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Study of the Absolute Branching Fraction of $\Upsilon(4S) \to B^0\bar{B}^0$ with Partial Reconstruction of $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ at BABAR

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Based on a data sample of 81.7 fb^{-1} collected at the $\Upsilon(4S)$ resonance with the BaBar detector at the PEP-II asymmetric-energy B Factory at SLAC, we present the current status of the measurement of the branching fraction of $\Upsilon(4S) \to B^0\bar{B}^0$. Our study of the decay was performed through the exclusive decays $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ using a partial reconstruction method, where the D^{*+} is detected only through the soft pion daughter from the decay $D^{*+} \to D^0\pi^+$.

I. INTRODUCTION

The exclusive decay $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ ($D^{*+} \to D^0\pi^+$) has been previously analyzed using a partial reconstruction technique [1]. In this technique, the D^{*+} is identified without reconstructing the D^0 meson, and the presence of an undetected neutrino is inferred by conservation of momentum and energy. This approach is possible due to the extremely low decay energy of this mode. The soft π^+ carries sufficient information to determine an approximate four-momentum of the D^{*+} meson. The partial reconstruction technique may result in a gain of as much as a factor of 10 in statistics compared to the full reconstruction technique, though the effective gain may be less due to background.

This study can improve the understanding of the branching fraction of all B decays measurements, including studies of CP violation and the Cabibbo-Kobayashi-Maskawa quark-mixing matrix element, V_{cb}. Furthermore, this study can be a significant contribution to enhance our knowledge of isospin violation in $\Upsilon(4S)$ decay. The isospin violation is due to the mass difference of the u and d quarks and due to electromagnetic interactions. All currently published branching fraction measurements based on an admixture of B mesons at the $\Upsilon(4S)$ assume that $\mathcal{B}(\Upsilon(4S) \to B\bar{B}) \approx 100\%$ [2]. All measurements of fundamental parameters at the $\Upsilon(4S)$ are limited by the uncertainty on the ratio of the branching fraction of $\Upsilon(4S) \to B^+\bar{B}^-$ to the branching fraction of $\Upsilon(4S) \to B^0\bar{B}^0$ defined as $\frac{f_{+-}}{f_{00}} \equiv R^{+/0}$. The current measurements of $\frac{f_{+-}}{f_{00}}$ are limited its ratio within an uncertainty of 8% [3]. Its values depend on the ratio of the charged and neutral B meson lifetime as well as the assumption of isospin symmetry.

The B meson velocity in the $\Upsilon(4S)$ rest frame is relatively small. Thus $\beta =$V$/c$:

$$\beta = \sqrt{1 - \frac{4m_B^2}{m_{\Upsilon(4S)}^2}} \approx 0.065, \tag{1}$$

where m_B and $m_{\Upsilon(4S)}$ are the masses of the B meson and the $\Upsilon(4S)$ resonance, respectively. Since the final state B mesons are non-relativistic and have low momentum, it was suggested that the final state interactions of the B meson can be treated using non-relativistic field theory combined with chiral perturbation theory. One can also calculate the dominant Coulomb correction using non-relativistic time-dependent perturbation theory. The current theoretical predictions of $\frac{f_{+-}}{f_{00}}$ has a variation effect and its ratio range from 1.03 to 1.25 [4]:

$$\frac{f_{+-}}{f_{00}} \equiv R^{+/0} \equiv \frac{\Gamma(\Upsilon(4S) \to B^+B^-)}{\Gamma(\Upsilon(4S) \to B^0\bar{B}^0)} \approx 1.03 - 1.25. \tag{2}$$

The exclusive decay of $B \to D^*\ell\nu$ has the largest branching fraction of any exclusive B decay and a relatively simple theoretical interpretation. Figure 1 shows the spectator quark-level Feynman diagram, where the heavy b quark decays to either a c or u quark and a lepton pair created from the virtual W boson. The flavor of the B meson can be indicated from the charge of the lepton. More precisely, a positively charged lepton indicates a B meson with a $\bar{b}$ quark, whereas a negatively charged lepton indicates a $\bar{B}$ meson with a b quark.

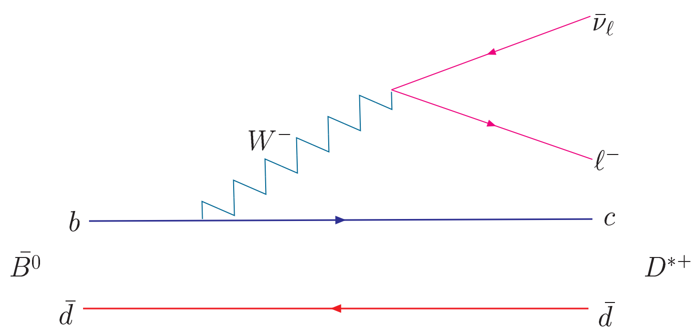

FIG. 1. Quark-level Feynman diagram for spectator B decays.

The main focus of this paper is to describe the procedure used in determining the absolute branching fraction of $\Upsilon(4S) \to B^0\bar{B}^0$, f_{00}, with partial reconstruction of $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$. The mechanism for $B^0\bar{B}^0$ production in e^+e^- collisions at the $\Upsilon(4S)$ resonance is shown in Fig. 2.

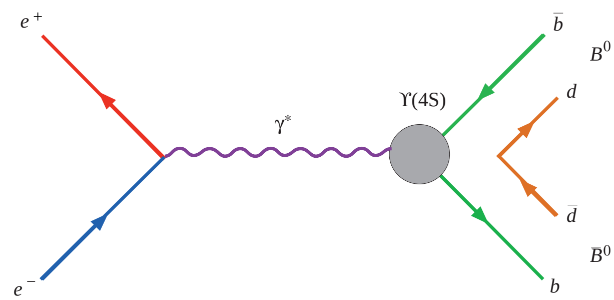

FIG. 2. The mechanism for $B^0\bar{B}^0$ production in e^+e^- collisions.

II. DATA SAMPLE AND EVENT SELECTION

The data used in this paper were collected with the BaBar detector at the PEP-II asymmetric-energy B Factory at SLAC. The ARGUS [5] and UA1 [6] discovery of B^0 mixing, made possible by the surprisingly massive top quark [7], provided B^0 decays that could interfere. Plans were soon begun to construct an asymmetric B Factory based on PEP to search for CP violation [8]. This has now led to a data sample of 81.7 fb^{-1} at the $\Upsilon(4S)$ resonance (on-resonance) and 9.6 fb^{-1} below the resonance (off-resonance). The total number of the simulated generic Monte Carlo (MC) for $B^0\bar{B}^0$ and $B^+\bar{B}^-$ events are equivalent to about 160 fb^{-1} for each pair.

Hadronic events are selected by requiring at least four tracks from charged hadrons reconstructed by the Silicon Vertex Detector (SVT) [9] and the Drift Chamber (DCH) [10]. This selection helps to remove Bhabha and muon pair events. All lepton candidates (electrons and muons) are required to have momenta between 1.5 GeV/c and 2.3 GeV/c to suppress the leptons from the other charm decays. Soft pion candidates were selected among all the charged particles with momenta between 60 MeV/c and 200 MeV/c.

Electrons are identified by exploiting information from the Electromagnetic Calorimeter (EMC) [11]. The ratio E/p is used to provide a good discrimination between electrons and other charged particles species. E is the measured energy of a shower in the calorimeter and p is the measured momentum of the corresponding charged track. The efficiency for electrons in the acceptance of the electromagnetic calorimeter is 90%, with a hadron mis-identification probability of less than 1%. We also require the measurements of the specific ionization (dE/dx) from the drift chamber as well as an information from the Detection of Internally Reflected Cherenkov ring imaging detector (DIRC) [12].

Muons are identified in the Instrumented Flux Return (IFR) [13]. We use a "Tight Muon" selection which provided an efficiency of about 70% with a hadron mis-identification probability about 2%. Kaons are rejected using information from the Cherenkov light emission in the DIRC by requiring the consistency with the kaon hypothesis to be smaller than 5%. More details of the BaBar detector are described elsewhere [14].

III. ANALYSIS METHOD

To partially reconstruct $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$, lepton candidates are combined with soft charged pions from the decay $D^{*+} \to D^0\pi^+$. The D^* is just massive enough to create a D meson and a soft pion. These two daughters therefore have very little momentum in the D^* rest frame. This pion is often referred to as the "soft pion," and its direction coincides approximately with the direction of the parent D^*. This condition allows us to do an approximation of the D^* four-vector by measuring only the pion four-vector momentum, without the D meson reconstruction.

The approximate four-momentum of the D^*, $(\widetilde{E}_{D^*}, \widetilde{\mathbf{p}}_{D^*})$, is calculated by scaling the soft pion momentum:

$$E_{D^*} \simeq \frac{E_\pi}{E_\pi^{CM}} m_{D^*} \equiv \widetilde{E}_{D^*}, \text{ and} \tag{3}$$

$$\mathbf{p}_{D^*} \simeq \hat{\mathbf{p}}_\pi \times \sqrt{\widetilde{E}^2_{D^*} - m^2_{D^*}} \equiv \widetilde{\mathbf{p}}_{D^*}, \tag{4}$$

where E_π is the pion energy, $E_\pi^{CM} \approx 145$ MeV is the energy of the pion in the D^* center of mass frame, and $m_{D^*} = 2.01$ GeV$/c^2$ is the mass of the D^*.

Since the B meson has a very small momentum, one may use an approximation for the missing mass squared $(\widetilde{\mathcal{M}_\nu}^2)$ with $|\vec{P}_B| = 0$:

$$\widetilde{\mathcal{M}}^2_\nu \equiv (E_{\text{beam}} - \widetilde{E}_{D^*} - E_\ell)^2 - (\widetilde{\mathbf{p}}_{D^*} + \mathbf{p}_\ell)^2 \; . \tag{5}$$

The $\widetilde{\mathcal{M}_\nu}^2$ distribution will peak near zero if the decay has been properly reconstructed and the neutrino is the only missing particle.

IV. TAG EVENTS SELECTION

The 'single tag' events are referred at least one neutral B partially reconstructed through the exclusive decays $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell(D^{*+} \to D^0\pi^+)$. The total signal yield of these events is denoted as N_s. The 'double tag' events are referred to two neutral B partially reconstructed in the same decay channel as above. These events are obtained by reconstructing the other B mesons within the single tag events. Its total signal yield is denoted as N_d.

The total numbers of the single tag and the double tag reconstructed signal events, N_s and N_d, have the following relationships to the branching fractions respectively:

$$N_s = 2 \times N_{B\bar{B}} f_{00} \times \mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell) \times \mathcal{B}(D^{*+} \to D^0\pi^+) \times \epsilon_{0+} \tag{6}$$

$$N_d = N_{B\bar{B}} f_{00} \times [\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell) \times \mathcal{B}(D^{*+} \to D^0\pi^+) \times \epsilon_{0+}]^2 \tag{7}$$

where f_{00} is the fraction of neutral B mesons in $\Upsilon(4S)$ events, and ϵ_{0+} is the reconstruction efficiency for the respective $B \to D^*\ell\nu$ $(D^{*+} \to D^0\pi^+)$ modes.

Combining these yields, one solves for f_{00}

$$f_{00} = \frac{N_s^2}{4N_d N_{B\bar{B}}} \tag{8}$$

where $N_{B\bar{B}}$ is the total numbers of $B\bar{B}$ events. This study has several advantages both over the measurements with fully reconstructed B mesons and the measurements of the ratio of charged to neutral production of B mesons at the $\Upsilon(4S)$ resonance. First, a lower systematic error may be obtained since this method is independent of the branching fraction on the D^* decays with its large uncertainty. Secondly, by combining it with another direct measurement of f_{+-} this method could address the question of additional substantial $\Upsilon(4S)$ decay modes [15].

V. BACKGROUNDS

The continuum background events are non-resonant decays of $e^+e^- \to \gamma^* \to q\bar{q}$ where $q = u, d, s, c$. These backgrounds are generally collimated into two back-to-back jets events while $\Upsilon(4S) \to B\bar{B}$ events are much more isotropic in the $\Upsilon(4S)$ rest frame. To reduce the continuum background events, the ratio $R_2 = H_2/H_0$ of Fox-Wolfram moments has been used [16]. This variable can take values between 0 and 1, and tends toward higher values for jet-like events and lower values for events with isotropic distributions of final state particles. By requiring $R_2 < 0.4$, we retain nearly all $B\bar{B}$ events while reducing the contribution from $q\bar{q}$ continuum by approximately 50%.

The contribution from the continuum background events are estimated by analyzing the off-resonance data and scaling the result to correct for differences in the integrated luminosity and center of mass energy. The average continuum scaling factor, $\lambda_{continuum}$, is

$$\lambda_{continuum} = \frac{\mathcal{L}_{on}}{\mathcal{L}_{off}} \frac{E^2_{off}}{E^2_{on}} = 8.44. \tag{9}$$

The combinatoric background, also known as uncorrelated background, for single tag events is defined as a random combination of real leptons from B decays that are paired with right sign soft pions that come from the other B. This background can also be due to the low momentum soft pions not necessarily coming from a D^*, produced by either the same or other B. The combinatoric background events are estimated using Monte Carlo data simulation (MC). Its normalization is obtained by fitting the Monte Carlo simulation to the data in the sideband region, $-8 < \widetilde{\mathcal{M}}^2_\nu < -4$ GeV$^2/c^4$. The overall $\widetilde{\mathcal{M}}^2_\nu$ distribution of the combinatoric background is dominated by phase space, i.e., a hard lepton and soft pion distributed isotropically will produce a distribution similar to signal events. A simple overall test of its reliability is the counting of the wrong sign ($\ell^+ - \pi^+$) candidates, where no signal is expected as shown in Fig. 3.

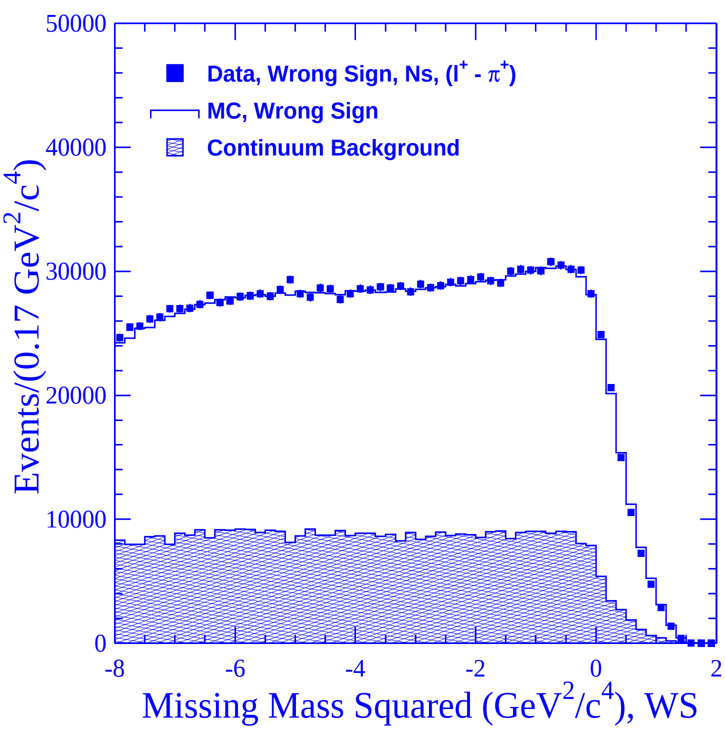

FIG. 3. The single tag distribution in $\widetilde{\mathcal{M}}^2_\nu$ for the wrong-sign ($\ell^+ - \pi^+$) candidates. The plot shows data on resonance (dotted), Monte Carlo normalized to data in the sideband region (solid histogram) and the scaled continuum background (hatched). Note: the scaled continuum background has been subtracted from the data.

The correlated background is obtained from the right sign combination of leptons with soft pions either from the same or different B, however, the soft pions come from $B \to D^* \pi \ell \bar{\nu}_\ell$. The relatively high momentum cut of 1.5 GeV$/c$ on the leptons is chosen to reduce the contribution of the correlated background, which is believed to be small but it is otherwise difficult to separate them kinematically from the tag signal events in $\widetilde{\mathcal{M}}_\nu^2$ distribution. The single tag and double tag events accumulate in the signal region, $\widetilde{\mathcal{M}_\nu}^2 > -2.0$ GeV$^2/c^4$, as shown in Fig. 4.

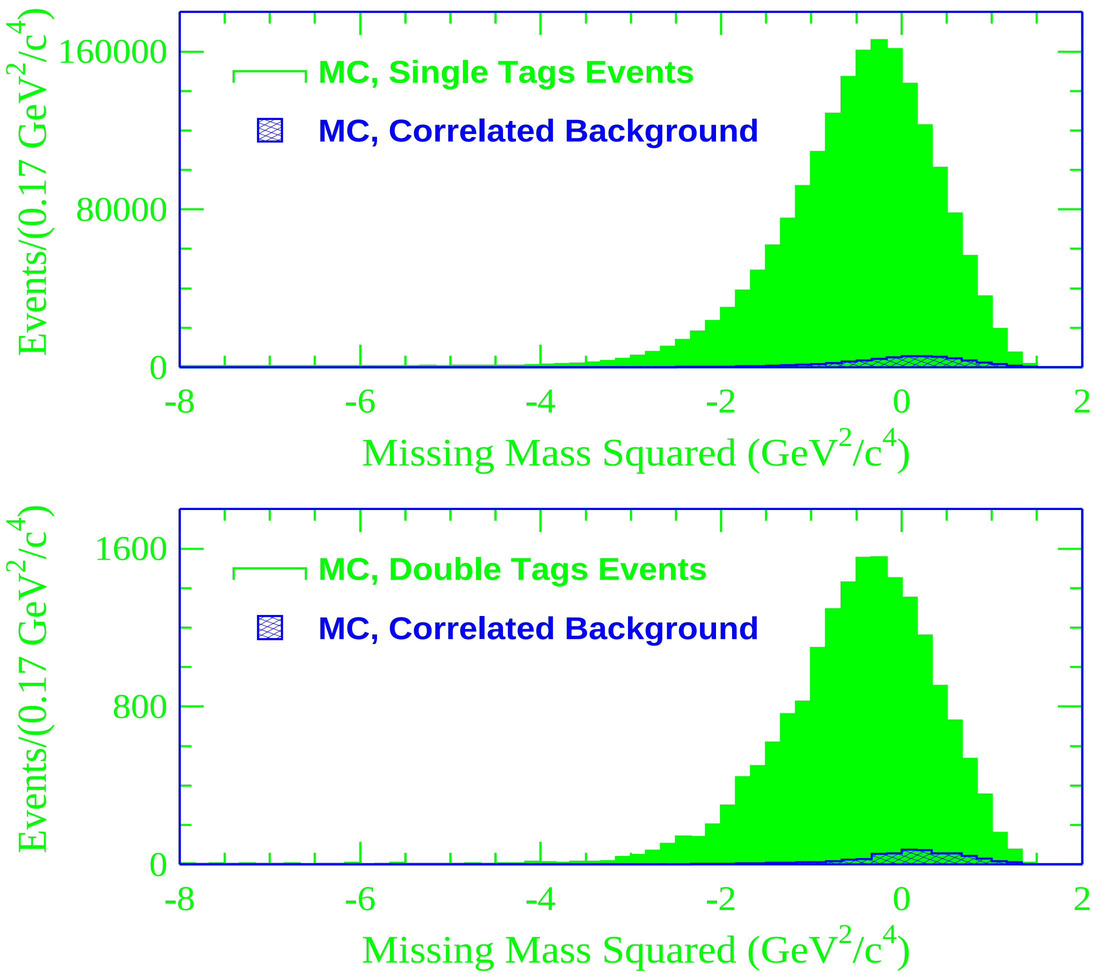

FIG. 4. The right sign data distributions in $\widetilde{\mathcal{M}}_\nu^2$ of Monte Carlo data simulation. The upper plot shows the single tag events (solid histogram) and correlated background (shaded). The lower plot shows the double tag events (solid histogram) and correlated background (shaded).

All contributions of the correlated background come from the decays of the type $\bar{B} \to D^*\pi\ell^-\bar{\nu}_\ell$ through the channels:

$$
\begin{aligned}
B^- &\to D^{*+}\pi^-\ell^-\bar{\nu}_\ell \\
\bar{B}^0 &\to D^{*0}\pi^+\ell^-\bar{\nu}_\ell \\
B^- &\to D^{*0}\pi^0\ell^-\bar{\nu}_\ell \\
\bar{B}^0 &\to D^{*+}\pi^0\ell^-\bar{\nu}_\ell \ ,
\end{aligned}
$$

where $D^*\pi$ may or may not be from an excited charm resonance such as the $D_1(2420)^0$ [17] and the additional pion is not detected. However, only the modes with D^{*+} could contribute to $\widetilde{\mathcal{M}}_\nu^2$. These modes has been extensively studied by the ARGUS, CLEO and BaBar Collaborations [1].

VI. SIGNAL YIELDS

After all background subtractions described above, the total signal yield for the single tag and double tag events are extracted by counting $(\ell^- - \pi^+)$ candidates which fall in the signal region, $\widetilde{\mathcal{M}}_\nu^2 > -2$ GeV$^2/c^4$. Figure 5 and Figure 6 show the total signal yield for the single tag and double tag events respectively.

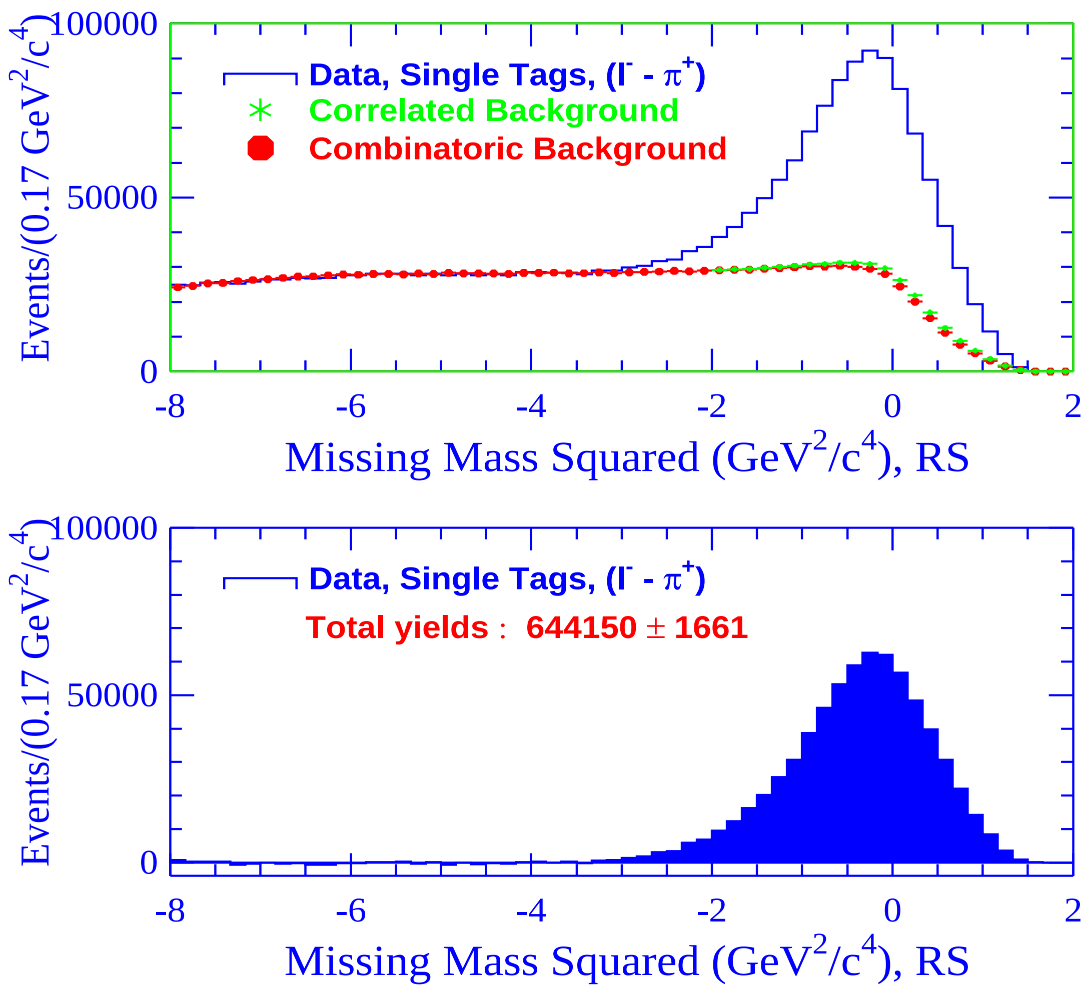

FIG. 5. The single tag yield in $\widetilde{\mathcal{M}}_\nu^2$. The upper plot shows the right sign data with the continuum background subtracted, correlated background (asterisk) and the combinatoric background (dotted) estimated by Monte Carlo simulation. The lower plot shows the total signal yield of the single tag candidates after all backgrounds are subtracted.

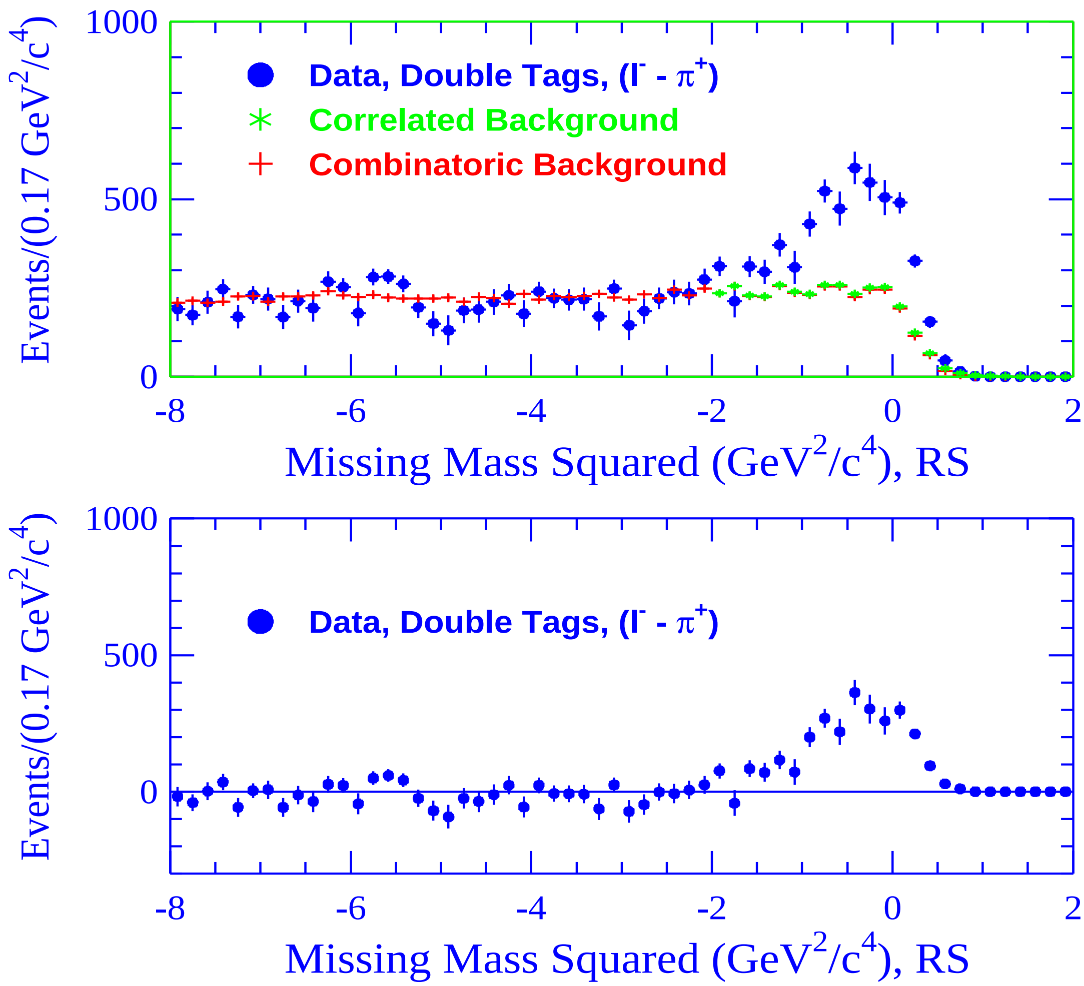

FIG. 6. The double tag yield in $\widetilde{\mathcal{M}}_\nu^2$. The upper plot shows the right sign data, correlated background (asterisk) and the combinatoric background (plus sign) estimated by Monte Carlo simulation. The lower plot shows the total signal yield of the double tag candidates after all backgrounds are subtracted.

In order to have a better understanding of the Monte Carlo simulation modeling, the signal yield of the single tag events is extracted in bins of 20 MeV/c in the soft pion momentum. There is an excellent agreement between the data of the combinatoric background and Monte Carlo simulation in the sideband region, $-8 < \widetilde{\mathcal{M}}_\nu^2 < -4$ GeV/c^4, as shown in Fig. 7.

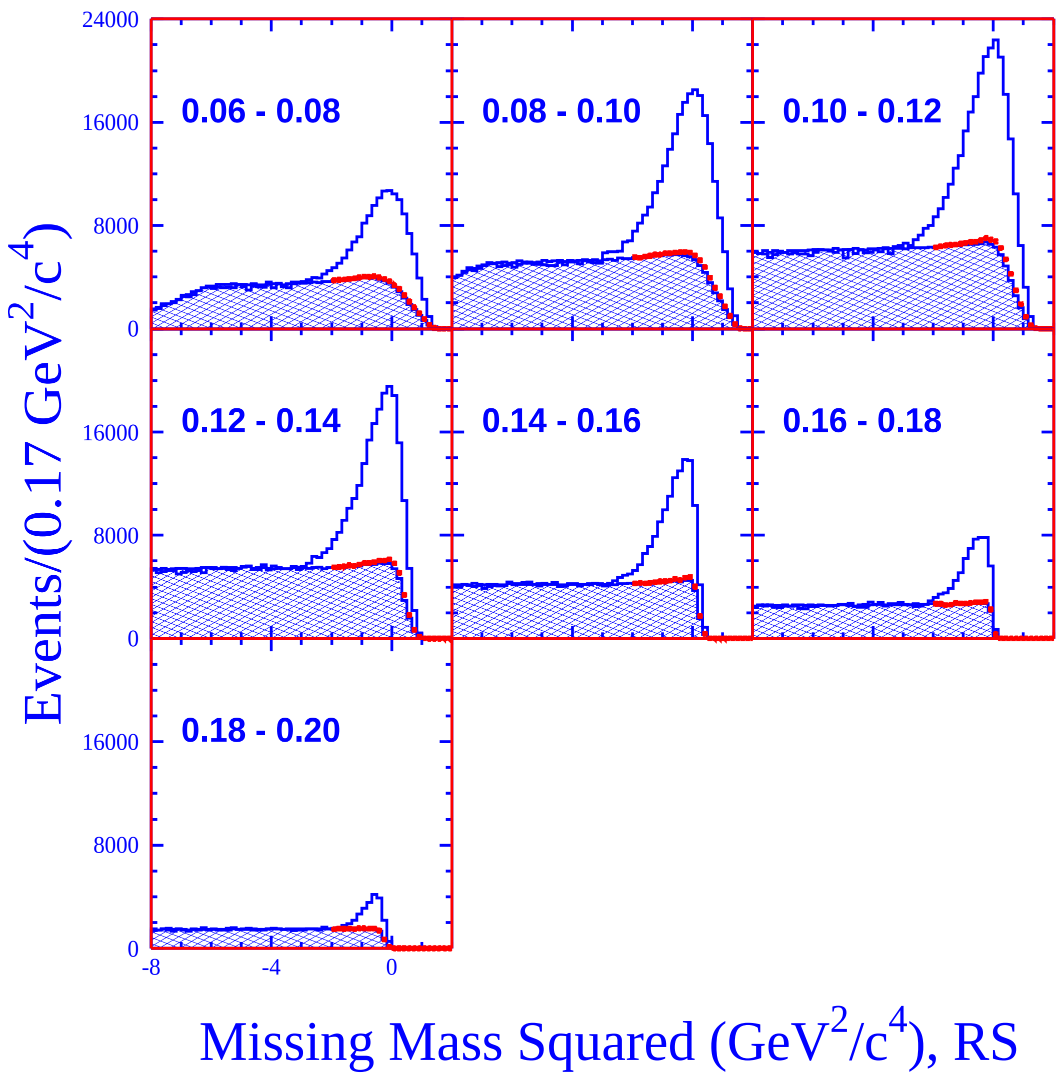

FIG. 7. The single tag distributions in $\widetilde{\mathcal{M}}_\nu^2$ for 20 MeV/c bins of soft pion momentum. The plot shows the right sign data (solid histogram), the combinatoric background (shaded) and correlated background (dotted) estimated by Monte Carlo simulation.

VII. CONCLUSION

This analysis will be the first measurement of the absolute branching fraction of $\Upsilon(4S) \rightarrow B^0\bar{B}^0$ with partial reconstruction of $\bar{B}^0 \rightarrow D^{*+}\ell^-\bar{\nu}_\ell$. It is a direct experimental measurement of $\Upsilon(4S) \rightarrow B^0\bar{B}^0$ that is independent of $\bar{B}^0$ lifetime as well as the branching fractions of $\bar{B}^0$ and D^{*+}. The currently published measurements of the ratio of charged to neutral production of B mesons at the $\Upsilon(4S)$ resonance, $\frac{f_{+-}}{f_{00}}$, is consistent with unity within an error of 8% [3].

By comparing the number of events with both one and two reconstructed $\bar{B}^0 \rightarrow D^{*+}\ell^-\bar{\nu}_\ell$ candidates, the absolute branching fraction of $\Upsilon(4S) \rightarrow B^0\bar{B}^0$ will be obtained. The analysis is currently under review and will be published soon. The expected statistical uncertainty is less than 6%. The major systematic uncertainties for the f_{00} value have been studied, for example, the systematic error due to the B counting is about 1.1% [18]. It is mainly due to the uncertainties in the tracking efficiency.

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[1] CLEO Collaboration, S. B. Athar *et al.*, Phys. Rev. D **66**, 052003 (2002);
OPAL Collaboration, G. Abbiendi *et al.*, Phys. Lett. B **482**, 15 (2000);
DELPHI Collaboration, P. Abreu *et al.*, Z. Phys. C **74**, 19 (1997);
ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. B **324**, 249 (1994);
BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **89**, 011802 (2002).

[2] Particle Data Group, K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002).

[3] BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. D **65**, 032001 (2002);
CLEO Collaboration, J. P. Alexander *et al.*, Phys. Rev. Lett. **86**, 2737, (2001).

[4] N. Byers and E. Eichten, Phys. Rev. D **42**, 3885 (1990);
G. P. Lepage, Phys. Rev. D **42**, 3251 (1990);
D. Atwood and W. J. Marciano, Phys. Rev. D **41**, 1736 (1990);
E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane, Phys. Rev. D **21**, 203 (1980);
R. Kaiser, A. V. Manohar, and T. Mehen, Phys. Rev. Lett. **90**, 142001 (2003);
M. B. Voloshin, Mod. Phys. Lett. A **18**, 1783 (2003).

[5] ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. B **192**, 245 (1987).

[6] UA1 Collaboration, C. Albajar *et al.*, Phys. Lett. B **186**, 247 (1987).

[7] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **74**, 2626 (1995);
D0 Collaboration, S. Abachi *et al.,* Phys. Rev. Lett. **74**, 2632 (1995).

[8] P. Oddone, Annals N.Y. Acad. Sci. **578**, 237 (1989).

[9] BaBar Collaboration, P. Burchat, Nucl. Instrum. Meth. A **342**, 292 (1994);
E691 Collaboration, J. C. Anjos *et al.*, Phys. Rev. Lett. **58**, 1818 (1987);
ACCMOR Collaboration, R. Bailey *et al.*, Phys. Lett. B **139**, 320 (1984).

[10] BaBar Collaboration, P. Burchat, J. Hiser, A. Boyarski, and D. Briggs, Nucl. Instrum. Meth. A **316**, 217 (1992).

[11] BaBar Collaboration, R. J. Barlow *et al.*, Nucl. Instrum. Meth. A **420**, 162 (1999).
[12] BaBar Collaboration, J. Schwiening *et al.*, Nucl. Instrum. Meth. A **502**, 67 (2003).
[13] BaBar Collaboration, F. Anulli *et al.*, Nucl. Instrum. Meth. A **494**, 455 (2002).
[14] BaBar Collaboration, B. Aubert *et al.*, Nucl. Instrum. Meth. A **479**, 1 (2002).
[15] BaBar Collaboration, P. F. Harrison and H. R. Quinn, ed., "The BaBar Physics Book," **SLAC-R-504** (1998).
[16] G. C. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).
[17] ARGUS Collaboration, H. Albrecht *et al.*, Phys. Rev. Lett. **56**, 549 (1986);
E691 Collaboration, J. C. Anjos *et al.*, Phys. Rev. Lett. **62**, 1717 (1989).
[18] BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. D **67**, 032002 (2003).