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Measurement of the Branching Fraction of $e^+e^- \to B^0\overline{B}^0$ at the $\Upsilon(4S)$ Resonance

The *BABAR* Collaboration

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We report a measurement of the branching fraction $e^+e^- \to B^0\overline{B}^0$ with a data sample of 81.7 fb^{-1} collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage ring. Using partial reconstruction of the decay $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ we obtain a preliminary result of $f_{00} = 0.486 \pm 0.010(stat.) \pm 0.009(sys.)$. Our result does not depend on branching fractions of the $\overline{B}^0$ and the D^{*+} decay chains, on the simulated reconstruction efficiency, on the ratio of the charged and neutral B meson lifetimes, nor on assumption of isospin symmetry. This measurement is important for normalizing many B decay branching fractions, and contributes to our understanding of isospin violation in the $\Upsilon(4S)$ system.

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1 INTRODUCTION

Isospin violation in decays of $e^+e^- \to B^0\overline{B}^0$ at the $\Upsilon(4S)$ resonance results in a difference between the branching fractions $f_{00} \equiv \mathcal{B}(e^+e^- \to B^0\overline{B}^0)$ and $f_{+-} \equiv \mathcal{B}(e^+e^- \to B^+B^-)$. Measurements of the ratio $R^{+/0} \equiv f_{+-}/f_{00}$, summarized in Table 1, are consistent with unity within the errors [1]. Theoretical predictions for $R^{+/0}$ range from 1.03 to 1.25 [2]. Currently, almost all published measurements of B meson branching fractions make the assumption that $R^{+/0} = 1$. Precision measurements of f_{00}, f_{+-}, and $R^{+/0}$ can be used to eliminate this assumption and re-normalize all B meson branching fractions.

Table 1: Summary of previous measurements of $R^{+/0}$

Decay $B \to$	$\int \mathcal{L}dt$	$R^{+/0}$	Source
$J/\psi(K^+/K_s^0)$	81.9 fb^{-1}	$1.006 \pm 0.036 \pm 0.031$	*BABAR* [3]
$D^{*(+/0)}\ell\bar{\nu}$	2.73 fb^{-1}	$1.058 \pm 0.084 \pm 0.136$	CLEO [4]
$J/\psi h^{(+/0)}$	20.7 fb^{-1}	$1.10 \pm 0.06 \pm 0.05$	*BABAR* [5]
$J/\psi K^{*(+/0)}$	9.2 fb^{-1}	$1.04 \pm 0.07 \pm 0.04$	CLEO [6]

In this paper we report the first direct measurement of f_{00}. The measurement is based on partial reconstruction of the decay $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ (the inclusion of charge-conjugate states is implied throughout this paper). This allows a sizeable sample of double tagged events to be identified. Comparison of the double-tag and the single-tag yields allows a determination of f_{00} with minimal input from simulation.

The technique used to measure f_{00} is as follows: in every event we reconstruct the decay $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$, as described further below. The sample of events in which at least one $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ candidate decay is found is labeled as "single-tag sample". The number of signal decays found in this sample is

$$N_s = 2N_{B\overline{B}} f_{00}\, \epsilon_s\, \mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell), \tag{1}$$

where $N_{B\overline{B}} = (88726 \pm 23) \times 10^3$ is the total number of $B\overline{B}$ events in the data sample and ϵ_s is the reconstruction efficiency of the decay $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$. The technique for measuring $N_{B\overline{B}}$ is described in [7]. The data sample has a mean energy of 10.580 GeV [8] and an energy spread of only 4.6 MeV. Such a small spread means that any energy dependence of f_{00} has a negligible effect on the central value. The subset of single-tag events in which two $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ candidates are found is labeled as "double-tag sample". The number of such events is

$$N_d = N_{B\overline{B}}\, f_{00}\, \epsilon_d\, [\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell)]^2, \tag{2}$$

where ϵ_d is the efficiency to reconstruct two $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays in the same event. Note that every double-tag event contributes two entries to the single-tag sample. Using Eq. (1) and Eq. (2), the ratio f_{00} is given by

$$f_{00} = \frac{CN_s^2}{4N_d N_{B\overline{B}}}, \tag{3}$$

where we have defined the coefficient $C \equiv \epsilon_d/\epsilon_s^2$. $C = 1$ if the efficiencies for detecting each B meson are uncorrelated in double-tag events.

2 THE *BABAR* DETECTOR AND DATASET

The *BABAR* data sample used in this paper consists of 81.7 fb^{-1} collected at the $\Upsilon(4S)$ resonance (the on-resonance sample) and 9.6 fb^{-1} collected 40 MeV below the resonance (the off-resonance sample). Simulated $B\overline{B}$ events were analyzed through the same analysis chain as the data. The equivalent luminosity of the simulated sample is approximately three times that of the on-resonance data.

A detailed description of the *BABAR* detector and the algorithms used for track reconstruction and particle identification is provided elsewhere [9]. A brief summary is given here. High-momentum particles are reconstructed by matching hits in the silicon vertex tracker (SVT) with track elements in the drift chamber (DCH). Lower momentum tracks, which do not leave signals on many wires in the DCH due to the bending induced by a magnetic field, are reconstructed by the SVT alone. Electrons are identified with the ratio of the track momentum to the associated energy deposited in the calorimeter (EMC), the transverse profile of the shower, the energy loss in the drift chamber, and the information from a Cherenkov detector (DIRC). Muons are identified in the instrumented flux return (IFR), composed of resistive plate chambers and layers of iron. Muon candidates are required to have a path length and hit distribution in the instrumented flux return and energy deposition in the EMC consistent with that expected for a minimum-ionizing particle. The Cherenkov light emission in the DIRC is then employed to further reject kaons misidentified as muons by requiring muon candidates to have a kaon hypothesis probability less than 5%.

Hadronic events are selected by requiring at least four charged particle tracks reconstructed by the silicon vertex detector and the drift chamber. To reduce background from continuum $e^+e^- \to q\overline{q}$, where q stands for a u, d, s, or c quark, the ratio $R_2 = H_2/H_0$ of the second to the zeroth Fox-Wolfram moments is used [10].

3 ANALYSIS METHOD

We reconstruct the decays $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ with a partial reconstruction technique. The application of the technique to this mode was first proposed by the ARGUS Collaboration [11] and has been used by CLEO [4], DELPHI [12], OPAL [13], and *BABAR* [14]. In this technique, only the lepton from the decay $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ and the soft pion from the decay $D^{*+} \to D^0\pi^+$ are used. No attempt is made to reconstruct the D^0, resulting in high reconstruction efficiency.

To suppress leptons from charm decays, all lepton candidates (electrons and muons) are required to have momentum between 1.5 GeV/c and 2.5 GeV/c in the e^+e^- center-of-mass (CM) frame. Soft pion candidates are required to have CM momentum between 60 MeV/c and 200 MeV/c. As a consequence of the limited phase space available in the D^{*+} decay, the soft pion is emitted within a one radian-wide cone centered about the D^{*+} direction in the CM frame. The D^{*+} four-momentum can therefore be computed by approximating its direction as that of the soft pion, and parameterizing its momentum as a linear function of the soft pion momentum, with parameters obtained from the simulation. The presence of an undetected neutrino is inferred from conservation of momentum and energy. The neutrino invariant mass squared is calculated:

$$\mathcal{M}^2 \equiv (E_{\mathrm{beam}} - E_{D^*} - E_\ell)^2 - (\mathbf{p}_{D^*} + \mathbf{p}_\ell)^2 \;, \quad (4)$$

where E_{beam} is the beam energy and E_ℓ (E_{D^*}) and $\mathbf{p}_\ell$ ($\mathbf{p}_{D^*}$) are the CM energy and momentum of the lepton (the D^* meson). If the decay is properly reconstructed and the neutrino is the only missing particle, the $\mathcal{M}^2$ distribution will peak near zero for signal events. Background events, however, are spread over a wide range of $\mathcal{M}^2$ values.

In what follows, we use the symbol $\mathcal{M}_s^2$ to denote $\mathcal{M}^2$ for any candidate in the single-tag sample. In the double-tag sample, we randomly choose one of the two reconstructed $\overline{B}^0 \to D^{*+}\ell^-\nu_l$ candidates as "first" and the other as "second". Their $\mathcal{M}^2$ values are labeled $\mathcal{M}_1^2$ and $\mathcal{M}_2^2$, respectively. For each of the variables $\mathcal{M}_i^2$ $(i = s, 1, 2)$, we define a signal region $\mathcal{M}_i^2 > -2$ GeV$^2/c^4$ and the sideband $-8 < \mathcal{M}_i^2 < -4$ GeV$^2/c^4$.

In addition to signal $\overline{B}^0 \to D^{*+}\ell^-\nu_l$ decays, the single-tag and double-tag samples contain several types of events:

- Continuum $e^+e^- \to q\overline{q}$ background.
- Combinatorial $B\overline{B}$ background, formed from random combinations of reconstructed leptons and soft pions. This background can also be due to the low momentum soft pions not coming from a D^*, produced by either the same B or other B [15].
- Peaking $B\overline{B}$ background, composed of $\overline{B} \to D^*(n\pi)\ell\bar{\nu}_\ell$ decays with or without an excited charmed resonance (D^{**}) [16], where the reconstructed soft pion comes from the decay $D^{*+} \to D^0\pi^+$, leading to an accumulation of these events at high values of $\mathcal{M}_i^2$. These events are peaking background and are produced both by $\overline{B}^0$ and B^- decays. Their $\mathcal{M}_i^2$ distribution differs from the signal, which allows us to extract their contribution in a fit. Such events are suppressed by the requirement $p_\ell > 1.5\,\mathrm{GeV}/c$ on the lepton CM momentum.
- The decays $\overline{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ and $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell(n\gamma)$ may be used for the measurement of f_{00} and are therefore considered as signal. These events peak in $\mathcal{M}_i^2$ and come from $\overline{B}^0$ decays.

The double-tag sample contains two additional types of background: $\mathcal{M}_1^2$-combinatorial and $\mathcal{M}_1^2$-peaking. In $\mathcal{M}_1^2$-combinatorial ($\mathcal{M}_1^2$-peaking) background events the first candidate is combinatorial (peaking) background.

To determine N_s and N_d, we perform binned χ^2 fits to one-dimensional histograms of the $\mathcal{M}_s^2$ and $\mathcal{M}_2^2$ distributions of on-resonance data events, ranging from -8 to 2 GeV$^2/c^4$. Before fitting, we subtract the continuum background contribution from the histograms. This is done using the $\mathcal{M}_s^2$ and $\mathcal{M}_2^2$ distributions of off-resonance data, scaled to account for the ratio of on-resonance to off-resonance luminosities and the CM energy dependence of the continuum production cross-section. In addition, the contributions of the $\mathcal{M}_1^2$-combinatorial and $\mathcal{M}_1^2$-peaking backgrounds are subtracted from the $\mathcal{M}_2^2$ histogram before the fit. The $\mathcal{M}_1^2$-combinatorial background is determined from the $\mathcal{M}_1^2$ sideband, which contain only continuum and combinatorial background events. This histogram is scaled by the ratio of the number of combinatorial events in the signal region and the sideband, determined from the simulation. The $\mathcal{M}_1^2$-peaking background subtraction is based on the simulated $\mathcal{M}_1^2$-peaking events.

After the subtraction, the $\mathcal{M}_s^2$ and $\mathcal{M}_2^2$ histograms are fit separately, using a function whose value for bin j of the histogram is

$$f_j = \sum_t N^t P_j^t, \tag{5}$$

where N^t is the number of events of type t (t = signal, combinatorial, peaking) populating the histogram, and P_j^t is the bin j value of a discrete probability density function (PDF) obtained from simulated events of type t, normalized such that $\sum_j P_j^t = 1$. The fit determines the parameters N^t

by minimizing:

$$\chi^2 = \sum_j \frac{(H_j - f_j)^2}{\sigma^2_{H_j} + \sigma^2_{f_j}}, \tag{6}$$

where H_j is the number of entries in bin j of the histogram being fit; σ_{H_j} is the statistical error on H_j, including uncertainties due to the background subtractions described above; and σ_{f_j} is the error on f_j, determined from the errors on P^t_j, which are due to the finite size of the simulated sample.

The results of the fits are presented in Table 2. The $\mathcal{M}^2_s$ and $\mathcal{M}^2_2$ distributions are shown in Fig. 1, with the contributions of the different event types indicated. The fits yield the values $N_s = 786300 \pm 1950$ and $N_d = 3560 \pm 80$. Using the simulation we determine $C = 0.9946 \pm 0.0078$, where the error is due to the finite size of the simulated sample. Eq. (3) then gives $f_{00} = 0.486 \pm 0.010$, where the error is due to data statistics only.

Table 2: Numbers of entries of different types found by the fits to the $\mathcal{M}^2_s$ and $\mathcal{M}^2_2$ histograms in the signal region. Also shown are the numbers of entries of subtracted backgrounds and the confidence levels of the fits.

Source	$\mathcal{M}^2_s$	$\mathcal{M}^2_2$
Combinatorial $B\overline{B}$	558090 ± 760	1520 ± 40
Peaking $B\overline{B}$	68170 ± 260	300 ± 20
Signal	786300 ± 2000	3560 ± 80
Continuum	238500 ± 1300	160 ± 40
$\mathcal{M}^2_1$-combinatorial	—	180 ± 20
$\mathcal{M}^2_1$-peaking	—	60 ± 10
χ^2/d.o.f.	41/56	48/56
Confidence level	93%	77%

To determine how well the simulation reproduces the $\mathcal{M}^2_s$ and $\mathcal{M}^2_2$ distributions of the combinatorial background in the data, we study the distributions of a sample of same-charge candidates, in which the lepton and soft pion have the same electric charge. This sample contains only continuum and combinatorial $B\overline{B}$ background. We fit the continuum-subtracted $\mathcal{M}^2_s$ and $\mathcal{M}^2_2$ histograms of the same-charge sample using the function $f'_j = NP'_j$, where P'_j is the bin j value of the PDF of same-charge simulated $B\overline{B}$ events, normalized such that $\sum_j P'_j = 1$, and the parameter N is determined by the fit. The histograms, overlaid with the fit function, are shown in Fig. 2. The ratio between these two histograms is fitted to a constant both for the $\mathcal{M}^2_s$ and $\mathcal{M}^2_2$ summed over the signal region and over all bins are shown in Fig. 3. The accumulated differences $D \equiv \sum_j (H'_j - f'_j)$ between the same-charge data histograms H'_j and the fit functions are summarized in Table 3. Their consistency with zero indicates that the distributions of simulated combinatorial $B\overline{B}$ background events do not lead to significant fake signal yields.

4 SYSTEMATIC STUDIES

We consider several sources of systematic uncertainties in f_{00}. All estimated errors are an absolute systematic uncertainties in f_{00} and summarized in Table 4.

Table 3: The difference $D \equiv \sum_j (H'_j - f'_j)$ between the same-charge data histogram and the fit function, summed over all bins or over the signal region only. Also shown are the fit χ^2/d.o.f. values and confidence levels.

	Signal region		All bins	
	$\mathcal{M}_s^2$	$\mathcal{M}_2^2$	$\mathcal{M}_s^2$	$\mathcal{M}_2^2$
D	-1300 ± 2100	-80 ± 80	-700 ± 3000	-70 ± 80
χ^2/d.o.f.	17/19	13/19	40/55	34/53
C.L.(%)	59	84	94	98

Table 4: Summary of the absolute systematic errors for f_{00}.

Source	$\delta(f_{00})$
$\mathcal{M}_1^2$-combinatorial	0.0005
$\mathcal{M}_1^2$-peaking	0.0005
Same charged events	0.0025
Peaking background	0.004
B-meson counting	0.0055
$\Upsilon(4S) \to$ non-$B\overline{B}$	0.0025
Efficiency correlation	0.004
Monte Carlo statistics	0.002
Total	0.009

1. The systematic uncertainty from the $\mathcal{M}_1^2$-combinatorial contribution subtraction in the $\mathcal{M}_2^2$ histogram is 0.0005. The error is obtained by varying the total $\mathcal{M}_1^2$-combinatorial background by its statistical error and repeating the analysis.

2. An error of 0.0005 is estimated due to the subtraction of the $\mathcal{M}_1^2$-peaking contribution in the $\mathcal{M}_2^2$ histogram. The error is obtained by comparing the ratio between the numbers of subtracted $\mathcal{M}_1^2$-peaking and $\mathcal{M}_1^2$-combinatorial events with their ratio of peaking and combinatorial events in Table 2.

3. Propagating the errors on the quantities D (same charged events) of Table 3 leads to an error of 0.0025 on f_{00}. To determine this error we vary the signal events both for the single-tag and the double-tag samples. The largest uncertainty then is taken for the uncertainty on f_{00}.

4. The PDFs P^t (t = peak) of the peaking background come from simulated event samples containing different D^{**} resonances or non-resonant events. We vary the ratio of the branching fraction of the resonant and the non-resonant production such that the variation of this ratio is wide enough to include poorly known decays. We repeat the analysis procedure to determine N_s and N_d. The resulting error on f_{00} is 0.004.

5. Uncertainties in the branching fractions of $\overline{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ and $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell(n\gamma)$ relative to $\overline{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ lead to uncertainties in the PDFs P^t (t = signal) of the signal events. This uncertainty in f_{00} is negligible.

6. The error due to the uncertainty in $N_{B\overline{B}}$ is 0.0055. It includes the uncertainties for differences in the cross sections and efficiencies for muon pairs and continuum events between on-resonance and off-resonance samples, hadronic selection criteria and the uncertainties in the tracking efficiency.

7. In this paper the impact of non-$B\overline{B}$ decays of the $\Upsilon(4S)$ on B-meson counting has been accounted for as a systematic error. The upper limit for the branching fraction of $\Upsilon(4S)$ decays into non-$B\overline{B}$ is 4% at 95% confidence level [17]. We conservatively estimate the systematic error by decreasing the 4% upper limit on the branching fraction to 2%. From this variation we estimate an error of 0.0025 due to the effect on $N_{B\overline{B}}$ of a possible decay.

8. We note that the lepton momentum spectrum in the Monte Carlo simulation is different from the one we observe in the data. We tune the simulation to the data by rejecting simulated events in such a way that the two lepton momentum spectra agree. We repeat the analysis procedure without the rejected events. The systematic error due to the uncertainty in the lepton momentum spectrum is negligible.

9. There is a small efficiency correlation between the single-tag and the double-tag samples. The systematic uncertainty due to this efficiency correlation is estimated by propagating the Monte Carlo simulation systematics error of C into f_{00}. The simulation statistical error in C leads to a 0.004 error in f_{00}. In addition to the Monte Carlo simulation systematics error of C, we study the effect of track multiplicity on the efficiency correlation.

10. We perform a similar procedure as mentioned above for the pion momentum spectrum. The error due to the uncertainty in the pion momentum spectrum is negligible.

11. An error of 0.002 is due to the finite size of the simulated sample, calculated using σ_{f_j} in Eq. (6).

12. The χ^2 estimator used in Eq. (6) can be biased. We did an alternative binned likelihood fit and found that the result differed by only 0.03% for f_{00}.

We combine the uncertainties given above in quadrature to determine an absolute systematic error of 0.009 in f_{00}.

5 SUMMARY

To summarize, using partial reconstruction of the decay $\overline{B}^0 \to D^{*+}\ell^-\nu_l$ we have obtained a preliminary result for the branching fraction

$$f_{00} = 0.486 \pm 0.010 \pm 0.009, \tag{7}$$

where the first error is statistical and the second is systematic. Since this measurement is done by comparing the numbers of events with one and two reconstructed $\overline{B}^0 \to D^{*+}\ell^-\nu_l$ decays, it does not depend on branching fractions of the $\overline{B}^0$ and the D^{*+} decay chains, on the simulated reconstruction efficiency, on the ratio of the charged and neutral B meson lifetimes, nor on assumptions of isospin symmetry.

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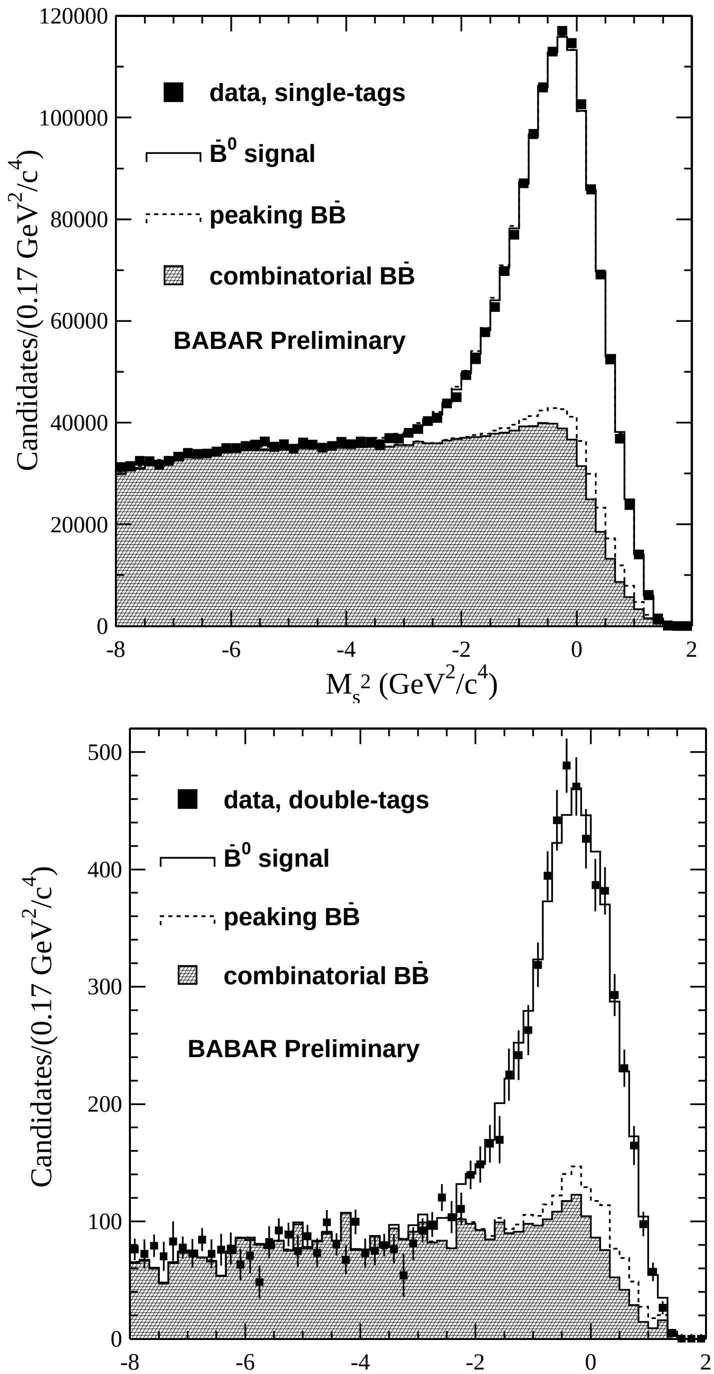

Figure 1: The $\mathcal{M}_s^2$ (top) and $\mathcal{M}_2^2$ (bottom) distributions of the on-resonance samples. The continuum background has been subtracted from the $\mathcal{M}_s^2$ distribution. For the $\mathcal{M}_2^2$ distribution, the $\mathcal{M}_1^2$-combinatorial, and the $\mathcal{M}_1^2$-peaking have been subtracted. The levels of the simulated signal, peaking $B\overline{B}$ and combinatorial $B\overline{B}$ background contributions are obtained from the fit.

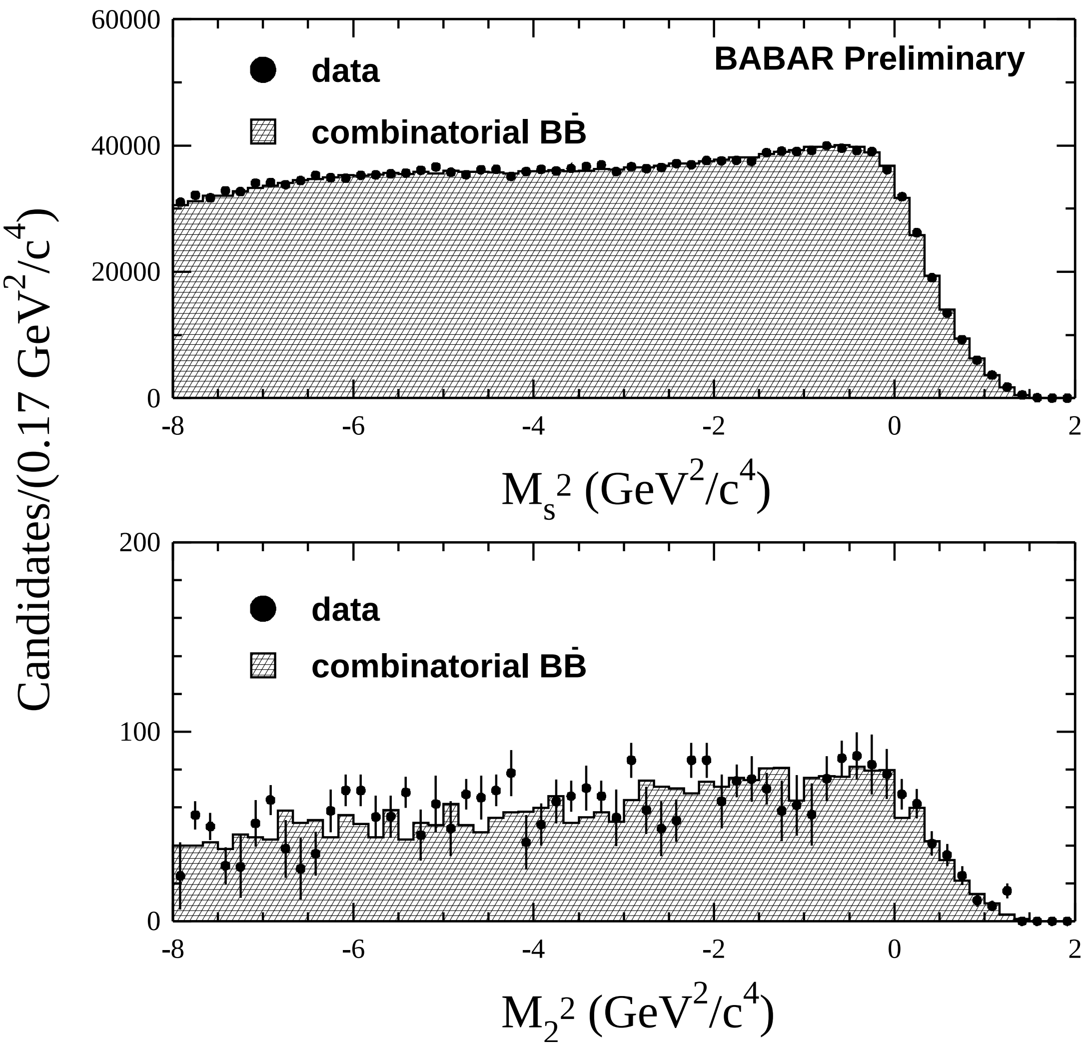

Figure 2: The $\mathcal{M}_s^2$ (top) and $\mathcal{M}_2^2$ (bottom) distributions of the same-charge on-resonance samples. The continuum background has been subtracted from the $\mathcal{M}_s^2$ distribution. For the $\mathcal{M}_2^2$ distribution, the continuum background, the $\mathcal{M}_1^2$-combinatorial and the $\mathcal{M}_1^2$-peaking backgrounds have been subtracted. The level of the simulated combinatorial $B\overline{B}$ background is obtained from the fit.

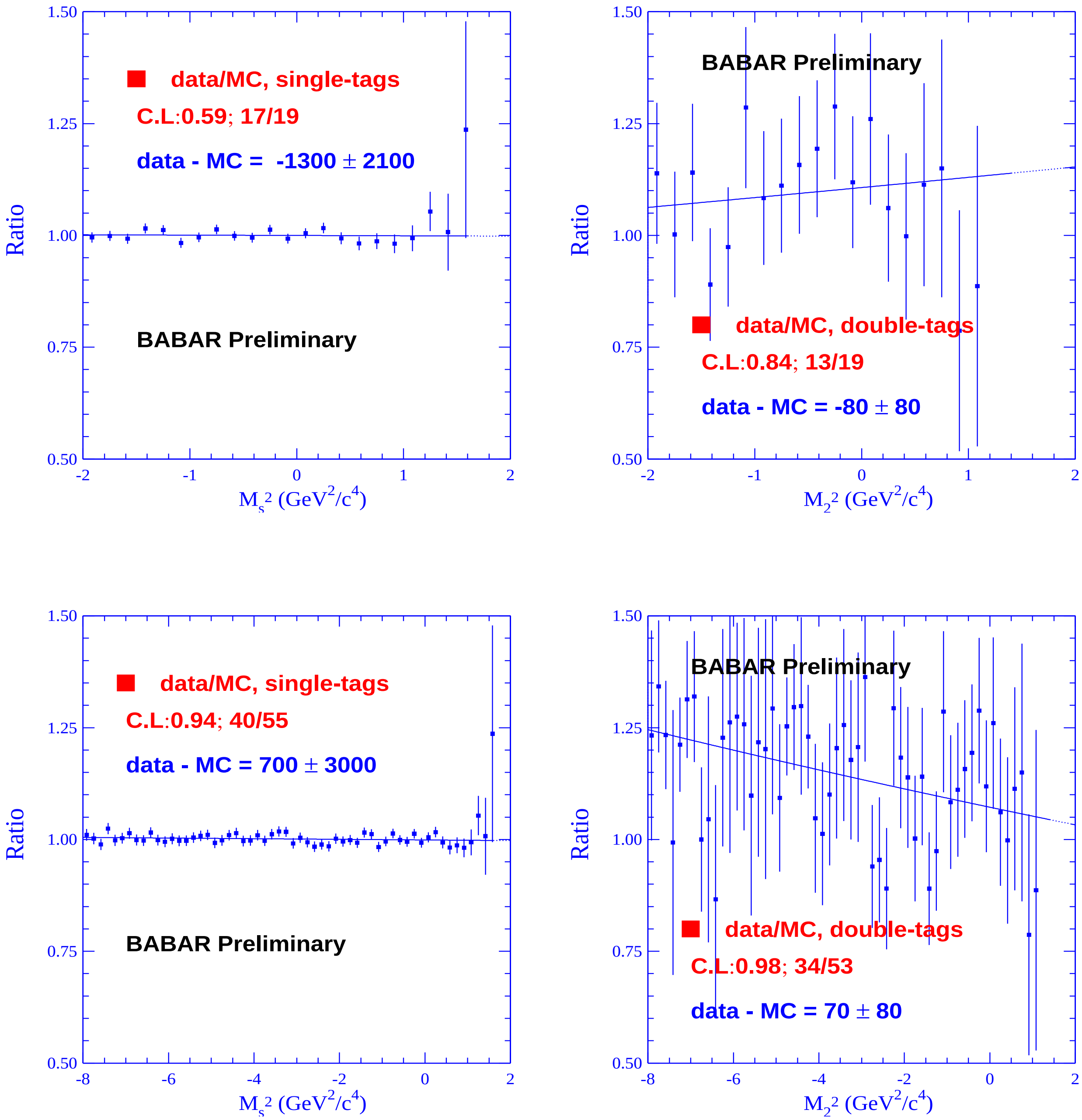

Figure 3: The ratio between data and the combinatorial $B\overline{B}$ background of the same-charge sample both for the $\mathcal{M}_s^2$ and $\mathcal{M}_2^2$ summed over the signal region and over all bins. The values are fit to a constant. upper left: for the $\mathcal{M}_s^2$ summed over the signal region; upper right: for the $\mathcal{M}_2^2$ summed over the signal region; lower left: for the $\mathcal{M}_s^2$ summed over all bins; lower right: for the $\mathcal{M}_2^2$ summed over all bins.