

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

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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 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 $m_Q \gg \Lambda_{QCD}$, 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 $h_b, h'_b, \eta_b, \eta'_b$, described below) have been measured accurately and enable precision tests of Eq. 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 $\Upsilon(nS)$ region). Charmonium-like states are e.g. produced in B meson decays. Bottomonium-states are e.g. produced in radiative decays of $\Upsilon(nS)$ 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] [5] [6] [7] [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.

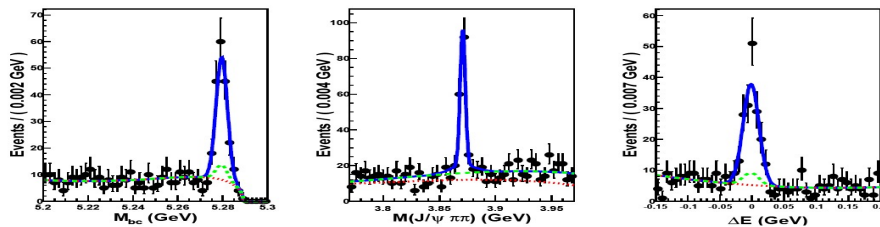


Fig. 1 Invariant mass $m(J/\psi\pi^+\pi^-)$ for $B^+ \rightarrow K^+ X(3872) (\rightarrow J/\psi\pi^+\pi^-)$.

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 $\Upsilon(4S)$ resonance), and is listed in Tab. 1 in comparison with mass measurements from other experiments. Fig. 1 shows the beam constrained mass $M_{bc} = \sqrt{(E_{beam}^{cms}/2)^2 - (p_B^{cms})^2}$ (with the energy in the center-of-mass system E_{beam}^{cms} and the momentum of the B meson in the center-of-mass system p_B^{cms}), the invariant mass $m(J/\psi\pi^+\pi^-)$ and the energy difference $\Delta E = E_B^{cms} - E_{beam}^{cms}$ (with the energy of the B meson in the center-of-mass system E_B^{cms}). 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 $D^{*0}\bar{D}^0$ molecular state [11] [12]. In this case, the binding energy E_b would be given by the mass difference $m(X) - m(D^{*0}) - m(D^0)$. Including the new Belle result, the new world average mass of the X(3872) is $m = 3871.68 \pm 0.17$ 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 $O(\geq 10 \text{ fm})$.

One of the surprising properties of the X(3872) is isospin violation. It was found, that in the decay $X(3872) \rightarrow J/\psi\pi^+\pi^-$ the invariant mass peaks at

Table 1 Mass measurements of the X(3872).

Experiment	Mass of X(3872)	
CDF2	$3871.61 \pm 0.16 \pm 0.19$ MeV	[5]
BaBar (B^+)	$3871.4 \pm 0.6 \pm 0.1$ MeV	[4]
BaBar (B^0)	$3868.7 \pm 1.5 \pm 0.4$ MeV	[4]
D0	$3871.8 \pm 3.1 \pm 3.0$ MeV	[6]
Belle	$3871.84 \pm 0.27 \pm 0.19$ MeV	[9]
LHCb	$3871.95 \pm 0.48 \pm 0.12$ MeV	[7]
New World Average	3871.68 ± 0.17 MeV	[10]

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 [14]. There are only two additional isospin violating transitions known in the charmonium system [10], namely $\psi' \rightarrow J/\psi \pi^0$ ($\mathcal{B}=1.3 \pm 0.1 \cdot 10^{-3}$) and $\psi' \rightarrow h_c \pi^0$ ($\mathcal{B}=8.4 \pm 1.6 \cdot 10^{-4}$). 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.

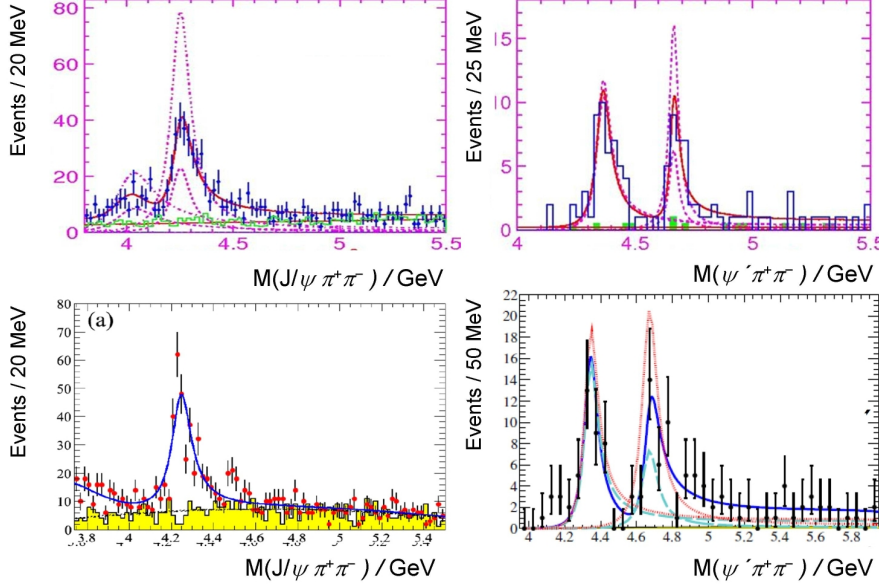
The Y(4260) family. Another new charmonium-like state was observed by BaBar and confirmed by several experiments (see Tab. 2 for a list of the measured masses and widths) at a high mass of $m \simeq 4260$ MeV, far above the $D\bar{D}$ threshold. The width is ≤ 100 MeV, which is quite narrow for such 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. $e^+e^- \rightarrow \gamma Y(4260)$, 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 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 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

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

	BaBar [15]	CLEO-c [16]	Belle [17]	Belle [18]	BaBar [19]	BaBar [20]
\mathcal{L}	211 fb $^{-1}$	13.3 fb $^{-1}$	553 fb $^{-1}$	548 fb $^{-1}$	454 fb $^{-1}$	454 fb $^{-1}$
N	125 \pm 23	14.1 $^{+5.2}_{-4.2}$	165 \pm 24	324 \pm 21	344 \pm 39	—
Significance	$\simeq 8\sigma$	$\simeq 4.9\sigma$	$\geq 7\sigma$	$\geq 15\sigma$	—	—
m / MeV	4259 $\pm 8^{+2}_{-6}$	4283 $^{+17}_{-16} \pm 4$	4295 $\pm 10^{+10}_{-3}$	4247 $\pm 12^{+17}_{-32}$	4252 $\pm 6^{+2}_{-3}$	4244 $\pm 5 \pm 4$
Γ / MeV	88 $\pm 23^{+6}_{-4}$	70 $^{+40}_{-25}$	133 $\pm 26^{+13}_{-6}$	108 $\pm 19 \pm 10$	105 $\pm 18^{+4}_{-6}$	114 $^{+16}_{-15} \pm 7$

**Fig. 2** Observations of the Y states. Invariant mass $m(J/\psi\pi^+\pi^-)$ at Belle [18] (top left) and at BaBar [19] (bottom left). Invariant mass $m(\psi'\pi^+\pi^-)$ at Belle [21] (top right) and at BaBar [22].

$\Upsilon(5S)$ decays [23]. Fig. 4 shows the background-subtracted missing mass for a $\Upsilon(5S)$ data set of 121.4 fb $^{-1}$. Among several known states such as the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and $\Upsilon(1D)$, there are additional peaks arising from the transitions $\Upsilon(3S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$, with the $\Upsilon(3S)$ and $\Upsilon(2S)$ being produced in the decay of the primary $\Upsilon(5S)$. 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 $m=9898.3 \pm 1.1^{+1.0}_{-1.1}$ MeV and $m=10259.8 \pm 0.6^{+1.4}_{-1.0}$ MeV, respectively. For the h_b , this measurement is consistent with the first evidence (3.1σ stat. significance) by BaBar in $\Upsilon(3S)$ decays with a mass of $9902 \pm 4(\text{stat.}) \pm 2(\text{syst.})$ MeV [24]. The masses can be compared to predictions from potential model calculations [25] with 9901 MeV and 10261 MeV, respectively, i.e. the deviations are only 2.7 MeV and 1.2 MeV.

The $\eta_b(1S)$ and $\eta_b(2S)$ states. The $\eta_b(1S)$ is the bottomonium ground state 1^1S_0 with $J^{PC}=0^{-+}$. It was discovered by BaBar in the radiative decay $\Upsilon(3S) \rightarrow \gamma\eta_b$. The measured mass was $9388.9^{+3.1}_{-2.3}(\text{stat.}) \pm 2.7(\text{syst.})$ MeV. The observation was confirmed by CLEO III using 6 million Upsilon(3S)

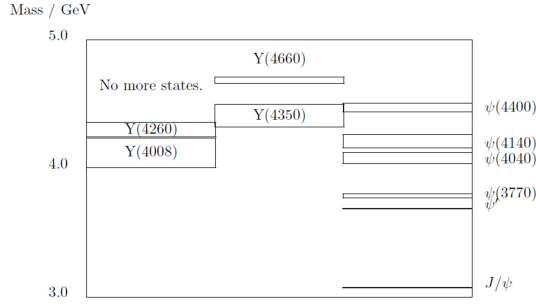


Fig. 3 Level scheme for $J^{PC}=1^{--}$ states: states decaying into $J/\psi\pi^+\pi^-$ (left column), states decaying into $\psi'\pi^+\pi^-$ (center column), and known ψ states (radial quantum number $n=1,\dots,6$).

decays with a measured mass $m=9391.8\pm 6.6\pm 2.0$ MeV. The observation of the h_b (see above) by Belle also enabled a search for the radiative decay $h_b(1P)\rightarrow\eta_b(1S)\gamma$, which was observed with a very high significance $>13\sigma$ in a dataset of 133.4 fb^{-1} at the $\Upsilon(5S)$ and in the nearby continuum [26]. In addition, even the $\eta_b(2S)$ was observed in $h_b(2P)\rightarrow\eta_b(2S)\gamma$. Fig. 5 shows the $\pi^+\pi^-\gamma$ missing mass for the case of the $\eta_b(1S)$ (left) and $\eta_b(2S)$ (right), where the charged pion pair originates from the transition $\Upsilon(5S)\rightarrow h_b(1P,2P)\pi^+\pi^-$. The measured masses are $m(\eta_b(1S))=9402.4\pm 1.5\pm 1.8$ 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 $5\leq\Gamma\leq 20$ MeV. The measurements of the $\eta_b(1S)$ and $\eta_b(2S)$ allow precision determination of the hyperfine mass splittings $\Upsilon(1S)-\eta_b(1S)$ and $\Upsilon(2S)-\eta_b(2S)$, using the masses of the $\Upsilon(1S)$ and $\Upsilon(2S)$ from [10]. The mass splittings are listed in Tab. 3. The splittings are in good agreement with the expectation from a potential model with relativistic corrections [25], and Lattice QCD calculations with kinetic terms up to $O(v^6)$ [28]. However, lattice QCD calculations to $O(v^4)$ with charm sea quarks predict higher splittings which are $\simeq 10$ MeV larger. Note that perturbative non-relativistic QCD calculations up to order $(m_b\alpha_S)^5$ predict significant smaller splittings e.g. $39\pm 11^{+9}_{-8}$ MeV [29].

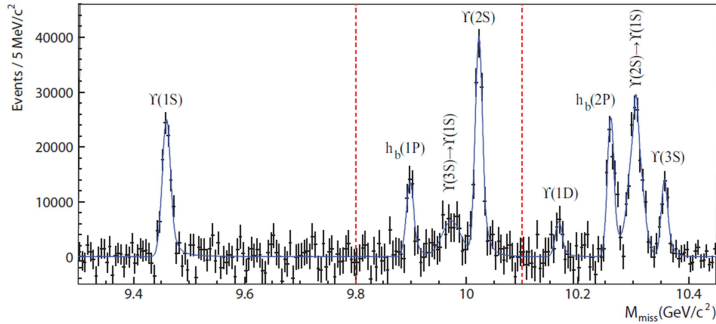


Fig. 4 Observation of the $h_b(1S)$ and $h_b(2S)$ at Belle. For details see text.

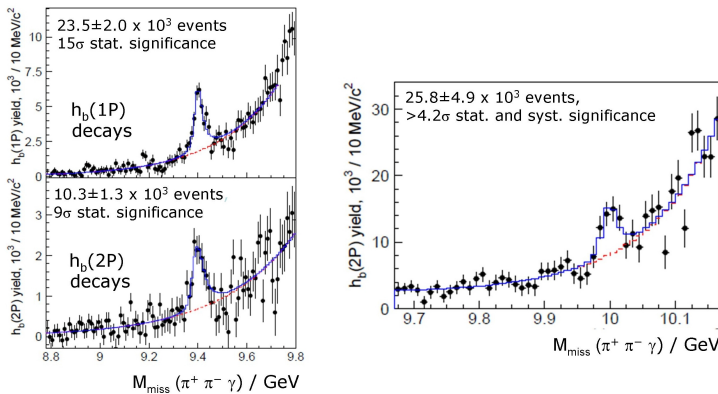


Fig. 5 Observations of the $\eta_b(1P)$ (left) and $\eta_b(2P)$ (right) at Belle. For details see text.

	Belle [26]	Potential [25]	LQCD [27]	LQCD [28]
$\Upsilon(1S) - \eta_b$	57.9 ± 2.3 MeV	60.0	70 ± 9 MeV	$60.3 \pm 5.5 \pm 5.0 \pm 2.1$ MeV
$\Upsilon(2S) - \eta_b'$	$24.3^{+4.0}_{-4.5}$ MeV	30.0	35 ± 3 MeV	$23.5 \pm 4.1 \pm 2.1 \pm 0.8$ MeV

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

The new mass measurements enable for the first time a precision test of the flavour independence of the $c\bar{c}$ and $b\bar{b}$ systems. The important question is, if the level spacing is independent from the quark mass. According to [30], 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 level spacing would increase linearly with mass, i.e. $\Delta E(b\bar{b}) \simeq 3\Delta E(c\bar{c})$. 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. $\Delta E(b\bar{b}) \simeq 0.5\Delta E(c\bar{c})$. 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 $b\bar{b}$ 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 $\nu \rightarrow 0$) the level spacing is $\Delta E \propto \lambda \mu^0$. This means, the flavour independence 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 independence is, that the Coulomb potential with $\Delta E(b\bar{b}) \simeq 3\Delta E(c\bar{c})$ (see above) and the linear potential with $\Delta E(b\bar{b}) \simeq 0.5\Delta E(c\bar{c})$ (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 $b\bar{b}$ 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').

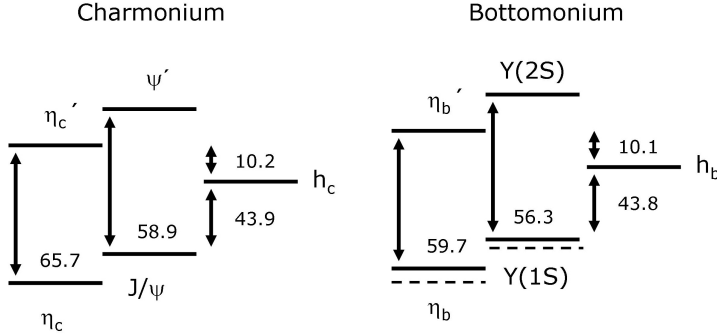


Fig. 6 Mass splittings (in MeV) based upon the new measurements [26] of the h_b , η_b and η'_b , using masses from [10] for the other states, for charmonium (left) and bottomonium (right). The dotted lines indicate levels for the theoretical case of exact flavour independence.

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 [31] is an upgrade of the Belle experiment with a luminosity increased by a factor ≤ 40 to $L=8 \cdot 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$. The above mentioned analysis of the $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ was (in addition to the above mentioned results) able to determine an upper limit on the width of the $X(3872)$ of $\Gamma \leq 1.2 \text{ MeV}$ (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 $\simeq 3-4 \text{ MeV}$. Belle II will be able to perform a width measurement in another decay channel $X(3872) \rightarrow J/\psi \gamma$, 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 $\Gamma \leq 1 \text{ MeV}$.

As another future experiment PANDA 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 $\Delta p/p \geq 2 \times 10^{-5}$. The planned luminosity of $L=2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ 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 $p\bar{p} \rightarrow X(3872)$ at PANDA were performed. For 20 scan points with data taking of 2 days each and an input width 100 keV a width of $86.9 \pm 16.8 \text{ keV}$ was reconstructed. The error represents the error of the fit. For details see [32] [33] [34].

5 Summary

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

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