Recent quarkonium(-like) results at Belle II

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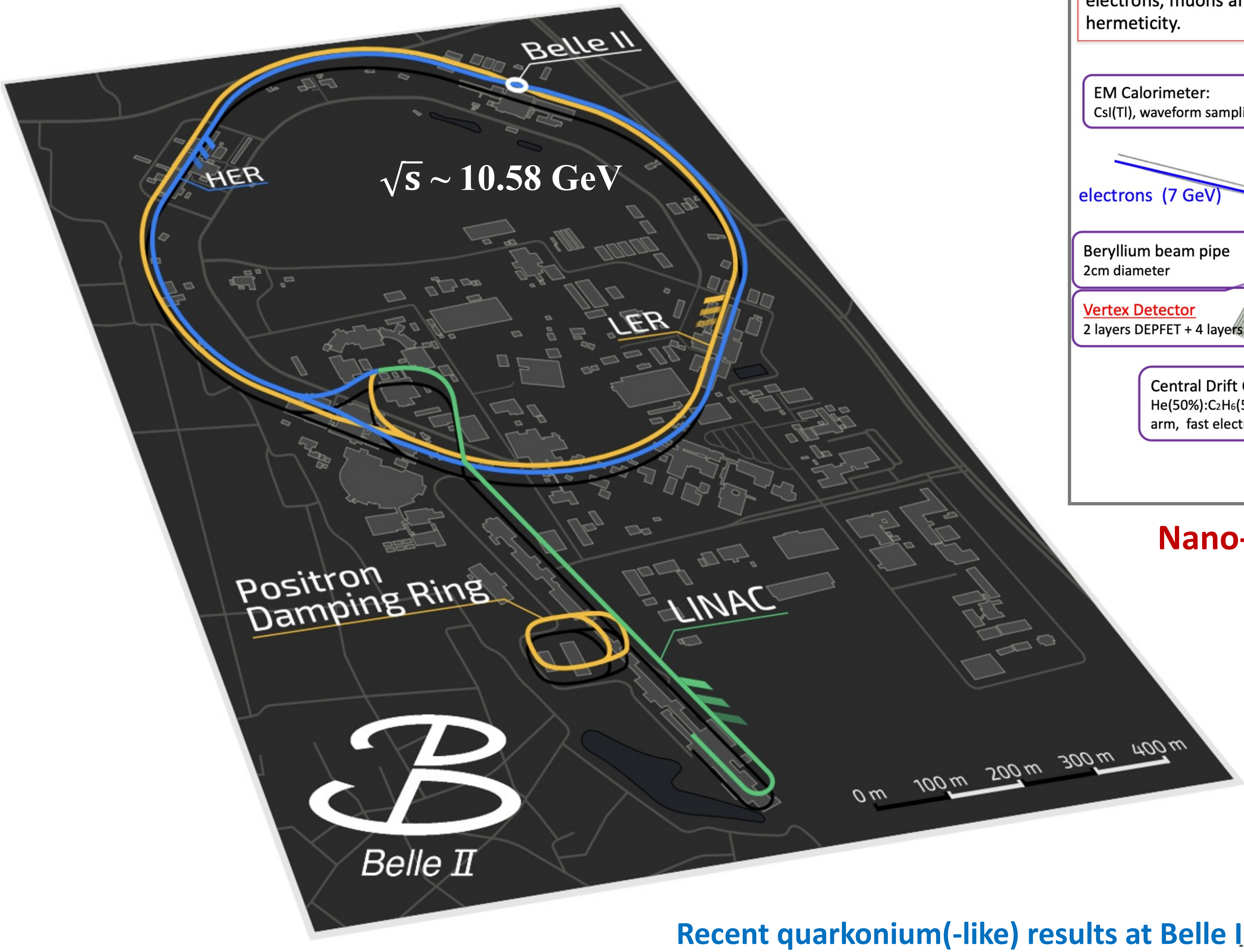
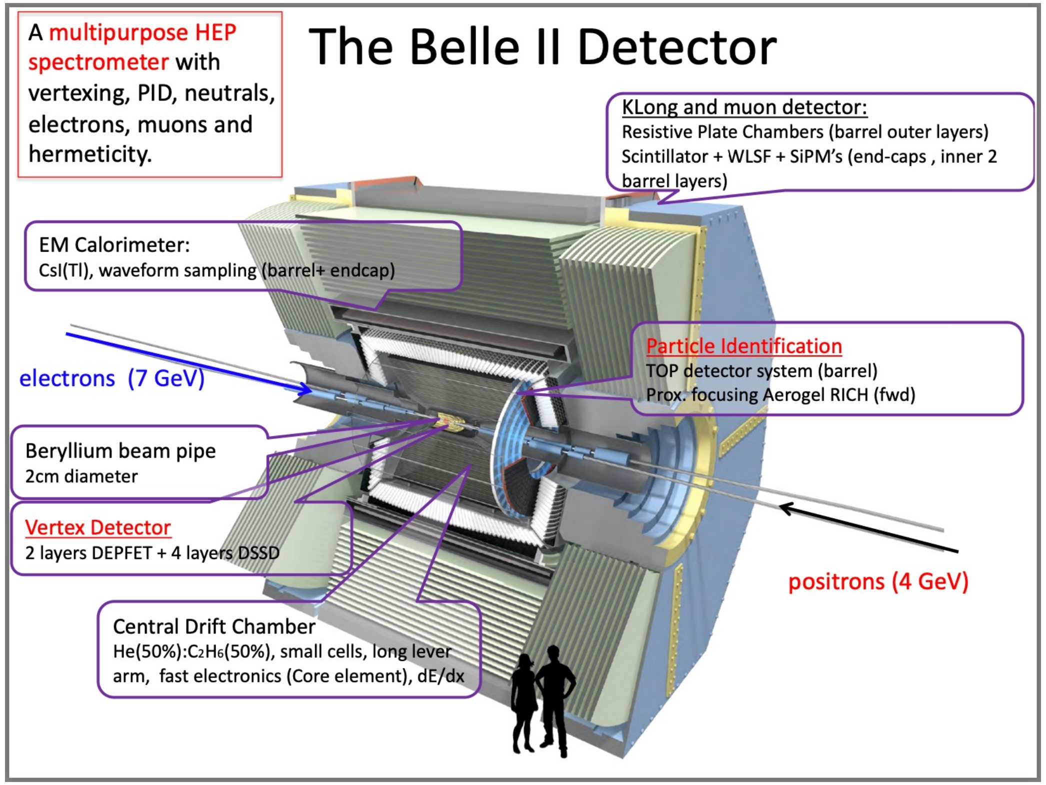
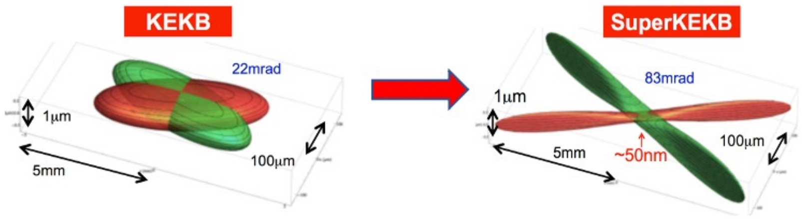
2026年7月22日至27日
第十一届XYZ研讨会，贵州民族大学

SuperKEKB and Belle II





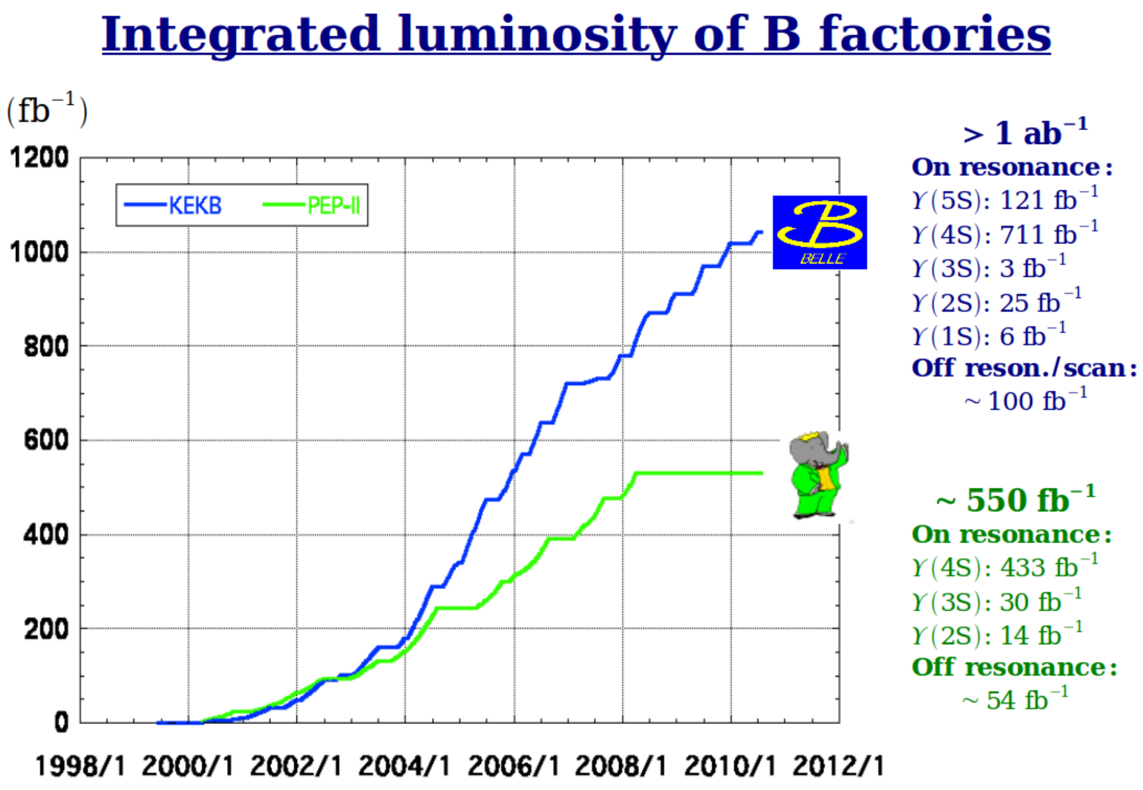
Nano-beam design:



Nano-beam design:
Beam squeezing: ×20 smaller;
Beam current: ×2 larger
Target peak luminosity: KEKB×30

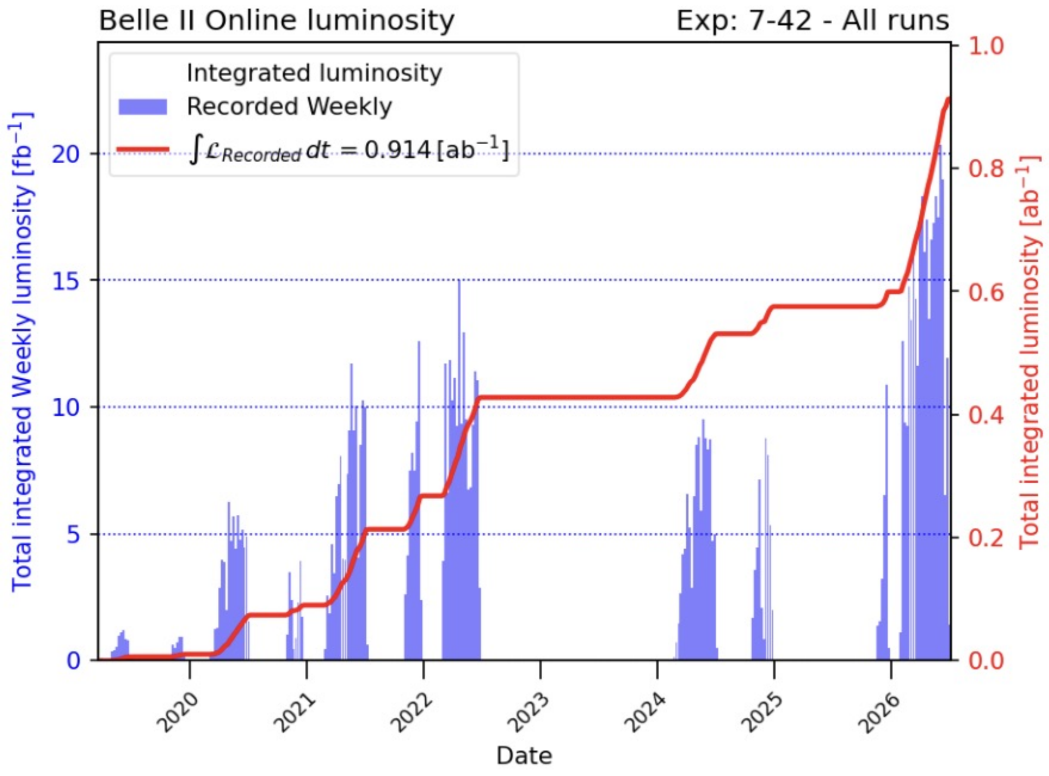
Belle and Belle II Datasets

- **Belle (1999 - 2010)**
- **Belle II RUN-I (2019 - 2023)**
- **Belle II RUN-II (2024 - 2026)**



In March 2026

WORLD RECORD: 5.2×10^{34} cm^{-2}s^{-1}



Most data at or near the $\Upsilon(4S)$ resonance, and 19.6 fb^{-1} near $\Upsilon(10753)$

Outline:

- $X(3872) \to \pi^0 \chi_{cJ}(1P)$
- ISR of $e^+e^- \to h^+h^- J/\psi$ ($h = \pi, K, p$)
- $D^*_{s0}(2317)^+ \to D_s^{*+}\gamma$

Charm / Charmonium spectroscopy

- $e^+e^- \to \Upsilon_J(1D)\eta$ and $e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-$
- $e^+e^- \to \omega\chi_{b1,b2}$ and $e^+e^- \to (\pi^+\pi^-\pi^0)_{non-\omega}\chi_{b1,b2}$
- $e^+e^- \to \eta\Upsilon(1S, 2S)$

Bottomonium spectroscopy

$X(3872) \to \pi^0 \chi_{cJ}(1P)$

[arXiv:2606.24578, submitted to PRL]

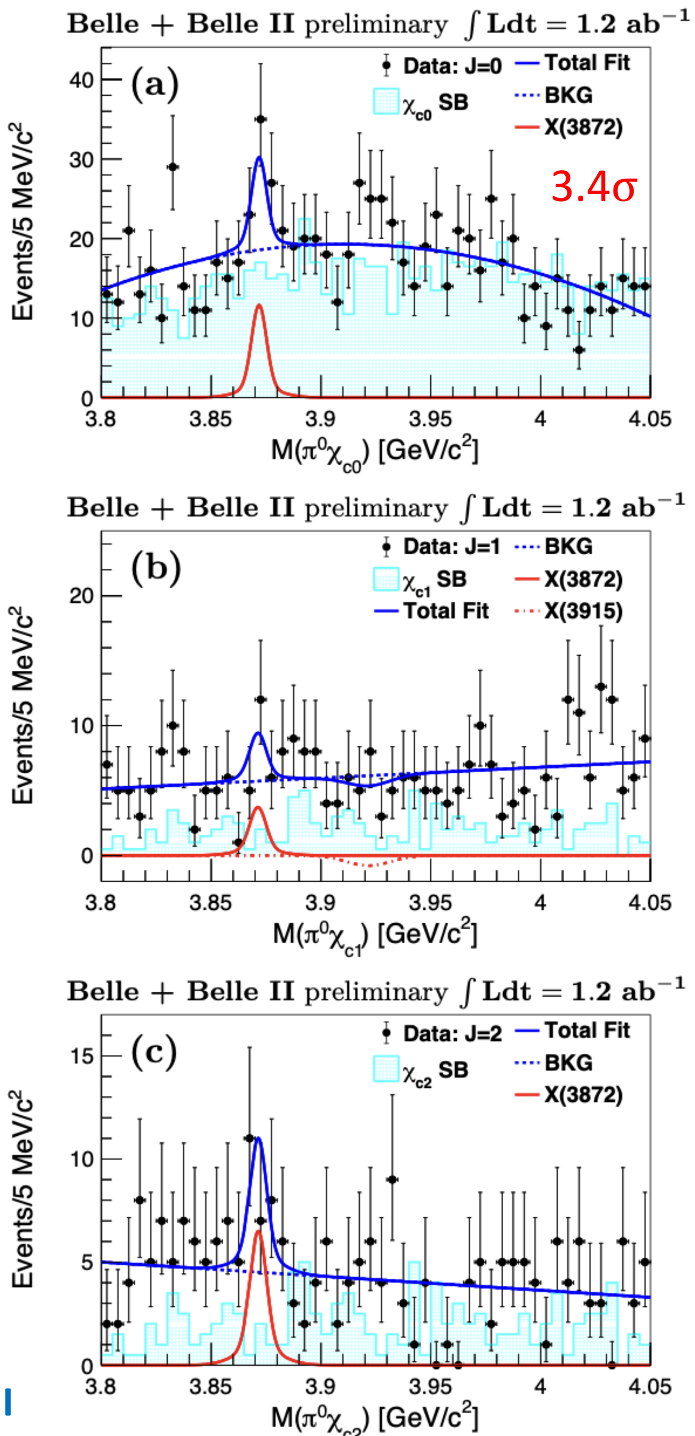
Motivation

- $X(3872)$
  - Observed in $\pi^+\pi^- J/\psi$ by Belle in B^+ decay [PRL 91, 262001 (2003)]
  - Its nature remains unclear
- The pionic transitions $X(3872) \to \pi^0 \chi_{cJ}(1P)$
  - Sensitive to its internal structure [PRD 77, 014013 (2008)].
  - As a charmonium 2^3P_1 state: expected to be weak
    - for example, $\Gamma(2^3P_1 \to \chi_{c1}\pi^0) \sim 0.06$ keV
    - J=0 mode is further suppressed, $\Gamma(2^3P_1 \to \chi_{c0}\pi^0) \sim 0$
    - $\Gamma_0 : \Gamma_1 : \Gamma_2 \sim$0:2.7:1
  - As a four-quark/molecular state: greatly enhanced and exhibit comparable rates
    - $\Gamma_0 : \Gamma_1 : \Gamma_2 \sim$2.88:0.97:1
  - Other theoretical papers also studied these decays and calculated the partial widths, ratios, and rates to $X(3872) \to \pi^+\pi^- J/\psi$ [PRD 78, 094019 (2008)][PRD 79, 094013 (2009)] [PRD 100, 094025 (2019)] [EPJC 81, 193(2021)]
- BESIII ever observed the $X(3872) \to \pi^0 \chi_{c1}$ [PRL 122, 202001 (2019)], but Belle did not [PRD 99, 111101 (2019)]. No signals for $X(3872) \to \pi^0 \chi_{c0,c2}$ in experiments [PRD 105, 072009 (2022)].

Fit to data

- $\chi_{c1,2} \to \gamma J/\psi(\ell^+\ell^-)$
- $\chi_{c0} \to \pi^+\pi^-/K^+K^-/K^+K^-K^+K^-$

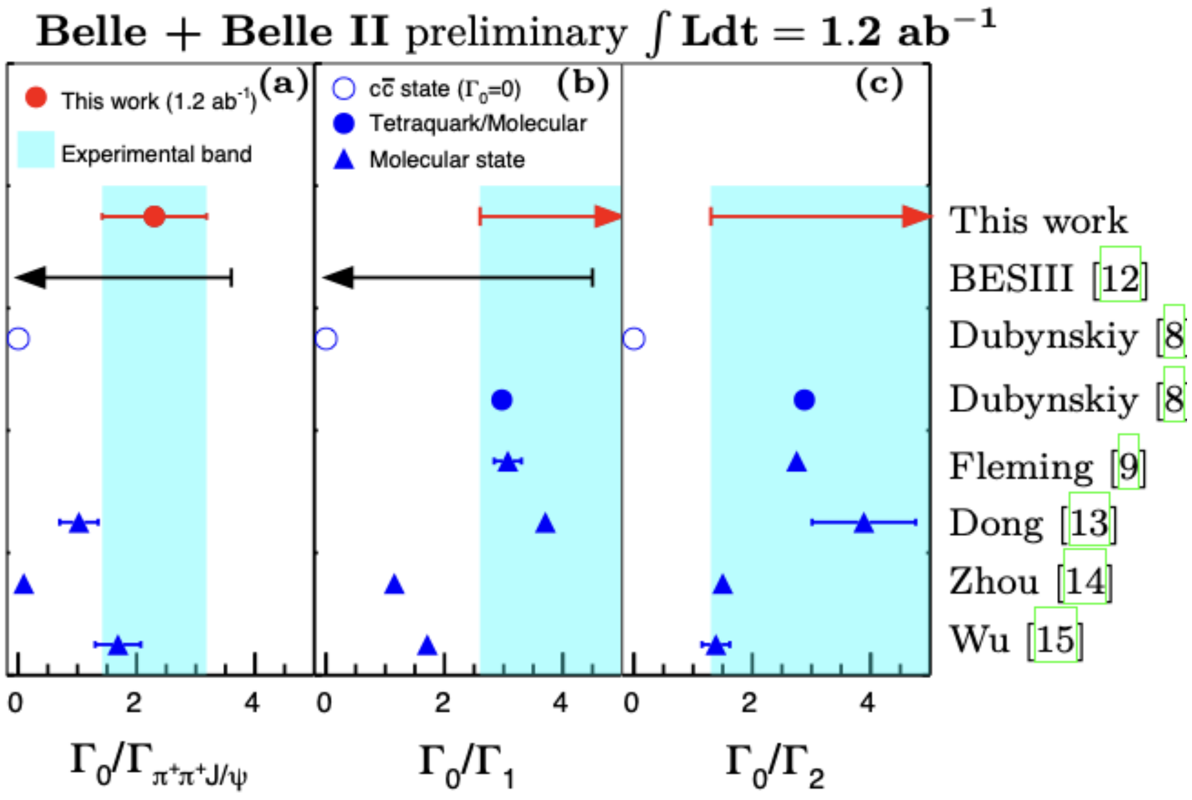
- Fit strategy: For each χ_{cJ}, unbinned simultaneous fit to all $M(\pi^0\chi_{cJ})$ spectra from different reconstruction mode in Belle and Belle II
  - For each spectrum, Signal shapes: fixed to signal MC
  - Yield: Relative signal yield to total one is fixed as expected
  - Backgrounds: 2nd order polynomial for χ_{c0}, straight line for $\chi_{c1,c2}$
- Fit results
  - First evidence of $X(3872) \to \pi^0\chi_{c0}$: 23.7±8.1 events, statistical significance 3.6σ, systematic significance 3.4σ
  - Total yield of $X(3872) \to \pi^0\chi_{cJ}$: 46.7±11.5 events, significances of 4.3σ (3.9σ)
  - No significant signals for other modes are observed
  - 90% confidence level upper limits: $\int_0^{x^{UL}} \mathcal{L}(x)dx \,/\, \int_0^{+\infty} \mathcal{L}(x)dx = 0.90$
- The fit procedure has been tested using mock data and toyMC methods



Branching fractions

- $\Gamma_J/\Gamma_{\pi\pi J/\psi}$: Importing previous Belle measurement $\mathcal{B}(B^+ \to X(3872)K^+)\times\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) = (8.63 \pm 0.82 \pm 0.52)\times10^{-6}$ [PRD 84, 052004 (2011)]
  - $\Gamma_0/\Gamma_{\pi\pi J/\psi} = 2.3 \pm 0.8 \pm 0.4$, $\Gamma_1/\Gamma_{\pi\pi J/\psi} = 0.3 \pm 0.2 \pm 0.1$, $\Gamma_2/\Gamma_{\pi\pi J/\psi} = 1.0 \pm 0.4 \pm 0.2$
  - 90% CL upper limits: $\Gamma_1/\Gamma_{\pi\pi J/\psi} < 0.9$, $\Gamma_2/\Gamma_{\pi\pi J/\psi} < 1.8$
- $\Gamma_0/\Gamma_1, \Gamma_0/\Gamma_2$: Lower limits at 90% credibility level
  - $\Gamma_0/\Gamma_1 > 2.6$, $\Gamma_0/\Gamma_2 > 1.3$
  - Combined with previous BESIII measurement: $\Gamma_1/\Gamma_{\pi^+\pi^- J/\psi} = 0.88^{+0.33}_{-0.27} \pm 0.10$, we obtain $\Gamma_0/\Gamma_1 = 2.6 \pm 1.5$, where uncertainty combined from statistical and systematic ones in both experiment
- $\mathcal{B}\left(X(3872) \to \pi^0\chi_{cJ}\right)$ determined by importing PDG average $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) = (4.3 \pm 1.4)\%$
  - $\mathcal{B}(X(3872) \to \pi^0\chi_{c0}) = (9.9 \pm 4.8)\%$, uncertainty includes statistical, systematic, and one from PDG BF
  - $\mathcal{B}(X(3872) \to \pi^0\chi_{c1}) < 3.8\%$, $\mathcal{B}(X(3872) \to \pi^0\chi_{c2}) < 7.6\%$, at 90% CL

Results



- A comparison on (a) $\Gamma_0/\Gamma_{\pi^+\pi^- J/\psi}$, (b) Γ_0/Γ_1, (c) Γ_0/Γ_2
- Our result **disfavors a pure charmonium interpretation**
  - $\Gamma(X(3872) \to \pi^0\chi_{c0})$ should be zero as $\chi_{c1}(2P)$
- **Consistent with most of predictions with molecular scenario**
- Absolute BF of $X(3872) \to \pi^0\chi_{c0}$ at $(9.9 \pm 4.8)\%$, might be the largest hidden charm decay mode up to now

[8] Phys. Rev. D 77, 014013 (2008)

[9] Phys. Rev. D 78, 094019 (2008)

[12] Phys. Rev. D 105, 072009 (2022)

[13] Phys. Rev. D 79, 094013 (2009)

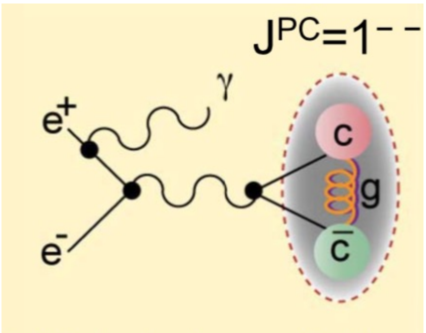
[14] Phys. Rev. D 100, 094025 (2019)

[15] Eur. Phys. J. C 81, 193 (2021)

$e^+e^- \to h^+h^-J/\psi$ (h = π, K, p) via initial-state radiation (ISR) at Belle II

Adavantages of ISR:
- Allows to study energies below $E_{c.m.}$
- Wide energy range available
- Measure more precisely the line-shapes

Disadvantages of ISR:
- The effective integrated luminosity decreases as the c.m. energy decreases
- The detection efficiency is also smaller

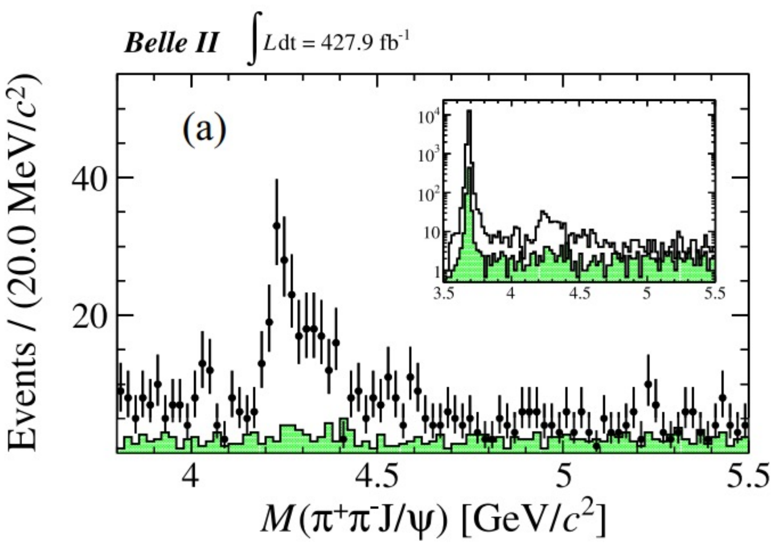


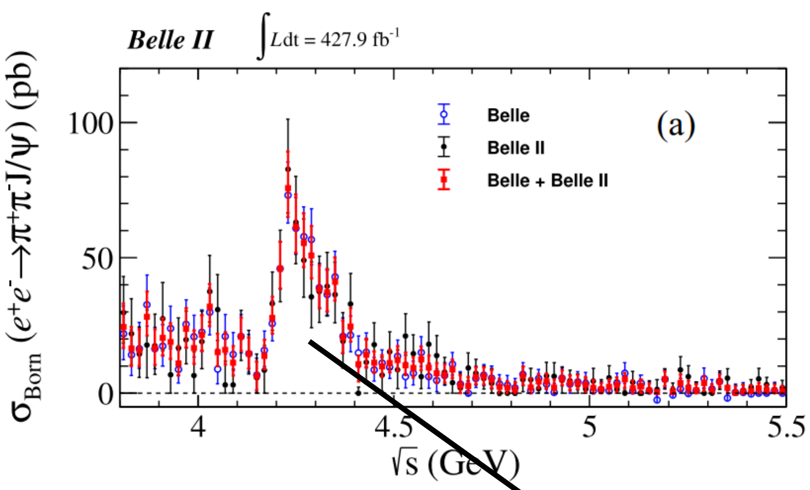
Initial state radiation

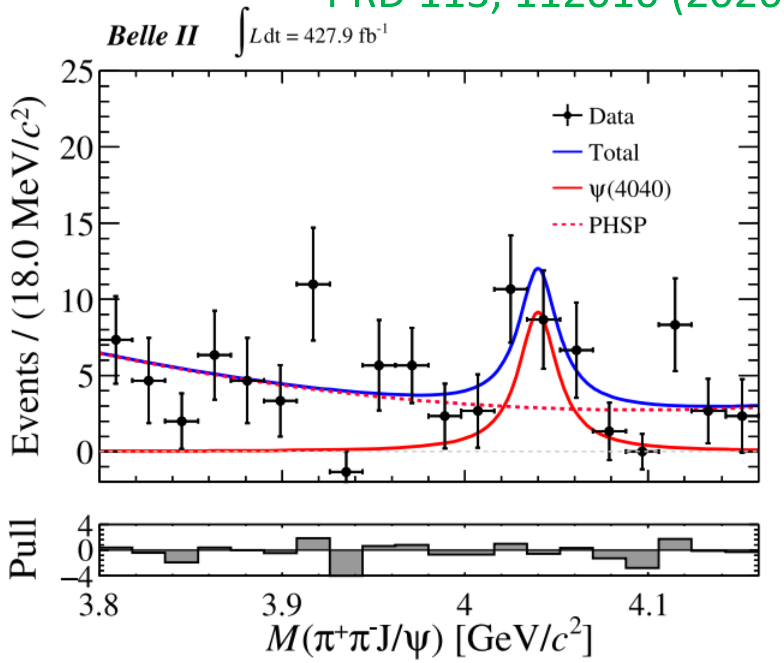
The first ISR result at Belle II!

$e^+e^- \to \pi^+\pi^-J/\psi$ via ISR:

PRD 113, 112010 (2026)







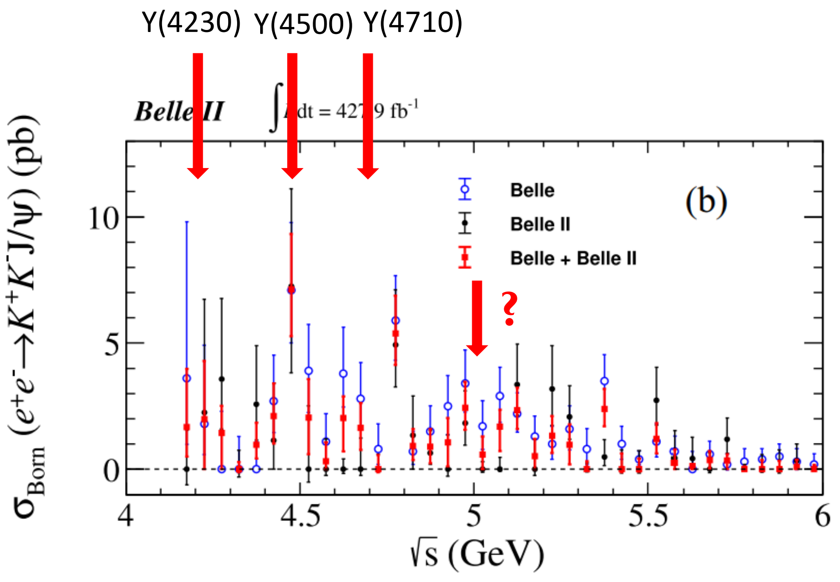
- **We can see the Y(4008) evidence and Y(4260) signal.**
- **The significance of $\psi(4040)$ is 2.0σ.**

There seem to be two peaks (Y(4230) and Y(4320)).

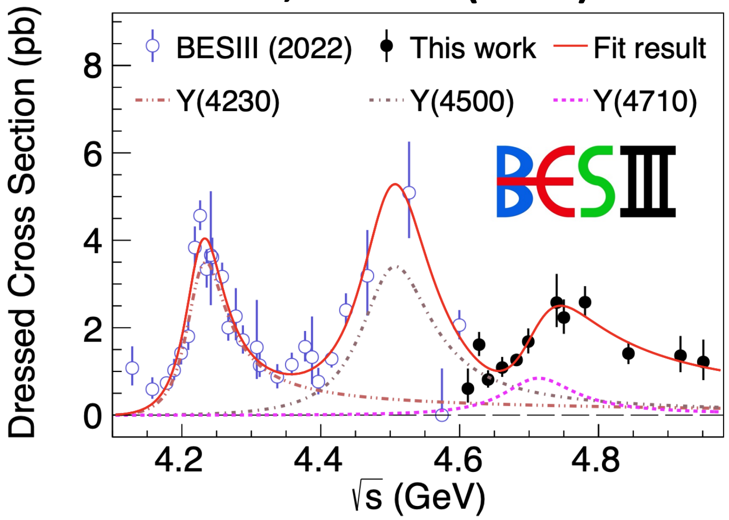
$e^+e^- \to h^+h^-J/\psi$ (h = π, K, p) via initial-state radiation at Belle II

PRD 113, 112010 (2026)

$e^+e^- \to K^+K^-J/\psi$ via ISR:



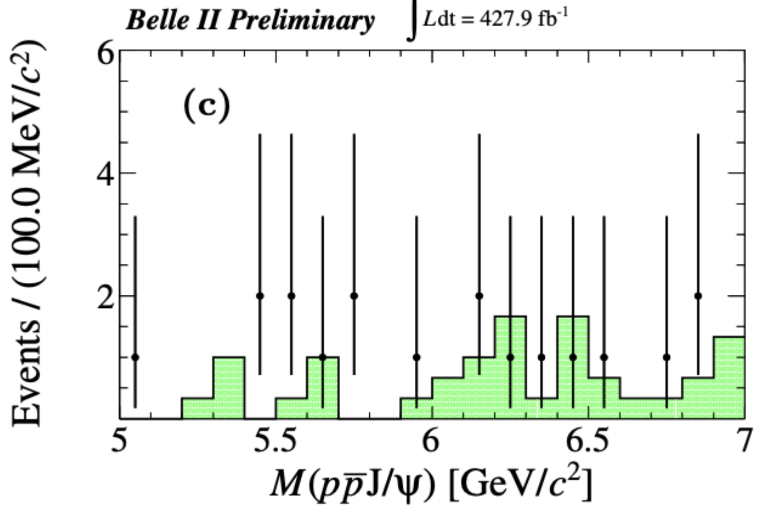
PRL 131, 211902 (2023)

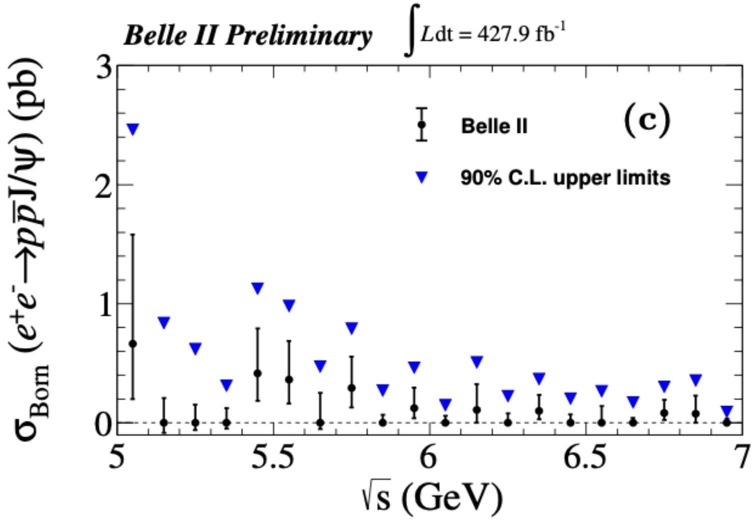


- **No clear signals were observed at Belle II.**
- **More data are needed.**

$e^+e^- \to p\bar{p}J/\psi$ via ISR:

The cross section for $e^+e^- \to P_c\bar{p}$ is estimated to be $\lesssim \mathcal{O}(0.1$ pb) [PLB 872 (2026) 140007].





First observation of $D_{s0}^{*}(2317)^{+} \to D_{s}^{*+}\gamma$

PRL 136, 241901 (2026)

$D_{s0}^{*}(2317)^{\pm}$ **DECAY MODES**

$D_{s0}^{*}(2317)^{-}$ modes are charge conjugates of modes below.

	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$D_s^+ \pi^0$	(100^{+0}_{-20}) %		298
Γ_2	$D_s^+ \gamma$	<5 %	CL=90%	323
Γ_3	$D_s^*(2112)^+ \gamma$	<6 %	CL=90%	
Γ_4	$D_s^+ \gamma\gamma$	<18 %	CL=95%	323
Γ_5	$D_s^*(2112)^+ \pi^0$	<11 %	CL=90%	
Γ_6	$D_s^+ \pi^+ \pi^-$	$< 4 \times 10^{-3}$	CL=90%	194
Γ_7	$D_s^+ \pi^0 \pi^0$	not seen		205

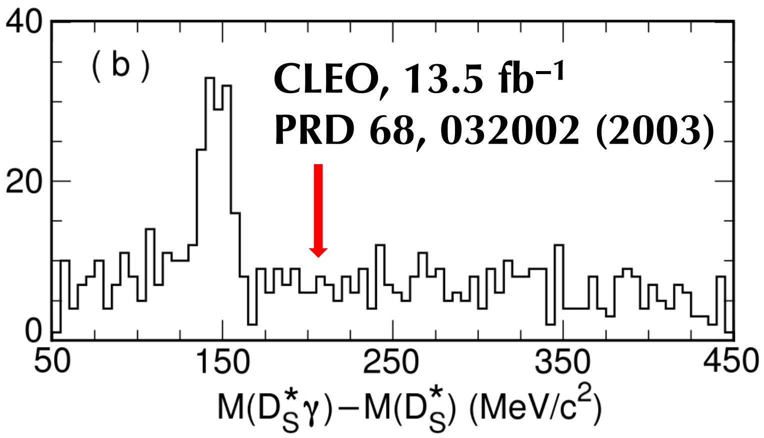
Mass of $D_{s0}^{*}(2317)^{+}$ is much lower than the quark model predictions of the lowest $c\bar{s}$ mesons with $J^P = 0^+$

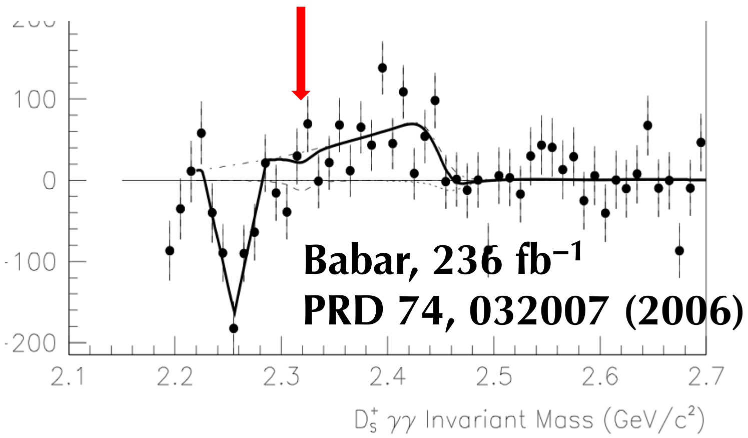
- molecular states
- quark-antiquark configurations
- tetraquark structures
- mixed states

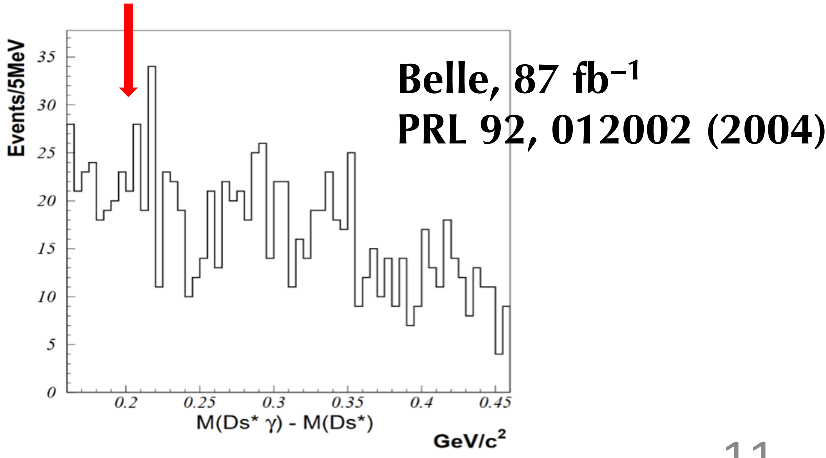
Partial decay widths:
unique in discriminating between various models

The $D_{s0}^{*}(2317)^{+} \to D_s^{+}\pi^0$ was first observed by BaBar in 2006 [PRL 90, 242001 (2003)].

The $D_{s0}^{*}(2317)^{+} \to D_s^{*+}\gamma$ was searched from by CLEO, Belle, and BaBar, but no signals were found.







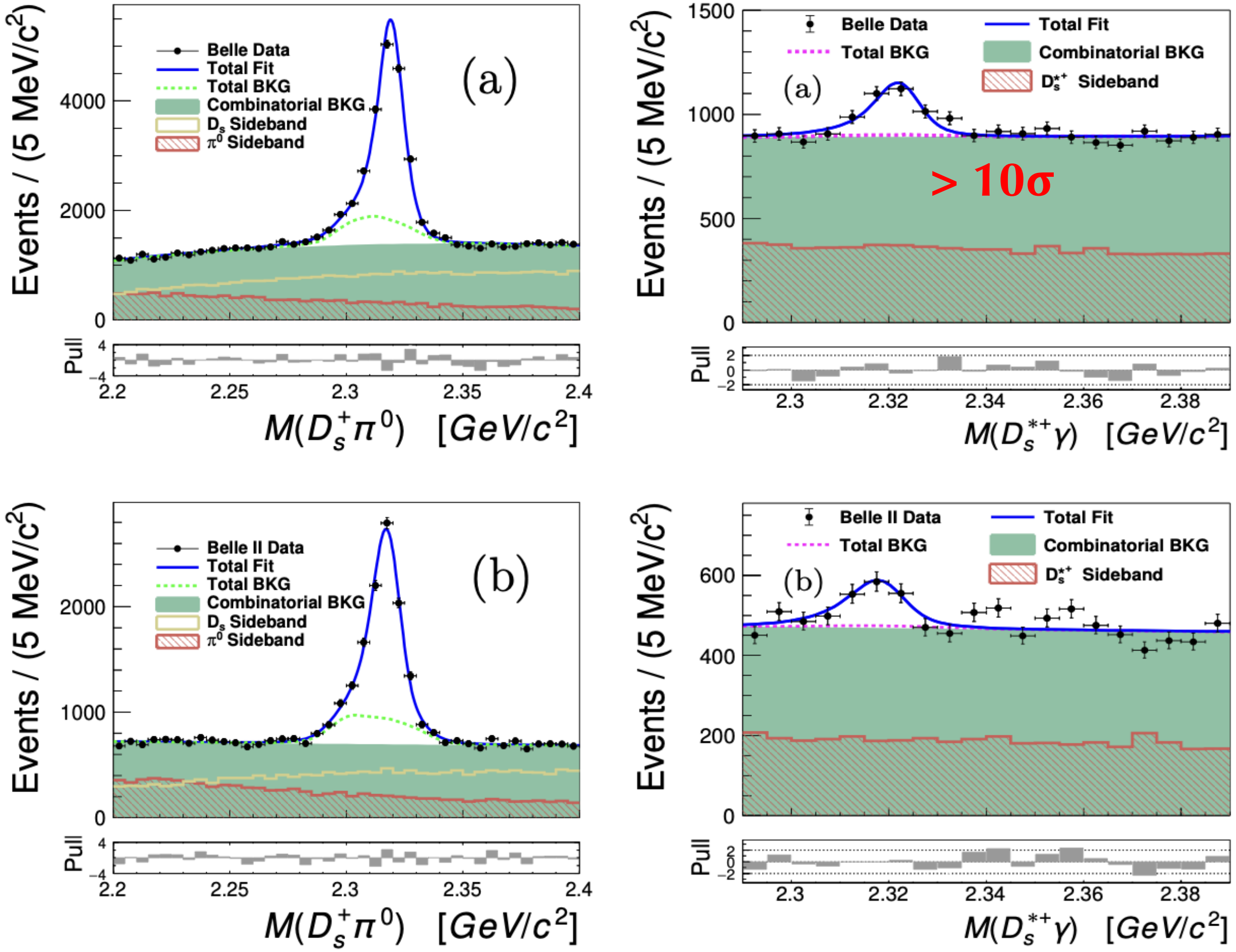
First observation of $D_{s0}^{*}(2317)^{+} \to D_s^{*+}\gamma$

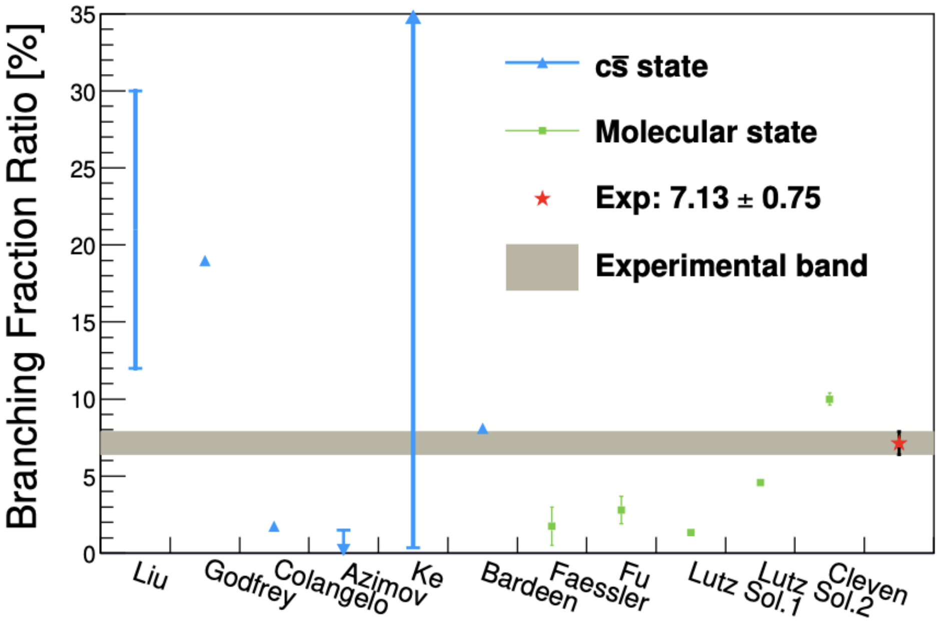
PRL 136, 241901 (2026)

- Target: $D_{s0}^{*}(2317)^{+} \to D_s^{*+}\gamma$
- Control channel: $D_{s0}^{*}(2317)^{+} \to D_s^{+}\pi^{0}$
- Using all Belle data (983 fb^{-1}) and Belle II data (427 fb^{-1})

$$\mathcal{R} = \frac{\mathcal{B}(D_{s0}^{*}(2317)^{+} \to D_s^{*+}\gamma)}{\mathcal{B}(D_{s0}^{*}(2317)^{+} \to D_s^{+}\pi^{0})}$$

$$= [7.14 \pm 0.70(\text{stat.}) \pm 0.23(\text{syst.})]\%$$

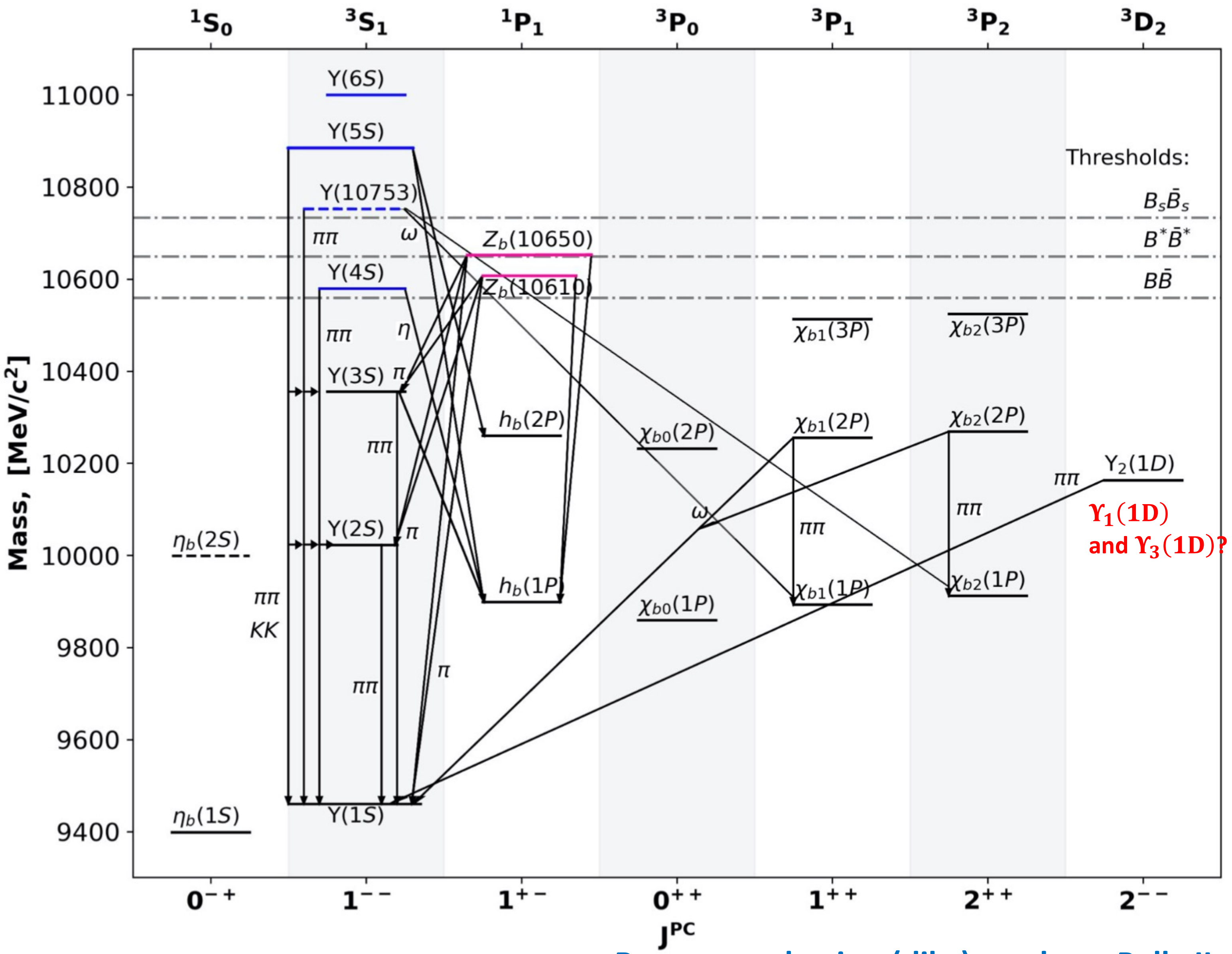




The results provides important inputs to discriminate the nature of the $D_{s0}^{*}(2317)^{+}$.

For more details, please see Yubo's talk "Belle实验DsJ粒子性质研究".

Bottomonium



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

Up to now, only one D-wave bottomonium state, $\Upsilon_2(1D)$, was observed.

In 2019, the Υ(10753) was first observed in $\pi^+\pi^-\Upsilon(nS)$ final states using Belle scan data [JHEP 10, 220 (2019)].

The Υ(10753) was widely interpreted as conventional bottomonium, tetraquark, or hybrid states.

Belle II collected the data of 19.8 fb^{-1} at $\sqrt{s}$ around 10.75 GeV to study the nature of the $\Upsilon(10753)$.

$e^+e^- \to \Upsilon_J(1D)\eta$ and $e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-$

[arXiv:2607.04369, submitted to PRL]

Motivation

- Up to now, only one D-wave bottomonium state, $\Upsilon_2(1D)$, was observed by CLEO and BaBar [PRD 70, 032001 (2004), PRD 82, 111102 (2010)]. The mass of $\Upsilon_2(1D)$ is (10163.7±1.4) MeV/c^2.
- Belle studied $e^+e^- \to \Upsilon_J(1D)\eta$ and $e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-$ at $\sqrt{s}$ = 10.866 GeV in the recoil mass spectra of η and $\pi^+\pi^-$ [EPJC 78, 633 (2018), PRL 108, 032001 (2012)].
- The $\Upsilon_J(1D)$ mass have been predicted by theory. However there are no reported experimental results in the mass differences among $\Upsilon_1(1D)$, $\Upsilon_2(1D)$, and $\Upsilon_3(1D)$.

References	$\Upsilon_1(1D)$ mass (MeV/c^2)	$\Upsilon_2(1D)$ mass (MeV/c^2)	$\Upsilon_3(1D)$ mass (MeV/c^2)
PRD 93, 074027 (2016)	10117	10122	10127
PRD 92, 054034 (2015)	10138	10147	10155
PRD 95, 074002 (2017)	10146	10153	10157
EPJC 78, 915 (2018)	10153	10162	10170

- Within the hadronic loop mechanism, the branching fractions for $\Upsilon(10860,11020) \to \Upsilon_J(1D)\eta$ and $\Upsilon(10860) \to \Upsilon_J(1D)\pi^+\pi^-$ range in magnitude from 10^{-4} to 10^{-3} [PRD 94, 094039 (2016), PRD 97, 094018 (2018), PRD 102, 114037 (2020)].

Dataset used in this work:

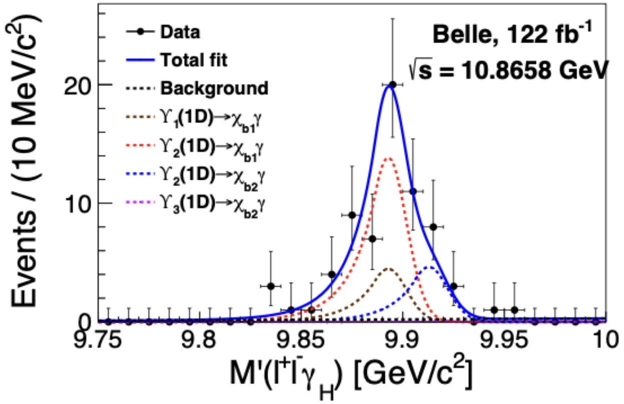
$\sqrt{s}$ (MeV)	$\mathcal{L}$ (fb^{-1})
10731.3	0.946
10771.2	0.955
10829.5	1.697
10848.9	0.989
10857.4	0.988
10865.8	122.0
10877.8	0.978
10882.8	1.848
10888.9	0.990
10898.3	2.408
10907.3	0.980
10928.7	1.149
10957.5	0.969
10975.3	0.999
10990.4	0.985
11003.9	0.976
11014.8	0.771
11018.5	0.859
11020.8	0.982

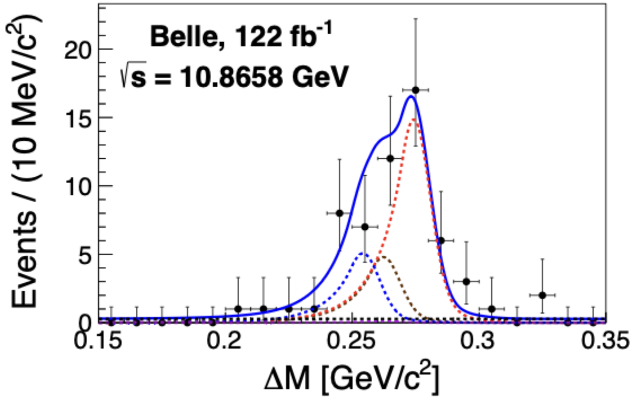
First evidences for $\Upsilon_1(1D)$ and $\Upsilon_3(1D)$

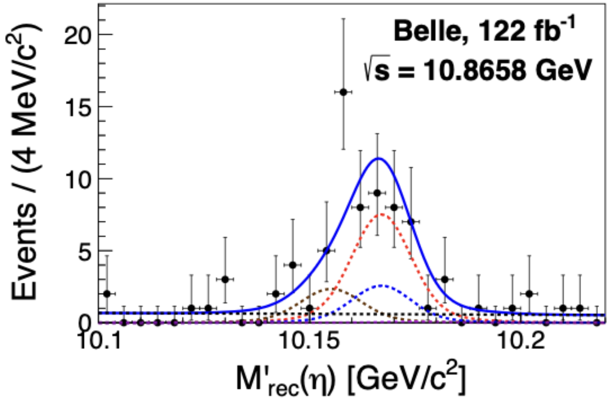
$\Upsilon_J(1D) \to \chi_{b1,b2}\gamma_L$,
$\chi_{b1,b2} \to \Upsilon(1S)\gamma_H$,
$\Upsilon(1S) \to \ell^+\ell^-$

$e^+e^- \to \Upsilon_J(1D)\eta$

Three-dimensional fit results

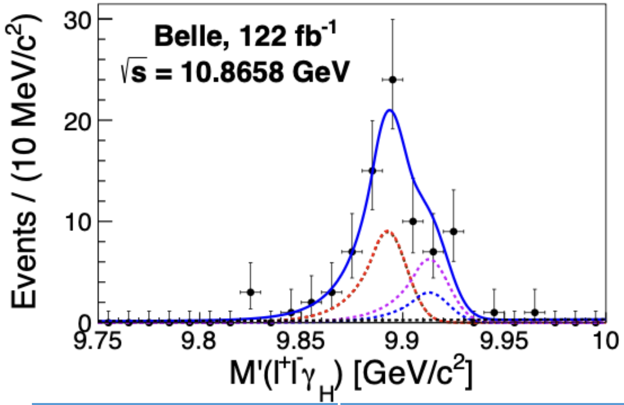


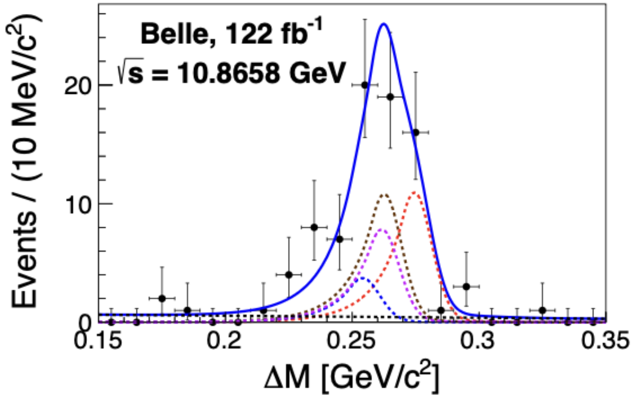


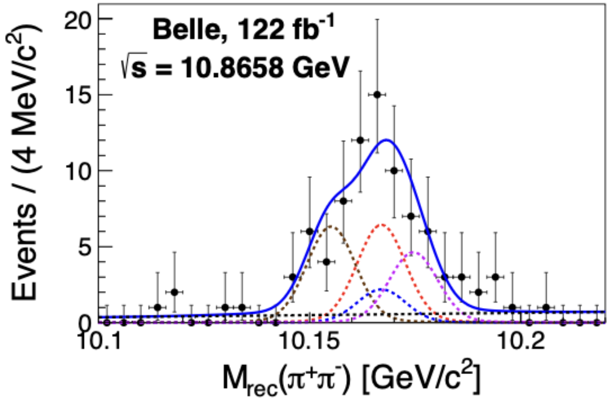


$e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-$

$\Delta M = M(\ell^+\ell^-\gamma_H\gamma_L) - M(\ell^+\ell^-\gamma_H)$







$\Upsilon_2(1D)$ mass
$(10167.0\pm1.0\pm0.2)$ MeV/c^2
$\Delta m_{21} = m(\Upsilon_2(1D)) - m(\Upsilon_1(1D))$
$(11.8\pm1.5\pm0.4)$ MeV/c^2
$\Delta m_{32} = m(\Upsilon_3(1D)) - m(\Upsilon_2(1D))$
$(7.6\pm2.4\pm0.6)$ MeV/c^2

The systematic uncertainty is calculated by changing the fit models.

Channel	N^{sig} $(e^+e^- \to \Upsilon_J(1D)\eta)$	N^{sig} $(e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-)$	$\Sigma_{stat.}$ $(\Sigma_{syst.})$
$\Upsilon_1(1D) \to \chi_{b1}\gamma$	12.2±6.3	24.7±6.5	5.1σ (4.8σ)
$\Upsilon_2(1D) \to \chi_{b1}\gamma$	37.8±8.0	25.0±6.7	>10σ (>10σ)
$\Upsilon_2(1D) \to \chi_{b2}\gamma$	12.9±6.0	8.5±4.2	
$\Upsilon_3(1D) \to \chi_{b2}\gamma$	0.3±2.8	17.9±6.7	3.1σ (3.0σ)

From the fit:

$$\frac{\mathcal{B}(\Upsilon_2(1D)\to\chi_{b2}\gamma)}{\mathcal{B}(\Upsilon_2(1D)\to\chi_{b1}\gamma)} = 0.66\pm0.27\pm0.15$$

Consistent with the prediction of ≈0.3 in PRD 92, 054034 (2015).

Born cross sections and branching fractions at $\sqrt{s}$ = 10.866 GeV

$$\sigma^{(1)}_{\rm Born} = \sigma_{\rm Born}(e^+e^- \to \Upsilon_J(1D)\eta)\,\mathcal{B}(\Upsilon_J(1D) \to \chi_{b1,b2}\gamma) = \frac{N^{\rm sig}\,|1-\Pi|^2}{\mathcal{L}\,\sum_{i=1}^{2} \varepsilon_i \mathcal{B}_i^{\rm int}\,(1+\delta_{\rm ISR})}$$

$$\mathcal{B}^{(1)}_{\Upsilon(10860)} = \mathcal{B}(\Upsilon(10860) \to \Upsilon_J(1D)\eta)\,\mathcal{B}(\Upsilon_J(1D) \to \chi_{b1,b2}\gamma) = \frac{N^{\rm sig}}{N_{\Upsilon(10860)}\,\sum_{i=1}^{2} \varepsilon_i \mathcal{B}_i^{\rm int}}$$

$$\sigma^{(2)}_{\rm Born} = \sigma_{\rm Born}(e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-)\,\mathcal{B}(\Upsilon_J(1D) \to \chi_{b1,b2}\gamma) = \frac{N^{\rm sig}\,|1-\Pi|^2}{\mathcal{L}\,\varepsilon\,\mathcal{B}^{\rm int}\,(1+\delta_{\rm ISR})}$$

$$\mathcal{B}^{(2)}_{\Upsilon(10860)} = \mathcal{B}(\Upsilon(10860) \to \Upsilon_J(1D)\pi^+\pi^-)\,\mathcal{B}(\Upsilon_J(1D) \to \chi_{b1,b2}\gamma) = \frac{N^{\rm sig}}{N_{\Upsilon(10860)}\,\varepsilon\,\mathcal{B}^{\rm int}}$$

Here, i = 1 represents $\eta \to \gamma\gamma$; and i = 2 represents $\eta \to \pi^+\pi^-\pi^0$.

- To calculate the radiative correction factor, we assume the dressed cross section measured in this work.
- $N_{\Upsilon(10860)} = \mathcal{L}\sigma(e^+e^- \to b\bar{b})$ = $(4.2\pm0.2)\times10^7$ [PRL 113, 142001 (2014)]

Channel	$\varepsilon_{\eta\to\gamma\gamma,\eta\to\pi^+\pi^-\pi^0}$	$N^{\rm sig}$	$\mathcal{B}^{(1)}_{\Upsilon(10860)}(\times10^{-3})$	$\sigma^{(1)}_{\rm Born}$(pb)
$e^+e^- \to \Upsilon_1(1D)\eta,\ \Upsilon_1(1D) \to \chi_{b1}\gamma$	0.102, 0.041	12.2 ± 6.3	$0.34\pm0.18\pm0.06$	$0.17\pm0.09\pm0.03$
$e^+e^- \to \Upsilon_2(1D)\eta,\ \Upsilon_2(1D) \to \chi_{b1}\gamma$	0.103, 0.042	37.8 ± 8.0	$1.05\pm0.22\pm0.12$	$0.52\pm0.11\pm0.06$
$e^+e^- \to \Upsilon_2(1D)\eta,\ \Upsilon_2(1D) \to \chi_{b2}\gamma$	0.103, 0.042	12.9 ± 6.0	$0.70\pm0.33\pm0.18$	$0.34\pm0.17\pm0.09$
$e^+e^- \to \Upsilon_3(1D)\eta,\ \Upsilon_3(1D) \to \chi_{b2}\gamma$	0.104, 0.043	0.3 ± 2.8	$0.02\pm0.15\pm0.02$	$0.01\pm0.07\pm0.01$
Channel	$\varepsilon_{\pi^+\pi^-}$	$N^{\rm sig}$	$\mathcal{B}^{(2)}_{\Upsilon(10860)}(\times10^{-3})$	$\sigma^{(2)}_{\rm Born}$(pb)
$e^+e^- \to \Upsilon_1(1D)\pi^+\pi^-,\ \Upsilon_1(1D) \to \chi_{b1}\gamma$	0.177	24.7 ± 6.5	$0.19\pm0.05\pm0.03$	$0.09\pm0.02\pm0.01$
$e^+e^- \to \Upsilon_2(1D)\pi^+\pi^-,\ \Upsilon_2(1D) \to \chi_{b1}\gamma$	0.180	25.0 ± 6.7	$0.19\pm0.06\pm0.03$	$0.09\pm0.03\pm0.01$
$e^+e^- \to \Upsilon_2(1D)\pi^+\pi^-,\ \Upsilon_2(1D) \to \chi_{b2}\gamma$	0.181	8.5 ± 4.2	$0.13\pm0.06\pm0.04$	$0.06\pm0.03\pm0.02$
$e^+e^- \to \Upsilon_3(1D)\pi^+\pi^-,\ \Upsilon_3(1D) \to \chi_{b2}\gamma$	0.182	17.9 ± 6.7	$0.27\pm0.09\pm0.03$	$0.13\pm0.05\pm0.02$

The dressed cross sections as a function of C.M. energy:

We combine the $\Upsilon_1(1D)$, $\Upsilon_2(1D)$, and $\Upsilon_3(1D)$ states due to significant cross feeds among them.

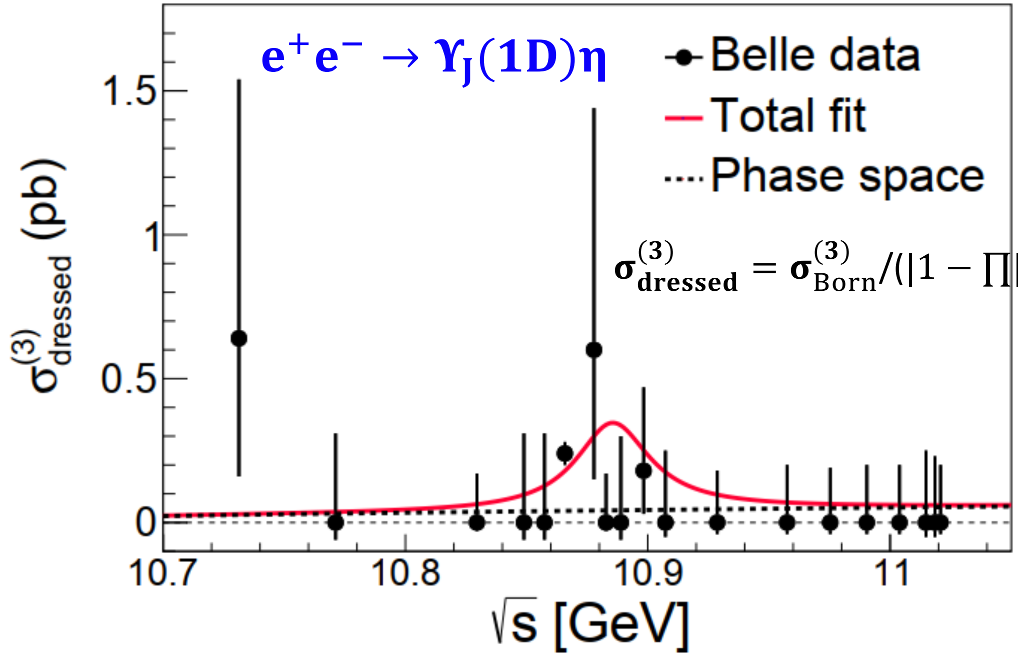
$$\sigma^{(3)}_{\rm Born} = \sigma_{\rm Born}(e^+e^- \to \Upsilon_J(1D)\eta)\,\mathcal{B}(\Upsilon_J(1D) \to \chi_{b1,b2}\gamma)\,\mathcal{B}(\chi_{b1,b2} \to \Upsilon(1S)\gamma)$$

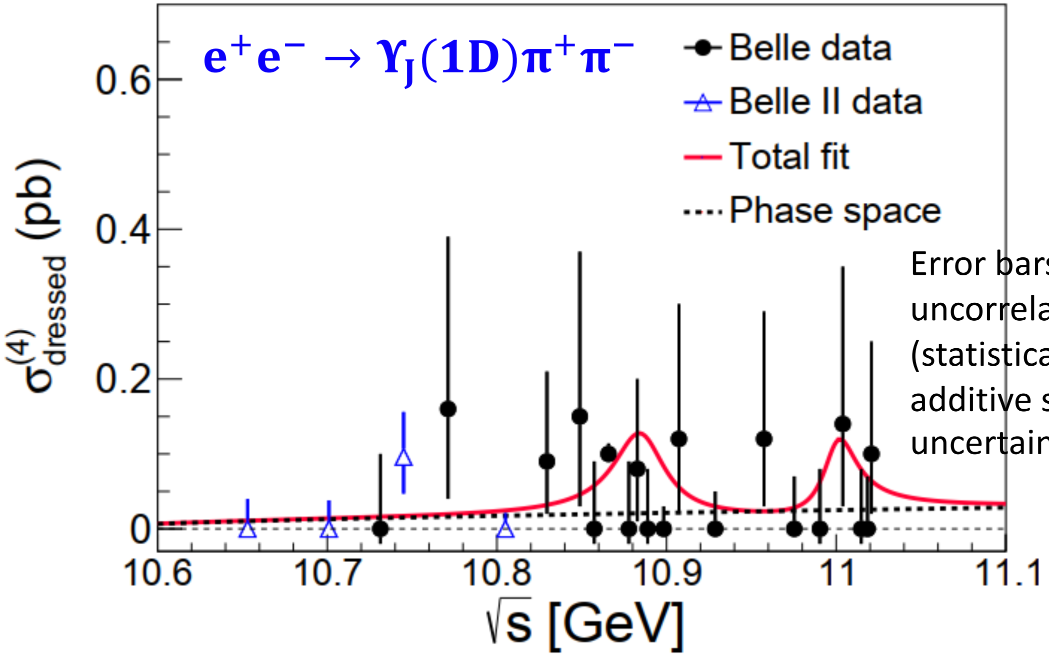
$$\sigma^{(4)}_{\rm Born} = \sigma_{\rm Born}(e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-)\,\mathcal{B}(\Upsilon_J(1D) \to \chi_{b1,b2}\gamma)\,\mathcal{B}(\chi_{b1,b2} \to \Upsilon(1S)\gamma)$$

The fit function as below

$$\left|\sum_{i=1}^{2} \frac{\sqrt{12\pi\Gamma_{ee,i}\mathcal{B}_i\Gamma_i}}{s - M_i^2 - iM_i\Gamma_i}\sqrt{\frac{\Phi(\sqrt{s})}{\Phi(M_i)}}e^{i\phi}\right|^2 + c_{\rm NR}\Phi(\sqrt{s})$$

2 BWs + phase-space





Error bars represent the total uncorrelated uncertainties (statistical uncertainty + additive systematic uncertainty).

The signal significances of fit outputs are less than 3σ, the upper limits at 90% C.L. are also given in square brackets.

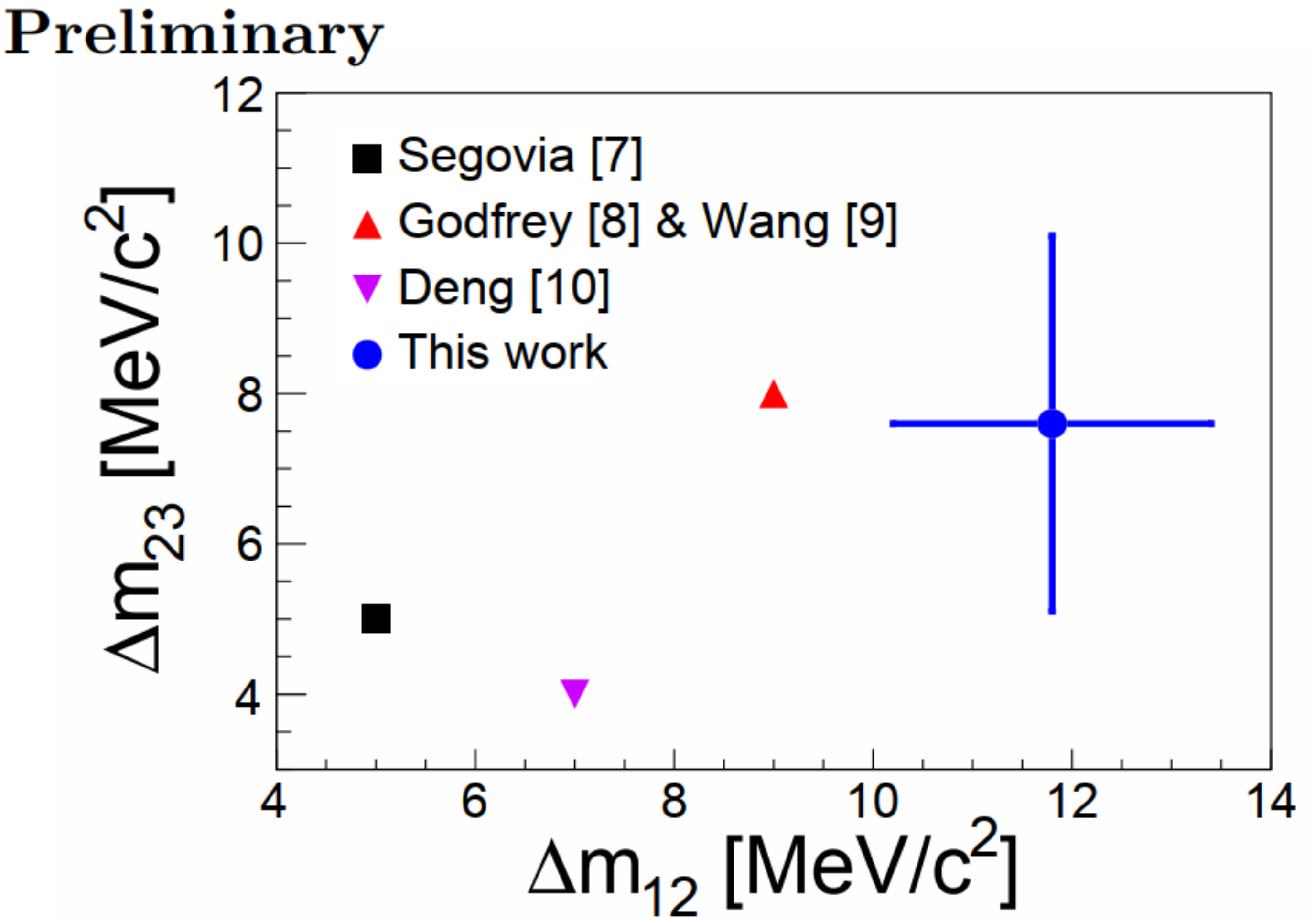
$\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to \Upsilon_J(1D)\eta)\mathcal{B}_f$	$(0.091 \pm 0.039 \pm 0.016)$	$[< 0.14]$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to \Upsilon_J(1D)\eta)\mathcal{B}_f$	$(0.000 \pm 0.018 \pm 0.005)$	$[< 0.04]$
$\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to \Upsilon_J(1D)\pi^+\pi^-)\mathcal{B}_f$	$(0.034 \pm 0.013 \pm 0.006)$	$[< 0.06]$
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to \Upsilon_J(1D)\pi^+\pi^-)\mathcal{B}_f$	$(0.020 \pm 0.016 \pm 0.005)$	$[< 0.05]$

$\mathcal{B}_f = \mathcal{B}(\Upsilon_J(1D) \to \chi_{b1,b2}\gamma)\mathcal{B}(\chi_{b1,b2} \to \Upsilon(1S)\gamma)$

- The dots show the dressed cross sections measured in this work.
- The triangles show the dressed cross sections for $e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-$ at Belle II [JHEP 06 (2026) 278].

The comparison of mass splittings Δm_{12} and Δm_{23} with different theoretical predictions.

[arXiv:2607.04369]



Segovia [7]: nonrelativistic constituent quark model [PRD 93, 074027 (2016)]

Godfrey [8]: relativistic quark model [PRD 92, 054034 (2015)]

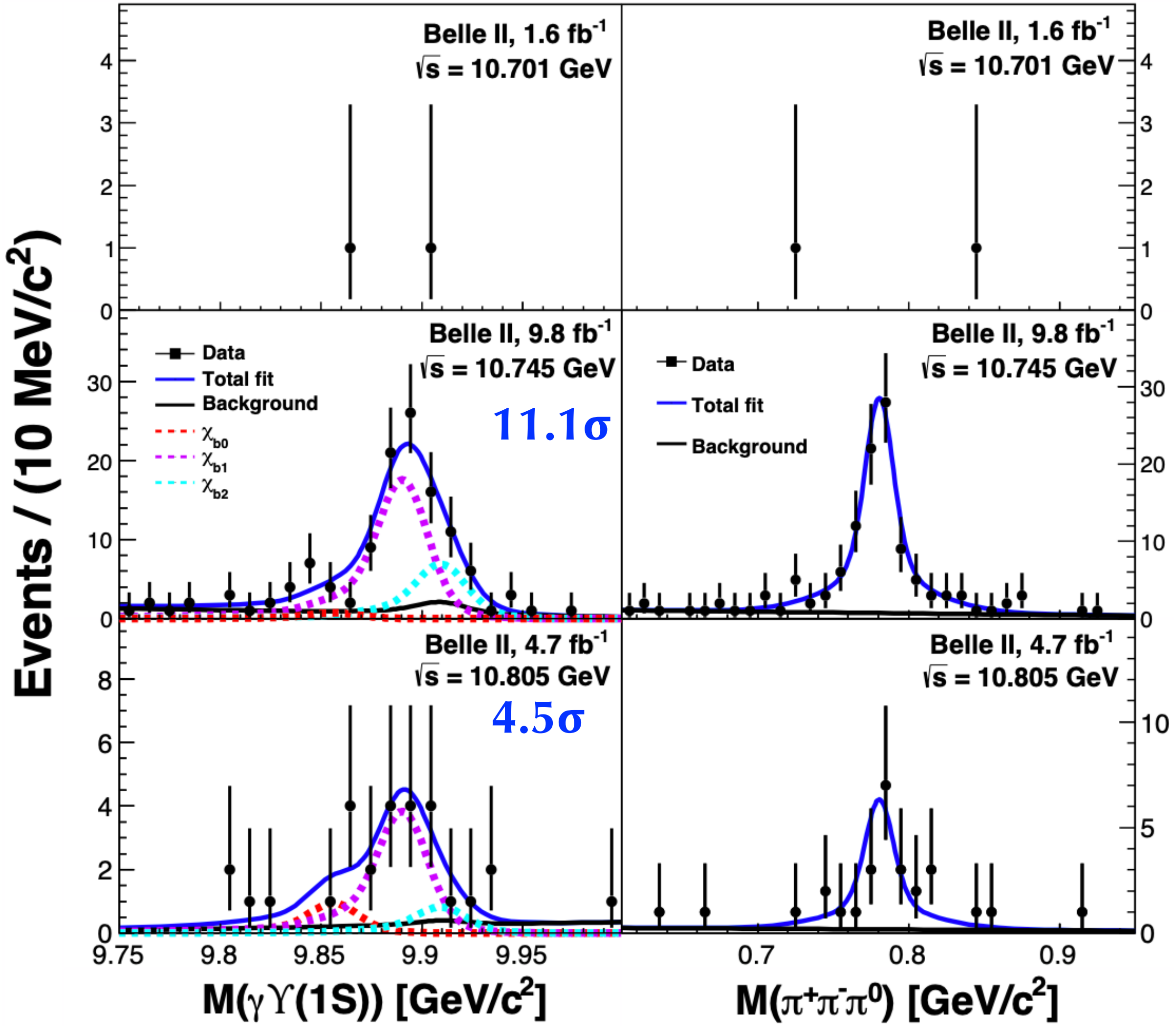
Wang [9]: modified relativistic quark model with a screening effect [EPJC 78, 915 (2018)]

Deng [10]: screened potential model [PRD 95, 074002 (2017)]

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

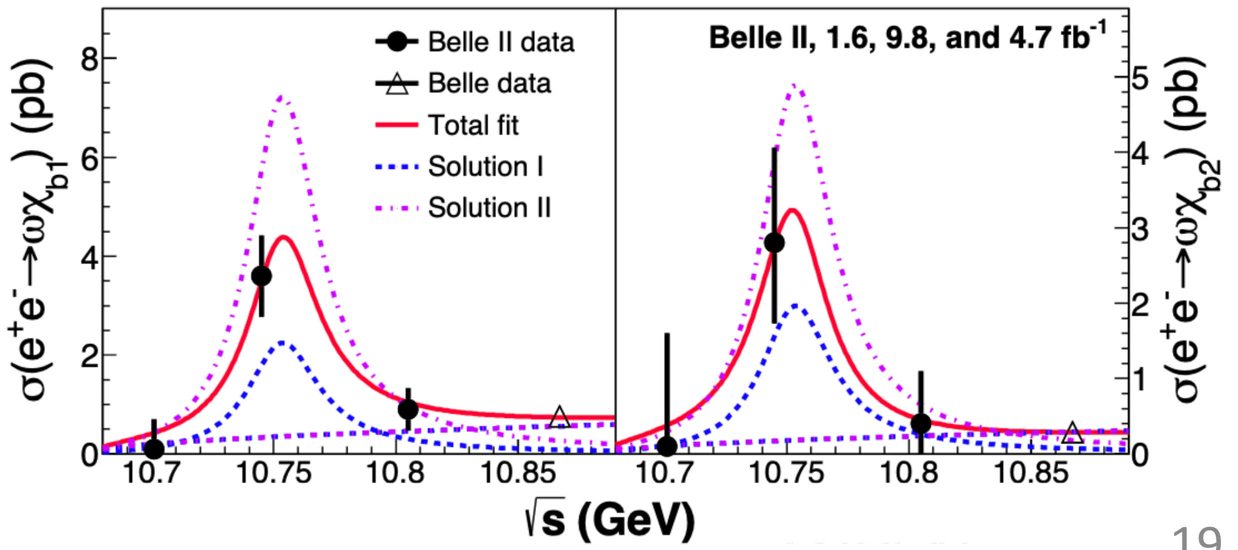
PRL 130, 091902 (2023)

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.

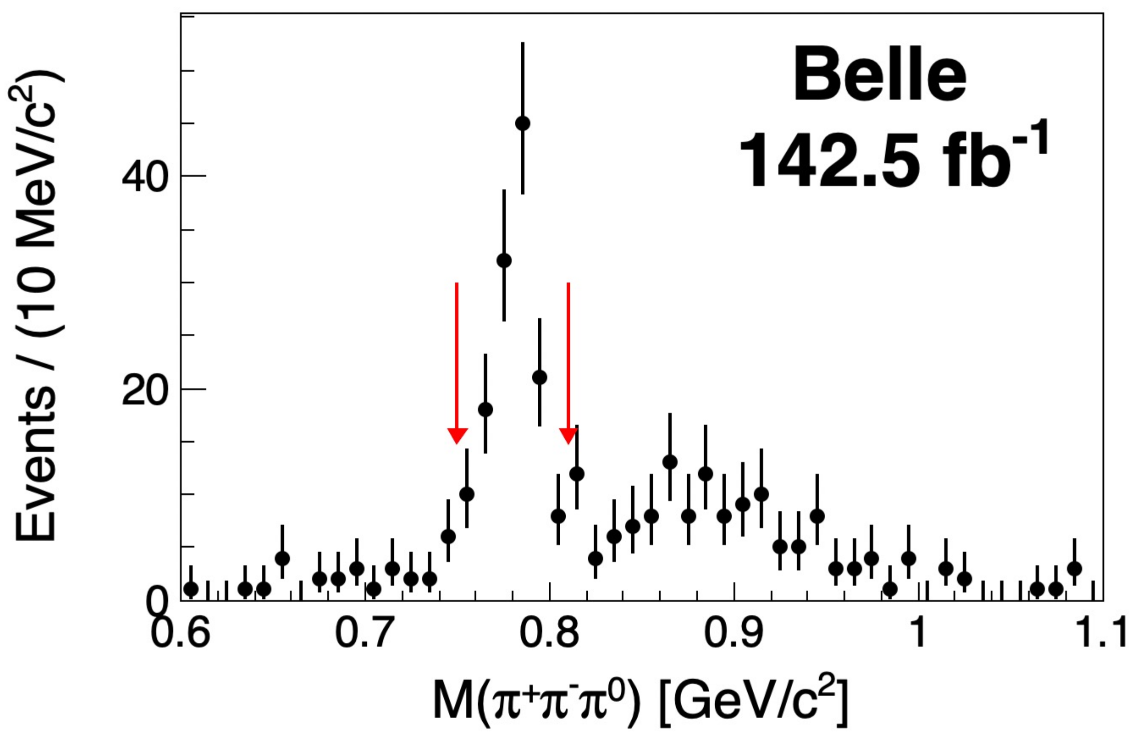
The $e^+e^- \to \omega\chi_{bJ}$ (J = 1, 2) cross sections peak at $\Upsilon(10753)$.



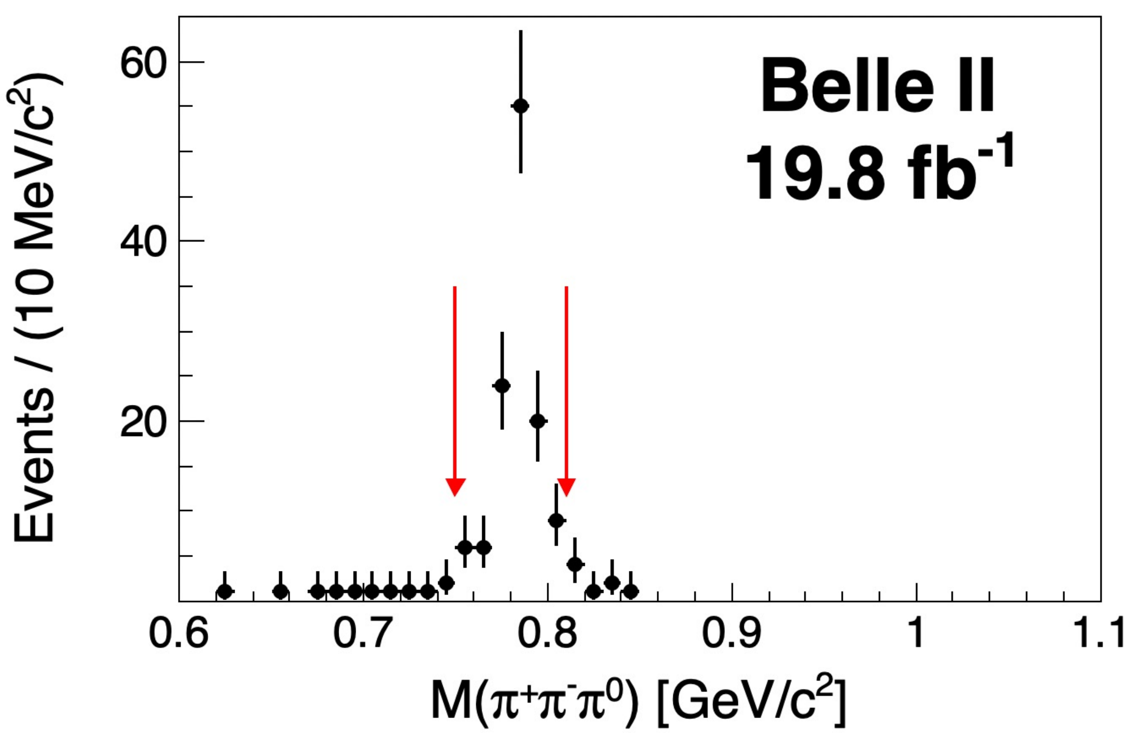
$e^+e^- \to \omega\chi_{bJ}$ and $e^+e^- \to (\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}$ at Belle and Belle II

JHEP 04 (2026) 101

$\sqrt{s} \in [10.73, 11.02]$ GeV



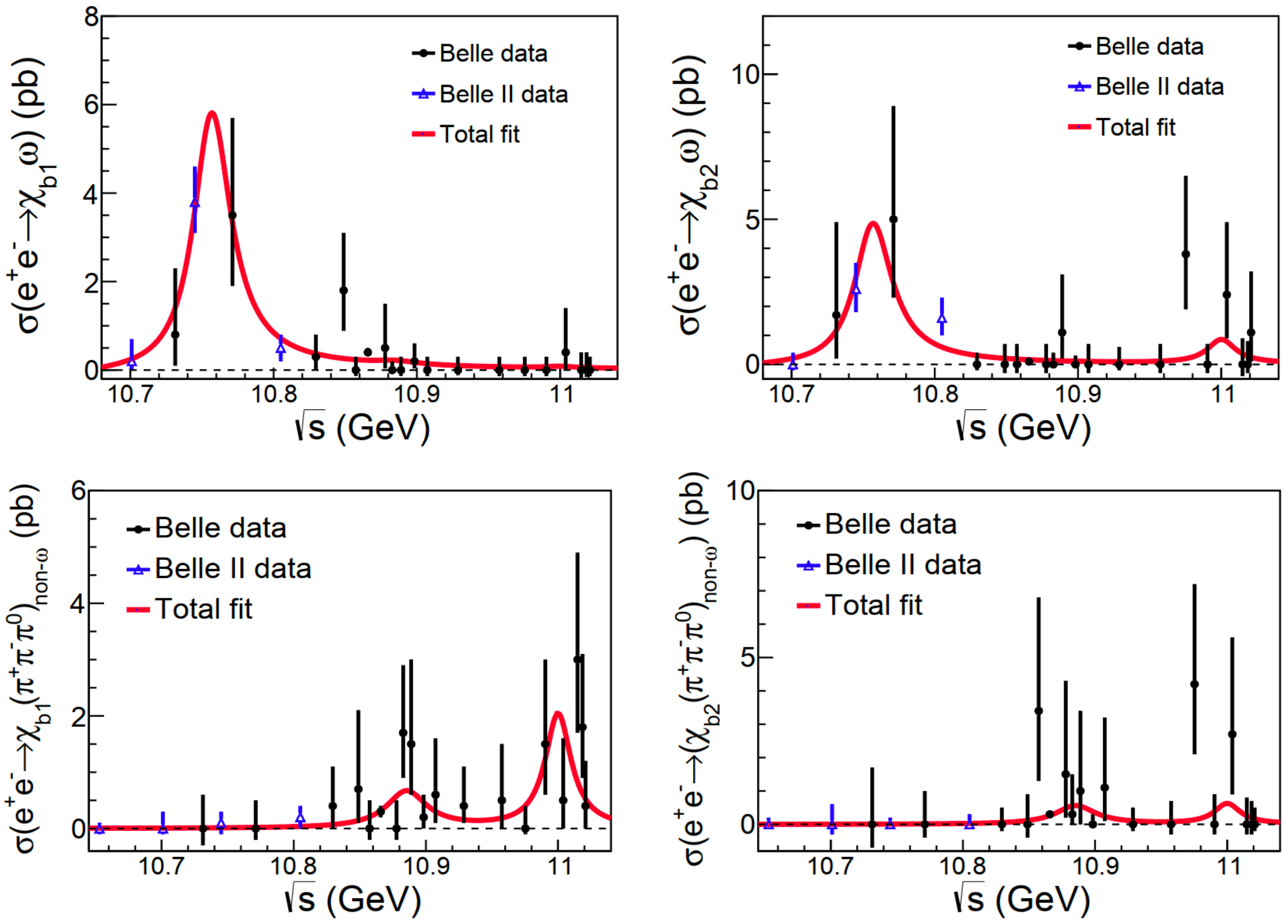
$\sqrt{s} \sim 10.75$ GeV



- In addition to ω signal candidates, there are some events from non-ω decays at Belle.
- We require $M(\pi^+\pi^-\pi^0) < 0.75$ GeV/c^2 and $M(\pi^+\pi^-\pi^0) > 0.81$ GeV/c^2 to select non-ω events.

$e^+e^- \to \omega\chi_{bJ}$ and $e^+e^- \to (\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}$ at Belle and Belle II

JHEP 04 (2026) 101



$\Upsilon(10753)$ mass	(10756.1 ± 4.3) MeV/c^2
$\Upsilon(10753)$ width	(32.2 ± 18.7) MeV

- The mass and width are consistent with those from $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ measuremnt [JHEP 07, 116 (2024)].

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

1.5 at $\sqrt{s}\sim 10.75$ GeV   0.15 at $\sqrt{s}\sim 10.867$ GeV

This may indicate the difference in the internal structures of $\Upsilon(10753)$ and $\Upsilon(10860)$.

$\mathcal{B}(\Upsilon(10753)\to\chi_{b1}\,\omega)/\mathcal{B}(\Upsilon(10753)\to\chi_{b2}\,\omega)$

$\Downarrow$

$1.13\pm0.38\pm0.34$

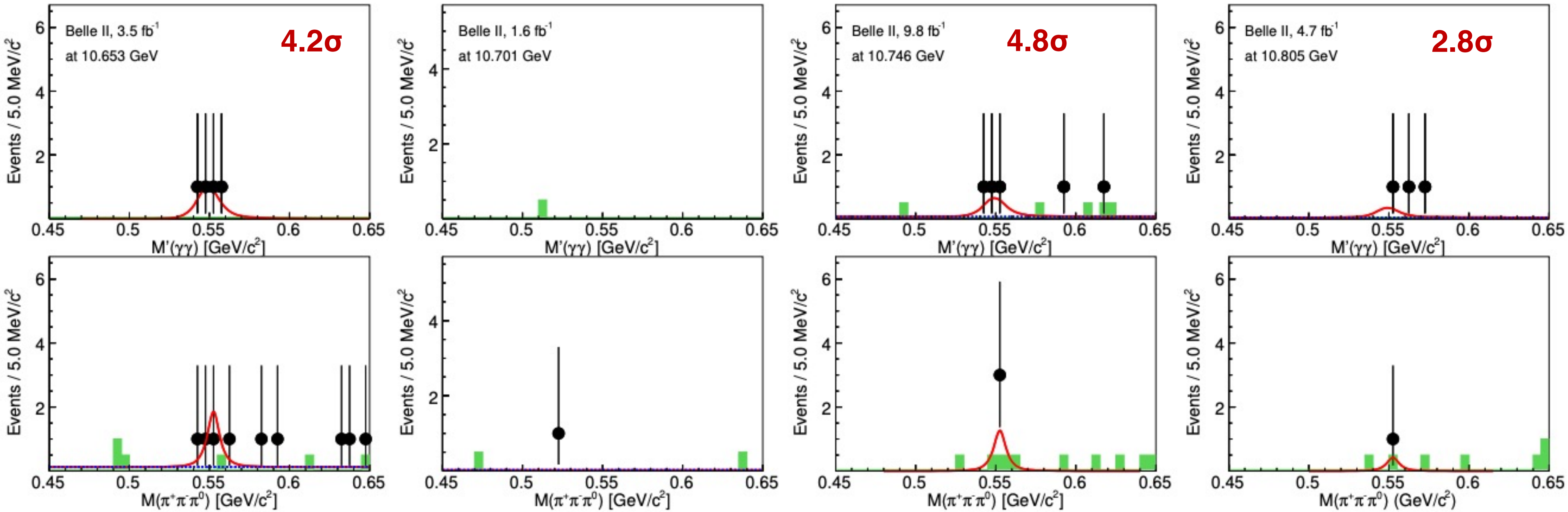
- The $(\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}$ excess maybe due the cascade decay of $\Upsilon(10860, 11020)\to Z_b\pi\to\chi_{bJ}\rho\pi$ [PRD 90, 014036 (2014)].

$e^+e^- \to \eta\Upsilon(1S, 2S)$

$\eta \to \gamma\gamma, \Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S), \Upsilon(1S) \to \ell^+\ell^-$
$\eta \to \pi^+\pi^-\pi^0, \Upsilon(2S) \to \ell^+\ell^-$

PRD 113, L051102 (2026)

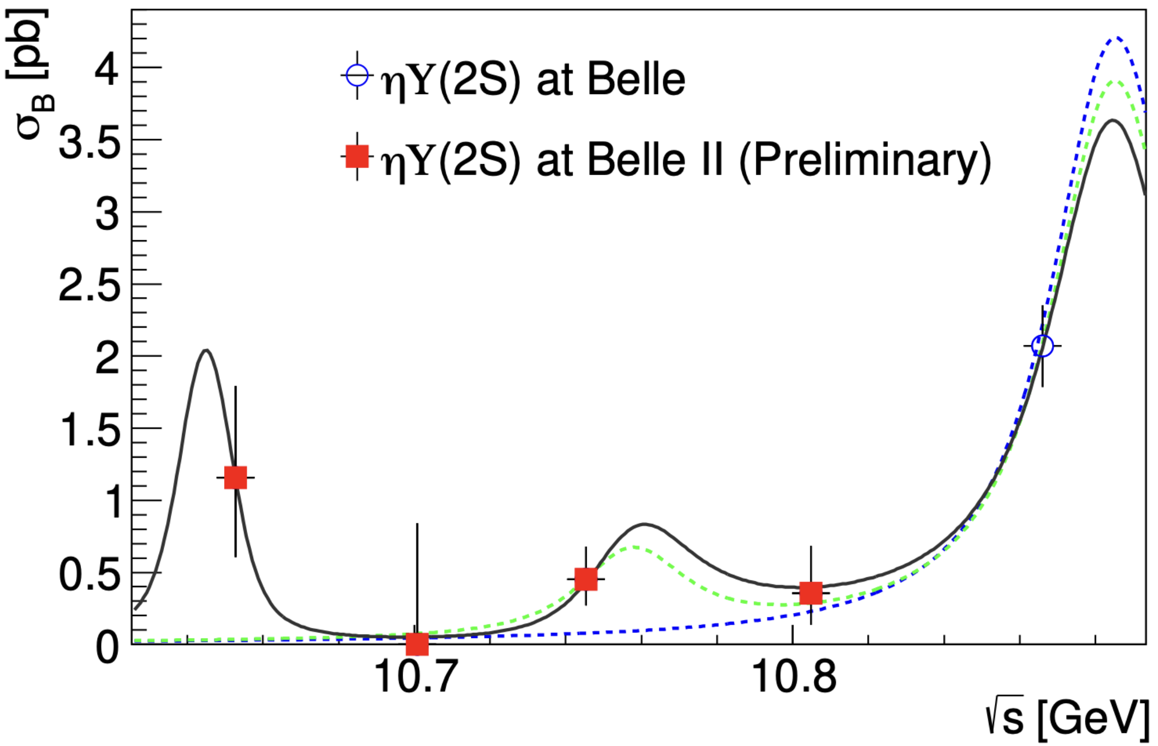
After requiring $\Upsilon(2S)$ signal region, simultaneous fit to M($\gamma\gamma$) and M($\pi^+\pi^-\pi^0$) for each energy point.



- Combining all of the energy points, the signal yields for $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ are $6.0^{+1.7}_{-1.5}$ and $11.5^{+3.3}_{-2.8}$.
- The statistical significance is 6.4σ for $e^+e^- \to \eta\Upsilon(2S)$ at $\sqrt{s} \sim 10.75$ GeV.
- No clear signals were observed for $e^+e^- \to \eta\Upsilon(1S)$ at $\sqrt{s} \sim 10.75$ GeV.

$e^+e^- \to \eta\Upsilon(2S)$

PRD 113, L051102 (2026)



Fit the with 3 different hypotheses:

- H_1: only $\Upsilon(5S)$ [blue curve]
- H_2: $\Upsilon(10753) + \Upsilon(5S)$ [Green curve]
- H_3: $B^*\bar{B}^*$ bound state + $\Upsilon(10753) + \Upsilon(5S)$ [Black curve], the default fit.

The significance of $B^*\bar{B}^*$ bound state is larger than 3.6σ

$$\frac{\sigma_{Born}(e^+e^- \to \eta\Upsilon(2S))}{\sigma_{Born}(e^+e^- \to \pi^+\pi^-\Upsilon(2S))}$$

>22.6 at 90% C.L. at $\sqrt{s}$ = 10.653 GeV

0.31 ± 0.17 at $\sqrt{s}$ = 10.75 GeV

These imply a strong **violation of heavy quark spin symmetry** [Mod. Phys. Lett. A 32 (2017) 04, 1750025], which predicts a production ratio of order 10^{-3}, and might be a further **indication of a $B^*\bar{B}^*$ molecular state**.

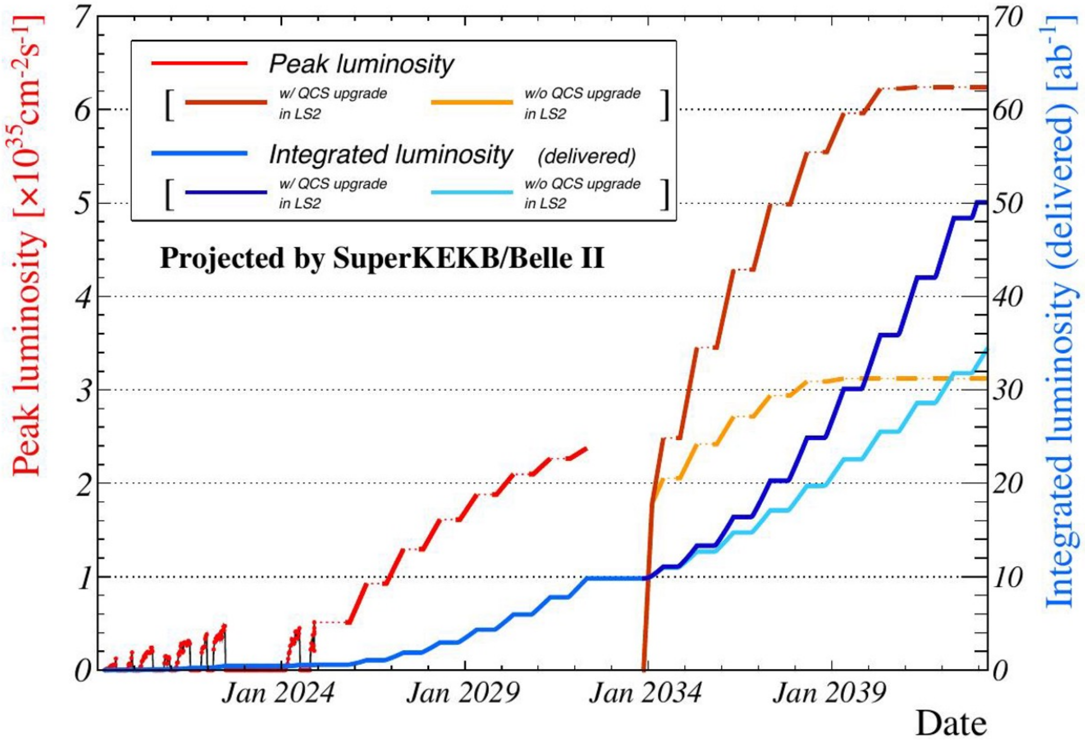
- The Born cross section of $e^+e^- \to \eta\Upsilon(2S)$ around $B^*\bar{B}^*$ mass is relatively large.
- A rapid increase of $\sigma_{B^*\bar{B}^*}$ just above the threshold [JHEP 10 (2024) 114].

A new bottomonium-like state around $B^*\bar{B}^*$ threshold?

The $Y_b(10650)$ has been predicted in Refs. [arXiv:2505.02742, arXiv:2508.11127, arXiv:2505.03647].

Future prospects

From https://www.belle2.org/research/luminosity/



- Until 2026, about 1 ab^{-1} data, comparable to Belle
- Until 2029, about 4 ab^{-1} data.

Charmonium-like states:

- ➢ B decay ($B \to KX_{c\bar{c}}$)

$B \to KX(3872)$

- ➢ Initial-state radiation (ISR)

$e^+e^- \to \Upsilon(4260) \to \pi^+\pi^- J/\psi$ via ISR

- ➢ Two-photon process

$\gamma\gamma \to X(3915) \to \omega J/\psi$

- ➢ Double charmonium

$e^+e^- \to J/\psi X(3940)$

} Need more data

Bottomonium-like states:

- ➢ Direct production via operation at center-of-mass energy

$e^+e^- \to \Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$

- ➢ Decays of higher mass states

$\Upsilon(5S) \to \pi Z_b \to \pi\pi\Upsilon(nS)$

} New collision energy points

Physics Reports 1191 (2026) 1–62

Contents lists available at ScienceDirect

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Review article

Exotic hadrons associated with *b*-quark

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ARTICLE INFO

Article history:
Received 17 March 2026
Received in revised form 13 June 2026
Accepted 18 June 2026

Editor: Gao Yuanning

Keywords:
Exotic hadrons
Belle II experiment
LHCb experiment
X_b, Y_b, and Z_b states
B and λ_b meson decays

ABSTRACT

Compared to charmonium-like states, exotic hadrons associated with *b*-quark offer distinct advantages for exploring the nature of multiquark phenomena and the dynamics of the strong interaction. Due to the heavier bottom quark mass, theoretical calculations, particularly those based on effective field theories and potential models, tend to be more reliable and under better control in the bottomonium sector. With its clean e^+e^- collision environment and high luminosity, the Belle and Belle II experiments are ideally suited to explore these exotic hadrons associated with *b*-quark, including Z_b, X_b, and Y_b states, and charmonium-like states in B decays. Utilizing the large proton–proton collision dataset, the LHCb experiment has conducted extensive investigations of heavy-flavor multiquark states through B and Λ_b decay channels. The relevant phenomenological interpretations are also reviewed.

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Review Contents:

1. Exotic states with b quark [Belle (II)]
- Z_b
- X_b
- Y_b

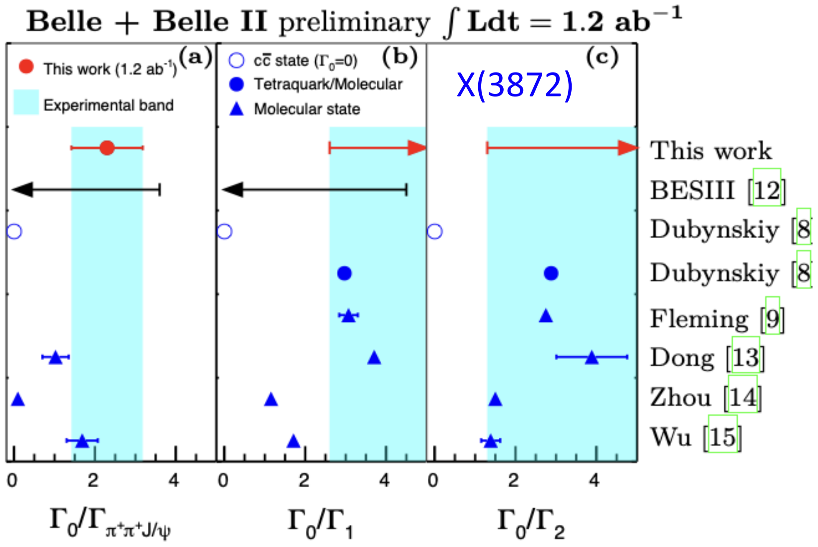
2. Exotic states in B hadron decays [LHCb + Belle (II)]
- ***Exotic charmed-strange states***
- ***Hidden charm tetraquarks***
- ***Pentaquarks***

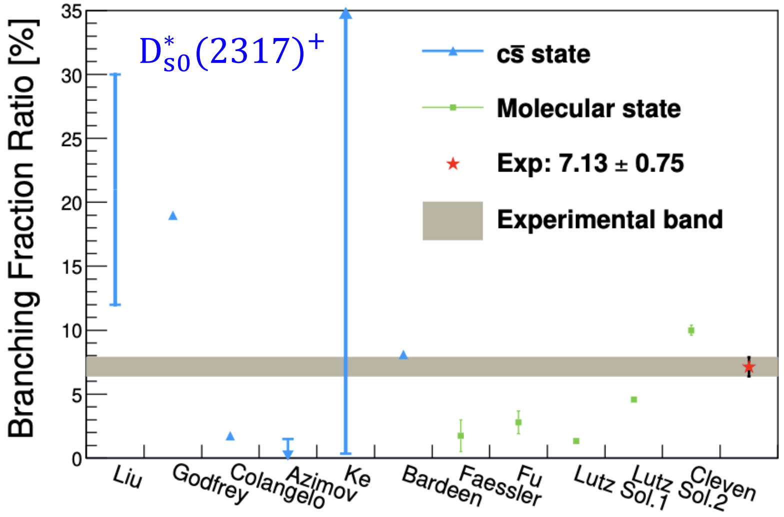
3. Further prospects

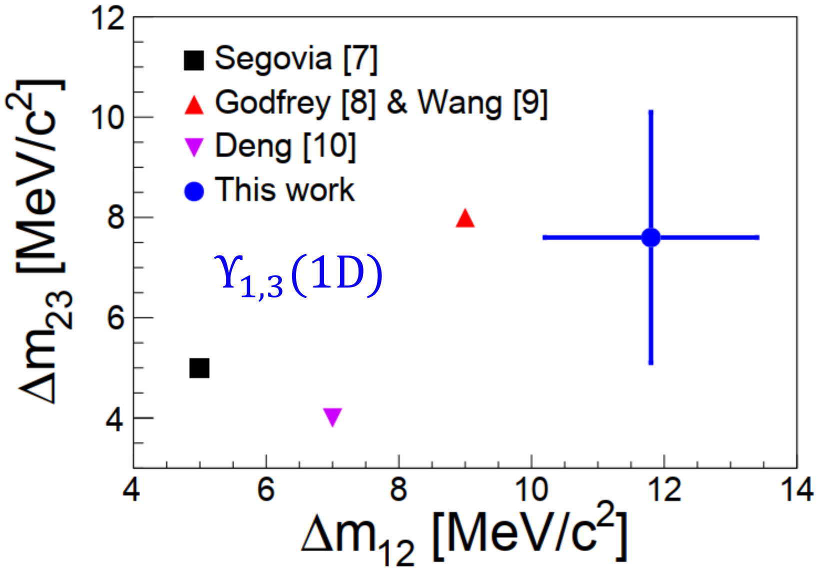
理论预期 + 实验结果 + 结果解释

Summary

- First evidence of $X(3872) \rightarrow \pi^0\chi_{c0}$
  - disfavors the pure charmonium $\chi_{c1}(2P)$ state
  - consistent with most theoretical predictions on molecular/tetraquark scenario
- First observation of $D_{s0}^*(2317)^+ \rightarrow D_s^{*+}\gamma$
  - help to discriminate the nature of the $D_{s0}^*(2317)^+$
- First evidence for the $\Upsilon_1(1D)$ and $\Upsilon_3(1D)$ states
  - The mass splittings Δm_{12}= (11.8$\pm$1.5$\pm$0.4) MeV/c^2 and Δm_{23} = (7.6$\pm$2.4$\pm$0.6) MeV/c^2.
- The observation of $\Upsilon(10753) \rightarrow \omega\chi_{bJ}$ and the possible evidence for $\Upsilon_b(10650)$.







Thanks for your attention!