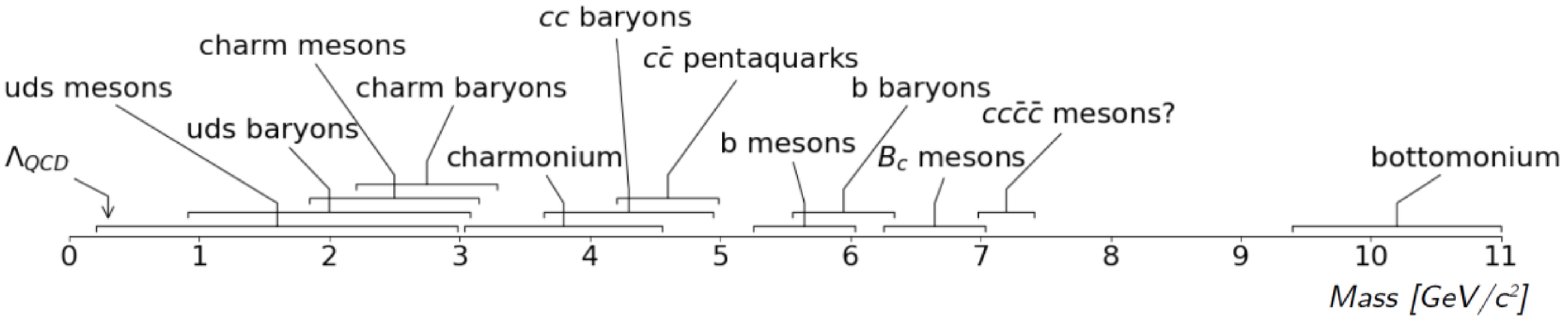
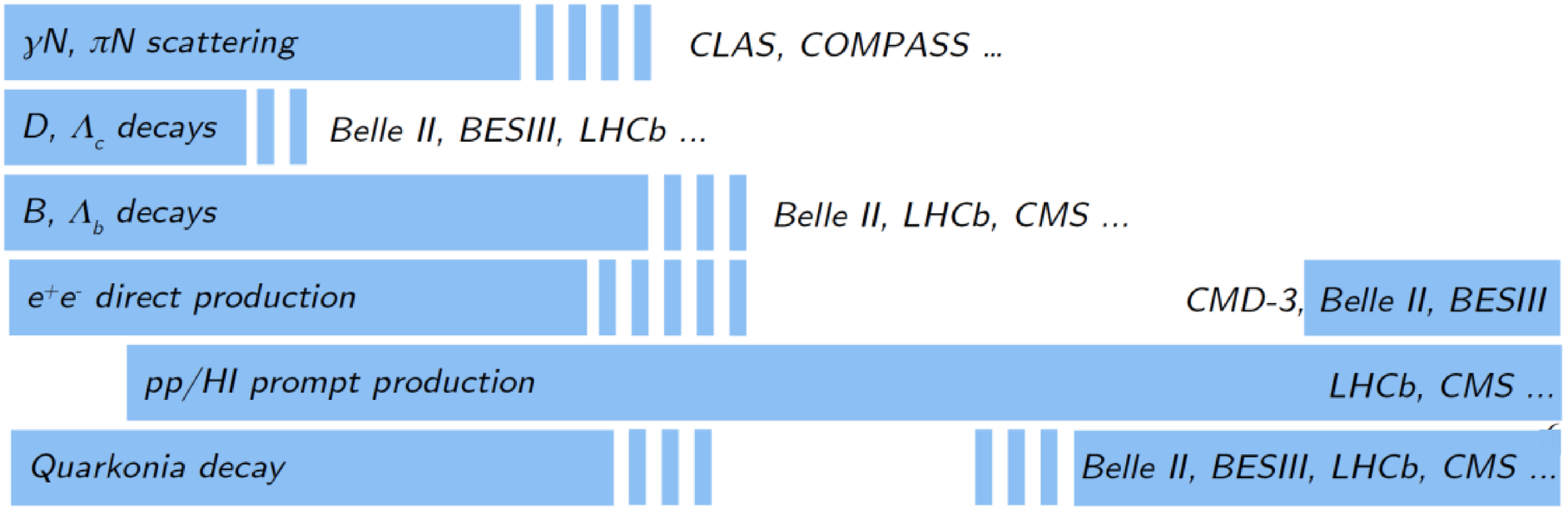
Recent spectroscopy results from Belle II experiment

Speaker: Junhao Yin (on behalf of Belle II experiment)
Nankai University

17th Heavy Quark and Lepton, Beijing

The Hadron spectroscopy

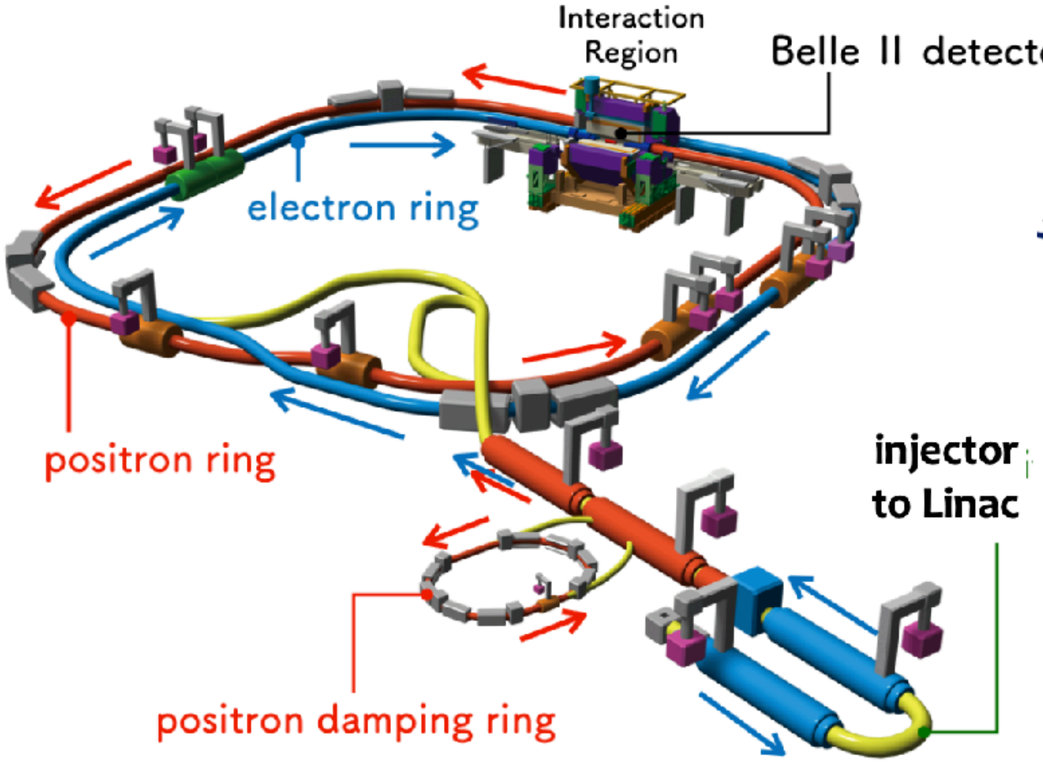


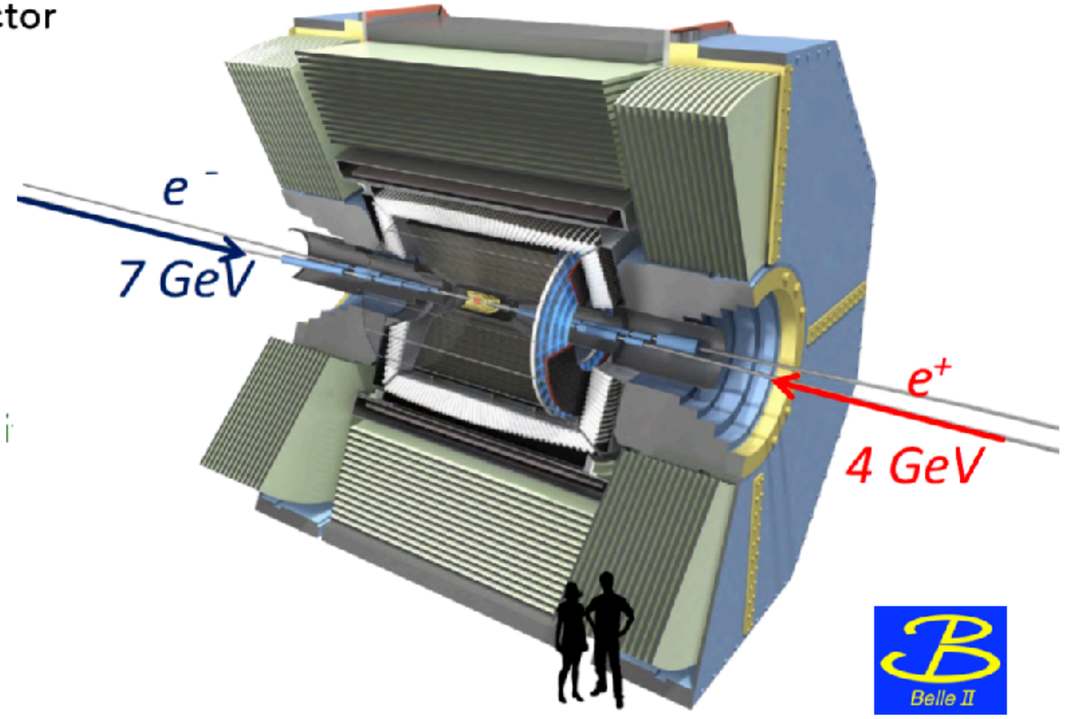


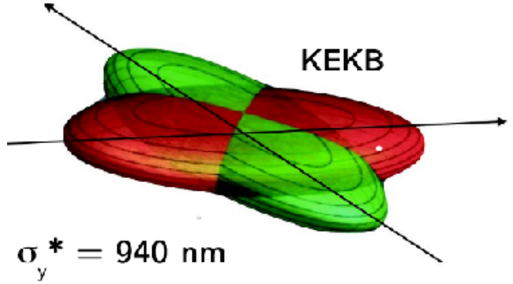
SuperKEKB

$$e^- \xrightarrow{7\ \text{GeV}} (\star) \xleftarrow{4\ \text{GeV}} e^+$$

Belle II



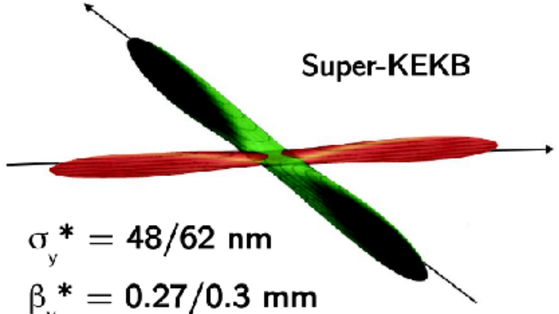




$\sigma_y^* = 940$ nm

$\beta_y^* = 5.9$ mm

$\sigma_x^* = 147/170$ μm



$\sigma_y^* = 48/62$ nm

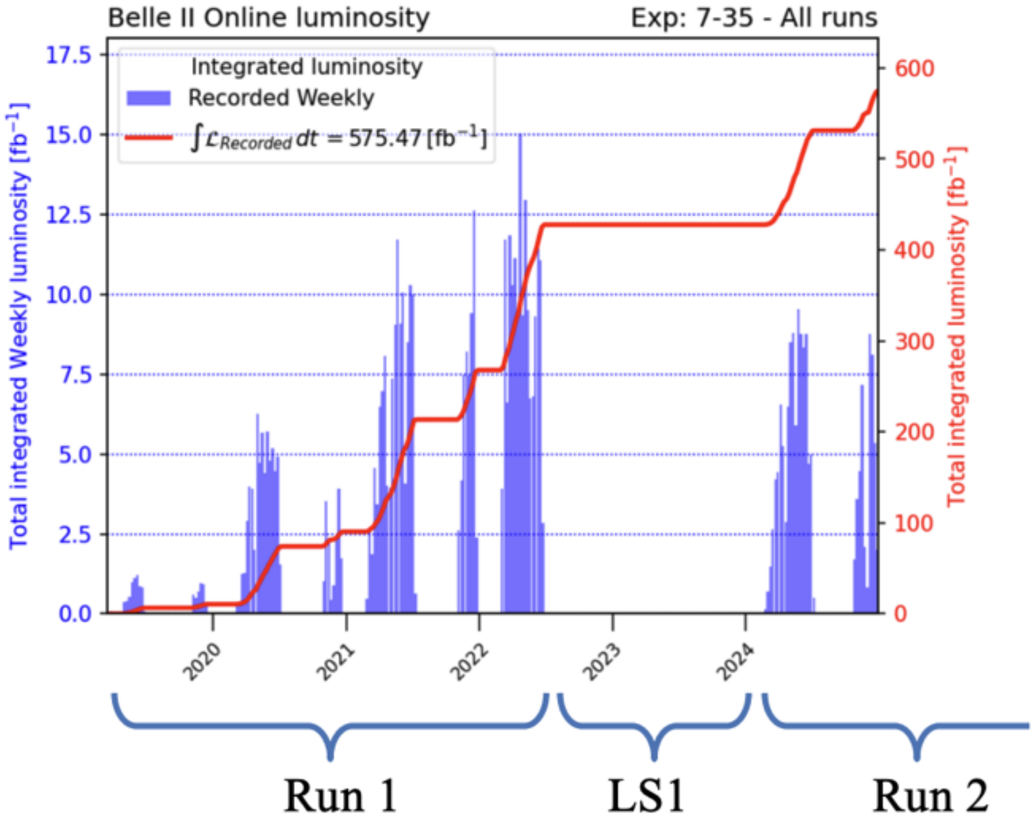
$\beta_y^* = 0.27/0.3$ mm

$\sigma_x^* = 10.1/10.7$ μm

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

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

- So far collect 575 fb^{-1}
  - Mostly at $\sqrt{s} = 10.58$ GeV, $\Upsilon(4S) \to B\bar{B}$
  - Continuum data at $\sqrt{s} = 10.52$ GeV
  - $\Upsilon(10753)$ scan data around $\sqrt{s} = 10.75$ GeV
- World luminosity record: $5.1 \times 10^{34}/cm^2/s$



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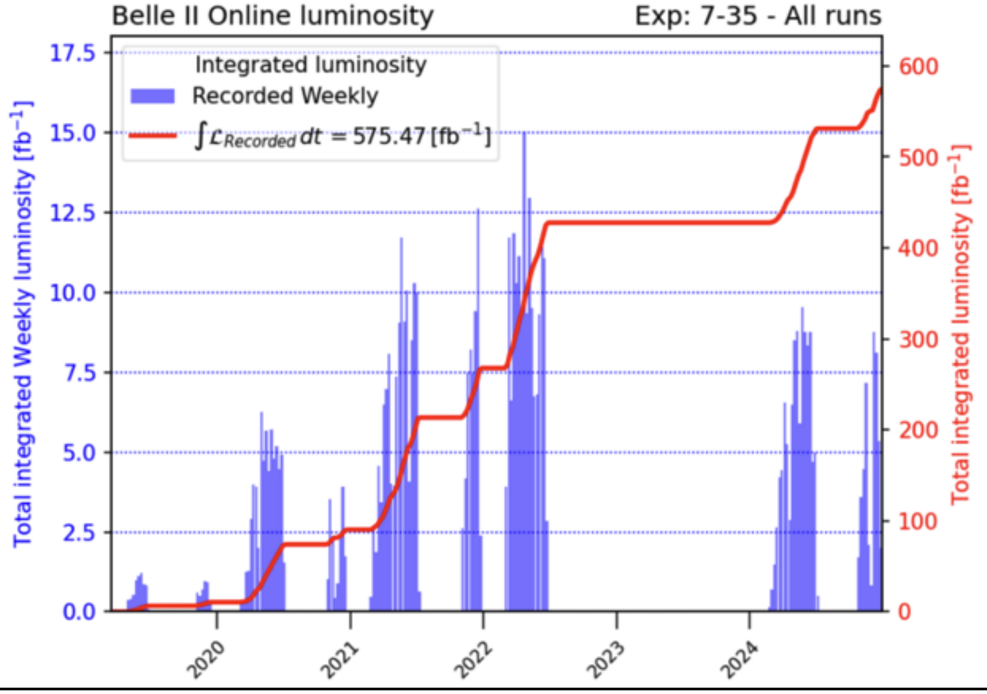
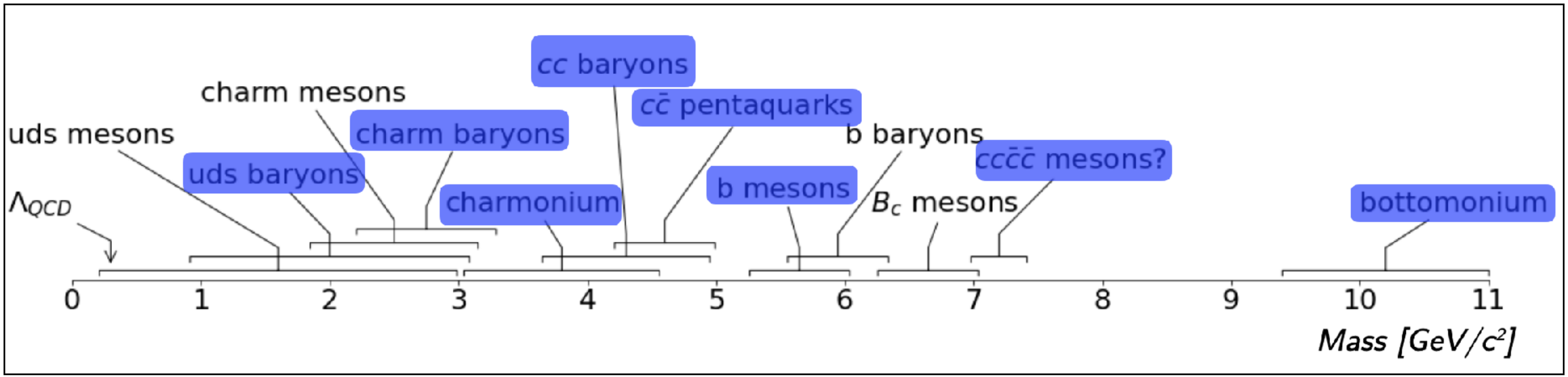


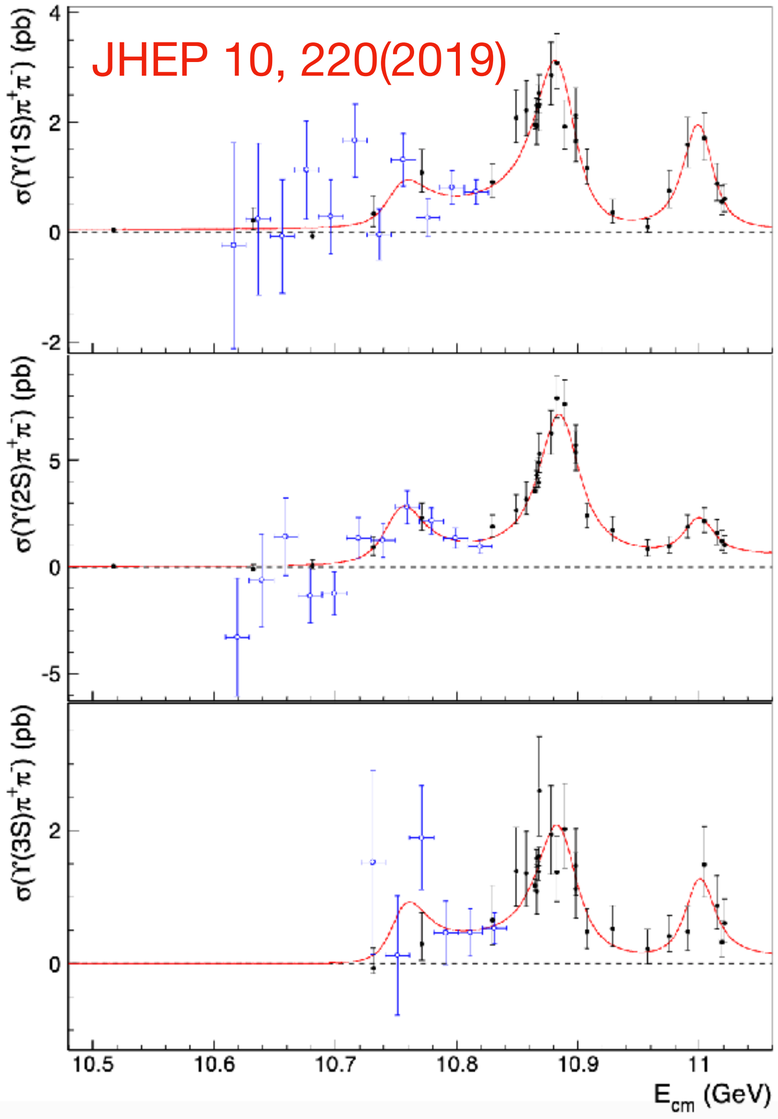


In this talk

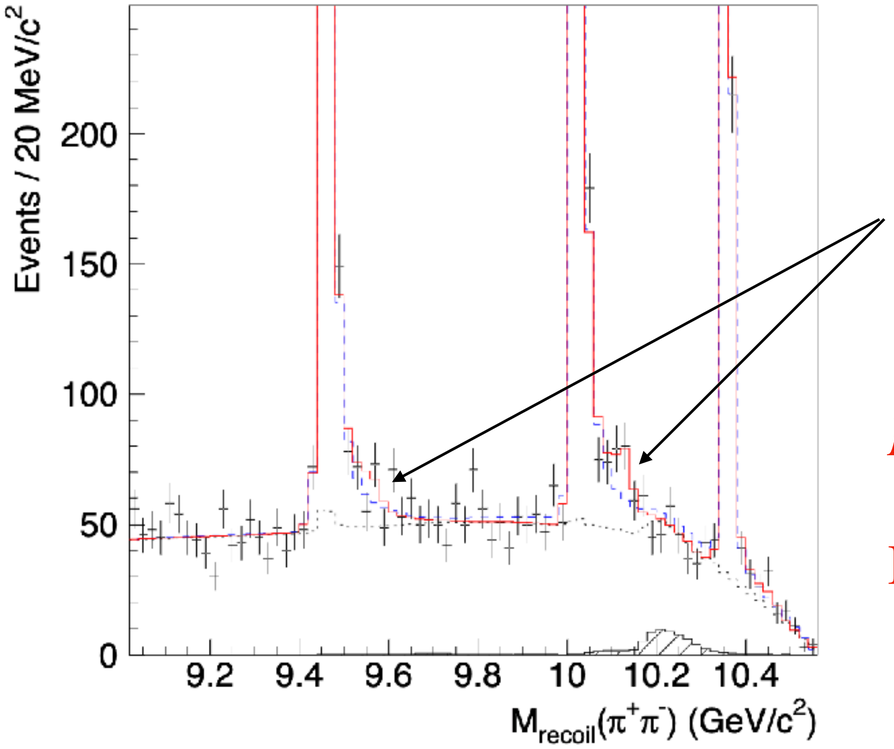
- Investigate of $\Upsilon(10753)$
  - Observation of $e^+e^- \to \eta\Upsilon(2S)$ and search for $\Upsilon(10753) \to \gamma X_b$ near $\sqrt{s} = 10.75$ GeV arXiv:2509.01917
  - Search for $\Upsilon(10753) \to \gamma\chi_{bJ}$ arXiv:2509.01917
- Light hadron production and decays
  - Observation of $D_{s0}^*(2317)^+ \to D_s^*\gamma$ preliminary
  - Observation of $B^+ \to \Sigma_c(2455)^{++}\bar{\Xi}_c^-$ and $B^0 \to \Sigma_c(2455)^0\bar{\Xi}_c^0$ arXiv: 2507.05094
  - Observation of $\Xi_c^+ \to pK_S^0$, $\Lambda\pi^+$, and $\Sigma^0\pi^+$ JHEP 03 2025, 061 (2025)
  - Measurements of $\Xi_c^+ \to \Sigma^+K_S^0$, $\Xi^0\pi^+$, and Ξ^0K^+ arXiv:2503.17643
- Mass difference of B^0/B^+ preliminary

Investigation of $\Upsilon(10753)$

$\Upsilon(10753)$ — discovery and studies



- The $\Upsilon(10753)$ was firstly observed in the process of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-(n = 1,2,3)$ by Belle.
- Simultaneous fit to cross sections and $M_{\text{recoil}}(\pi\pi)$



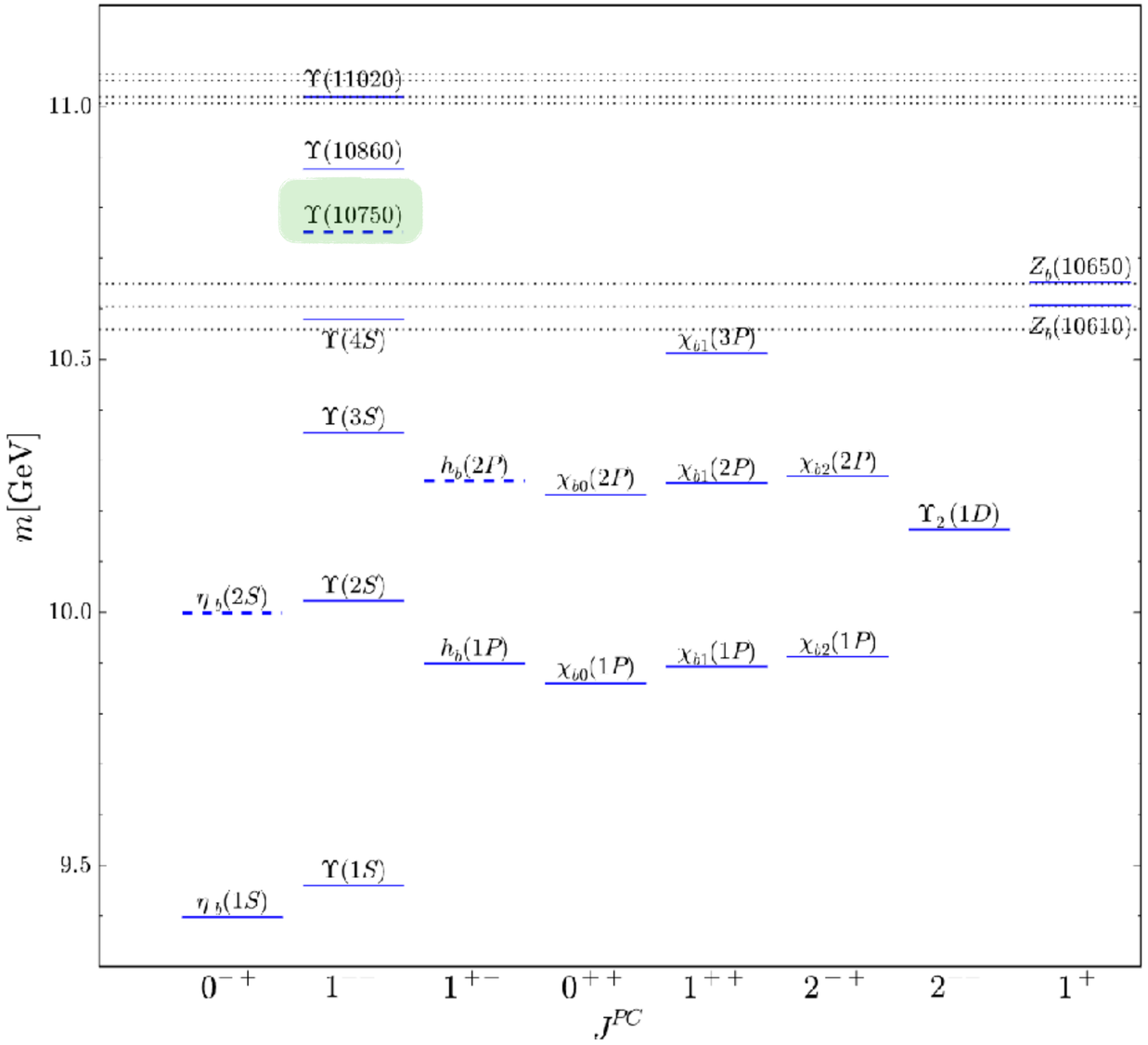
Existence of $\Upsilon(10753)$

Computed as blue dots in left plot

$M = (10752.7 \pm 5.9^{+0.7}_{-1.1})$ MeV/c^2

$\Gamma = (35.5^{+17.6\ +3.9}_{-11.3\ -3.3})$ MeV

Interpretation of $\Upsilon(10753)$



Bottomonium?

Phys. Rev. D 101, 014020 (2020)

Phys. Lett. B 803, 135340 (2020)

Eur. Phys. J. C 80, 59 (2020)

Phys. Rev. D 102, 014036 (2020)

Prog. Part. Nucl. Phys. 117, 103845 (2021)

Phys. Rev. D 104, 034036 (2021)

Phys. Rev. D 105, 074007 (2022)

etc…

Hybrid?

Phys. Rept. 873, 1 (2020)

Phys. Rev. D 104, 034019 (2021)

etc…

Tetraquark?

Phys. Lett. B 802, 135217 (2020)

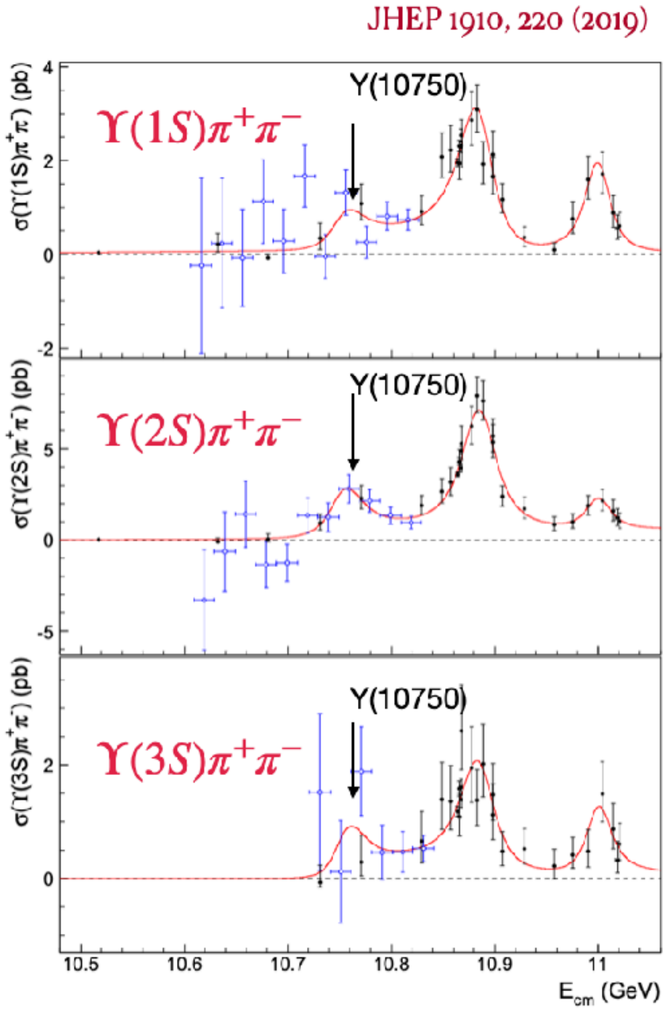
Chin. Phys. C 43, 123102 (2019)

Phys. Rev. D 103, 074507 (2021)

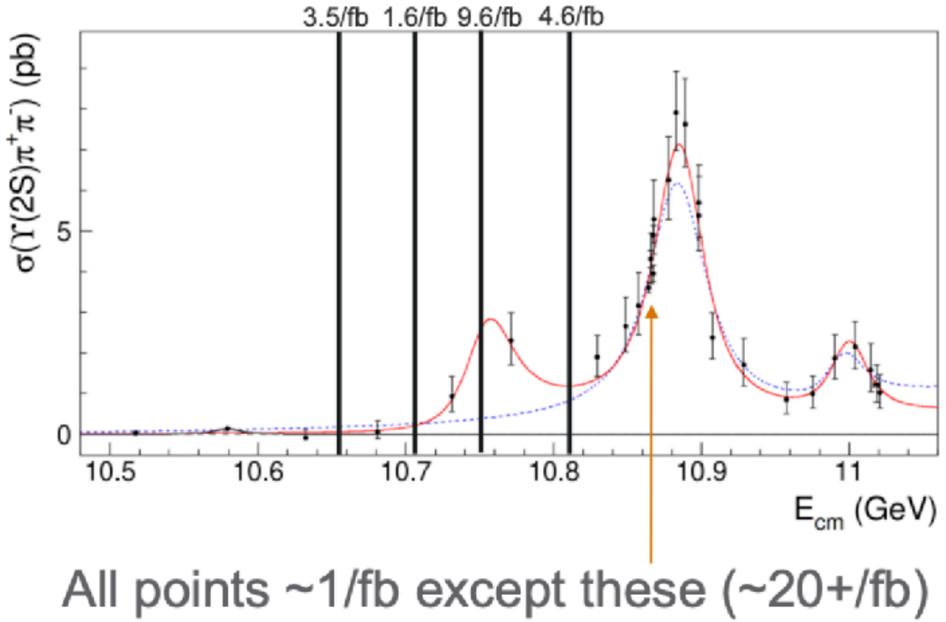
Phys. Rev. D 107, 094515 (2023)

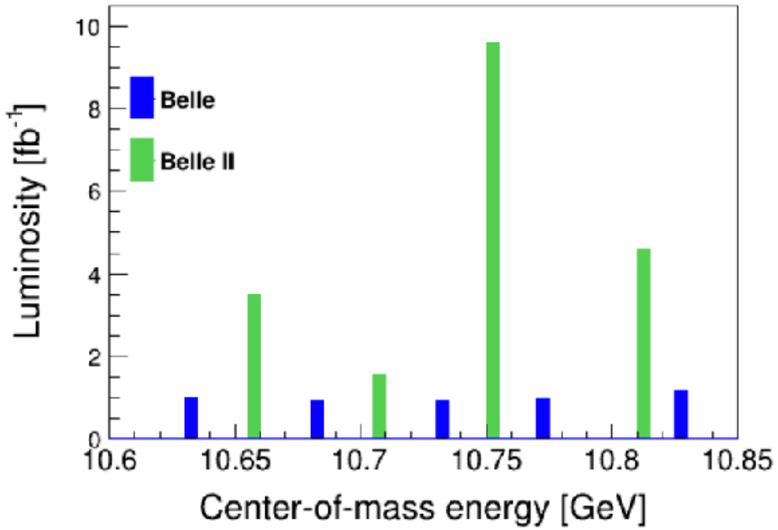
etc…

A little data may tell a big story



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





With 19.6 fb^{-1} $\Upsilon(10753)$ scan data on Belle II:

$$\Upsilon(10753) \to \pi^+\pi^-\Upsilon(1,2,3S)$$

Precise measurement; intermediate state investigation

[JHEP 07 2024, 116(2024)]

$$\Upsilon(10753) \to \eta\Upsilon(1,2S)$$

Prediction of a sizable BF

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

Existence confirmation; new channel; indicating different nature against $\Upsilon(5S)$

[PRL 130, 091902(2023)]

$$\Upsilon(10753) \to \gamma\chi_{bJ}$$

Prediction of a sizable BF

$$\Upsilon(10753) \to \omega\eta_b$$

Indicating not a tetraquark; different structure from $Y(4230)$

[PRD 109, 072013(2024)]

$$\Upsilon(10753) \to B^{(*)}\bar{B}^{(*)}$$

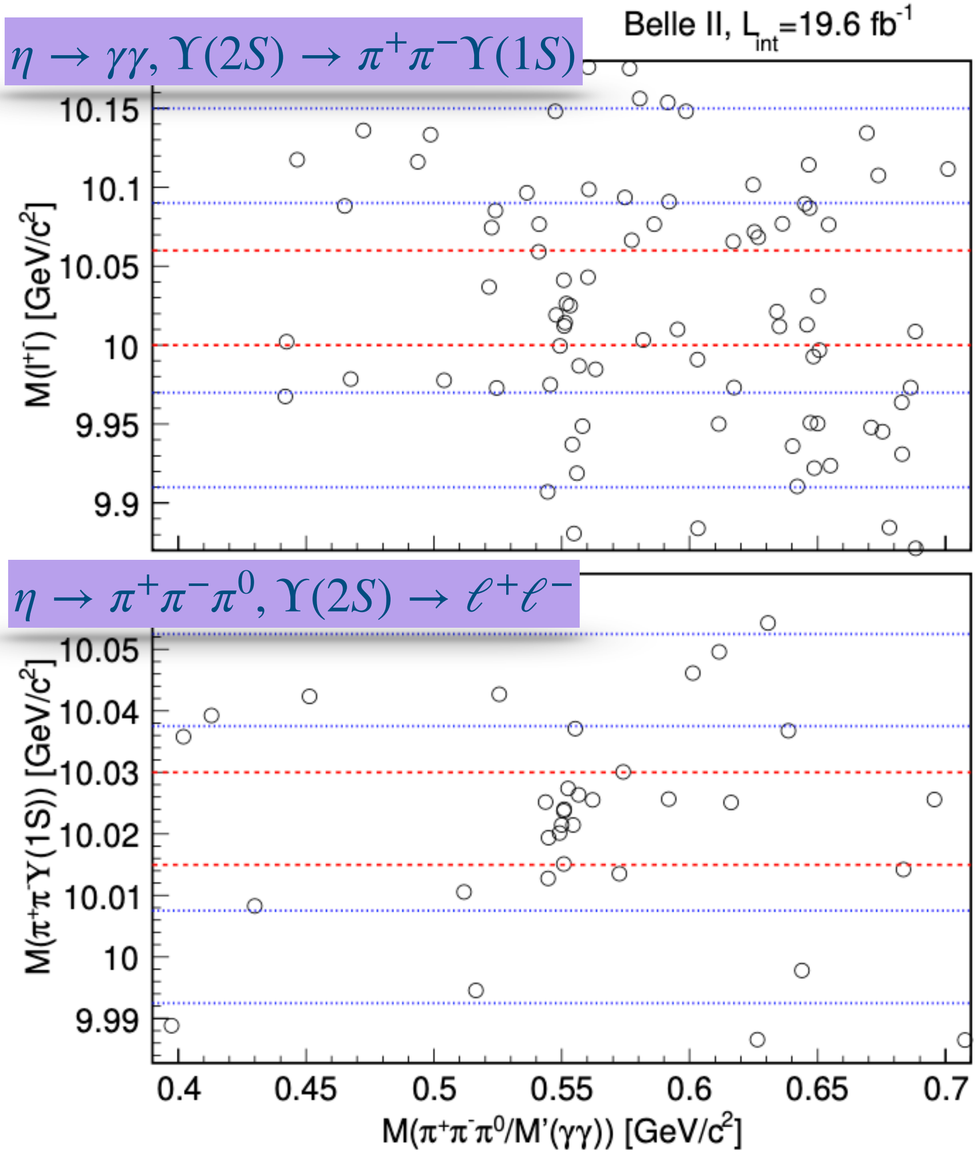
Suggesting a new state near $B^*\bar{B}^*$ *threshold*

[JHEP 10 2024, 114(2024)]

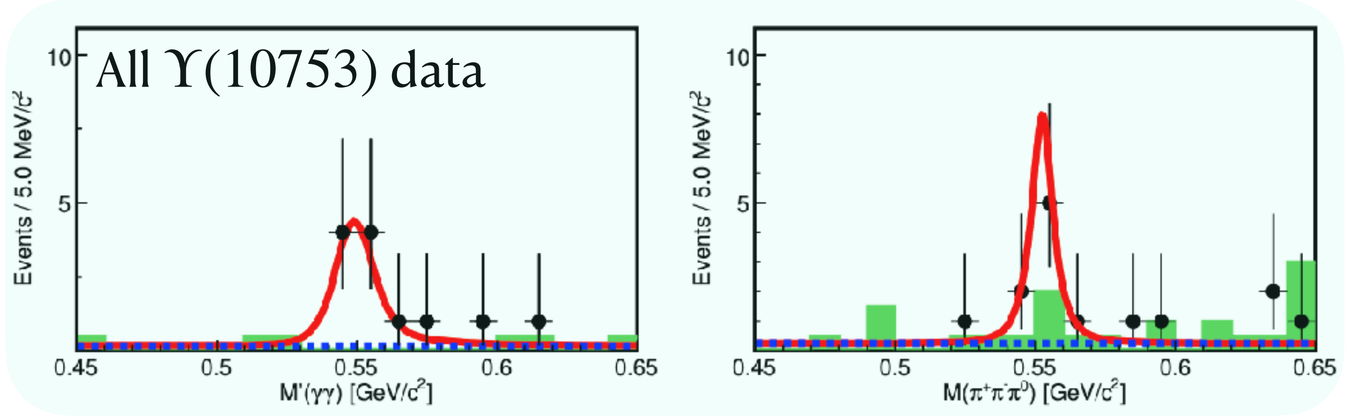
$\Upsilon(10753) \to \eta\Upsilon(2S)$

arXiv:2509.01917

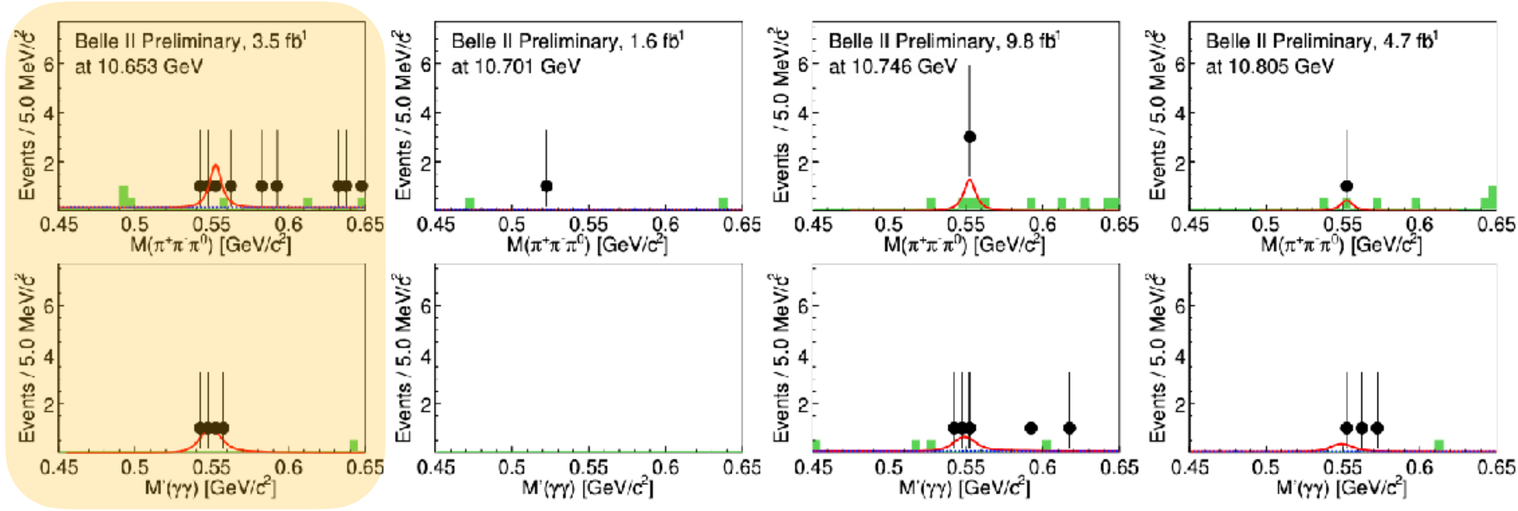
$\eta \to \gamma\gamma, \Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$



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



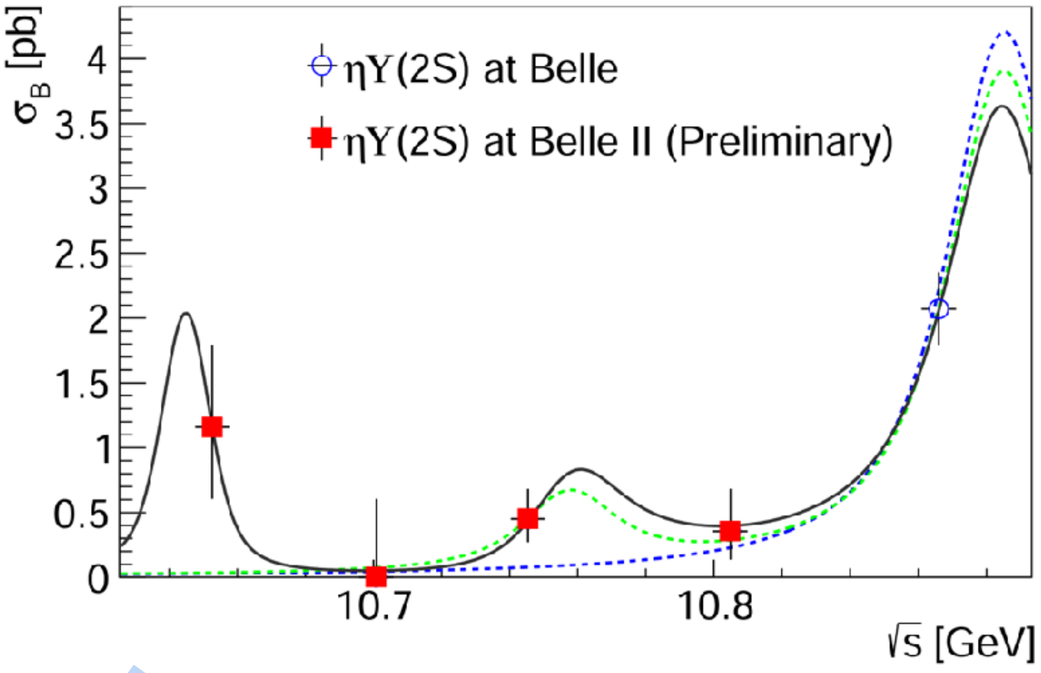
- Clear signal found in $\eta\Upsilon(2S)$ signal region.
- Simultaneous fit performed
  - >6σ significance

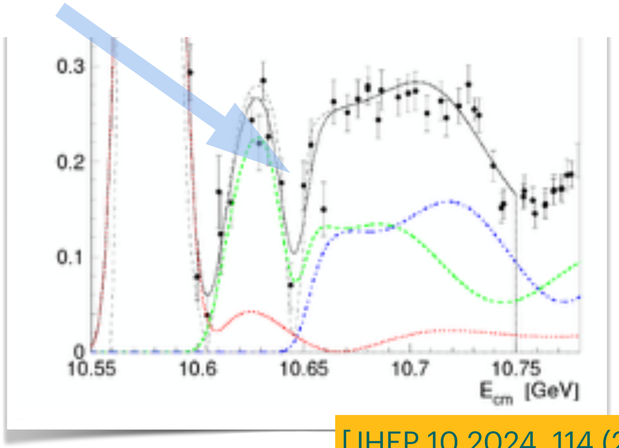


More events with smaller data

Fit to $e^+e^- \to \eta\Upsilon(2S)$ Born cross sections

arXiv:2509.01917





[JHEP 10 2024, 114 (2024)]

Unbinned maximum likelihood fit to the σ^{Born} together with Belle measurement.

Fit the with 3 different hypotheses:

1. $\Upsilon(5S)$ only (blue dashed curve);
2. $\Upsilon(5S) + \Upsilon(10753)$ (green dashed curve)
3. $\Upsilon(5S) + \Upsilon(10753) + \Upsilon_{new}$ (solid curve) , *default*

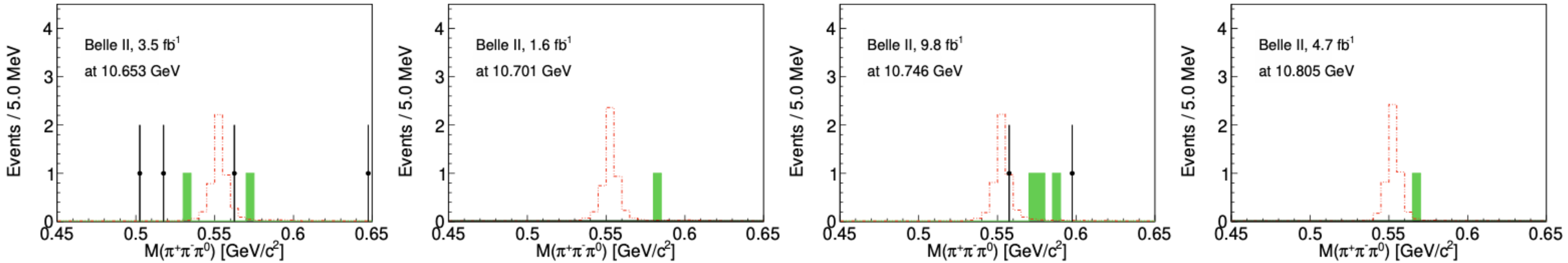
**All parameters fixed, including* parameters of Υ_{new}, which is obtained from $e^+e^- \to B^*\bar{B}^*$ measurement [JHEP 10 2024, 114 (2024)]

***Other fit hypotheses tested, e.g.* $\Upsilon(5S) + \text{cont.}$, *significance of* Υ_{new} *is always greater than* 3σ.

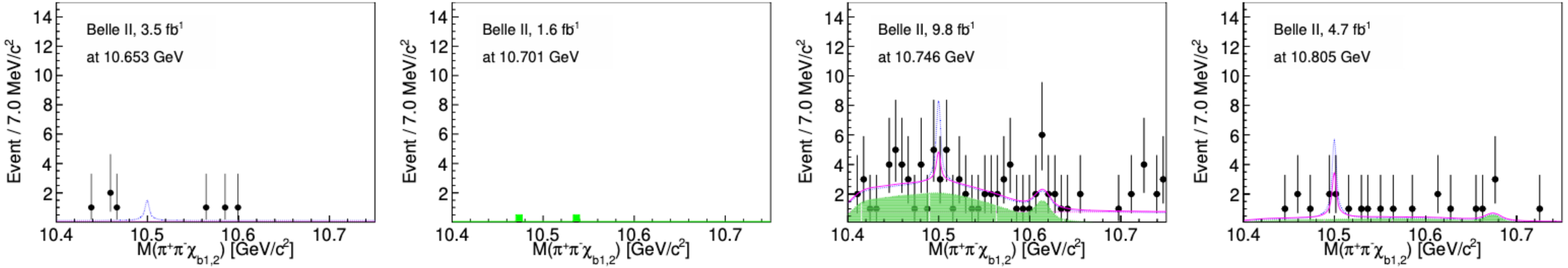
**** Not from tail of* $\Upsilon(4S)$; $\sigma(\eta\Upsilon(2S))$ *@ 10.58 GeV* < 0.01 pb.

arXiv:2509.01917

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



$e^+e^- \to \gamma X_b[X_b \to \pi^+\pi^-\chi_{bJ}]$



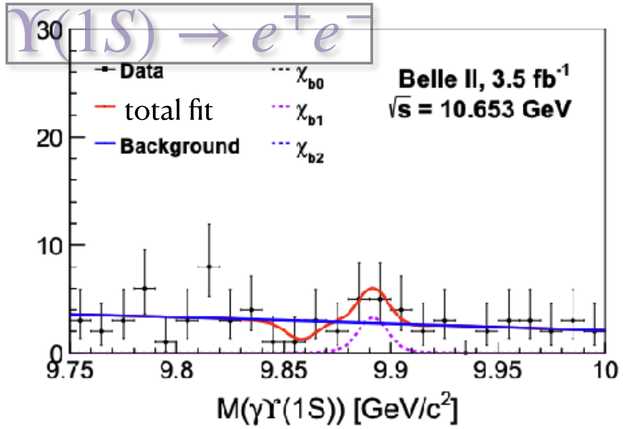
No evident signal of $\eta\Upsilon(1S)$ nor $\gamma X_b[\pi\pi\chi_{bJ}]$. Upper limits @90% C.L. estimated.

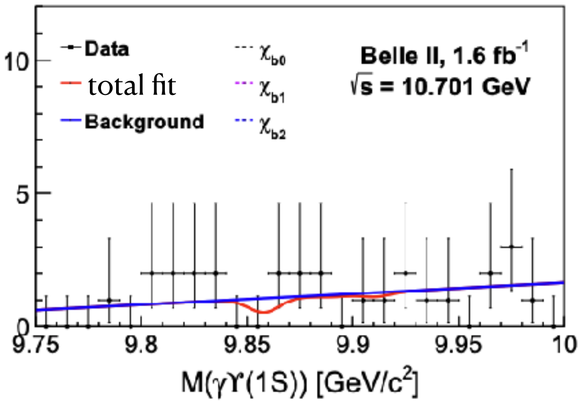
arXiv: 2508.16036

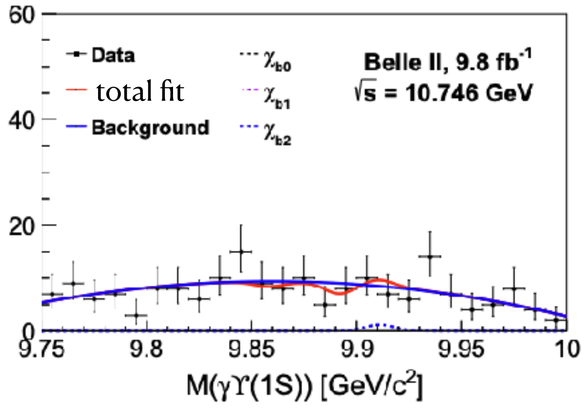
$e^+e^- \to \gamma\chi_{bJ}$

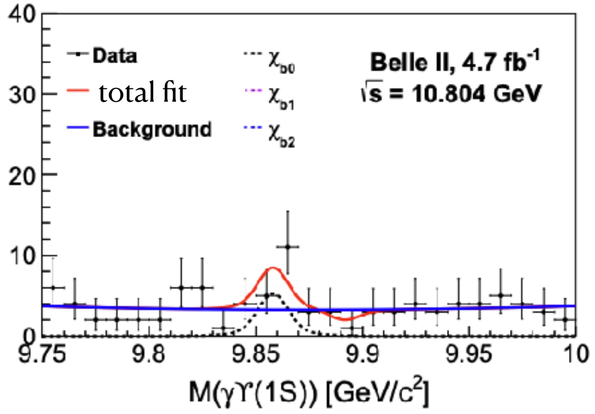
- The study of the radiative decay of $\Upsilon(10753)$ is helpful to understand its nature.
- If $\Upsilon(10753)$ is a pure 2D state, the BF for $\Upsilon(10753) \to \gamma\chi_{b1}$ can reach 12% [PRD 92,054034(2015), EPJC 78,915(2018)].

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

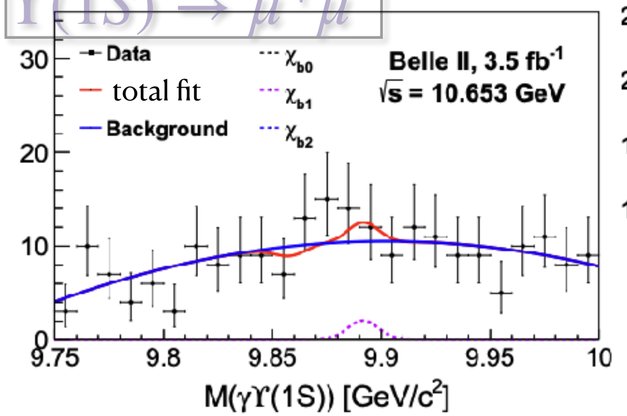


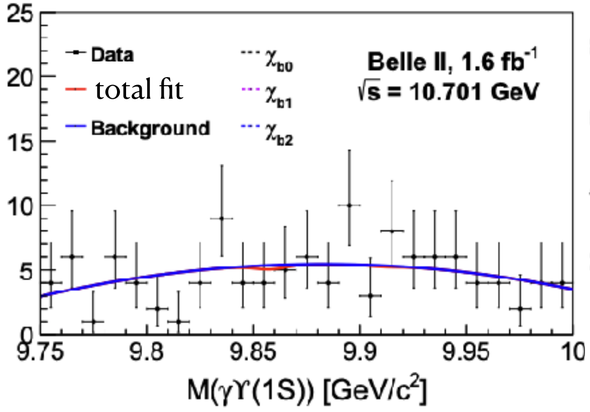


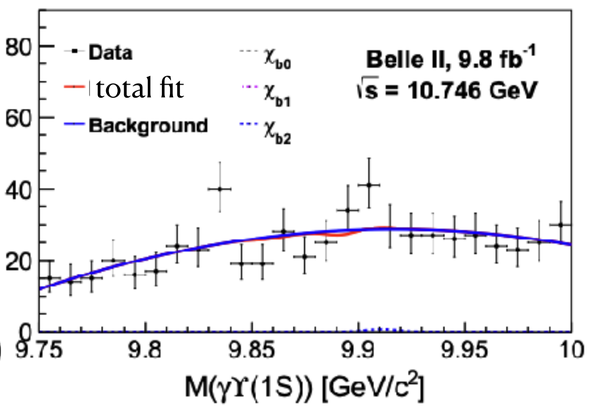


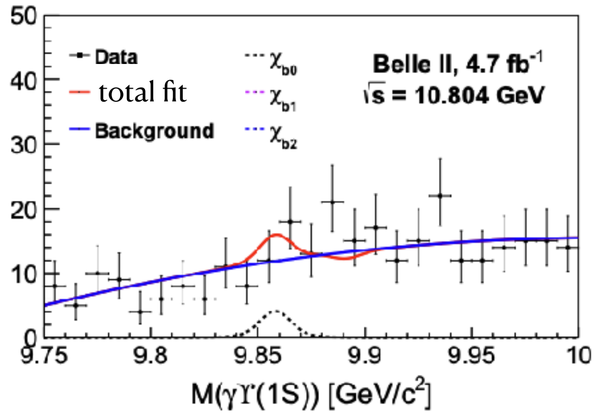


$\Upsilon(1S) \to \mu^+\mu^-$









No evident signal found, with $\mathcal{B}(\Upsilon(10753) \to \gamma\chi_{b1}) < 10^{-3}$, indicating D-wave in $\Upsilon(10753)$ could be small.

Light hadron production and decays

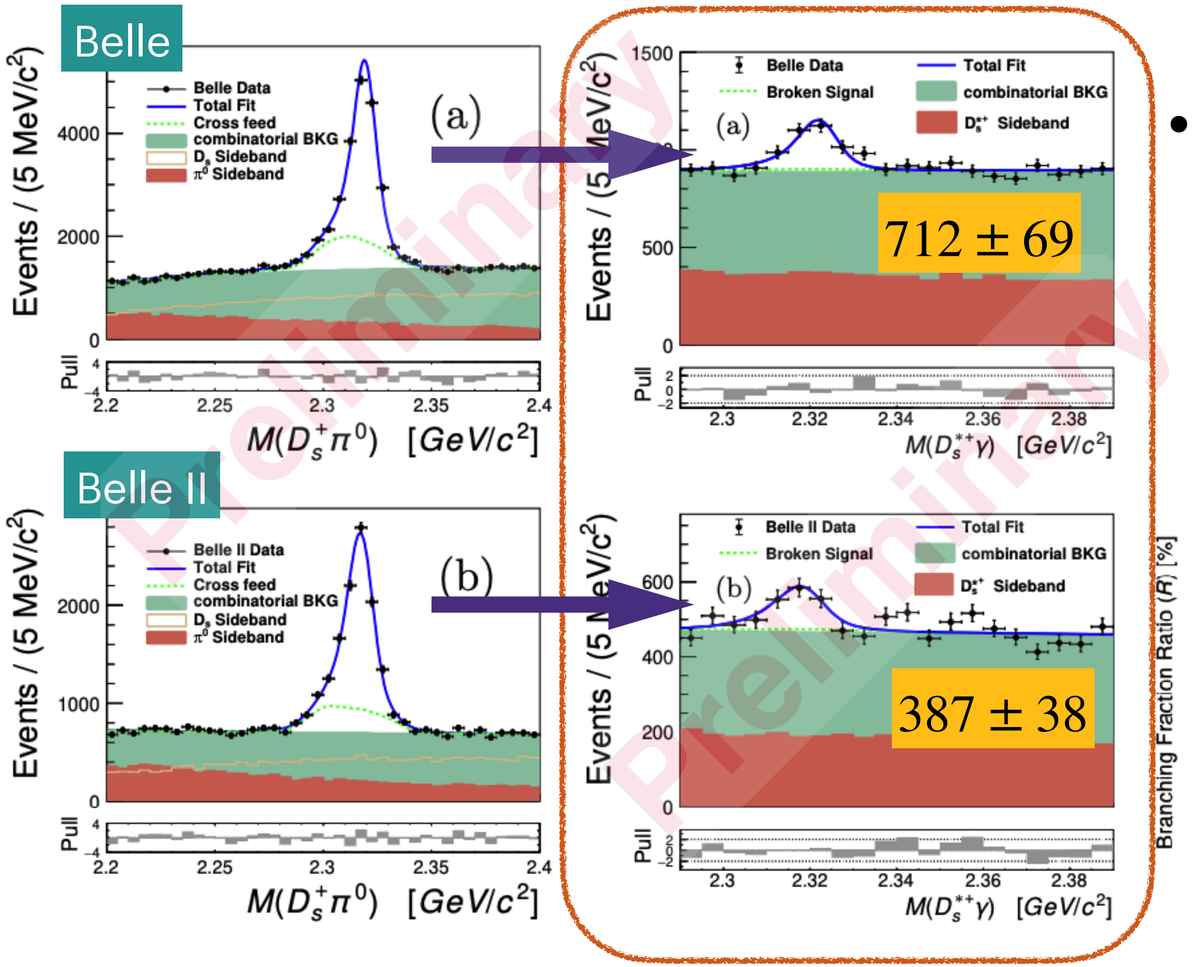
Preliminary

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

983 fb^{-1} *and* 427.9 fb^{-1}
Belle and Belle II

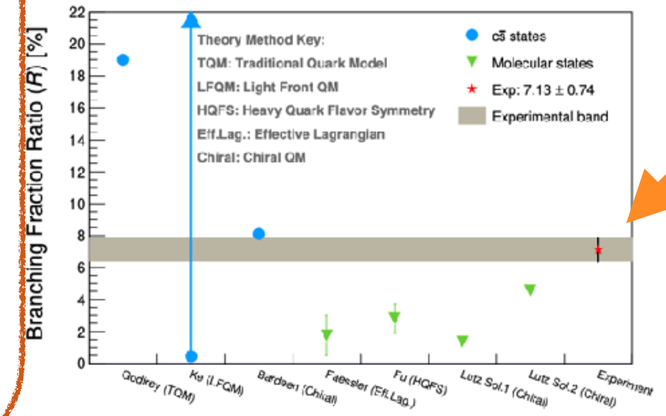
$D_s^{*+} \to D_s^{+}\pi^0$

- $D_{s0}^{*}(2317)$ draws significant attention as its mass significantly lower than expectation
- Its radiative transition will provide a direct experimental constraint on various theoretical models.



- Simultaneous fit to $M(D_s^{*+}\gamma)$ from Belle and Belle II:
  Significance $> 10\sigma$;
  Relative ratio

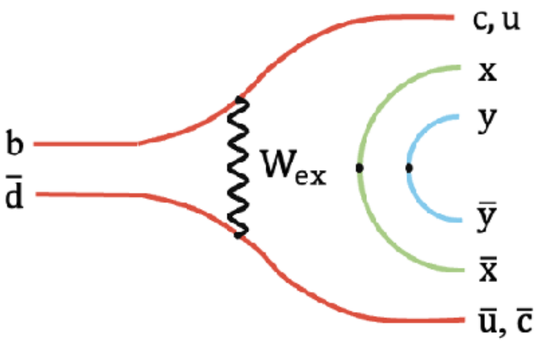
$$\mathcal{R} \equiv \frac{\mathcal{B}(D_{s0}^{*}(2317)^{+} \to D_s^{*+}\gamma)}{\mathcal{B}(D_{s0}^{*}(2317)^{+} \to D_s^{+}\pi^0)} = (7.14 \pm 0.70 \pm 0.23)\,\%$$

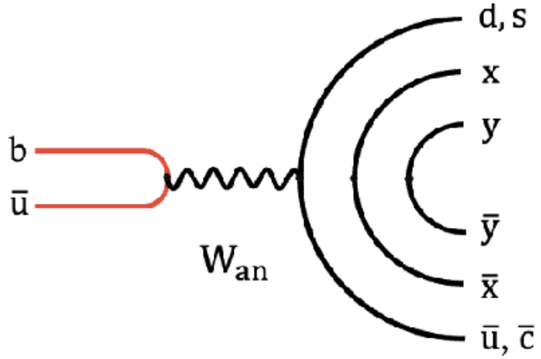


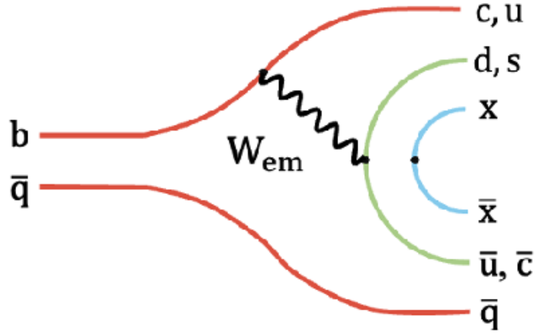
Not favor molecular interpretation.
Could be a mixture of pure $c\bar{s}$ and molecular state

$B^{+/0} \to \Sigma_c(2455)^{++/0}\bar{\Xi}_c^{-/0}$

- The tree-level two-body baryonic B decays can proceed through W-exchange (W_{ex}), W-annihilation (W_{an}), and internal W-emission (W_{em}) diagrams.



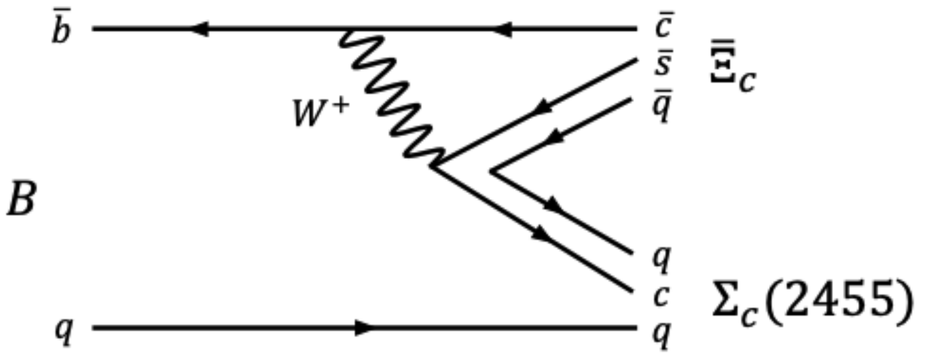




W_{ex} and W_{an}: helicity suppressed

: non-factorizable amplitude

- The decays $B \to \Sigma_c(2455)\bar{\Xi}_c$ proceed through a pure W_{em} diagram, providing a clean and ideal environment for studying non-factorizable effects.
- BF predicted to be 4×10^{-3} (sum rule) [NPB 345, 137 (1990)] or of the order 10^{-4} (di-quark model) [ZPC 51, 445 (1991)].

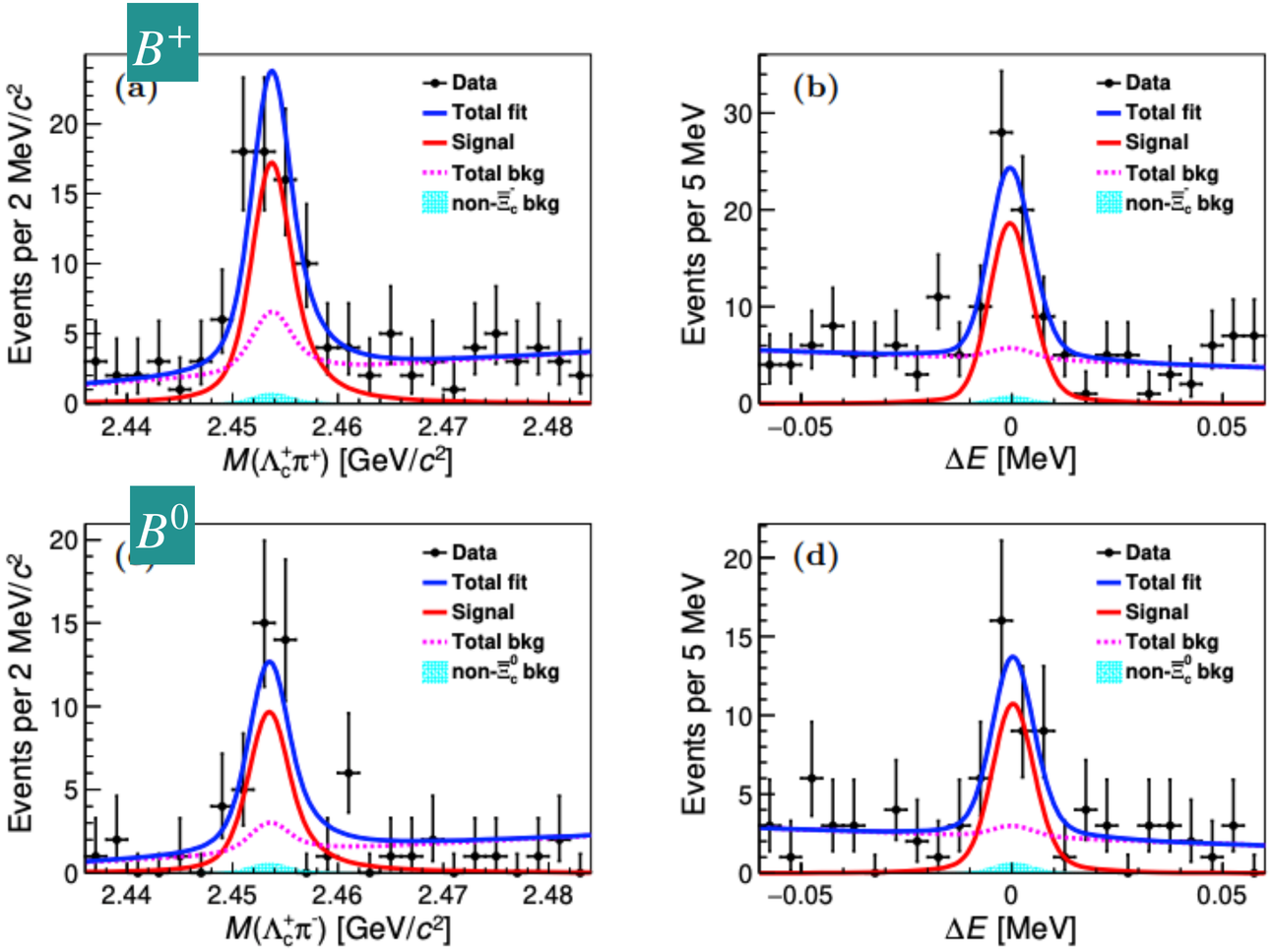


$B^{+/0} \to \Sigma_c(2455)^{++/0}\bar{\Xi}_c^{-/0}$

[arXiv: 2507.05094]

$(772 \pm 11) \times 10^6$ *and* $(387 \pm 6) \times 10^6$ $\Upsilon(4S)$
Belle and Belle II

2D fit to the unbinned $M(\Lambda_c^+\pi^\pm)$ and ΔE distributions, simultaneously using four data sets: events from the signal and sideband regions of $M(\bar{\Xi}_c^{-,0})$.



	N_{ss}^{sig}	S	$\mathcal{B}(\times 10^{-4})$
B^+	52.8 ± 10.2	7.3σ	$5.74 \pm 1.11 \pm 0.42^{+2.47}_{-1.53}$
B^0	31.1 ± 7.2	6.2σ	$4.83 \pm 1.12 \pm 0.37^{+0.72}_{-0.60}$

Ξ_c decays

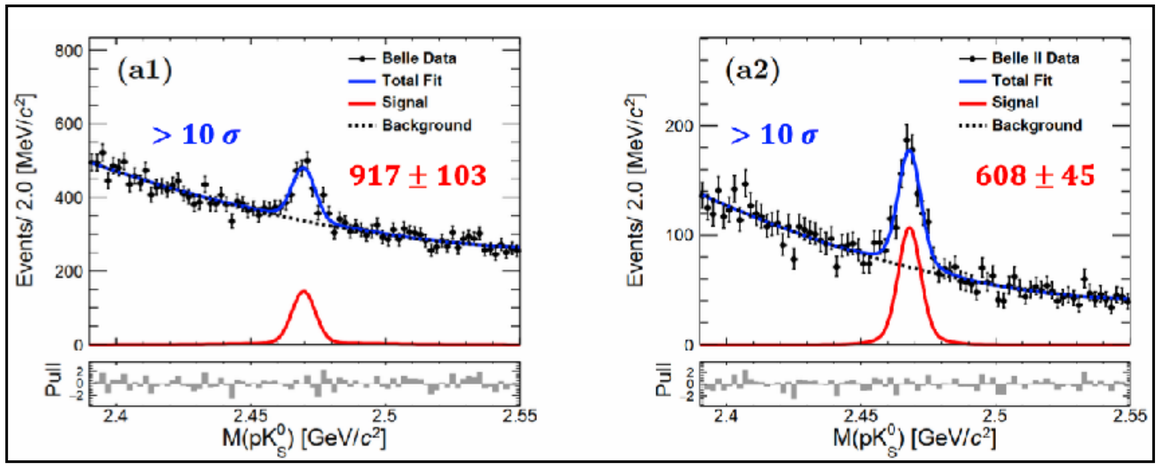
- First observation of $B^{+/0} \to \Sigma_c(2455)^{++/0}\bar{\Xi}_c^{-/0}$
- Consistent with expectation of the di-quark model
- Larger than $B^+ \to \Sigma_c(2455)^0 p$ by $\mathcal{O}(100)$
  - Similar size of CKM matrix elements $(V_{bc} * V_{cs} \sim V_{bc} * V_{ud})$
  - Smaller phase-space

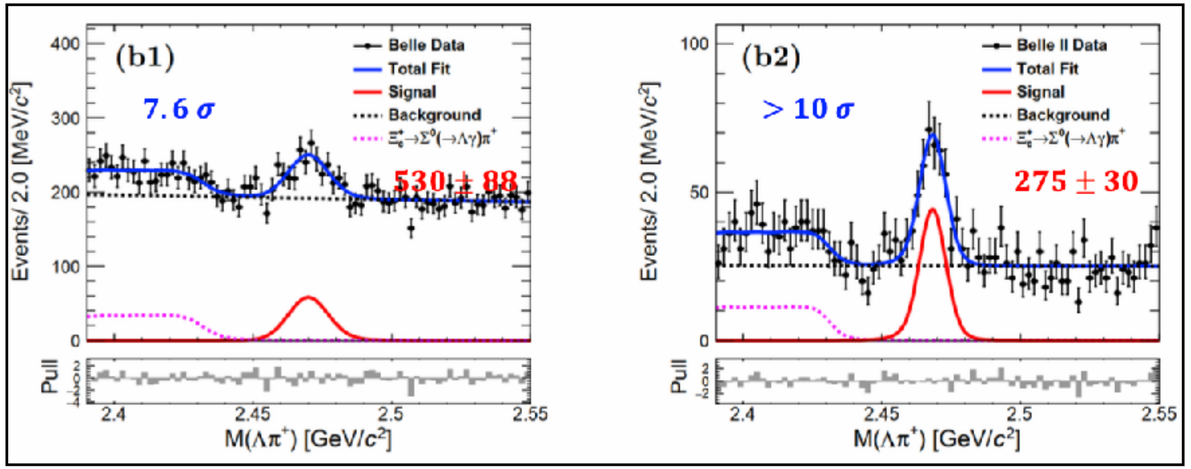
$\Xi_c^+ \to pK_S^0$, $\Lambda\pi^+$, and $\Sigma^0\pi^+$

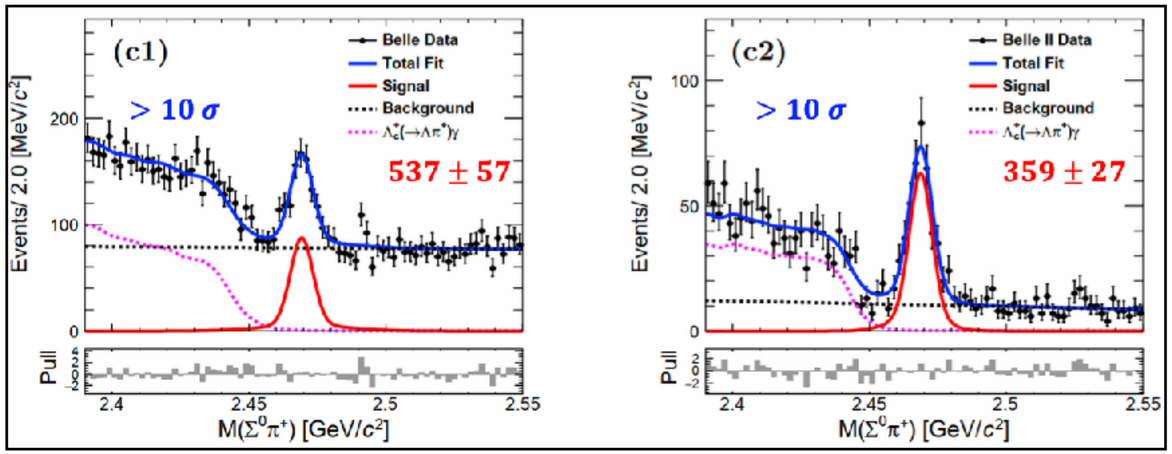
983 fb^{-1} *and* 427.9 fb^{-1}
Belle and Belle II

JHEP 03 2025, 061 (2025)

- Study of charmed baryons is valuable for exploring the subtle interplay between the strong and weak interactions.
- With Belle and Belle II data, SCS decays $\Xi_c^+ \to pK_S^0$, $\Lambda\pi^+$, and $\Sigma^0\pi^+$ are searched for the first time.







$$\frac{B(\Xi_c^+ \to pK_S^0)}{B(\Xi_c^+ \to \Xi^-\pi^+\pi^+)} = (2.47 \pm 0.16 \pm 0.07)\%,$$

$$\frac{B(\Xi_c^+ \to \Lambda\pi^+)}{B(\Xi_c^+ \to \Xi^-\pi^+\pi^+)} = (1.56 \pm 0.14 \pm 0.09)\%,$$

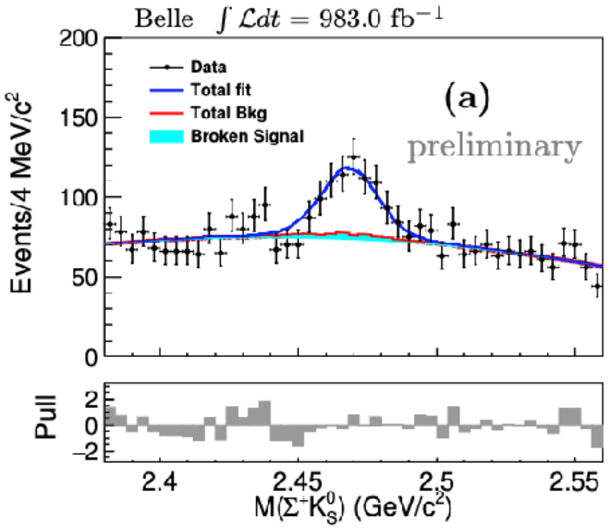
$$\text{and } \frac{B(\Xi_c^+ \to \Sigma^0\pi^+)}{B(\Xi_c^+ \to \Xi^-\pi^+\pi^+)} = (4.13 \pm 0.26 \pm 0.22)\%$$

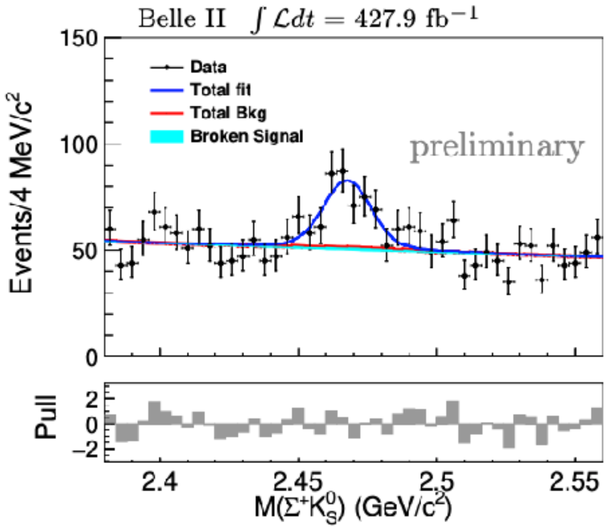
$\Xi_c^+ \to \Sigma^+ K_S^0$, $\Xi^0 \pi^+$, and $\Xi^0 K^+$

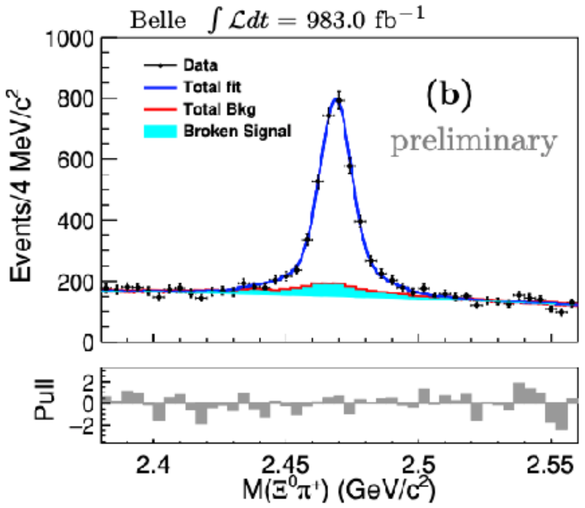
983 fb^{-1} *and* 427.9 fb^{-1}
Belle and Belle II

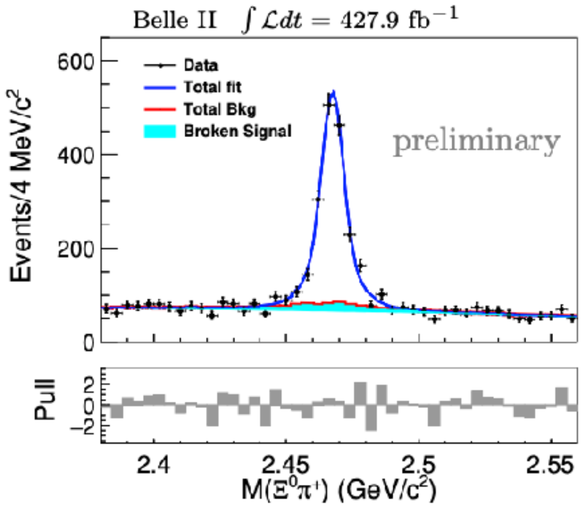
arXiv:2503.17643

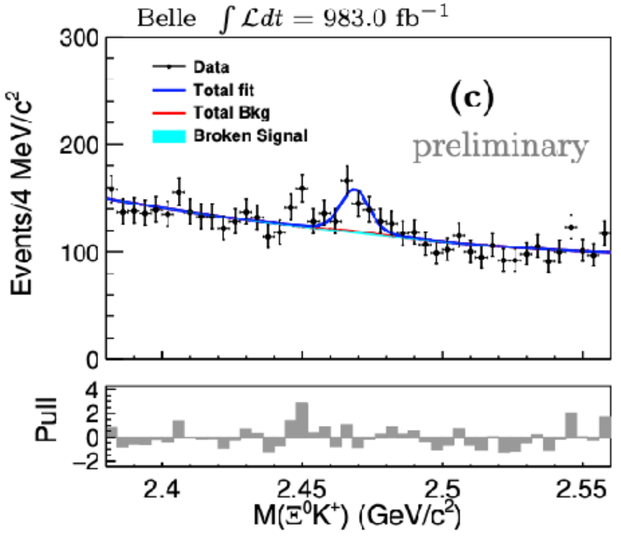
- Experimental results will give important inputs to understand the hadronic weak decays $\Xi_c^+ \to B + P$

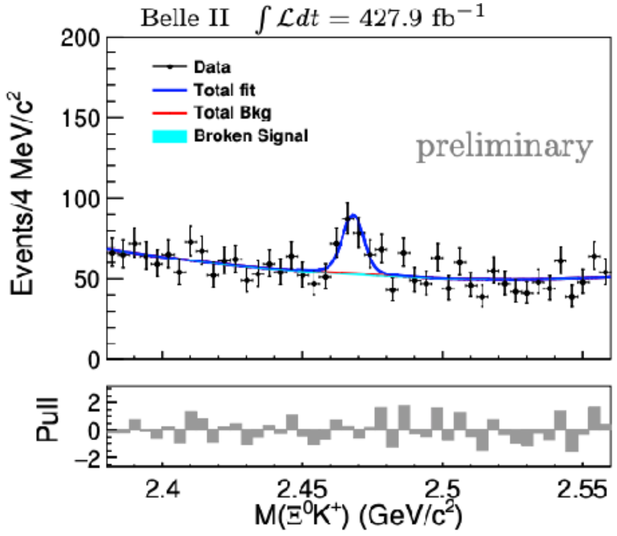










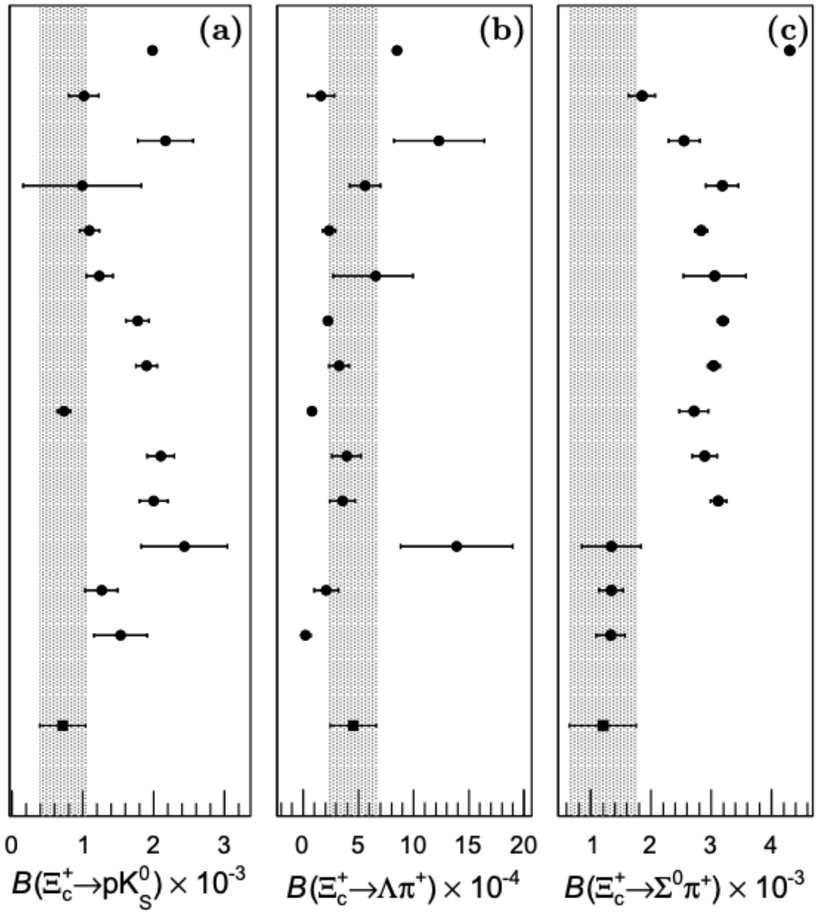


$$\mathcal{B}(\Xi_c^+ \to \Sigma^+ K_S^0) = (0.186 \pm 0.020 \pm 0.009 \pm 0.083)\%,$$
$$\mathcal{B}(\Xi_c^+ \to \Xi^0 \pi^+) = (0.677 \pm 0.024 \pm 0.030 \pm 0.303)\%,$$
$$\mathcal{B}(\Xi_c^+ \to \Xi^0 K^+) = (0.046 \pm 0.007 \pm 0.002 \pm 0.021)\%,$$

Unc. from $\Xi_c^+ \to \Xi^- \pi^+ \pi^-$

Comparison with various predictions

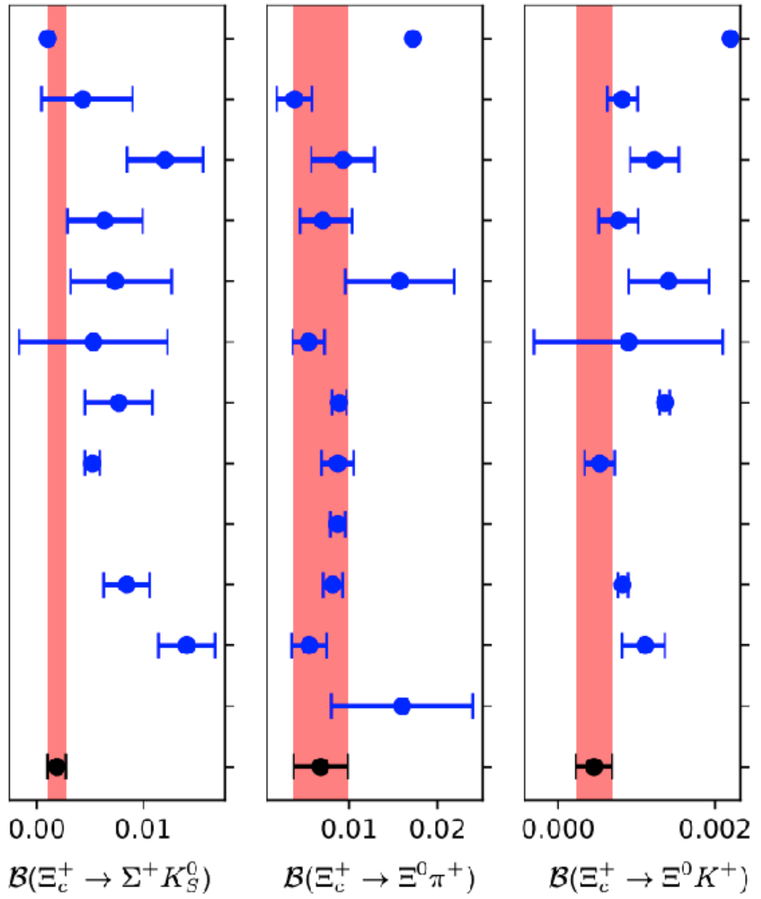
JHEP 03 2025, 061 (2025)



Zou *et.al* [12]
Geng *et.al* [13]
Geng *et.al* [14]
Huang *et.al* [15]
Zhong *et.al* (I) [16]
Zhong *et.al* (II) [16]
Xing *et.al* [17]
Geng *et.al* [18]
Liu [19]
Zhong *et.al* (I) [20]
Zhong *et.al* (II) [20]
Zhao *et.al* [21]
Hsiao *et.al* (I) [22]
Hsiao *et.al* (II) [22]

Belle and Belle II
combined measurement

arXiv:2503.17643



Zou *et al.* [9]
Geng *et al.* [10]
Zhao *et al.* [11]
Hsiao *et al.* (I) [12]
Hsiao *et al.* (II) [12]
Huang *et al.* [13]
Xing *et al.* [14]
Liu *et al.* (I) [15]
Liu *et al.* (II) [15]
Zhong *et al.* (I) [16]
Zhong *et al.* (II) [16]
CLEO Collaboration [17]
Belle and Belle II
combined measurements

Consistent with different predictions.

Mass difference between B^+ and B^0

Mass difference between B^+ and B^0

$571\ \mathrm{fb}^{-1}$ *and* $365\ \mathrm{fb}^{-1}\ \Upsilon(4S)$ *from Belle and Belle II*

- $\Delta m = m_{B^0} - m_{B^+}$ is a basic property of B-meson system
  - Important input for quark model
  - Contains information on $m_d - m_u$
- $\mathscr{R} = \sigma(B^0\bar{B}^0)/\sigma(B^+B^-)$ vs. energy provides information about strong isovector potential in $B\bar{B}$ system, which is important for understanding of molecular states.
- Current WA is dominated by BaBar measurement $\Delta m = (0.33 \pm 0.05 \pm 0.03)\ \mathrm{MeV}/c^2$ [PRD78, 011103(2008)]
  - PHSP hypothesis was used ($\mathscr{R} = (p_{B^0}/p_{B^+})^3$). Shift in Δm could be up to $0.4\ \mathrm{MeV}/c^2$ [JHEP05 (2022)170]

Approach:

- Simultaneous fit to $\bar{M}_{bc} = \sqrt{5.29^2 - p_B^2}$, E_{cm} dependent $\mathscr{R} = \sigma(B^0\bar{B}^0)/\sigma(B^+B^-)$, $\sigma(e^+e^- \to b\bar{b})$, and $\sigma(e^+e^- \to b\bar{b} \to D^0/\bar{D}^0X)$

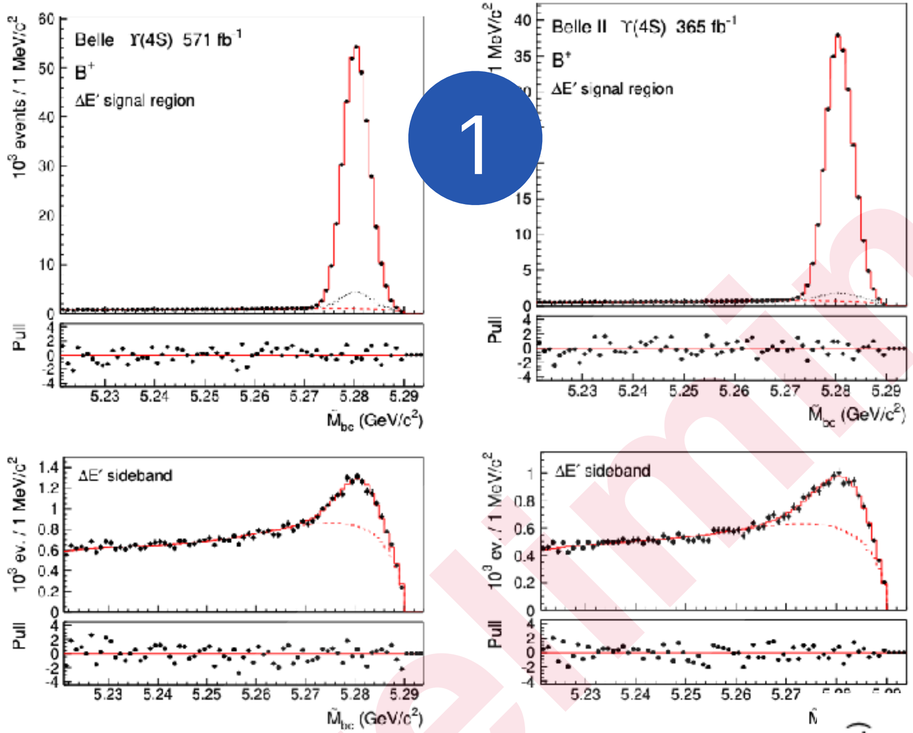
$$\sigma(e^+e^- \to B^+B^-) = p_{B^+}^3\ P_{11}(E_{\mathrm{cm}})$$
$$\sigma(e^+e^- \to B^0\bar{B}^0) = p_{B^0}^3\ P_{11}(E_{\mathrm{cm}})\ P_2(E_{\mathrm{cm}})$$

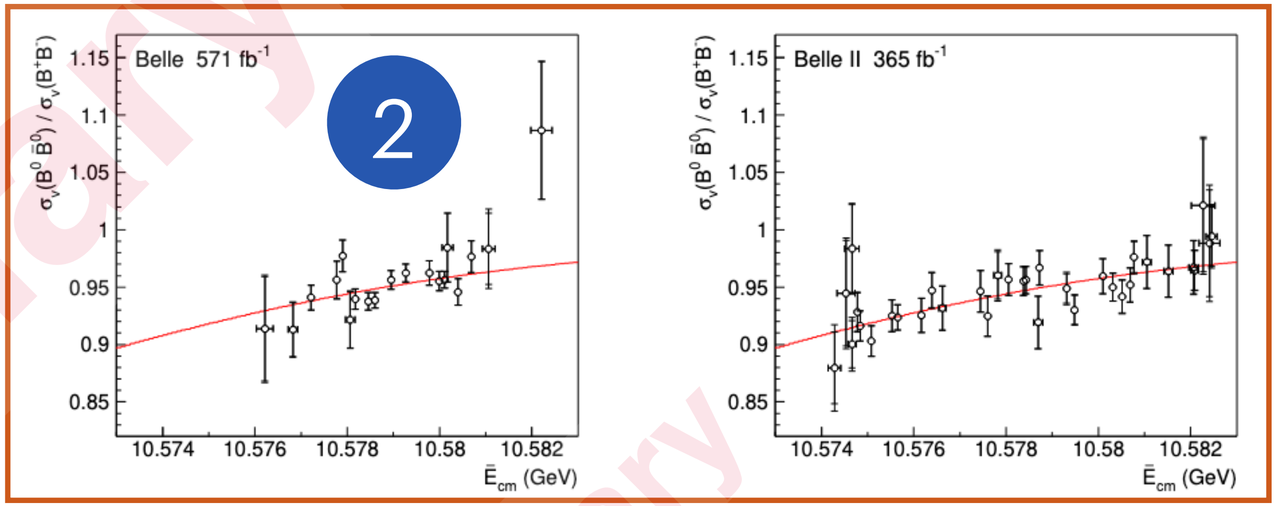
P_{11}: 11^{th}-order polynomial for E_{cm} dependence

P_2: 2^{nd}-order polynomial for additional dependence

Fit results

571 fb^{-1} and 365 fb^{-1} $\Upsilon(4S)$ from Belle and Belle II

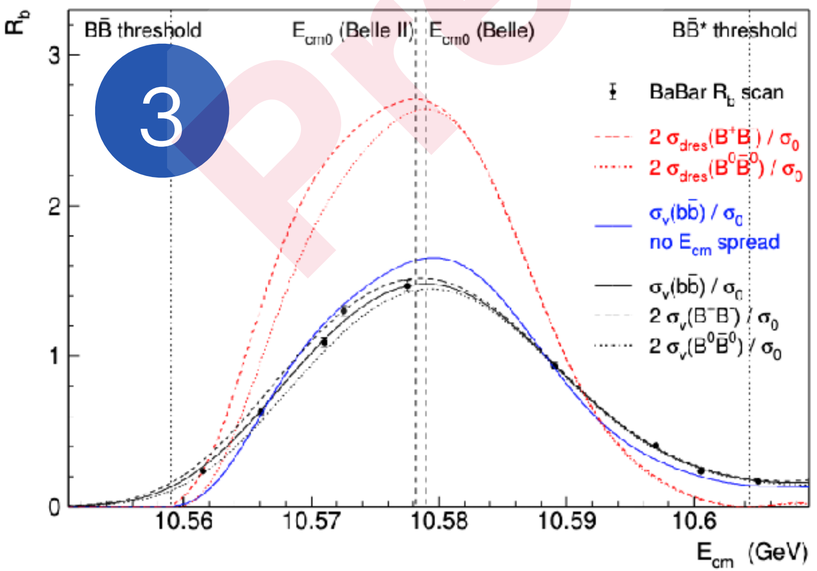


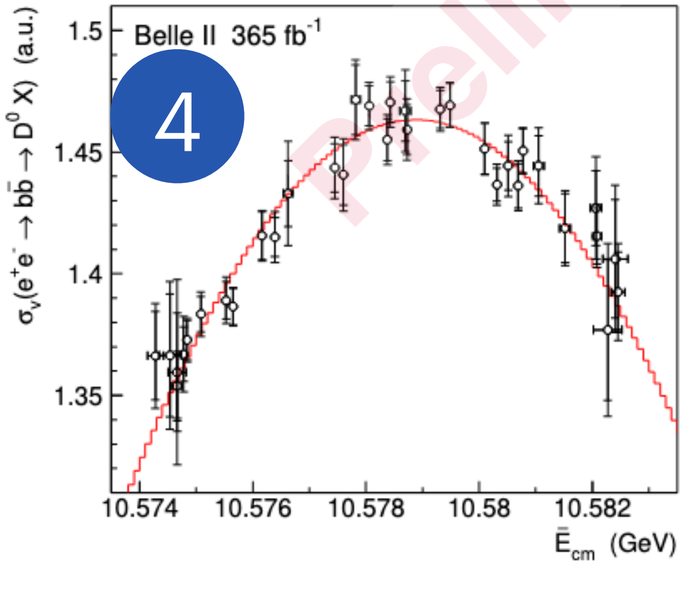


Fit results:

$\Delta m = (0.495 \pm 0.024 \pm 0.005)\ \mathrm{MeV}/c^2$

$\Delta m_{BaBar} = (0.33 \pm 0.05 \pm 0.03)\ \mathrm{MeV}/c^2$





Very different to BaBar's result:

- Use PHSP hypothesis get:

  $\Delta m = (0.386 \pm 0.006)\ \mathrm{MeV}/c^2$

  Rejected by 10σ level
- Significantly depends on $\mathscr{R}_v$.

Summary

- As the world's highest-luminosity electron-positron collider, Belle II will become a cornerstone in the exploration the spectroscopy in his unique way.
  - SuperKEKB is a unique experimental facility in which the phenomena discussed can be studied under well controlled conditions.
  - Bottomonium states give us a lot of surprises with the new data
    - Understanding of the hidden bottom hadronic transitions is very incomplete. More experimental data are needed.
- Belle II will restart data taking in November 2025.

Thank you!

Back up

$\Upsilon(10753) \to \eta\Upsilon(1,2S)$

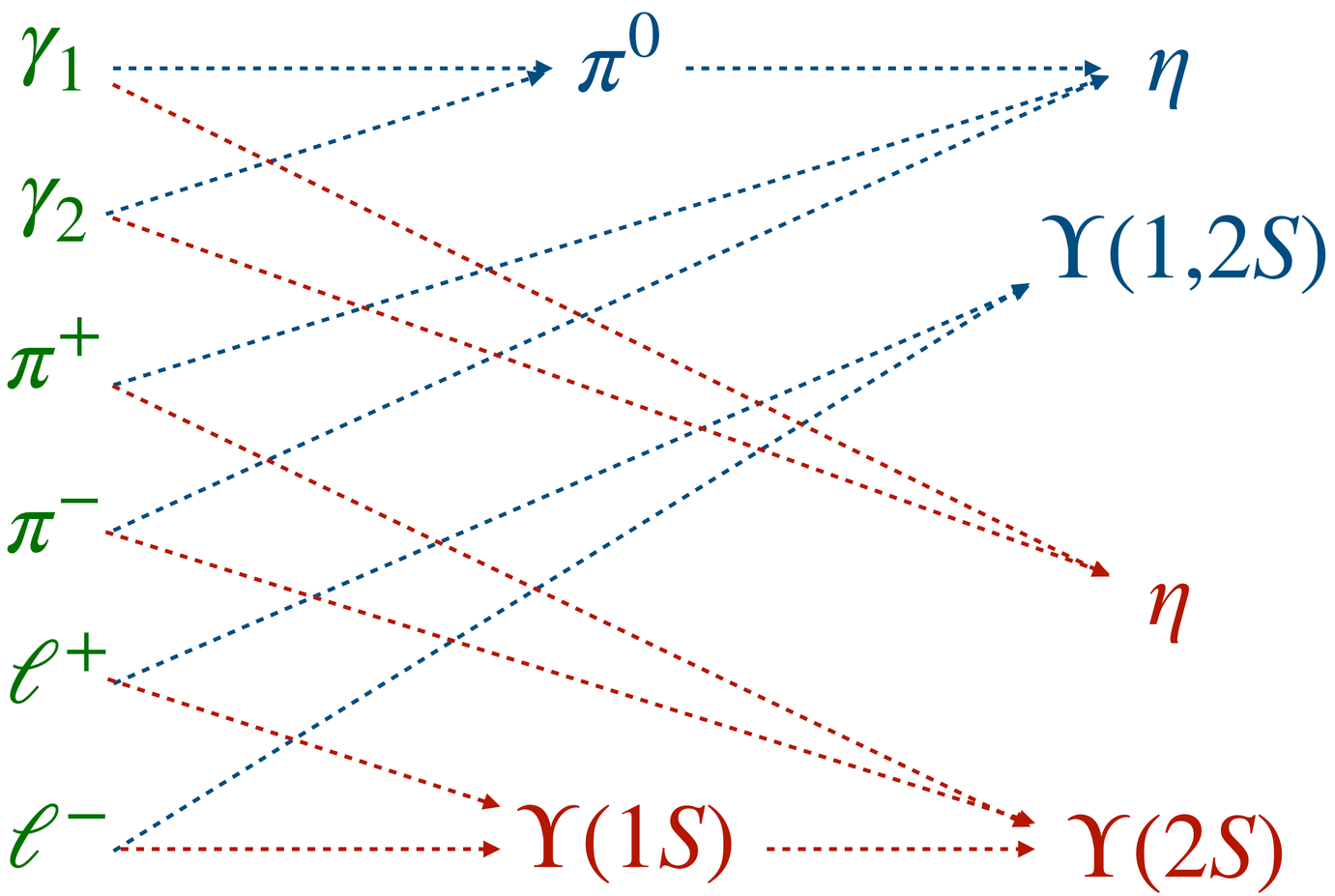
arXiv:2509.01917

Final states of $\gamma\gamma\pi^+\pi^-\ell^+\ell^-[\ell = e, \mu]$ is used in this work.

$E > 20(22.5)$ MeV from barrel and FW endcap (BW endcap)

Tracks with $p < 1$ GeV, at least one with eID<0.1, $\cos\theta_{\pi\pi} < 0.98$.

Tracks with $p > 3$ GeV, $E/p > 0.7(< 0.3)$ to identify $e(\mu)$



Cross sections results of $e^+e^- \to \eta\Upsilon(1,2S)$ and γX_b

Mode	$N_{\rm prod}$ $(\times 10^3)$	$(1+\delta)$	$\epsilon(\%)$	$\sigma_B^{(UL)}$ (pb)
$\sqrt{s} = (10653.30 \pm 1.14)$ MeV,		$\mathcal{L} = 3.512$ fb^{-1}		
$\eta\Upsilon(2S)$	$(3.7^{+1.6}_{-1.3}), 4.2\sigma$	0.843	19.2/15.1	$1.16^{+0.51}_{-0.41} \pm 0.38$
$\eta\Upsilon(1S)$	< 0.4	0.895	23.9	< 0.10
γX_b	< 0.3	0.784	32.0	< 0.14
$\sqrt{s} = (10700.90 \pm 0.63)$ MeV,		$\mathcal{L} = 1.632$ fb^{-1}		
$\eta\Upsilon(2S)$	$(0.0^{+1.0}_{-0.0})$	1.691	13.2/7.6	$0.00^{+0.34}_{-0.00} \pm 0.50$
$\eta\Upsilon(1S)$	< 0.4	0.901	24.0	< 0.22
γX_b	< 0.1	0.803	31.3	< 0.09
$\sqrt{s} = (10746.30 \pm 0.48)$ MeV,		$\mathcal{L} = 9.818$ fb^{-1}		
$\eta\Upsilon(2S)$	$(3.2^{+1.6}_{-1.2}), 4.8\sigma$	0.673	17.4/14.2	$0.45^{+0.23}_{-0.17} \pm 0.05$
$\eta\Upsilon(1S)$	< 0.9	0.906	23.8	< 0.09
γX_b	< 1.4	0.817	29.8	< 0.17
$\sqrt{s} = (10804.50 \pm 0.70)$ MeV,		$\mathcal{L} = 4.689$ fb^{-1}		
$\eta\Upsilon(2S)$	$(1.5^{+1.3}_{-0.9}), 2.8\sigma$	0.822	17.1/15.2	$0.36^{+0.33}_{-0.21} \pm 0.04$
$\eta\Upsilon(1S)$	< 0.4	0.912	24.6	< 0.08
γX_b	< 1.3	0.833	28.2	< 0.32