Search for a light Higgs boson in single-photon decays of $\Upsilon(1S)$ using $\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$ tagging method

S. Jia,14 C. P. Shen,14 I. Adachi,28,16 H. Aihara,86 S. Al Said,80,40 D. M. Asner,3 H. Atmacan,8 T. Aushev,22 R. Ayad,80 V. Babu,9 P. Behera,28 K. Belous,31 J. Bennett,54 M. Bessner,19 V. Bhardwaj,25 B. Bhuyan,26 T. Bilka,5 A. Bobrov,4,66 D. Bodrov,22,46 G. Bonvicini,90 J. Borah,26 M. Bracko,51,37 P. Branchini,33 T. E. Browder,19 A. Budano,33 M. Campajola,32,58 D. Červenkov,5 M.-C. Chang,13 P. Chang,61 V. Chekelian,52 A. Chen,60 B. G. Cheon,18 K. Chilikin,35 E. Kovalenko,4,66 L. E. Piilonen,33 A. Budano,40 S. Cunliffe,33 S. Das,50 N. Dash,28 G. De Nardo,12,55 G. De Pietro,33 R. Dhamija,27 F. Di Capua,32,58 Z. Doležal,5 T. V. Dong,11 D. Epifanov,4,66 T. Ferber,7 D. Ferlewicz,51 B. G. Fulsom,68 R. Garg,69 V. Gaur,89 N. Gabyshev,4,66 A. Giri,27 P. Goldenzweig,38 B. Golob,47,37 E. Graziani,33 Y. Guan,8 K. Gudkova,4,66 C. Hadjivasilious,68 T. Hara,20,16 K. Hayasaka,64 H. Hayashii,59 M. T. Hedges,19 W.-S. Hou,61 K. Inami,57 G. Inguglia,30 A. Ishikawa,20,16 R. Itoh,20,16 M. Iwasaki,67 Y. Iwasaki,20 W. W. Jacobs,29 E.-J. Jang,17 Y. Jin,86 K. K. Joo,6 J. Kahn,38 A. B. Kaliyar,81 K. H. Kang,39 T. Kawasaki,41 C. Kiesling,52 C. H. Kim,18 D. Y. Kim,77 K.-H. Kim,92 Y.-K. Kim,92 K. Kinoshita,8 P. Kodyš,5 S. Kohani,19 T. Komno,41 A. Korobov,4,66 S. Korpar,51,37 E. Kovalenko,4,66 P. Križan,47,37 R. Kroeger,54 P. Krokovny,4,66 M. Kumar,50 R. Kumar,71 K. Kumara,90 Y.-J. Kwon,92 T. Lam,89 M. Laurenza,33,74 S. C. Lee,44 J. Li,44 L. K. Li,8 Y. Li,14 Y. B. Li,14 L. Li Gioi,52 J. Libby,28 K. Lieret,48 D. Liventsev,90,20 A. Martini,9 M. Masuda,85,72 T. Matsuda,55 D. Matvienko,4,66,46 S. K. Maurya,26 F. Meier,50 M. Merola,42,58 F. Metzner,58 K. Miyabayashi,59 R. Mizuk,46,22 G. B. Mohanty,81 R. Mussa,34 M. Nakao,20,16 D. Narwal,26 Z. Natkaniec,62 A. Natochi,19 L. Nayak,27 N. K. Nisar,8 S. Nishida,20,16 K. Nishimura,19 K. Ogawa,64 S. Ogawa,83 H. Ono,63,64 P. Oskin,46 P. Pakhlov,46,56 G. Pakhlova,22,46 T. Pang,70 S. Pardi,32 S.-H. Park,20 S. Patra,25 S. Paul,82,52 T. K. Pedlar,49 R. Pestonik,37 L. E. Piilonen,89 T. Podobnik,47,37 E. Prencipe,23 M. T. Prim,2 M. Röhren,9 A. Rostomyan,9 N. Rout,28 G. Russo,58 D. Sahoo,35 S. Sandilya,27 A. Sangal,8 L. Santelj,47,37 T. Sanuki,84 V. Savinov,70 G. Schnell,1,24 J. Schueler,19 C. Schwanda,30 Y. Seino,64 K. Senyo,91 M. E. Sevior,53 M. Shapkin,31 C. Sharma,50 V. Shebalin,19 J.-G. Shiu,61 B. Shwartz,4,66 J. B. Singh,69,8 A. Sokolov,31 E. Solovieva,46 S. Stančić,65 M. Starić,37 Z. S. Stottler,89 M. Sumihama,15,72 K. Sumisawa,20,16 T. Sunimoshi,88 W. Sutcliffe,2 M. Takizawa,70,21,73 U. Tamponi,34 K. Tanida,36 F. Tenchini,9 K. Trabelsi,45 M. Uchida,87 S. Uehara,20,16 T. Uglow,46,22 Y. Unno,58 K. Uno,64 S. Uno,40,16 P. Urquijo,53 S. E. Vahsen,19 R. Van Tonder,2 G. Varner,19 A. Vinokurova,4,66 E. Waheed,20 D. Wang,12 E. Wang,70 M.-Z. Wang,61 S. Watamuki,92 E. Won,43 B. D. Yabsley,79 W. Yan,75 S. B. Yang,43 H. Ye,9 J. Yelton,12 J. H. Yin,43 Y. Yusa,64 Y. Zhai,35 Z. P. Zhang,75 V. Zhilich,4,66 and V. Zhukova,46
(The Belle Collaboration)

1Department of Physics, University of the Basque Country UPV/EHU, 48080 Bilbao
2University of Bonn, 53115 Bonn
3Brookhaven National Laboratory, Upton, New York 11973
4Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090
5Faculty of Mathematics and Physics, Charles University, 112 11 Prague
6Chonnam National University, Gwangju 61186
7Chung-Ang University, Seoul 06974
8University of Cincinnati, Cincinnati, Ohio 45221
9Deutsches Elektronen-Synchrotron, 22607 Hamburg
10Duke University, Durham, North Carolina 27708
11Institute of Theoretical and Applied Research (ITAR), Duy Tan University, Hanoi 100000
12Institute of Physics, Fu Jen Catholic University, Taipei 24305
13Department of Physics, SOKENDAI (The Graduate University for Advanced Studies), Hayama 240-0193
14Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) and Institute of Modern Physics, Fudan University, Shanghai 200443
15SOKENDAI (The Graduate University for Advanced Studies), Hayama 240-0193
We search for a light Higgs boson ($A^0$) decaying into a $\tau^+\tau^-$ or $\mu^+\mu^-$ pair in the radiative decays of $\Upsilon(1S)$. The production of $\Upsilon(1S)$ mesons is tagged by $\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$ transitions, using 158 million $\Upsilon(2S)$ events accumulated with the Belle detector at the KEKB asymmetric energy electron-positron collider. No significant $A^0$ signals in the mass range from the $\tau^+\tau^-$ or $\mu^+\mu^-$ threshold to 9.2 GeV/$c^2$ are observed. We set the upper limits at 90% credibility level (C.L.) on $f_{\Upsilon(1S)}$ and mixing angle $\sin\theta_{A^0}$ are also given.

In 2012, the last missing Standard Model (SM) particle, a Higgs boson, was discovered by ATLAS and CMS [1, 2], demonstrating that the Higgs mechanism would break the electroweak symmetry and give rise to
the masses of $W$ and $Z$ bosons as well as quarks and leptons [3, 4]. Besides this massive Higgs boson, three $CP$-even, two $CP$-odd, and two charged Higgs bosons are predicted by the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [5–9]. NMSSM adds an additional singlet chiral superfield to the Minimal Supersymmetric Standard Model (MSSM) [10] to address the so-called “little hierarchy problem” [11], in which the value of the supersymmetric Higgs mass parameter $\mu$ is many orders of magnitude below the Planck scale.

The lightest $CP$-odd Higgs boson, denoted as $A^0$, could have a mass smaller than twice the mass of the $b$ quark, making it accessible via radiative $\Upsilon(nS) \rightarrow \gamma A^0$ ($n = 1, 2, 3$) decays [5–9, 12]. The coupling of the $A^0$ to $\tau^+\tau^-$ and $b\bar{b}$ is proportional to $\tan\beta\cos\theta_A$, where $\tan\beta$ is the ratio of vacuum expectation values for the two Higgs doublets, and $\theta_A$ is the mixing angle between doublet and singlet $CP$-odd Higgs bosons [7]. The branching fraction of $\Upsilon(nS) \rightarrow \gamma A^0$ could be as large as $10^{-4}$, depending on the values of the $A^0$ mass, $\tan\beta$, and $\cos\theta_A$ [7]. For $2m_\tau < m_{A^0} < 2m_b$, the decay of $A^0 \rightarrow \tau^+\tau^-$ is expected to dominate [7, 13]. For $m_{A^0} < 2m_\tau$, the $A^0 \rightarrow \mu^+\mu^-$ events can be copiously produced [13].

Identifying the origin and nature of dark matter (DM) is a longstanding unsolved problem in astronomy and particle physics. One type of DM, often called the weakly interacting massive particle (WIMP), is generally expected to be in the mass region ranging from $O(1)$ MeV [14, 15] to $O(100)$ TeV [16–21]. An extensive experimental search program has been devoted to WIMPs with the electroweak mass, but no clear evidence has been found to date [22]. In recent years, the possibility that WIMPs have a mass at or below the GeV-scale has gained much attraction. For example, the decay of $\Upsilon(nS) \rightarrow \gamma H$ followed by the $H$ decaying into a lepton pair such as $\tau^+\tau^-$ and $\mu^+\mu^-$ is suggested to be searched for in the $B$-factories [23–25], where $H$ is the mediator having an interaction between the WIMP and SM particles.

BaBar and Belle have searched for $A^0$ decaying into a pair of low mass dark matter with the invisible final-states in $\Upsilon(1S)$ radiative decays [26, 27]. Searches for $A^0$ decaying into $\tau^+\tau^-$ and $\mu^+\mu^-$ have also been performed in $\Upsilon(1S, 2S, 3S)$ radiative decays by CLEO [28] and BaBar [29–32]. No significant signals were found. The upper limits at 90% C.L. on the product of branching fractions $\mathcal{B}(\Upsilon(nS) \rightarrow \gamma A^0)\mathcal{B}(A^0 \rightarrow \tau^+\tau^-/\mu^+\mu^-)$ ($n = 1, 2, 3$) have been set at levels of $10^{-6}$ and $10^{-5}$. In particular, for $\Upsilon(1S)$ decays, more stringent upper limits are obtained by BaBar [29, 30].

In this Letter, we conduct a search for the light $CP$-odd Higgs boson $A^0$ in $\Upsilon(1S)$ radiative decays with $A^0 \rightarrow \tau^+\tau^-$ and $A^0 \rightarrow \mu^+\mu^-$. This search is based on an $\Upsilon(2S)$ data sample with the integrated luminosity of 24.91 fb$^{-1}$, corresponding to $(158 \pm 4) \times 10^6 \Upsilon(2S)$ events, collected by the Belle detector [33] at the KEKB asymmetric-energy $e^+e^-$ collider [34]. A detailed description of the Belle detector can be found in Refs. [33]. The $\Upsilon(1S)$ mesons are selected via the $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ transitions. In this case one must trigger and reconstruct final states in which two extra low momentum pions are identified in the detector, trying to avoid collecting too many background events and at the same time maintaining a high trigger efficiency. We assume that the width of $A^0$ can be neglected compared to the experimental resolution and the lifetime of $A^0$ is short enough [35].

We useEvtGen [36] to generate signal Monte Carlo (MC) events to determine signal line shapes and efficiencies, and optimize selection criteria. The VVPIPI model [36] is used to generate the decay $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$. The angle of the radiative photon in the $\Upsilon(1S)$ frame ($\theta_r$) is distributed according to $1+\cos^2\theta_r$ for $\Upsilon(1S) \rightarrow \gamma A^0$. The effect of final-state radiation (FSR) is taken into account in the simulation using the PHOTOS package [37]. The simulated events are processed with a detector simulation based on Geant3 [38]. Multiple $A^0$ masses are generated: $3.6(0.22)$ GeV/$c^2$ to 9.2 GeV/$c^2$ in steps of 0.5 GeV/$c^2$ or less for $A^0 \rightarrow \tau^+\tau^-/\mu^+\mu^-$. Inclusive MC samples of $\Upsilon(2S)$ decays with four times the luminosity as the real data are produced to check possible peaking backgrounds from $\Upsilon(2S)$ decays [39].

The entire decay channel can be written as $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S), \Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow \tau^+\tau^-/\mu^+\mu^-$. In selecting $A^0 \rightarrow \tau^+\tau^-$ candidates, at least one tau lepton decays leptonically, resulting in five different combinations: $\tau\tau \rightarrow e\mu, \mu\mu, e\mu, \mu\tau, \mu\pi$, writing with neutrinos omitted. Note that $\tau^+ \rightarrow \pi^-\nu_\tau, \tau^- \rightarrow \pi^+\nu_\tau + n_\pi^0$ ($n \geq 1$), are all included in $\tau \rightarrow \pi$. Events in which both tau leptons decay hadronically ($\tau\tau \rightarrow \pi\pi$) suffer from significantly larger and poorly modeled backgrounds than in the leptonic channels, and therefore this mode is excluded.

The charged tracks and particle identifications for the pions and leptons are performed using the same method as in Ref. [40]. An electromagnetic calorimeter cluster is treated as a photon candidate if it is isolated from the projected path of charged tracks in the central drift chamber. The energy of photons is required to be larger than 50 MeV. The most energetic photon is regarded as the $\Upsilon(1S)$ radiative photon.

For $A^0 \rightarrow \tau^+\tau^-$, the missing energy in the laboratory frame is required to be greater than 2 GeV to suppress non-$\tau$ decays and ISR backgrounds. The dominant backgrounds come from $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)(\rightarrow \ell^+\ell^- (\gamma))$ ($\ell = e, \mu$, or $\tau$) decays, which have an event topology similar to that of the signal. The backgrounds from $\pi^0$ decays are also large, where photons from $\pi^0$ decays are misidentified as $\Upsilon(1S)$ radiative photons, especially when
the energy of $\Upsilon(1S)$ radiative photon is low. To reduce such backgrounds, a likelihood function is employed to distinguish isolated photons from $\pi^0$ daughters using the invariant mass of the photon pair, photon energy in the laboratory frame, and the angle with respect to the beam direction in the laboratory frame [41]. We combine the signal photon candidate with any other photon and then reject both photons of a pair whose $\pi^0$ likelihood is larger than 0.3. To further suppress $\pi^0$ backgrounds in $p^+ p^- \rightarrow \pi^+ \pi^0$, we require $\cos \theta(\gamma \pi^0) < 0.4$, where $\cos \theta(\gamma \pi^0)$ is the cosine of the angle between the photon from $\Upsilon(1S)$ decays and $\pi^0$ from $\tau^+ \tau^-$ decays in the laboratory frame. We impose requirements of $\cos \theta(\gamma e) < 0.95$ and $\cos \theta(\gamma \mu) < 0.8$ to remove FSR and $\Upsilon(1S)$ backgrounds, where $\cos \theta(\gamma e)$ and $\cos \theta(\gamma \mu)$ are the cosine of the angle between the $\Upsilon(1S)$ radiative photon and $e$ and $\mu$ from $\tau$ decays in the laboratory frame. All of the above selection criteria have been optimized by maximizing FOM = $N_{\text{sig}}/\sqrt{N_{\text{sig}} + N_{\text{bkg}}}$, where $N_{\text{sig}}$ is the expected signal yield from signal MC samples assuming $B(\Upsilon(1S) \rightarrow \gamma A^0)B(A^0 \rightarrow \mu^+\mu^-) = 10^{-5}$ [28, 29], and $N_{\text{bkg}}$ is the number of normalized background events from inclusive MC samples.

For $A^0 \rightarrow \mu^+\mu^-$, a four-constraint (4C) kinematic fit constraining the four-momenta of the final-state particles to the initial $e^+e^-$ collision system is performed to suppress backgrounds with multiple photons and improve mass resolutions. The $\chi^2$/ndf of the 4C fit is required to be less than 12.5, where the number of degrees of freedom (ndf) is four. The cosine of the angle between the $\Upsilon(1S)$ radiative photon and $\mu$ is required to be less than 0.8 to suppress FSR and $\Upsilon(1S) \rightarrow \mu^+\mu^-$ backgrounds. These requirements have also been optimized using the FOM method assuming $B(\Upsilon(1S) \rightarrow \gamma A^0)B(A^0 \rightarrow \mu^+\mu^-) = 10^{-5}$ [28, 30].

The $\Upsilon(1S)$ is tagged by the requirement on the mass recoiling against a pion pair (recoil mass). The best candidate is chosen by selecting the recoil mass of dipion closest to the $\Upsilon(1S)$ nominal mass [42].

Considering $\tau$ decays with undetected neutrinos, we identify the $A^0$ signal using the photon energy in the $\Upsilon(1S)$ rest frame ($E^*(\gamma)$), which can be converted to $M(\tau^+\tau^-)$ via $M^2(\tau^+\tau^-) = m^2_{\Upsilon(1S)} - 2m_{\Upsilon(1S)} E^*(\gamma)$, where $m_{\Upsilon(1S)}$ is the nominal mass of $\Upsilon(1S)$ [42]. Hereinafter, $M$ represents a measured invariant mass. For $A^0 \rightarrow \mu^+\mu^-$, we identify the $A^0$ signal using the invariant mass distribution of $\mu^+\mu^-$ ($M(\mu^+\mu^-)$). After requiring the events within the $\Upsilon(1S)$ signal region of [9.45, 9.47] GeV/c$^2$ and the application of the above requirements, the $E^*(\gamma)$ and $M(\mu^+\mu^-)$ distributions from the $\Upsilon(2S)$ data sample are as shown in Fig. 1. No significant signals are seen.

For $A^0 \rightarrow \tau^+\tau^-$, we perform a series of two-dimensional (2D) unbinned maximum-likelihood fits to

![FIG. 1: The (a) $E^*(\gamma)$ and (b) $M(\mu^+\mu^-)$ distributions from the $\Upsilon(2S)$ data sample.](image-url)

$E^*(\gamma)$ and $M_{\text{rec}}(\pi^+\pi^-)$ distributions to extract the $\Upsilon(1S) \rightarrow \gamma A^0(\rightarrow \tau^+\tau^-)$ signal yields. The 2D fitting function $f(E, M)$ is expressed as

$$f(E, M) = N_{\text{sig}} s_1(E) s_2(M) + N_{\text{bg}} b_1(E) b_2(M) + N_{\text{bkg}} b_1(E) b_2(M),$$

(1)

where $s_1(E)$ and $b_1(E)$ are the signal and background probability density functions (PDFs) for the $E^*(\gamma)$ distributions, and $s_2(M)$ and $b_2(M)$ are the corresponding PDFs for the $M_{\text{rec}}(\pi^+\pi^-)$ distributions. Here, $N_{\text{sig}}$, $N_{\text{bg}}$, and $N_{\text{bkg}}$ denote the numbers of peaking background events in the $E^*(\gamma)$ and $M_{\text{rec}}(\pi^+\pi^-)$ distributions, respectively, and $N_{\text{bkg}}$ is the number of combinatorial backgrounds in both $A^0$ and $\Upsilon(1S)$ candidates. For $A^0 \rightarrow \mu^+\mu^-$, similar 2D unbinned maximum-likelihood fits to the $M(\mu^+\mu^-)$ and $M_{\text{rec}}(\pi^+\pi^-)$ distributions are performed.

In each 2D unbinned fit, the $A^0$ signal in the $E^*(\gamma)$ distribution is described by a Crystal Ball function [43], and that in the $M(\mu^+\mu^-)$ distribution by a double Gaussian function. The $\Upsilon(1S)$ signal in the $M_{\text{rec}}(\pi^+\pi^-)$ distribution is described by a double Gaussian function. The values of the signal parameters are fixed to those obtained from the fits to the corresponding signal MC distributions. The background shapes are described by a polynomial function. All parameters are floated in the fits. We choose the order of the polynomial to minimize the Akaike information test [44], and find that the first-order polynomial for $M(\mu^+\mu^-)$ and second-order polynomials for $E^*(\gamma)$ and $M_{\text{rec}}(\pi^+\pi^-)$ are suitable. The fitting step is approximately half of the resolution in $E^*(\gamma)$ or $M(\mu^+\mu^-)$, resulting in total of 724 and 2671 points for $A^0 \rightarrow \tau^+\tau^-$ and $A^0 \rightarrow \mu^+\mu^-$, respectively. From the $\tau^+\tau^-(\mu^+\mu^-)$ threshold (3.6 (0.22) GeV/c$^2$) to 9.2 GeV/c$^2$, the resolution of the $E^*(\gamma)$ distribution decreases from 5.5 MeV to 0.5 MeV, and the mass resolution of the $M(\mu^+\mu^-)$ distribution increases from 1.4 MeV/c$^2$ to 10.0 MeV/c$^2$. For each 2D unbinned fit in $A^0 \rightarrow \mu^+\mu^-$ ($m_{A^0} > 3.0$ GeV/c$^2$) and $A^0 \rightarrow \tau^+\tau^-$, the fitting range covers a ±10σ region. Since the number of selected signal candidate events in the $\mu^+\mu^-$ mode with $m_{A^0} < 3.0$ GeV/c$^2$ is small, we select the following fitting intervals for different $A^0$ masses: $2m_{\pi} \leq M(\mu^+\mu^-) \leq 2.2$ GeV/c$^2$ for 0.22 GeV/c$^2 \leq m_{A^0} \leq 2.0$ GeV/c$^2$. and
1.8 GeV/c^2 \leq M(\mu^+\mu^-) \leq 3.2 GeV/c^2 for 2.0 GeV/c^2 < m_{\gamma\gamma} \leq 3.0 GeV/c^2.

Figures 2 and 3 show the fitted results when the A^0 masses are fixed at 9.2 GeV/c^2 and 8.51 GeV/c^2 for A^0 \rightarrow \tau^+\tau^- and A^0 \rightarrow \mu^+\mu^-, respectively, where we find the maximum local signal significances for possible A^0 peaks. We define the local signal significance as sign(\sqrt{-2 \ln(L_0/L_{\text{max}})})^{[45]}, where L_0 and L_{\text{max}} are the maximized likelihoods without and with the A^0 signal, respectively. The signal yields are 116.5 \pm 33.4 and 22.6 \pm 8.2 with statistical significances of 3.5\sigma and 3.0\sigma, respectively. The global significances are obtained to be 2.2\sigma and 2.0\sigma with look-elsewhere-effect included by extending the searched mass ranges to be 0.15–0.4 GeV in the E^*(\gamma) distribution for A^0 \rightarrow \tau^+\tau^- and 8.3–8.7 GeV/c^2 in the M(\mu^+\mu^-) distribution for A^0 \rightarrow \mu^+\mu^-, respectively [46]. The statistical signal significances as a function of A^0 mass for A^0 \rightarrow \tau^+\tau^- and A^0 \rightarrow \mu^+\mu^- are shown in Figs. 4(a) and 4(b).

The sources of systematic uncertainties in the measurements of upper limits on B(\Upsilon(1S) \rightarrow \gamma A^0)B(A^0 \rightarrow \tau^+\tau^-/\mu^+\mu^-) include detection efficiency, MC statistics, trigger simulation, branching fractions of intermediate states, signal parameterization, background parameterization, and total number of \Upsilon(2S) events. The detection efficiency uncertainties include those for tracking efficiency (0.35%/track), particle identification effi-

ciency (1.1%/pion, 1.2%/electron, and 2.8%/muon), and photon reconstruction efficiency (2.0%/photon). The above individual uncertainties from different \tau^+\tau^- decay modes are added linearly, weighted by the product of the detection efficiency and all secondary branching fractions. Assuming these uncertainties are independent and adding them in quadrature, the final uncertainty related to the detection efficiency is 6.4% for A^0 \rightarrow \tau^+\tau^-.

For A^0 \rightarrow \mu^+\mu^-, the total uncertainty of detection efficiency is obtained by adding all sources in quadrature; it is 6.5%. The statistical uncertainty in the determination of efficiency from signal MC samples is 1.0%. We include uncertainties of 1.5% and 1.3% from trigger simulations for A^0 \rightarrow \tau^+\tau^- and A^0 \rightarrow \mu^+\mu^-, respectively. The uncertainty of 1.5% from B(\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)) is included [42]. The uncertainties of the branching fractions of \tau decays can be neglected [42].

Using the control sample of \pi^0/\eta \rightarrow \gamma\gamma, the maximum energy bias and fudge factor for the radiative photon are 1.004 and 1.05 [47], respectively. Thus, in the fitting to the E^*(\gamma) spectrum for A^0 \rightarrow \tau^+\tau^-, we change the central value by 0.4% and energy resolution by 5% for each A^0 mass point to recalculate the 90% C.L. upper limit, and the difference compared to the previous result is taken as the uncertainty of signal parameterization. For A^0 \rightarrow \mu^+\mu^-, the systematic uncertainty in the mass resolution is estimated by comparing the upper limit when the mass resolution is changed by 10% for each A^0 mass point. By comparing the upper limits in different fit ranges and using higher-order polynomial functions, the systematic uncertainty attributed to the background parameterization can be estimated. The uncertainties on the total number of \Upsilon(2S) events is 2.3%. All the uncertainties are summarized in Table 1 and, assuming all the sources are independent, summed in quadrature for the total systematic uncertainties.

We compute 90% C.L. upper limits \lambda^{UL} on the signal yields and the products of branching fractions by solving the equation \int_0^{\lambda^{UL}} \mathcal{L}(x)dx/\int_0^{\infty} \mathcal{L}(x)dx = 0.90, where x is the assumed signal yield or product of branching fractions, and \mathcal{L}(x) is the corresponding maximized likelihood of the fit to the assumption. To take into account systematic uncertainties, the above likelihood is convolved with a Gaussian function whose width equals the total systematic uncertainty. The upper limits at 90% C.L. on the product branching fractions of \Upsilon(1S) \rightarrow \gamma A^0 and A^0 \rightarrow \tau^+\tau^-/\mu^+\mu^- are calculated using

\begin{equation}
\mathcal{B}^{UL}(\Upsilon(1S) \rightarrow \gamma A^0)B(A^0 \rightarrow \tau^+\tau^-/\mu^+\mu^-) = \frac{N^{UL}}{N_{\text{total}}^{\Upsilon(2S)} \times \varepsilon},
\end{equation}

where \mathcal{B}^{UL} is the upper limit at 90% C.L. on the signal yield, N_{\text{total}}^{\Upsilon(2S)} = 1.58 \times 10^8 is the number of \Upsilon(2S) events, and \varepsilon is the reconstruction efficiency with the branching fractions of \Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S) and \tau decays included.
For $A^0 \rightarrow \tau^+\tau^-$, the reconstruction efficiency decreases from 2.1% to 0.7% with the increased $A^0$ mass, and for $A^0 \rightarrow \mu^+\mu^-$ the reconstruction efficiency decreases from 4.7% to 0.6% in the studied mass range from the $\mu^+\mu^-$ threshold to 9.2 GeV/$c^2$.

The upper limits at 90% C.L. on the product branching fractions of $\Upsilon(1S) \rightarrow \gamma A^0$ and $A^0 \rightarrow \tau^+\tau^-/\mu^+\mu^-$ are shown by the blue curves in Figs. 4(c) and 4(d), where the $B_1$, $B_2$, and $B_3$ represent $B(\Upsilon(1S) \rightarrow \gamma A^0)$, $B(A^0 \rightarrow \tau^+\tau^-)$, and $B(A^0 \rightarrow \mu^+\mu^-)$, respectively. Note that the systematic uncertainties have been taken into account. The corresponding results from BaBar [29] are also shown by the red curves. For $A^0 \rightarrow \tau^+\tau^-$, in most $A^0$ mass points, our limits are lower than those from BaBar [29]. The most stringent upper limit can reach $4 \times 10^{-6}$ from Belle. While from BaBar, the typical upper limit is at the level of $10^{-5}$. More stringent constraints on $A^0 \rightarrow \tau^+\tau^-$ production in radiative $\Upsilon(1S)$ decays are given. For $A^0 \rightarrow \mu^+\mu^-$, the upper limits at Belle are almost at the same level as those from BaBar [30].

The upper limit at 90% C.L. on the product branching fractions can be converted to the Yukawa coupling $f_{\Upsilon(1S)}$ directly via [12, 48, 49]

$$\frac{B(\Upsilon(1S) \rightarrow \gamma A^0)}{B(\Upsilon(1S) \rightarrow \ell^+\ell^-)} = \frac{f_{\Upsilon(1S)}^2}{2\pi\alpha}(1 - \frac{m_{A^0}^2}{m_{\Upsilon(1S)}^2}),$$

where $\ell = e$ or $\mu$ and $\alpha$ is the fine structure constant.

The upper limits at 90% C.L. on the $f_{\Upsilon(1S)}^2 B(A^0 \rightarrow \tau^+\tau^-/\mu^+\mu^-)$ as a function of $A^0$ mass are shown by blue curves in Figs. 4(e) and 4(f). The results from BaBar [29] are also shown by red curves.

The limit on the $A^0$ production in $\Upsilon(1S)$ radiative decays is related to the mixing angle ($\sin\theta_{A^0}$), which can be compared with those from other experiments. The mixing angle is defined as [25]

$$\sin^2\theta_{A^0} = \frac{G_F m_b^2}{\sqrt{2}\pi\alpha} \sqrt{(1 - \frac{m_{A^0}^2}{m_{\Upsilon(1S)}^2})},$$

where $G_F$ is the Fermi constant and $m_b$ is the mass of bottom quark [42]. When the mass of $A^0$ is smaller than $\tau^+\tau^-$ threshold, upper limits from $A^0 \rightarrow \mu^+\mu^-$ are used to calculate the $\sin\theta_{A^0}$; on the contrary, upper

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TABLE I: Relative systematic uncertainties (%) in the measurements of upper limits for $A^0 \rightarrow \tau^+\tau^-$ and $A^0 \rightarrow \mu^+\mu^-$. 

| Sources                     | $A^0 \rightarrow \tau^+\tau^-$ | $A^0 \rightarrow \mu^+\mu^-$ |
|-----------------------------|---------------------------------|-------------------------------|
| Detection efficiency        | 6.4                             | 6.5                           |
| MC statistics               | 1.0                             | 1.0                           |
| Trigger                     | 1.5                             | 1.3                           |
| Branching fractions         | 1.5                             | 1.5                           |
| Signal parameterization     | 0.1 - 24.4                      | 0.1 - 19.4                    |
| Background parameterization | 0.1 - 19.6                      | 0.1 - 17.2                    |
| Total number of $\Upsilon(2S)$ events | 2.3                             | 2.3                           |
| Sum                         | 7.2 - 32.2                      | 7.3 - 26.9                    |
limits from $A^0 \to \tau^+\tau^-$ are used. The ratios of $B(A^0 \to \mu^+\mu^-)/B(A^0 \to \text{hadrons})$ and $B(A^0 \to \tau^+\tau^-)/B(A^0 \to \text{hadrons})$ are taken from Ref. [13]; they are changed from 0.08 to 0.28 and 0.7 to 1.0 for $A^0 \to \mu^+\mu^-$ and $A^0 \to \tau^+\tau^-$, respectively. The surviving parameter space on the plane of $\sin\theta_{A^0}$ and $m_{A^0}$ (the same as $m_\phi$ and $m_H$ in Refs. [13] and [25]) from different processes are shown in Fig. 5.

![Diagram showing the surviving parameter space on the plane of $\sin\theta_{A^0}$ and $m_{A^0}$](image)

**FIG. 5:** The surviving parameter space on the plane of $\sin\theta_{A^0}$ and $m_{A^0}$. The constraints from LEP [50] (direct production of Higgs), BESIII [51] ($J/\psi$ decay), Belle ($\Upsilon(1S)$ decay), LHCb [52, 53] ($B^{+/0}$ decay), NA62 [54–56] ($K^+$ decay), KTeV [13, 57, 58] ($K_L$ decay), CHARM [13, 59–62] (beam dump), PS191 [63] (beam dump), SN1987A [64], BBN [65], and the prospect of future SHiP [13, 62] (beam dump) are shown.

To conclude, we have searched for the light $CP$-odd Higgs boson in $\Upsilon(1S) \to \gamma A^0$ with $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ tagging method using the largest data sample of $\Upsilon(2S)$ at Belle. The upper limits at 90% C.L. on the product branching fractions for $\Upsilon(1S) \to \gamma A^0$ and $A^0 \to \tau^+\tau^-/\mu^+\mu^-$ are set. In comparisons with previous studies [28–30], our results can further constrain the parameter space in NMSSM models [6, 7] for $\Upsilon(1S) \to \gamma A^0(\to \tau^+\tau^-)$ and have the same restrictions for $\Upsilon(1S) \to \gamma A^0(\to \mu^+\mu^-)$. Our limits are applicable to any light scalar or pseudo-scalar boson and dark matter, which arises in various extensions of SM. We have used the branching fraction limits to set limits on the Yukawa coupling $f_{\Upsilon(1S)}$ and mixing angle $\sin\theta_{A^0}$. For the latter, different processes from different experiments are compared to it.

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* also at University of Petroleum and Energy Studies, Dehradun 248007

[1] G. Aad et al. (ATLAS Collaboration), Phys. Lett. B 716, 1 (2012).
[2] S. Chatrchyan et al. (CMS Collaboration), Phys. Lett. B 716, 30 (2012).
[3] P. W. Higgs, Phys. Lett. 12, 132 (1964).
[4] P. W. Higgs, Phys. Rev. Lett. 13, 508 (1964).
[5] G. Hiller, Phys. Rev. D 70, 034018 (2004).
[6] R. Dermišek and J. F. Gunion, Phys. Rev. Lett. 95, 041801 (2005).
[7] R. Dermišek, J. F. Gunion, and B. McElrath, Phys. Rev. D 76, 051105 (2007).
[8] R. Dermišek and J. F. Gunion, Phys. Rev. D 77, 015013 (2008).
[9] R. Dermišek and J. F. Gunion, Phys. Rev. D 81, 075003 (2010).
[10] H. E. Haber and G. L. Kane, Phys. Rep. 117, 75 (1985).
[11] A. Delgado, C. Kolda, and A. D. Puente, Phys. Lett. B 710, 460 (2012).
[12] F. Wilczek, Phys. Rev. Lett. 39, 1304 (1977).
[13] M. W. Winkler, Phys. Rev. D 99, 015018 (2019).
[14] C. Boehm, T. A. Ennslin and J. Silk, J. Phys. G 30, 279 (2004).
[15] C. Boehm, D. Hooper, J. Silk, M. Casse and J. Paul, Phys. Rev. Lett. 92, 101301 (2004).
[16] H. Murayama and J. Shu, Phys. Lett. B 686, 162 (2010).
[17] T. Hambye and M. H. G. Tytgat, Phys. Lett. B 683, 39 (2010).
[18] K. Hamaguchi, E. Nakamura, S. Shirai and T. T. Yanagida, JHEP 04, 119 (2010).
[19] O. Antipin, M. Redi and A. Strumia, JHEP 01, 157 (2015).
[20] O. Antipin, M. Redi, A. Strumia and E. Vigiani, JHEP 07, 039 (2015).
[21] R. Huo, S. Matsumoto, Y. L. Sming Tsai and T. T. Yanagida, JHEP 09, 162 (2016).
[22] G. Arcadi, A. Djouadi, and M. Raidal, Phys. Rept. 842, 1 (2020).
[23] G. Arcadi, M. Lindner, F. S. Queiroz, W. Rodejohann, and S. Vogl, JCAP 03, 042 (2018).
[24] S. Matsumoto, Y. L. Sming Tsai, and P. Y. Tseng, JHEP
[25] T. Hara, M. Kanemura, and T. Katayose, Report No. OU-HET-1104, arXiv:2109.03555 (2021).
[26] P. del Amo Sanchez et al. (BABAR Collaboration), Phys. Rev. Lett. 107, 021804 (2011).
[27] I. S. Seong et al. (BABAR Collaboration), Phys. Rev. Lett. 122, 011801 (2019).
[28] W. Love et al. (CLEO Collaboration), Phys. Rev. Lett. 101, 151802 (2008).
[29] J. P. Lees et al. (BaBar Collaboration), Phys. Rev. D 88, 071102 (2013).
[30] J. P. Lees et al. (BaBar Collaboration), Phys. Rev. D 87, 031102 (2013) [Erratum: Phys. Rev. D 87, 059903 (2013)].
[31] B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. 103, 081803 (2009).
[32] B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. 103, 181801 (2009).
[33] A. Abashian et al. (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 479, 117 (2002); also, see detector section in J. Brodzicka et al., Prog. Theor. Exp. Phys. 2012, 04D001 (2012).
[34] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A 499, 1 (2003), and other papers included in this volume; T. Abe et al., Prog. Theor. Exp. Phys. 2013, 03A001 (2013).
[35] E. Fullana and M. A. Sanchis-Lozano, Phys. Lett. B 653, 67 (2007).
[36] D. J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A 462, 152 (2001).
[37] E. Barberio and Z. W. Cern, Comput. Phys. Commun. 79, 291 (1994).
[38] R. Brun et al., CERN Report No. DD/EE/84-1 (1984).
[39] X. Y. Zhou, X. Du, G. Li, and C. P. Shen, Comput. Phys. Commun. 258, 107540 (2021).
[40] Y. B. Li et al. (Belle Collaboration), Phys. Rev. Lett. 127, 121803 (2021).
[41] P. Koppenburg et al. (Belle Collaboration), Phys. Rev. Lett. 93, 061803 (2004).
[42] P. A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.
[43] T. Skwarnicki, Ph.D. thesis, Institute for Nuclear Physics, 1986; DESY Report No. DESY F31-86-02, 1986.
[44] J. E. Cavanaugh, Statistics and Probability Letters 33, 201 (1997).
[45] S. S. Wilks, Ann. Math. Stat. 9, 60 (1938).
[46] E. Gross and O. Vitells, Eur. Phys. J. C 70, 525 (2010).
[47] U. Tamponi, Ph.D thesis, Section 3.2.3, http:// inspirehep.net/files/812c03ed6208c941b08d754c0d025d59.
[48] M. L. Mangano and P. Nason, Mod. Phys. Lett. A 22, 1373 (2007).
[49] P. Nason, Phys. Lett. B175, 223 (1986).
[50] M. Acciarri et al. (L3 Collaboration), Phys. Lett. B 385, 454 (1996).
[51] M. Ablikim et al. (BESIII Collaboration), arXiv: 2109.12625 (2021).
[52] R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 115, 161802 (2015).
[53] R. Aaij et al. (LHCb Collaboration), Phys. Rev. D 95, 071101 (2017).
[54] E. Cortina Gil et al. (NA62 Collaboration), JHEP 03, 058 (2021).
[55] E. Cortina Gil et al. (NA62 Collaboration), JHEP 06, 093 (2021).
[56] E. Cortina Gil et al. (NA62 Collaboration), JHEP 02, 201 (2021).
[57] A. A. Harati et al. (KTeV Collaboration), Phys. Rev. Lett. 93, 021805 (2004).
[58] E. Abouzaid et al. (KTeV Collaboration), Phys. Rev. D 77, 112004 (2008).
[59] J. D. Clarke, R. Foot, and R. R. Volkas, JHEP 02, 123 (2014).
[60] F. Bezrukov and D. Gorbunov, JHEP 05, 010 (2010).
[61] K. S. Hoberg, F. Staub, and M. W. Winkler, Phys. Lett. B 727, 506 (2013).
[62] S. Alekhin et al., Rept. Prog. Phys. 79, 124201 (2016).
[63] D. Gorbunov, I. Krasnov, and S. Suvorov, Phys. Lett. B 820, 136524 (2021).
[64] P. S. B. Dev, R. N. Mohapatra, and Y. Zhang, JCAP 08, 003 (2020) [Erratum: JCAP 11, E01 (2020)].
[65] A. Fradette and M. Pospelov, Phys. Rev. D 96, 075033 (2017).