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Measurement of the $B^0 \to D^{*-} a_1^+$ Branching Fraction with Partially Reconstructed D^*

The *BABAR* Collaboration

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Abstract

The $B^0 \to D^{*-} a_1^+$ branching fraction has been measured with the data collected by the *BABAR* experiment in 1999 and 2000, corresponding to a total integrated luminosity of 20.6 fb^{-1}. Signal events have been selected using a partial reconstruction technique, in which only the a_1^+ and the slow pion (π_s) from the D^{*-} decay are identified. A signal yield of 18400 ± 1200 events has been found, corresponding to a branching fraction of $(1.20 \pm 0.07(\mathrm{stat}) \pm 0.14(\mathrm{syst}))\%$.

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1 Introduction

A partial reconstruction technique has been used in the past to select large samples of reconstructed B mesons with a D^{*-} in the final state [1] and to measure properties of the B^0. In this method the $\overline{D}^0$ is not reconstructed, but its four-momentum is inferred from the kinematics of the a_1^+, the slow pion (π_s) from D^{*-} decay and the decay constraints. The $B^0 \to D^{*-} a_1^+$ branching fraction[4] measurement is performed as one of the necessary steps to prove that this technique can provide a way to measure the combination of the Cabibbo-Kobayashi-Maskawa [2] unitarity triangle angles $\sin(2\beta + \gamma)$ using this channel[5].

2 The *BABAR* detector

The *BABAR* experiment is located at the PEP-II storage ring at the Stanford Linear Accelerator Center. A detailed description of the detector and of the algorithms used for the track reconstruction and selection of $B\overline{B}$ events can be found in Ref. [3]. For the partial reconstruction analysis of $B^0 \to D^{*-} a_1^+$ only charged tracks are used: particles with transverse momentum $p_T > 170$ MeV/c are reconstructed by matching hits in the Silicon Vertex Tracker (SVT) with track segments in the Drift Chamber (DCH). Low p_T particles do not leave signals on many wires of the DCH due to the bending caused by the magnetic field and are reconstructed using only the information from the SVT.

Electron, muon and kaon identification is used in the analysis as a veto in the selection of pions used to reconstruct the a_1 candidates. Electron candidates are identified by the ratio of the energy deposited in the electromagnetic calorimeter (EMC) to the track momentum (E/p) and by the energy loss in the DCH (dE/dx). Muons are primarily identified by the measured number of hadronic interaction lengths traversed from the outside radius of the DCH through the instrumented flux return iron (IFR). Kaons are distinguished from pions and protons on the basis of the dE/dx in the SVT and DCH and the number of Cherenkov photons and the Cherenkov angle in the Detector for Internally Reflected Cherenkov radiation (DIRC).

3 Data sample

The data used in this analysis were collected by the *BABAR* detector in 1999 and 2000. These data correspond to an integrated luminosity of 20.6 fb^{-1} collected at the $\Upsilon(4S)$ resonance and 2.6 fb^{-1} collected 40 MeV below the resonance for background studies (the "off-resonance" sample). Monte Carlo samples of $B\overline{B}$ events and continuum events were analyzed using the same analysis procedure as the data. The equivalent luminosity of the generic simulated data is approximately one fourth of the on-resonance data, while the number of signal $B^0 \to D^{*-} a_1^+$ Monte Carlo (MC) events is approximately ten times the number expected in the on-resonance data.

[4] By a_1^+ we refer to the $\pi^+ \pi^- \pi^+$ final state with the criteria specified in Sec. 5.

[5] Since the selection of $D^{*-} a_1^+$ and $D^{*+} a_1^-$ are identical, the charge conjugate state is implied throughout the paper.

4 The partial reconstruction technique

In the decay chain $B^0 \to D^{*-} a_1^+$, $D^{*-} \to \overline{D}^0 \pi_s^-$ only the a_1 and the π_s from D^* decay are reconstructed. In particular, in this analysis the a_1 is reconstructed via the decay chain $a_1^+ \to \rho^0 \pi^+$. The angle between the momenta of the B and the a_1 in the Center of Mass frame (CM) is then computed:

$$\cos\theta_{Ba_1} = \frac{M^2_{D^{*-}} - M^2_{B^0} - M^2_{a_1} + E_{CM}E_{a_1}}{2P_B|\vec{p}_{a_1}|} \tag{1}$$

where M_x is the mass of particle x, E_{a_1} and p_{a_1} are the measured CM energy and momentum of the a_1, E_{CM} is the total CM energy of the beams and $P_B = \sqrt{E^2_{CM}/4 - M^2_{B^0}}$. Given $\cos\theta_{Ba_1}$ and the measured four-momenta of the π_s and the a_1, the B four-momentum can be calculated up to an unknown azimuthal angle ϕ around $\vec{p}_{a_1}$. For every value of ϕ, the expected $\overline{D}^0$ four-momentum, $P_{\overline{D}^0}$, is determined from four-momentum conservation and the ϕ-dependent "missing mass" is calculated, $m_{\rm miss}(\phi) \equiv \sqrt{|P_{\overline{D}^0}|^2}$. With m_{min} and m_{max} being the minimum and maximum values of $m_{\rm miss}(\phi)$ obtained by varying ϕ, the missing mass $m_{\rm miss} \equiv \frac{1}{2}(m_{max} + m_{min})$ is defined. For signal events, this variable peaks at the $\overline{D}^0$ mass, while for background events it has a broader distribution. For this reason, $m_{\rm miss}$ can be used to determine the fractions of signal and background events in the data sample.

5 Event selection

Data and Monte Carlo events are first selected with the following initial loose requirements:

- $R2$, the ratio of the 2nd to the 0th Fox Wolfram moments [4], is required to be less than 0.35;
- at least one a_1 candidate such that:
  - the a_1 invariant mass m_{a_1} is between 1.0 and 1.6 GeV/c^2;
  - the a_1 momentum p_{a_1}, computed in the CM frame, is between 1.85 and 2.30 GeV/c;
  - the vertex probability obtained from a vertex fit of the 3 pions is greater than 1%;
  - the invariant mass of at least one of the two possible $\pi^+\pi^-$ combinations ($m_{\pi\pi}$) is in the range [0.278, 1.122] GeV/c^2;
- at least one additional track (the π_s) with CM momentum p_{π_s} between 50 and 700 MeV/c;
- for each selected $D^* a_1$ candidate, there must be at least 2 additional particles (charged or neutral).

The fraction of events selected by applying these cuts on the signal and background MC samples and on the off-resonance data is summarized in Table 1.

The main source of background in this analysis is continuum $q\overline{q}$ events, where $q = u, d, s, c$. A neural network is used in order to separate $B\overline{B}$ events, irrespective of any particular B decay channel, from the continuum background.

The NN has three layers, with 11 input nodes, 15 hidden nodes and one output. Its definition relies on the different topologies of signal and background at a B Factory: while $B\overline{B}$ events are more "spherical", $q\overline{q}$ events are more "jet-like". The variables used to discriminate jet-like from isotropic events are R_2; the thrust of the event [4]; the two invariant masses squared, obtained by adding the four momenta of all particles going into each of the hemispheres divided by the plane perpendicular to the thrust axis and the angle of the thrust axis with respect to the e^+e^- direction.

The signal to background separation becomes more complicated when one or more gluons are emitted, which is more likely to happen when light quarks are produced. In this case there are multiple privileged axes, so that the event shape more closely resembles that of the signal. To discriminate further between signal and background in this case, the tracks are clustered into 3 or 4 jets using the so called "Durham" algorithm [5,6].

The event is first clustered into four jets and the following discriminating variables are added to the previously defined ones in order to build up the network: $\mathbf{y}_4$, the jet metric [5,6] obtained when the event is clustered in 4 jets; the QCD matrix element [7]; the cosine of the maximum angle between each pair of jets; the angle between the plane defined by the two most energetic jets and that defined by the other two jets; the angle between the lowest and second lowest energy jet. Then, the event is further clustered into 3 jets and the jet metric $\mathbf{y}_3$ is also added to the list of network input variables.

The distributions of $B\overline{B}$ MC events and on-resonance data that passed the event selection criteria are shown in Fig. 1. The on-resonance distribution is shown after the subtraction of the off-resonance distribution, scaled by the ratio of the on-resonance to off-resonance luminosities and the CM energy squared. By selecting events for which the NN output (O_{NN}) is greater than 0.25, 66% of the continuum events are rejected. The fractions of events selected by this cut in the various samples analyzed are shown in Table 1.

After the NN cut, further selection requirements are applied. There must be at least one $a_1\pi$ combination with net charge equal 0; the three pion invariant mass must be in the range [1.0, 1.45] GeV/c^2; the three pion momentum in the CM frame must be in the range [1.9, 2.25] GeV/c; of the 3 a_1 daughter π's, at least one $\pi^+\pi^-$ combination must have invariant mass in the range [0.65, 0.9] GeV/c^2; the vertex probability of the 3π plus the π_s must be greater than 3%.

The fractions of events selected by these cuts are summarized in Table 1.

Table 1: Fractions of events selected by the cuts applied in the analysis on MC samples and off-resonace data events.

Cuts applied	$B^0 \to D^{*-}a_1^+$	$B^0\overline{B^0}$ (no signal)	B^+B^-	$q\overline{q}$ MC
Reconstruction Efficiency	38.3%	14.6%	13.9%	6.4%
$O_{NN} > 0.25$	85.4%	91.9%	92.1%	45.2%
$q_{a_1-\pi} = 0$	94.2%	86.7%	85.2%	83.5%
$1.0 \leq m_{a_1} \leq 1.45$ GeV/c^2	81.7%	71.8%	71.7%	73.6%
$1.9 \leq p_{a_1} \leq 2.25$ GeV/c	94.8%	92.4%	92.5%	93.3%
$0.65 \leq m_{\pi\pi} \leq 0.9$ GeV/c^2	76.4%	59.1%	60.5%	64.3%
Vertex Prob $4\pi > 0.03$	80.0%	74.2%	73.9%	76.9%
Total Efficiency	14.6%	3.4%	3.2%	0.82%

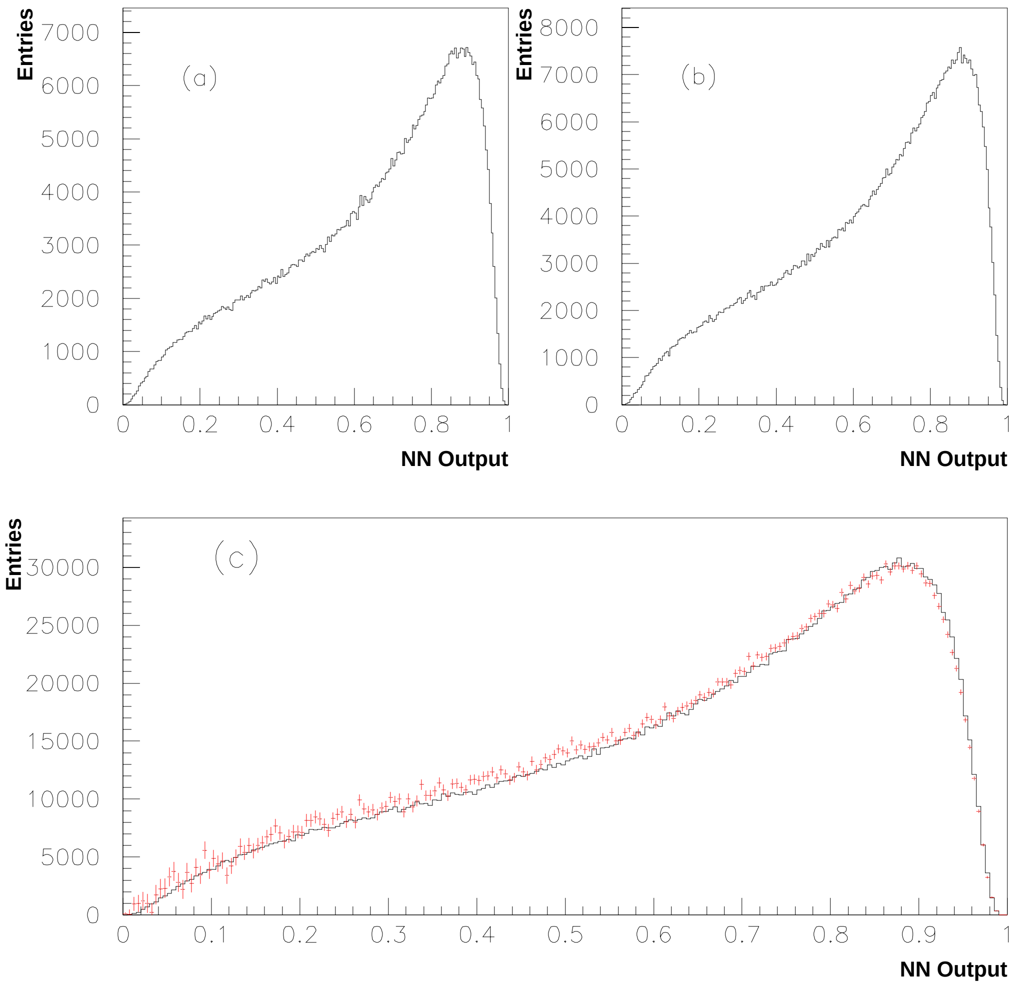

Figure 1: Distribution of the neural net output for (a) $B^0\overline{B^0}$ MC, (b) B^+B^- MC and (c) on-resonance (off-resonance subtracted) data events, superimposed on the total $B\overline{B}$ MC events. All events satisfy the event selection criteria.

6 Results

Applying all of the selection criteria, the $m_{\rm miss}$ distribution of on-resonance and off-resonance data is obtained for "right-sign"events, which are events where the a_1 and π_s candidates have opposite electrical charges. The off-resonance distribution is then scaled to take into account the difference in luminosities and CM energies between the two samples and subtracted bin-by-bin from the on-resonance distribution. The resulting plot is fitted, using a minimum χ^2 fit, to a linear combination of the $m_{\rm miss}$ distributions of the following two types of events:

1. $B\overline{B}$ Monte Carlo events, excluding correctly reconstructed signal events;

2. correctly reconstructed signal Monte Carlo events.

In Fig. 2(a) the $m_{\rm miss}$ distribution of "right-sign" on-resonance data, off-resonance subtracted, is shown, together with the distributions of $B\overline{B}$ background MC and signal MC events. The signal yield that is obtained is 18400 ± 1200 events. The $B\overline{B}$ contribution to the fit is 0.995 ± 0.015 of the value expected, given the total number of $B\overline{B}$ events in the data and in the Monte Carlo.

Given this yield, the a_1 branching fraction[6], the total signal efficiency of Table 1 and the fraction of events with multiple signal candidates, the following branching fraction is obtained:

$$\mathcal{B}(B^0 \to D^{*-} a_1^+) = (1.20 \pm 0.07)\%, \tag{2}$$

where the error is statistical only. The result is in very good agreement with the current best measurement of $(1.30 \pm 0.27)\%$ [8–11].

Several tests were conducted to verify that the background shapes in data and MC agree and do not give rise to spurious signal. Charged a_1 candidates were combined with tracks of the same charge into "wrong-sign" combinations, and were analyzed in the same way as "right-sign" combinations. The $m_{\rm miss}$ distribution of these candidates, shown in Fig. 2(b), shows a good agreement between data and MC in the signal region ($m_{\rm miss} > 1.854$ GeV/c^2). The $B\overline{B}$ contribution to the fit is 0.990 ± 0.016 of the value expected from MC simulation.

Among events collected on-resonance, the fraction containing more than one $a_1\pi$ combination that passes all the analysis cuts in the signal region, defined by $m_{\rm miss} > 1.854$ GeV/c^2, is $F = (15.10 \pm 0.14)$ %. This agrees with the fraction $F_{MC} = (15.51 \pm 0.26)$ % obtained on a weighted mix of off-resonance, $B\overline{B}$ and signal MC events. It was verified that the reconstruction efficiency in $q\overline{q}$ MC and data are in good agreement.

7 Systematic errors

The selection criteria applied in the analysis are varied within a certain range around their chosen values. The branching fraction and its error are recalculated for each cut value, obtaining N different measurements for N different choices of the cut [12]. The variation of the N results with respect to their average, taking into account statistical correlations between them [13], is taken as a systematic error. The method of Ref. [14] is used in order to disentangle the statistical fluctuations from the systematic ones.

The final contributions to the error on the branching ratio due to the variation of the cuts are shown in Table 2. It has been verified that the systematic error obtained for each cut does not depend on the range studied for each cut value.

[6] In this analysis it is assumed that $\mathcal{B}(a_1^+ \to \rho^0\pi^+) = 0.4920$, based on isospin considerations and phase space corrections.

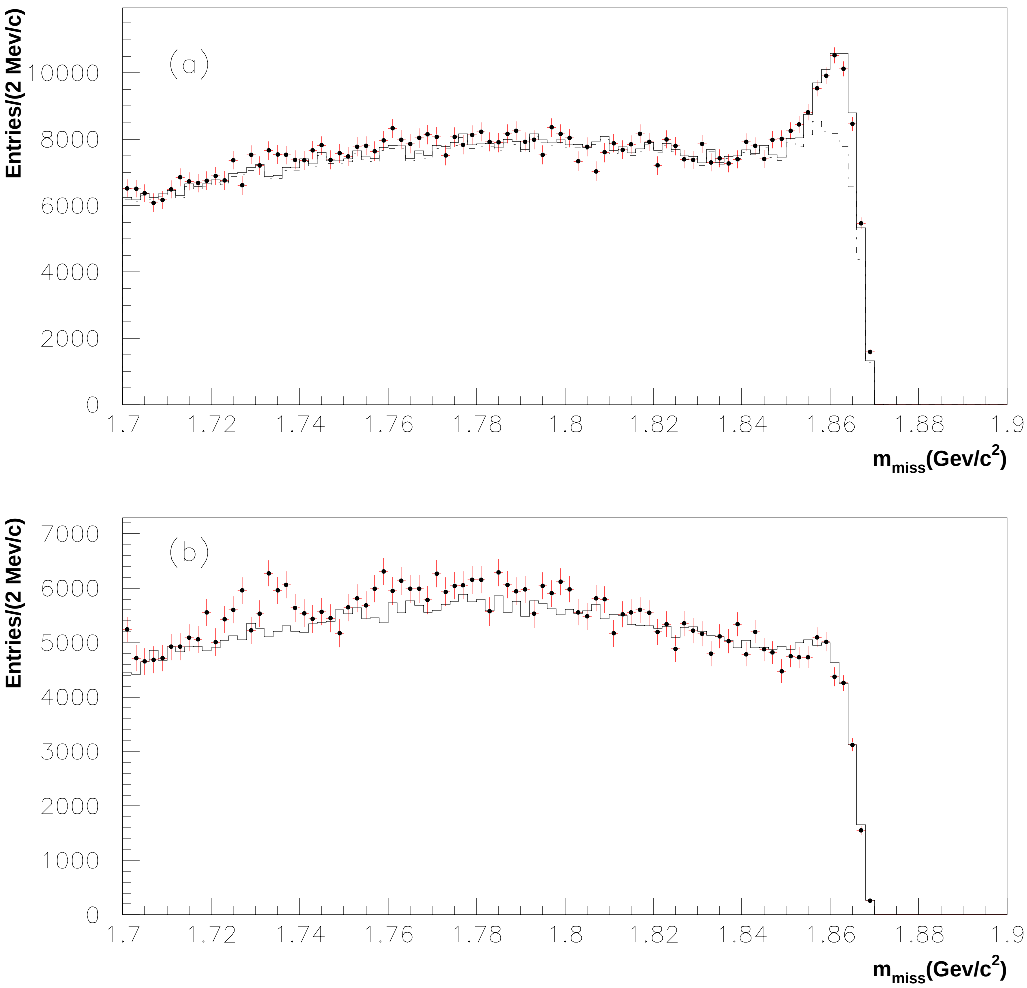

Figure 2: (a) $m_{\rm miss}$ distribution of continuum-subtracted on-resonance data events (data points), $B\overline{B}$ background MC events (dashed histogram) and $B\overline{B}$ background plus signal events (solid histogram) for "right-sign" $a_1\pi$ combinations. The histograms are the result of the fit procedure described in the text. (b) Same distributions for "wrong-sign" $a_1\pi$ combinations.

Table 2: Systematic errors on $\mathcal{B}(B^0 \to D^{*-}a_1^+)$ due to changing the value of some of the cuts in the analysis.

Cut applied	Range Studied	$\tilde{\chi}^2_{min}$	N	Error (%)
$O_{NN} > O_{\rm min}$	$O_{\rm min} = 0.15$ to 0.35	1.37	5	4.2
$m_{\rm min} \leq m_{a_1} \leq m_{\rm max}$	$m_{\rm min} = 1.0$ GeV/c^2			
	$m_{\rm max} = 1.4$ to 1.5 GeV/c^2	0.99	5	negl.
$p_{\rm min} \leq p_{a_1} \leq p_{\rm max}$	$p_{\rm min} = 1.85$ to 1.95 GeV/c^2			
	$p_{\rm max} = 2.15$ to 2.25 GeV/c^2	1.96	5	6.6
Vertex Prob $3\pi > P_{\rm min}$	$P_{\rm min} = 0.01$ to 0.15	1.15	5	2.4
Vertex Prob $4\pi > P_{\rm min}$	$P_{\rm min} = 0.01$ to 0.1	1.10	5	2.2
$m_{\rm min} \leq m_{\rho} \leq m_{\rm max}$	$m_{\rm min} = 0.65$ to 0.75 GeV/c^2			
	$m_{\rm max} = 0.8$ to 0.9GeV/c^2	1.45	5	4.6
Total error				9.6

A conservative systematic error of 0.35% is determined from MC due to the dependence of the π_s reconstruction efficiency on the π_s momentum. The systematic error due to track reconstruction efficiency is 4.2% and the uncertainty in the total number of B mesons in the data sample is 1.6%.

The $B\overline{B}$ background peaks slightly under the signal $m_{\rm miss}$ peak (Fig. 2). This is due mostly to signal events in which one or more of the selected tracks did not originate from the signal B^0. The contribution of this background is varied in the $B\overline{B}$ MC by $\pm\sqrt{(0.07/1.2)^2 + 0.104^2}$, i.e., by the relative statistical error in the central value of the branching fraction plus the total relative systematic error calculated up to this point, added in quadrature. This results in a 4.5% variation of the signal yield, which is added to the total systematic error. The total systematic error is 11.5%.

Other possible sources of systematic error have been investigated. The non-resonant decay channel $B^0 \to D^{*-}\rho^0\pi^+$ would contribute to the peaking background under the signal peak. The measured branching fraction of this mode is $0.57 \pm 0.31\%$ [8,10]. Since the central value is inconsistent with the total $\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)$, this channel is ignored in our fit. A branching fraction of 0.57% is then used to evaluate a possible bias in our measurement, yielding a systematic bias of $\sigma_{syst}^{\mathcal{B}(B^0 \to D^{*-}\rho^0\pi^+)} \;=\; -\,3.3\% \times \mathcal{B}(B^0 \to D^{*-}\rho^0\pi^+)/0.57\%$.

The decay $B \to D^{**}a_1$ could affect the signal yield obtained in the analysis[7]. To study its effect, D^{**} MC events are added to the generic $B\overline{B}$ sample at the level of $\mathcal{B}^{**} = \mathcal{B}(B \to D^{**}a_1) \times \mathcal{B}(D^{**} \to D^*\pi) = 0.35\%$ [15], and the fit to the missing mass distribution is repeated. This results in a reduction of the signal yield of 4.3%. Since the $\mathcal{B}(B \to D^{**}a_1)$ has not yet been measured, based on this result the following systematic bias is quoted: $\sigma_{syst}^{\mathcal{B}^{**}} \;=\; -\,4.3\% \times \mathcal{B}^{**}/0.35\%$.

8 Conclusions

With a partial reconstruction, 18247 ± 1200 $B^0 \to D^{*-}a_1^+$ events have been found in the *BABAR* data set of 20.6 fb^{-1} on-resonance events. This corresponds to the branching fraction

$$\mathcal{B}(B^0 \to D^{*-}a_1^+) = (1.20 \pm 0.07 \pm 0.14)\%, \tag{3}$$

[7] D^{**} denotes the sum of D_1, $D_1^{'}$ and D_2^* states.

where the first error is statistical and the second is systematic. The bias due to the uncertainty in the contribution of $B^0 \to D^{*-}\rho^0\pi^+$ events in the signal sample is $-3.3\% \times \mathcal{B}(B^0 \to D^{*-}\rho^0\pi^+)/0.57\%$ and that due to the unknown value of $\mathcal{B}^{**} = \mathcal{B}(B \to D^{**}a_1) \times \mathcal{B}(D^{**} \to D^*\pi)$ is found to be $-4.3\% \times \mathcal{B}^{**}/0.35\%$. The result is in good agreement with the current world average value of $(1.30 \pm 0.27)\%$ [8–11] and has half the uncertainty.

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