

## Search for $B^+$ -meson decay to $a_1^+ K^{*0}$

The *BABAR* Collaboration

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### Abstract

We present the preliminary result of a search for the decay  $B^\pm \rightarrow a_1^\pm K^{*0}$ . The data, collected with the *BABAR* detector at the Stanford Linear Accelerator Center, represent 465 million  $B\bar{B}$  pairs produced in  $e^+e^-$  annihilation at the  $\Upsilon(4S)$  energy. The result for the branching fraction is:

$$\mathcal{B}(B^+ \rightarrow a_1^+ K^{*0}) \times \mathcal{B}(a_1^+ \rightarrow \pi^+ \pi^- \pi^+) = (0.7_{-0.4}^{+0.5+0.7}) \times 10^{-6},$$

corresponding to an upper limit at 90% confidence level of  $1.6 \times 10^{-6}$ . The first error quoted is statistical, the second systematic.

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# 1 INTRODUCTION

Recent searches for decays of  $B$  mesons to final states with an axial-vector meson  $a_1$  or  $b_1$  and a pion or kaon have revealed modes with branching fractions that are rather large among charmless decays:  $(15\text{--}35)\times 10^{-6}$  for  $B \rightarrow a_1(\pi, K)$  [1, 2], and  $(7\text{--}11)\times 10^{-6}$  for a charged pion and kaon in combination with a  $b_1^0$  or a  $b_1^+$  meson [3, 4]. On the other hand the experimental search for  $B^0 \rightarrow b_1^- \rho^+$  set an upper limit of  $1.7 \times 10^{-6}$  at the 90% confidence level for the branching fraction [5], although a branching fraction of  $25 \times 10^{-6}$  was expected [6].

The available theoretical estimates of the branching fractions of  $B^+$  mesons to  $a_1^+ K^{*0}$  come from calculations based on naïve factorization [7], and on QCD factorization [6]. The latter incorporates light-cone distribution amplitudes evaluated from QCD sum rules, and predicts branching fractions in quite good agreement with the measurements for  $B \rightarrow a_1 \pi$  and  $B \rightarrow a_1 K$  [1, 2]. The expected branching fraction for  $B^+ \rightarrow a_1^+ K^{*0}$  from naïve factorization is  $0.51 \times 10^{-6}$  and that from QCD factorization is  $9.7_{-3.5}^{+4.9+32.9} \times 10^{-6}$  with a prediction for the longitudinal polarization fraction  $f_L = 0.38_{-0.40}^{+0.51}$ . The first theoretical error corresponds to the uncertainties due to the variation of Gegenbauer moments, decay constants, quark masses, form factors and a  $B$  meson wave function parameter. The second theoretical error corresponds to the uncertainties due to the variation of penguin annihilation parameters [6]. For the longitudinal polarization fraction, all errors are added in quadrature, since the theoretical uncertainty is dominated by uncertainties in the size of the penguin-annihilation amplitude. This mode is expected to be substantially enhanced by penguin annihilation and thus it is important to study this mechanism. In this paper we present the first search for the decay  $B^+ \rightarrow a_1^+ K^{*0}$ .

# 2 THE BABAR DETECTOR AND DATASET

The data for this measurement were collected with the *BABAR* detector [8] at the PEP-II asymmetric  $e^+e^-$  collider located at the Stanford Linear Accelerator Center. An integrated luminosity of  $424 \text{ fb}^{-1}$ , corresponding to  $(465 \pm 5) \times 10^6$   $B\bar{B}$  pairs, was produced in  $e^+e^-$  annihilation at the  $\Upsilon(4S)$  resonance (center-of-mass energy  $\sqrt{s} = 10.58 \text{ GeV}$ ). Charged particles from the  $e^+e^-$  interactions are detected, and their momenta measured by a combination of five layers of double-sided silicon microstrip detectors and a 40-layer drift chamber both operating in the 1.5 T magnetic field of the BaBar superconducting solenoid. Photons and electrons are identified with a CsI(Tl) electromagnetic calorimeter (EMC). Further charged particle identification (PID) is provided by the average energy loss ( $dE/dx$ ) in the tracking devices and by an internally reflecting ring imaging Cherenkov detector (DIRC) covering the central region.

A detailed Monte Carlo program (MC) is used to simulate the  $B$  meson production and decay sequences, and the detector response [9]. Dedicated signal MC events for the decay  $B^+ \rightarrow a_1^+ K^{*0}$  with  $a_1^+ \rightarrow \rho^0 \pi^+$  has been produced. For the  $a_1(1260)$  meson parameters we use a mass of  $1230 \text{ MeV}/c^2$  and a width of  $400 \text{ MeV}/c^2$ . We account for the uncertainties of these resonance parameters in the determination of systematic uncertainties. The  $a_1^+ \rightarrow \pi^- \pi^+ \pi^+$  decay proceeds mainly through the intermediate states  $(\pi\pi)_{\rho\pi}$  and  $(\pi\pi)_{\sigma\pi}$  [10]. No attempt is made to separate contributions of the dominant P wave  $(\pi\pi)_{\rho}$  from the S wave  $(\pi\pi)_{\sigma}$  in the channel  $\pi\pi$ . The difference in efficiency for the S wave and P wave cases is accounted for as a systematic error.



### 3 ANALYSIS METHOD

We reconstruct  $a_1^+$  candidates through the decay sequence  $a_1^+ \rightarrow \rho^0 \pi^+$  and  $\rho^0 \rightarrow \pi^+ \pi^-$ . The other primary daughter of the  $B$  meson is reconstructed as  $K^{*0} \rightarrow K^+ \pi^-$ . For the  $\rho^0$ , the invariant mass of the pion pair is required to lie between 0.55 and 1.0 GeV/ $c^2$ . For the  $a_1$  and  $K^*$  we accept a range that includes sidebands. The  $a_1$  invariant mass is required to lie between 0.9 and 1.8 GeV/ $c^2$ , while the  $K^*$  invariant mass is required to lie between 0.8 and 1.0 GeV/ $c^2$ . Secondary charged pion candidates from  $a_1$  and  $K^*$  decays are rejected if classified as protons, kaons, or electrons by their DIRC,  $dE/dx$ , and EMC PID signatures. We reconstruct the  $B$  meson candidate by combining the four-momenta of a pair of primary daughter mesons, using a fit that constrains all particles to a common vertex. From the kinematics of  $\Upsilon(4S)$  decay we determine the energy-substituted mass  $m_{\text{ES}} = \sqrt{\frac{1}{4}s - \mathbf{p}_B^2}$  and energy difference  $\Delta E = E_B - \frac{1}{2}\sqrt{s}$ , where  $(E_B, \mathbf{p}_B)$  is the  $B$  meson four-momentum vector, and all values are expressed in the  $\Upsilon(4S)$  rest frame. We require  $5.25 \text{ GeV}/c^2 < m_{\text{ES}} < 5.29 \text{ GeV}/c^2$  and  $|\Delta E| < 100 \text{ MeV}$ . To reduce fake meson candidates we require a  $B$ ,  $a_1$  and  $K^*$  vertex  $\chi^2$  probability  $> 0.01$ .

We also impose restrictions on the helicity-frame decay angle  $\theta_{K^*}$  of the  $K^*$  mesons. The helicity frame of a meson is defined as the rest frame of the meson with the  $z$  axis along the direction of boost to that frame from the parent rest frame. For the decay  $K^* \rightarrow K\pi$ ,  $\theta_{K^*}$  is the polar angle of the daughter kaon, and for  $a_1 \rightarrow \rho\pi$ ,  $\theta_{a_1}$  is the polar angle of the normal to the  $a_1$  decay plane. We define  $\mathcal{H}_i = \cos(\theta_i)$ , where  $i = (K^*, a_1)$ . Since many background candidates accumulate near  $|\mathcal{H}_{K^*}| = 1$ , we require  $-0.98 \leq \mathcal{H}_{K^*} \leq 0.8$ .

Backgrounds arise primarily from random combinations of particles in continuum  $e^+e^- \rightarrow q\bar{q}$  events ( $q = u, d, s, c$ ). We reduce these with a requirement on the angle  $\theta_T$  between the thrust axis [11] of the  $B$  candidate in the  $\Upsilon(4S)$  frame and that of the charged tracks and neutral calorimeter clusters in the rest of the event (ROE). The distribution is sharply peaked near  $|\cos\theta_T| = 1$  for jet-like continuum events, and nearly uniform for  $B$  meson decays. The requirement, which optimizes the expected signal yield relative to its background-dominated statistical uncertainty, is  $|\cos\theta_T| < 0.8$ .  $B\bar{B}$  background arising from  $b \rightarrow c$  transitions is suppressed by removing events with  $D$  meson candidates, reconstructed in the decays  $D^0 \rightarrow K^-\pi^+$  and  $D^+ \rightarrow K^-\pi^+\pi^+$ , with an invariant mass within  $\pm 0.02 \text{ GeV}/c^2$  of the nominal mass value.

The number of events which pass the selection is 15802. Besides the signal events, these samples contain  $q\bar{q}$  (dominant) and  $B\bar{B}$  with  $b \rightarrow c$  combinatorial backgrounds, and a fraction of other charmless  $B\bar{B}$  background modes. The average number of candidates found per event in the selected data sample is 1.5 (2.0 to 2.4 in signal MC depending on the polarization). We choose the candidate that is most likely a signal decay, as judged from the output of a neural network, where we use the  $\rho$  meson mass and the vertex fit  $\chi^2$  probabilities of  $B$ ,  $a_1$  and  $K^*$  candidates as input variables.

We discriminate further against  $q\bar{q}$  background with a Fisher discriminant  $\mathcal{F}$  [12] that combines four variables: the polar angle of the  $B$  candidate momentum and of the  $B$  thrust axis with respect to the beam axis in the  $\Upsilon(4S)$  rest frame; and the zeroth and second angular moments  $L_{0,2}$  of the energy flow, excluding the  $B$  candidate, with respect to the  $B$  thrust axis. The moments are defined by  $L_j = \sum_i p_i \times |\cos\theta_i|^j$ , where  $\theta_i$  is the angle with respect to the  $B$  thrust axis of a track or neutral cluster  $i$ ,  $p_i$  is its momentum.

We obtain yields and the longitudinal polarization  $f_L$  from an extended maximum likelihood (ML) fit with the input observables  $\Delta E$ ,  $m_{\text{ES}}$ ,  $\mathcal{F}$ , the resonance masses  $m_{a_1}$  and  $m_{K^*}$  and the helicity distributions  $\mathcal{H}_{K^*}$  and  $\mathcal{H}_{a_1}$ .

Since the correlation between the observables in the selected data and in MC signal events is small, we take the probability density function (PDF) for each event to be a product of the PDFs for the individual observables. Corrections for the effects of possible correlations are made on the basis of MC studies described below.

We determine the PDFs for the signal and  $B\bar{B}$  background components from fits to MC samples. We develop PDF parameterizations for the combinatorial background with fits to the data from which the signal region ( $5.26 \text{ GeV}/c^2 < m_{\text{ES}} < 5.29 \text{ GeV}/c^2$  and  $|\Delta E| < 60 \text{ MeV}$ ) has been excluded.

The  $m_{\text{ES}}$  and  $\Delta E$  distributions are parametrized as linear combinations of the so-called Crystal-Ball function [13] and Gaussian. In case of  $m_{\text{ES}}$  for  $q\bar{q}$  and  $B\bar{B}$  background we use the threshold function  $x\sqrt{1-x^2}\exp[-\xi(1-x^2)]$ , with argument  $x \equiv 2m_{\text{ES}}/\sqrt{s}$  and shape parameter  $\xi$ . This function is discussed in more detail in Ref. [14]. In case of  $\Delta E$  for  $q\bar{q}$  and  $B\bar{B}$  background we use a polynomial function. The PDFs for the Fisher discriminant  $\mathcal{P}_j(\mathcal{F})$  are parametrized as single or double Gaussian. The PDFs for the invariant masses of the  $a_1$  and  $K^*$  mesons are constructed as linear combinations of relativistic Breit Wigner and polynomial functions. We use a joint PDF  $\mathcal{P}_j(\mathcal{H}_{K^*}, \mathcal{H}_{a_1})$  for the helicity distributions, the signal component is parametrized as the product of the ideal angular distribution in  $\mathcal{H}_{K^*}$  and  $\mathcal{H}_{a_1}$  from Ref. [15], times an empirical acceptance function  $\mathcal{G}(\mathcal{H}_{K^*}, \mathcal{H}_{a_1})$  while the helicity PDF for the other components is the product of the helicity PDFs for  $\mathcal{H}_{K^*}$  and  $\mathcal{H}_{a_1}$ . The  $\mathcal{H}_i$  distributions in case of  $q\bar{q}$  and  $B\bar{B}$  background are based on Gaussian and polynomial functions. We allow the most important parameters (first coefficient of the polynomial function for  $\Delta E$ , the invariant masses of the  $a_1$  and the  $K^*$ , and the width of the Breit Wigner for the invariant mass of the  $K^*$ ) for the determination of the combinatorial background PDFs to vary in the fit, along with the yields for the signal and  $q\bar{q}$  background.

The likelihood function is

$$\mathcal{L} = \exp\left(-\sum_j Y_j\right) \prod_i \sum_j Y_j \times \mathcal{P}_j(m_{\text{ES}}^i) \mathcal{P}_j(\mathcal{F}^i) \mathcal{P}_j(\Delta E^i) \mathcal{P}_j(m_{a_1}^i) \mathcal{P}_j(m_{K^*}^i) \mathcal{P}_j(\mathcal{H}_{K^*}^i, \mathcal{H}_{a_1}^i), \quad (1)$$

where  $N$  is the number of events in the sample, and for each component  $j$  (signal,  $q\bar{q}$  background,  $b \rightarrow c B\bar{B}$  background, or charmless  $B\bar{B}$  background),  $Y_j$  is the yield of component  $j$  and  $\mathcal{P}_j(x^i)$  is the probability for variable  $x$  of event  $i$  to belong to component  $j$ .

We validate the fitting procedure by applying it to ensembles of simulated experiments with the  $q\bar{q}$  component drawn from the PDF, and with embedded known numbers of signal and  $B\bar{B}$  background events randomly extracted from the fully simulated MC samples. By tuning the number of embedded events until the fit reproduces the yields found in the data, we find a positive bias

Table 1: Summary of results for  $B^+ \rightarrow a_1^+ K^{*0}$ . Signal yield  $Y$ , fit bias  $Y_b$ , the branching fraction of  $K^{*0} \rightarrow K^+ \pi^-$   $\mathcal{B}(K^{*0} \rightarrow K^+ \pi^-)$ , branching fraction  $\mathcal{B} = \mathcal{B}(B^+ \rightarrow a_1^+ K^{*0}) \times \mathcal{B}(a_1^+ \rightarrow \pi^+ \pi^- \pi^+)$ , significance  $S$  (see text) and upper limit UL. The given uncertainties on fit yields are statistical only, the uncertainties on the fit bias include the corresponding systematic uncertainties.

$Y$	$Y_b$	$\mathcal{B}(K^{*0} \rightarrow K^+ \pi^-)$	$\mathcal{B}(10^{-6})$	$S$	UL ( $10^{-6}$ )
$55_{-17}^{+19}$	$27 \pm 14$	$\frac{2}{3}$	$0.7_{-0.4-0.7}^{+0.5+0.7}$	0.9	1.6

$Y_b$ , to be subtracted from the observed signal yield  $Y$ : the corresponding numbers are reported in Table 1.

In the fitting procedure we allow the longitudinal polarization  $f_L$  to vary, finding the best value  $f_L = 1.1 \pm 0.2$ , where the error is statistical only; systematic uncertainties are not evaluated and we do not report a measurement on this quantity, since the observed signal is not statistically significant.

We compute the branching fraction by subtracting the fit bias from the measured yield, and dividing the result by the number of produced  $B\bar{B}$  pairs and by the product of the selection efficiency times the branching ratio for the  $\mathcal{B}(K^{*0} \rightarrow K^+\pi^-)$  decay. We assume that the branching fractions of the  $\Upsilon(4S)$  to  $B^+B^-$  and  $B^0\bar{B}^0$  are equal, consistent with measurement [10]. The efficiency for longitudinally and transversely polarized signal events, obtained from MC signal model, is 12.9% and 18.6%, respectively. The results are given in Table 1, along with the significance, computed as the square root of the difference between the value of  $-2 \ln \mathcal{L}$  (with additive systematic uncertainties included) for zero signal and the value at its minimum. In order to obtain the most conservative upper limit, we assume  $f_L = 1$  in estimating the branching fraction. In Figure 1 we show the projections of data with PDFs overlaid. The data plotted are subsamples enriched in signal with the requirement of a minimum value of the ratio of signal to total likelihood, computed without the plotted variable.

## 4 SYSTEMATIC STUDIES

Systematic uncertainties on the branching fractions arise from the imperfect knowledge of the PDFs,  $B\bar{B}$  backgrounds, fit bias, and efficiency. PDFs uncertainties not already accounted for by free parameters in the fit are estimated from varying the signal-PDF parameters within their uncertainties. For  $K^*$  resonance parameters we use the uncertainties from Ref. [10] and for the  $a_1$  resonance parameters from Ref. [1]. The uncertainty from fit bias (Table 1) includes its statistical uncertainty from the simulated experiments, and half of the correction itself, added in quadrature. We vary the  $B\bar{B}$  background component yields by 100% for charmless background and by 20% for the  $b \rightarrow c B\bar{B}$  background.

In the systematic uncertainty we account for a possible  $B^+ \rightarrow a_2^+ K^{*0}$  contribution by parameterizing its PDFs on a dedicated sample of simulated events; for the helicity part of this component we use the corresponding joint ideal angular distribution from Ref. [15], as we do for our signal component. We conservatively assume  $B^+ \rightarrow a_2^+ K^{*0}$  branching ratio could be as large as the  $B^+ \rightarrow a_1^+ K^{*0}$  and vary the  $B^+ \rightarrow a_2^+ K^{*0}$  from 0 to 19 events.

The uncertainty from the polarization is obtained by varying  $f_L$  within errors found in studies where  $f_L$  was allowed to vary in the fit. Uncertainties in our knowledge of the tracking efficiency include 0.3% per track in the  $B$  candidate. The uncertainties in the efficiency from the event selection are below 0.6%. We determine the systematic uncertainty on the determination of the integrated luminosity to be 1.1%. All systematic uncertainties on the branching fraction are summarized in Table 2.

## 5 RESULTS

We obtain as a preliminary result for the product of branching fractions:

$$\mathcal{B}(B^+ \rightarrow a_1^+ K^{*0}) \times \mathcal{B}(a_1^+ \rightarrow \pi^+\pi^-\pi^+) = (0.7_{-0.4}^{+0.5+0.7}) \times 10^{-6},$$

Table 2: Summary of systematic uncertainties of the determination of the  $B^+ \rightarrow a_1^+ K^{*0}$  branching fraction.

Source of systematic uncertainty	
Additive errors (events)	
$b \rightarrow c B\bar{B}$ background	6
Charmless $B\bar{B}$ background	12
$B^+ \rightarrow a_2^+ K^{*0}$ background	14
$a_1$ meson parametrization	4
PDF parametrization	3
Variation on $f_L$	2
ML Fit Bias	14
Total additive (events)	26
Multiplicative errors (%)	
Tracking efficiency	1.2
Determination of the integrated luminosity	1.1
MC statistics (signal efficiency)	0.6
Differences in the selection efficiency for the $a_1$ decay	3.3
Particle identification (PID)	1.4
Event shape restriction ( $\cos\theta_T$ )	1.0
Total multiplicative (%)	4.1
Total systematic error [ $\mathcal{B}(10^{-6})$ ]	$\pm 0.7$

corresponding to an upper limit of  $1.6 \times 10^{-6}$ .

Assuming  $\mathcal{B}(a_1^\pm(1260) \rightarrow \pi^+\pi^-\pi^\pm)$  is equal to  $\mathcal{B}(a_1^\pm(1260) \rightarrow \pi^\pm\pi^0\pi^0)$ , and that  $\mathcal{B}(a_1^\pm(1260) \rightarrow 3\pi)$  is equal to 100%, we obtain:

$$\mathcal{B}(B^+ \rightarrow a_1^+ K^{*0}) = (1.5_{-0.9}^{+1.0+1.4}) \times 10^{-6},$$

corresponding to an upper limit of  $3.3 \times 10^{-6}$ . The first error quoted is statistical and the second systematic. Since the signal significance is 0.9 standard deviations, we quote a 90% confidence level upper limit.

The upper limit from this measurement is, on the one hand, in agreement with the prediction from naïve factorization [7], and on the other hand, significantly lower than the QCD factorization estimation [6], though not inconsistent with it.

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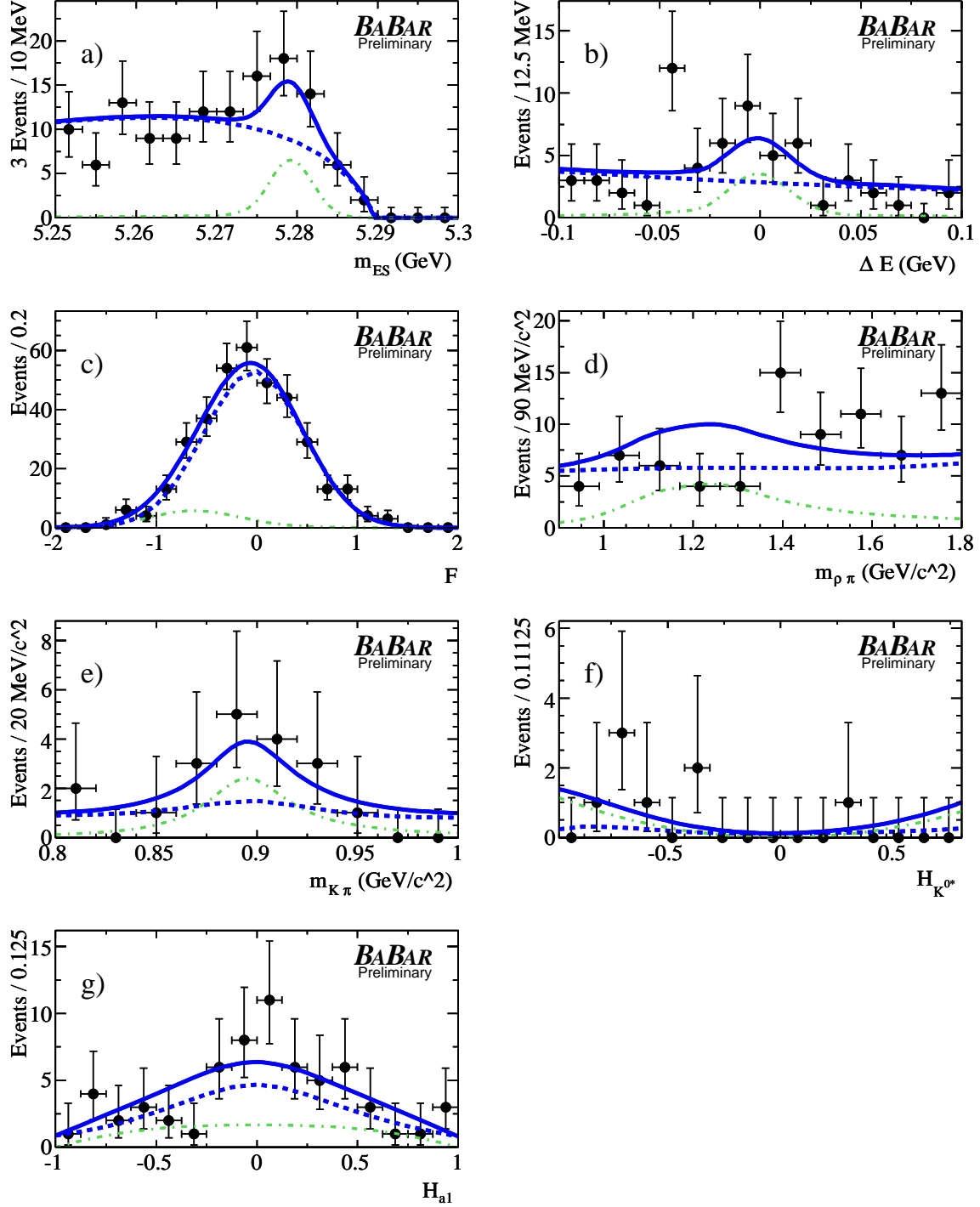


Figure 1: Distributions for signal-enhanced subsets (see text) of the data projected onto the fit observables for the decay  $B^+ \rightarrow a_1^+ K^{*0}$ ; (a)  $m_{ES}$ , (b)  $\Delta E$ , (c)  $\mathcal{F}$ , (d)  $m(\rho\pi)$  for the  $a_1$  candidate, (e)  $m(K\pi)$  for the  $K^*$  candidate, (f)  $\mathcal{H}_{K^*}$  and (g)  $\mathcal{H}_{a_1}$ . The solid lines represent the results of the fit, and the dot-dashed and dashed lines the signal and background contributions, respectively. These plots are made with cuts on the ratio of signal to total likelihood. With respect to the nominal fit 19% to 46% (depending on the variable) of signal events remain.

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