Results on Hadron Spectroscopy from the Belle and Belle II Experiments

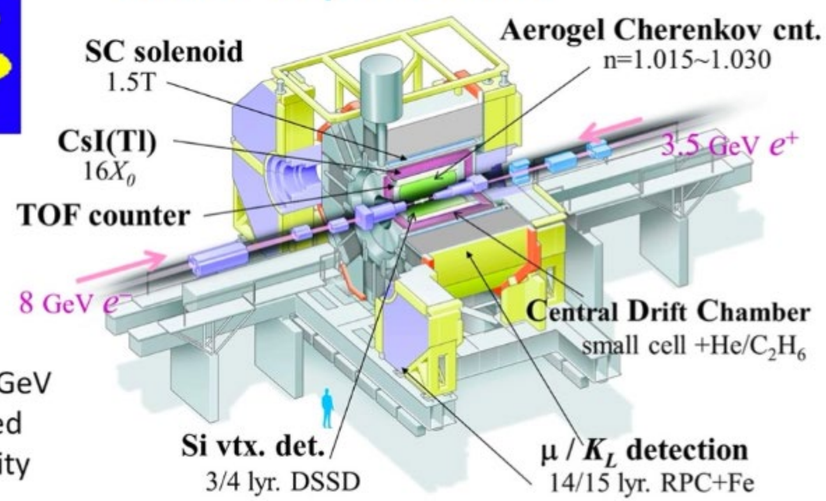
John Yelton
University of Florida

I review some spectroscopy results with particular emphasis on studies of the $\mathbf{\Upsilon(10753)}$ in scan points at high energy, and recent results from Belle data on pentaquark searches and charmed baryons and hyperons.

BELLE

Data taken 1999-2010
BIG data set (~ 1 ab^{-1})
Most data taken around the $\Upsilon(4S)$ but data also taken at “narrow” resonances $\Upsilon(1S)$ $\Upsilon(2S)$ $\Upsilon(3S)$ as well as in the $\Upsilon(5S)/\Upsilon(6S)$ region

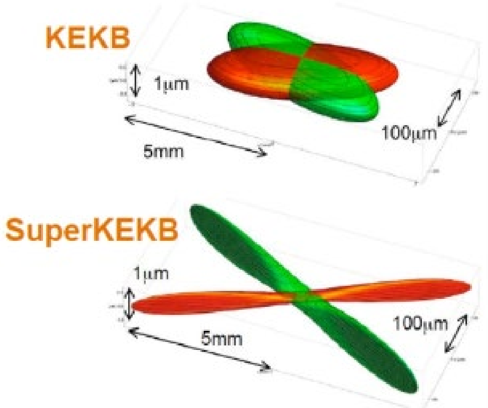
Belle experiment



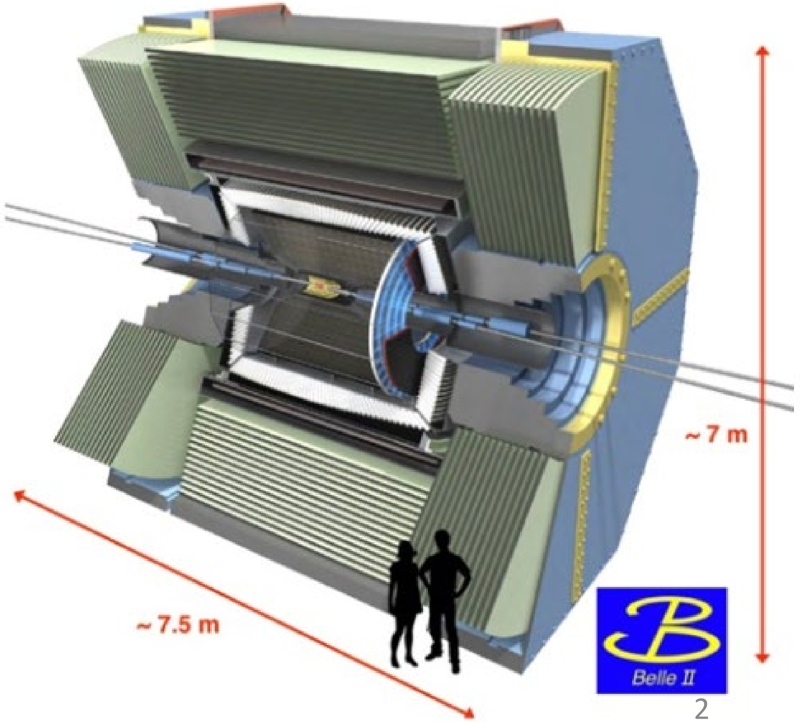
- √s~10.6 GeV
- Integrated Luminosity ~ 1 ab^{-1}

BELLE II

Designed for higher luminosities and thus higher event rates and backgrounds
Revamped tracker, PID, etc. etc.
Data taken 2020-Present
Integrated luminosity not yet caught up to BELLE
Most data taken around the $\Upsilon(4S)$, but data also taken at higher energies

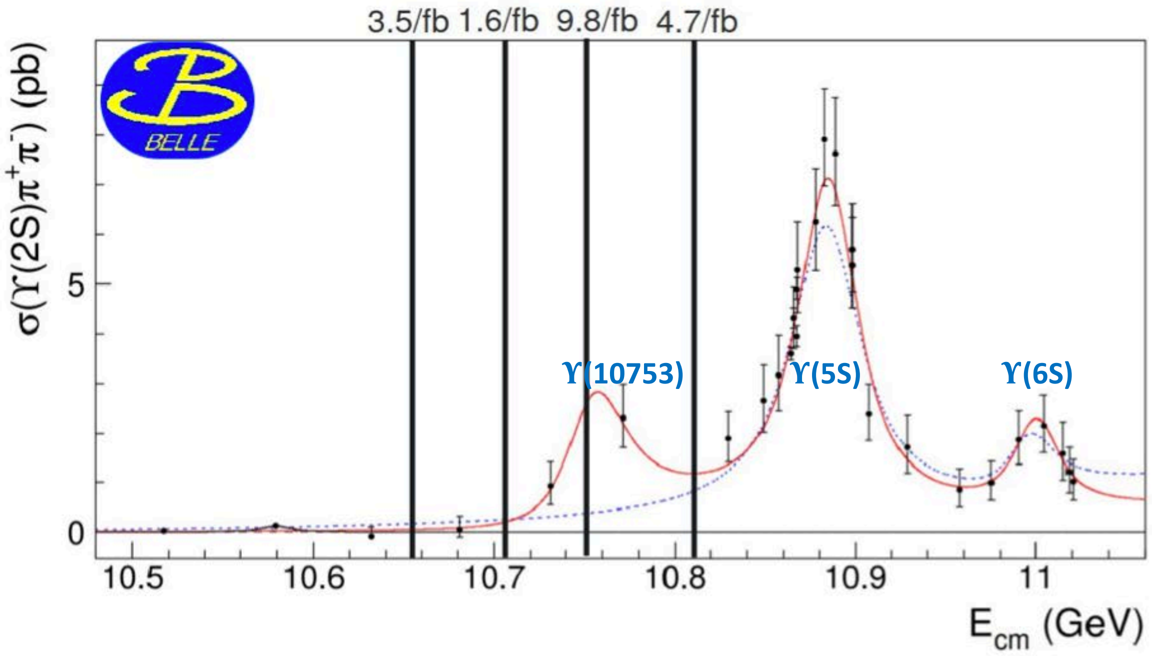


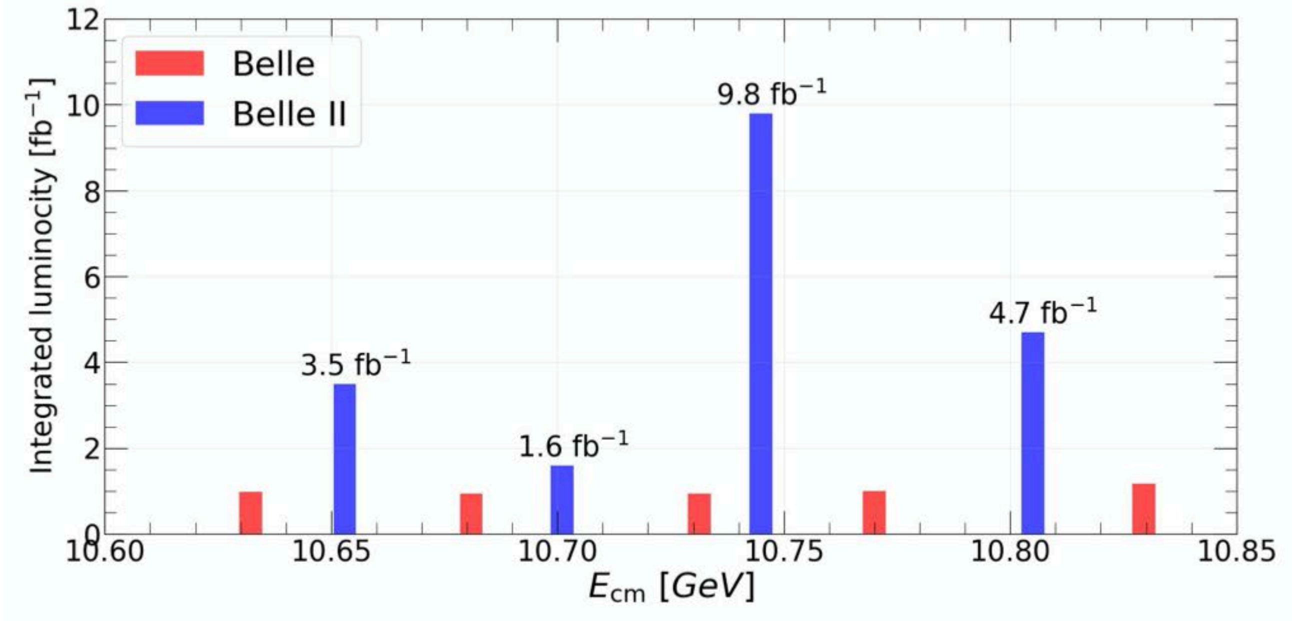
Belle II at SuperKEKB has TINY beamspot



$\Upsilon(10753)$

Wide resonance between the $\Upsilon(4S)$ and $\Upsilon(5S)$ discovered by Belle (R. Mizuk et al, JHEP, 10, 220 (2019))
Found in $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ (n=1,2,3). What is it? Bottomonium, hybrid, tetraquark, mixing of conventional states, etc.

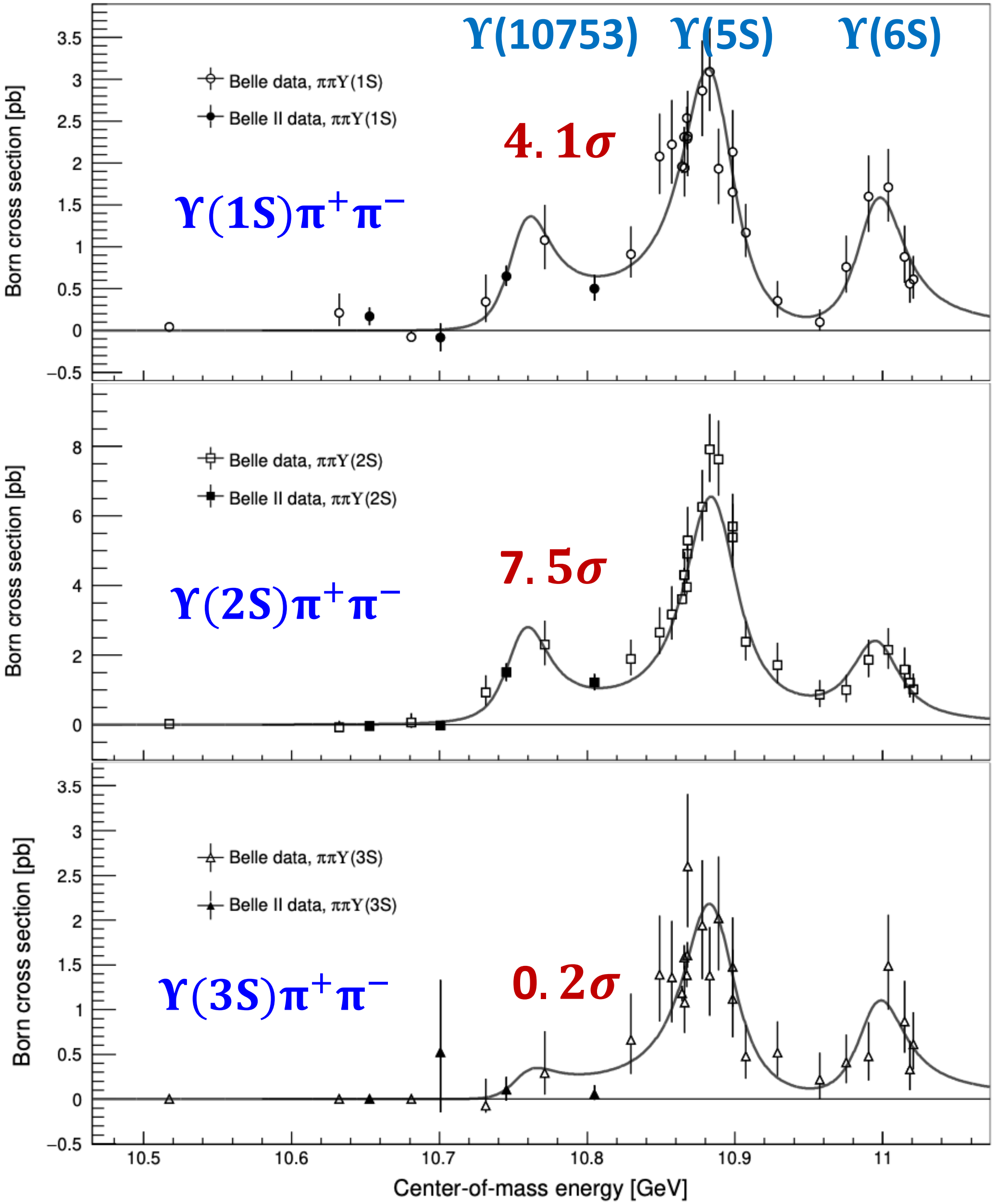




In November 2021, Belle II collected 19 fb^{-1} of unique data at energies above the $\Upsilon(4S)$: four energy scan points around 10.75 GeV in this region

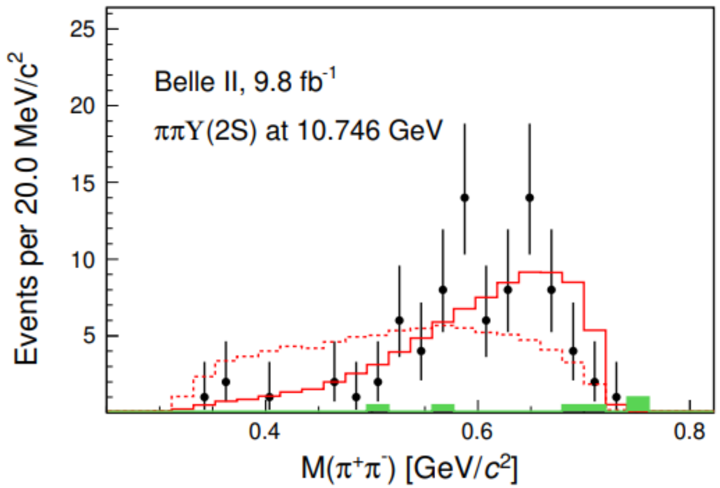
Physics goal: understand the nature of the $\Upsilon(10753)$ energy region.

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



Belle II confirms the peak!

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



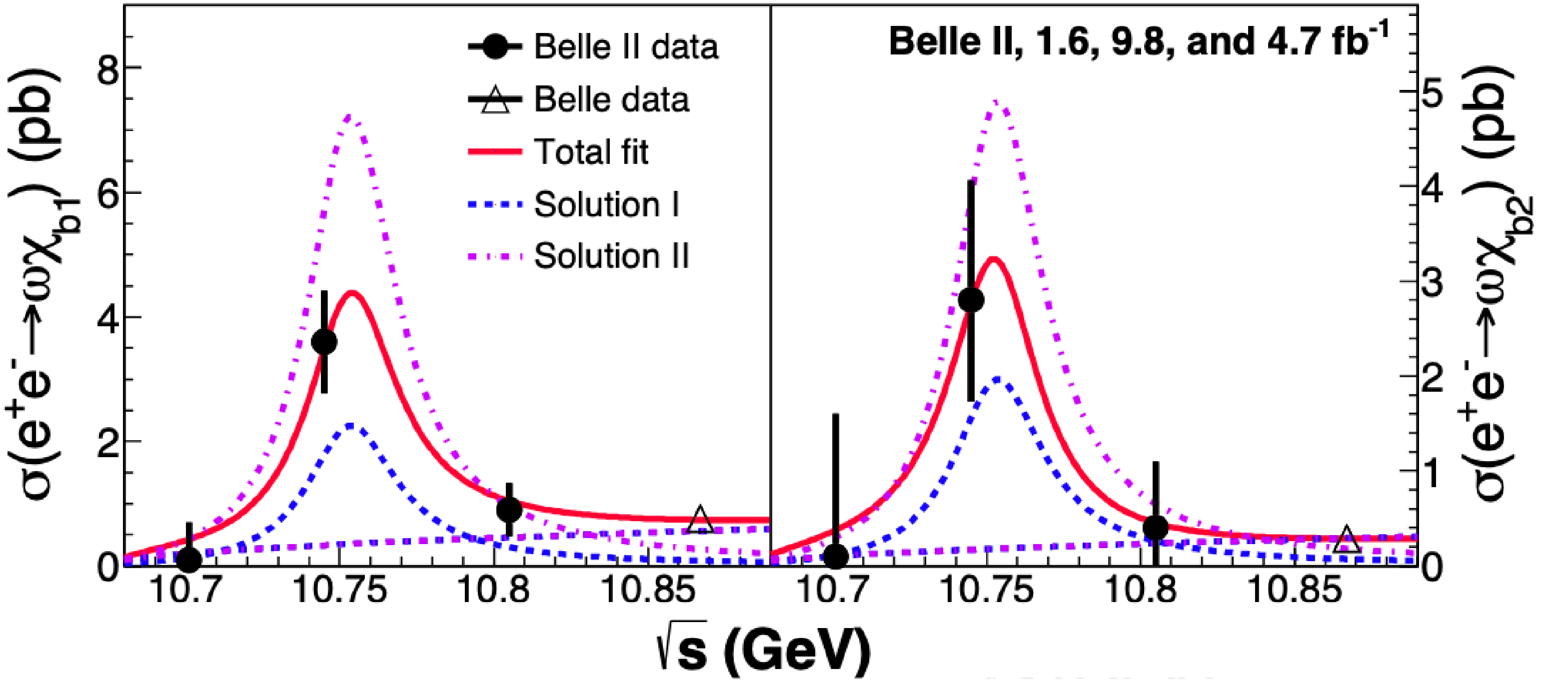
In the $\Upsilon(2S)\pi^+\pi^-$ case, the $\pi\pi$ invariant mass is **not** phase-space. This agrees with the $\Upsilon(2S)$decays themselves

[JHEP 07, 116 (2024)]

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

[PRL 130, 091902 (2023)]

$\omega\chi_{b1}$ $\omega\chi_{b2}$



$$\frac{\sigma(\Upsilon(10753) \to \omega\chi_{b1})}{\sigma(\Upsilon(10753) \to \omega\chi_{b2})} = 1.3 \pm 0.6$$

Prediction for pure D-wave state: 15

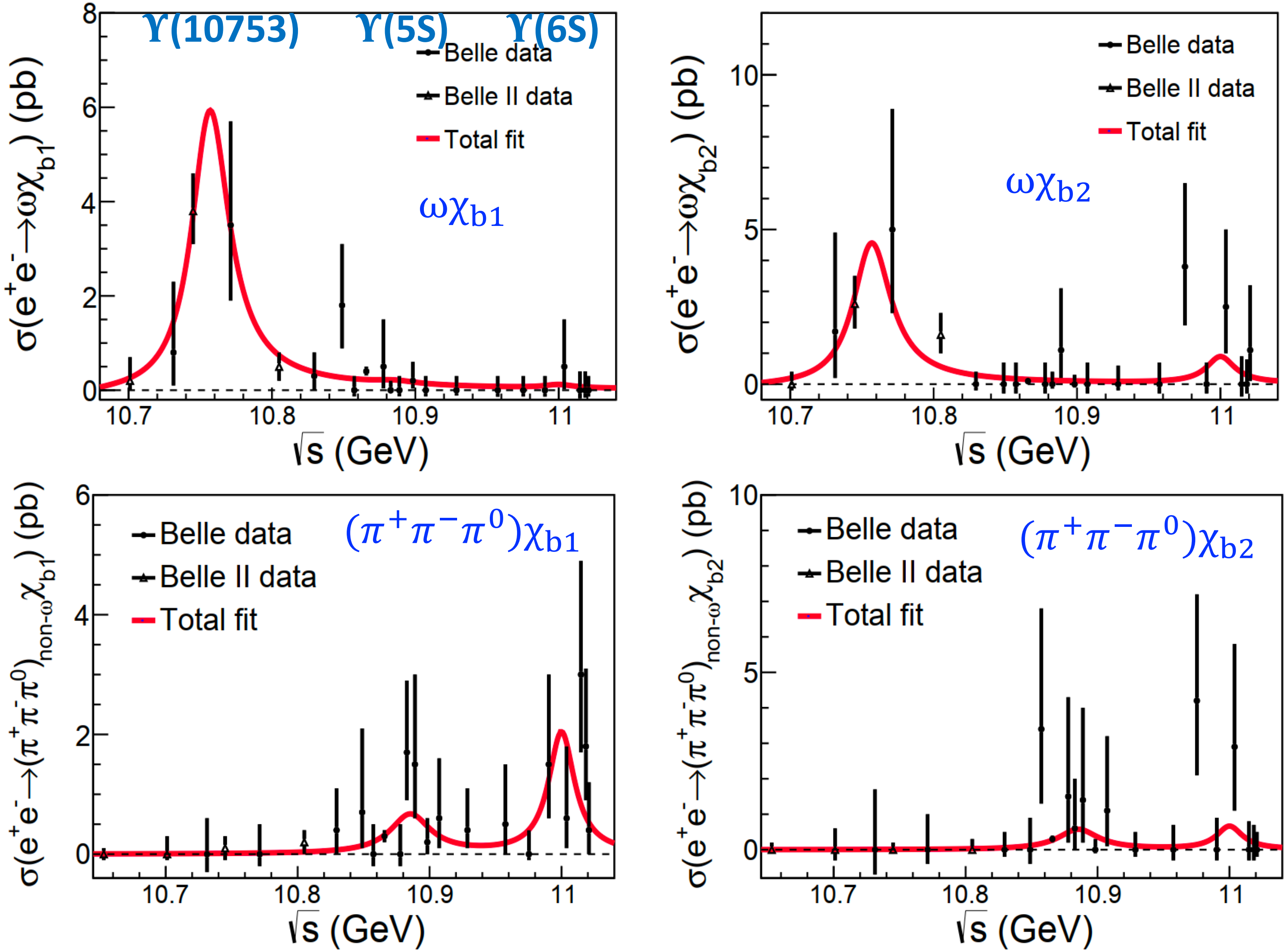
Prediction for 4S-3D mixed state: 0.2

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

indicate different internal structure

Extended (preliminary) analysis of $\sigma(e^+e^- \to \omega\chi_{bJ}(1P))$ and also $\sigma(e^+e^- \to (\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}(1P))$

Belle II + BELLE



The measured mass and width of $\Upsilon(10753)$ using $e^+e^- \to \omega\chi_{b1,b2}(1P)$ are consistent with those measued using $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$

The $\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b1})$ and $\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b2})$ are compatible with previous slide

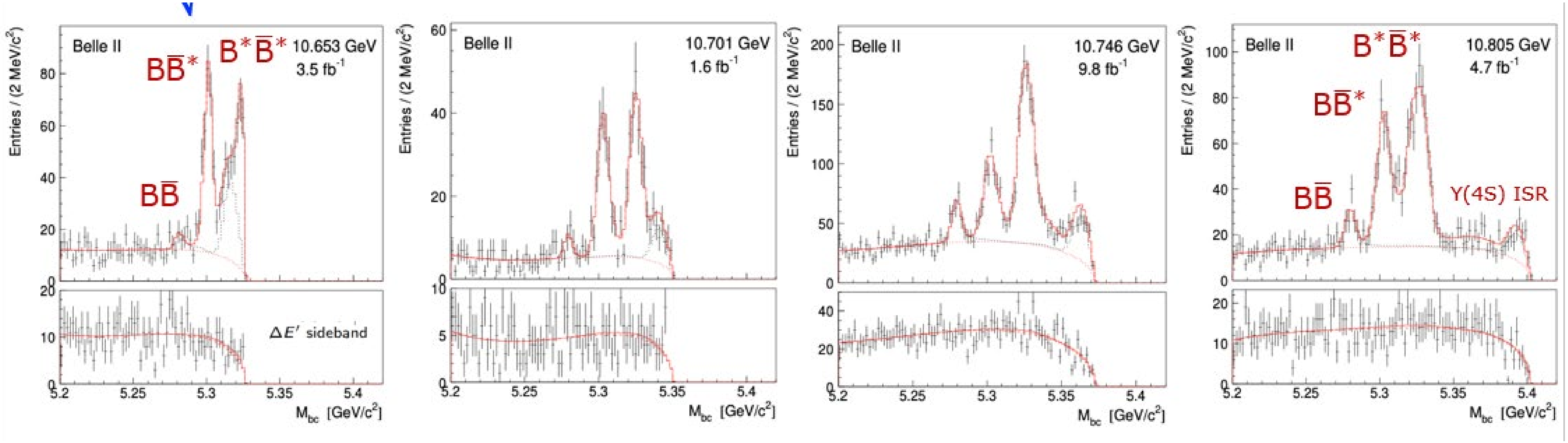
The $\Upsilon(5S)$ and $\Upsilon(6S)$ decay with a noticeable probability to $(\pi^+\pi^-\pi^0)_{non-\omega\chi_{bJ}}$.

(It is possible that this observation is explained by the fact that $(\pi^+\pi^-\pi^0)_{non-\omega\chi_{bJ}}$ is a consequence of the cascade decay of $\Upsilon(10860, 11020) \to Z_b\pi \to \chi_{bJ}\rho\pi$)

Belle II Preliminary

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

For each fixed center-of-mass energy, we calculate: $M_{bc} = \sqrt{(E_{cm}/2)^2 - P_B^2}$

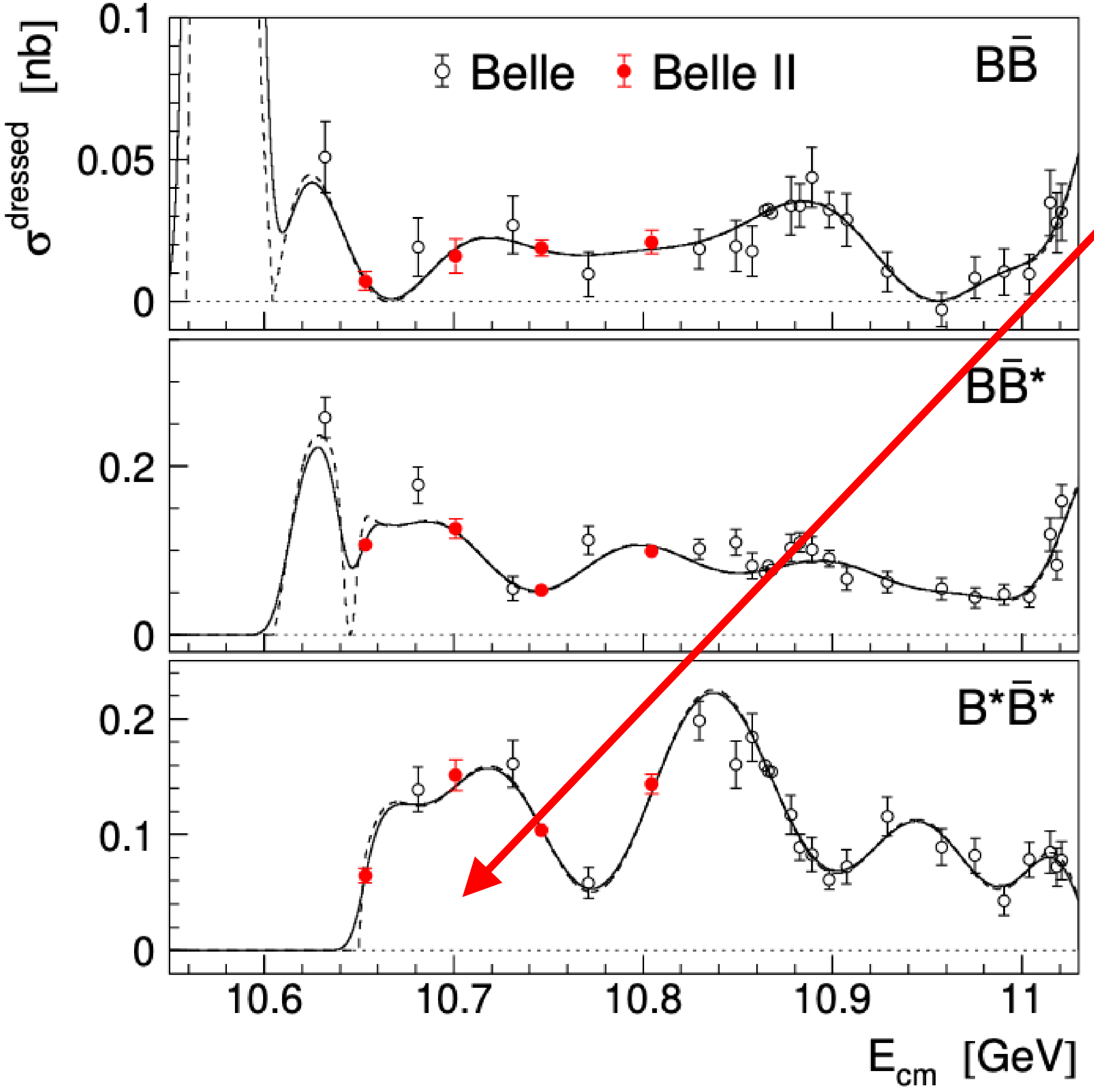


$e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ signals at $\sqrt{s} \sim 10.75$ GeV can be clearly observed

Contribution of $\Upsilon(4S) \to B\bar{B}$ production via ISR is visible well (black dotted histograms)

Energy dependence of the cross sections (continued)

[JHEP 10, 114 (2024)]



Rapid increase in cross section above B*B* threshold

Possible interpretation: resonance or bound state $B^*\bar{B}^*$ near threshold

(can also give destructive interference between $B\bar{B}^*$ and $B^*\bar{B}^*$)

Similar behavior has been seen in $D^*\bar{D}^*$ cross-section

BELLE Analyses using the "narrow" resonance datasets

Belle took 5.8 fb^{-1} at the $\Upsilon(1S)$
24.5 fb^{-1} at the $\Upsilon(2S)$
2.9 fb^{-1} at the $\Upsilon(3S)$

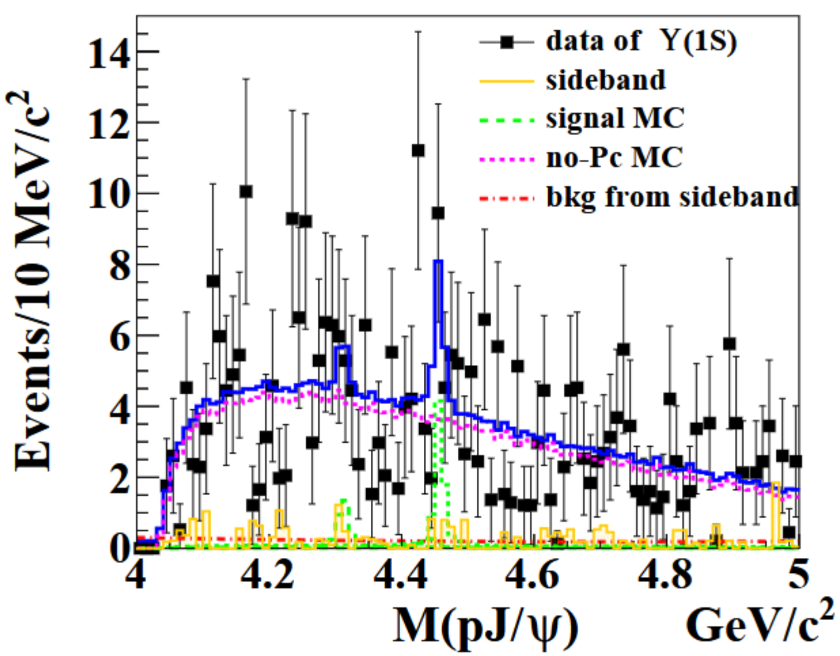
Because of the high cross-sections, this is around 3 x 10^{8} events

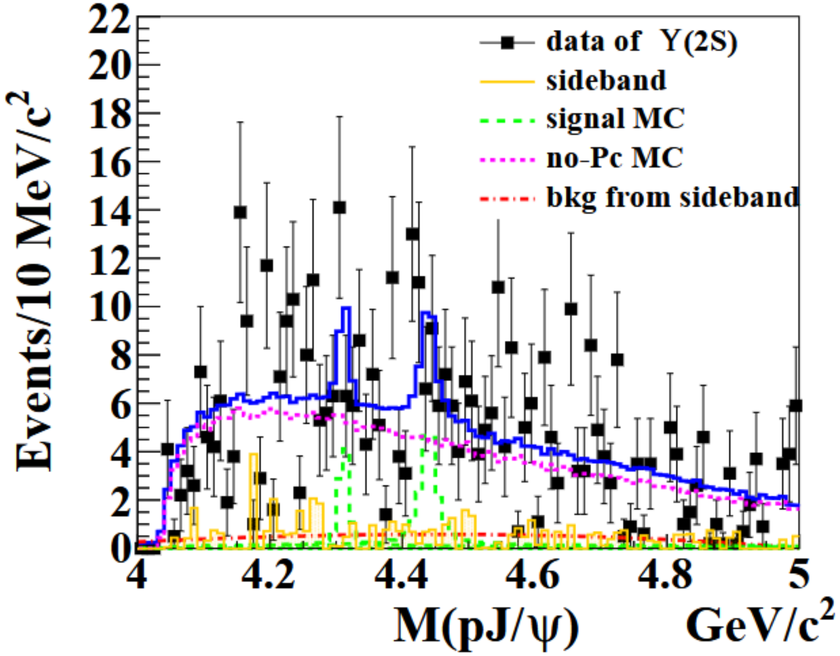
"Narrow resonance" data is a unique environment for searches for new particles, particularly favoring baryons, strange particles and unusual quark configurations such as $qq\overline{qq}$ and $qqqq\overline{q}$

LHCb have made observations of P_c^+(4312, 4440, and 4457) in the decay of pJ/ψ substructure of Λ_b decays, the $P_{c\bar{c}s}(4459)^0$ in the $\Lambda J/\psi$ substructure of Ξ_b decays (3.1σ) and the $P_{c\bar{c}s}(4338)^0$ in the $\Lambda J/\psi$ substructure of B^-decays (15σ).

Belle has targeted analyses of the inclusive $\Upsilon(1S)$, $\Upsilon(2S)$ decays into (firstly) pJ/ψ and later $\Lambda J/\psi$ final states looking in particular for signs of pentaquark production. The J/ψ is easily reconstructed in $l^+l^-(l = e, \mu)$

BELLE data $\Upsilon(1S,2S)$ decays to pJ/ψ





No pentaquarks are found – only very slight excesses in the place of the LHCb results

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}

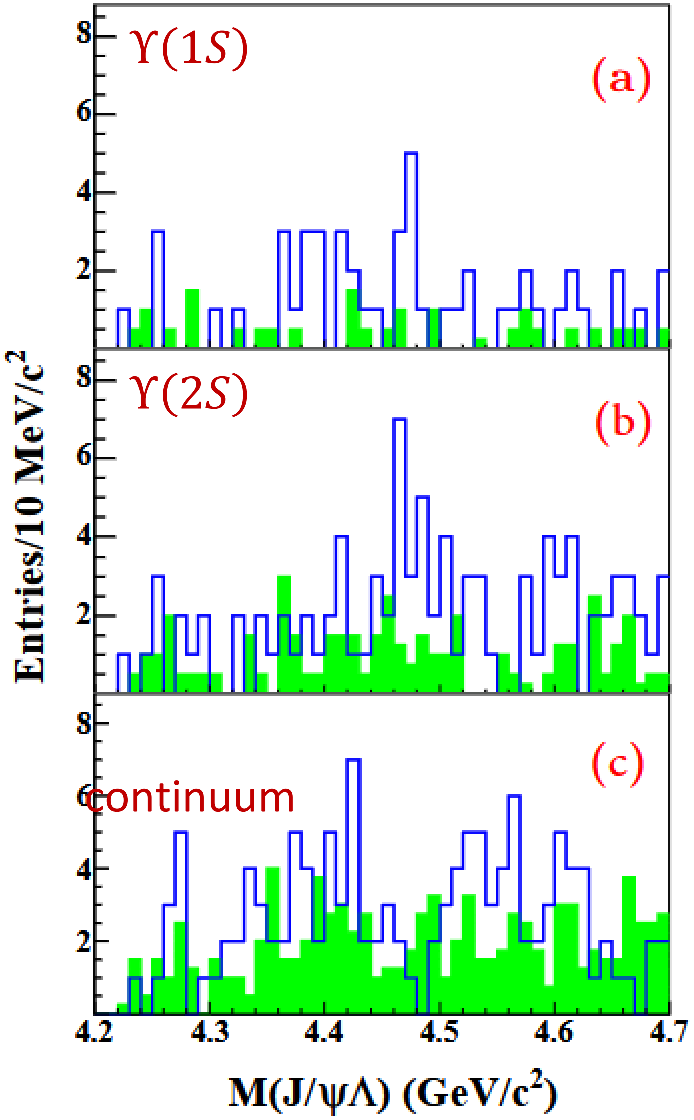
σ(pJ/ψ+X)=(57.5±2.1±2.5) fb at 10.52 GeV

$$\mathcal{B}[\Upsilon(1S) \to P_c(4312)^+ + anything] \cdot \mathcal{B}[P_c(4312)^+ \to pJ/\psi] < 3.9 \times 10^{-6},$$
$$\mathcal{B}[\Upsilon(1S) \to P_c(4440)^+ + anything] \cdot \mathcal{B}[P_c(4440)^+ \to pJ/\psi] < 6.2 \times 10^{-6},$$
$$\mathcal{B}[\Upsilon(1S) \to P_c(4457)^+ + anything] \cdot \mathcal{B}[P_c(4457)^+ \to pJ/\psi] < 5.5 \times 10^{-6},$$
$$\mathcal{B}[\Upsilon(2S) \to P_c(4312)^+ + anything] \cdot \mathcal{B}[P_c(4312)^+ \to pJ/\psi] < 4.7 \times 10^{-6},$$
$$\mathcal{B}[\Upsilon(2S) \to P_c(4440)^+ + anything] \cdot \mathcal{B}[P_c(4440)^+ \to pJ/\psi] < 7.2 \times 10^{-6},$$
$$\mathcal{B}[\Upsilon(2S) \to P_c(4457)^+ + anything] \cdot \mathcal{B}[P_c(4457)^+ \to pJ/\psi] < 2.6 \times 10^{-6},$$

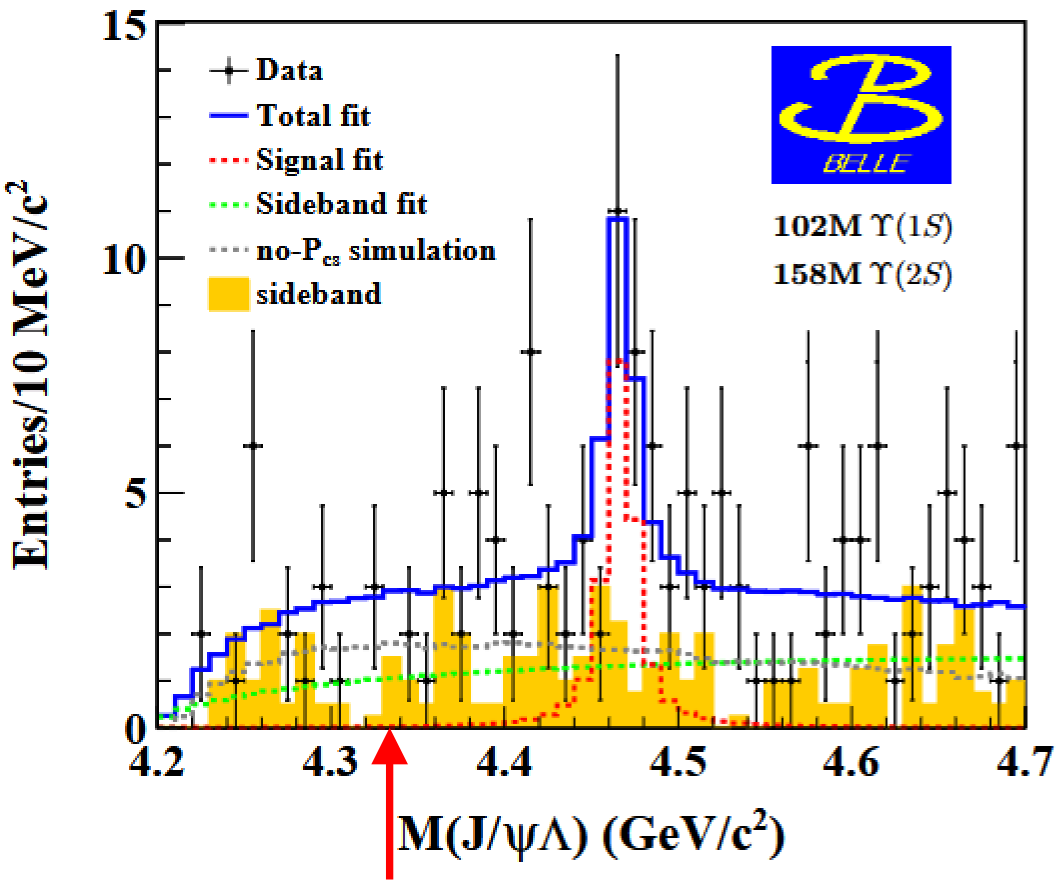
X. Dong et al, arXiv:2403.04340

BELLE data $\Upsilon(1S, 2S)$ decays to $\Lambda J/\psi$

PRELIMINARY



Green – sidebands Blue - signal



No sign of the 4338

Peak observed in the region of the $P_{c\bar{c}s}(4459)^0$

Assuming it to be the same particle, the significance is 3.3 σ

Assuming it is NOT the same particle, Belle finds 3.8 σ

M = 4471.7 ± 4.8 ± 0.6 MeV/c²

Γ = 21.9 ± 13.1 ± 2.7 MeV

note that LHCb found

$M = 4458.8 \pm 2.9^{+4.7}_{-1.1}\ MeV/c^2$

$\Gamma = 17.3 \pm 6.5^{+8.0}_{-4.7}\ MeV$

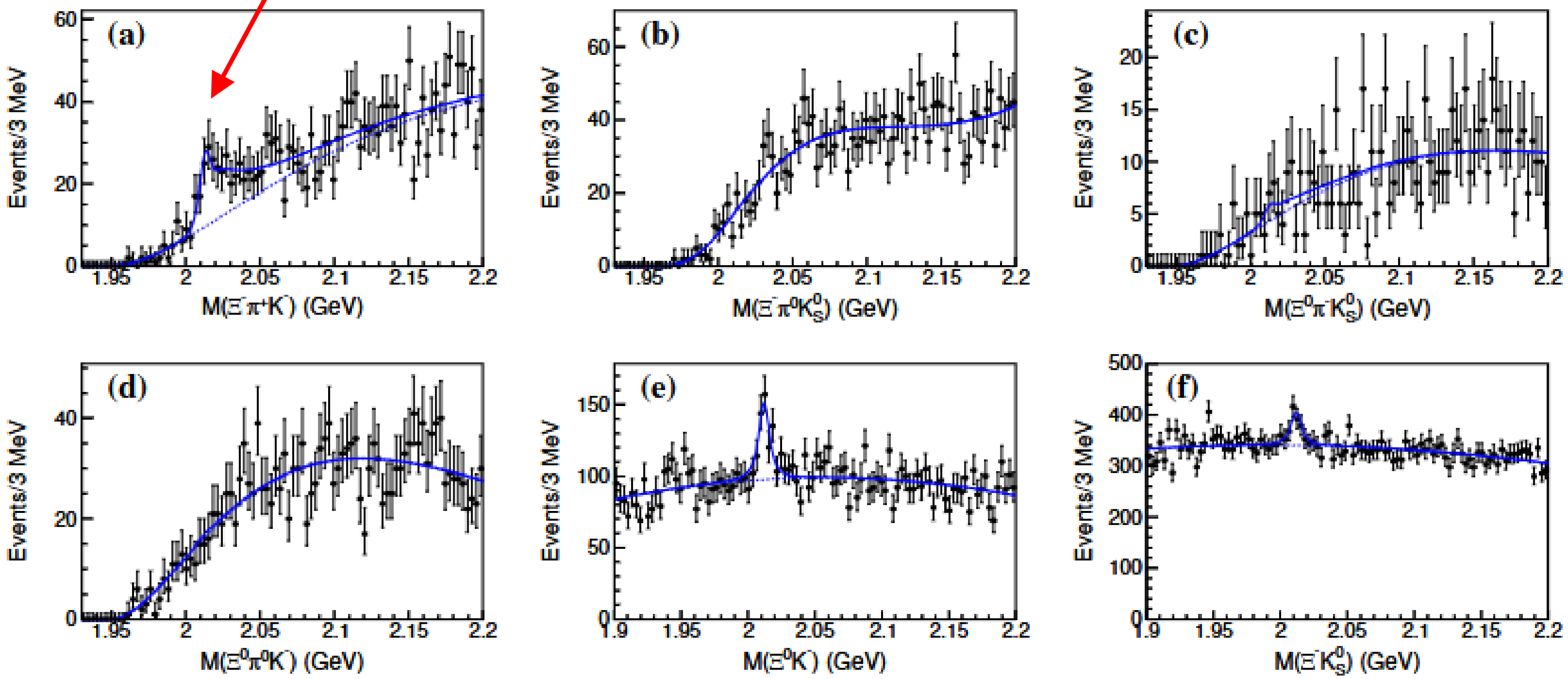
The data shows the first observation of $\Upsilon(1S)$, $\Upsilon(2S)$ decays into $\Lambda J/\psi$ final states and makes measurements of their branching fractions

arXiv:2502.09951

Ω(2012) Studies in Narrow Resonance Data

Ω(2012) discovered by BELLE, J. Yelton et al, PRL 121, 5, 052003 (2018) in two-body (ΞK) decays.
Confirmed by BES III (low statistics) and ALICE (15σ)

Big 3-body signal of 267 ± 60 events



Search in 3 body decays Ω(2012)→ ΞπK where the Ξπ resonates through Ξ*(1530).
This is only possible if the high-mass tail of the parent distribution decays to the low-mass tail of the daughter.

Sees a significant signal (5.2σ)

Ratio of branching fractions (3 body:2 body) = 0.99 ± 0.26 ± 0.06

Strongly suggests a $J^P = \frac{3}{2}^-$ particle

Ratio of couplings $\frac{g_3}{g_2} = 22.9^{+17.9}_{-22.4} \pm 2.2$

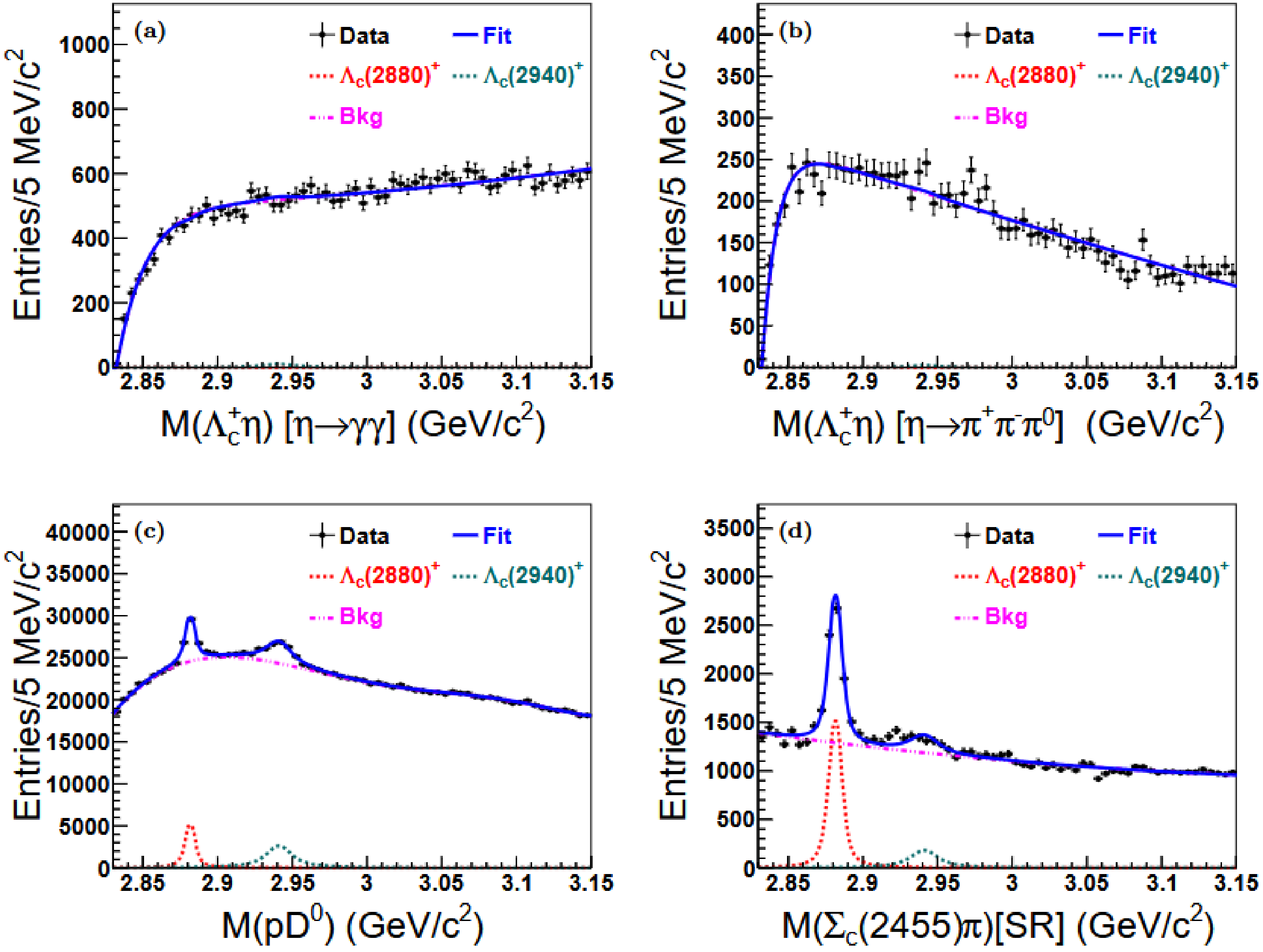
n.b. coupling ratio very poorly measured, because the phase-space comparison of 3-body to 2-body decays so poorly constrained.

S. Jia et al, Phys. Lett.B 860 (2025), 139224

Search for charmed baryons decaying to $\Lambda_c\eta$

(and compare with those decaying pD^0 and $\Sigma_c(2455)\pi$)

Rationale – in hyperons there are excited Λ hyperons which decay to $\Lambda\eta$, why not in the charmed sector also?



No excess found in $\Lambda_c\eta$ at either of the known particles or any new ones.

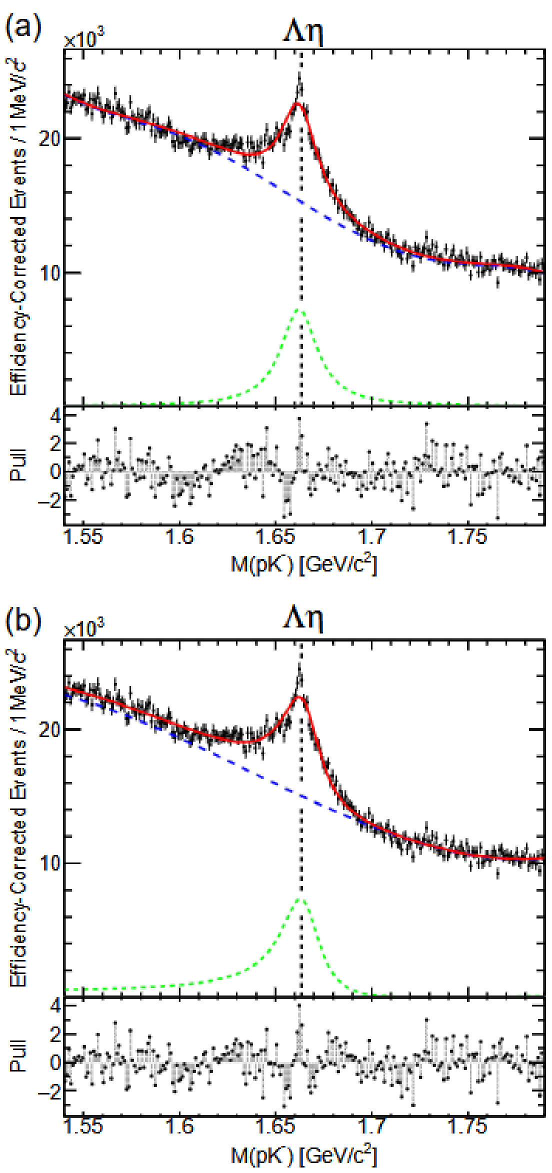
By-product of the analysis is the ratio of decay fractions of the 2880 and 2940 to pD^0 and $\Sigma_c(2455)\pi$

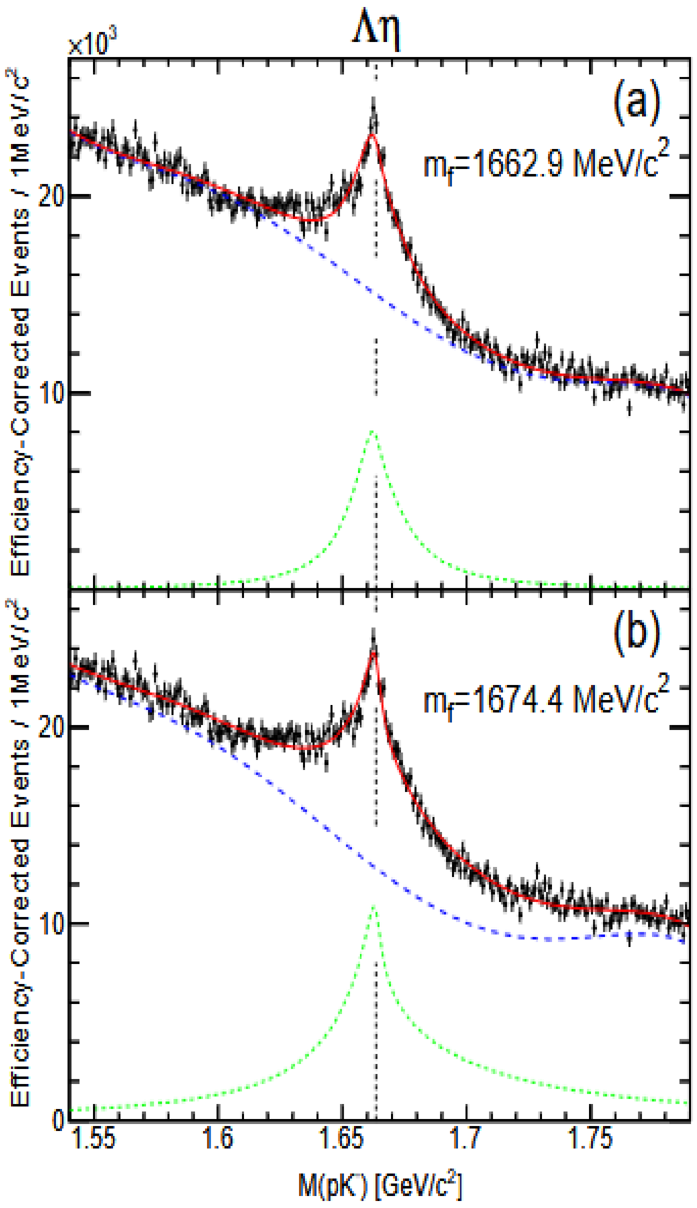
$$R_{pD^0}(2880) = 0.75 \pm 0.03 \pm 0.07,$$
$$R_{pD^0}(2940) = 3.59 \pm 0.21 \pm 0.56,$$

The Λ_c (2880) behaves much as we would expect a $J^P=5/2^+$ excited baryon would behave, but was is the Λ_c (2940)?

S. Li et al, Phys. Rev. D 110, 3, 032021 (2024)

Study of the shape of the $\Lambda(1670)$ in the pK^- substructure of $\Lambda_c \to pK^-\pi$





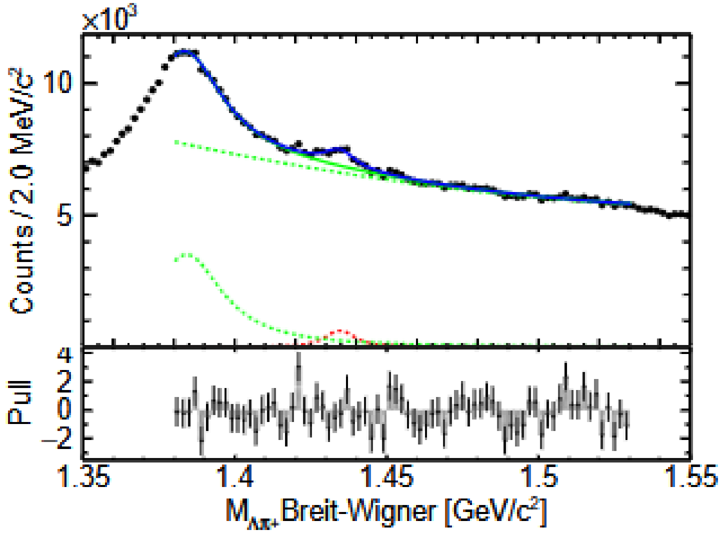
The left plots are fits to a Breit-Wigner. This is clearly unsatisfactory! The right plots show a fit to a Flatte distribution –much better – note the $\Lambda\eta$ threshold.

Clearly, this "resonance" is not a simple resonance at all and should not be treated as such.

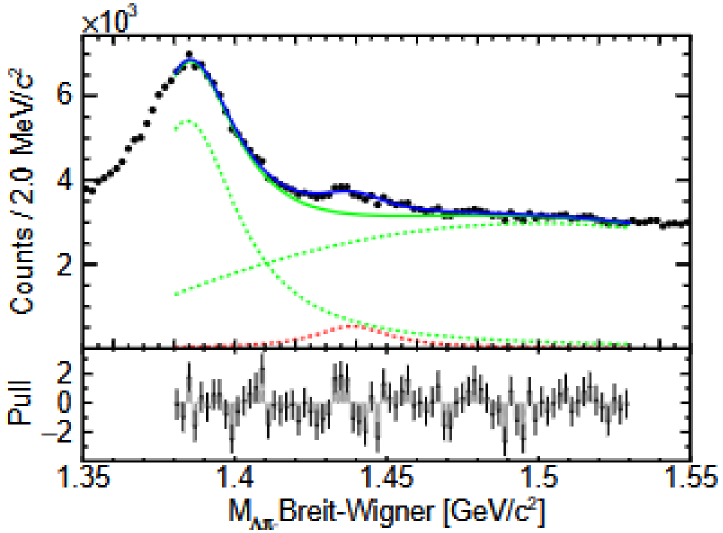
(See Duan, Bayar and Oset for a theoretical interpretation of this result. Phys. Lett. B 857 (2024), 139003)

K. Tanida et al, PRD 108, L031104 (2023)

Investigation of the $\Lambda\pi^+$ and $\Lambda\pi^-$ substructure of $\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$ decays



(a)



(b)

Clear excesses appear close to the NK threshold.

Are these cusps? Are they standard resonances? The data is not sufficient to discriminate. If they are interpreted as resonance, we find:

	Mass (MeV/c^2)	**Width (MeV)**
$\Lambda\pi^+$	$1434.3 \pm 0.6 \pm 0.9$	$11.5 \pm 2.8 \pm 5.3$
$\Lambda\pi^-$	$1438.5 \pm 0.9 \pm 2.5$	$33.0 \pm 2.8 \pm 23.6$

Mass thresholds: pK^0 1435.8 MeV, nK^- 1433.2 MeV

This is an analysis that should benefit greatly from the improved detector of Belle II

Y. Ma et al, PRL 130 (2023) 15, 151903

CONCLUSIONS and OUTLOOK

High energy (i.e. above the Υ(4S) mass) running of Belle and Belle II has shown very interesting results, particularly concerning the nature of the $\Upsilon(10753)$. Its decay via ω transitions indicates that it is very different from the other resonances in the region. Many more studies on this dataset are being performed. It would take rather little time out of the Υ(4S) running to greatly enhance these studies.

The Belle dataset has not been surpassed by Belle II but now analyses combine the two data from the two experiments.

Soon, the Belle II dataset will dwarf that of Belle. Moreover, the improved experimental set up means better signal-to-noise ratio for many signals. For instance, we can tag on the finite lifetime of charmed particles.

Stay tuned for many results on spectroscopy from Belle II in the next few years