# Review of Belle and Belle II experiments


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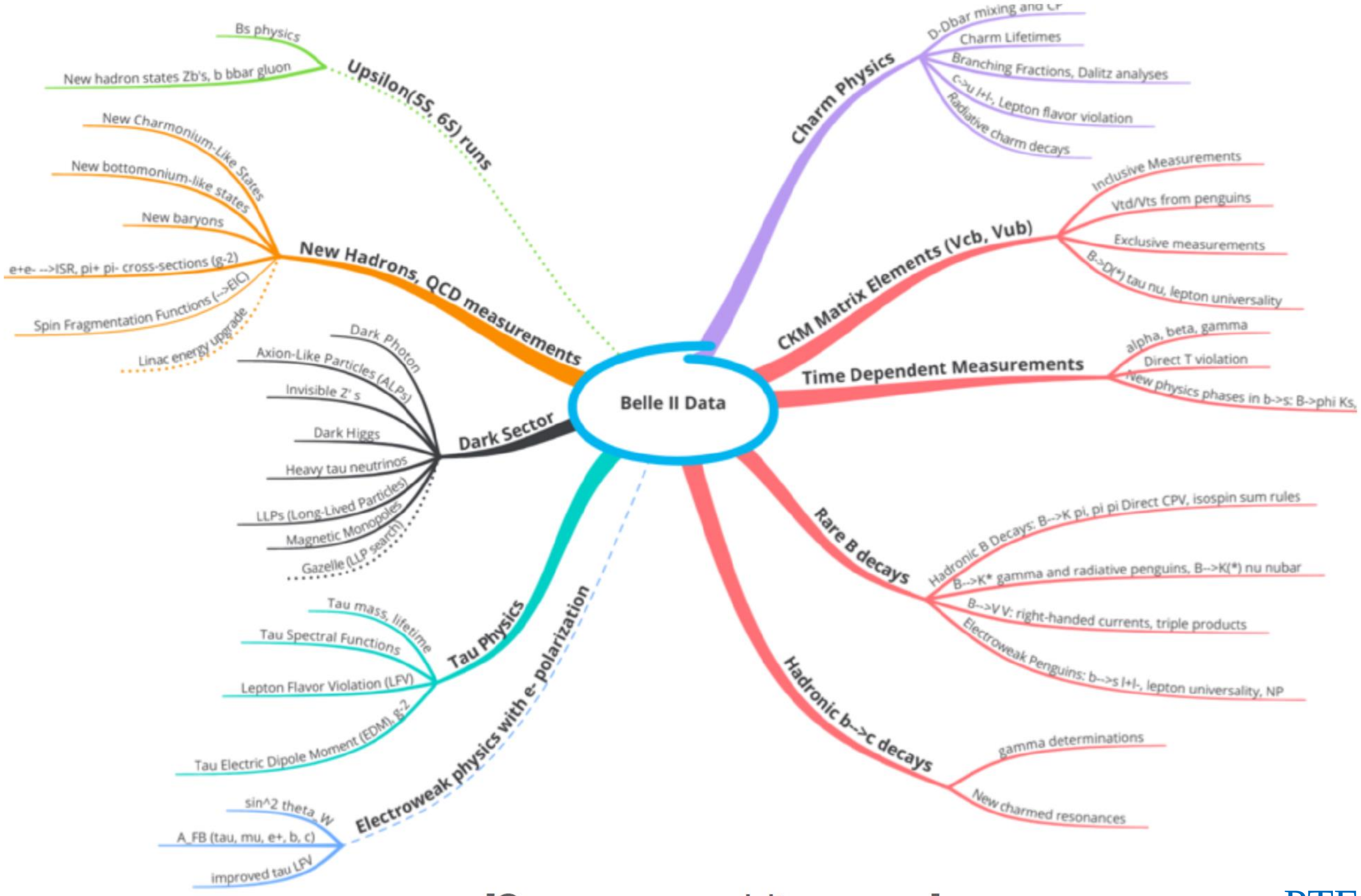
on behalf of the Belle and Belle II Collaborations



International workshop on J-PARC hadron physics 2023 (J-PARC Hadron 2023)
Sep. 12-15, Japan

# A diversified physics program

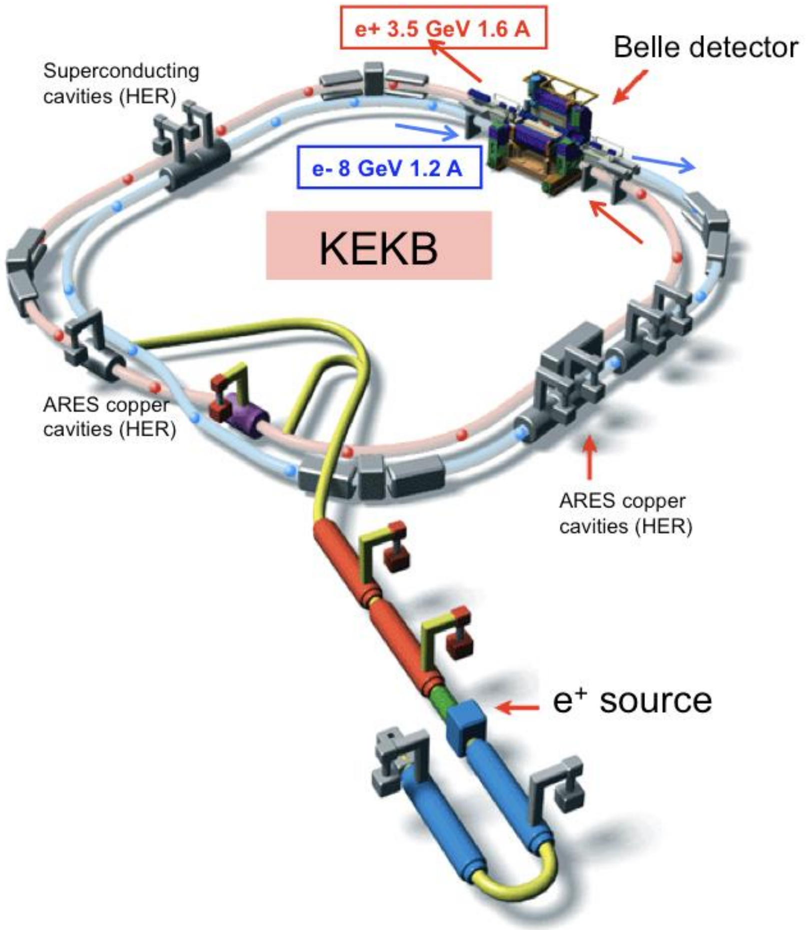


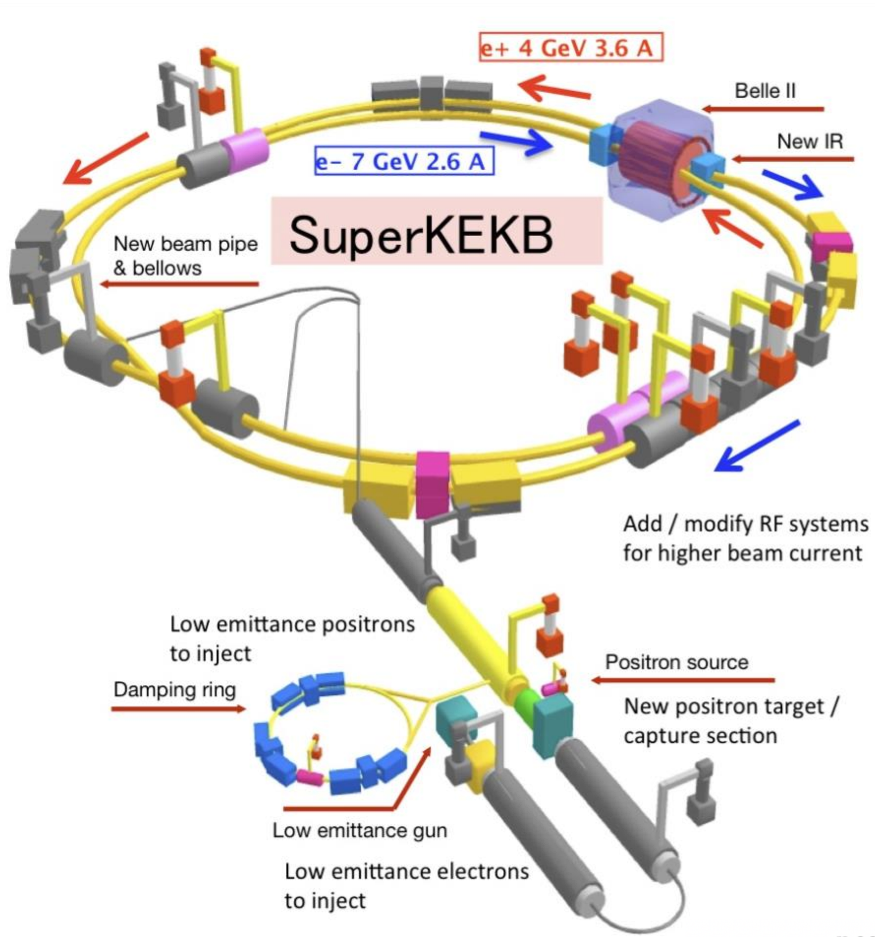

[Snowmass white paper]

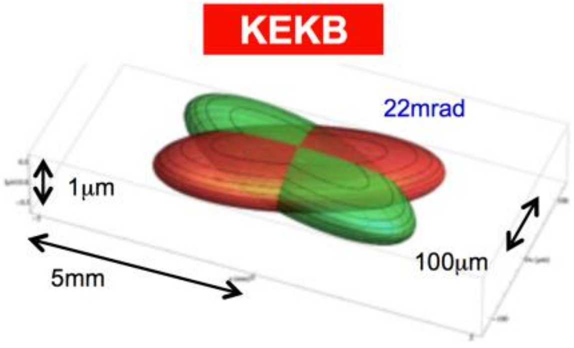
Due to the time limitation, today I mainly focused on the quarkonium and exotic states from Belle and Belle II.

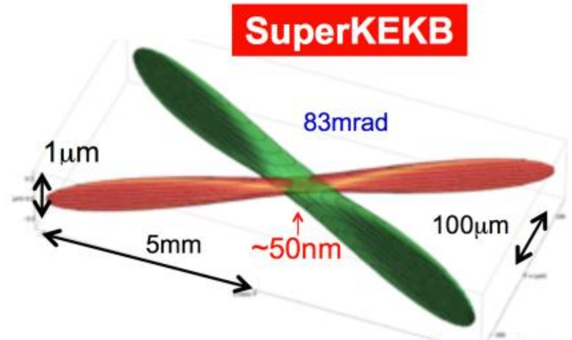
PTEP 2019 123C01

# From KEKB to SuperKEKB



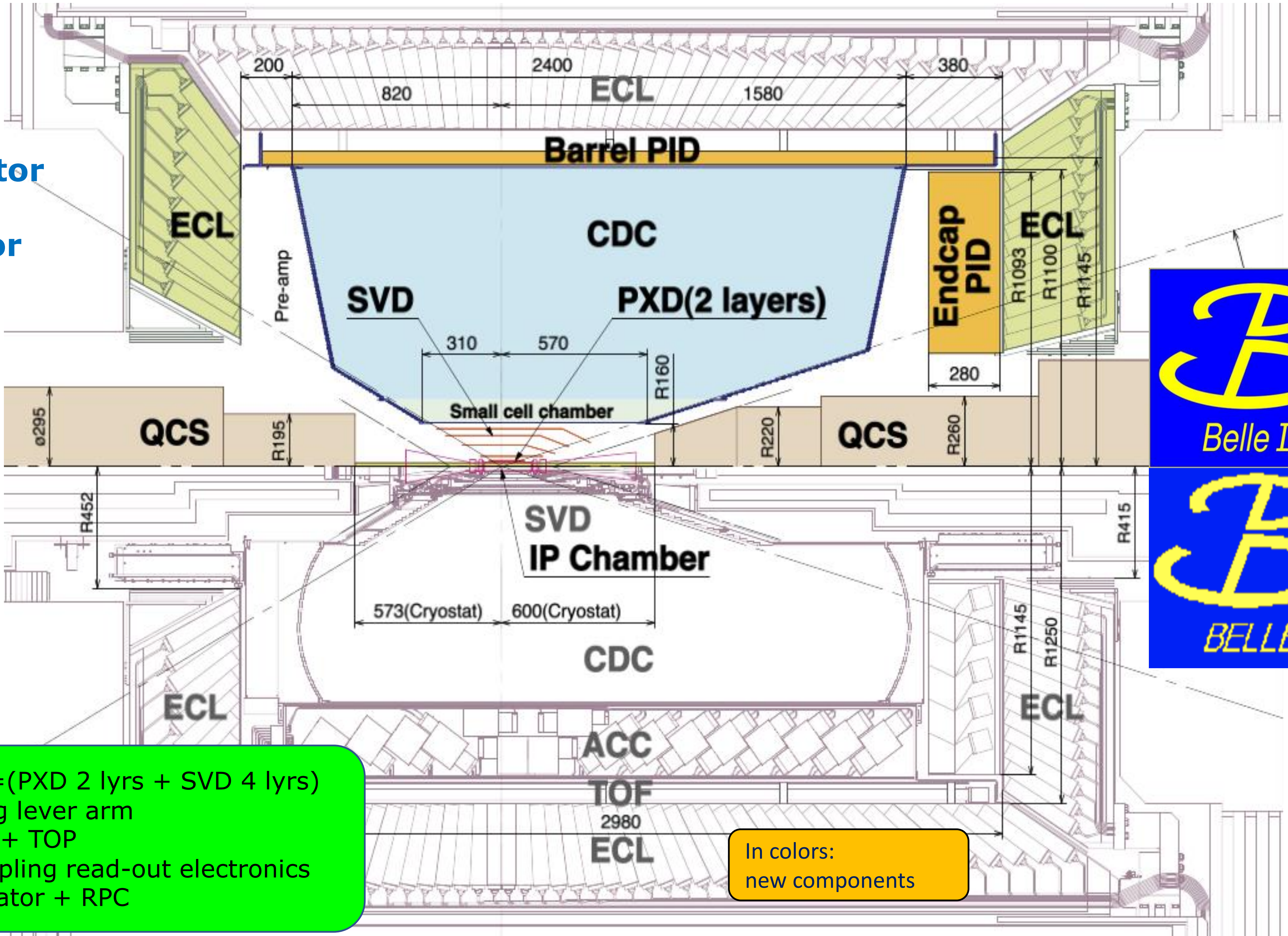

$$\mathcal{L} = \frac{\gamma_\pm}{2 e r_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

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

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

- **moderately increased beam currents**
- **Squeeze beams @IP by ~1/20**

# Belle II detector
# Vs.
# Belle detector



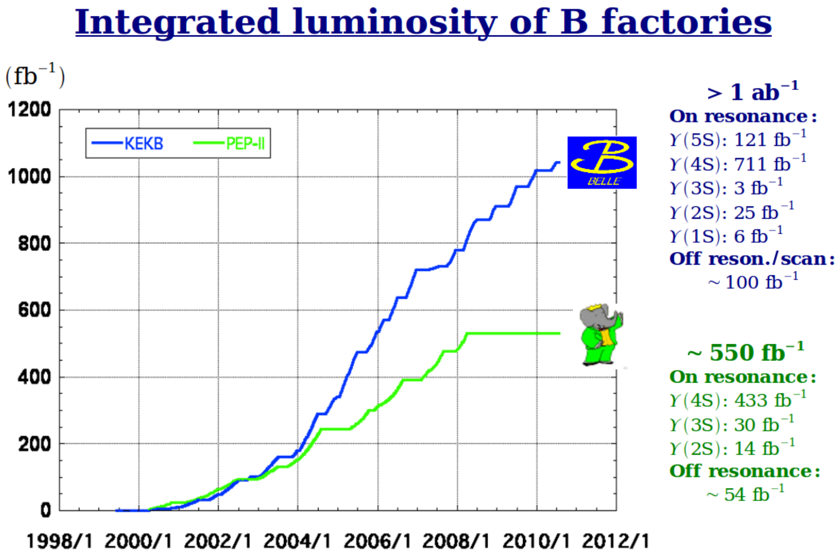

Belle II

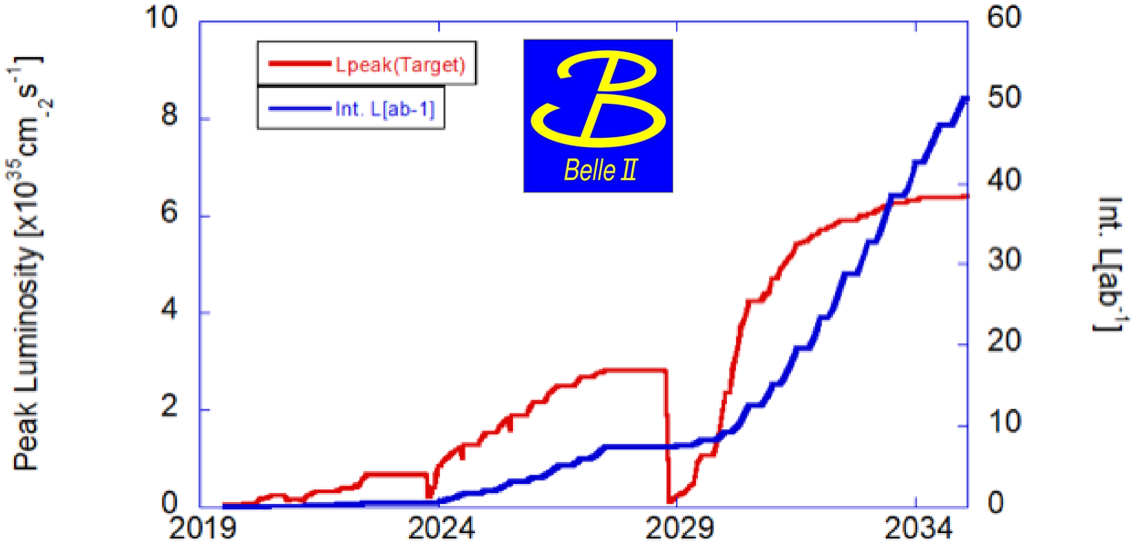
BELLE

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 at Belle and Belle II





Data taking: 1999 – 2010

On/off/Scan Υ(nS) peaks

772M $B\bar{B}$ events @Υ(4S)

- Collected ~424 fb$^{-1}$ around Υ(4S) until now
- LS1 starts in summer 2022 to fully install the pixel detector and accelerator machine study
- Operation will be resumed around the end of 2023

# *Selected topics:*

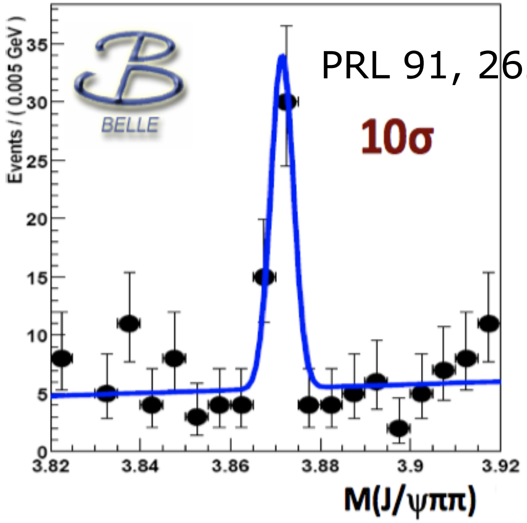
Quarkonium/exotic states at Belle and Belle II:

- ❑ $X(3872) \to D^0\bar{D}^{*0}$ [PRD 107, 112011 (2023)]
- ❑ $e^+e^- \to \eta_c J/\psi$ [JHEP 08 (2023) 121]
- ❑ $e^+e^- \to \omega\chi_{bJ}$ 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]
- ❑ Updated measurement of $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ [Preliminary]

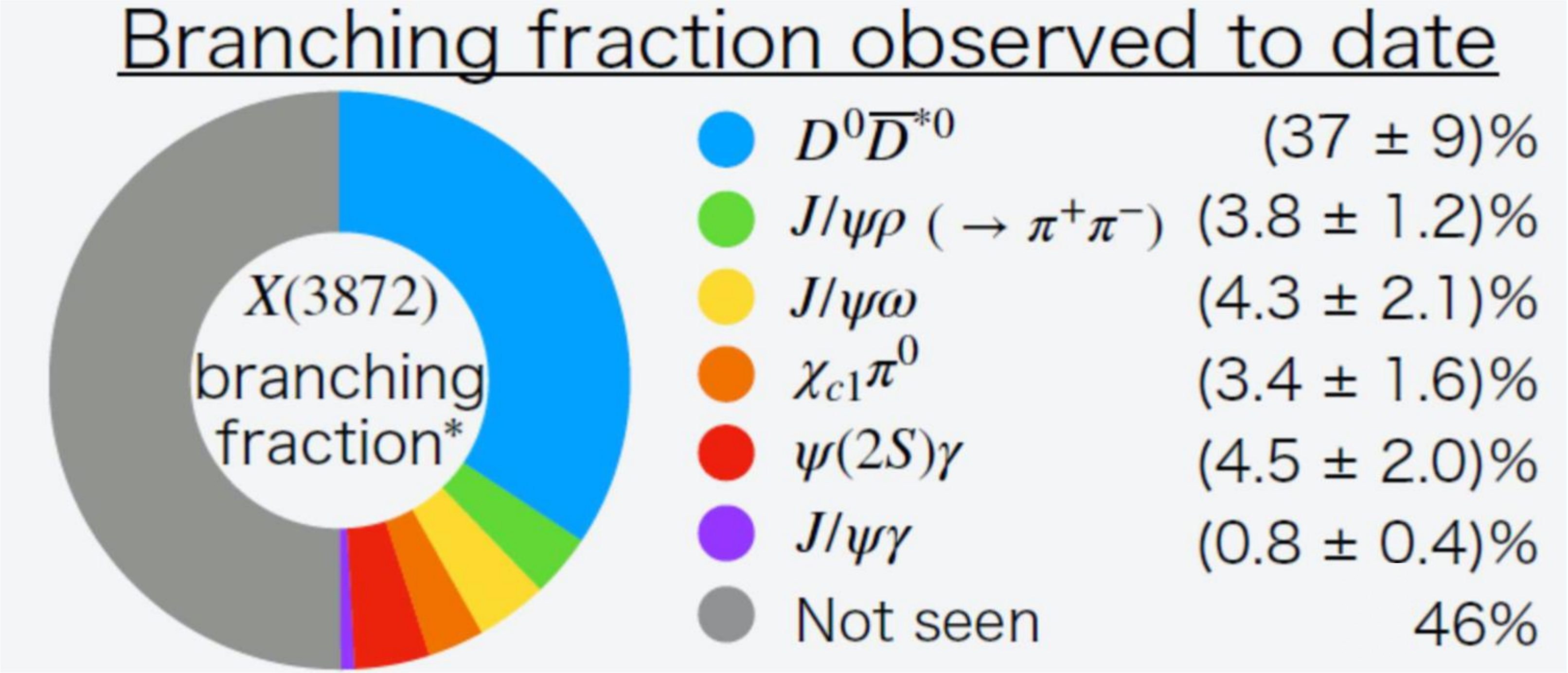
# A new measurement of $X(3872) \to D^0\bar{D}^{*0}$ at Belle

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 $\rho$ decays thus isospin-violating process



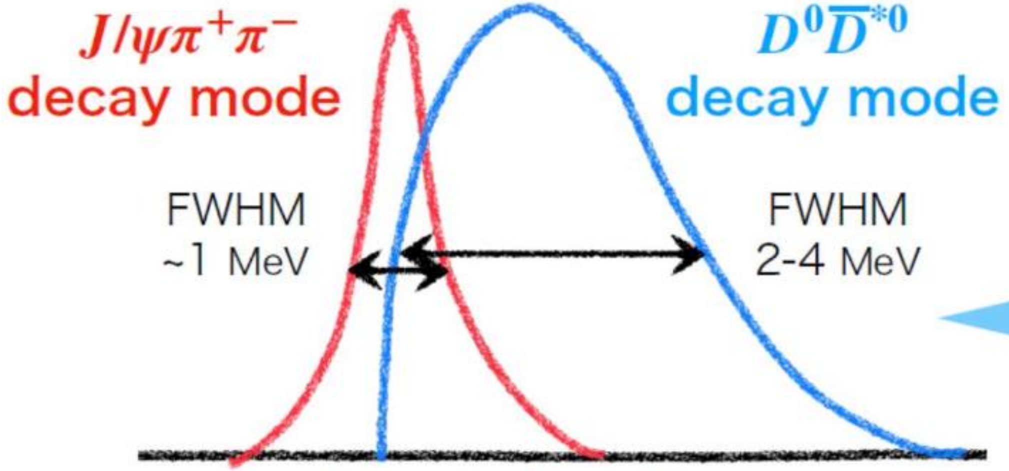

PRL 91, 262001 (2003)




- 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

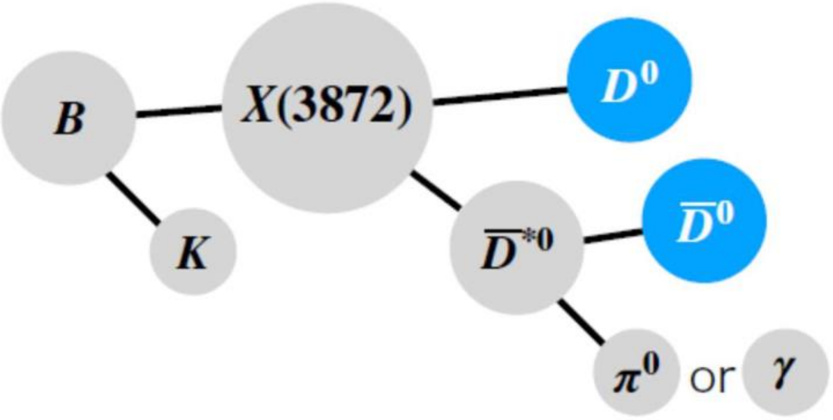
# Analysis strategy

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




$X(3872)$ 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 $D^{*0} \to D^0\gamma, D^0\pi^0$ can be reconstructed.



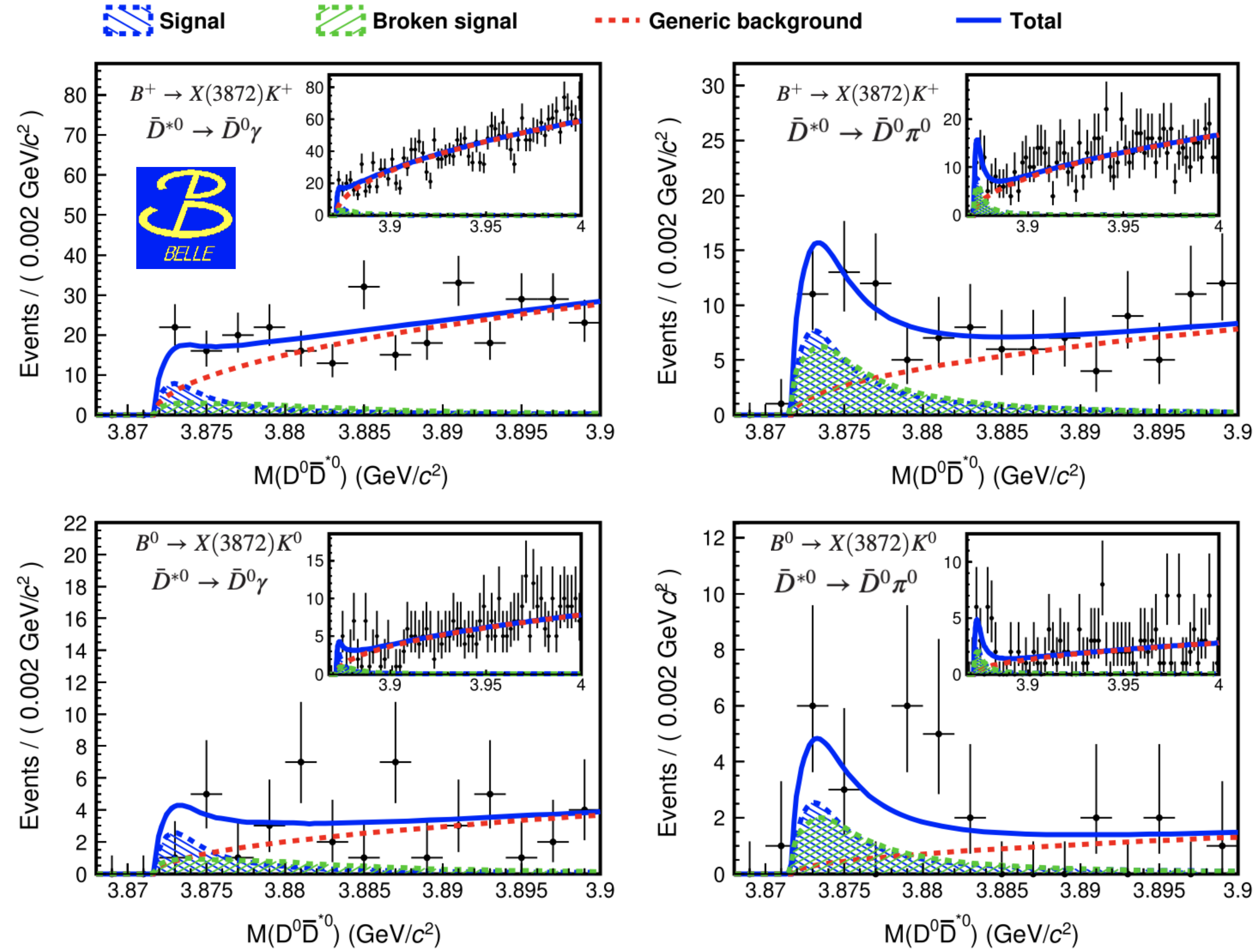

We reconstruct B →K X(3872).

$$D^0 \to \begin{cases} K^-\pi^+ \\ K^-\pi^+\pi^0 \\ K^-\pi^+\pi^-\pi^+ \\ K_S^0\pi^+\pi^- \\ K^+K^- \\ \boxed{K_S^0\pi^+\pi^-\pi^0} \end{cases}$$

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: $7.5\sigma$ in total
- First observation from the $B^0$ decay ($5.2\sigma$)
- 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)]

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

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

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

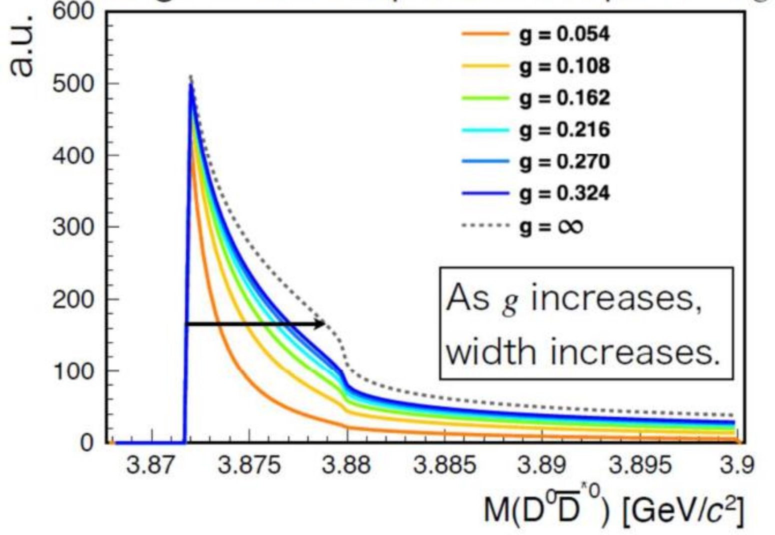
Coupling to $D\overline{D}^*$ channel
… $g$ : Coupling constant to $D\overline{D}^*$ channel
… $k_a$ : Momentum for channel $a$

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

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

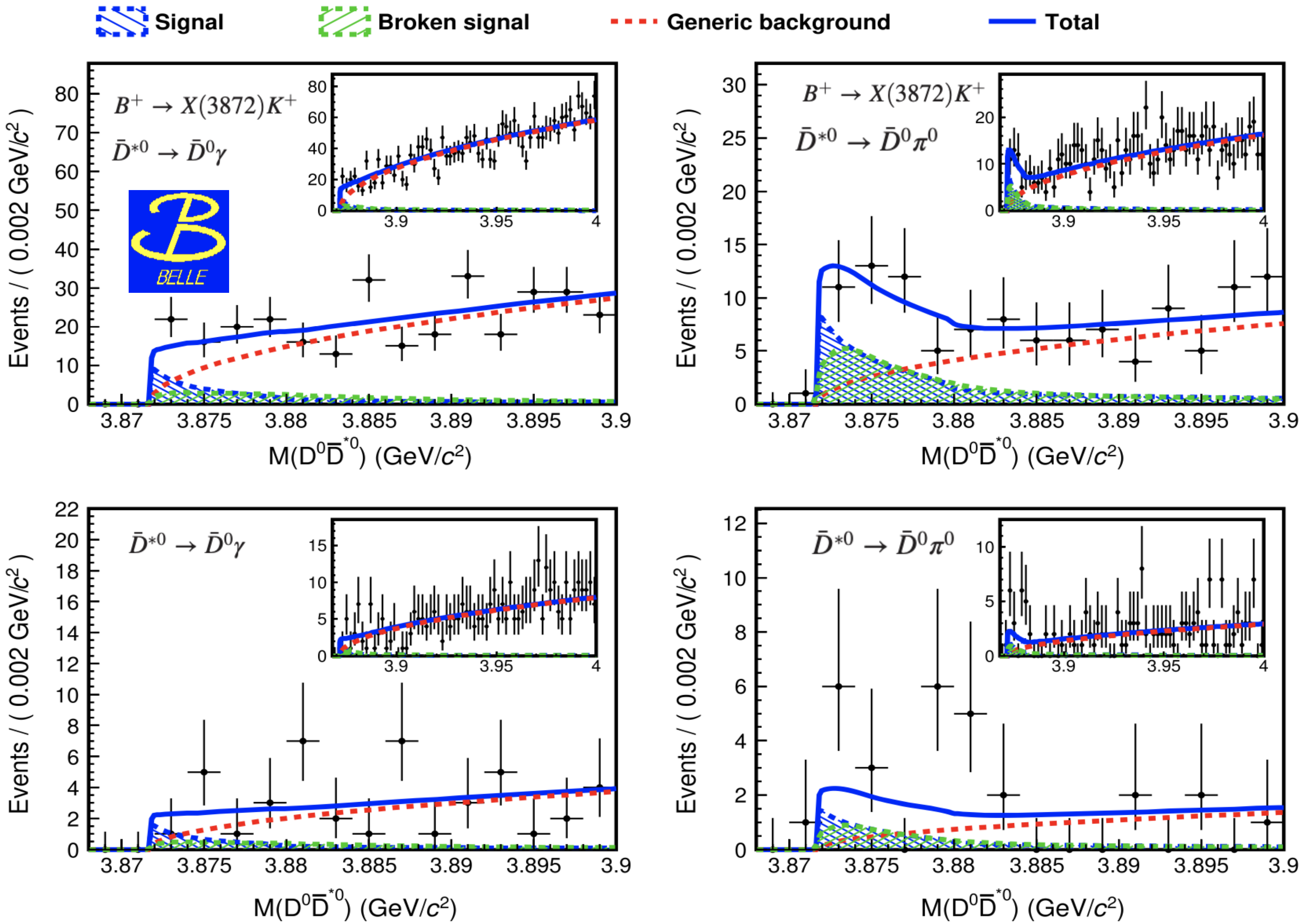
⟹ Only $g$ is floated

Change in lineshape with respect to $g$



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

[PRD 107, 112011 (2023)]




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

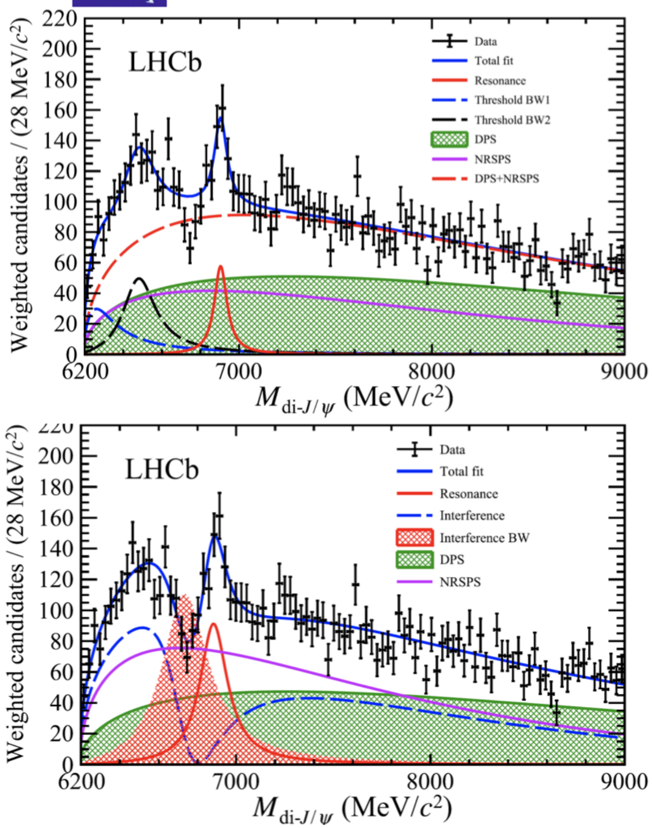
⇒ Lower limit: g > 0.094 (90% C.L.) including systematic uncertainty

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

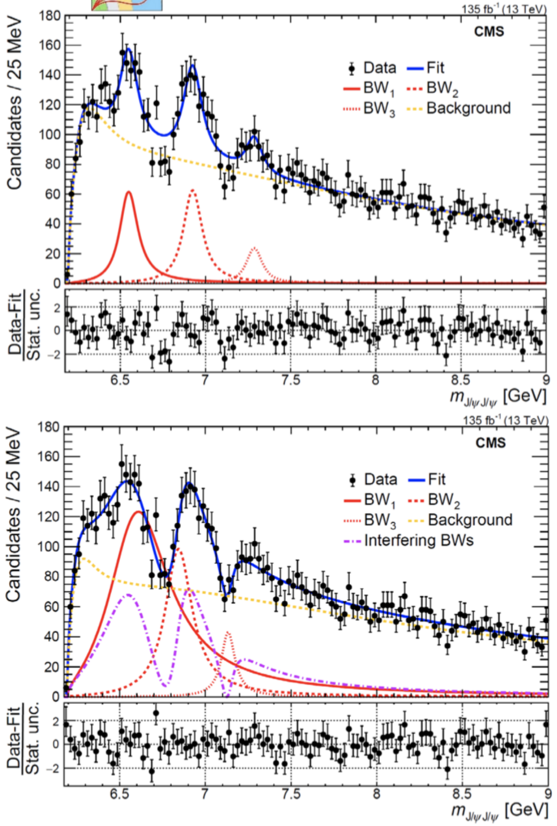
# Search for the double-charmonium state with $\eta_c J/\psi$ at Belle

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

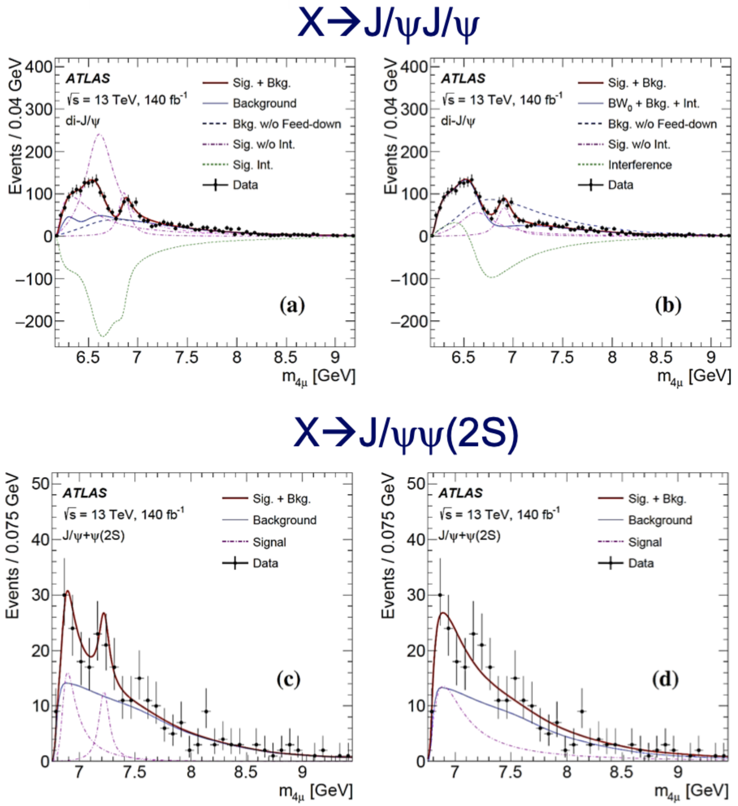
LHCb Sci.Bull. 65 (2020) 1983




CMS arXiv:2306.07164



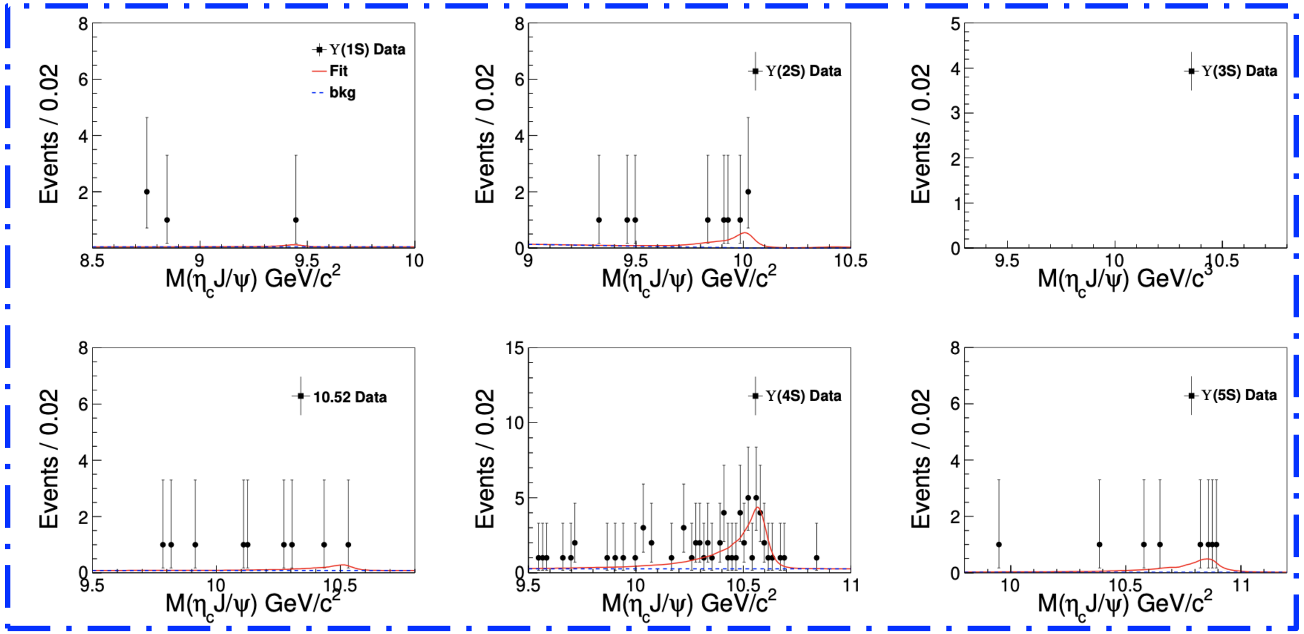

ATLAS EXPERIMENT arXiv:2304.08962

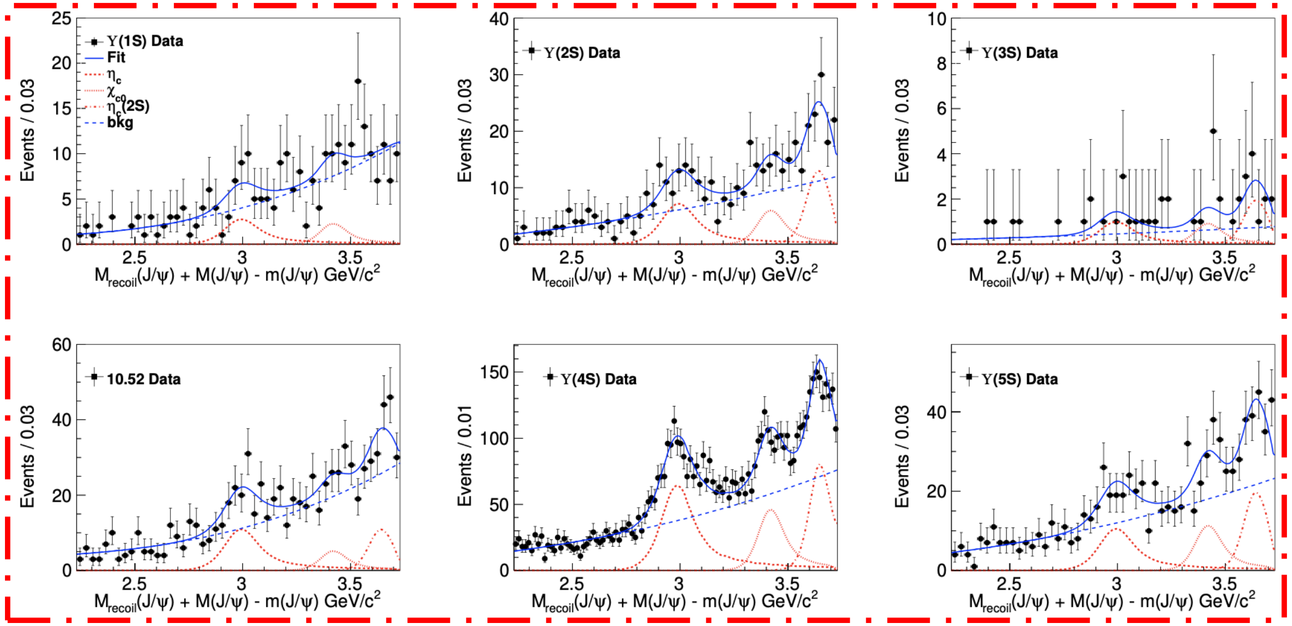



- The lowest mass combination of charmonia to which a vector $cc\bar{c}\bar{c}$ ($Y_{cc}$) could decay is $\eta_c J/\psi$, and this process may have a relative large branching fraction [Phys. Rev. D 73, 094510 (2006)].

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

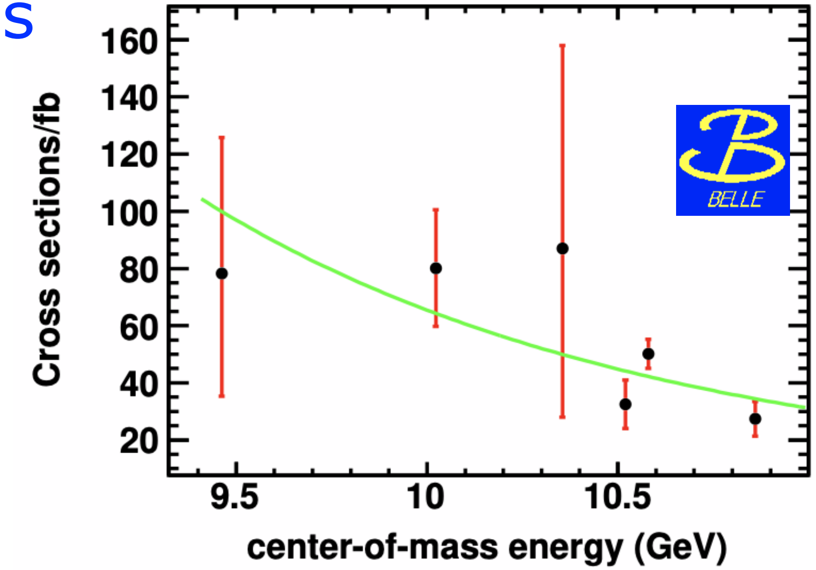
Exclusive process




Inclusive process

[JHEP 08 (2023) 121]



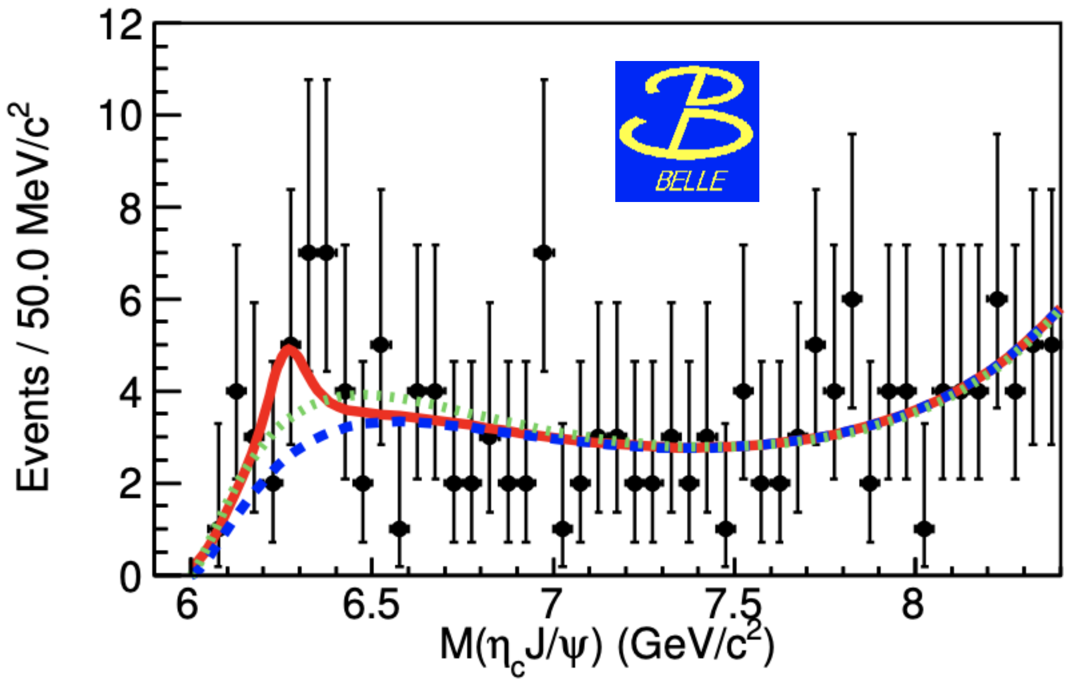

$$\sigma = A\frac{\sqrt{2\mu\Delta M}}{(\frac{s}{s_0})^n}$$

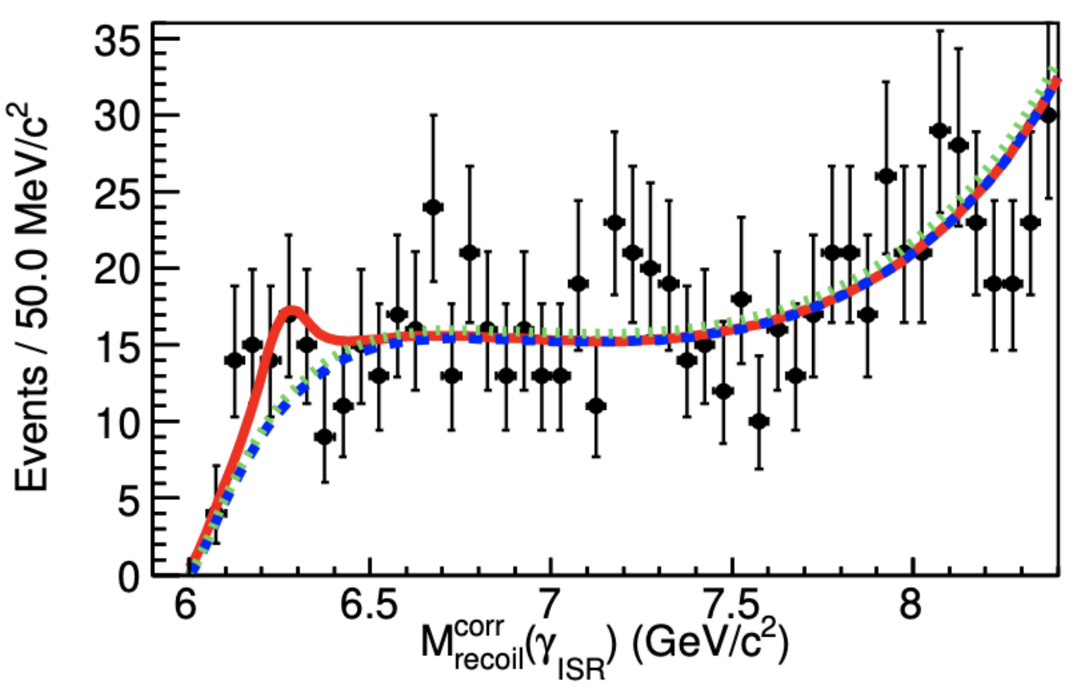
empirical function: $\mu$ is the reduced mass, $\Delta M = \sqrt{s} - m(\eta_c) - m(J/\psi)$ is the mass difference

n = $4.5 \pm 1.3$

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

[JHEP 08 (2023) 121]

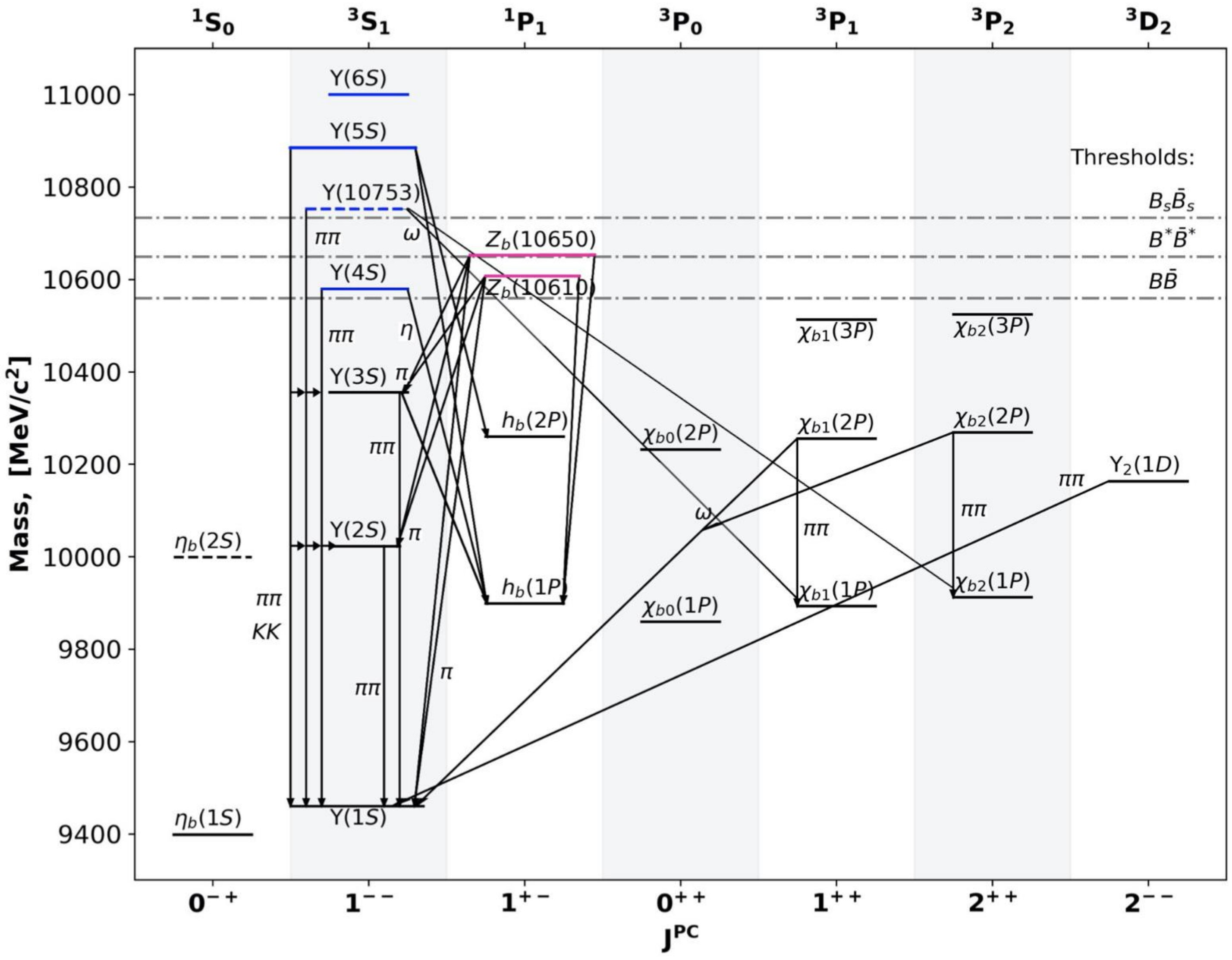



- Red solid curve: best fits
- Blue dashed curve: the background component
- Green dotted curve: fits without the signal component

| Parameters | Exclusive | Inclusive |
|---|---|---|
| Mass | $(6267\pm43)$ MeV/$c^2$ | |
| Width | $(121\pm72)$ MeV | |
| Yield | $9\pm4$ | $23\pm11$ |
| Significance | $2.2\sigma$ | |

# Bottomonium

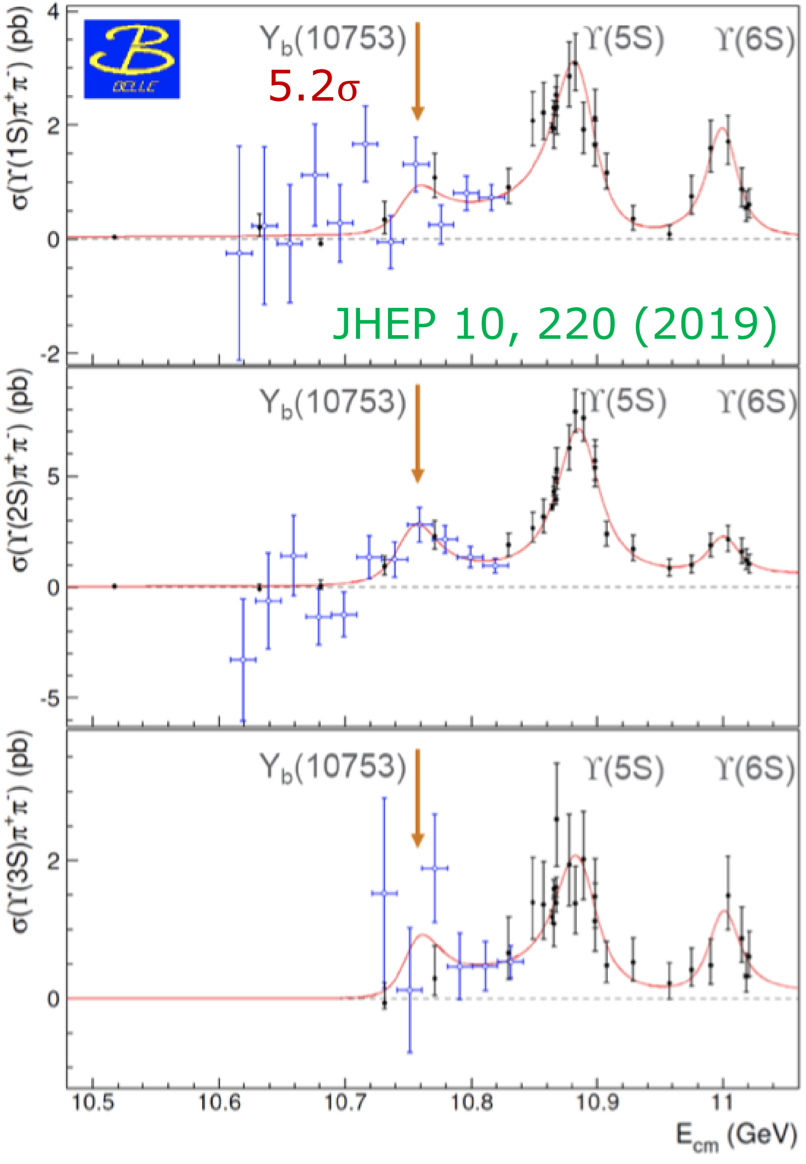



- Below $B\bar{B}$ thresholds – bottomonia are well described by the potential models.
- Above $B\bar{B}$ thresholds – bottomonia express unexpected properties:

- 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);

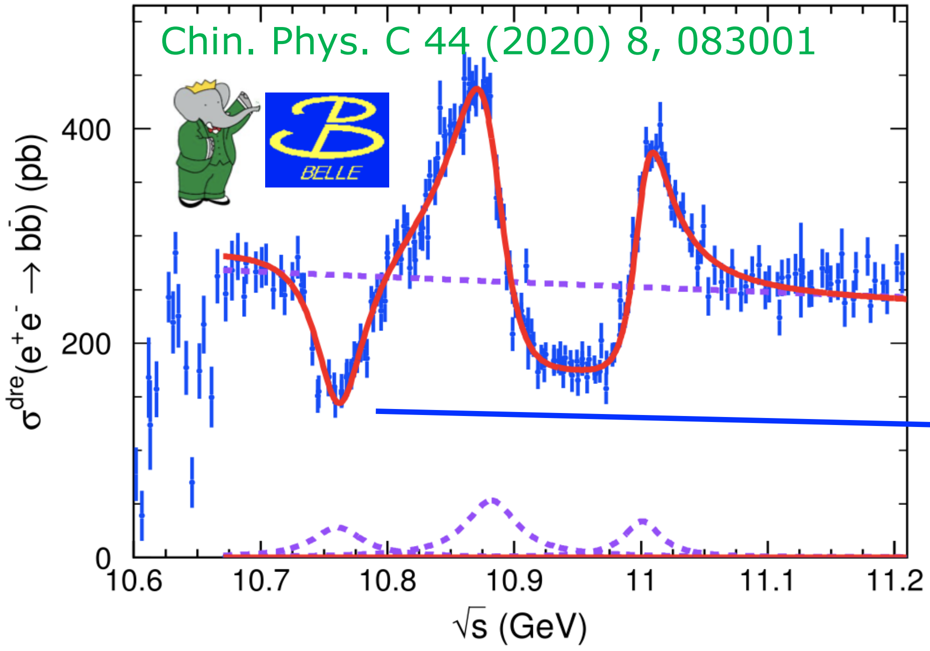
Conventional bottomonium (pure $b\bar{b}$ states)
Bottomonium-like states (mix of $b\bar{b}$ and $B\bar{B}$)
Exotic charged states ($Z_b^+$)

# Discovery of $\Upsilon(10753)$




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

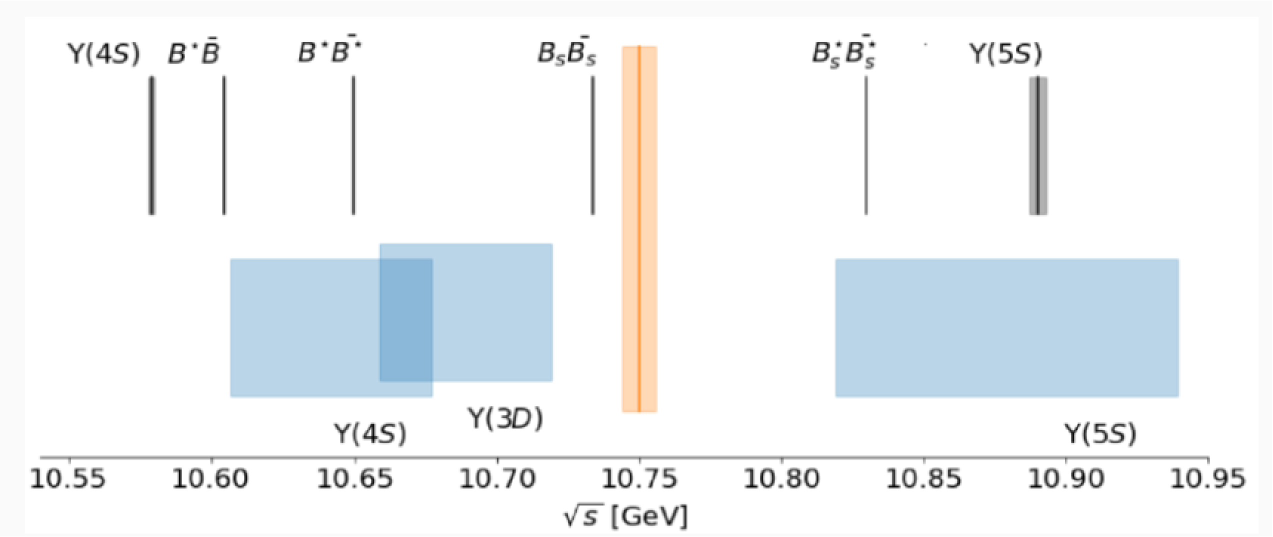
| | $\Upsilon(10860)$ | $\Upsilon(11020)$ | New structure |
|---|---|---|---|
| M (MeV/c$^2$) | $10885.3 \pm 1.5\,^{+2.2}_{-0.9}$ | $11000.0^{+4.0\,+1.0}_{-4.5\,-1.3}$ | $10752.7 \pm 5.9\,^{+0.7}_{-1.1}$ |
| Γ (MeV) | $36.6^{+4.5\,+0.5}_{-3.9\,-1.1}$ | $23.8^{+8.0\,+0.7}_{-6.8\,-1.8}$ | $35.5^{+17.6\,+3.9}_{-11.3\,-3.3}$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




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)

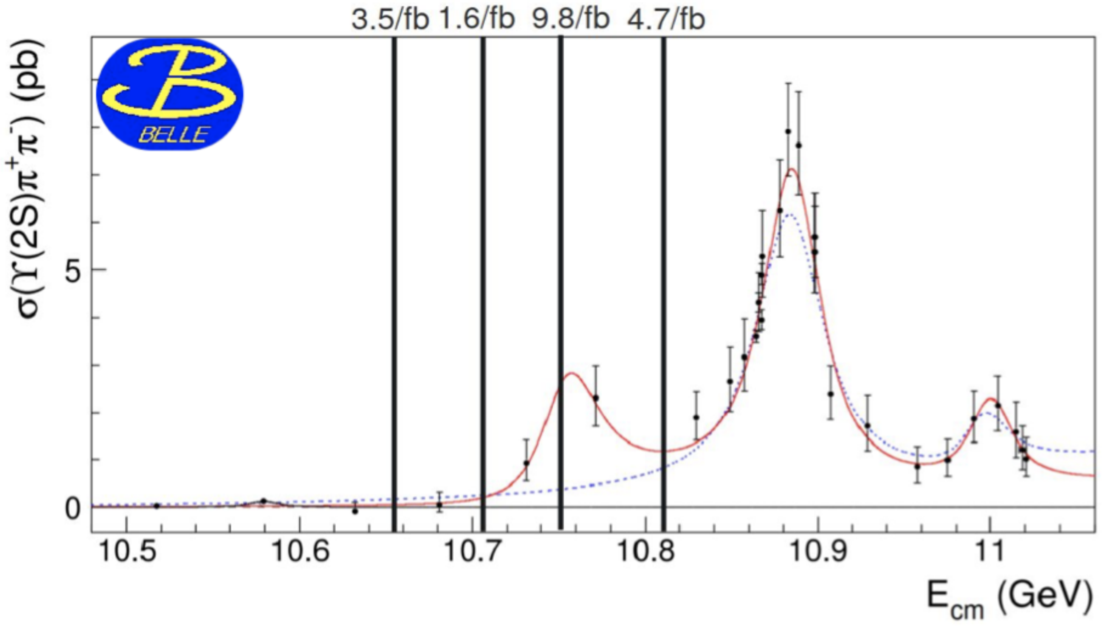
❑ Hybrid

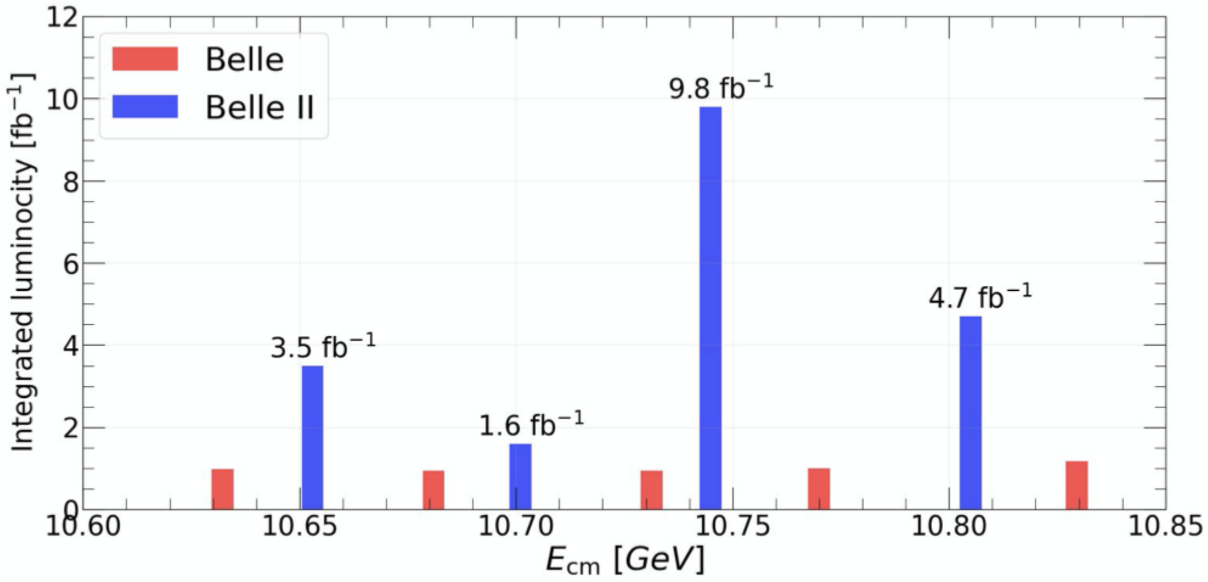
Phys. Rept. 873, 1 (2020)
Phys. Rev. D 104, 034019 (2021)

❑ 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 $\Upsilon(4S)$: 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 $\Upsilon(10753)$ energy region.

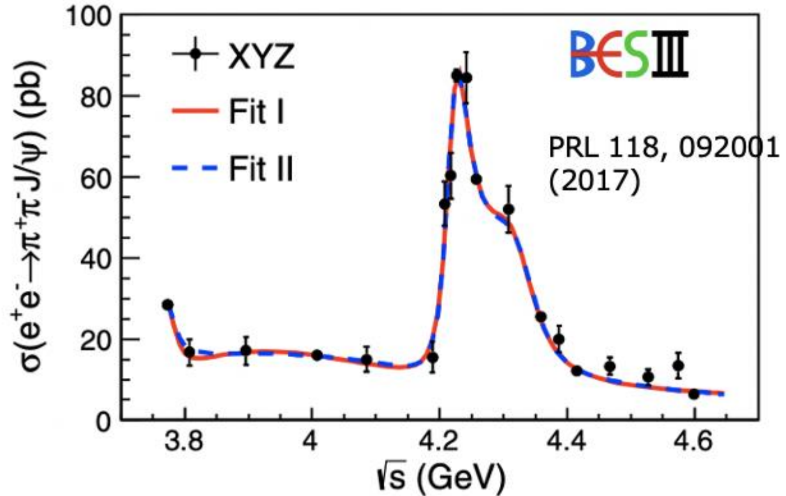
# Motivation to search for $\Upsilon(10753) \to \omega\chi_{bJ}$

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 $\Upsilon$(4S) - $\Upsilon$(3D) mixing state for $\Upsilon$(10753).

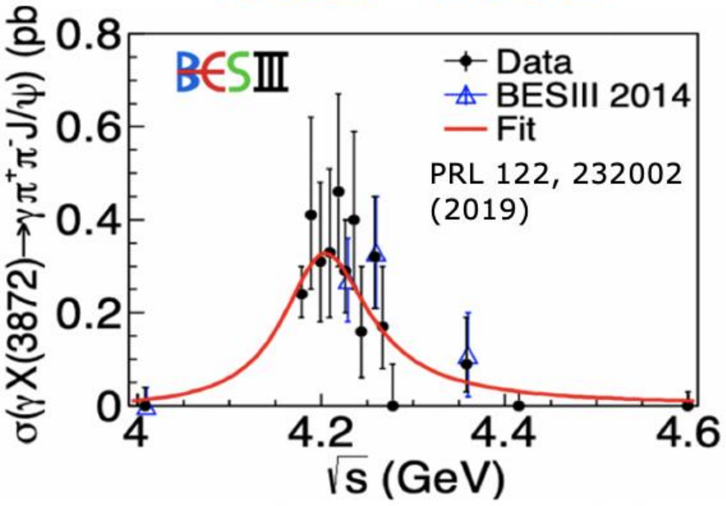
Charmonium sector:

- 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 $\omega\chi_{bJ}$.

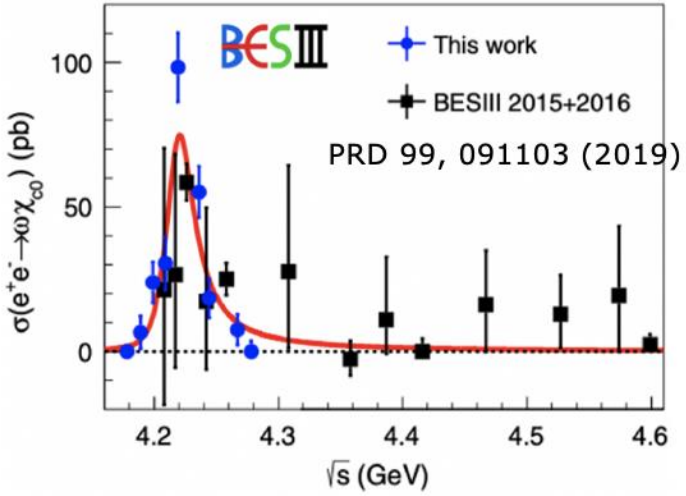
$Y(4220)/Y(4320) \to \pi^+\pi^- J/\psi$




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



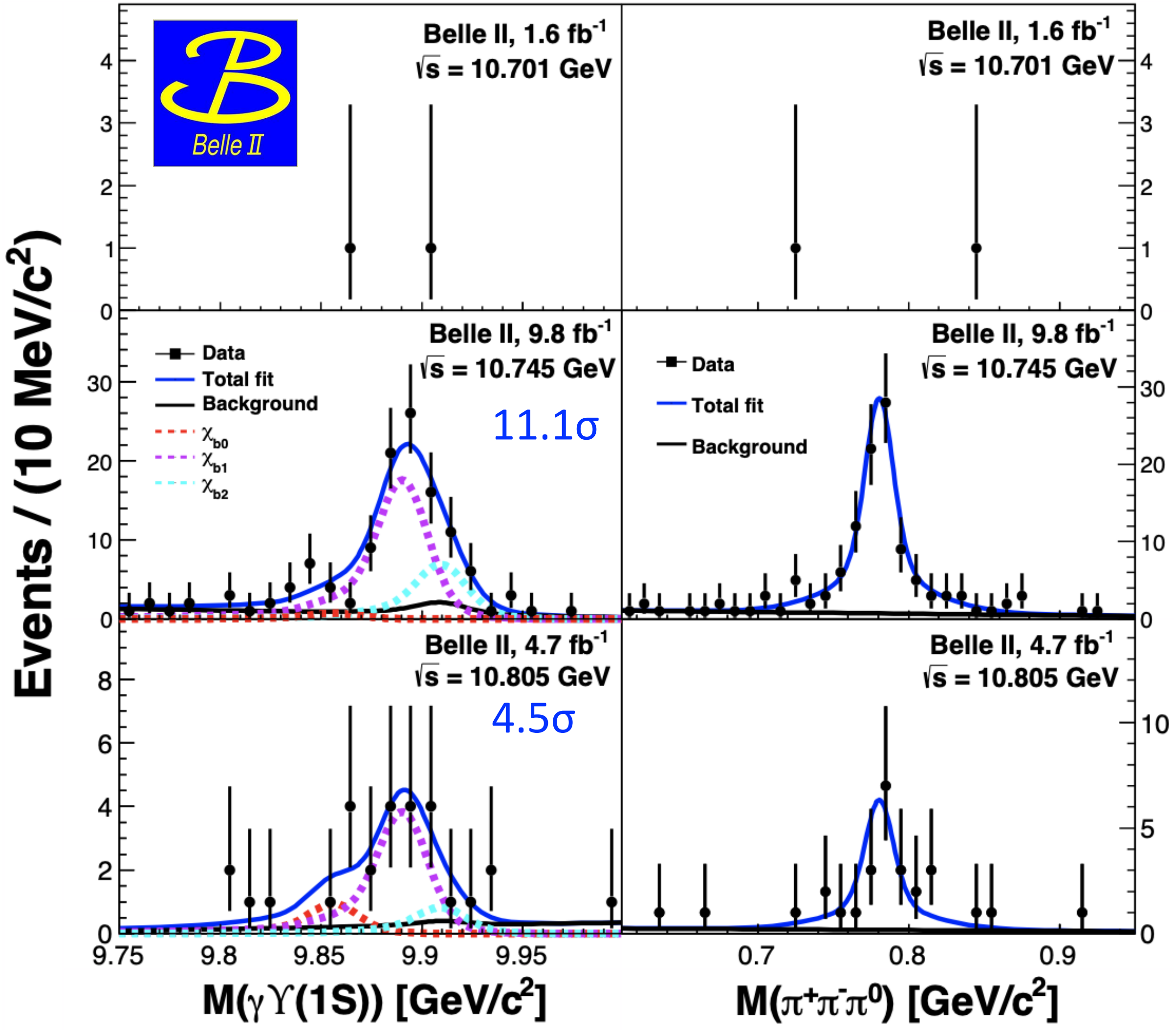

$Y(4220) \to \omega\chi_{c0}$



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

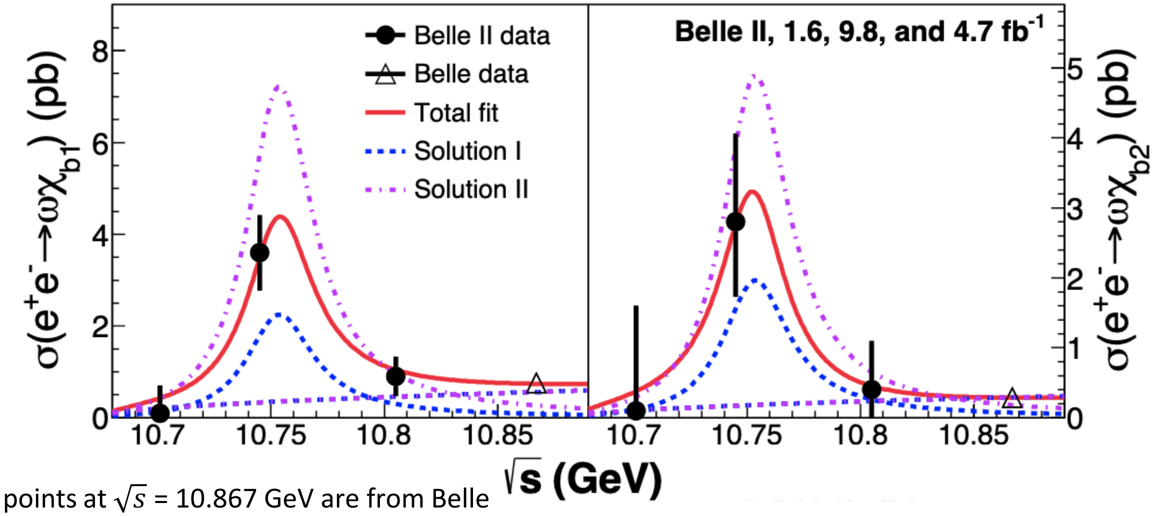
PRL 130, 091902 (2023)

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




| Channel | $\sqrt{s}$ (GeV) | $N^{sig}$ | $\sigma^{(UL)}_{Born}$ (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 $e^+e^- \rightarrow \omega\chi_{bJ}$ (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

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

→ ~1.5 at $\sqrt{s}$ = 10.745 GeV [PRL 130, 091902 (2023)]

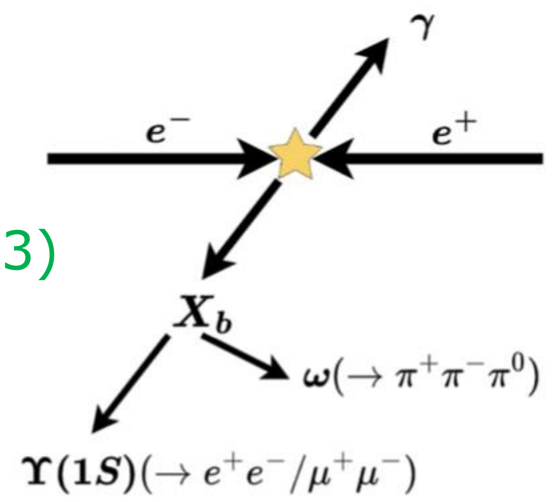
→ ~ 0.15 at $\sqrt{s}$ = 10.867 GeV [PRL 113, 142001 (2014)]

- $\Upsilon(5S)$ 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**.

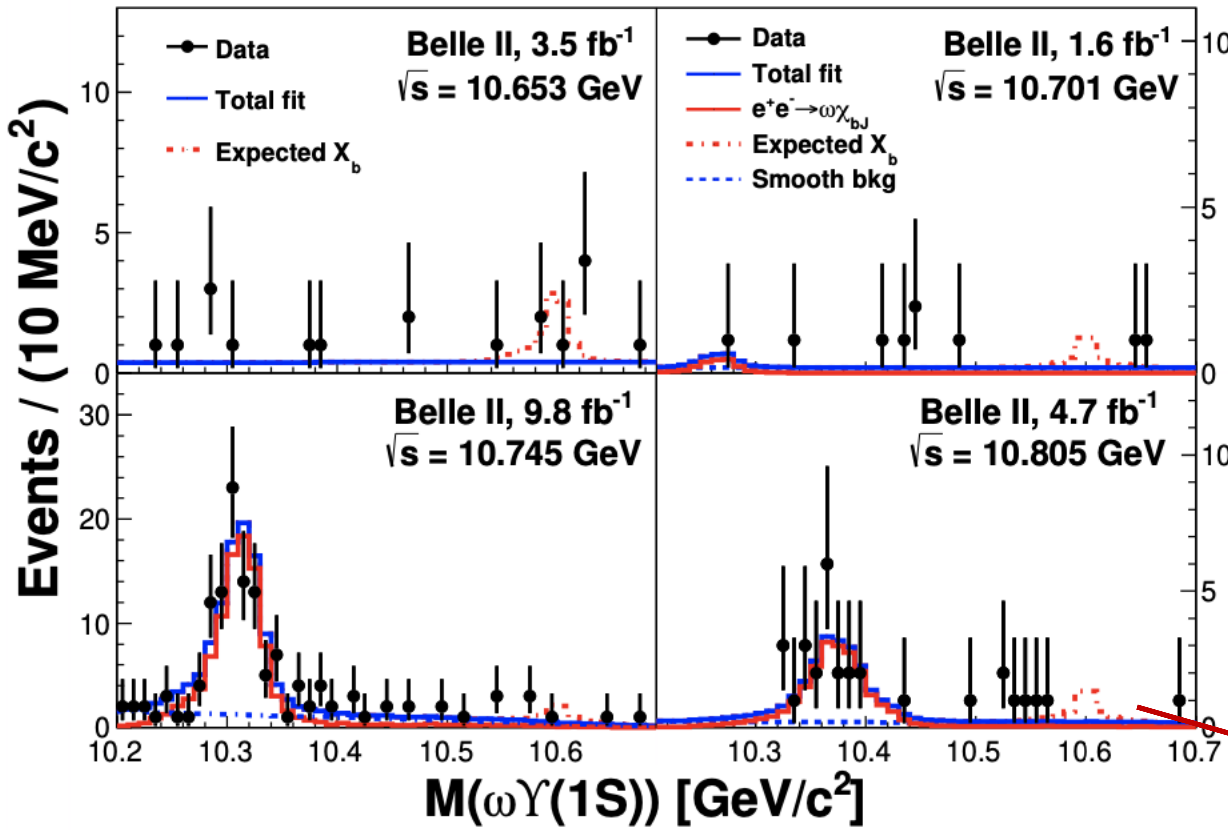
$$\frac{\sigma(e^+e^-\to\chi_{b1}(1P)\omega)}{\sigma(e^+e^-\to\chi_{b2}(1P)\omega)} = 1.3\pm0.6 \text{ at } \sqrt{s} = 10.745 \text{ GeV [PRL 130, 091902 (2023)]}$$

- **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/c²
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/c² | 0.46 | 0.33 | 0.10 | 0.14 |
| | $m(X_b)$ = (10.45, 10.65) GeV/c² | (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

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

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

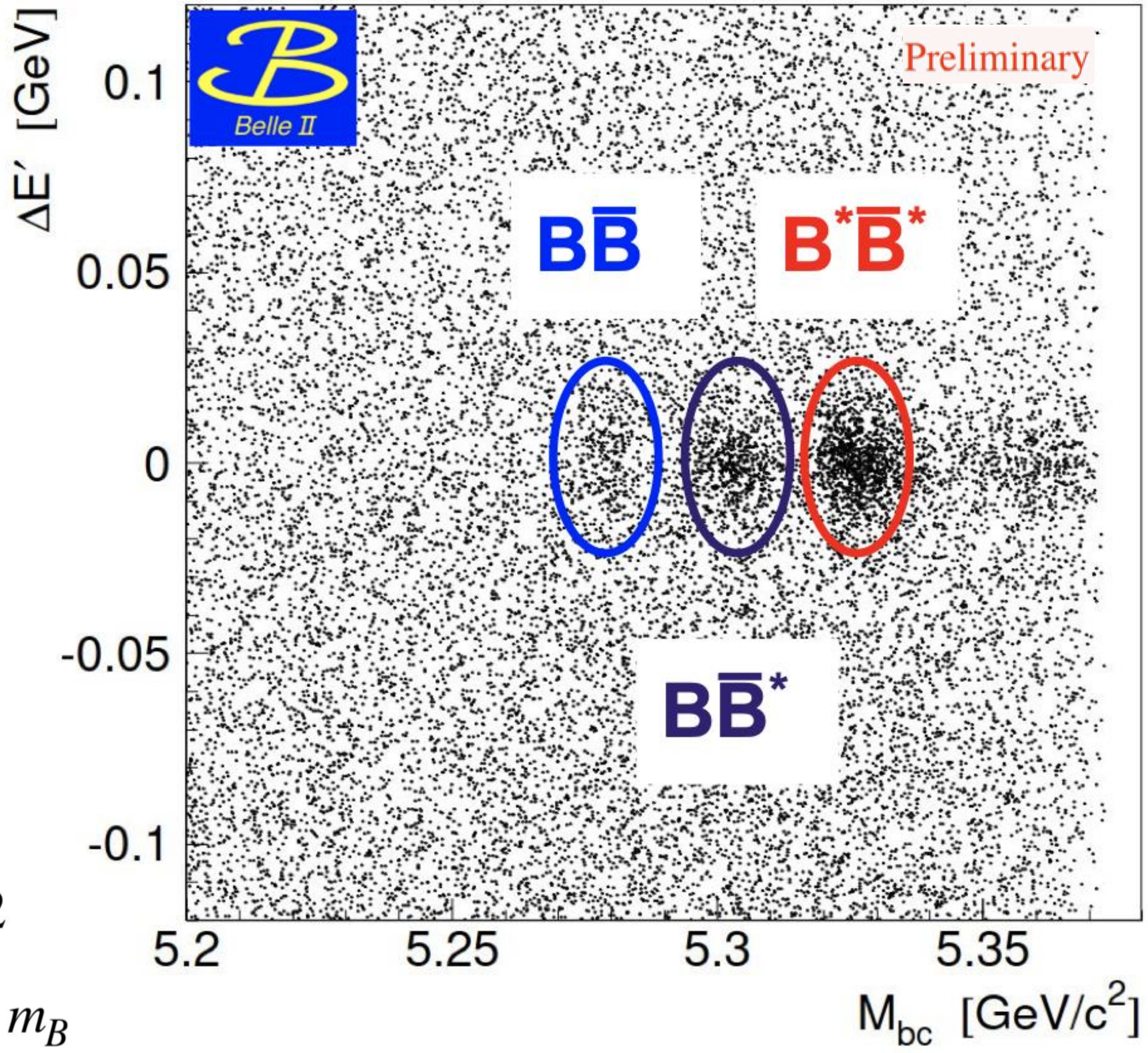
Method:

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

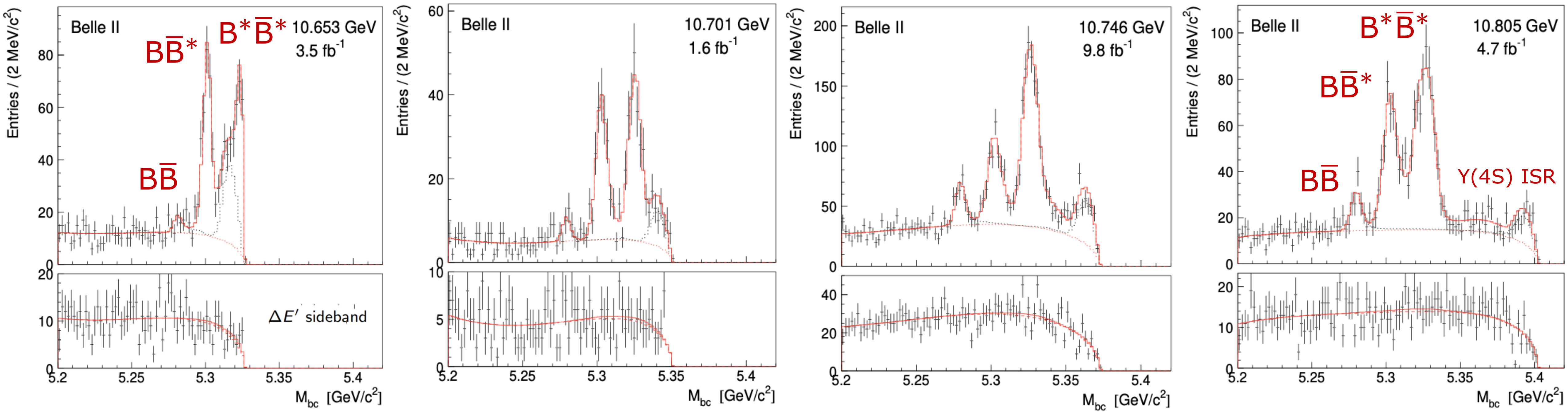
$$M_{bc} = \sqrt{(E_{cm}/2)^2 - P_B^2}$$

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

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

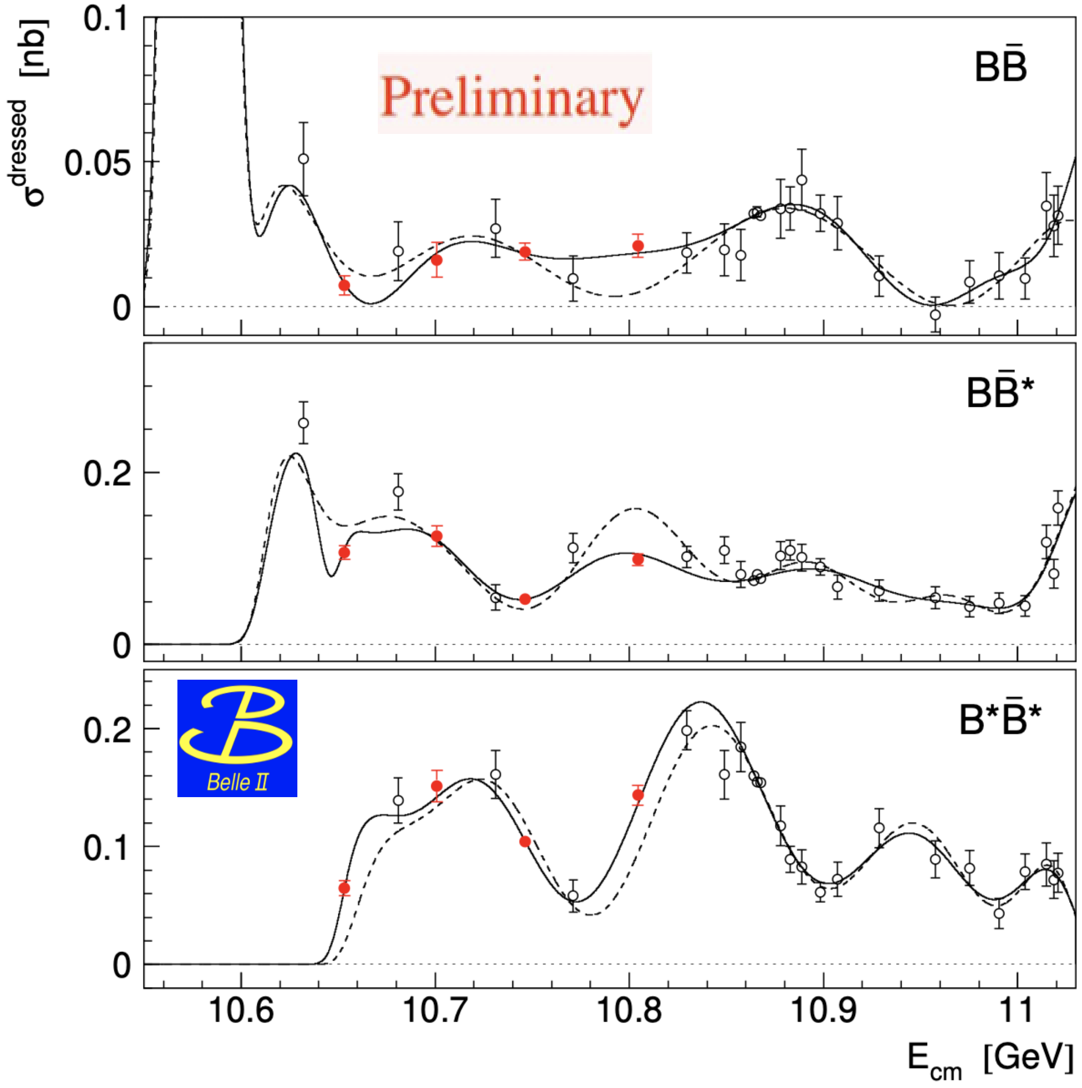


# $M_{bc}$ fit at scan energies




- $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ 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))

# 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, 123102 (2019)].

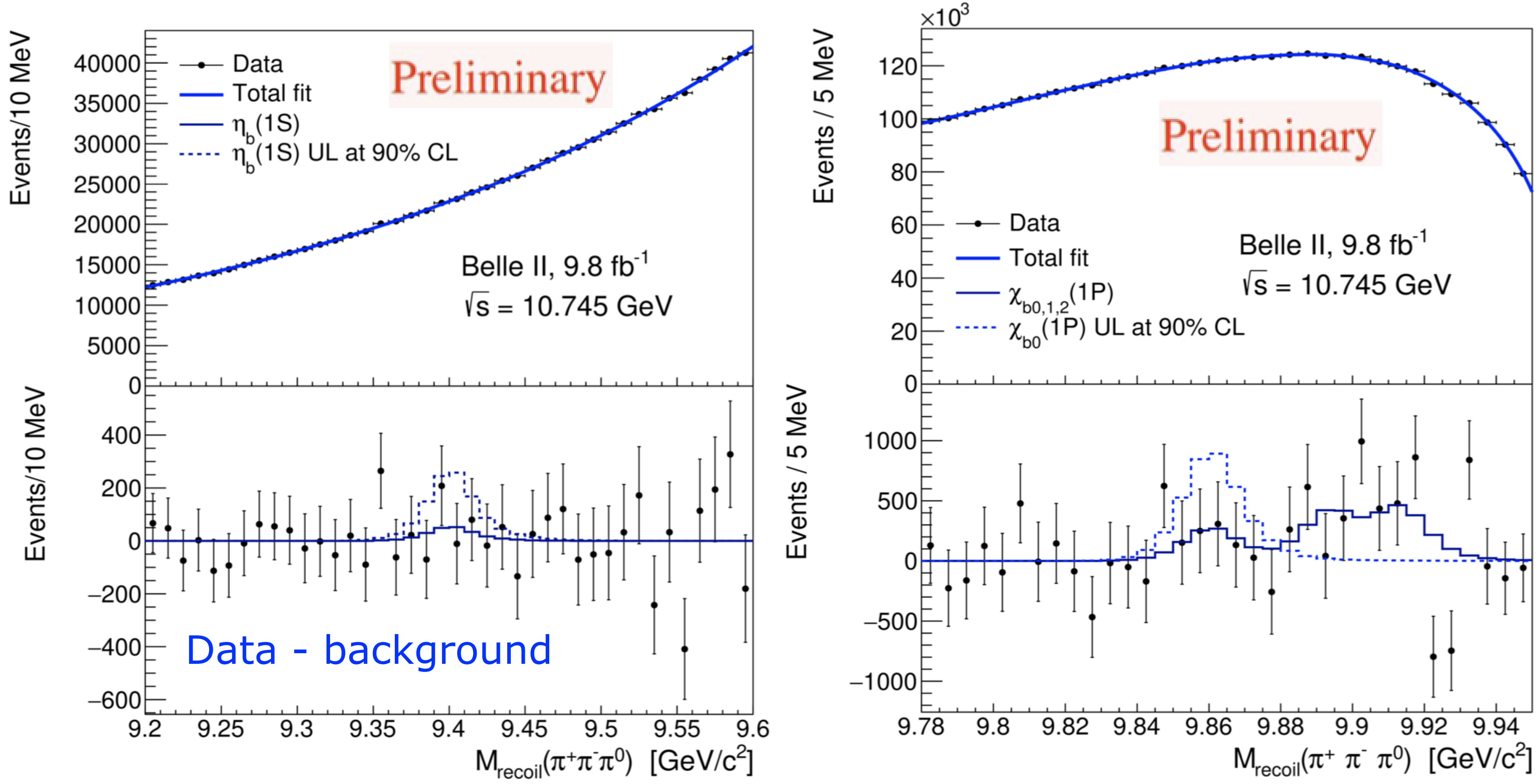
$$\frac{\Gamma(\eta_b\,\omega)}{\Gamma(\Upsilon\,\pi^+\pi^-)} \sim 30$$

- 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 $\mathcal{B}[\chi_{b0}(1P) \to \gamma\Upsilon(1S)] = (1.94 \pm 0.27)\%$.

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

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

# 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

Preliminary

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

| 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)]:

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

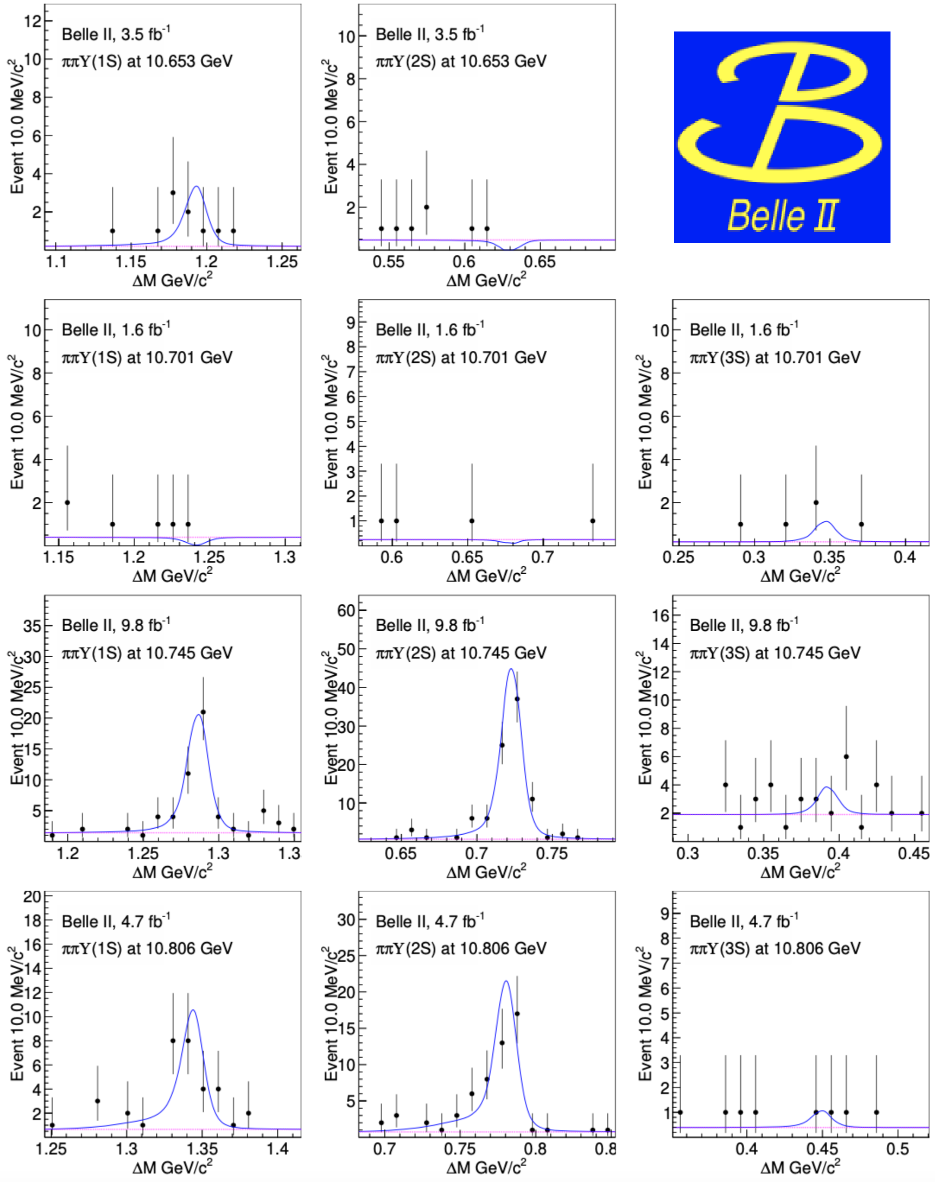
This measurement and JHEP 10, 220 (2019):

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

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

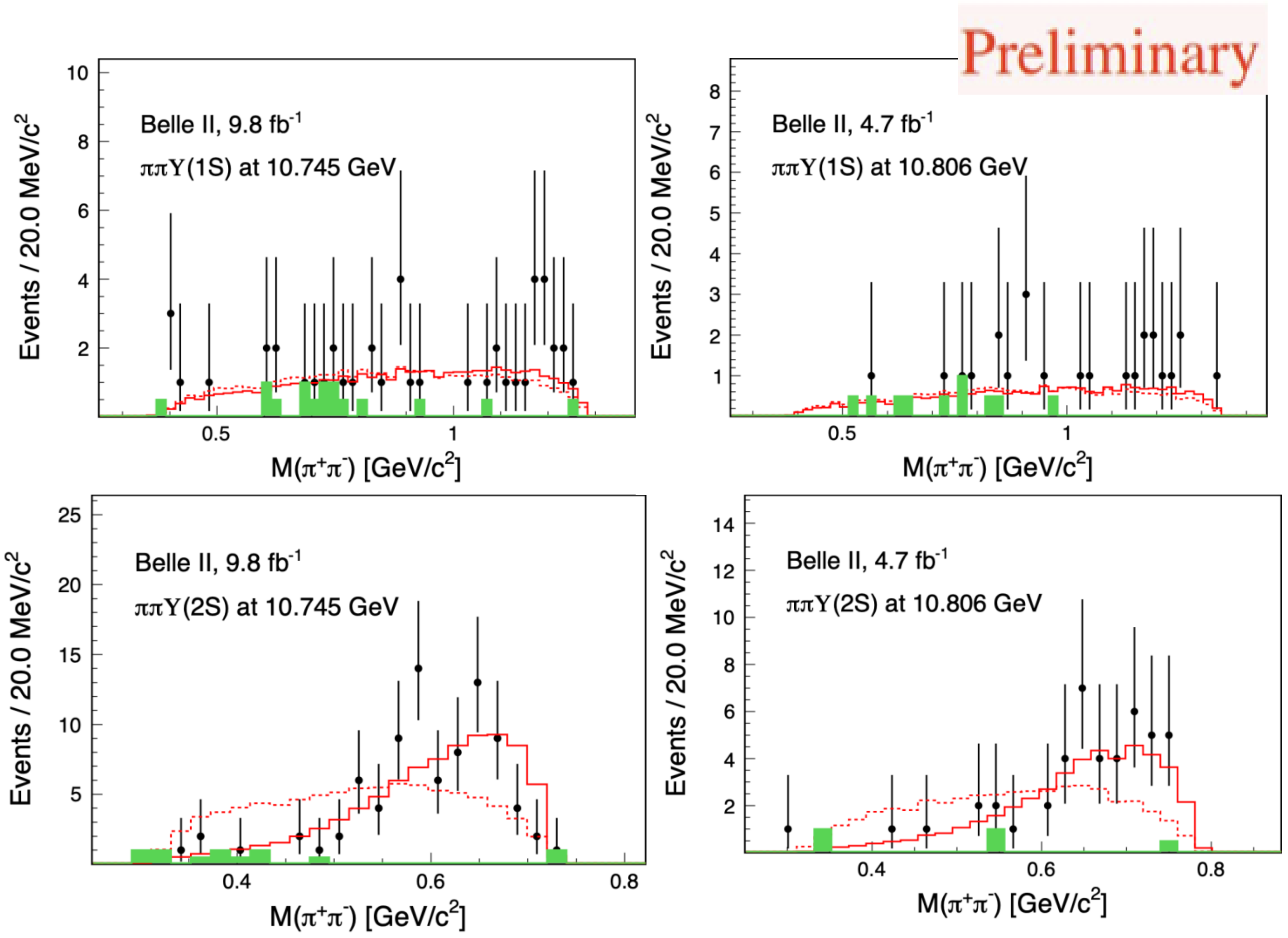
# Updated measurement of the energy dependence of the $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ cross sections

Preliminary




- $\Delta M = M(\pi^+\pi^-\mu^+\mu^-) - M(\mu^+\mu^-)$ is defined to extract the signal.
- Significant signals for $\Upsilon(1S, 2S)\pi^+\pi^-$ at $\sqrt{s} = 10.745,\ 10.806$ GeV
- No evident signals for $\Upsilon(3S)\pi^+\pi^-$
- Significance for $\Upsilon(1S)\pi^+\pi^-$ at $\sqrt{s} = 10.653$ GeV is only $1.7 \sim 2.3\sigma$, depending on different background assumptions.

# Intermediate state —$M(\pi\pi)$




Dots: events in signal region

Green: nearest sidebands, scaled with area

Red dashed: signal MC, simulated uniformly

Red solid： re-weighted signal MC

$\Upsilon(1S)\pi\pi$ ：

Consistent with PHSP

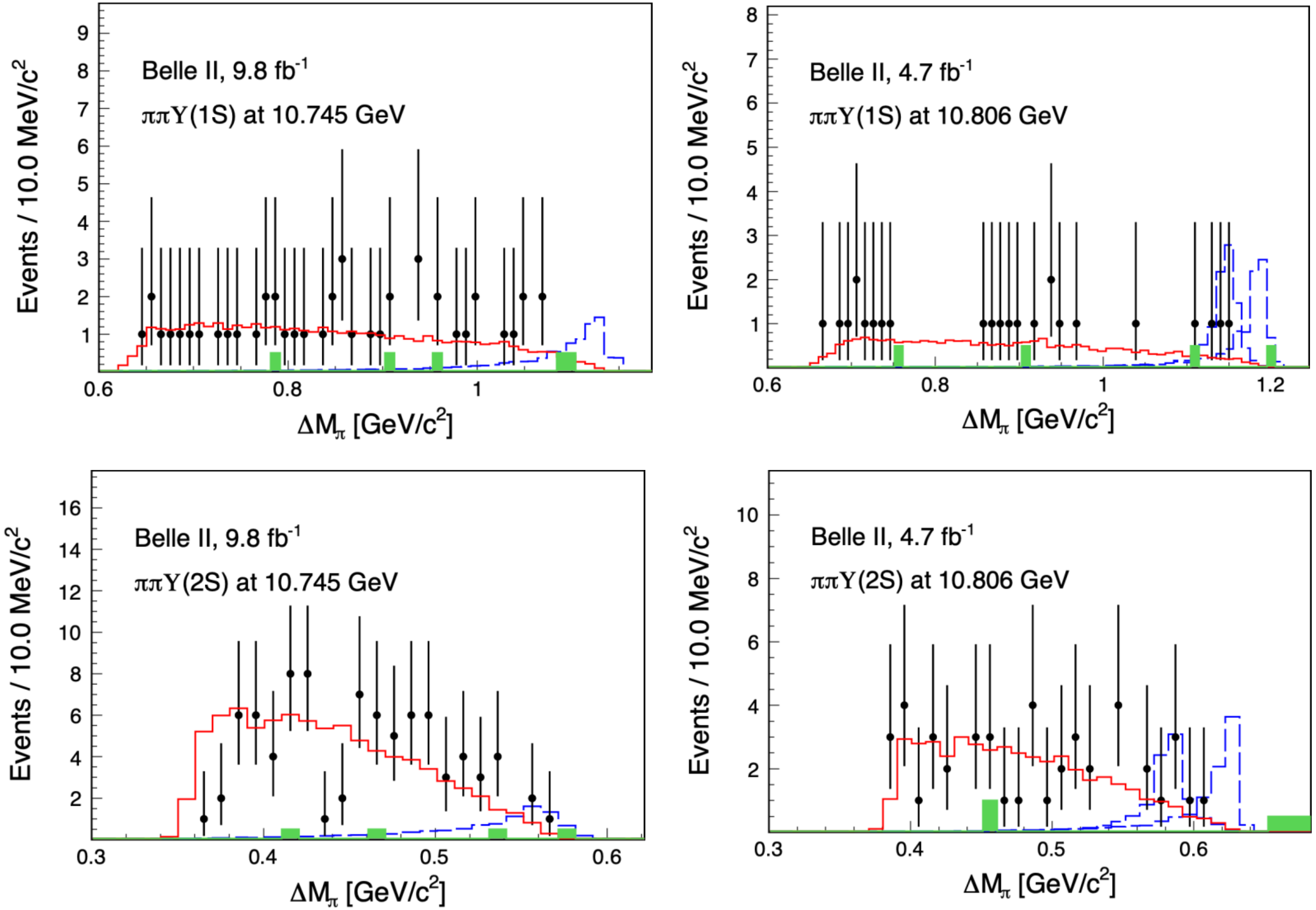
$(\chi^2 = 0.98, 1.14\ )$

$\Upsilon(2S)\pi\pi$ ：

Not consistent with PHSP

$(\chi^2 = 3.45, 2.43)$

# Intermediate state $-M_{\mathrm{recoil}}(\pi)$




- No evidence of $Z_b(10610/10650)$.
- Upper limits estimated at 90% C.L.

Preliminary

| Mode | 10.745 GeV $\pi\Upsilon(1S)$ | 10.745 GeV $\pi\Upsilon(2S)$ | 10.805 GeV $\pi\Upsilon(1S)$ | 10.805 GeV $\pi\Upsilon(2S)$ |
|---|---|---|---|---|
| $N_{\mathrm{UL}}(Z_{b1})$ | $< 4.9$ | $< 13.8$ | $< 5.2$ | $< 12.3$ |
| $N_{\mathrm{UL}}(Z_{b2})$ | – | – | $< 5.8$ | $< 6.0$ |
| $\epsilon_1$ | 0.247 | 0.399 | 0.256 | 0.472 |
| $\epsilon_2$ | – | – | 0.395 | 0.270 |
| $\sigma^B_{\mathrm{UL}}(Z_{b1})$ (pb) | $< 0.13$ | $< 0.14$ | $< 0.43$ | $< 0.35$ |
| $\sigma^B_{\mathrm{UL}}(Z_{b2})$ (pb) | – | – | $< 0.28$ | $< 0.30$ |

# Updated cross sections

Fit with three coherent BW, convoluting a Gaussian modeling energy spread:

$$\sigma \propto |\sum_i^3 \frac{\sqrt{12\pi\Gamma_i\mathcal{B}_i}}{s - M_i + iM_i\Gamma_i} \cdot \sqrt{\frac{f(\sqrt{s})}{f(M_i)}} e^{i\phi_i}|^2 \otimes G(0, \delta E)$$

All parameters are free, except $\delta E = 0.0056 \ \ \mathrm{GeV}$

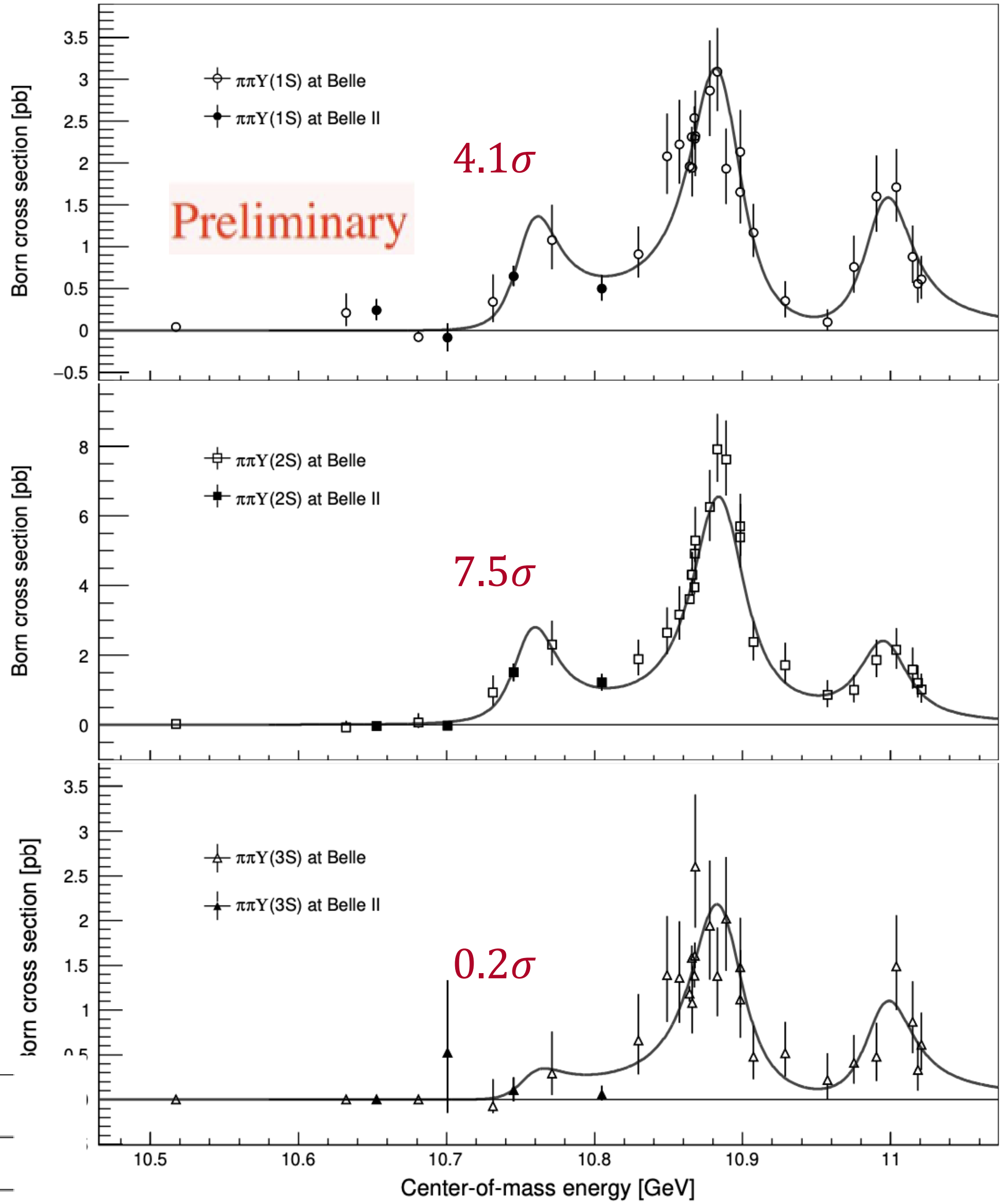
Parameters of $\Upsilon(10753)$:

$M = 10756.3 \pm 2.7_{(stat.)} \pm 0.6_{(syst.)} \mathrm{MeV}/c^2$

$\Gamma = 29.7 \pm 8.5_{(stat.)} \pm 1.1_{(syst.)} \mathrm{MeV}$

Relative ratios of cross section at different resonance peaks

| | $\mathcal{R}^{\Upsilon(10753)}_{\sigma(1S/2S)}$ | $\mathcal{R}^{\Upsilon(10753)}_{\sigma(3S/2S)}$ | $\mathcal{R}^{\Upsilon(5S)}_{\sigma(1S/2S)}$ | $\mathcal{R}^{\Upsilon(5S)}_{\sigma(3S/2S)}$ | $\mathcal{R}^{\Upsilon(6S)}_{\sigma(1S/2S)}$ | $\mathcal{R}^{\Upsilon(6S)}_{\sigma(3S/2S)}$ |
|---|---|---|---|---|---|---|
| Ratios | $0.46^{+0.15}_{-0.12}$ | $0.10^{+0.05}_{-0.04}$ | $0.45^{+0.04}_{-0.04}$ | $0.32^{+0.04}_{-0.03}$ | $0.64^{+0.23}_{-0.13}$ | $0.41^{+0.16}_{-0.12}$ |



# Summary

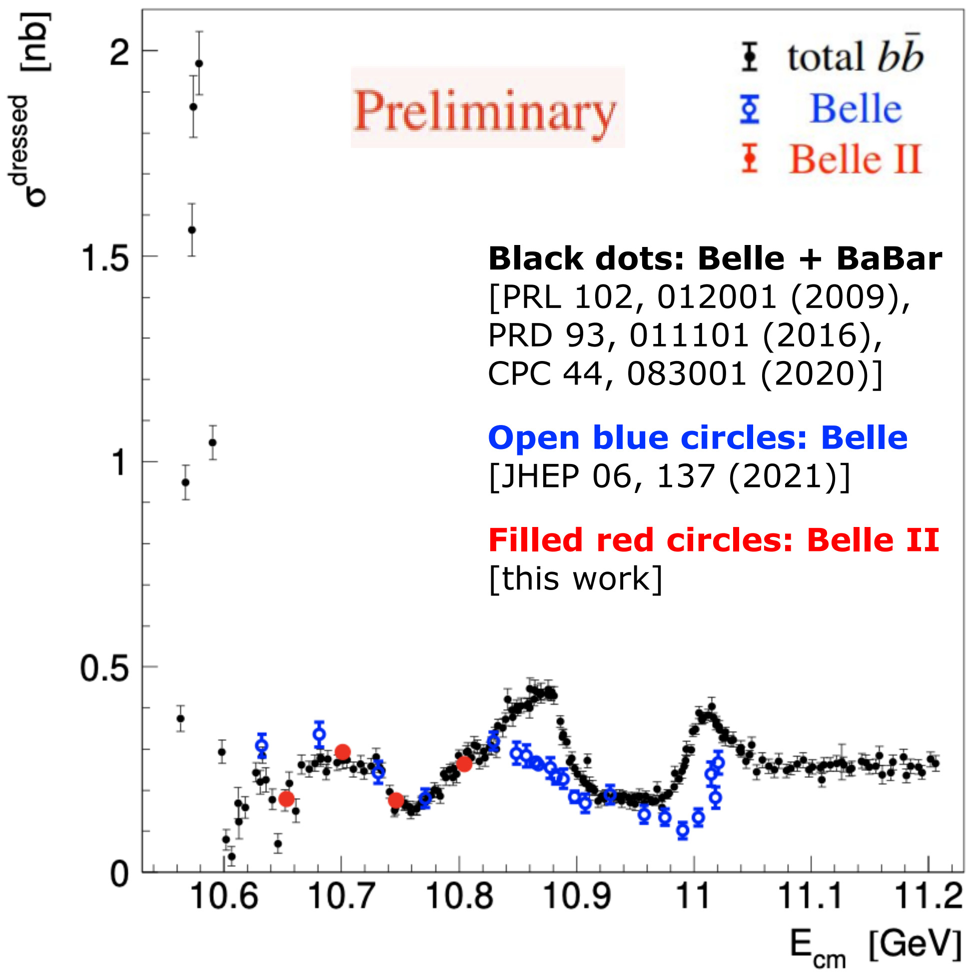
- The $g > 0.094$ (90% C.L.) is determined for $X(3872) \to D^0\bar{D}^{*0}$
- We search for the signal near the threshold in $e^+e^- \to \eta_c J/\psi$ via ISR
- New decay modes of $\Upsilon(10753) \to \omega\chi_{bJ}$ are observed
- The rapid increase of $\sigma_{B^*\bar{B}^*}$ above the threshold 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
- Updated measurement of $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ cross sections was done by adding Belle II data. The $\Upsilon(10753)$ parameters were improved.

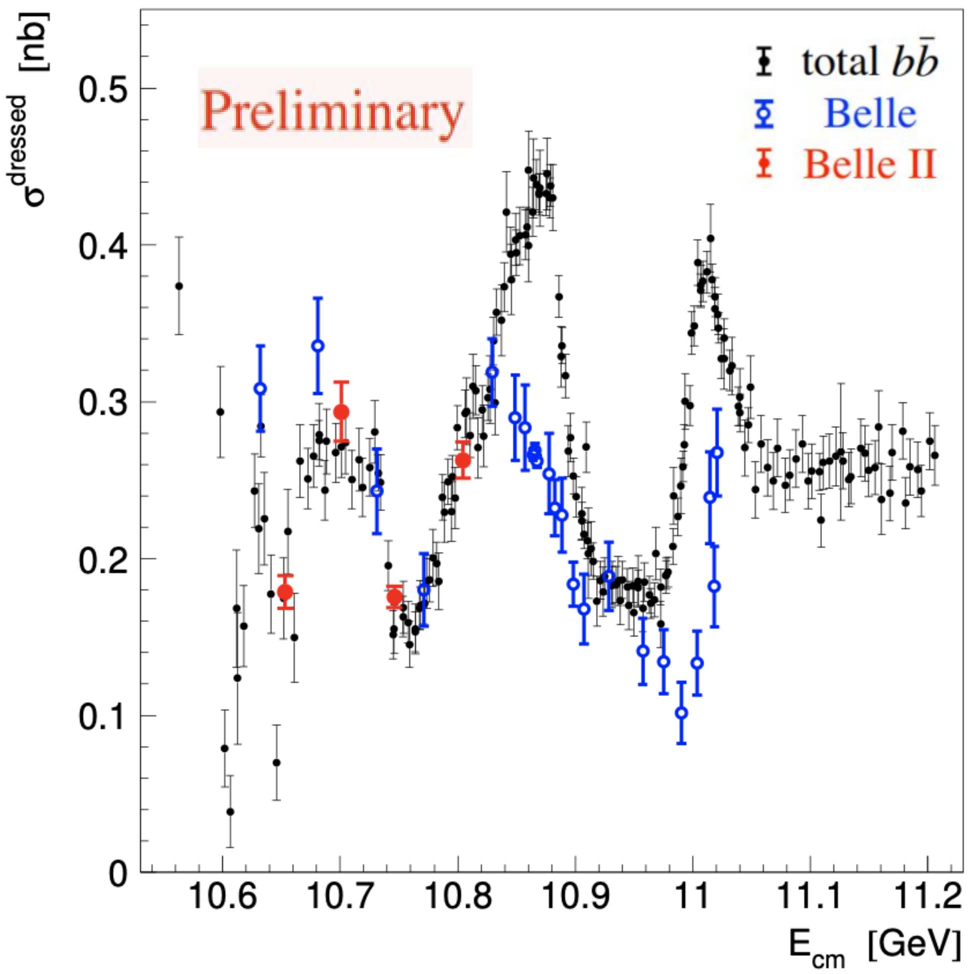
- Many other new results, including unique/world class ones, were presented in 2023 summer conferences

***Thanks for your attention!***

# Backup slides

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



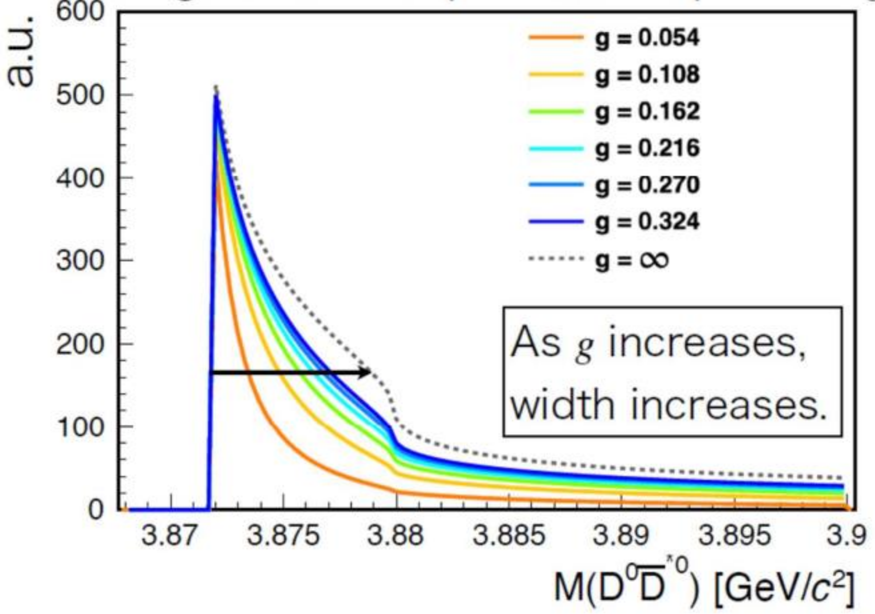




- Agreement at low energy
- Departure at high energy is due to $B_s^{(*)}\bar{B}_s^{(*)}$, multi-body $B^{(*)}\bar{B}^{(*)}\pi(\pi)$, and bottomonia

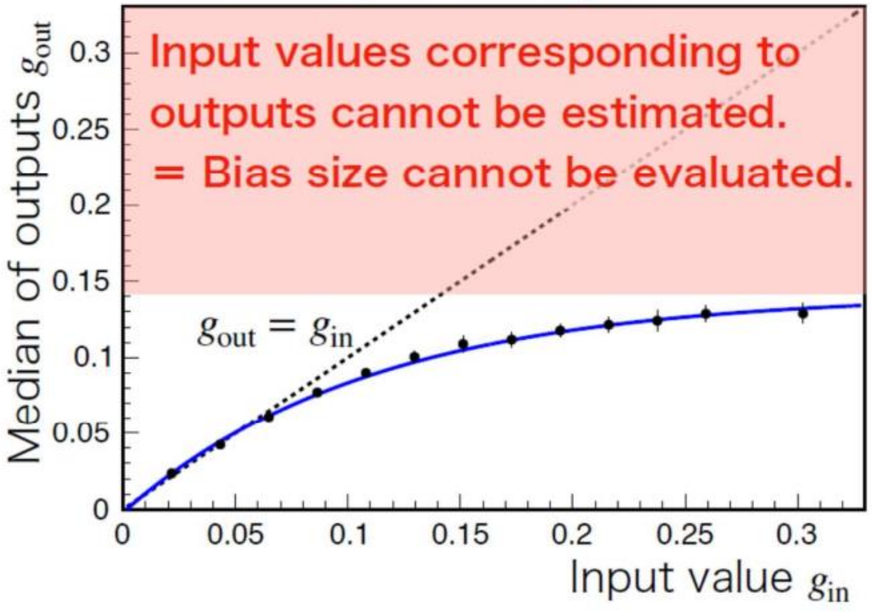
# Fit bias

- Lineshape converges to a fixed form for large $g$

Change in lineshape with respect to $g$



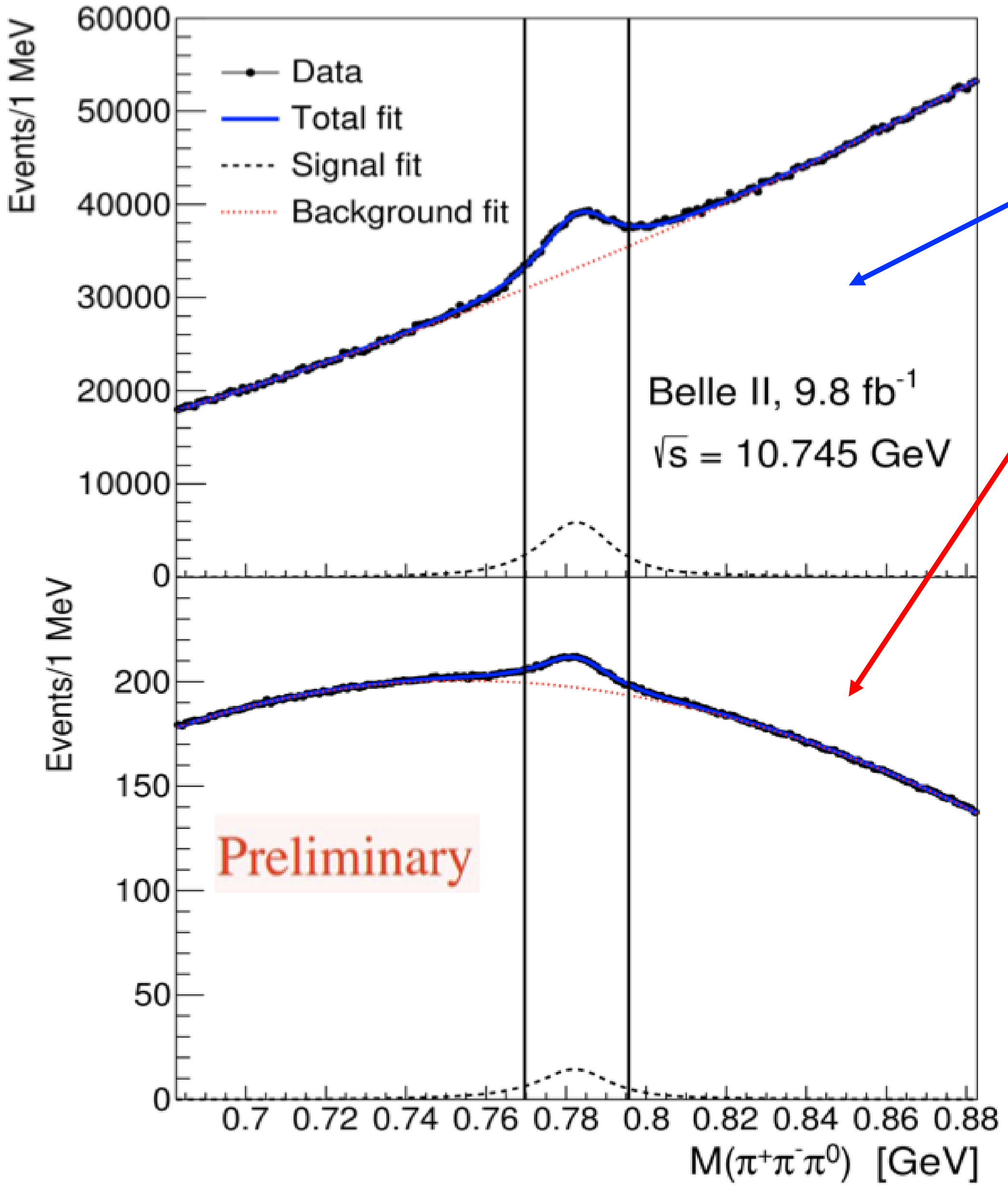

Result of pseudo experiments*




*excluding failed fit results

→ Only lower limit can be obtained for large $g$

# 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 $\chi_{bJ}(1P)$

# Bottomonium(-like) prospects at Belle II

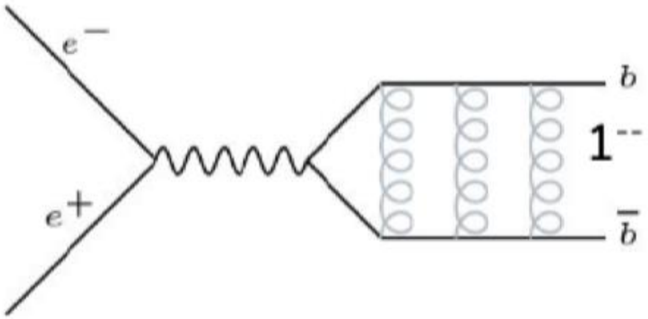
## Four ways to access bottomonia:

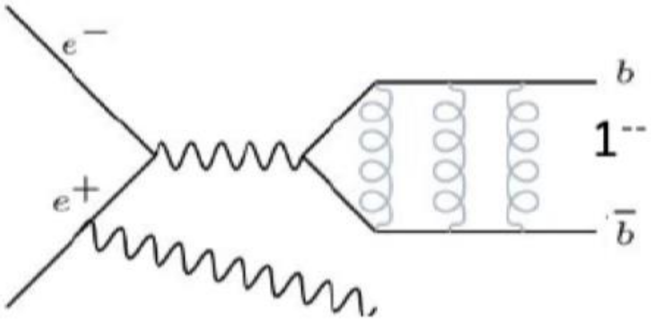
- Direct production from $e^+e^-$: $J^{PC} = 1^{--}$: $\Upsilon(nS)$
- ISR production: $J^{PC} = 1^{--}$: $\Upsilon(nS)$
- Hadronic transitions from $\Upsilon(nS)$ through $\eta$, $\pi\pi$, …

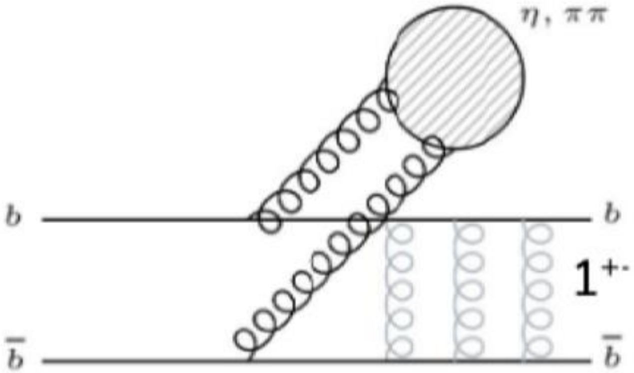
$J^{PC} = 0^{-+}, 1^{--}, 1^{+-}$ … : $\Upsilon(nS)$, $\eta_b(nS)$, $h_b(nS)$, …

- 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, …