

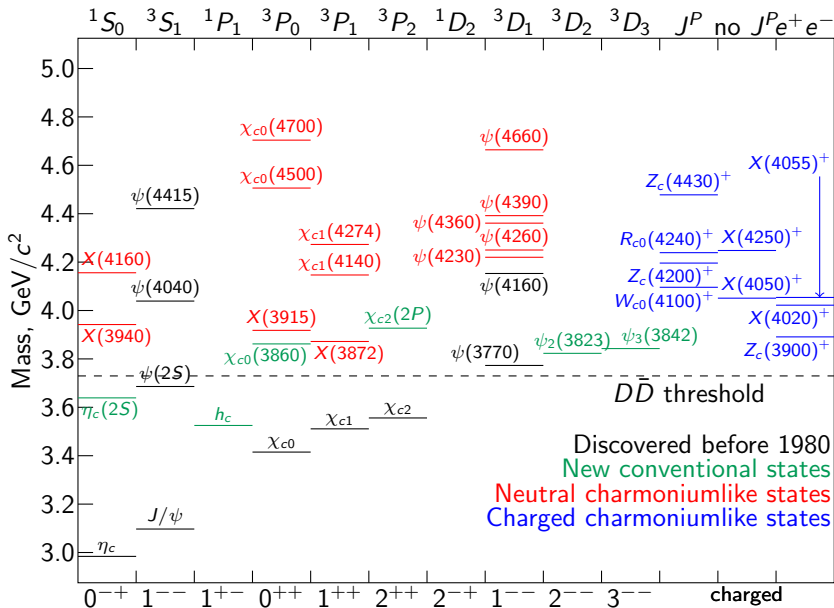
Belle (II) XYZ results in the B sector

K. Chilikin (Belle and Belle II Collaborations)

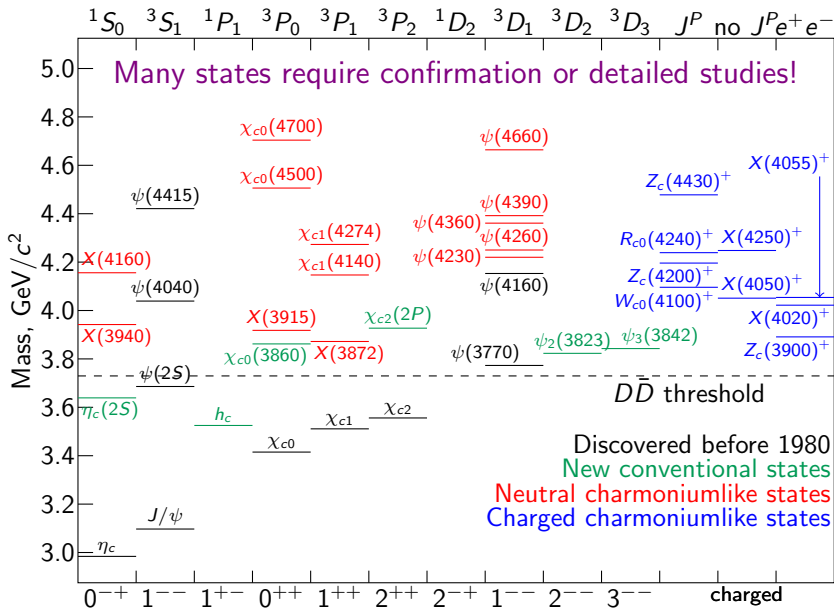
P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia

Workshop on experimental and theoretical status of and perspectives
for XYZ states, 13 April 2021

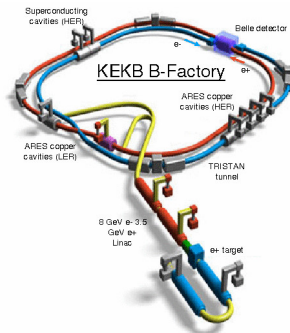
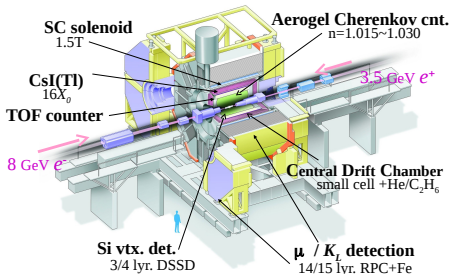
Charmonium states (as of PDG 2020)



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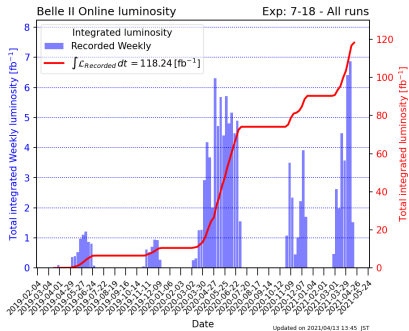
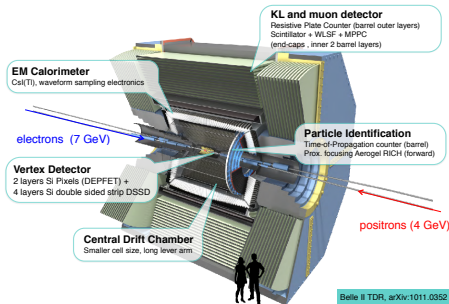


Belle Detector



The full data samples for conventional or exotic charmonium analyses are

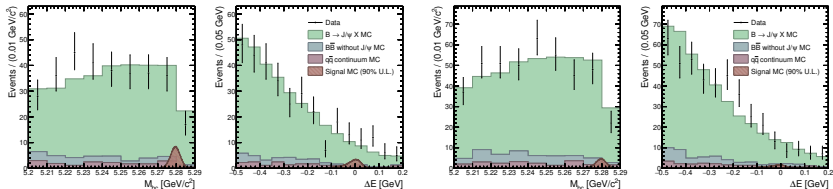
- From B decays (this talk): 711 fb^{-1} , $772 \times 10^6 B\bar{B}$ pairs.
- Double charmonium production, ISR (all energies): 980 fb^{-1} .



- The Belle II experiment operates at the e^+e^- collider SuperKEKB (the operation is mostly planned at the $\Upsilon(4S)$ resonance with $B\bar{B}$ pair production). The experiment and collider are designed to collect a much larger data sample compared to the old Belle experiment: $\approx 1 \text{ ab}^{-1} \rightarrow 50 \text{ ab}^{-1}$.
- A data sample of $\approx 118 \text{ fb}^{-1}$ is collected as of 13 April 2020. The detector is collecting data now.
- The Belle II data sample is currently too small for new charmonium results. However, it is already possible to look at known quarkonium states, including non-conventional states like the $X(3872)$.

1. Recent Belle results.
 - Search for $B^0 \rightarrow X(3872)\gamma$.
 - Search for $X(3872)$ and $X(3915)$ decays into $\chi_{c1}\pi^0$.
 - Search for $B \rightarrow Y(4260)K$, $Y(4260) \rightarrow J/\psi\pi^+\pi^-$.
2. Overview of old Belle results.
 - $X(3872)$.
 - $X(3915)$.
 - Charged Z_c^+ states.
3. Belle II results.
4. Some open questions for XYZ states in B decays.

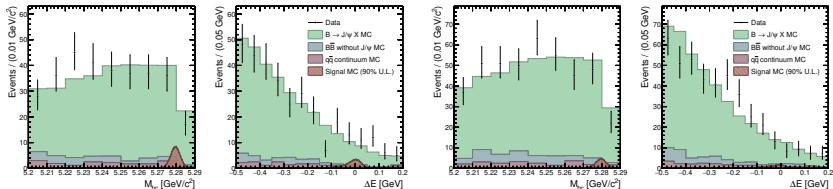
Part 1. Recent Belle results.



Left: J/ψ muon channel, right: J/ψ electron channel.

A search for the decay $B^0 \rightarrow X(3872)\gamma$ was performed. The branching fraction is expected to be smaller than that of the decay $B^0 \rightarrow J/\psi\gamma$ due to admixture of non- $c\bar{c}$ components; the limit for $\mathcal{B}(B^0 \rightarrow J/\psi\gamma)$ is 1.5×10^{-6} at 90% C.L. (predictions vary from 7.65×10^{-9} to 4.5×10^{-7}). No significant signal was found; an upper limit for the branching fraction was set:

$$\mathcal{B}(B^0 \rightarrow X(3872)(\rightarrow J/\psi\pi^+\pi^-)\gamma) < 5.1 \times 10^{-7} \text{ (90\% C.L.)}$$

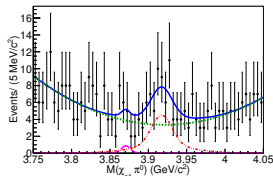
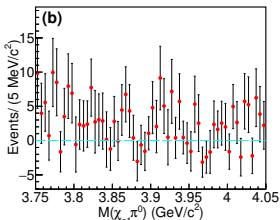
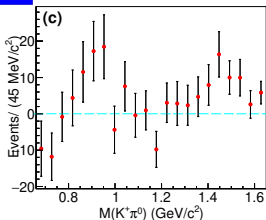


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$$\mathcal{B}(B^0 \rightarrow X(3872)(\rightarrow J/\psi\pi^+\pi^-)\gamma) < 5.1 \times 10^{-7} \text{ (90\% C.L.)}$$

Belle II is expected to be able to measure (or set upper limits) for both $B^0 \rightarrow J/\psi\gamma$ and $B^0 \rightarrow X(3872)\gamma$ with better precision.



A one-dimensional search for $X(3872)$ and $X(3915)$ decays to $\chi_{c1}\pi^0$ was performed using $B^+ \rightarrow \chi_{c1}\pi^0 K^+$ decays. No significant signal was found (0.3σ for the $X(3872)$ and 2.3σ for the $X(3915)$). The corresponding branching fractions were constrained:

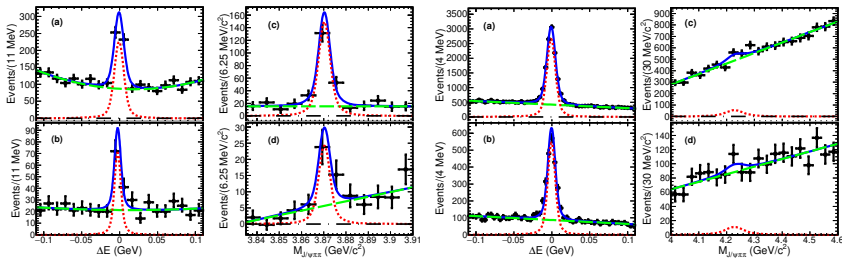
$$\mathcal{B}(B^+ \rightarrow X(3872)(\rightarrow \chi_{c1}\pi^0)K^+) < 8.1 \times 10^{-6},$$

$$\mathcal{B}(B^+ \rightarrow X(3915)(\rightarrow \chi_{c1}\pi^0)K^0) < 2.8 \times 10^{-5},$$

$$\mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^0)/\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-) < 0.97 \text{ (90\% C.L.)}.$$

The decay $X(3872) \rightarrow \chi_{c1}\pi^0$ is now observed by BESIII in PRL **122**, 202001 (2019) with

$$\mathcal{B}(X(3872) \rightarrow \chi_{c1}\pi^0)/\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-) = 0.88^{+0.33}_{-0.27} \pm 0.10.$$



Top plots: $B^+ \rightarrow J/\psi\pi^+\pi^-K^+$, bottom plots: $B^0 \rightarrow J/\psi\pi^+\pi^-K_S^0$.

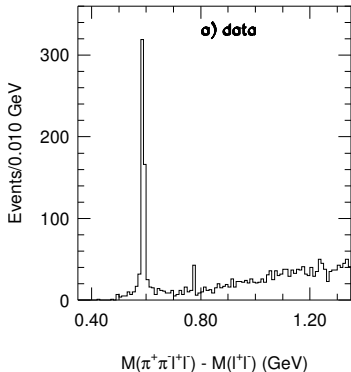
A one-dimensional search for the $Y(4260)$ was performed in $B \rightarrow J/\psi\pi^+\pi^-K$. No significant signal was found (2.1σ in $B^+ \rightarrow J/\psi\pi^+\pi^-K^+$ and 0.9σ in $B^0 \rightarrow J/\psi\pi^+\pi^-K_S^0$).

The corresponding branching fractions were constrained:

$$\mathcal{B}(B^+ \rightarrow Y(4260)(\rightarrow J/\psi\pi^+\pi^-)K^+) < 1.4 \times 10^{-5},$$

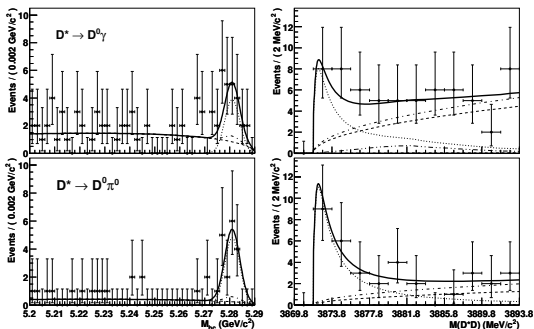
$$\mathcal{B}(B^0 \rightarrow Y(4260)(\rightarrow J/\psi\pi^+\pi^-)K^0) < 1.7 \times 10^{-5} \text{ (90\% C.L.)}.$$

Part 2. Overview of old Belle results.

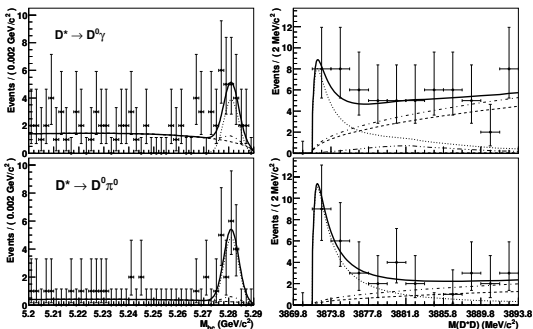


The $X(3872)$ was observed by Belle in $B^+ \rightarrow J/\psi\pi^+\pi^-K^+$ decays with 10.3σ significance. Initially, the parameters were measured to be $M = 3872.0 \pm 0.6 \pm 0.5 \text{ MeV}/c^2$, $\Gamma < 2.3 \text{ MeV}$ (90% C.L.).

The $X(3872)$ was confirmed by many other experiments and studied in detail. Further studies of the $X(3872)$ at Belle are presented in the following slides.

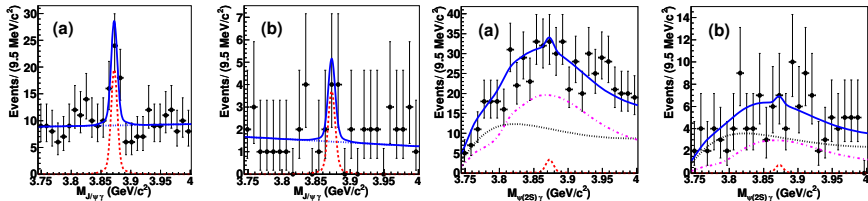


The decay $X(3872) \rightarrow D^{*0}\bar{D}^0$ was observed. The parameters were measured to be $M = 3972.9^{+0.6+0.4}_{-0.4-0.5}$ MeV/c², $\Gamma = (3.9^{+2.8}_{-1.4} \text{ } ^{+0.2}_{-1.11})$ MeV, $\mathcal{B}(B \rightarrow X(3872)(\rightarrow D^{*0}\bar{D}^0)K) = (0.80 \pm 0.20 \pm 0.10) \times 10^{-4}$.



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The D^{*0} mass was constrained in this analysis. What are the results without the mass constraint? One can use the decay $X(3872) \rightarrow D^0\pi^0\bar{D}^0$ to measure the $X(3872)$ width.



(a): $B^+ \rightarrow X(3872)K^+$, (b): $B^0 \rightarrow X(3872)K^0$.

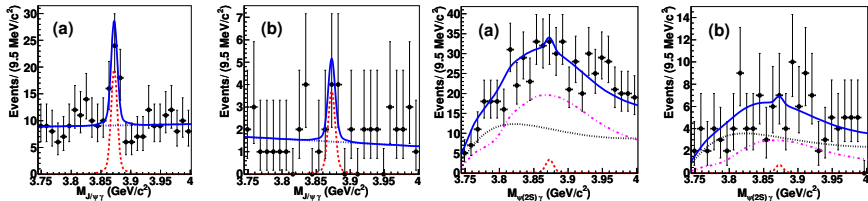
The decay $X(3872) \rightarrow J/\psi\gamma$ was observed with

$$\mathcal{B}(B^+ \rightarrow X(3872)(\rightarrow J/\psi\gamma)K^+) = (1.78^{+0.48}_{-0.44} \pm 0.12) \times 10^{-6};$$

the decay $X(3872) \rightarrow \psi(2S)\gamma$ was not found:

$$\mathcal{B}(B^+ \rightarrow X(3872)(\rightarrow \psi(2S)\gamma)K^+) < 3.45 \times 10^{-6} \text{ (90\% C.L.)}.$$

Evidence for the decay to $\psi(2S)\gamma$ was found by BABAR [PRL 102 (2009) 132001] and LHCb [NPB 886, 665 (2013)].



(a): $B^+ \rightarrow X(3872)K^+$, (b): $B^0 \rightarrow X(3872)K^0$.

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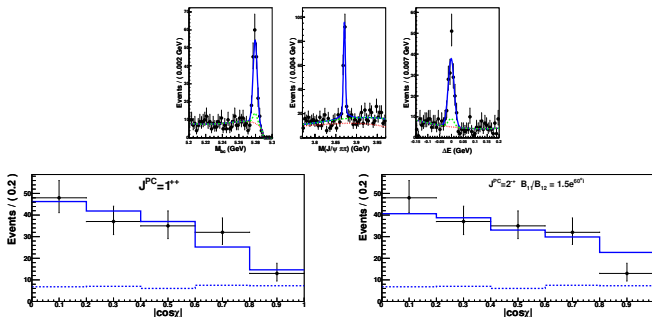
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Since the channels in question include photons, Belle II is expected to be able to improve the measurement of

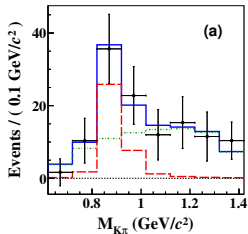
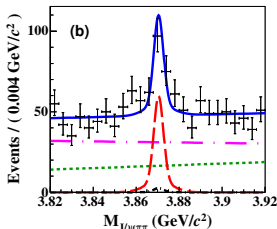
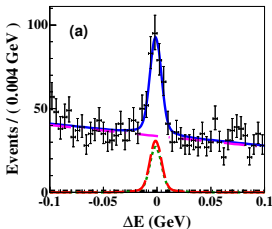
$$\mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma) / \mathcal{B}(X(3872) \rightarrow J/\psi\gamma).$$



χ is the angle between \vec{p}_{π^+} and $-\vec{p}_K$ in the $X(3872)$ rest frame; 2 other angles (one-dimensional distributions) were also used.

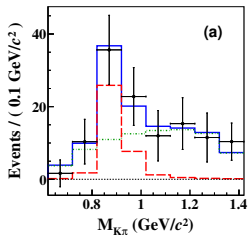
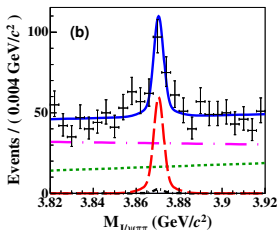
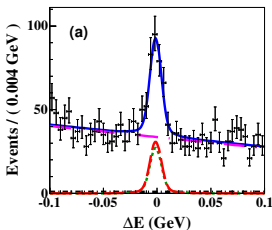
The decays $B \rightarrow X(3872)(\rightarrow J/\psi\pi^+\pi^-)K$ were studied again with full Belle statistics. The parameters were found to be $M = 3871.85 \pm 0.27 \pm 0.19$ MeV/ c^2 , $\Gamma < 1.2$ MeV (90% C.L.), $\mathcal{B}(B^+ \rightarrow X(3872)(\rightarrow J/\psi\pi^+\pi^-)K^+) = (8.63 \pm 0.8 \pm 0.52) \times 10^{-6}$, $\mathcal{B}(B^0 \rightarrow X(3872)K^0)/\mathcal{B}(B^+ \rightarrow X(3872)K^+) = 0.50 \pm 0.14 \pm 0.04$. Charged X decaying to $J/\psi\pi^+\pi^0$ was not found. The quantum numbers were found to be either 1^{++} or 2^{-+} (analysis of 1D distributions).

Now LHCb determined $J^P = 1^{++}$ [PRL **110**, 222001 (2013); PRD **92**, 011102 (2015)] and width [PRD **102**, 092005 (2020); JHEP **08**, 123 (2020)].



The histograms are for the channel $B^0 \rightarrow X(3872)\pi^- K^+$.

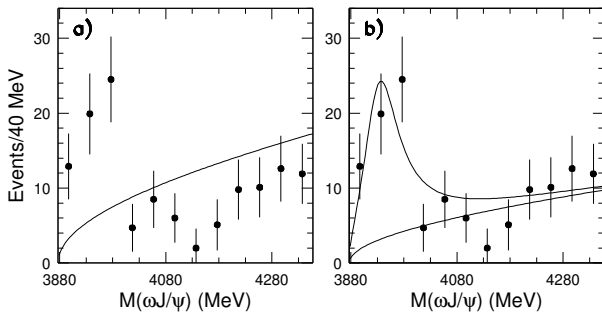
The decay $B^0 \rightarrow X(3872)\pi^- K^+$ was observed with 7.0σ significance; evidence for $B^+ \rightarrow X(3872)\pi^+ K^0$ was found (3.7σ). The branching fractions are $\mathcal{B}(B^0 \rightarrow X(3872)\pi^- K^+) = (7.9 \pm 1.3 \pm 0.4) \times 10^{-6}$, $\mathcal{B}(B^+ \rightarrow X(3872)\pi^+ K^0) = (10.6 \pm 3.0 \pm 0.9) \times 10^{-6}$. The fit fraction of the $K^*(892)$ is low: $0.34 \pm 0.09 \pm 0.02$.



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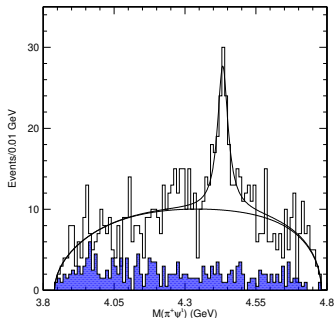
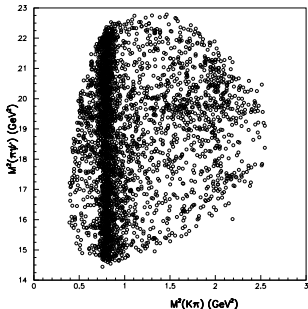
There is no independent confirmation yet. Low fraction of the $K^*(892)$ is unusual; it may suggest a significant contribution of states decaying to $X(3872)\pi^+$. A full amplitude analysis is necessary (requires much larger statistics).



Left: fit without X , right: fit with X .

The $X(3915)$ was observed by Belle in $B \rightarrow J/\psi\omega K$ decays. The parameters were measured to be: $M = 3943 \pm 11 \pm 13 \text{ MeV}/c^2$, $\Gamma = 87 \pm 22 \pm 26 \text{ MeV}$. Initially this state was called $Y(3940)$, but then this name was changed to $X(3915)$ (precise mass measurement + “ Y ” is for new 1^{--} states).

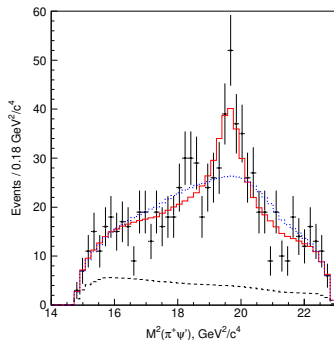
Confirmation in B decays by BABAR: PRD **82**, 011101 (2010), also seen in $\gamma\gamma \rightarrow J/\psi\omega$ by Belle [PRL **104**, 092001 (2010)] and BABAR [PRD **86**, 072002 (2012)].



The $Z_c(4430)^+$ was initially observed as a relatively narrow peak in the $\psi(2S)\pi^+$ mass distribution in the decays $\bar{B}^0 \rightarrow \psi(2S)\pi^+K^-$. The parameters were:

$$M = 4433 \pm 4 \pm 2 \text{ MeV}/c^2, \Gamma = 45_{-13}^{+18}{}_{-13}^{+30} \text{ MeV}, 6.5\sigma.$$

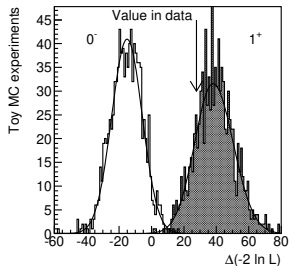
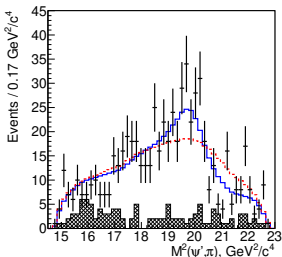
However, this analysis was one-dimensional and did not take interference into account.



Thus, a two-dimensional (Dalitz) analysis has been performed using the same data. The parameters changed:

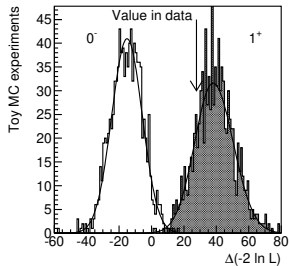
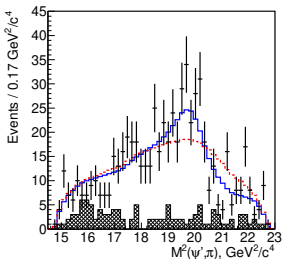
$$M = 4443_{-12}^{+15}{}_{-13}^{+19} \text{ MeV}/c^2, \quad \Gamma = 107_{-43}^{+86}{}_{-46}^{+74} \text{ MeV}.$$

However, this analysis still integrates over phase space (two variables in case of $\psi(2S) \rightarrow \ell^+\ell^-$); it is not sensitive to the $Z_c(4430)^+$ quantum numbers.



Finally, full amplitude analysis was performed (the data set differs: only $\psi(2S) \rightarrow \ell^+ \ell^-$ decays were used, but also full Belle data were used). The $Z_c(4430)^+$ was confirmed with $M = 4485_{-22}^{+22} {}_{-11}^{+28}$, $\Gamma = 200_{-46}^{+41} {}_{-35}^{+26}$, $J^P = 1^+$ preferred over $0^-, 1^-, 2^-,$ and 2^+ hypotheses at the levels of $3.4\sigma, 3.7\sigma, 4.7\sigma,$ and 5.1σ , respectively.

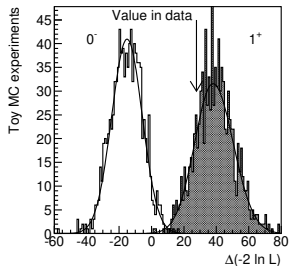
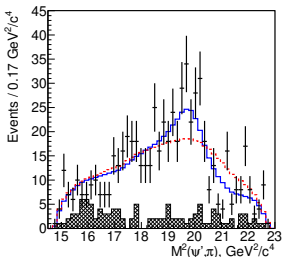
Later confirmed by LHCb: PRL **112**, 222002 (2014) (similar method), PRD **92**, 112009 (2015) (model-independent).



Finally, full amplitude analysis was performed (the data set differs: only $\psi(2S) \rightarrow \ell^+\ell^-$ decays were used, but also full Belle data were used). The $Z_c(4430)^+$ was confirmed with $M = 4485^{+22+28}_{-22-11}$, $\Gamma = 200^{+41+26}_{-46-35}$, $J^P = 1^+$ preferred over 0^- , 1^- , 2^- , and 2^+ hypotheses at the levels of 3.4σ , 3.7σ , 4.7σ , and 5.1σ , respectively.

Later confirmed by LHCb: PRL **112**, 222002 (2014) (similar method), PRD **92**, 112009 (2015) (model-independent).

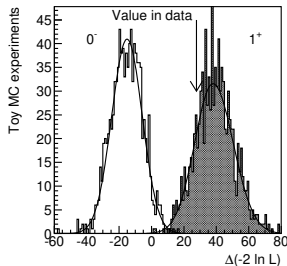
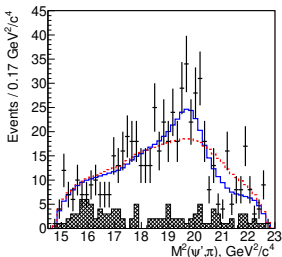
The peak observed by the initial 1D analysis is the $Z_c(4430)^+$ signal indeed. However, it is *due to constructive interference below the nominal $Z_c(4430)^+$ mass*. Conclusion: amplitude analyses should be preferred!



Finally, full amplitude analysis was performed (the data set differs: only $\psi(2S) \rightarrow \ell^+ \ell^-$ decays were used, but also full Belle data were used). The $Z_c(4430)^+$ was confirmed with $M = 4485_{-22}^{+22} {}_{-11}^{+28}$, $\Gamma = 200_{-35}^{+41} {}_{-35}^{+26}$, $J^P = 1^+$ preferred over 0^- , 1^- , 2^- , and 2^+ hypotheses at the levels of 3.4σ , 3.7σ , 4.7σ , and 5.1σ , respectively.

Later confirmed by LHCb: PRL **112**, 222002 (2014) (similar method), PRD **92**, 112009 (2015) (model-independent).

The $Z_c(4430)^+$ is confirmed and its properties are well established.

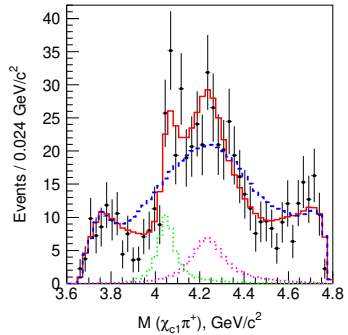
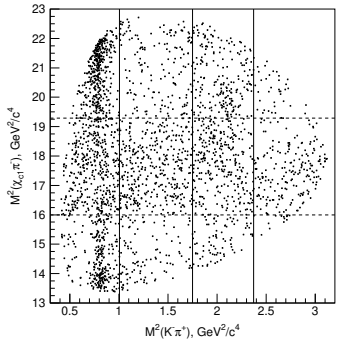


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Later confirmed by LHCb: PRL **112**, 222002 (2014) (similar method), PRD **92**, 112009 (2015) (model-independent).

The $Z_c(4430)^+$ is confirmed and its properties are well established.

One can also search for the $Z_c(4430)^0$ in $B^+ \rightarrow \psi(2S)\pi^0 K^+$ or study other decays (see page about $\bar{B}^0 \rightarrow J/\psi \pi^+ K^-$ below).

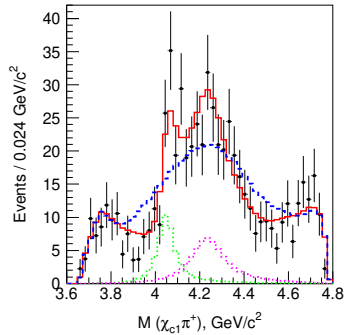
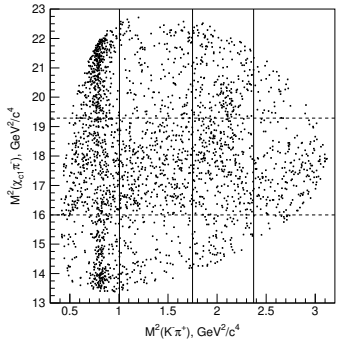


Two new states decaying to $\chi_{c1}\pi^+$ were observed by Dalitz analysis:

$Z_c(4050)^+$: $M = 4051 \pm 14^{+20}_{-40}$ MeV/ c^2 , $\Gamma = 82^{+21}_{-17}{}^{+47}_{-22}$ MeV.

$Z_c(4250)^+$: $M = 4248^{+44}_{-29}{}^{+180}_{-35}$ MeV/ c^2 , $\Gamma = 177^{+54}_{-39}{}^{+316}_{-61}$ MeV.

Significance of one state: 6.2σ , two states over one: 5.0σ .



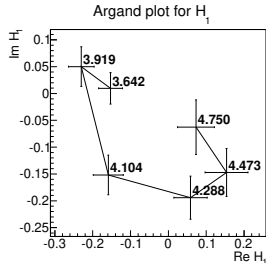
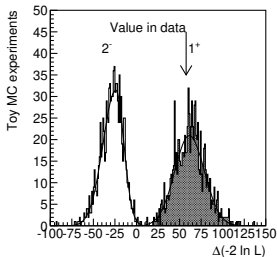
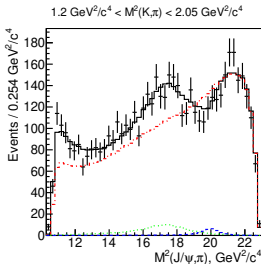
Two new states decaying to $\chi_{c1}\pi^+$ were observed by Dalitz analysis:

$Z_c(4050)^+$: $M = 4051 \pm 14^{+20}_{-40}$ MeV/c^2 , $\Gamma = 82^{+21+47}_{-17-22}$ MeV .

$Z_c(4250)^+$: $M = 4248^{+44+180}_{-29-35}$ MeV/c^2 , $\Gamma = 177^{+54+316}_{-39-61}$ MeV .

Significance of one state: 6.2σ , two states over one: 5.0σ .

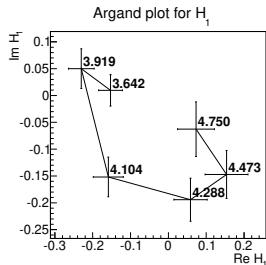
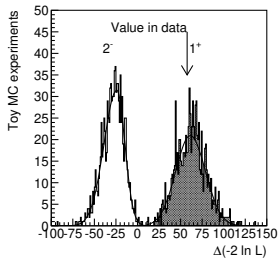
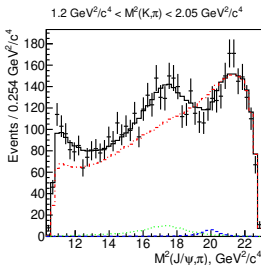
There is no independent confirmation yet. There is no full amplitude analysis. What are the quantum numbers? What are the results in $B^+ \rightarrow \chi_{c1}\pi^0 K^+$?



New charged state $Z_c(4200)^+$ decaying to $J/\psi\pi^+$ was observed by full amplitude analysis: $M = 4196^{+31+17}_{-29-13}$ MeV/c², $\Gamma = 370^{+70}_{-70}$ MeV, 6.2σ .

Preferred assignment of quantum numbers is $J^P = 1^+$; other hypotheses: $0^-, 1^-, 2^-, 2^+$ are excluded at the levels of $6.1\sigma, 7.4\sigma, 4.4\sigma$ and 7.0σ , respectively. Evidence for $Z_c(4430)^+ \rightarrow J/\psi\pi^+$ is found.

The $Z_c(4200)^+$ is confirmed by LHCb model-independent analysis PRL **122**, 152002 (2019).



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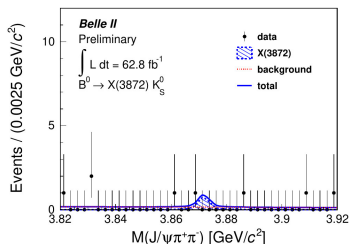
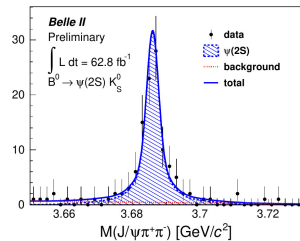
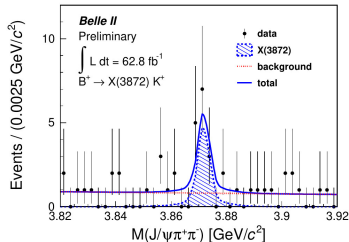
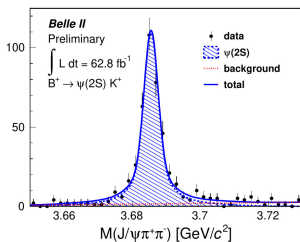
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The $Z_c(4200)^+$ is confirmed by LHCb model-independent analysis PRL **122**, 152002 (2019).

Is there a state with $M \approx 4.6$ GeV/ c^2 observed by model-independent analysis? What are $Z_c(4430)^+$ results without restrictions on its parameters? What are the results in $B^+ \rightarrow J/\psi\pi^0 K^+$?

Part 3. Belle II results.

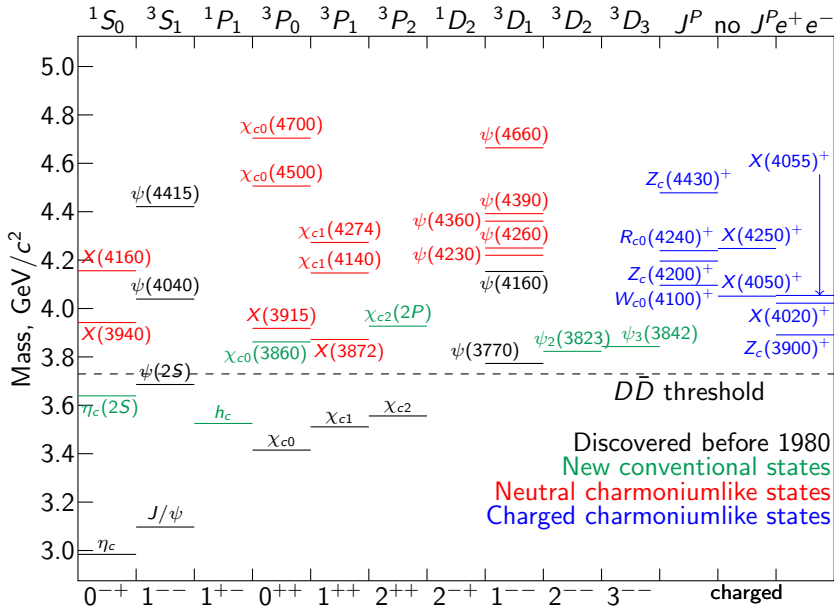
Evidence for the $X(3872)$ in Belle II data



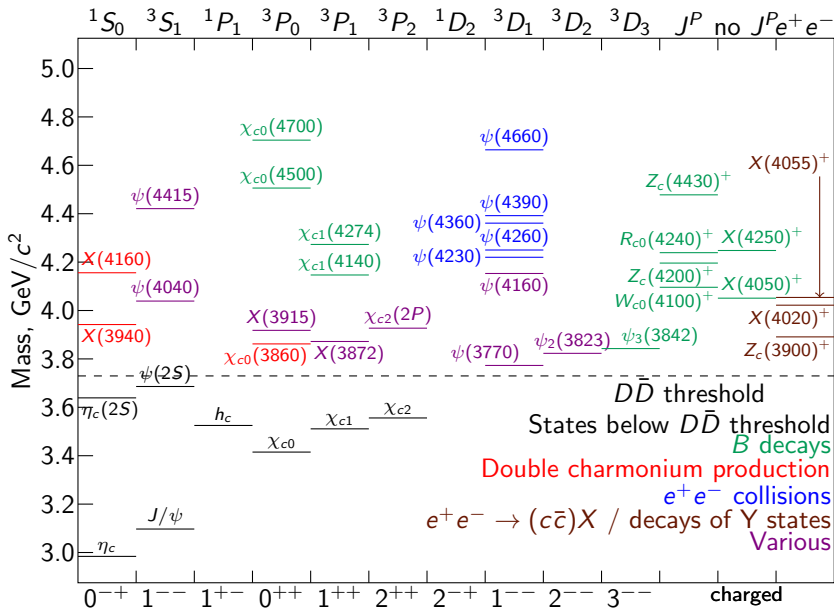
Using a data sample of 62.8 fb^{-1} , evidence for the $X(3872)$ was found with 4.6σ significance.

Part 4. Some open questions for XYZ states in B decays.

Charmonium states (as of PDG 2020)



Charmonium states by production mechanism



Some states are not seen in B decays

1. States from double charmonium production:

- Their properties are consistent with conventional charmonium. In this case, such states should be seen in B decays.
- LHCb did not observe a significant signal of the $\chi_{c0}(3860)$ in $B^+ \rightarrow D^+ D^- K^+$, but did not measure upper limit on $\mathcal{B}(B^+ \rightarrow \chi_{c0}(3860)K^+) \times \mathcal{B}(\chi_{c0}(3860) \rightarrow D^+ D^-)$ [PRD **102**, 112002 (2020)]. There are no measurements for other states.
- Thus, there is no quantitative information on production of the states from double-charmonium production in B -meson decays \Rightarrow search for them at Belle II (and LHCb).

2. States from $e^+ e^-$ collisions:

- There are limits measured by Belle:

$$\mathcal{B}(\bar{B}^0 \rightarrow Z_c(3900)^+ K^-) \times \mathcal{B}(Z_c(3900)^+ \rightarrow J/\psi \pi^+) < 9 \times 10^{-7},$$

$$\mathcal{B}(B^+ \rightarrow Y(4260)(\rightarrow J/\psi \pi^+ \pi^-) K^+) < 1.4 \times 10^{-5},$$

$$\mathcal{B}(B^0 \rightarrow Y(4260)(\rightarrow J/\psi \pi^+ \pi^-) K^0) < 1.7 \times 10^{-5} \text{ (90\% C.L.)}.$$
- It would be interesting to have information for other states \Rightarrow study at Belle II (and LHCb).

There are several unconfirmed states observed in B decays:

1. For example, the $X(4050)^+$ and $X(4250)^+$ were observed only by Belle ($B^0 \rightarrow \chi_{c1}\pi^- K^+$).
2. There are states observed by LHCb only as well, e.g. $\chi_{c0}(4500)$ and $\chi_{c0}(4700)$ in $B^+ \rightarrow J/\psi\phi K^+$.
3. Confirmation is necessary \Rightarrow study at Belle II (and LHCb).

Several charged states decaying to a conventional charmonium states and π^+ have been observed by Belle and LHCb. All of them should have neutral partners, however, no such neutral partners have been observed yet. Their search requires reconstruction of a $\pi^0 \Rightarrow$ it is a good task for Belle II.

Unknown J^P , phase dependence on mass

1. States that were not observed from full amplitude analyses generally have unknown quantum numbers, for example, $X(4050)^+$ and $X(4250)^+$ from $B^0 \rightarrow \chi_{c1}\pi^-K^+$ or $X(3915)$ from $B \rightarrow J/\psi\omega K$ (the $X(3915)$ has a measurement in $\gamma\gamma \rightarrow J/\psi\omega$ by BABAR, but it assumed $\lambda = \pm 2$ in case of $J = 2$; LHCb analysis of $B^+ \rightarrow D^+D^-K^+$ find 2 states in this mass region, thus, it is better to measure $X(3915)$ quantum numbers in $B \rightarrow J/\psi\omega K$, too). The quantum numbers can be studied at Belle II (and LHCb).
2. Some states, e.g. the $Z_c(4430)^+$, have measured Argand diagrams that show resonant phase dependence on mass. The phase motion should be studied for other states, too, if possible, since it confirms resonant character of the states \Rightarrow study at Belle II (and LHCb).

- Several exotic charmonium states were observed and studied by Belle experiment.
- The expected Belle II data sample of 50 ab^{-1} will provide a lot of new opportunities for exotic-charmonium analyses.
- For further details about Belle II physics prospects, see the Belle II Physics Book: PTEP **2019**, 123C01 (2019).