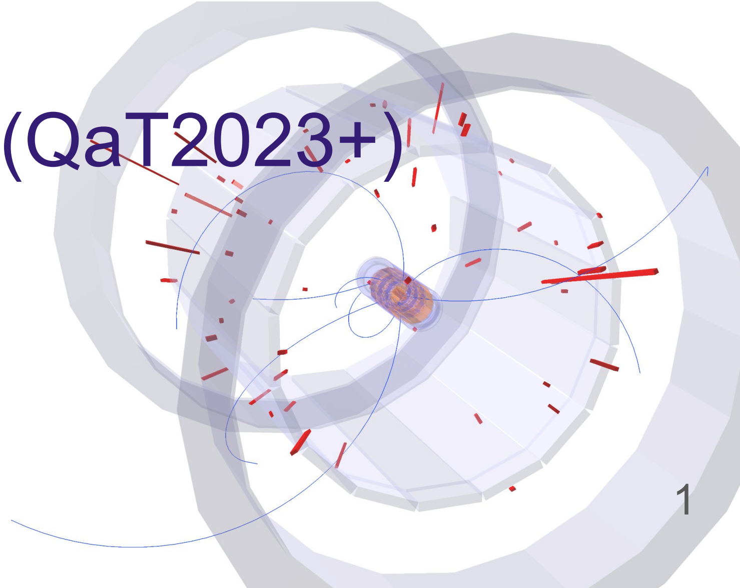
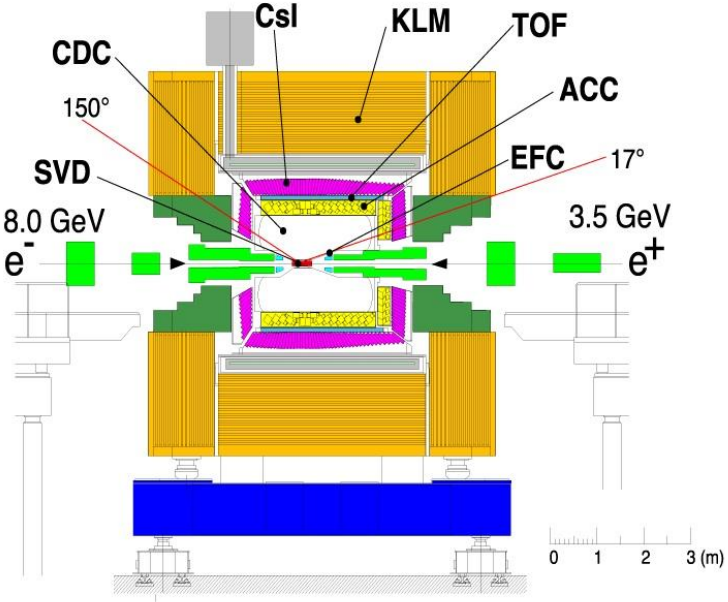
Quarkonium measurements at Belle-II

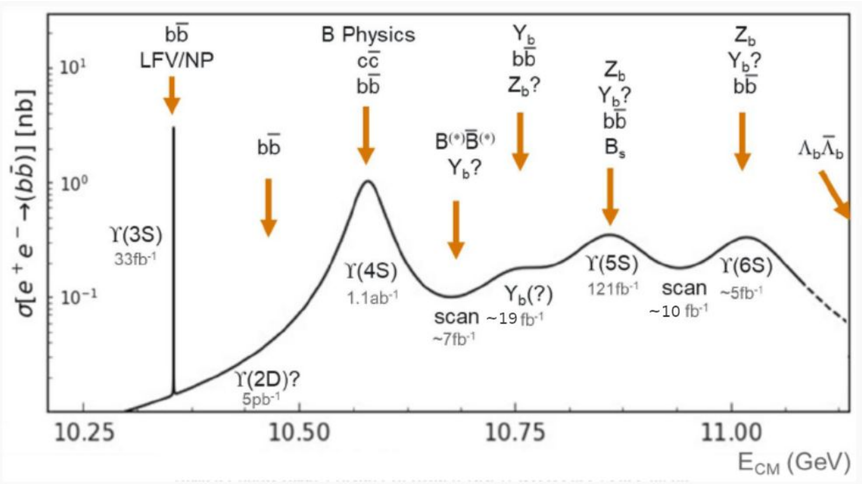
Quarkonia as Tools 2023 (QaT2023+)

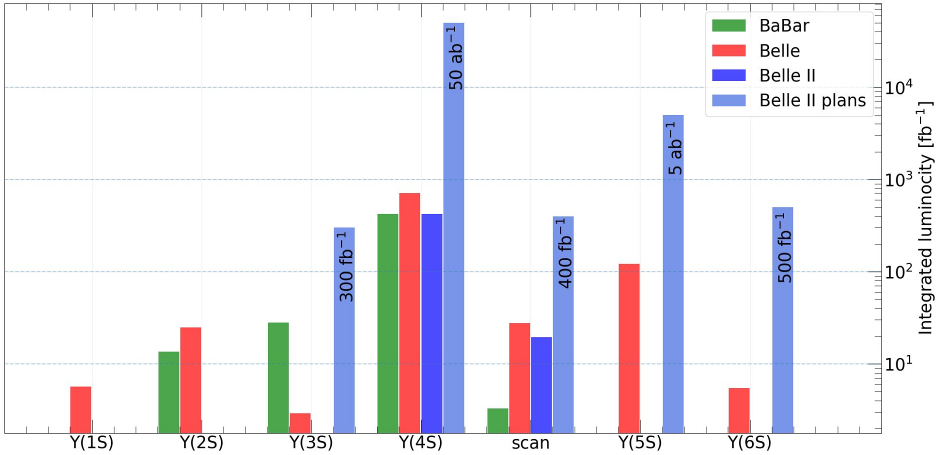
Pavel Oskin
(IJCLab)



KEKB and Belle







Collected data from 1999 to 2010:

- 121 fb^{-1} at Υ(5S) ~7.11 × 10^6 B_sB_s
- 711 fb^{-1} at Υ(4S) ~771 × 10^6 BB
- 3 fb^{-1} at Υ(3S)
- 24 fb^{-1} at Υ(2S)
- 6 fb^{-1} at Υ(1S)
- 26 fb^{-1} scan above Υ(4S)

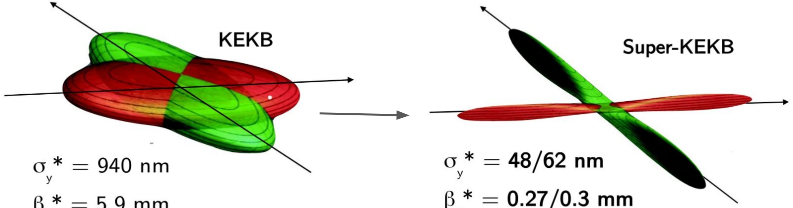
SuperKEKB and Belle II

Beam current increased by **x2**

$$L = \frac{\gamma_\pm}{2 e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Vertical beta function at IP reduced by **1/20**
"Nano-beam" scheme

x40 instant luminosity increase



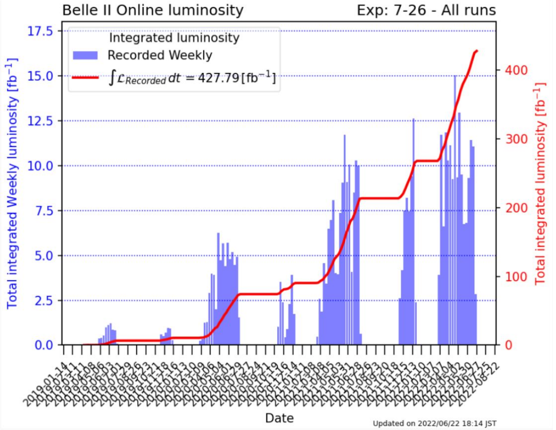
KEKB	Super-KEKB
$\sigma_y^* = 940$ nm	$\sigma_y^* = 48/62$ nm
$\beta_y^* = 5.9$ mm	$\beta_y^* = 0.27/0.3$ mm
$\sigma_x^* = 147/170$ µm	$\sigma_x^* = 10.1/10.7$ µm

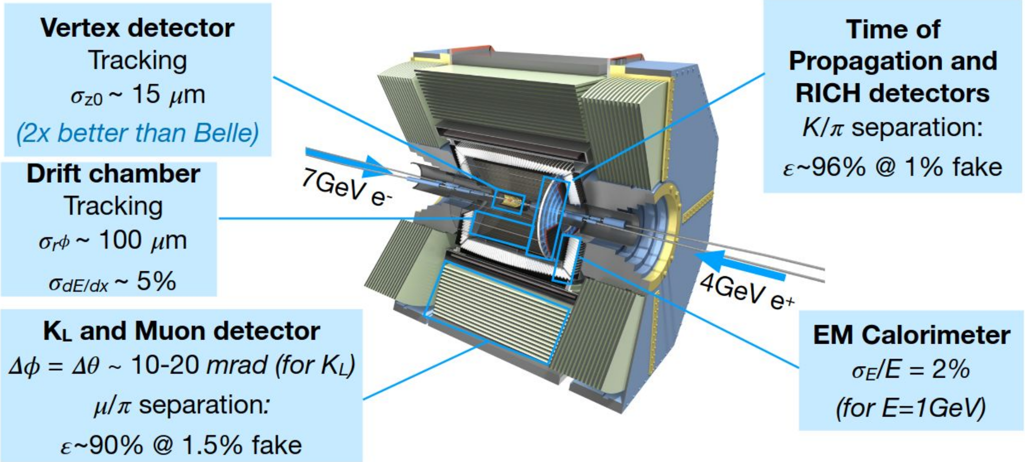
Collected data:

- 424 fb^{-1} at Υ(4S)
- 19 fb^{-1} scan above Υ(4S)

Goal:

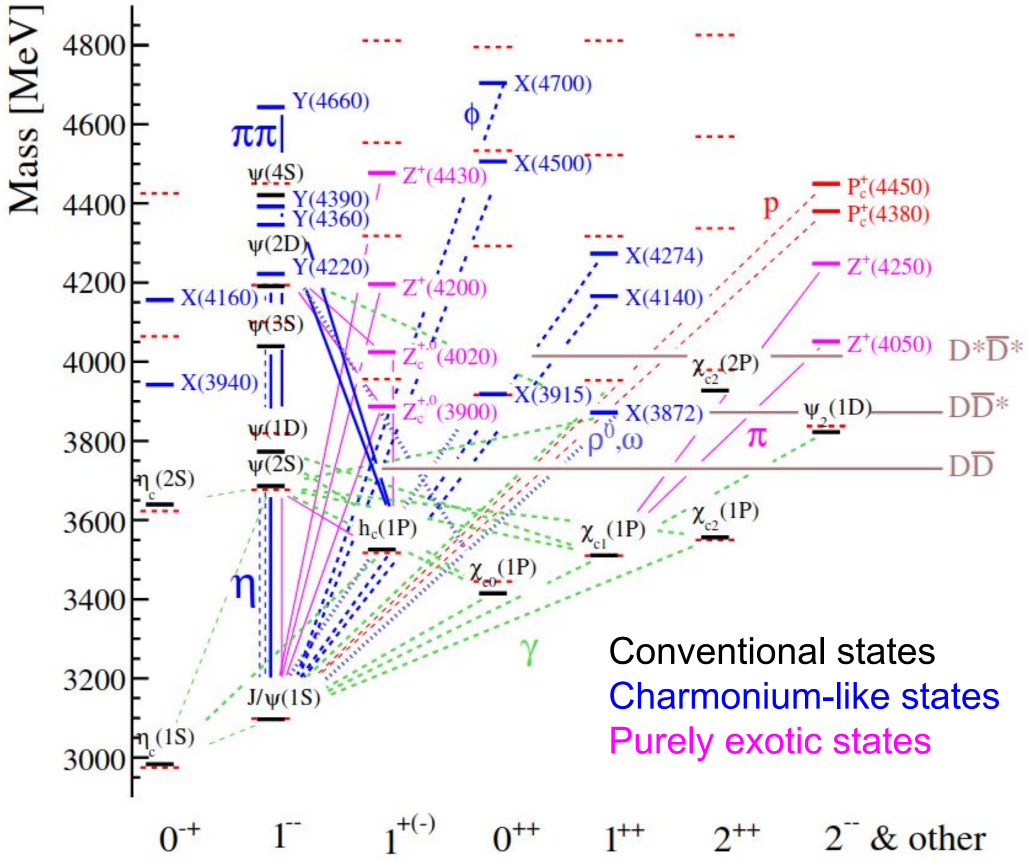
- 50 ab^{-1} at Υ(4S)





PTEP 2020 (2020) 2, 029201

Charmonium nomenclature



Below $D\bar{D}$ threshold: well described by potential models

Above $D\bar{D}$ threshold:

X states such as X(3872)
- neutral non-vector non-conventional states

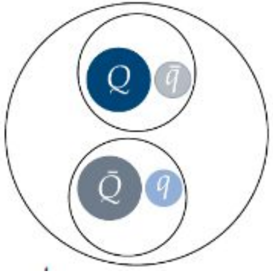
Y states such as Y(4260) and Y(4660)
- neutral vector non-conventional states $J^{PC} = 1^{--}$ states.

Z states such as $Z^+_c(3900)$ and $Z^+_b(10650)$
- charged states, can not be pure quarkonium
- similar for b- and c- onium

Theoretical models

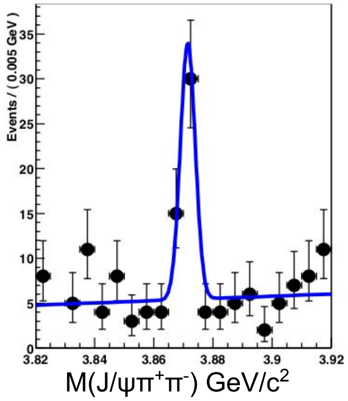
PhysRep, 873, 1-154

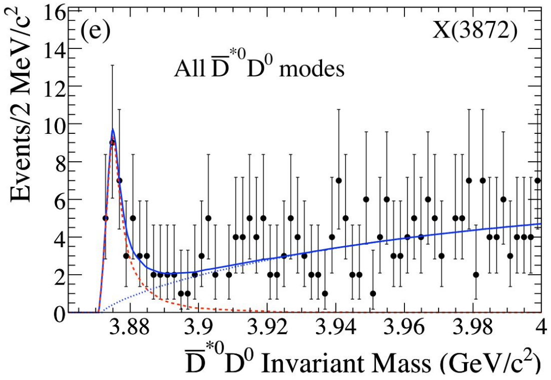
Hadronic molecule



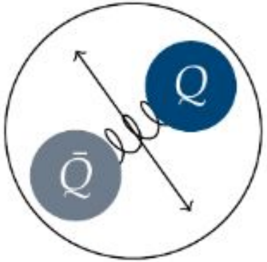
Compound state of two hadrons. The most promising model.
The charmonium-like states can be described as a mixture of pure charmonium and a molecular component:

$X(3872) = C_1 \cdot |c\bar{c}> + C_2 \cdot |D^0 \bar{D}^{0*}>$



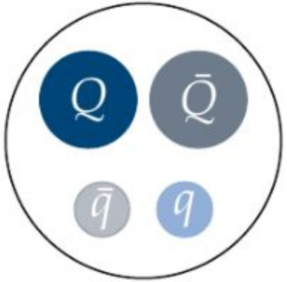


Hybrid



Conventional quark-antiquark mesons with excited gluon degrees of freedom.

Compact tetraquark



States containing four constituent quarks irrespective of their clustering.

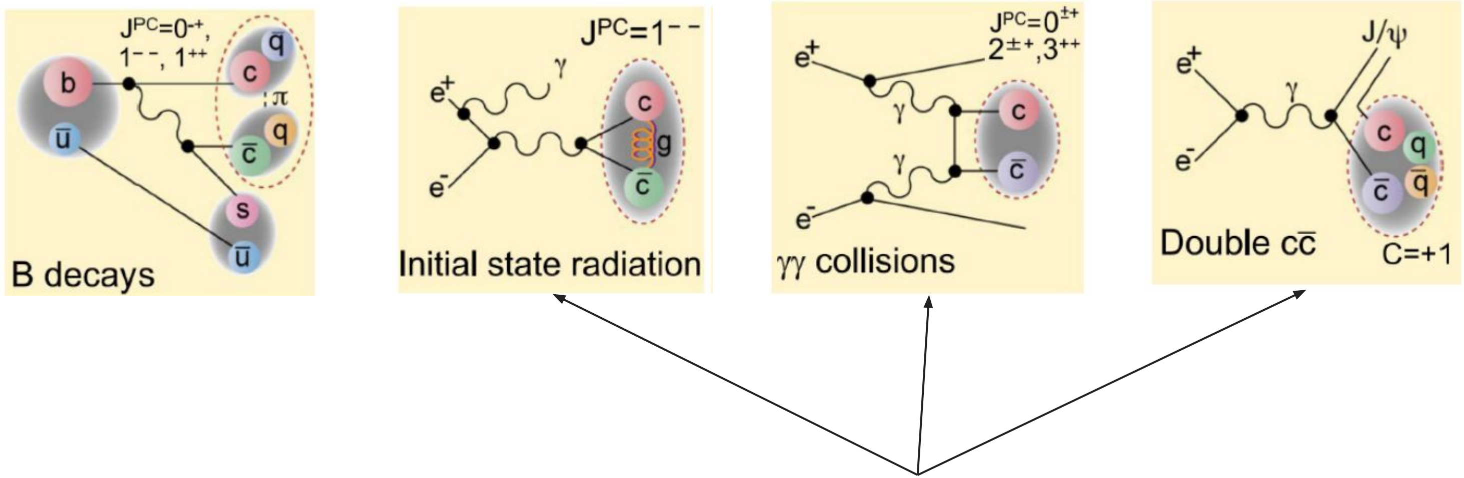
Hadroquarkonium

Compact quarkonium core surrounded by an excited light-quark cloud.

Charmonium production at Belle II

At Belle / Belle II charmonium events comes “for free”:

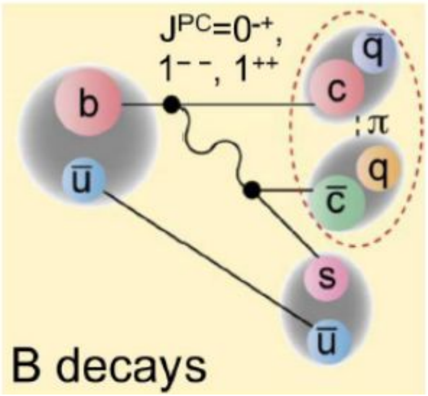
- We don`t need to develop special triggers.
- We don`t need to tune accelerator.
- Uniquely clean environment compare to pp production.

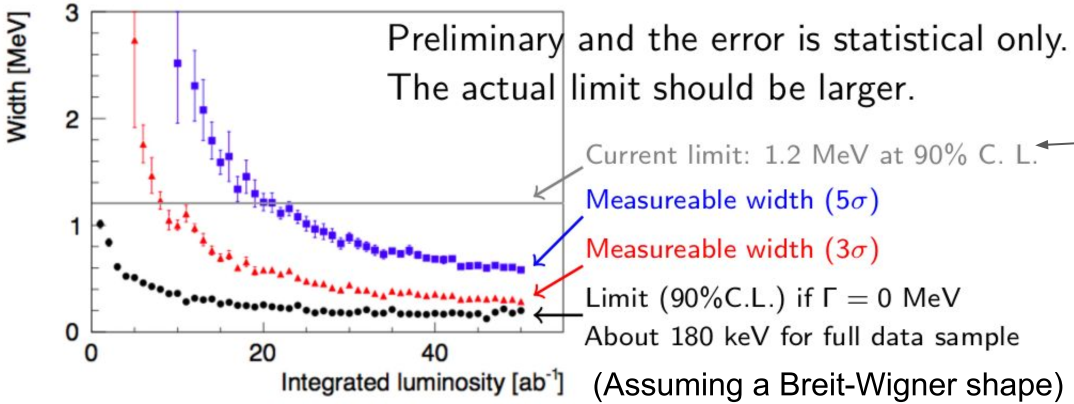


Unique for Belle II !

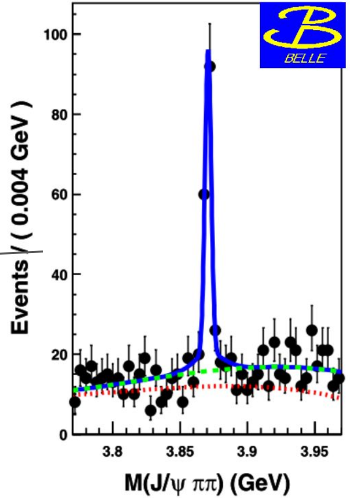
B decays

- $B \to KX_{c\bar{c}}$ is CKM favoured process with large branching fractions ~ 10^{-3} - 10^{-4}.
- Due to the known number of B pairs, it is possible to measure absolute BF[$B \to X_{c\bar{c}} K$].
- Access to X(3872) lineshape with $D^0\bar{D}^0\pi^0$ channel.
- Access to unknown / hardly reconstructable modes with the B-tagging technique.





(Assuming a Breit-Wigner shape)



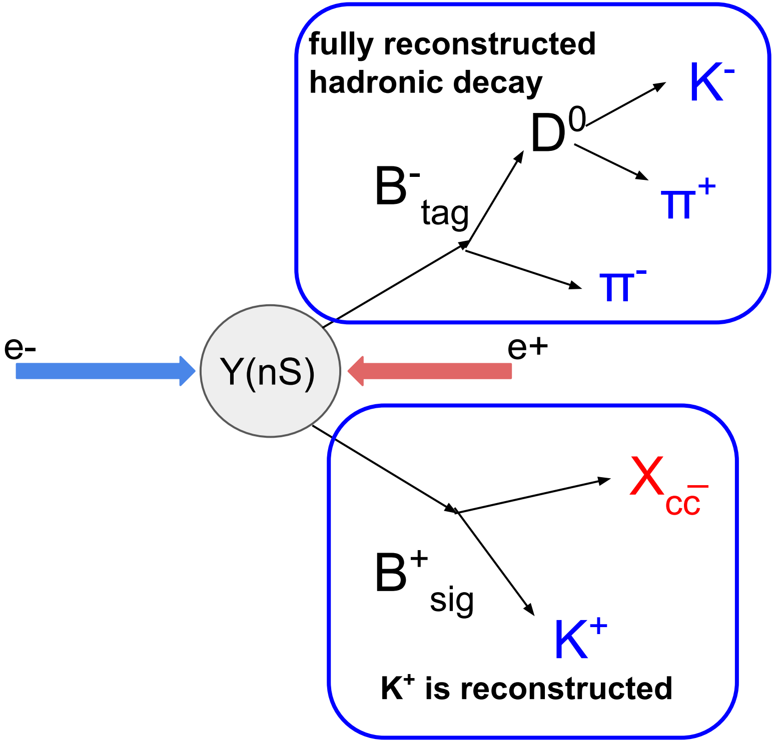
Phys. Rev. D 84, 052004 (2011)

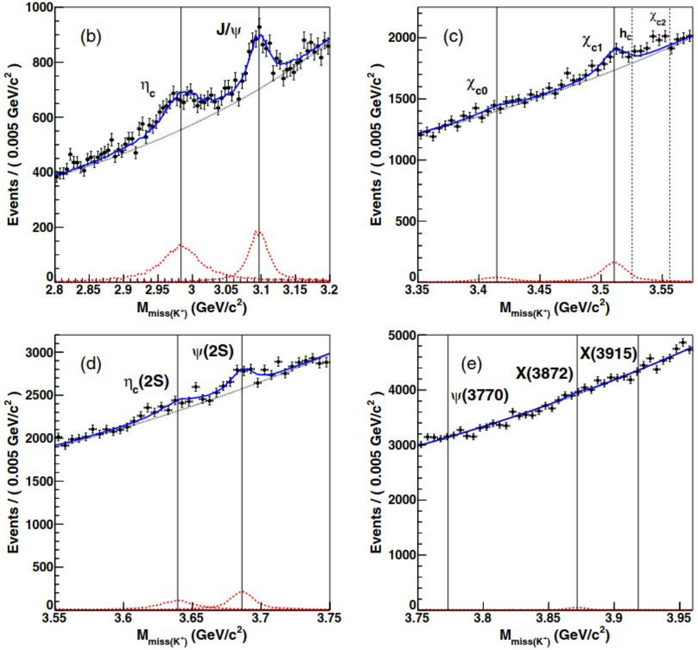
Charmonium + B-tagging

[PRD 97, 012005 (2018)]

Precise measurement of the e^+e^- energy allows to observe mass peaks with partial reconstruction:

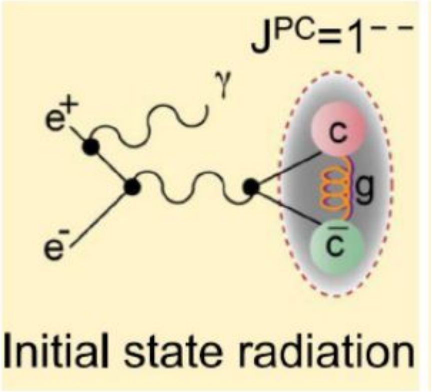
$$M_{X_{cc}} = \sqrt{p_{e^+e^-} - p_{B_{tag}} - p_K}$$





Mode	Yield	Significance (σ)	$\epsilon(10^{-3})$	$\mathcal{B}$ (10^{-4})	World average for $\mathcal{B}$ (10^{-4}) [10]
η_c	2590 ± 180	14.2	2.73 ± 0.02	$12.0 \pm 0.8 \pm 0.7$	9.6 ± 1.1
J/ψ	1860 ± 140	13.7	2.65 ± 0.02	$8.9 \pm 0.6 \pm 0.5$	10.26 ± 0.031
χ_{c0}	430 ± 190	2.2	2.67 ± 0.02	$2.0 \pm 0.9 \pm 0.1$ (<3.3)	$1.50^{+0.15}_{-0.14}$
χ_{c1}	1230 ± 180	6.8	2.68 ± 0.02	$5.8 \pm 0.9 \pm 0.5$	4.79 ± 0.23
$\eta_c(2S)$	1050 ± 240	4.1	2.77 ± 0.02	$4.8 \pm 1.1 \pm 0.3$	3.4 ± 1.8
$\psi(2S)$	1410 ± 210	6.6	2.79 ± 0.02	$6.4 \pm 1.0 \pm 0.4$	6.26 ± 0.24
$\psi(3770)$	-40 ± 310	-	2.76 ± 0.02	$-0.2 \pm 1.4 \pm 0.0$ (<2.3)	4.9 ± 1.3
$X(3872)$	260 ± 230	1.1	2.79 ± 0.01	$1.2 \pm 1.1 \pm 0.1$ (<2.6)	(<3.2)
$X(3915)$	80 ± 350	0.3	2.79 ± 0.01	$0.4 \pm 1.6 \pm 0.0$ (<2.8)	-

Initial state radiation



- 50 ab^{-1} data corresponds to 2000-2800 pb^{-1} /10 MeV at 4-5 GeV, which is compatible with BES III (500 pb^{-1} /10 MeV, but higher efficiency).
- Access to 1^{--} states with masses > 4.6 GeV.
- Effective luminosity and detection efficiency are relatively low.
- c-baryons ($\Lambda^+_c \Sigma^-_c$, $\Sigma^+_c \Sigma^-_c$) and cs-mesons pairs production ($D_s D_{s2}$ (2573), $D_s D^*_{s0}$ (2317)).

Golden Channels	$E_{c.m.}$ (GeV)	Statistical error (%)	Related XYZ states
$\pi^+\pi^- J/\psi$	4.23	7.5 (3.0)	$Y(4008)$, $Y(4260)$, $Z_c(3900)$
$\pi^+\pi^- \psi(2S)$	4.36	12 (5.0)	$Y(4260)$, $Y(4360)$, $Y(4660)$, $Z_c(4050)$
$K^+K^- J/\psi$	4.53	15 (6.5)	Z_{cs}
$\pi^+\pi^- h_c$	4.23	15 (6.5)	$Y(4220)$, $Y(4390)$, $Z_c(4020)$, $Z_c(4025)$
$\omega\chi_{c0}$	4.23	35 (15)	$Y(4220)$
		10 ab^{-1} 50 ab^{-1}	

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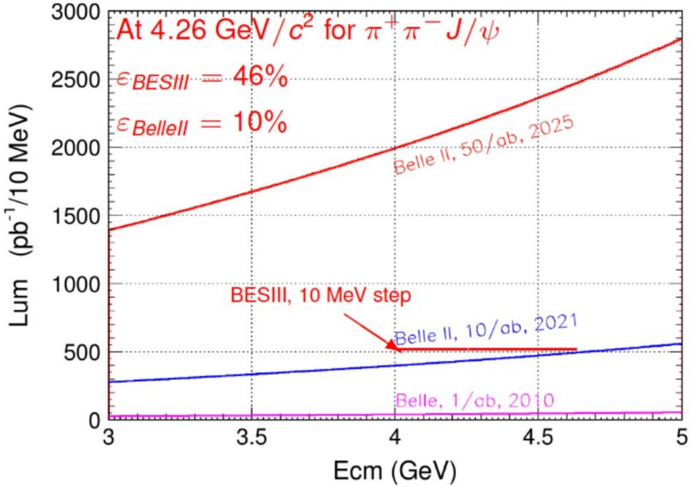
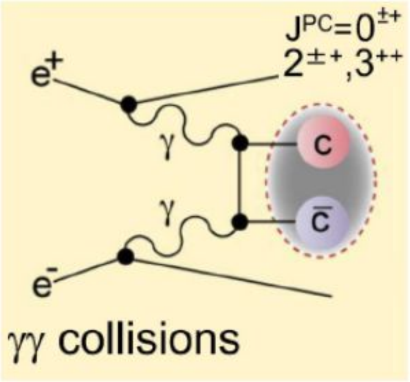
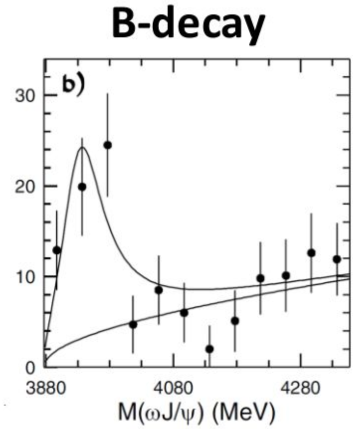


Two-photon production

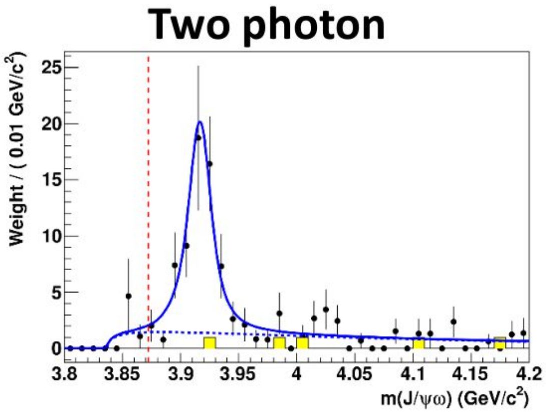
- Access to a wide range of quantum numbers. J/ψω and J/ψφ in particular.
- Provides a better S/B ratio compare to B-decays.
- Allows to measure the Q^2 dependence of $c\bar{c}$ production.



The $e^+e^- \to e^+e^- H$ cross section is largest in the kinematic regions where the Q^2 value is very close to zero and M_H is small when compared with the beam energy. In contrast, in regions where either W or Q^2 is much larger than the typical QCD energy scale (~ 1 GeV), the cross section decreases rapidly



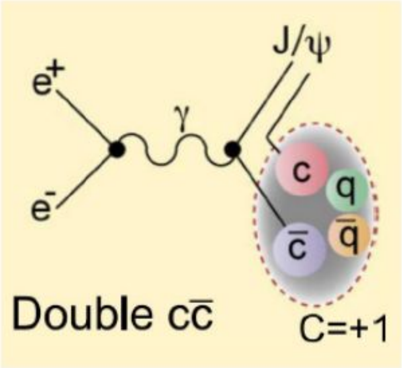
PRL 94, 182002 (2005)

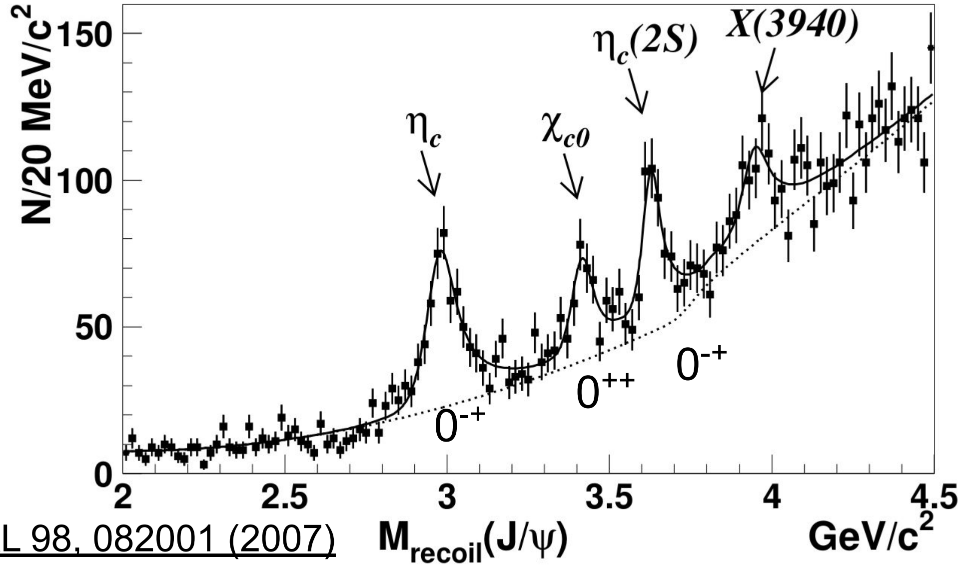


PRD 86, 072002 (2012)

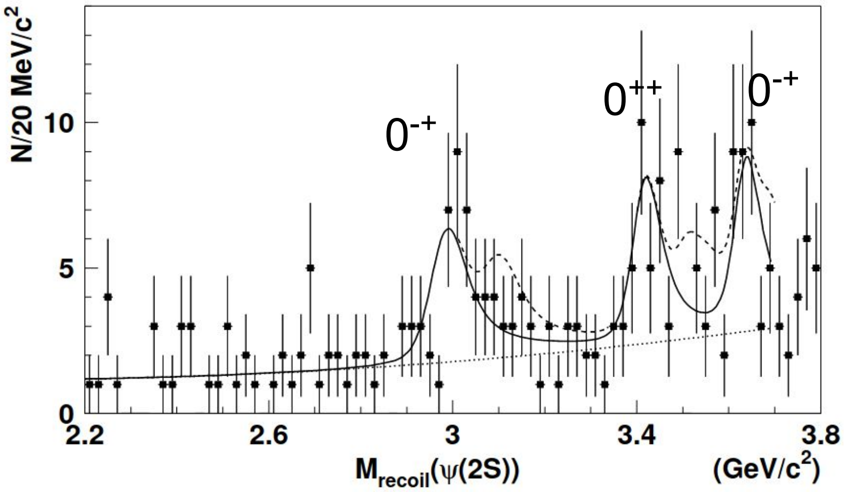
Double charmonium production

- All observed processes are of the type $e^+e^- \to c\bar{c}$ (J=1) $c\bar{c}$ (J=0). Belle II will allow to study $e^+e^- \to \eta_c X_{(c\bar{c})}$ and $e^+e^- \to \chi_{c0} X_{(c\bar{c})}$ processes.
- $e^+e^- \to \psi(2S) X_{(c\bar{c})}$ can be studied at Belle II with larger statistics.
- Large cross section revealed importance of the next order corrections in NRQCD.



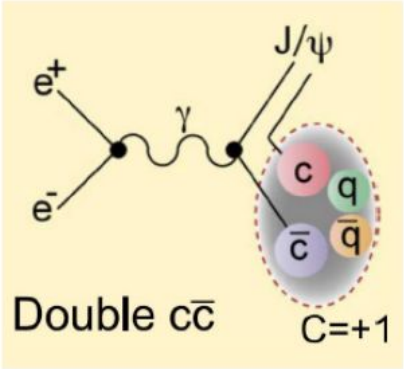


PRL 98, 082001 (2007)



PRD 70, 071102(R) (2004)

Double charmonium production



- All observed processes are of the type $e^+e^-\to c\bar{c}$ (J=1) $c\bar{c}$ (J=0). Belle II will allow to study $e^+e^-\to\eta_c X_{(c\bar{c})}$ and $e^+e^-\to\chi_{c0} X_{(c\bar{c})}$ processes.
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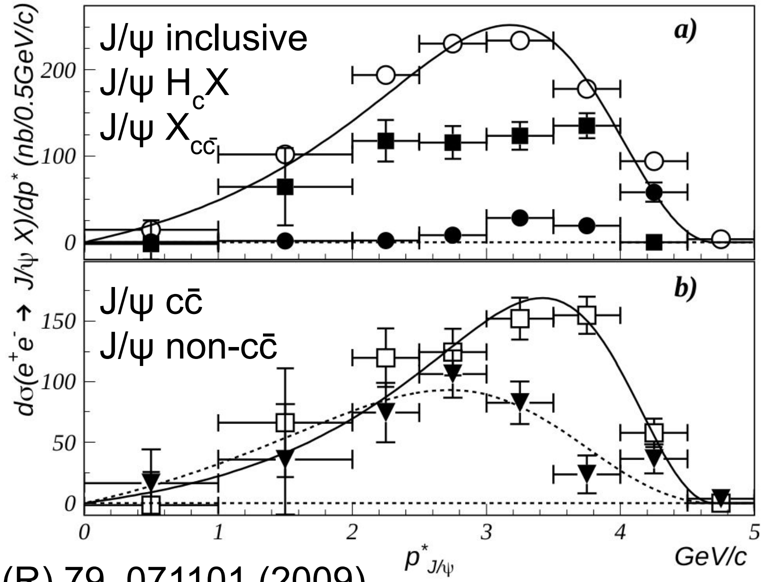
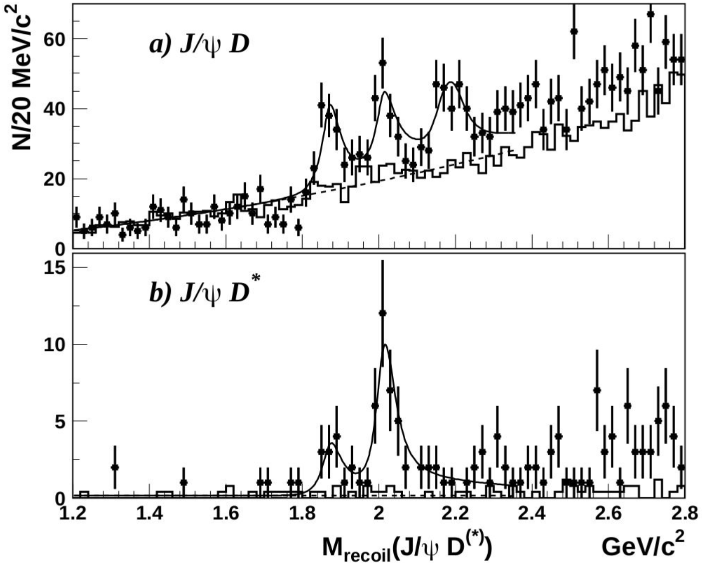


PRD(R) 79, 071101 (2009)



PRL 100, 202001 (2008)

Double charmonium production

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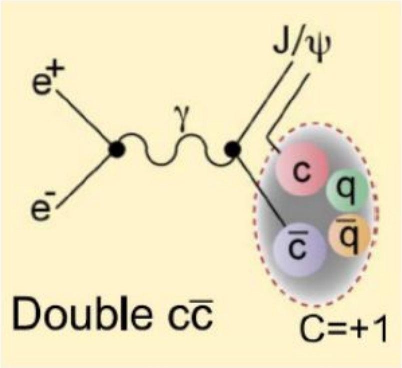


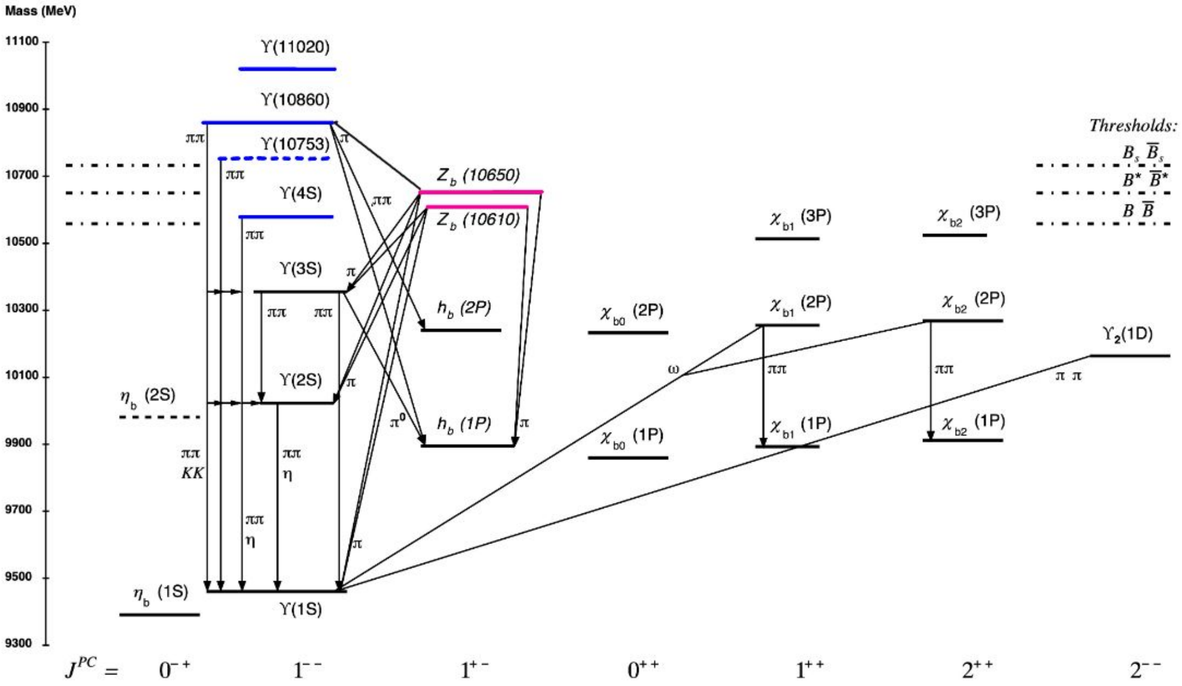
$N_{charged}$ > 4

Dominance of the e + e − → J/ψ cc production mechanism. It should be noted that in this analysis (unlike that of PRL 89, 142001 (2002)) no correction for the charged track multiplicity ($N_{charged}$ > 4) requirement was applied for any of the processes. For e^+e^- → J/ψ non-cc, such corrections are only possible by relying on a model, while for e^+e^- → J/ψ cc they are close to unity.

PRD(R) 79, 071101 (2009)

PRL 100, 202001 (2008)

Bottomonium



Conventional bottomonium (pure bb states)

Bottomonium-like states (mixture of bb and B$\bar{B}$)

Purely exotic states

We have two type of states:

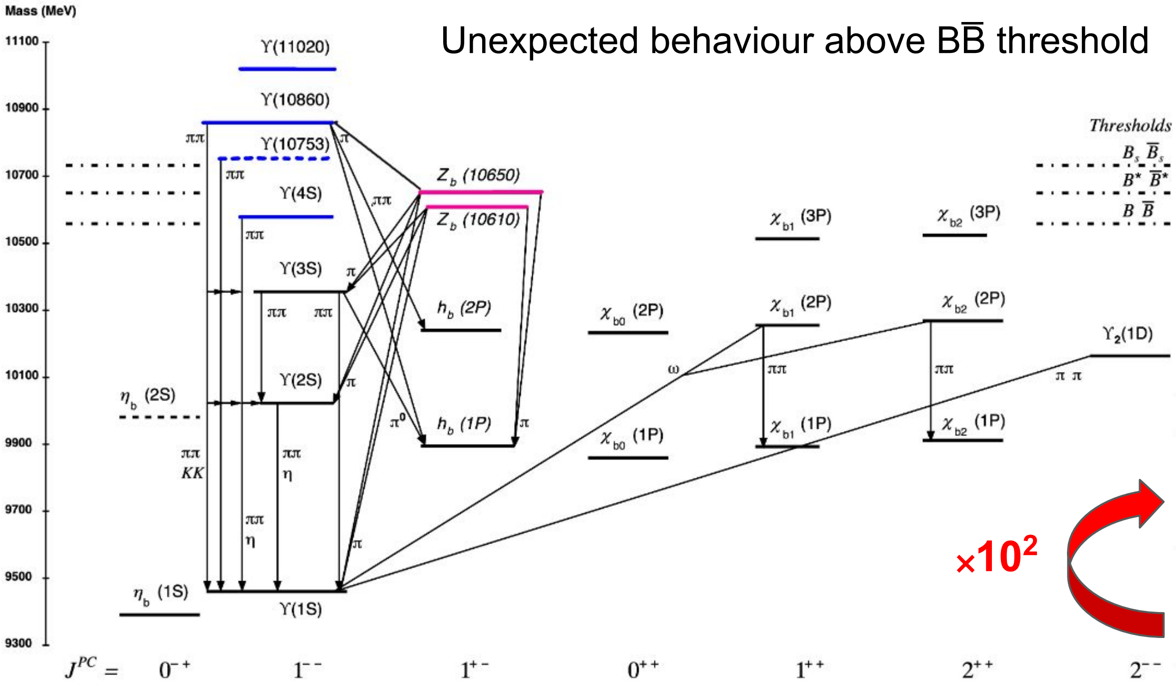
- Below B$\bar{B}$ threshold
- Above B$\bar{B}$ threshold

The states below B$\bar{B}$ mesons threshold are well described by the potential models.

Bottomonium

[Mod. Phys. Lett. A 32, №04, 1750025]

Unexpected behaviour above $B\bar{B}$ threshold



Process	Γ, MeV
$\Upsilon(5S) \to \Upsilon(1S)\eta$	0.039 ± 0.011
$\Upsilon(5S) \to \Upsilon(2S)\eta$	0.204 ± 0.44
$\Upsilon(4S) \to \Upsilon(1S)\eta$	0.004 ± 0.0008
$\Upsilon(4S) \to h_b(1P)\eta$	0.045 ± 0.007
$\Upsilon(3S) \to \Upsilon(1S)\eta$	$< 0.002 \cdot 10^{-3}$
$\Upsilon(2S) \to \Upsilon(1S)\eta$	$(0.0093 \pm 0.0015) \cdot 10^{-3}$

$\times 10^2$

Process	Γ, MeV
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52 \, ^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060 ± 0.0005
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009 ± 0.00008
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019 ± 0.0002

Conventional bottomonium (pure bb states)

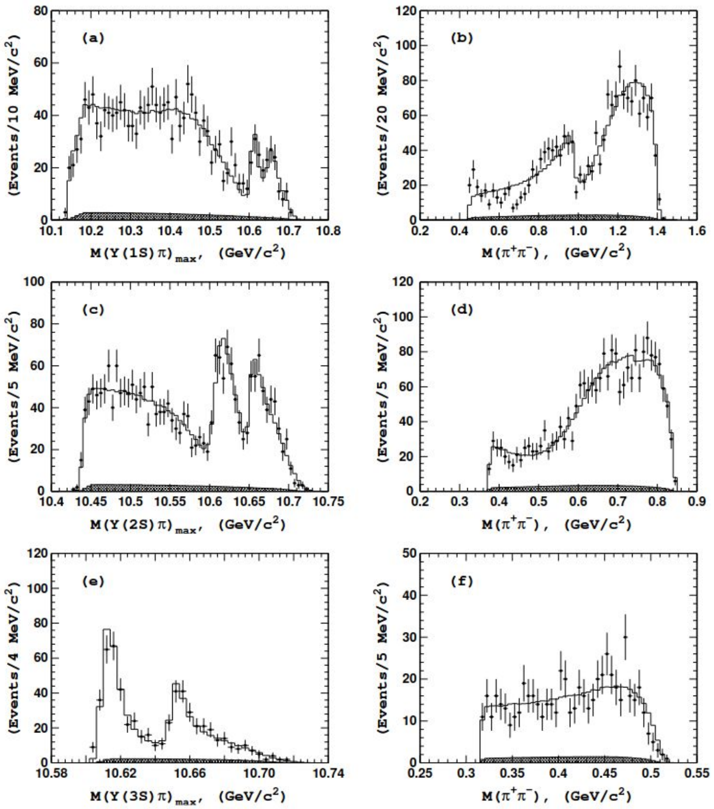
Bottomonium-like states (mixture of bb and BB)

Purely exotic states

[PRL 100, 112001 (2008)]

Bottomonium

Mod. Phys. Lett. A 32, №04, 1750025



PRL 108 (2012) 122001

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$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019 ± 0.0002

$\times 10^2$

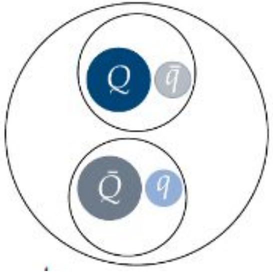
PRL 100, 112001 (2008)

Proceed via intermediate exotic state
$Y(5S) \to [Z_b^+ \to Y(nS)\pi^+]\pi^-$

Theoretical models

PhysRep, 873, 1-154

Hadronic molecule



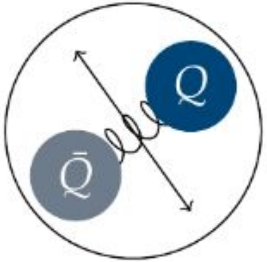
Compound state of two hadrons. The most promising model.
The bottomonium-like states can be described as a mixture of pure bottomonium and a molecular component:

$$Y(10860) = C_1 \cdot |bb > + C_2 \cdot |B_{(s)}^{((*)*)} B_{(s)}^{((*)*)}>$$

Z_b decay mode	Branching fraction
$Z_b^+(10610) \to \Upsilon(nS)/h_b(mP)\pi^+$	$14.4^{+2.5}_{-1.9}\%$
$Z_b^+(10610) \to B^+\bar{B}^{*0}/B^+\bar{B}^0$	$85.6^{+2.1}_{-2.9}\%$
$Z_b^+(10650) \to \Upsilon(nS)/h_b(mP)\pi^+$	$26.6^{+5.0}_{-4.7}\%$
$Z_b^+(10650) \to B^{*+}\bar{B}^{*0}$	$74^{+4}_{-6}\%$

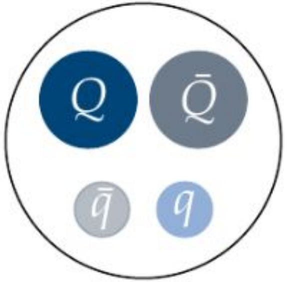
PRL, 108, 122001 (2012)

Hybrid



Conventional quark-antiquark mesons with excited gluon degrees of freedom.

Compact tetraquark



States containing four constituent quarks irrespective of their clustering.

Hadroquarkonium

Compact quarkonium core surrounded by an excited light-quark cloud.

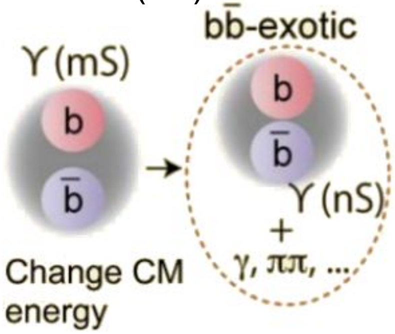
Bottomonium production

Prompt production

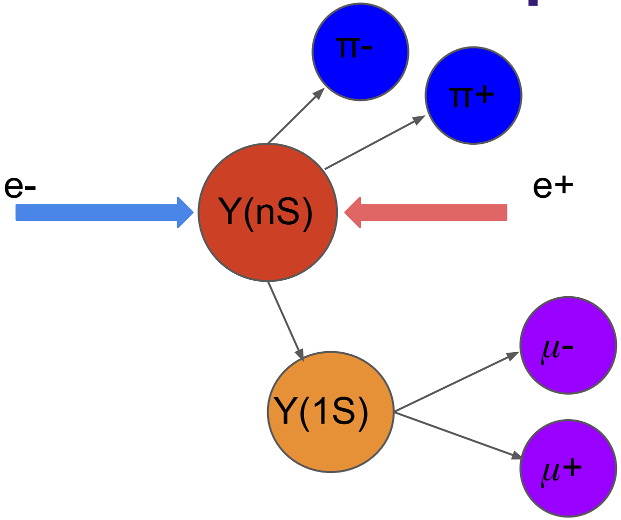
Direct production in e^+e^- collisions

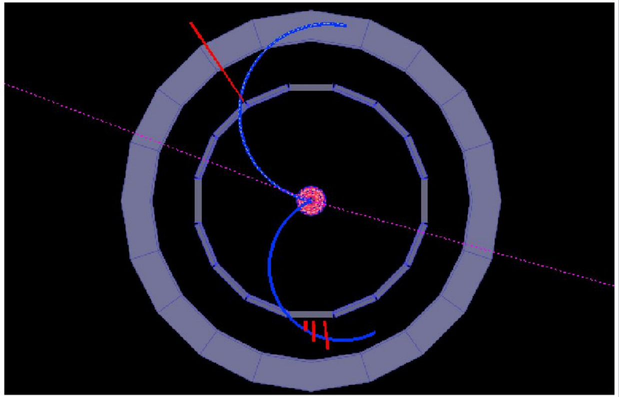
- Provides a unique clean environment (we have only bottomonium in the event);
- Precise measurement of the beam energy gives access to “unreconstructable” particles and decay modes;
- Allows tuning CM energy
- Only Υ(nS) states can be produced with quantum numbers of the photon 1^{--}
- Other quantum numbers can be obtained via hadronic or radiative transitions from 1^{--} states;

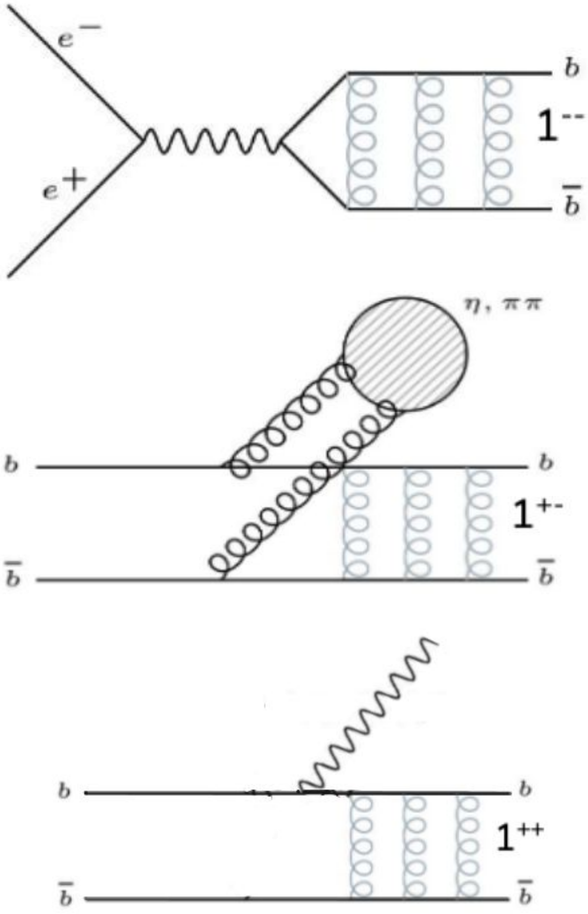
gives access to exotic states above Υ(4S)



Bottomonium production







- Provides a unique clean environment (we have only bottomonium in the event);
- Precise measurement of the beam energy gives access to "unreconstructable" particles and decay modes;
- Allows tuning CM energy
- Only ϒ(nS) states can be produced with quantum numbers of the photon 1^{--}
- Other quantum numbers can be obtained via hadronic or radiative transitions from 1^{--} states;

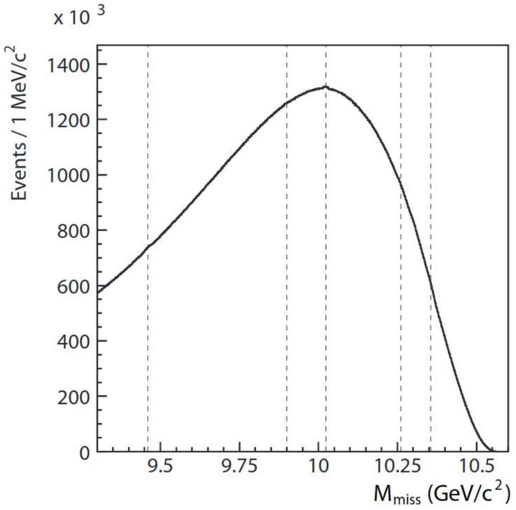
Missing mass technique for bottomonium

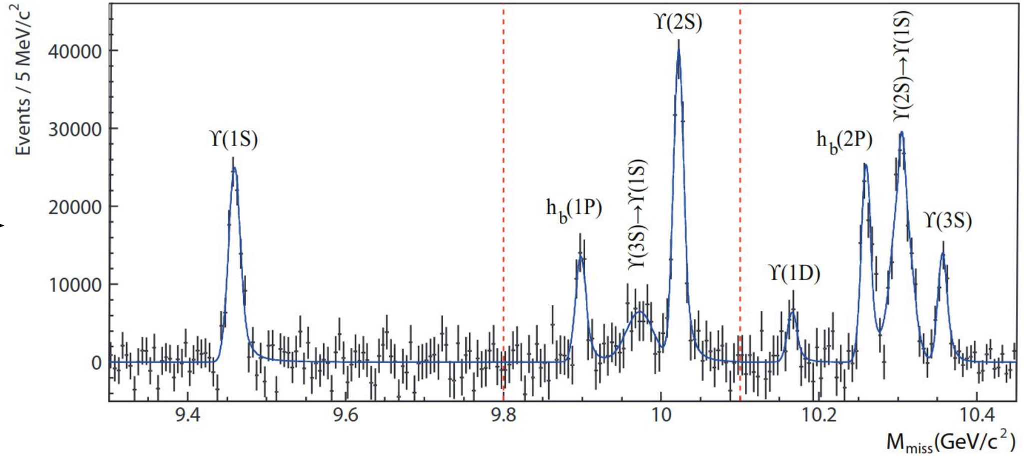
Precise measurement of the e^+e^- energy allows to observe mass peaks with partial reconstruction:

$\pi^+ \pi^-$ missing mass has better resolution than $M(\mu^+\mu^-)$

$$M_{\rm miss}(\pi\pi) = \sqrt{(E_{\rm c.m.} - E^*_{\pi\pi})^2 - p^{*2}_{\pi\pi}}$$

$\Upsilon(5S) \to X_{b\bar{b}}\, \pi^+ \pi^-$ transitions:





PRL 108 (2012) 032001

Very important for unreconstructable bottomonium states $\eta_b(nS)$, $h_b(nP)$

Discovery of the Υ(10753)

Υ(10753) state was observed in the $e^+e^- \rightarrow \Upsilon(nS)\,\pi^+\pi^-$ (n = 1,2,3) cross section energy dependence.

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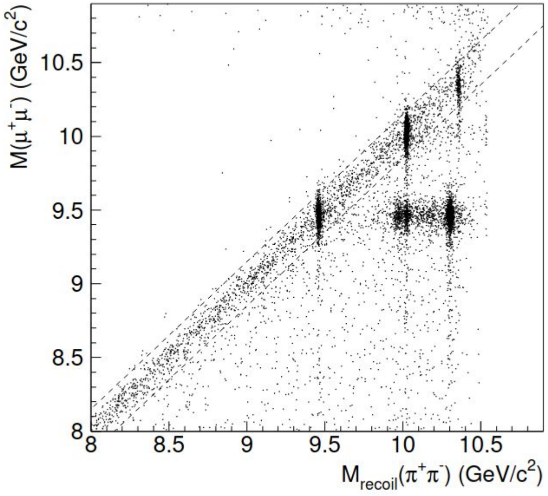
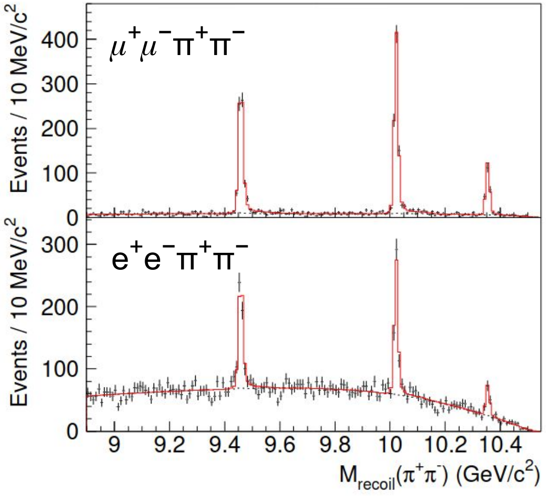
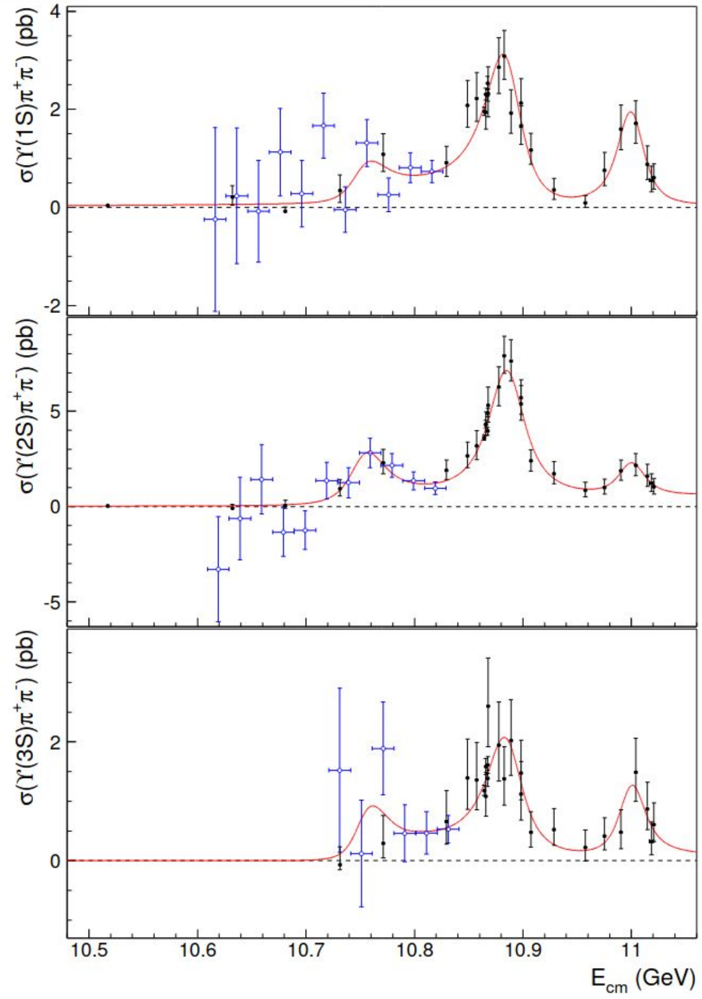
measurement at $\sqrt{s}$ = 10.864 GeV with L = 47.647 fb^{-1}:

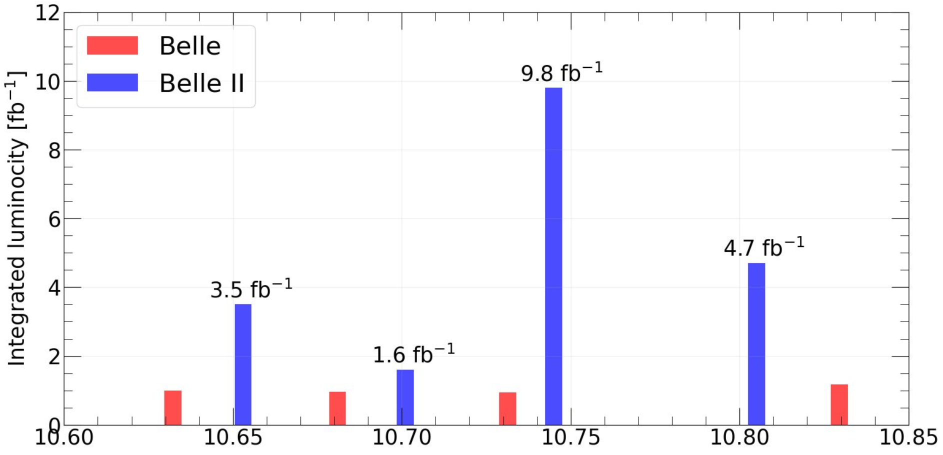


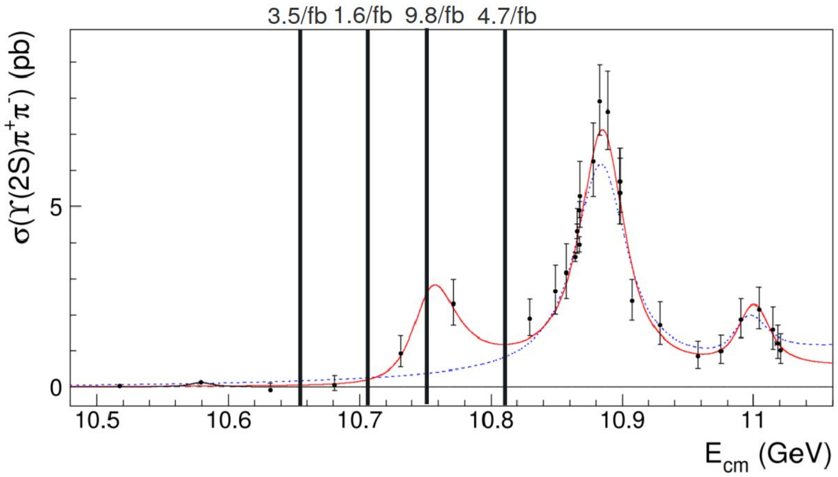




Belle II energy scan above Υ(4S)

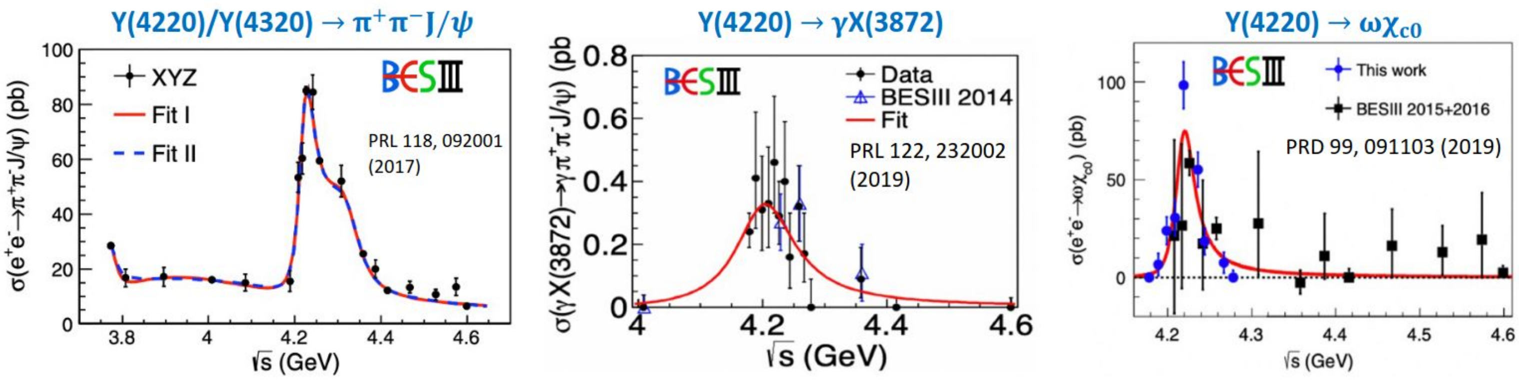
- Unique data provide an opportunity to study Υ(10753) in different final states and understand its nature.
- Scan above Υ(4S) has a good potential for early physics impact by Belle II even with small statistics.



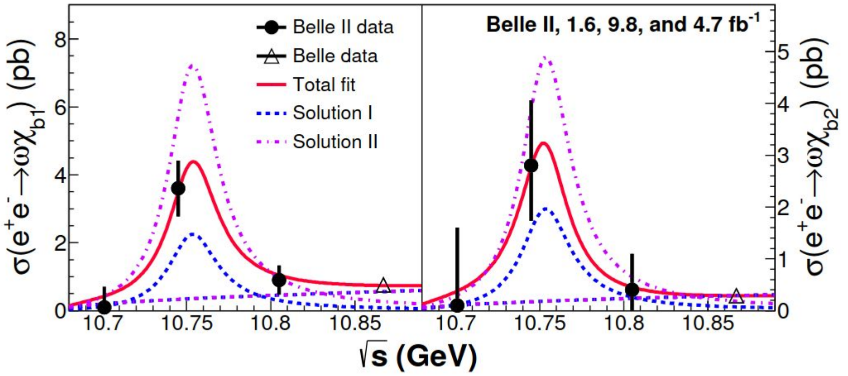


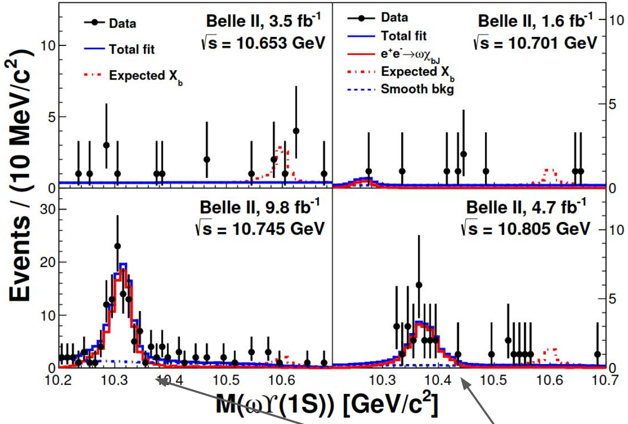
Observation of e+e→ $\omega\chi_{bJ}$(1P) at √s = 10.745 GeV

- Similar to Y(10753) structure named Y(4220) was observed in $e^+e^- \to J/\Psi\ \pi^+\pi^-$ cross section dependence by BES III (PRL 118, 092001 (2017)).
- BES III also observed the Y(4220) peak in $\gamma X(3872)$ and $\omega\chi_{c0}$ final states (PRL, 122, 232002 (2019), PRD 99, 091103(R) (2019)).
- $\omega\chi_{b1,2}$ production was found to be enhanced near Y(5S) (PRL 113, 142001 (2014)).
- We expect Y(10753) to decay into $\gamma[X_b \to \omega Y(1S)]$ and $\omega\chi_{bJ}$ final states.



Observation of e+e→ $\omega\chi_{bJ}$(1P) at √s = 10.745 GeV

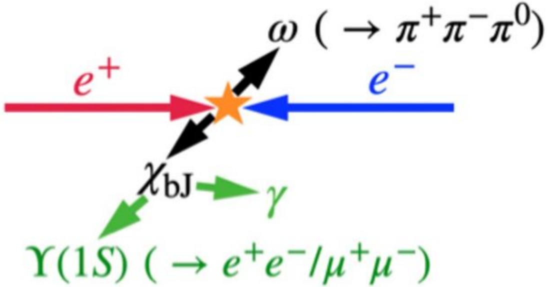


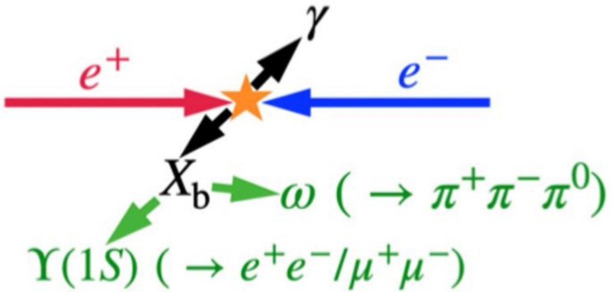


Strongly enhanced at 10.745 GeV.

$$\sigma(e^+e^-\to\omega\chi_{b1}) = 3.6\pm0.7\pm0.5\ \text{pb}$$
$$\sigma(e^+e^-\to\omega\chi_{b2}) = 2.8^{+1.2}_{-1.0}\pm0.4\ \text{pb}$$

No evidence of X_b ($b\bar{b}$ partner of X(3872)) state. These are reflections of $\omega\chi_{bJ}$(1P).



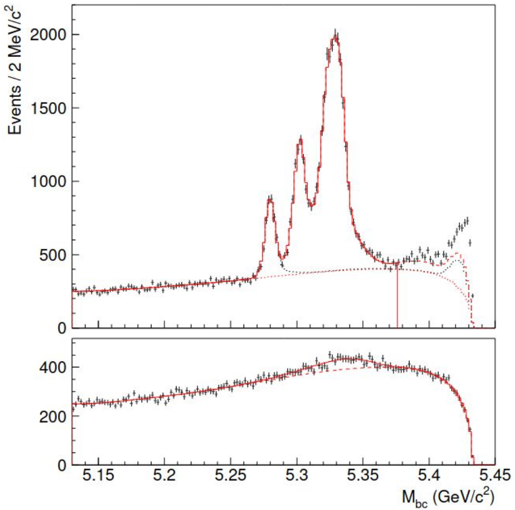


arXiv:2208.13189

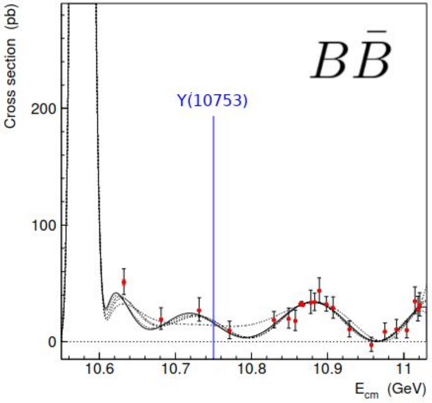
$B\bar{B}$ decomposition with B-tagging

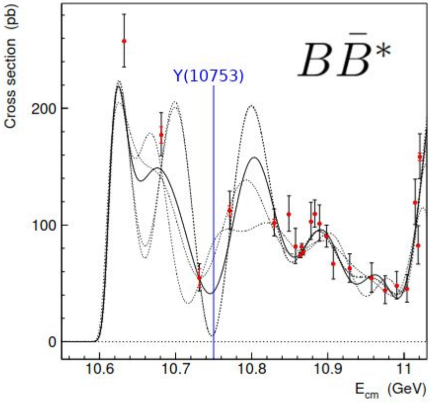
Study the energy dependence of the $B\bar{B}$ pairs production.

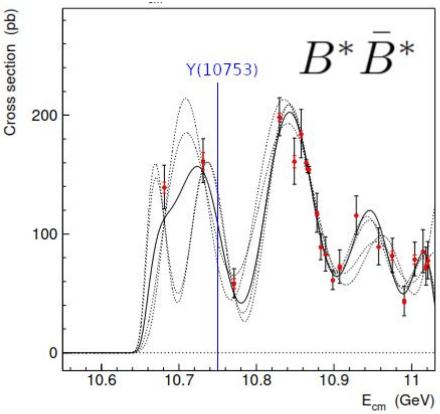
- B-tagging can be used to measure the $B_{(s)}^{((*)*)}\bar{B}_{(s)}^{((*)*)}$ cross section energy dependence.
- Yet another unique way to study bottomonium at Belle / Belle II.
- A good probe for bottomonium models (especially the molecular model).



$$M_{\rm bc} = \sqrt{(E_{\rm cm}/2)^2 - p_B^2}$$







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Belle II potential charmonium

The main source of improvements and new results is the increase in statistics.

- Measure double charmonium production cross sections with $e^+e^-\to\psi(2S)X_{(c\bar{c})}$ and search for $e^+e^-\to\eta_c X_{(c\bar{c})}$ and $e^+e^-\to\chi_{c0}X_{(c\bar{c})}$.
- Measure X(3872) lineshape with $D^0\bar{D}^0\pi^0$ channel.
- Study high energy region (E > 4.6 GeV) unapproachable for BES III with ISR production.
- Search for new charmonium-like states or new decay modes. Confirm the states and transitions obtained with low statistics. Measure quantum numbers of observed charmonium-like states.
- Search for new charmonium state with improved B-tagging method.
- Larger statistics will allow to measure $p^*_{c\bar{c}}$, Q^2 production dependence.

Belle II potential bottomonium

Scan above $\Upsilon(4S)$ gives an opportunity for a lot of unique studies:

- $\Upsilon(10753)$ decays to different exclusive and inclusive final states. Study of its properties;
- Energy dependence of the various final state cross sections;
- $B\overline{B}$ decomposition and its cross section dependence on CM energy;

Wide range of long-term non-$\Upsilon(4S)$ possibilities:

- Increase the above-$\Upsilon(4S)$ scan statistics;
- $\Upsilon(6S)$ region study with high statistics after accelerator upgrade;

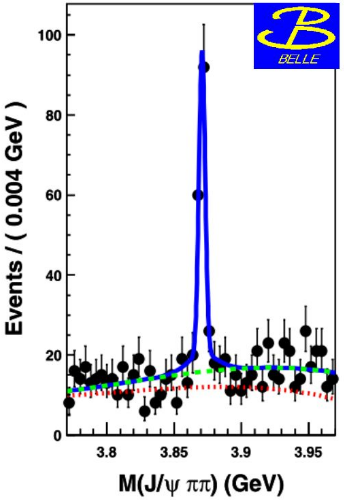
Golden Modes
$e^+e^- \to \pi^+\pi^-\Upsilon(pS)(\to \ell^+\ell^-)$ $B\overline{B}$ decomposition $\pi^+\pi^-$ Dalitz $Y_b \to \omega\eta_b(1S)$ $Y_b \to \omega\chi_{bJ}(1P)$
Silver Modes
$Y_b \to \pi^+\pi^- X$ (inclusive) $Y_b \to \eta X$ (inclusive) $Y_b \to \eta\Upsilon(1S, 2S)(\to \ell^+\ell^-)$ $Y_b \to \eta'\Upsilon(1S)(\to \ell^+\ell^-)$ $Y_b \to \Upsilon(1S)$ (inclusive)
Bronze Modes
$Y_b \to \gamma X_b$ $Y_b \to \pi^0\pi^0\Upsilon(pS)(\to \ell^+\ell^-)$ $Y_b \to KK(\phi)\Upsilon(pS)(\to \ell^+\ell^-)$ $Y_b \to \pi^0\pi^0 X$ (inclusive) $Y_b \to \pi^0 X$ (incl. or excl.) ...

Backup

X(3872) lineshape with $D^0\bar{D}^0\pi^0$ channel

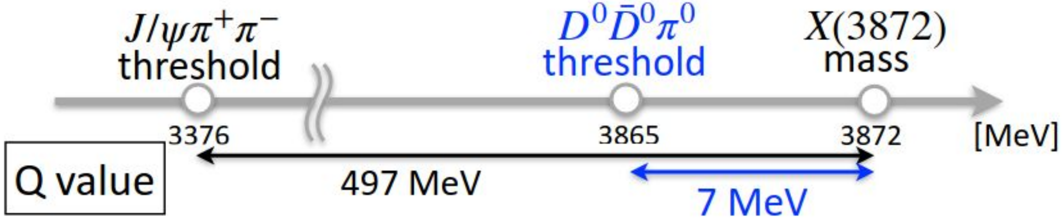
Γ_{tot}		Mass resolution
< 1.2 MeV (90% C.L.)	<	1.86 ± 0.01 MeV/c²

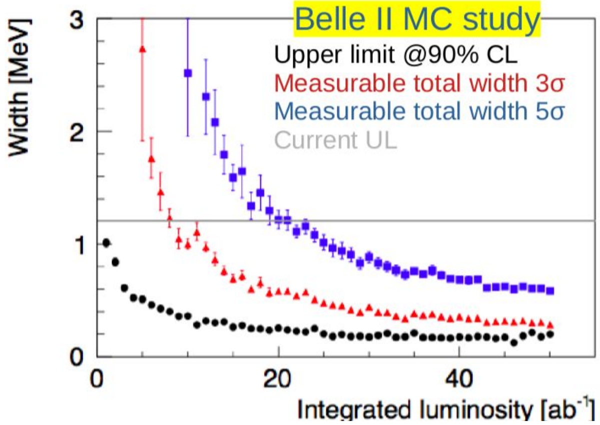
Phys. Rev. D 84, 052004 (2011)



- Improvement of mass resolution is more essential than that of statistics.
- We can use channel with good mass resolution:
  - Mass resolution: 684 ± 8 keV
  - Signal yield with 1 ab^{-1}: 64.5 ± 23.9

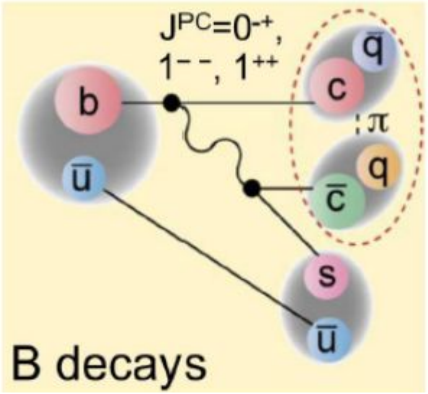
Comes from large error of
$\mathrm{Br}(B^\pm \to K^\pm X(3872)) \times \mathrm{Br}(X(3872) \to D^0\bar{D}^0\pi^0)$





(Assuming a Breit-Wigner shape)

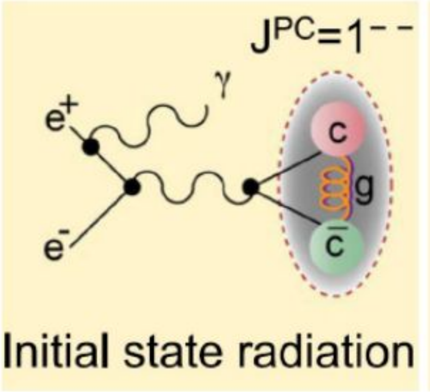
B decays



S - seen (observed)
NS - not seen or excluded
N - not performed (in a given mass range)
MF - missing fit (fit have not been extended to this mass range)
– no search has been performed in this mode

State	J^{PC}	$\psi\pi\pi$	$\psi\omega$	$\psi\gamma$	$\psi\phi$	$\psi\eta$	$\psi'\pi\pi$	$\psi'\omega$	$\psi'\gamma$	$\chi_c\gamma$	$p\bar{p}$	$\Lambda\bar{\Lambda}$	$\Lambda_c\bar{\Lambda}_c$	$D\bar{D}$	$D\bar{D}^*$	$2D^*$	$2D_s^{(*)}$	$\gamma\gamma$
X(3872)	1^{++}	S	S	S	—	NS	—	—	S	NS	MF	MF	—	—	S	—	—	NS
Y(3940)	J^{P+}	MF	S	NS	—	—	—	—	MF	—	MF	MF	—	MF	NS	—	N	N
Z(3930)	2^{++}	MF	MF	NS	—	—	—	—	MF	—	MF	MF	—	MF	MF	—	N	N
Y(4140)	J^{P+}	MF	MF	N	S	—	N	—	N	—	MF	MF	—	MF	N	N	N	N
X(4160)	0^{P+}	MF	MF	N	MF	—	N	—	N	—	MF	MF	—	MF	N	N	N	N
Y(4260)	1^{--}	NS	—	—	—	MF	N	—	—	N	MF	MF	—	N	N	N	N	—
X(4350)	J^{P+}	MF	MF	N	MF	—	N	N	N	—	MF	MF	—	N	N	N	N	N
Y(4350)	1^{--}	MF	—	—	—	MF	N	—	—	N	MF	MF	—	N	N	N	N	—
Y(4660)	1^{--}	N	—	—	—	MF	N	—	—	N	MF	MF	MF	N	N	N	N	—

Initial state radiation



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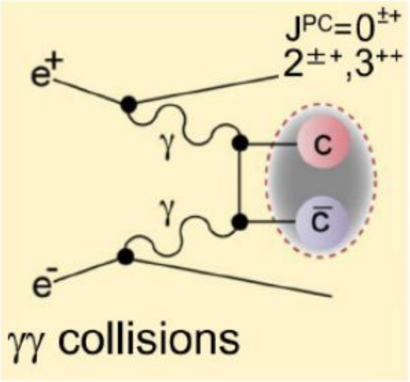
N - not performed (in a given mass range)
MF - missing fit (fit have not been extended to this mass range)
– no search has been performed in this mode

State	J^{PC}	$\psi\pi\pi$	$\psi'\pi\pi$	$\psi\eta$	$\chi_c\gamma$	$p\bar{p}$	$\Lambda\bar{\Lambda}$	$\Lambda_c\bar{\Lambda}_c$	$D\bar{D}$	$D\bar{D}^*$	$2D^*$	$2D_s^{(*)}$
Y(4260)	1^{--}	S	NS	NS	NS	NS	MF	—	NS	NS	NS	NS
Y(4350)	1^{--}	NS	S	MF	MF	MF	MF	—	MF	MF	MF	MF
Y(4660)	1^{--}	NS	S	MF	MF	MF	MF	S	MF	MF	MF	MF

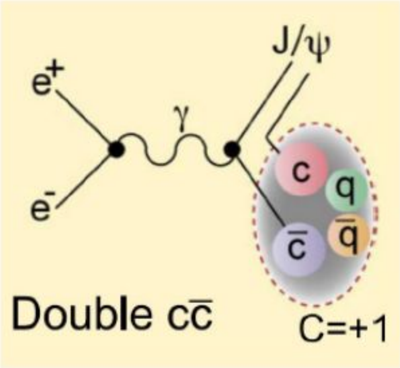
Two-photon production



S - seen (observed)
NS - not seen or excluded
N - not performed (in a given mass range)
MF - missing fit (fit have not been extended to this mass range)
– no search has been performed in this mode

State	J^{PC}	$\psi\pi\pi$	$\psi\omega$	$\psi\gamma$	$\psi\phi$	$\psi'\pi\pi$	$\psi'\omega$	$\psi'\gamma$	$p\bar{p}$	$\Lambda\bar{\Lambda}$	$\Lambda_c\bar{\Lambda}_c$	$D\bar{D}$	$D\bar{D}^*$	$2D^*$	$2D_s^{(*)}$
X(3872)	1^{++}	N	hard	hard	—	—	—	hard	MF	MF	—	MF	N	—	—
Y(3915)	0^{++}	N	S	hard	—	—	—	hard	MF	MF	—	MF	N	—	N
Z(3930)	2^{++}	N	MF	hard	—	—	—	hard	MF	MF	—	S	N	—	N
Y(4140)	J^{P+}	N	MF	hard	NS	N	—	hard	N	N	—	MF	N	N	N
X(4160)	0^{P+}	N	MF	hard	NS	N	—	hard	N	N	—	MF	N	N	N
X(4350)	J^{P+}	N	N	hard	S	N	N	hard	N	N	N	N	N	N	N

Double charmonium production



S - seen (observed)
NS - not seen or excluded
N - not performed (in a given mass range)
MF - missing fit (fit have not been extended to this mass range)
– no search has been performed in this mode

State	J^{PC}	$\psi\pi\pi$	$\psi\omega$	$\psi\gamma$	$\psi\phi$	$\psi'\pi\pi$	$\psi'\omega$	$\psi'\gamma$	$\chi_c\gamma$	$p\bar{p}$	$\Lambda\bar{\Lambda}$	$\Lambda_c\bar{\Lambda}_c$	$D\bar{D}$	$D\bar{D}^*$	$2D^*$
X(3872)	1^{++}	hard	N	hard	—	hard	—	hard	hard	hard	hard	—	MF	MF	—
X(3940)	0^{-+}	hard	N	hard	—	hard	—	hard	hard	hard	hard	—	NS	S	—
Z(3930)	2^{++}	hard	N	hard	—	hard	—	hard	hard	hard	hard	—	MF	MF	—
Y(4140)	J^{P+}	hard	N	hard	N	hard	—	hard	hard	hard	hard	—	MF	MF	MF
X(4160)	0^{P+}	hard	N	hard	N	hard	—	hard	hard	hard	hard	—	MF	S	MF
X(4350)	J^{P+}	hard	N	hard	N	hard	N	hard	hard	hard	hard	hard	MF	MF	MF