

# 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  $\Upsilon(10753)$  in scan points at high energy, and recent results from Belle data on pentaquark searches, charmed baryons and hyperons.

# BELLE

Data taken 1999-2010

BIG data set ( $\sim 1 \text{ ab}^{-1}$ ) s-1

Peak Luminosity:  $2.1 \times 10^{34} \text{ cm}^{-2}$

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 II

Designed for higher luminosities and thus higher event rates and backgrounds

Revamped tracker, PID, etc. etc.

Data taken 2020-Present

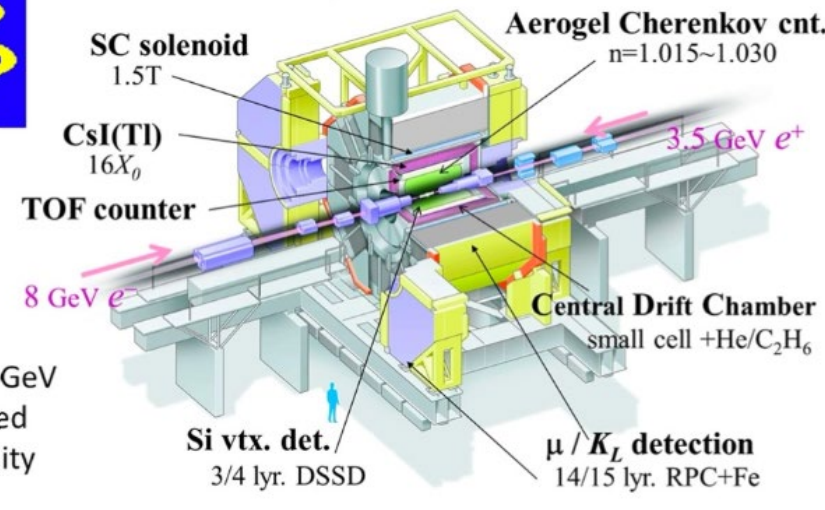
Peak Luminosity:  $5.1 \times 10^{34} \text{ cm}^{-2}$

Integrated luminosity not yet caught up to BELLE

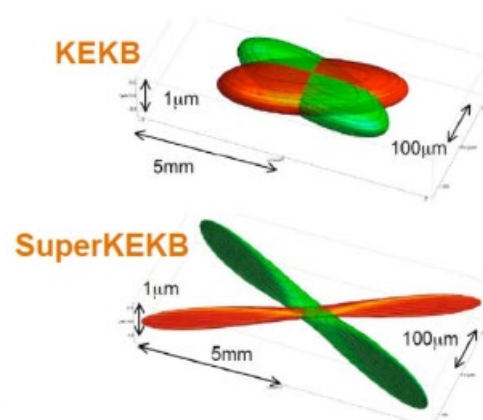
Most data taken around the  $\Upsilon(4S)$ , but data also taken at higher energies



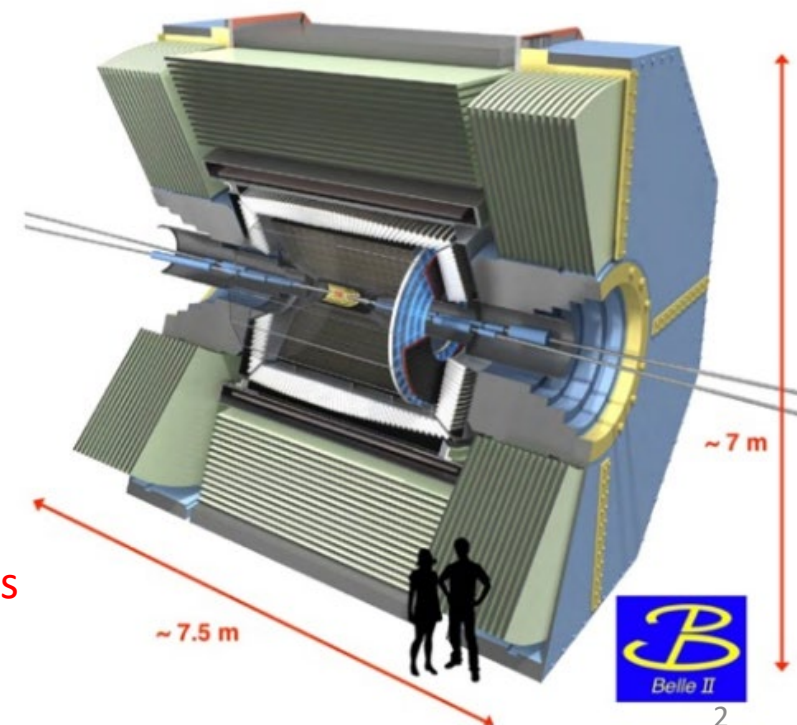
## Belle experiment



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



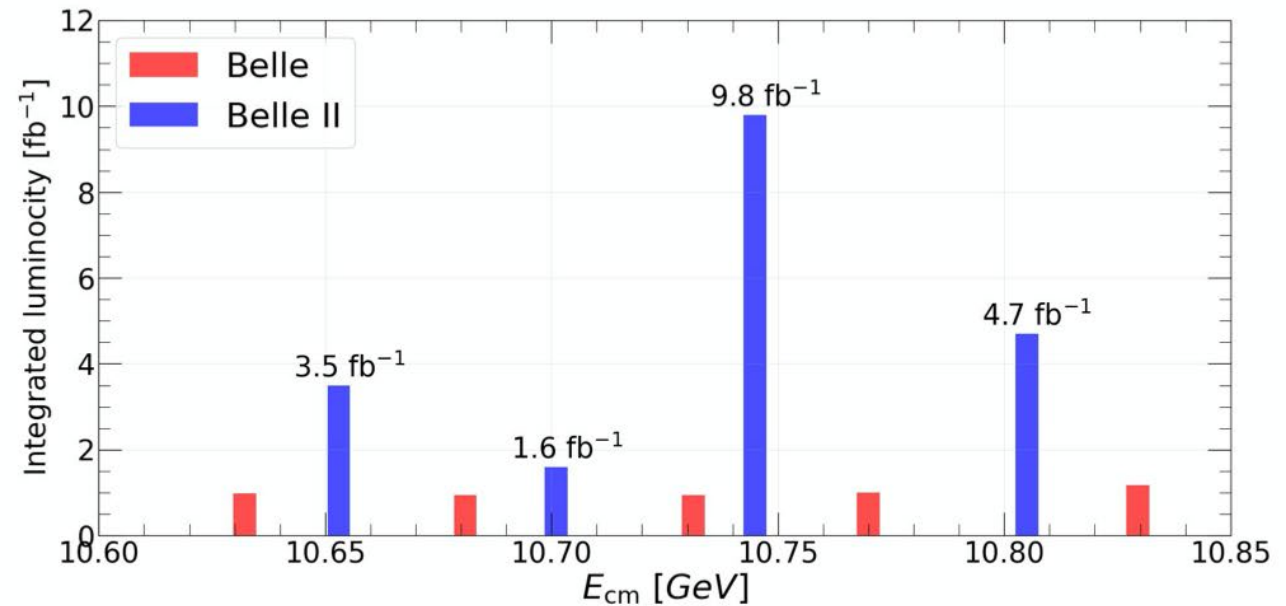
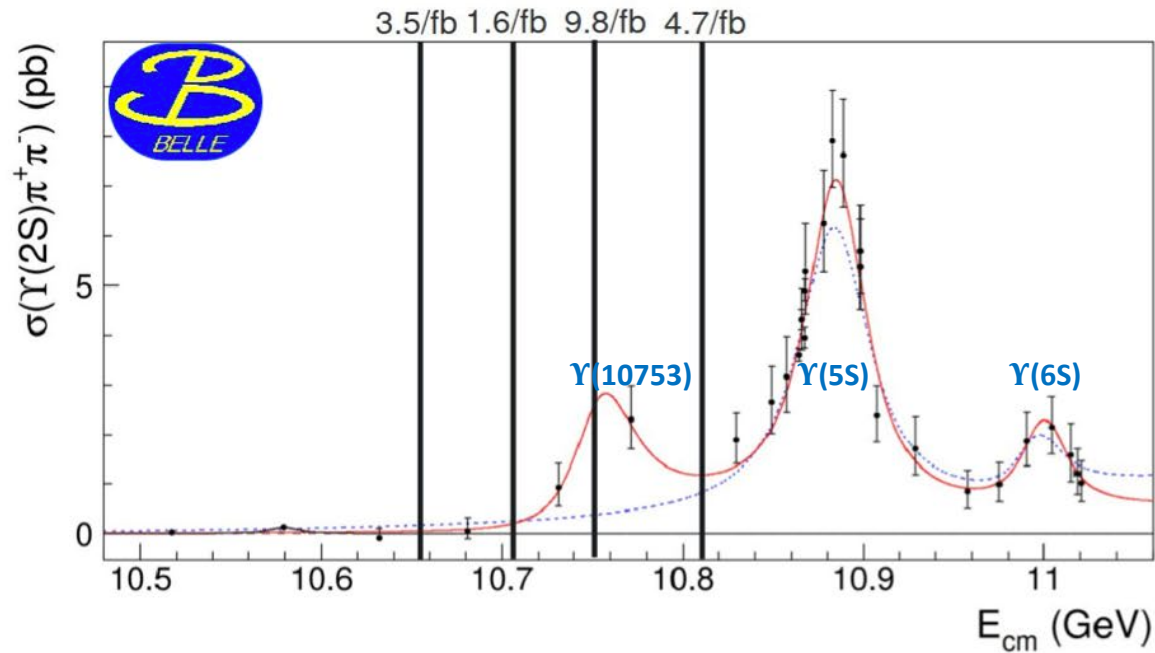
Belle II at SuperKEKB has TINY beamspot



# $\Upsilon(10753)$

Wide resonance between the  $\Upsilon(4S)$  and  $\Upsilon(5S)$  discovered by Belle (R. Mizuk et al, JHEP, 10, 220 (2019))

Found in  $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(nS)$  ( $n=1,2,3$ ). What is it? Bottomonium, hybrid, tetraquark, mixing of conventional states, etc.



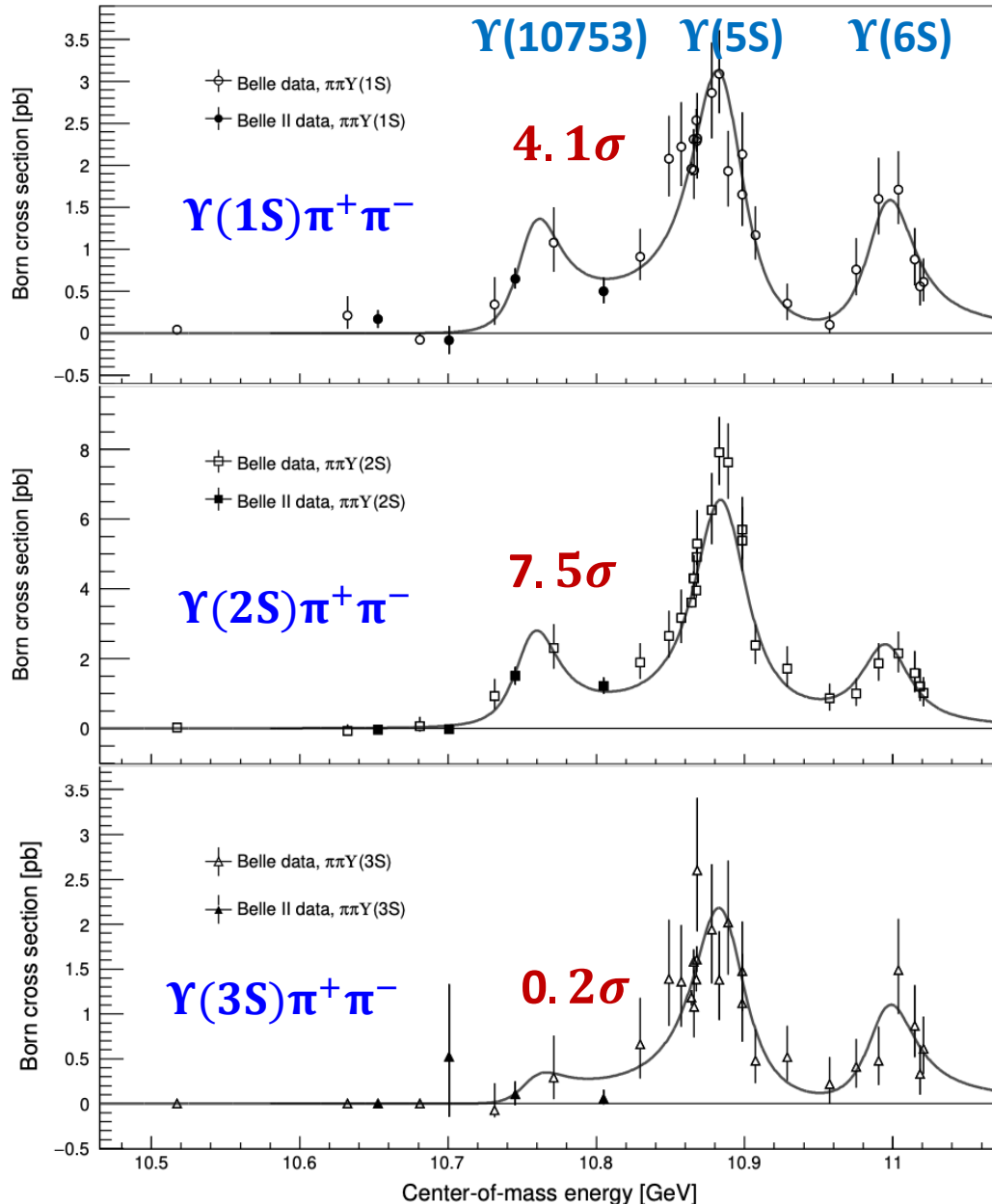
In November 2021, Belle II collected 19  $\text{fb}^{-1}$  of unique data at energies above the  $\Upsilon(4S)$ : four energy scan points around 10.75 GeV in this region

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

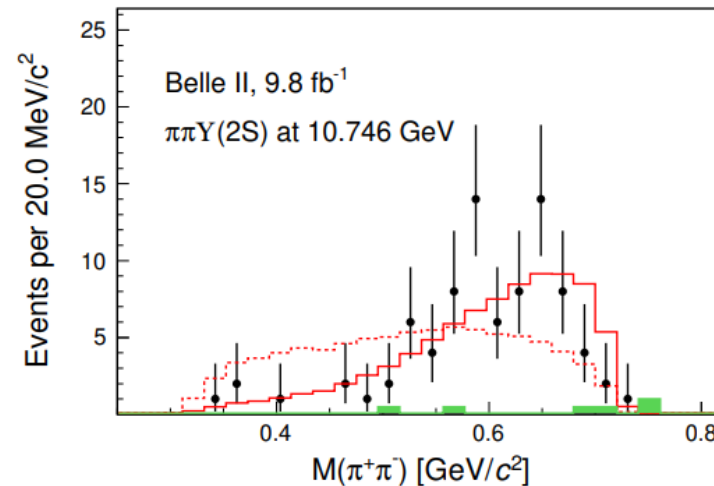
# Updated measurement of $\Upsilon(10753) \rightarrow \pi^+ \pi^- \Upsilon(nS)$ at Belle II



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  $\square$  invariant mass is **not** phase-space. This agrees with the  $\Upsilon(2S)$  decays themselves

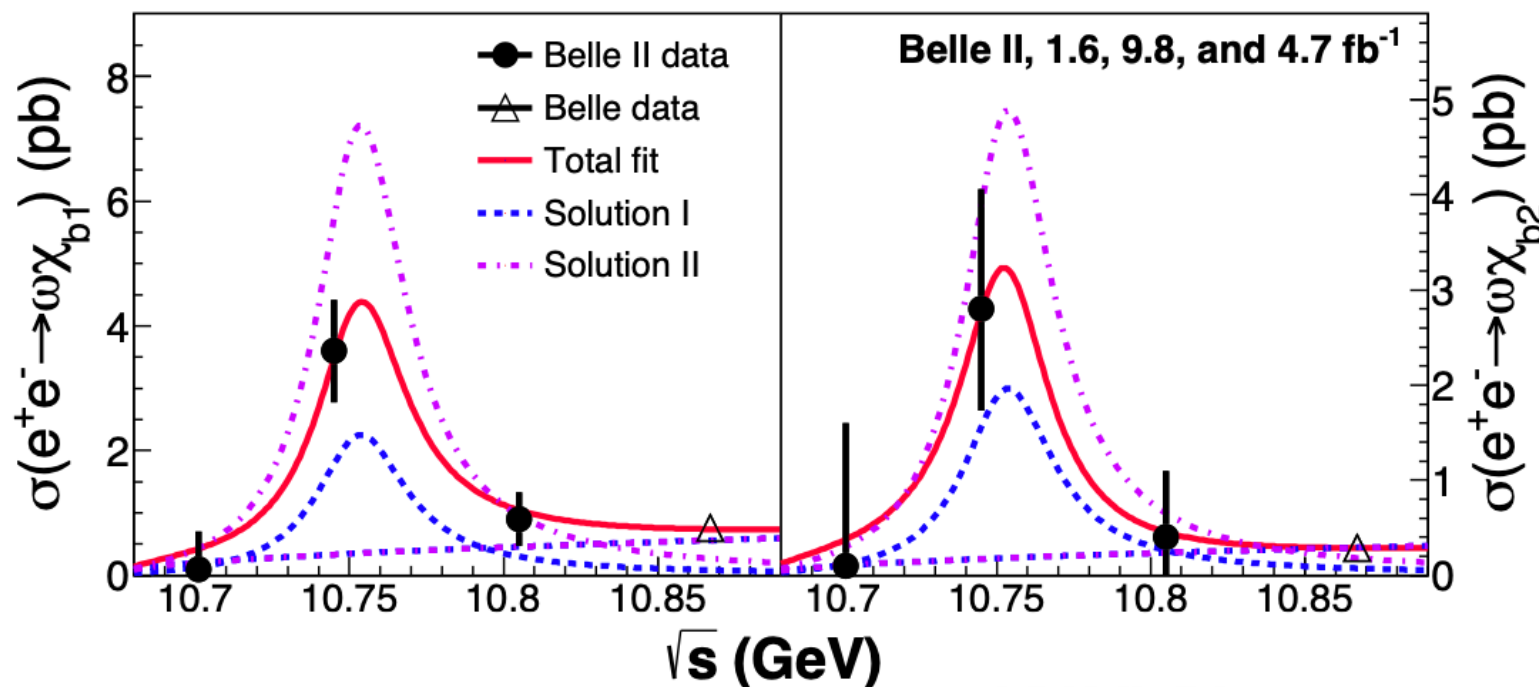
[JHEP 07, 116 (2024)]

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

[PRL 130, 091902 (2023)]

$\omega\chi_{b1}$

$\omega\chi_{b2}$



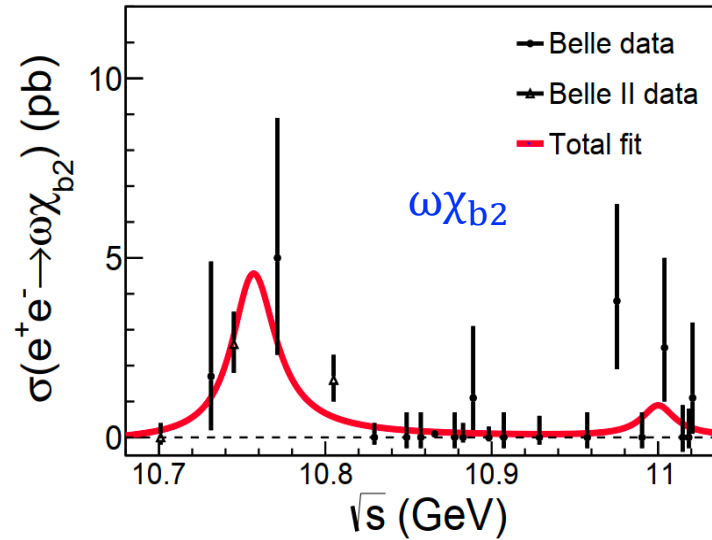
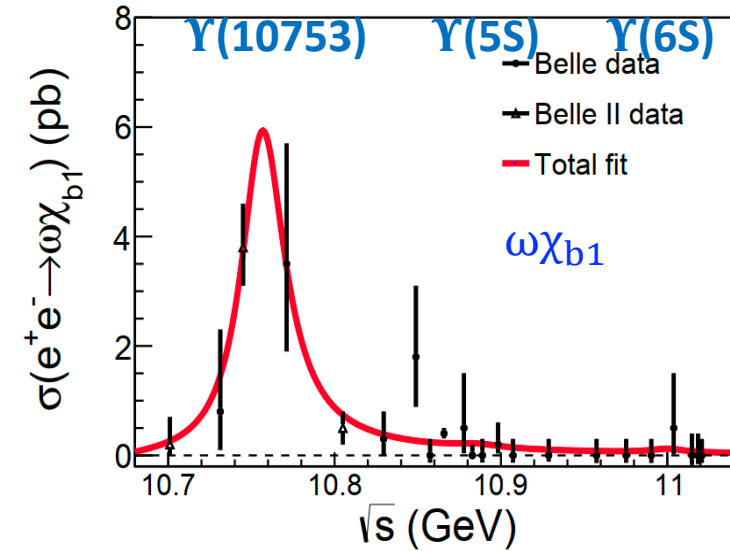
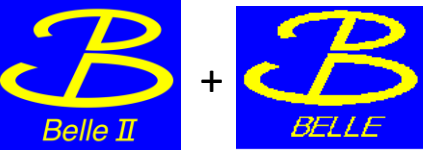
$$\frac{\sigma(\Upsilon(10753) \rightarrow \omega\chi_{b1})}{\sigma(\Upsilon(10753) \rightarrow \omega\chi_{b2})} = 1.3 \pm 0.6$$

Prediction for pure D-wave state: 15  
Prediction for 4S-3D mixed state: 0.2

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

indicate different internal structure

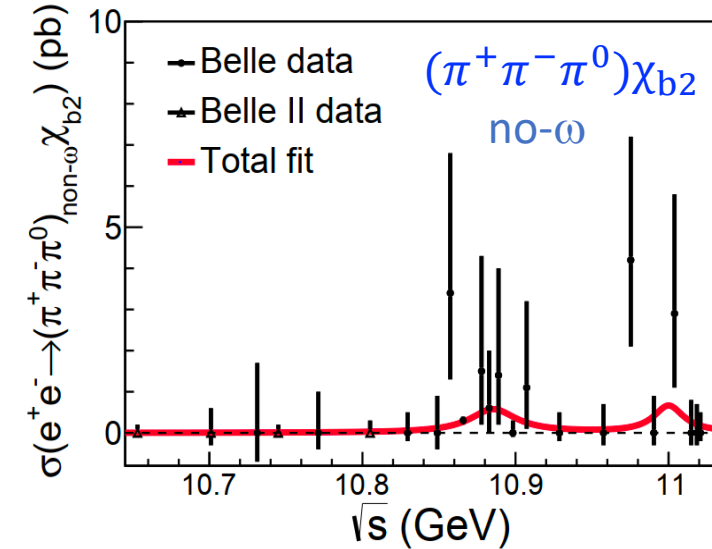
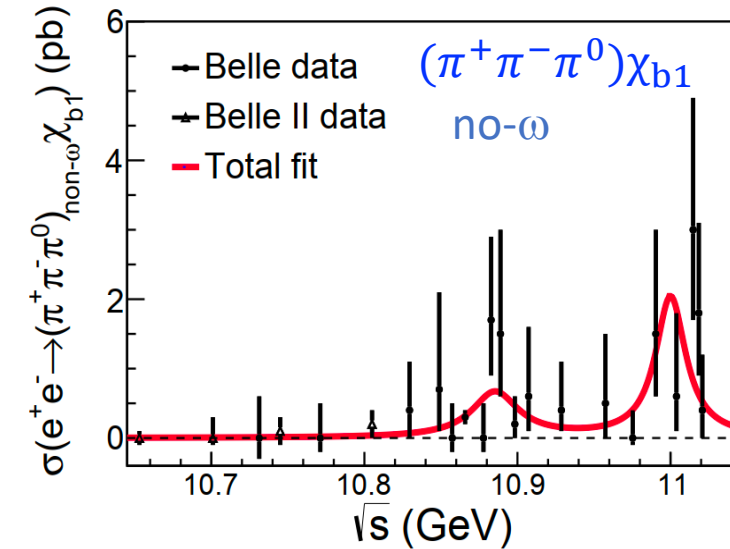
# Extended (preliminary) analysis of $\sigma(e^+e^- \rightarrow \omega\chi_{bJ}(1P))$ and also $\sigma(e^+e^- \rightarrow (\pi^+\pi^-\pi^0)_{\text{non-}\omega}\chi_{bJ}(1P))$



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

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

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



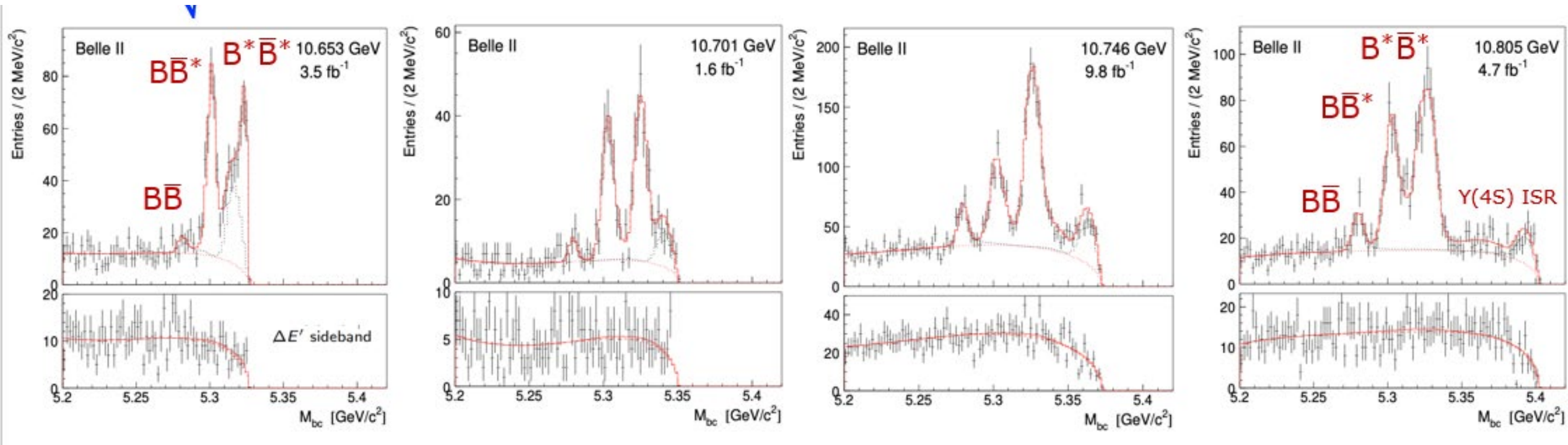
(It is possible that this observation is explained by the fact that  $(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\chi_{bJ}$  is a consequence of the cascade decay of  $Y(10860, 11020) \rightarrow Z_b\pi \rightarrow \chi_{bJ}\rho\pi$ )

Belle II Preliminary

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



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

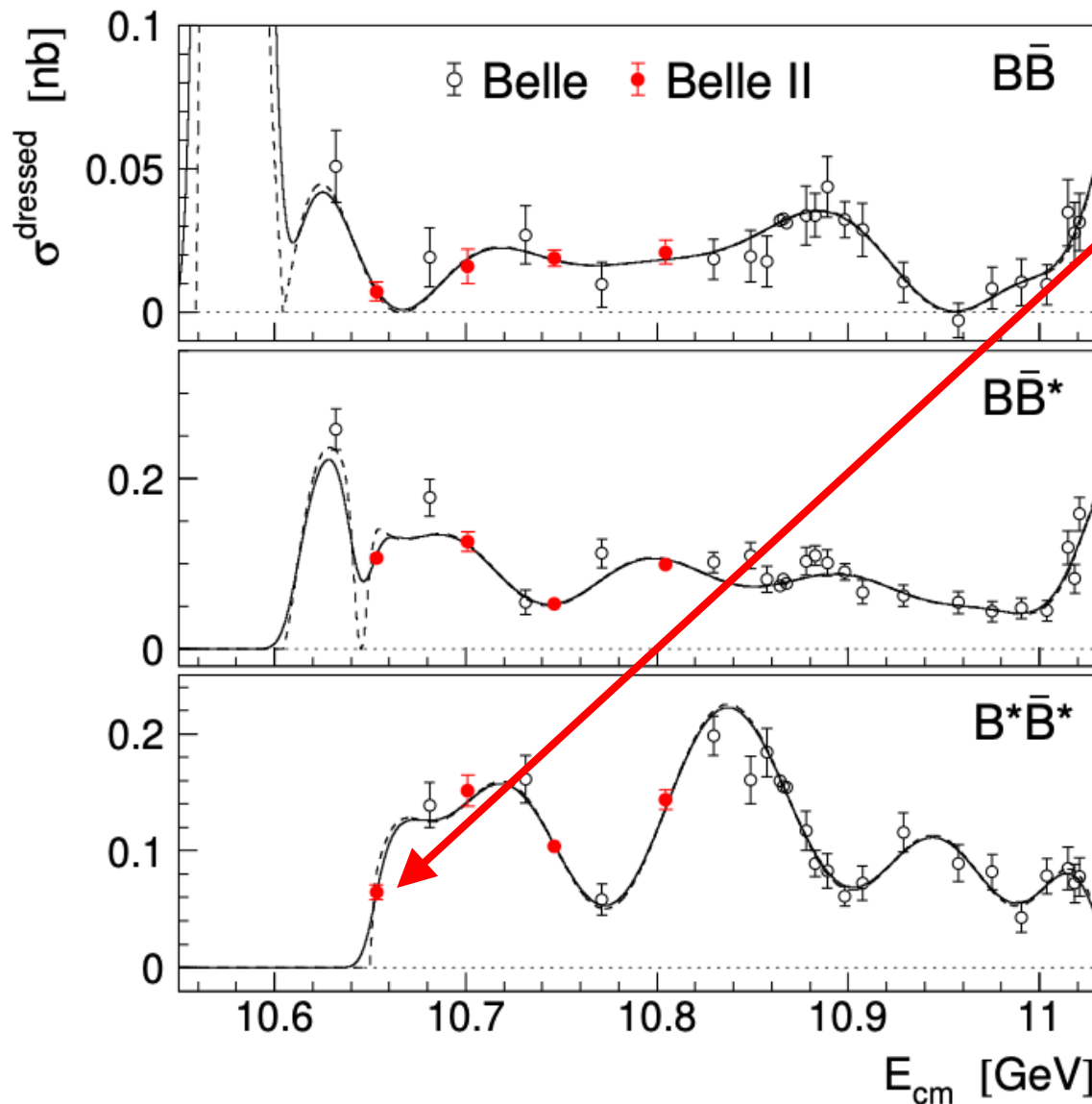


$e^+e^- \rightarrow B\bar{B}, B\bar{B}^*$  and  $B^*\bar{B}^*$  signals at  $\sqrt{s} \sim 10.75 \text{ GeV}$  can be clearly observed

Contribution of  $Y(4S) \rightarrow B\bar{B}$  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  $5.8 \text{ fb}^{-1}$  at the  $\Upsilon(1S)$   
 $24.5 \text{ fb}^{-1}$  at the  $\Upsilon(2S)$   
 $2.9 \text{ fb}^{-1}$  at the  $\Upsilon(3S)$

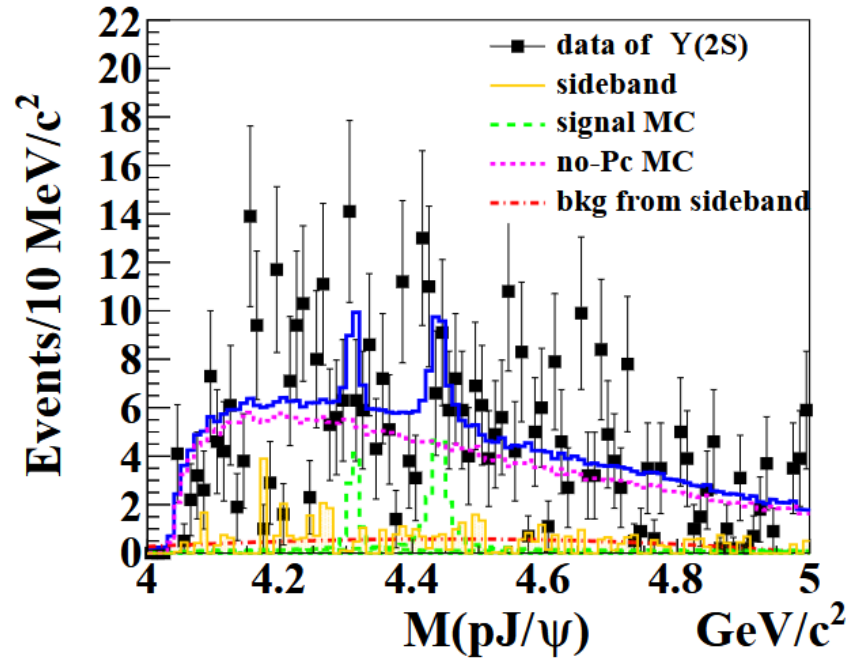
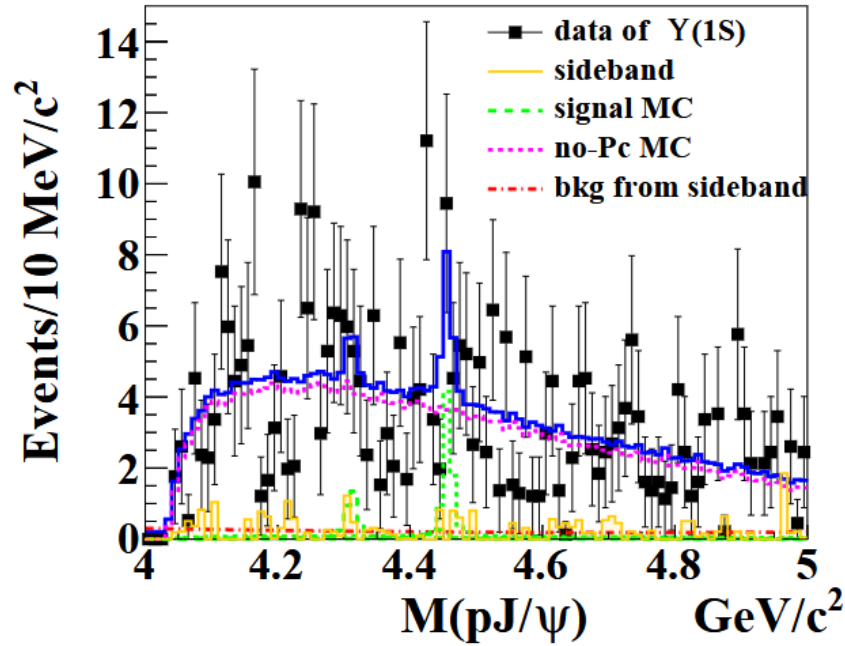
Because of the high cross-sections, this is around  $3 \times 10^8$  events

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

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

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

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



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

$$\mathcal{B}(\Upsilon(1S) \rightarrow pJ/\psi + X) = (4.27 \pm 0.16 \pm 0.20) \times 10^{-5}$$

$$\mathcal{B}(\Upsilon(2S) \rightarrow pJ/\psi + X) = (3.59 \pm 0.14 \pm 0.16) \times 10^{-5}$$

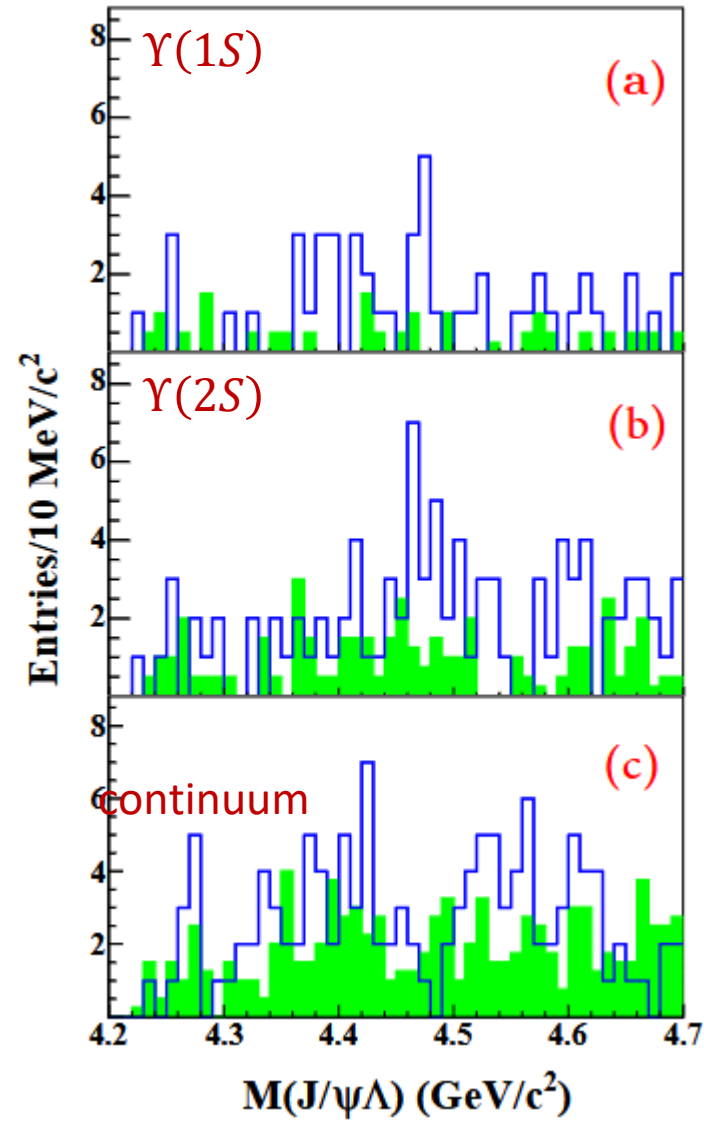
$$\sigma(pJ/\psi + X) = (57.5 \pm 2.1 \pm 2.5) \text{ fb at } 10.52 \text{ GeV}$$

X. Dong et al, arXiv:2403.04340

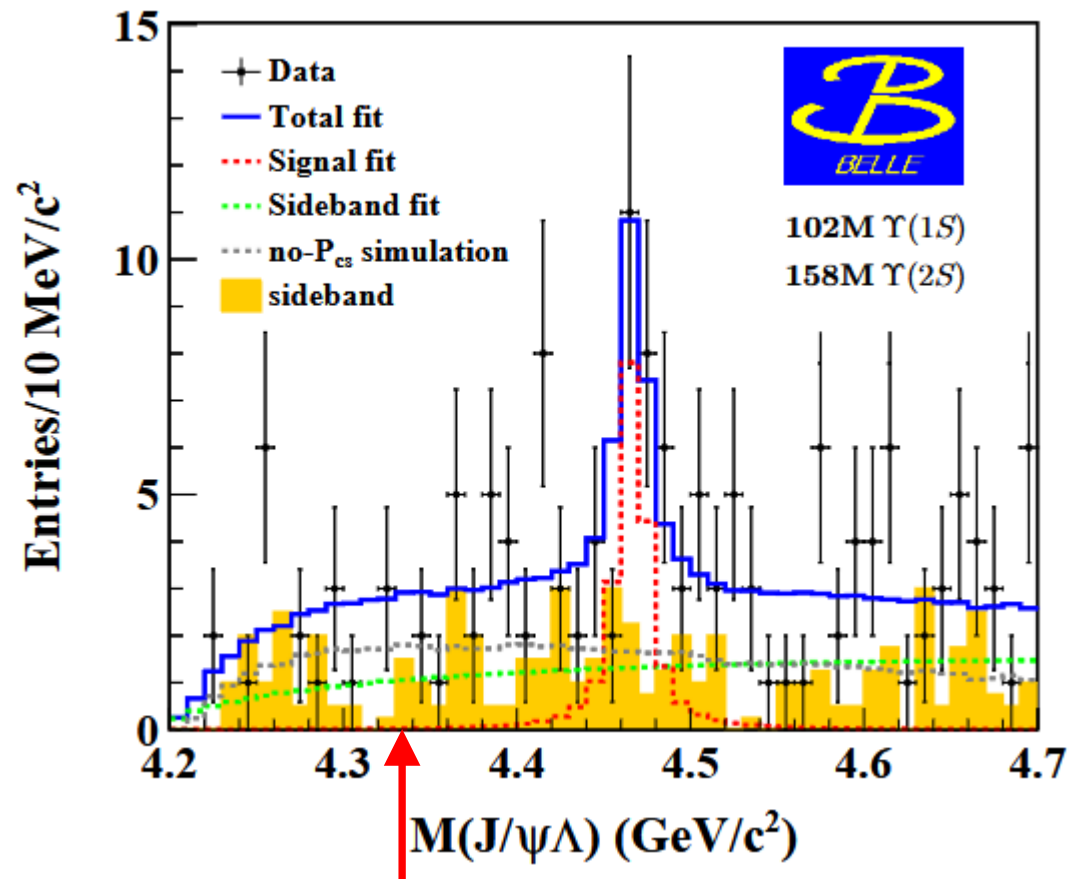
$$\begin{aligned} \mathcal{B}[\Upsilon(1S) \rightarrow P_c(4312)^+ + \text{anything}] \cdot \mathcal{B}[P_c(4312)^+ \rightarrow pJ/\psi] &< 3.9 \times 10^{-6}, \\ \mathcal{B}[\Upsilon(1S) \rightarrow P_c(4440)^+ + \text{anything}] \cdot \mathcal{B}[P_c(4440)^+ \rightarrow pJ/\psi] &< 6.2 \times 10^{-6},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

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

PRELIMINARY



Green – sidebands      Blue - signal



No sign of the 4338

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

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

Assuming it to be the same particle, the significance is  $3.3 \sigma$

Assuming it is NOT the same particle, Belle finds  $3.8 \sigma$

$$M = 4471.7 \pm 4.8 \pm 0.6 \text{ MeV}/c^2$$

$$\Gamma = 21.9 \pm 13.1 \pm 2.7 \text{ MeV}$$

*note that LHCb found*

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

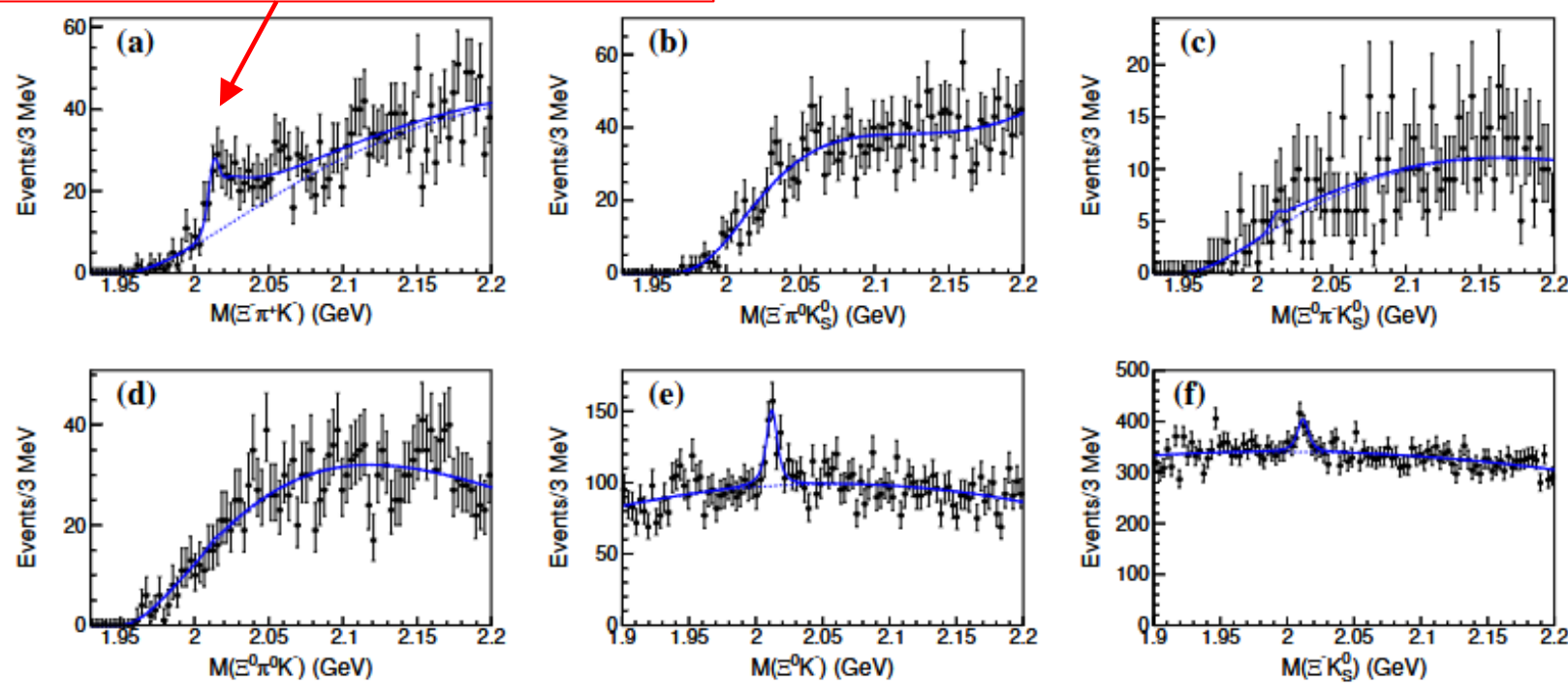
$$\Gamma = 17.3 \pm 6.5^{+8.0}_{-4.7} \text{ MeV}$$

# $\Omega(2012)$ Studies in Narrow Resonance Data



$\Omega(2012)$  discovered by BELLE, J. Yelton et al, PRL 121, 5, 052003 (2018) in two-body ( $\Xi K$ ) decays.  
Confirmed by BES III (low statistics) and ALICE ( $15\sigma$ )

Big 3-body signal of  $267 \pm 60$  events



Search in 3 body decays  
 $\Omega(2012) \rightarrow \Xi \pi K$  where the  $\Xi \pi$  resonates through  $\Xi^*(1530)$ .  
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 ( $5.2\sigma$ )

Ratio of branching fractions (3 body:2 body) =  $0.99 \pm 0.26 \pm 0.06$

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

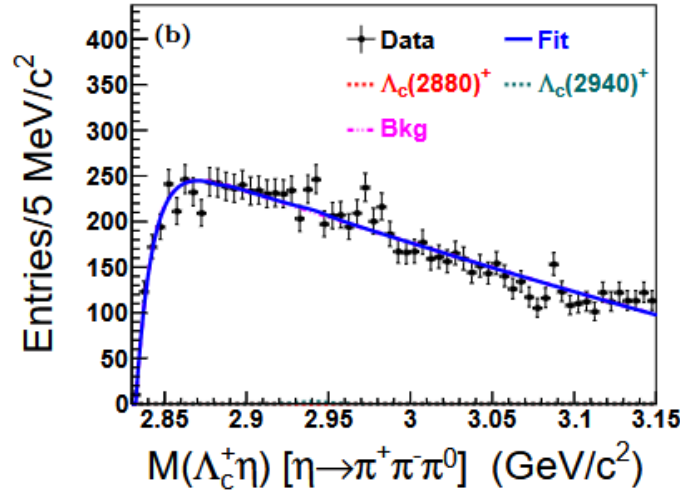
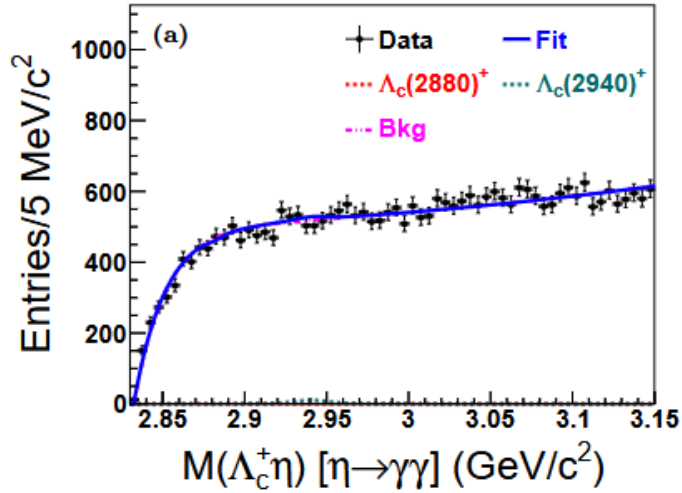
n.b. coupling ratio very poorly measured, because the phase-space comparison of 3-body to 2-body decays so poorly constrained.

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

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

# 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  $\Lambda$  hyperons which decay to  $\Lambda \eta$ , why not in the charmed sector also?

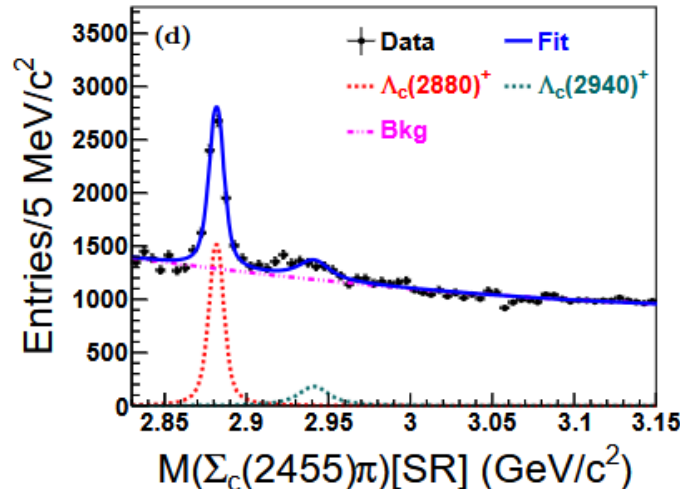
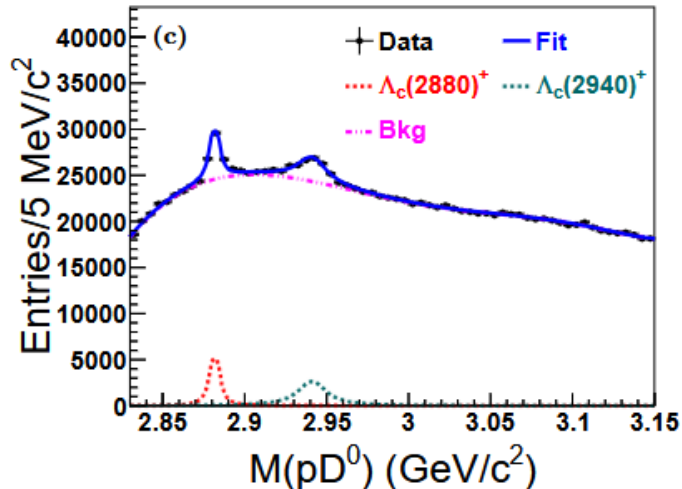


No excess found in  $\Lambda_c \eta$  at either of the known particles or any new ones.

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

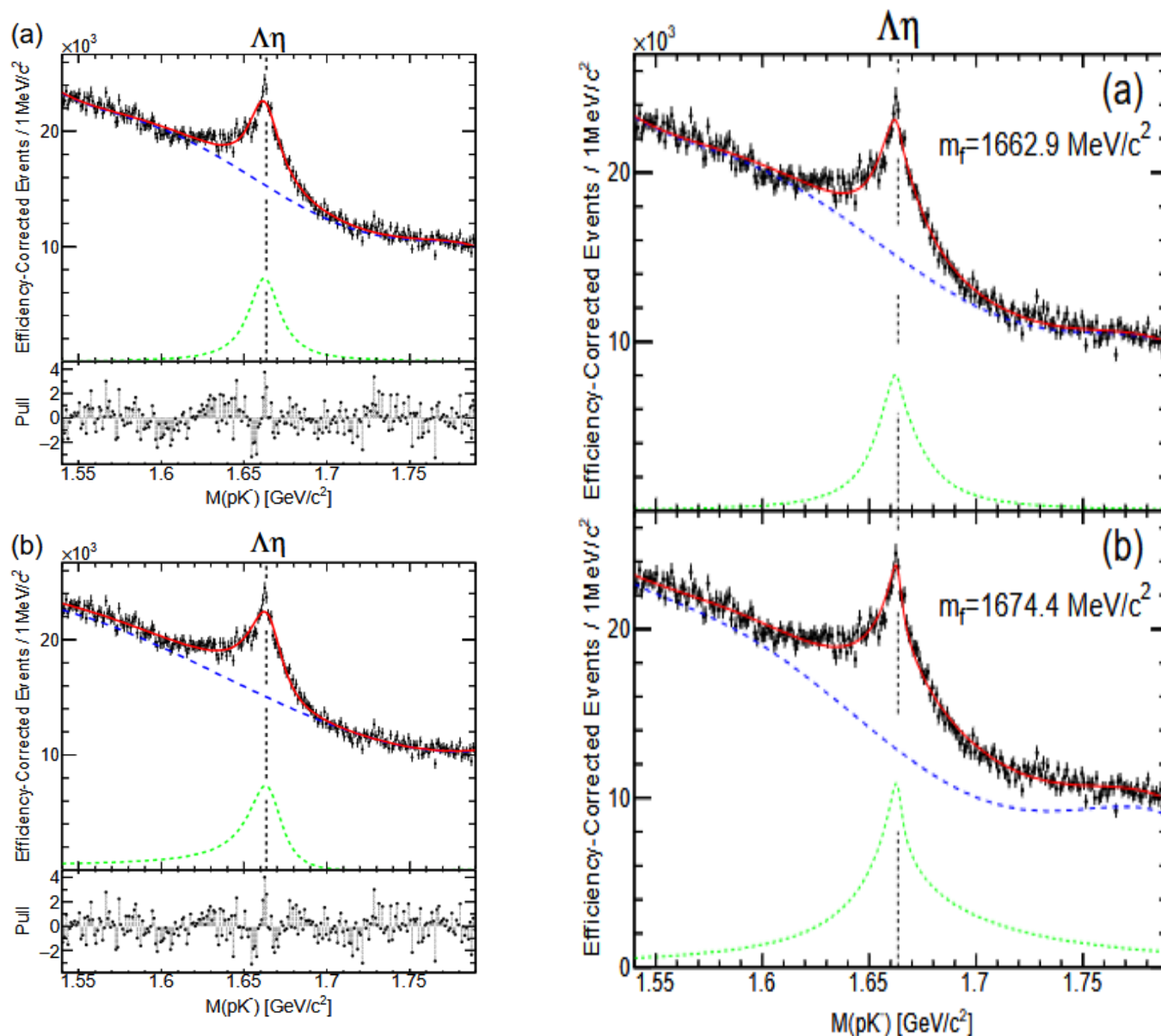
$$R_{pD^0}(2880) = 0.75 \pm 0.03 \pm 0.07,$$

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



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

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

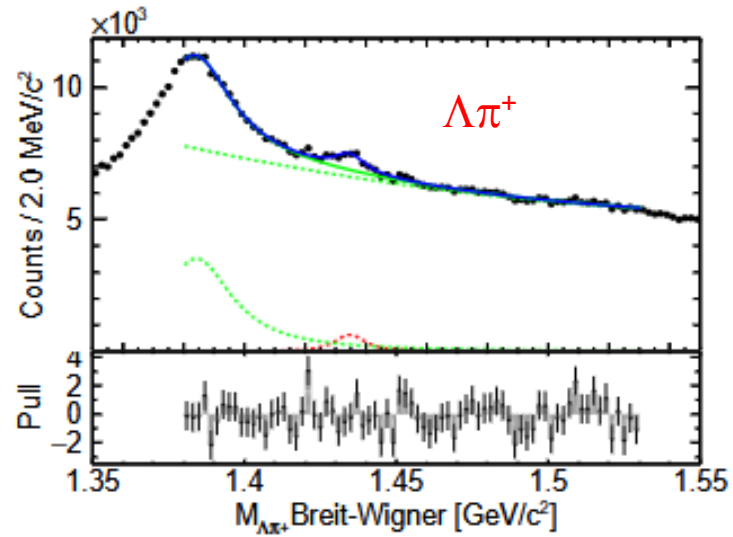


The left plots are fits to a Breit-Wigner. This is clearly unsatisfactory! The right plots show a fit to a Flatté distribution –much better – note the  $\Lambda\eta$  threshold.

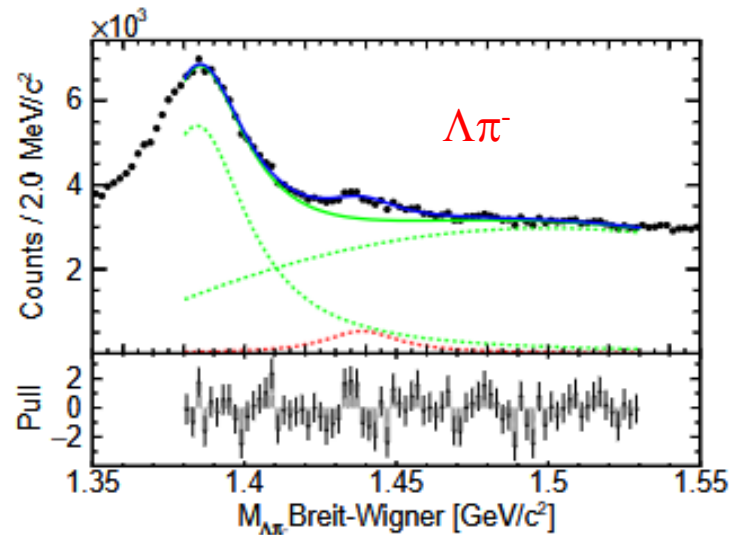
Clearly, this “resonance” is not a simple resonance at all and should not be treated as such.

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

# Investigation of the $\Lambda_c^+$ and $\Lambda_c^-$ substructure of $\Lambda_c^+ \rightarrow \Lambda^+ \pi^- \pi^+$



(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 <sup>2</sup> ) | 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  $\Upsilon(4S)$  mass) running of Belle and Belle II has shown very interesting results, particularly concerning the nature of the  $\Upsilon(10753)$ . Its decay via  $\omega$  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  $\Upsilon(4S)$  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!**

For more discussion and more analysis of Belle (II) analyses, see

**Murad Yasaveev** (today 4.45 p.m. in Meson Spectroscopy) for more results from the high-energy running

**Jing Yuan** (tomorrow 6.05 p.m. in Decays of Hadrons) for more on charmed baryons and their decays.