  in  $B^- \to D_S^{*-}\phi$ decay, where the polarization of the two vector mesons in the final state is not known. For this reason, the decay angle of the bachelor  $\phi$  is not used in the definition of the likelihood for the  $B^- \to D_S^{*-}\phi$  mode. The background PDFs for these variables are constant functions of  $\cos \theta$ . In addition, in the likelihood we also use the polar angle of the  $B^-$  candidate in the CM frame ( $\theta_B$ ). The signal is expected to follow a  $\sin^2 \theta_B$  distribution, while the background is independent of  $\cos \theta_B$ .

The final component of the likelihood is a Fisher discriminant constructed from the quantities  $L_0 = \sum_i p_i$  and  $L_2 = \sum_i p_i \cos^2 \theta_i$  calculated in the CM frame. Here,  $p_i$  is the momentum and  $\theta_i$  is the angle with respect to the thrust axis of the  $B^-$  candidate of tracks and clusters not used to reconstruct the  $B^-$ . The signal and background PDFs for this variable are modelled as bifurcated Gaussians with different means and standard deviations. Note that this Fisher discriminant is highly correlated with the  $|\cos \theta_T|$  variable defined above. It is because of this correlation that the  $|\cos \theta_T|$  variable is treated separately and not included in the likelihood.

The combined efficiency of the requirements on likelihood and  $|\cos \theta_T|$  varies between 71 and 83%, depending on the mode. These requirements provide a rejection factor of about 7 against backgrounds. They were chosen from studies of off-resonance data as well as simulated background and signal events.

After applying the requirements on relative likelihood and  $|\cos \theta_T|$ , we also demand that  $\Delta E$  be within 30 MeV ( $\sim 3\sigma$ ) of its expected mean value for signal events. This mean value is determined from simulation, and varies between -3 and 0 MeV, depending on the mode.

Table 1: Efficiency  $(\epsilon_i)$ , branching fractions  $(BR_i)$ , and products of efficiency and branching fractions for the modes used in the  $B^- \to D_S^{(*)-} \phi$  search. The uncertainties on the  $\epsilon_i$  and  $BR_i$  are discussed in the text. Here  $BR_i$  is the product of branching fractions for the secondary and tertiary decays in the *i*-th decay mode.

Mode	$\epsilon_i$	$BR_i$	$\epsilon_i \cdot \mathrm{BR}_i$
$B^- \to D_S^- \phi,  D_S^- \to \phi \pi^-$	0.192	$11.6 \cdot 10^{-3}$	$2.22 \cdot 10^{-3}$
$B^- \to D_S^- \phi,  D_S^- \to K^- K_S$	0.177	$8.20 \cdot 10^{-3}$	$1.45 \cdot 10^{-3}$
$B^- \rightarrow D_S^- \phi,  D_S^- \rightarrow K^{*0} K^-$	0.140	$14.5\cdot10^{-3}$	$2.03\cdot 10^{-3}$
$B^- \to D_S^{*-} \phi,  D_S^- \to \phi \pi^-$	0.109	$10.9 \cdot 10^{-3}$	$1.19 \cdot 10^{-3}$
$B^- \to D_S^{*-}\phi,  D_S^- \to K^-K_S$	0.100	$7.70 \cdot 10^{-3}$	$0.77\cdot10^{-3}$
$B^- \to D_S^{*-}\phi,  D_S^{} \to K^{*0}K^-$	0.083	$13.6\cdot10^{-3}$	$1.14 \cdot 10^{-3}$

The efficiencies of our selection requirements, shown in Table 1, are determined from simulations. In the case of the  $B^- \to D_S^{*-} \phi$  mode we take the average of the efficiencies calculated assuming fully longitudinal or transverse polarization for the two vector meson final state. These efficiencies are found to be the same to within 1%. The quantities BR<sub>i</sub> in Table 1 are the product of the known branching fractions for the secondary decay modes. These are taken from the compilation of the Particle Data Group [6], with the exception of the branching fraction for the  $D_S \to \phi \pi$  mode, for which we use the latest most precise measurement  $\mathcal{B}(D_S \to \phi \pi) = (4.8 \pm 0.6)\%$  [7]. Since the branching fractions for the other two  $D_S$  modes are measured with respect to the  $D_S \to \phi \pi$  mode, we have also rescaled their tabulated values from the Particle Data Group accordingly.

## 4 Systematic studies

The systematic uncertainties on the products of efficiency and branching ratio for the secondary decays in the decay chain of interest are summarized in Table 2. The largest systematic uncertainty is associated with the uncertainty on the  $D_S \rightarrow \phi \pi$  branching ratio, which is only known to 12% [7], and which is used to normalize all other  $D_S$  branching ratios.

From a purely experimental point of view, the most important uncertainty is due to the uncertainty in the efficiency of the kaon identification requirements. The efficiency of these requirements is calibrated using a sample of kinematically identified  $D^{*0} \to D^0 \pi^+$ ,  $D^0 \to K^- \pi^+$ , and is known at the level of 2%. Thus, this uncertainty result in a systematic uncertainty of 8% for the efficiency of the modes with four charged kaons, i.e. those with  $D_S^- \to K^{*0}K^-$  and  $D_S^- \to \phi\pi$ , and 6% for the mode with three charged kaons  $(D_S^- \to K_S K^-)$ . A second class of uncertainties is associated with the detection efficiency for tracks and clusters in the BABAR detector. From studies of a variety of control samples, the tracking efficiency is understood at the level of 1.4% or 0.6% for transverse momenta below or above 200 MeV/c. There is also a 1.9% uncertainty associated with the reconstruction of the  $K_S \to \pi^+ \pi^-$  decay which can occur a few centimeters away from the interaction point. Given the multiplicity and momentum spectrum of tracks in the decay modes of interest, the uncertainty on the efficiency to reconstruct the tracks in the B-decay chain is estimated to be 3.7%. In the  $B^- \to D_S^{*-}\phi$  search there is an additional uncertainty of 1.8% due to the uncertainty on the efficiency to reconstruct the photon in the  $D_S^{*-} \to D_S \gamma$  decay, and also a 1% uncertainty from the unknown polarization in the final state. Finally, to ascertain the systematic due to the efficiency of the other event selection requirements, we compute the following efficiency variations: shifting the  $\Delta E$  by 3 MeV (0.3%); shifting the mean of the  $D_S$  and  $\phi$  masses and  $\Delta M$  by 1 MeV (0.2%, 0.1%, 0.2%, respectively); increasing the width of the  $D_S$  and  $\phi$  masses and  $\Delta M$  by 1 MeV (1.5%, 0.4%, 1.5%, respectively); using a Fisher distribution obtained from the data sample of a similar analysis,  $B \to D\pi$  with  $D \to K\pi$  (3%). Thus we assign a 5% systematic on the combined efficiency of these selection criteria.

#### 5 Physics results

We determine the yield of signal events from an unbinned extended maximum-likelihood fit to the  $m_{\rm ES}$  distribution of  $B^-$  candidates satisfying all of the requirements listed above. We fit simultaneously in two  $|\Delta E|$  regions: In the signal region the distribution is parametrized as a Gaussian and the combinatorial background as a threshold function [8]; in a sideband of  $\Delta E$  $(|\Delta E| < 200 \text{ MeV}, \text{ excluding the signal region})$  we fit solely for the  $\zeta$  parameter of the threshold function. In our fit, the amplitude of the Gaussian is allowed to fluctuate to negative values, but,

Table 2: Systematic uncertainties on  $\sum_i \epsilon_i \cdot BR_i$ , where the index *i* runs over the three  $D_S^-$  modes used in this analysis,  $\epsilon_i$  are the experimental efficiencies and  $BR_i$  are the branching fractions for the i-th mode.

	$B^- \to D^S \phi$	$B^- \to D_S^{*-} \phi$
$D_S$ branching fraction	14%	14%
$D_S^*$ branching fraction	-	2.5%
Other branching fractions	1.5%	1.5%
Charged kaon ID	7.5%	7.5%
Selection requirements	5%	5%
Tracking and $K_S$ efficiency	3.7%	3.7%
Photon efficiency	-	1.8%
Final state polarization	-	1%
Simulation statistics	0.6%	0.6%
Total	17%	17%

for reasons of numerical stability, the sum of the Gaussian and the threshold function is constrained to be positive over the full  $m_{\rm ES}$  fit range. The mean and the standard deviations of the Gaussian are constrained to the values determined from Monte Carlo simulation. The fitting procedure was extensively tested with sets of simulated data, and was found to provide an unbiased estimate of the signal yield.

Figure 2 shows the  $m_{\rm ES}$  distribution of the selected candidates. We see no evidence for  $B^- \to D_S^{(*)-}\phi$ . The fitted event yields are  $N = -1.6^{+0.7}_{-0.0}$  and  $N = 3.4^{+2.8}_{-2.1}$  for the  $B^- \to D_S^-\phi$  and  $B^- \to D_S^-\phi$  modes, respectively, where the quoted uncertainties correspond to changes of  $\frac{1}{2}$  in the log-likelihood for the fit. The likelihood curves are shown in Figure 3. The requirement that the sum of the Gaussian and the threshold function be always positive results in an effective constraint N > -1.6 in the  $B \to D_S \phi$  mode. This is the source of the sharp edge at N = -1.6 in the likelihood distribution of Figure 3(a).

We use a Bayesian approach with a flat prior to set 90% confidence level upper limits on the branching fractions for the  $B^- \to D_S^- \phi$  and  $B^- \to D_S^{*-} \phi$  modes. In a given mode, the upper limit on the number of observed events  $(N_{UL})$  is defined as

$$\int_0^{N_{UL}} \mathcal{L}(N) \ dN \quad = \quad \frac{9}{10} \int_0^{+\infty} \mathcal{L}(N) \ dN \tag{1}$$

where  $\mathcal{L}(N)$  is the likelihood as a function of the number of signal events N as determined from the  $m_{\text{ES}}$  fit described above. Then the upper limit  $\mathcal{B}$  on the branching fraction is

$$\mathcal{B} < \frac{N_{UL}}{N_{BB} \sum_{i} \epsilon_i \cdot \mathrm{BR}_i} \tag{2}$$

where  $N_{BB} = (233.9 \pm 2.5) \times 10^6$  is the number of  $B\overline{B}$  events, *i* is an index that runs through the three  $D_{\overline{S}}^-$  decay modes,  $\epsilon_i$  is the acceptance in the i-th mode, and BR<sub>i</sub> is the product of all secondary and tertiary branching fractions (see Table 1).

We account for systematic uncertainties by numerically convolving  $\mathcal{L}(N)$  with a Gaussian distribution with width determined by the total systematic uncertainties (Table 2) in the two modes, including the 1.1% uncertainty in  $N_{BB}$  added in quadrature. We find limits  $\mathcal{B}(B^- \to D_S^- \phi) <$   $1.8 \times 10^{-6}$  and  $\mathcal{B}(B^- \to D_S^{*-}\phi) < 1.1 \times 10^{-5}$  at the 90% confidence level. As in Section 3, these limits are calculated using  $\mathcal{B}(D_S \to \phi\pi) = (4.8 \pm 0.6)\%$  from Reference [7]. If we were to use the value  $\mathcal{B}(D_S \to \phi\pi) = (3.6 \pm 0.9)\%$  from the Particle Data Group, we would find  $\mathcal{B}(B^- \to D_S^-\phi) < 2.6 \times 10^{-6}$  and  $\mathcal{B}(B^- \to D_S^{*-}\phi) < 1.7 \times 10^{-5}$ . For completeness, we also compute  $\mathcal{B}(B^- \to D_S^-\phi) \times \mathcal{B}(D_S \to \phi\pi) < 8.1 \times 10^{-8}$  and  $\mathcal{B}(B^- \to D_S^{*-}\phi) \times \mathcal{B}(D_S \to \phi\pi) < 5.3 \times 10^{-7}$ , also at the 90% confidence level.

In summary, we have searched for  $B^- \to D_S^{(*)-} \phi$ , and we have found no evidence for these decays. Our limits are about two orders of magnitude lower than the previous results, but are still one order of magnitude higher than the Standard Model expectation. Our limits, however, are much lower than expectations based on *R*-parity violating supersymmetric models [3]. The upper limit in the  $B^- \to D_S^- \phi$  mode is also about a factor of four below the expectation from a two Higgs doublet model [3].

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Figure 2: Distribution of  $m_{\rm ES}$  for (a)  $B^- \to D_S^- \phi$  and (b)  $B^- \to D_S^{*-} \phi$  candidates. The superimposed curves are the result of the fits described in the text. The dashed red curve is the background contribution and the solid blue curve is the sum of the signal and backgound components.



Figure 3: Likelihood from the fit in arbitrary units as a function of the number of signal events. (a)  $B^- \to D_S^- \phi$ ; (b)  $B^- \to D_S^{*-} \phi$ .