Studies of hadron spectroscopy at Belle and Belle II

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On behalf of Belle (II) Collaboration

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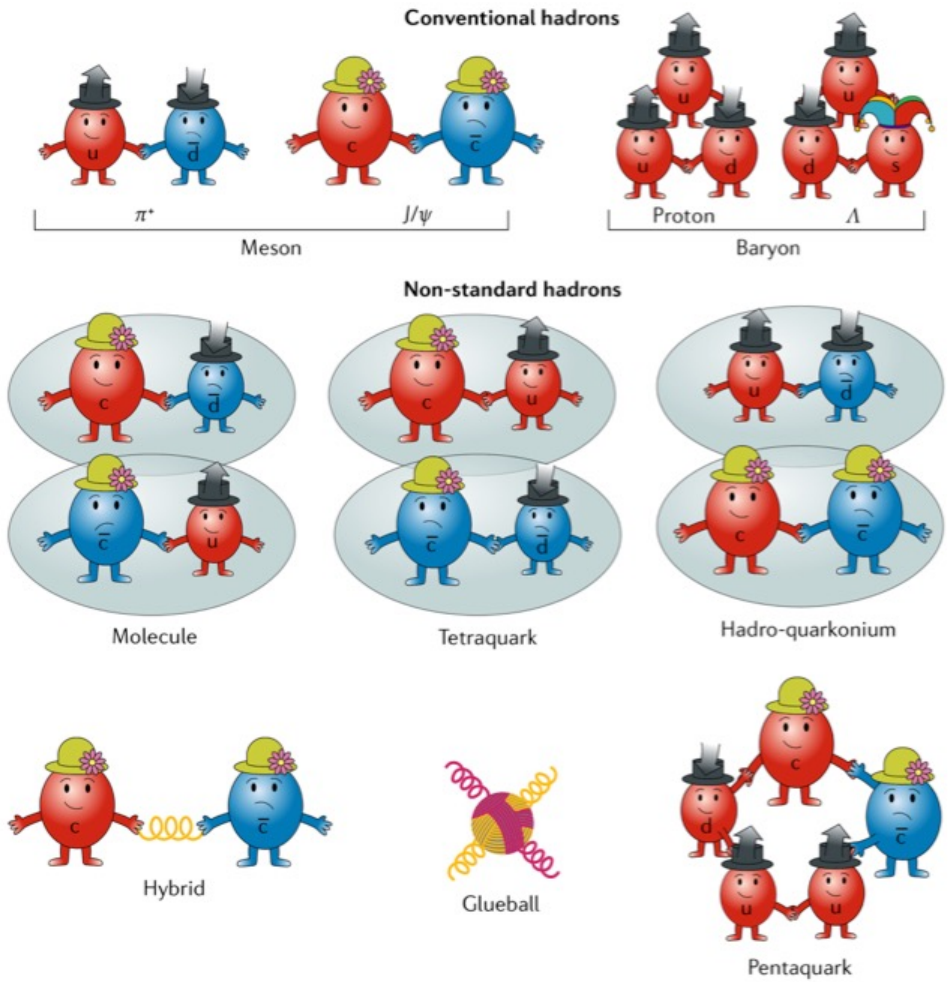
Exotic Hadron Spectroscopy 2024 @ Swansea

Hadron Spectroscopy



Nature Rev. Phys. 1 (2019) no.8, 480-494

Many hadron states are observed experimentally, such as the X(3872), Y(4260) and Υ(10753) , but no unambiguous interpretation exists

Although several hadron states, like the glueball, are predicted theoretically, they have not yet been seen

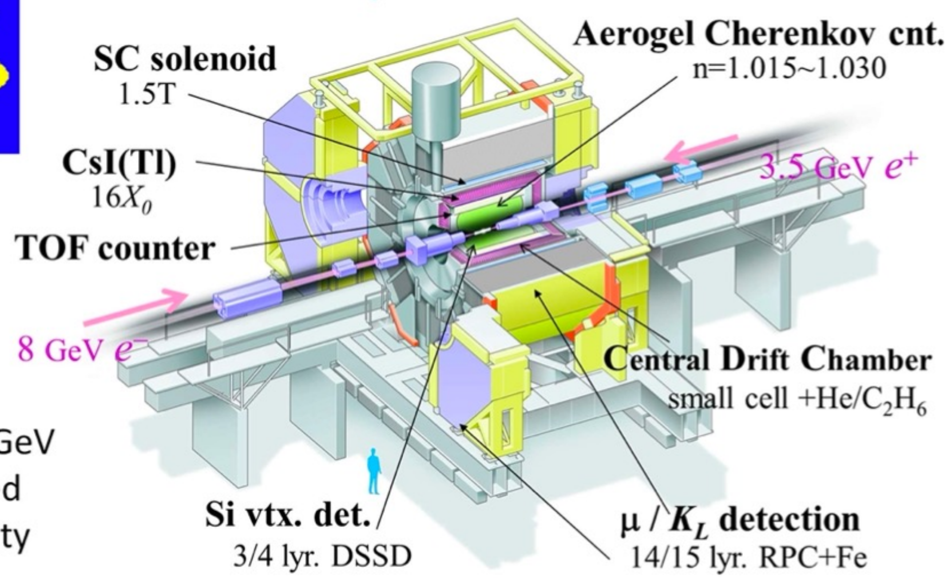
We do not understand the strong interaction in the low energy region well

Belle Experiment

- Very successful physics programs with a total recorded sample over 1.05 ab^{-1}

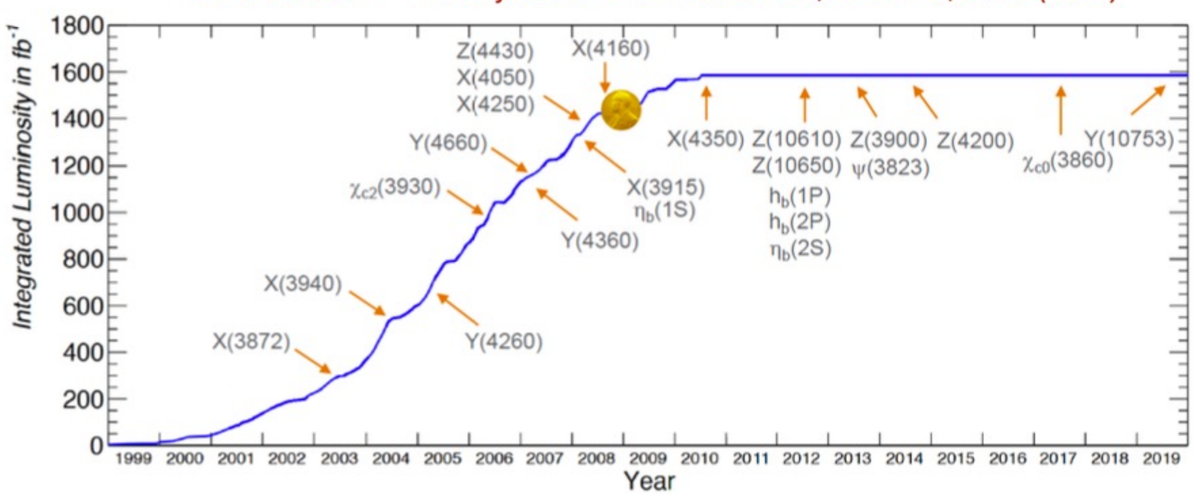
Belle experiment

- $\sqrt{s}$~10.6 GeV
- Integrated Luminosity ~ 1 ab^{-1}

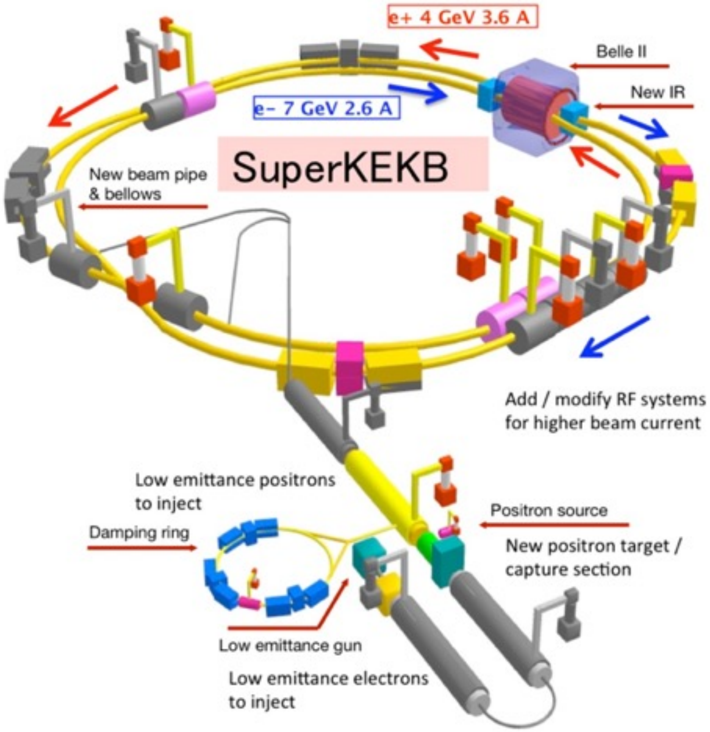


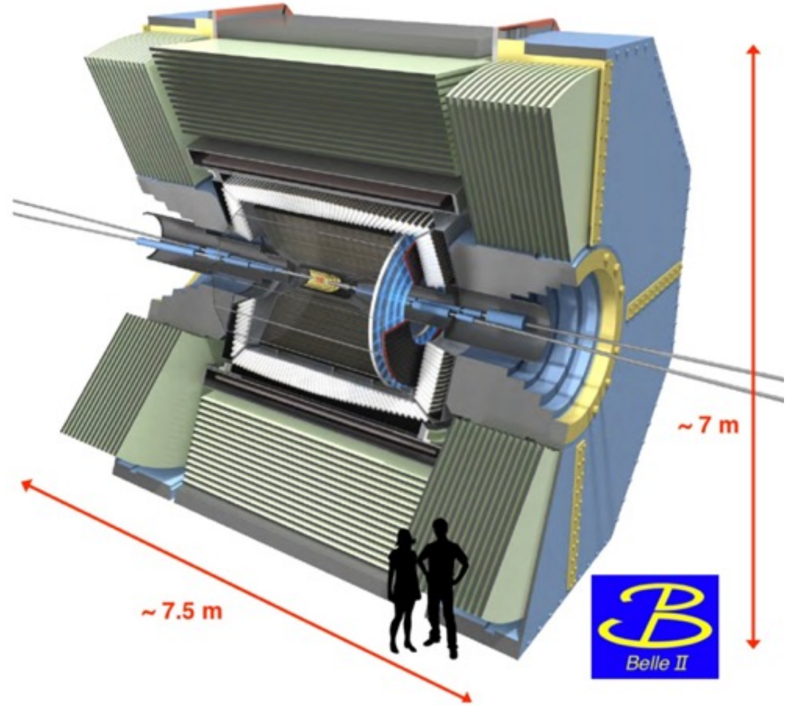
- Even >10 years after data taking, still producing new results in hadron spectroscopy

More details in "The Physics of the B Factories", EPJC 74, 3026 (2014)



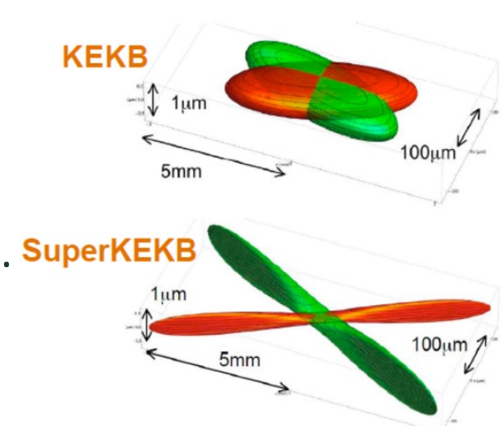
Belle II Experiment





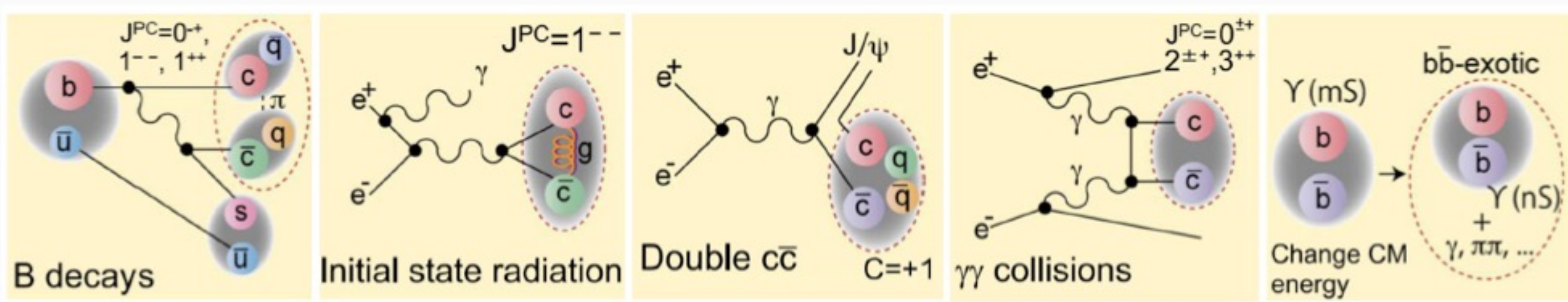
From Belle to Belle II:

- ❑ Nano-beams × current increase (x2) = x30 inst. luminosity increase
- ❑ New detector: tracker, PID, calorimeters electronics…
- ❑ Higher background
- ❑ Higher event rate (~ 30 kHz)
- ❑ Boost change



Advantages of studying hadron spectroscopy at Belle (II)

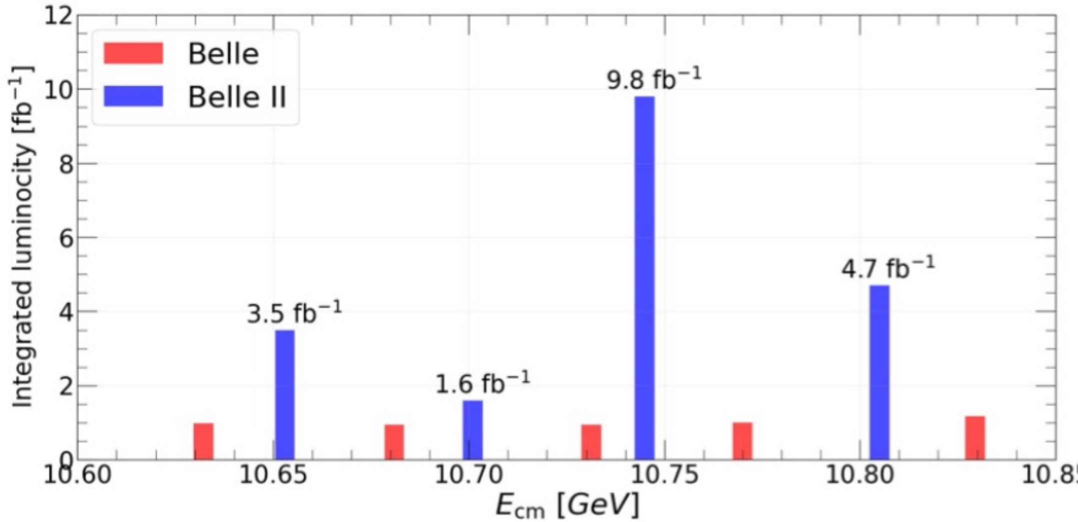
- "Clean" environment;
- Full event reconstruction, decays with neutral/soft particles;
- Nominal $\sqrt{s} = 10.58$ GeV $= m(\Upsilon(4S))$, potential to reach 11 GeV;
- Decay with neutrals $(\gamma, \pi^0, K_l, \nu)$ in final state;
- Multiple production mechanisms;
- Larger statistics $\rightarrow$ Complementary to LHC results;

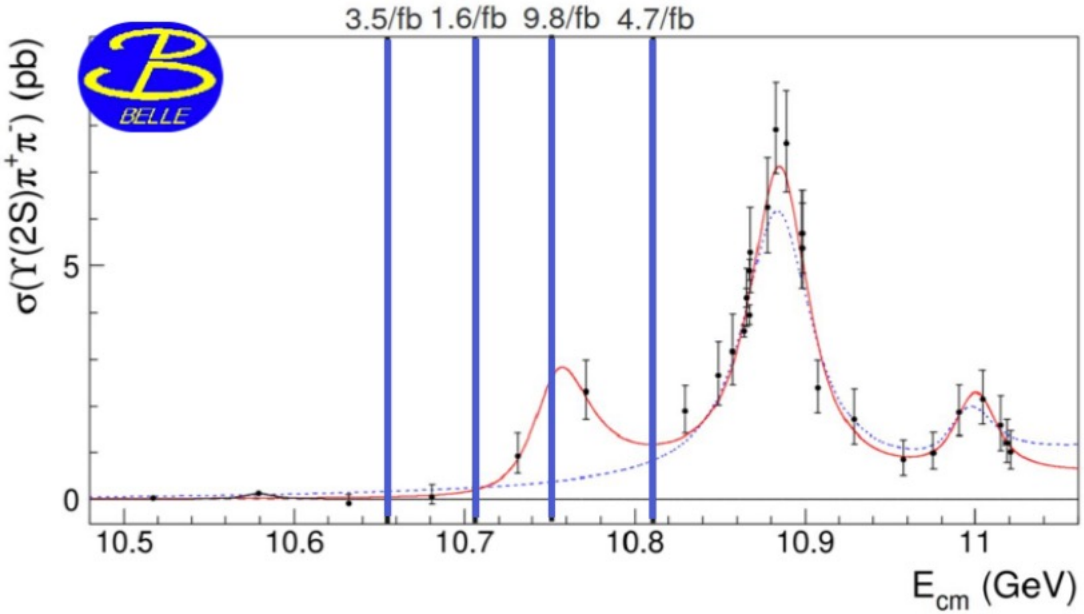


Energy Scan Data Samples

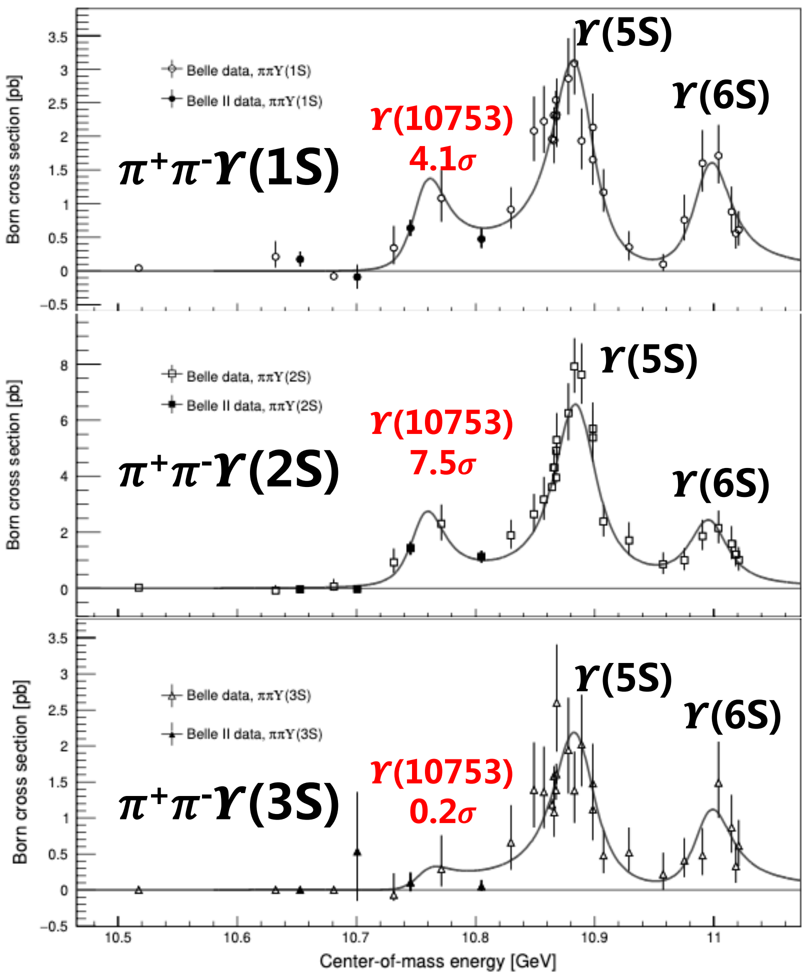
Belle II / SuperKEKB performed an energy scan in November 2021 with a total luminosity of 19 fb^{-1} with main goal to confirm and study the $\Upsilon(10753)$:

- **Belle II collected the data in the gap between the Belle points**
- **The point with the hightest statistic is near the peak**





Study of $\Upsilon(10753)$ decays to $\pi^+\pi^-\Upsilon(nS)$ final states at Belle II



The state $\Upsilon(10753)$ was observed by Belle
JHEP 10 (2019) 220

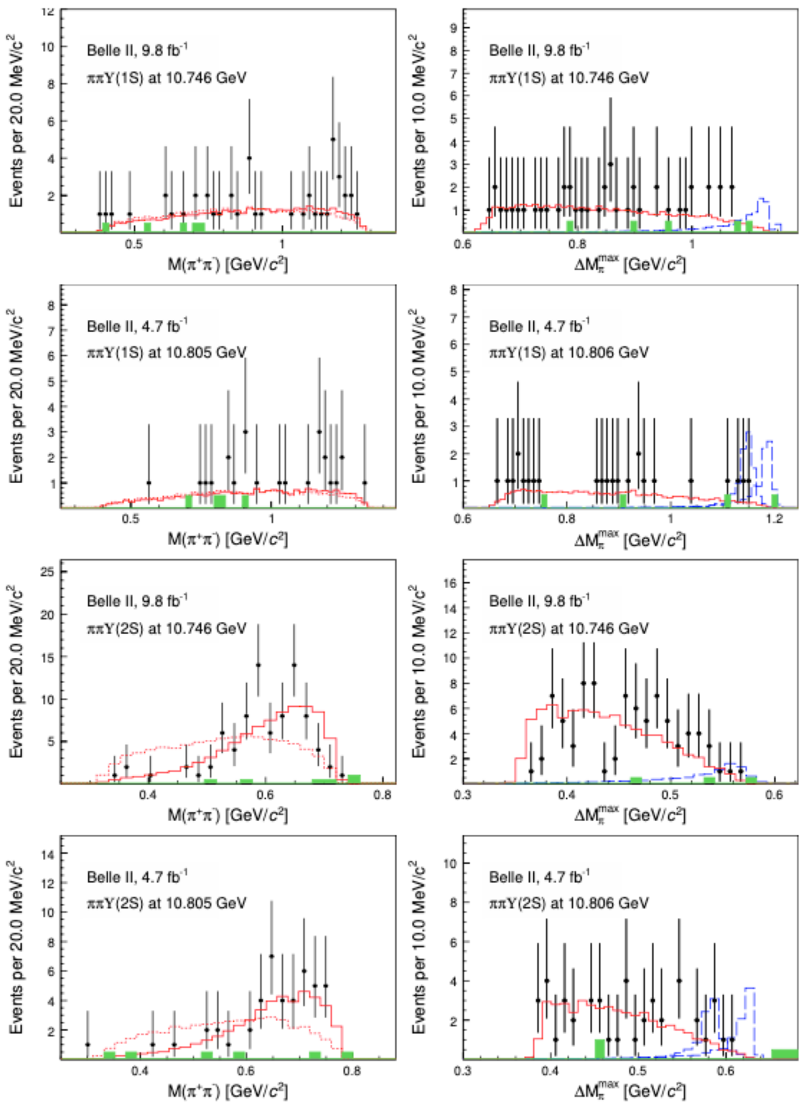
The dip on the open bottom cross section likely caused by the interference
CPC 44, 8, 083001 (2020)

Mass does not fit the $\Upsilon(3D)$ predictions: Hybrid? Tetraquark? Molecule?

Belle II confirms the peak!

	Belle + Belle II (MeV)	Belle (MeV)
$M_{\Upsilon(10753)}$	$10756.6 \pm 2.7 \pm 0.9$	$10752.7 \pm 5.9^{+0.7}_{-1.1}$
$\Gamma_{\Upsilon(10753)}$	$29.0 \pm 8.8 \pm 1.2$	$35.5^{+17.6+3.9}_{-11.3-3.3}$

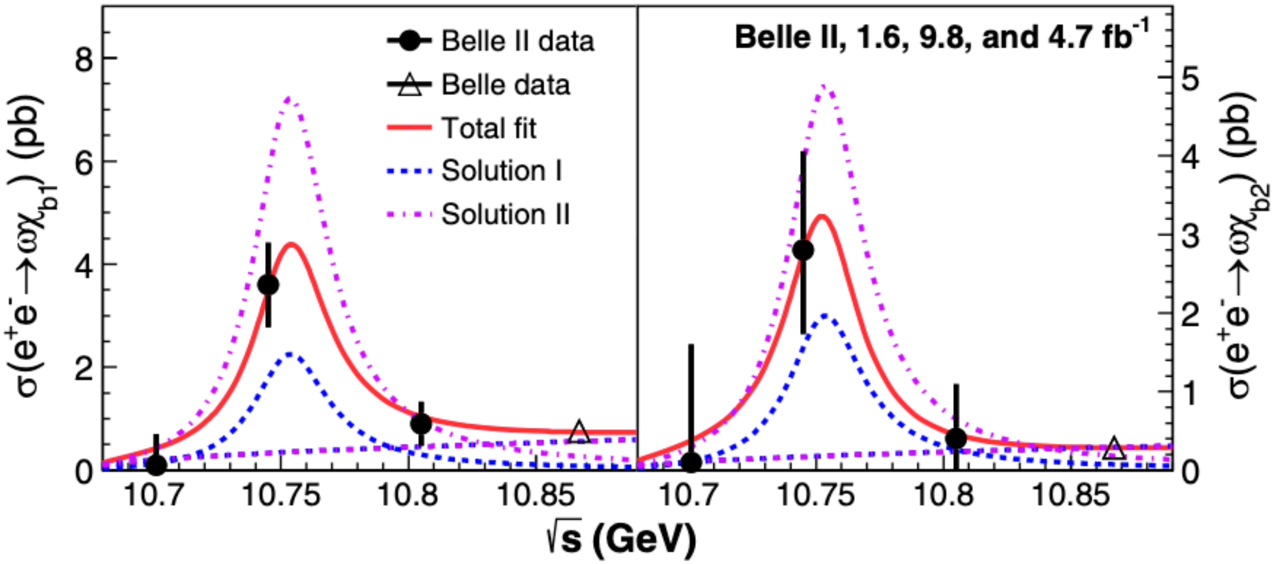
Study of $\Upsilon(10753)$ decays to $\pi^+\pi^-\Upsilon(nS)$ final states at Belle II



- **No signal of intermediate $Z_b^+(10610)$ or $Z_b^+(10650)$ resonance is observed;**
- **$\pi^+\pi^-\Upsilon(1S)$: $M(\pi^+\pi^-)$ distribution is consistent with PHSP**
- **$\pi^+\pi^-\Upsilon(2S)$: large valus of $M(\pi^+\pi^-)$ which is similar to $\Upsilon(2S)$ to $\pi^+\pi^-\Upsilon(1S)$**

Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$ and Search for $X_b \to \omega\Upsilon(1S)$ at $\sqrt{s}$ near 10.75 GeV

Expect similar nature of $\Upsilon(10753)$ and Y(4260), and Y(4260) was observed in $\omega\chi_{c0}$ and $\gamma X(3872)$

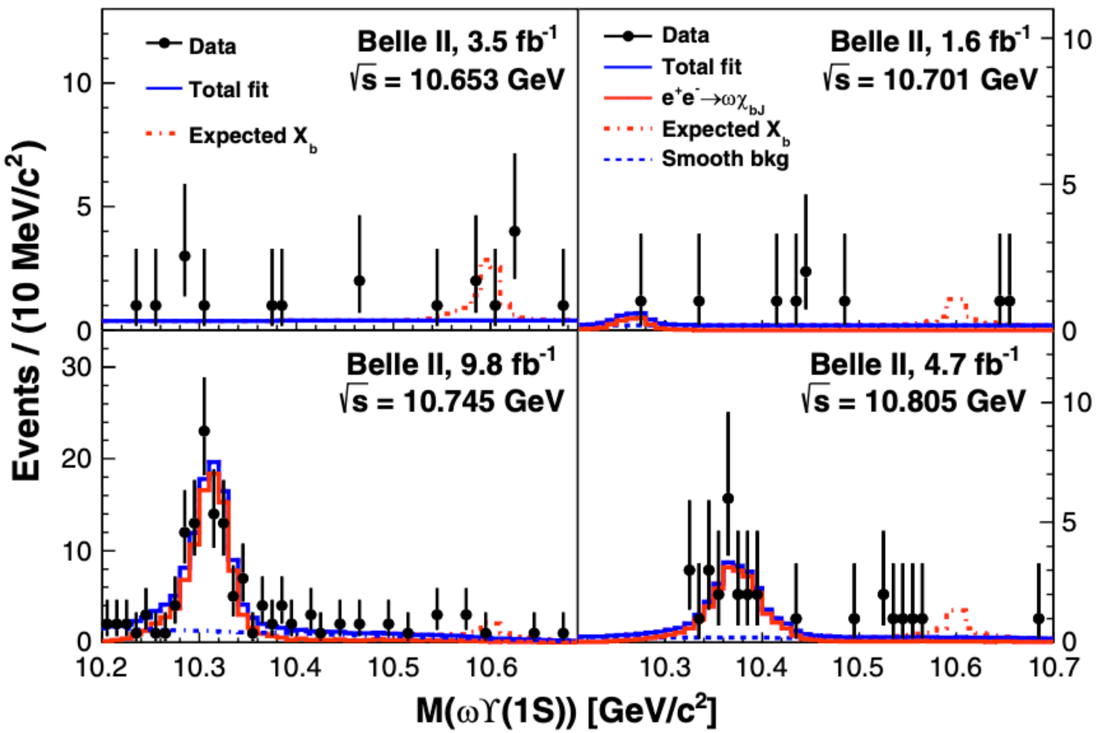


- **Measured ratio:**
  - $\frac{\sigma(\Upsilon(10753) \to \omega\chi_{b1})}{\sigma(\Upsilon(10753) \to \omega\chi_{b2})} = 1.3 \pm 0.6$
  - **Prediction for a pure *D*-wave state: 15** PLB 738, 172 (2014)
  - **Prediction for a $4S - 3D$ mixed state: 0.18 - 0.22** PRD 104, 034036 (2021)

- $\frac{\sigma(e^+e^- \to \omega\chi_{bJ})}{\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)} \sim \begin{cases} 1.5 \text{ at } \Upsilon(10753) \text{ GeV} \\ 0.15 \text{ at } \Upsilon(5S) \text{ GeV} \end{cases}$

indicate different internal structure

Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$ and Search for $X_b \to \omega\Upsilon(1S)$ at $\sqrt{s}$ near 10.75 GeV

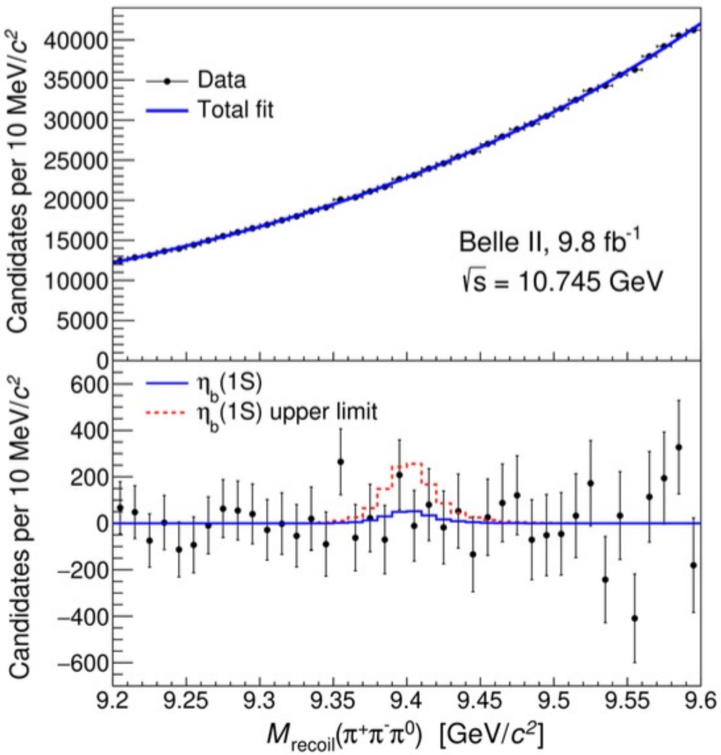


No X_b, which is posited counterpart of X(3872), is observed!

Upper limits on cross sections are set for $M(X_b) \in$ (10.45-10.65) GeV

$\sqrt{s}$ GeV	$\sigma_B(e^+e^- \to \gamma X_b) \times \mathcal{B}(X_b \to \omega\Upsilon(1S))$
10.653	(0.14-0.55) pb
10.701	(0.25–0.84) pb
10.745	(0.06–0.14) pb
10.805	(0.08–0.37) pb

Search for the $e^+e^- \rightarrow \eta_b(1S)\omega$ and $e^+e^- \rightarrow \chi_{b0}(1P)\omega$ processes at $\sqrt{s}$ = 10.745 GeV

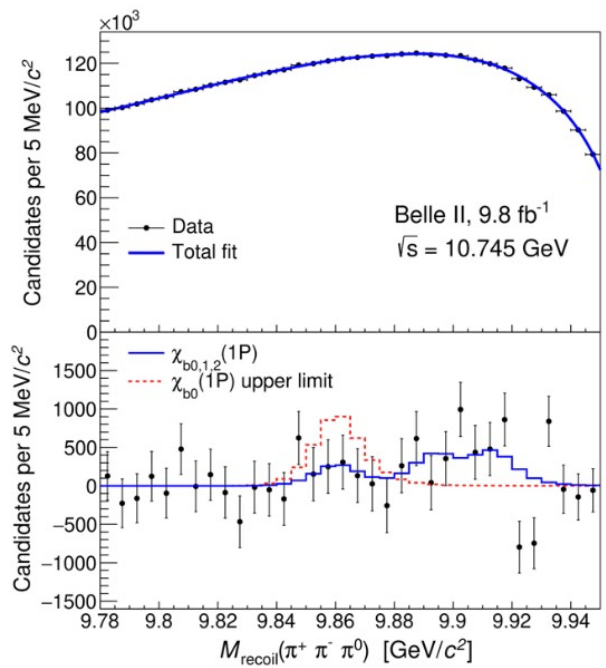


- No significant $\omega\ \eta_b(1S)$ signal is observed.
- Upper limits at the 90% C.L. on the Born cross section are set.
- $\sigma(e^+e^- \rightarrow \omega\eta_b(1S)) < 2.5$ pb

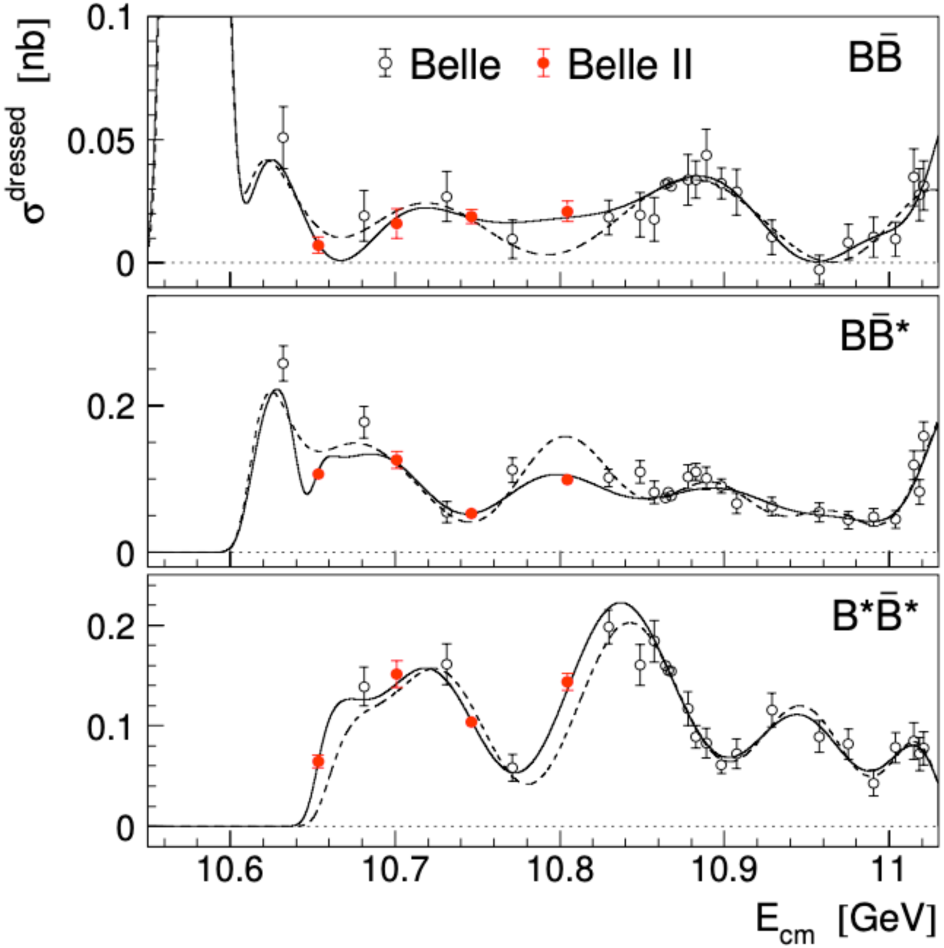
Ratio:

- $\dfrac{\sigma(\omega\eta_b)}{\sigma(\pi^+\pi^-\Upsilon(nS))} < 1.25$
- Prediction for a tetra quark model: ~30 CPC 43 (2019) 12, 123102
- Prediction for a $4S - 3D$ mixed state: 0.2 - 0.4

PRD 109, 014039 (2024)

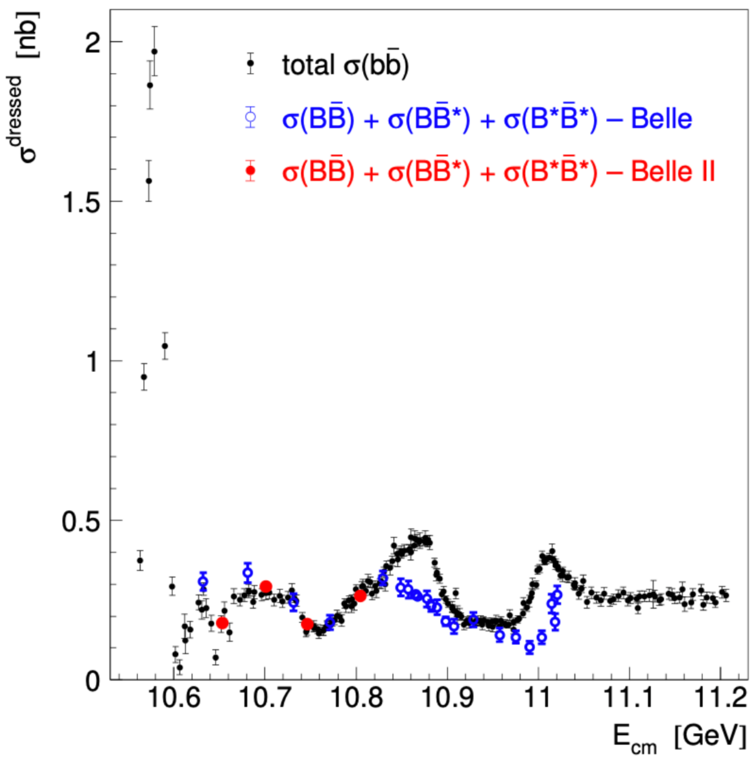


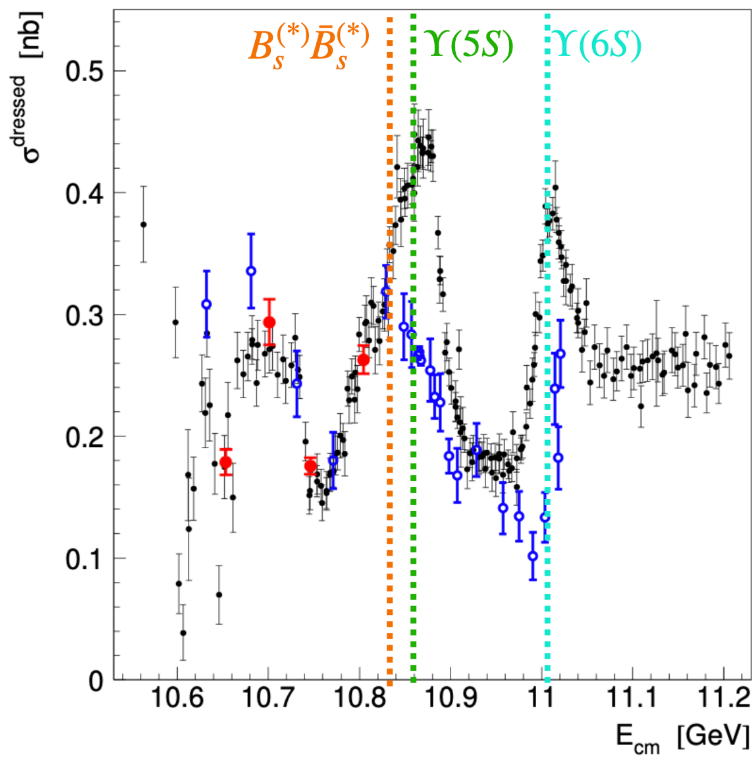
Measurement of the energy dependence of the $e^+e^- \to \bar{B}B$, $\bar{B}B^*$, and $\bar{B}^*B^*$ cross sections at Belle II



- ❖ The open flavor final states make dominant contribution to $\bar{b}b$ cross-section, and the measured cross sections can be used in the coupled channel analysis of all available scan data to extract the parameters of the Υ states.
- ❖ The obtained cross sections at four energy points are consistent with Belle results
- ❖ Rapid increase above $\bar{B}^*B^*$ threshold, which is similar to $\bar{D}^*D^*$: bound state near threshold?

Measurement of the energy dependence of the $e^+e^- \to \bar{B}B$, $\bar{B}B^*$, and $\bar{B}^*B^*$ cross sections at Belle II





- Saturate the $\sigma_{b\bar{b}}$ cross-section below the $B_s^{(*)}\bar{B}_s^{(*)}$ threshold.
- Previously observed deviation at high energy is presumably due to $B_s^{(*)}\bar{B}_s^{(*)}$, multi-body $B^{(*)}\bar{B}^{(*)}\pi(\pi)$, etc.

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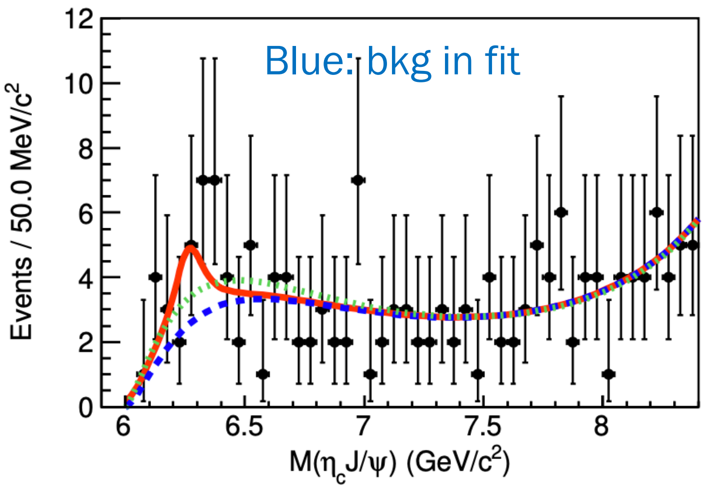
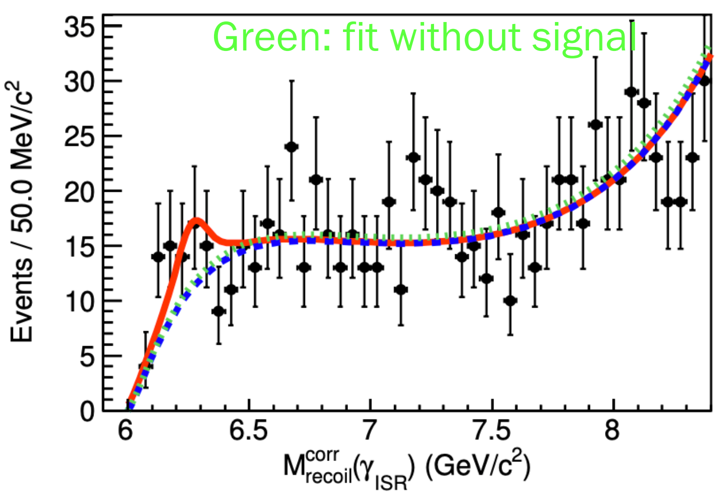
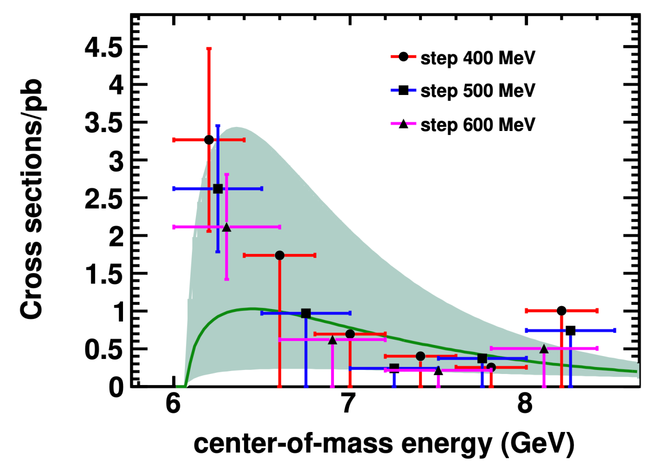
Search for the double-charmonium state with $\eta_c J/\psi$ at Belle



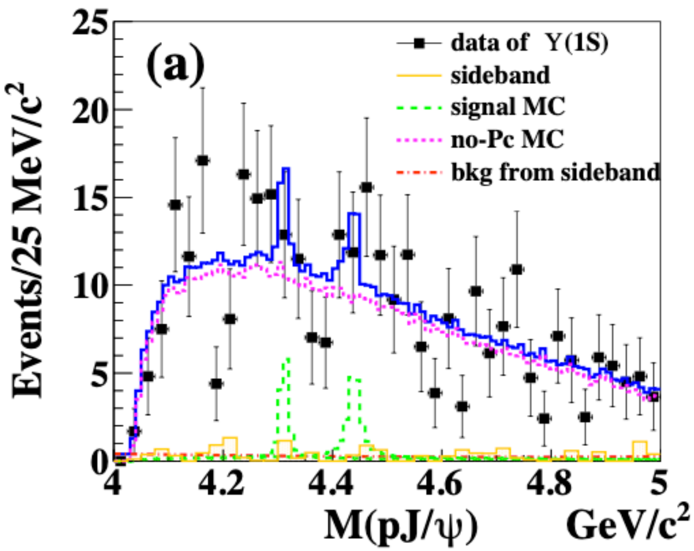


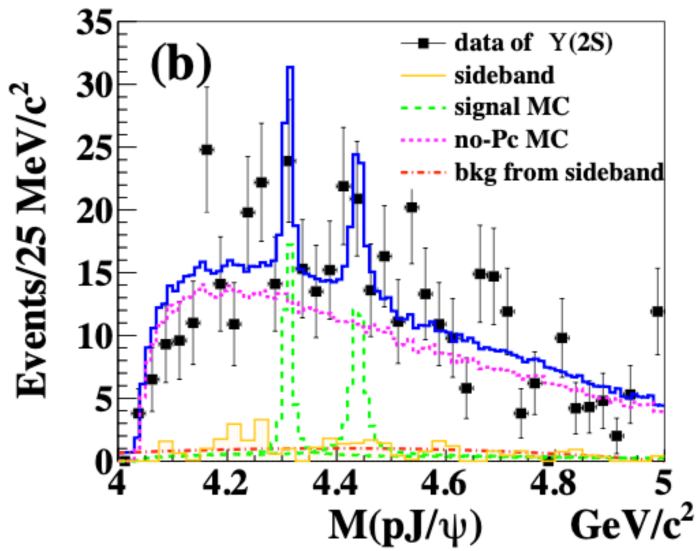
- Observation of enhancement in prompt double J/ψ production at the LHC: pure charmed four-quark state?
- Simultaneous fit to exclusive ($\eta_c J/\psi$) and inclusive (γISR recoil): Significance for Breit-Wigner contribution is 2.1σ
- The cross sections for $e^+e^- \to \eta_c J/\psi$ nearest the threshold are significantly larger than in neighbouring bins.



Search for a pentaquark state decaying into pJ/ψ in Υ(1,2S) inclusive decays at Belle

Pentaquark states are observed in pJ/ψ in Λ_b decays at LHCb





No pentaquakr signal is observed!

B(Υ(1S)→ pJ/ψ+X)=(4.27±0.16±0.20)×10^{-5}

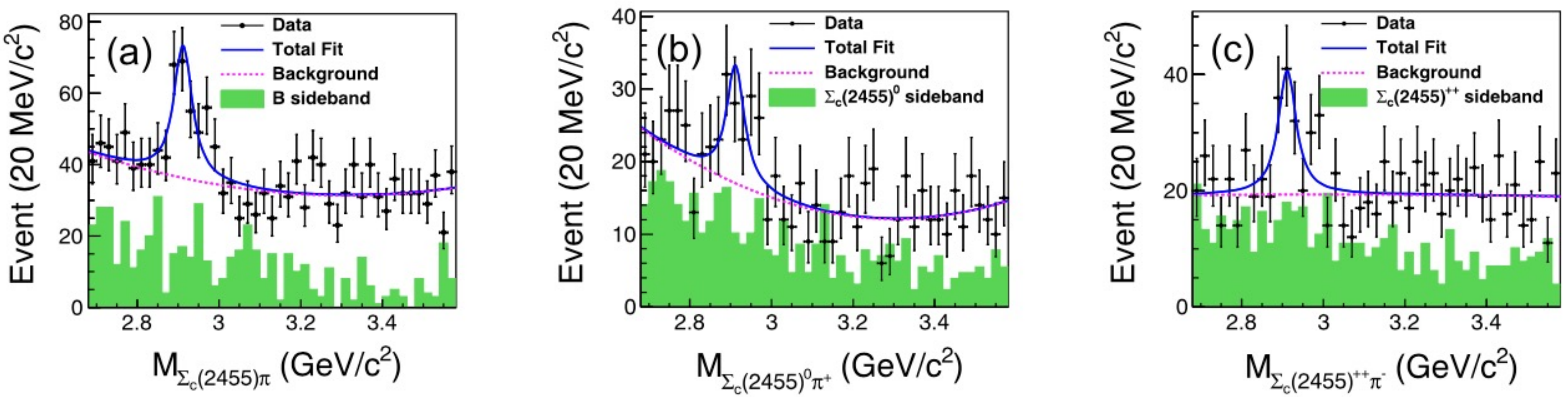
B(Υ(2S)→ pJ/ψ+X)=(3.59±0.14±0.16)×10^{-5}

σ(Υ(2S)→ pJ/ψ+X)=(57.5±2.1±2.5) fb at 10.52 GeV

	$\Upsilon(1S)$ decays			$\Upsilon(2S)$ decays		
—	$P_c(4312)^+$	$P_c(4440)^+$	$P_c(4457)^+$	$P_c(4312)^+$	$P_c(4440)^+$	$P_c(4457)^+$
$N_{\rm fit}^{\rm A}$	10 ± 8	14 ± 12	-3 ± 9	30 ± 16	33 ± 15	0 ± 3
$N_{\rm fit}^{\rm A,UL}$	26	37	14	52	60	6
$N_{\rm fit}^{\rm B}$	10 ± 8	12 ± 11	3 ± 9	29 ± 12	31 ± 15	0 ± 3
$N_{\rm fit}^{\rm B,UL}$	26	33	17	50	57	7
$N_{\rm sig}^{\rm UL}$	31	47	34	56	77	26
$\mathcal{B}^{\rm UL}$ ($\times 10^{-6}$)	4.5	6.8	4.9	5.3	7.2	2.4

Evidence of a New Excited Charmed Baryon Decaying to $\Sigma_c(2455)^{0,++}\pi^{\pm}$

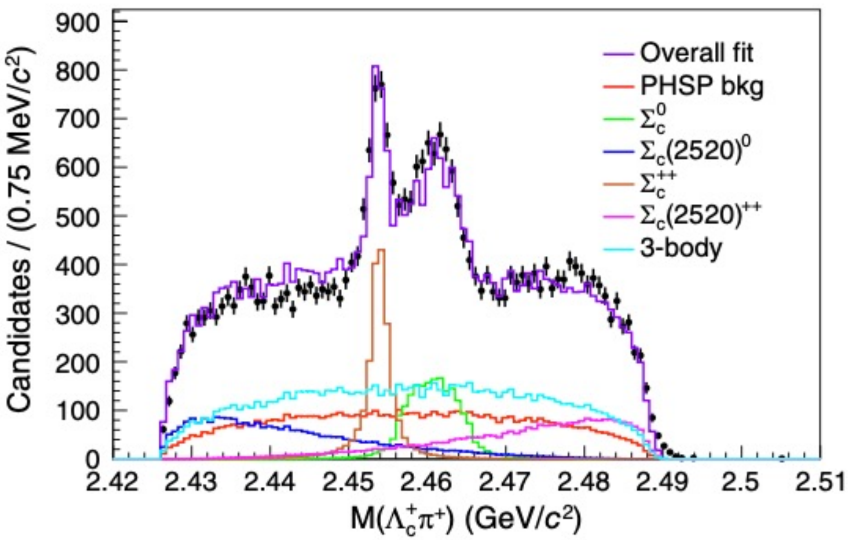
4.2σ after considering possible $\Lambda_c(2880)^+$ or $\Lambda_c(2940)^+$ contribution.

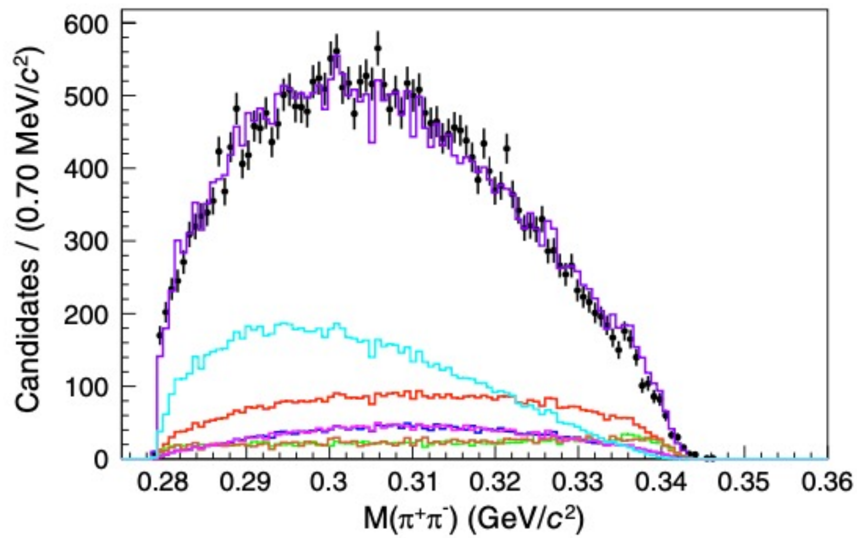


State	Mass (MeV/c^2)	Width (MeV)
$\Lambda_c(2880)^+$	2881.63 ± 0.24	$5.6^{+0.8}_{-0.6}$
$\Lambda_c(2940)^+$	$2939.6^{+1.3}_{-1.5}$	20^{+6}_{-5}
$\Lambda_c(2910)^+$ (this analysis)	$2913.8 \pm 5.6 \pm 3.8$	$51.8 \pm 20.0 \pm 18.8$

Measurement of the mass and width of the $\Lambda_c(2625)^+$ charmed baryon and the branching ratios of $\Lambda_c(2625)^+ \to \Sigma^0\pi^+$ and $\Lambda_c(2625)^+ \to \Sigma^{++}\pi^-$

A Dalitz plot fit is performed in the $\Lambda_c(2625)^+ \to \Lambda_c\pi^+\pi^-$ final states, with 1C constrain to the Λ_c mass





$$M(\Lambda_c(2625)^+) - M(\Lambda_c^+) = 341.518 \pm 0.006 \pm 0.049\ \mathrm{MeV}/c^2.$$

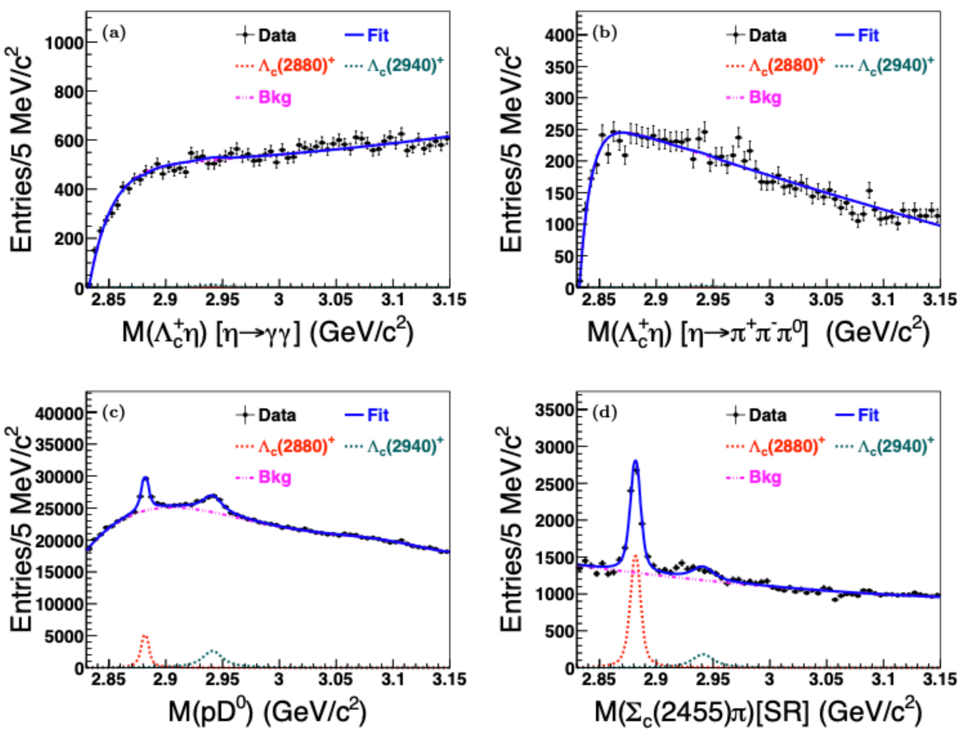
$$\Gamma(\Lambda_c(2625)^+) < 0.52\ \mathrm{MeV}/c^2$$

$$\frac{\mathcal{B}(\Lambda_c(2625)^+ \to \Sigma_c^0\pi^+)}{\mathcal{B}(\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-)} = (5.19 \pm 0.23 \pm 0.40)\%,$$

$$\frac{\mathcal{B}(\Lambda_c(2625)^+ \to \Sigma_c^{++}\pi^-)}{\mathcal{B}(\Lambda_c(2625)^+ \to \Lambda_c^+\pi^+\pi^-)} = (5.13 \pm 0.26 \pm 0.32)\%.$$

These information could be used to check a few models: chiral and heavy quark symmetry, $^3P_0$ model

Search for charmed baryons in the $\Lambda_c^+\eta$ system and measurement of the branching fractions of $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ decaying to $\Lambda_c^+\eta$ and pD^0 relative to $\Sigma_c(2455)\pi$



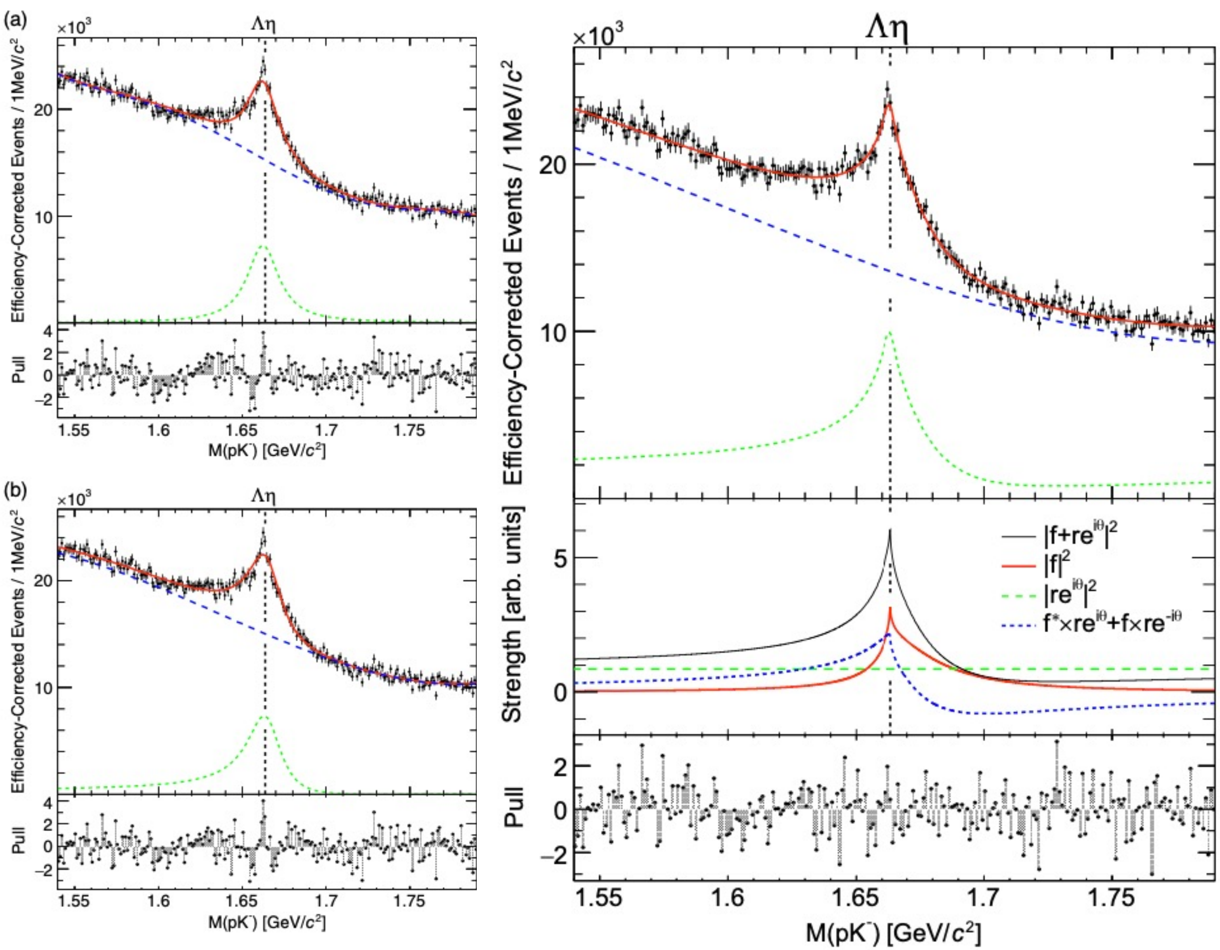
- ❖ No significant excess is found in the $M(\Lambda_c\eta)$ spectrum. This is in contrast to excited hyperons, where resonances decaying into $\Lambda\eta$ have been observed.
- ❖ Clear $\Lambda_c(2880)^+$ and $\Lambda_c(2940)^+$ signals are observed in the pD^0 mass spectrum.

$$R_{pD^0}(2880) = 0.75 \pm 0.03 \pm 0.07,$$
$$R_{pD^0}(2940) = 3.59 \pm 0.21 \pm 0.56,$$

- ❖ Any signal in $\Lambda_c^+\eta$ is likely to be an excited Λ_c rather than a Σ_c , as for the latter decays to $\Lambda_c\,\pi$ are allowed by isospin and are likely to dominate
- ❖ Much attention has been paid to the pD^0 system as an analogue to the NK system, where there exists $\Lambda(1405)$ resonance as a NK quasi-bound state near threshold

PHYSICAL REVIEW D 108, L031104 (2023)

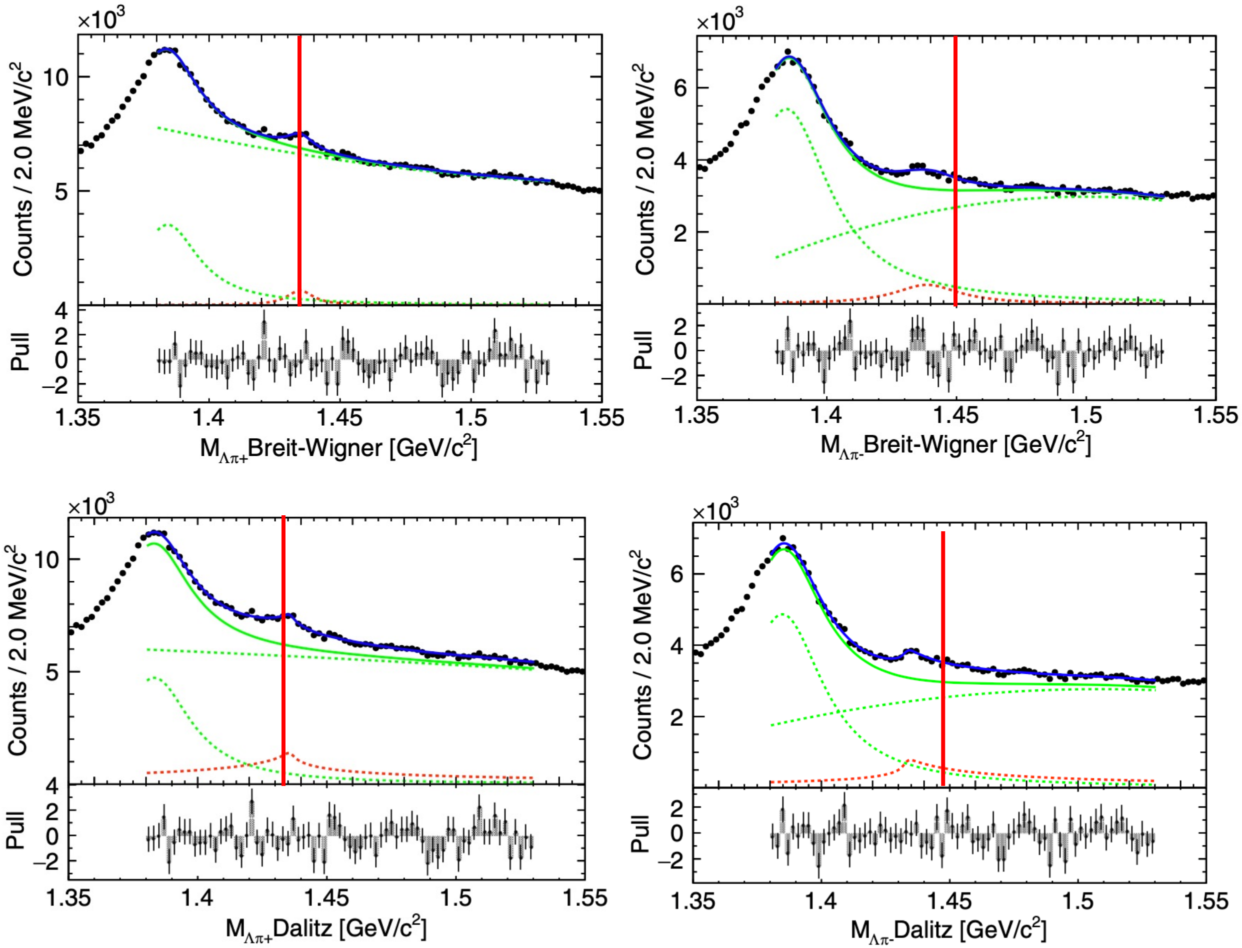
Observation of a threshold cusp at the Λη threshold in the pK⁻ mass spectrum with $\Lambda_c^+ \to pK^-\pi^+$ decays



- BW fit is not very good especially near the peak
- Faltte fit is better than BW by 7σ
- The fit explains the peak as a threshold cusp with nearby Λ(1670): First identification of a threshold cusp from the spectrum shape

PHYSICAL REVIEW LETTERS 130, 151903 (2023)

First Observation of $\Lambda\pi^+$ and $\Lambda\pi^-$ Signals near the $\bar{K}N(I = 1)$ Mass Threshold in $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$ Decay



Cusp candidates are observed in **Λπ** invariant mass spectra ;

Dalitz model gives slightly better χ^2, but the difference is small:

BW interpretation: implies the existence of an exotic state, *Σ*(1435)

Mode	$E_{\rm BW}$ (MeV/c^2)	Γ (MeV/c^2)	χ^2/NDF
$\Lambda\pi^+$	1434.3 ± 0.6	11.5 ± 2.8	74.4/68
$\Lambda\pi^-$	1438.5 ± 0.9	33.0 ± 7.5	92.3/68

Dalitz:

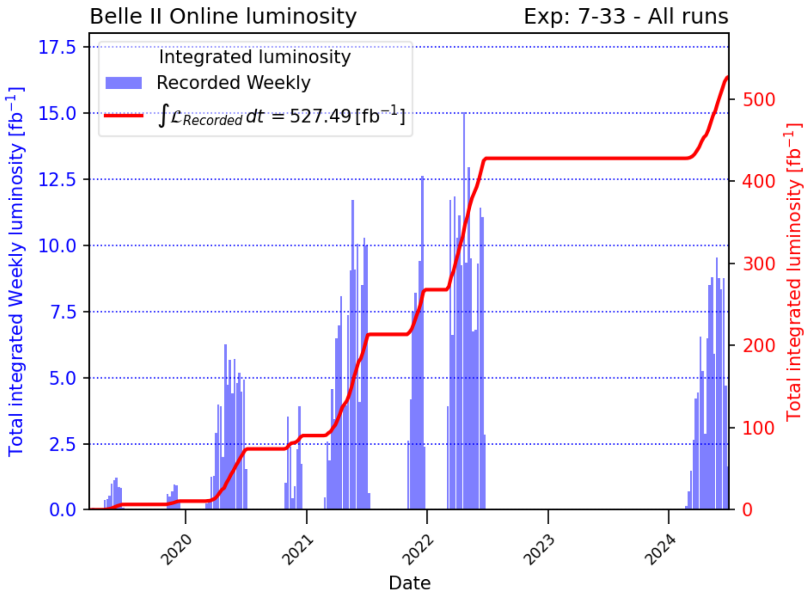
Mode	a (fm)	b (fm)	χ^2/NDF
$\Lambda\pi^+$	0.48 ± 0.32	1.22 ± 0.83	68.9/68
$\Lambda\pi^-$	1.24 ± 0.57	0.18 ± 0.13	78.1/68

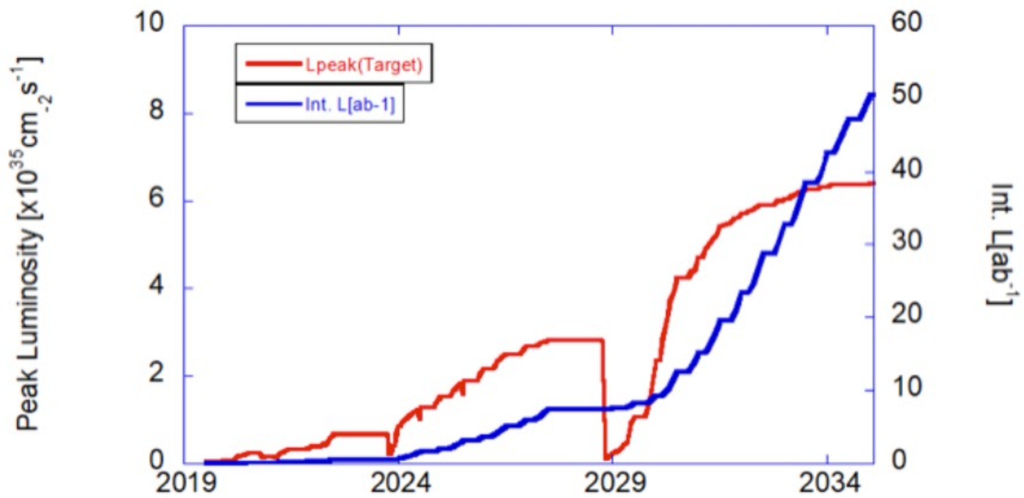
Summary

As B-factory, Belle (II) continues the studies of conventional and potentially exotic hadron states:

- Confirm the existence of $\Upsilon(10753)$, and further investigate its nature
- Open bottom cross sections are measured, which are important to understand the vector bottomonium states
- Double charmonium state with $\eta_c J/\psi$ is searched, and significance is low
- Pentaquark in pJ/ψ decay mode is searched in $\Upsilon(1,2S)$ decays , and no signal is observed
- Charmed baryons are stuied, and new features, such as cusp effect, are found in the decays

Prospects : More data will come!





Our official message: *"We are back to the conditions of end of Run 1 with instantaneous luminosity close to 4x10^34 with LER/HER currents above 1A (LER) but we are still suffering from sudden beam loss events, with sometimes large doses at IR (happened few times in 3 months). This is why we have decided to turn off PXD for now until we understand better the origin for these events. The PXD is still operating well, with 98% of the channels live. However, to preserve this high level of performance we have decided to turn it off for now until the sudden beam loss events are understood and beam operations stabilize, as Run 2 will be long."*

Thanks very much!