Hyperfine Interact (2013) 215:53–61
DOI 10.1007/s10751-013-0791-z

QCD studies and discoveries with e^+e^- colliders and future perspectives

Jens Sören Lange for the Belle Collaboration

Published online: 14 February 2013

Abstract Observations of new charmonium(-like) and bottomonium(-like) states (sometimes refered to as "XYZ" states) at e^+e^- colliders have changed our picture of quarkonia systems as QCD bound states. Potential models with a linear confinement ansatz, which were able to predict many conventional states with an accuracy of ~1 MeV, absolutely fail in describing many of the new states. Symmetries play an important role e.g. in the determination of the quantum numbers (such as charge conjugation in the radiative decays) or in trying to explain surprising properties such as isospin violation.

Keywords Strong interaction · Confinement · Heavy quarks

1 Introduction

The static quark anti-quark potential in strong interaction is often using the ansatz

$$V(r) = \frac{-4}{3}\frac{\alpha_S}{r} + kr + V_{LS} + V_{SS} + V_T \ . \quad (1)$$

The first term is a Coulomb-like term describing one-gluon exchange. which is very similar to the Coulomb term in QED potentials for e.g. positronium or the hydrogen atom, except that here the coupling constant is given by α_S instead of α_{em}. The second term is a linear term which phenomenologically describes QCD confinement, and which is completely absent in QED. The linear shape is e.g. supported by Lattice QCD calculations, and the parameter k is the string constant of QCD string

The 5th International Symposium on Symmetries in Subatomic Physics (SSP 2012), Groningen, The Netherlands, 18–22 June 2012.

J. S. Lange (✉)
II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
e-mail: soeren.lange@exp2.physik.uni-giessen.de

Table 1 Mass measurements of the X(3872)

Experiment	Mass of X(3872)	
CDF2	$3{,}871.61 \pm 0.16 \pm 0.19$ MeV	[5]
BaBar (B^+)	$3{,}871.4 \pm 0.6 \pm 0.1$ MeV	[4]
BaBar (B^0)	$3{,}868.7 \pm 1.5 \pm 0.4$ MeV	[4]
D0	$3{,}871.8 \pm 3.1 \pm 3.0$ MeV	[6]
Belle	$3{,}871.84 \pm 0.27 \pm 0.19$ MeV	[9]
LHCb	$3{,}871.95 \pm 0.48 \pm 0.12$ MeV	[7]
New world average	$3{,}871.68 \pm 0.17$ MeV	[10]

between the quark and the anti-quark. The other terms represent spin-orbit, spin-spin and tensor potentials, leading to mass splittings in the spectrum. Heavy quark combinations such as the charm anti-charm (called charmonium) and the beauty anti-beauty (called bottomonium) are in particular interesting, as they can be treated (a) as non-relativistic systems and (b) perturbatively due to $m_Q >> \Lambda_{QCD}$, where $\Lambda_{QCD} \simeq 200$ MeV is the QCD scale. Charmonium- and bottomonium spectroscopy has been a flourishing field recently, as many new states have been observed. Masses of expected states (such as the h_b, h'_b, η_b, η'_b, described below) have been measured accurately and enable precision tests of (1) to a level of $\Delta m/m \leq 10^{-4}$. In addition, several non-expected states were found (such as the X(3872) and Y(4260), described below), which do not fit into any potential model. The results presented here were taken with the Belle [1] and BaBar [2] experiments in e^+e^- collisions at beam energies 10.5–11.0 GeV (i.e. in the Υ(nS) region). Charmonium-like states are e.g. produced in B meson decays. Bottomonium-states are e.g. produced in radiative decays of $\Upsilon(\mathrm{n}S)$ resonances.

2 Charmonium

The X(3872) state has been discovered in B meson decay in the decay X(3872) $\rightarrow J/\psi\pi^+\pi^-$ by Belle [3] and confirmed by other experiments [4–8]. Among the newly observed and yet unexplained charmonium-like states (sometimes referred to as XYZ states) the X(3872) is the only one observed in several decay channels. It has a surprisingly very narrow width $\Gamma_{X(3872)} \leq 1.2$ MeV (90 % C.L.), although its mass is above the open charm threshold.

A recent mass measurement of the X(3872) at Belle was based upon the complete Belle data set of 711 fb^{-1} (collected at the Υ(4S) resonance), and is listed in Table 1 in comparison with mass measurements from other experiments. Figure 1 shows the beam constrained mass $M_{\mathrm{bc}} = \sqrt{(E^{\mathrm{cms}}_{\mathrm{beam}}/2)^2 - (p^{\mathrm{cms}}_B)^2}$ (with the energy in the center-of-mass system $E^{\mathrm{cms}}_{\mathrm{beam}}$ and the momentum of the B meson in the center-of-mass system p^{cms}_B), the invariant mass $m(J/\psi\pi^+\pi^-)$ and the energy difference $\Delta E = E^{\mathrm{cms}}_B - E^{\mathrm{cms}}_{\mathrm{beam}}$ (with the energy of the B meson in the center-of-mass system E^{cms}_B). Data and fit (as a result of a 3-dimensional fit to the observables shown) for the decay $B^+ \rightarrow K^+$X(3872)($\rightarrow J/\psi\pi^+\pi^-$) are shown (blue line: signal, dashed green line: background). The fitted yield is 151 ± 15 events. For details of the analysis procedure see [9]. As the X(3872) does not fit into any potential model prediction, it was discussed as a possible S-wave $D^{*0}\overline{D}^0$ molecular state [11, 12]. In this case, the binding energy E_b would be given by the mass difference $m(\mathrm{X}) - m(D^{*0}) - m(D^0)$. Including the new Belle result, the new world average mass of the X(3872) is

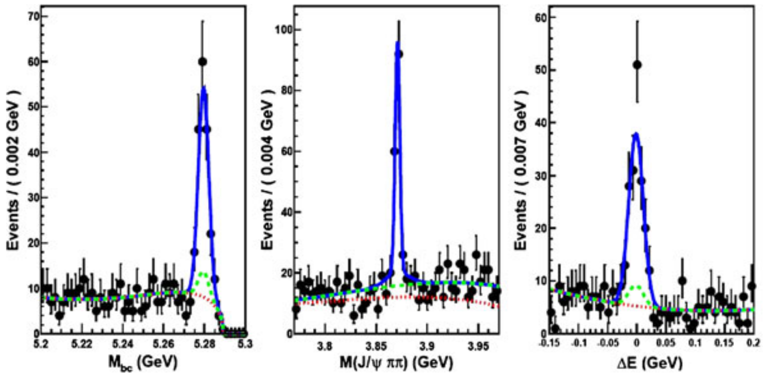

Fig. 1 Invariant mass $m(J/\psi\pi^+\pi^-)$ for $B^+ \to K^+$X(3872)($\to J/\psi\pi^+\pi^-$)

Table 2 Summary of the mass and width measurements of the Y(4260)

	BaBar [17]	CLEO-c [18]	Belle [19]	Belle [20]	BaBar [21]	BaBar [22]
$\mathcal{L}$	211 fb^{-1}	13.3 fb^{-1}	553 fb^{-1}	548 fb^{-1}	454 fb^{-1}	454 fb^{-1}
N	125±23	$14.1^{+5.2}_{-4.2}$	165±24	324±21	344±39	–
Significance	$\simeq 8\sigma$	$\simeq 4.9\sigma$	$\geq 7\sigma$	$\geq 15\sigma$	–	–
m/MeV	$4{,}259\pm8^{+2}_{-6}$	$4{,}283^{+17}_{-16}\pm4$	$4{,}295\pm10^{+10}_{-3}$	$4{,}247\pm12^{+17}_{-32}$	$4{,}252\pm6^{+2}_{-3}$	4,244±5±4
Γ/MeV	$88\pm23^{+6}_{-4}$	70^{+40}_{-25}	$133\pm26^{+13}_{-6}$	108±19±10	$105\pm18^{+4}_{-6}$	$114^{+16}_{-15}\pm7$

$m = 3871.68 \pm 0.17$ MeV [10]. Using the current sum of the masses $m(D^0) + m(D^{*0}) = 3871.84 \pm 0.28$ MeV [10], a binding energy of $E_b = -0.16 \pm 0.33$ MeV can be calculated, which is surprisingly small and would indicate a very large radius of the molecular state O($\geq$10 fm) [13–15].

One of the surprising properties of the X(3872) is isospin violation. It was found, that in the decay X(3872)$\to J/\psi\pi^+\pi^-$ the invariant mass peaks at the mass of the ρ^0 meson. The ρ^0 carries isospin $I = 0$, but the initial state (if assumed to be a pure $c\bar{c}$ state) has $I = 0$ (as it would not contain any u or d valence quarks). One of the possible explanations might be ρ/ω mixing [16]. There are only two additional isospin violating transitions known in the charmonium system [10], namely $\psi' \to J/\psi\pi^0$ ($\mathcal{B} = 1.3 \pm 0.1 \cdot 10^{-3}$) and $\psi' \to h_c\pi^0$ ($\mathcal{B} = 8.4 \pm 1.6 \cdot 10^{-4}$). For the X(3872) the branching fraction of isospin violating transition is (among the known decays) order of O(10 %) and thus seems to be largely enhanced.

The Y(4260) family Another new charmonium-like state was observed by BaBar and confirmed by several experiments (see Table 2 for a list of the measured masses and widths) at a high mass of $m \simeq 4{,}260$ MeV, far above the $D\overline{D}$ threshold. The width is $\leq$100 MeV, which is quite narrow for such a high state. The observed decay is again a $\pi^+\pi^-$ transition to the J/ψ, similar to the first observed decay of the X(3872). However, the production mechanism is not B meson decay but instead ISR (initial state radiation), i.e. $e^+e^- \to \gamma$Y(4260), i.e. a photon is radiated by either the e^+ or the e^- in the initial state, lowering the $\sqrt{s}$ and producing the Y(4260) by a virtual photon. In fact, not only one state, but four states have been observed and are shown in Fig. 2, i.e. the Y(4008), the Y(4260), the Y(4250) and the Y(4660). In a search by Belle no

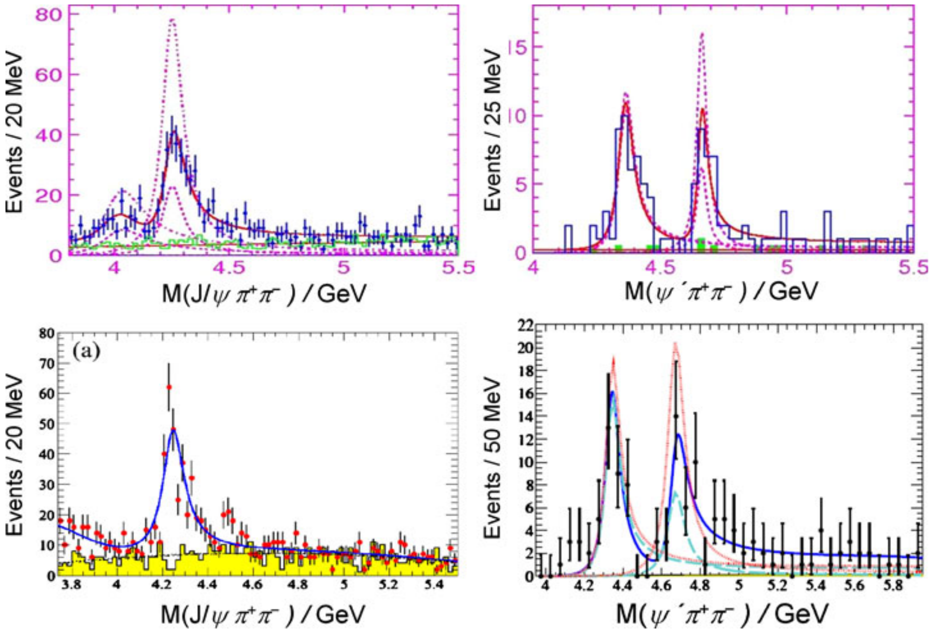

Fig. 2 Observations of the Y states. Invariant mass $m(J/\psi\pi^+\pi^-)$ at Belle [20] (*top left*) and at BaBar [21] (*bottom left*). Invariant mass $m(\psi'\pi^+\pi^-)$ at Belle [23] (*top right*) and at BaBar [24]

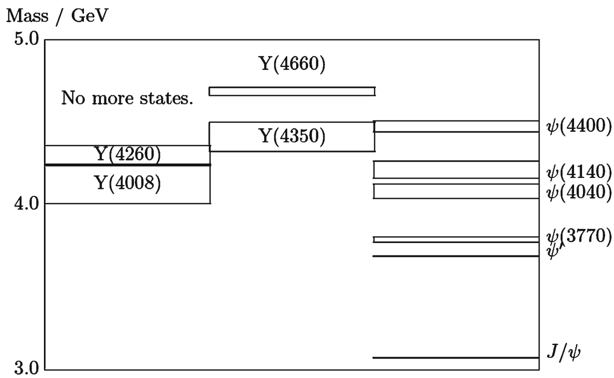

Fig. 3 Level scheme for $J^{PC} = 1^{--}$ states: states decaying into $J/\psi\pi^+\pi^-$ (*left column*), states decaying into $\psi'\pi^+\pi^-$ (*center column*), and known ψ states (radial quantum number $n = 1, ..., 6$)

additional state up to $m \leq 7$ GeV was found. All the Y states must have the quantum numbers $J^{PC} = 1^{--}$, due to the observation in an initial state radiation process. As an intriguing fact, there are known and assigned $J^P = 1^{--}$ charmonium states: J/ψ, $\psi(2S)$, $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$. Thus, there is a clear over-population of 1^{--} states in the $m \geq 4$ GeV region. Despite partial overlap, apparently there seems to be no mixing: (a) no mixing among them, i.e. the Y(4008) and the Y(4260) decay to $J/\psi\pi^+\pi^-$, and the Y(4350) and the Y(4660) decay to $\psi'\pi^+\pi^-$, and neither of one has been observed in the other channel, and (b) no mixing with ψ states with the Y states was observed so far. The pattern of the Y states appears non-trivial (see Fig. 3): two non-mixing doublets without parity flip and without charge flip. It

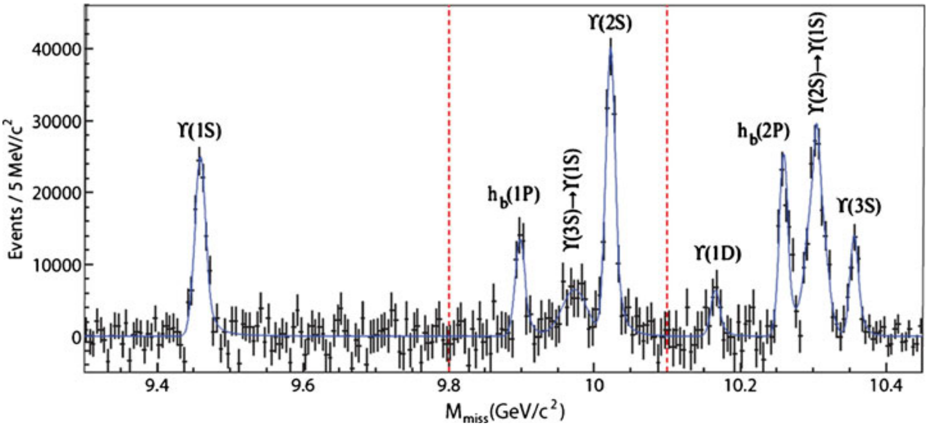

Fig. 4 Observation of the h_b(1S) and h_b(2S) at Belle. For details see text

remains completely unclear what the underlying symmetry is. In addition, there is no obvious pattern so far, how the masses of the ψ states and the masses of the Y states might be related.

3 Bottomonium

The h_b(1P) and h_b(2P) states In a recent analysis by Belle, by usage of a particular technique, namely study of missing masses to a $\pi^+\pi^-$ pairs in Υ(5S) decays [25]. Figure 4 shows the background-subtracted missing mass for a Υ(5S) data set of 121.4 fb^{-1}. Among several known states such as the Υ(1S), Υ(2S), Υ(3S) and Υ(1D), there are additional peaks arising from the transitions $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$, with the Υ(3S) and Υ(2S) being produced in the decay of the primary Υ(5S). In addition to the expected signals, first observations of the bottomonium singlet P-wave states h_b(1P) and h_b(2P) were made. Their measured masses are $m = 9{,}898.3 \pm 1.1^{+1.0}_{-1.1}$ MeV and $m = 10{,}259.8 \pm 0.6^{+1.4}_{-1.0}$ MeV, respectively. For the h_b, this measurement is consistent with the first evidence (3.1σ stat. significance) by BaBar in Υ(3S) decays with a mass of 9902±4(stat.)±2(syst.) MeV [26]. The masses can be compared to predictions from potential model calculations [27] with 9.901 MeV and 10.261 MeV, respectively, i.e. the deviations are only 2.7 MeV and 1.2 MeV.

The η_b(1S) and η_b(2S) states The η_b(1S) is the bottomonium ground state 1^1S_0 with J^{PC}=0^{-+}. It was discovered by BaBar in the radiative decay $\Upsilon(3S)\to\gamma\eta_b$. The measured mass was $9388.9^{+3.1}_{-2.3}$(stat)±2.7(syst) MeV, The observation was confirmed by CLEO III using 6 million Upsilon(3S) decays with a measured mass m=9391.8±6.6±2.0 MeV. The observation of the h_b (see above) by Belle also enabled a search for the radiative decay $h_b(1P)\to\eta_b(1S)\gamma$, which was observed with a very high significance >13σ in a dataset of 133.4 fb^{-1} at the Υ(5S) and in the nearby continuum [28]. In addition, even the η_b(2S) was observed in $h_b(2P)\to\eta_b(2S)\gamma$. Figure 5 shows the $\pi^+\pi^-\gamma$ missing mass for the

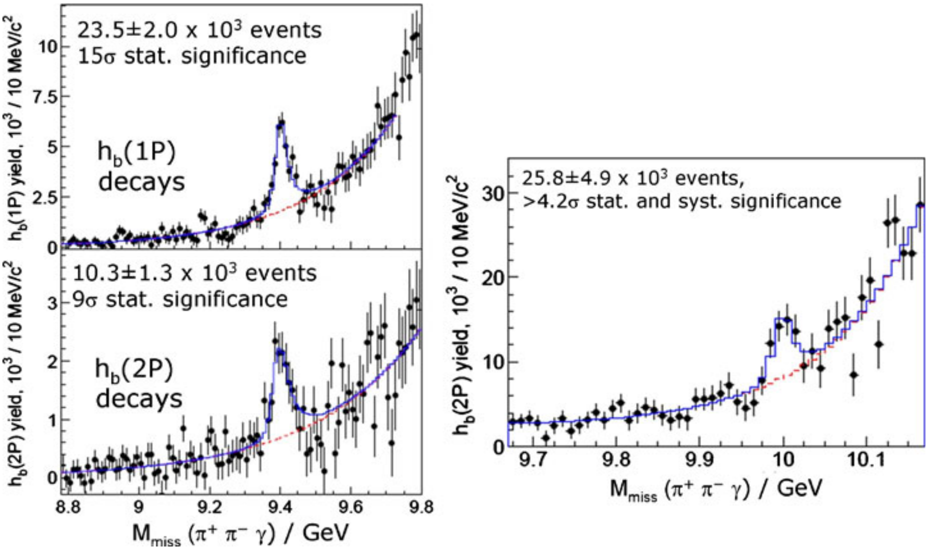

Fig. 5 Observations of the η_b (1P) (*left*) and η_b (2P) (*right*) at Belle. For details see text

Table 3 Bottomonium hyperfine splittings: measurement, calculated by potential model and calculated by Lattice QCD (LQCD)

	Belle [28]	Potential [27]	LQCD [29]	LQCD [30]
$\Upsilon(1S) - \eta_b$	57.9±2.3 MeV	60.0	70±9 MeV	60.3±5.5±5.0±2.1 MeV
$\Upsilon(2S) - \eta_b'$	$24.3^{+4.0}_{-4.5}$ MeV	30.0	35±3 MeV	23.5±4.1±2.1±0.8 MeV

case of the η_b(1S) (left) and η_b(2S) (right), where the charged pion pair originates from the transition Υ(5S)$\rightarrow h_b$(1P,2P)$\pi^+\pi^-$. The measured masses are $m(\eta_b$(1S))=9402.4±1.5±1.8 MeV and $m(\eta_b$(2S))=9999.0 $\pm 3.5^{+2.8}_{-1.9}$ MeV. Due to the high resolution, this measurement also enabled the measurement of the width of the η_b as $\Gamma = 10.8^{+4.0+4.5}_{-3.7-2.0}$, which is consistent with the expectation from potential models to 5≤Γ≤20 MeV. The measurements of the η_b $(1S)$ and η_b $(2S)$ allow precision determination of the hyperfine mass splittings Υ(1S)-η_b(1S) and Υ(2S)-η_b(2S), using the masses of the Υ(1S) and Υ(2S) from [10]. The mass splittings are listed in Table 3. The splittings are in good agreement with the expectation from a potential model with relativistic corrections [27]. and Lattice QCD calculations with kinetic terms up to O(v^6) [30]. However, lattice QCD calculations to O(v^4) with charm sea quarks predict higher splittings which are ≃10 MeV larger. Note that perturbative non-relativistic QCD calculations up to order $(m_b\alpha_S)^5$ predict significant smaller splittings e.g. $39\pm11^{+9}_{-8}$ MeV [31].

The new mass measurements enable for the first time a precision test of the flavour independance of the $c\bar{c}$ and $b\bar{b}$ systems. The important question is, if the level spacing is independant from the quark mass. According to [32], for a potential of the form $V(r) = \lambda r^\nu$ the level spacing is $\Delta E \propto (2\mu/\hbar^2)^{-\nu/(2+\nu)}|\lambda|^{2/(2+\nu)}$. Where μ is the (reduced) quark mass. For a pure Coulomb potential ($\nu = -1$), which should be dominating for the low lying states, this leads to $\Delta E \propto \mu$, This would imply that the

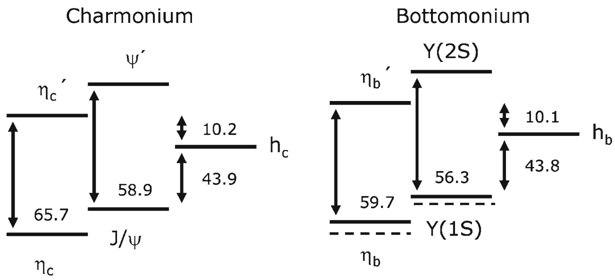

Fig. 6 Mass splittings (in MeV) based upon the new measurements [28] of the h_b, η_b and η_b', using masses from [10] for the other states, for charmonium (*left*) and bottomonium (*right*). The dotted lines indicate levels for the theoretical case of exact flavour independance

level spacing would increase linearly with mass, i.e. $\Delta E(b\overline{b}) \simeq 3\Delta E(c\bar{c})$. For a pure linear potential it would be $\Delta E \propto \mu^{-1/3}$, thus the level spacing would decrease for higher quark masses, i.e. $\Delta E(b\overline{b}) \simeq 0.5\Delta E(c\bar{c})$. As can be seen in Fig. 6, for the mass splittings involving the h_b (S=0, L=1) the agreement between $c\bar{c}$ and $b\overline{b}$ is excellent, i.e. 10.2 vs. 10.1 MeV and 43.9 vs. 43.8 MeV. There are two possible explanations of this remarkable symmetry. (1) For a pure logarithmic potential V(r)=$\lambda \ln r$ (i.e. the limit $\nu \to 0$) the level spacing is $\Delta E \propto \lambda \mu^0$. This means, the flavour independance would be strictly fulfilled. However, due to the vector nature of the gluon the short-range potential must have a Coulomb-like part, and a pure logarithmic potential is therefore not possible. (2) The other way to reach the flavour independance is, that the Coulomb potential with $\Delta E(b\overline{b}) \simeq 3\Delta E(c\bar{c})$ (see above) and the linear potential with $\Delta E(b\overline{b}) \simeq 0.5\Delta E(c\bar{c})$ (see above) cancel each other quantitatively and exact. It also implies that the size of the according λ pre-factors ($\lambda = -4/3\alpha_S$ for the Coulomb-like potential and $\lambda = k$ for the linear potential) just seem to have the exactly correct size assigned by nature in a fundamental way.

For the ground states (S=0, L=0) the agreement of the mass splittings between $c\bar{c}$ and $b\overline{b}$ is not as good, i.e. 65.7 vs. 59.7 MeV, and may point to the fact, that there is an additional effect which lowers the η_c mass. This might be mixing of the η_c with the light quark states of the same quantum number 0^{-+} (i.e. η or η').

4 Future projects

One of the important steps would be to measure not only the *masses* of newly observed states, but also the *widths*. As many states have natural widths in the sub-MeV regime, the experiments must be able to reach according precision. Two future projects should be mentioned here.

The Belle II experiment [33] is an upgrade of the Belle experiment with a luminosity increased by a factor $\leq$40 to L= $8\cdot 10^{35}$ cm^{-2} s^{-1}. The above mentioned analysis of the X(3872)$\to J/\psi\pi^+\pi^-$ was (in addition to the above mentioned results) able to determine an upper limit on the width of the X(3872) of $\Gamma \leq$1.2 MeV (90 % C.L.). This was only possible using a 3-dimensional fit (see Fig. 1). The kinematical over-constraint thus provided access to observables smaller than detector resolution of about $\simeq$3–4 MeV. Belle II will be able to perform a width measurement in another decay channel X(3872)$\to J/\psi\gamma$, for which the branching fraction is about one order of magnitude smaller than for $J/\psi\pi^+\pi^-$. The particular advantage of $J/\psi\gamma$ compared to $J/\psi\pi^+\pi^-$ is, that the monoenergetic photon will provide an additional constraint, which is absent for the $\pi^+\pi^-$ pair. For the existing Belle data, this width measurement is not possible due to limited statistics, however for Belle II the expected yield for $J/\psi\gamma$ is $\simeq$1750 events, which will be even a factor $\simeq$10 more than the existing yield for $J/\psi\pi^+\pi^-$ and thus sufficient to possibly reach $\Gamma\leq$1 MeV.

As another future experiment $\overline{\text{P}}$ANDA at FAIR (Facility for Antiproton and Ion research) at GSI Darmstadt, Germany, will be using cooled antiproton beams. The cooling will use both stochastic cooling and e^--cooling techniques, providing a momentum resolution of the antiproton beam of down to $\Delta p/p\geq2\times10^{-5}$. The planned luminosity of L=$2{\cdot}10^{32}$ cm^{-2} s^{-1} would translate into a number of $2{\cdot}10^9$ J/ψ per year, if running only at the $\sqrt{s} = m(J/\psi)$. Detailed Monte-Carlo simulation studies of a resonance scan for $p\overline{p}\rightarrow$X(3872) at $\overline{\text{P}}$ANDA were performed. For 20 scan points with data taking of 2 days each and an input width 100 keV a width of 86.9±16.8 keV was reconstructed. The error represents the error of the fit. For details see [34–36].

5 Summary

e^+e^- collisions enable unique precision tests of the $q\overline{q}$ potential in the charmonium and bottomonium region. The standard potential model fails for many observations, clearly indicating non-$q\overline{q}$ phenomena. Future facilities (Belle II, $\overline{\text{P}}$ANDA) will provide precision tests not only of masses, but also widths in the sub-MeV regime.

References

1. Belle Collaboration: Nucl. Instr. Methods **A479**, 117 (2002)
2. BaBar Collaboration: Nucl. Instr. Methods **A479**, 1 (2002)
3. Belle Collaboration: Phys. Rev. Lett. **91**, 262001 (2003)
4. BaBar Collaboration: Phys. Rev. **D71**, 071103 (2005)
5. CDF-II Collaboration: Phys. Rev. Lett. **93**, 072001 (2004)
6. D0 Collaboration: Phys. Rev. Lett. **93**, 162002 (2004)
7. LHCb Collaboration: Eur. Phys. J. **C72**, 1972 (2012). arXiv:1112.5310 [hep-ex]
8. CMS Collaboration: CERN-CMS-DP-2011-005 (public detector performance note)
9. Belle Collaboration: Phys. Rev. **D84**, 052004 (2011). arXiv:1107.0163 [hep-ex]
10. Beringer, J., et al., (Particle Data Group): Phys. Rev. **D86**, 010001 (2012)
11. Tornqvist, N.A.: Phys. Lett. **B590**, 209 (2004)
12. Tornqvist, N.A.: Phys. Rev. Lett. **67**, 556 (1991)
13. Braaten, E., Lu, M.: Phys. Rev. **D76**, 094028 (2007)
14. Braaten, E., Lu, M.: Phys. Rev. **D77**, 014029 (2008)
15. Braaten, E., Kusunoki, M.: Phys. Rev. **D69**, 074005 (2004)
16. Terasaki, K.: Prog. Theor. Phys. **122**, 1285 (2010)
17. BaBar Collaboration: Phys. Rev. Lett. **95**, 142001 (2005)
18. CLEO-c Collaboration: Phys. Rev. **D74**, 091104 (2006). arXiv:hep-ex/0611021
19. Belle Collaboration: arXiv:hep-ex/0612006 (2006)
20. Belle Collaboration: Phys. Rev. Lett. **99**, 182004 (2007)
21. BaBar Collaboration: arXiv:0808.1543 [hep-ex] (2008)
22. BaBar Collaboration: arXiv:1204.2158 [hep-ex] (2012)
23. Belle Collaboration: Phys. Rev. Lett. **99**, 142002 (2007). arXiv:0707.3699
24. BaBar Collaboration: Phys. Rev. Lett. **98**, 212001 (2007). arXiv:hep-ex/0610057
25. Belle Collaboration: Phys. Rev. Lett. **108**, 032001 (2012). arXiv:1103.3419 [hep-ex]
26. BaBar Collaboration: Phys. Rev. **D84**, 091101 (2011). arXiv:1102.4565 [hep-ex]
27. Ebert, D., Faustov, R.N., Galkin, V.O.: Phys. Rev. **D67**, 014027 (2003). hep-ph/0210381
28. Belle Collaboration: subm. to Phys. Rev. Lett. (2012). arXiv:1205.6351 [hep-ex]

29. Dowdall, R.J., Colquhoun, B., Daldrop, J.O., Davies, C.T.H., Kendall, I.D., Follana, E., Hammant, T.C., Horgan, R.R. , Lepage, G.P., Monahan, C.J., Müller, E.H. (HPQCD collaboration): arXiv:1110.6887 [hep-lat] (2011)
30. Meinel, S.: arXiv:1007.3966 [hep-lat] (2010)
31. Penin, A.A.: arXiv:0905.4296 [hep-ex] (2009)
32. Quigg, C.: hep-ph/9707493 (1997)
33. Technical Design Report: arXiv:1011.0352 [hep-ex] (2010)
34. Lange, J.S., Galuska, M., Geßler, Th., Kühn, W., Künze, S., Liang, Y., Münchow, Spruck, B., Ullrich, M., Werner, M.: arXiv:1010.2350 [hep-ex] (2010)
35. Galuska, M.: Simulation of $X(3872)$ Decays using the PandaRoot framework. Master thesis, Justus-Liebig-Universität Giessen (2011)
36. Galuska, M., Kühn, W., Lange, J.S., Spruck, B.: Results for a Simulated Resonance Scan of the X(3872) at $\overline{\text{P}}$ANDA, PoS(Bormio2012)018. http://pos.sissa.it/archive/conferences/160/018/Bormio2012_018.pdf (2012)