Search for an $H$-dibaryon with mass near $2m_A$ in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays

B. H. Kim, 46 S. L. Olsen, 46 I. Adachi, 10 H. Aihiara, 52 D. M. Asner, 43 V. Aulchenko, 2 A. Bay, 25 K. Belous, 16 B. Bhuyan, 12 G. Bonvicini, 56 A. Bozek, 38 M. Bračko, 27, 19 T. E. Browder, 9 V. Chekelian, 28 A. Chen, 45 B. G. Cheon, 8 K. Chilikin, 18 R. Chistov, 18 I.-S. Cho, 58 K. Cho, 22 V. Chobanova, 28 S.-K. Choi, 7 Y. Choi, 47 D. Cinabro, 56 J. Dalseno, 28, 49 Z. Doležal, 3 S. Eidelman, 2 D. Epifanov, 2 S. Esen, 4 H. Farhat, 56 J. E. Fast, 43 V. Gaur, 48 S. Ganguly, 56 R. Gillard, 56 Y. M. Goh, 8 K. Hayasaka, 33 H. Hayashii, 34 Y. Hoshi, 50 W.-S. Hou, 37 Y. B. Hsiung, 37 H. J. Hyun, 24 K. Inami, 32 A. Ishikawa, 51 R. Itoh, 10 Y. Iwasaki, 10 T. Julius, 29 D. H. Kah, 24 J. H. Kang, 58 P. Kapusta, 38 E. Kato, 51 H. Kichimi, 10 H. J. Kim, 24 H. O. Kim, 24 J. H. Kim, 22 K. T. Kim, 23 M. J. Kim, 24 S. K. Kim, 46 Y. J. Kim, 22 K. Kinoshita, 4 J. Klucar, 19 B. R. Ko, 23 P. Kodyš, 3 S. Korpar, 27, 19 R. T. Kouzes, 43 P. Križan, 26, 19 P. Krockovny, 2 T. Kumiita, 54 A. Kuzmin, 2 Y.-J. Kwon, 58 J. S. Lange, 5 S.-H. Lee, 23 J. Li, 46 X. Li, 46 Y. Li, 55 J. Libby, 13 D. Liventsev, 10 D. Matviienko, 2 K. Miyabayashi, 34 H. Miyata, 40 R. Mizuk, 18, 30 G. B. Mohanty, 48 A. Moll, 28, 49 N. Muramatsu, 45 R. Mussa, 17 E. Nakano, 42 E. Nedelkovska, 28 C. Ng, 52 N. Nellis, 49 M. N. Wagner, 2 M. Peters, 9 M. Petrič, 19 L. E. Piilonen, 55 M. Ritter, 28 S. Ryu, 46 H. Sahoo, 9 Y. Sakai, 10 S. Sandilya, 48 T. Samuk, 51 V. Savinov, 44 O. Schneider, 25 G. Schnell, 11 C. Schwanda, 15 A. J. Schwartz, 4 D. Semmler, 5 K. Senyo, 57 M. E. Senvir, 29 M. Shapkin, 16 V. Shebalin, 3 C. P. Shen, 32 T.-A. Shibata, 53 J.-G. Shiù, 37 B. Shwartz, 2 F. Simon, 28, 49 P. Smerkol, 19 Y.-S. Sohn, 58 A. Sokolov, 16 E. Solovieva, 18 S. Stanič, 41 M. Starić, 19 M. Sumihama, 6 T. Sumiyoshi, 54 U. Tamponi, 17 K. Tanida, 46 G. Tatishvili, 43 Y. Teramoto, 42 K. Thabenski, 43 Y. T. Kim, 10 M. Uchida, 53 S. Uehara, 10 T. Uglow, 18, 31 Y. Unno, 8 S. Uno, 10 Y. Usos, 2 C. Van Hulse, 1 G. Varner, 9 V. Vorgorobyev, 2 M. N. Wagner, 5 C. H. Wang, 36 P. Wang, 14 Y. Watanabe, 39 K. M. Williams, 55 E. Won, 23 Y. Yamashita, 39 V. Zhilich, 2 and A. Zupanc 21 (The Belle Collaboration)

1 University of the Basque Country UPV/EHU, 48080 Bilbao
2 Budker Institute of Nuclear Physics SB RAS and Novosibirsk State University, Novosibirsk 630090
3 Faculty of Mathematics and Physics, Charles University, 121 16 Prague
4 University of Cincinnati, Cincinnati, Ohio 45221
5 Justus-Liebig-Universität Gießen, 35392 Gießen
6 Gifu University, Gifu 501-1193
7 Gyeongsang National University, Chinju 660-701
8 Kangwon National University, 233-701
9 University of Hawaii, Honolulu, Hawaii 96822
10 High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801
11 Ikerbasque, 48011 Bilbao
12 Indian Institute of Technology Guwahati, Assam 781039
13 Indian Institute of Technology Madras, Chennai 600036
14 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049
15 Institute of High Energy Physics, Vienna 1050
16 Institute of High Energy Physics, Protvino 142281
17 INFN - Sezione di Torino, 10125 Torino
18 Institute for Theoretical and Experimental Physics, Moscow 117218
19 J. Stefan Institute, 1000 Ljubljana
20 Kanagawa University, Yokohama 221-8686
21 Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie, 76131 Karlsruhe
22 Korea Institute of Science and Technology Information, Daejeon 305-806
23 Korea University, Seoul 136-713
24 Kyungpook National University, Daegu 702-701
25 École Polytechnique Fédérale de Lausanne (EPFL), Lausanne 1015
26 Faculty of Mathematics and Physics, University of Ljubljana, 1000 Ljubljana
27 University of Maribor, 2000 Maribor
28 Max-Planck-Institut für Physik, 80805 München
29 School of Physics, University of Melbourne, Victoria 3010
30 Moscow Physical Engineering Institute, Moscow 115409
31 Moscow Institute of Physics and Technology, Moscow Region 141700
32 Graduate School of Science, Nagoya University, Nagoya 464-8602
33 Kobayashi-Maskawa Institute, Nagoya University, Nagoya 464-8602
34 Nara Women’s University, Nara 630-8506
In 1977, Jaffe predicted the existence of a doubly strange, six-quark structure \((uuddss)\) with quantum numbers \(I = 0\) and \(J^P = 0^+\) and a mass that is \(\simeq 80\ \text{MeV}\) below the \(2m_{\Lambda}\) threshold, which he dubbed the \(H\)-dibaryon \([1]\). An \(S = -2\), baryon-number \(B = 2\) particle with mass below \(2m_{\Lambda}\) would decay via weak interactions and, thus, be long-lived with a lifetime comparable to that of the \(\Lambda\) and negligible natural width.

Jaffe’s specific prediction was ruled out by the observation of double-\(\Lambda\) hypernuclei events \([2, 4]\), especially the famous “Nagara” event that has a relatively unambiguous signature as a \(^6\)\He hypernucleus produced via \(\Xi^-\) capture in emulsion \([3]\). The measured \(\Lambda\Lambda\) binding energy, \(B_{\Lambda\Lambda} = 7.13 \pm 0.87\ \text{MeV}\), establishes, with a 90\% confidence level (CL), a lower limit of \(M_H > 2223.7\ \text{MeV}\), severely narrowing the window for a stable \(H\) to the binding energy range \(B_H \equiv 2m_{\Lambda} - M_H < 7.9\ \text{MeV}\).

Although Jaffe’s original prediction for \(B_H \simeq 81\ \text{MeV}\) has been ruled out, the theoretical case for an \(H\)-dibaryon with a mass near \(2m_{\Lambda}\) continues to be strong and has been recently strengthened by lattice QCD calculations (LQCD) by the NPLQCD \([3, 6]\) and HALQCD \([7]\) collaborations that both find a bound \(H\)-dibaryon, albeit for non-physical values for the pion mass. NPLQCD’s linear (quadratic) extrapolation to the physical pion mass gives \(B_H = -0.2 \pm 8.0\ \text{MeV} \ (7.4 \pm 6.2\ \text{MeV})\) \([6]\). Carames and Valcarce \([8]\) recently studied the \(H\) with a chiral constituent model constrained by \(\Lambda N, \Sigma N, \Xi N\) and \(\Lambda \Lambda\) cross section data and find \(B_H\) values that are similar to the NPLQCD extrapolated values.

These recent theoretical results motivate searches for the \(H\) with mass near the \(M_H = 2m_{\Lambda}\) threshold. For masses below threshold, the \(H\) would predominantly decay via \(\Delta S = -1\) weak transitions to \(\Lambda n, \Sigma^- p, \Xi^0 n\) or \(\Lambda p\pi^-\) final states. For masses above \(2m_{\Lambda}\), but below \(m_{\Xi^0} + m_{\Lambda}\) \(\ (= 2m_{\Lambda} + 23.1\ \text{MeV}\)\), the \(H\) would decay via strong interactions to \(\Lambda\Lambda\) 100\% of the time. The E522 collaboration at KEK studied \(\Lambda\Lambda\) production in the \(^{12}\text{C}(K^-, K^+\Lambda\Lambda X)\) reaction and reported an intriguing near-threshold enhancement but with limited statistics \([9]\). The BNL-E836 collaboration searched for the \(\Delta S = +2\) reaction \(^3\text{He}(K^-, K^+\Lambda)\) and established cross section limits spanning the range \(50\ \text{MeV} \leq B_H \leq 380\ \text{MeV}\) \([10]\). Searches for a bound \(H\) decaying to \(\Lambda p\pi^-\) reported negative results \([11, 12]\). Earlier searches, also with negative results, are listed in Ref. \([13]\).

Decays of narrow \(\Upsilon(1S)(nS)\) \((n = 1, 2, 3)\) bottomonium \((b\bar{b})\) resonances are particularly well suited for searches...
for multiquark states with non-zero strangeness. The Υ(nS) states are flavor-SU(3) singlets and primarily decay via the three-gluon annihilation process (e.g., \(B(\Upsilon(1S) \to gg) = 81.7 \pm 0.7\%\)). The gluons materialize into \(uu, dd\) and \(ss\) pairs in roughly equal numbers. The high density of quarks and antiquarks in the limited final-state phase space is conducive to the production of multiquark systems, as demonstrated by large branching fractions for inclusive antideuteron (\(\bar{D}\)) production: \(B(\Upsilon(1S) \to \bar{D}X) = (2.9 \pm 0.3) \times 10^{-5}\) and \(B(\Upsilon(2S) \to \bar{D}X) = (3.4 \pm 0.6) \times 10^{-5}\). An upper limit for the production of a six-quark \(S = -2\) state in \(\Upsilon(nS)\) decays is that substantially below that for the six-quark antideuteron would be strong evidence against its existence.

Here we report results of a search for \(H\)-dibaryon production in the inclusive processes \(\Upsilon(1,2S) \to H X; H \to \Lambda p\pi^-\) and \(\Lambda \Lambda\). We use data samples containing 102 million \(\Upsilon(1S)\) and 158 million \(\Upsilon(2S)\) decays collected with the Belle detector operating at the KEKB \(e^+e^-\) collider[25]. The data were accumulated at center-of-mass system (cms) energies of \(\sqrt{s} = 9.460\) GeV and 10.023 GeV, which correspond to the \(\Upsilon(1S)\) and \(\Upsilon(2S)\) resonance peaks, respectively. Contributions from the \(e^+e^- \to q\bar{q}\) (\(q = u, d, s\), and \(c\)) continuum process are inferred from a 63.7 fb\(^{-1}\) sample collected at \(\sqrt{s} = 10.53\) GeV and scaled by luminosity and 1/s. We assume equal \(\Upsilon(1S)\) and \(\Upsilon(2S)\) branching fractions; i.e., \(B(\Upsilon(1S) \to HX) = B(\Upsilon(2S) \to HX)\).

Belle is a large-solid-angle magnetic spectrometer consisting of a silicon vertex detector, a cylindrical drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-offlight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. Measurements of \(dE/dz\) in the CDC, ACC light yields, TOF flight times and ECL energy deposits are combined to form particle identification (pid) likelihoods \(\mathcal{L}(h) = h = e^+,\pi^+, K^+ or p\) for charged tracks. The \(\mathcal{R}(h|\ell^+) = \mathcal{L}(h)/\mathcal{L}(\ell^+)\) ratios are used to make pid assignments. Belle is described in detail elsewhere[18].

Samples of simulated \(\Upsilon(1S)\) and \(\Upsilon(2S)\) Monte Carlo (MC) events, generated with PYTHIA[13] and simulated using GEANT3[20], are used to study backgrounds and determine efficiencies. For signal MC for various \(H\) decay modes, we use PYTHIA with the \(\Sigma^{\pm}(1530)\) mass, width and decay-table entries replaced with hypothesized parameters for the \(H\). For MC-based optimization of selection criteria, we optimize a figure of merit defined as \(\text{FoM} = n_{\text{sig}}/\sqrt{n_{\text{sig}} + n_{\text{bkg}}\)\), where \(n_{\text{sig}}\) (\(n_{\text{bkg}}\)) is the number of selected signal (background) events assuming \(B(\Upsilon(nS) \to HX) = 3 \times 10^{-5}\).

For both investigated channels, event selection starts with the identification of a \(\Lambda\) candidate reconstructed via its \(p\pi^-\) decay using the \(\Lambda\)-momentum-dependent criteria based on proton pid, track vertex information, decay length, and \(M(p\pi^-)\) described in Ref.[21]. The \(M(p\pi^-)\) distribution for selected candidates is well fitted by a Lorentzian function with a FWHM resolution for the \(\Lambda\) peak of \(1.50 \pm 0.01\) MeV. For \(\Lambda\) candidates, we require \(\Delta M_{\Lambda} = |M(p\pi^-) - m_{\Lambda}| < 3.0\) MeV.

For the \(H \to \Lambda p\pi^-\) search, the \(p\pi^-\) track selection requirements are optimized using FoMs determined by MC assuming \(\tau_H = \tau_{\Lambda}\). Both the \(p\) and \(\pi^-\) are required to be well identified by the pid measurements: \(R(p|\pi^+) > 0.9\) (\(\pi^- = K^+ or \pi\)) \(\mathcal{R}(\pi^-|\pi^-) > 0.9\) and \(\mathcal{R}(\pi^-|K^-) > 0.6\). We require that the \(p\) and \(\pi^-\) tracks and the \(\Lambda\) trajectory satisfy a fit to a common vertex with \(\chi^2_{\Lambda p\pi^-} < 50\). In addition we require \(c\tau_{\Lambda p\pi^-} \geq 0.0\), where \(c\tau \equiv \tilde{r} \cdot \vec{p}_H M_H/|\vec{p}_H|^2\) and \(\tilde{r}\) is the displacement between the run-dependent average interaction point (IP) and the fitted vertex position. In some cases, the tracking algorithm finds two reconstructed tracks with nearly the same parameters from CDC hits produced by a single particle. Contamination from this source is removed by the requirements \(M(p_1p_2) \geq 1878\) MeV, \(M(\pi^+\pi^-) \geq 280\) MeV and \(N_{\text{hits}}(p_1) + N_{\text{hits}}(p_2) \geq 50\), where \(H \to \Lambda p\pi^-; \Lambda \to p_1\pi^-\) and \(N_{\text{hits}}(p_i)\) is the number of CDC hits used to reconstruct the \(i\)th proton. In the \(\Lambda p\pi^-\) mode, there is a large background from \(\Lambda\) and \(p\) production via secondary interactions in the material of the beampipe and inner detector. This is removed by requiring \(|\vec{p}_H| < 0.5\) GeV for both \(h = \Lambda\) and \(h = p\); this requirement is not applied to the \(\bar{\Lambda}p\pi^+\) channel. In 6.3\% (5.2\%) of the data (MC) events, there are two or more entries that have one or more tracks in common. In these cases, the combination with the smallest \(\chi^2_{\Lambda p\pi^-}\) value is selected. For signal MC events, this chooses the correct combination 93.4\% of the time. The \(\Lambda \to p_1\pi^-\) candidate is subjected to a kinematic fit that constrains \(M(p_1\pi^-)\) to \(m_{\Lambda}\). The final selection efficiencies are determined from MC by averaging \(\Upsilon(1S)\&\Upsilon(2S)\) signal MC to be \(\epsilon_1 = 7.7\%\) for \(H \to \Lambda p\pi^-\) and \(\epsilon_2 = 8.8\%\) for \(\bar{H} \to \bar{\Lambda}p\pi^+\).

The resulting continuum-subtracted \(M(\Lambda p\pi^-)\) (\(M(\bar{\Lambda}p\pi^+)\)) distribution for the combined \(\Upsilon(1S)\&\Upsilon(2S)\) samples, shown in the top (bottom) panel of Fig. 4 has no evident \(H \to \Lambda p\pi^-\) (\(\bar{H} \to \bar{\Lambda}p\pi^+)\) signal. The curve in the figure is the result of a fit using an ARGUS-like threshold function to model the background[22]; fit residuals are also shown.

For the second \(\Lambda (\Lambda_2)\) in the \(H \to \Lambda_1\Lambda_2\) (\(\Lambda_1 \to p_i\pi_i^-\)) channel, in addition to the criteria used for \(\Lambda_1\) selection, FoMs based on MC events are used to optimize the additional requirements \(\chi^2_{\Lambda_1\Lambda_2} < 200\) from a \(\Lambda_1\) vertex and IP constrained fit, and \(c\tau_{\Lambda_2} \geq 0.5\) cm. Entries in which two of the selected tracks originate from a single particle are removed by the requirements \(M(p_1p_2) \geq 1878\) MeV,
\[ \Omega \rightarrow \ell^+ \ell^- \] is shown in the top (bottom) panel of Fig. 2, where there may be a typographical error in the text. The error in this factor is included in the result of a background-only fit described in the text. Bottom: The corresponding \( M(\Omega \ell^+ \ell^-) \) distributions.

\[ H \rightarrow \Lambda \pi^+ \]

\[ \Lambda \Lambda \rightarrow \ell^+ \ell^- \]

\[ H \rightarrow \Lambda \Lambda \]

\[ H \rightarrow \Xi^+ \] is no sign of a near-threshold enhancement similar to that reported by the E522 collaboration [9] nor any observed signal for \( H \rightarrow \Lambda \Lambda (H \rightarrow \Xi^+) \). The curve is the result of a background-only fit using the functional form described above; fit residuals are also shown.

For each channel, we do a sequence of binned fits to the invariant mass distributions in Figs. 1 and 2 using a signal function to represent \( H \rightarrow f_1 (f_1 = \Lambda \rho \pi^- \) & \( f_2 = \Lambda \bar{\Lambda} \)) and an ARGUS function to represent the background. In the fits, the signal peak position is confined to a 4 MeV window that is scanned in 4 MeV steps across the ranges (\( m_\Lambda + m_\pi + m_\pi^- \)) \( \leq M(\Lambda \rho \pi^-) \leq 2m_\Lambda \) and \( 2m_\Lambda \leq M(\Lambda \Lambda) \leq 2m_\Lambda + 28 \text{ MeV} \). For the \( \Delta \rho \pi^- (\Lambda \rho \pi^+) \) mode, the signal function is a Gaussian whose resolution width is fixed at its MC-determined value scaled by a factor \( f = 0.85(1.12) \) that is determined from a comparison of data and MC fits to inclusive \( \Xi^- \rightarrow \Lambda \pi^- \) and \( \Xi^+_c(2470) \rightarrow \Xi^- \pi^+ \) signals found in the same data samples. For the \( \Lambda \Lambda \) mode, the signal function is a Lorentzian with FWHM fixed at either \( \Gamma = 0 \) or 10 MeV convolved with a Gaussian. Since the \( f_1 \) and \( f_2 \) acceptances are different, we fit the particle and antiparticle distributions separately.

None of the fits exhibit a positive signal with greater than 3\( \sigma \) significance. The fit results are translated into
90% CL upper limits on the signal yield, \( N_{UL}^i(M_H) \) and \( N_{UL}^j(M_H) \), by convolving the fit likelihood distribution with a Gaussian whose width equals the systematic error (discussed below) and then determining the yield below which 90% of the area above \( N_i = 0 \) is contained. These values are used to determine upper limits on the inclusive product branching fractions via the relation

\[
B(\Upsilon(1,2S) \rightarrow H X) \cdot B(H \rightarrow f_i) < \frac{1}{2N_Y(B_{\Lambda \rightarrow p\pi^-})^{-1}} \cdot \frac{N_{UL}^i(M_H)}{\epsilon_i},
\]

where \( N_Y = (260 \pm 6) \times 10^6 \) is the total number of \( \Upsilon(1S) \) plus \( \Upsilon(2S) \) events in the data sample \( [24] \) and \( B_{\Lambda \rightarrow p\pi^-} = 0.639 \pm 0.005 \) \( [14] \).

Sources of systematic errors and their contributions are listed in Table I. The tracking, pid and \( \Lambda \) reconstruction uncertainties are common to other Belle analyses and are determined from data-MC comparisons of various control samples. For the channel-specific vertex requirements, we use data-MC differences found in high-statistics samples of inclusive \( \Upsilon(1,2S) \rightarrow \Lambda\bar{\Lambda} \) and \( \Lambda\bar{\Lambda} \) events with \( M(\Lambda\bar{\Lambda}) < 2.28 \text{ GeV} \) \( (M(\Lambda\bar{\Lambda}) < 2.38 \text{ GeV}) \) selected with the same vertex criteria. The continuum subtraction systematic error contribution is determined from the errors in the relative on- and off-resonance luminosity measurements. Systematic errors associated with the MC-determined acceptance and minimum momentum requirement are determined by varying parameters used in the PYTHIA generator and GEANT simulation programs. The systematic errors associated with the signal fitting are determined from changes induced by variations in the binning and fitting ranges in fits to an inclusive \( \Xi^0(2470) \rightarrow \Xi^- \pi^+ \) signal seen in the same data sample. Quadratic sums of the individual contributions are taken as the total systematic errors.

### Table I: Systematic error sources (in percent). When the \( H \) and \( \bar{H} \) values differ, the \( \bar{H} \) values are given in parentheses.

| Source                  | \( H \rightarrow \Lambda p\pi^- \) | \( H \rightarrow \Lambda \bar{\Lambda} \) |
|-------------------------|-----------------------------------|-----------------------------------------|
| \( N_{15S} + N_{12S} \) | 2.3                               | 2.3                                     |
| tracking                | 3.6                               | 3.6                                     |
| particle id             | 7.2                               | 4.3                                     |
| \( \Lambda \) reconstruction | 3.5 (5.3)                    | 12.6 (9.6)                              |
| Vertex requirements     | 3.9                               | 3.5                                     |
| Signal efficiency       | 2.0 (15.7)                        | 1.9 (15.8)                              |
| Continuum subtraction   | 1.4                               | 1.4                                     |
| \( B(\Lambda \rightarrow p\pi^-) \) | 0.8                               | 1.6                                     |
| Fitting                 | 2.0                               | 2.0                                     |
| Resolution              | 2.6                               | 2.6                                     |
| Quadrature sum          | 10.2 (19.1)                       | 14.7 (19.8)                             |

For the final limits, we use the branching fraction value that contains <90% of the above-zero area of the product of the \( H \) and \( \bar{H} \) likelihood functions. Figure 3 shows the resulting \( M_H - 2m_\Lambda \)-dependent upper limits for the \( \Lambda p\pi^- \) and \( \Lambda \bar{\Lambda} \) (for \( \Gamma = 0 \)) modes. The upper limit values, listed in Table II are all more than an order of magnitude lower than the average of measured values of \( B(\Upsilon(1,2S) \rightarrow \bar{D} X) \), shown in Fig. 3 as a horizontal dotted line.

The \( H \rightarrow \Lambda p\pi^- \) limits quoted in Table II and shown in Fig. 3 are determined for an \( H \) lifetime \( \tau_H = 0.263 \text{ ns} \), \( \text{i.e., the } \Lambda \text{ lifetime. The acceptance decreases and, therefore, the limits increase, with increasing lifetime: for } \tau_H = 5\tau_\Lambda \text{, the acceptance is a factor of two lower and the limits are correspondingly twice as high. Conversely, for shorter lifetimes, the acceptance increases: for } \tau = 0.5\tau_\Lambda \text{, the acceptance is higher and the limits are more stringent by } 12 \pm 2\% .

### Table II: 90% CL upper limits \( (\times10^{-7}) \) on the product branching fraction \( B(\Upsilon(1,2S) \rightarrow H X) \cdot B(H \rightarrow f_i) \) for a narrow \( (\Gamma = 0) \) \( H \)-dibaryon vs. \( M_H - 2m_\Lambda \).

| \( \delta M \) (MeV) | 2  | 6  | 10 | 14 | 18 | 22 | 26 | 30 | 34 |
|-----------------------|----|----|----|----|----|----|----|----|----|
| \( f_1 = \Lambda p\pi^- \) | 15.9 | 9.7 | 7.1 | 6.3 | 5.1 | 4.2 | 3.7 | 4.4 | 3.3 |
| \( f_2 = \Lambda \bar{\Lambda} \) | 6.0 | 9.6 | 2.2 | 11.4 | 9.2 | 2.5 |
| \( \Gamma = 10 \text{ MeV} \) | 16.0 | 17.0 | 15.0 | 37.4 | 44.0 | 42.0 | 33.0 |

The results reported here are some of the most stringent constraints to date on the existence of an \( H \)-dibaryon with mass near the \( 2m_\Lambda \) threshold \( [25] \). These upper limits are between one and two orders of magnitude below the average of the PDG value for inclusive \( \Upsilon(1S) \) and \( \Upsilon(2S) \) decays to antideuterons. Since \( \Upsilon \rightarrow \) hadrons decays produce final states that are flavor-SU(3) symmetric, this suggests that if an \( H \)-dibaryon exists in this mass range, it must have very different dynamical properties than the deuteron, or, in the case of
$M_H < 2m_\Lambda$, a strongly suppressed $H \to \Delta p\pi^-$ decay mode.

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