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*Search for the rare decays B[superscript 0]$\rightarrow$D[subscript s][superscript (*)+]a[-over subscript 0(2)]*

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# Search for the rare decays $B^0 \rightarrow D_s^{(*)+} a_{0(2)}^-$

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We have searched for the decays $B^0 \rightarrow D_s^+ a_0^-$, $B^0 \rightarrow D_s^{*+} a_0^-$, $B^0 \rightarrow D_s^+ a_2^-$ and $B^0 \rightarrow D_s^{*+} a_2^-$ in a sample of about $230 \times 10^6$ $\Upsilon(4S) \rightarrow B\bar{B}$ decays collected with the *BABAR* detector at the PEP-II asymmetric-energy $B$ Factory at SLAC. We find no evidence for these decays and set upper limits at 90% C.L. on the branching fractions: $\mathcal{B}(B^0 \rightarrow D_s^+ a_0^-) < 1.9 \times 10^{-5}$, $\mathcal{B}(B^0 \rightarrow D_s^{*+} a_0^-) < 3.6 \times 10^{-5}$, $\mathcal{B}(B^0 \rightarrow D_s^+ a_2^-) < 1.9 \times 10^{-4}$, and $\mathcal{B}(B^0 \rightarrow D_s^{*+} a_2^-) < 2.0 \times 10^{-4}$.

The time-dependent decay rates for neutral $B$ mesons into a $D$ meson and a light meson provide sensitivity to the Cabibbo-Kobayashi-Maskawa (CKM) [1] quark mixing matrix phases $\beta$ and $\gamma$ [2]. A $CP$-violating term emerges through the interference between $B^0\bar{B}^0$ mixing mediated and direct decay amplitudes. The time-dependent $CP$-asymmetries in the decay modes $B^0 \rightarrow D^{(*)-}\pi^+$ [3] have been studied by *BABAR* and BELLE [4,5]. In these modes, the $CP$-asymmetries arise due to a phase difference between two amplitudes of very different magnitudes: one decay amplitude is suppressed by the product of two small CKM elements $V_{ub}$ and $V_{cd}$, while the other is CKM favored. Therefore, the decay rate is dominated by the CKM-favored part of the amplitude, resulting in a very small $CP$-violating asymmetry.

Recently it was proposed to consider other types of light mesons in the two-body final states [6]. The idea is that decay amplitudes with light scalar or tensor mesons, such as $a_0^+$ or $a_2^+$, emitted from a weak current, are significantly suppressed because of the small coupling constants $f_{a_{0(2)}}$. In the $SU(2)$ limit, $f_{a_0} = 0$ (since the coupling constant of a light scalar is proportional to the mass difference between $u$ and $d$ quarks), and any nonzero value of $f_{a_0}$ is of the order of isospin conservation breaking effects. Since the light tensor meson $a_2^+$ has spin 2, it cannot be emitted by a $W$-boson (i.e. $f_{a_2} \equiv 0$), and thus could only appear in a $V_{cb}$-mediated process via final state hadronic interactions and rescattering. Therefore, the absolute values of the CKM-suppressed and favored parts of the decay amplitude (see Fig. 1, top two diagrams) could become comparable, potentially resulting in a large $CP$-asymmetry. No $B \rightarrow a_{0(2)}X$ transitions have been observed yet. A summary of the theoretical predictions for the values of $V_{ub}$ and $V_{cb}$-mediated parts of the $B^0 \rightarrow D^{(*)-}a_{0(2)}^+$ branching fractions can be found in [7].

The $V_{ub}$-mediated amplitudes in [7] were computed in the factorization framework. In addition to model uncertainties, significant uncertainty in the theoretical calculations is due to unknown $B \rightarrow a_{0(2)}X$ transition form factors. One way to verify the numerical assumptions and test the validity of the factorization approach experimentally is to measure the branching fractions for the $SU(3)$ conjugated

decay modes $B^0 \rightarrow D_s^{(*)+}a_{0(2)}$. These decays are represented by a single tree diagram (Fig. 1, bottom diagram) with external $W^+$ emission, without contributions from additional tree or penguin diagrams. The $V_{ub}$-mediated part of the $B^0 \rightarrow D^{(*)+}a_{0(2)}^-$ decay amplitude can be related to $B^0 \rightarrow D_s^{(*)+}a_{0(2)}^-$ using $\tan(\theta_{\text{Cabibbo}}) \approx |V_{cd}/V_{cs}|$ and the ratio of the decay constants $f_{D_s^{(*)}}/f_{D^{(*)}}$.

Branching fractions of $B^0 \rightarrow D_s^{(*)+}a_2^-$ are predicted to be in the range 1.3–1.8 (2.1–2.9) in units of $10^{-5}$ [8]. Branching fraction estimates for $B^0 \rightarrow D_s^{(*)+}a_0^-$ of approximately $8 \times 10^{-5}$ are obtained using $SU(3)$ symmetry from the predictions made for $B^0 \rightarrow D^{(*)+}a_0^-$ in [7].

In this paper we present the first search for the decays $B^0 \rightarrow D_s^+ a_0^-$, $B^0 \rightarrow D_s^{*+} a_0^-$, $B^0 \rightarrow D_s^+ a_2^-$ and $B^0 \rightarrow D_s^{*+} a_2^-$. The analysis uses a sample of approximately 210 fb$^{-1}$, which corresponds to about $230 \times 10^6$ $\Upsilon(4S)$ decays into $B\bar{B}$ pairs collected in the years 1999–2004 with the *BABAR* detector at the asymmetric-energy $B$-factory PEP-II [9]. The *BABAR* detector is described elsewhere [10] and only the components crucial to this analysis are summarized here. 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


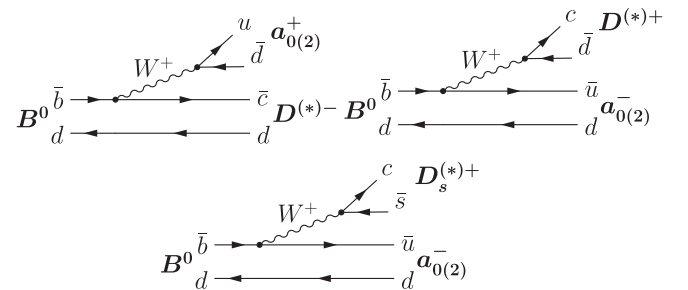
FIG. 1. Top two diagrams: tree diagrams contributing to the decay amplitude of $B^0 \rightarrow D^{(*)-}a_{0(2)}^+$ (including the $B^0\bar{B}^0$ mixing mediated part of the amplitude). Bottom diagram: tree diagram representing the decay amplitude of $B^0 \rightarrow D_s^{(*)+}a_{0(2)}^-$.

device are used. Photons are identified and measured using the electromagnetic calorimeter, which is comprised of 6580 thallium-doped CsI crystals. These systems are located inside a 1.5 T solenoidal superconducting magnet. We use GEANT4 [11] software to simulate interactions of particles traversing the *BABAR* detector, taking into account the varying detector conditions and beam backgrounds.

The optimal selection criteria as well as the shapes of the distributions of selection variables are determined by a blind analysis based on Monte Carlo (MC) simulation of both signal and background. For the calculation of the expected signal yield we assume $\mathcal{B}(B^0 \rightarrow D_s^{(*)+} a_2^-)$ to be the mean values of the predicted intervals from [8] and an estimate of $\mathcal{B}(B^0 \rightarrow D_s^{(*)+} a_0^-)$ is obtained from $\mathcal{B}(B^0 \rightarrow D^{(*)+} a_0^-)$ predicted in [7] and assuming $SU(3)$ symmetry. We use MC samples of our signal modes and, to simulate background, inclusive samples of $B^+ B^-$ (800 fb$^{-1}$), $B^0 \bar{B}^0$ (782 fb$^{-1}$), $c\bar{c}$ (263 fb$^{-1}$), and $q\bar{q}$, $q = u, d, s$ (279 fb$^{-1}$). In addition, we use large samples of simulated events of rare background modes which have final states similar to the signal. We have verified that our MC correctly describes real data by comparing distributions of various selection variables.

Candidates for $D_s^+$ mesons are reconstructed in the modes $D_s^+ \rightarrow \phi \pi^+$, $\bar{K}^{*0} K^+$, and $K_S^0 K^+$, with $\phi \rightarrow K^+ K^-$, $\bar{K}^{*0} \rightarrow K^- \pi^+$ and $K_S^0 \rightarrow \pi^+ \pi^-$. The $K_S^0$ candidates are reconstructed from two oppositely-charged tracks, with an invariant mass close to the nominal $K_S^0$ mass [12], that come from a common vertex displaced from the $e^+ e^-$ interaction point. All other tracks are required to originate less than 1.5 cm away from the $e^+ e^-$ interaction point in the transverse plane and less than 10 cm along the beam axis. Charged kaon candidates must satisfy kaon identification criteria that are typically around 95% efficient, depending on momentum and polar angle, and have a misidentification rate at the 10% level. The $\phi \rightarrow K^+ K^-$, $\bar{K}^{*0} \rightarrow K^- \pi^+$ and $K_S^0 \rightarrow \pi^+ \pi^-$ candidates are required to have invariant masses close to their nominal masses [12] (we require the absolute differences between their measured masses and the nominal values [12] to be in the range 12–15 MeV, 35–60 MeV and 7–12 MeV, respectively, depending on the $B^0$ and $D_s^+$ decay modes). The polarizations of the $\bar{K}^{*0}$ and $\phi$ mesons in the $D_s^+$ decays are used to reject backgrounds through the use of the helicity angle $\theta_H$, defined as the angle between the $K^-$ momentum vector and the direction of flight of the $D_s^+$ in the $\bar{K}^{*0}$ or $\phi$ rest frame. The $\bar{K}^{*0}$ candidates are required to have $|\cos\theta_H|$ greater than 0.25–0.5 and $\phi$ candidates are required to have $|\cos\theta_H|$ greater than 0.3–0.5, depending on the $B^0$ decay mode. We also apply a vertex fit to the $D_s^+$ candidates that decay into $\phi \pi^+$ and $\bar{K}^{*0} K^+$, since all charged daughter tracks of $D_s^+$ are supposed to come from a common vertex. The $\chi^2$ of the vertex fit is required to be less than 10–16 (which corresponds to a probability

of better than 0.1%–1.9% for the 3 track vertex fit), depending on the reconstructed mode.

The $D_s^{*+}$ candidates are reconstructed in the mode $D_s^{*+} \rightarrow D_s^+ \gamma$. The photons are required to have an energy greater than 100 MeV. The $D_s^+$ and $D_s^{*+}$ candidates are required to have invariant masses less than about $\pm 2\sigma$ from their nominal values [12] (both $D_s^+$ and $D_s^{*+}$ mass resolutions are around 6 MeV/$c^2$). The invariant mass of the $D_s^{*+}$ is calculated after the mass constraint on the daughter $D_s^+$ has been applied. Subsequently, all $D_s^{*+}$ candidates are subjected to a mass-constrained fit.

We reconstruct $a_0^-$ and $a_2^-$ candidates in their decay to the $\eta \pi^-$ final state. For reconstructed $\eta \rightarrow \gamma\gamma$ candidates we require the energy of each photon to be greater than 250 MeV for $a_0^+$ candidates, and greater than 300–400 MeV for $a_2^+$ candidates, depending on the $D_s^+$ mode. The $\eta$ mass is required to be within a $\pm 1\sigma$ or $\pm 2\sigma$ interval of the nominal value [12], depending on the background conditions in a particular $B^0$, $D_s^+$ decay mode (the $\eta$ mass resolution is measured to be around 15 MeV/$c^2$). The $a_0^+$ and $a_2^+$ candidates are required to have a mass $m_{\eta \pi^+}$ in the range 0.9–1.1 GeV/$c^2$ and 1.2–1.5 GeV/$c^2$, respectively. We also require that photons from $\eta$ and $D_s^{*+}$ are inconsistent with $\pi^0$ hypothesis when combined with any other photon in the event (the $\pi^0$ veto window varies from $\pm 10$ to $\pm 15$ MeV/$c^2$). Finally, the $B^0$ meson candidates are formed using the reconstructed combinations of $D_s^+ a_0^-$, $D_s^+ a_2^-$, $D_s^{*+} a_0^-$ and $D_s^{*+} a_2^-$.

The background from continuum $q\bar{q}$ production (where $q = u, d, s, c$) is suppressed based on the event topology. We calculate the angle ($\theta_T$) between the thrust axis of the $B$ meson candidate and the thrust axis of all other particles in the event. In the center-of-mass frame (c.m.), $B\bar{B}$ pairs are produced approximately at rest and have a uniform $\cos\theta_T$ distribution. In contrast, $q\bar{q}$ pairs are produced in the c.m. frame with high momentum, 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 0.70–0.75. We further suppress backgrounds using a Fisher discriminant ($\mathcal{F}$) [13] constructed from the scalar sum of the c.m. 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. The more isotropic the event, the larger the value of $\mathcal{F}$. We require $\mathcal{F}$ to be larger than a threshold that retains 75% to 86% of the signal while rejecting 78% to 65% of the background, depending on the background level. In addition, the ratio of the second and zeroth order Fox-Wolfram moments [14] must be less than a threshold in the range 0.25–0.40 depending on the decay mode.

We extract the signal using the kinematical variables $m_{\mathrm{ES}} = \sqrt{E_b^{*2} - (\sum_i \mathbf{p}_i^*)^2}$ and $\Delta E = \sum_i \sqrt{m_i^2 + \mathbf{p}_i^{*2}} - E_b^*$, where $E_b^*$ is the beam energy in the c.m. frame, $\mathbf{p}_i^*$ is the c.m. momentum of the daughter particle $i$ of the $B^0$ meson candidate, and $m_i$ is the mass hypothesis for particle $i$. For

signal events, $m_{ES}$ peaks at the $B^0$ meson mass with a resolution of about 2.7 MeV/$c^2$ and $\Delta E$ peaks near zero with a resolution of 20 MeV, indicating that the $B^0$ candidate has a total energy consistent with the beam energy in the c.m. frame. The $B^0$ candidates are required to have $|\Delta E| < 40$ MeV and $m_{ES} > 5.2$ GeV/$c^2$.

The fraction of multiple $B^0$ candidates per event is estimated using the MC simulation and found to be around 2% for $D_s^+ a_{0(2)}^-$ and 5% for $D_s^{*+} a_{0(2)}^-$ combinations. In each event with more than one $B^0$ candidate that passed the selection requirements, we select the one with the lowest $|\Delta E|$ value.

After all selection criteria are applied, we estimate the $B^0$ reconstruction efficiencies, excluding the intermediate branching fractions (see Table I).

Background events that pass these selection criteria are mostly from $q\bar{q}$ continuum, and their $m_{ES}$ distribution is described by a threshold function [15]:

$$f(m_{ES}) \sim m_{ES}\sqrt{1 - x^2}\exp[-\xi(1 - x^2)],$$

where $x = 2m_{ES}/\sqrt{s}$, $\sqrt{s}$ is the total energy of the beams in their center-of-mass frame, and $\xi$ is the fit parameter. A study using simulated events of $B^0$ and $B^+$ decay modes with final states similar to our signal mode, including $D_s^{(*)+}\pi^-$ and $D_s^{(*)+}\rho^-$, shows that these modes do not peak in $m_{ES}$.

Figure 2 shows the $m_{ES}$ distributions for the reconstructed candidates $B^0 \to D_s^+ a_0^-$, $B^0 \to D_s^+ a_2^-$, $B^0 \to D_s^{*+} a_0^-$ and $B^0 \to D_s^{*+} a_2^-$. For each mode, we perform an unbinned maximum-likelihood fit to the $m_{ES}$ distributions using the candidates from all $D_s^+$ decay modes combined. We fit the $m_{ES}$ distributions with the sum of the function $f(m_{ES})$ characterizing the combinatorial background and a Gaussian function to describe the signal. The total signal yield in each $B^0$ decay mode is calculated as a sum over $D_s^+$ modes ($i = \phi\pi^+$, $\bar{K}^{*0}K^+$, $K_S^0 K^+$):

$$n_{\mathrm{sig}} = \mathcal{B} \cdot N_{B\bar{B}} \cdot \sum_i \mathcal{B}_i \cdot \epsilon_i,$$

where $\mathcal{B}$ is the branching fraction of the $B^0$ decay mode, $N_{B\bar{B}}$ is the number of produced $B\bar{B}$ pairs, $\mathcal{B}_i$ is the product of the intermediate branching ratios and $\epsilon_i$ is the reconstruction efficiency. The mean and the width of the Gaussian function are fixed to values obtained from simulated signal events for each decay mode. The threshold shape parameter $\xi$, along with the branching ratio $\mathcal{B}$ are

TABLE I. Reconstruction efficiencies for $B^0 \to D_s^{(*)+} a_{0(2)}^-$ decays (excluding the intermediate branching fractions).

| Decay mode | $D_s^+ \to \phi\pi^+$ | $D_s^+ \to \bar{K}^{*0}K^+$ | $D_s^+ \to K_S^0 K^+$ |
|---|---|---|---|
| $B^0 \to D_s^+ a_0^-$ | 4.7% | 2.9% | 2.5% |
| $B^0 \to D_s^+ a_2^-$ | 1.9% | 1.1% | 1.1% |
| $B^0 \to D_s^{*+} a_0^-$ | 2.2% | 1.5% | 1.3% |
| $B^0 \to D_s^{*+} a_2^-$ | 0.9% | 0.7% | 0.5% |

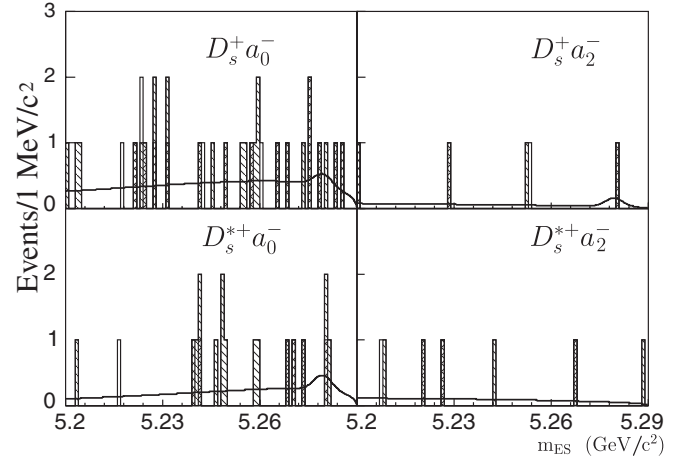

FIG. 2. Distributions of $m_{ES}$ for $B^0 \to D_s^{(*)+} a_{0(2)}^-$ candidates overlaid with the projection of the maximum-likelihood fit. Contributions from the three $D_s^+$ decay modes are shown with different hatching styles: $\phi\pi^+$ is cross hatched, $\bar{K}^{*0}K^+$ is hatched, and $K_S^0 K^+$ is white. The fit procedure and results are described in the text.

free parameters of the fit. The likelihood function is given by:

$$\mathcal{L} = \frac{e^{-N}}{N!} \prod_{i=1}^{N}(n_{\mathrm{sig}}P_i^{\mathrm{sig}} + (N - n_{\mathrm{sig}})P_i^{bkg}),$$

where $P_i^{\mathrm{sig}}$ and $P_i^{bkg}$ are the probability density functions for the corresponding hypotheses, $N$ is the total number of events in the fit and $i$ is the index over all events in the fit.

Table II (second column) shows the signal event yields from the $m_{ES}$ fit. Because of a lack of entries in the signal region for the $B^0 \to D_s^{*+} a_2^-$ mode, the fit did not yield any central value for the number of signal events in this mode. Accounting for the estimated reconstruction efficiencies and daughter particles branching fractions, we measure the branching fractions shown in the third column of Table II.

The systematic errors include a 14% relative uncertainty for $D_s^+$ decay rates [16]. Uncertainties in the $m_{ES}$ signal and background shapes result in 11% relative error in the measured branching fractions. The rest of the systematic error sources, which include uncertainties in photon and $\eta$ reconstruction efficiencies, the $a_0^+$ and $a_2^+$ masses and

TABLE II. Signal yields, branching fractions and upper limits on the branching fractions for $B^0 \to D_s^{(*)+} a_{0(2)}^-$ decays. Numbers in parentheses in the third and fourth columns indicate the branching fractions and the upper limits multiplied by the branching fractions of the decays $D_s^+ \to \phi\pi^+$ and $a_{0(2)}^+ \to \eta\pi^+$.

| $B^0$ mode | $n_{\mathrm{sig}}$ | $\mathcal{B}[10^{-5}(10^{-7})]$ | U.L.$[10^{-5}]$ |
|---|---|---|---|
| $D_s^+ a_0^-$ | $0.9^{+2.2}_{-1.7}$ | $0.6^{+1.4}_{-1.1} \pm 0.1 (2.6^{+6.6}_{-5.1} \pm 0.5)$ | 1.9(0.09) |
| $D_s^+ a_2^-$ | $0.6^{+1.0}_{-0.6}$ | $6.4^{+10.4}_{-5.7} \pm 1.5 (4.5^{+7.3}_{-4.0} \pm 0.8)$ | 19(0.13) |
| $D_s^{*+} a_0^-$ | $1.5^{+2.3}_{-1.8}$ | $1.4^{+2.1}_{-1.6} \pm 0.3 (6.5^{+10.1}_{-7.8} \pm 1.2)$ | 3.6(0.17) |
| $D_s^{*+} a_2^-$ | — | $-(-)$ | 20(0.13) |

widths, track and $K_S^0$ reconstruction, charged kaon identification, range between 3% and 10%. We assume the branching fraction for $a_0^+ \rightarrow \eta \pi^+$ to be 100% and assign an asymmetric systematic error of $-10\%$ to this assumption. The systematic error in the number of produced $B\bar{B}$ pairs is 1.1%. There is an additional $\pm 15\%$ systematic error for $B^0 \rightarrow D_s^{*+} a_2^-$ mode due to the unknown polarization state of the decay products. It was checked that the selection of the best candidate based on $|\Delta E|$ does not introduce any significant bias in the $m_{\mathrm{ES}}$ fit. The total relative systematic errors are estimated to be around 25% for each mode.

We use a Bayesian approach with a flat prior above zero to set 90% confidence level upper limits on the branching fractions. In a given mode, the upper limit on the branching fraction ($\mathcal{B}_{\mathrm{UL}}$) is defined by:

$$\int_0^{\mathcal{B}_{\mathrm{UL}}} \mathcal{L}(\mathcal{B})d\mathcal{B} = 0.9 \times \int_0^\infty \mathcal{L}(\mathcal{B})d\mathcal{B}$$

where $\mathcal{L}(\mathcal{B})$ is the likelihood as a function of the branching fraction $\mathcal{B}$ as determined from the $m_{\mathrm{ES}}$ fit described above. We account for systematic uncertainties by numerically convolving $\mathcal{L}(\mathcal{B})$ with a Gaussian distribution with a width determined by the relative systematic uncertainty multiplied by the branching fraction obtained from the $m_{\mathrm{ES}}$ fit. In cases with asymmetric errors we took the larger for the width of this Gaussian function. In case of $D_s^{*+} a_2^-$ (where no central value was determined from the fit) we conservatively estimate the absolute systematic error by taking the numerically calculated 90% confidence level upper limit (without the systematic uncertainties) instead of the fitted branching fraction. The resulting upper limits are summarized in Table II (fourth column). The likelihood curves are shown in Fig. 3.

We have also calculated upper limits without including the intermediate branching fractions of the decays $D_s^+ \rightarrow \phi \pi^+$ [16] and $a_{0(2)}^+ \rightarrow \eta \pi^+$ [12]. The relative systematic errors in this case are reduced to 18% for each of the $B^0$ meson decay modes. The results are presented in Table II (third and fourth columns, numbers in parenthesis).

In conclusion, we do not observe any evidence for the decays $B^0 \rightarrow D_s^+ a_0^-$, $B^0 \rightarrow D_s^+ a_2^-$, $B^0 \rightarrow D_s^{*+} a_0^-$ and $B^0 \rightarrow D_s^{*+} a_2^-$, and set 90% C.L. upper limits on their
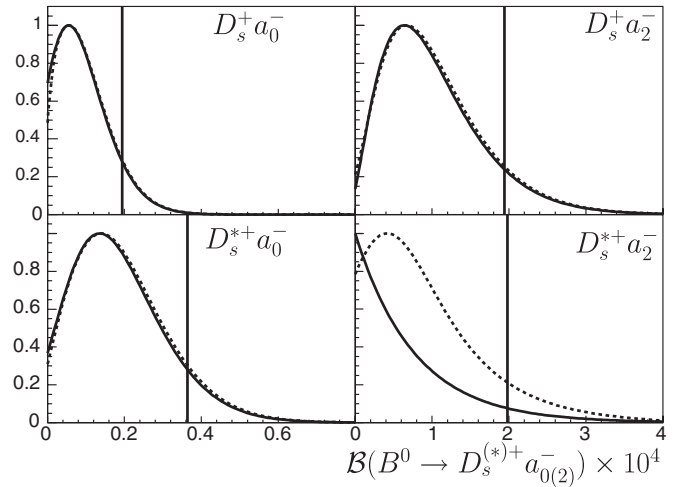


FIG. 3. Likelihood functions of the fit for the $m_{\mathrm{ES}}$ distributions of the selected $B^0 \rightarrow D_s^{(*)+} a_{0(2)}^-$ candidates. Solid curves represent the original likelihood scan from the fit, the dashed lines show the result of the convolution with the systematic errors Gaussian. Vertical lines indicate the 90% Bayesian C.L. upper limit value.

branching fractions. The upper limit value for $B^0 \rightarrow D_s^+ a_0^-$ is lower than the theoretical expectation, which might indicate the need to revisit the $B \rightarrow a_0 X$ transition form factor estimate. It might also imply the limited applicability of the factorization approach for this decay mode. The upper limits suggest that the branching ratios of $B^0 \rightarrow D^{(*)+} a_{0(2)}^-$ are too small for $CP$-asymmetry measurements given the present statistics of the $B$-factories.

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