Belle II prospects in quarkonium physics

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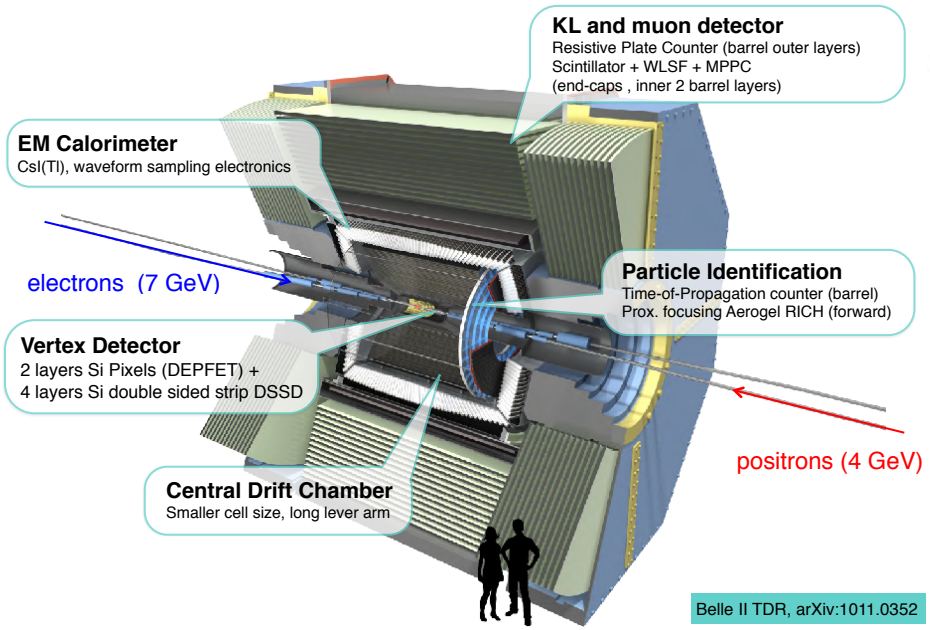
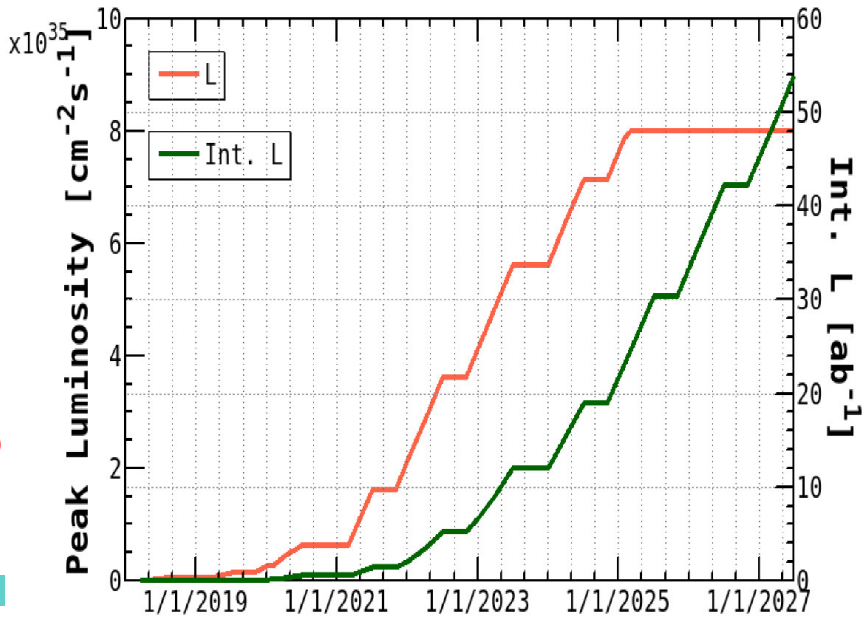
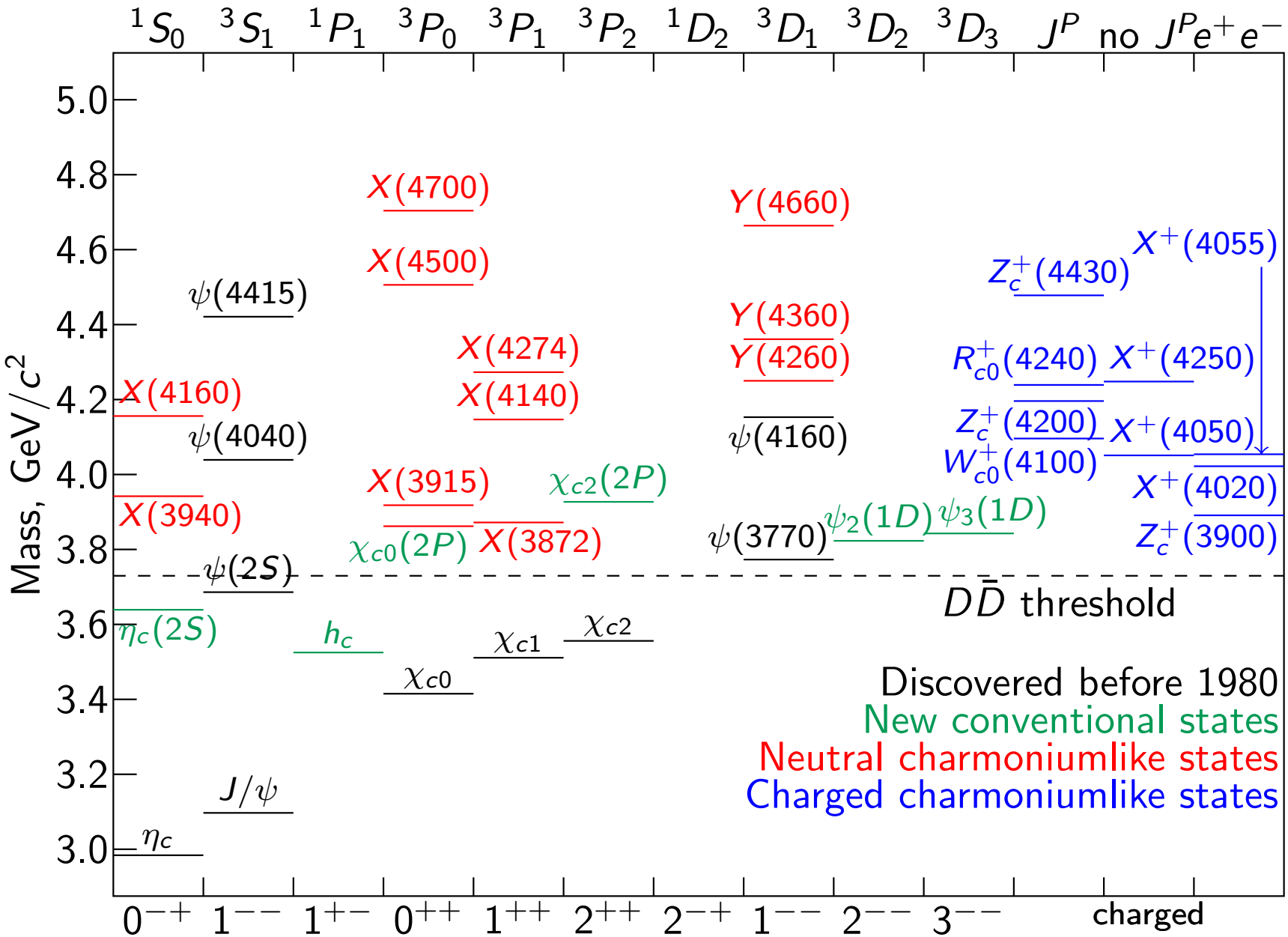
The Belle II experiment



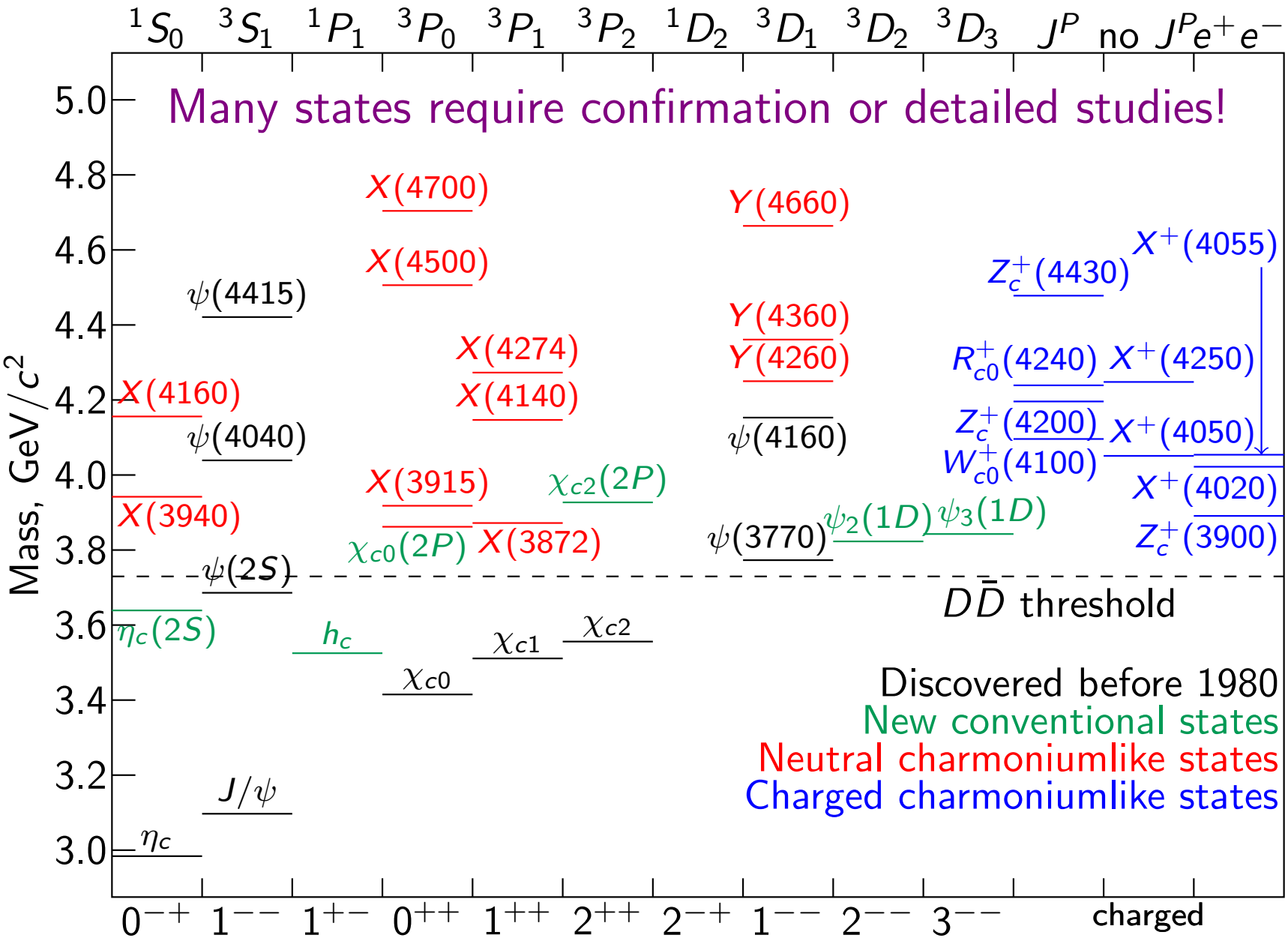


- The Belle II experiment operates at the e^+e^- collider SuperKEKB (the operation is mostly planned at the $\Upsilon(4S)$ resonance with $B\bar{B}$ pair producton). The experiment and collider are designed to collect a much larger data sample compared to the old Belle experiment: $\approx 1\ \mathrm{ab}^{-1} \to 50\ \mathrm{ab}^{-1}$.
- Approximately 0.5 fb^{-1} were collected in 2018 during the "phase 2" data-taking period. The data taking is ongoing now.
- The data sample is currently too small for new quarkonium results $\Rightarrow$ only prospects are discussed.

Charmonium states



Charmonium states



Outline

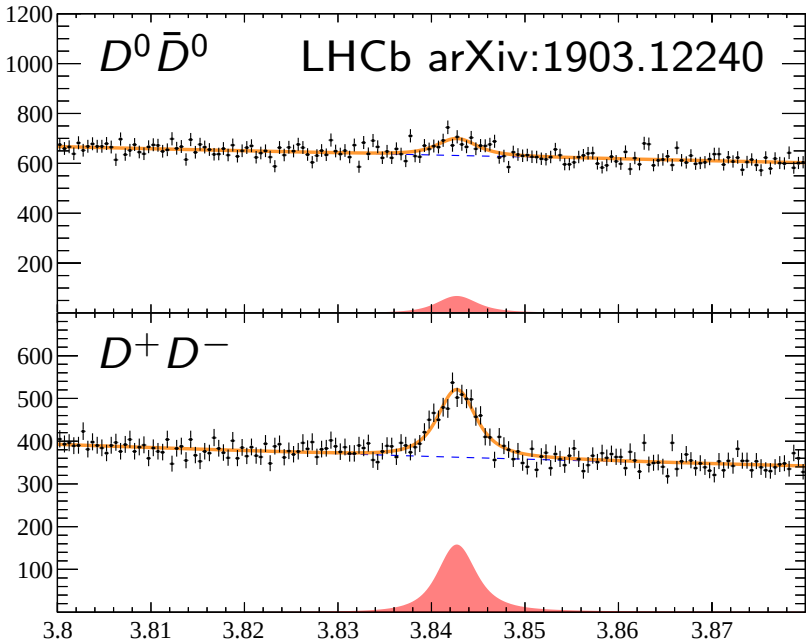
The talk includes summaries of the current status followed by examples of possible analyses at Belle II for the following topics:

1. Conventional charmonium.
2. Double charmonium production.
3. Charmonium in two-photon processes.
4. Charmonium in initial-state radiation (ISR).
5. Charged charmoniumlike states.
6. Neutral charmoniumlike states.
7. The $X(3872)$ width.
8. Bottomonium: $\Upsilon(3S)$ data.
9. Bottomonium: $\Upsilon(5S)$ data.
10. Bottomonium: $\Upsilon(6S)$ data and $\Upsilon(5S) - \Upsilon(6S)$ scan.

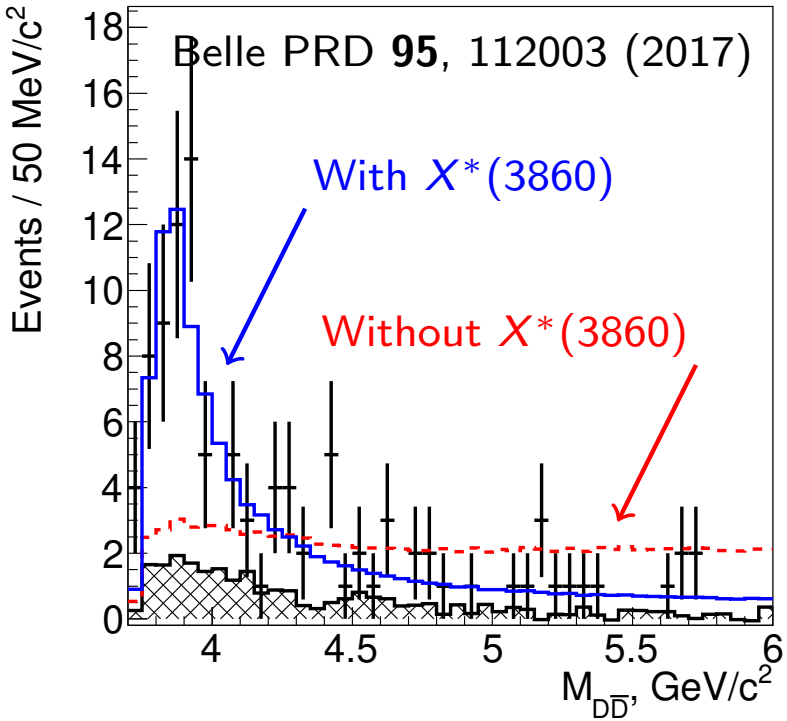
Please note: the selected examples are mostly in the areas of spectroscopy and amplitude analyses.

Conventional charmonium: current status

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



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



The only charmonium state without open-charm decays that remains unobserved is the $\eta_{c2}(1D)$. 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 $\eta_{c2}(1D)$ using the channel $\eta_{c2}(1D) \to h_c\gamma$.
2. Search for the $\psi_3(1D)$ in B decays ($B \to D\bar{D}K$).
3. 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 $\chi_{c0}(2P)$).

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Can be done at Belle II and LHCb.

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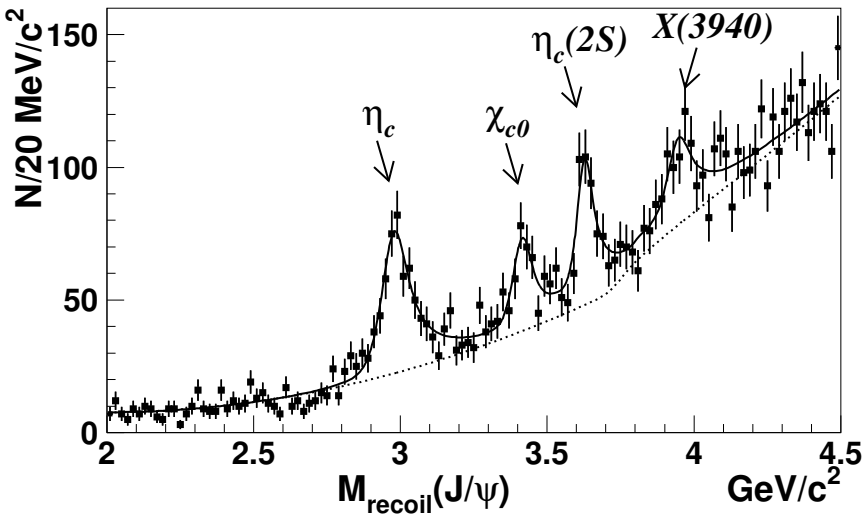
Can be done at Belle II and LHCb.

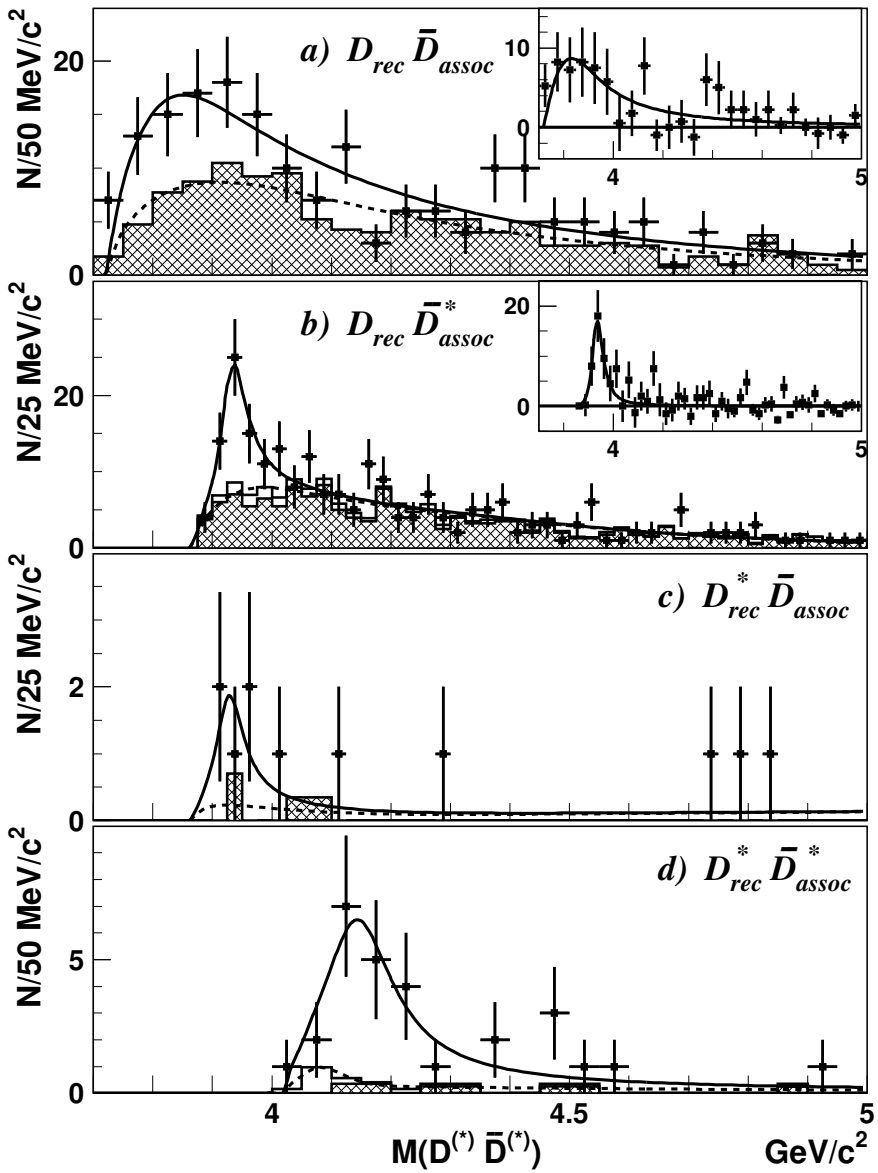
Belle II has a good sensitivity for channels with photons.

Double charmonium production: current status

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



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



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.

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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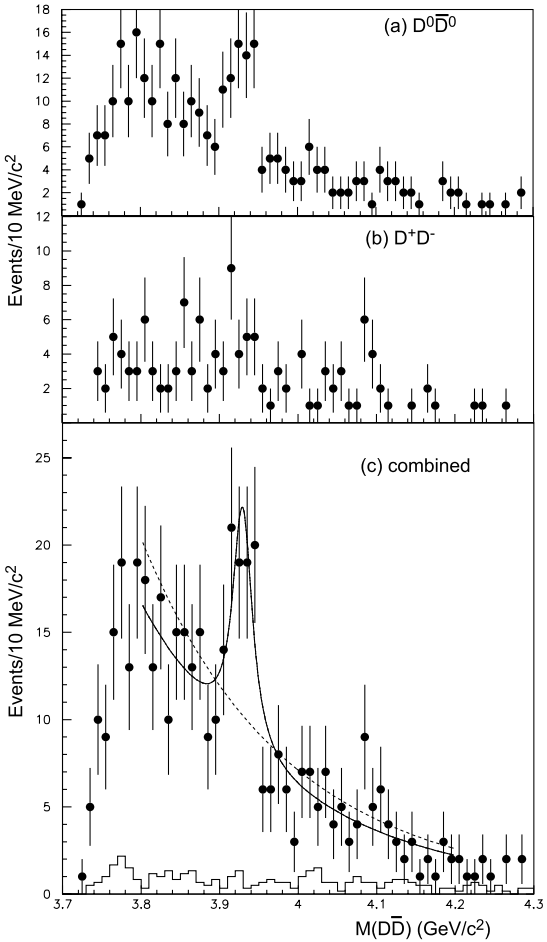
3. Analysis of the $e^+e^- \to \psi(2S) D^{(*)} \bar{D}^{(*)}$, measurement of the $X^*(3860)$, $X(3940)$, $X(4160)$ production in the above processes.

Unique for Belle II!

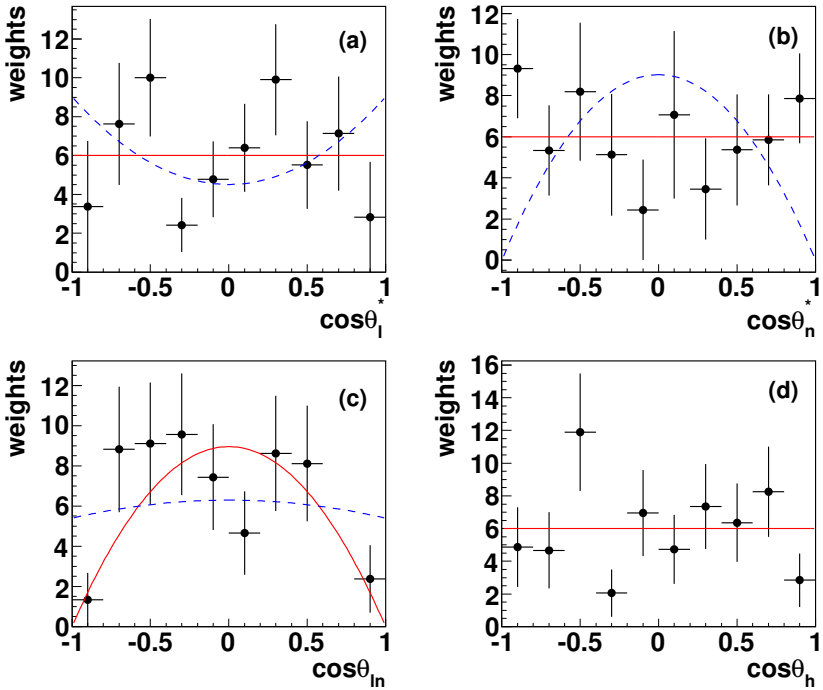
Charmonium in two-photon processes: current status

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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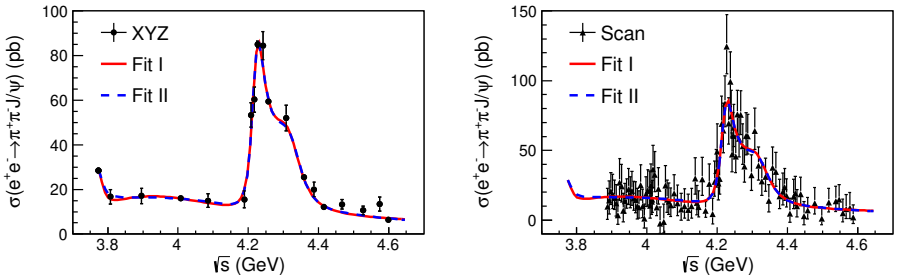
Unique for Belle II!

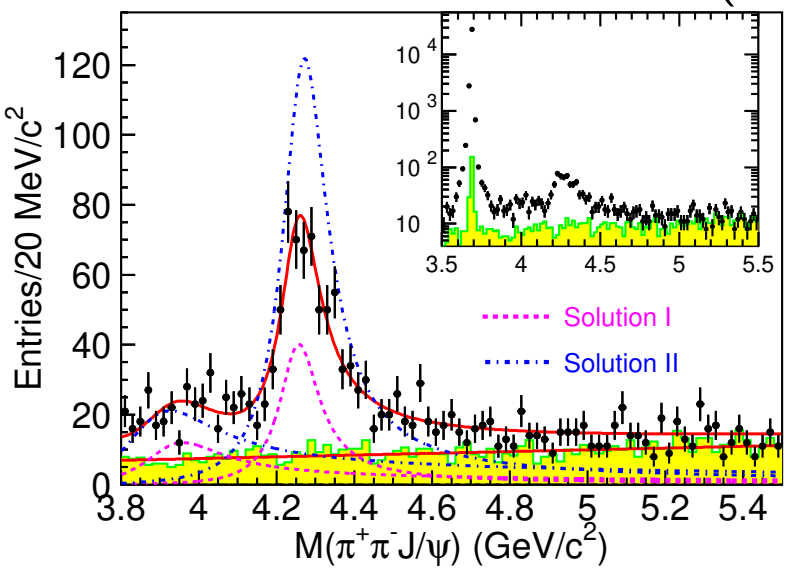
Charmonium in ISR: current status

Cross section of $e^+e^- \to J/\psi\pi^+\pi^-$

BESIII PRL **118**, 092001 (2017)



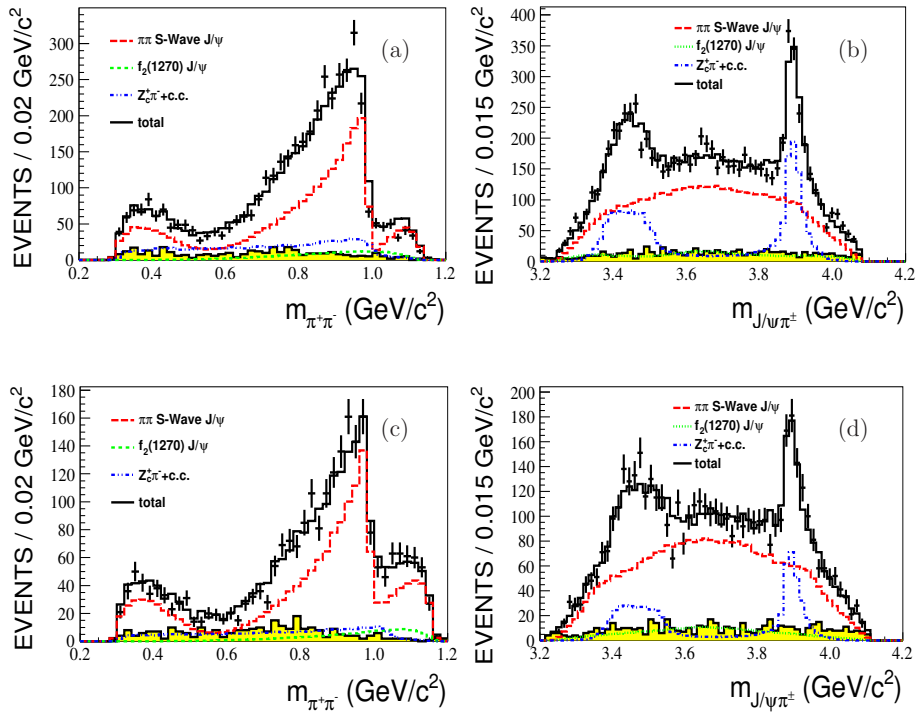
Belle PRL **110**, 252002 (2013)



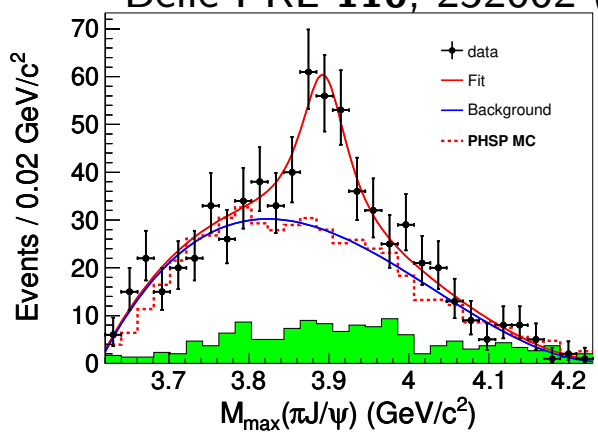
Comparison of Belle and BESIII (latest high-statistic analyses for BESIII).

Observation of $Z_c(3900)^+ \to J/\psi\pi^+$

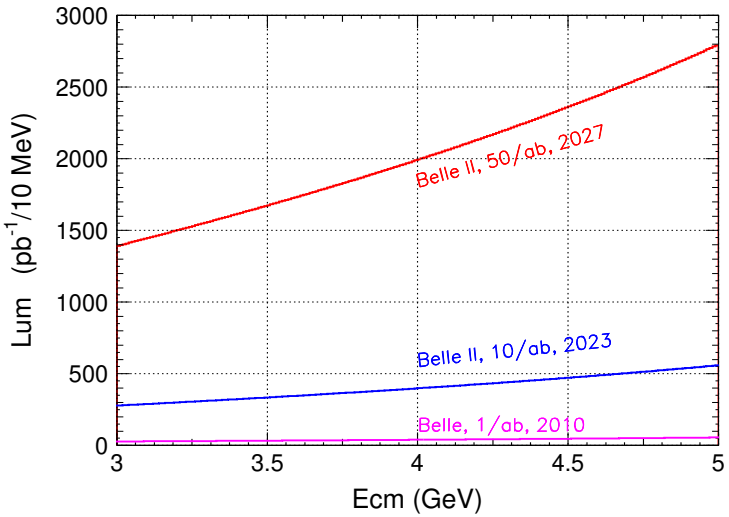
BESIII PRL **119**, 072001 (2017)



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



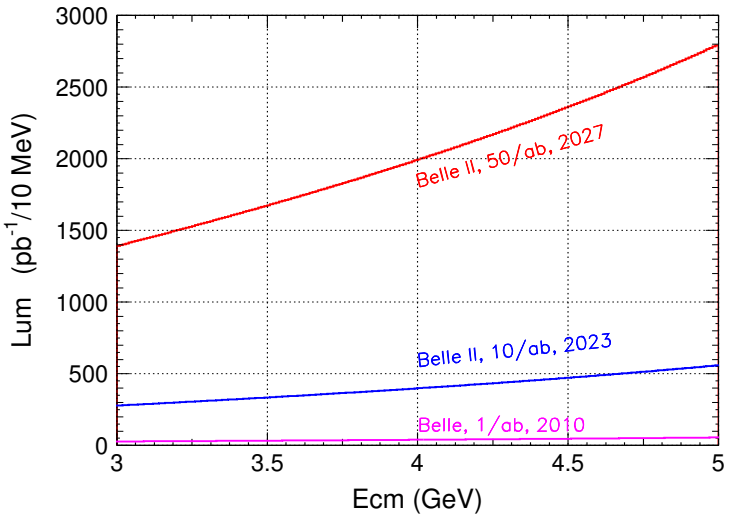
Charmonium in ISR: can be done



- 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.

1. Improved measurements and fits of $e^+e^- \to \gamma_{\rm ISR}(c\bar{c})(X)$ cross sections.
2. Improved measurements and fits of the open-charm cross-sections, for example $e^+e^- \to \gamma_{\rm ISR} D^{(*)}\bar{D}^{(*)}(X)$
3. Measurements of higher mass open-charm channels, for example $e^+e^- \to \gamma_{\rm ISR}\Sigma_c^+\overline{\Sigma}_c^-$.
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



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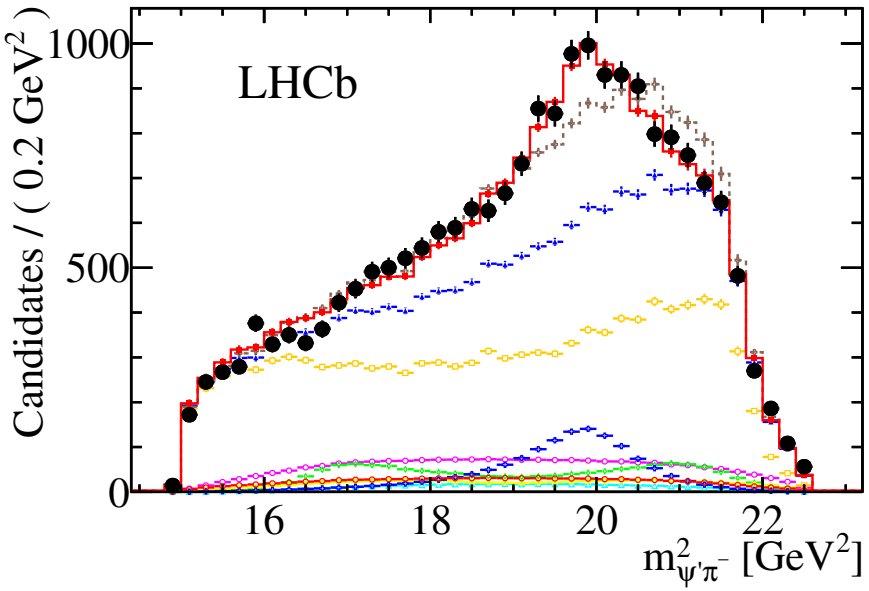
4. Analyses of the channels that are currently studied at BESIII only, for example $e^+e^- \to h_c\pi^+\pi^-$ with confirmation of the $Z_c(4020)^+$.

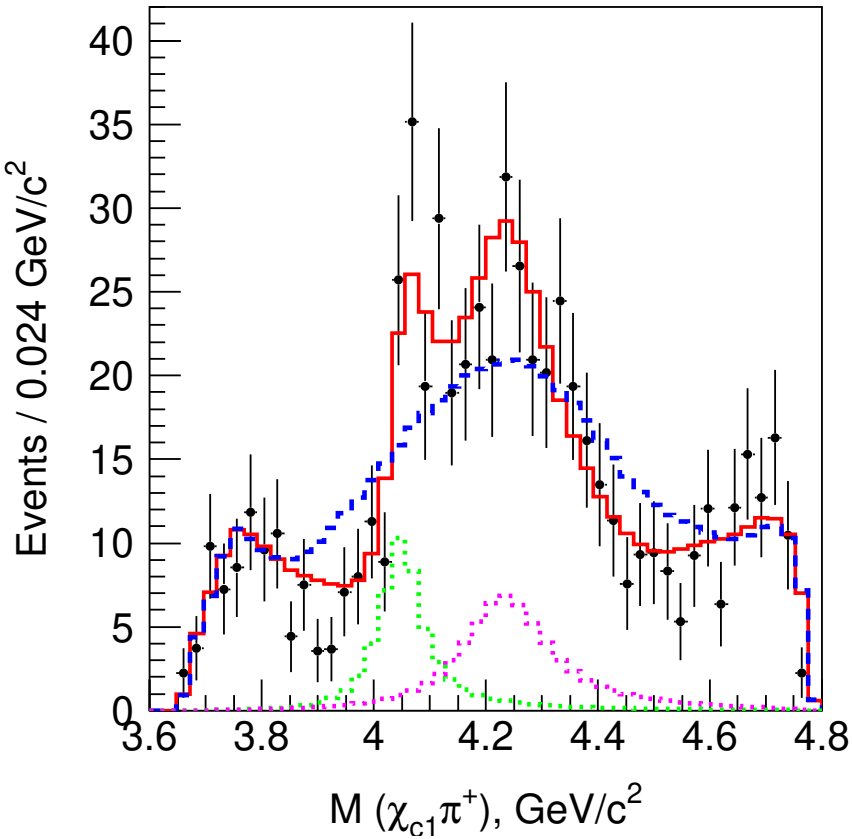
Can be done at Belle II and BESIII with direct production.

Charged charmoniumlike states: current status

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



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



Belle: see PRD **88**, 074026 (2013)

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 $\bar{B}^0 \to X(3872)\pi^+K^-$ (theoretical expectations presented by Eric Braaten).
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 $B \to D^{(*)}\bar{D}^{(*)}K$.

Charged charmoniumlike states: can be done

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Can be done at Belle II and LHCb.

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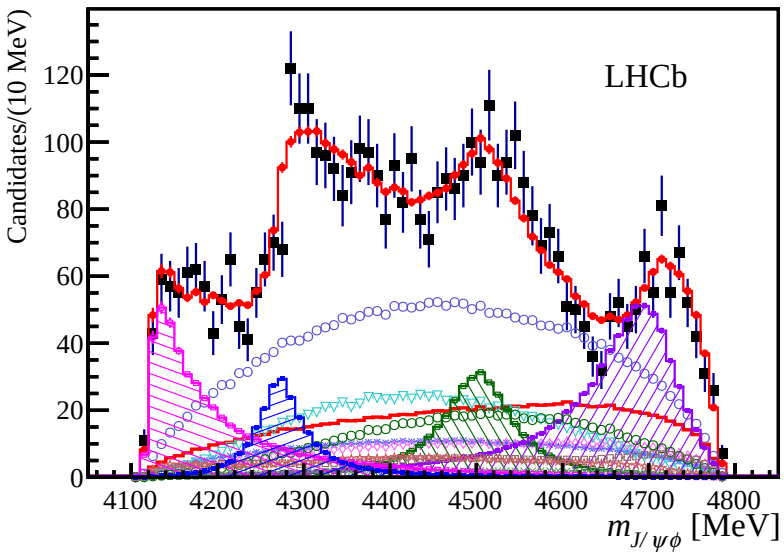
Can be done at Belle II and LHCb.

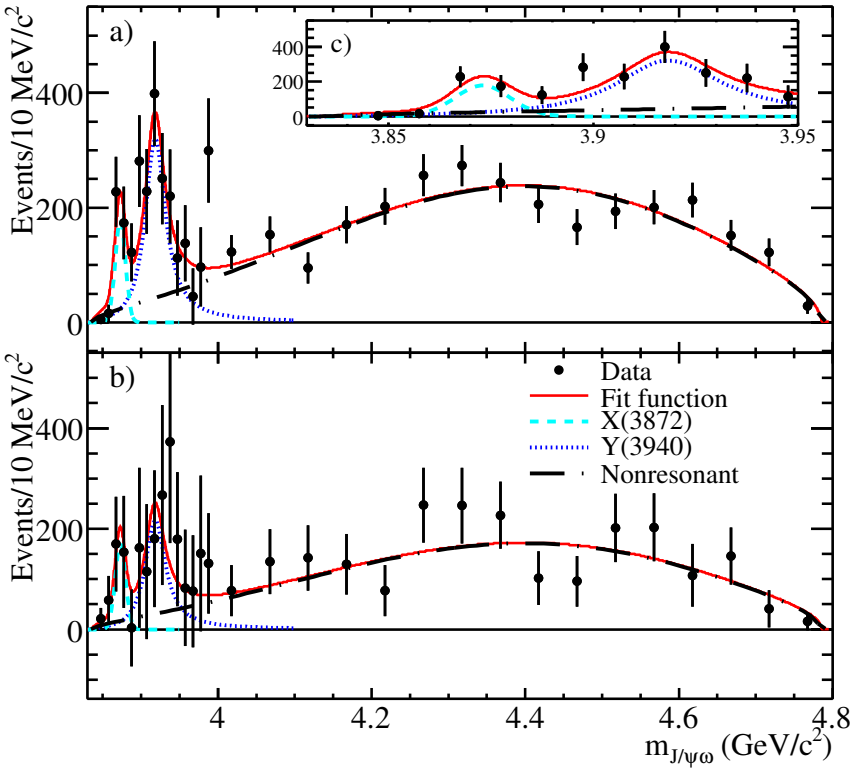
Belle II has a good sensitivity for neutral partners.

Neutral charmoniumlike states: current status

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



$B \to J/\psi\omega K$
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. 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).
6. Absolute branching fractions for $B \to X(3872)K$, $B \to X(3915)K$.

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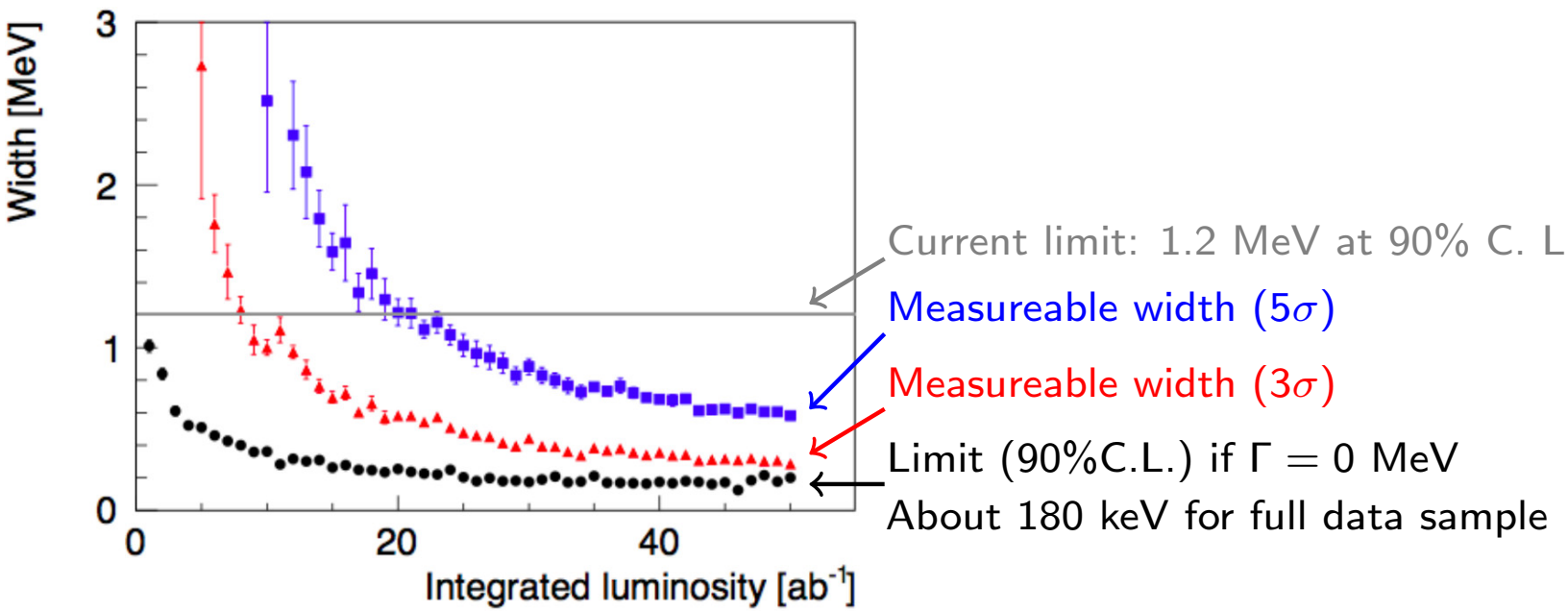
Can be done at Belle II and LHCb.

Absolute branching fractions are unique for Belle II!

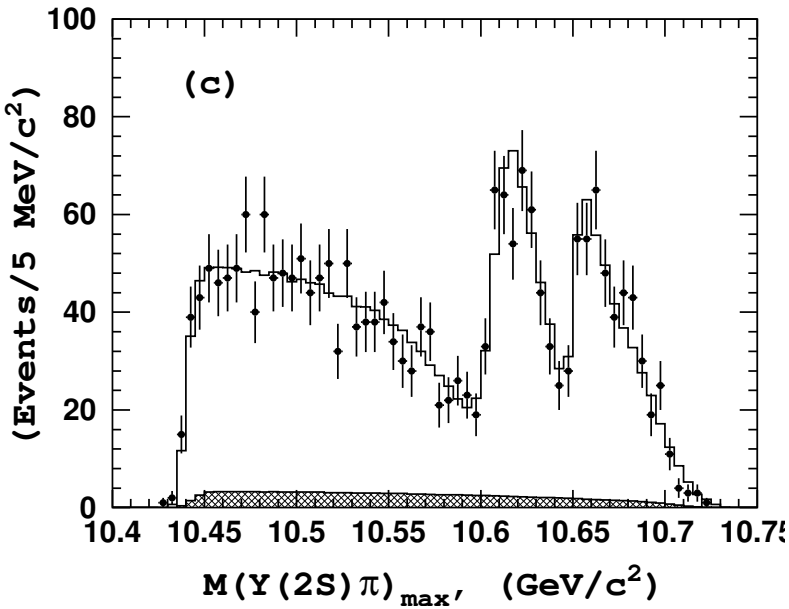
The $X(3872)$ width: sensitivity

- 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.

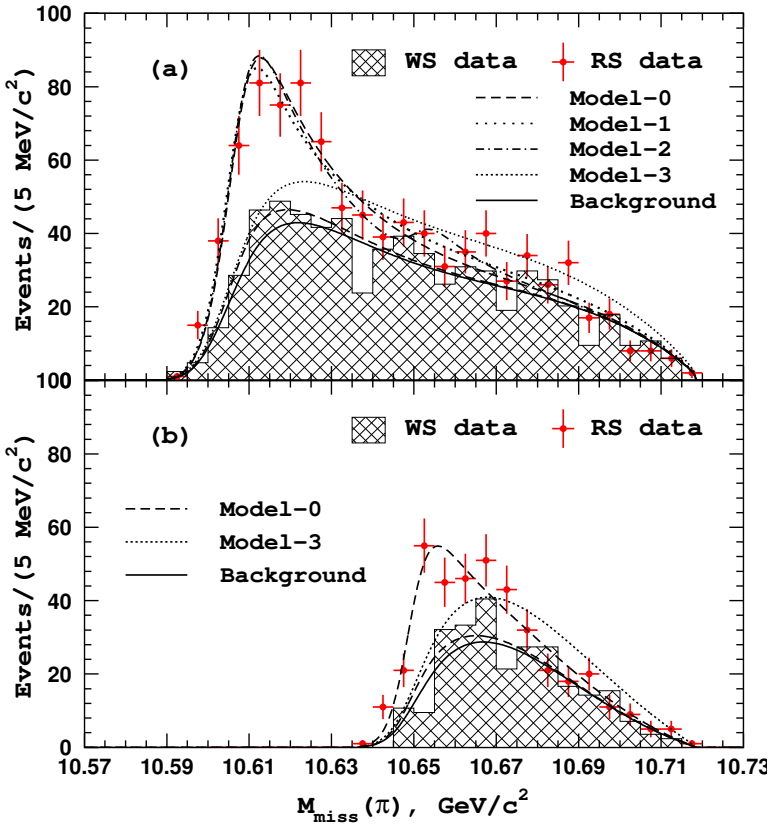


Bottomonium ($\Upsilon(5S)$ data): current status

Observation of the Z_b^+ states
Belle PRL **108**, 122001 (2012)



Observation of $Z_b^+ \to B^* \bar{B}^{(*)}$
Belle PRL **116**, 212001 (2016)



The $Z_b(10610)^+$ and $Z_b(10650)^+$ were observed in $\Upsilon\pi$, $h_b\pi$, and $B^*\bar{B}^{(*)}$. However, Belle is currently the only experiment that has the $Y(5S)$ data necessary to see them: formally they need confirmation.

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.
5. Study of baryons in bottomonia decays.
6. Correlation in $D\bar{D}^*$ production.
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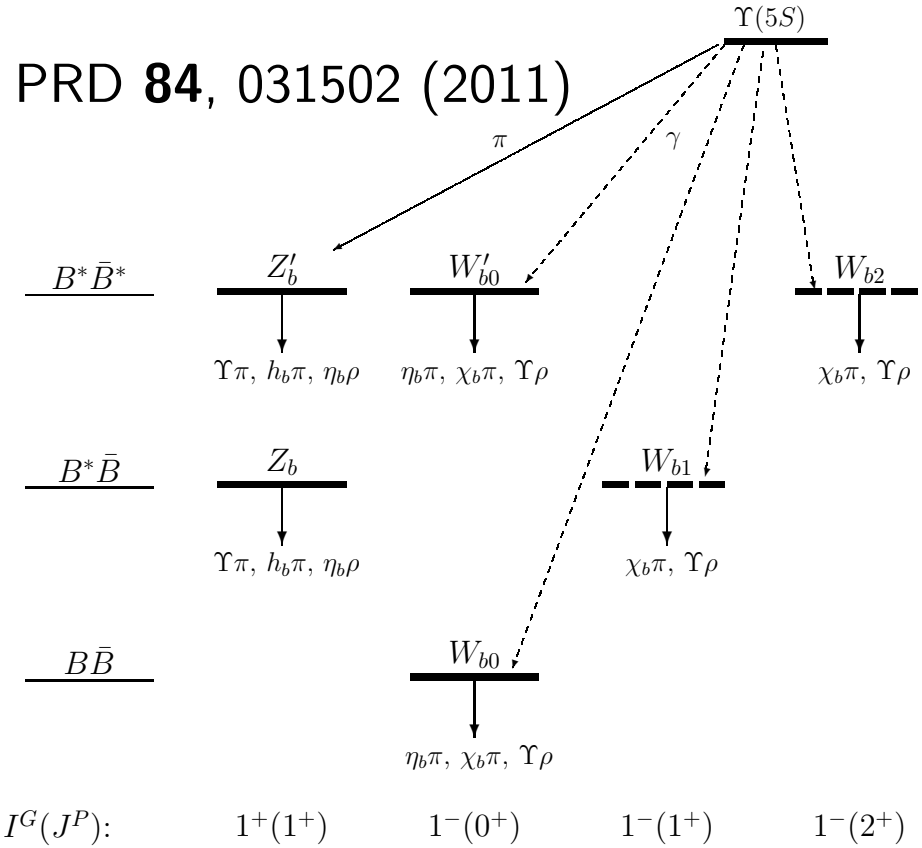
Unique for Belle II!

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.

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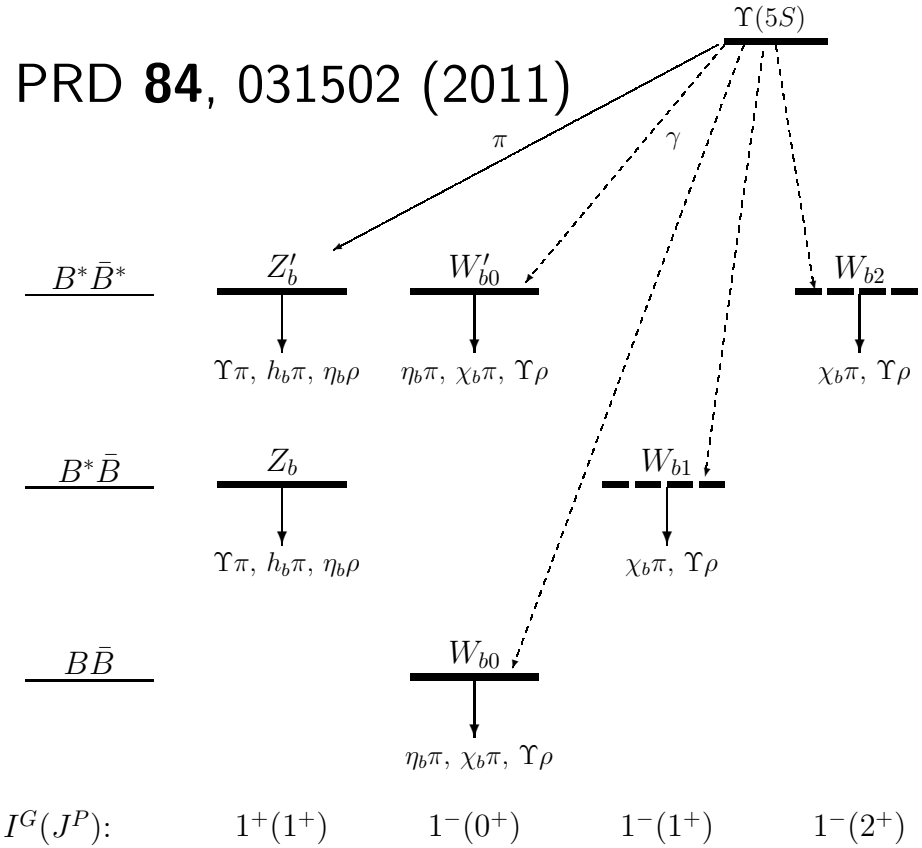

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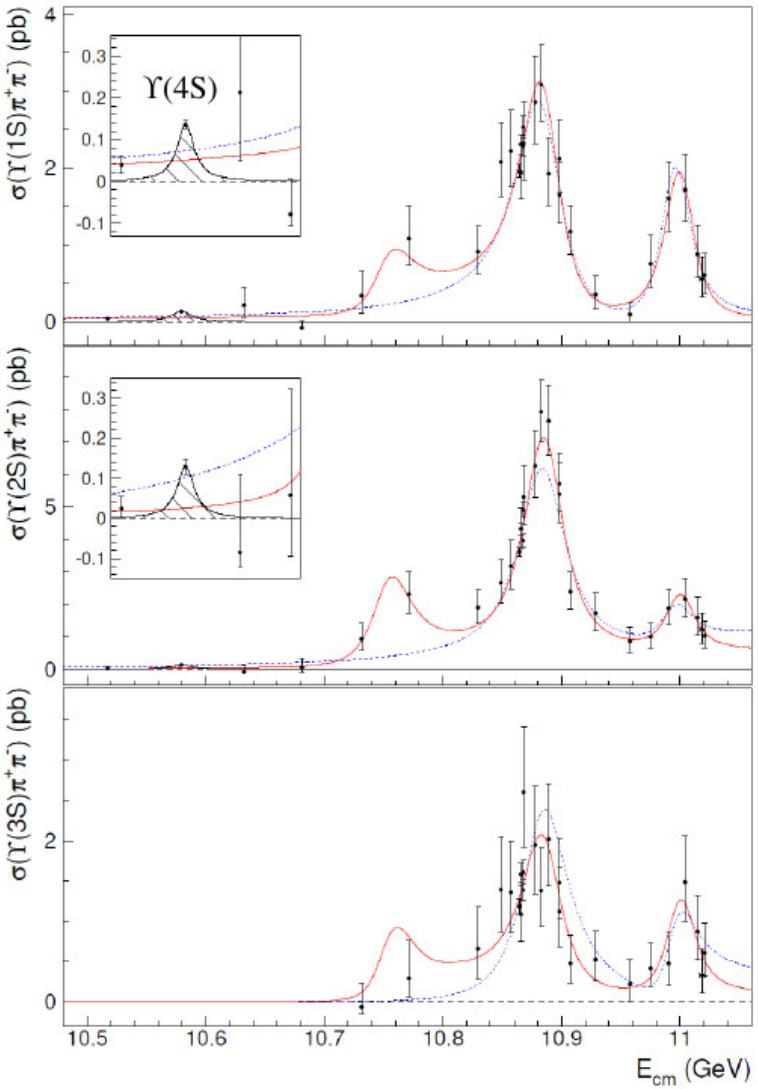

A new structure has just been observed by Belle in the scan data in the channel $\Upsilon\pi^+\pi^-$ (presented by Roman Mizuk).

Can be done:

1. A study with higher statistics will be possible.
2. Study of $\Upsilon(5S)$ and $\Upsilon(6S)$ lineshapes in other channels.
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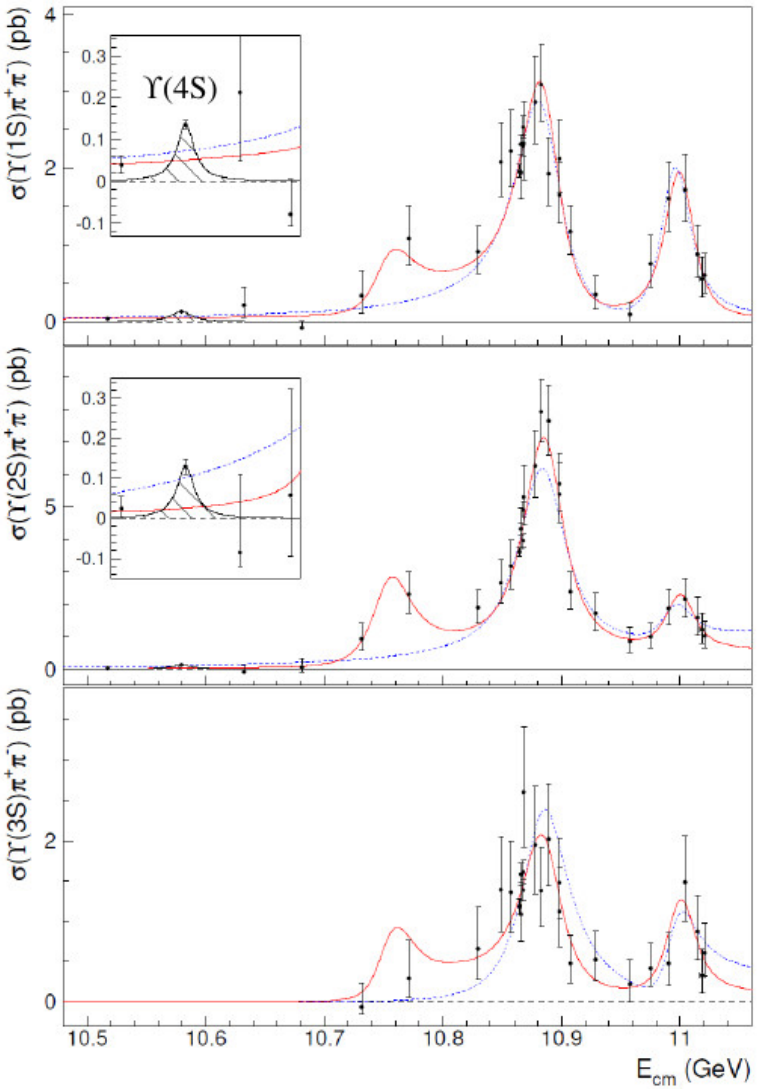

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Summary

- 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.
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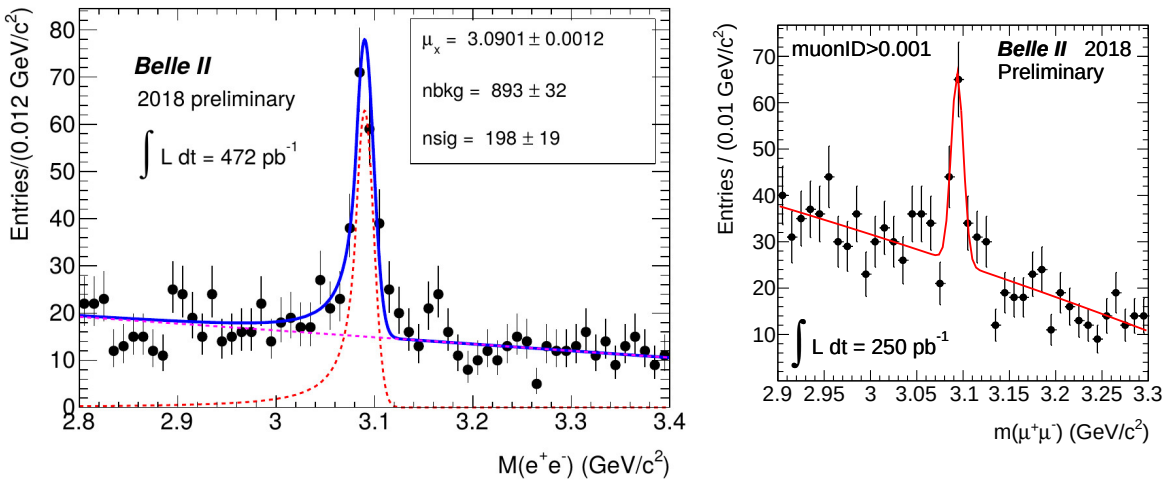

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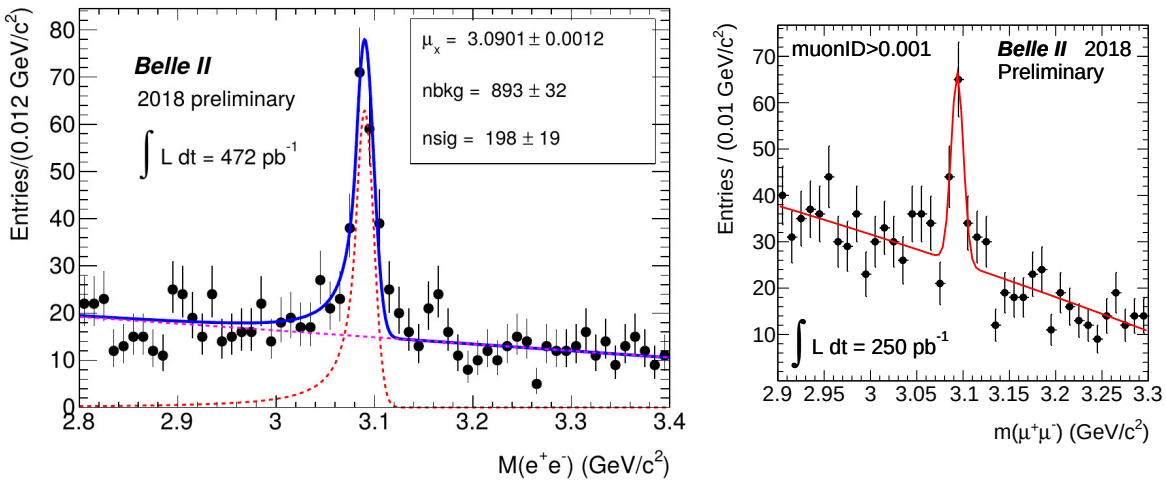

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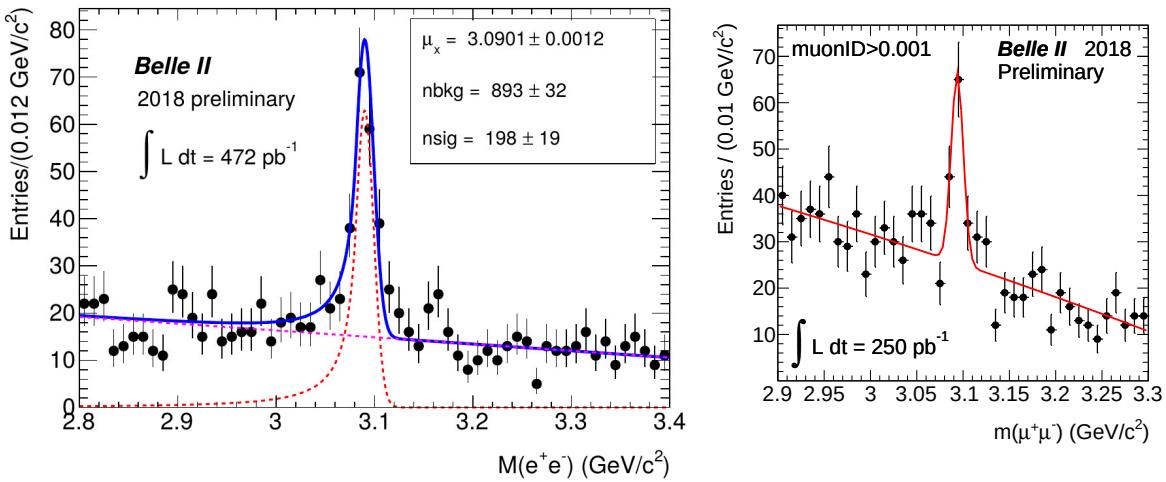

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For further details about Belle II physics prospects, see the Belle II Physics Book (arXiv:1808.10567 [hep-ex]).