Quarkonium physics at Belle II

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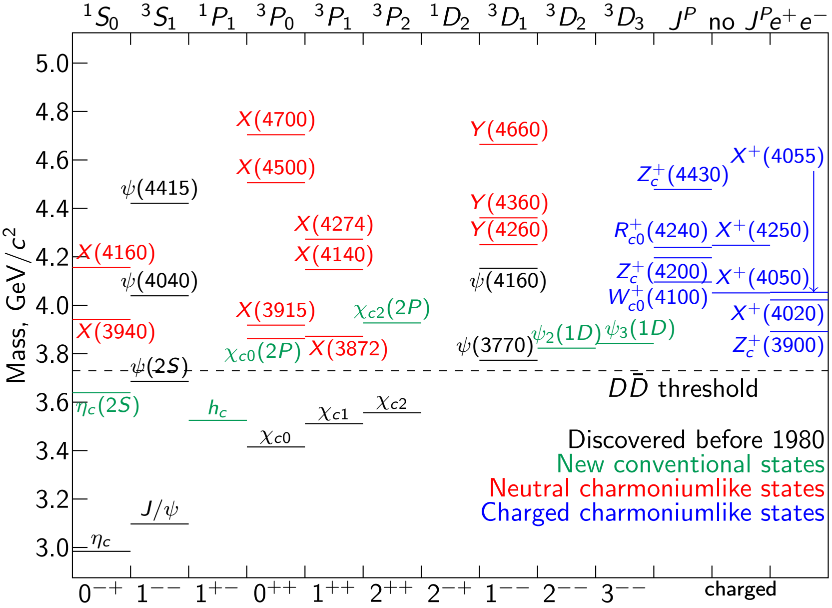
Excited QCD 2020, 4 February 2020

Charmonium states



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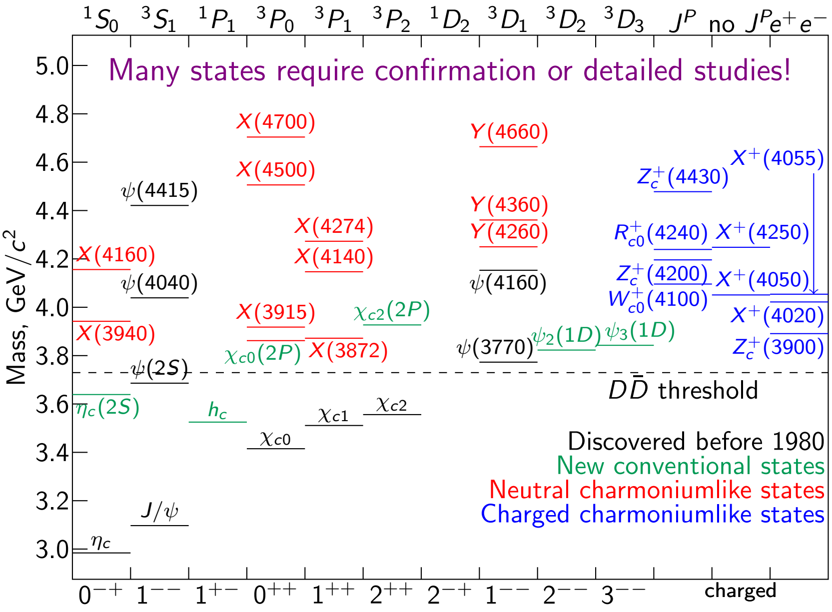
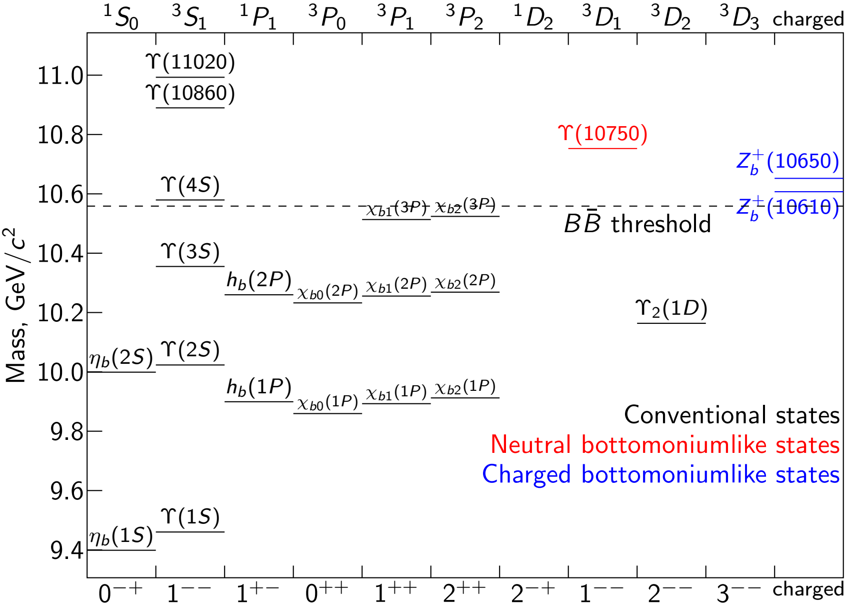


Bottomonium states



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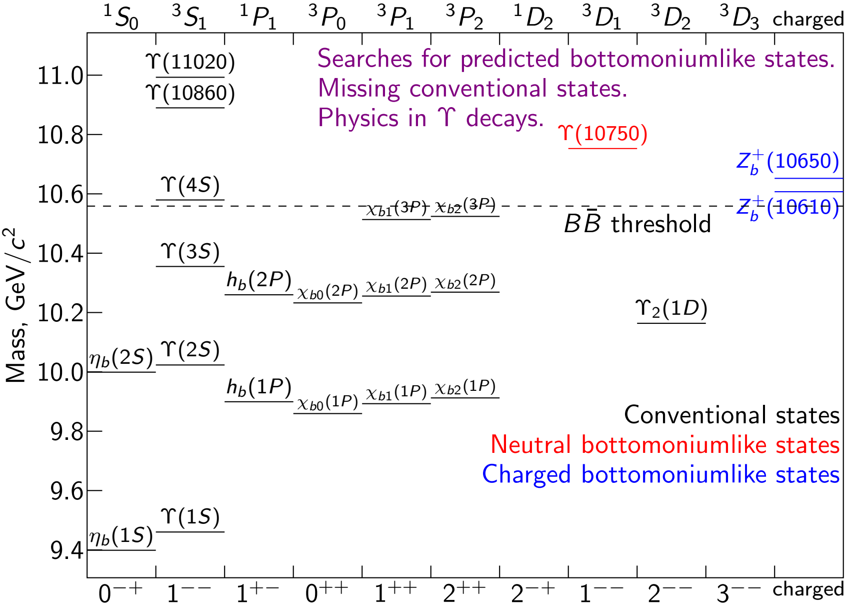
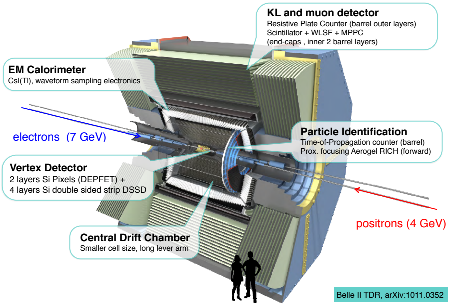
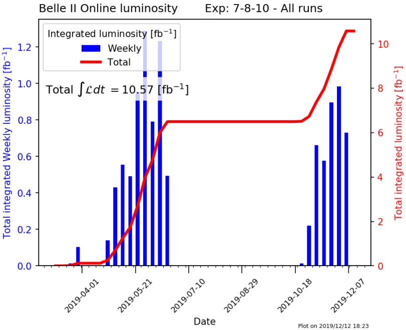


The Belle II experiment



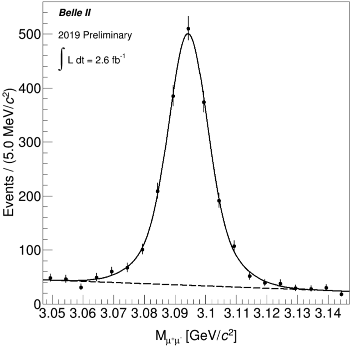


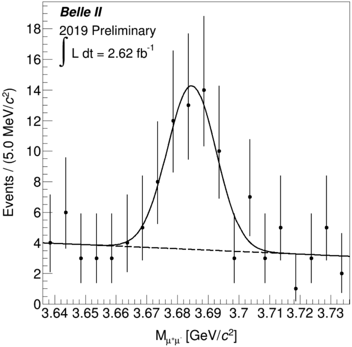
- The Belle II experiment operates at the e^+e^- collider SuperKEKB (the operation is mostly planned at the $\Upsilon(4S)$ resonance with $B\bar{B}$ pair producton). The experiment and collider are designed to collect a much larger data sample compared to the old Belle experiment: $\approx 1\ \mathrm{ab}^{-1} \to 50\ \mathrm{ab}^{-1}$.
- A data sample of $\approx 10\ \mathrm{fb}^{-1}$ was collected in 2019. The 2020 run will start soon.
- The data sample is currently too small for new quarkonium results. However, it is already possible to look at some known quarkonium states or exclusive B decays to the J/ψ or $\psi(2S)$ and other particles.

Current quarkonium studies

Inclusive J/ψ and $\psi(2S)$ from B decays

Inclusive production of the J/ψ and $\psi(2S)$ in B decays is observed in the $\mu^+\mu^-$ decay mode using a data sample of 2.62 fb^{-1}. The tracks are required to be identified as muons. Charmonia produced from B decays are selected by requiring $R_2 < 0.3$, $p_{\text{cms}} < 4.25$ GeV$/c$, and $N_{\text{tracks}} > 4$, where R_2 is the second normalized Fox-Wolfram moment.





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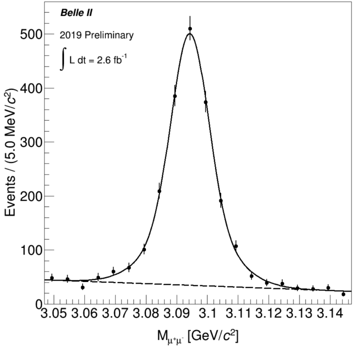
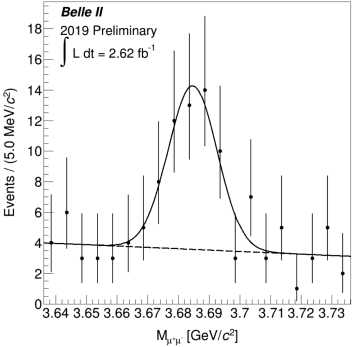
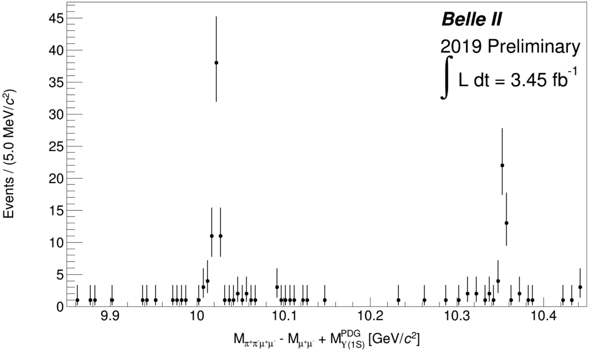




Inclusive production of ψ states is observed.

$\Upsilon(nS) \to \Upsilon(1S)\pi^+\pi^-$

The $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances produced via initial-state radiation are observed in the channel $\Upsilon(nS) \to \Upsilon(1S)\pi^+\pi^-$ using a data sample of 3.45 fb^{-1}. The $\Upsilon(1S)$ is reconstructed in the $\Upsilon(1S) \to \mu^+\mu^-$ decay mode with the requirement $|M_{\Upsilon(1S)} - m_{\Upsilon(1S)}| < 50$ MeV$/c^2$, where $M_{\Upsilon(1S)}$ and $m_{\Upsilon(1S)}$ are the reconstructed and nominal masses, respectively.



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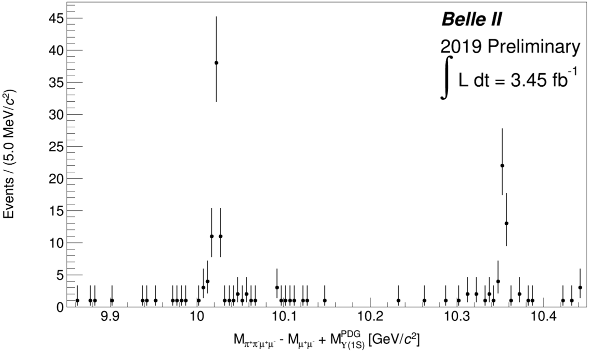
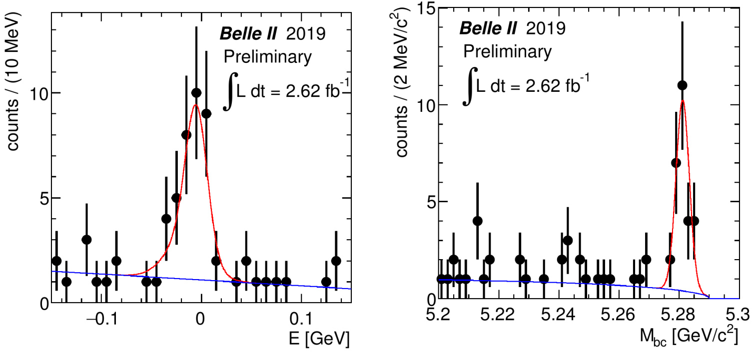


Inclusive production of Υ states is observed.

$B^0 \to J/\psi K_S^0$

The decay $B^0 \to J/\psi K_S^0$ is observed using a data sample of 2.62 fb^{-1}. The decay modes used for reconstruction are $J/\psi \to \mu^+\mu^-$, $J/\psi \to e^+e^-$, and $K_S^0 \to \pi^+\pi^-$.
Fit: ΔE: 2 Gaussians + first-order polynomial, M_{bc}: Gaussian + ARGUS. Yield: 26.9 ± 5.2 (expected: 27.5).



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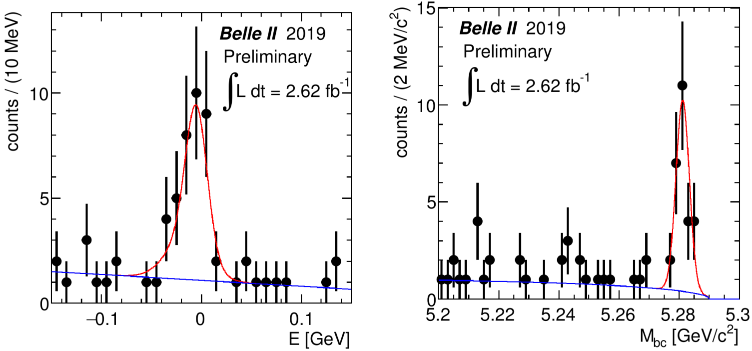
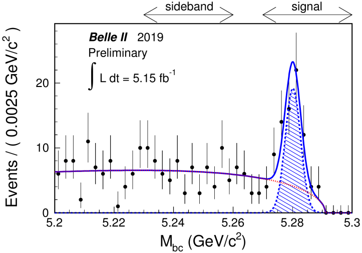


This decay mode is important for CP violation studies.

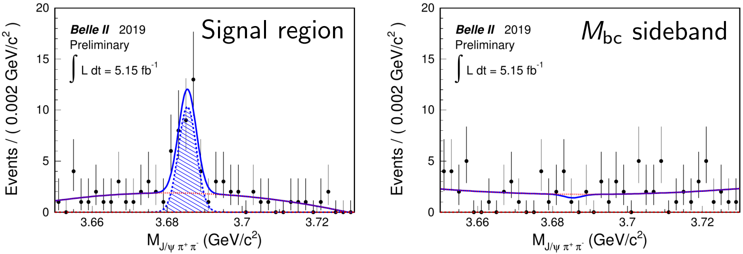
$B \to \psi(2S)K$

The decay $B \to \psi(2S)K$ ($K = K^+, K_S^0$) is observed using a data sample of 5.15 fb^{-1}. The decay modes used for reconstruction are $\psi(2S) \to J/\psi\pi^+\pi^-$, $J/\psi \to \mu^+\mu^-$, $J/\psi \to e^+e^-$, and $K_S^0 \to \pi^+\pi^-$.

M_{bc} fit: ARGUS + Gaussian:



$M_{\psi(2S)}$ fit: Gaussian + second-order polynomial:



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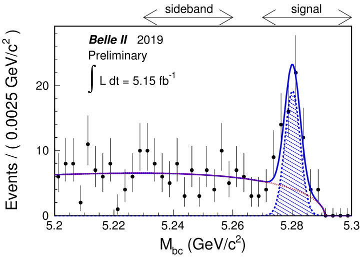

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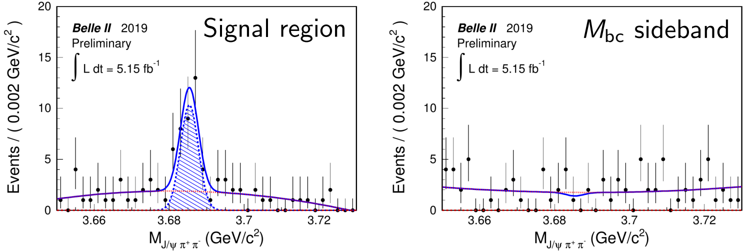
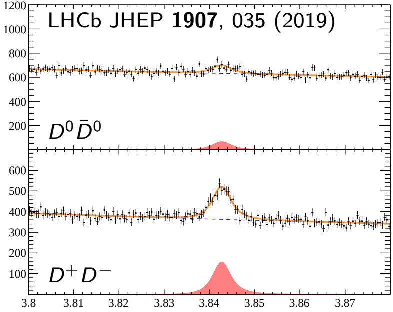


The decay mode $B \to J/\psi\pi^+\pi^-K$ is the $X(3872)$ observation mode.

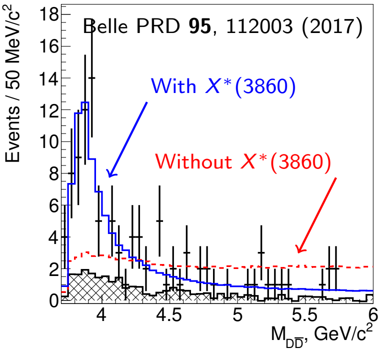
Quarkonium physics program

Conventional charmonium: current status

Observation of the $\psi_3(1D)$ (prompt production)



Observation of the $X^*(3860)$ ($e^+e^- \to J/\psi X^*(3860)(\to D\bar{D})$)



The $\psi_3(1D)$ has not been observed in B decays (although its production should be suppressed because of its high spin: the decay $B \to \psi_3(1D)K$ proceeds in the F-wave). None of the states observed in double charmonium production were observed in B decays.

Conventional charmonium: can be done

1. Search for the $\psi_3(1D)$ in B decays ($B \to D\bar{D}K$).
2. Search for excited conventional states using $B \to D^{(*)}\bar{D}^{(*)}K$, for example, $X^*(3860) \to D\bar{D}$ (expected to be seen in B decays if the $X^*(3860)$ is the $\chi_{c0}(2P)$).
3. Search for the $\eta_{c2}(1D)$ using the channel $\eta_{c2}(1D) \to h_c\gamma$.

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Can be done at Belle II and LHCb.

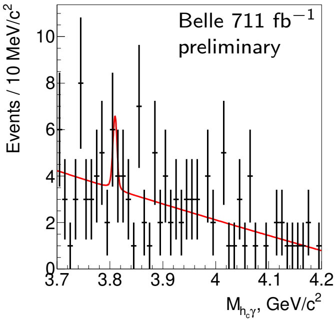
Belle II has a good sensitivity for channels with photons.

The $\eta_{c2}(1D)$ is the only charmonium state without open-charm decays that remains unobserved.

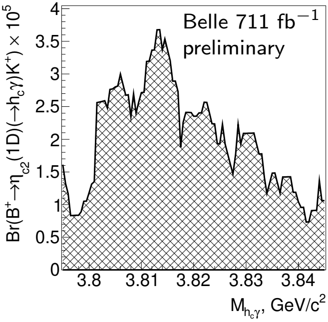
Detailed discussion of the $\eta_{c2}(1D)$ search follows.

A search for the $\eta_{c2}(1D)$ is performed in 4 B decays: $B^+ \to \eta_{c2}(1D)K^+$, $B^0 \to \eta_{c2}(1D)K^0_S$, $B^0 \to \eta_{c2}(1D)\pi^- K^+$, $B^+ \to \eta_{c2}(1D)\pi^+ K^0_S$ with $\eta_{c2}(1D) \to h_c\gamma$, $h_c \to \eta_c\gamma$, and $\eta_c \to$ 10 channels. The $\eta_{c2}(1D)$ search region is from 3795 to 3845 MeV/c^2. No significant signal is found.

$B^+ \to \eta_{c2}(1D)K^+$ signal fit.



$\mathcal{B}$ confidence intervals (90%).



Conventional charmonium: $\eta_{c2}(1D)$ at Belle

NEW

Upper limits (90% C. L.) for any mass within the search range:
$\mathcal{B}(B^+ \to \eta_{c2}(1D)K^+) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma) < 3.7 \times 10^{-5}$,
$\mathcal{B}(B^0 \to \eta_{c2}(1D)K^0_S) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma) < 3.5 \times 10^{-5}$,
$\mathcal{B}(B^0 \to \eta_{c2}(1D)\pi^- K^+) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma) < 1.0 \times 10^{-4}$,
$\mathcal{B}(B^+ \to \eta_{c2}(1D)\pi^+ K^0_S) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma) < 1.1 \times 10^{-4}$.

Theoretical prediction (PRD **94**, 034005 (2016)):
$\mathcal{B}(B^+ \to \eta_{c2}(1D)K^+) = (1.72 \pm 0.42) \times 10^{-5}$, thus,
$\mathcal{B}(B^+ \to \eta_{c2}(1D)K^+) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma) \sim 1.0 \times 10^{-5}$.

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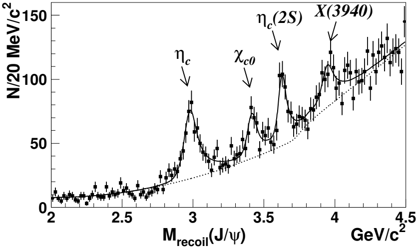
Simple estimate of the required luminosity for Belle II by rescaling:
Sensitivity $\propto S/\sqrt{S+B} \propto \sqrt{\mathcal{L}}$.
Required luminosity: $\mathcal{L} \propto (\mathcal{B}_{\text{observed limit}}/\mathcal{B}_{\text{theory}})^2 \mathcal{L}_{\text{Belle}} \approx 10\ \text{ab}^{-1}$.
While this estimate does not account for difference of reconstruction efficiency or background conditions, that can modify it, with full luminosity of 50 ab^{-1} Belle II should certaintly be able to observe the $\eta_{c2}(1D)$ or exclude the predicted branching fraction.

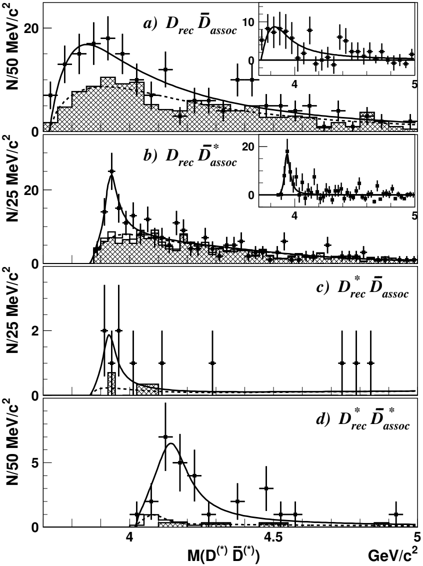
Double charmonium production: current status

Belle PRL **98**, 092001 (2007)



The $X(3940)$ ($X(4160)$) was observed in $e^+e^- \to J/\psi D^* \bar{D}^{(*)}$. The $X(3940)$ was also observed in inclusive $e^+e^- \to J/\psi X$ events. Channels without the J/ψ require more statistics for their study. It was done in PRD **79**, 071101 for the $\psi(2S)$, χ_{c1}, and χ_{c2}, but only the $e^+e^- \to \psi(2S)X$ spectrum has significant signals.

Belle PRL **100**, 202001 (2008)



Double charmonium production: can be done

1. All observed exclusive processes are of the type $e^+e^- \to (c\bar{c})_{J=1}(c\bar{c})_{J=0}$. Is this rule valid for the reconstructed state that is not the J/ψ or $\psi(2S)$? One can try to study $e^+e^- \to \eta_c X$, $e^+e^- \to \chi_{c0} X$; these analyses are difficult due to hadronic decays of the reconstructed charmonium states and, if possible, require large statistics.
2. Amplitude analyses of $e^+e^- \to J/\psi D^* \bar{D}$ and $e^+e^- \to J/\psi D^* \bar{D}^*$ to measure the quantum numbers of the $X(3940)$ and $X(4160)$, respectively. Updated amplitude analysis of $e^+e^- \to J/\psi D\bar{D}$ to measure the $X^*(3860)$ quantum numbers with certainty.
3. Analysis of the $e^+e^- \to \psi(2S) D^{(*)} \bar{D}^{(*)}$, measurement of the $X^*(3860)$, $X(3940)$, $X(4160)$ production in the above processes.

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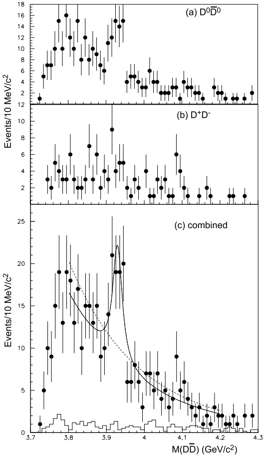
Unique for Belle II!

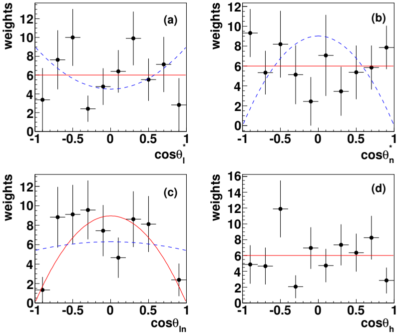
Charmonium in two-photon processes: current status

Conventional states, e.g.: $\chi_{c2}(2P)$
Belle PRL **96**, 082003 (2006)



This is the only state with an open-charm decay observed in $\gamma\gamma$.

J^P of the $X(3915)$: 0^+ vs. 2^+
BaBar PRD **86**, 072002 (2012)



BaBar assumed that for $J = 2$ $\lambda = \pm 2$, without this assumption 2^+ is not excluded [see PRL **115**, 022001 (2015)].

Charmonium in two-photon processes: can be done

1. Measurement of the $X(3915)$ quantum numbers without any restrictions on its helicity.
2. Amplitude analysis of the $\chi_{c2}(2P)$, measurement of the production amplitudes with $\lambda = \pm 2$ and $\lambda = 0$.
3. Search for charmonium states produced in $\gamma\gamma$ decaying to $D^* \bar{D}$ or $D^* \bar{D}^*$.
4. Updated analysis of the $J/\psi\phi$, check of the $X(4350)$ existence.

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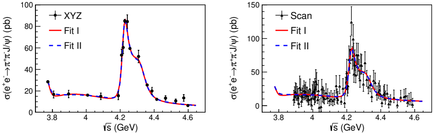
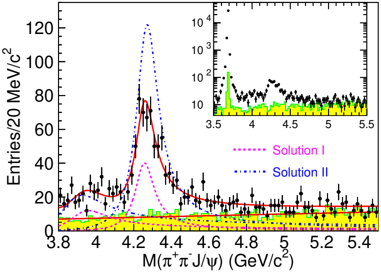
Unique for Belle II!

Charmonium in ISR: current status

Cross section of $e^+e^- \to J/\psi\pi^+\pi^-$
BESIII PRL **118**, 092001 (2017)



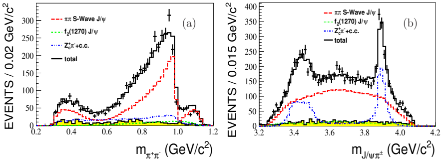
Belle PRL **110**, 252002 (2013)



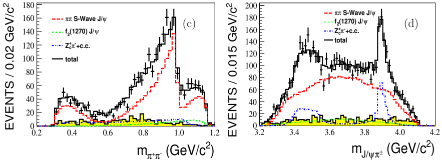
Comparison of Belle and BESIII (latest high-statistic analyses for BESIII).

Observation of $Z_c(3900)^+ \to J/\psi\pi^+$
BESIII PRL **119**, 072001 (2017)

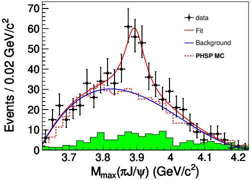
$\sqrt{s} = 4.23$ GeV



$\sqrt{s} = 4.63$ GeV



Belle PRL **110**, 252002 (2013)



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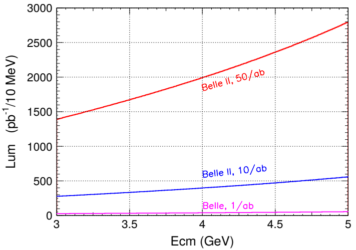
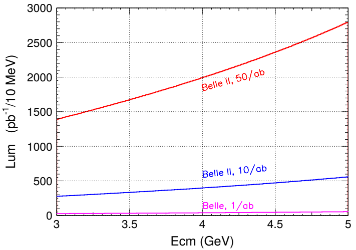


- Comparable samples for e.g. $e^+e^- \to J/\psi\pi^+\pi^-$.
- Access for high-energy region (current limit for BESIII is 4.6 GeV).
- Data are accumulated at the same time for all energies - simplifies lineshape analysis.

1. Improved measurements and fits of $e^+e^- \to \gamma_{\text{ISR}}(c\bar{c})(X)$ cross sections.
2. Improved measurements and fits of the open-charm cross-sections, for example $e^+e^- \to \gamma_{\text{ISR}} D^{(*)}\bar{D}^{(*)}(X)$
3. Measurements of higher mass open-charm channels, for example $e^+e^- \to \gamma_{\text{ISR}}\Sigma_c^+\overline{\Sigma}_c^-$.
4. Analyses of the channels that are currently studied at BESIII only, for example $e^+e^- \to h_c\pi^+\pi^-$ with confirmation of the $Z_c(4020)^+$.

Charmonium in ISR: can be done



- Comparable samples for e.g. $e^+e^- \to J/\psi\pi^+\pi^-$.
- Access for high-energy region (current limit for BESIII is 4.6 GeV).
- Data are accumulated at the same time for all energies - simplifies lineshape analysis.

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2. Improved measurements and fits of the open-charm cross-sections, for example $e^+e^- \to \gamma_{\rm ISR}D^{(*)}\bar{D}^{(*)}(X)$
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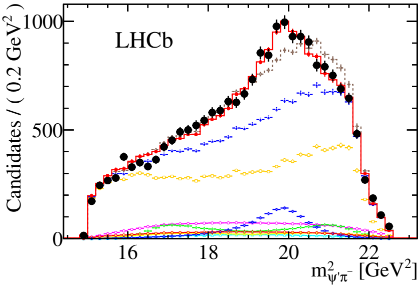
4. Analyses of the channels that are currently studied at BESIII only, for example $e^+e^- \to h_c\pi^+\pi^-$ with confirmation of the $Z_c(4020)^+$.

Can be done at Belle II and BESIII with direct production.

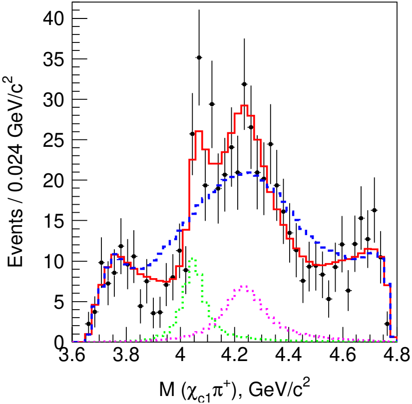
Charged charmoniumlike states: current status

$Z_c(4430)^+$ ($B^0 \to \psi(2S)\pi^- K^+$)
LHCb PRL **112**, 222002 (2014)



Belle (first J^P): PRD **88**, 074026 (2013)
(These analyses are the latest ones; observed by Belle in PRL **100**, 142001 (2008).)

$Z_c(4050)^+$, $Z_c(4250)^+$
($B^0 \to \chi_{c1}\pi^- K^+$)
Belle PRD **78**, 072004 (2008)



Only the $Z_c(4430)^+$ is confirmed (seen by Belle and LHCb), it is studied relatively well now. Other charged charmoniumlike states observed in B decays are not confirmed; the analyses were performed either only at Belle or only at LHCb.

Charged charmoniumlike states: can be done

1. Updated amplitude analysis of $\bar{B}^0 \to \psi(2S)\pi^+ K^-$: confirmation of the LHCb observation of the resonant character of the $Z_c(4430)^+$, confirmation of the $Z_c(4240)^+$ / $R_{c0}(4240)^+$.
2. Confirmation of the $W_{c0}(4100)^+$ in $\bar{B}^0 \to \eta_c \pi^+ K^-$
3. Amplitude analysis of $\bar{B}^0 \to \chi_{c1}\pi^+ K^-$, measurement of the $Z_c(4050)^+$ and $Z_c(4250)^+$ quantum numbers.
4. Search for the neutral partners of all charged charmoniumlike states observed in B decays.
5. Amplitude analyses of unexplored channels, for example $\bar{B}^0 \to X(3872)\pi^+ K^-$.
6. Search for the $Z_c(3900)^+$ in $\bar{B}^0 \to J/\psi \pi^+ \pi^- K^+$.
7. Search for decays of charged charmoniumlike states to $D^{(*)}\bar{D}^{(*)}$ in $B \to D^{(*)}\bar{D}^{(*)} K$.

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Can be done at Belle II and LHCb.

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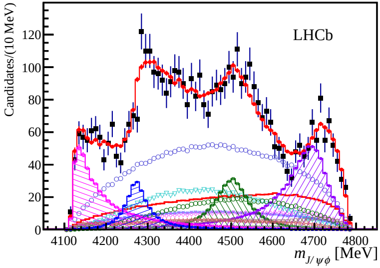
Can be done at Belle II and LHCb.

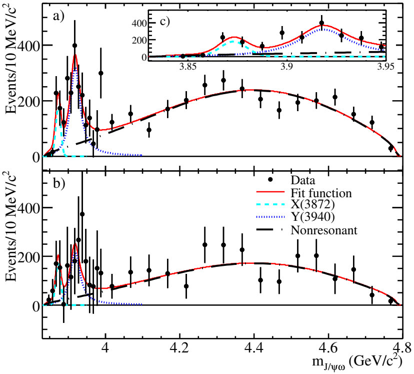
Belle II has a good sensitivity for neutral partners.

Neutral charmoniumlike states: current status

$B^+ \to J/\psi\phi K^+$
LHCb PRL **118**, 022003 (2017)
(amplitude analysis)



$B \to J/\psi\omega K$
BaBar PRD **82**, 011101 (2010)



While the $X(4140)$ and $X(4274)$ are seen by many experiments, the only amplitude analysis (and observation of two other states), has been performed by LHCb. The $X(3915)$ is also seen by Belle and BaBar, but the amplitude analysis of the decay $B \to J/\psi\omega K$ has never been performed.

Neutral charmoniumlike states: can be done

1. Amplitude analysis of $B \to J/\psi\phi K$, confirmation of 4 states observed by LHCb.
2. Amplitude analysis of $B \to J/\psi\omega K$, measurement of the $X(3915)$ quantum numbers in B decays.
3. Updated search for $B \to Y(4260)(\to J/\psi\pi^+\pi^-)K$ and other $J^{PC} = 1^{--}$ charmoniumlike states.
4. Amplitude analyses of unexplored channels with a J/ψ such as $B \to J/\psi\eta K$ or $B \to J/\psi\eta' K$.
5. Analyses of the above channels with K_S^0.
6. Search for decays of known charmoniumlike states to other final states, for example, $X(3915) \to \eta_c\eta$ ($X(3915)$ should decay to this channel if it is a $c\bar{c}s\bar{s}$ state).
7. Absolute branching fractions for $B \to X(3872)K$, $B \to X(3915)K$.

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Can be done at Belle II and LHCb.

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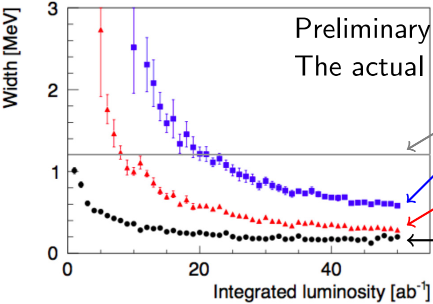
Absolute branching fractions are unique for Belle II!

The $X(3872)$ width: sensitivity

- The current upper limit on the $X(3872)$ width is 1.2 MeV at 90% C. L (Belle PRD **84**, 052004 (2011), from $B \to J/\psi \pi^+ \pi^- K$ data).
- Using the $B \to (D^0 \bar{D}^0 \pi^0)K$ data can significantly improve the mass resolution (near-threshold decay), and, consequently, the total-width sensitivity.
- The sensitivity has been estimated on MC (H. Hirata, master thesis, 2019), the expectation is shown below.



Preliminary and the error is statistical only.
The actual limit should be larger.

Current limit: 1.2 MeV at 90% C. L.

Measureable width (5σ)

Measureable width (3σ)

Limit (90%C.L.) if $\Gamma = 0$ MeV
About 180 keV for full data sample

Bottomonium: $\Upsilon(3S)$ data

Current samples in fb^{-1} (millions of events)

Experiment	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$	$\Upsilon(6S)$	$\frac{\Upsilon(nS)}{\Upsilon(4S)}$
CLEO	1.2 (21)	1.2 (10)	1.2 (5)	16 (17.1)	0.1 (0.4)	-	23%
BaBar	-	14 (99)	30 (122)	433 (471)	R_b scan	R_b scan	11%
Belle	6 (102)	25 (158)	3 (12)	711 (772)	121 (36)	5.5	23%
BelleII	-	-	300 (1200)	5×10^4 (5.4×10^4)	1000 (300)	100+400(scan)	3.6%

1. Inclusive production of charmonium(-like) states in $\Upsilon(nS)$ decays.
2. Double production of charmonium(-like) states in $\Upsilon(nS)$ decays.
3. Amplitude analyses of $\Upsilon(3S) \to \Upsilon(1S, 2S)\pi^+\pi^-$ (possible contribution from bottomonium states).
4. Search for missing $\pi\pi$ and η transitions to lower-mass bottomonium states, suppressed radiative transitions.
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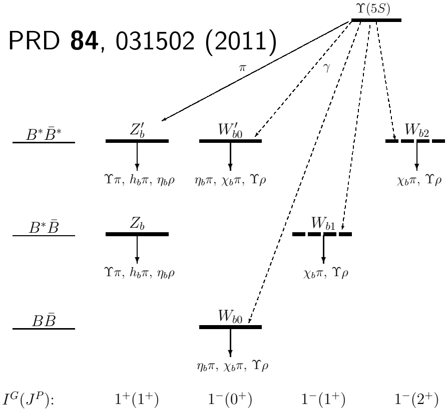
Can be done at Belle and (some topics) LHC experiments.

Bottomonium ($\Upsilon(5S)$ data): can be done

M. Voloshin PRD **84**, 031502 (2011)



Molecular states with quantum numbers other than $I^G = 1^+$, $J^P = 1^+$ are expected to exist. The transitions to such states are radiative and they are consequently suppressed by $\sim \alpha$. However, using the high statistics their observation might be possible.

Bottomonium ($\Upsilon(5S)$ data): can be done

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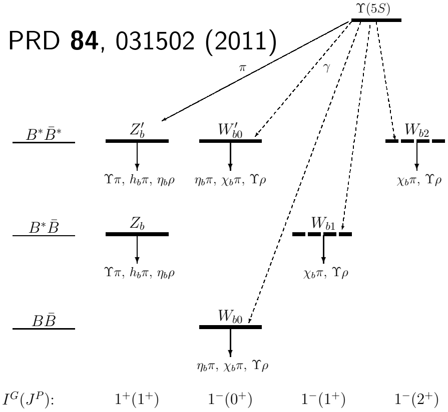

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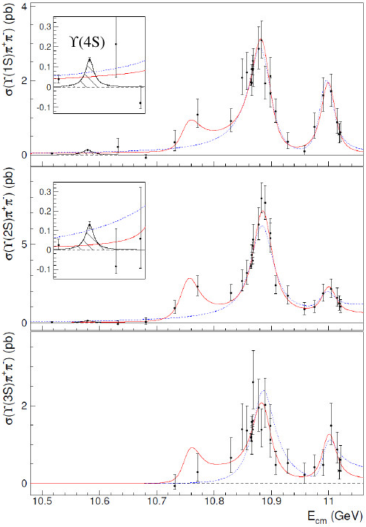
Unique for Belle II!

Bottomonium: $\Upsilon(6S)$ data and $\Upsilon(5S) - \Upsilon(6S)$ scan

Belle JHEP **1910**, 220 (2019)

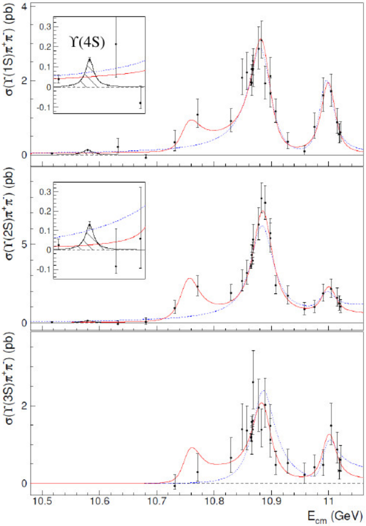


The $\Upsilon(10750)$ is observed by Belle in the scan data in the channel $\Upsilon(nS)\pi^+\pi^-$. Can be done:

1. A study with higher statistics will be possible.
2. Study of $\Upsilon(5S)$ and $\Upsilon(6S)$ lineshapes in other channels.
3. Study of exotic states (e.g. Z_b^+ at $\Upsilon(6S)$).

Bottomonium: $\Upsilon(6S)$ data and $\Upsilon(5S)$ – $\Upsilon(6S)$ scan

Belle JHEP **1910**, 220 (2019)



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Summary

- The expected Belle II data sample of 50 ab^{-1} will provide a lot of new opportunities for physics analyses in the area of quarkonium.
- Some of them, for example, double charmonium production, charmonium in two-photon processes, or bottomonium physics, are unique for Belle II.
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For further details about Belle II physics prospects, see the Belle II Physics Book (PTEP **2019**, 123C01 (2019)).