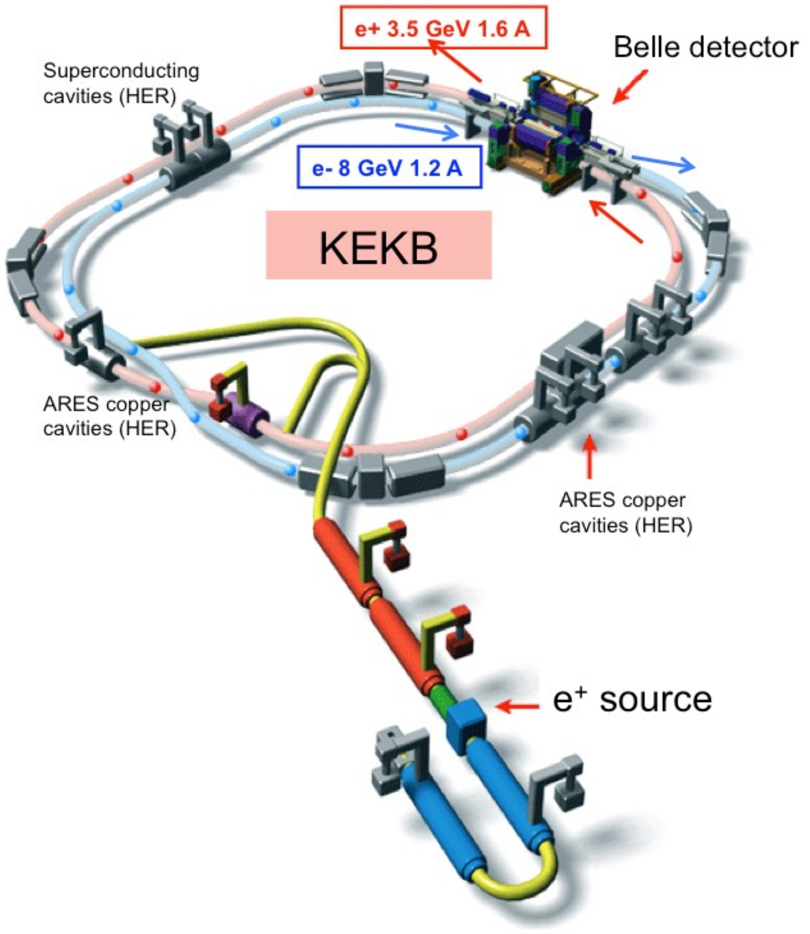
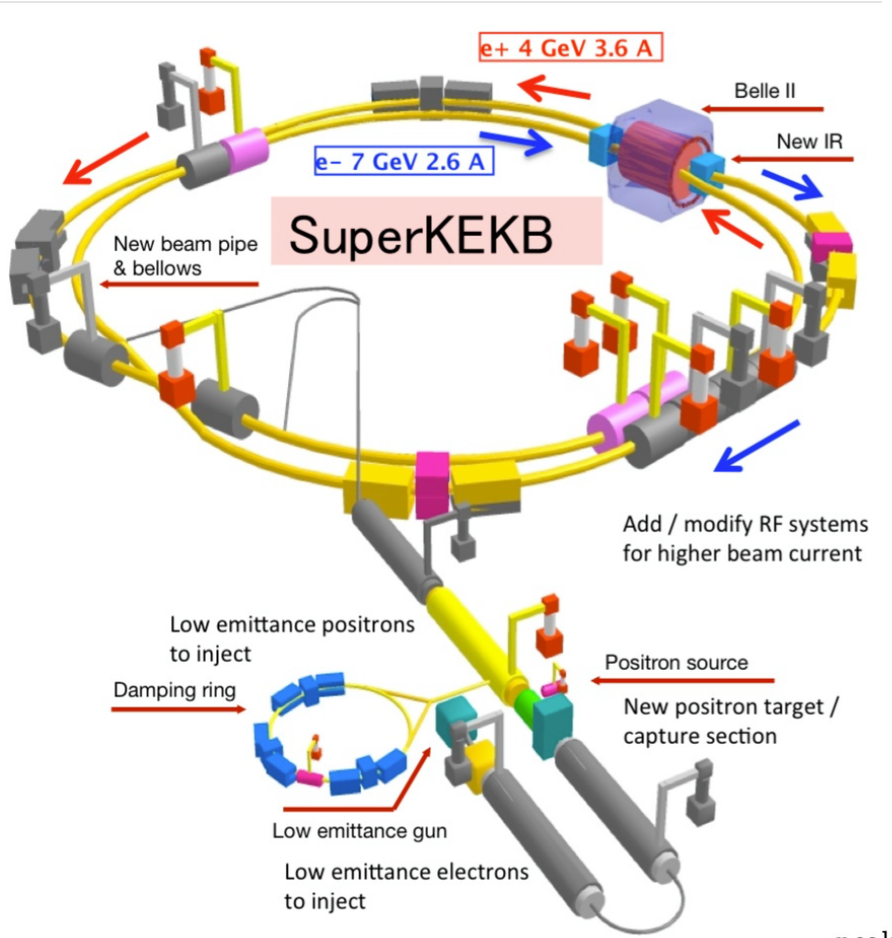
Quarkonium(-like) states at Belle and Belle II

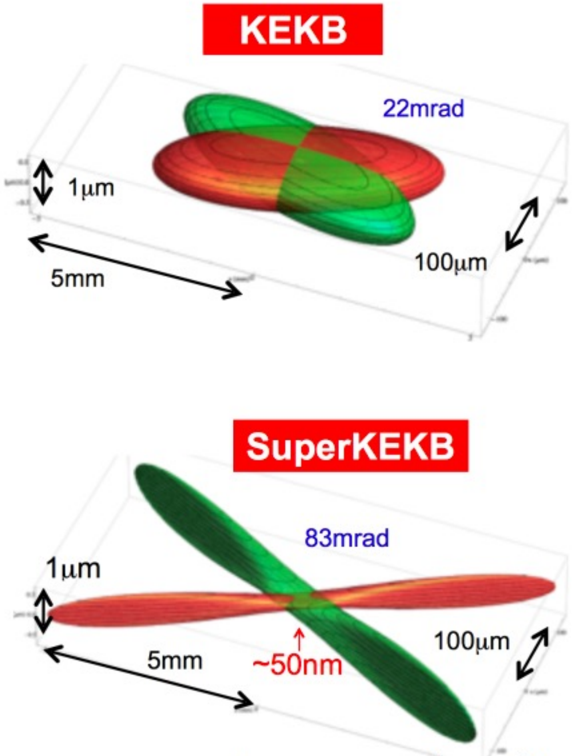
贾森 (东南大学)
on behalf of the Belle and Belle II Collaboration

第八届XYZ粒子研讨会
2023年7月25 – 30 日, 长春

From KEKB to SuperKEKB







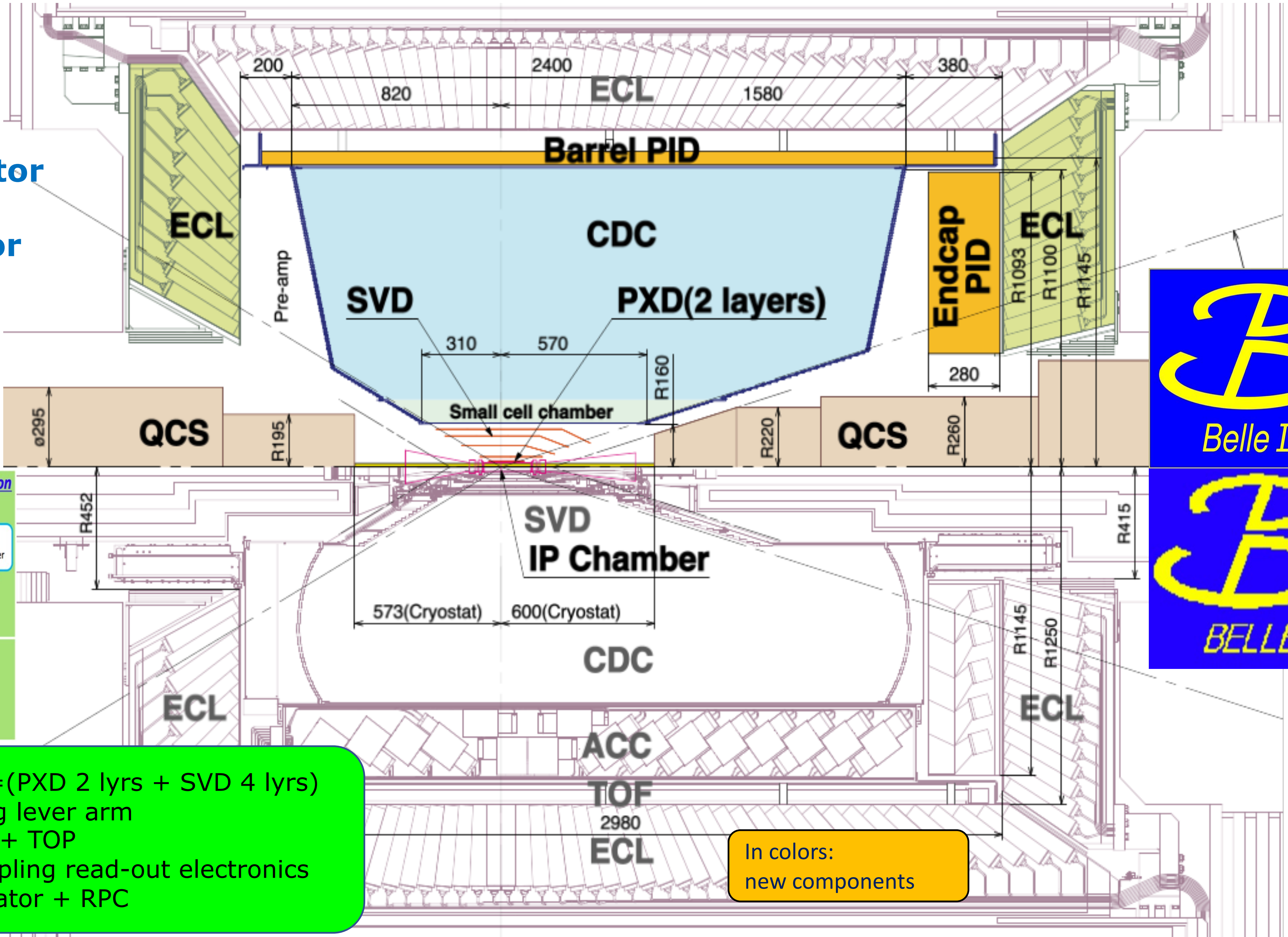
$$\mathcal{L} = \frac{\gamma_{\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

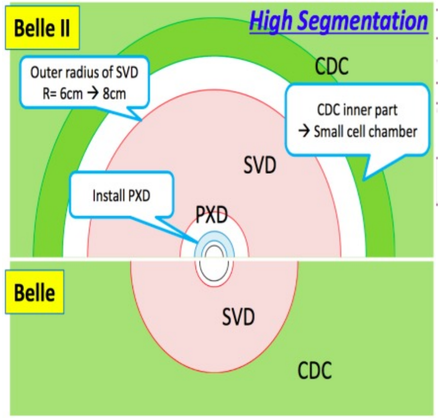
- Double beam currents
- Squeeze beams @IP by ~1/20

$$\mathcal{L}_{\rm II}^{\rm peak} \approx 30 \times \mathcal{L}_{\rm I}^{\rm peak}$$

$$\int^{\rm goal} \mathcal{L}_{\rm II}\, dt = 50\ {\rm ab}^{-1} \approx 50 \int \mathcal{L}_{\rm I}\, dt$$

Belle II detector
Vs.
Belle detector



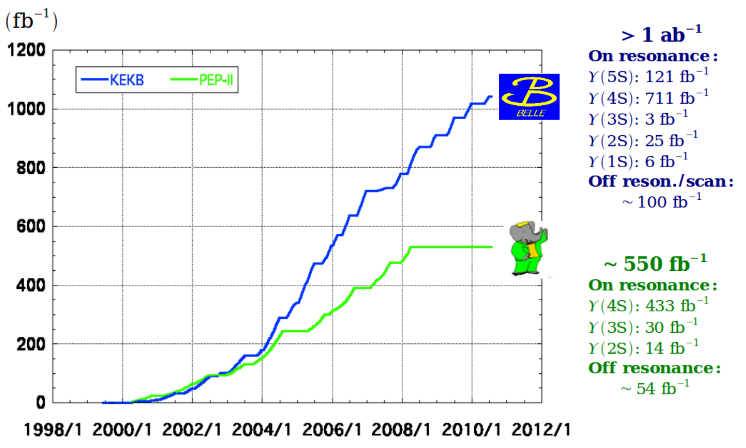


SVD: 4 lyrs → VXD=(PXD 2 lyrs + SVD 4 lyrs)
CDC: small cell, long lever arm
ACC+TOF → ARICH + TOP
ECL: waveform sampling read-out electronics
KLM: RPC → Scintillator + RPC

In colors:
new components

Datasets and new quarkonia at Belle

Integrated luminosity of B factories

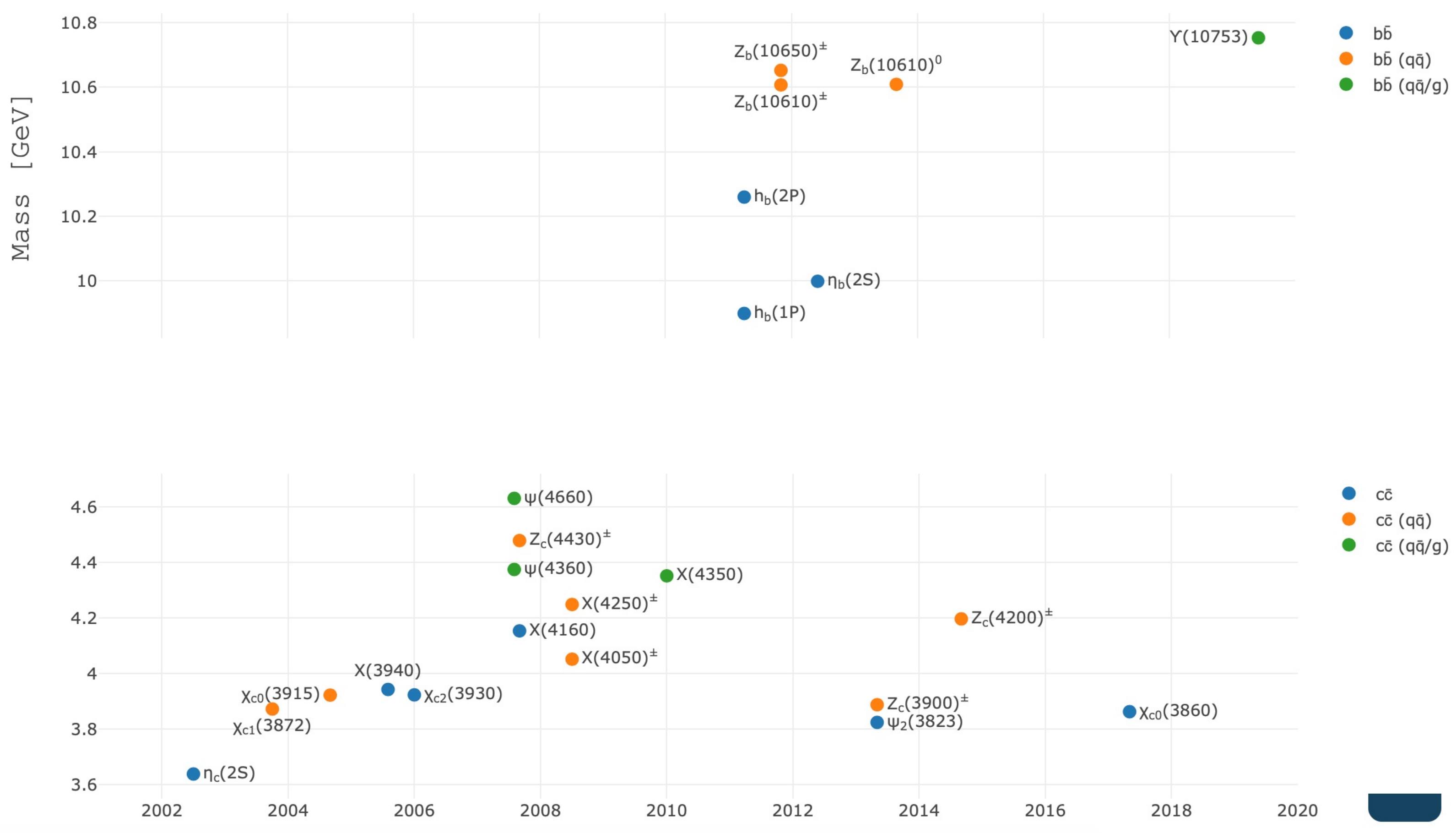


Data taking: 1999 – 2010

On/off/Scan $\Upsilon(nS)$ peaks

772M $B\overline{B}$ events @$\Upsilon(4S)$

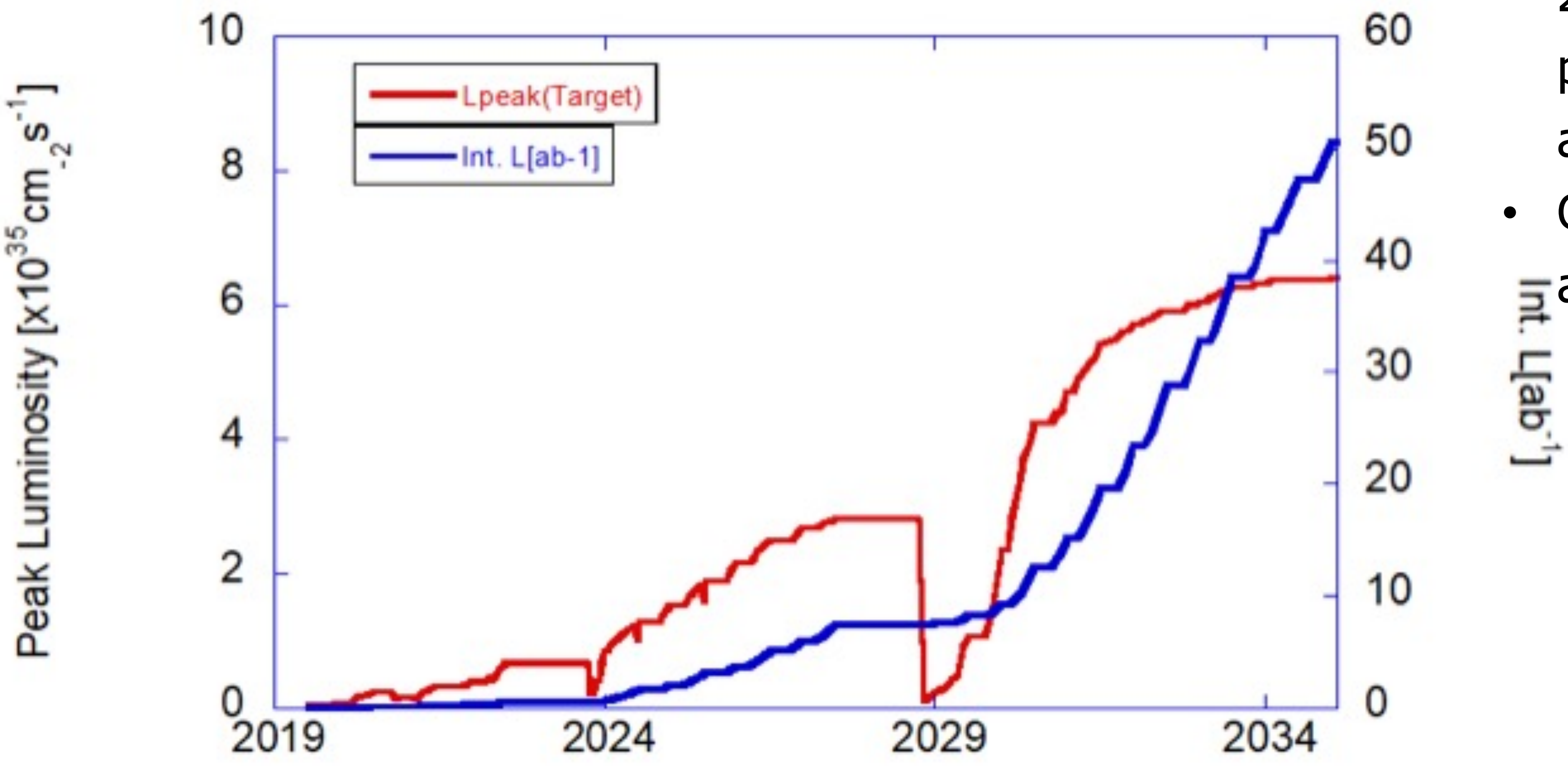
From QWG website:



Datasets at Belle II

In June 2022

WORLD RECORD: 4.7 x 10^{34} $cm^{-2}s^{-1}$



- Collected ~428 fb^{-1} around $\Upsilon(4S)$ until now
- LS1 starts from summer 2022 to fully install the pixel detector and accelerator machine study
- Operation will be resumed around the end of 2023

Selected topics:

Quarkonium at Belle:

- ❑ $X(3872) \to D^0\bar{D}^{*0}$ [PRD 107, 112011 (2023)]
- ❑ $e^+e^- \to \eta_c J/\psi$ [arXiv: 2305.17947]

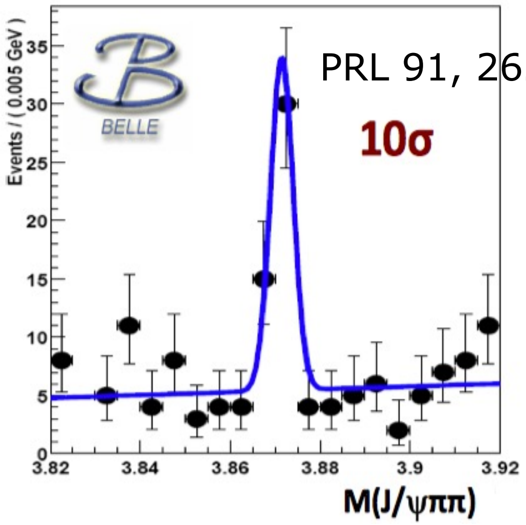
Quarkonium at Belle II:

- ❑ $e^+e^- \to \omega\chi_{bJ}$ and $X_b \to \omega\Upsilon(1S)$ [PRL 130, 091902 (2023)]
- ❑ $e^+e^- \to$ $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ [Preliminary]
- ❑ $e^+e^- \to \omega\eta_b(1S)$ and $e^+e^- \to \omega\chi_{b0}(1P)$ [Preliminary]

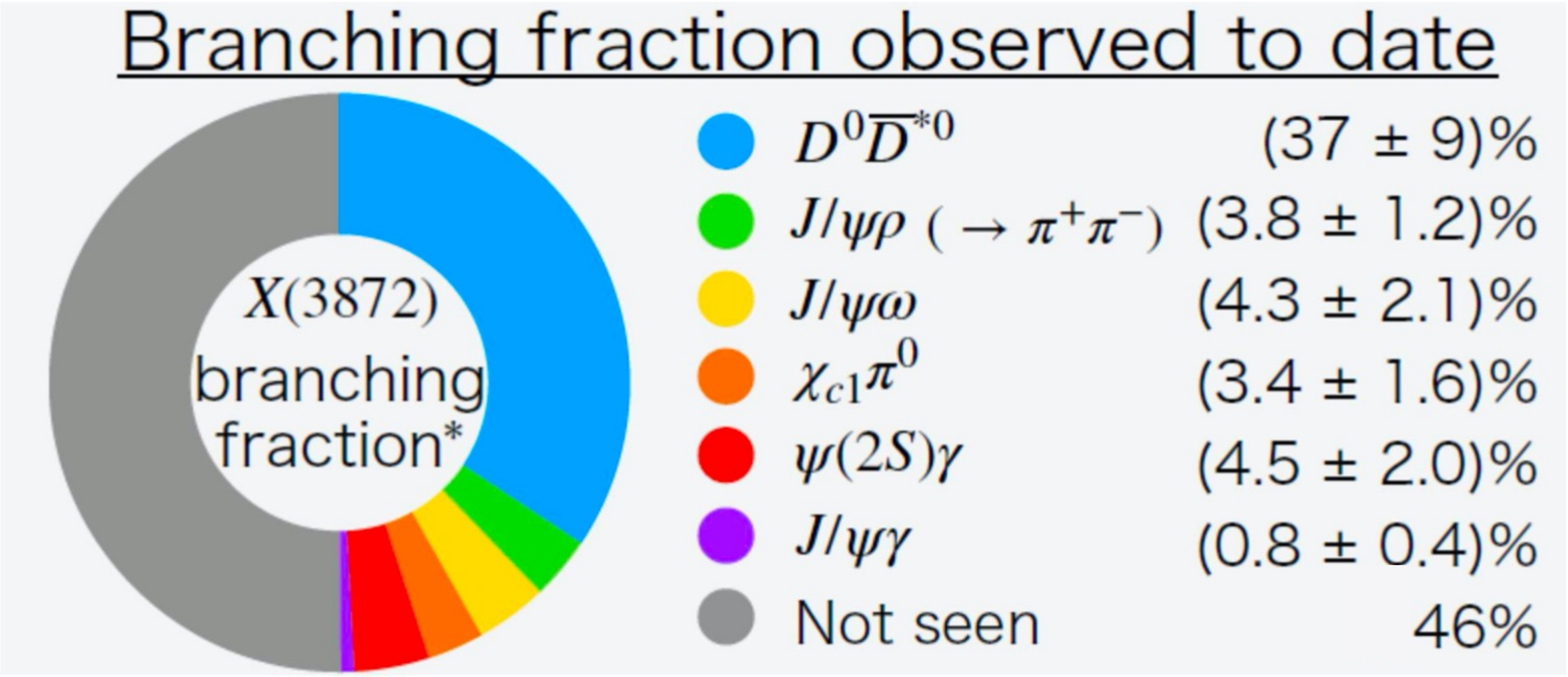
Quarkonium at Belle

A new measurement of $X(3872) \to D^0\bar{D}^{*0}$ at Belle

$X(3872)$ (aka $\chi_{c1}(3872)$) – very famous exotic states
- Narrow width
- Close to DD* threshold
- No place in charmonium potential model
- $\pi\pi$ from ρ decays thus isospin-violating process



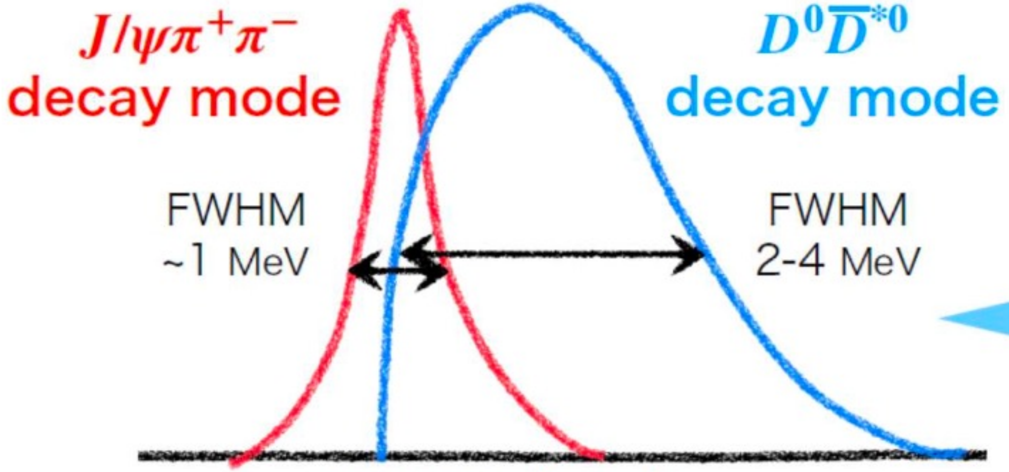
PRL 91, 262001 (2003)



- The $X(3872) \to D^0\bar{D}^{*0}$ decay has the largest BR.
- Determining $X(3872) \to D^0\bar{D}^{*0}$ coupling strength is important to discuss the structure

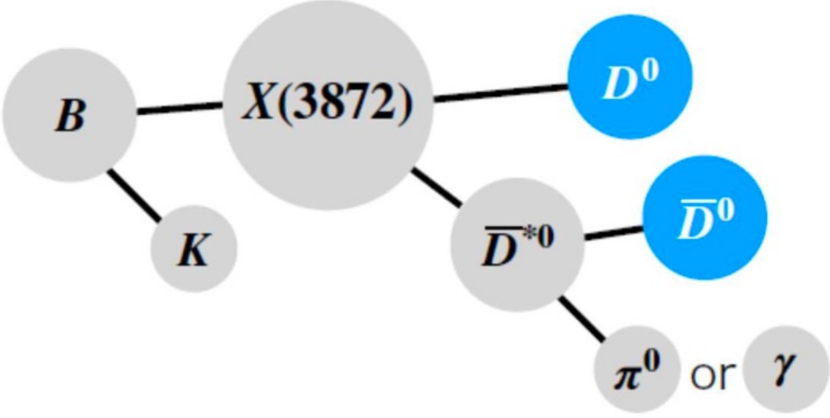
Analysis strategy

$X(3872) \rightarrow \pi^+\pi^- J/\psi$ or $X(3872) \rightarrow D^0\bar{D}^{*0}$?



X(3872) lineshape

- **Wider lineshape**
  because of phase space and threshold effect
- **Better mass resolution**
  thanks to small Q-value (~100 keV, ~1/20 of $J/\psi\pi^+\pi^-$)
- **Belle experiment is suitable**
  because $D^{*0} \rightarrow D^0\gamma, D^0\pi^0$ can be reconstructed.

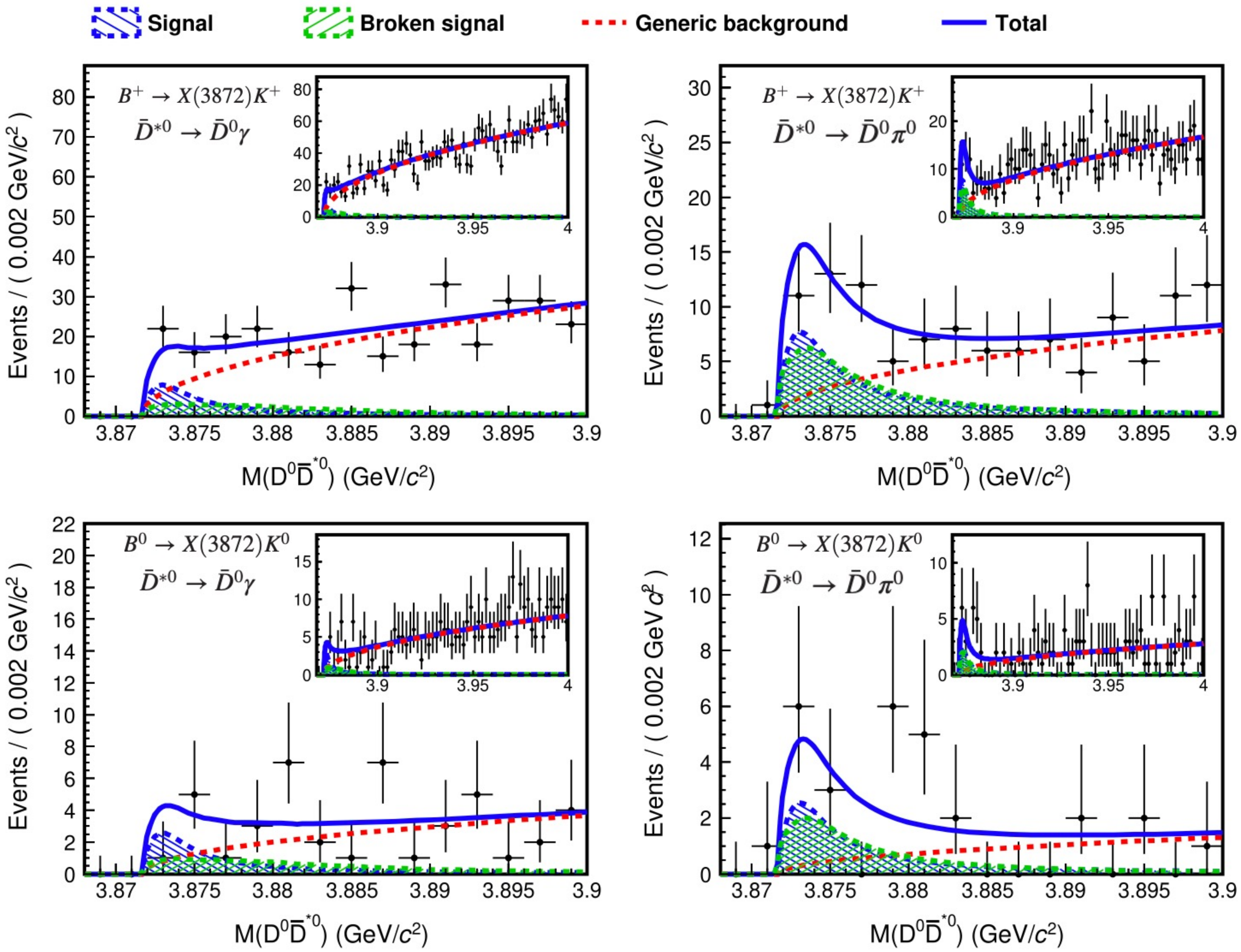


$$D^0 \rightarrow \begin{cases} K^-\pi^+ \\ K^-\pi^+\pi^0 \\ K^-\pi^+\pi^-\pi^+ \\ K^0_S\pi^+\pi^- \\ K^+K^- \\ \boxed{K^0_S\pi^+\pi^-\pi^0} \end{cases}$$

Signal efficiency is improved by a factor of 1.9 compared to previous Belle measurement [PRD 81, 031103 (2010)].

Fits to $M(D^0\bar{D}^{*0})$ with a BW function

[PRD 107, 112011 (2023)]



Broken signal: at least one of the final states is wrongly assigned.

The yield ratio between signal and broken signal is fixed based on MC simulations.

Results:

- Significance: 7.5σ in total
- First observation from the B^0 decay (5.2σ)
- Branching ratios

$$\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to D^0\bar{D}^{*0})$$
$$= (0.97^{+0.21}_{-0.18}(\text{stat}) \pm 0.10(\text{syst})) \times 10^{-4},$$
$$\mathcal{B}(B^0 \to X(3872)K^0) \times \mathcal{B}(X(3872) \to D^0\bar{D}^{*0})$$
$$= (1.30^{+0.36}_{-0.31}(\text{stat})^{+0.12}_{-0.07}(\text{syst})) \times 10^{-4}.$$

- Mass and width

$$m_{\text{BW}} = 3873.71^{+0.56}_{-0.50}(\text{stat}) \pm 0.13(\text{syst})\ \text{MeV}/c^2$$
$$\Gamma_{\text{BW}} = 5.2^{+2.2}_{-1.5}(\text{stat}) \pm 0.4(\text{syst})\ \text{MeV}$$

- All are consistent with Ref. [PRD 81, 031103 (2010)]

Flatté-like model

[PRD 76, 034007 (2007)]

$$f(E) = \frac{g k_{D^0\bar{D}^{*0}}}{\left| E - E_f + \frac{i}{2}\left[\Gamma_0 + \Gamma_{J/\psi\rho}(E) + \Gamma_{J/\psi\omega}(E) + g\left(k_{D^0\bar{D}^{*0}} + k_{D^+D^{*-}}\right)\right]\right|^2}$$

Mass difference from $D^0\bar{D}^{*0}$ threshold

Partial widths for radiative, $J/\psi\rho$, and $J/\psi\omega$ decays

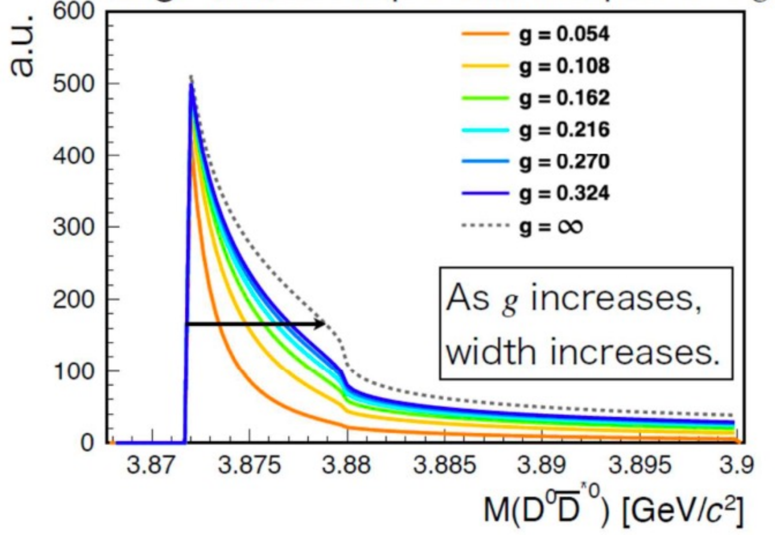
Coupling to $D\bar{D}^*$ channel
… g : Coupling constant to $D\bar{D}^*$ channel
… k_a : Momentum for channel a

Fit does not converge w/o constraints due to poor statistics. Thus,

- $\mathcal{J}_{\mathrm{J/\psi\omega}}$ is fixed by world-average BR
- E_f, $\mathcal{J}_{\mathrm{J/\psi\omega}}$, and $\mathcal{J}_{\mathrm{J/\psi\rho}}$ are fixed based on LHCb results [PRD 102, 092005 (2020)]

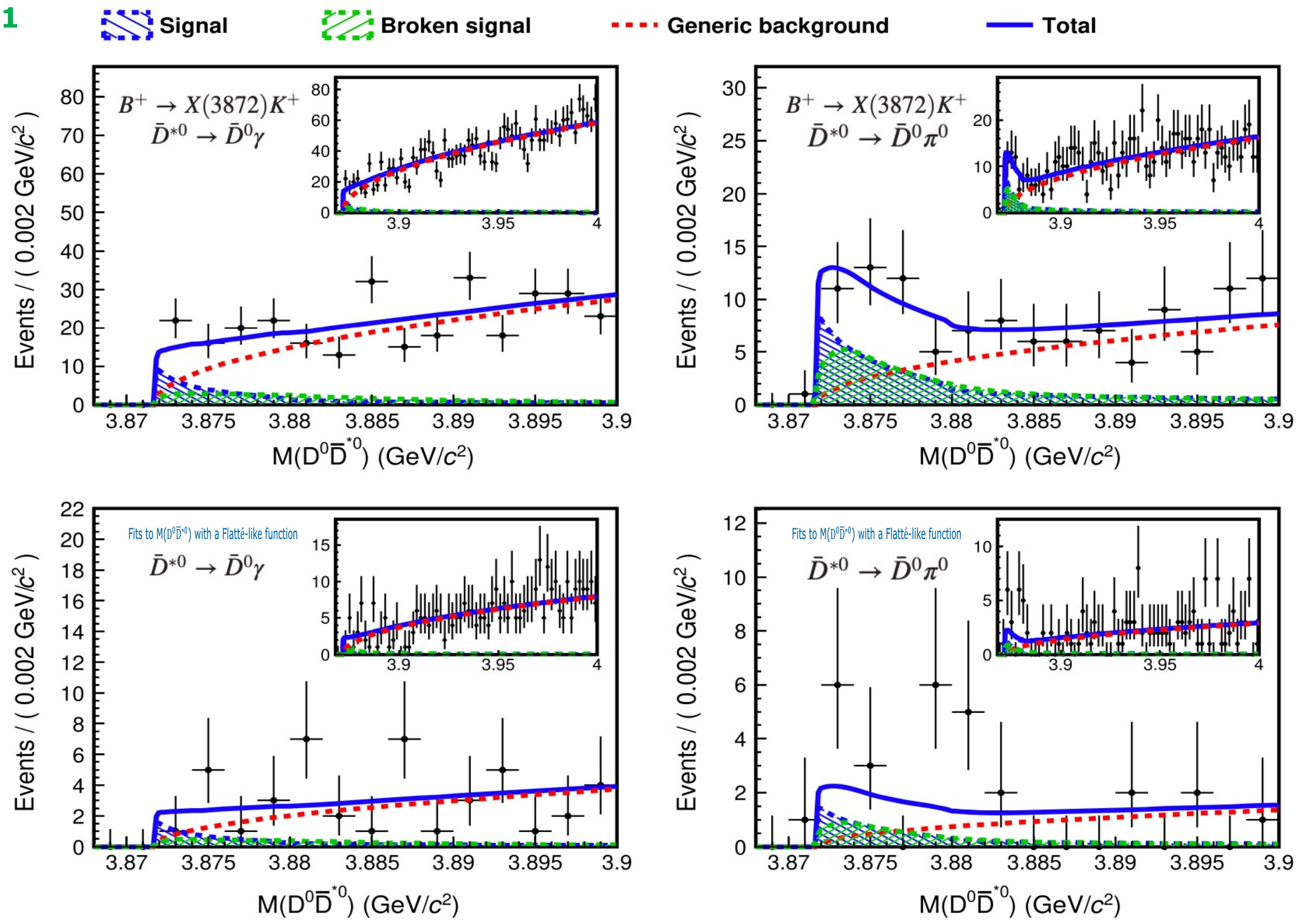
⟹ Only g is floated

Change in lineshape with respect to g

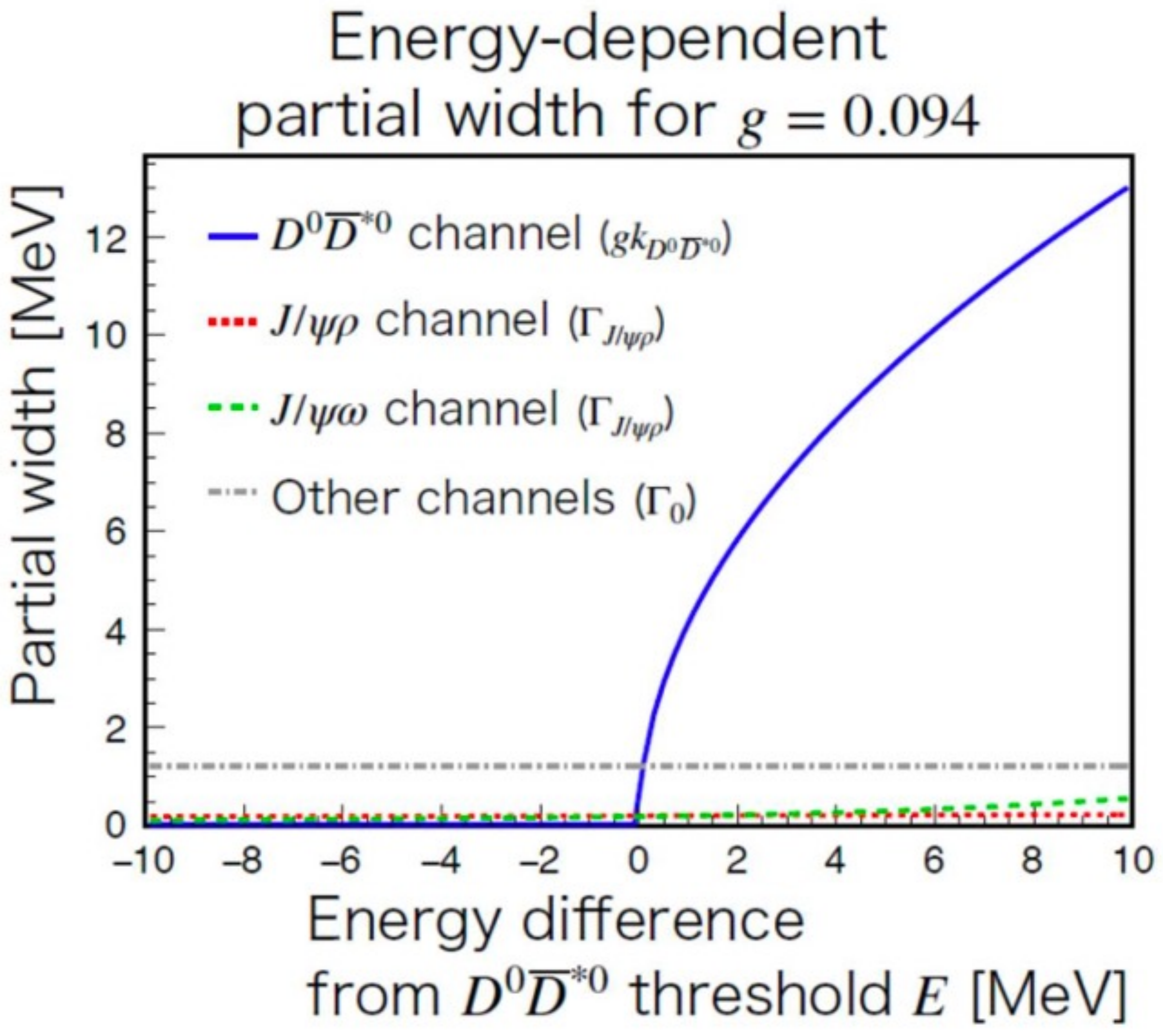


Fits to $M(D^0\bar{D}^{*0})$ with a Flatté-like function

[PRD 107, 112011 (2023)]



Result and discussion



[PRD 107, 112011 (2023)]

- Fit result: g = $0.29^{+2.69}_{-0.15}$ (stat. only)

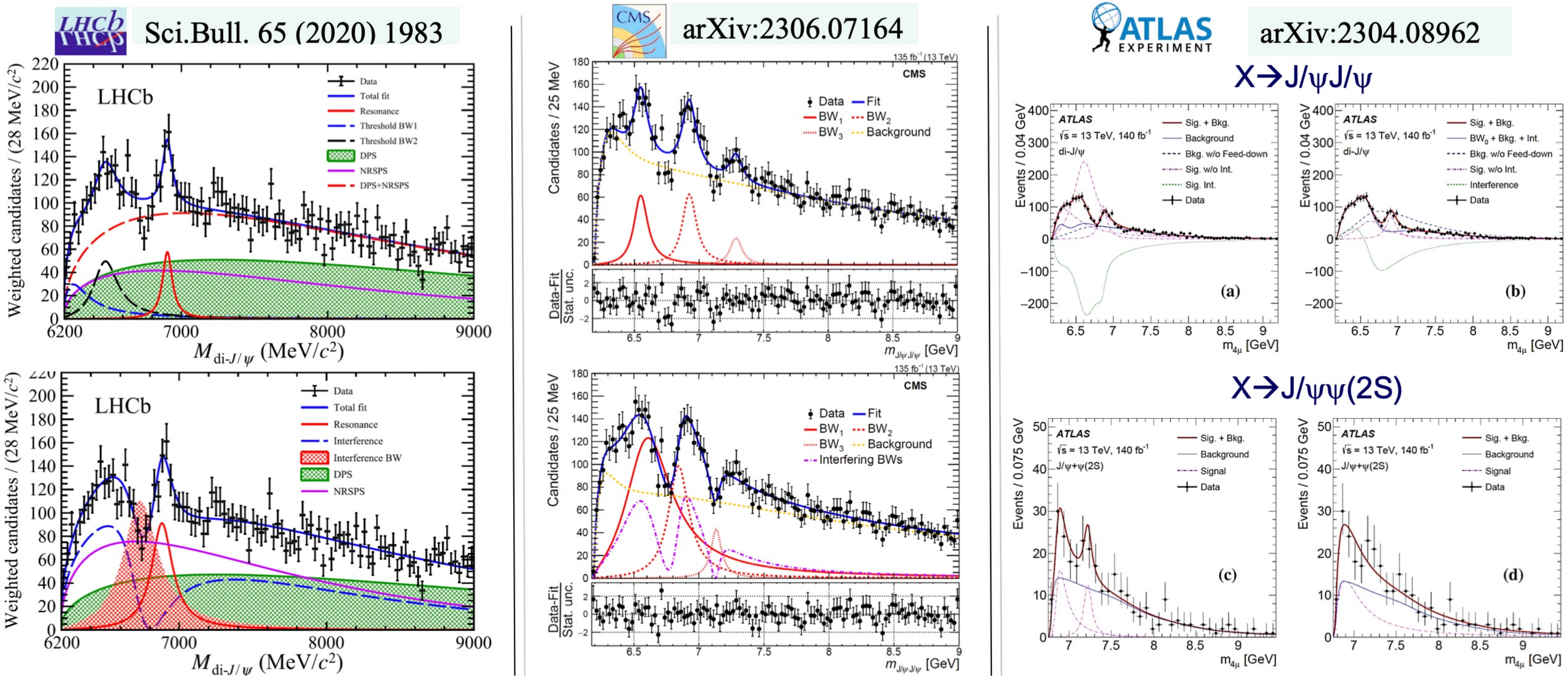
⇒ Lower limit: g > 0.094 (90% C.L.)

including systematic uncertainty

- Partial width for $D^0\overline{D}^{*0}$ channel is rather large

Search for the double-charmonium state with $\eta_c J/\psi$ at Belle

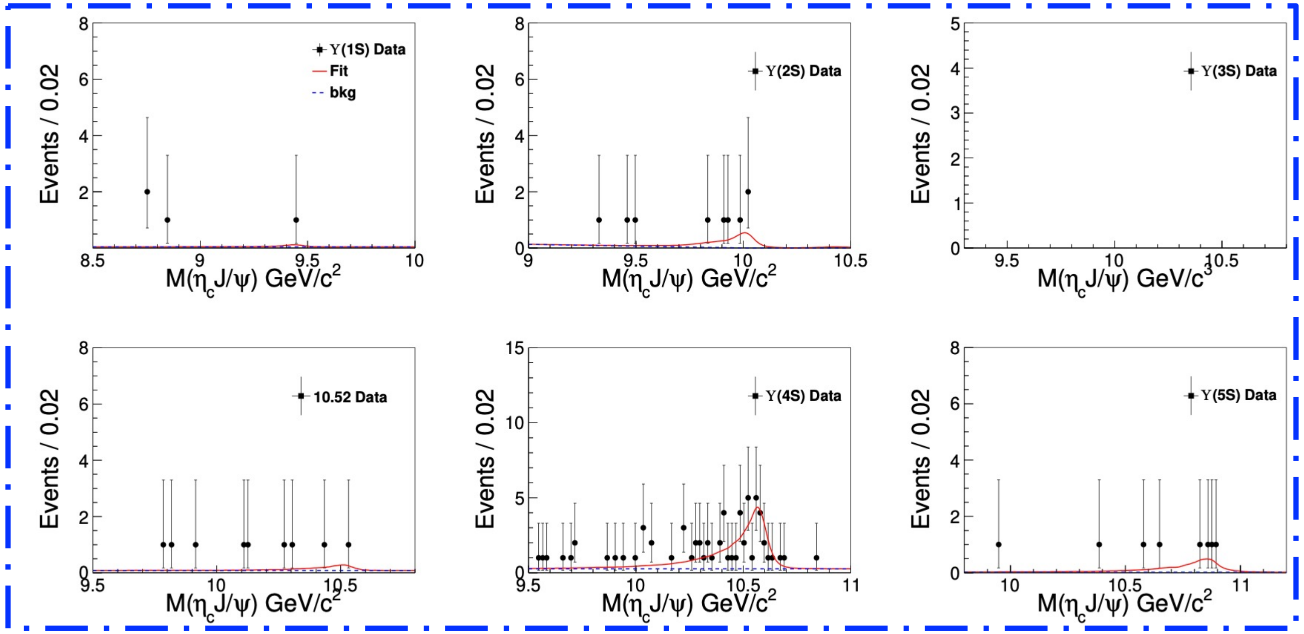
- LHCb, CMS, and ATLAS observed new resonances in the $J/\psi J/\psi$ ($cc\bar{c}\bar{c}$) invariant mass distributions.



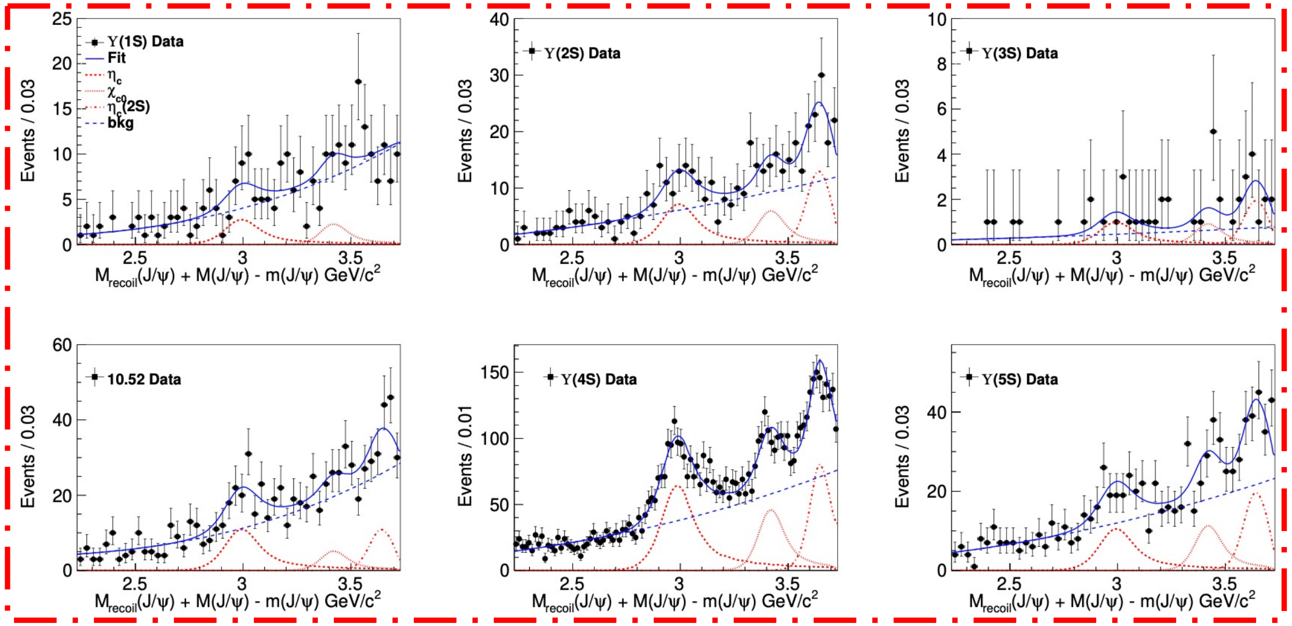
- The lowest mass combination of charmonia to which a vector $cc\bar{c}\bar{c}$ (Y_{cc}) could decay is $\eta_c J/\psi$, and this process may have a relative large branching fraction [Phys. Rev. D 73, 094510 (2006)].

The energy dependency of the Born cross sections for $e^+e^- \to \eta_c J/\psi$

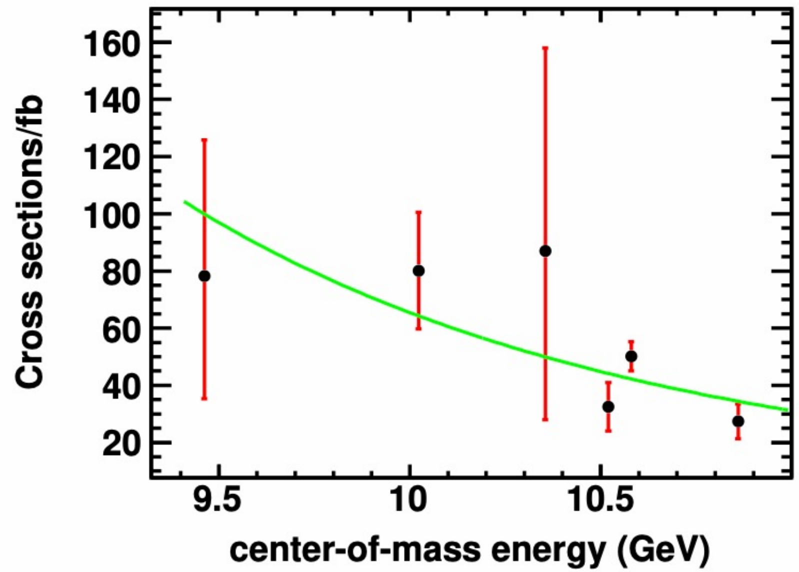
[arXiv: 2305.17947]



Exclusive process



Inclusive process

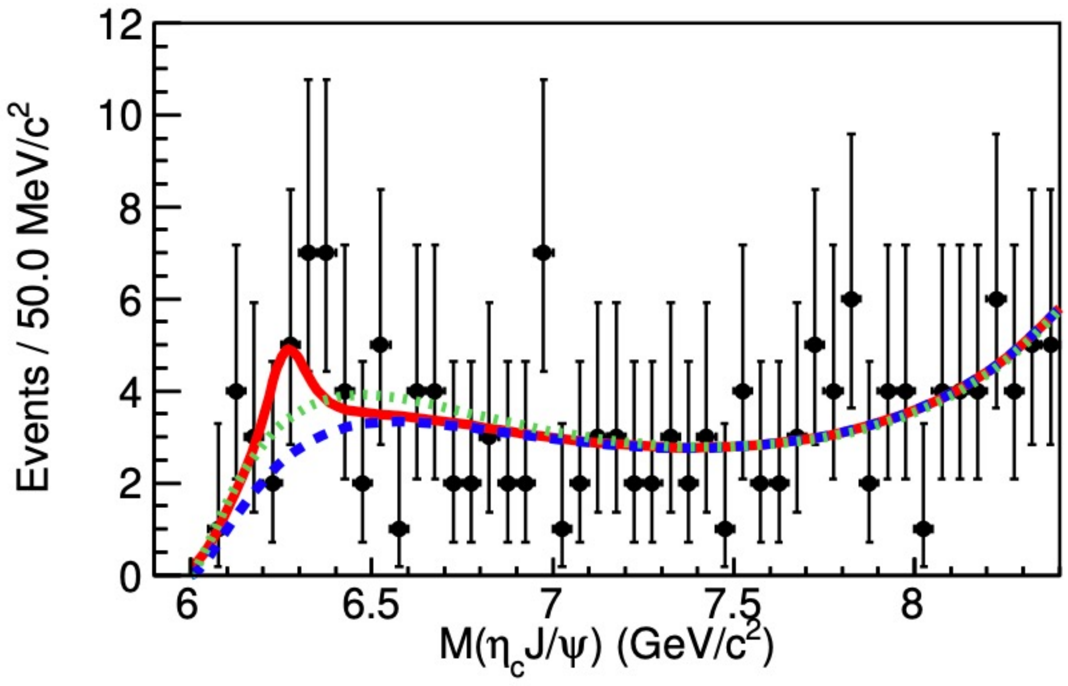


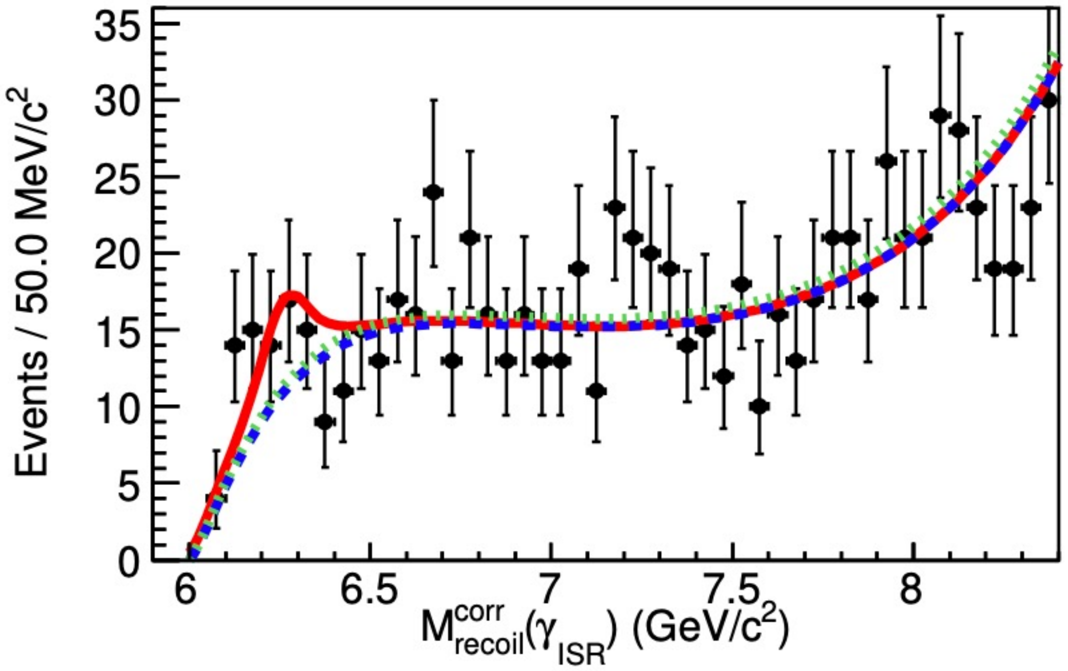
$$\sigma = A\frac{\sqrt{2\mu\Delta M}}{\left(\frac{s}{s_0}\right)^n}$$

n = 4.5±1.3

$e^+e^- \to \eta_c J/\psi$ near threshold

[arXiv: 2305.17947]





- Red solid curve: best fits
- Blue dashed curve: the background component
- Green dotted curve: fits without the signal component

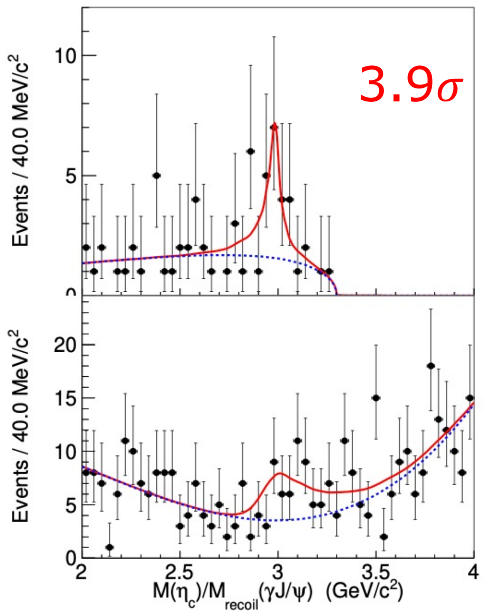
Parameters	Exclusive	Inclusive
Mass	(6267±43) MeV/c^2	
Width	(121±72) MeV	
Yield	9±4	23±11
Significance	2.2σ	

Measured cross sections of $e^+e^- \to \eta_c J/\psi$ near the threshold

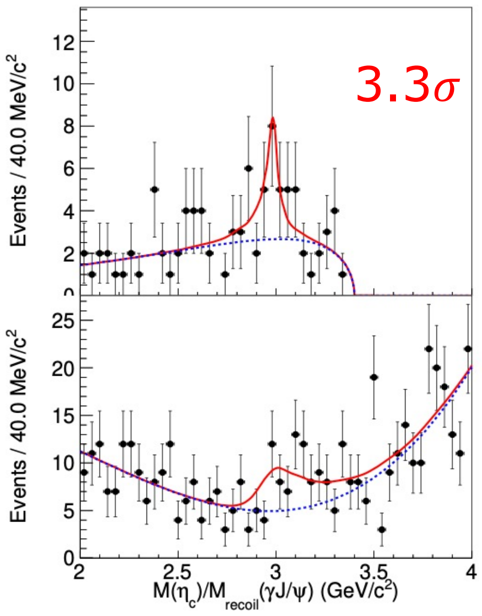
A simultaneous unbinned maximum likelihood fit for the η_c invariant mass and $\gamma_{ISR}J/\psi$ recoil mass:

[arXiv: 2305.17947]

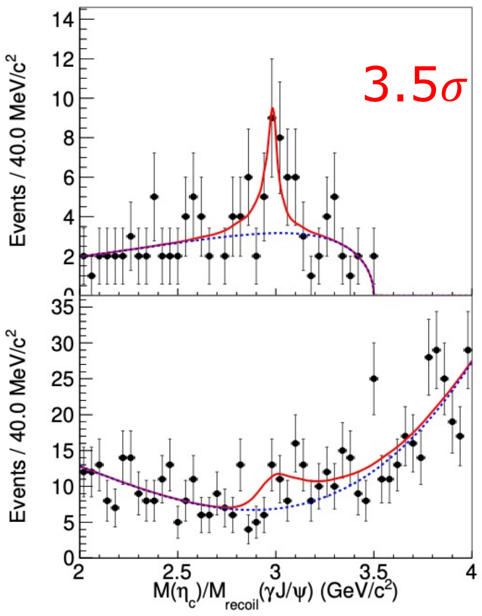
$\sqrt{s}$ = 6.0 - 6.4 GeV

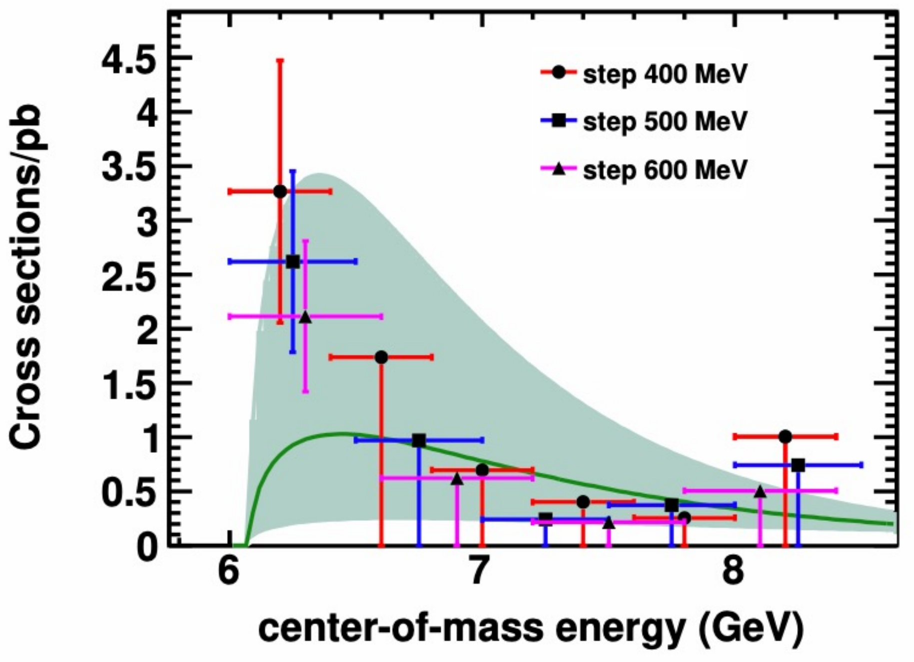


$\sqrt{s}$ = 6.0 - 6.5 GeV



$\sqrt{s}$ = 6.0 - 6.6 GeV



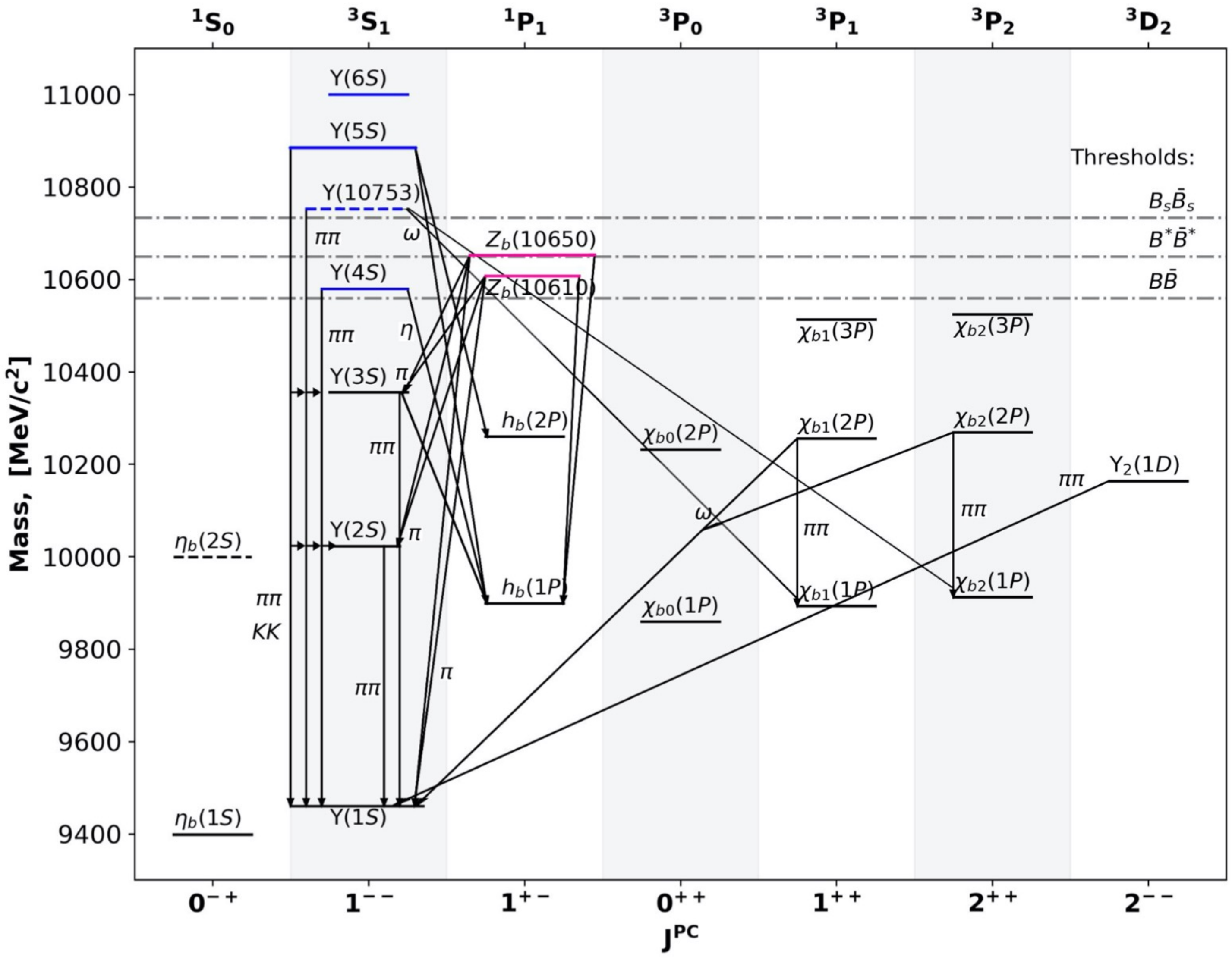


- Green solid curve: the fit
- Shadow area: $\pm 1\sigma$ region

The evidence for the enhancement of $e^+e^- \to \eta_c J/\psi$ near the threshold.

Quarkonium at Belle II

Bottomonium

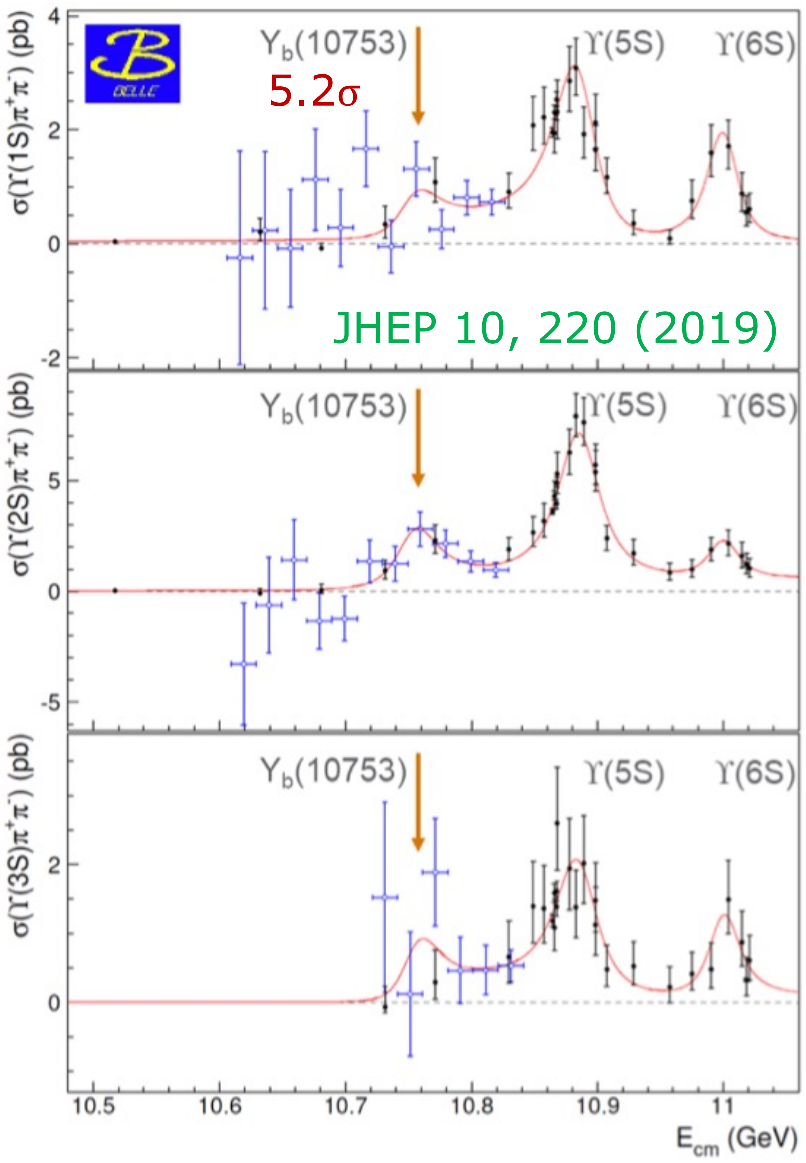


- Below $B\bar{B}$ thresholds – bottomonia are well described by the potential models.
- Above $B\bar{B}$ thresholds – bottomonia express unexpected properties:

- Two charged Z_b^+ states are observed ($B^{(*)}\bar{B}^*$ molecular?)
- Hadronic transitions are strongly enhanced (OZI rule violation);
- η transitions are not suppressed compare to $\pi^+\pi^-$ transitions (heavy quark spin-symmetry violation);

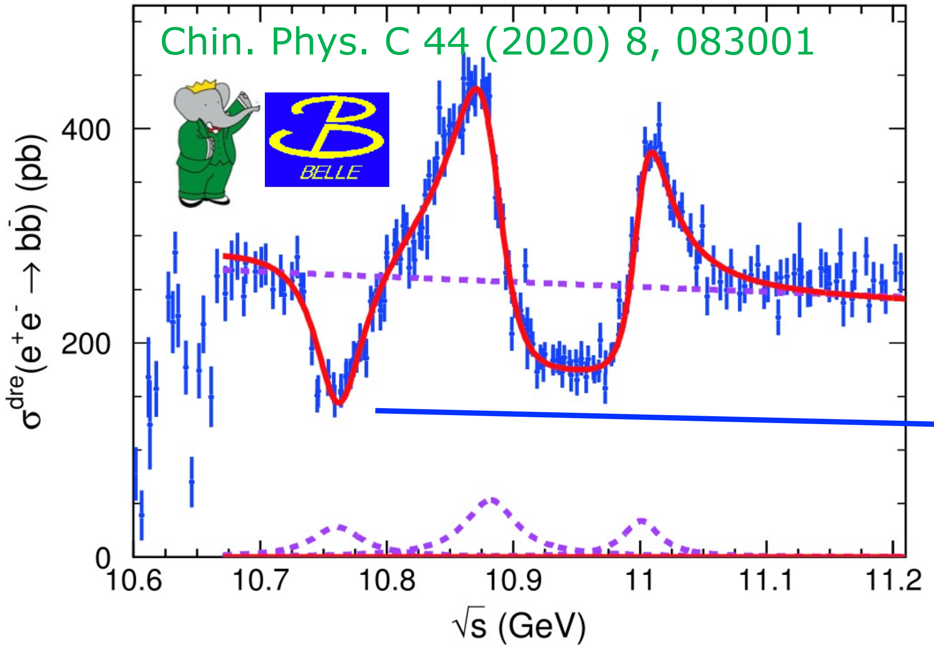
Conventional bottomonium (pure $b\bar{b}$ states)
Bottomonium-like states (mix of $b\bar{b}$ and $B\bar{B}$)
Exotic charged states (Z_b^+)

Discovery of $\Upsilon(10753)$



- Belle: several ~1fb^{-1} scan points below $\Upsilon(5S)$
- New structure observed in $\pi^+\pi^-\Upsilon(nS)$ transitions

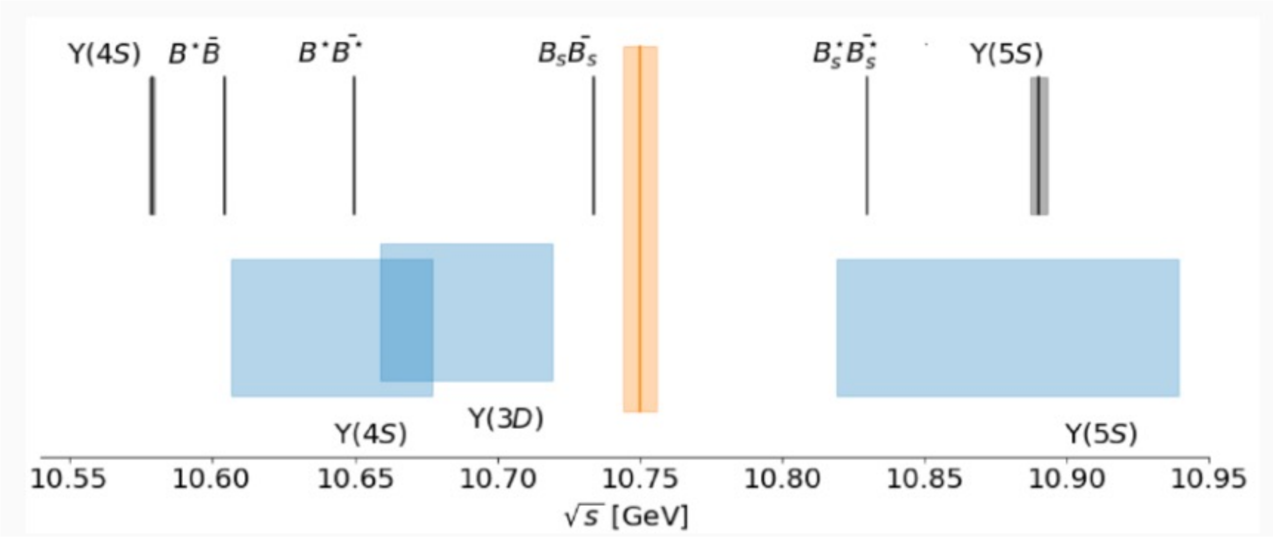
	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}\,^{+1.0}_{-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$



A dip at 10.75 GeV may correspond to $\Upsilon(10753)$.

Theoretical interpretations

Godfrey and Moats, PRD 92, 054034 (2015)



- Mass does not match ϒ(3D) theoretical predictions, and D-wave states are not seen in e^+e^- collisions.
- ϒ(4S) - ϒ(3D) mixing can be enhanced due to hadron loops.

❑ Conventional bottomonium

Eur. Phys. J. C 80, 59 (2020)
Phys. Rev. D 101, 014020 (2020)
Phys. Rev. D 102, 014036 (2020)
Phys. Lett. B 803, 135340 (2020)
Phys. Rev. D 104, 034036 (2021)
Prog. Part. Nucl. Phys. 117, 103845 (2021)
Eur. Phys. J. Plus 137, 357 (2022)
Phys. Rev. D 105, 114041 (2022)
Phys. Rev. D 106, 094013 (2022)
Phys. Rev. D 105, 074007 (2022)

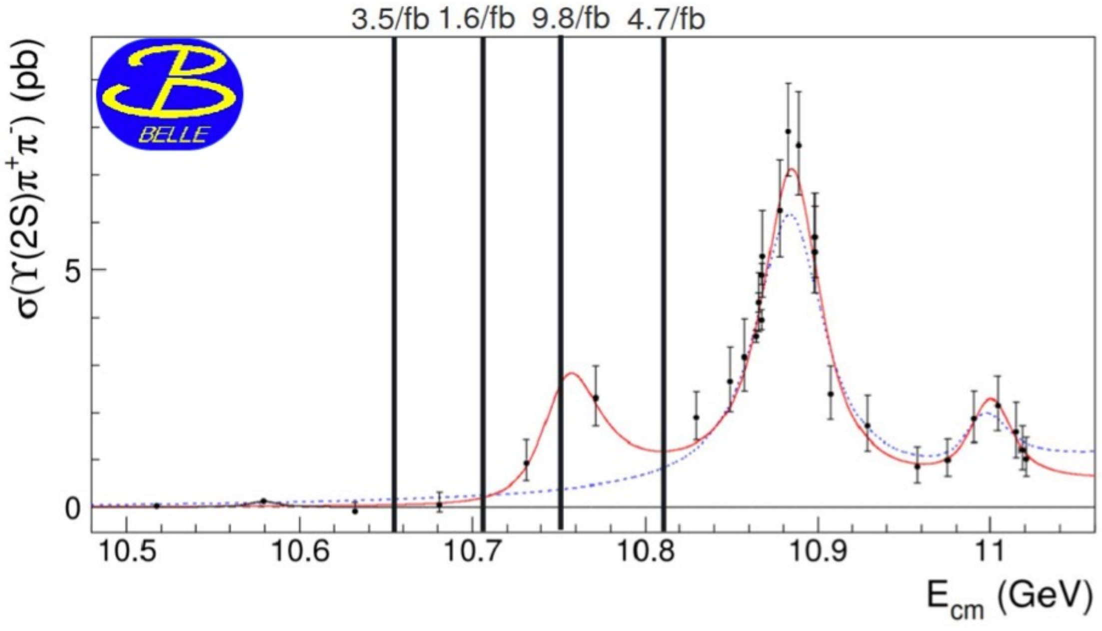
❑ Hybrid

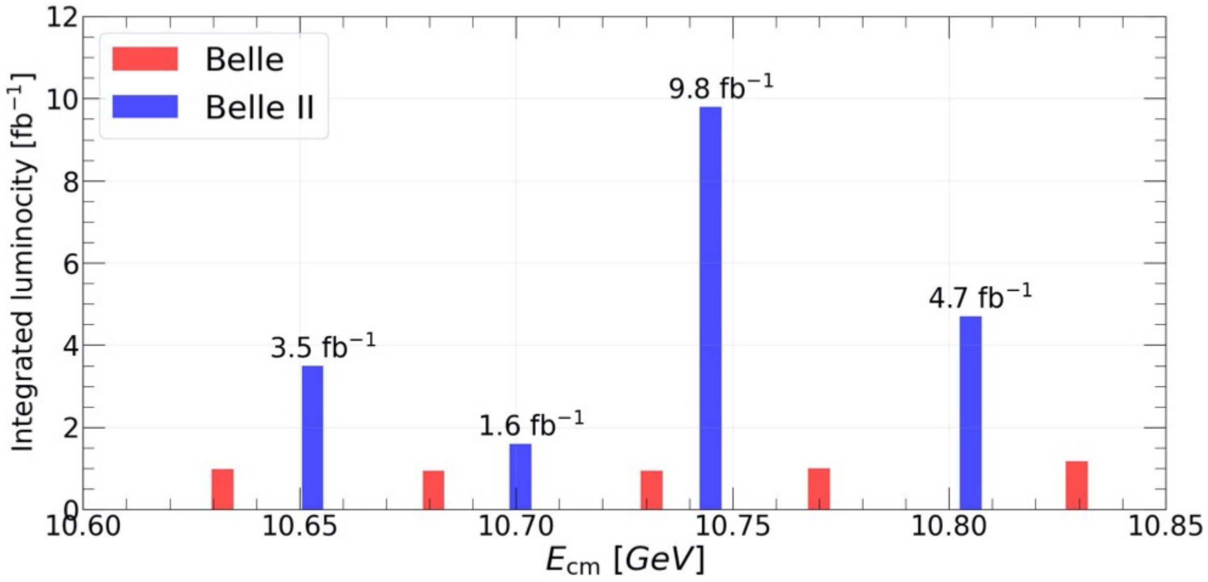
Phys. Rept. 873, 1 (2020)
Phys. Rev. D 104, 034019 (2021)

❑ Tetraquark

Chin. Phys. C 43, 123102 (2019)
Phys. Lett. B 802, 135217 (2020)
Phys. Rev. D 103, 074507 (2021)
Phys. Rev. D 107, 094515 (2023)

Unique scan data near $\sqrt{s}$ = 10.75 GeV





- In November 2021, Belle II collected 19 fb^{-1} of unique data at energies above the ϒ(4S): four energy scan points around 10.75 GeV.
- Belle II collected the data in the gaps between Belle energy scan points.
- Physics goal: understand the nature of the ϒ(10753) energy region.

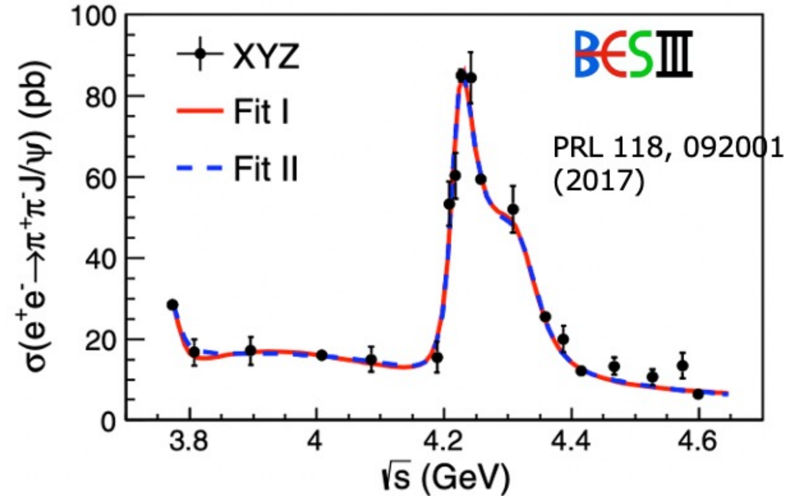
Motivation to search for $\Upsilon(10753) \to \omega\chi_{bJ}$

Theory: Branching fractions of 10^{-3} for $\Upsilon(10753) \to \omega\chi_{bJ}$ [PRD 104, 034036 (2021)] and $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$ [PRD 105, 074007 (2022)] assuming Υ(4S) - Υ(3D) mixing state for Υ(10753).

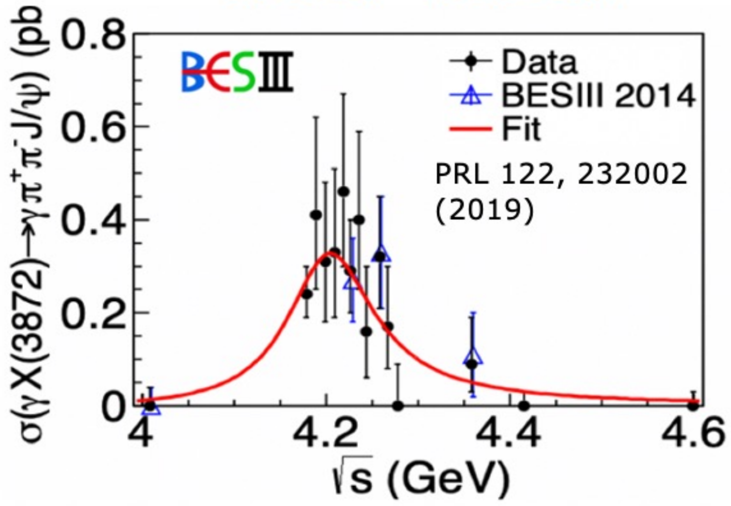
Charmonium sector:

- Two close peaks observed in the cross sections for $e^+e^- \to \pi^+\pi^- J/\psi$ by BESIII and $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ by Belle, respectively, may suggest similar nature.
- Y(4220) $\to \gamma X(3872)$ and $\omega\chi_{c0}$ observed by BESIII.
- So we expect the observations of $\Upsilon(10753) \to \gamma X_b$ and $\omega\chi_{bJ}$.

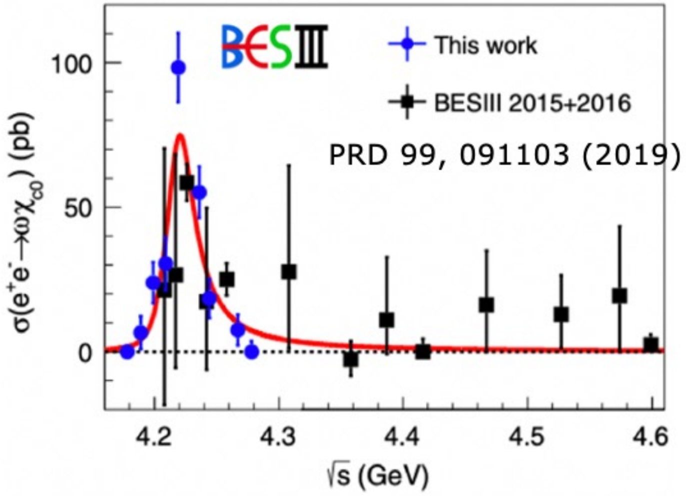
$Y(4220)/Y(4320) \to \pi^+\pi^- J/\psi$



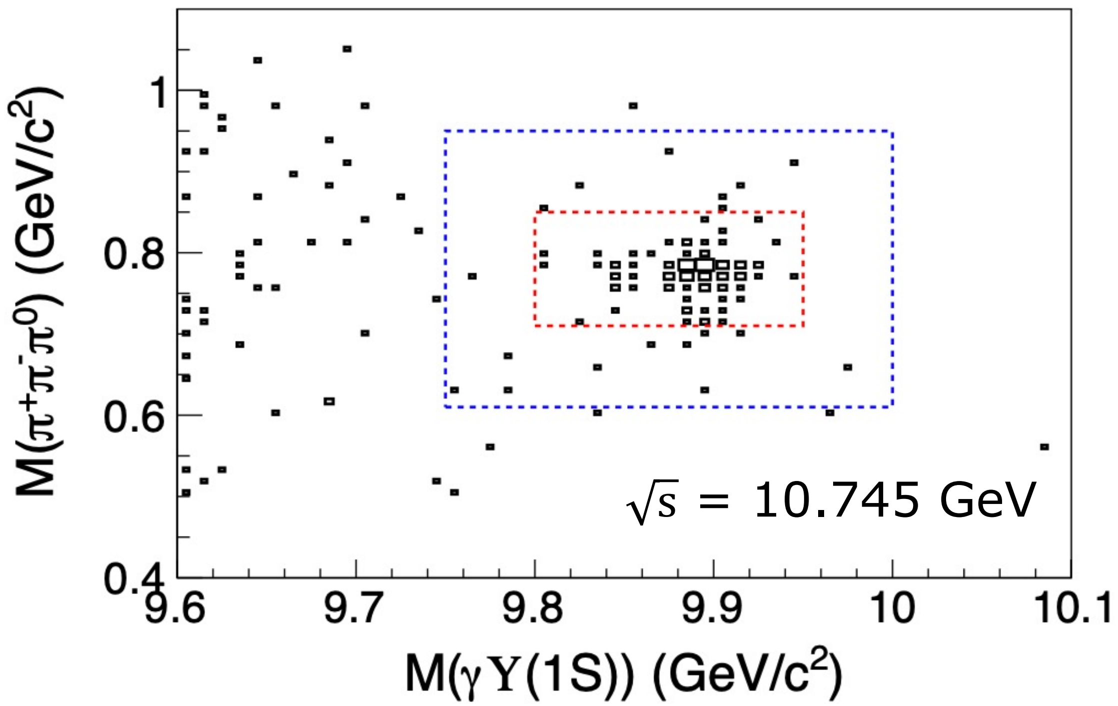
$Y(4220) \to \gamma X(3872)$

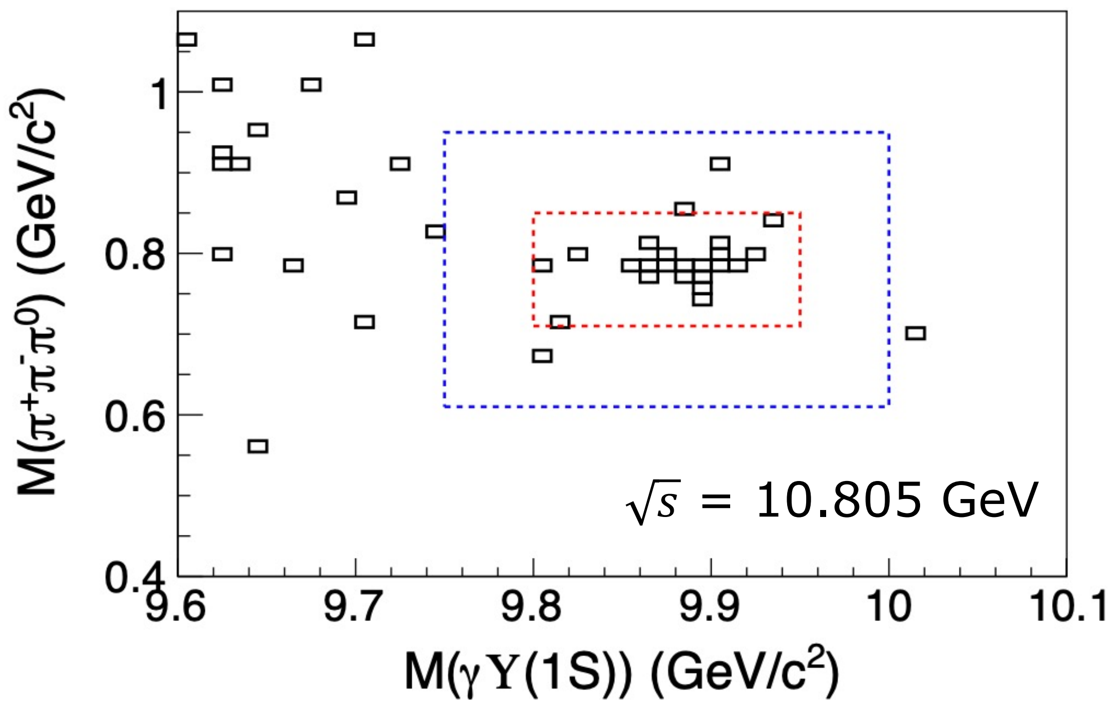


$Y(4220) \to \omega\chi_{c0}$



Mass distributions



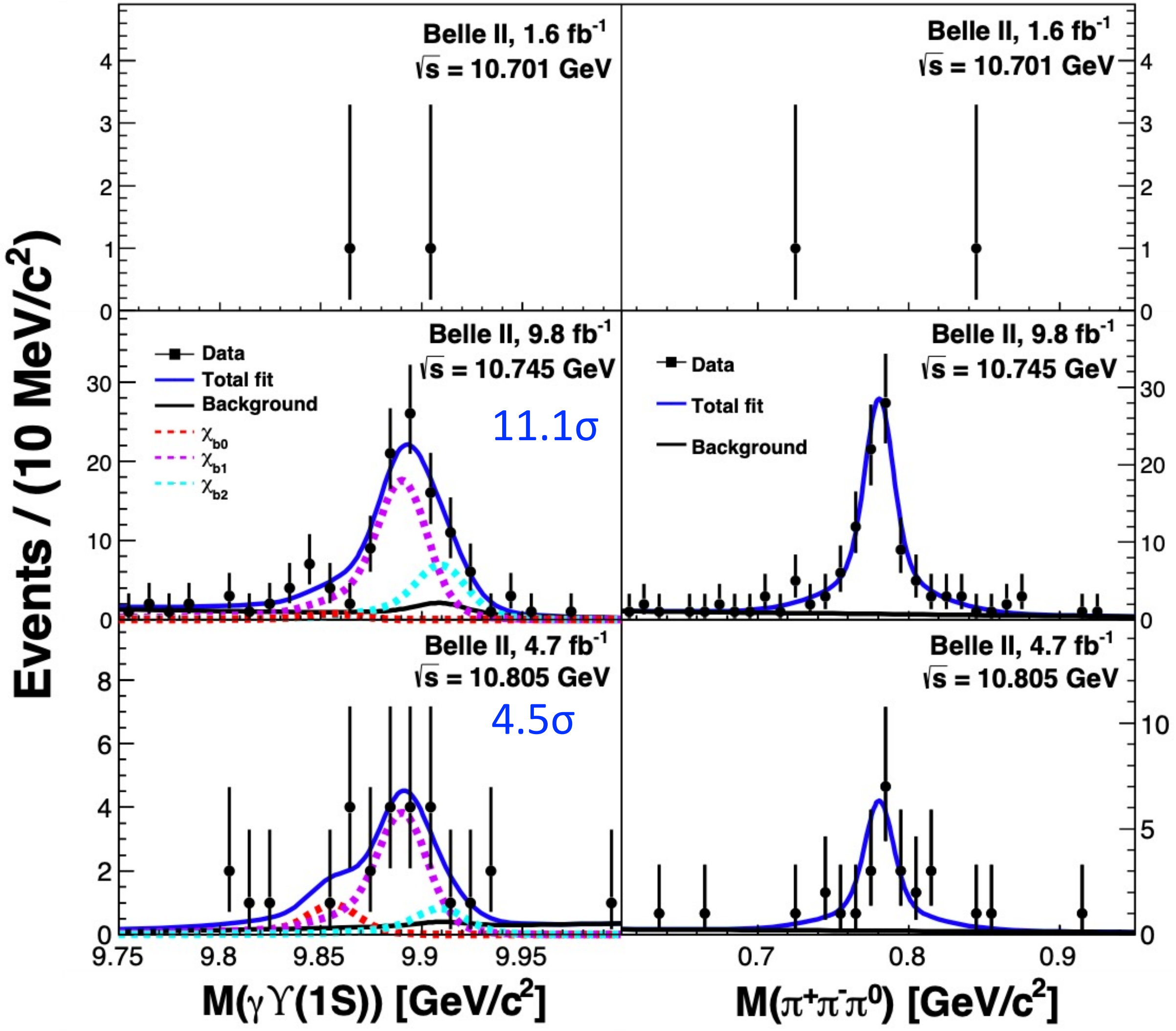


- Red boxes contains 95% of signals.
- Blue boxes show the fit ranges.

Observation of $\Upsilon(10753) \to \omega\chi_{bJ}$

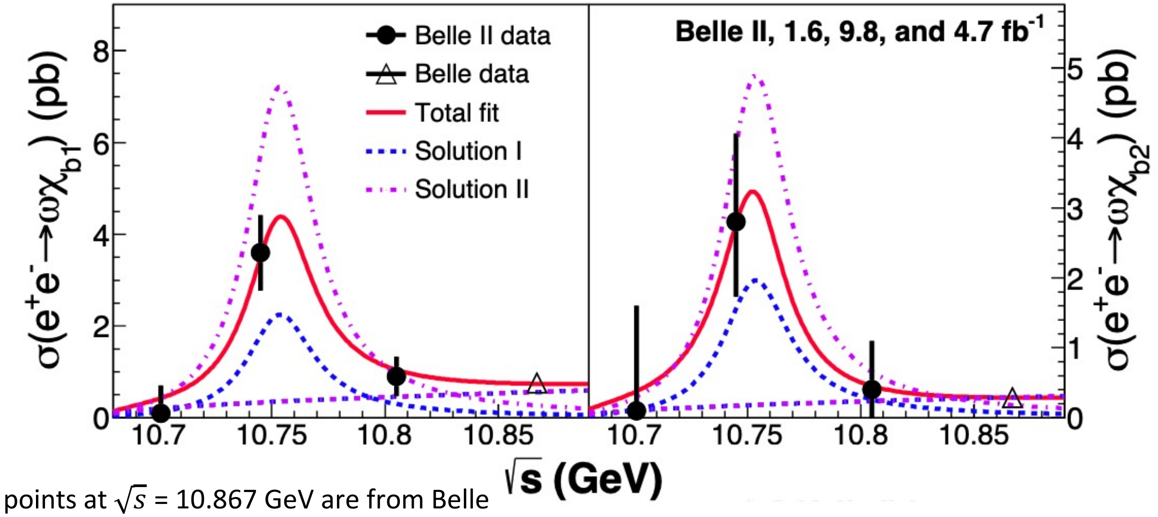
PRL 130, 091902 (2023)

Two dimensional unbinned maximum likelihood fits to the $M(\gamma\Upsilon(1S))$ and $M(\pi^+\pi^-\pi^0)$ distributions.



Channel	$\sqrt{s}$ (GeV)	N^{sig}	$\sigma_{Born}^{(UL)}$ (pb)
$\omega\chi_{b1}$	10.745	$68.9^{+13.7}_{-13.5}$	$3.6^{+0.7}_{-0.7} \pm 0.4$
$\omega\chi_{b2}$		$27.6^{+11.6}_{-10.0}$	$2.8^{+1.2}_{-1.0} \pm 0.5$
$\omega\chi_{b1}$	10.805	$15.0^{+6.8}_{-6.2}$	1.6 @90% C.L.
$\omega\chi_{b2}$		$3.3^{+5.3}_{-3.8}$	1.5 @90% C.L.

The $e^+e^- \to \omega\chi_{bJ}$ (J = 1, 2) cross sections peak at $\Upsilon(10753)$.



The points at $\sqrt{s}$ = 10.867 GeV are from Belle measurements [PRL 113, 142001 (2014)].

Discussion

$$\frac{\sigma(e^+e^-\to\chi_{bJ}(1P)\omega)}{\sigma(e^+e^-\to\Upsilon(nS)\pi^+\pi^-)} \sim$$

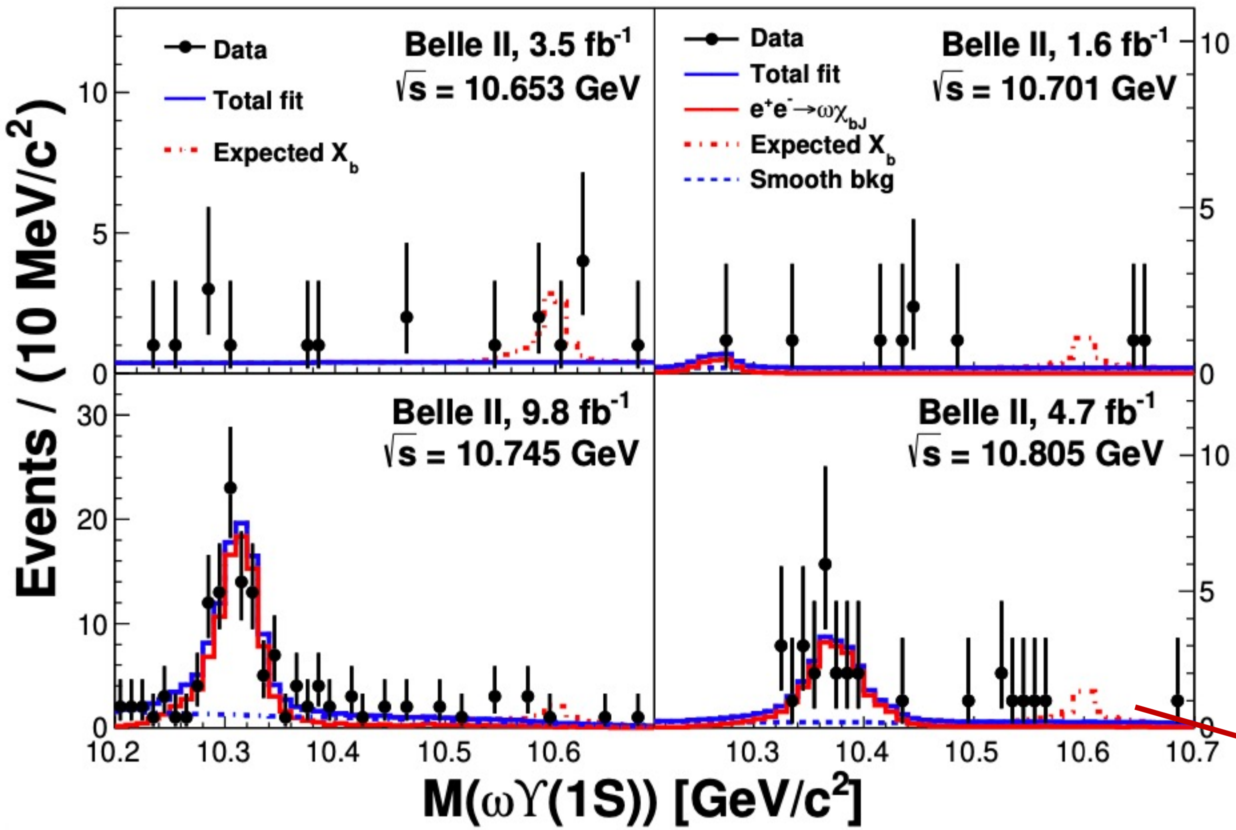
- $\sim$1.5 at $\sqrt{s}$ = 10.745 GeV [PRL 130, 091902 (2023)]
- $\sim$ 0.15 at $\sqrt{s}$ = 10.867 GeV [PRL 113, 142001 (2014)]

- ❑ $\Upsilon(5S)$ and $\Upsilon(10753)$ have same quantum numbers and similar masses, but the difference on the above ratio is large. This may indicate **the difference in the internal structures of these two states**.

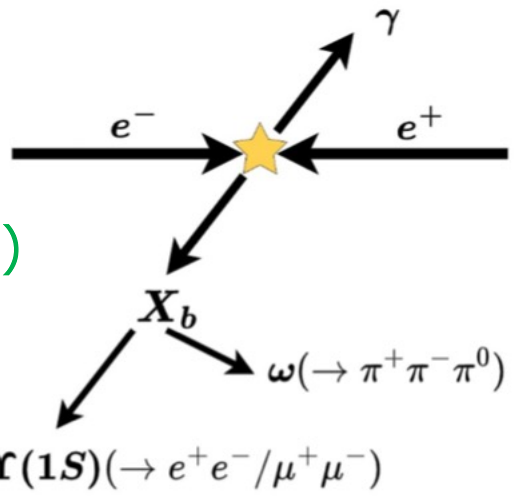
$$\frac{\sigma(e^+e^-\to\chi_{b1}(1P)\omega)}{\sigma(e^+e^-\to\chi_{b2}(1P)\omega)} = 1.3\pm0.6 \text{ at } \sqrt{s} = 10.745 \text{ GeV [PRL 130, 091902 (2023)]}$$

- ❑ **Contradicts the expectation for a pure D−wave bottomonium state of 15** [Phys. Lett. B 738, 172 (2014)]
- ❑ **An observation of 1.8σ difference with the prediction for a S−D−mixed state of 0.2** [Phys. Rev. D 104, 034036 (2021)]

Search for X_b



PRL 130, 091902 (2023)



- No significant X_b signal is observed.
- The peaks are the reflections of $e^+e^- \to \omega\chi_{bJ}$.

From simulated events with $m(X_b) = 10.6$ GeV/c^2
The yield is fixed at the upper limit at 90% C.L.

Upper limits at 90% C.L. on $\sigma_B(e^+e^- \to \gamma X_b) \cdot \mathcal{B}(X_b \to \omega\Upsilon(1S))$ (pb)	$\sqrt{s}$ (GeV)	10.653	10.701	10.745	10.805
	$m(X_b) = 10.6$ GeV/c^2	0.46	0.33	0.10	0.14
	$m(X_b) = (10.45, 10.65)$ GeV/c^2	(0.14, 0.55)	(0.25, 0.84)	(0.06, 0.14)	(0.08, 0.37)

Measurement of the energy dependence of the $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ cross sections

- The $B^{(*)}\bar{B}^{(*)}$ are expected to be dominant decay channels for excited bottomonium-like states. Their measurements are critical for understanding these states.

Method:

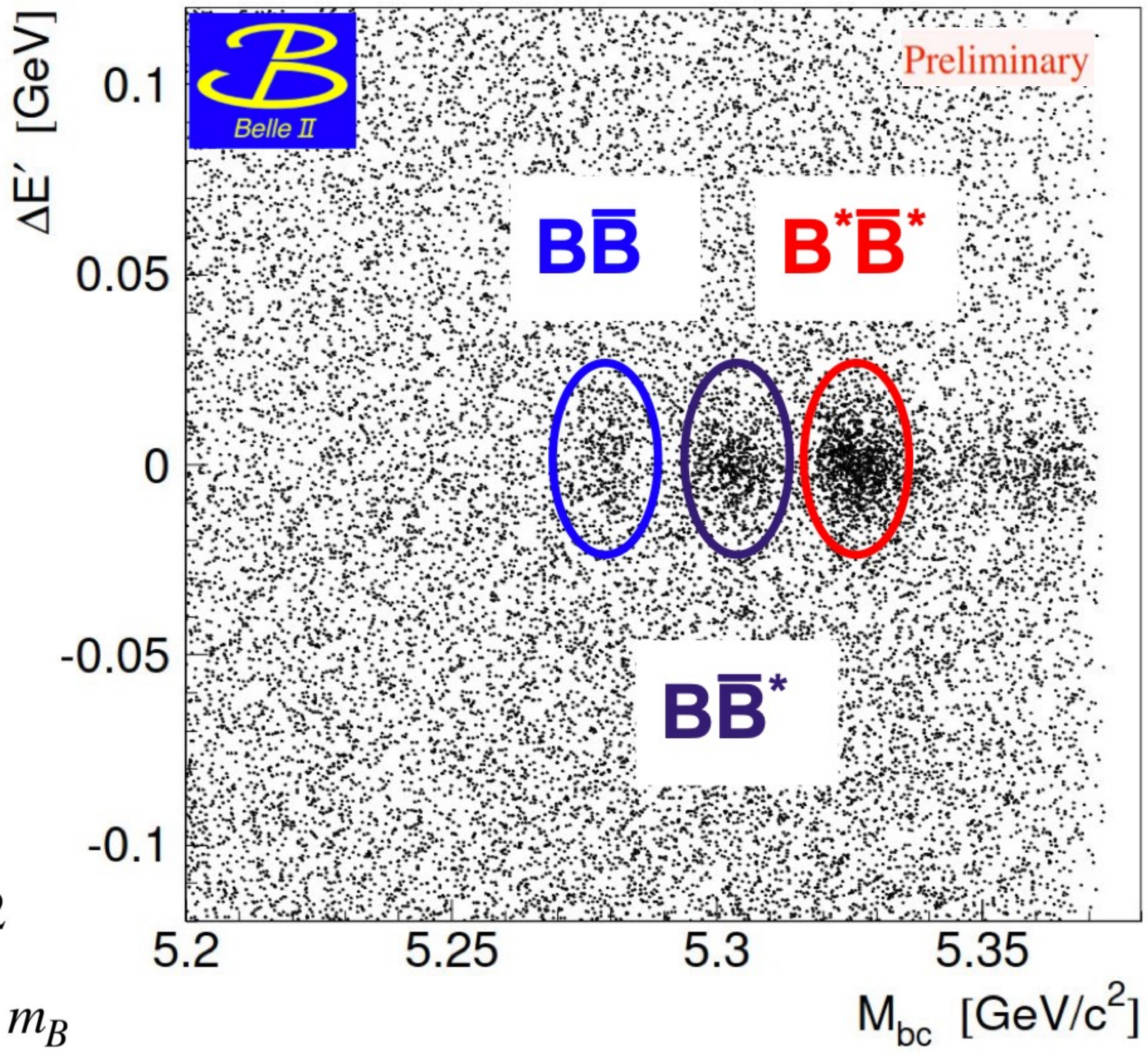
One B meson is reconstructed in hadronic channels, and signals are identified using

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

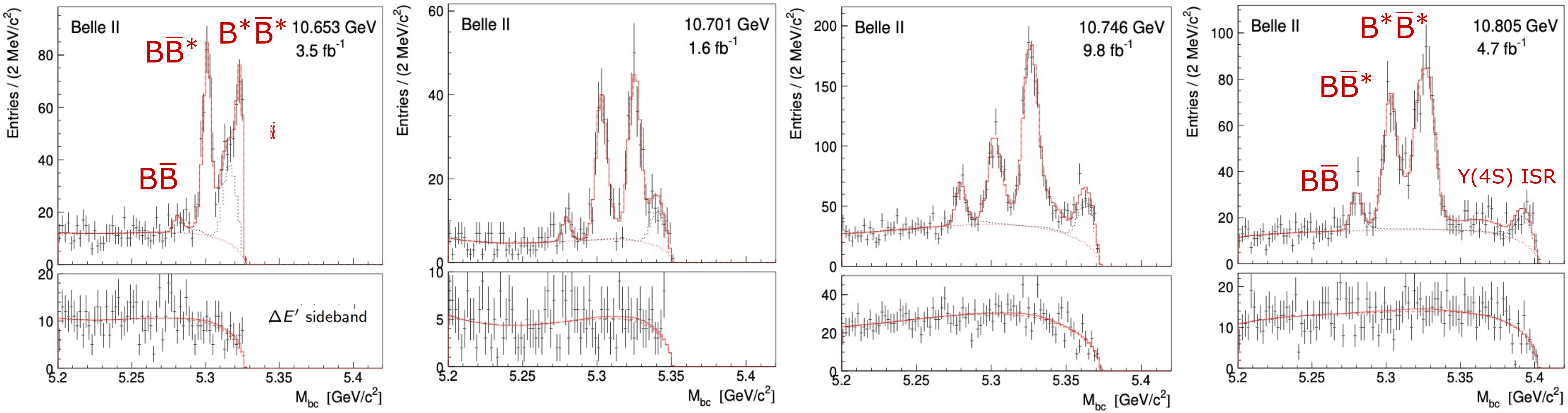
$$\Delta E = E_B - E_{cm}/2$$

$$\Delta E' = \Delta E + M_{bc} - m_B$$

$\sqrt{s} = 10.745$ GeV, 9.8 fb^{-1}

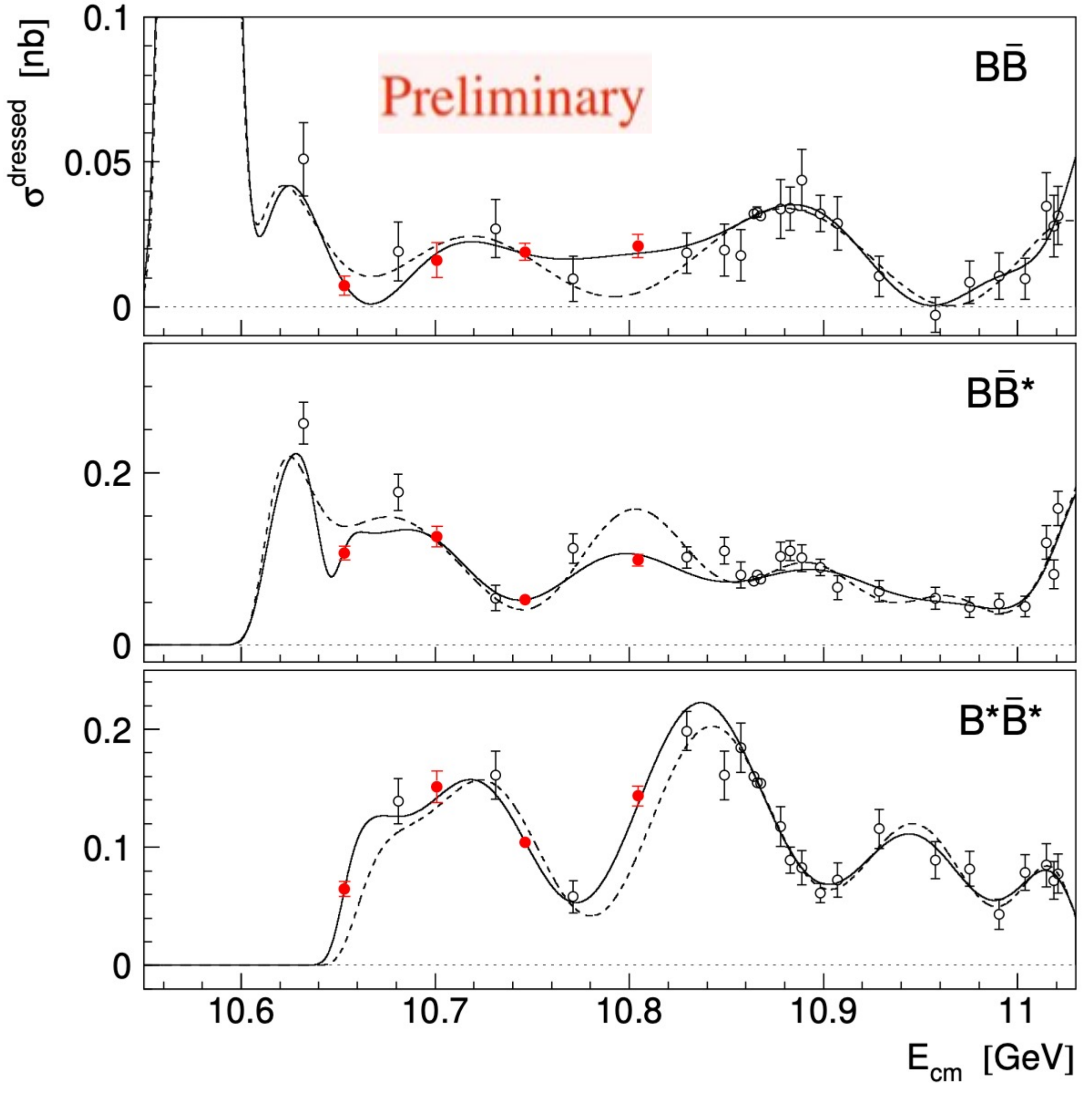


M_{bc} fit at scan energies



- $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ signals at $\sqrt{s} \sim 10.75$ GeV can be clearly observed
- Contribution of $\Upsilon(4S) \to B\bar{B}$ production via ISR is visible well (black dotted histograms)
- At $\sqrt{s}$ =10.653 GeV, the sharp cut of the data at right edge is due to threshold effect

Energy dependence of the cross sections

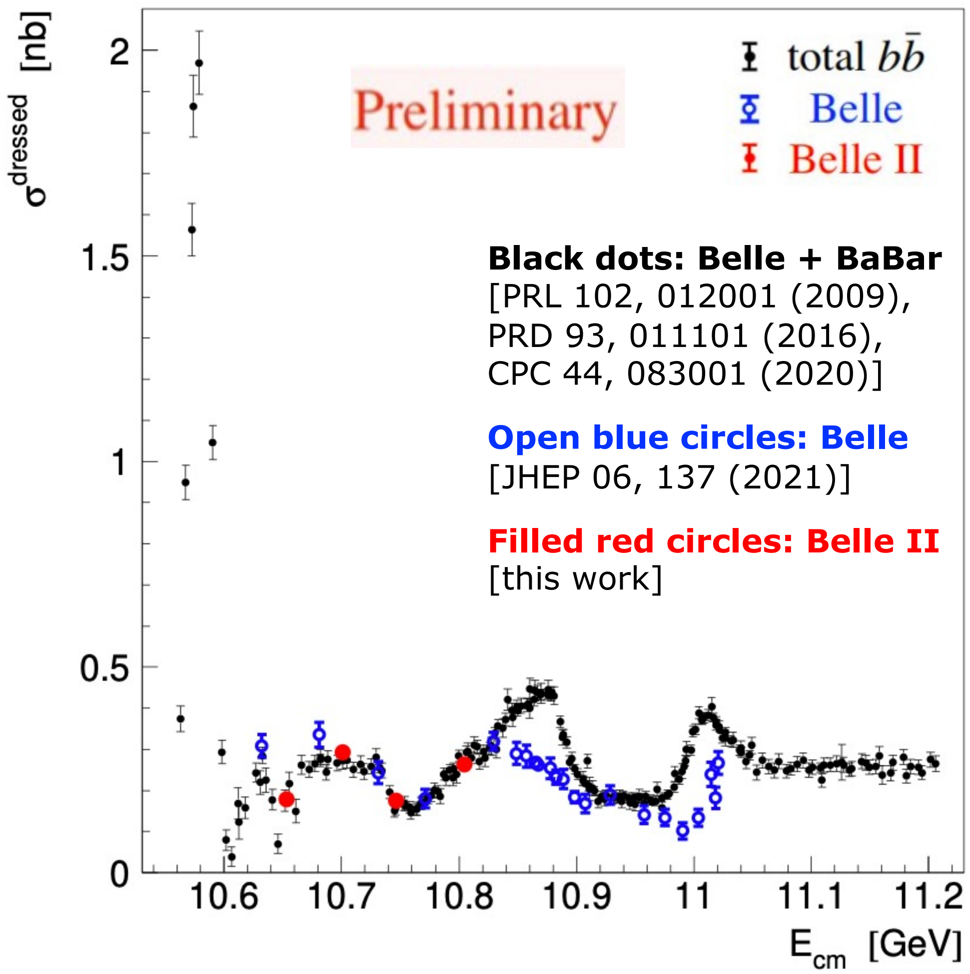


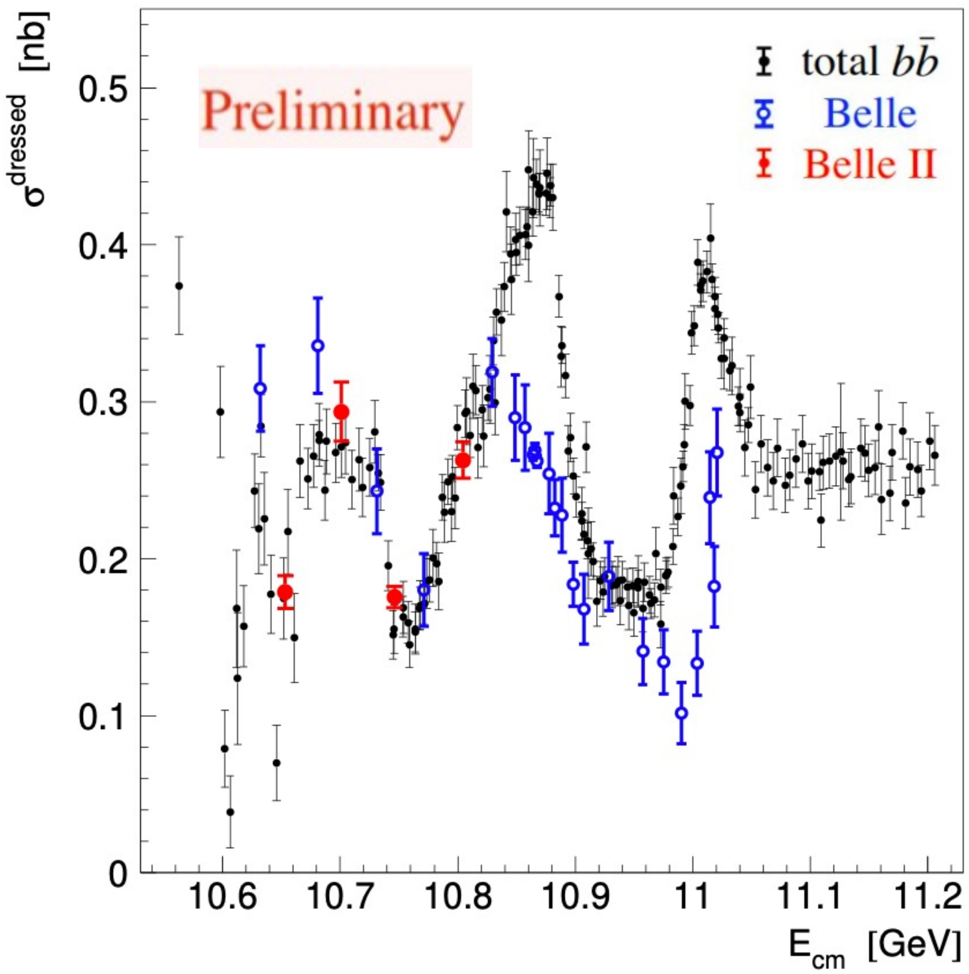
Solid curve – combined Belle + Belle II data fit
Dashed curve – Belle data fit only

New: rapid increase of $\sigma_{B^*\bar{B}^*}$ above the threshold

- Similar behaviour was seen for $D^*\bar{D}^*$ cross section (PRD 97, 012002 (2018))
- Possible interpretation: resonance or bound state ($B^*\bar{B}^*$ or $b\bar{b}$) near threshold (MPL A 21, 2779 (2006))
- Also explains a narrow dip in $\sigma(e^+e^- \to B\bar{B}^*)$ near $B^*\bar{B}^*$ threshold by destructive interference between $e^+e^- \to B\bar{B}^*$ and $e^+e^- \to B^*\bar{B}^* \to B\bar{B}^*$
- Inelastic channels $[\pi^+\pi^-\Upsilon(nS)$ and $h_b(1P)\eta]$ could also be enhanced (PRD 87, 094033 (2013))

Comparison of $\sigma_{b\bar{b}}$ and $\sigma_{B\bar{B}} + \sigma_{B\bar{B}^*} + \sigma_{B^*\bar{B}^*}$





- Agreement at low energy
- Departure at high energy is due to $B_s^{(*)}\bar{B}_s^{(*)}$, multi-body $B^{(*)}\bar{B}^{(*)}\pi(\pi)$, and bottomonia

Search for $e^+e^- \to \omega\eta_b(1S)$ and $e^+e^- \to \omega\chi_{b0}(1P)$

- Tetraquark (diquark-antidiquark) interpretation of this state predicts enhancement of $\Upsilon(10753) \to \omega\eta_b(1S)$ transition [Chin. Phys. C 43, no.12, 123102 (2019)].

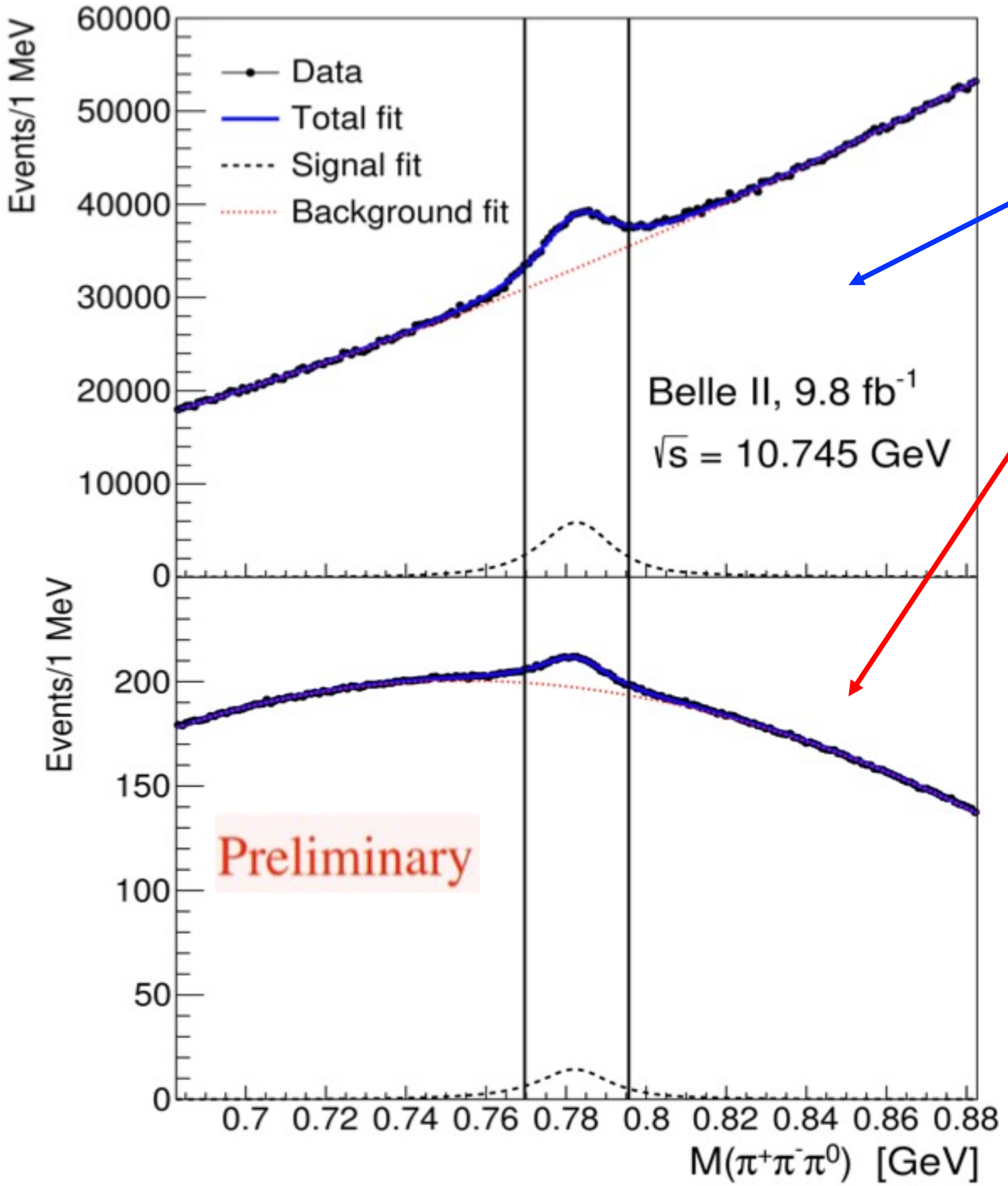
$$\frac{\Gamma(\eta_b\ \omega)}{\Gamma(\Upsilon\ \pi^+\pi^-)} \sim 30$$

- The $e^+e^- \to \omega\chi_{bJ}(1P)$ (J = 1, 2) was found to be enhanced at $\sqrt{s}$ = 10.745 GeV (PRL 130, 091902 (2023)). The $e^+e^- \to \omega\chi_{b0}(1P)$ transition was not observed due to low $\mathcal{B}[\chi_{b0}(1P) \to \gamma\Upsilon(1S)]$ = (1.94±0.27)%.

- We reconstruct only $\omega \to \pi^+\pi^-\pi^0$ and use its recoil mass to identify the signal.

$$M_{\mathrm{recoil}}(\pi^+\pi^-\pi^0) = \sqrt{\left(\frac{E_{\mathrm{c.m.}} - E^*}{c^2}\right)^2 - \left(\frac{p^*}{c}\right)^2}$$

Invariant mass distribution of $\pi^+\pi^-\pi^0$

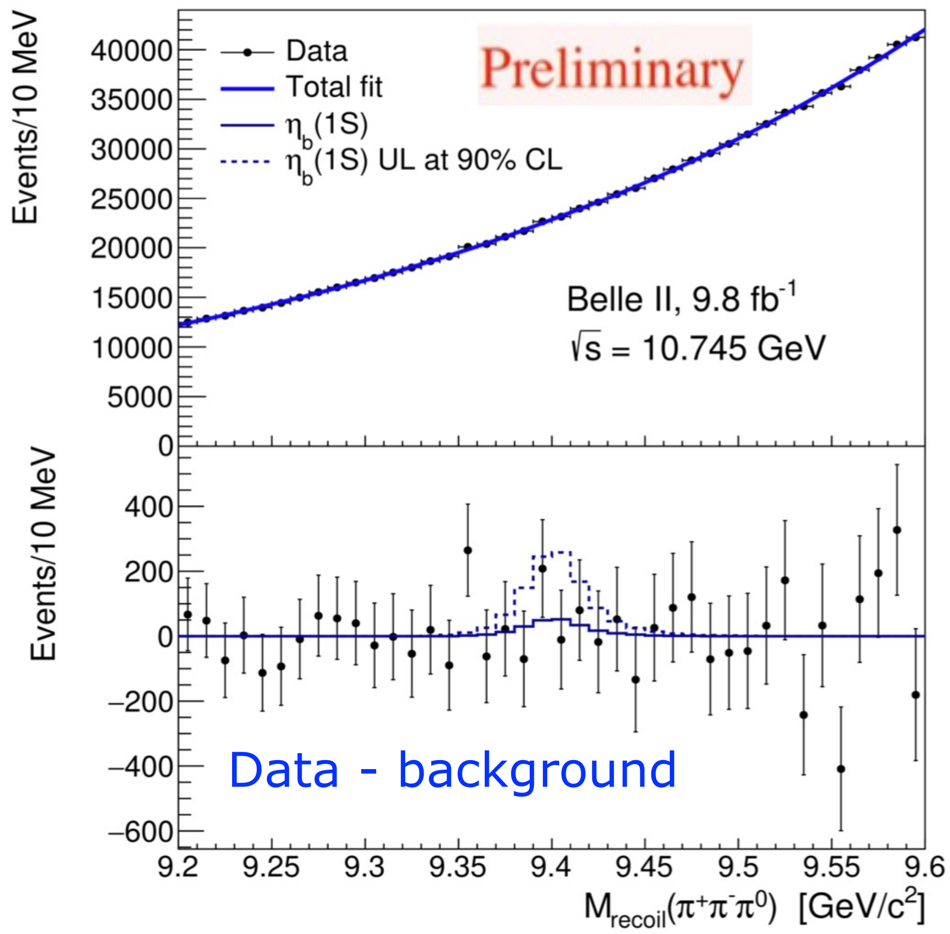


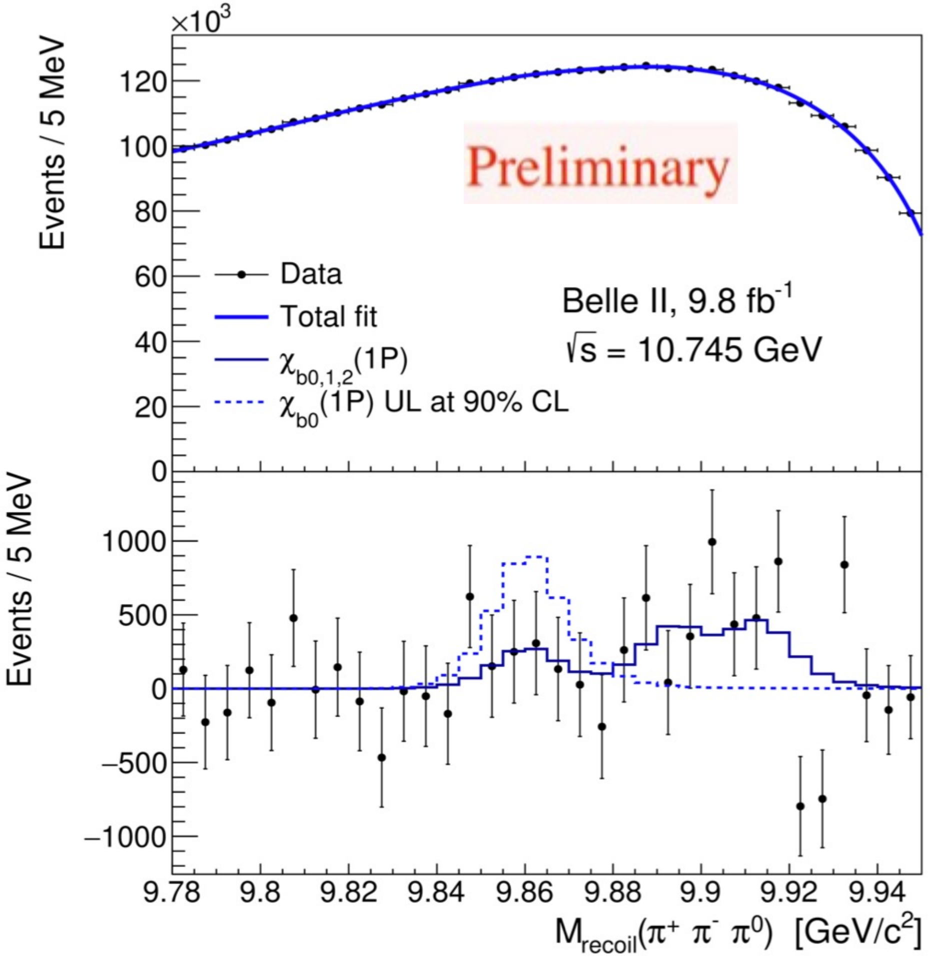
$9.2 < M_{rec}(\pi^+\pi^-\pi^0) < 9.6$ GeV/c² ($\eta_b(1S)$ included)

$9.78 < M_{rec}(\pi^+\pi^-\pi^0) < 9.95$ GeV/c² ($\chi_{bJ}(1P)$ included)

- A double-sided Crystal Ball + a Gaussian for ω signal
- 2nd or 3rd order Chebyshev polynomials for backgrounds
- The purities of ω-meson signals are 12.9% for $\eta_b(1S)$ and 5.3% for $\chi_{bJ}(1P)$

Recoil mass spectra of $\pi^+\pi^-\pi^0$





- A 3rd polynomial for $\eta_b(1S)$
- A product of a 4th polynomial and a square root function for $\chi_{b0}(1P)$
- Polynomial orders are chosen with maximum p-values
- The yields for $\chi_{b1}(1P)$ and $\chi_{b2}(1P)$ are fixed [PRL 130, 091902 (2023)].

Channel	$e^+e^- \to \eta_b(1S)\omega$	$e^+e^- \to \chi_{b0}(1P)\omega$
Yield	$(0.23 \pm 0.49 \pm 0.25) \cdot 10^3$	$(1.2 \pm 1.4 \pm 0.9) \cdot 10^3$

No clear $\eta_b(1S)$ and $\chi_{b0}(1P)$ signals are observed.

Born cross sections

$$\sigma_B[e^+e^- \to X\omega] = \frac{N \cdot |1-\Pi|^2}{\varepsilon \cdot \mathcal{L} \cdot (1+\delta_{ISR}) \cdot \mathcal{B}_{int}}$$

Preliminary

Channel	$e^+e^- \to \eta_b(1S)\omega$	$e^+e^- \to \chi_{b0}(1P)\omega$
Yield (10^3)	$0.23 \pm 0.49 \pm 0.25$	$1.2 \pm 1.4 \pm 0.9$
Born section section (pb)	$0.5 \pm 1.1 \pm 0.6$	$2.6 \pm 3.1 \pm 2.1$
Upper limit at 90% C.L. (pb)	<2.5	<8.7

Upper limits at the 90% CL are set using the Feldman-Cousins method [Phys. Rev. D 57, 3873 (1998)]

Tetraquark model in Ref. [CPC 43, 123102 (2019)]:

$$\Gamma(\Upsilon(10753) \to \eta_b(1S)\omega) = 2.64^{+4.70}_{-1.69}\ \text{MeV}$$
$$\Gamma(\Upsilon(10753) \to \Upsilon\pi^+\pi^-) = 0.08^{+0.20}_{-0.06}\ \text{MeV}$$

This measurement and JHEP 10, 220 (2019):

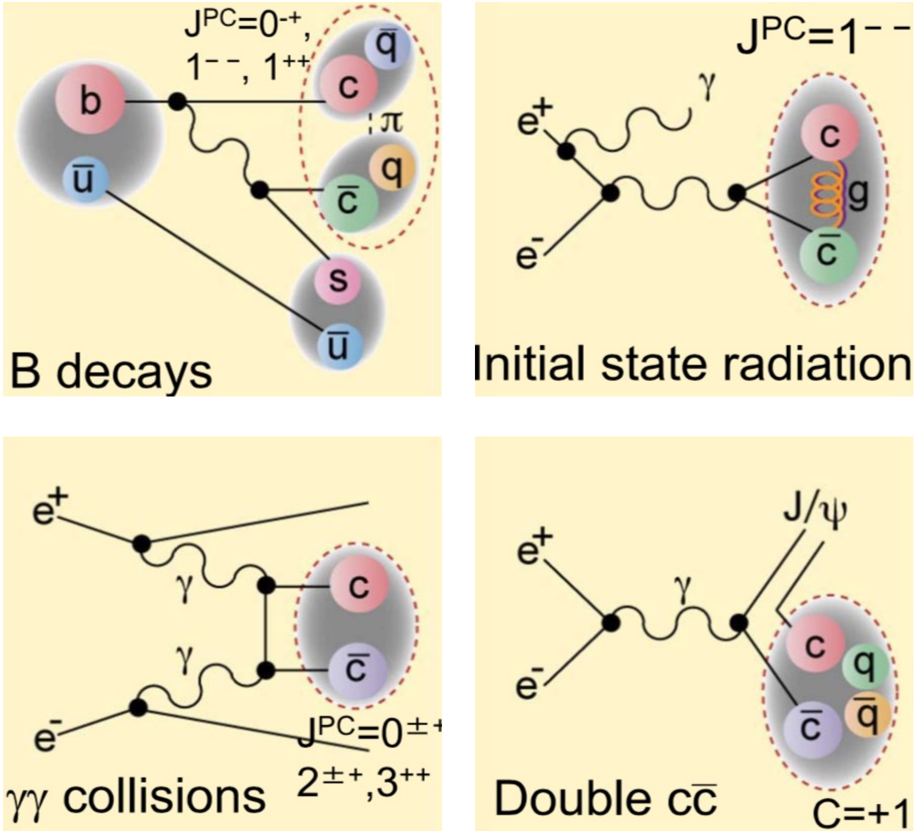
$$\sigma^B(\Upsilon(10753) \to \eta_b(1S)\omega) < 2.5\ \text{pb}$$
$$\sigma^B(\Upsilon(10753) \to \Upsilon(2S)\pi^+\pi^-) \approx (3 \pm 1)\ \text{pb}$$

Our results do not support the prediction within the tetraquark model that the $\Upsilon(10753) \to \omega\eta_b(1S)$ decay is enhanced.

Quarkonium prospects at Belle II

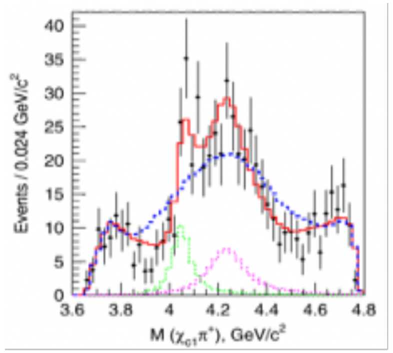
Production of Charmonium(-like) states at B-factory

- **B decay ($\mathbf{B \to KX_{c\bar{c}}}$)**
  - ✓ CKM favored process, large branching fractions $10^{-3}\sim10^{-4}$
  - ✓ $J^{PC} = 0^{-+}, 1^{--}, 1^{++}, \ldots$
- **Initial-state radiation (ISR)**
  - ✓ $J^{PC} = 1^{--}$
- **Two-photon process**
  - ✓ $J^{PC} = 0^{-+}, 0^{++}, 2^{++}, 2^{-+}, \ldots$
- **Double charmonium**
  - ✓ e.g. $e^+e^- \to J/\psi X(3940)$ [PRL 98,082001(2007)]

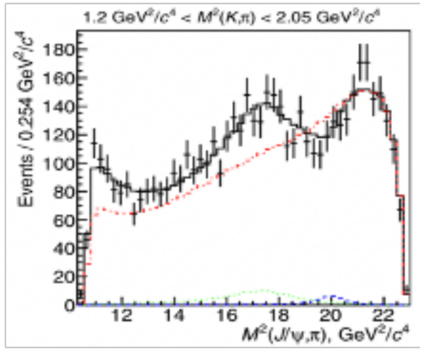


Charmonium(-like) states via B decays

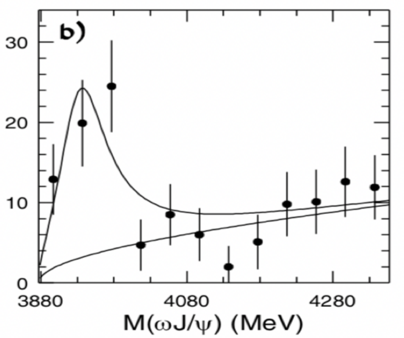
- ❑ Confirm Z_c states $Z(4050)^+$, $Z(4200)^+$, $Z(4250)^+$ and search for neutral partners
- ❑ Full amplitude analysis to $B \to K\omega J/\psi$ and $B \to K\omega\chi_{c1}$ to determine the spin-parties of $X(3915)$, $Z(4050)^+$ and $Z(4250)^+$.
- ❑ Confirmation of $X(3872)$ width measurement with $D^0\bar{D}^0\pi^0$ mode, search for more open-flavor decay modes, e.g., $B \to K(D\bar{D})$, $B \to K(D\bar{D}^*)$, $B \to K(D^*\bar{D}^*)$, $B \to K(D^*\bar{D}^{**})$… with more B mesons
- ❑ Absolute branching fractions are unique for Belle II
- ❑ Systematic investigations of charmonium plus light hadron final states: $B \to K(c\bar{c}+h)$



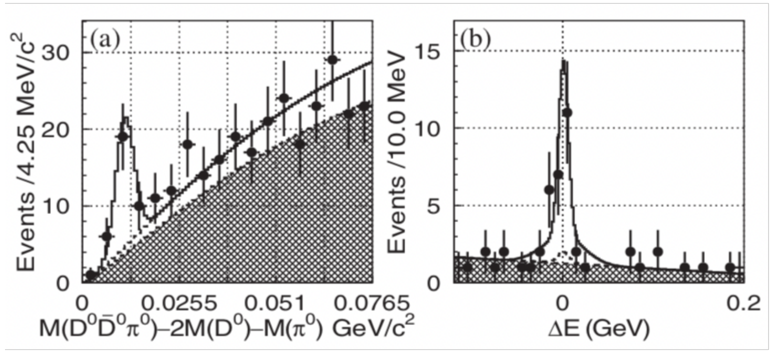
$Z(4050/4250) \to \pi^+\chi_{c1}$
PRD 78,072004



$Z(4200/4430) \to \pi^+J/\psi$
PRD 90,112009



$X(3915) \to \omega J/\psi$
PRL 94,182002



$B \to KX(3872)(\to D^0\bar{D}^0\pi^0)$
PRL 97,162002

Bottomonium(-like) prospects at Belle II

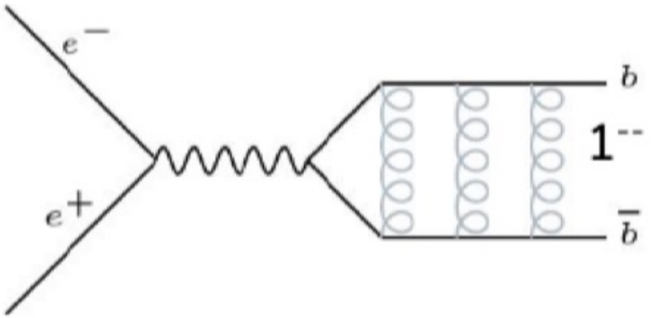
Four ways to access bottomonia:

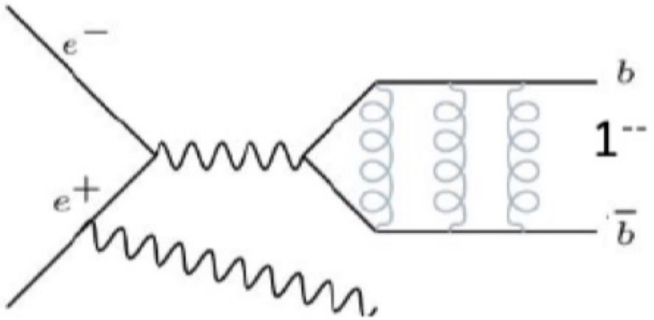
- Direct production from e^+e^-: $J^{PC} = 1^{--}$: $\Upsilon(nS)$
- ISR production: $J^{PC} = 1^{--}$: $\Upsilon(nS)$
- Hadronic transitions from $\Upsilon(nS)$ through η, $\pi\pi$, …

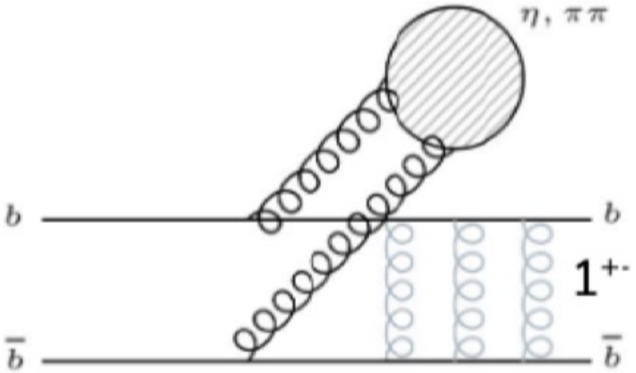
$J^{PC} = 0^{-+}, 1^{--}, 1^{+-}$ … : $\Upsilon(nS)$, $\eta_b(nS)$, $h_b(nS)$, …

- Radiative transitions from $\Upsilon(nS)$

$J^{PC} = 0^{-+}, 0^{++}, 1^{++}, 2^{++}$: $\eta_b(nS)$, $\chi_b(nP)$







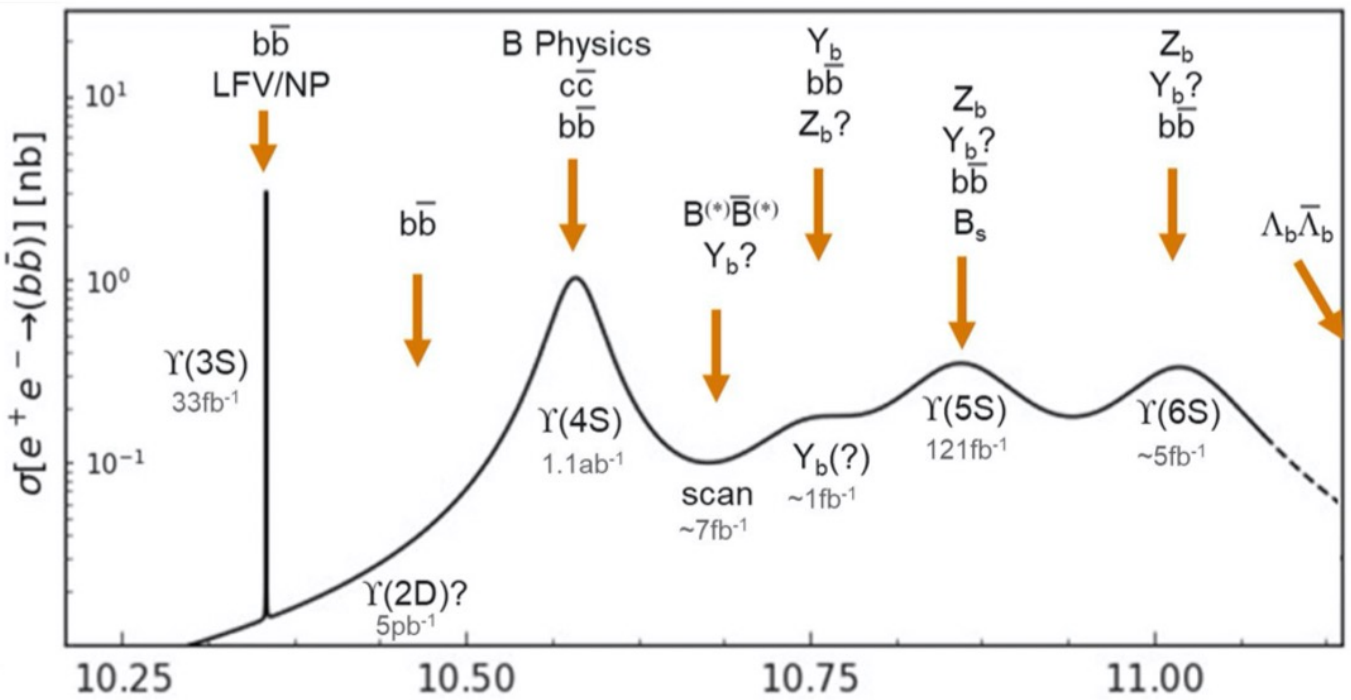
Bottomonium(-like) prospects at Belle II

Run at Υ(6S) and Υ(5S) and high energy scan:

- Search for new missing bottomonia $\eta_b(3S)$, $h_b(3P)$, $\Upsilon(D)$, exotic states Y_b, Z_b, etc
- Improve precision of already known processes and states, e.g., Z_b
- Measure the effect of the coupled channel contribution
- Study $B^{(*)}\bar{B}^{(**)}$ and $B_s^{(*)}B_s^{(**)}$ threshold regions (challenging for Super-KEKB)

Run at Υ(3S) and Υ(2S):

- Search for missing $\pi\pi/\eta$ transitions in inclusive decays to constrain further models
- Search for new physics: LFV, LFU, light Higgs, …



Summary

- The g > 0.094 (90% C.L.) is determined for $X(3872) \to D^0\bar{D}^{*0}$
- Evidence for $e^+e^- \to \eta_c J/\psi$ near the threshold
- New decay modes of $\Upsilon(10753) \to \omega\chi_{bJ}$ are observed
- The rapid increase of $\sigma_{B^*\bar{B}^*}$ above the threshold may imply a resonance of $B^*\bar{B}^*$ or $b\bar{b}$
- The stringent upper limit is set for the $e^+e^- \to \omega\eta_b(1S)$ at $\sqrt{s}$ = 10.745 GeV
- We expect more promising quarkonium results in the near future at Belle II with larger data samples

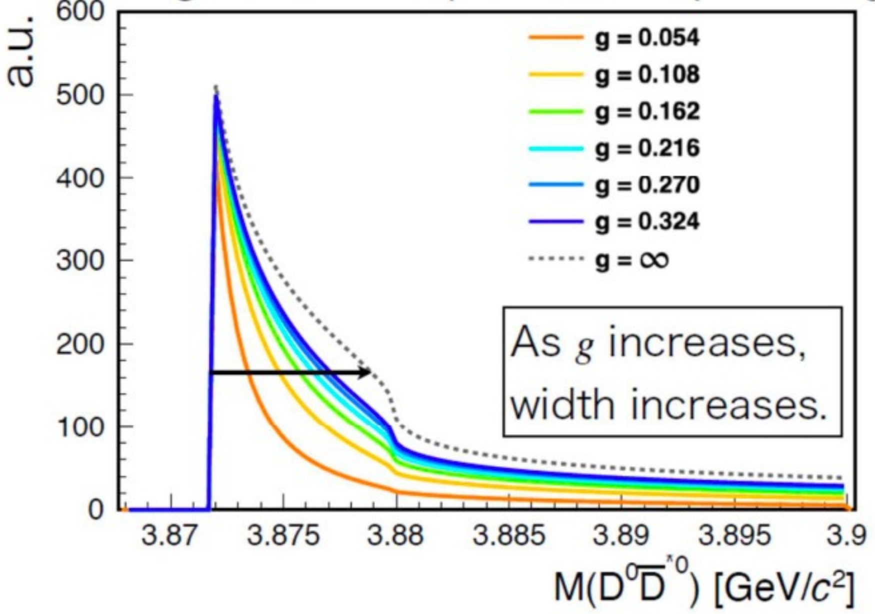
Thanks for your attention!

Backup slides

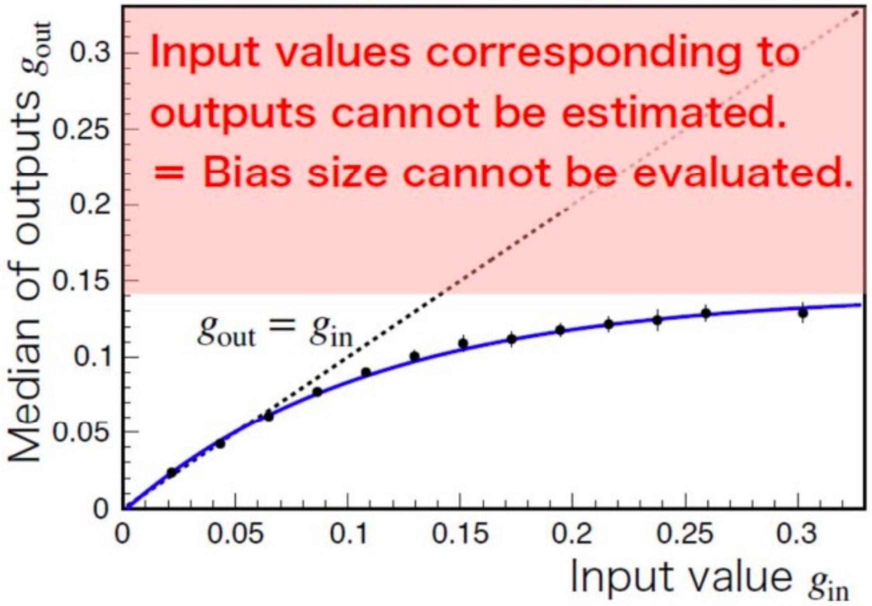
Fit bias

- Lineshape converges to a fixed form for large g

Change in lineshape with respect to g



Result of pseudo experiments*



*excluding failed fit results

→ Only lower limit can be obtained for large g