Flavour Physics Lecture 味物理讲座
2025年第21期
总第九十四期

Belle II实验上重味夸克偶素的研究

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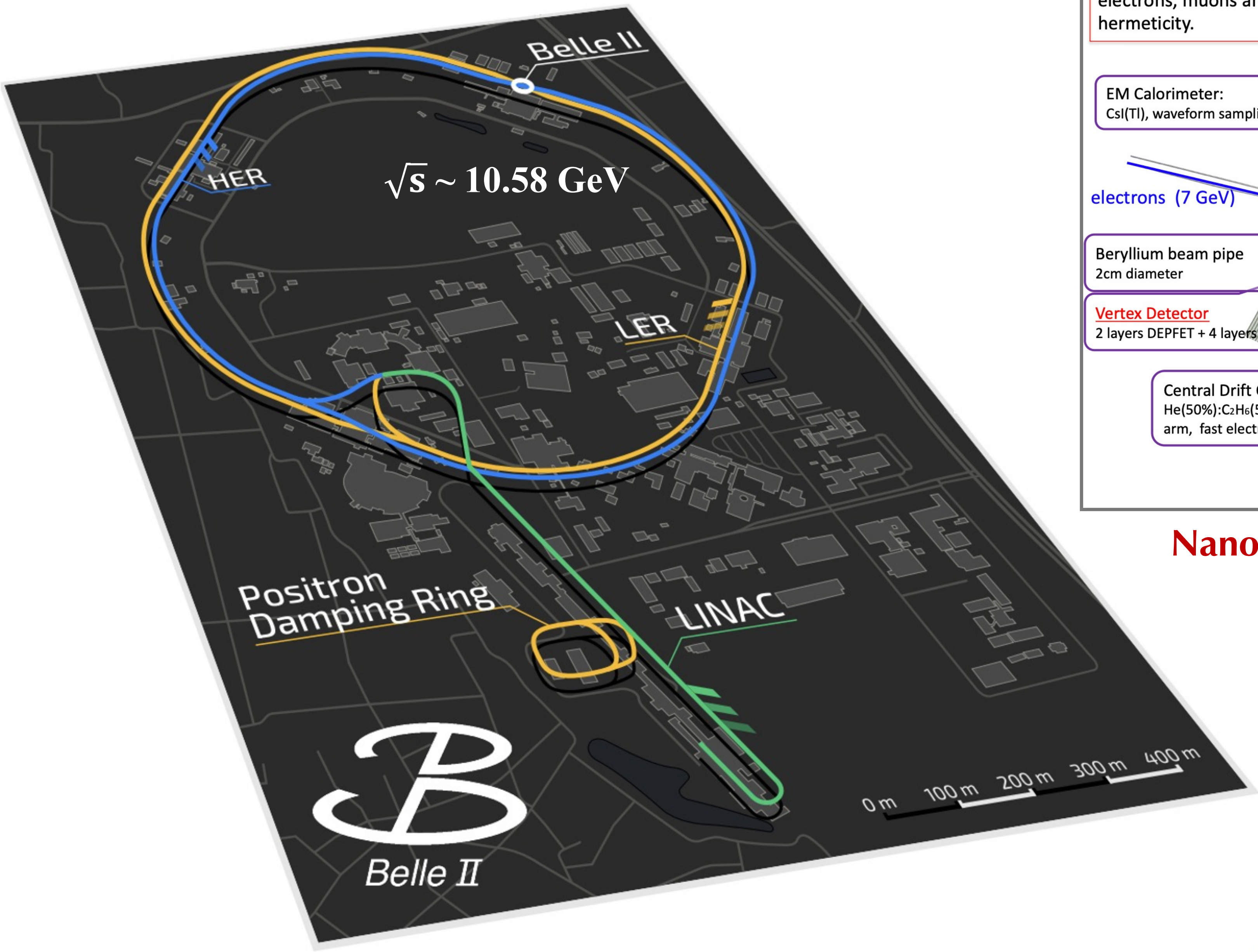
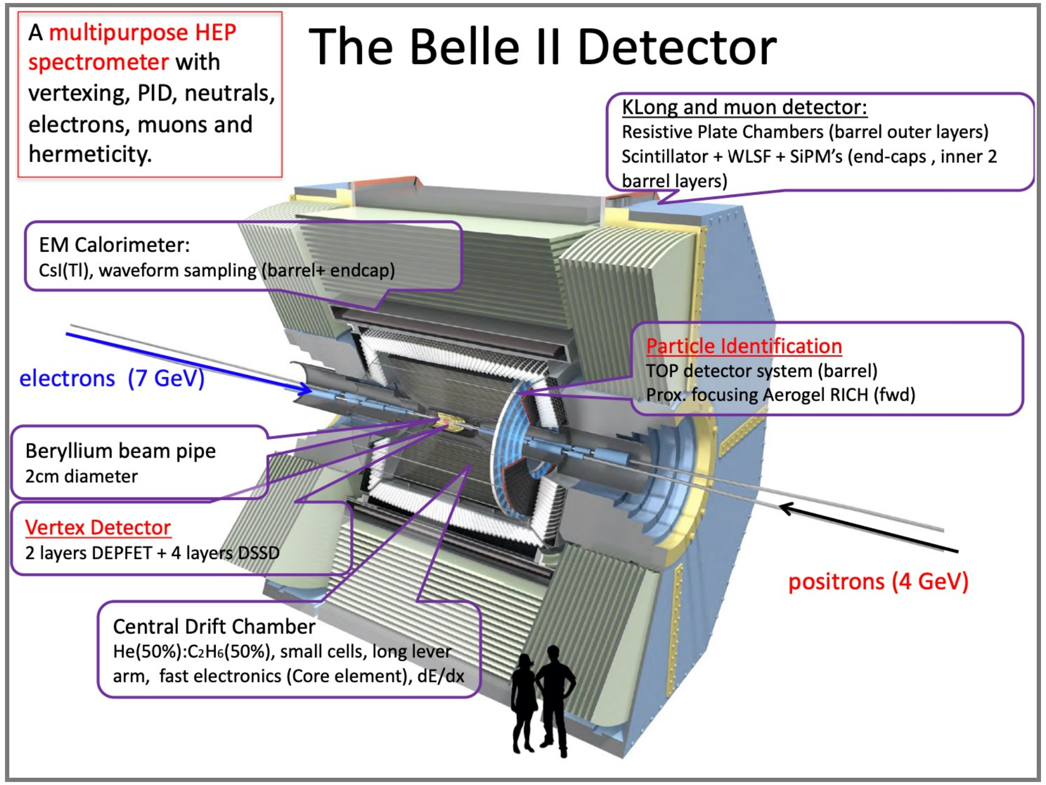
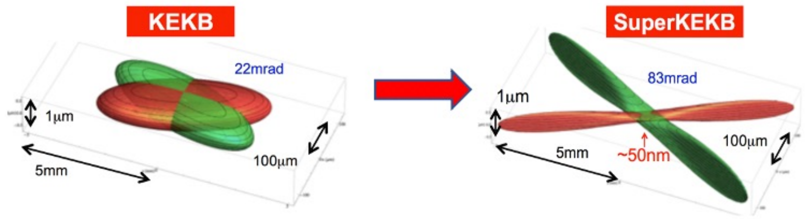
味物理讲座，2025年11月20日

SuperKEKB and Belle II





Nano-beam design:



Nano-beam design:

Beam squeezing: ×20 smaller;

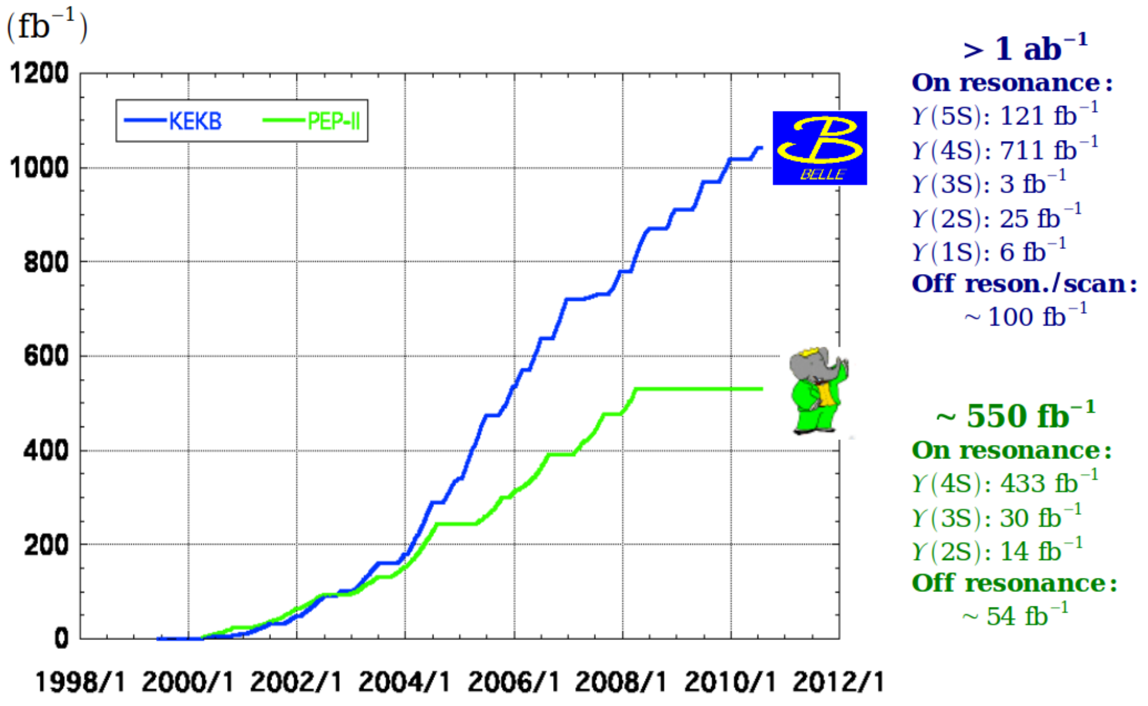
Beam current: ×2 larger

Target peak luminosity: KEKB×30

Belle and Belle II Datasets

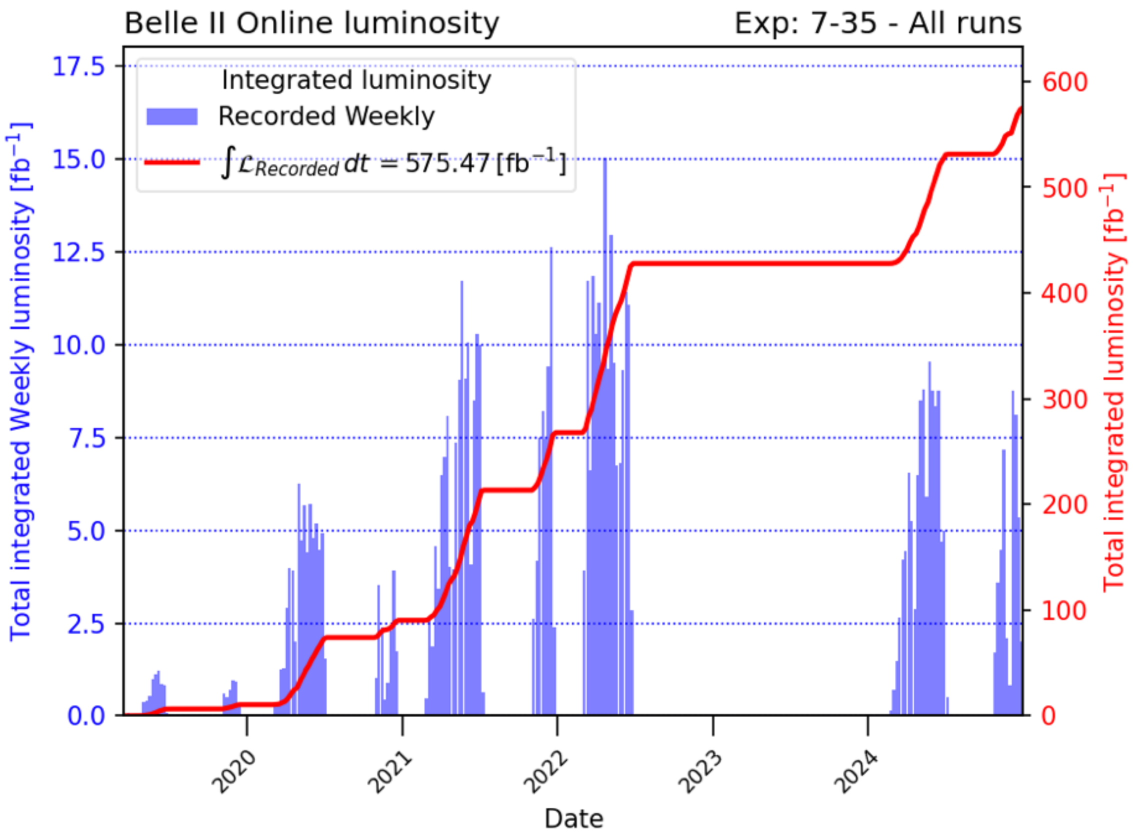
- **Belle (1999 - 2010)**
- **Belle II RUN-I (2019 - 2023)**
- **Belle II RUN-II (2024 - 2025)**

Integrated luminosity of B factories



In December 2024

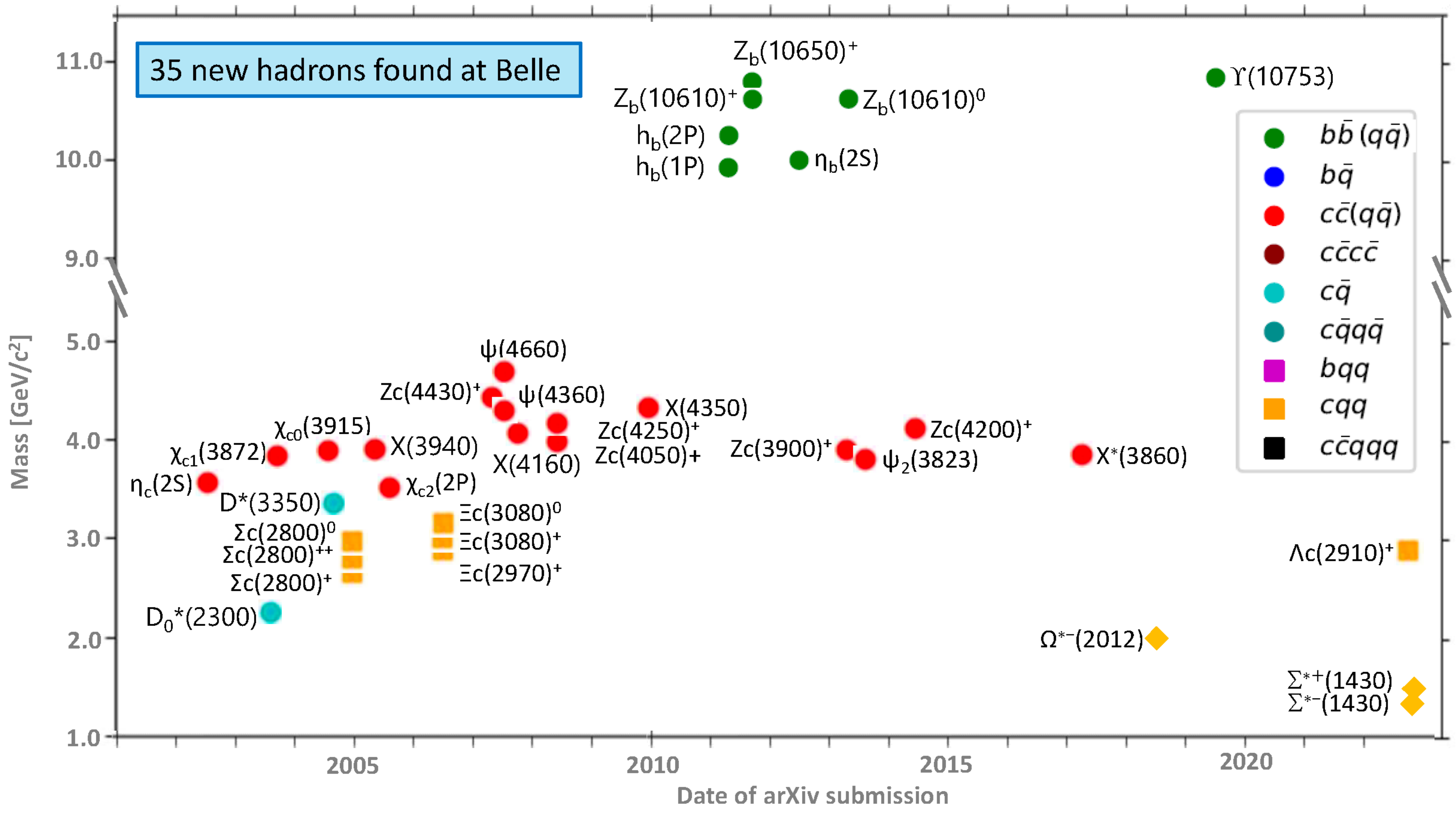
WORLD RECORD: 5.1×10^{34} cm^{-2}s^{-1}



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

The Belle II experiment began collecting data on 18 November.

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.

Charm spectroscopy

Selected topic:

1. $\mathbf{D_{s0}^{*}(2317)^{+} \rightarrow D_{s}^{*+}\gamma}$
2. **ISR of** $\mathbf{e^{+}e^{-} \rightarrow h^{+}h^{-}J/\psi}$ **(h = π, K, p)**
3. **Br(B → X(3872) K) [MC study]**

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

arXiv: 2510.27174

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

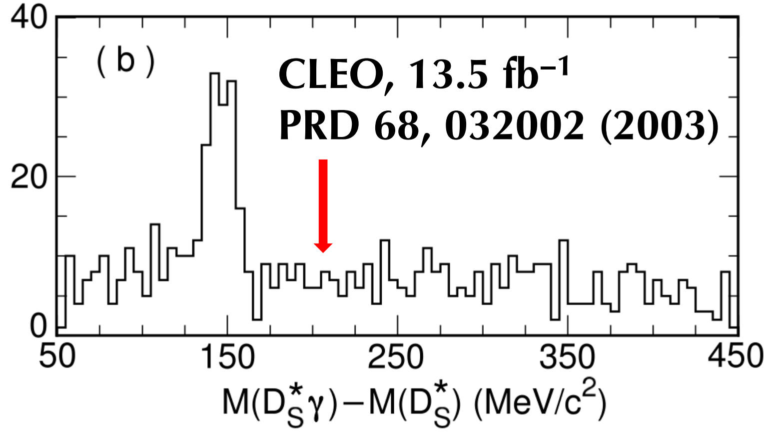
Mass of $D_{s0}^*(2317)^+$ is much lower than the quark model predictions of the lowest $c\bar{s}$ mesons with $J^P = 0^+$

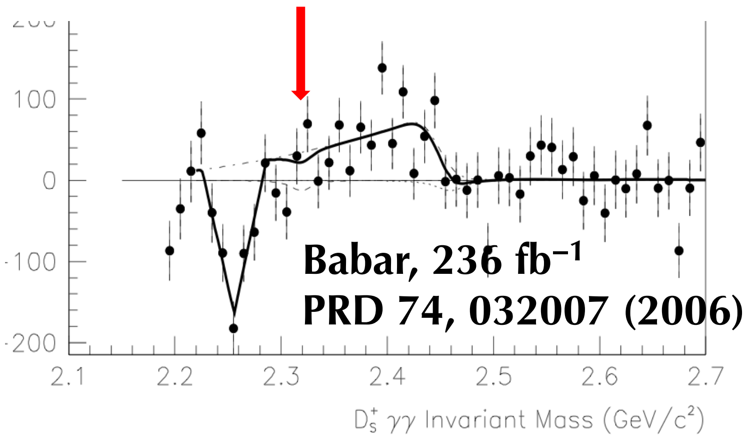
- **Modifying the $c\bar{s}$ quark model**
- **D^*K hadronic molecule**
- **Compact tetraquarks**
- **Chiral partners of the ground state D_s^* meson**

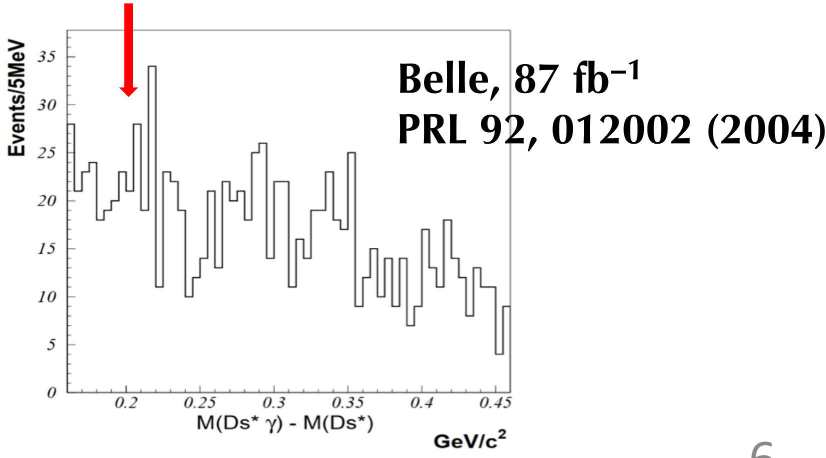
Partial decay widths:
unique in discriminating between various models

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.







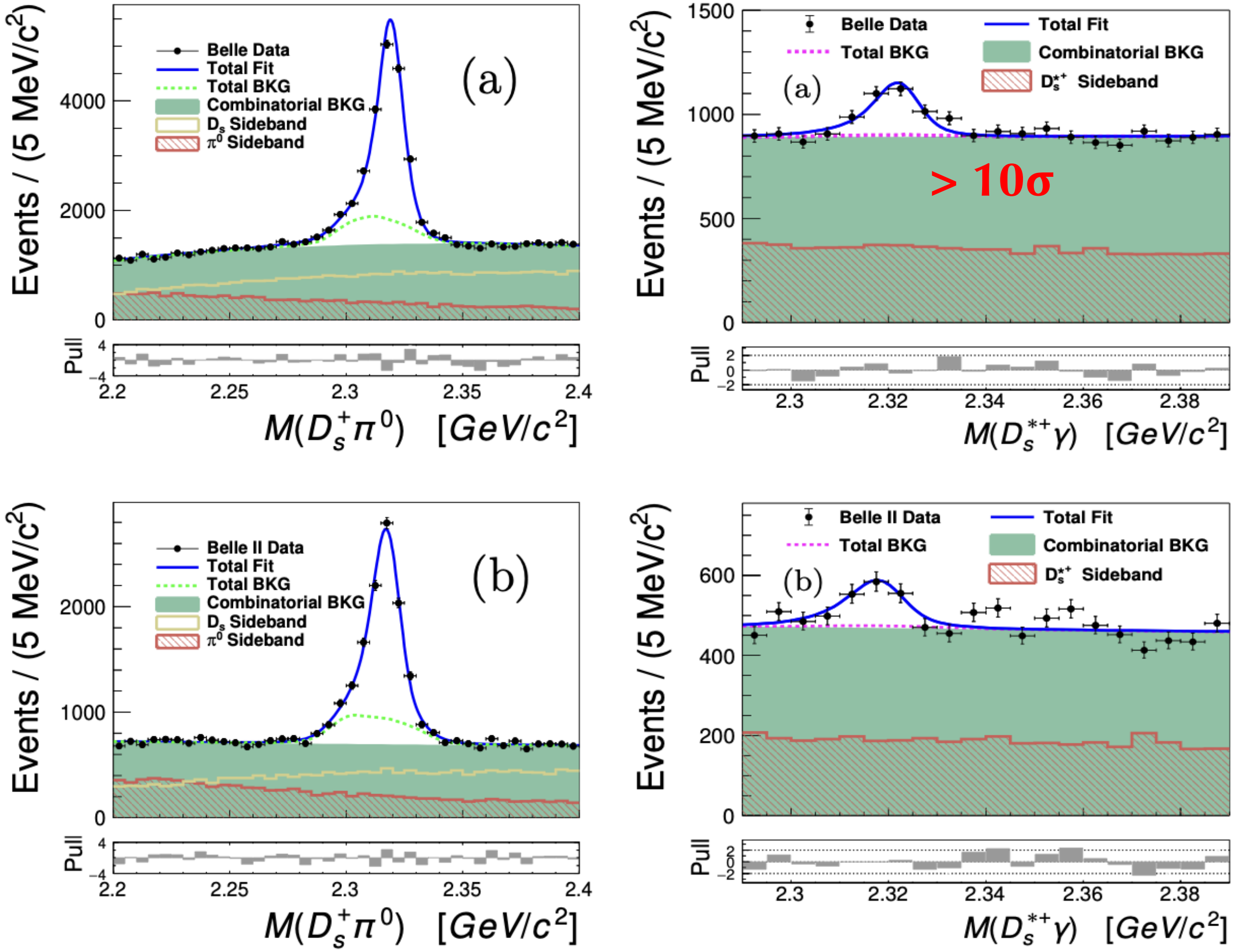
First observation of $D_{s0}^{*}(2317)^{+} \to D_{s}^{*+}\gamma$

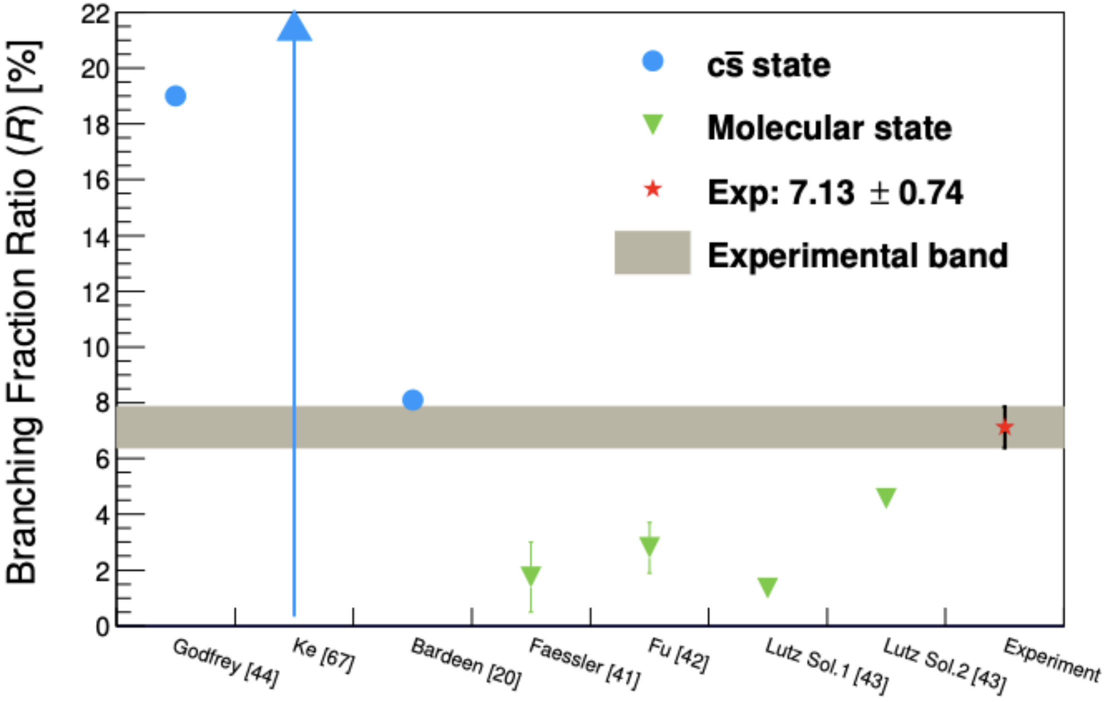
arXiv: 2510.27174

- 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})

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

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





$D_{s0}^{*}(2317)^{+}$ could be the mixture state of pure $c\bar{s}$ state and molecular state.

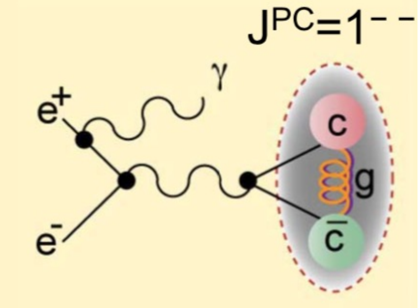
$e^+e^- \to h^+h^-J/\psi$ ($h = \pi, K, p$) via initial-state radiation (ISR) at Belle II

Adavantages of ISR:

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

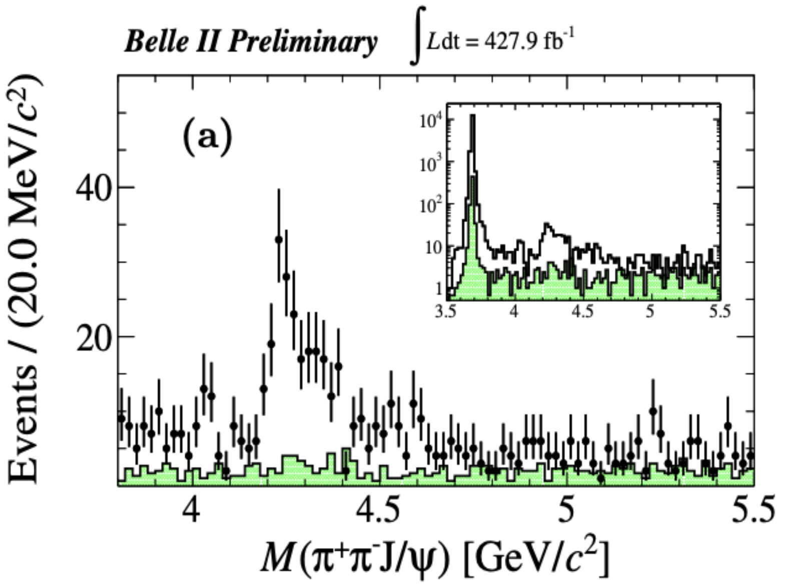
Disadvantages of ISR:

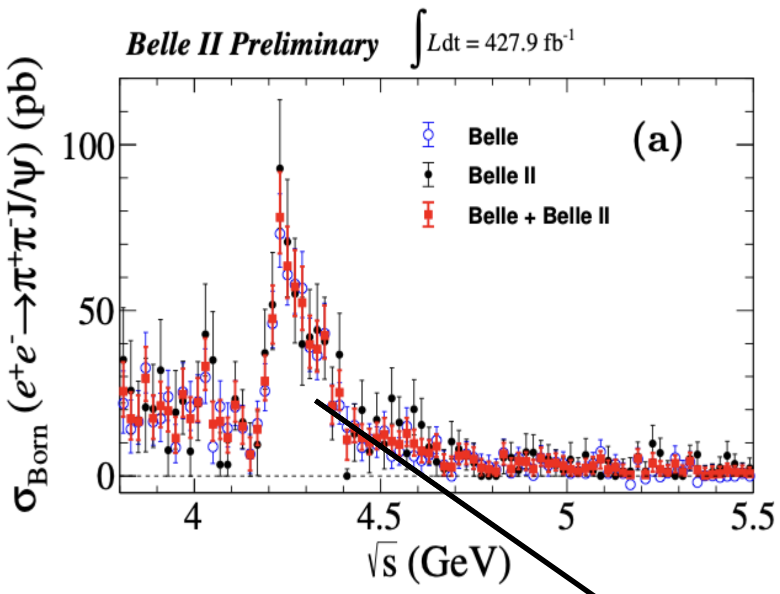
- The effective integrated luminosity decreases as the c.m. energy decreases
- The detection efficiency is also smaller

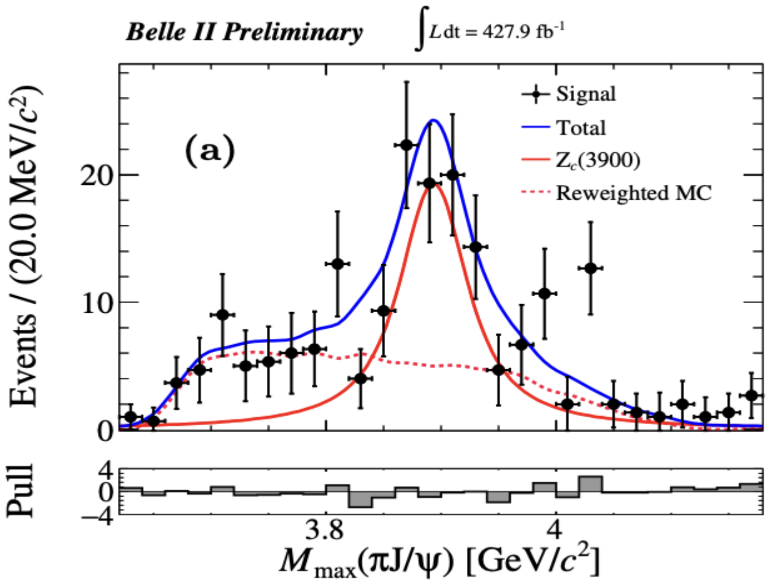


Initial state radiation

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





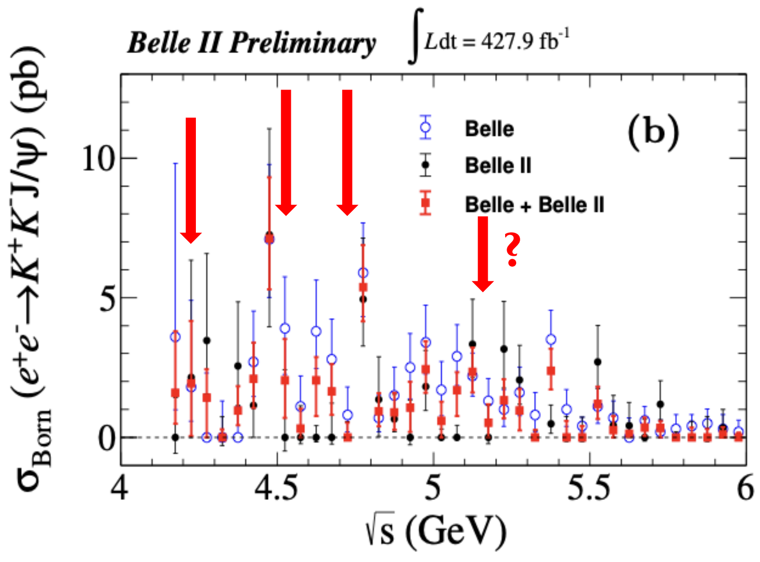


- **We can see the Y(4008) evidence and Y(4260) signal.**
- **The significance of $Z_c(3900)$ is 5.3σ.**

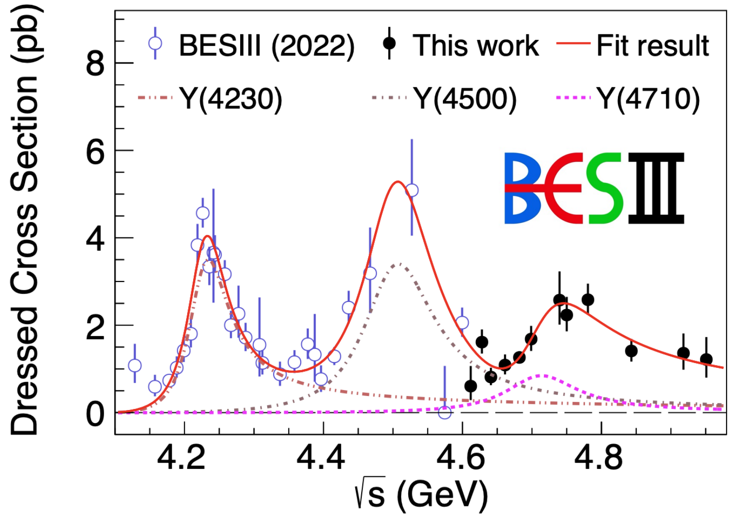
There seem to be two peaks.

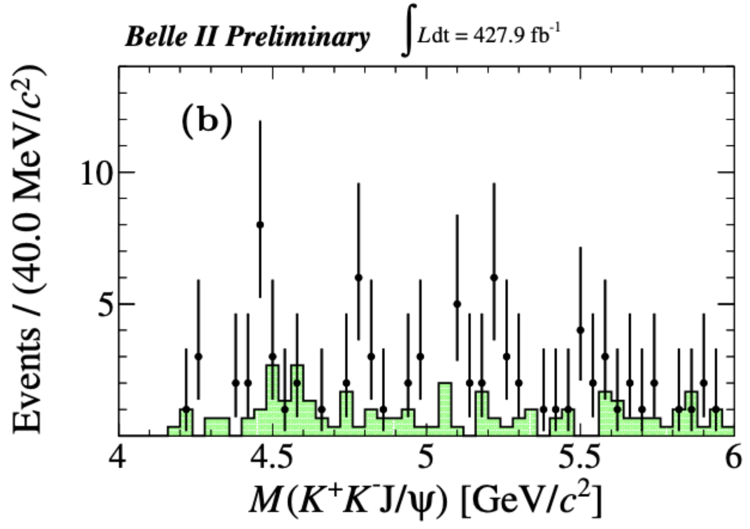
$e^+e^- \to h^+h^-J/\psi$ ($h = \pi, K, p$) via initial-state radiation at Belle II

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



PRL 131, 211902 (2023)

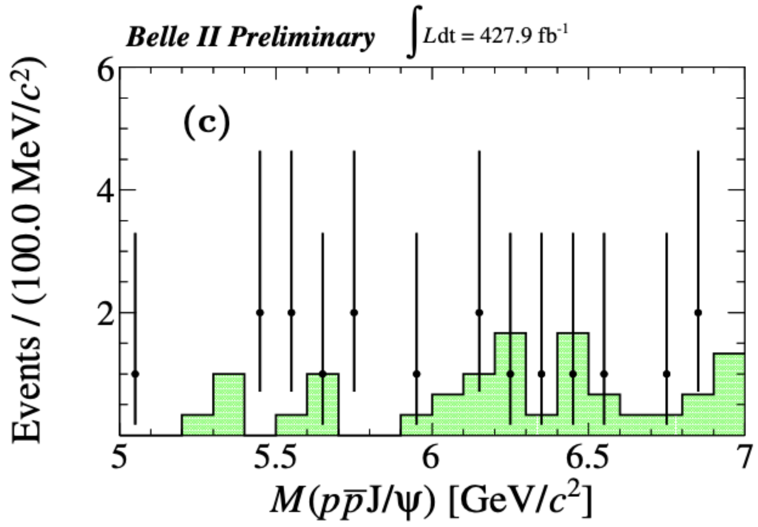


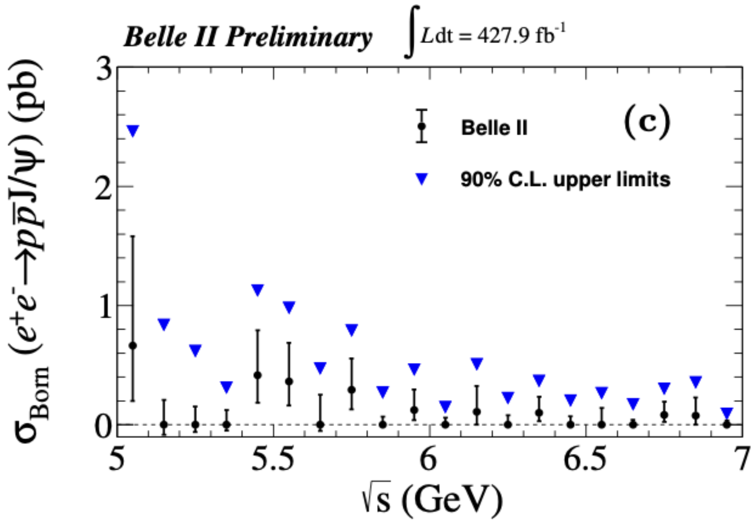


- **No clear signals were observed at Belle II.**
- **More data are needed.**

$e^+e^- \to p\bar{p}J/\psi$ 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].



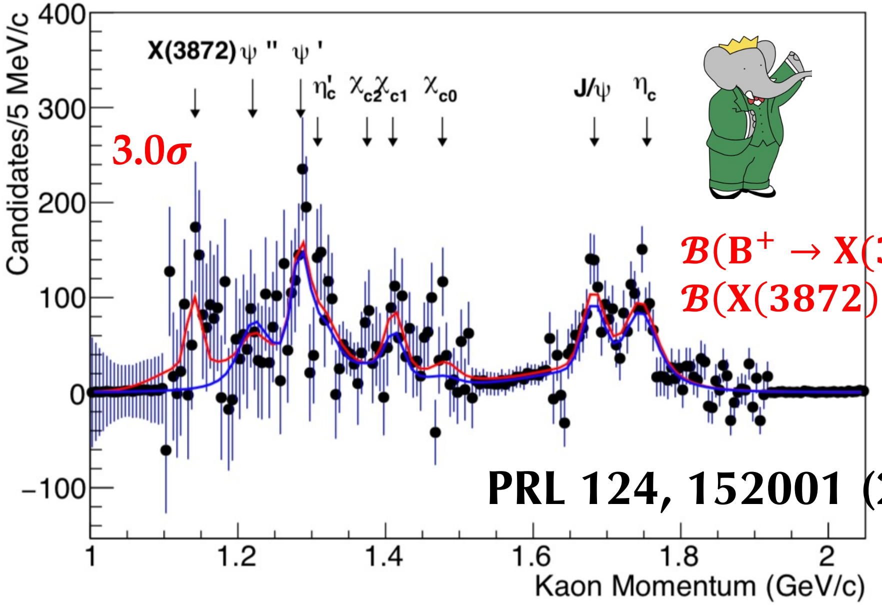


Inclusive measurement of Br(B → X(3872) K)

- Determination of the Br(B → X(3872) K) leads to the absolute branching fraction for the X(3872) decay, bringing useful information regarding complex nature of the X(3872).

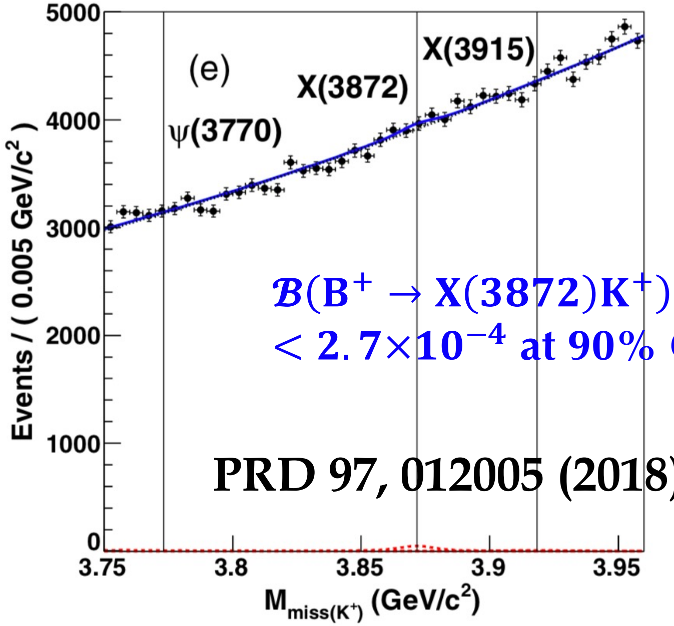
Branching fraction	Structure
$\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) \sim 50\%$	Tetraquark State [PRD 71, 014028 (2005)]
$\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 10\%$	Molecular state [PRD 72, 054022 (2005), PRD 69, 054008 (2004)]

- BaBar reported an evidence for X(3872) in the inclusive measuremnt; Belle set upper limits.



$\mathcal{B}(B^+ \to X(3872)K^+) = (2.1 \pm 0.6 \pm 0.3) \times 10^{-4}$
$\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (4.1 \pm 1.3)\%$

PRL 124, 152001 (2020)



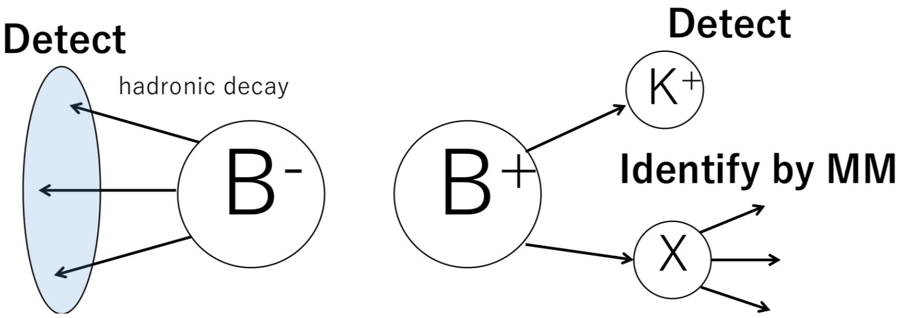
$\mathcal{B}(B^+ \to X(3872)K^+) < 2.7 \times 10^{-4}$ at 90% C.L.

PRD 97, 012005 (2018)

Inclusive measurement of Br(B → X(3872) K)

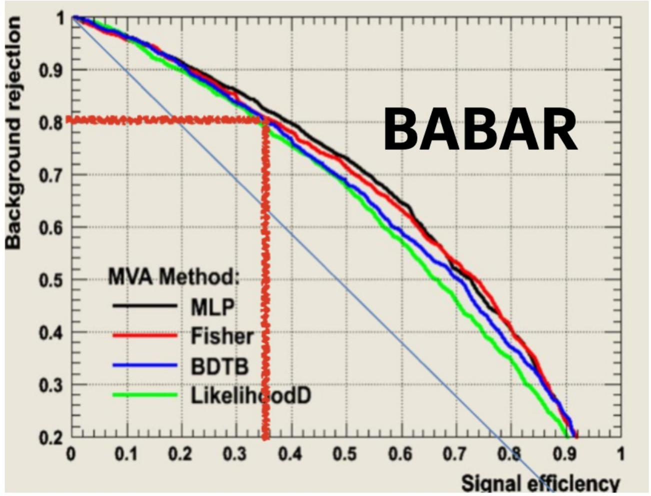
Analysis method:

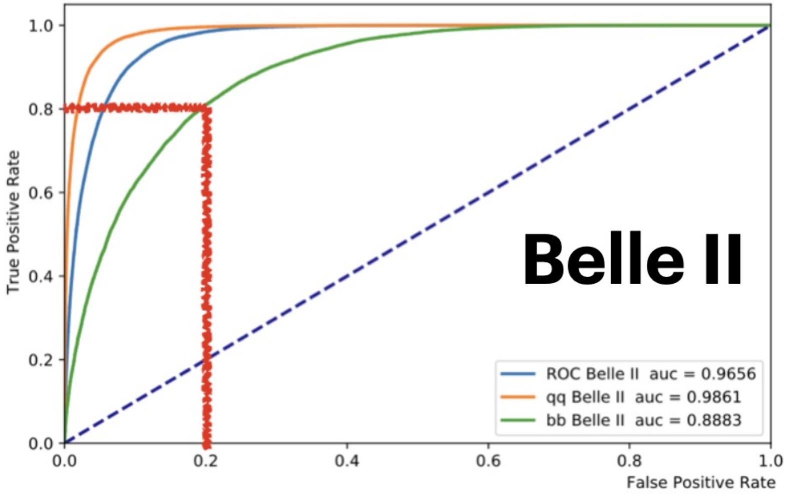
- Fully reconstruct one of the two charged B mesons (B_{tag})
- Identify the signal by calculating K momentum in the B_{sig} system or the recoil mass of K

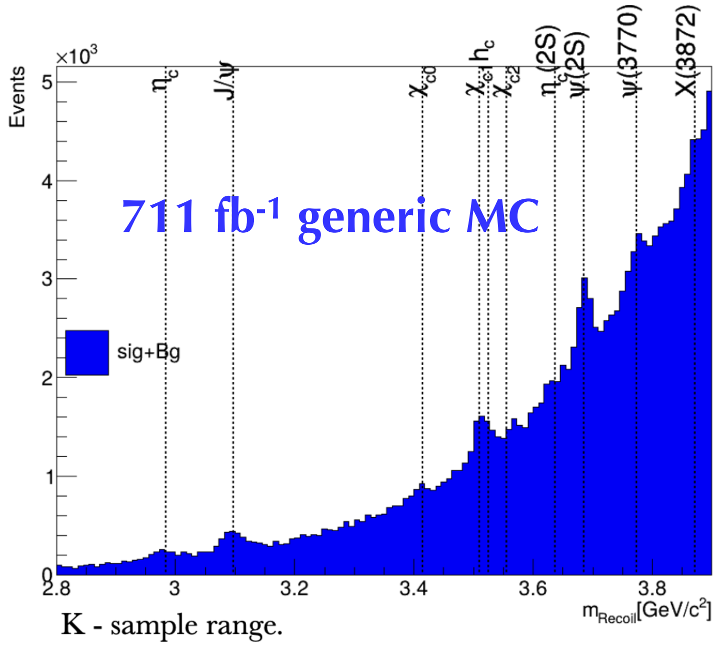


Well known		Measure		Extract
$Br(B^+ \to K^+ J/\psi\pi^+\pi^-)$	=	$Br(B^+ \to K^+ X)$	×	$Br(X \to J/\psi\pi^+\pi^-)$

- **A more efficient tagging reconstruction algorithm (FEI)**
- **Better performing deep NN to suppress combinatorial Bg.**



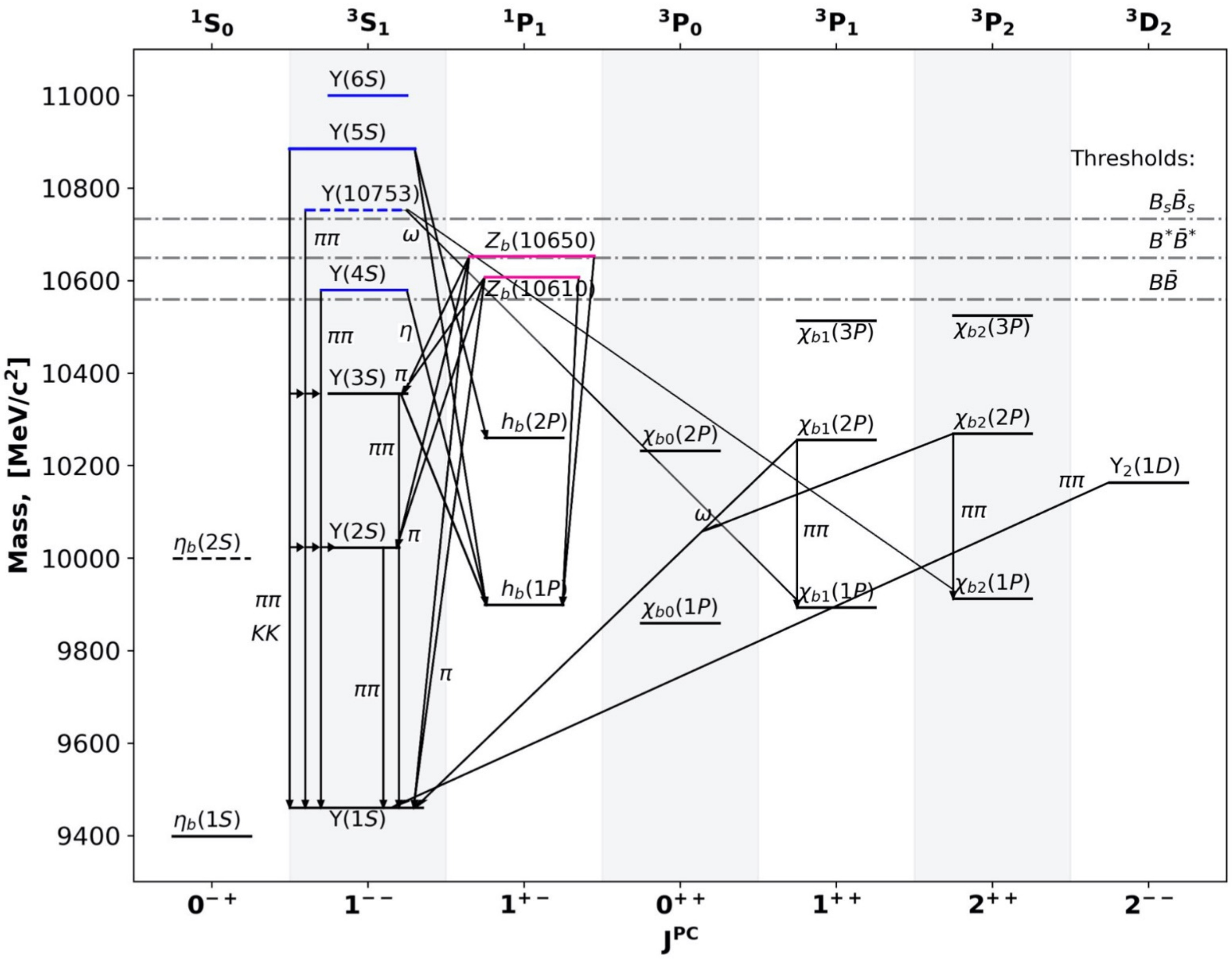




A better separation: for the same Bg rejection of 80% in the X(3872) region:
Belle II: 80% sig-efficiency; Babar: 36% sig-efficiency

Bottomonium(-like)
—*Focus on* $\Upsilon(10753)$ *and* X_b—

Bottomonium



Conventional bottomonium (pure $b\bar{b}$ states)

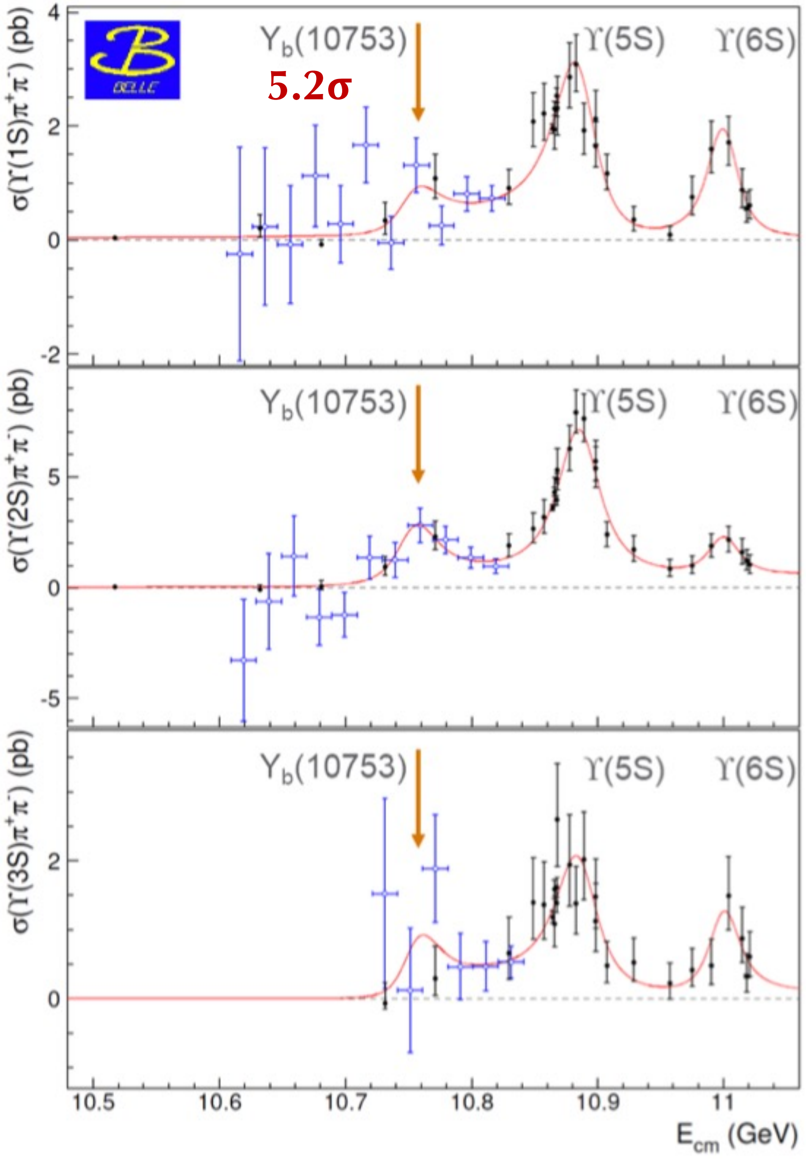
Bottomonium-like states (mix of $b\bar{b}$ and $B\bar{B}$)

Exotic charged states ($Z_b^{\pm}$)

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

Discovery of Υ(10753)

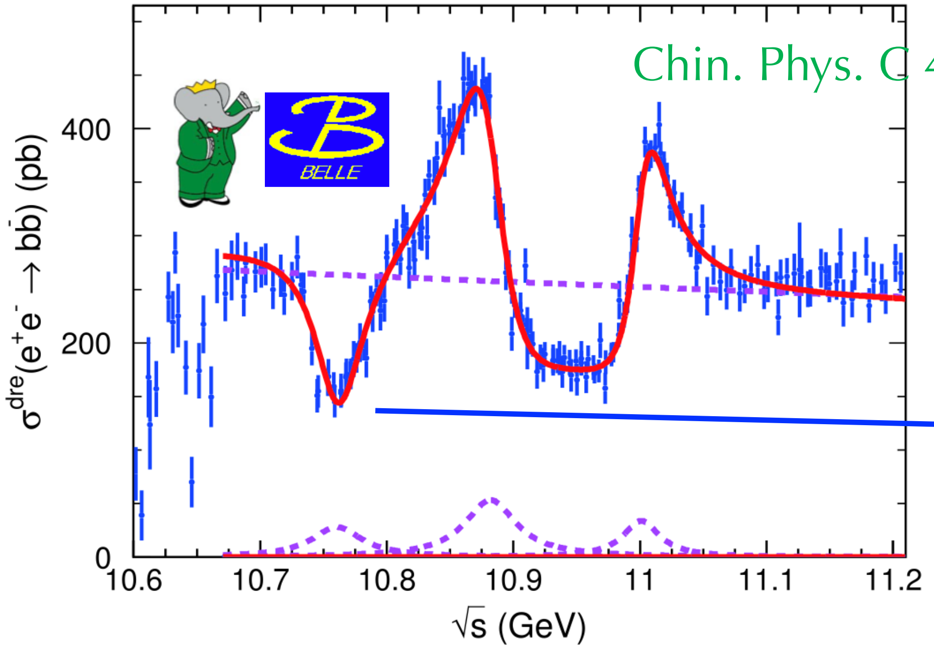
JHEP 10, 220 (2019)



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

	Υ(10860)	Υ(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)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$

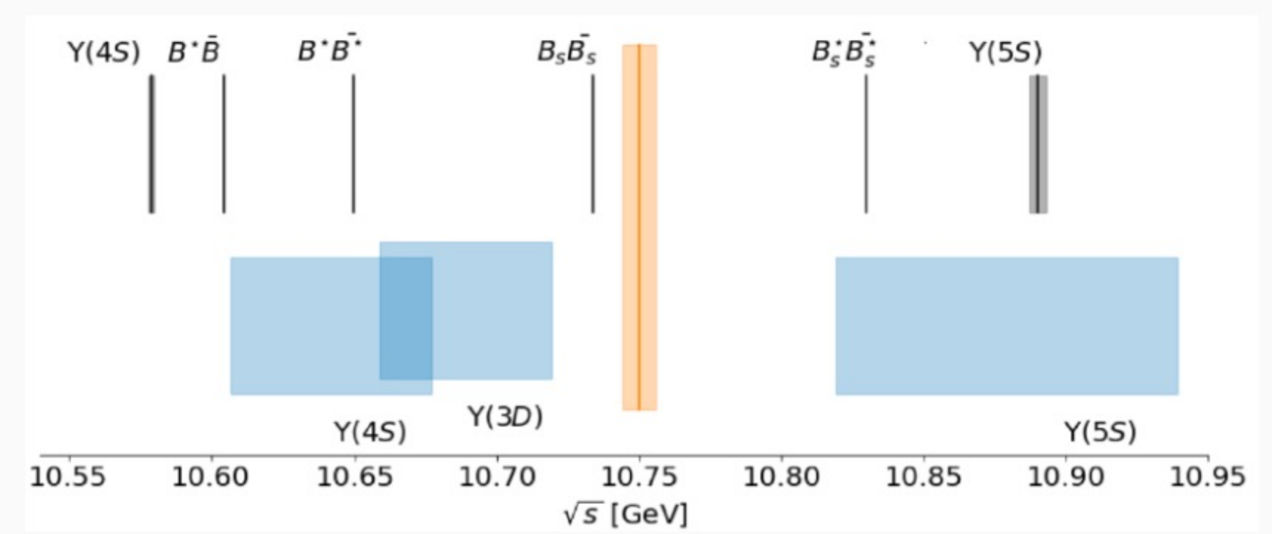
Chin. Phys. C 44 (2020) 8, 083001



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

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.

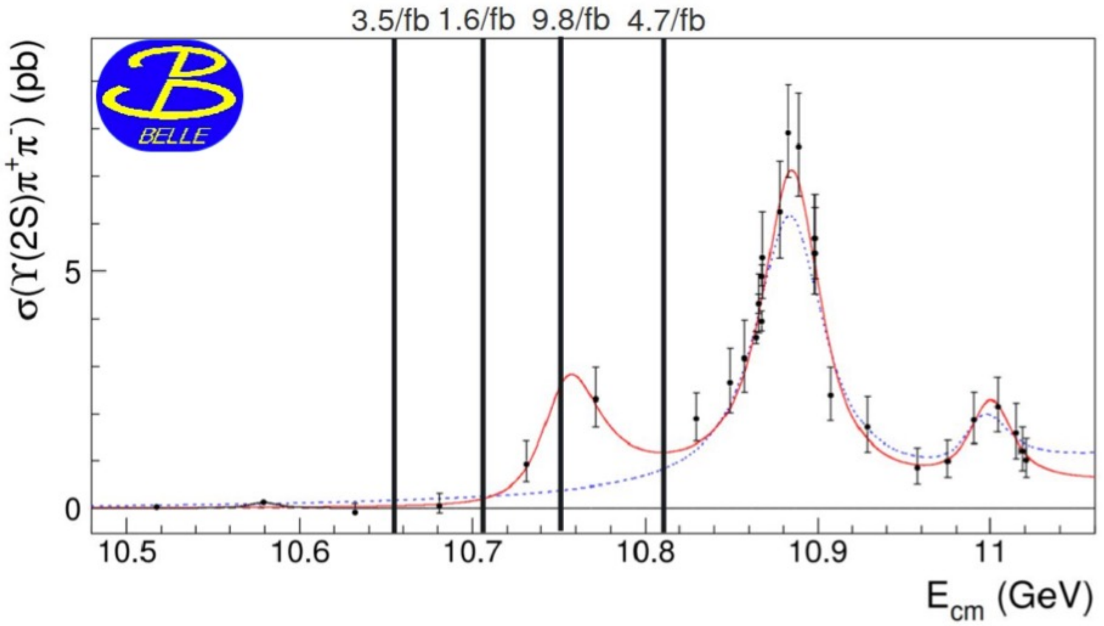
❑ Conventional bottomonium

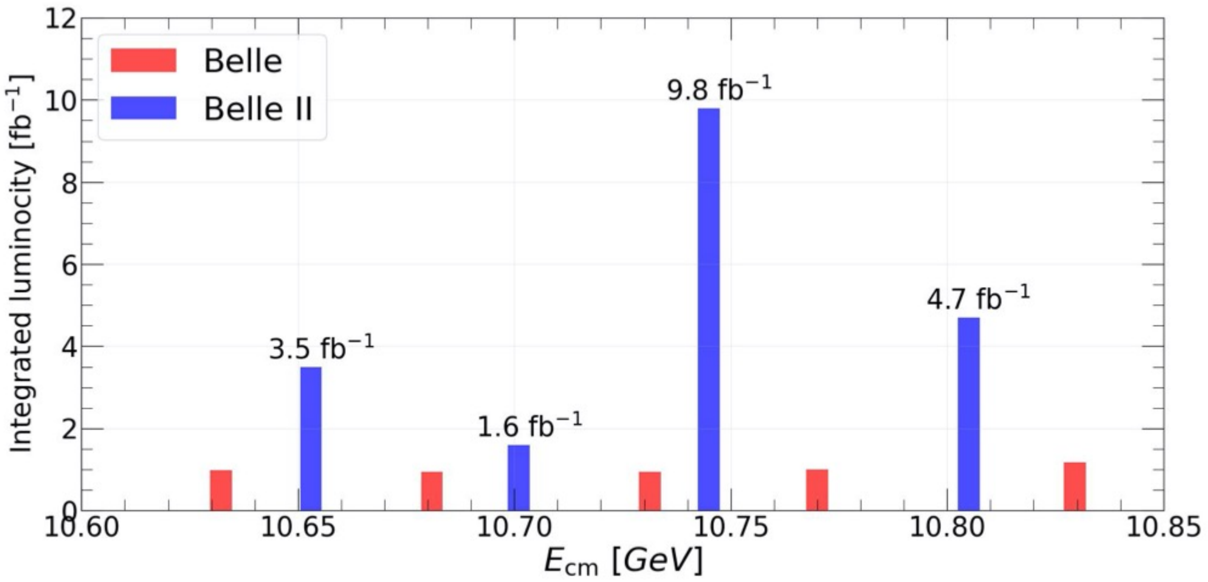
Eur. Phys. J. C 80, 59 (2020)
Phys. Rev. D 101, 014020 (2020)
Phys. Rev. D 102, 014036 (2020)
Phys. Lett. B 803, 135340 (2020)
Phys. Rev. D 104, 034036 (2021)
Prog. Part. Nucl. Phys. 117, 103845 (2021)
Eur. Phys. J. Plus 137, 357 (2022)
Phys. Rev. D 105, 114041 (2022)
Phys. Rev. D 106, 094013 (2022)
Phys. Rev. D 105, 074007 (2022)
Phys. Rev. D 109, 014039 (2024)
Phys. Rev. D 109, 114007 (2024)
Phys. Rev. D 111, 114027 (2025)
Phys. Lett. B 870, 139960 (2025)
Eur. Phys. J. C 85, 814 (2025)
Chin. Phys. C 49, 073102 (2025)

❑ Tetraquark / Hybrid

Chin. Phys. C 43, 123102 (2019)
Phys. Lett. B 802, 135217 (2020)
Phys. Rept. 873, 1 (2020)
Phys. Rev. D 103, 074507 (2021)
Phys. Rev. D 104, 034019 (2021)
Phys. Rev. D 107, 094515 (2023)
Phys. Part. Nucl. Lett. 20, 381 (2023)
arXiv: 2503.00552

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





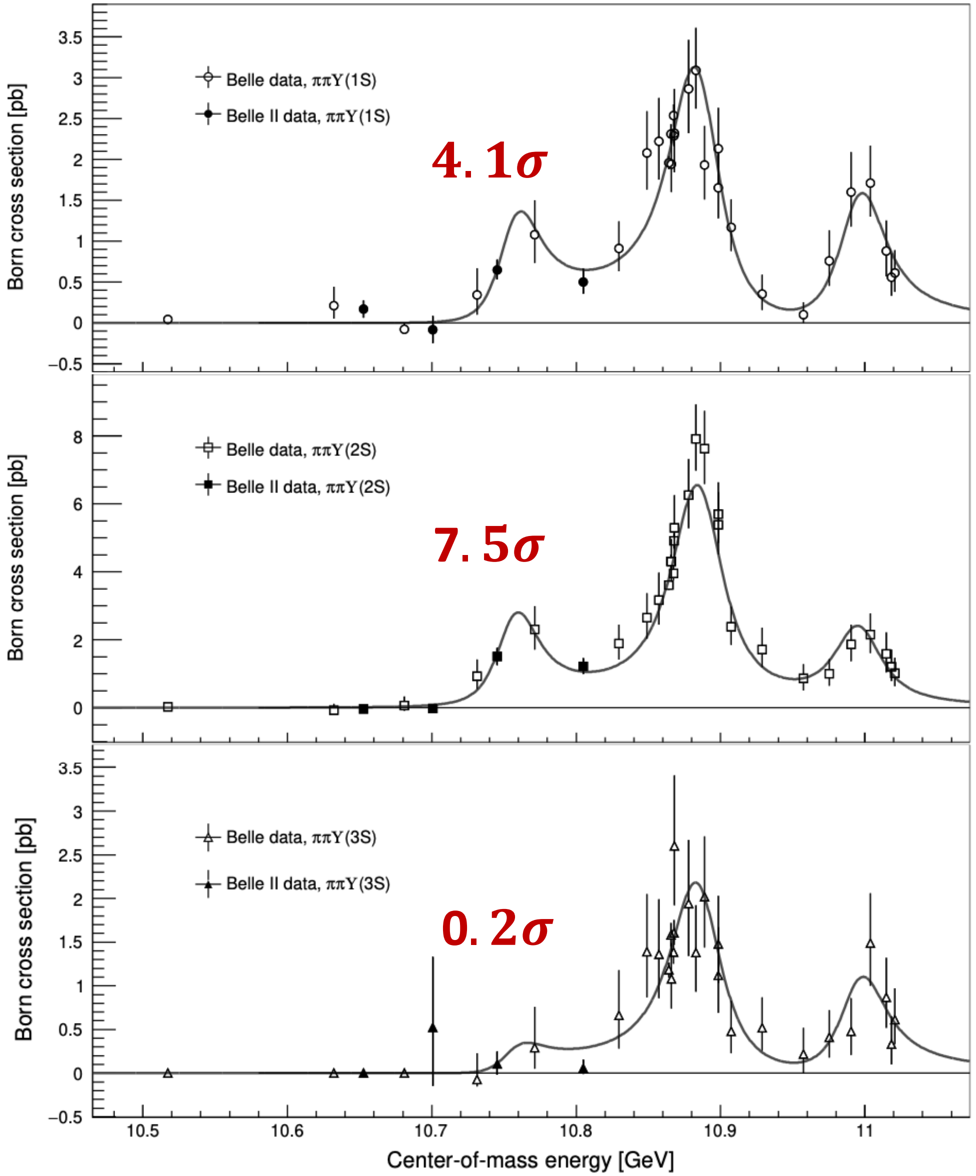
- In November 2021, Belle II collected 19 fb^{-1} of unique data at energies above the $\Upsilon(4S)$: four energy scan points around 10.75 GeV.
- Belle II collected the data in the gaps between Belle energy scan points.
- Physics goal: understand the nature of the $\Upsilon(10753)$ energy region.

Channels Analyzed

- ✓ $e^+e^-\to\pi^+\pi^-\Upsilon(nS)$ ($n = 1, 2, 3$)
- ✓ $e^+e^-\to\omega\chi_{b1,b2}$ and $e^+e^-\to(\pi^+\pi^-\pi^0)_{non-\omega}\chi_{b1,b2}$
- ✓ $e^+e^-\to\omega\eta_b(1S)$ and $e^+e^-\to\omega\chi_{b0}$
- ✓ $e^+e^-\to B\bar{B}$, $B\bar{B}^*$, and $B^*\bar{B}^*$
- ✓ $e^+e^-\to\eta\Upsilon(1S, 2S)$
- ✓ $e^+e^- \to \pi^+\pi^-\Upsilon_J(1D)$ ($J = 2, 3$)
- ✓ $e^+e^- \to \gamma\chi_{bJ}$ ($J = 0, 1, 2$)

Measurement of $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$ at Belle II

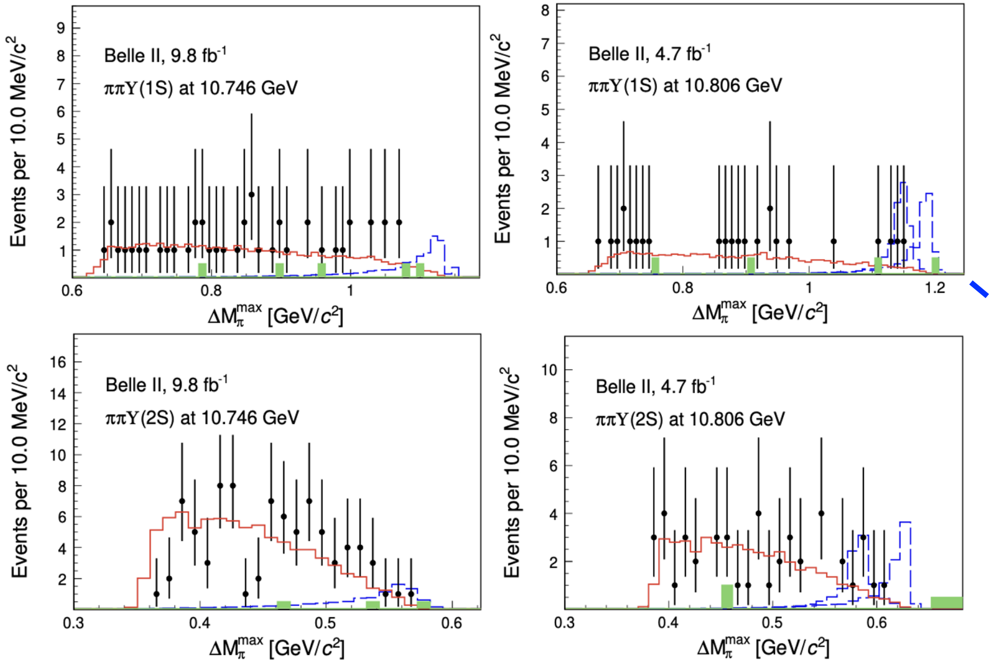
JHEP 07 (2024) 116



- New measurement **confirms** previous Belle result.

Mass	$(10756.3 \pm 2.7 \pm 0.9)$ MeV/c^2
Width	$(29.0 \pm 8.8 \pm 1.2)$ MeV
$\mathcal{R}^{\Upsilon(10753)}_{\sigma(1S/2S)}$	$0.46^{+0.15}_{-0.12}$
$\mathcal{R}^{\Upsilon(10753)}_{\sigma(3S/2S)}$	$0.10^{+0.05}_{-0.04}$

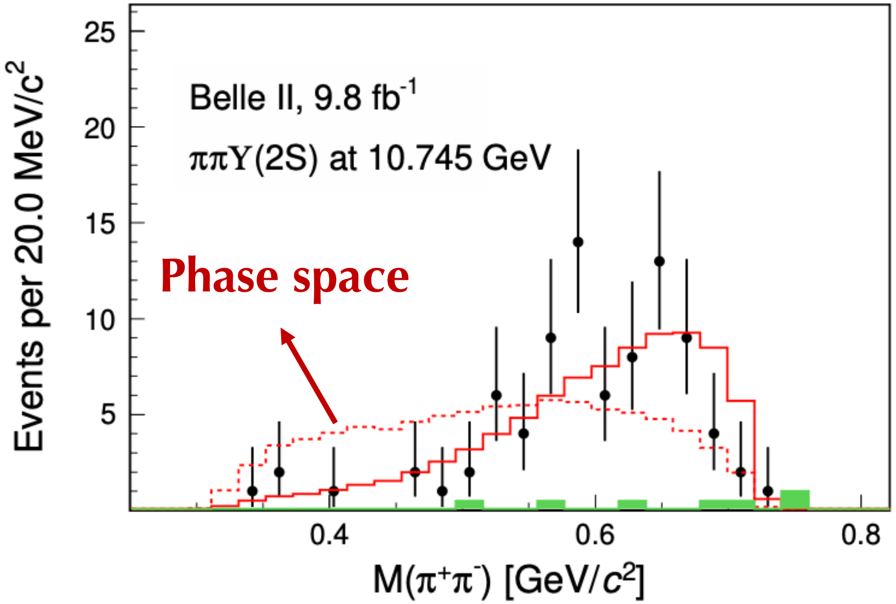
- Search for $Z_b^\pm \to \pi^\pm\Upsilon(1S)$ with $\Delta M_\pi^{max} = M(\pi^\pm\mu^+\mu^-) - M(\mu^+\mu^-)$

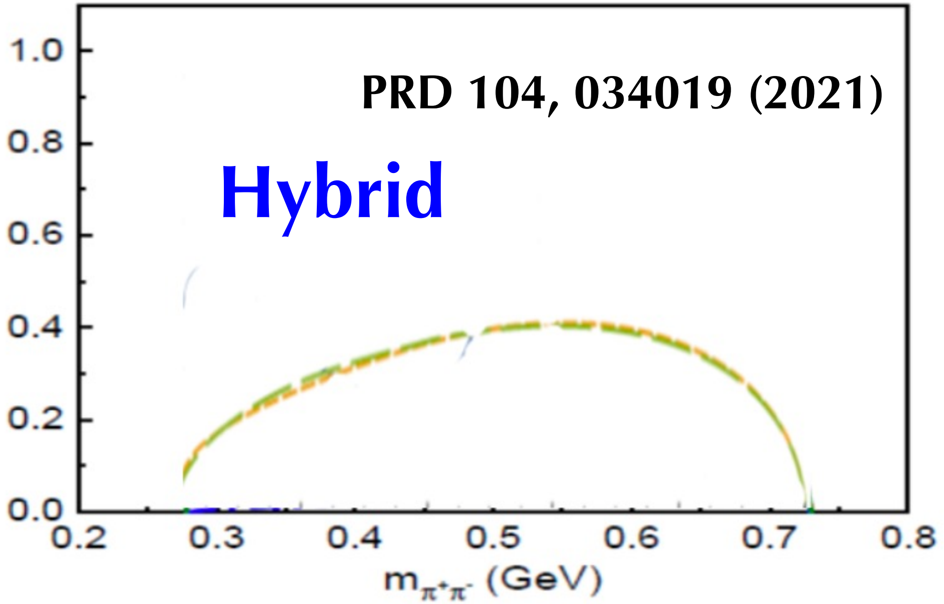


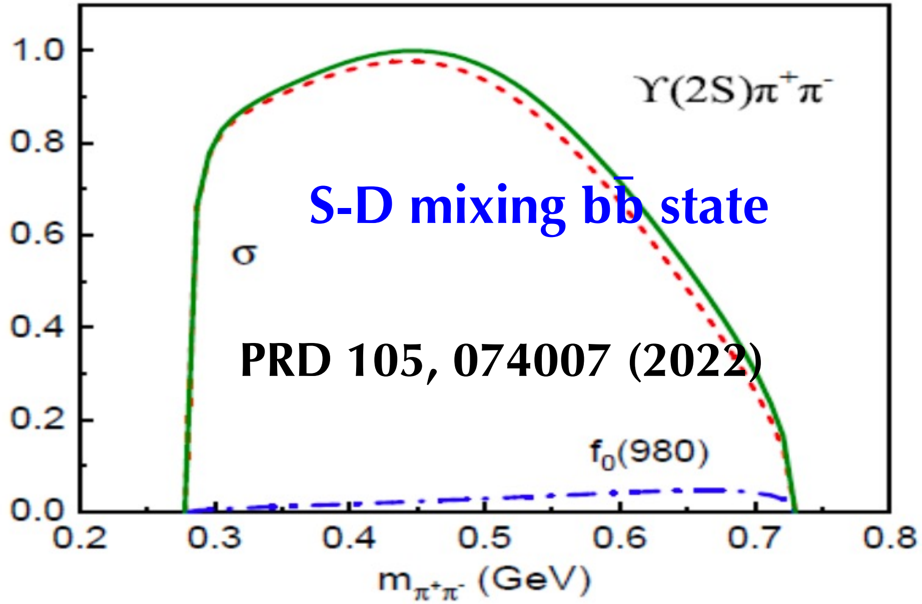
Simulated $Z_b^\pm$ events arbitrarily

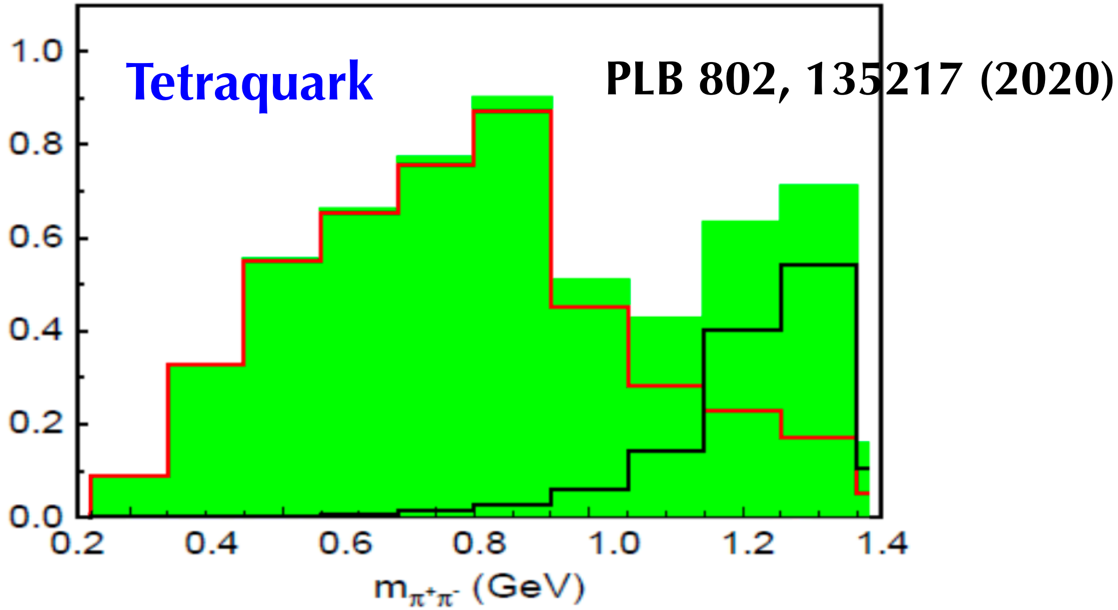
$M(\pi^+\pi^-)$ distributions

JHEP 07 (2024) 116





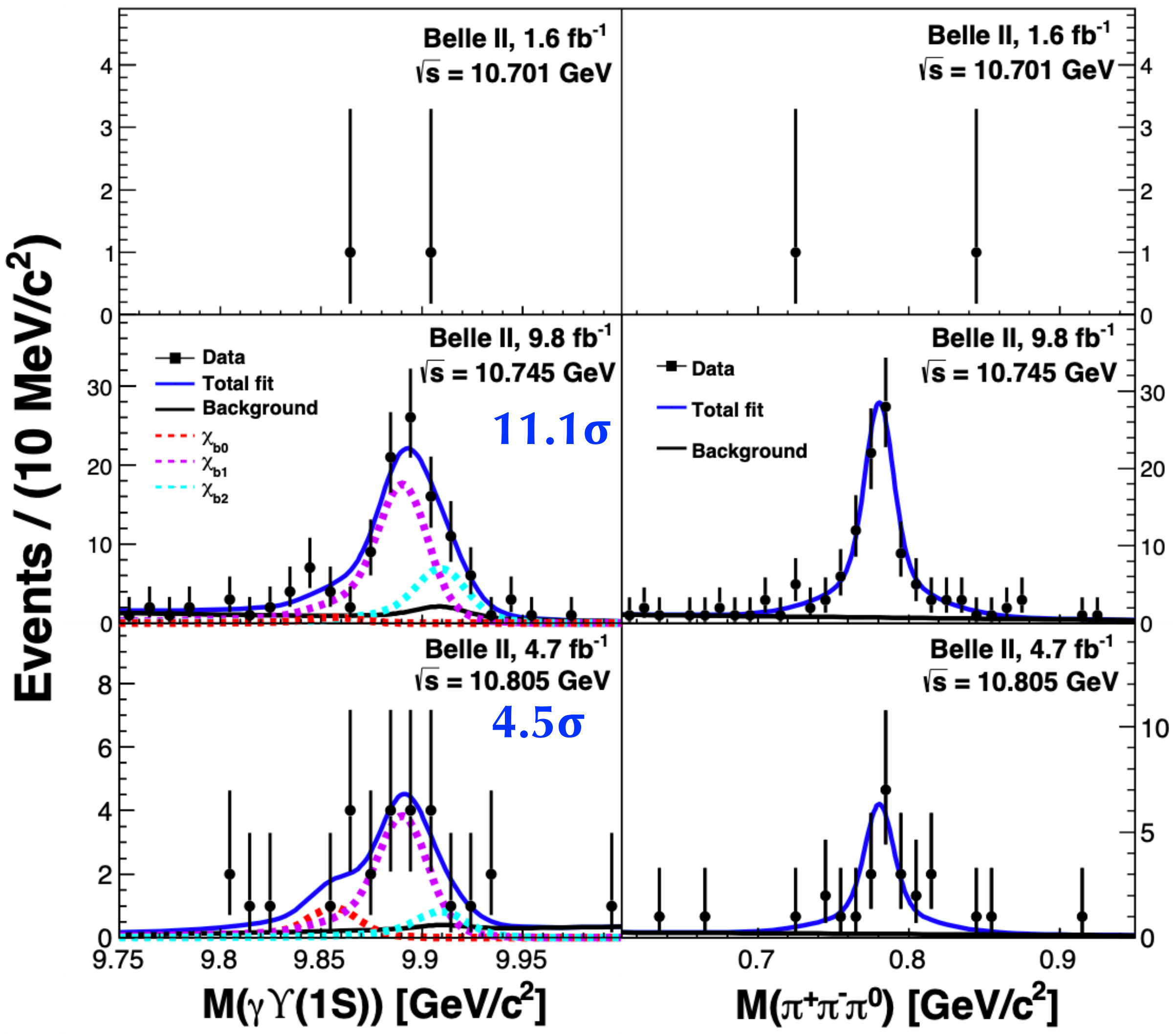




Observation of $\Upsilon(10753) \to \omega\chi_{bJ}$

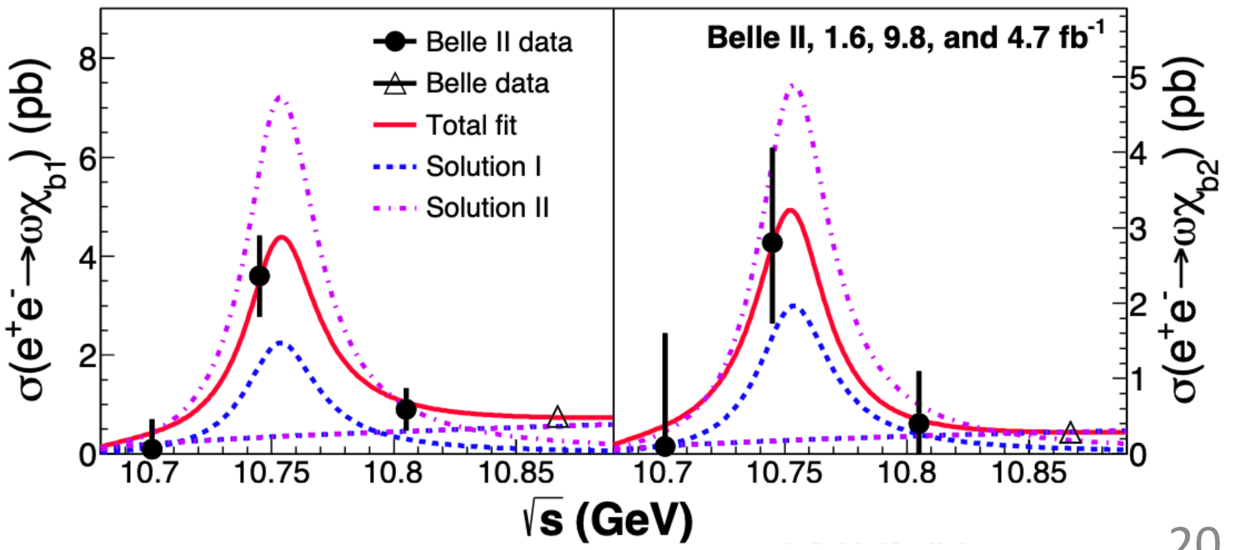
PRL 130, 091902 (2023)

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}	$\sigma^{(UL)}_{Born}$ (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.

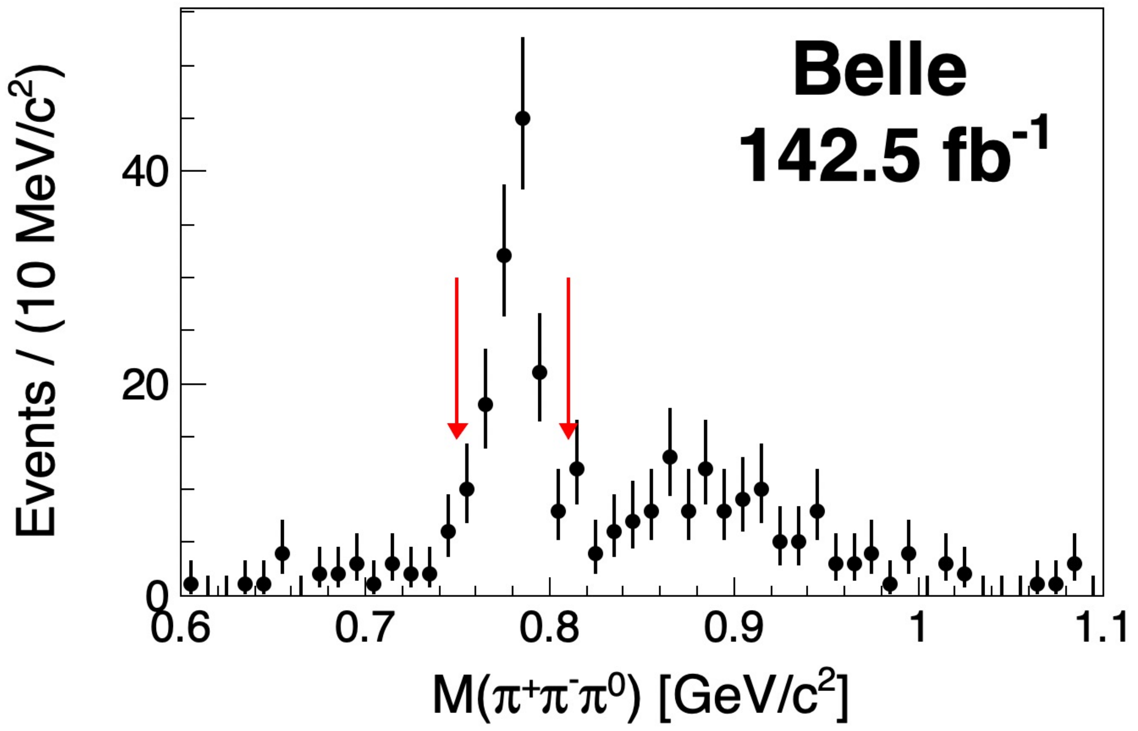
The $e^+e^- \to \omega\chi_{bJ}$ (J = 1, 2) cross sections peak at $\Upsilon(10753)$.



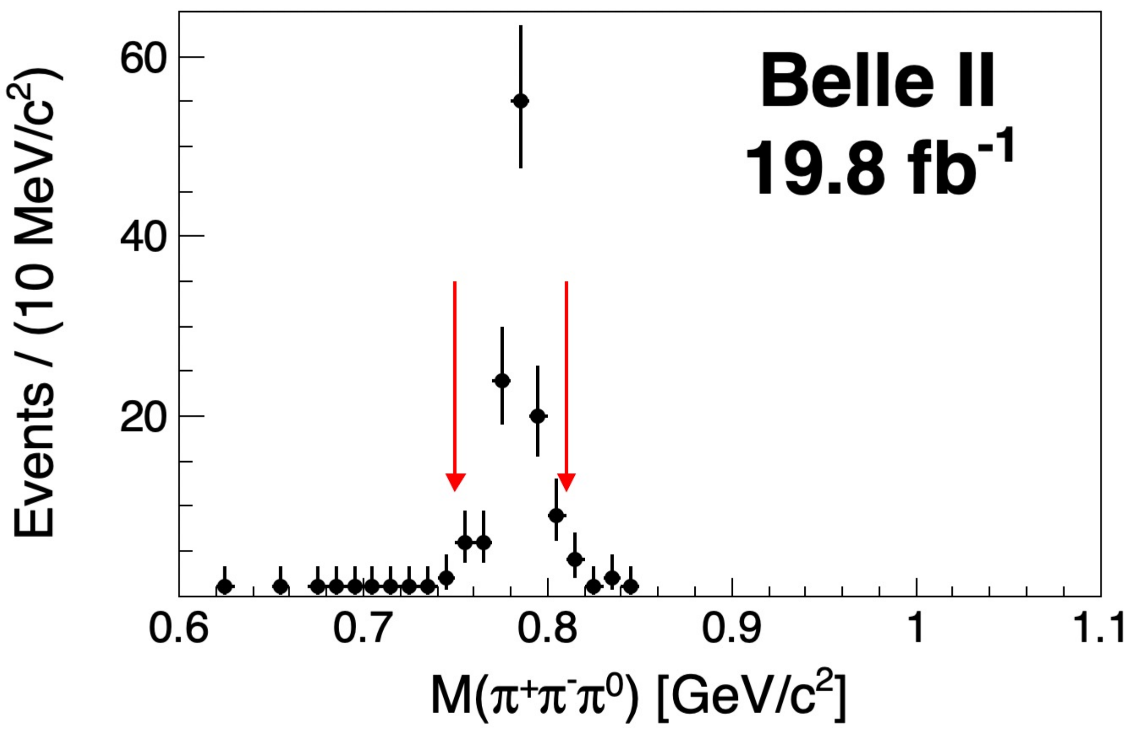
$e^+e^- \to \omega\chi_{bJ}$ and $e^+e^- \to (\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}$ at Belle and Belle II

arXiv: 2510.25461

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



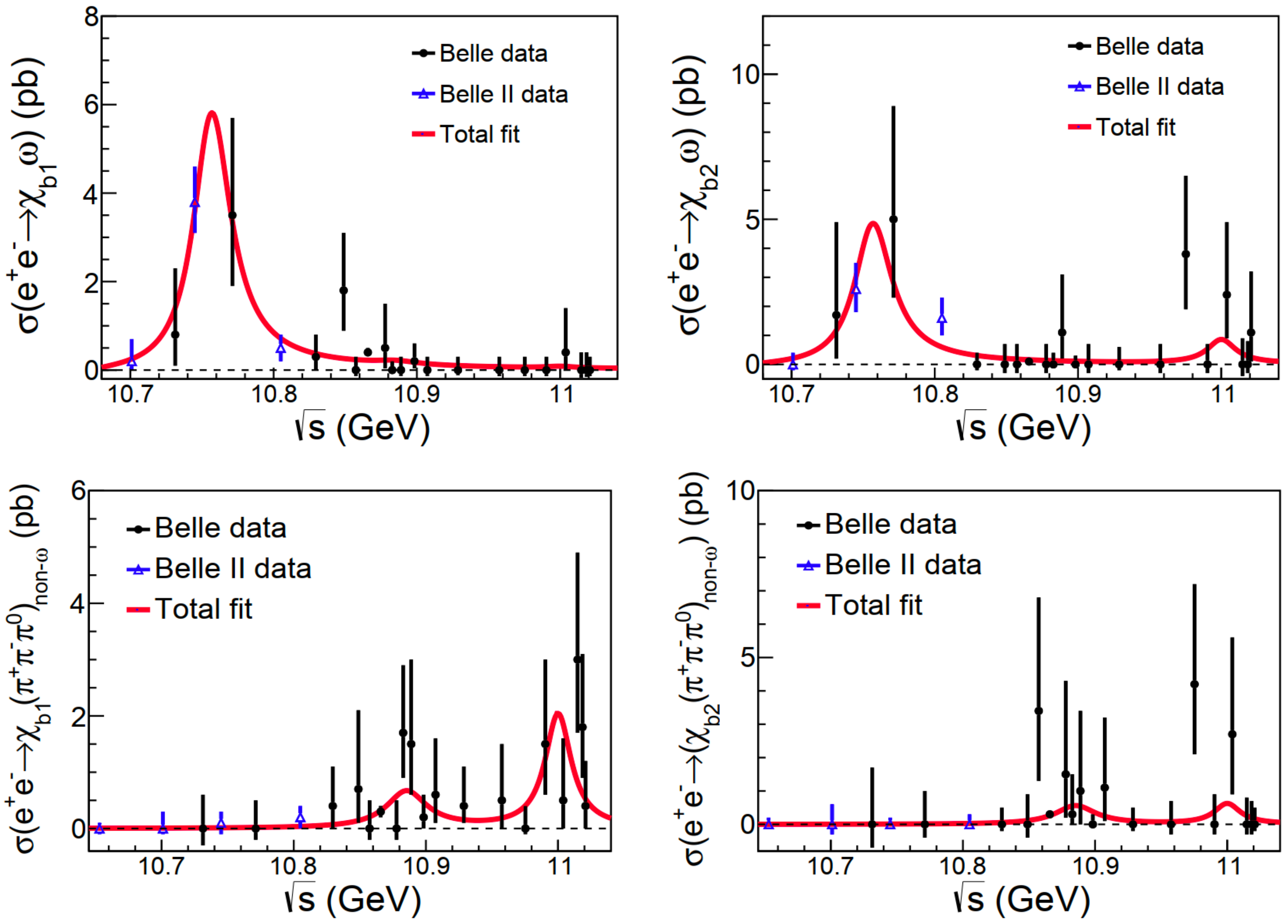
$\sqrt{s} \sim 10.75$ GeV



In addition to ω signal candidates, there are some events from non-resonant decays at Belle.

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

arXiv: 2510.25461



$\Upsilon(10753)$ 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 $\Upsilon(10860)$.

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

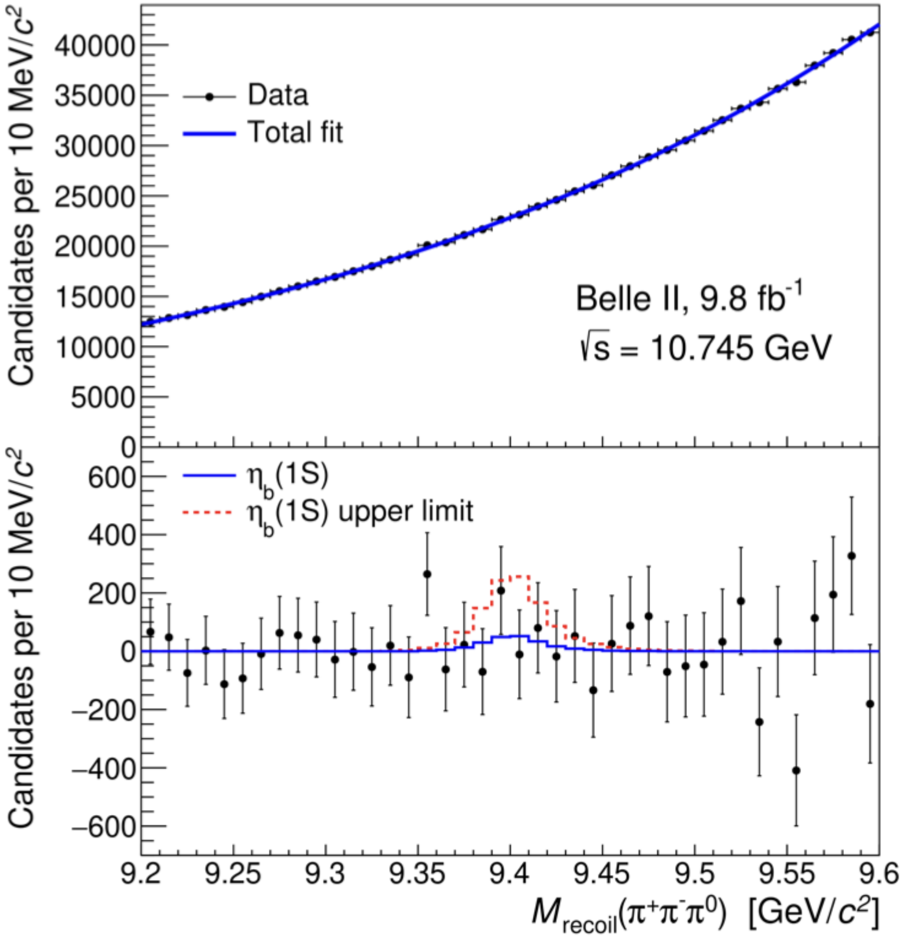
$$1.13\pm0.38\pm0.34$$

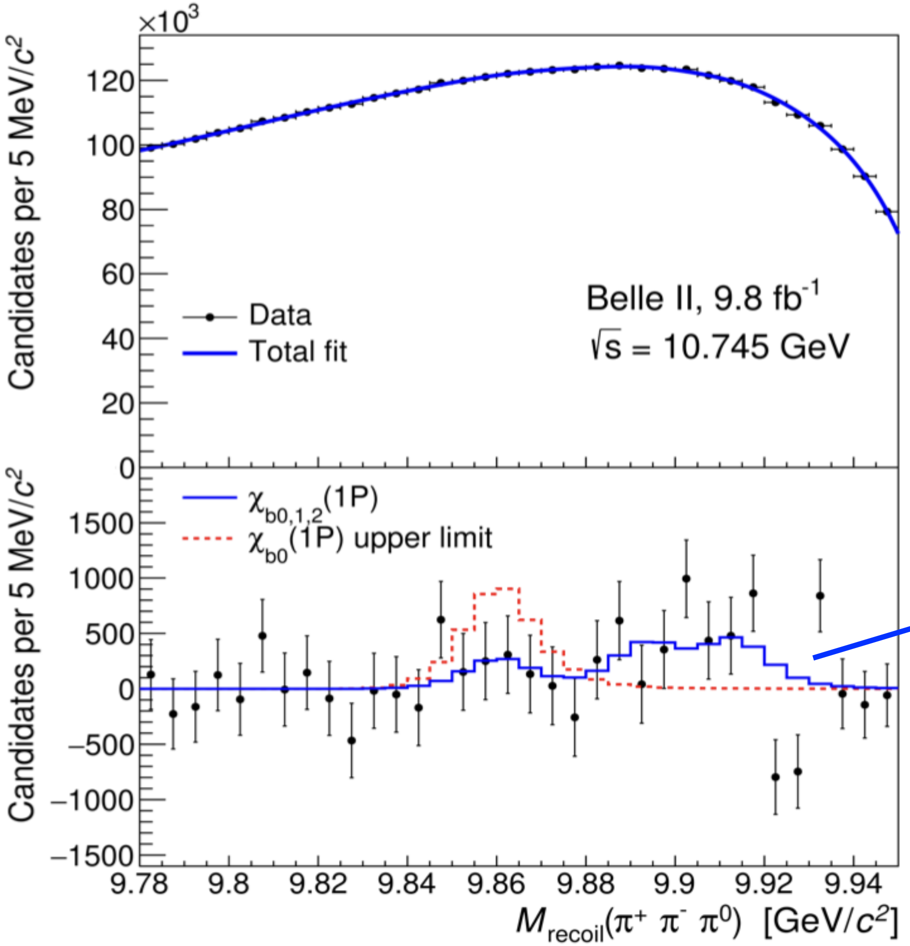
- **The $(\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}$ excess maybe due the cascade decay of $\Upsilon(10860, 11020) \to Z_b\pi \to \chi_{bJ}\rho\pi$ [PRD 90, 014036 (2014)].**

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

PRD 109, 072013 (2024)

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





Orders of the polynomial functions are chosen to give the maximal p-value for the fit.

The yields for $\chi_{b1}(1P)$ and $\chi_{b2}(1P)$ are fixed [PRL 130, 091902 (2023)].

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

This measurement and JHEP 10, 220 (2019):

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

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

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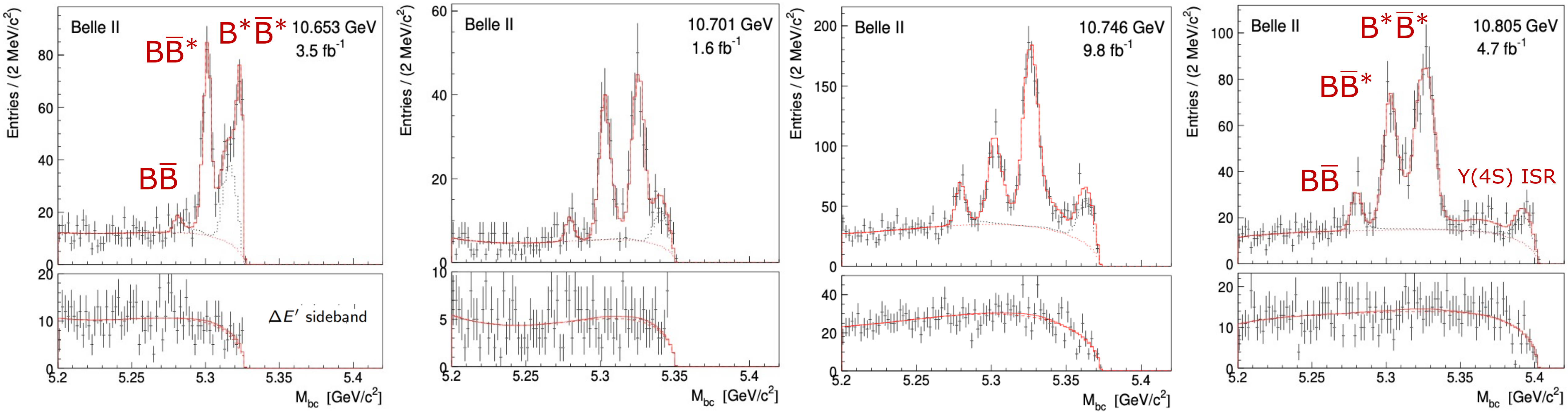
$M_{bc}=\sqrt{(E_{cm}/2)^2 - P_B^2}$



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

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

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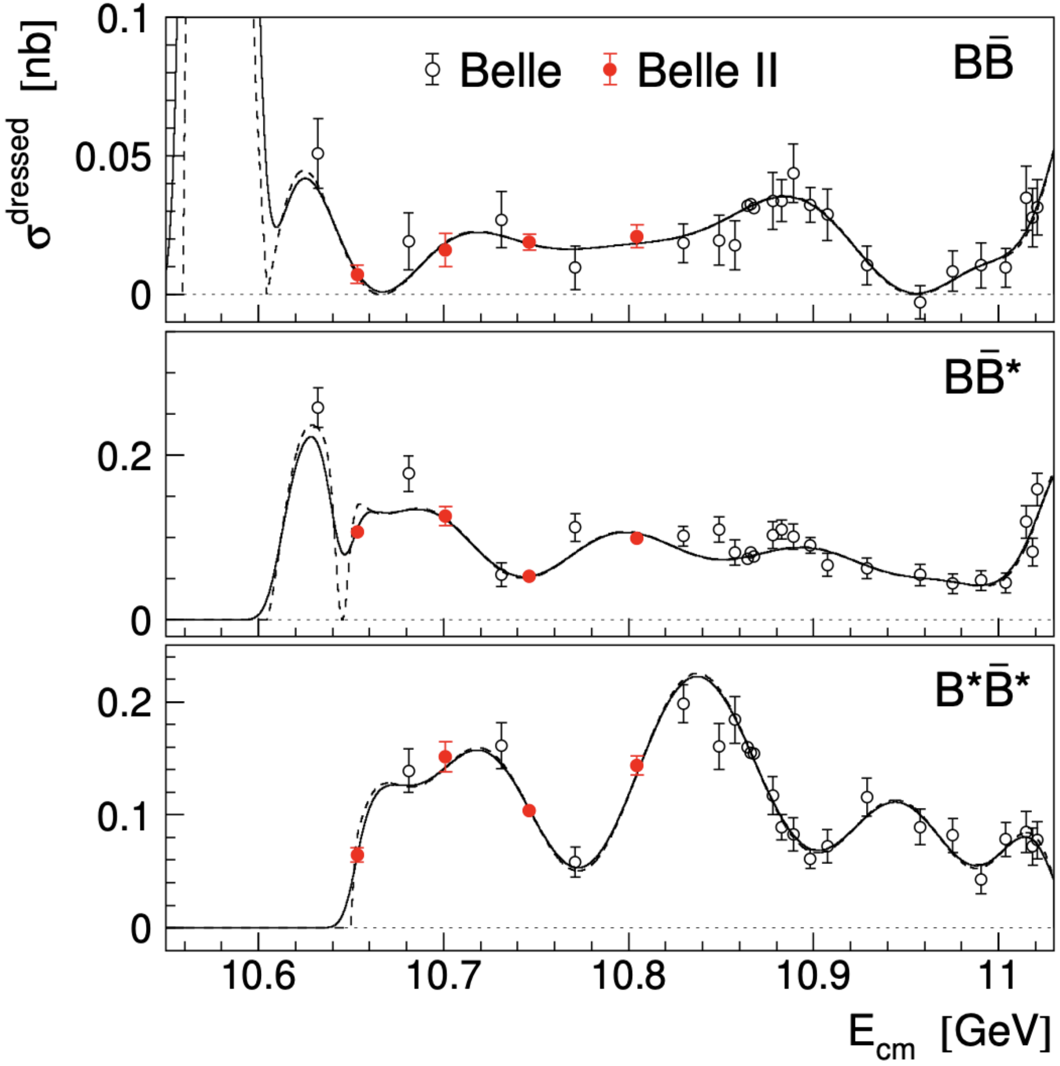


Solid curve – combined Belle + Belle II data fit
Dashed curve – Belle data fit only

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

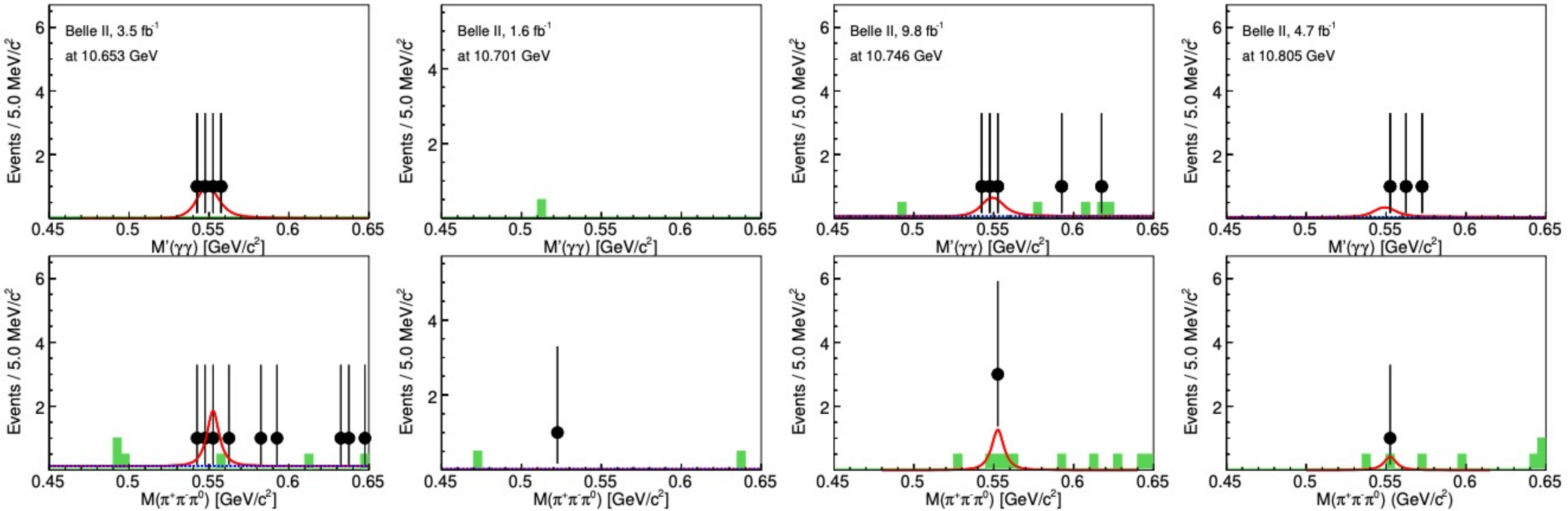
- **Similar behaviour was seen for $D^*\bar{D}^*$ cross section (PRD 97, 012002 (2018))**
- **Possible interpretation: resonance or bound state ($B^*\bar{B}^*$ or $b\bar{b}$) near threshold (MPL A 21, 2779 (2006))**
- **Also explains a narrow dip in $\sigma(e^+e^- \to B\bar{B}^*)$ near $B^*\bar{B}^*$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

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

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

arXiv: 2509.01917

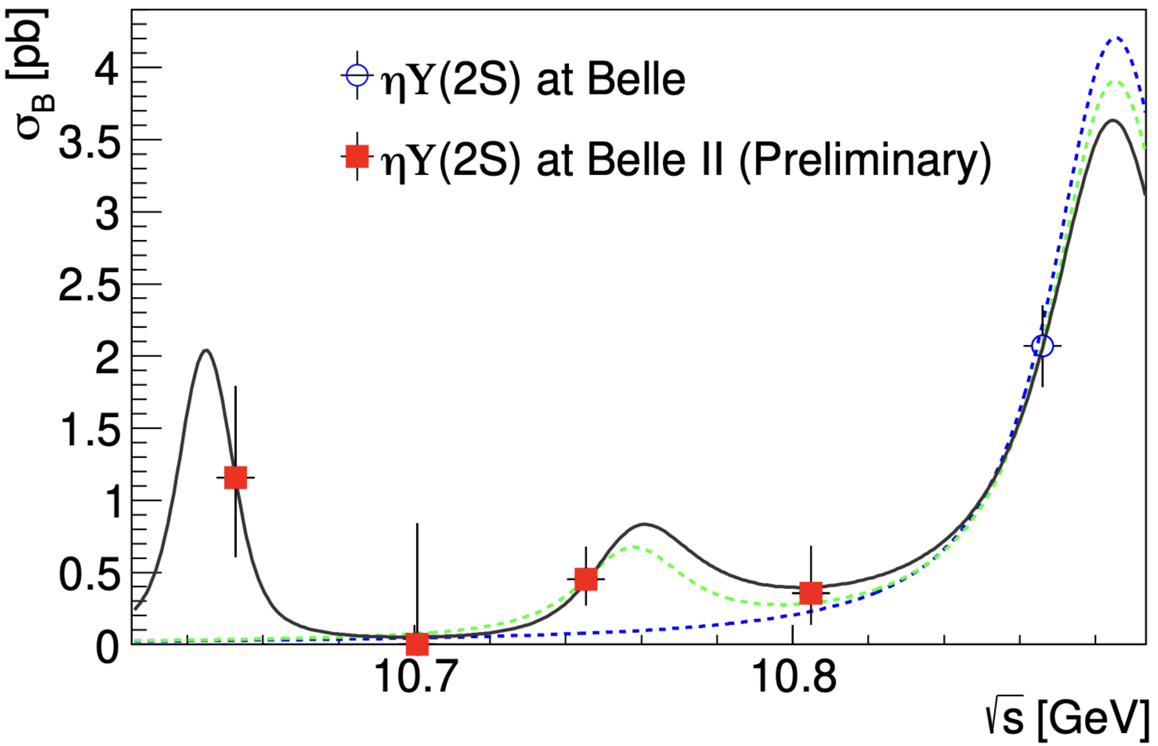
After requiring $\Upsilon(2S)$ signal region, simultaneous fit to $M(\gamma\gamma)$ and $M(\pi^+\pi^-\pi^0)$ for each energy point.



- 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.

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

arXiv: 2509.01917



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 masses and widths of $B^*\bar{B}^*$ bound state, $\Upsilon(10753)$, and $\Upsilon(5S)$ are fixed.

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

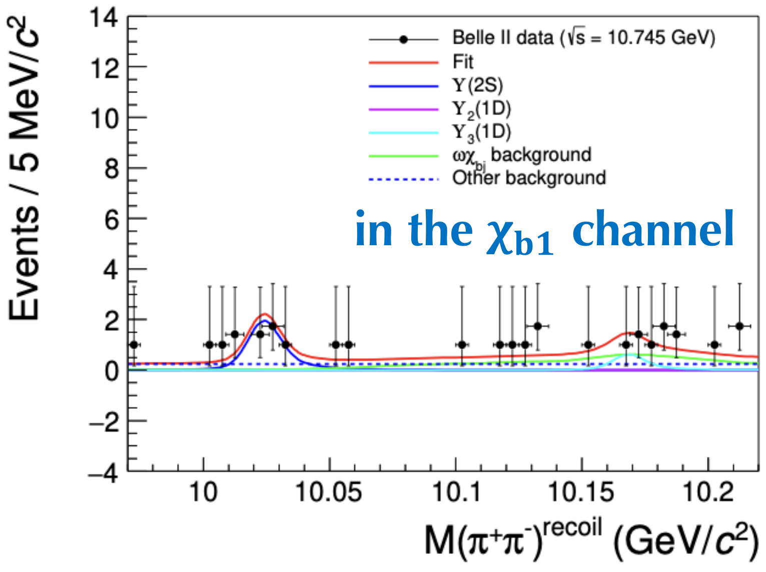
1.The Born cross section of $e^+e^- \to \eta\Upsilon(2S)$ around $B^*\bar{B}^*$ mass is relatively large.
2. A rapid increase of $\sigma_{B^*\bar{B}^*}$ just above the threshold.

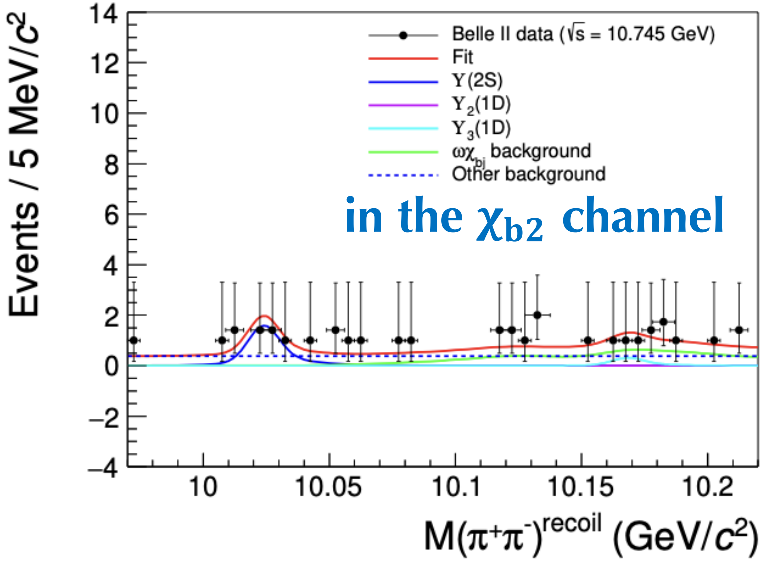
A new bottomonium-like state around $B^*\bar{B}^*$ threshold?
The $Y_b(10650)$ is predicted in Refs. [arXiv:2505.02742, arXiv:2508.11127, arXiv:2505.03647].

$e^+e^- \to \pi^+\pi^-\Upsilon_J(1D)$ $(J = 2, 3)$

$\Upsilon_{2,3}(1D) \to \gamma\chi_{b1,b2}$, $\chi_{b1,b2} \to \gamma\Upsilon(1S)$,
$\Upsilon(1S) \to \ell^+\ell^-$

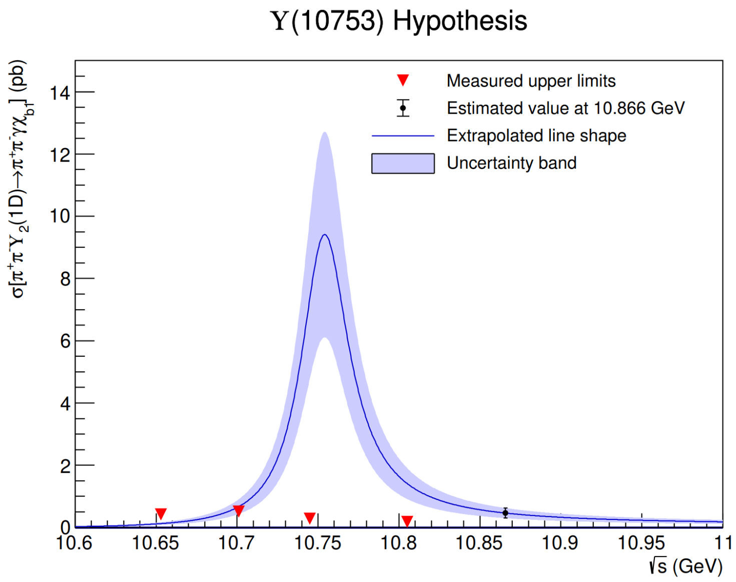
[Belle II Preliminary]

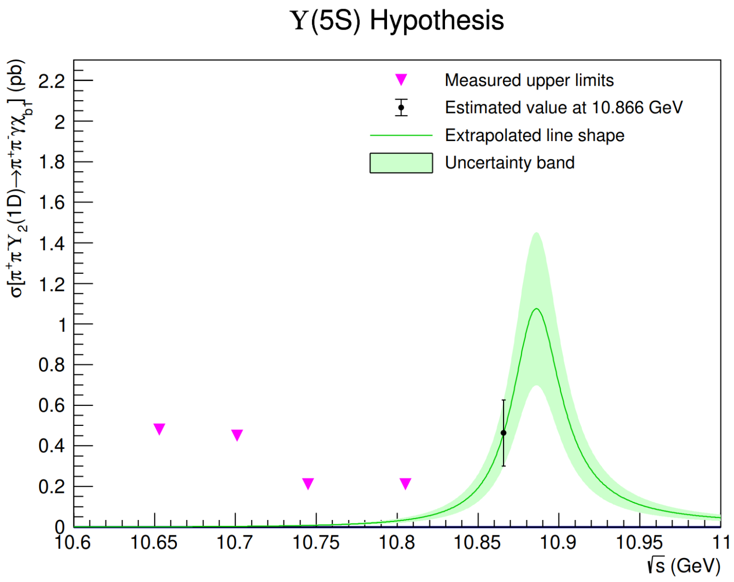




No significant $\Upsilon_J(1D)$ signal is observed.

Inverted triangles: the 90% C.L. upper limits on the product $\sigma(e^+e^- \to \pi^+\pi^-\Upsilon_2(1D))\mathcal{B}(\Upsilon_2(1D) \to \gamma\chi_{b1})$ as a function of C.M. energy.



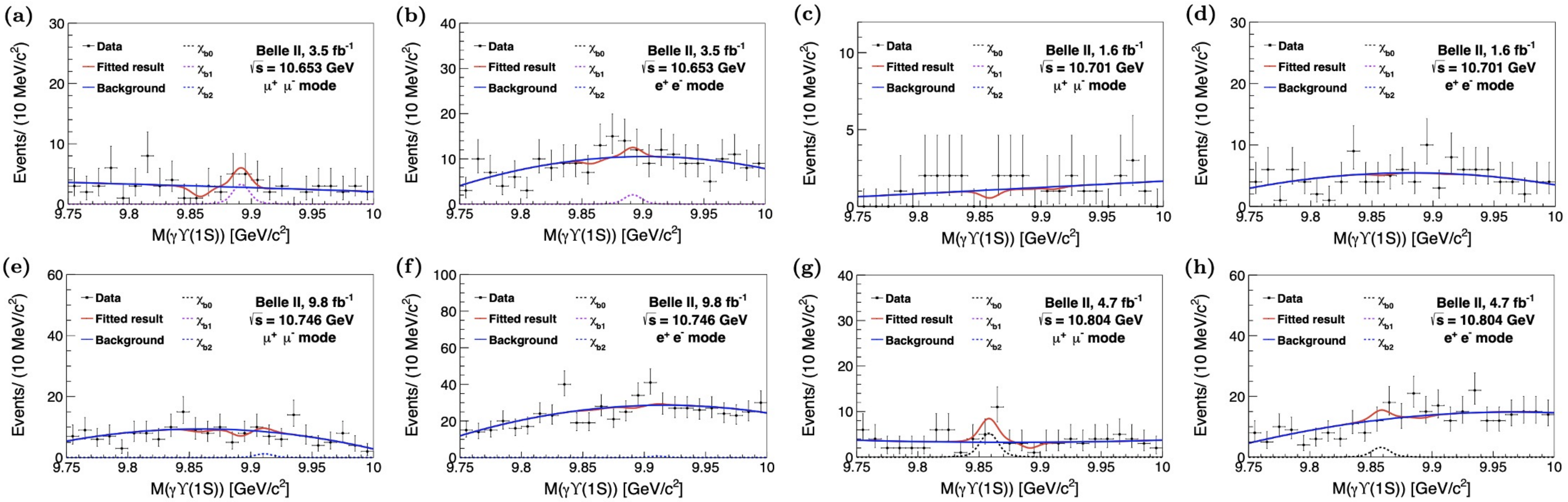


- **A pronounced suppression in the coupling of the $\Upsilon(10753)$ resonance to $\Upsilon_J(1D)$ states via dipion transitions.**
- **The upper limits do not conflict with the $\Upsilon(10860)$ line shape.**

$e^+e^- \to \gamma\chi_{bJ}$ $(J = 0, 1, 2)$

arXiv: 2508.16036

The radiative decay is enhanced if the D component is large [PRD 92, 054034 (2015), EPJC 78, 915 (2018)].



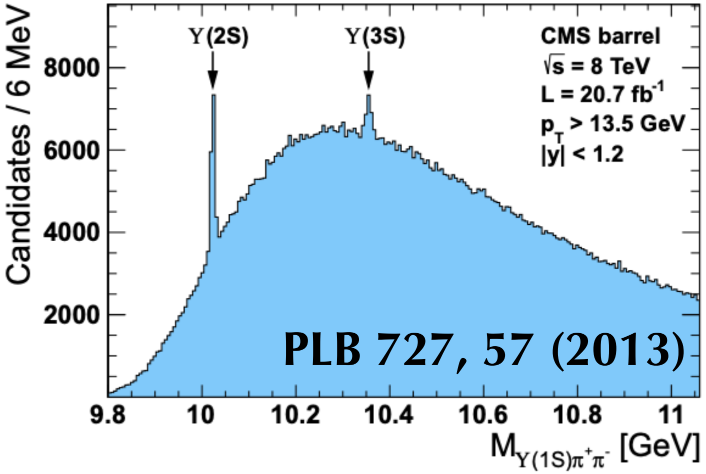
- No clear signal of $e^+e^- \to \gamma\chi_{bJ}$ can be seen.
- $\sigma^{UL}_{Born}(e^+e^- \to \gamma\chi_{b1})$ at $\sqrt{s}$ = 10.746 GeV is 0.26 pb ($\mathcal{B}^{UL}_{Born}(e^+e^- \to \gamma\chi_{b1}) \sim 10^{-4}$), which is much smaller than the Born cross sections for $e^+e^- \to \omega\chi_{bJ}$ and $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$.

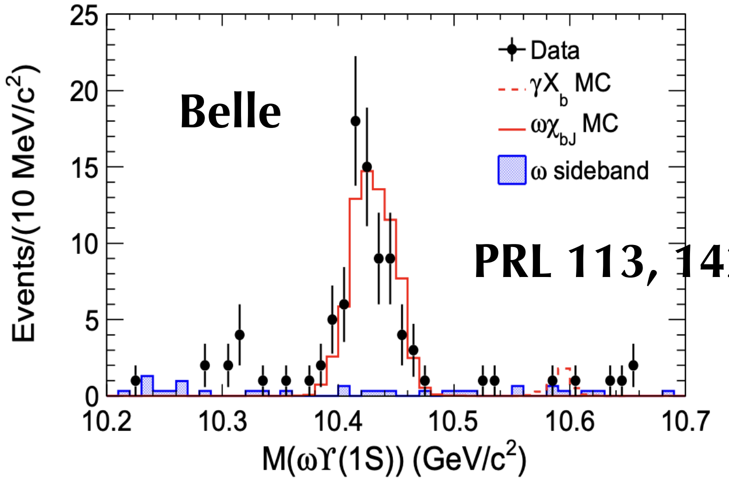
Summary for $\Upsilon(10753)$

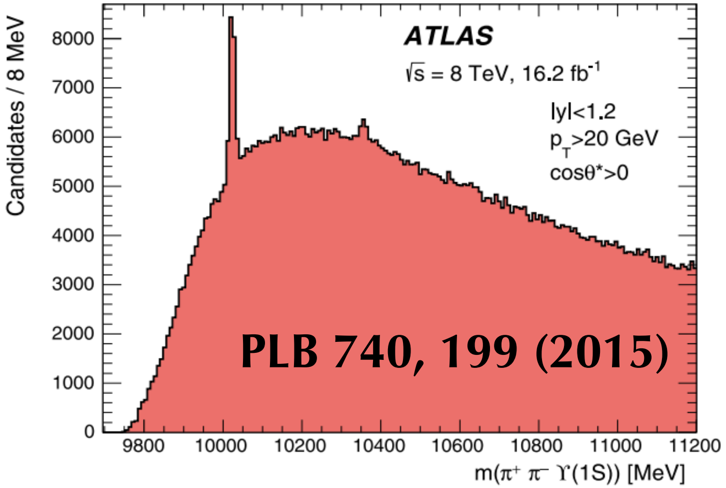
Channel	Results
$e^+e^-\to\pi^+\pi^-\Upsilon(nS)$	Update the mass and width of $\Upsilon(10753)$; More events are accumulated in the higher side of $M(\pi^+\pi^-)$
$e^+e^-\to\omega\chi_{b1,b2}$	Large discrepancy of $\sigma(e^+e^-\to\chi_{bJ}(1P)\omega)/\sigma(e^+e^-\to\Upsilon(nS)\pi^+\pi^-)$ at $\sqrt{s}$ = 10.750 and 10.867 GeV
	$\frac{\sigma(e^+e^-\to\chi_{b1}(1P)\omega)}{\sigma(e^+e^-\to\chi_{b2}(1P)\omega)} = 1.1\pm0.5$
$e^+e^-\to(\pi^+\pi^-\pi^0)_{non-\omega}\chi_{b1,b2}$	The excess maybe due the $\Upsilon(10860, 11020)\to Z_b\pi\to\chi_{bJ}\rho\pi$
$e^+e^-\to\omega\eta_b(1S)$	$\sigma(\Upsilon(10753)\to\omega\eta_b(1S))\sim\sigma(\Upsilon(10753)\to\Upsilon(nS)\pi^+\pi^-)$
$e^+e^-\to B^{(*)}\bar{B}^{(*)}$	Rapid increase of $\sigma_{B^*\bar{B}^*}$ above the threshold
$e^+e^-\to\eta\Upsilon(2S)$	$\sigma(e^+e^-\to\eta\Upsilon(2S))$ around $B^*\bar{B}^*$ mass is relatively large
$\pi^+\pi^-\Upsilon_J(1D)$ $(J=2,3)$	A pronounced suppression
$e^+e^-\to\gamma\chi_{bJ}$	$\sigma(e^+e^-\to\gamma\chi_{bJ})$ is much smaller than $\sigma(e^+e^-\to\omega\chi_{bJ})$ and $\sigma(e^+e^-\to\pi^+\pi^-\Upsilon(nS))$

About X_b

- The X(3872) state was first observed by Belle in 2003 in B decays [PRL 91, 262001 (2003)].
- It is natural to search for a similar state with $J^{PC} = 1^{++}$ (X_b) in the bottomonium system.
- CMS, ATLAS, and Belle searched for X_b states, but found no significant signals.

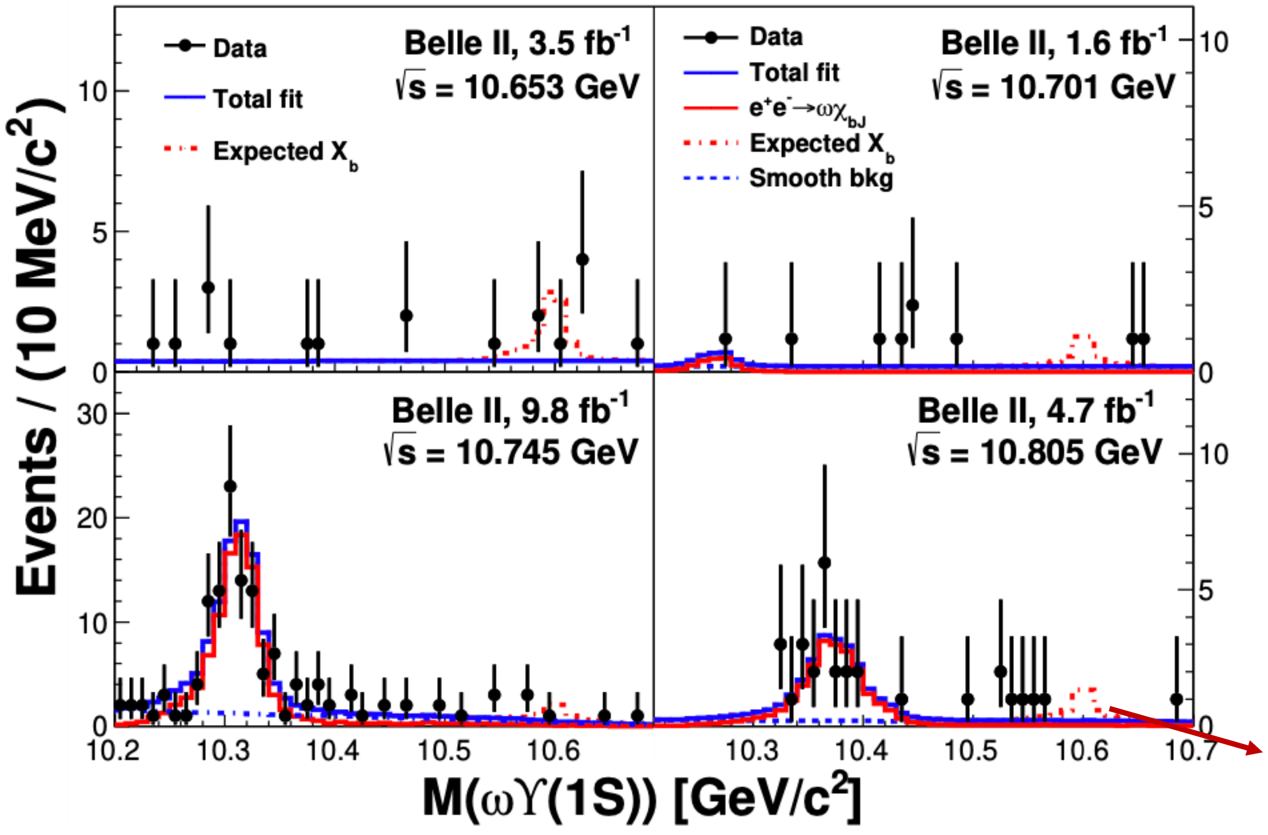


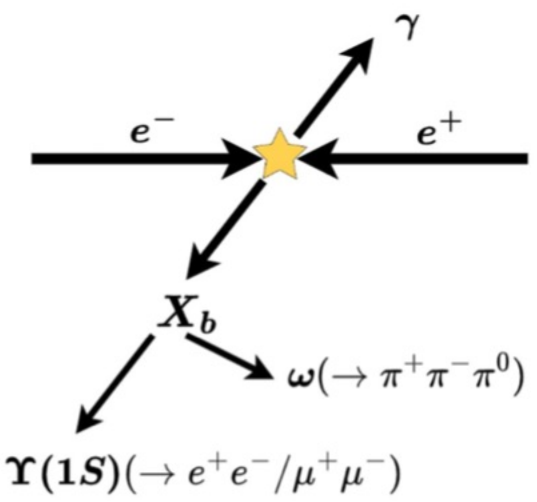




CMS	UL on $BR(X_b)/BR(\Upsilon(2S)) < 0.9–5.4\%$ ($10 < m(X_b) < 11$ GeV/c^2)
ATLAS	UL on $BR(X_b)/BR(\Upsilon(2S)) < 0.8–4.0\%$ (10.05–10.31 GeV/c^2 and 10.40–11.00 GeV/c^2)
Belle	$Br(\Upsilon(10860) \to \gamma X_b) Br(X_b \to \omega \Upsilon(1S)) < 2.9 \times 10^{-5}$

$X_b \to \omega\Upsilon(1S)$ at Belle II





PRL 130, 091902 (2023)

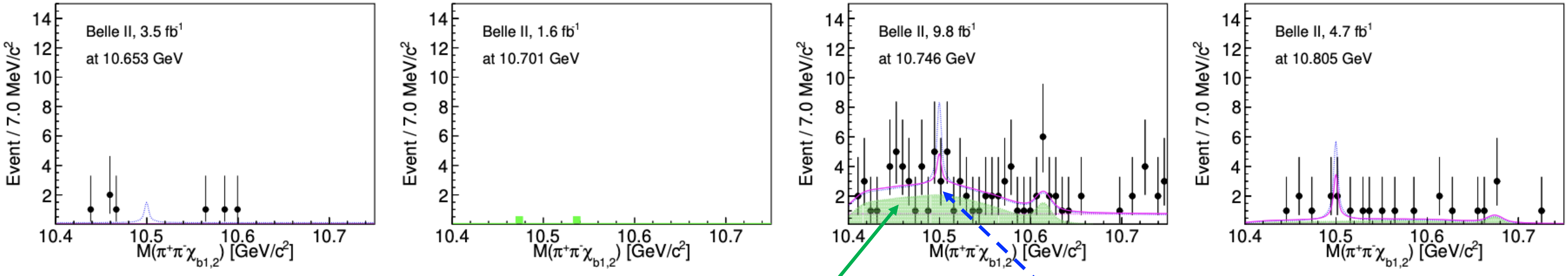
- No significant X_b signal is observed.
- The peaks are the reflections of $e^+e^- \to \omega\chi_{bJ}$.

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)

$X_b \to \pi^+\pi^-\chi_{bJ}$ at Belle II

- **No significant X_b signal is observed.**

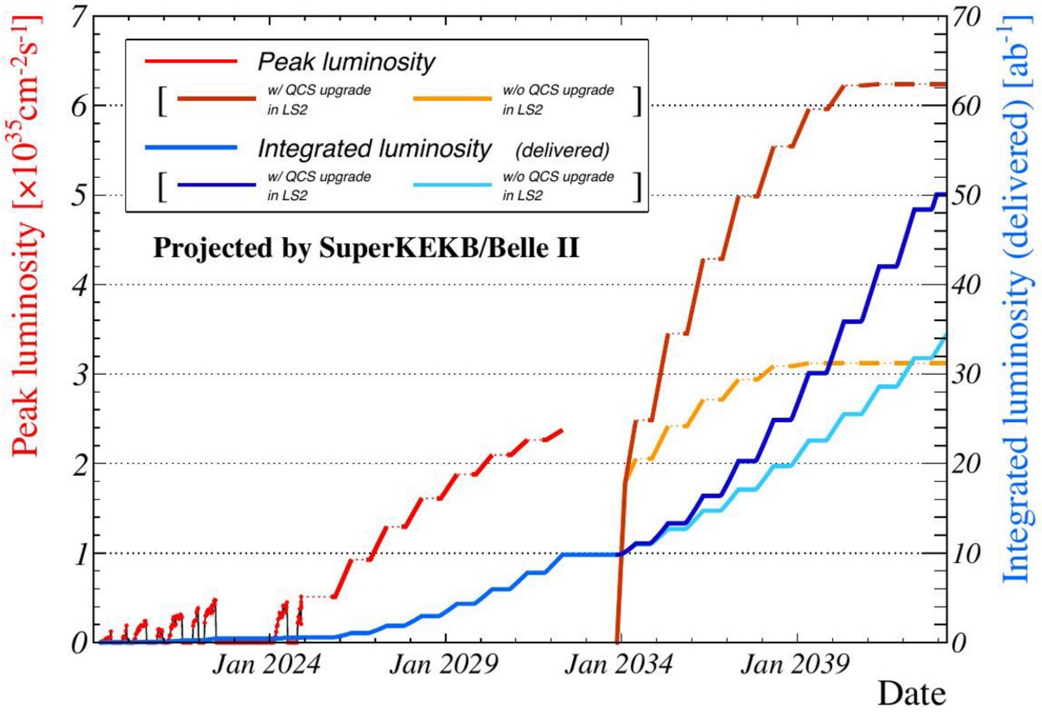


The shaded histograms: the background from $\omega\chi_{bJ}$ and $\pi^+\pi^-\Upsilon(2S)(\to\gamma\chi_{bJ})$.
The blue dashed lines: the fit results with the contribution of X_b set to the maximum upper limits at 90% C.L.

Upper limits at 90% C.L. on $\sigma_B(e^+e^- \to \gamma X_b) \cdot \mathcal{B}(X_b \to \pi^+\pi^-\chi_{bJ})$ (pb)	$\sqrt{s}$ (GeV)	10.653	10.701	10.746	10.805
	$m(X_b)$ = 10.5 GeV/c^2	0.14	0.09	0.17	0.32

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)

$e^+e^- \to Y(4260) \to \pi^+\pi^- J/\psi$ 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

Summary

- Measure the ratio of radiative decay to hadronic decay of charmed strange mesons to distinguish their internal structure.
- Start to measure ISR processes with larger combined Belle and Belle II datasets.
- Provide more decay modes for Y(10753).
- Only 1% 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!

Backup slides

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

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