

**First observation of the  $Z_b^0(10610)$  in a Dalitz analysis of  $\Upsilon(10860) \rightarrow \Upsilon(nS)\pi^0\pi^0$** 

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We report the first observation of  $Y(10860) \rightarrow Y(1, 2, 3S)\pi^0\pi^0$  decays. The neutral partner of the  $Z_b^\pm(10610)$ , the  $Z_b^0(10610)$  decaying to  $Y(2, 3S)\pi^0$ , is observed for the first time with a  $6.5\sigma$  significance using a Dalitz analysis of  $Y(10860) \rightarrow Y(2, 3S)\pi^0\pi^0$  decays. The results are obtained with a  $121.4 \text{ fb}^{-1}$  data sample collected with the Belle detector at the  $Y(10860)$  resonance at the KEKB asymmetric-energy  $e^+e^-$  collider.

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## I. INTRODUCTION

Two charged bottomoniumlike resonances,  $Z_b^\pm(10610)$  and  $Z_b^\pm(10650)$ , have been observed by the Belle Collaboration [1] in the  $Y(nS)\pi^\pm$  invariant mass in  $Y(10860) \rightarrow Y(nS)\pi^+\pi^-$  decays ( $n = 1, 2, 3$ ) and in  $h_b(mP)\pi^\pm$  mass spectra in the recently observed  $Y(10860) \rightarrow h_b(mP)\pi^+\pi^-$  decays ( $m = 1, 2$ ) [2]. An

angular analysis suggests that these states have  $I^G(J^P) = 1^+(1^+)$  quantum numbers [3]. Analysis of the quark composition of the initial and final states allows us to assert that these hadronic objects are the first examples of states of an exotic nature with a  $b\bar{b}$  quark pair:  $Z_b$  should be comprised of (at least) four quarks. Several models have been proposed to describe the internal structure of these states [4–6]. The proximity of the  $Z_b^\pm(10610)$  and  $Z_b^\pm(10650)$

masses to thresholds for the open beauty channels  $B^*\bar{B}$  and  $B^*\bar{B}^*$  suggests a ‘‘molecular’’ structure for these states, which is consistent with many of their observed properties [7]. More recently, Belle reported the observation of both  $Z_b^\pm(10610)$  and  $Z_b^\pm(10650)$  in an analysis of the three-body  $Y(10860) \rightarrow [B^{(*)}B^*]^\mp \pi^\pm$  decay [8]. The dominant  $Z_b$  decay mode is found to be  $B^{(*)}B^*$ , supporting the molecular hypothesis. It would be natural to expect the existence of neutral partners of these states. This motivates us to search for  $Z_b^0$  in the resonant substructure of  $Y(10860) \rightarrow Y(nS)\pi^0\pi^0$  decays.

## II. DATA SAMPLE AND DETECTOR

We use a  $(121.4 \pm 1.7) \text{ fb}^{-1}$  data sample collected on the peak of the  $Y(10860)$  resonance with the Belle detector [9] at the KEKB asymmetric-energy  $e^+e^-$  collider [10]. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector, a central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters, and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid that provides a 1.5 T magnetic field. An iron flux return located outside the coil is instrumented to detect  $K_L^0$  mesons and to identify muons (KLM). The detector is described in detail elsewhere [9].

## III. SIGNAL SELECTION

$Y(10860)$  candidates are formed from  $Y(nS)\pi^0\pi^0$  ( $n = 1, 2, 3$ ) combinations. We reconstruct  $Y(nS)$  candidates from pairs of leptons ( $e^+e^-$  and  $\mu^+\mu^-$ , referred to as  $\ell^+\ell^-$ ) with an invariant mass between 8 and 11  $\text{GeV}/c^2$ . An additional decay channel is used for the  $Y(2S)$ :  $Y(2S) \rightarrow Y(1S)[\ell^+\ell^-]\pi^+\pi^-$ . Charged tracks are required to have a transverse momentum,  $p_t$ , greater than

50  $\text{MeV}/c$ . We also impose a requirement on the impact parameters of  $dr < 0.3 \text{ cm}$  and  $|dz| < 2.0 \text{ cm}$ , where  $dr$  and  $dz$  are the impact parameters in the  $r - \phi$  and longitudinal directions, respectively. Muon candidates are required to have associated hits in the KLM detector that agree with the extrapolated trajectory of a charged track provided by the drift chamber [11]. Electron candidates are identified based on the ratio of ECL shower energy to the track momentum, ECL shower shape,  $dE/dx$  from the CDC, and the ACC response [12]. No particle identification requirement is imposed for the pions. Candidate  $\pi^0$  mesons are selected from pairs of photons with an invariant mass within 15  $\text{MeV}/c^2$  ( $3\sigma$ ) of the nominal  $\pi^0$  mass. An energy greater than 50 (75)  $\text{MeV}$  is required for each photon in the barrel (end cap). We use the quality of the  $\pi^0$  mass-constrained fits,  $\chi^2(\pi_1^0) + \chi^2(\pi_2^0)$ , to suppress the background. This sum must be less than 20 (10) for the  $Y(nS) \rightarrow \mu^+\mu^-$ ,  $Y(1S)\pi^+\pi^-$  ( $Y(nS) \rightarrow e^+e^-$ ).

We use the energy difference  $\Delta E = E_{\text{cand}} - E_{\text{CM}}$  and momentum  $P$  to suppress background, where  $E_{\text{cand}}$  and  $P$  are the energy and momentum of the reconstructed  $Y(10860)$  candidate in the center-of-mass (c.m.) frame, and  $E_{\text{CM}}$  is the c.m. energy of the two beams.  $Y(10860)$  candidates must satisfy the requirements  $-0.2 \text{ GeV} < \Delta E < 0.14 \text{ GeV}$  and  $P < 0.2 \text{ GeV}/c$ . The potentially large background from QED processes such as  $e^+e^- \rightarrow \ell^+\ell^-(n)\gamma$  is suppressed using the missing mass associated with the  $\ell^+\ell^-$  system, calculated as  $M_{\text{miss}}(\ell^+\ell^-) = \sqrt{(E_{\text{CM}} - E_{\ell^+\ell^-})^2 - P_{\ell^+\ell^-}^2}$ , where  $E_{\ell^+\ell^-}$  and  $P_{\ell^+\ell^-}$  are the energy and momentum of the  $\ell^+\ell^-$  system measured in the c.m. frame. We require  $M_{\text{miss}}(\ell^+\ell^-) > 0.15(0.30) \text{ GeV}/c^2$  for the  $Y(nS) \rightarrow \mu^+\mu^-$  ( $e^+e^-$ ). We select the candidate with the smallest  $\chi^2(\pi_1^0) + \chi^2(\pi_2^0)$  in the rare cases (1–2%) when there is more than one candidate in the event. Figures 1(a) and 1(b) show the  $M_{\text{miss}}(\pi^0\pi^0)$  distributions for the  $Y(10860) \rightarrow Y(nS)[\ell^+\ell^-]\pi^0\pi^0$

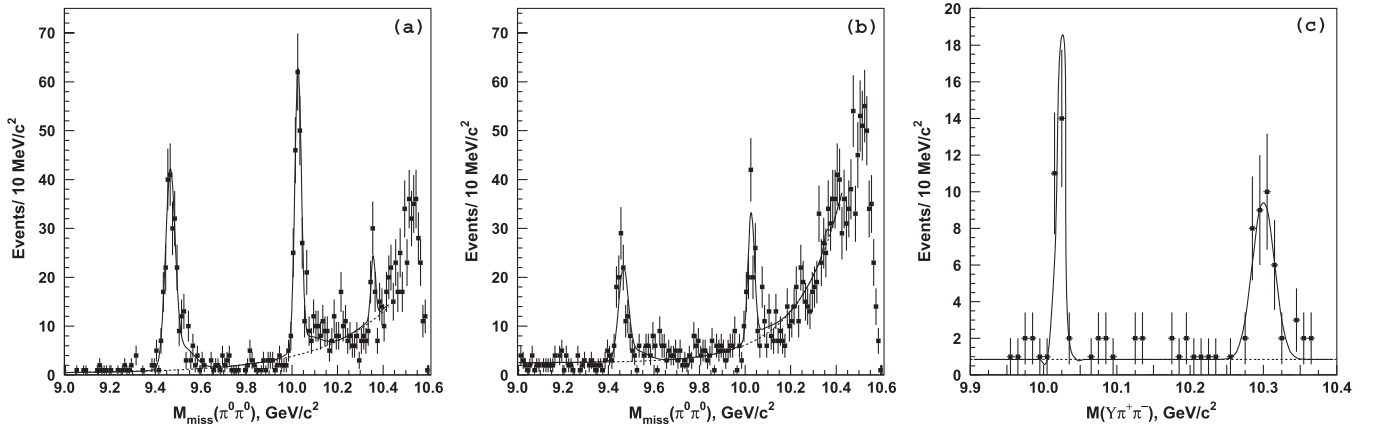


FIG. 1. The  $\pi^0\pi^0$  missing mass distribution for  $Y(nS)\pi^0\pi^0$  candidates, using (a)  $Y(nS) \rightarrow \mu^+\mu^-$  and (b)  $Y(nS) \rightarrow e^+e^-$  candidates. The  $M(Y(1S)\pi^+\pi^-)$  distribution for  $Y(2S) \rightarrow Y(1S)\pi^+\pi^-$  candidates is shown in (c). Points with error bars represent the data. In each panel, the solid curve shows the fit result, while the dashed curve corresponds to the background contribution.

candidates, which are evaluated similarly to  $M_{\text{miss}}(\ell^+\ell^-)$ . Clear peaks of the  $Y(1S)$ ,  $Y(2S)$ , and  $Y(3S)$  can be seen.

For  $Y(10860) \rightarrow Y(2S)[Y(1S)\pi^+\pi^-]\pi^0\pi^0$  decays,  $Y(1S)$  candidates are selected from  $\ell^+\ell^-$  pairs with invariant mass within 150 MeV/ $c^2$  of the nominal  $Y(1S)$  mass. A mass-constrained fit is used for  $Y(1S)$  candidates to improve the momentum resolution. We apply the requirements on  $\Delta E$  and  $P$  for  $Y(10860)$  candidates described earlier. We select signal candidates with the invariant mass of  $Y(1S)\pi^+\pi^-$  within 20 MeV/ $c^2$  of the nominal  $Y(2S)$  mass. Figure 1(c) shows the  $M(Y(1S)\pi^+\pi^-)$  distribution for the  $[Y(1S)\pi^+\pi^-]\pi^0\pi^0$  events. The clear peak of the  $Y(2S)$  can be seen. The peak around 10.3 GeV/ $c^2$  corresponds to a reflection from the decay  $Y(10860) \rightarrow Y(2S)\pi^+\pi^-$ ,  $Y(2S) \rightarrow Y(1S)\pi^0\pi^0$ .

#### IV. $e^+e^- \rightarrow Y(ns)\pi^0\pi^0$ CROSS SECTIONS AT $Y(10860)$

The signal yields for  $Y(10860) \rightarrow Y(ns)[\ell^+\ell^-]\pi^0\pi^0$  decays are extracted by a binned maximum likelihood fit to the  $M_{\text{miss}}(\pi^0\pi^0)$  distributions. The signal probability density function (PDF) is described by a sum of two Gaussians for each  $Y(ns)$  resonance with parameters fixed from the signal Monte Carlo (MC) sample. The correctly reconstructed events ( $\sim 80\%$ ) are described by a core Gaussian with the resolution of 21, 14, and 10 MeV/ $c^2$  for  $Y(1S)$ ,  $Y(2S)$ , and  $Y(3S)$ , respectively. A sizable fraction ( $\sim 20\%$ ) of events with misreconstructed  $\gamma$  from  $\pi^0$  decay are described by a wider Gaussian with a shifted mean. The background PDF is parametrized by the sum of a constant and an exponential function.

For the  $Y(2S)[Y(1S)\pi^+\pi^-]$  decay, we fit the invariant mass of  $Y(1S)\pi^+\pi^-$ . The signal PDF is described by a Gaussian function with a resolution of 5 MeV/ $c^2$  (fixed from signal MC). The background PDF is described by a constant. The cross-feed from the decay  $Y(10860) \rightarrow Y(2S)[Y(1S)\pi^0\pi^0]\pi^+\pi^-$  contributes as a broad peak around 10.3 GeV/ $c^2$ . Its shape is parametrized by a Gaussian function with parameters fixed from MC. The fit results are also shown in Figs. 1(a)–1(c).

Though  $Y(ns)\pi^0\pi^0$  final states are expected to be produced from the decay of the  $Y(10860)$  resonance, here we present the signal rates as the cross sections of  $e^+e^- \rightarrow Y(ns)\pi^0\pi^0$  since the fraction of the resonance among  $b\bar{b}$  hadronic events is unknown and the energy dependence of the  $Y(ns)\pi^+\pi^-$  yield is found to be rather different from that of  $b\bar{b}$  hadronic events [13]. Table I summarizes the signal yield, MC efficiency, and measured visible cross section (with only the statistical uncertainty shown). The reconstruction efficiency is obtained from MC using the matrix element determined from the Dalitz plot fit described below. The systematic uncertainty due to the corresponding fit model is found to be negligible. The visible cross section is calculated from

$$\sigma_{\text{vis}} = \frac{N_{\text{sig}}}{\epsilon \mathcal{B}(Y(ns) \rightarrow X) \mathcal{L}}, \quad (1)$$

where  $N_{\text{sig}}$  is the number of signal events,  $\epsilon$  is the reconstruction efficiency,  $\mathcal{B}(Y(ns) \rightarrow X)$  is the branching fraction of the  $Y(ns)$  to the reconstructed final state  $X$  ( $\mu^+\mu^-$ ,  $e^+e^-$  or  $Y(1S)[\ell^+\ell^-]\pi^+\pi^-$ ), and  $\mathcal{L}$  is the integrated luminosity. The cross section corrected for the initial state radiation (ISR), the “dressed” cross section, is calculated as

$$\sigma = \sigma_{\text{vis}} / (1 + \delta_{\text{ISR}}). \quad (2)$$

The ISR correction factor,  $(1 + \delta_{\text{ISR}}) = 0.666 \pm 0.013$ , is determined using the formulas in Ref. [14]. We assume the energy dependence of  $e^+e^- \rightarrow Y(ns)\pi^0\pi^0$  to be the same as for the isospin-related channel  $e^+e^- \rightarrow Y(ns)\pi^+\pi^-$ , given by Ref. [13]. Since  $\mathcal{B}(Y(3S) \rightarrow e^+e^-)$  has not been measured, we assume it to be equal to  $\mathcal{B}(Y(3S) \rightarrow \mu^+\mu^-)$ .

Table II shows the dominant sources of systematic uncertainties for the cross section measurements. The uncertainty on the data/MC difference is estimated by varying the requirements on  $P$ ,  $|\Delta E|$ ,  $M_{\text{miss}}(\ell^+\ell^-)$ , and  $\chi^2(\pi^0)$ . We obtain a 4% uncertainty on both  $Y(1, 2S)\pi^0\pi^0$  samples. The same value is used for  $Y(3S)\pi^0\pi^0$  due to the small sample size in this final state. The uncertainty on the signal and background PDFs in the fit is estimated by a variation

TABLE I. Signal yield ( $N_{\text{sig}}$ ), MC efficiency, visible cross section ( $\sigma_{\text{vis}}$ ), definition of the signal region, number of selected events, and fraction of signal events ( $f_{\text{sig}}$ ).

Final state	$N_{\text{sig}}$	$\epsilon$ , %	$\sigma_{\text{vis}}$ , pb	Signal region, GeV/ $c^2$	Events	$f_{\text{sig}}$
$Y(1S) \rightarrow \mu^+\mu^-$	$261 \pm 15$	11.2	$0.77 \pm 0.04$	$9.41 < M_{\text{miss}}(\pi^0\pi^0) < 9.53$	247	0.95
$Y(1S) \rightarrow e^+e^-$	$123 \pm 13$	5.61	$0.76 \pm 0.08$	$9.41 < M_{\text{miss}}(\pi^0\pi^0) < 9.53$	140	0.78
$Y(2S) \rightarrow \mu^+\mu^-$	$241 \pm 18$	8.04	$1.28 \pm 0.10$	$9.99 < M_{\text{miss}}(\pi^0\pi^0) < 10.07$	253	0.87
$Y(2S) \rightarrow e^+e^-$	$108 \pm 13$	3.58	$1.30 \pm 0.16$	$9.99 < M_{\text{miss}}(\pi^0\pi^0) < 10.07$	151	0.66
$Y(2S) \rightarrow Y(1S)\pi^+\pi^-$	$24 \pm 5$	2.27	$1.00 \pm 0.21$	$10.00 < M(Y\pi^+\pi^-) < 10.05$	28	0.86
$Y(3S) \rightarrow \mu^+\mu^-$	$49 \pm 12$	2.60	$0.71 \pm 0.17$	$10.33 < M_{\text{miss}}(\pi^0\pi^0) < 10.39$	103	0.43
$Y(3S) \rightarrow e^+e^-$	$9 \pm 14$	1.19	$0.29 \pm 0.44$	not used	—	—

TABLE II. Systematic uncertainties for the cross section measurements (in %).

Source	$Y(1S)[\mu^+\mu^-]$	$Y(1S)[e^+e^-]$	$Y(2S)[\mu^+\mu^-]$	$Y(2S)[e^+e^-]$	$Y(2S)[Y\pi^+\pi^-]$	$Y(3S)[\mu^+\mu^-]$	$Y(3S)[e^+e^-]$
Data/MC difference	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Signal/background PDF	3.0	3.0	4.0	5.0	5.0	15.0	50
$\mathcal{B}(Y(nS) \rightarrow X)$ [15]	2.0	4.6	8.8	8.4	3.3	9.6	9.6
Leptons ID	1.0	3.0	1.0	3.0	2.5	1.0	3.0
Tracking	0.7	0.7	0.7	0.7	1.7	0.7	0.7
$\pi^0$ 's reconstruction	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Luminosity	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Trigger efficiency	2.0	2.0	2.0	2.0	2.0	2.0	2.0
$(1 + \delta_{\text{ISR}})$	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Sum for $\sigma_{\text{vis}}$	7.8	9.3	11.9	12.3	9.6	19.1	52
Sum for $\sigma$	8.1	9.5	12.1	12.5	9.8	19.2	52

of the fit range and changing the parametrization to a single Gaussian for the signal and a third- and fourth-order polynomial for the background. The systematic uncertainties on lepton identification (ID) are estimated using the process  $Y(10860) \rightarrow Y(nS)\pi^+\pi^-$ ,  $Y(nS) \rightarrow \ell^+\ell^-$ . The tracking uncertainty is obtained from partially and fully reconstructed  $D^* \rightarrow \pi^+D^0$ ,  $D^0 \rightarrow K_S^0\pi^+\pi^-$  decays. The  $\pi^0$  reconstruction uncertainty is estimated using  $\tau^- \rightarrow \pi^-\pi^0\nu_\tau$ . The trigger efficiency is determined by MC to be 94–99%, depending on the final state. We conservatively estimate its error as 2%. The uncertainty of the ISR correction factor is determined by the modification of the parametrization of the  $e^+e^- \rightarrow Y(nS)\pi^+\pi^-$  cross section (variation of  $Y(10860)$  mass and width within its errors, including a possible contribution of the nonresonant term) and variation of selection criteria. We combine different  $Y(nS)$  decay modes assuming a 100% correlation for all sources of systematic errors except lepton ID. The total systematic errors are 8.6%, 12.3% and 19.2% for  $Y(nS)\pi^0\pi^0$ ,  $n = 1, 2$ , and 3, respectively. We calculate the weighted average of  $\sigma(e^+e^- \rightarrow Y(nS)\pi^0\pi^0)$  in the various  $Y(nS)$  decay channels and obtain [16]

$$\begin{aligned}\sigma_{\text{vis}}(e^+e^- \rightarrow Y(1S)\pi^0\pi^0) &= (0.77 \pm 0.04 \pm 0.07) \text{ pb}, \\ \sigma_{\text{vis}}(e^+e^- \rightarrow Y(2S)\pi^0\pi^0) &= (1.25 \pm 0.08 \pm 0.15) \text{ pb}, \\ \sigma_{\text{vis}}(e^+e^- \rightarrow Y(3S)\pi^0\pi^0) &= (0.66 \pm 0.16 \pm 0.13) \text{ pb}\end{aligned}\quad (3)$$

and

$$\begin{aligned}\sigma(e^+e^- \rightarrow Y(1S)\pi^0\pi^0) &= (1.16 \pm 0.06 \pm 0.10) \text{ pb}, \\ \sigma(e^+e^- \rightarrow Y(2S)\pi^0\pi^0) &= (1.87 \pm 0.11 \pm 0.23) \text{ pb}, \\ \sigma(e^+e^- \rightarrow Y(3S)\pi^0\pi^0) &= (0.98 \pm 0.24 \pm 0.19) \text{ pb}.\end{aligned}\quad (4)$$

These are approximately one-half of the corresponding values of  $\sigma(e^+e^- \rightarrow Y(nS)\pi^+\pi^-)$  [8,13], consistent with the expectations from isospin conservation. The Born cross section  $\sigma_{\text{Born}}$  can be obtained by multiplying by the vacuum polarization correction factor,

$$\sigma_{\text{Born}} = \sigma|1 - \Pi|^2, \quad (5)$$

where  $|1 - \Pi|^2 = 0.9286$  [17]. The branching fractions listed in PDG can be obtained by

$$\begin{aligned}\mathcal{B}(Y(10860) \rightarrow Y(nS)\pi^0\pi^0) \\ = \frac{\sigma_{\text{vis}}(e^+e^- \rightarrow Y(nS)\pi^0\pi^0)}{\sigma_{b\bar{b}}(\text{at } Y(10860))},\end{aligned}\quad (6)$$

where  $\sigma_{b\bar{b}}(\text{at } Y(10860)) = (0.340 \pm 0.016) \text{ nb}$  [18].

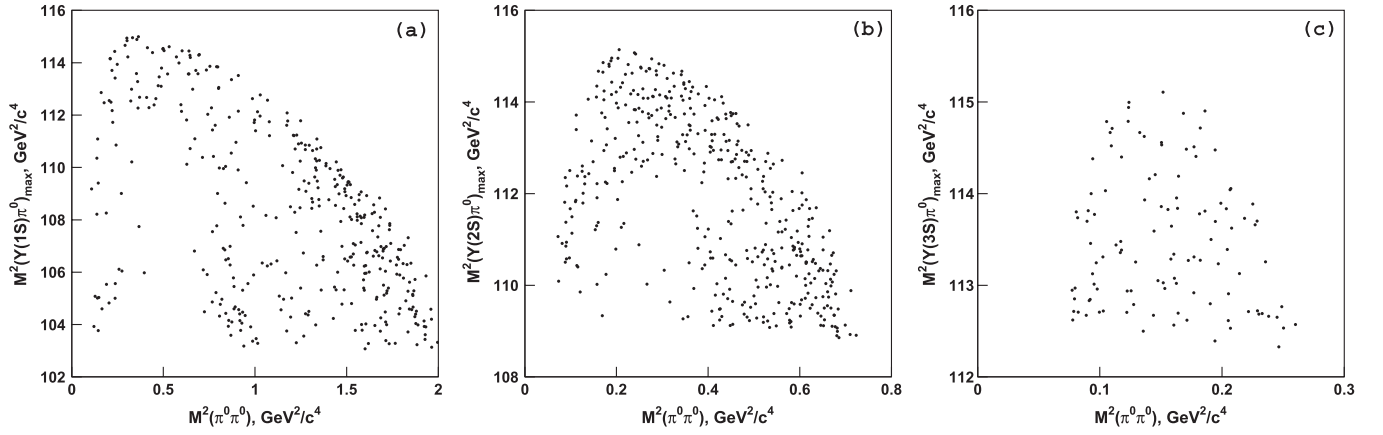
## V. DALITZ ANALYSIS

Figure 2 shows the Dalitz distributions for the selected  $Y(10860) \rightarrow Y(nS)\pi^0\pi^0$  candidates in the signal regions given in Table I. A mass-constrained fit is performed for the  $Y(nS)$  candidates. Samples of background events are selected in the  $M_{\text{miss}}(\pi^0\pi^0)$  sidebands for  $Y(nS) \rightarrow \ell^+\ell^-$  and in the  $M(Y(1S)\pi^+\pi^-)$  sidebands for  $Y(2S) \rightarrow Y(1S)\pi^+\pi^-$ . Then we refit candidates to the nominal mass of the corresponding  $Y(nS)$  state to match the phase space boundaries. We use the following sideband regions: [9.20: 9.35] GeV/ $c^2$  and [9.60: 9.75] GeV/ $c^2$  for  $Y(1S)[\ell^+\ell^-]\pi^0\pi^0$ , [9.80: 9.95] GeV/ $c^2$  and [10.15: 10.30] GeV/ $c^2$  for  $Y(2S)[\ell^+\ell^-]\pi^0\pi^0$ , [9.90: 9.95] GeV/ $c^2$  and [10.10: 10.20] GeV/ $c^2$  for  $Y(2S)[Y\pi^+\pi^-]\pi^0\pi^0$ , and [10.15: 10.30] GeV/ $c^2$  and [10.45: 10.50] GeV/ $c^2$  for  $Y(3S)[\ell^+\ell^-]\pi^0\pi^0$ . We parametrize the background PDF by the following function:

$$B(s_1, s_2) = 1 + p_1 e^{-q_1 s_3} + p_2 e^{-q_2 (s_{\text{min}} - c_2)}, \quad (7)$$

where  $p_1$ ,  $p_2$ ,  $q_1$ , and  $q_2$  are the fit parameters,  $s_3 = M^2(\pi^0\pi^0)$ ,  $s_{\text{min}} = \min(s_1, s_2)$ , and  $s_{1,2} = M^2(Y(nS)\pi_{1,2}^0)$ ;  $c_2$  is defined as  $(m_{Y(nS)} + m_{\pi^0})^2$ .

Variation of the reconstruction efficiency over the Dalitz plot is determined using a large sample of MC with a uniform phase space distribution. We use the following function to parametrize the efficiency:

FIG. 2. Dalitz plots for selected (a)  $Y(1S)\pi^0\pi^0$ , (b)  $Y(2S)\pi^0\pi^0$ , and (c)  $Y(3S)\pi^0\pi^0$  candidates.

$$\epsilon = 1 + \alpha \{1 - e^{-(s_3 - c_0)/b_0}\} \{1 - e^{-(c_1 - s_{\max})/b_1}\}, \quad (8)$$

where  $\alpha$ ,  $b_0$ , and  $b_1$  are fit parameters,  $s_{\max} = \max(s_1, s_2)$ , and  $c_0$  and  $c_1$  are defined as  $c_0 = 4m_{\pi^0}^2$  and  $c_1 = (m_{Y(10860)} - m_{\pi^0})^2$ .

The amplitude analysis of the three-body  $Y(10860) \rightarrow Y(nS)\pi^0\pi^0$  decays closely follows Ref. [1]. We describe the three-body signal amplitude with a sum of quasi-two-body contributions:

$$\mathcal{M}(s_1, s_2) = A_{Z_1} + A_{Z_2} + A_{f_0} + A_{f_2} + a^{\text{nr}}, \quad (9)$$

where  $A_{Z_1}$  and  $A_{Z_2}$  are the amplitudes for contributions from the  $Z_b^0(10610)$  and  $Z_b^0(10650)$ , respectively. The amplitudes  $A_{f_0}$ ,  $A_{f_2}$ , and  $a^{\text{nr}}$  account for the contributions from the  $\pi^0\pi^0$  system in an  $f_0(980)$ , an  $f_2(1275)$ , and a nonresonant state, respectively. We assume that the dominant contributions to  $A_{Z_k}$  are from amplitudes that preserve the orientation of the spin of the heavy quarkonium state, and, thus, both pions in the cascade decay  $Y(10860) \rightarrow Z_b^0\pi^0 \rightarrow Y(nS)\pi^0\pi^0$  are emitted in an  $S$  wave with respect to the heavy quarkonium system. As demonstrated in

Ref. [3], angular analysis supports this assumption. Consequently, we parametrize both amplitudes with an  $S$ -wave Breit–Wigner function, neglecting the possible  $s$  dependence of the resonance width:

$$\text{BW}(s, M, \Gamma) = \frac{\sqrt{M\Gamma}}{M^2 - s - iM\Gamma}. \quad (10)$$

Both amplitudes are symmetrized with respect to  $\pi^0$  interchange:

$$A_{Z_k}(k = 1, 2) = a_k e^{i\delta_k} (\text{BW}(s_1, m_k, \Gamma_k) + \text{BW}(s_2, m_k, \Gamma_k)). \quad (11)$$

The masses and widths are fixed to the values obtained in the  $Y(nS)\pi^+\pi^-$  and  $h_b(mP)\pi^+\pi^-$  analyses:  $M(Z_1) = 10607.2 \text{ MeV}/c^2$ ,  $\Gamma(Z_1) = 18.4 \text{ MeV}$ ,  $M(Z_2) = 10652.2 \text{ MeV}/c^2$ , and  $\Gamma(Z_2) = 11.5 \text{ MeV}$  [1]. We use a Flatté function [19] for the  $f_0(980)$  and a Breit–Wigner function for the  $f_2(1275)$ . Coupling constants of the  $f_0(980)$  are fixed at the values from the  $B^+ \rightarrow K^+\pi^+\pi^-$  analysis:  $M = 950 \text{ MeV}/c^2$ ,  $g_{\pi\pi} = 0.23$ , and

TABLE III. Two solutions found in the Dalitz plot fit of  $Y(2S)\pi^0\pi^0$  events. The phases are in degrees. The nonresonant amplitude  $a_1^{\text{nr}}$  and its phase are fixed to 10.0 and 0.0, respectively.

Solutions	w/o $Z_b^0$	with $Z_1^0$	with $Z_b^0$ 's	w/o $Z_b^0$	with $Z_1^0$	with $Z_b^0$ 's
	A	A	A	B	B	B
$A(Z_1^0)$	0.0 (fixed)	$0.46^{+0.15}_{-0.11}$	$0.58^{+0.21}_{-0.14}$	0.0 (fixed)	$1.35^{+0.64}_{-0.33}$	$1.42 \pm 0.48$
$\phi(Z_1^0)$	—	$243 \pm 14$	$247 \pm 14$	—	$88 \pm 18$	$91 \pm 21$
$A(Z_2^0)$	0.0 (fixed)	0.0 (fixed)	$0.37^{+0.20}_{-0.16}$	0.0 (fixed)	0.0 (fixed)	$0.66 \pm 0.40$
$\phi(Z_2^0)$	—	—	$235 \pm 27$	—	—	$124 \pm 37$
$A(f_2)$	$28.2 \pm 7.0$	$23.9 \pm 7.3$	$18.2 \pm 7.3$	$41.8 \pm 9.0$	$48.7 \pm 15.4$	$43.3 \pm 15.6$
$\phi(f_2)$	$28 \pm 10$	$28 \pm 13$	$36 \pm 21$	$359 \pm 14$	$10 \pm 16$	$132 \pm 19$
$A(f_0)$	$8.2 \pm 2.1$	$10.5 \pm 1.9$	$11.5 \pm 1.9$	$13.3 \pm 3.6$	$13.4 \pm 4.2$	$12.6 \pm 4.9$
$\phi(f_0)$	$210 \pm 8$	$213 \pm 7$	$211 \pm 6$	$131 \pm 11$	$134 \pm 15$	$132 \pm 19$
$a_2^{\text{nr}}$	$24.6 \pm 4.2$	$31.8 \pm 4.3$	$34.7 \pm 4.9$	$44.2 \pm 10.1$	$50.4 \pm 12.2$	$50.8 \pm 13.7$
$\phi_2^{\text{nr}}$	$93 \pm 15$	$85 \pm 13$	$80 \pm 12$	$290 \pm 16$	$291 \pm 22$	$288 \pm 25$
$-2 \ln \mathcal{L}$	−154.5	−186.6	−193.1	−155.4	−186.3	−191.2

TABLE IV. Results of the Dalitz plot fit of  $Y(1, 3S)\pi^0\pi^0$  events. The phases are in degrees. The nonresonant amplitude  $a_1^{\text{nr}}$  and its phase are fixed to 10.0 and 0.0, respectively.

Model	$Y(1S)\pi^0\pi^0$ with $Z_b^0$ 's	$Y(1S)\pi^0\pi^0$ w/o $Z_b^0$ 's	$Y(3S)\pi^0\pi^0$ with $Z_b^0$ 's	$Y(3S)\pi^0\pi^0$ with $Z_1^0$ only	$Y(3S)\pi^0\pi^0$ w/o $Z_b^0$ 's
$A(Z_1^0)$	$0.50^{+0.34}_{-0.30}$	0.0 (fixed)	$1.07^{+1.45}_{-0.33}$	$1.09^{+0.75}_{-0.31}$	0.0(fixed)
$\phi(Z_1^0)$	$324 \pm 50$	—	$158 \pm 25$	$149 \pm 24$	—
$A(Z_2^0)$	$0.60^{+0.51}_{-0.47}$	0.0 (fixed)	$0.32^{+1.18}_{-0.32}$	0.0 (fixed)	0.0 (fixed)
$\phi(Z_2^0)$	$301 \pm 60$	—	$252 \pm 81$	—	—
$A(f_2)$	$15.7 \pm 2.0$	$14.6 \pm 1.6$	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)
$\phi(f_2)$	$60 \pm 11$	$51 \pm 9$	—	—	—
$A(f_0)$	$1.07 \pm 0.15$	$0.97 \pm 0.12$	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)
$\phi(f_0)$	$168 \pm 11$	$163 \pm 10$	—	—	—
$a_2^{\text{nr}}$	$15.2 \pm 1.2$	$13.9 \pm 0.7$	$50.5 \pm 14.1$	$44.8 \pm 12.5$	$48.0 \pm 12.7$
$\phi_2^{\text{nr}}$	$162 \pm 4$	$161 \pm 4$	$155 \pm 15$	$153 \pm 14$	$151 \pm 15$
$-2 \ln \mathcal{L}$	-316.7	-312.4	-31.3	-30.7	-5.3

$g_{KK} = 0.73$  [20]. The mass and width of the  $f_2(1275)$  resonance are fixed to the world average values [15]. Following suggestions in Ref. [21], the nonresonant amplitude  $a^{\text{nr}}$  is parametrized as

$$a^{\text{nr}} = a_1^{\text{nr}} e^{i\phi_1^{\text{nr}}} + a_2^{\text{nr}} e^{i\phi_2^{\text{nr}}} s_3, \quad (12)$$

where  $a_1^{\text{nr}}$ ,  $a_2^{\text{nr}}$ ,  $\phi_1^{\text{nr}}$ , and  $\phi_2^{\text{nr}}$  are free parameters in the fit. As there is only sensitivity to the relative amplitudes and phases between decay modes, we fix  $a_1^{\text{nr}} = 10.0$  and  $\phi_1^{\text{nr}} = 0.0$ . Since the phase space of the decay  $Y(10860) \rightarrow Y(3S)\pi^0\pi^0$  is very limited, contributions from  $f_0$  and  $f_2$  are not included in the fit.

We perform an unbinned maximum likelihood fit. The likelihood function is defined as

$$\mathcal{L} = \prod \epsilon(s_1, s_2) (f_{\text{sig}} S(s_1, s_2) + (1 - f_{\text{sig}}) B(s_1, s_2)), \quad (13)$$

where the product runs over all signal candidates.  $S(s_1, s_2)$  is  $|\mathcal{M}(s_1, s_2)|^2$  convoluted with the detector resolution (6.0 MeV/ $c^2$  for  $M(Y(nS)\pi^0)$ );  $\epsilon(s_1, s_2)$  describes the variation of the reconstruction efficiency over the Dalitz plot. The fraction  $f_{\text{sig}}$  is the fraction of signal events in the

data sample determined separately for each  $Y(nS)$  decay mode (see Table I). The function  $B(s_1, s_2)$  describes the distribution of background events over the phase space. Both products  $S(s_1, s_2)\epsilon(s_1, s_2)$  and  $B(s_1, s_2)\epsilon(s_1, s_2)$  are normalized to unity.

To ensure that the fit converges to the global minimum, we perform  $10^3$  fits with randomly assigned initial values for amplitudes and phases. We find two solutions for the  $Y(2S)\pi^0\pi^0$  sample with similar values of  $-2 \ln \mathcal{L}$  (see Table III). Solution A has better consistency with the Dalitz plot fit result for the  $Y(10860) \rightarrow Y(2S)\pi^+\pi^-$  decay [8]. We find single solutions for the  $Y(1, 3S)\pi^0\pi^0$  samples. Table IV shows the values and errors of amplitudes and phases obtained from the fit to the  $Y(1S)\pi^0\pi^0$  and  $Y(3S)\pi^0\pi^0$  Dalitz plots. Projections of the fits are shown in Figs. 3–5. These projections are very similar to the corresponding distributions in  $Y(nS)\pi^+\pi^-$  [1]. The  $Z_b^0$  signal is most clearly observed in  $M(Y(2S)\pi^0)_{\text{max}}$ ,  $M(Y(3S)\pi^0)_{\text{max}}$ , and  $M(Y(3S)\pi^0)_{\text{min}}$ .

The  $Z_b^0$  significance is calculated from a large number of pseudoexperiments, each with the same statistics as in the data. MC samples are generated using models without the  $Z_b^0$  contribution. We fit them with and without the  $Z_b^0(10610)$  contribution and examine the  $\Delta(-2 \ln \mathcal{L})$

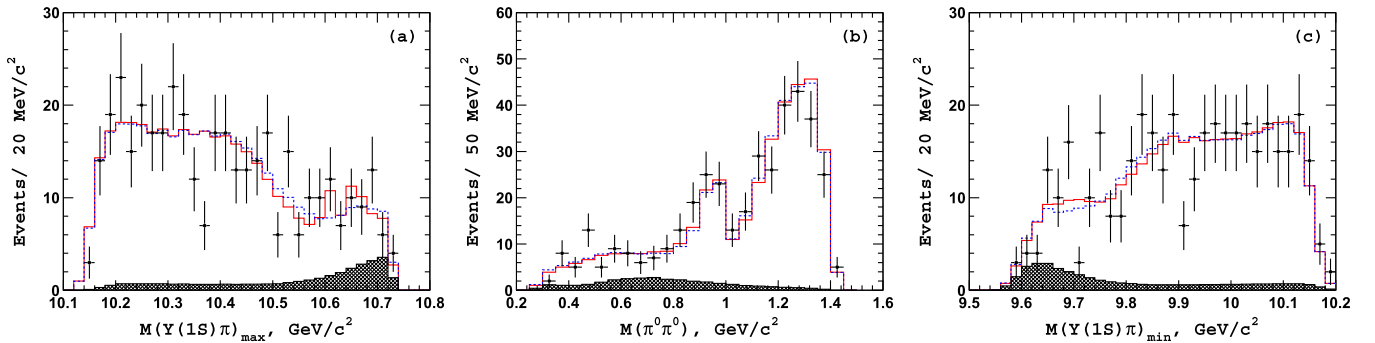


FIG. 3 (color online). Comparison of the (a)  $M(Y(1S)\pi^0)_{\text{max}}$ , (b)  $M(\pi^0\pi^0)$ , and (c)  $M(Y(1S)\pi^0)_{\text{min}}$  distributions for the  $Y(1S)\pi^0\pi^0$  events in the signal region (points with error bars) and results of the fit (open histograms). Solid red and dashed blue open histograms show the fit with and without  $Z_b^0$ 's, respectively. Hatched histograms show the background components.

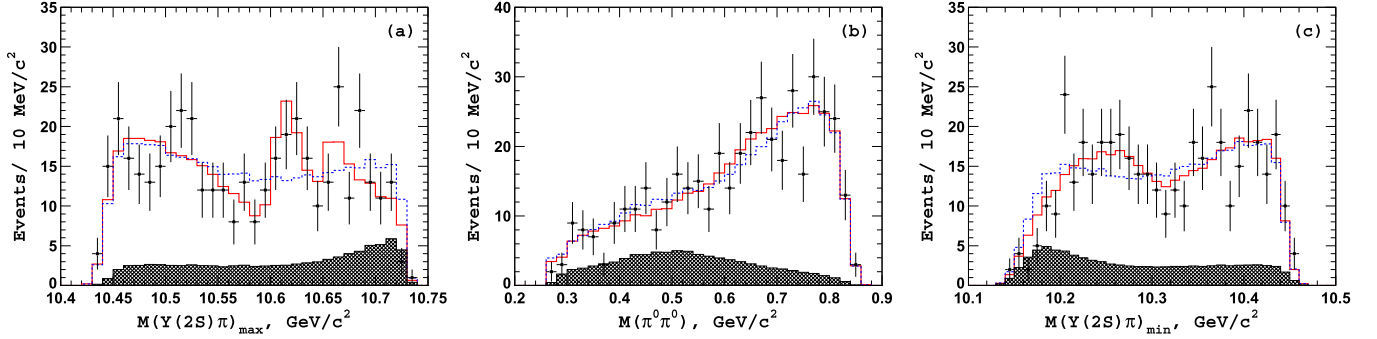


FIG. 4 (color online). Comparison of the (a)  $M(Y(2S)\pi^0)_{\max}$ , (b)  $M(\pi^0\pi^0)$ , and (c)  $M(Y(2S)\pi^0)_{\min}$  distributions for the  $Y(2S)\pi^0\pi^0$  events in the signal region (points with error bars) and results of the fit (open histograms). The legends are the same as in Fig. 3. Only solution A is shown. Both solutions give indistinguishable plots.

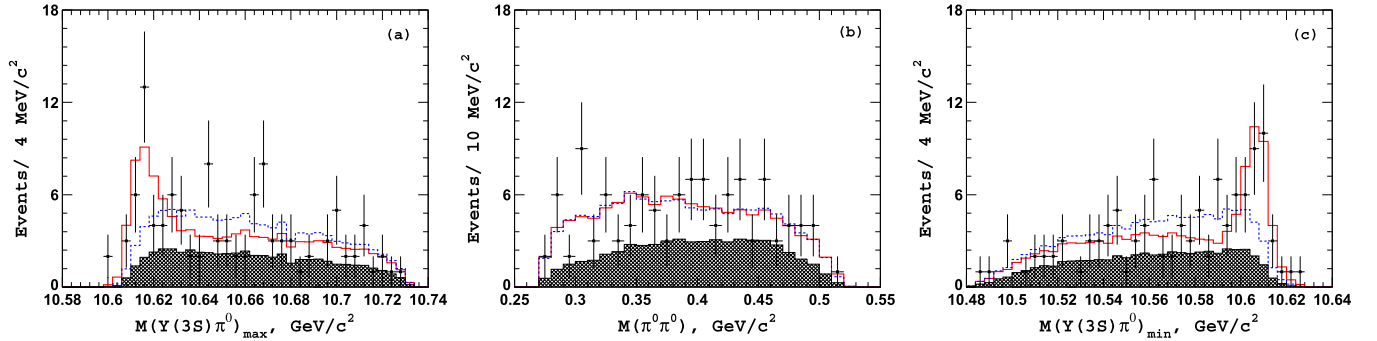


FIG. 5 (color online). Comparison of the (a)  $M(Y(3S)\pi^0)_{\max}$ , (b)  $M(\pi^0\pi^0)$ , and (c)  $M(Y(3S)\pi^0)_{\min}$  distributions for the  $Y(3S)\pi^0\pi^0$  events in the signal region (points with error bars) and results of the fit (open histograms). The legends are the same as in Fig. 3.

distributions. We find  $5.3\sigma$  for the  $Z_b^0(10610)$  statistical significance in both solutions for  $Y(2S)\pi^0\pi^0$ . In addition, the  $Z_b^0(10610)$  statistical significance is  $4.7\sigma$  in the fit to the  $Y(3S)\pi^0\pi^0$  sample. The  $Z_b^0(10610)$  signal is not significant in the fit to the  $Y(1S)\pi^0\pi^0$  events due to the smaller relative branching fraction. The signal for the  $Z_b^0(10650)$  is not significant in any of the  $Y(1, 2, 3S)\pi^0\pi^0$  data sets.

We calculate the relative fit fraction of each resonance as the ratio  $f_R = \frac{\int_{\text{Dalitz}} |M_{AR}^2|}{\int_{\text{Dalitz}} |M_{\text{all}}^2|}$  from the central values of the fit given in Tables III and IV. Errors and 90% C.L. upper limits for nonsignificant fractions are obtained using pseudoexperiments. Results are summarized in Table V. The sum of individual contributions is not equal to 100%

due to interference between amplitudes. Reasonable agreement is observed with the corresponding fit fractions in the  $Y(nS)\pi^+\pi^-$  analysis [8]. Table VI shows the product of cross sections and branching fractions  $\sigma(e^+e^- \rightarrow Z_b^0\pi^0) \cdot \mathcal{B}(Z_b^0 \rightarrow Y(nS)\pi^0)$ .

We perform a simultaneous fit of the  $Y(2S)\pi^0\pi^0$  and  $Y(3S)\pi^0\pi^0$  data samples. No constraints between samples are imposed on signal model parameters and the background description. The combined significance of the  $Z_b^0(10610)$  signal is  $6.8\sigma$ . Results for the simultaneous fit are exactly the same as in separate fits of  $Y(2, 3S)\pi^0\pi^0$  samples, as expected. We also perform a simultaneous fit with the  $Z_b^0(10610)$  mass as a free parameter and find  $m(Z_b^0(10610)) = (10609 \pm 4 \pm 4) \text{ MeV}/c^2$ ; this is consistent with the mass of the  $Z_b^\pm(10610)$ .

TABLE V. Summary of results for the fit fractions of individual channels in the  $Y(nS)\pi^0\pi^0$  final state.

Fraction, %	Y(1S)	Y(2S) solution A	Y(2S) solution B	Y(3S)
$Z_b^0(10610)$	$0.9^{+2.2+0.5}_{-0.9-0.3} (<4.6)$	$13.5^{+6.8+3.2}_{-2.7-4.4}$	$25.4^{+6.2+4.2}_{-5.9-11}$	$84^{+17+14}_{-23-11}$
$Z_b^0(10650)$	$0.6^{+2.5+0.5}_{-0.6-0.3} (<4.8)$	$2.7^{+3.0+1.5}_{-1.4-1.2} (<8.0)$	$2.7^{+5.8+1.2}_{-1.6-1.2} (<12.4)$	$4.3^{+2.4+3.5}_{-2.2-1.9} (<10.9)$
$f_2(1275)$	$26.3 \pm 4.2^{+7.8}_{-4.5}$	$3.9^{+3.4+3.8}_{-2.0-2.1}$	$8.7^{+4.6+3.9}_{-2.0-4.5}$	—
Total S wave	$72.4 \pm 4.7^{+5.6}_{-3.4}$	$95.5^{+5.2+6.0}_{-6.2-6.5}$	$110^{+7+6}_{-9-18}$	$65^{+12+18}_{-15-17}$
Sum	$100^{+9}_{-6} \pm 1$	$116^{+10}_{-4} \pm 3$	$145^{+12}_{-10} \pm 9$	$153^{+38}_{-22} \pm 15$



TABLE VI. Product of the  $\sigma(e^+e^- \rightarrow Z_b^0\pi^0) \cdot \mathcal{B}(Z_b^0 \rightarrow Y(nS)\pi^0)$ .

$\sigma \cdot \mathcal{B}$ , fb	Y(1S)	Y(2S) solution A	Y(2S) solution B	Y(3S)
$Z_b^0(10610)$	$10^{+26+6}_{-10-4} (<59)$	$252^{+127+67}_{-52-88}$	$475^{+119+98}_{-114-214}$	$823^{+317+256}_{-367-234}$
$Z_b^0(10650)$	$7^{+29+6}_{-7-4} (<62)$	$50^{+56+28}_{-26-22} (<168)$	$50^{+108+22}_{-30-22} (<260)$	$42^{+26+35}_{-24-20} (<141)$

TABLE VII. Systematic uncertainty on the fractions of individual channels in the  $Y(nS)\pi^0\pi^0$  final states.

Uncertainty, %	Model	Efficiency	Resolution	Background	Beam energy	Sum
Y(1S), $Z_b^0(10610)$	+0.5 -0.3	+0.2 -0.1	$\pm 0.04$	$\pm 0.07$	$\pm 0.04$	+0.5 -0.3
Y(1S), $Z_b^0(10650)$	+0.5 -0.3	+0.2 -0.1	$\pm 0.02$	+0.13 -0.06	$\pm 0.01$	+0.5 -0.3
Y(1S), $f_2(1275)$	+7.7 -4.4	+0.7 -0.8	$\pm 0.02$	+0.5 -0.9	$\pm 0.1$	+7.8 -4.5
Y(1S), $S$ wave	+5.5 -2.8	+0.6 -1.0	$\pm 0.05$	+0.9 -1.4	$\pm 0.7$	+5.6 -3.4
Y(2S), solution A, $Z_b^0(10610)$	+1.4 -3.0	+0.6 -0.3	$\pm 2.1$	+1.8 -2.4	$\pm 0.2$	+3.2 -4.4
Y(2S), solution A, $Z_b^0(10650)$	+1.1 -0.6	+0.1 -0.03	$\pm 0.8$	+0.5 -0.6	$\pm 0.1$	+1.5 -1.2
Y(2S), solution A, $f_2(1275)$	+0.3 -0.8	$\pm 0.8$	$\pm 0.8$	+3.6 -1.6	$\pm 0.1$	+3.8 -2.1
Y(2S), solution A, $S$ wave	+3.8 -0.7	+2.5 -2.3	$\pm 0.5$	+3.9 -6.0	$\pm 0.5$	+6.0 -6.5
Y(2S), solution B, $Z_b^0(10610)$	+4.0 -11	+0.7 -1.6	$\pm 0.6$	+0.5 -2.2	$\pm 0.6$	+4.2 -11
Y(2S), solution B, $Z_b^0(10650)$	+0.3 -0.1	+0.07 -0.1	$\pm 1.0$	+0.4 -0.6	$\pm 0.3$	$\pm 1.2$
Y(2S), solution B, $f_2(1275)$	+0.4 -3.6	+0.8 -0.6	$\pm 0.3$	+3.2 -1.6	$\pm 2.1$	+3.9 -4.5
Y(2S), solution B, $S$ wave	+5 -15	+1.5 -1.4	$\pm 0.5$	+2 -10	$\pm 2$	+6 -18
Y(3S), $Z_b^0(10610)$	+2 -5	$\pm 5$	+1.3 -0.4	+13 -8	$\pm 0.8$	+14 -11
Y(3S), $Z_b^0(10650)$	+2.7 -0.8	+1.4 -0.6	+1.4 -1.0	+1.1 -1.2	$\pm 0.02$	+3.5 -1.9
Y(3S), $S$ wave	+12 -7	$\pm 1$	+2 -5	+13 -15	$\pm 0.3$	+18 -17

## VI. SYSTEMATIC UNCERTAINTIES IN THE DALITZ ANALYSIS

Table VII shows the main sources of systematic uncertainties for the measurement of fractions obtained from a fit of individual channels. The model uncertainty originates mainly from the parametrization of the nonresonant amplitude. Four additional models are used: a model with an additional  $f_0(500)$  resonance, parametrized by a Breit–Wigner function with  $M = 600$  MeV/ $c^2$  and  $\Gamma = 400$  MeV/ $c$ ; a model with  $a^{\text{nr}} = ae^{i\phi_a} + be^{i\phi_b}\sqrt{s}(\pi^0\pi^0)$ ; a model without the  $f_0(980)$  contribution; and a model without the  $a_2^{\text{nr}}$  contribution. Another source of systematic uncertainty is the determination of the signal efficiency. To estimate this effect, we perform two additional fits with a modified efficiency function by varying the momentum dependence of the  $\pi^0$  reconstruction efficiency. We also perform a fit with a modified detector resolution function: the resolutions are varied from 4 to 8 MeV/ $c^2$  instead of the nominal 6 MeV/ $c^2$  to take into account the effect of different momentum resolutions in the MC and data. We use different sideband subsamples to determine the background PDF parameters: the low-mass sideband only or the high-mass sideband or  $Y(nS) \rightarrow e^+e^-$  events only or  $Y(nS) \rightarrow \mu^+\mu^-$  events

only. We also vary the signal-to-background ratio within its errors. We considered the effect of the uncertainty of the c.m. energy (conservatively taken as  $\pm 3$  MeV).

The contribution of all experimental effects to the degradation of  $\Delta(-2\ln\mathcal{L})$  from the simultaneous fit of the  $Y(2, 3S)\pi^0\pi^0$  sample is smaller than 4.4. The corresponding limit for the model uncertainties is 4.5. We combine these two values in quadrature and decrease  $\Delta(-2\ln\mathcal{L})$  from the simultaneous fit by 6.3 in calculations of the  $Z_b^0(10610)$  significance. As a result, the  $Z_b^0(10610)$  significance is  $6.5\sigma$ . Fits with the  $Z_b^0(10610)$  mass as a free parameter yield values from 10606 to 10613 MeV/ $c^2$ . We use  $\pm 4$  MeV/ $c^2$  as a model uncertainty for the  $Z_b^0(10610)$  mass.

## VII. CONCLUSION

We report the observation of  $Y(10860) \rightarrow Y(nS)\pi^0\pi^0$  decays with  $n = 1, 2$ , and 3. The measured cross sections,  $\sigma(e^+e^- \rightarrow Y(10860) \rightarrow Y(1S)\pi^0\pi^0) = (1.16 \pm 0.06 \pm 0.10)$  pb,  $\sigma(e^+e^- \rightarrow Y(10860) \rightarrow Y(2S)\pi^0\pi^0) = (1.87 \pm 0.11 \pm 0.23)$  pb, and  $\sigma(e^+e^- \rightarrow Y(10860) \rightarrow Y(3S)\pi^0\pi^0) = (0.98 \pm 0.24 \pm 0.19)$  pb, are consistent with the expectations from isospin conservation based on  $\sigma(Y(10860) \rightarrow Y(nS)\pi^+\pi^-)$  [8,13].

The first observation of a neutral resonance decaying to  $Y(2, 3S)\pi^0$ , the  $Z_b^0(10610)$ , has been obtained in a Dalitz analysis of  $Y(10860) \rightarrow Y(2, 3S)\pi^0\pi^0$  decays. The statistical significance of the  $Z_b^0(10610)$  signal is  $6.8\sigma$  ( $6.5\sigma$  including experimental and model uncertainties). Its measured mass,  $m(Z_b^0(10610)) = (10609 \pm 4 \pm 4) \text{ MeV}/c^2$ , is consistent with the mass of the corresponding charged state, the  $Z_b^\pm(10610)$ . The  $Z_b^0(10650)$  signal is not significant in any of the  $Y(1, 2, 3S)\pi^0\pi^0$  channels. Our data are consistent with the existence of  $Z_b^0(10650)$ , but the available statistics are insufficient for the observation of this state.

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