

French Ukrainian Workshop 2025, 10–12 June 2025, Orsay

Bottomonium studies at Belle and Belle II

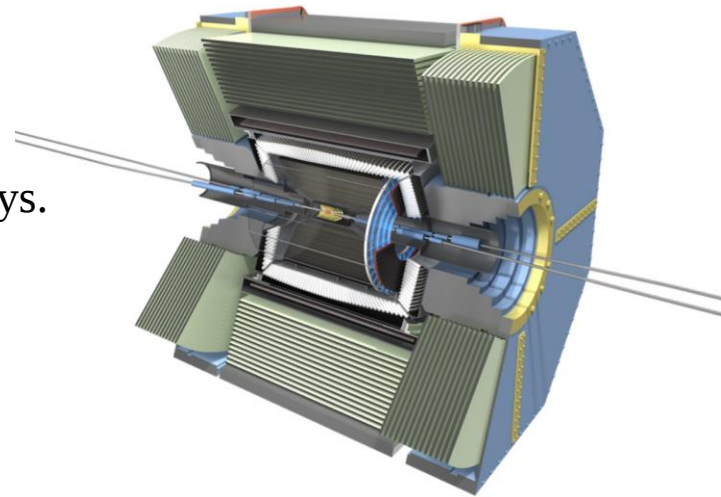
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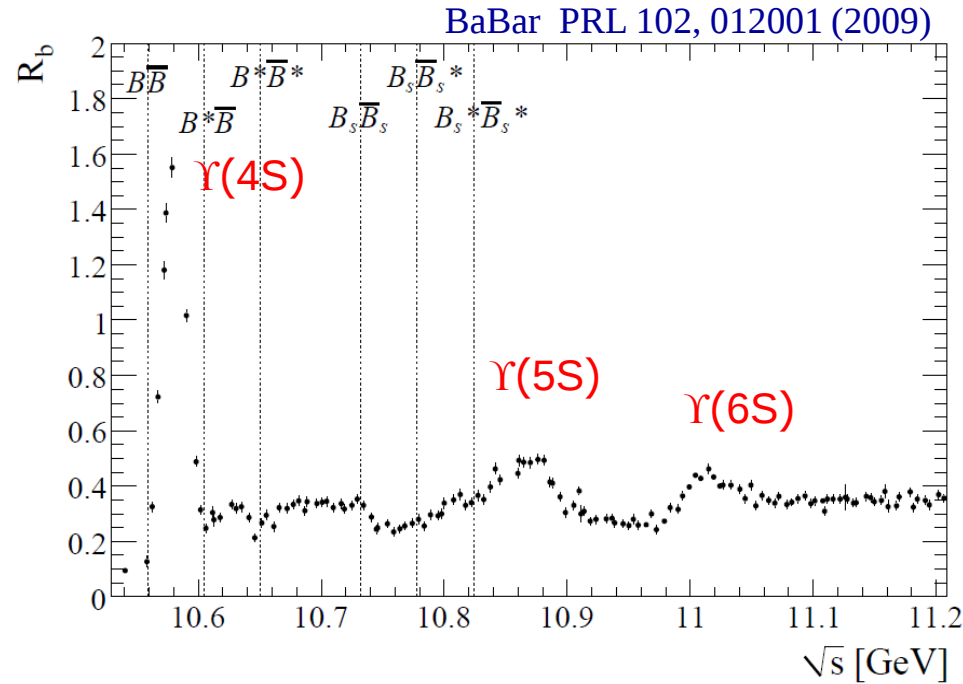
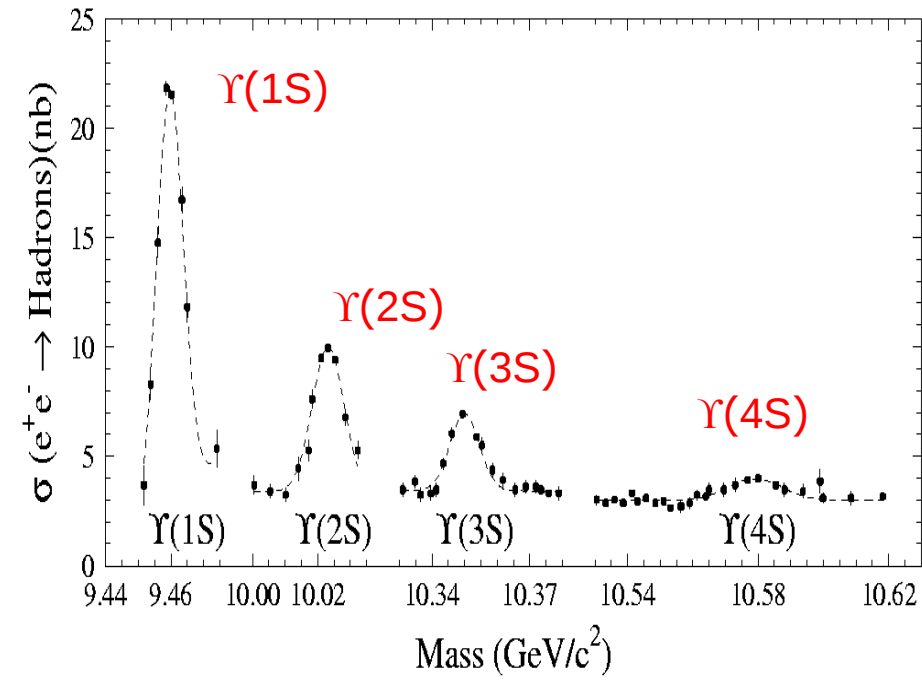
Belle II

e^+e^- collisions at $\sqrt{s} \sim 10 \text{ GeV}$, B-factory.

- BaBar 1999 – 2008, Belle 1999 – 2010:
CP violation in B mesons
[2008 Nobel Prize to Kobayashi and Maskawa].
- Belle II 2019 – :
 - Precision tests of Standard Model using B, D, τ decays.
 - Searches for New Physics.
- Complementary to LHC (indirect; neutrals).
- Belle : $1ab^{-1}$
 - $\Upsilon(4S)$: $711fb^{-1}$, $\Upsilon(5S)$: $121fb^{-1}$, continuum : $80fb^{-1}$,
 $\Upsilon(1S,2S,3S)$: $33fb^{-1}$, energy scan : $22fb^{-1}$.
- Belle II @ SuperKEKB
 - Target: instant. luminosity $\times 20$; $L = 50ab^{-1}$.
 - Achieved: instant. luminosity $\times 2.5$; $L = 575fb^{-1}$.
 $\Upsilon(4S)$: $500fb^{-1}$, continuum : $55fb^{-1}$, energy scan : $19fb^{-1}$.
- Analyses can use Belle + Belle II data samples.



Bottomonium: ($b\bar{b}$) bound states



$\Upsilon(nS)$ ($n = 1, 5$) $J^{PC} = 1^{--}$ 3S_1 : $S = 1, L = 0$ – radial excitations

Belle: observation of $\Upsilon(10753)$

JHEP 10, 220 (2019)

$e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-$ cross sections

Scan data: 22 points, $1fb^{-1}$ per point.

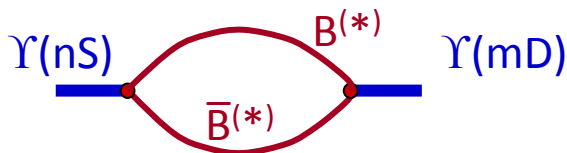
Extra state near 10.75 GeV
???

$J^{PC} = 1^{--} \quad {}^3D_1 : S = 1, L = 2$

S-D mixing is suppressed in bottomonium

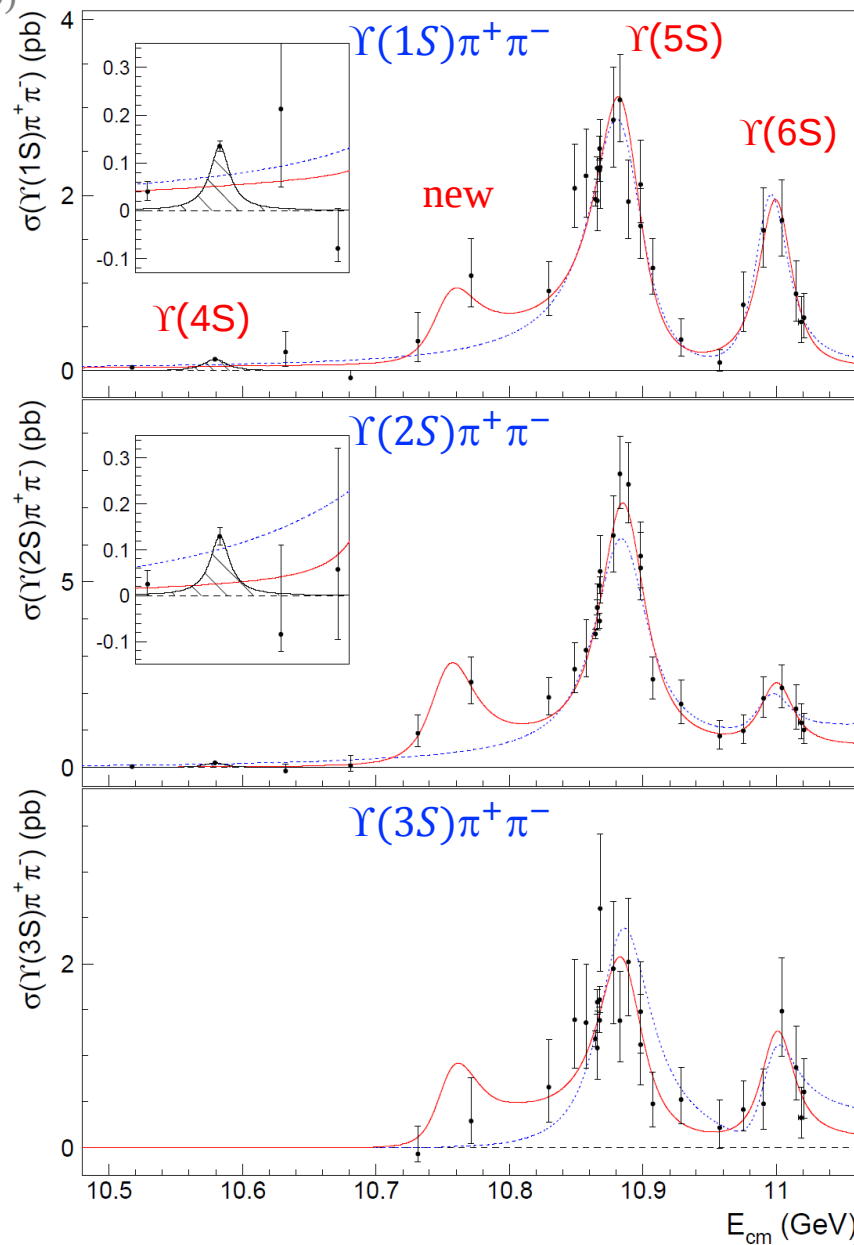
Badalian, Bakker, Danilkin PAN73, 138 (2010)

Above $B\bar{B}$ threshold: new mechanism –
hadron loops:



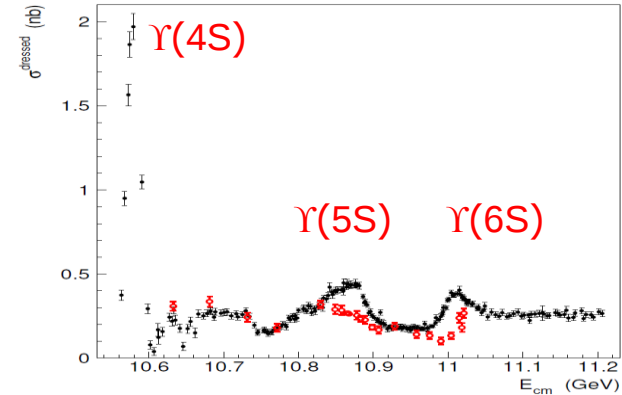
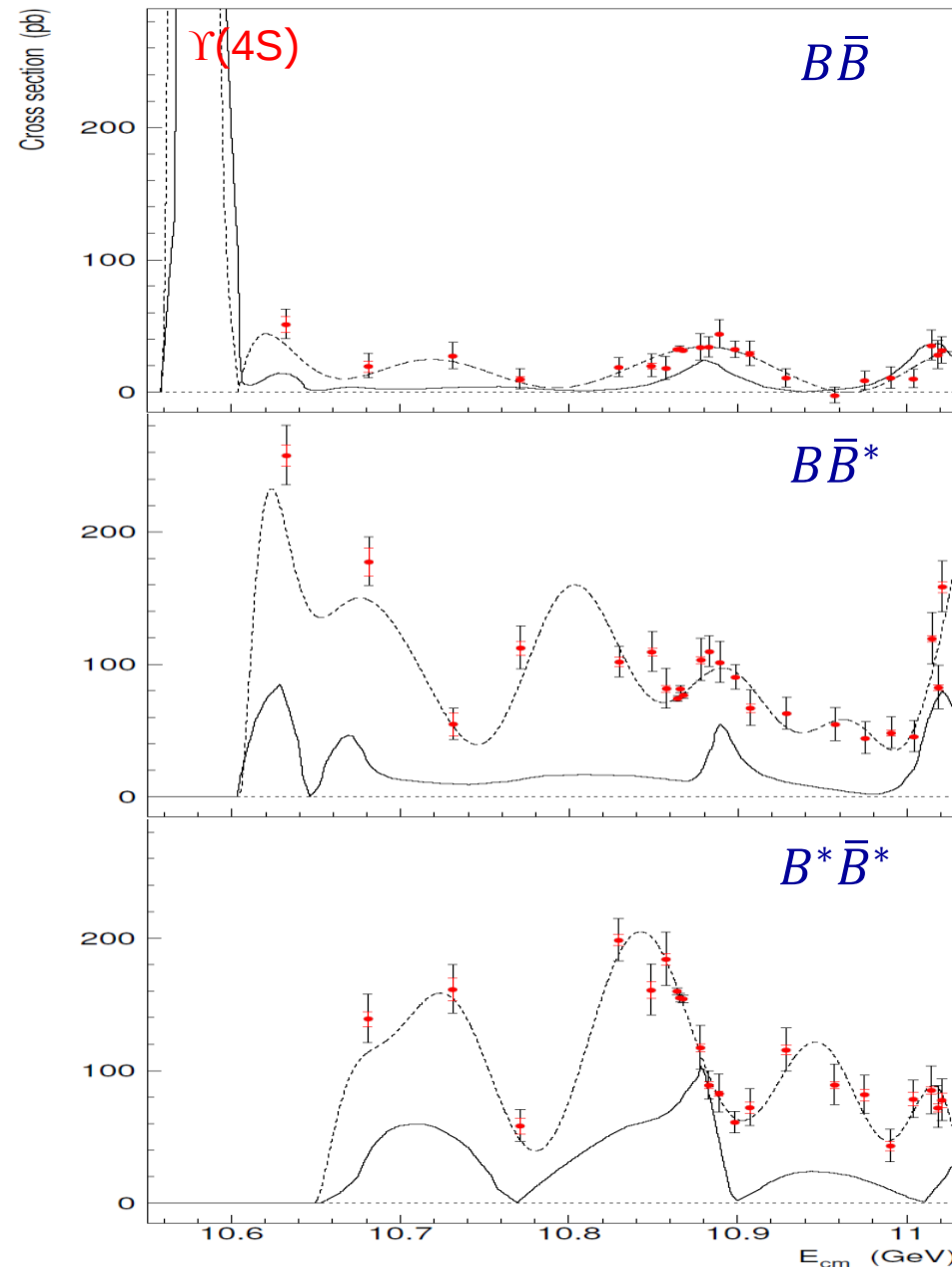
Exotic interpretations: hybrid ($b\bar{b}g$),
compact tetraquark ($b\bar{b}q\bar{q}$).

Global significance 5.2σ



$e^+e^- \rightarrow B\bar{B}, B\bar{B}^*, B^*\bar{B}^*$ cross sections

Belle, JHEP 06, 137 (2021)



“Oscillatory” behavior.
Prediction: minima and maxima
due to zeros in $\Upsilon(nS)$ wave-func.

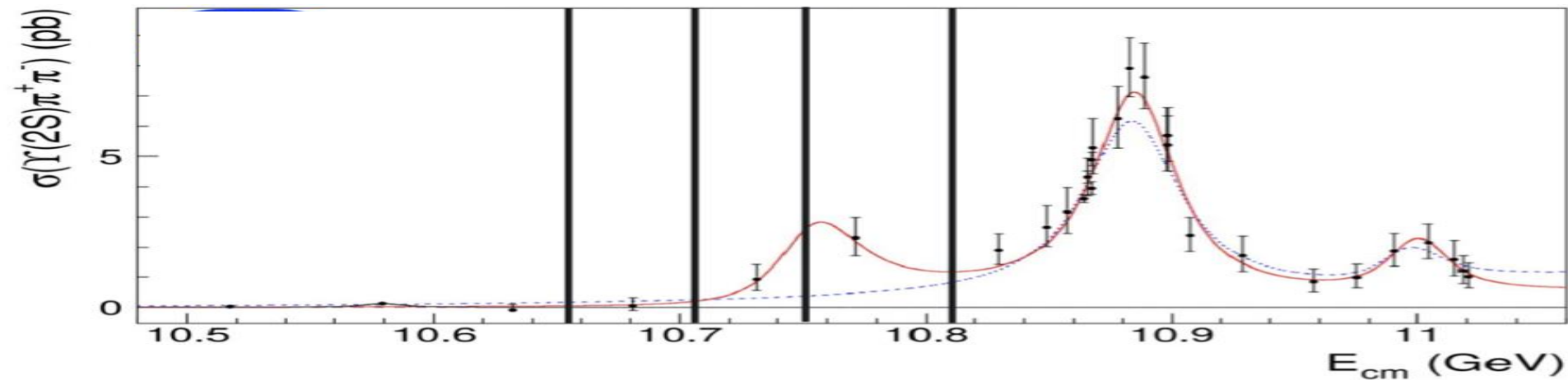
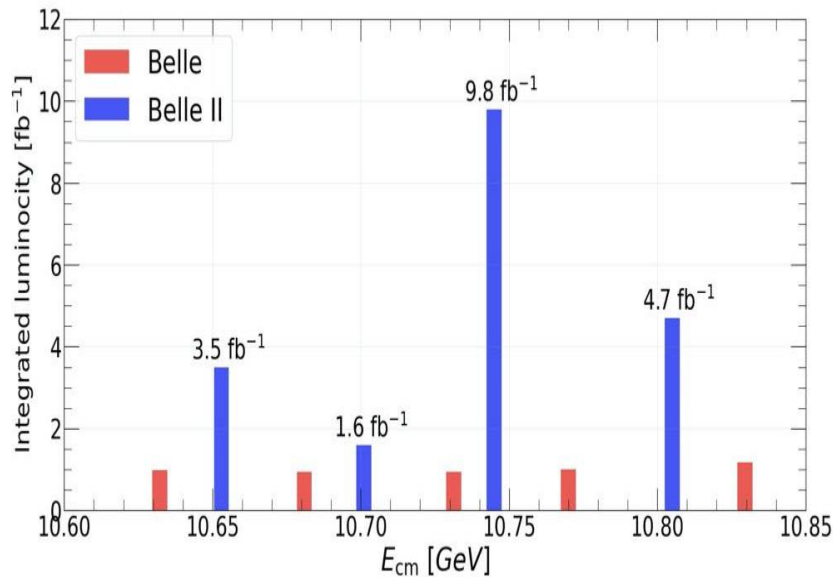
Ono, Sanda, Tornqvist PRD34, 186 (1986)

$\Rightarrow$ Information about w.-f.

Data: too big step, too low stat.

Energy scan at Belle II

In November 2021, $L=19 \text{ fb}^{-1}$ (3% of total sample)



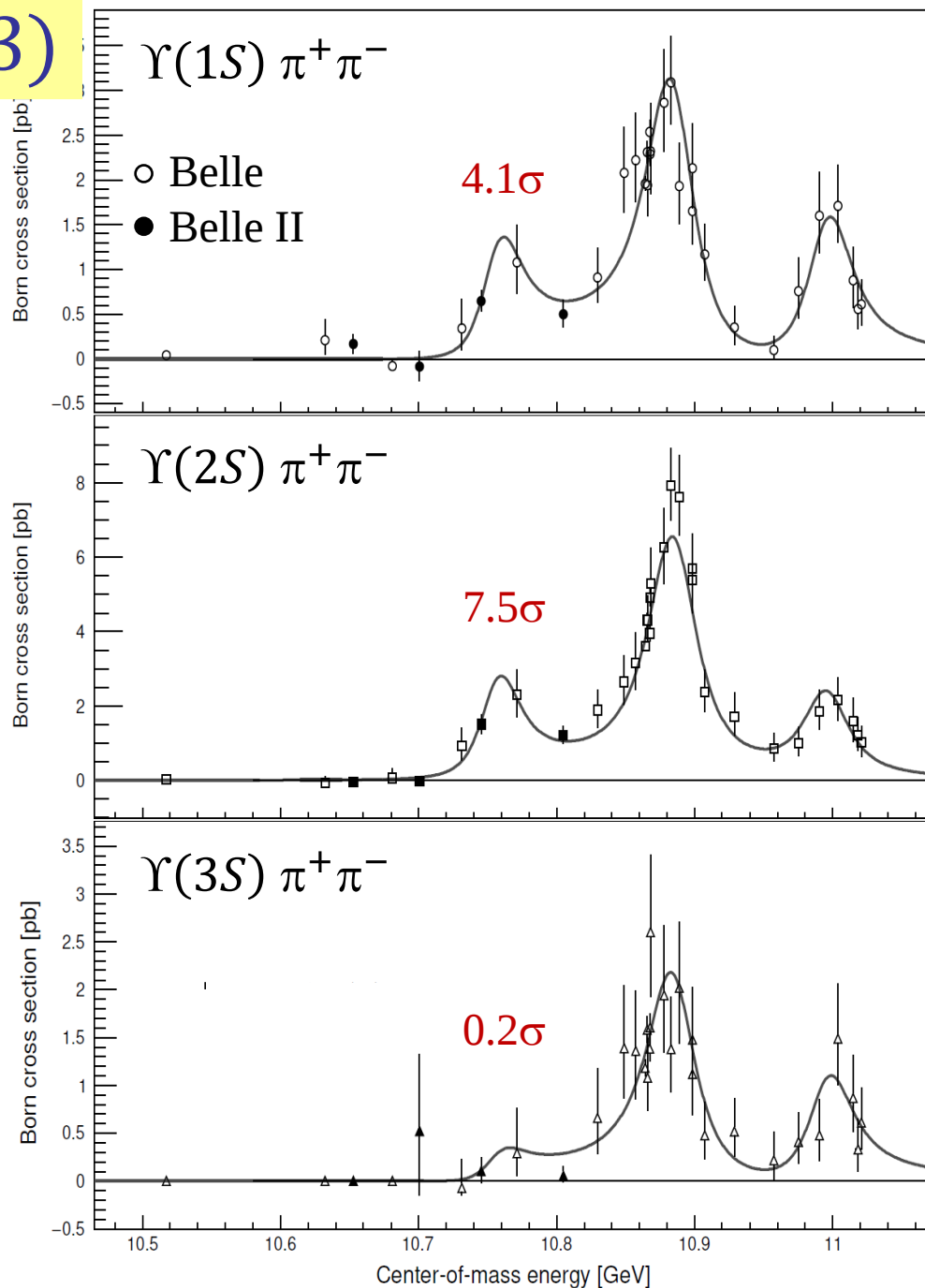
Confirmation of $\Upsilon(10753)$

JHEP 07, 116 (2024)

Combined fit to Belle + Belle II data

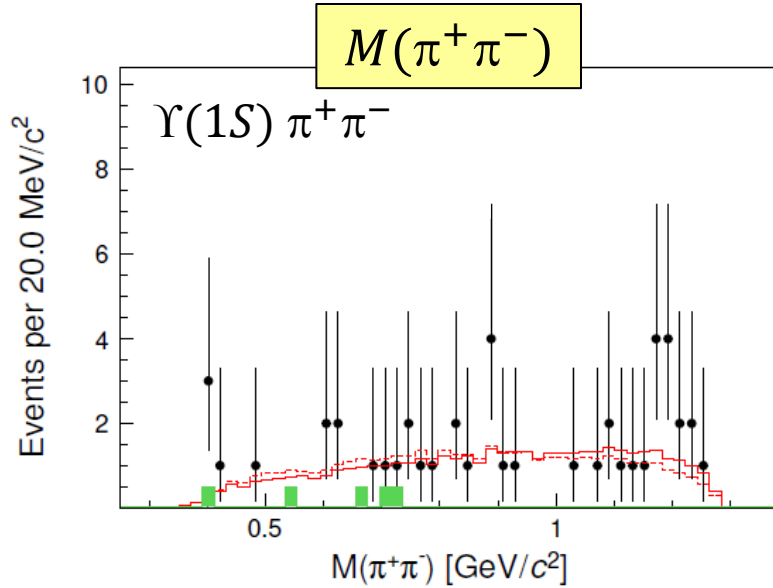
$$M = (10756.6 \pm 2.7 \pm 0.9) \text{ MeV}$$

$$\Gamma = (29.0 \pm 8.8 \pm 1.2) \text{ MeV}$$

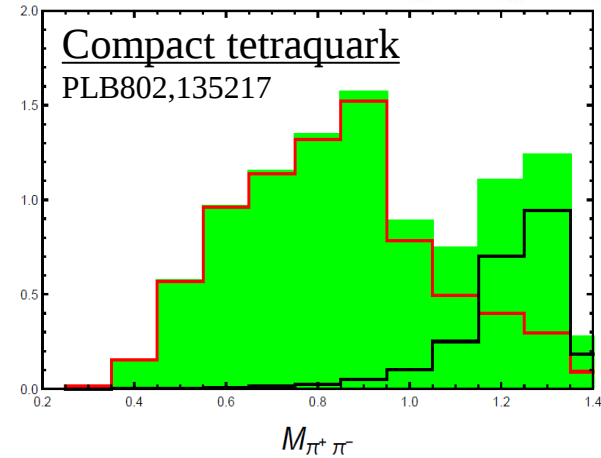
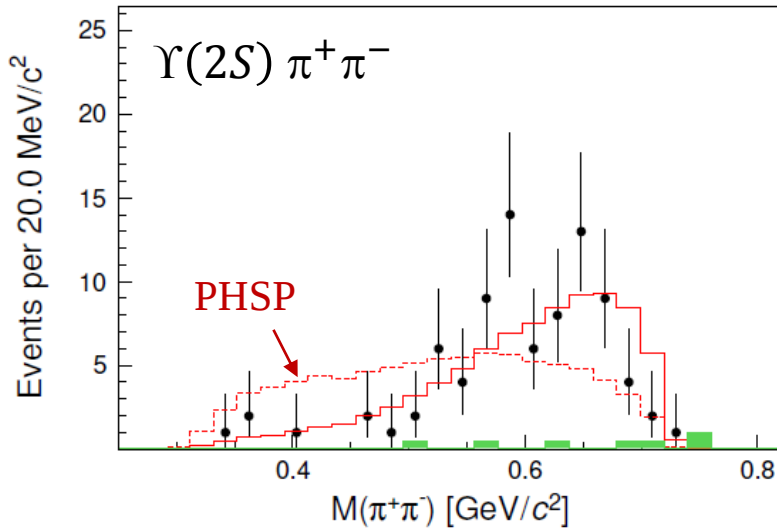
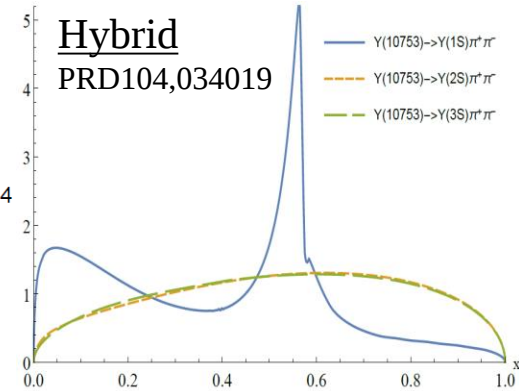
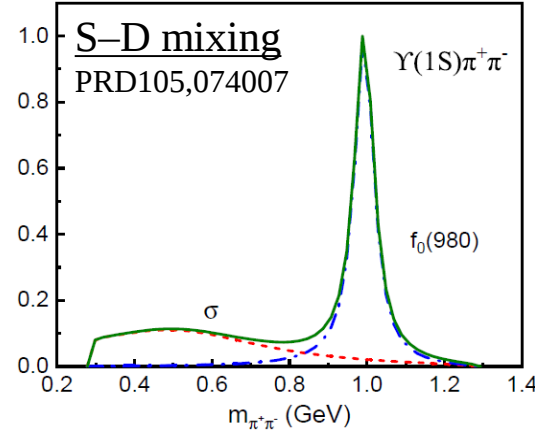


Resonant substructure of $\Upsilon(10753) \rightarrow \Upsilon(nS) \pi^+ \pi^-$

JHEP 07, 116 (2024)

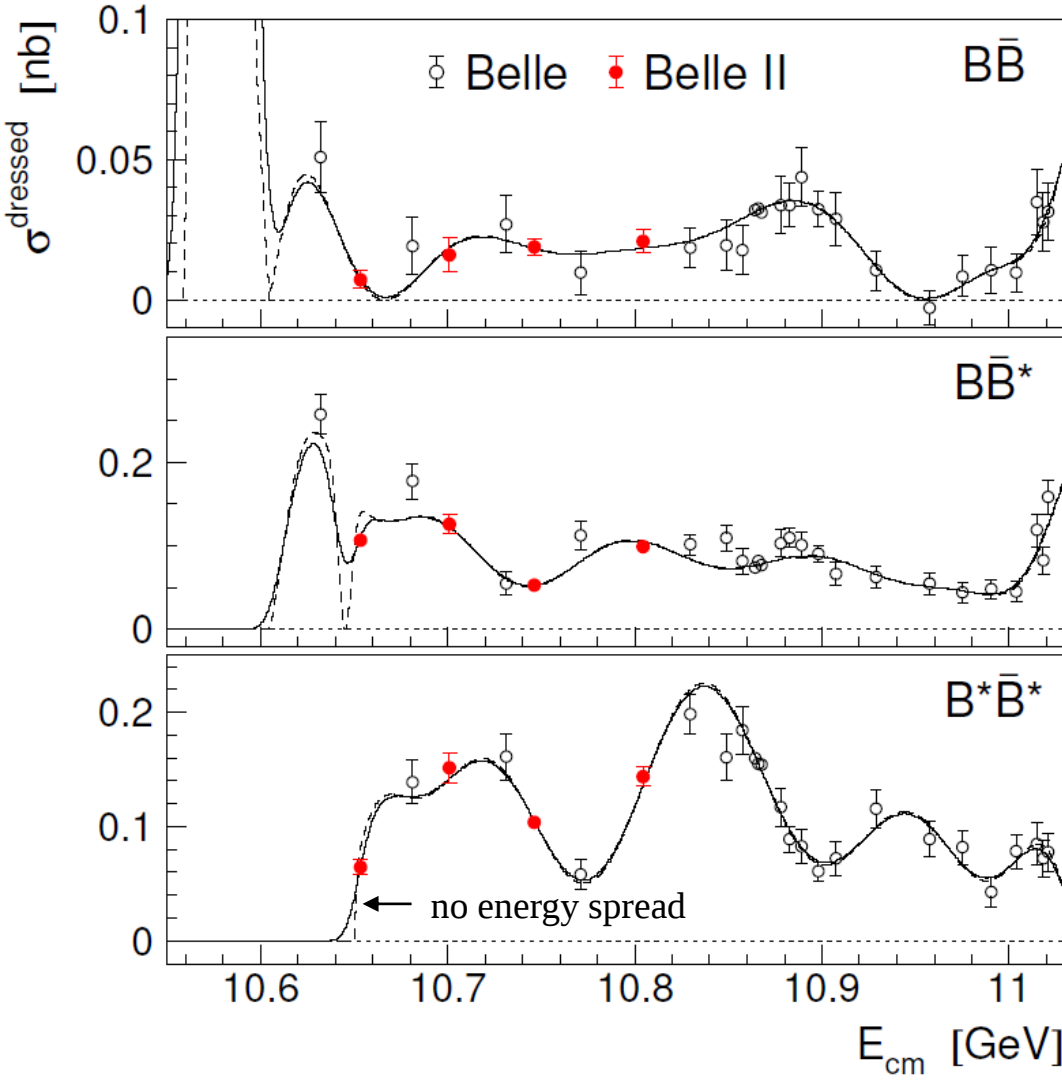


- $M(\pi^+ \pi^-)$ – no significant structures
- Models predict production of $f_0(980)$ – ?



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

JHEP 10, 114 (2024)

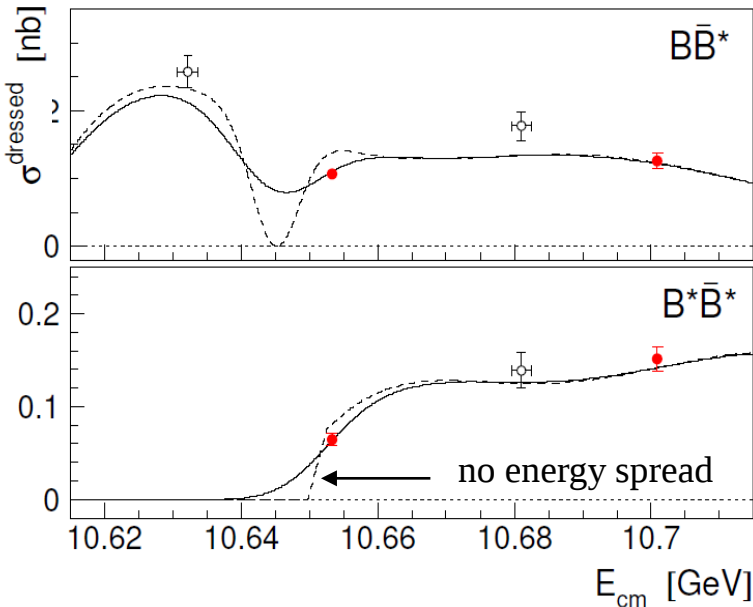


Addition of Belle II points helps to constrain shapes.

New: rapid rise of $B^*\bar{B}^*$ cross section near threshold $\Rightarrow$

Evidence for $B^* \bar{B}^*$ “molecular” state?

JHEP 10, 114 (2024)

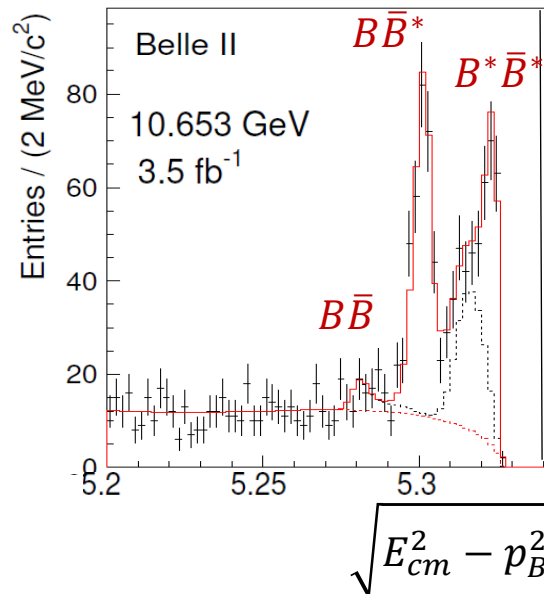


$B^* \bar{B}^*$ are in P-wave $\Rightarrow$ PHSP $\propto p_{B^*}^3$
 rapid rise $\Rightarrow$ very high amplitude near threshold

Similar phenomenon near $D^* \bar{D}^*$ threshold
 $\Leftarrow D^* \bar{D}^*$ molecular state
 Dubynskiy, Voloshin, MPLA 21, 2779 (2006)

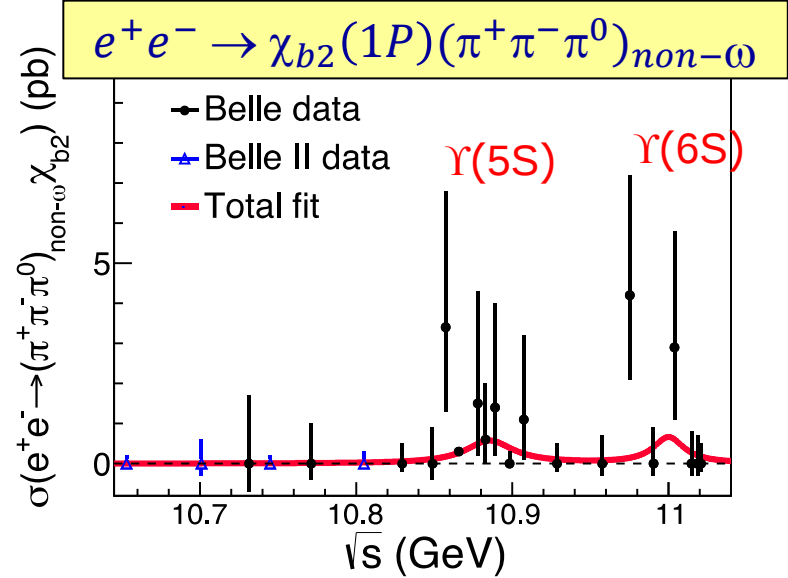
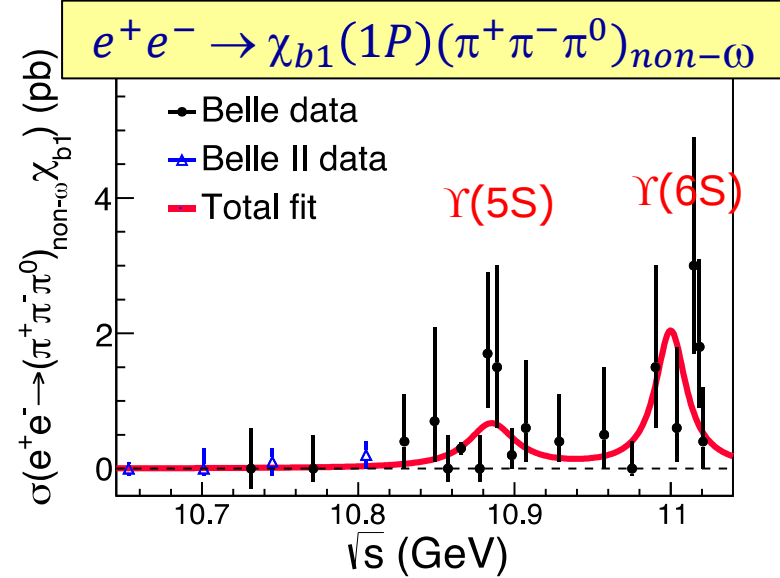
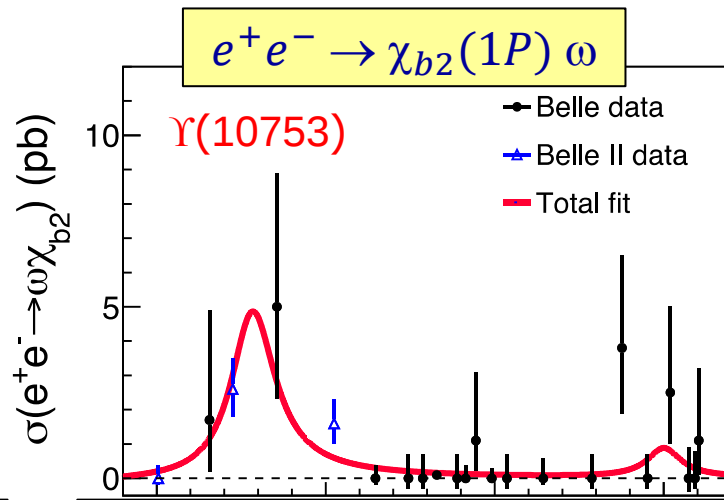
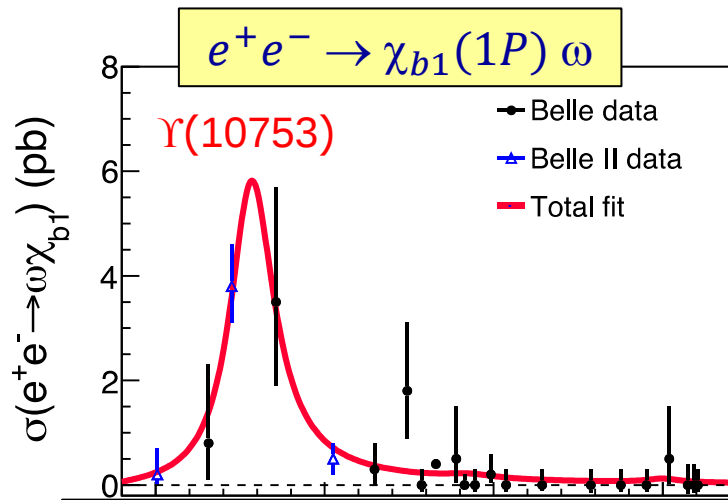
$B^* \bar{B}^*$ molecular state ?

- can explain dip in $\sigma(B \bar{B}^*)$
 destructive interference
- expect decays to bottomonium + light hadrons



Phenomenological analysis confirmed
 existence of the $B^* \bar{B}^*$ molecule

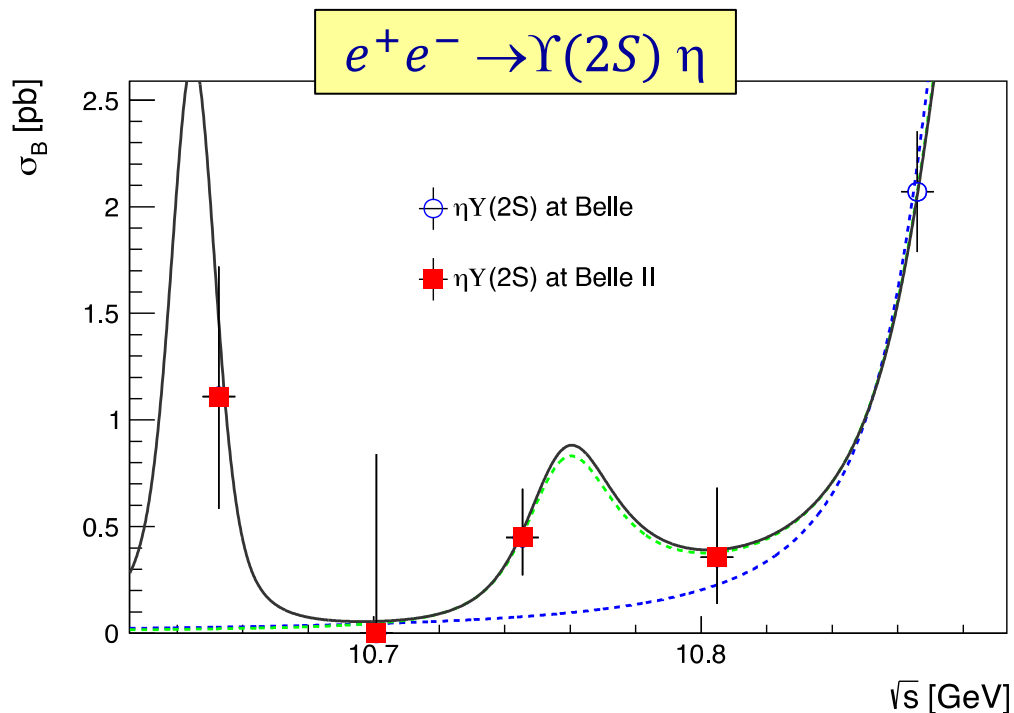
Salnikov, Bondar, Milstein, NPA 1041, 122764 (2023)



$\chi_{bJ}(1P) \omega$ – new decay channel of $\Upsilon(10753)$.

$\Upsilon(10753)$ and $\Upsilon(5S,6S)$ have different decay patterns $\Rightarrow$ different structure.

$\text{BF}(\Upsilon(10753) \rightarrow \chi_{b1} \omega) / \text{BF}(\Upsilon(10753) \rightarrow \chi_{b2} \omega) = 1.3 \pm 0.6$ expectation for mixed S-D state: 0.2.



$e^+e^- \rightarrow \Upsilon(1S)\eta$ –
no significant signals

Significance of the point at 10.653 GeV is 4.3σ . – $B^*\bar{B}^*$ threshold

Significance of $B^*\bar{B}^*$ state is 3.2σ (model with non-res. contribution).
Significance of $\Upsilon(10753)$ 2σ .

Need more data.

No significant signals:

- $e^+e^- \rightarrow \eta_b(1S) \omega$ PRD 109, 072013 (2024)
- $e^+e^- \rightarrow \chi_b(1P) \gamma$ PRELIMINARY

Under study:

- $e^+e^- \rightarrow h_b(1P) \eta$
- $e^+e^- \rightarrow \Upsilon_J(1D) \pi^+ \pi^-$
- $e^+e^- \rightarrow \Upsilon(1S) K^+ K^-$
- $e^+e^- \rightarrow B_s^{(*)} \bar{B}_s^{(*)}$
- ...

Goal: coupled channel analysis of all channels

$\Rightarrow$ pole positions, branching fractions of all states.

More data:

- at $\Upsilon(6S)$
- Threshold scans: $B\bar{B}^*$, $B^*\bar{B}^*$, $B_s^*\bar{B}_s^*$
- ...

Conclusions

Belle II energy scan:

- confirmation of $\Upsilon(10753)$, observation of new decay channel $\chi_{bJ} \omega$
- evidence for a $B^* \bar{B}^*$ in elastic and $\Upsilon(2S) \eta$ channels.

Theoretical predictions are unreliable. Experimental results help to develop theoretical approaches (Lattice QCD, EFT, models).

Bottomonium states above $B\bar{B}$ threshold are unique for Belle II.