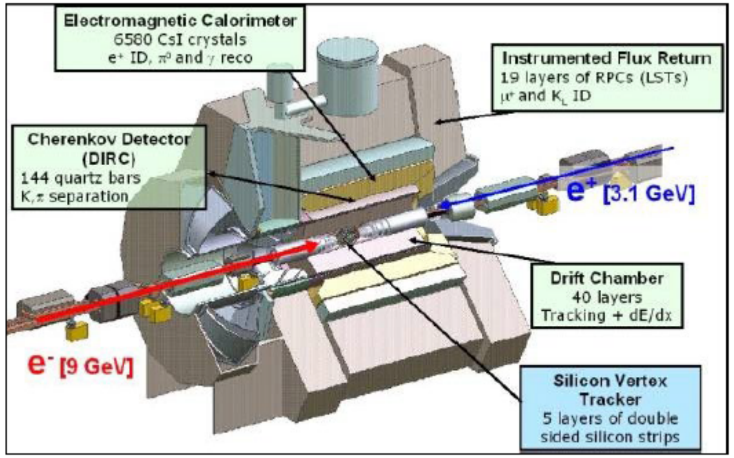
Belle/Belle II实验上强子谱的研究

Chengping Shen (Fudan University)

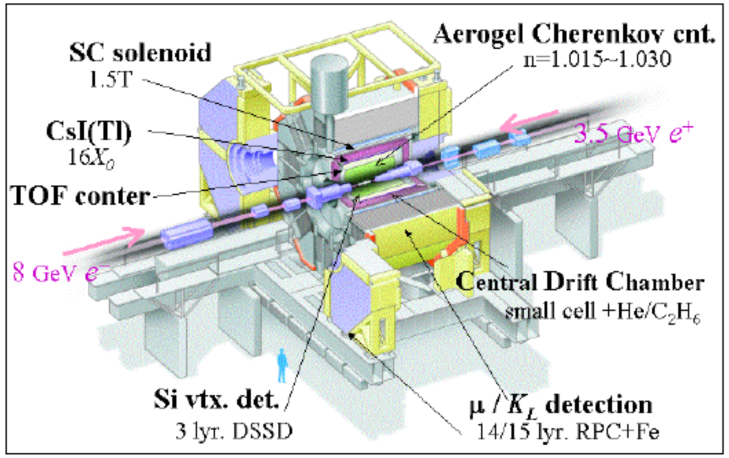
第九届强子谱和强子结构研讨会

Excellent Results by Belle and BaBar

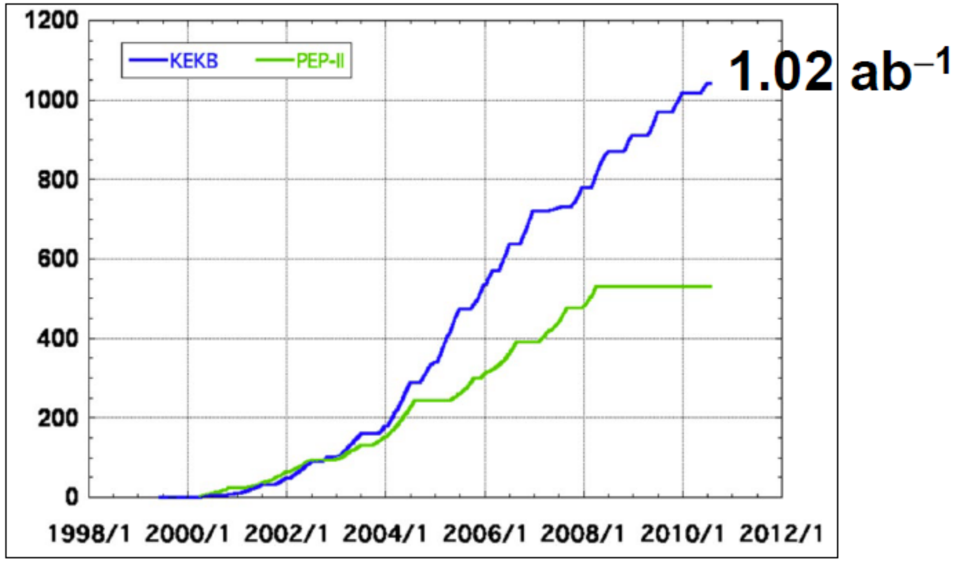
- Two experiments confirmed CP violation in the b quark sector
  - based on the precision measurements of the CKM matrix
  - 2008 Nobel Prize for Prof. Kobayashi and Prof. Maskawa
- Discovery of X(3872) in 2003 by Belle, followed by other exotic particles
- Belle and BaBar, each published over 600 papers.
- Detectors at B-Factories show versatile physics analysis abilities



BABAR / PEP II

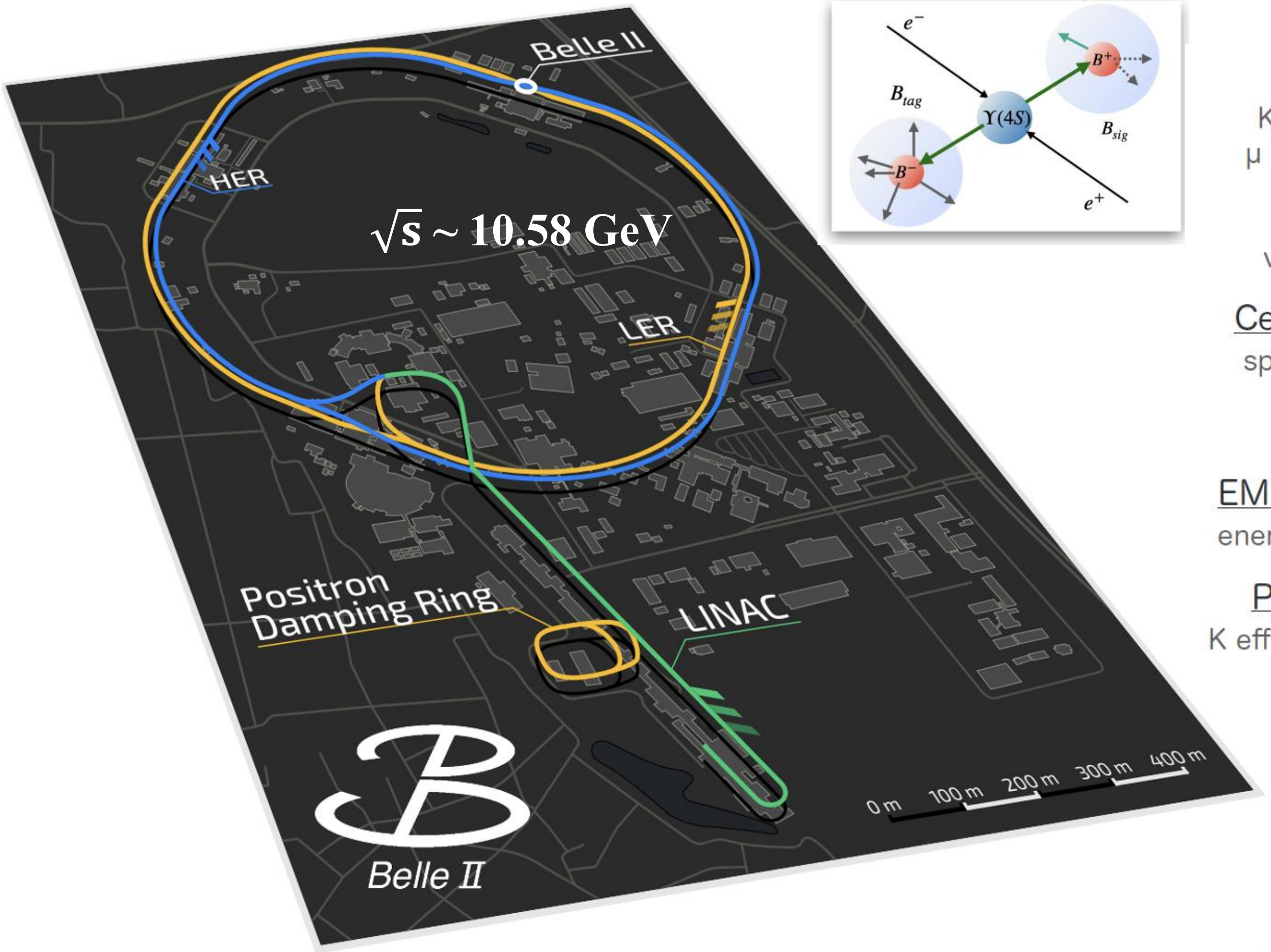


Belle / KEKB



SuperKEKB and Belle II

We have recorded 914/fb luminosity



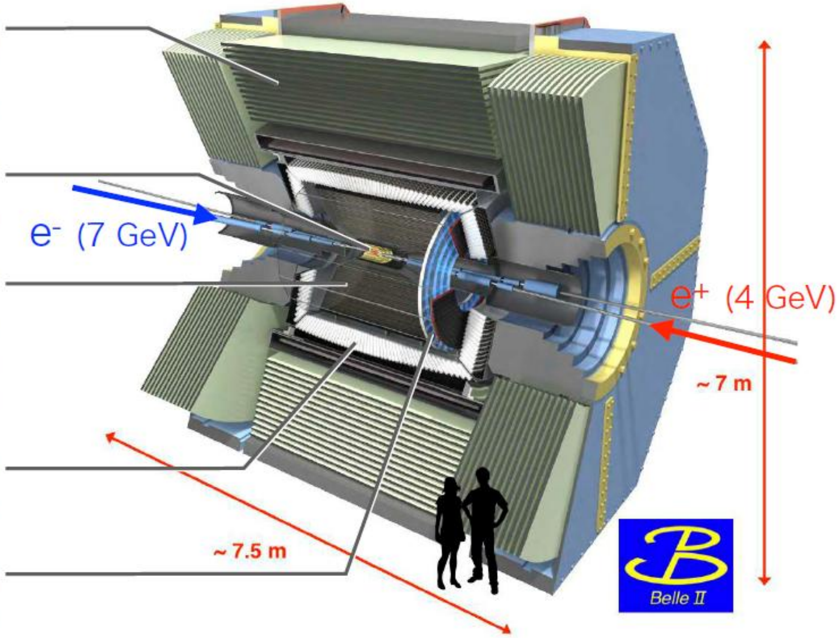
K_L and μ Detection
K_L^0 p resolution: 15 MeV
μ identification eff.: ~90%

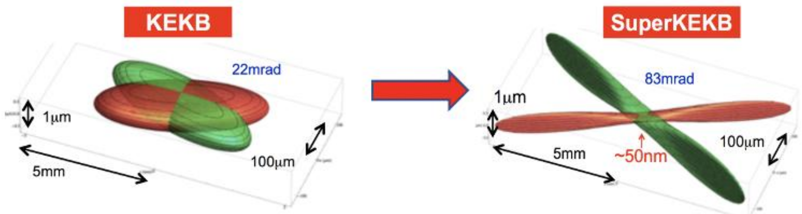
Vertex Detector
vertex resolution: 15 μm

Central Drift Chamber
spatial resolution: 100 μm
dE/dx resolution: 5%
P_T resolution: 0.4%

EM Calorimeter, CsI(Tl)
energy resolution: 1.6%-4%

Particle Identification
K eff.: 90%, fake π rate: 5%





Nano-beam design:

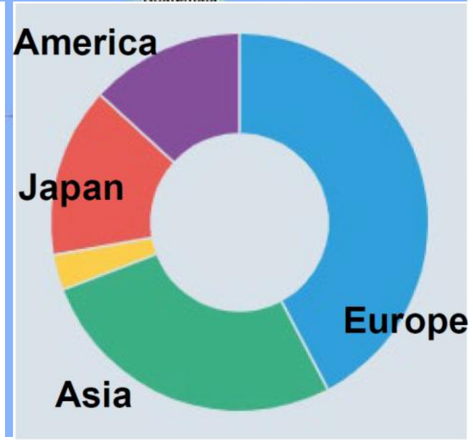
The target peak luminosity is much larger by squeezing beam sizes and enlarge beam currents.

Belle II Collaboration

28 Institutes ~1200 members

China

- Beihang: Beihang Univ.(BUAA)
- Fudan: Fudan Univ.
- HNU: Henan Normal University
- HUNNU: Hunan Normal University
- IHEP-China: Institute of High Energy Physics(IHEP)
- JLU: Jilin University
- LNNU: LiaoNing Normal University(LNNU)
- NNU: Nanjing Normal University
- Nankai: Nankai University
- SEU: Southeast University
- Shandong: Shandong University
- Soochow: Soochow University
- USTC: Univ. of Science and Technology of China(USTC)
- XJTU: Xi'an Jiaotong University
- ZZU: Zhengzhou University



第八届Belle II合作中国组会议

2026年5月29日-6月1日，大连

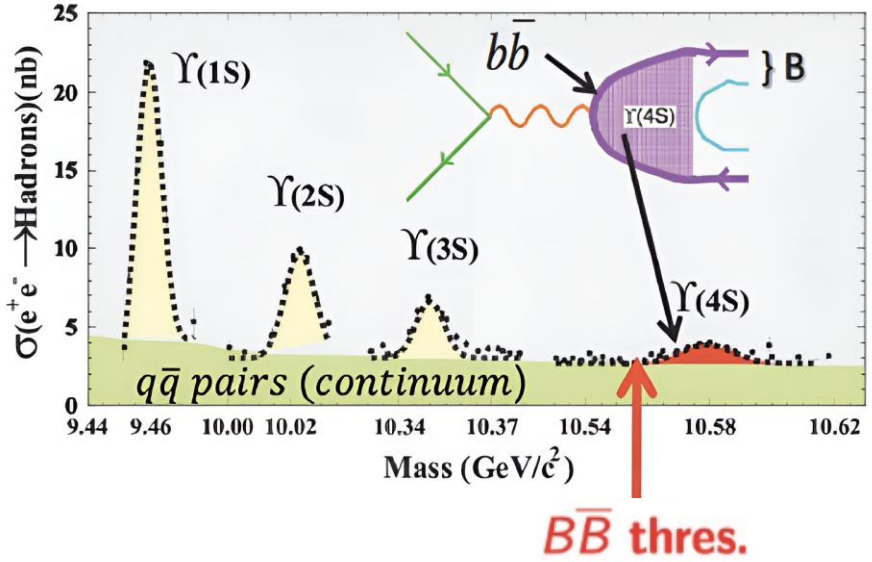
第一届Belle合作中国组会议

2010年6月11-12日，怀柔

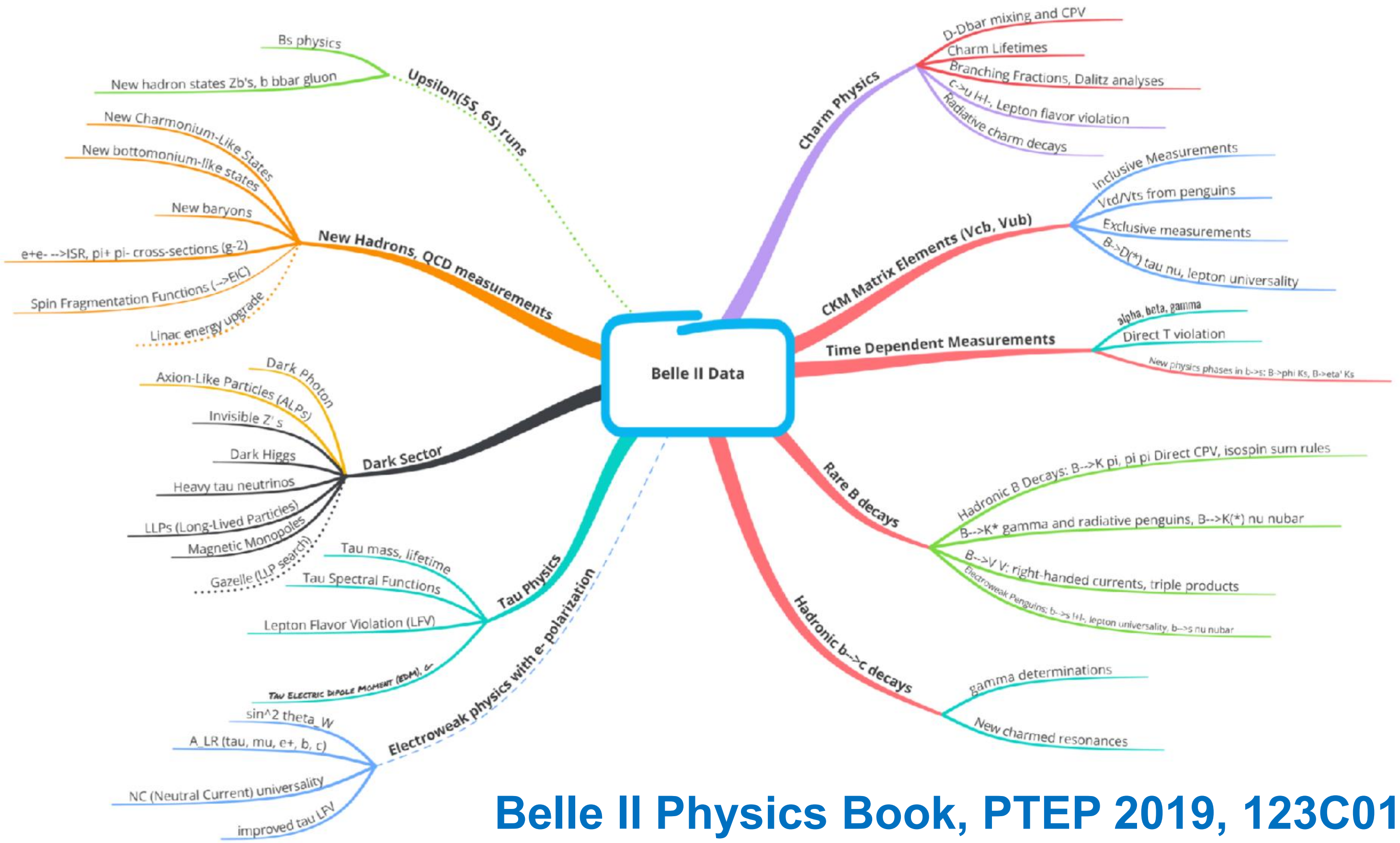
2010年（Belle）
高能所（7+8）
北京大学（1+2）
中国科技大学（2+3）
共23人

Belle II physics

The Belle II Physics Book: [PTEP 2019 (2019) 12, 123C01]



$e^+e^- \to$	Cross section [nb]
$\Upsilon(4S)$	1.05 ± 0.10
$c\bar{c}$	1.30
$s\bar{s}$	0.38
$u\bar{u}$	1.61
$d\bar{d}$	0.40
$\tau^+\tau^-(\gamma)$	0.919
$\mu^+\mu^-(\gamma)$	1.148
$e^+e^-(\gamma)$	300 ± 3



Belle II Physics Book, PTEP 2019, 123C01

Primarily a **B factory;** But not only B physics!

- Also **tau, charm** factories
- Clean background for **spectroscopy** and searching for dark sector

Various type of analyses:

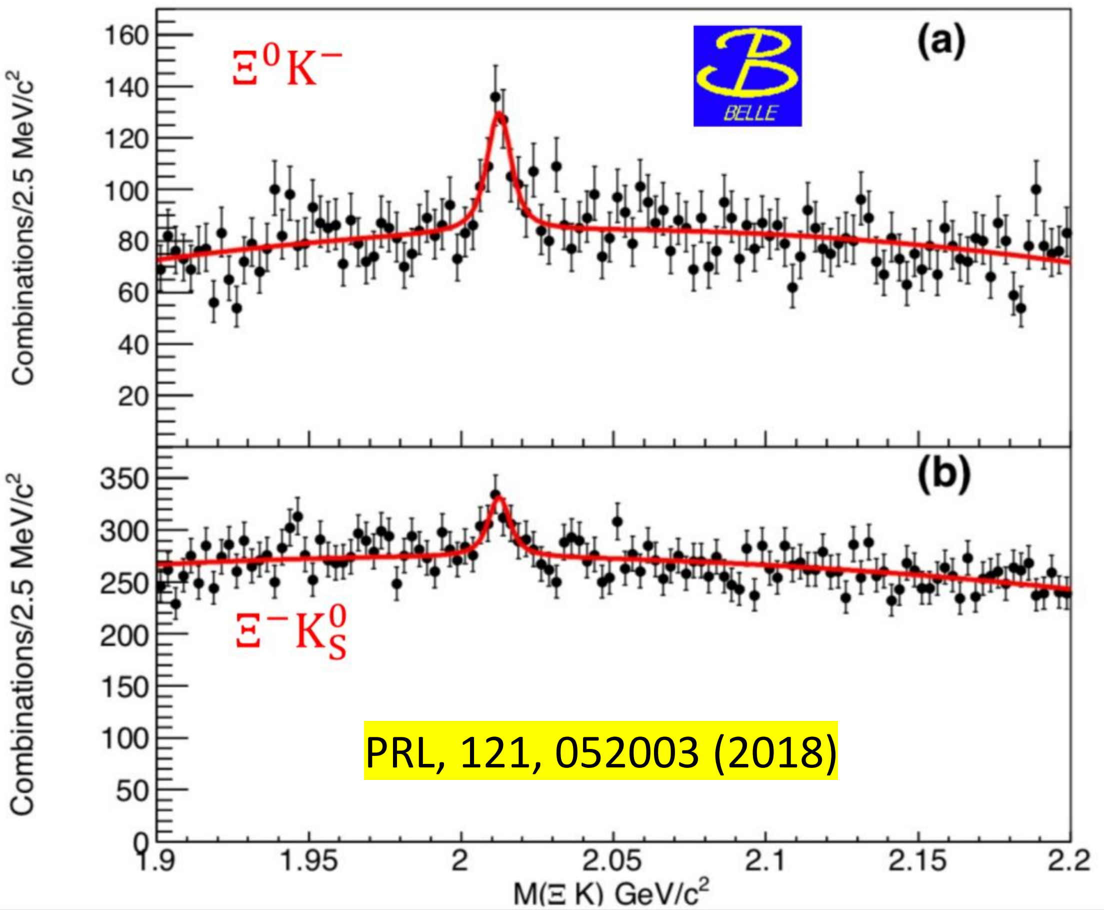
- Lifetime, time-dependent measurement
- well-suited for decays with missing energy and missing mass

Light hadrons

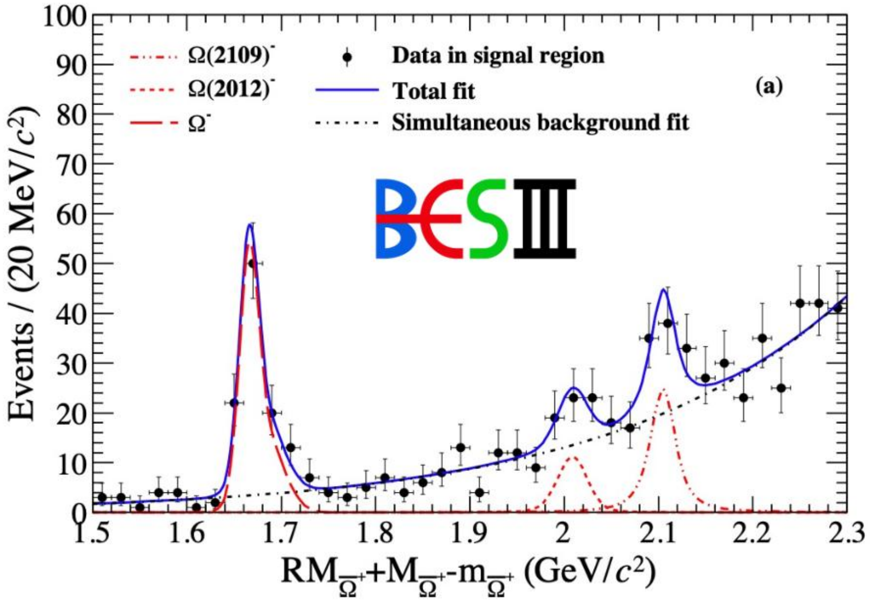
Discovery of $\Omega(2012)^-$

PRL 134, 131903 (2025)

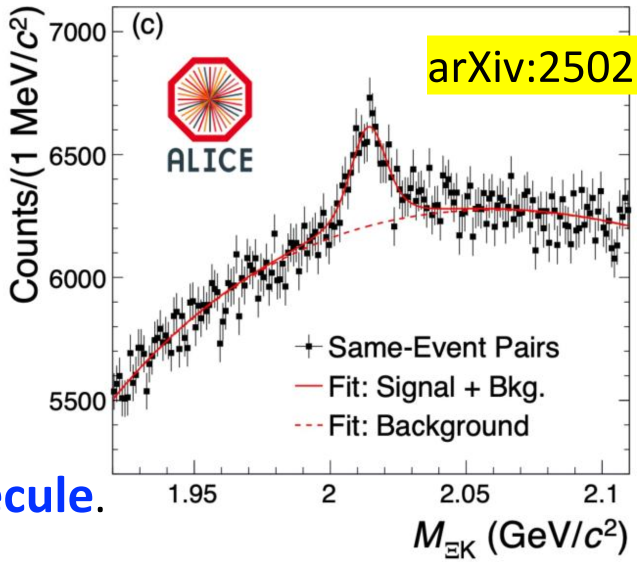
$\Omega(2012)$ was first observed by Belle in two-body (ΞK) decays,
Confirmed by BESIII (low statistics) and ALICE (15σ).



PRL, 121, 052003 (2018)



arXiv:2502.18063

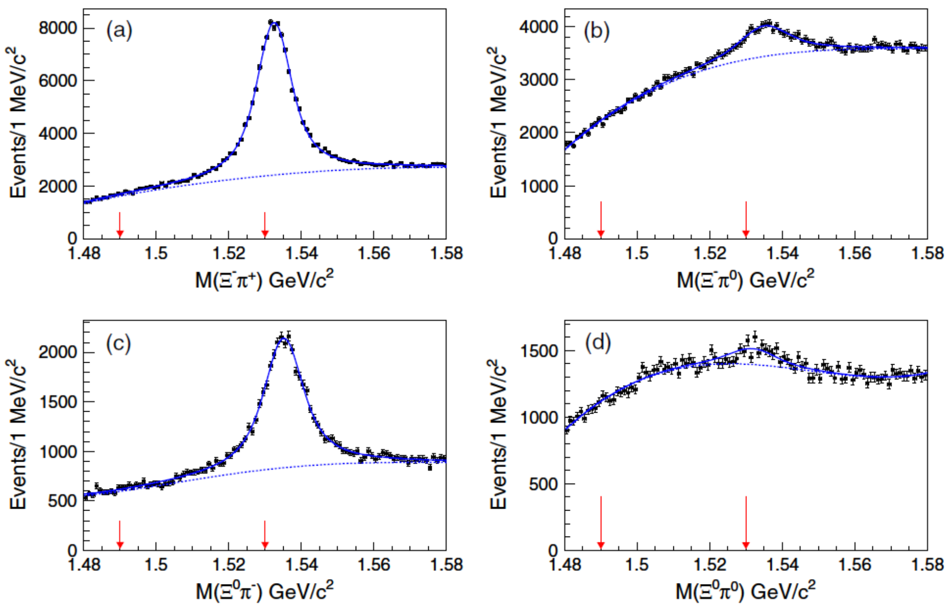


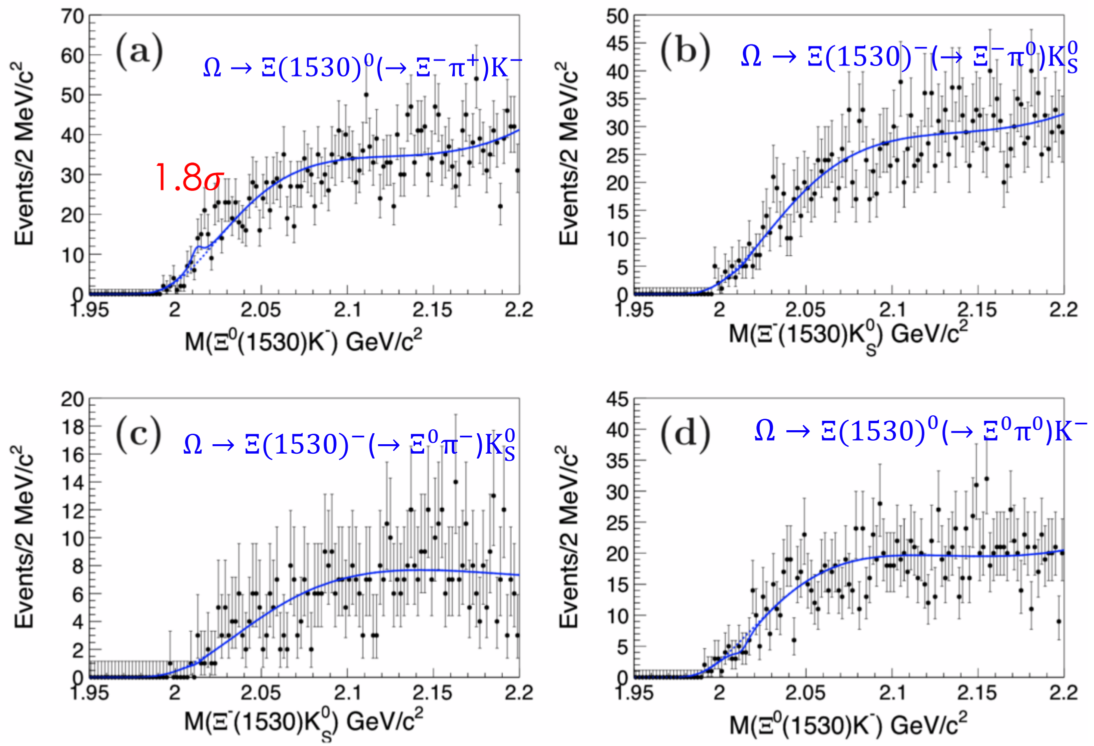
The $\Omega(2012)$ was interpreted as **a standard baryon or a $\Xi(1530)\bar{K}$ molecule**.

Search for Ω(2012) → KΞ(1530) → KπΞ

PRD 100, 032006 (2019)

We use the same data samples to search for Ω(2012) → KΞ(1530) → KπΞ in the decay of the narrow resonances Υ(1S), Υ(2S), and Υ(3S).





No clear Ω(2012) signals are observed.
We give the upper limit on the ratio of the branching fractions at 90% C.L.

$$R^{\Xi\pi K}_{\Xi K} = \frac{\mathcal{B}(\Omega\to\Xi(1530)(\to\Xi\pi)K)}{\mathcal{B}(\Omega\to\Xi K)} = (6.0\pm3.7(\text{stat.})\pm1.3(\text{syst.}))\%$$

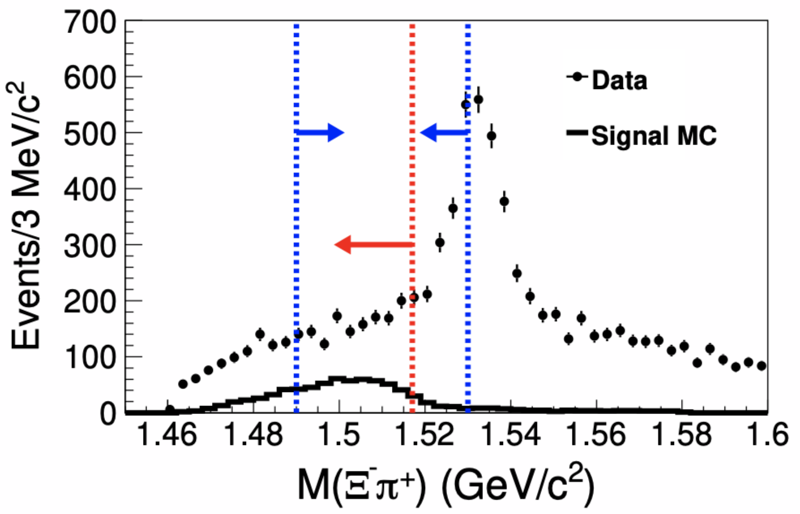
$$R^{\Xi\pi K}_{\Xi K} = \frac{\mathcal{B}(\Omega\to\Xi(1530)(\to\Xi\pi)K)}{\mathcal{B}(\Omega\to\Xi K)} < 11.9\% \text{ at } 90\% \text{ C.L.}$$

Revisit $\Omega(2012)^- \to \Xi(1530)\bar{K} \to \Xi\pi\bar{K}$

PLB 860, 139224 (2025)

The comparisons between the previous analysis [PRD 100, 032006 (2019)] and this work.

Analysis strategy	The previous analysis [40]	This work
The requirement of $M(\Xi\pi)$	$1.49 < M(\Xi\pi) < 1.53$ GeV/c^2	$M(\Xi\pi) < 1.517$ GeV/c^2
The signal shape of $\Omega(2012)^-$	A Breit-Wigner function	A Flatté-like function [41]
ϕ-induced backgrounds	No requirement	$\lvert M(K^-K^+) - m_\phi \rvert > 10$ MeV/c^2



The Flatté-like function [PRD 81, 094028 (2010)]

$$T_n(M) = \frac{g_n k_n(M_n)}{|M_n - m_{\Omega(2012)} + \frac{1}{2}\sum_{j=2,3} g_j[\kappa_j(M_j) + i k_j(M_j)]|^2}$$

- g_n is the effective coupling of to the n–body final state.
- k_n and κ_n parameterize the real and imaginary parts of the $\Omega(2012)^-$self-energy.

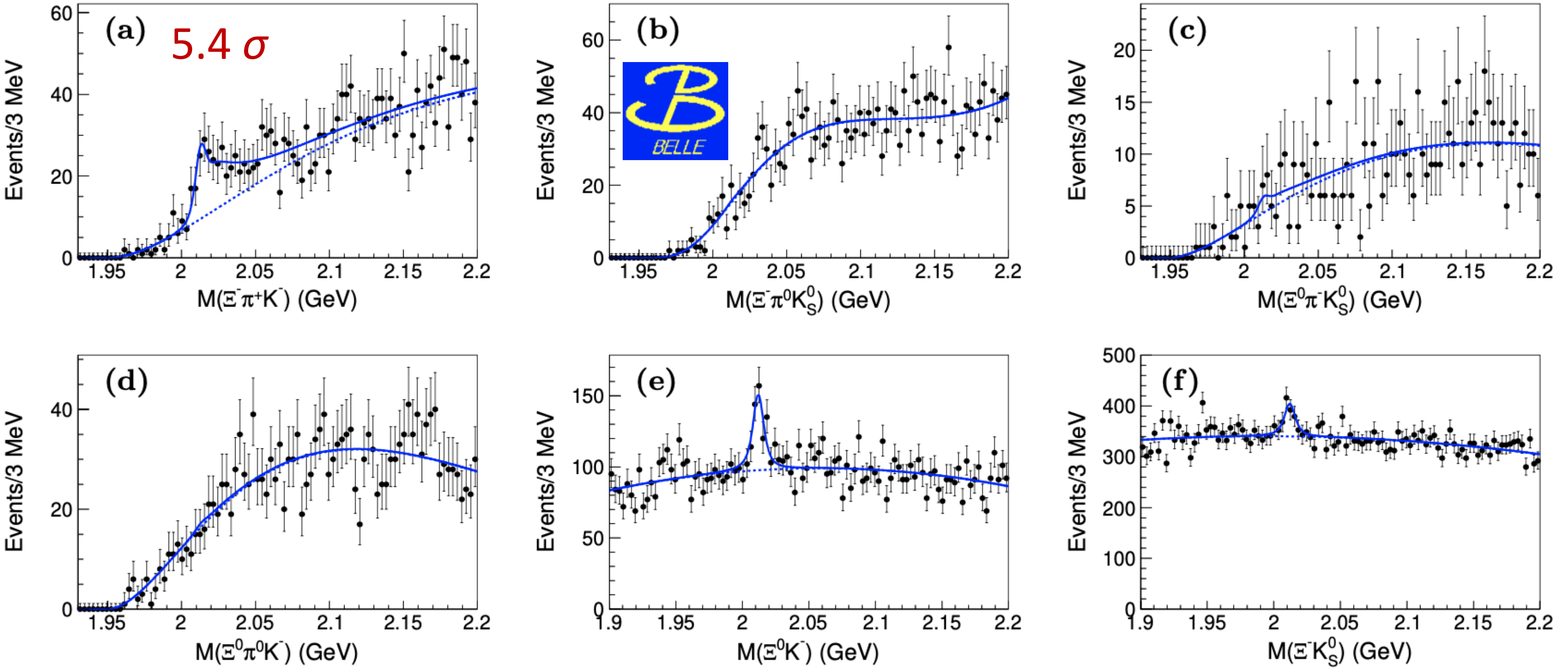
Above 2.02 GeV, the phase space k_3 increases sharply to cover more signal candidates.

The red arrow for this updated work; The blue arrow for the previous analysis.

Revisit $\Omega(2012)^- \to \Xi(1530)\bar{K} \to \Xi\pi\bar{K}$

PLB 860, 139224 (2025)

We fit simultaneously to the binned $\Xi^-\pi^+K^-$, $\Xi^-\pi^0K^0_S$, $\Xi^0\pi^-K^0_S$, $\Xi^0\pi^0K^-$, Ξ^0K^- and $\Xi^-K^0_S$ mass distributions from Υ(1S,2S,3S) data samples.



The mass and effective couplings :

$\Omega(2012)^-$ mass	(2012.5±0.7±0.5) MeV
The coupling to $\Xi\bar{K}$	$(1.7\pm0.3\pm0.3)\times10^{-2}$
The coupling to $\Xi(1530)\bar{K}$	$(39^{+31}_{-39}\pm9)\times10^{-2}$

$$\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} = \frac{\mathcal{B}(\Omega(2012)^- \to \Xi(1530)\bar{K} \to \Xi\pi\bar{K})}{\mathcal{B}(\Omega(2012)^- \to \Xi\bar{K})}$$

0.99±0.26(stat.)±0.06(syst.)

Our result is consistent with the molecular model of $\Omega(2012)^-$, which predicts comparable rates for $\Omega(2012)^-$ decay to $\Xi(1530)\bar{K}$ and $\Xi\bar{K}$.

Ω BARYONS ($S = -3$, $I = 0$)

$\Omega^- = s\,s\,s$

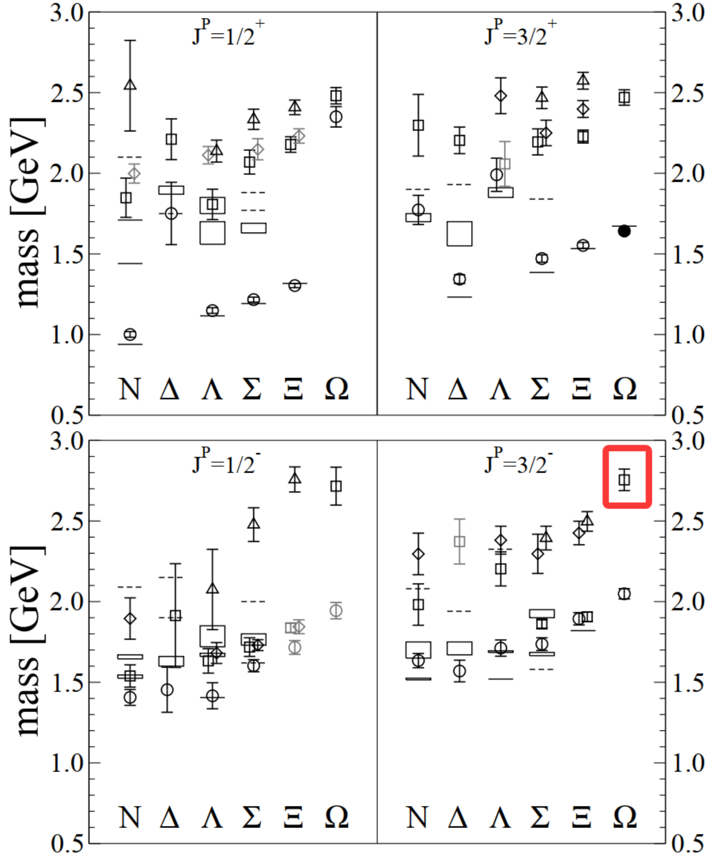
Ω^-	$3/2^+$	****
$\Omega(2012)^-$	$?^-$	***
$\Omega(2109)^-$		*
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

J.Phys.G 52 (2025) 6, 065103

Table 4. Table comparing the PDG masses and quantum numbers J^P in the Ω-baryon spectrum with those obtained in this work. The reported lattice masses are the extrapolated Ω masses obtained by taking a linear fit in m_π^2 to our lattice QCD results. The Nodes column indicates the number of radial nodes identified in the state wave function.

PDG			Lattice		
Resonance	J^P	m (MeV)	J^P	$m_\Omega\|_{phys}$ (MeV)	Nodes
$\Omega^-(1672)$	$3/2^+$	1672.5 ± 0.3	$3/2^+$	1656 ± 23	0
$\Omega^-(2012)$	$?^-$	2012.4 ± 0.9	$1/2^-$	2041 ± 55	0
			$3/2^-$	2051 ± 45	0
$\Omega^-(2250)$	$?^?$	2252 ± 9	$3/2^+$	2252 ± 91	1
$\Omega^-(2380)$	$?^?$	2380 ± 17	$1/2^+$	2341 ± 140	0
$\Omega^-(2470)$	$?^?$	2474 ± 12	$1/2^-$	2562 ± 184	1
			$3/2^-$	2646 ± 76	1
			$3/2^+$	2933 ± 48	2
			$1/2^+$	2970 ± 138	1
			$3/2^-$	3339 ± 218	2
			$1/2^-$	3485 ± 178	2

Phys. Rev. D 87, 074504 (2013)



Lattice method

Phys. Rev. D 92, no. 5, 054005 (2015)

TABLE VIII: Masses of the Ω states (in MeV).

J^P	Experiment [1] State	Status	Mass	Theory $NLnl_j$	Mass	J^P	Theory $NLnl_j$	Mass
$\frac{1}{2}^+$				$1D1s_1$	2301	$\frac{1}{2}^-$	$1P1s_1$	1941
							$2P1s_1$	2463
							$1P2s_1$	2580
$\frac{3}{2}^+$	Ω	****	1672.45 ± 0.29	$1S1s_1$	1678	$\frac{3}{2}^-$	$1P1s_1$	2038
				$2S1s_1$	2173		$2P1s_1$	2537
				$1S2s_1$	2304		$1P2s_1$	2636
				$1D1s_1$	2332			
				$3S1s_1$	2671			
$\frac{5}{2}^+$				$1D1s_1$	2401	$\frac{5}{2}^-$	$1F1s_1$	2653
$\frac{7}{2}^+$				$1D1s_1$	2369	$\frac{7}{2}^-$	$1F1s_1$	2599
						$\frac{9}{2}^-$	$1F1s_1$	2649

Eur. Phys. J. A 10, 447 (2001)

Exp. state [18]	PW	J^π	Rating	Mass range [MeV] [18]	Model state in model $\mathcal{A}$	Model state in model $\mathcal{B}$
	S_{31}	$\frac{1}{2}^-$			$[\Omega\frac{1}{2}^-]_2(2456)$	$[\Omega\frac{1}{2}^-]_2(2750)$
					$[\Omega\frac{1}{2}^-]_3(2498)$	$[\Omega\frac{1}{2}^-]_3(2766)$
					$[\Omega\frac{1}{2}^-]_4(2550)$	$[\Omega\frac{1}{2}^-]_4(2839)$
	D_{33}	$\frac{3}{2}^-$			$[\Omega\frac{3}{2}^-]_2(2446)$	$[\Omega\frac{3}{2}^-]_2(2748)$
					$[\Omega\frac{3}{2}^-]_3(2507)$	$[\Omega\frac{3}{2}^-]_3(2765)$
					$[\Omega\frac{3}{2}^-]_4(2524)$	$[\Omega\frac{3}{2}^-]_4(2824)$
					$[\Omega\frac{3}{2}^-]_5(2564)$	$[\Omega\frac{3}{2}^-]_5(2839)$
					$[\Omega\frac{3}{2}^-]_6(2594)$	$[\Omega\frac{3}{2}^-]_6(2851)$
	D_{35}	$\frac{5}{2}^-$			$[\Omega\frac{5}{2}^-]_1(2528)$	$[\Omega\frac{5}{2}^-]_1(2746)$
					$[\Omega\frac{5}{2}^-]_2(2534)$	$[\Omega\frac{5}{2}^-]_2(2772)$
					$[\Omega\frac{5}{2}^-]_3(2554)$	$[\Omega\frac{5}{2}^-]_3(2822)$
					$[\Omega\frac{5}{2}^-]_4(2617)$	$[\Omega\frac{5}{2}^-]_4(2846)$
	G_{37}	$\frac{7}{2}^-$			$[\Omega\frac{7}{2}^-]_1(2531)$	$[\Omega\frac{7}{2}^-]_1(2773)$
					$[\Omega\frac{7}{2}^-]_2(2577)$	$[\Omega\frac{7}{2}^-]_2(2818)$
	G_{39}	$\frac{9}{2}^-$			$[\Omega\frac{9}{2}^-]_1(2606)$	$[\Omega\frac{9}{2}^-]_1(2815)$

Table 18. Calculated positions of negative-parity Ω states in the $3\hbar\omega$ shell. Notation as in table 1.

Relativistic quark model

Phys. Rev. D 75, 074002 (2007).

Particle Name	Mass (MeV)	Assigned State
N	939	
Δ	1232	
$\Lambda_{1/2^+,0}$	1116	$\Lambda(1116)$
$\Lambda_{1/2^-,1}$	1405	$\Lambda(1405)$
$\Sigma_{1/2^+,0}$	1164	$\Sigma(1193)$
$\Sigma_{3/2^+,0}$	1385	$\Sigma(1385)$
$\Sigma_{1/2^-,1}$	1475	$\Sigma(1480)$?
$\Sigma_{3/2^-,1}$	1663	$\Sigma(1670)$
$\Xi_{1/2^+,0}$	1318	$\Xi(1318)$
$\Xi_{3/2^+,0}$	1539	$\Xi(1530)$
$\Xi_{1/2^-,1}$	1658(1660)*	$\Xi(1690)$?
$\Xi_{1/2^-,2}$	1616(1614)*	$\Xi(1620)$?
$\Xi_{3/2^-,1}$	1820	$\Xi(1820)$
$\Xi_{1/2^+,1}$	1932	$\Xi(1950)$?
$\Xi_{3/2^+,1}$	2120	$\Xi(2120)$?
$\Omega_{3/2^+,0}$	1694	$\Omega(1672)$
$\Omega_{1/2^-,1}$	1837	
$\Omega_{3/2^-,1}$	1978	
$\Omega_{1/2^+,1}$	2140	
$\Omega_{3/2^+,1}$	2282	$\Omega(2250)$?
$\Omega_{3/2^-,2}$	2604	

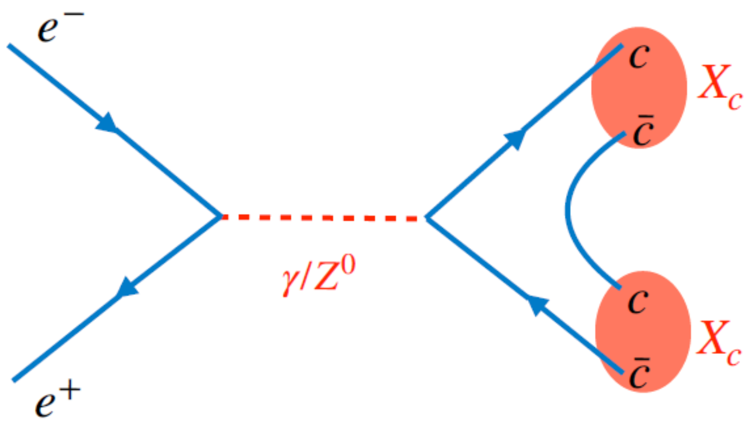
Skyrme model

Charm

Charm production at Belle II

- At Belle II, $\mathrm{e^+e^-}$ mainly collide at 10.58 GeV to make $\Upsilon(4S)$ resonance mainly decaying into $\mathrm{B\overline{B}}$.
- Meanwhile, **continuum processes $\mathrm{e^+e^-} \to \mathrm{q\overline{q}}$ (q = u, d, s, c) have large cross sections**.
- Two ways to produce charm samples: **1) $\mathrm{e^+e^-} \to \mathrm{c\bar{c}}$, and 2) B → charm decays**.

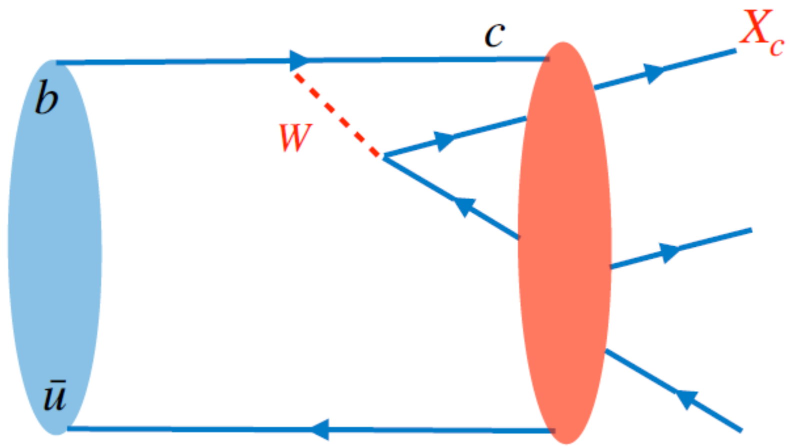
Two charmed hadrons produced from continuum



Large statistics but high level background

Only relative branching fractions can be measured
Absolute values obtained using external inputs

One or more charmed hadrons produced in B decays



Low statistics but very clean sample

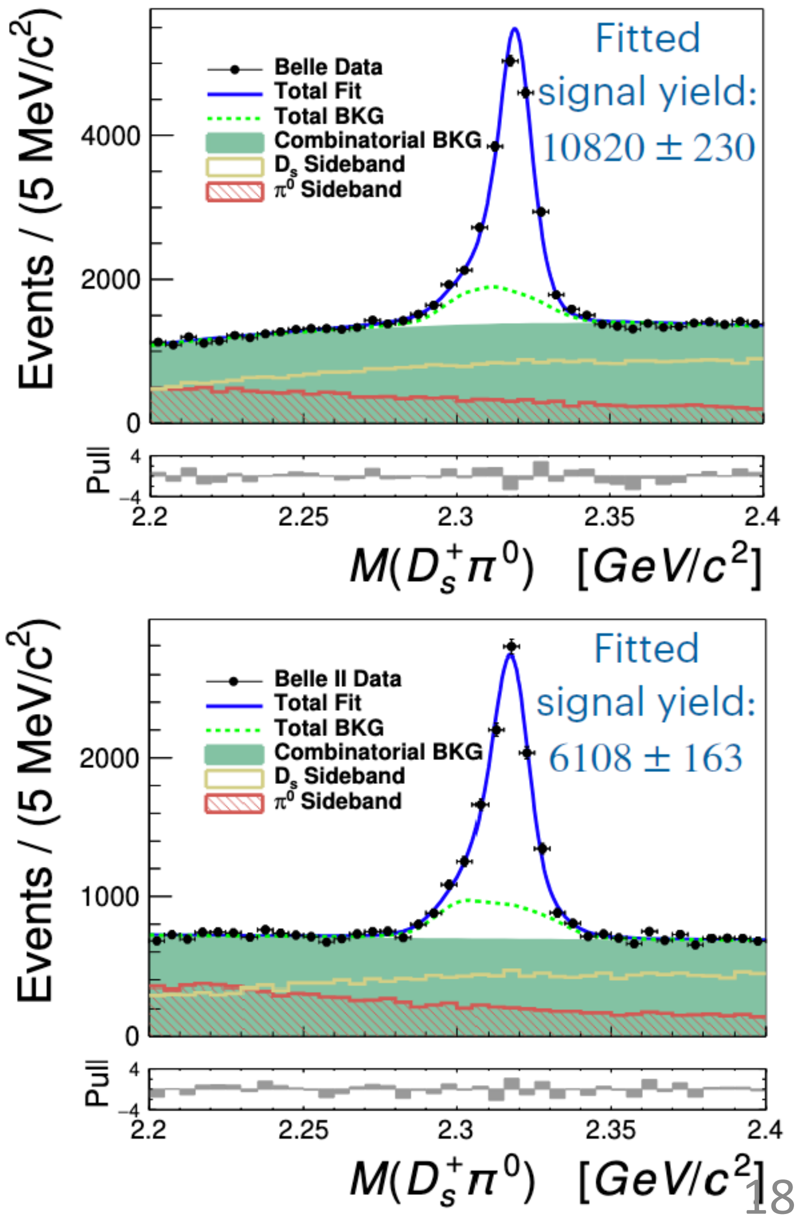
Absolute branching fractions can be obtained:
cross section of $B\bar{B}$ precisely measured

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

PRL 136, 241901 (2026)

Motivation and analysis strategy

- Nature of $D_{s0}^{*}(2317)^{+}$ and $D_{s1}(2460)^{+}$ unclear: $c\bar{s}$ states, hadronic molecules, mixed configs, tetraquarks → motivate further studies
- Reconstruct $D_s^{+} \to \phi[\to K^{+}K^{-}]\pi^{+}$ and $D_s^{+} \to \bar{K}^{*0}[\to K^{-}\pi^{+}]K^{+}$ decays
  $D_{s0}^{*}(2317)^{+}$ candidates from $D_s^{*+}\gamma$ or $D_s^{+}\pi^{0}$ combinations
- $D_{s0}^{*}(2317)^{+} \to D_s^{+}\pi^{0}$ as normalization channel: yield obtained from an unbinned maximum-likelihood fit to $M(D_s^{+}\pi^{0})$ spectra
- Detailed study of background sources: use D_s and π^{0} sidebands
  Peaking background from a missing γ in $D_{s1}(2460)^{+} \to D_s^{*+}\pi^{0}$ decays



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

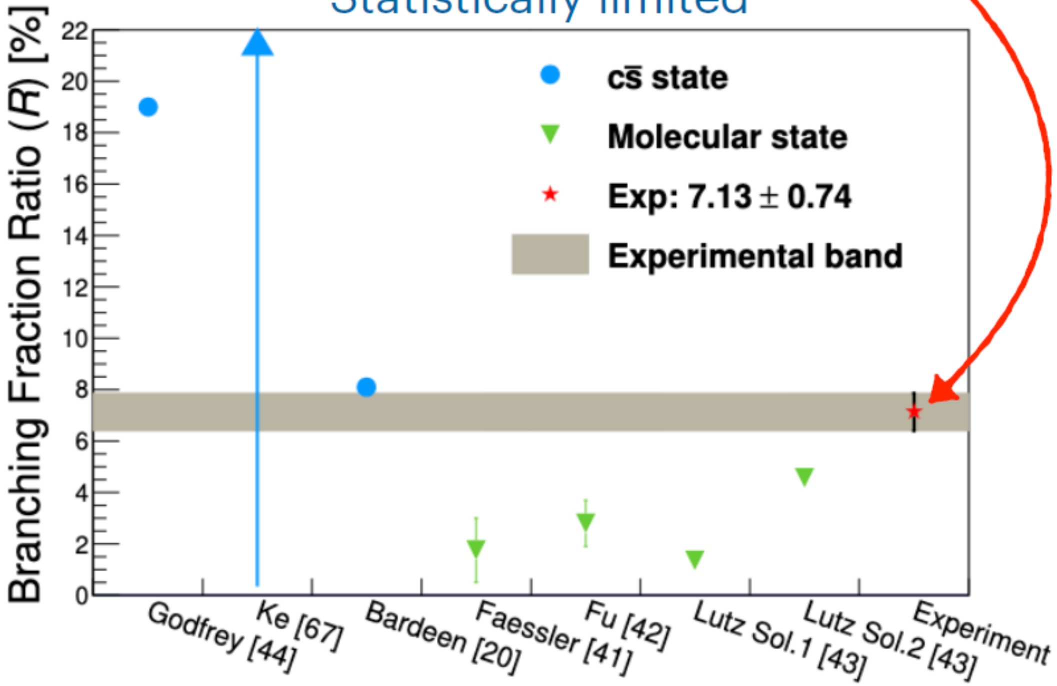
PRL 136, 241901 (2026)

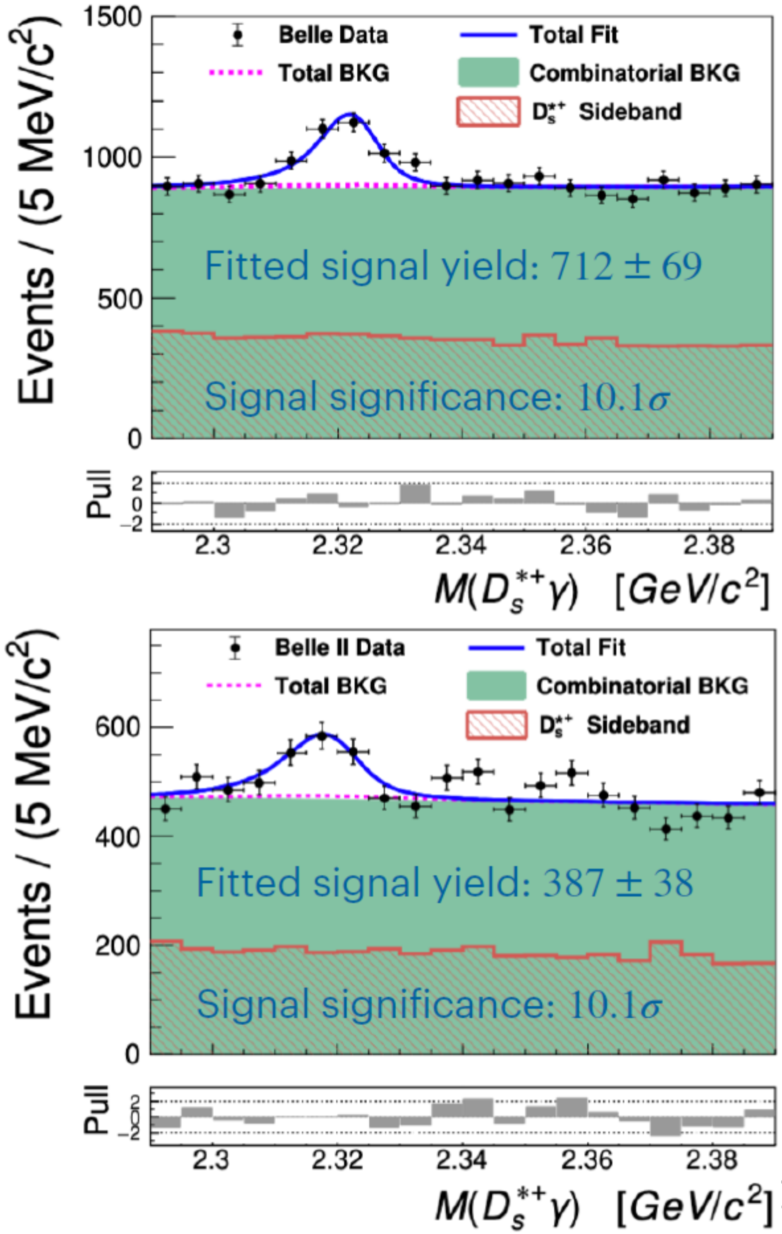
Results

First measurement of $R = \mathscr{B}(D_{s0}^{*+} \to D_s^{*+}\gamma)/\mathscr{B}(D_{s0}^{*+} \to D_s^{+}\pi^0)$ using a simultaneous unbinned maximum-likelihood fit to $M(D_s^{*+}\gamma)$ spectra

$$R = (7.14 \pm 0.70_{stat} \pm 0.23_{syst})\ \%$$

Statistically limited

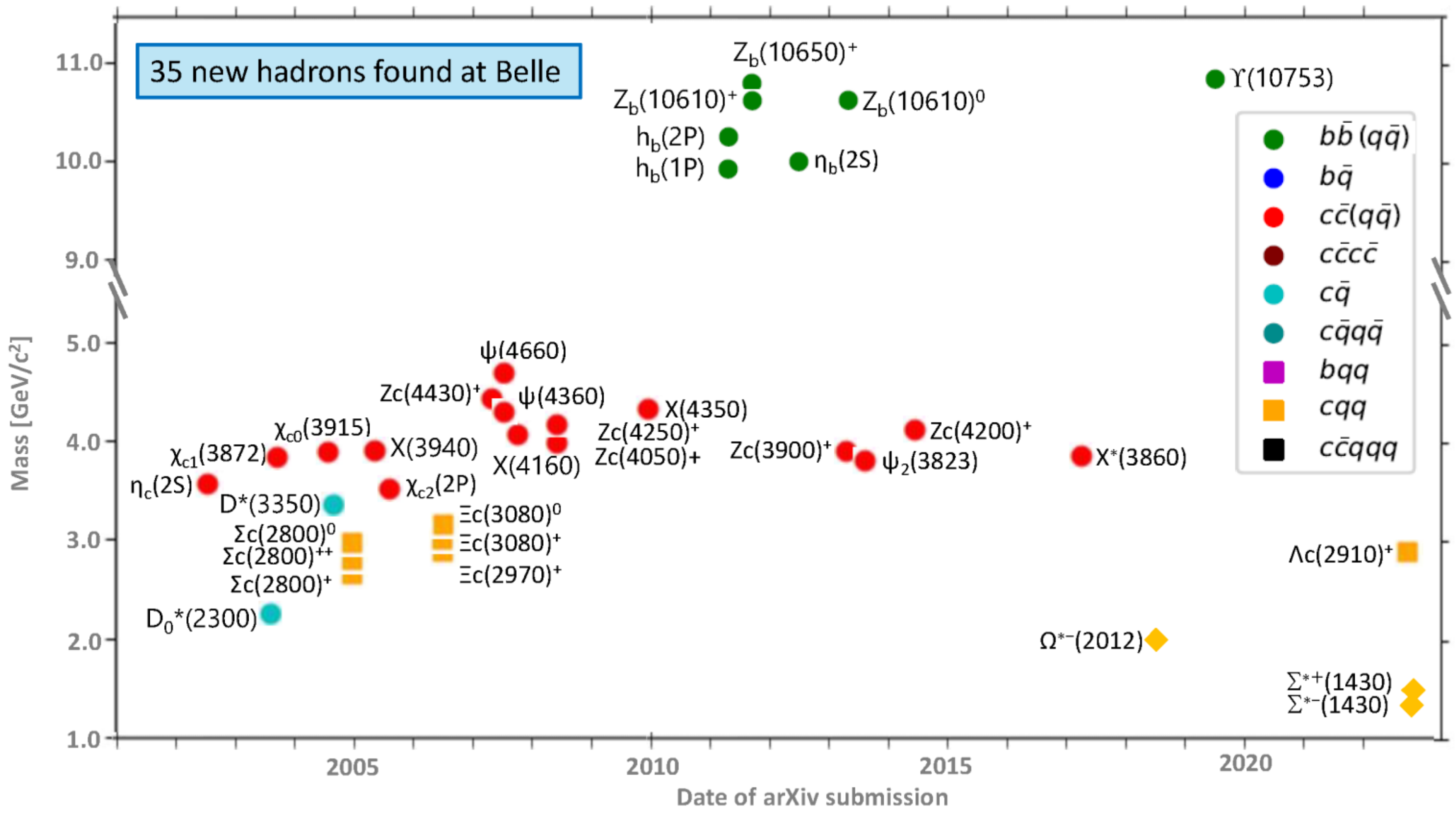




Above molecular predictions, below quark-model expectations: could be a mixed configuration

Quarkoium and exotic states

New hadrons found at Belle(II)

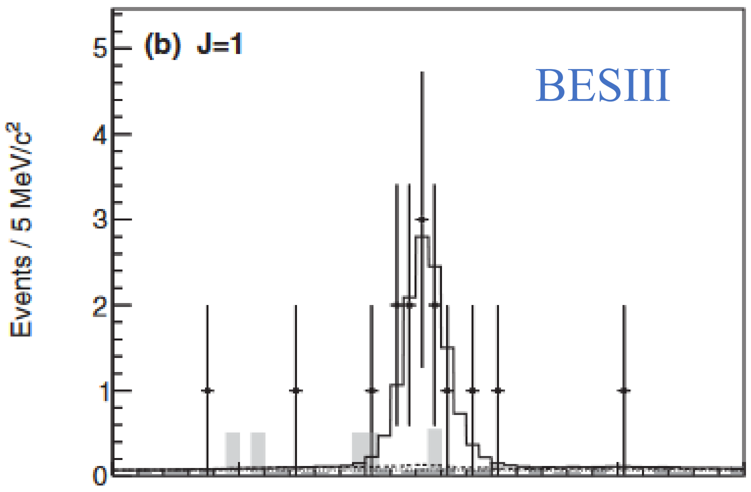


Belle II has been designed to make precise measurements of **weak interaction parameters, study exotic hadrons**, and search for **new phenomena** beyond the Standard Model of particle physics.

First evidence of $X(3872) \to \pi^0\chi_{c0}(1P)$ and search for $X(3915) \to \pi^0\chi_{c1}(1P)$

- 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, $\Gamma(2^3P_1 \to \chi_{c1}\pi^0)$~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; $\Gamma_0:\Gamma_1:\Gamma_2\sim 2.88:0.97:1$
- The $X(3915) \to \pi^0\chi_{c1}(1P)$ may be enhanced and searched for on the same mass spectrum
  - J=0 and J=2 modes are forbidden by P-conservation
- $X(3872) \to \pi^0\chi_{c1}$ was first observed by BESIII via $e^+e^- \to \gamma X(3872)$[PRL 122, 202001 (2019)]

- $\Gamma_1/\Gamma_{\pi\pi J/\psi} \equiv \mathcal{B}(X(3872) \to \pi^0\chi_{c1})/\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi = 0.88^{+0.33}_{-0.27} \pm 0.10$; $\Gamma_0/\Gamma_{\pi\pi J/\psi} < 19$; $\Gamma_2/\Gamma_{\pi\pi J/\psi} < 1.1$

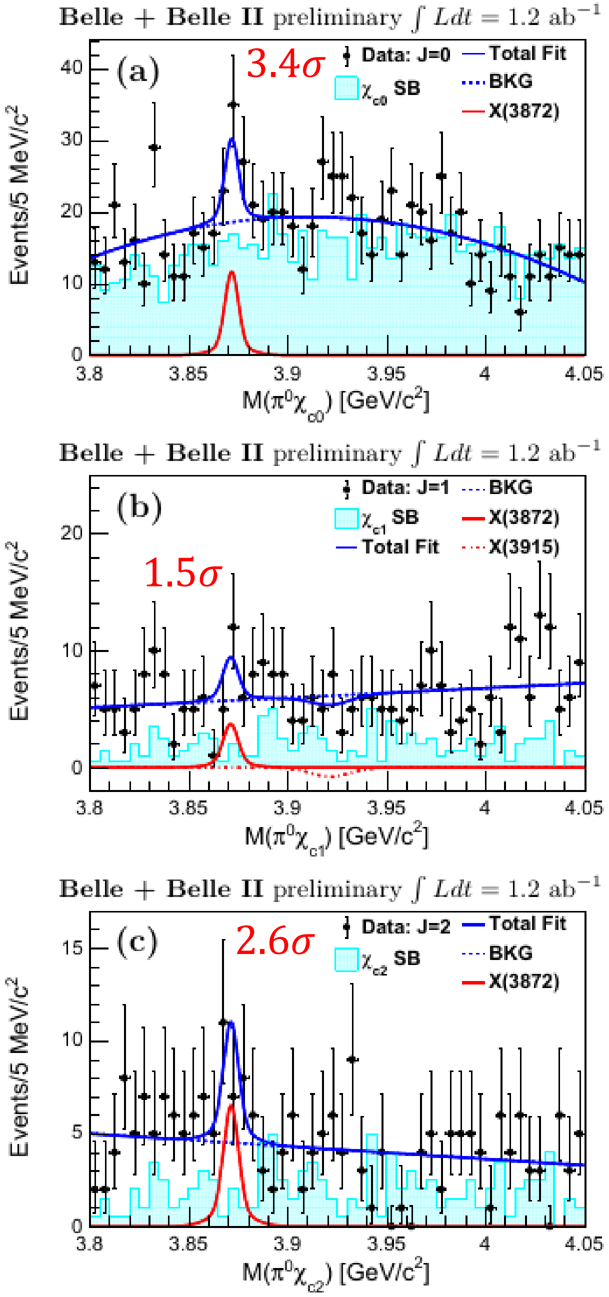


BESIII [PRL 122, 202001 (2019)]

- Belle reported the upper limit $\Gamma_1/\Gamma_{\pi\pi J/\psi} < 0.97$ [PRD 99, 111101 (2019)]
- BESIII updated the upper limit $\Gamma_0/\Gamma_{\pi\pi J/\psi} < 3.6$ [PRD 105, 072009 (2022)]
- No J=0 and J=2 modes are found yet

- Search for the $X(3872) \to \pi^0\chi_{cJ}$ and $X(3915) \to \pi^0\chi_{c1}$ decays via $B^+ \to \pi^0\chi_{cJ}K^+$ processes in Belle and Belle II

First evidence of $X(3872) \to \pi^0\chi_{c0}(1P)$ and search for $X(3915) \to \pi^0\chi_{c1}(1P)$

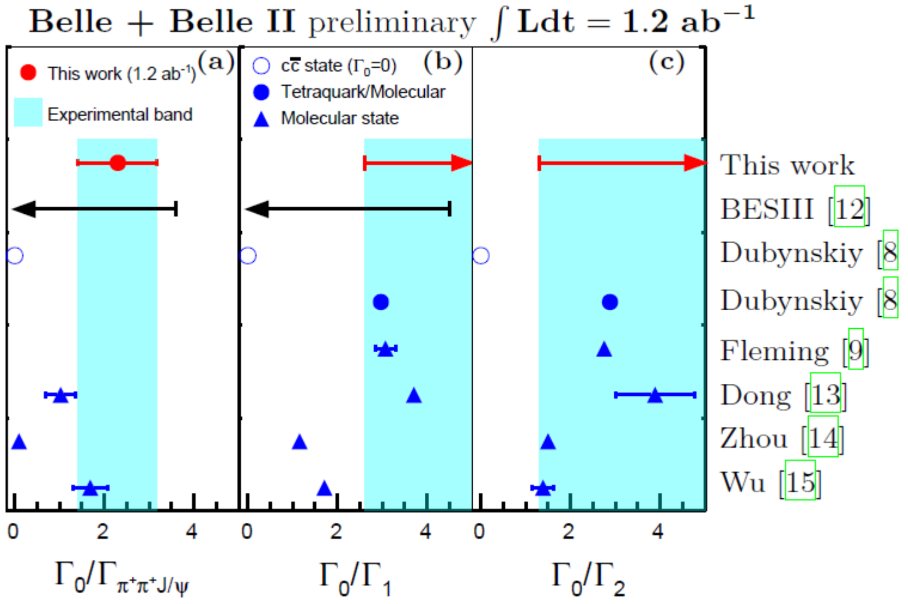


- First evidence of $X(3872) \to \pi^0\chi_{c0}$: 23.7 ± 8.1 events; $\Gamma_0/\Gamma_{\pi\pi J/\psi} = 2.3 \pm 0.8 \pm 0.4$
- No significant signals for other modes are observed:

$$\Gamma_1/\Gamma_{\pi\pi J/\psi} < 0.9,\ \ \Gamma_2/\Gamma_{\pi\pi J/\psi} < 1.8;\ \Gamma_0/\Gamma_1 > 2.6,\ \ \Gamma_0/\Gamma_2 > 1.3$$

arXiv:2606.24578

- A comparison on (a) $\Gamma_0/\Gamma_{\pi^+\pi^- J/\psi}$, (b) Γ_0/Γ_1, (c) Γ_0/Γ_2



[12] PRD 105, 072009 (2022)
[8] PRD 77, 014013 (2008)
[9] PRD 78, 094019 (2008)
[13] PRD 79, 094013 (2009)
[14] PRD 100, 094025 (2019)
[15] EPJC 81, 193 (2021)

- Disfavor a pure charmonium interpretation: $\Gamma(\chi_{c1}(2P) \to \pi^0\chi_{c0})$ should be zero
- Consistent with most of predictions in molecular scenario
- Absolute $\mathcal{B}(X(3872) \to \pi^0\chi_{c0}) = (9.9 \pm 4.8)\%$, might be the largest hidden charm decay mode up to now

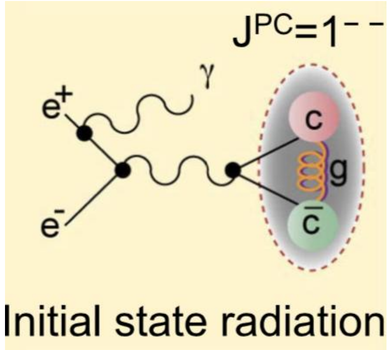
$e^+e^- \to h^+h^-J/\psi$ (h = π, K, p) via initial-state radiation (ISR) at Belle II

Adavantages of ISR:

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

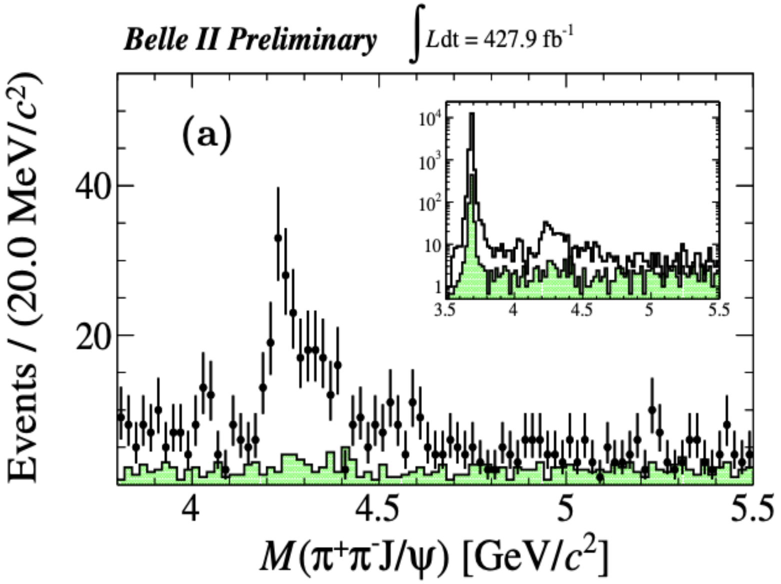
Disadvantages of ISR:

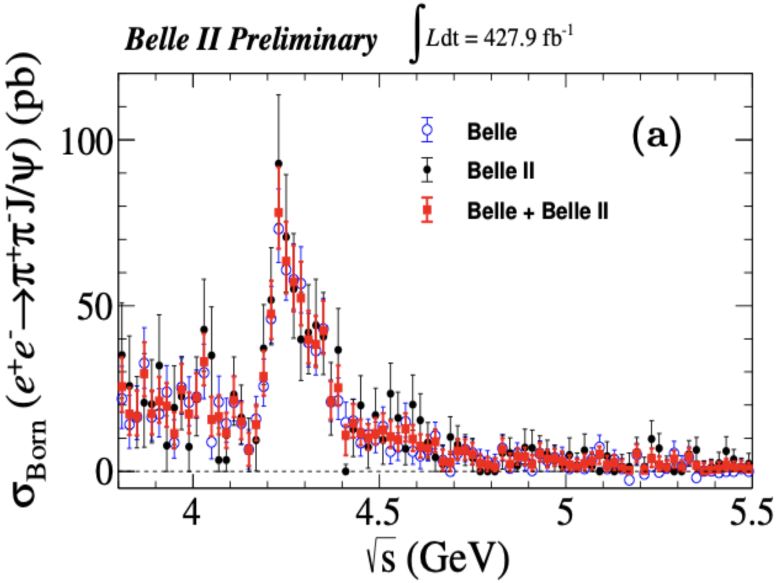
- The effective integrated luminosity decreases as the c.m. energy decreases
- The detection efficiency is also smaller

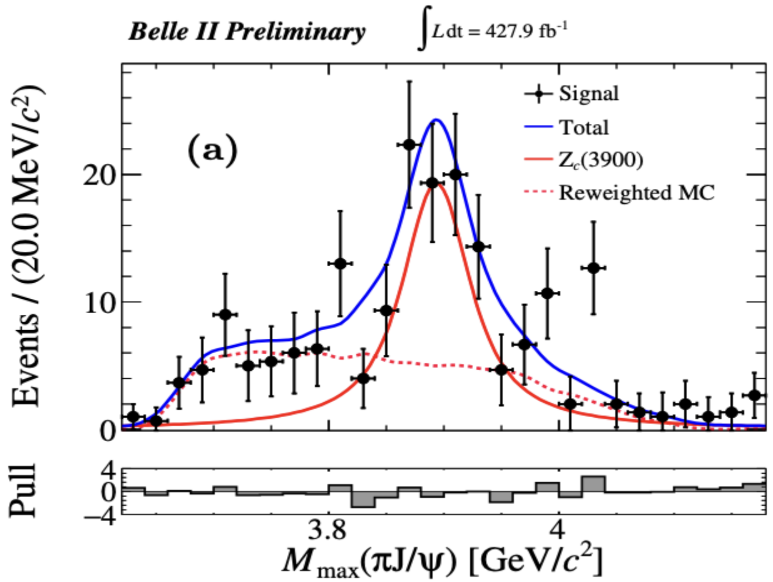


$e^+e^- \to \pi^+\pi^-J/\psi$ via ISR:

arXiv:2602.13569

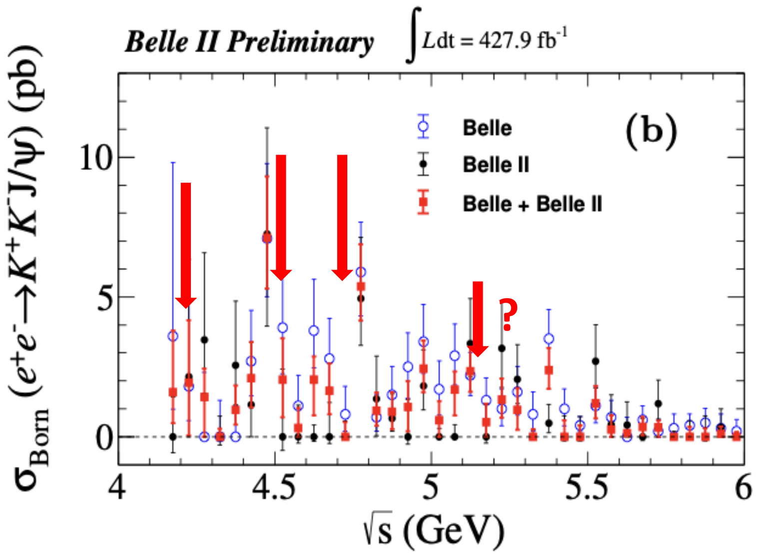




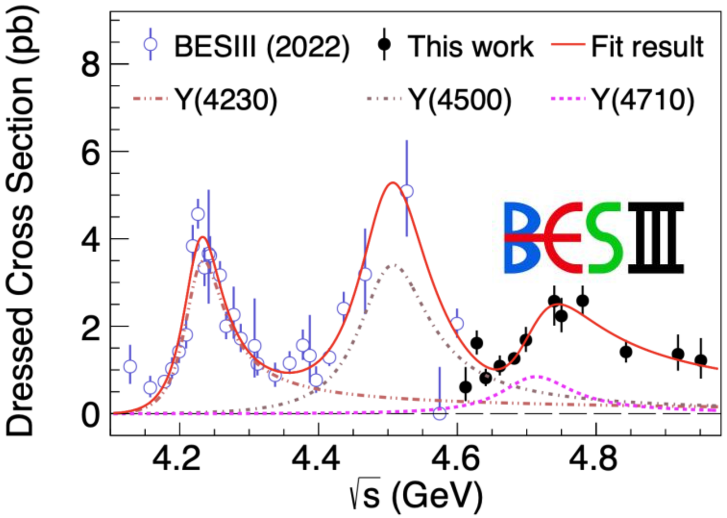


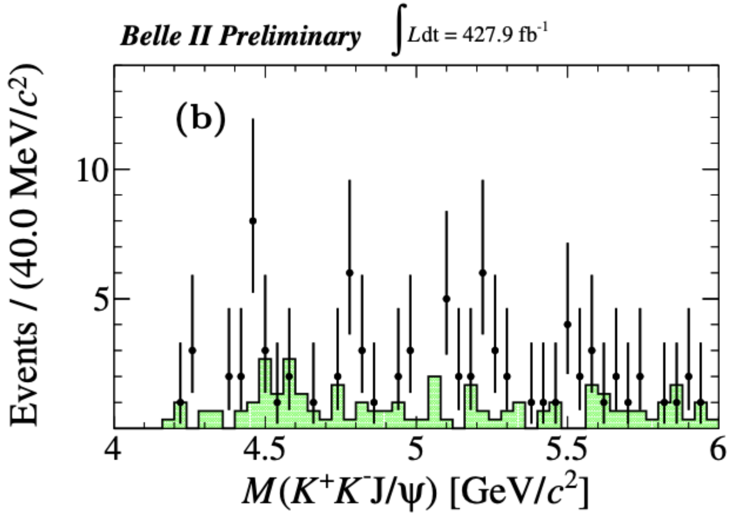
- **We can see the Y(4008) evidence and Y(4230/4320) signal.**
- **The significance of $Z_c(3900)$ is 5.3σ.**

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



PRL 131, 211902 (2023)

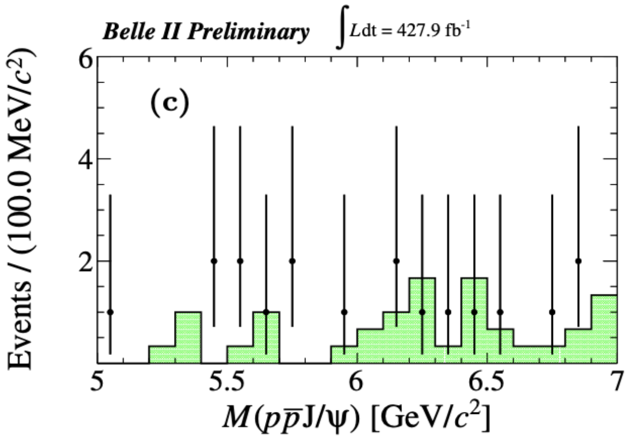


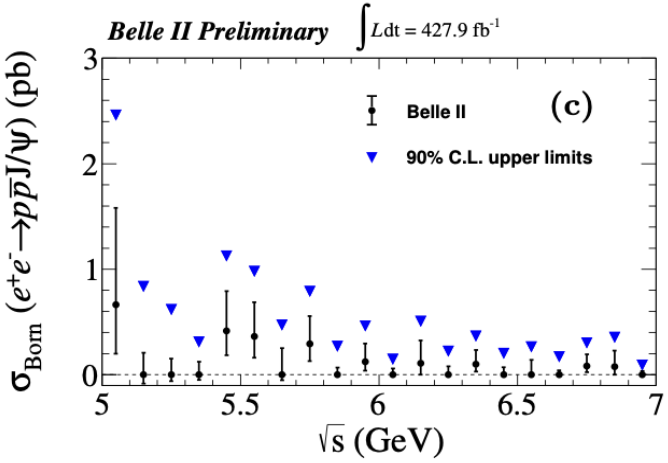


- **No clear signals were observed at Belle II.**
- **More data are needed.**

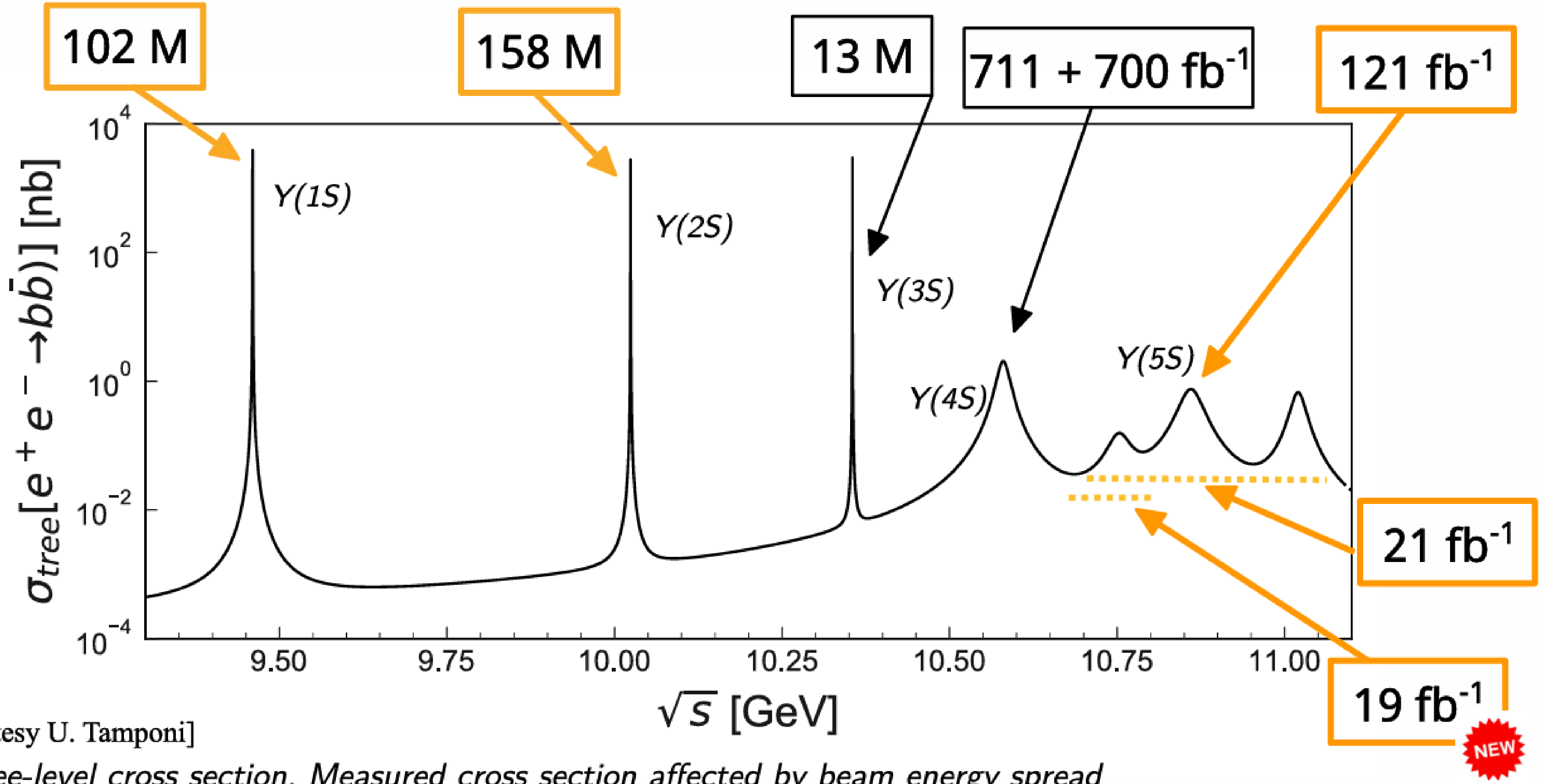
$e^+e^- \to p\bar{p}J/\psi$ via ISR:

The cross section for $e^+e^- \to P_c\bar{p}$ is estimated to be $\lesssim \mathcal{O}(0.1\ \text{pb})$ [arXiv: 2508.08694].





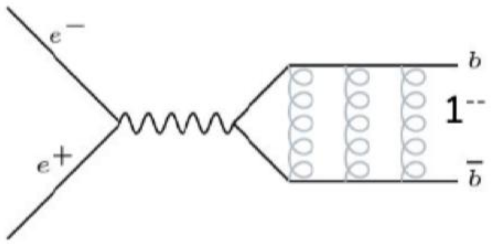
Bottomonium

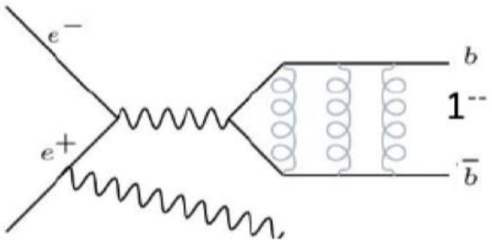


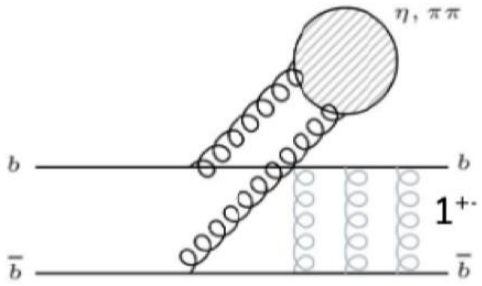
[Courtesy U. Tamponi]

*Tree-level cross section. Measured cross section affected by beam energy spread

Bottomonium Spectrum







Four main 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, ππ, etc

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

- Radiative transitions from $\Upsilon(nS)$

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

First measurement of the masses of the $\Upsilon_1(1D)$ and $\Upsilon_3(1D)$ states and energy dependences of cross sections for $e^+e^- \to \Upsilon_J(1D)\eta$ and $e^+e^- \to \Upsilon_J(1D)\pi^+\pi^-$

- 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 $\Upsilon_J(1D)$ masses 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)].

The table on the right shows the data used in this analysis.

$\sqrt{s}$ (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

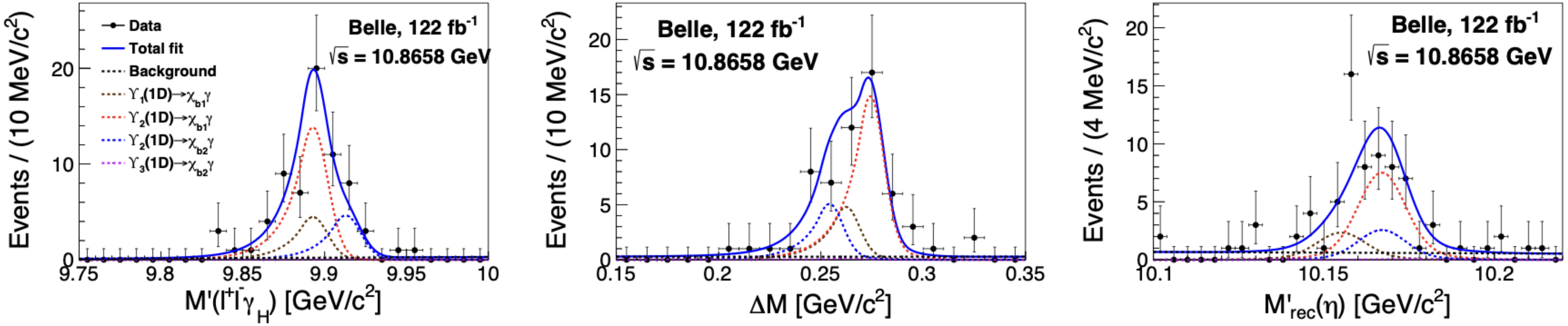
Yields and Masses at $\sqrt{s}$ = 10.866 GeV

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

Three-dimensional fit results

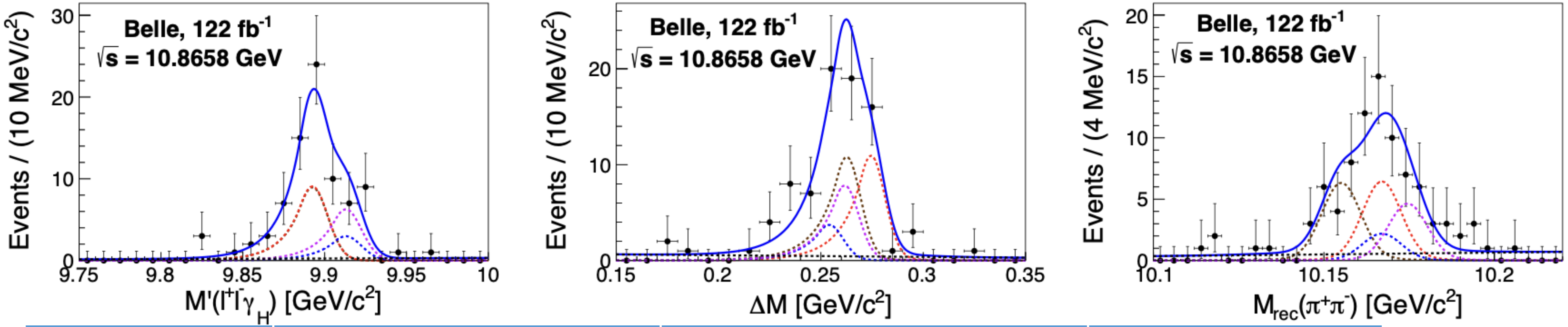
arXiv:2607.04369

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



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

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



The systematic uncertainty is calculated by changing the fit models, including the fit range, peak position, mass resolution, polynomial order, the yield ratio between $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$.

$\Upsilon_2(1D)$ mass
(10167.0±1.0±0.2) MeV/c^2
$\Delta m_{21} = m(\Upsilon_2(1D)) - m(\Upsilon_1(1D))$
(11.8±1.5±0.4) MeV/c^2
$\Delta m_{32} = m(\Upsilon_3(1D)) - m(\Upsilon_2(1D))$
(7.6±2.4±0.6) MeV/c^2

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)

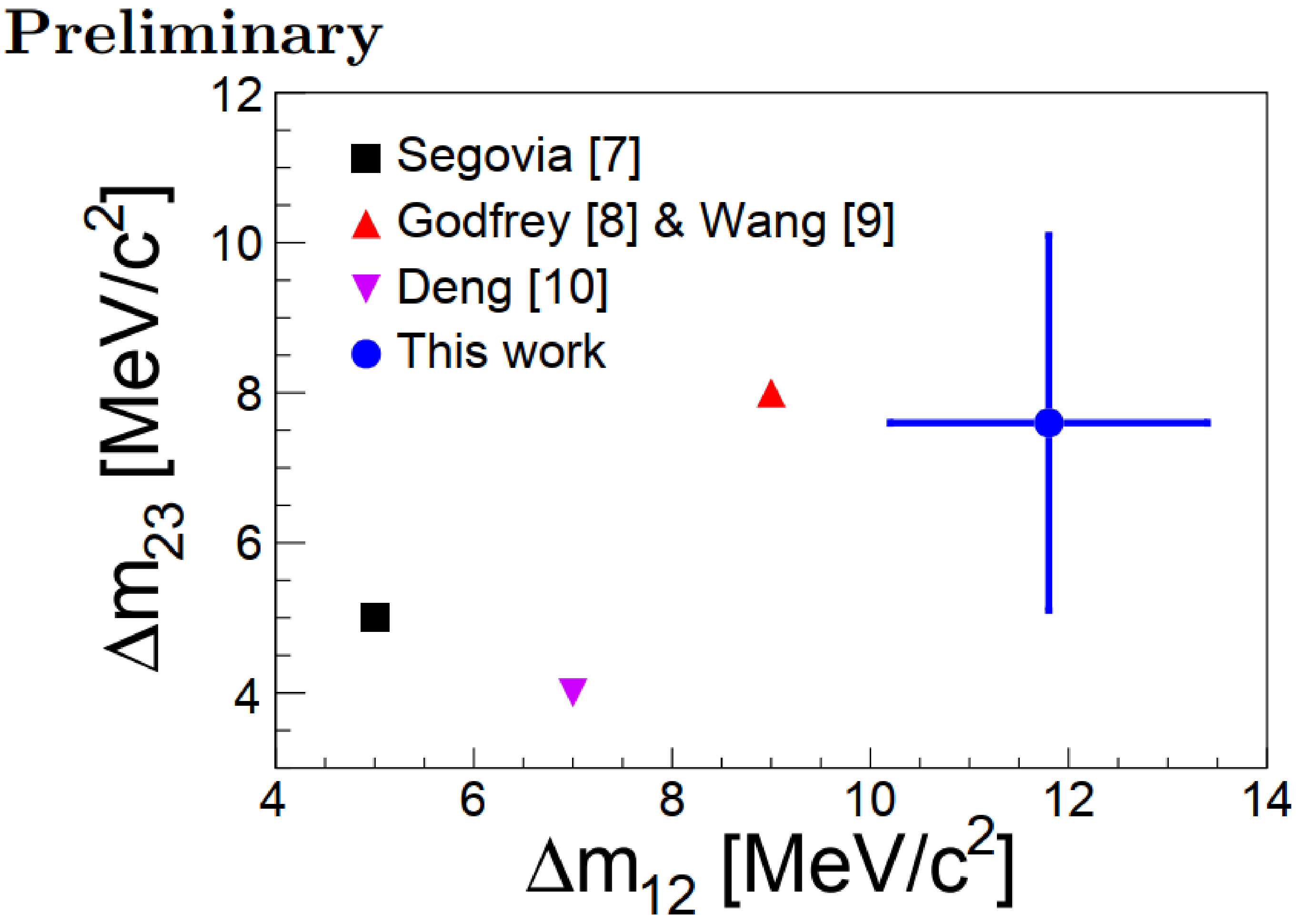
From the fit:

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

Consistent with the prediction of ≈0.3 in PRD 92, 054034 (2015) within ±1.2σ.

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)]

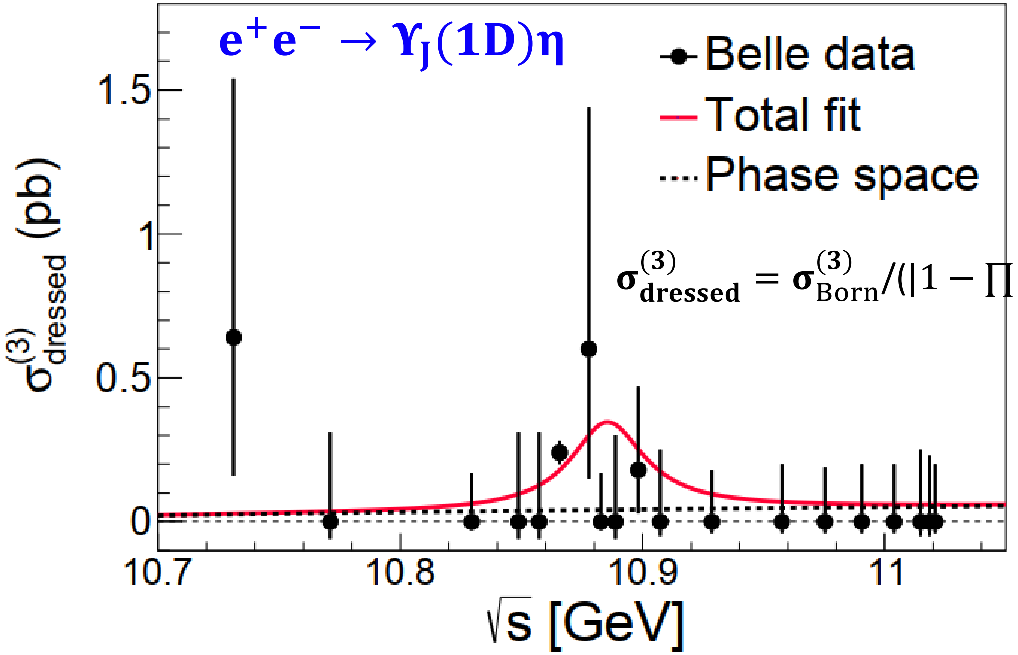
The dressed cross sections as a function of C.M. energy:

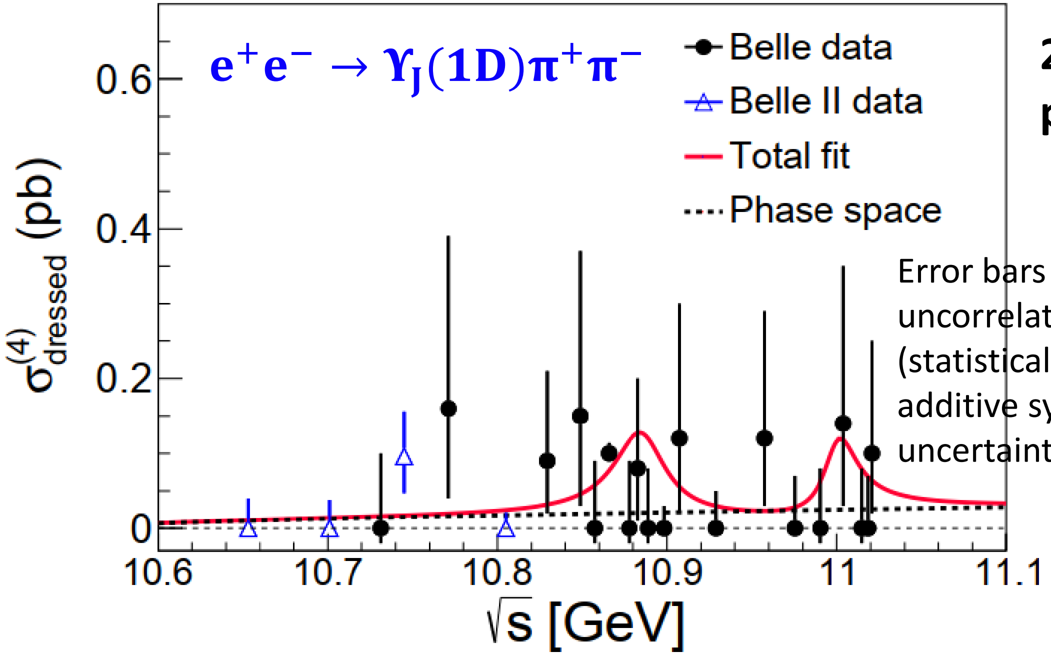
$$\sigma^{(3)}_{\rm Born} = \sigma_{\rm Born}(e^+e^- \to \Upsilon_J(1D)\eta)\,\mathcal{B}(\Upsilon_J(1D) \to \chi_{b1,b2}\gamma)\,\mathcal{B}(\chi_{b1,b2} \to \Upsilon(1S)\gamma)$$

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

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 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 [arXiv:2602.19807, accepted by JHEP].

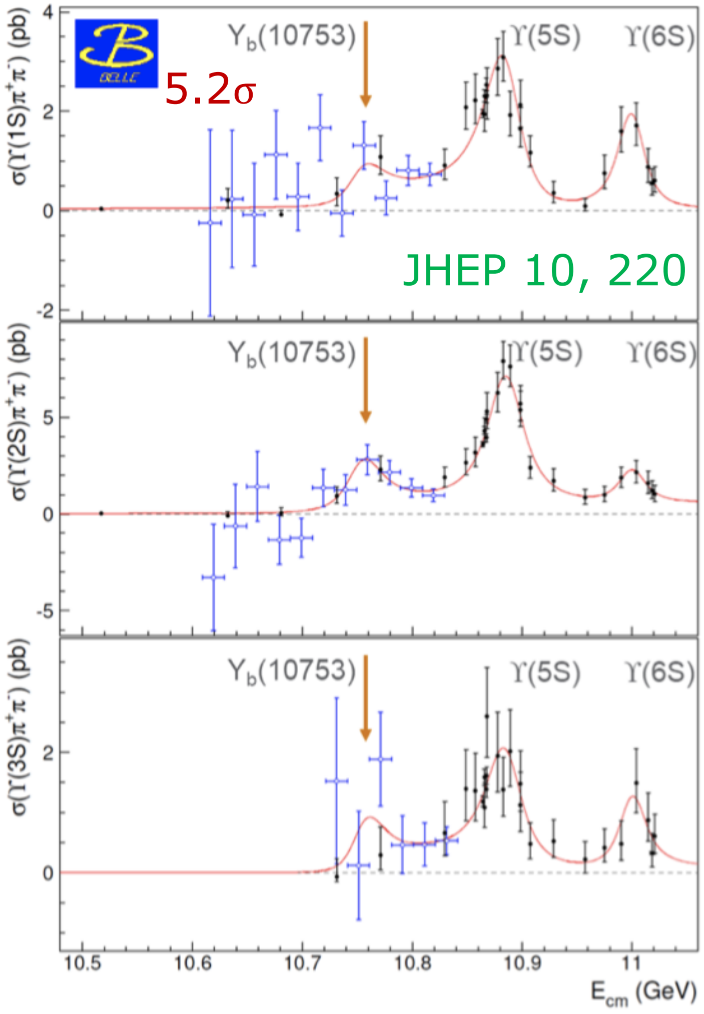
The signal significances of fit outputs are less than 3σ, the upper limits at 90% C.L. are also given in square brackets.

arXiv:2607.04369

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

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

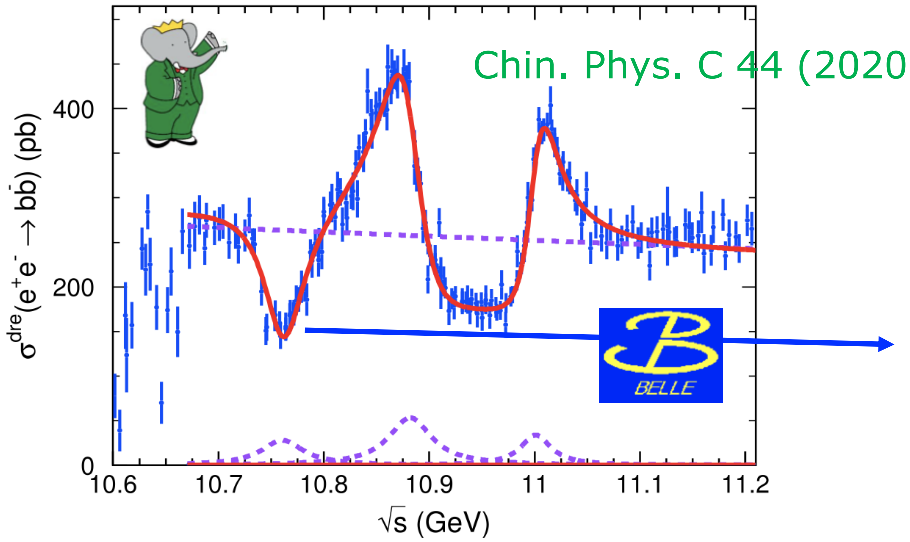
Discovery of Υ(10753)



JHEP 10, 220 (2019)

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

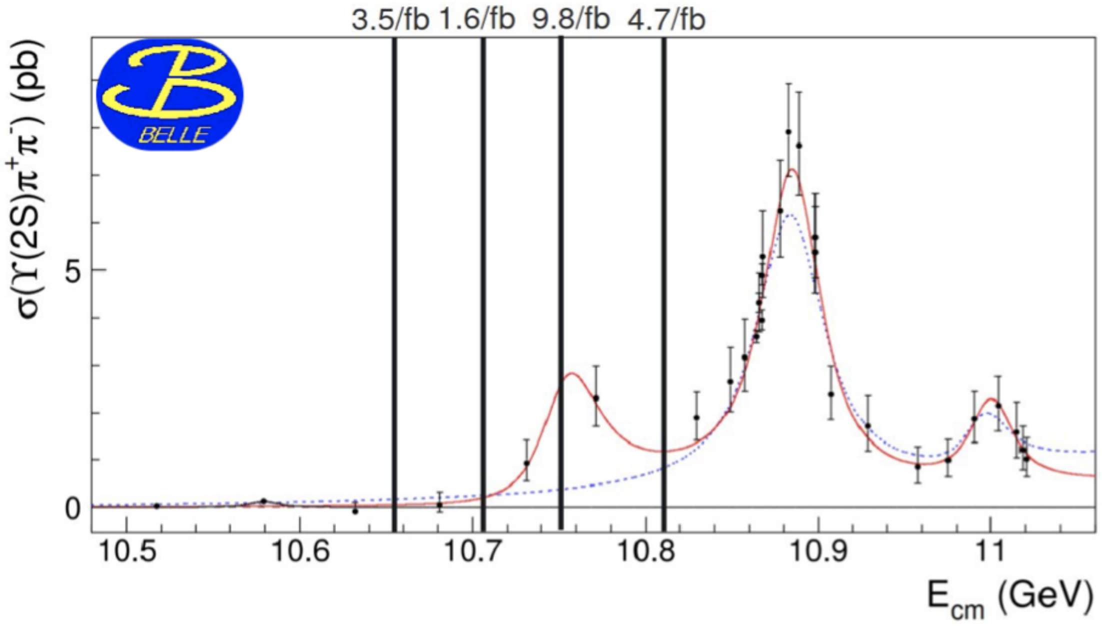
	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}\,^{+1.0}_{-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$

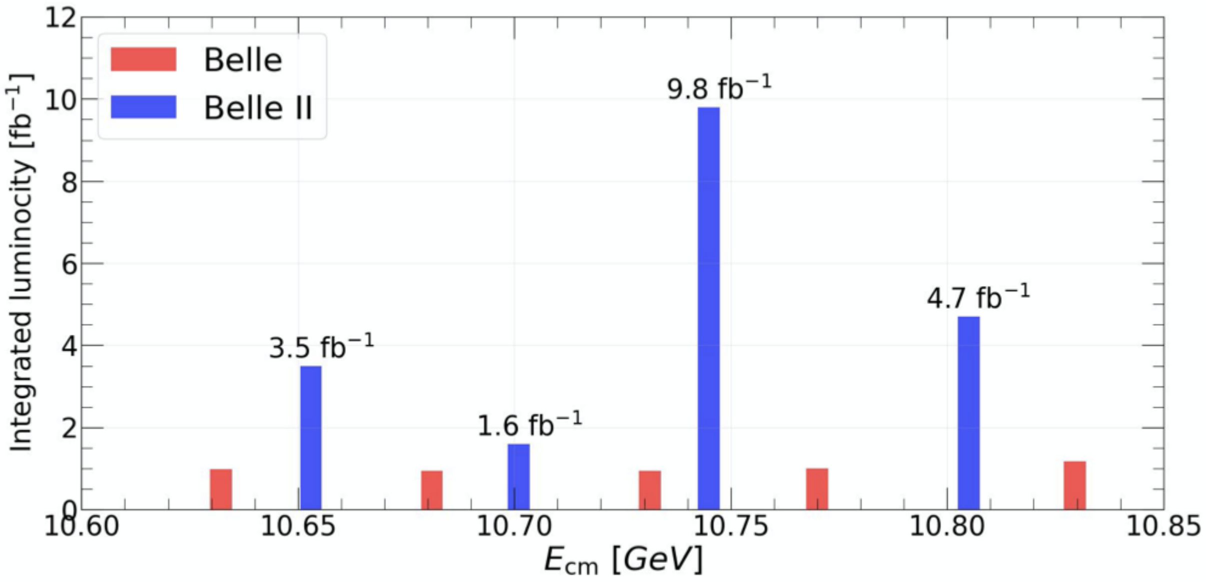


Chin. Phys. C 44 (2020) 8, 083001

A dip at 10.75 GeV may correspond to Υ(10753).

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

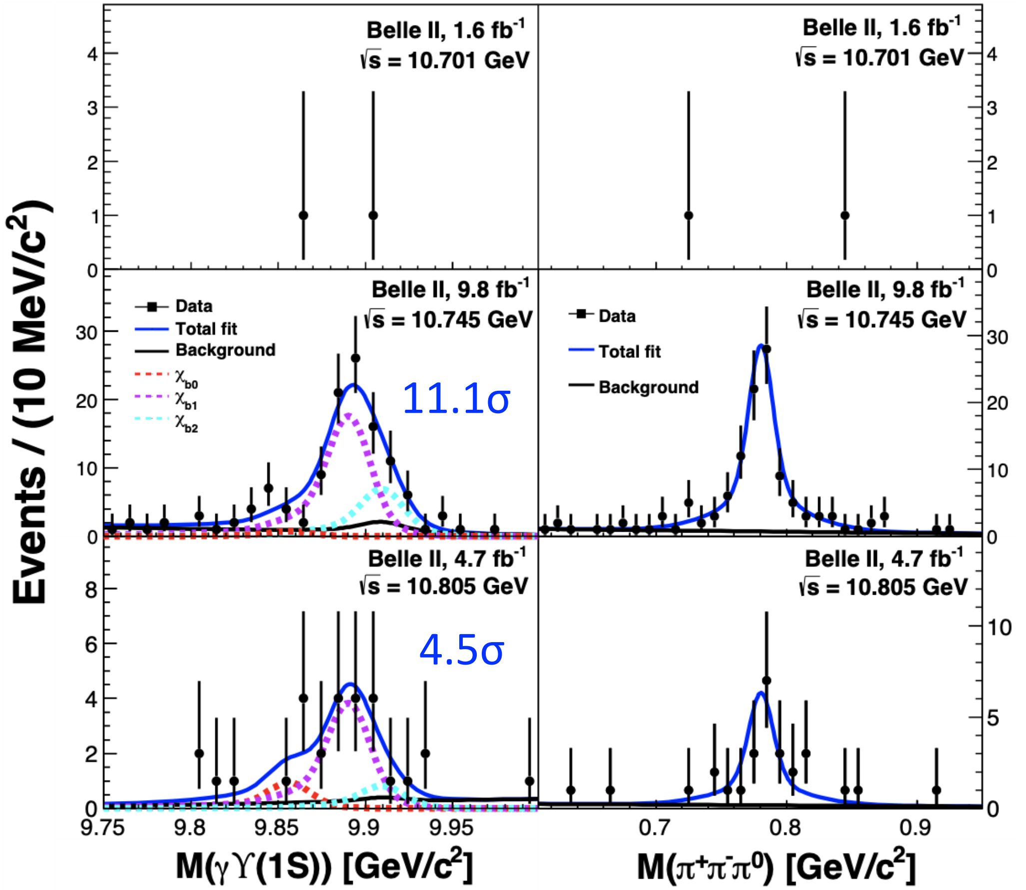




- In November 2021, Belle II collected 19 fb^{-1} of unique data at energies above the Υ(4S): four energy scan points around 10.75 GeV.
- Belle II collected the data in the gaps between Belle energy scan points.
- Physics goal: understand the nature of the Υ(10753) energy region.

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

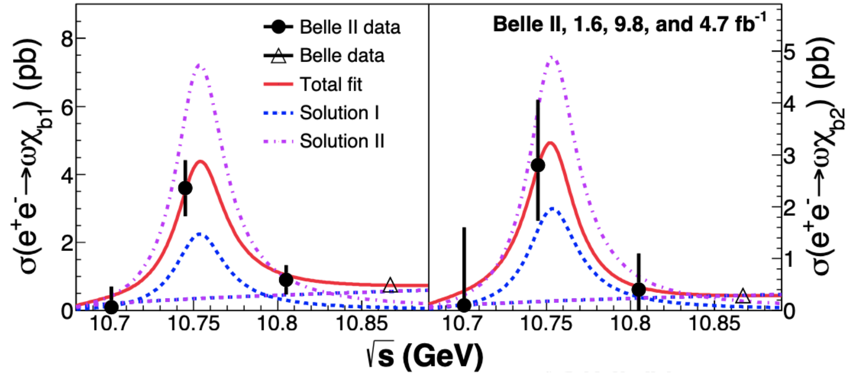
Two dimensional unbinned maximum likelihood fits to the $M(\gamma\Upsilon(1S))$ and $M(\pi^+\pi^-\pi^0)$ distributions.



PRL 130, 091902 (2023)

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.

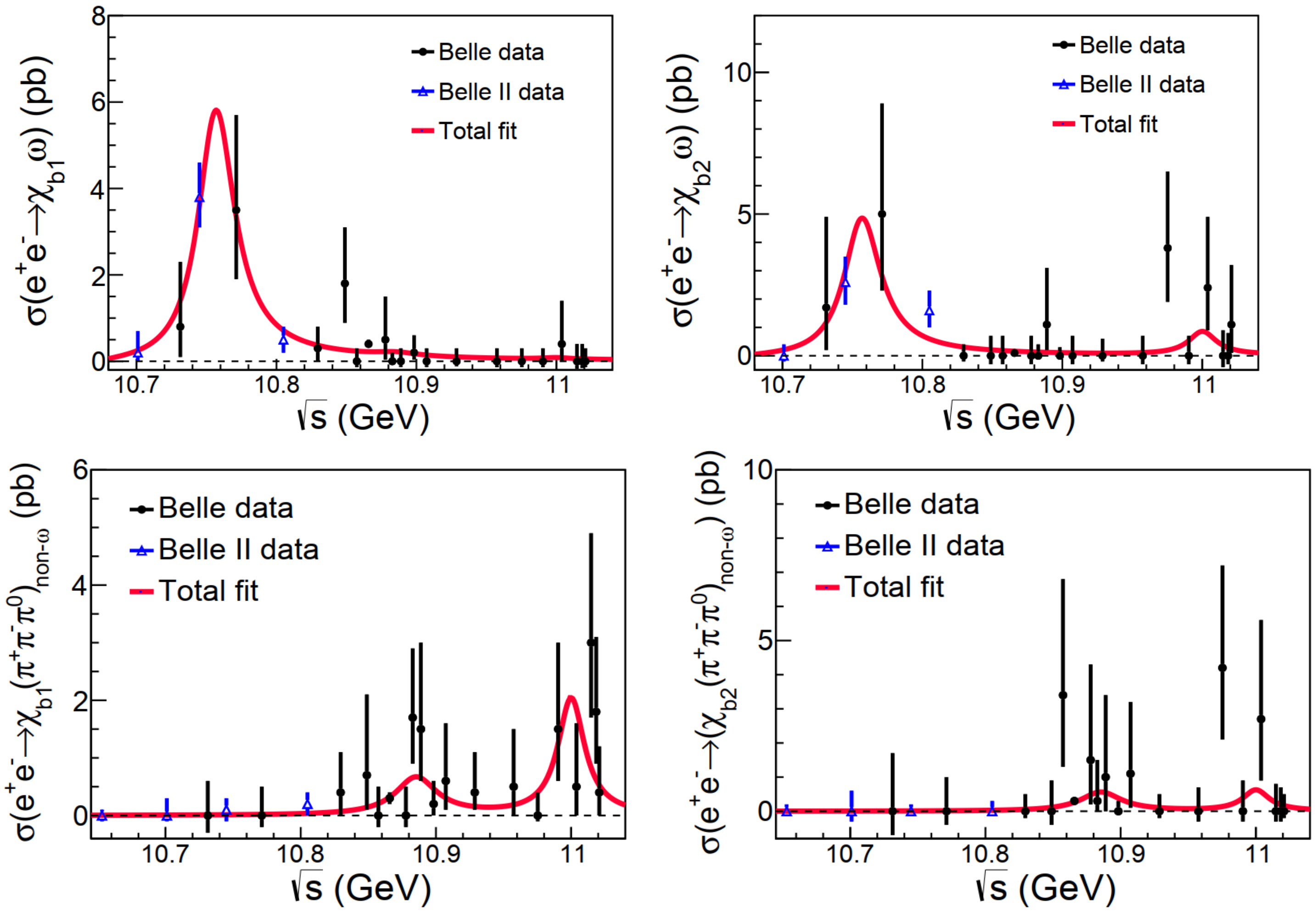
The $e^+e^- \to \omega\chi_{bJ}$ (J = 1, 2) cross sections peak at $\Upsilon(10753)$.



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

$e^+e^- \to \omega\chi_{bJ}$ 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

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

1.5 at $\sqrt{s}\sim10.75$ GeV

0.15 at $\sqrt{s}\sim10.867$ GeV

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

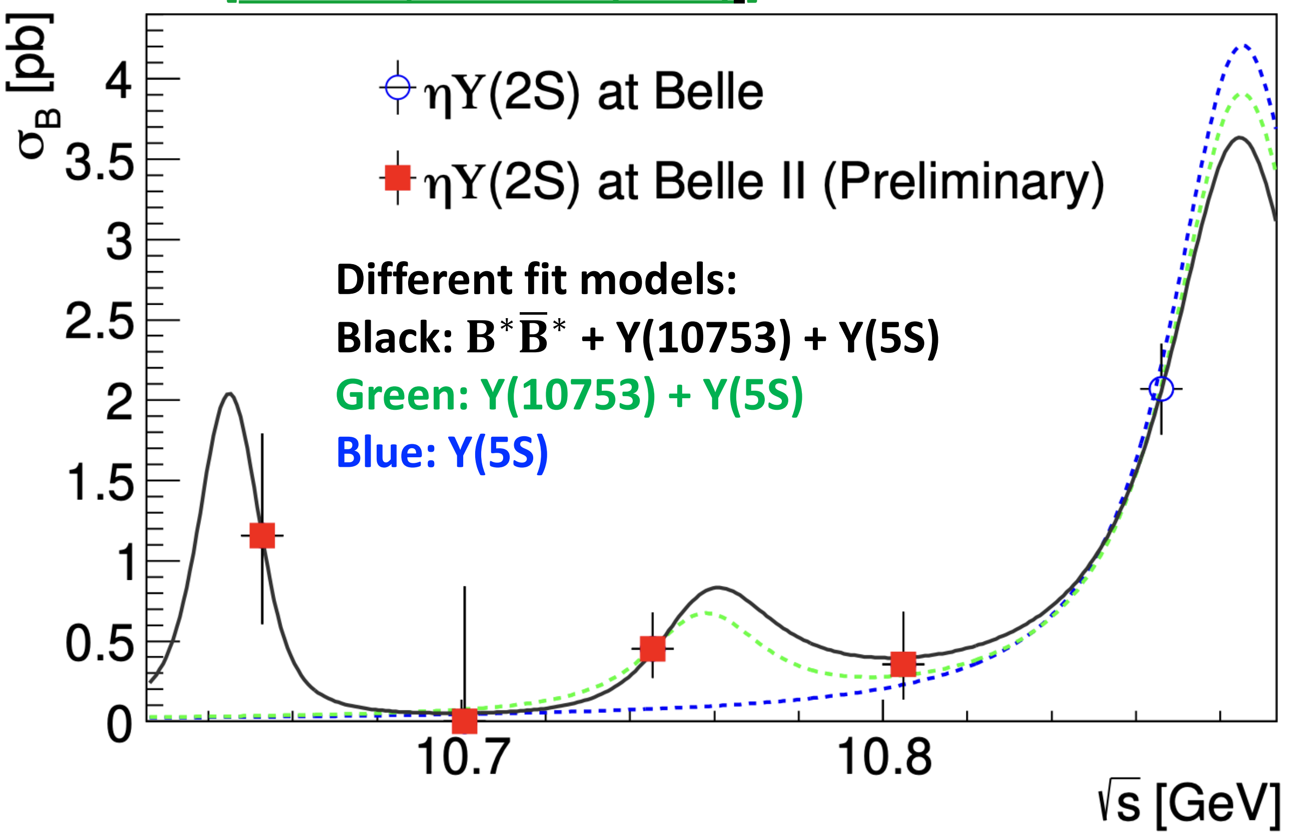
$\mathcal{B}(\Upsilon(10753)\to\chi_{b1}\,\omega)/\mathcal{B}(\Upsilon(10753)\to\chi_{b2}\,\omega)$

1.13±0.38±0.34

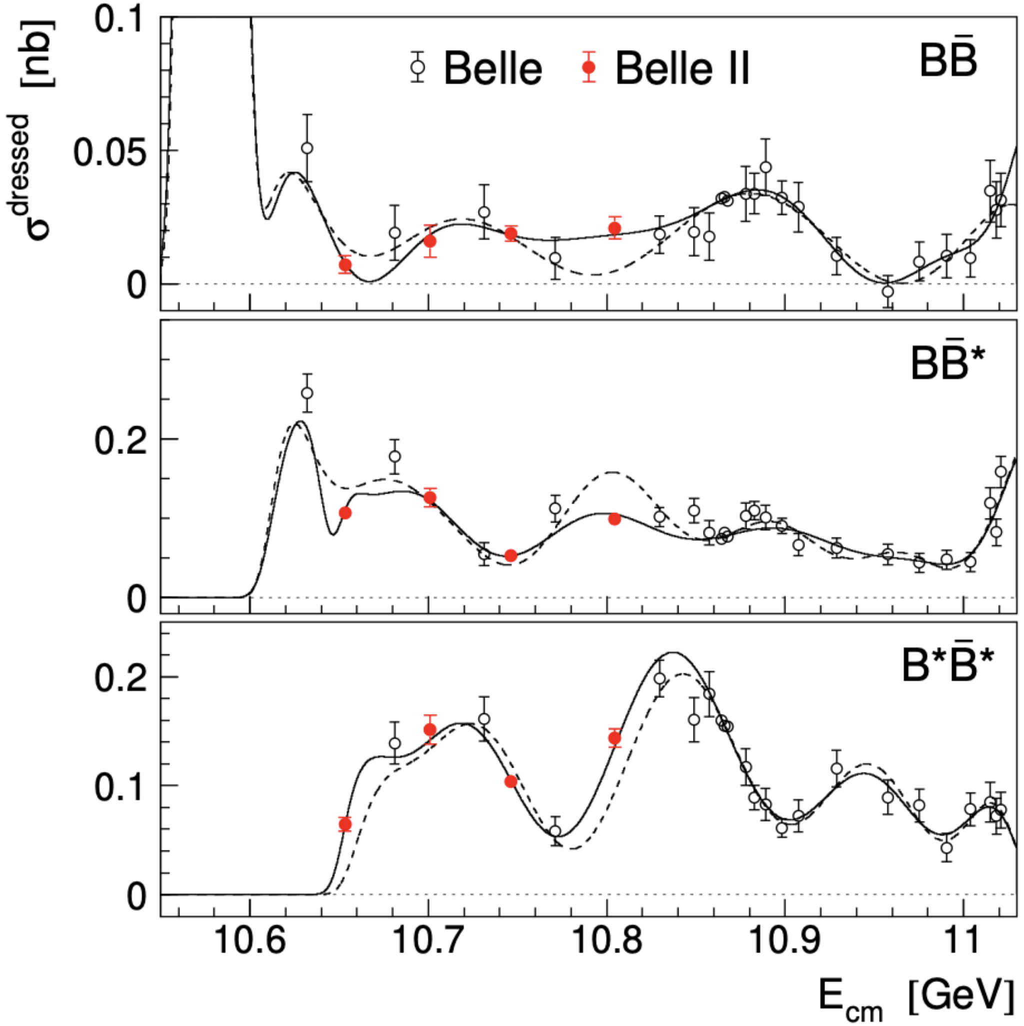
- The $(\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}$ excess maybe due the cascade decay of $\Upsilon(10860, 11020)\to Z_b\pi\to\chi_{bJ}\rho\pi$ [PRD 90, 014036 (2014)].

$e^+e^- \to \eta\Upsilon(2S)$ and $e^+e^- \to B^{(*)}\bar{B}^{(*)}$

[PRD 113, L051102 (2026)]



[JHEP 10 (2024) 114]



- The Born cross section of $e^+e^- \to \eta\Upsilon(2S)$ around $B^*\bar{B}^*$ mass is relatively large.

The significance of $B^*\bar{B}^*$ bound state is larger than 3.2σ

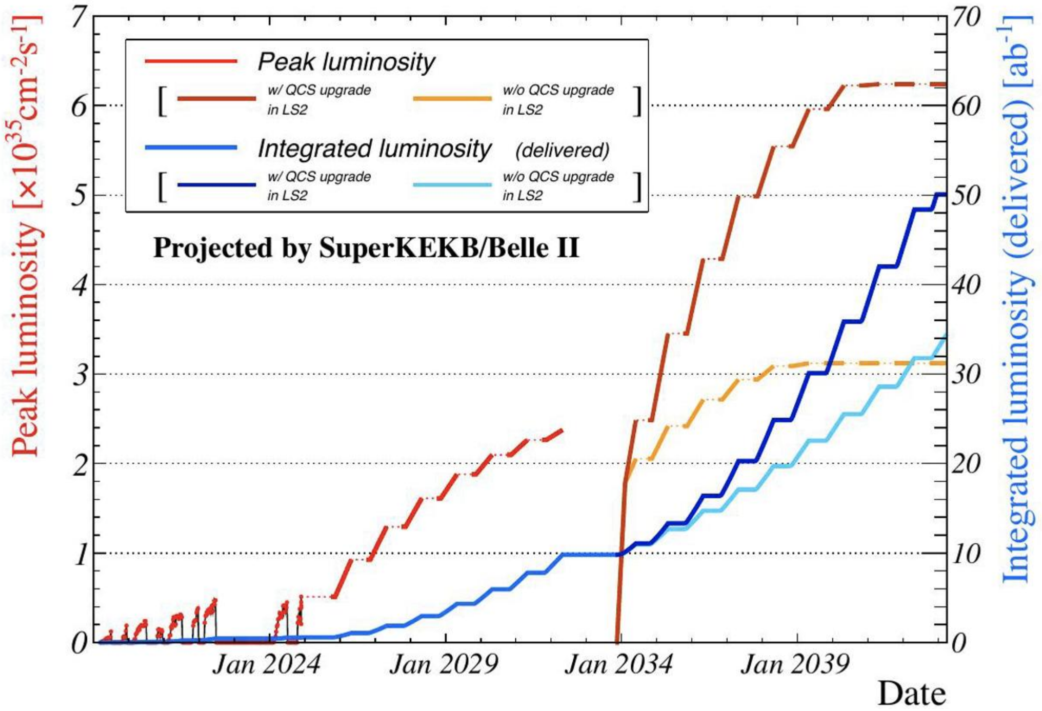
Rapid increase of $\sigma_{B^*\bar{B}^*}$ just above the threshold.

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

The $Y_b(10650)$ is 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.

During the long shutdown starting in 2032, upgrades are planned for the SuperKEKB accelerator and the Belle II detectors

From SNOWMASS2021 (https://arxiv.org/pdf/2203.10203)

Physics reach:

The goal of Belle II is to uncover new physics beyond the Standard Model.

- **Testing violations of lepton flavor conservation and universality and understanding their origins**
- **Checking the unitarity of the CKM matrix to high precision**
- **Identifying new weak (CP-violating) phases in the quark sector**
- **Probing the existence of dark-sector particles at MeV to GeV mass scales**
- **Reducing the uncertainty in the theory prediction for the muon g−2 anomaly**
- **Understanding the role of QCD in the production and binding of new hadronic states of matter**

XYZ particles: review articles, books, & web pages

- H.-X. Chen et al., The hidden-charm pentaquark and tetraquark states, Phys. Rept. 639 (2016) 1
- A. Hosaka et al., Exotic hadrons with heavy flavors: X, Y, Z, and related states, PTEP 2016 (2016) 062C01
- J.-M. Richard, Exotic hadrons: review and perspectives, Few Body Syst. 57 (2016) 1185
- R. F. Lebed, R. E. Mitchell, E. Swanson, Heavy-quark QCD exotica, PPNP 93 (2017) 143
- A. Esposito, A. Pilloni, A. D. Polosa, Multiquark resonances, Phys. Rept. 668 (2017) 1
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Summary

Belle II is presently increasing its instantaneous luminosity, perfect for B and charm decays, exotic/quarkonium studies, ….

- **Some are special at e^+e^- collider**

- **Only ~2% of target luminosity collected so far. Until 2026, about 1 ab^{-1} data at Belle II. Stay tuned for more exciting results from Belle II.**

Thanks for your attention!