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Partial Reconstruction of $B^0 \to D_s^{*+} D^{*-}$ Decays and Measurement of the $D_s^+ \to \phi\pi^+$ Branching Fraction

The *BABAR* Collaboration

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Abstract

We present preliminary results on the branching fractions $\mathcal{B}(B^0 \to D_s^{*+} D^{*-})$ and $\mathcal{B}(D_s^+ \to \phi\pi^+)$, based on a data sample of approximately 124×10^6 $B\overline{B}$ events collected by the *BABAR* detector at the PEP-II e^+e^- B–factory. $\mathcal{B}(B^0 \to D_s^{*+} D^{*-})$ is measured selecting neutral B meson decays to the final state $D^{*-} D_s^{*+}$ with partial reconstruction of the D_s^{*+}, in which only the D^{*-} and the soft photons from the decay $D_s^{*+} \to D_s^+\gamma$ are reconstructed. The branching fraction product $\mathcal{B}(B^0 \to D_s^{*+} D^{*-}) \cdot \mathcal{B}(D_s^+ \to \phi\pi^+)$ is measured via a complete reconstruction of the whole decay chain. Comparing these two measurements provides a model-independent determination of the $\mathcal{B}(D_s^+ \to \phi\pi^+)$ branching fraction. We obtain the following preliminary results:

$$\mathcal{B}(B^0 \to D_s^{*+} D^{*-}) = (1.85 \pm 0.09 \pm 0.16)\%$$
$$\mathcal{B}(D_s^+ \to \phi\pi^+) = (4.71 \pm 0.47 \pm 0.35)\%$$

where the first error in each measurement is statistical, the second systematic.

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1 INTRODUCTION

A precise measurement of the branching fraction for the $D_s^+ \to \phi\pi^+$ mode is important because nearly all D_s^+ branching fractions are determined by normalizing the measurements to $\mathcal{B}(D_s^+ \to \phi\pi^+)$ [1]. The present uncertainty of about 25% on $\mathcal{B}(D_s^+ \to \phi\pi^+)$ [2] thus affects many of the results regarding D_s^+ mesons.

In the factorization model for two-body decay rates, it is assumed that the transition amplitude of the process is the product of two currents that can be evaluated separately. This model has been successful [3] in describing the measured branching fractions and polarizations for B meson decays such as $B^0 \to D^{*-}\pi^+$ [4], $B^0 \to D^{*-}\rho^+$ and $B^0 \to D^{*-}a_1^+$ [5], in which the momentum transfer in the process is low ($q^2 \simeq m_\pi^2, m_\rho^2$). Measurements of decay rates for modes such as $B^0 \to D_s^{*+}D^{*-}$ allow tests of the predictions for high q^2 [6].

2 THE *BABAR* DETECTOR AND DATASET

The data used in this analysis were collected with the *BABAR* detector at the PEP-II storage ring and correspond to an integrated luminosity of $112.3\,\mathrm{fb}^{-1}$ and to $(124 \pm 1) \times 10^6$ $B\overline{B}$ pairs. A detailed description of the detector can be found in Ref. [7].

In addition to this data sample, several simulated event samples were used in order to study efficiencies and backgrounds. For background studies, we used a Monte Carlo simulation of $B^0\overline{B}^0$ and B^+B^- events (each equivalent to an integrated luminosity of $440\,\mathrm{fb}^{-1}$), $e^+e^- \to c\overline{c}$ ($230\,\mathrm{fb}^{-1}$) and $e^+e^- \to u\overline{u}$, $d\overline{d}$, $s\overline{s}$ ($180\,\mathrm{fb}^{-1}$).

3 ANALYSIS METHOD

The aim of this analysis is to measure the branching fractions $\mathcal{B}(B^0 \to D_s^{*+}D^{*-})$ and $\mathcal{B}(D_s^+ \to \phi\pi^+)$. To accomplish this, the $B^0 \to D_s^{*+}D^{*-} \to (D_s^+\gamma)(\overline{D}^0\pi^-)$ decay is reconstructed using two different methods.

The first method uses a partial reconstruction technique, in which only the D^{*-} is fully reconstructed, and then combined with the soft photon from the $D_s^{*+} \to D_s^+\gamma$ decay, without requiring explicit D_s^+ reconstruction. Denoting the measured event yield by $\mathcal{N}_{D_s}$, we can express the $B^0 \to D_s^{*+}D^{*-}$ branching fraction as:

$$\mathcal{B}_1 \equiv \mathcal{B}(B^0 \to D_s^{*+}D^{*-}) = \mathcal{K}\frac{\mathcal{N}_{D_s}}{\sum_i(\varepsilon_i \cdot \mathcal{B}_i^{D^0})}. \tag{1}$$

Here $\mathcal{K} \equiv [2N_{B^0\overline{B}^0}\mathcal{B}(D_s^{*+} \to D_s^+\gamma)\mathcal{B}(D^{*-} \to \overline{D}^0\pi^-)]^{-1}$, $N_{B^0\overline{B}^0}$ is the number of neutral B meson pairs, $\mathcal{B}_i^{D^0}$ are the branching fractions for the D^0 decay mode i, ε_i are the efficiencies for reconstructing and selecting the partially reconstructed B^0 into a final state containing a photon, a soft pion and a D^0 reconstructed into mode i. We assume $\mathcal{B}(\Upsilon(4S) \to B^0\overline{B}^0) = 0.5$.

$B^0 \to D_s^{*+}D^{*-}$ decays can also be fully reconstructed. In this paper we focus on the $D_s^+ \to \phi\pi^+$ mode, where the ϕ meson is reconstructed in the $K^+ K^-$ channel, determining from the measured yield $\mathcal{N}_{D_s\to\phi\pi}$ the product of branching fractions $\mathcal{B}(B^0 \to D_s^{*+}D^{*-}) \cdot \mathcal{B}(D_s^+ \to \phi\pi^+)$:

$$\mathcal{B}_2 \equiv \mathcal{B}(B^0 \to D_s^{*+}D^{*-})\mathcal{B}(D_s^+ \to \phi\pi^+) = \mathcal{K} \cdot \frac{\mathcal{N}_{D_s\to\phi\pi}}{\mathcal{B}(\phi \to K^+K^-)\sum_i(\varepsilon_i' \cdot \mathcal{B}_i^{D^0})}, \tag{2}$$

where ε'_i is the efficiency for detecting the fully reconstructed B^0, including reconstruction of $\phi \to K^+K^-$. The branching fraction $\mathcal{B}(D_s^+ \to \phi\pi^+)$ is measured from the ratio of the two yields:

$$\mathcal{B}(D_s^+ \to \phi\pi^+) = \frac{\mathcal{B}_2}{\mathcal{B}_1} = \frac{\mathcal{N}_{D_s\to\phi\pi} \sum_i(\varepsilon_i \cdot \mathcal{B}_i^{D^0})}{\mathcal{N}_{D_s}\mathcal{B}(\phi \to K^+K^-) \sum_i(\varepsilon'_i \cdot \mathcal{B}_i^{D^0})}, \tag{3}$$

where the factor $\mathcal{K}$ exactly drops off, and although the efficiencies ε_i and ε'_i are in general different, many systematic uncertainties cancel in the ratio, as will be discussed in Sec. 6.

4 PARTIAL RECONSTRUCTION ANALYSIS

4.1 Signal Extraction

We reconstruct the $B^0 \to D_s^{*+}D^{*-} \to (D_s^+\gamma)(\overline{D}^0\pi^-)$ decay by combining photons in the event with fully reconstructed D^{*-} mesons, without requiring reconstruction of the D_s^+ from the D_s^{*+} decay. In order to extract the signal, we compute the missing mass m_{miss} recoiling against the $D^{*-} - \gamma$ system (all quantities defined in the center-of-mass (CM) frame):

$$m_{\text{miss}} = \sqrt{(E_{\text{beam}} - E_{D^*} - E_\gamma)^2 - (\mathbf{p}_B - \mathbf{p}_{D^*} - \mathbf{p}_\gamma)^2}. \tag{4}$$

The m_{miss} distribution of signal events peaks at the nominal D_s^+ mass [1] with a spread of about $15\,\text{MeV}/c^2$. The kinematics of the event are not fully constrained with this procedure and one of the decay parameters must be chosen in an arbitrary way. In particular, taking the beam energy in the CM to be the B energy, the angle between the B momentum vector and the measured D^{*-} momentum vector can be calculated from 4-momentum conservation in the $B^0 \to D_s^{*+}D^{*-}$ decay

$$\cos\vartheta_{BD^*} = -\frac{m_B^2 + m_{D^*}^2 - m_{D_s^*}^2 - 2E_BE_{D^*}}{2|\mathbf{p}_B||\mathbf{p}_{D^*}|}. \tag{5}$$

The B four-momentum is therefore determined up to the azimuthal angle around the D^{*-} direction. However, an arbitrary choice of this angle (*e.g.* $\cos\phi_{BD^*} = 0$) introduces only a negligible spread (of the order of 1.5 MeV/c^2) in the missing mass distribution.

4.2 Event Selection

Random $D^{*-} - \gamma$ combinations are suppressed requiring $|\cos\vartheta_{BD^*}| < 1.2$. To reject events from continuum, we require the ratio of the second to the zeroth Fox-Wolfram moment (R_2) [8] to be less than 0.3.

Candidates for D^{*-} are reconstructed in the $\overline{D}^0\pi^-$ mode, using $\overline{D}^0$ decays to $K^+\pi^-$, $K^+\pi^-\pi^+\pi^-$ $K^+\pi^-\pi^0$, and $K_S^0\pi^+\pi^-$, here listed in order of decreasing purity. The χ^2 probabilities of both the D^0 and D^* vertex fits are required to be greater than 1%. The D^{*-} momentum in the $\Upsilon(4S)$ frame must satisfy $1.4\,\text{GeV}/c < p_{D^*}^{\text{CMS}} < 1.9\,\text{GeV}/c$. Moreover, we require the reconstructed mass of the D^0 to be within 3 standard deviations $\sigma_{m_{D^0}}$ of the nominal value $m_{D^0}^{PDG}$ [1], and $Q_{D^*} \equiv m_{D^*} - m_{D^0} - m_{\pi^-}$ to satisfy $Q_{\text{lo}} < Q_{D^*} < Q_{\text{hi}}$, where the limits $Q_{\text{lo}} = 4.10$ to $5.20\,\text{MeV}/c^2$ and $Q_{\text{hi}} = 6.80$ to $7.90\,\text{MeV}/c^2$ are chosen around the nominal value $Q_{D^*}^{PDG} = 5.851$ MeV/c^2 depending on the D^0 decay mode. Kaon identification is required for modes $K^+\pi^-\pi^0$ and $K^+\pi^-\pi^+\pi^-$. For mode $K_S^0\pi^+\pi^-$, the invariant mass of the $\pi^+\pi^-$ from the K_S^0 decay is required to lie within $15\,\text{MeV}/c^2$ of the nominal K_S^0 mass and its flight length must be greater than 3 mm.

If more than one D^{*-} candidate is found, for each D^0 decay mode we choose the best one based on the quality of the slow pion track and on the minimum value of $\chi^2 = [(Q_{D^*} - Q_{D^*}^{PDG})/\sigma_{Q_{D^*}}]^2 + [(m_{D^0} - m_{D^0}^{PDG})/\sigma_{m_{D^0}}]^2$, where $\sigma_{Q_{D^*}}$ is the measured resolution on Q_{D^*}. Finally, if candidates from different D^0 decay modes are present, we select the one with the best expected purity.

Photon candidates are chosen from energy releases in the electromagnetic calorimeter not associated with any charged tracks. In order to reduce random associations, we reject photon candidates which form, in combination with any other photon in the event, a π^0 whose invariant mass is between 115 and 155 MeV/c^2 and whose momentum in the CM is greater than 200 MeV/c. The selection of photon candidates is based on the optimization of the statistical significance of the observed signal ($S/\sqrt{S+B}$, where S and B are the number of signal and background photons respectively), using Monte Carlo events. We require a minimum photon energy in the $\Upsilon(4S)$ CM $E_\gamma^{\rm CMS}$ of 142 MeV, a minimum cluster lateral moment [9] of 0.016, and a minimum Zernike moment [10] of order $\{2,0\}$ of 0.82. In about 10 % of the events, more than one photon is selected. In these occurrences we choose the one that maximizes the value of a likelihood ratio based on four photon variables (E_γ, $E_\gamma^{\rm CMS}$, N_{cry}, LAT), where E_γ is the photon energy in the laboratory frame and N_{cry} is the number of calorimeter crystals in the electromagnetic shower.

4.3 Signal Yields

The signal reconstruction efficiency is determined from a Monte Carlo sample of $B^0 \to D_s^{*+} D^{*-}$ events by performing an unbinned maximum likelihood fit to the missing mass distribution. The signal peak is well described by a Gaussian probability density function (p.d.f.), while the background, which is mainly due to random $D^{*-} - \gamma$ combinations, is parametrized with the function $B(m_{\rm miss}) = B_0(1 - e^{-(m_{\rm miss} - m_{\rm max})/b})(m_{\rm miss}/m_{\rm max})^c$, where $m_{\rm max}$ is the end point of the missing mass distribution. In the fit, we allow seven parameters to vary: B_0, b, c and $m_{\rm max}$ in $B(m_{\rm miss})$, and the mean, width and area of the signal Gaussian. We perform a single fit to all D^0 decay modes; the sum of the branching fraction-weighted efficiencies for the four reconstruction modes is computed from the number of signal events fitted in the range $|m_{\rm miss} - m_{D_s}| < 45\,{\rm MeV}/c^2$. The result is $\langle\varepsilon\mathcal{B}\rangle \equiv \sum_i (\varepsilon_i \cdot \mathcal{B}_i^{D^0}) = (5.11 \pm 0.03) \times 10^{-3}$.

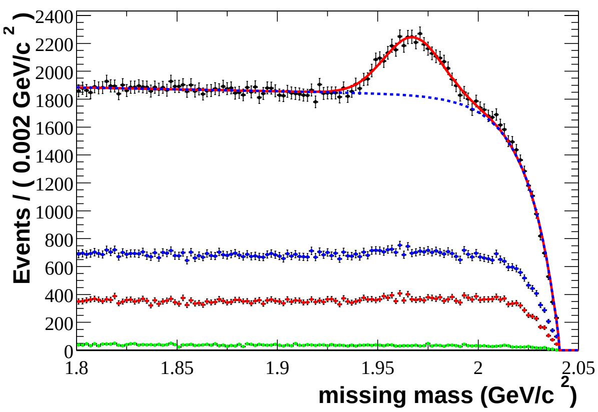
We have validated the fitting technique and the method of extracting the signal on the generic Monte Carlo sample. The distribution of the missing mass of partially reconstructed B^0 candidates is shown in Fig. 1a for $B^0\overline{B}^0$ (including signal), B^+B^-, and continuum Monte Carlo events. From the signal yield, using Eq. 2 we obtain the result $\mathcal{B}(B^0 \to D_s^{*+} D^{*-}) = (1.962 \pm 0.036)\,\%$, which is consistent with the value (1.97%) used in the generation of the Monte Carlo sample.

Figure 1b shows the missing mass distribution in our data sample. The same fitting procedure is used to extract the number of signal events. In the fit we allow all parameters to vary, except the width of the Gaussian signal, which is fixed to the value determined from fitting the signal Monte Carlo missing mass distribution. The result of the fit to the missing mass distribution is shown in Fig. 1b. The signal yield is 7414 ± 345 events, corresponding to a branching fraction $\mathcal{B}(B^0 \to D_s^{*+} D^{*-}) = (1.854 \pm 0.086)\,\%$. The result is stable over different run periods.

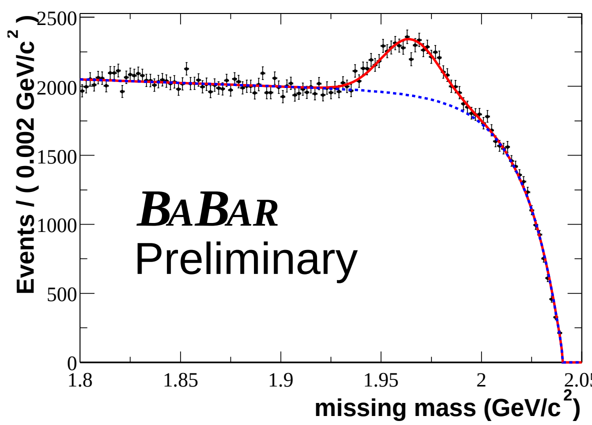
5 FULL RECONSTRUCTION ANALYSIS

5.1 Signal Extraction

The full decay chain used for the $B^0 \to D_s^{*+} D^{*-}$ exclusive reconstruction is $B^0 \to D_s^{*+} D^{*-} \to (D_s^+\gamma)(\overline{D}^0\pi^-)$ with $\overline{D}^0$ decaying in the four modes listed above, and $D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$.



(a)



(b)

Figure 1: Missing mass distributions in the Monte Carlo (a) and in the data sample (b). The $B(m_{\rm miss})$ background fit (dashed line) and $B(m_{\rm miss})$+Gaussian total fit (solid line) are superimposed. In (a) the different background components are also overlaid; starting from the bottom: $u\overline{u}$-$d\overline{d}$-$s\overline{s}$, $c\overline{c}$, B^+B^-, $B^0\overline{B}^0$ (including signal).

After applying selection cuts on the D_s^{*+} and D^{*-} candidates, the combination with the smallest value of $|\Delta E| \equiv |(E_{D^*} + E_{D_s^*}) - E_{\rm beam}|$ (all quantities defined in the CM frame) is selected. Finally, the number of fully reconstructed B^0 is obtained from a fit to the spectrum of the energy-substituted mass $m_{\rm ES} = \sqrt{E_{\rm beam}^2 - (\mathbf{p}_{D^*} + \mathbf{p}_{D_s^*})^2}$, where $\mathbf{p}_{D^*}$ and $\mathbf{p}_{D_s^*}$ are the D^{*-} and D_s^{*+} momenta, again in the CM frame.

5.2 Event Selection

The selection of D^{*-} candidates, and most of the requirements on photon candidates in the full reconstruction analysis, are identical to those in the partial reconstruction. In the full reconstruction the background level is very small. We can therefore relax the requirement on the minimum photon energy in the center-of-mass system $E_\gamma^{\rm CMS}$, thus maximizing the statistical significance of our sample.

ϕ candidates are reconstructed from two charged tracks, with at least one track satisfying stringent kaon selection criteria. We use the helicity angle ϑ_K, defined as the angle between the kaon direction in the ϕ rest frame and the ϕ meson direction in the D_s^+ frame, to further suppress background.

D_s^+ candidates are formed by combination with an additional track, with charge opposite to the slow pion from the D^{*-} decay. A mass window of ± 50 MeV$/c^2$ around the nominal D_s^+ mass [1] is required. D^{*-} and D_s^{*+} mass constraints are finally imposed in order to improve the ΔE resolution.

At the end of an optimization procedure based on generic Monte Carlo which minimizes the overall statistical error and the peaking background contribution, we require the $m_{D_s^*} - m_{D_s}$ mass difference to be between 0.125 and 0.160 GeV$/c^2$, the reconstructed ϕ mass to be between 1.0077 and 1.0347 GeV$/c^2$, $|\cos\vartheta_K| > 0.35$, $E_\gamma^{\rm CMS} > 0.09$ GeV, and $|\Delta E| < 0.05$ GeV.

5.3 Signal Yields

We determine the selection efficiency fitting the $m_{\rm ES}$ distribution of the signal Monte Carlo sample with a Crystal Ball function [11], defining the number of signal events as the integral of this p.d.f. in the signal region $5.27 < m_{\rm ES} < 5.29$ GeV/c^2. Summing the branching fraction-weighted efficiencies over the four D^0 reconstruction modes (see Sec. 4.2) yields $\langle \varepsilon' \mathcal{B}^{D^0} \rangle = (6.28 \pm 0.24) \times 10^{-3}$.

Monte Carlo studies show the presence of a peaking contribution due to real $B^0 \to D_s^{*+} D^{*-} \to (D_s^+ \gamma)(\overline{D}^0 \pi^-)$ events, where either the $\overline{D}^0$ does not decay to the reconstructed modes, or the D_s^+ does not decay to $\phi\pi^+$.

The total $m_{\rm ES}$ distribution is fitted with the sum of a Crystal Ball and a threshold function [12], accounting for the combinatorial background. All parameters are allowed to vary in the fit, except the end point of the threshold function, which is fixed to $5.29\,{\rm GeV}/c^2$. The signal yield is obtained from the integral of the Crystal Ball p.d.f. in the signal window, after subtraction of the peaking component discussed above.

The fit procedure is first checked on generic Monte Carlo samples, where no bias is found in the full reconstruction analysis technique.

Fig. 2 shows the fit to the total data sample and the corresponding yield. In order to subtract the peaking background from this yield, we scale the number of peaking events previously estimated from the Monte Carlo sample to the luminosity of the data sample. We then apply a correction factor to take into account the fact that the peaking events come from real $B^0 \to D_s^{*+} D^{*-}$ decays and the measured value of this branching fraction in data (1.85%) is slightly lower than in the Monte Carlo. In addition, the peaking component coming from events with D_s^+ not decaying to $\phi\pi^+$, is rescaled using the measured $(D_s^+ \to \phi\pi^+)$ branching ratio, with an iterative procedure. The resulting number of peaking background events expected in the data sample is 35, with a total uncertainty of 6 events which will be included in the systematic error. After subtraction of the peaking background events, the final yield on data is:

$$S_{\rm tot} = (212 \pm 19). \tag{6}$$

From equation 2 we therefore determine $\mathcal{B}_2 = \mathcal{B}(B^0 \to D_s^{*+} D^{*-}) \cdot \mathcal{B}(D_s^+ \to \phi\pi^+) = (8.71 \pm 0.78_{\rm stat}) \times 10^{-4}$. The result is stable over different data-taking periods.

6 SYSTEMATIC STUDIES

The main sources of systematic uncertainties on the $B^0 \to D_s^{*+} D^{*-}$ branching fraction measurement are listed in Table 1. The Monte-Carlo-statistics uncertainty is due to the statistical error on the efficiency determination. The uncertainty due to the use of a fixed width for the signal Gaussian is estimated from the spread in the fit results allowing the width to vary, and simultaneously fixing in the fit the background shape as determined in several different ways. We conservatively assign an error of 4.5 %. The systematic uncertainty due to tracking efficiency is 0.9% per track and 1.6% for the soft pions from D^{*-} decays. The systematic error due to the isolated photon reconstruction efficiency and particle identification are evaluated using control samples. We find a 7% difference in the overall selection efficiency between our samples with complete longitudinal or transverse polarization in the $B^0 \to D_s^{*+} D^{*-}$ decay. The uncertainty due to the dependence on polarization is computed taking into account the experimental measurement of the fraction of longitudinal polarization, $\Gamma_L/\Gamma = (51.9 \pm 5.7)\%$ [13]. Finally, the uncertainties on the D^0, D^{*-} and D_s^{*+} branching fractions [1] are propagated throughout the analysis.

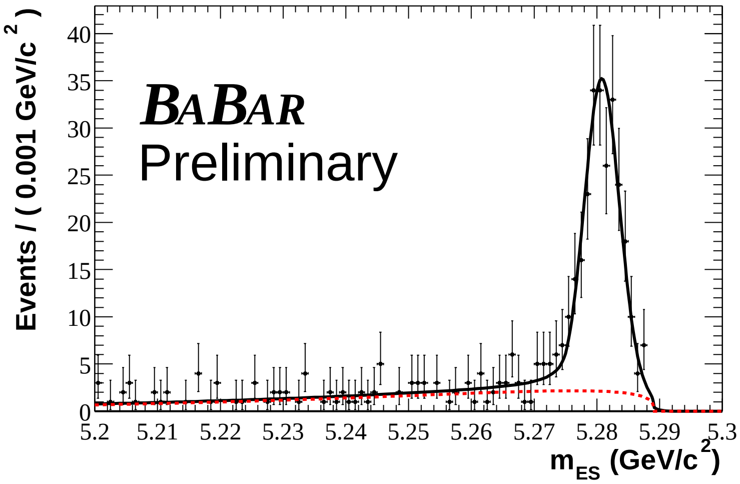


Figure 2: Total fit to the data sample. The Argus component parametrizing the background is also shown (dashed line).

Table 1: Fractional systematic uncertainties (%) for the $B^0 \to D_s^{*+} D^{*-}$ branching fraction measurement.

Source	Error (%)
Monte Carlo statistics	0.6
p.d.f. modelling	4.5
B counting	1.1
Tracking efficiency	2.4
Soft pion efficiency	1.6
Vertexing	2.0
Photon efficiency	4.6
Particle identification	0.9
Polarization uncertainty	0.8
D^0 branching fractions	3.2
$\mathcal{B}(D^{*-} \to \overline{D}^0 \pi^-)$	0.7
$\mathcal{B}(D_s^{*+} \to D_s^+ \gamma)$	2.7
Total systematic error	8.6

Table 2: Sources of systematic error (%) for the determination of $\mathcal{B}(D_s^+ \to \phi\pi^+)$.

	Source	Error (%)
Partial rec.	Monte Carlo statistics	0.6
	p.d.f. modelling	4.5
Full rec.	Monte Carlo statistics	3.2
	Tracking efficiency	2.6
	Particle identification	0.9
	Peaking background	2.8
	Combinatorial background	2.9
	$\mathcal{B}(\phi \to K^-K^+)$	1.2
	Total	7.5

Some systematic uncertainties, namely B counting, tracking efficiency, soft pion efficiency, photon efficiency, particle identification, polarization uncertainty, $\mathcal{B}(D^{*-} \to \overline{D}^0\pi^-)$ and $\mathcal{B}(D_s^{*+} \to D_s^+\gamma)$) cancel in the ratio (Eq. 3). All other sources are listed in Table 2. The error on peaking background is due to the Monte Carlo statistics and to the uncertainty on the relevant $\overline{D}^0$ and D_s^+ branching ratios; the error from the combinatorial background is estimated using the ΔE sideband data sample as an alternate way of computing the number of background events under the peak. The error on the $\mathcal{B}(\phi \to K^-K^+)$ is taken from [1].

7 SUMMARY

A measurement of the $B^0 \to D_s^{*+}D^{*-}$ branching fraction is performed, using data corresponding to an integrated luminosity of $112.3\,\mathrm{fb}^{-1}$, with a partial reconstruction technique. Including the systematic errors discussed in the previous section we obtain:

$$\mathcal{B}(B^0 \to D_s^{*+}D^{*-}) = (1.85 \pm 0.09_{\mathrm{stat}} \pm 0.16_{\mathrm{syst}})\%. \tag{7}$$

This preliminary result is compatible with, and improves on the precision of previously published experimental results [1, 13], and may be compared with the most recent theoretical results based on the factorization assumption [6]: $\mathcal{B}(B^0 \to D_s^{*+}D^{*-})_{\mathrm{theor}} = (2.4 \pm 0.7)\%$.

The preliminary $D_s^+ \to \phi\pi^+$ branching fraction result is

$$\mathcal{B}(D_s^+ \to \phi\pi^+) = (4.71 \pm 0.47_{\mathrm{stat}} \pm 0.35_{\mathrm{syst}})\%, \tag{8}$$

This new determination improves on published results [2, 14, 15].

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