Quarkonium at Belle II

17th International Workshop on Meson Physics
KRAKÓW, POLAND

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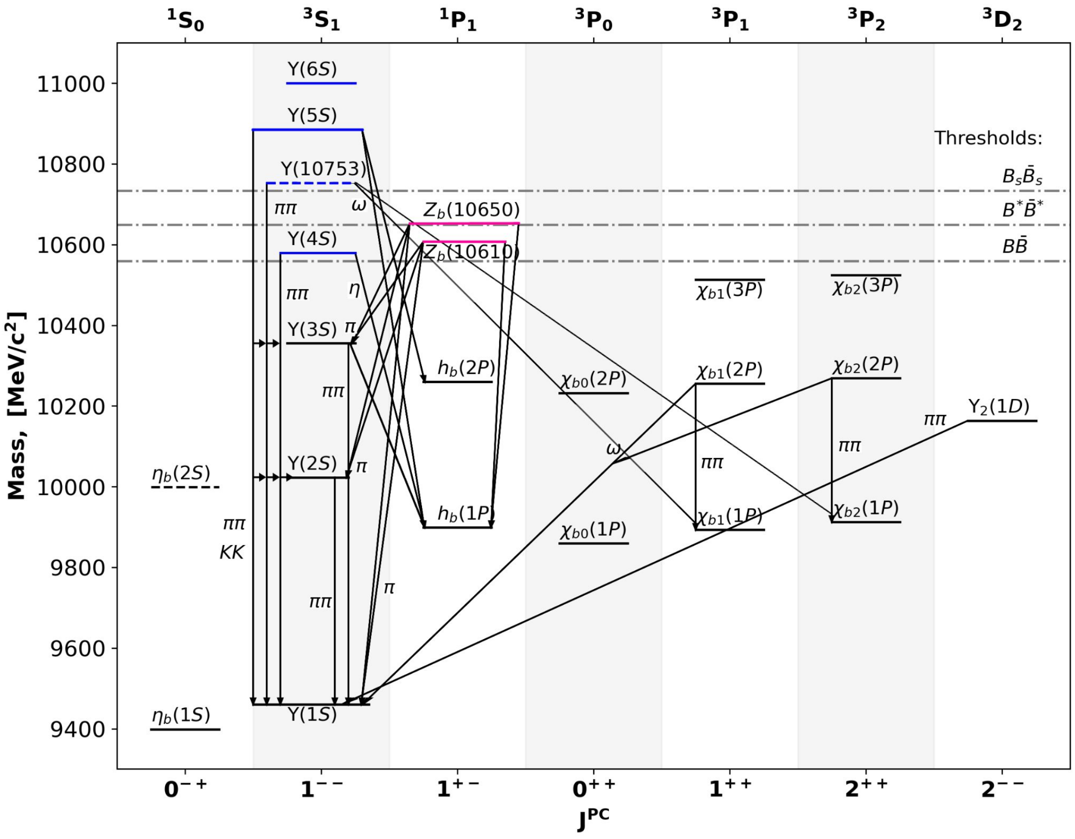
(on behalf of the Belle II Collaboration)

Bottomonium



Heavy quarkonium spectroscopy is an excellent laboratory to study non-perturbative QCD

Two type of states:

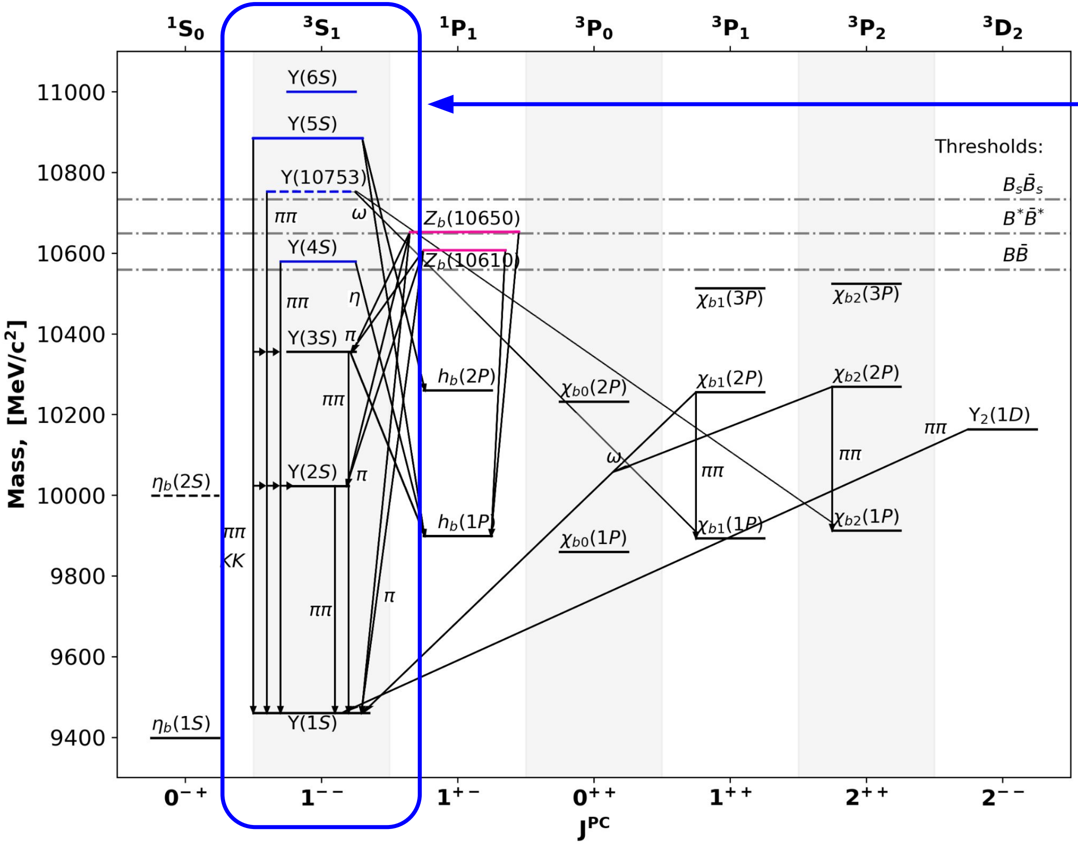
Below $B\bar{B}$ threshold states are well described by the potential models;

Above $B\bar{B}$ threshold states demonstrate unexpected properties:

- Hadronic transitions are strongly enhanced;
- η transitions are not suppressed compare to $\pi^+\pi^-$ transitions (HQSS violation);
- Two charged Z_b^+ states are observed;

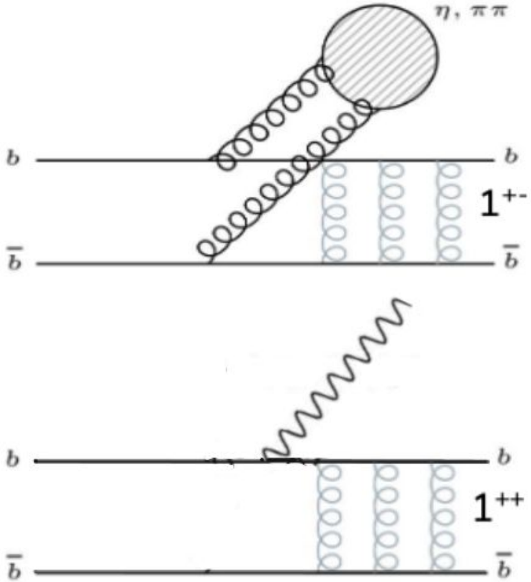
Conventional bottomonium (pure $b\bar{b}$ states)
Bottomonium-like states (mix of $b\bar{b}$ and $B\bar{B}$)
Purely exotic charged states (Z_b^+).

Bottomonium



Υ(nS) 1^{--} states can be produced in e^+e^- collisions.

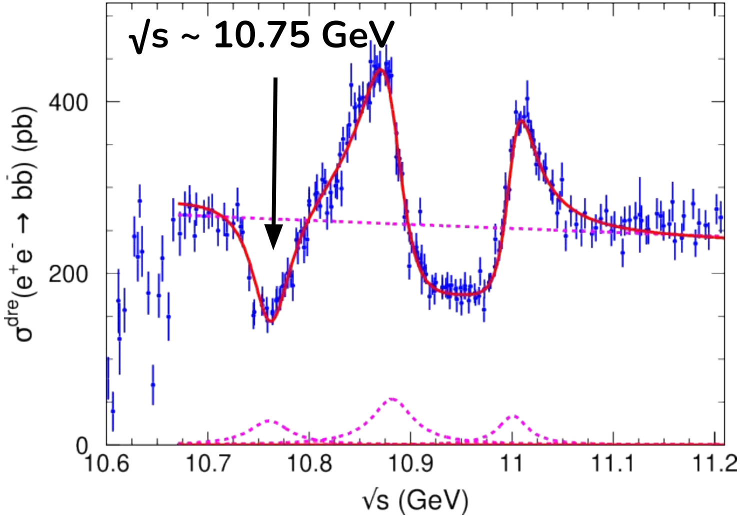
The other quantum numbers can be obtained via hadronic or radiative transitions:



Discovery of ϒ(10753)

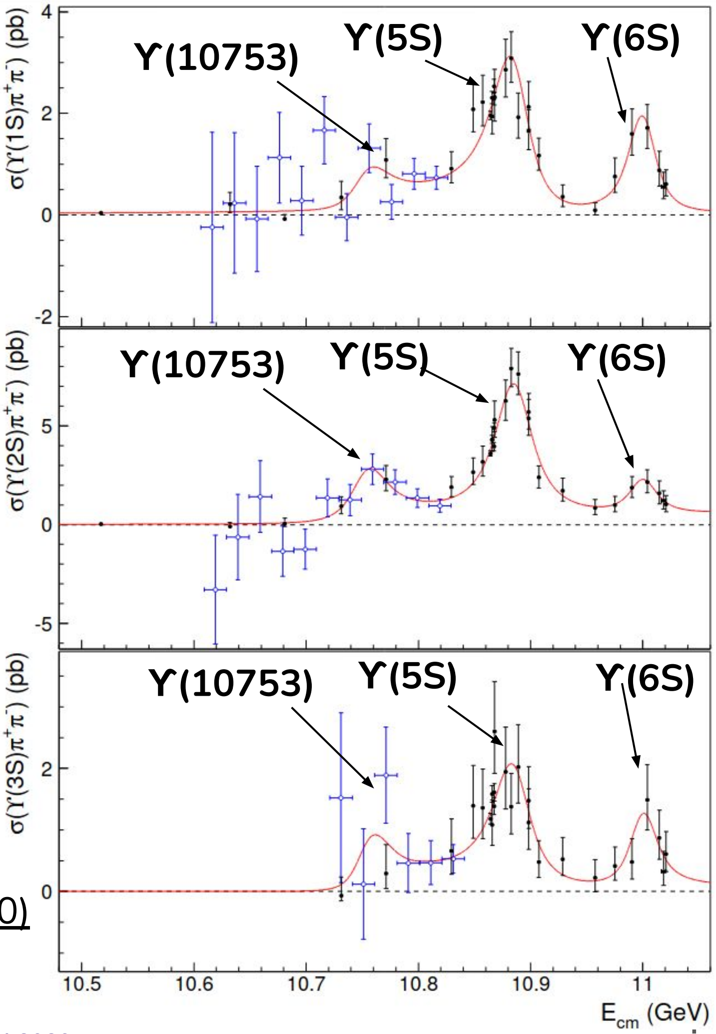
Observed in the **$e^+ e^- \to \Upsilon(nS)\, \pi^+ \pi^-$ (n = 1,2,3)** cross section energy dependence by Belle (JHEP 10 (2019) 220):

	ϒ(10860)	ϒ(11020)	New structure
M (MeV/c²)	$10885.3 \pm 1.5^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}{}^{+1.0}_{-1.3}$	$10752.7 \pm 5.9^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}{}^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}{}^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}{}^{+3.9}_{-3.3}$



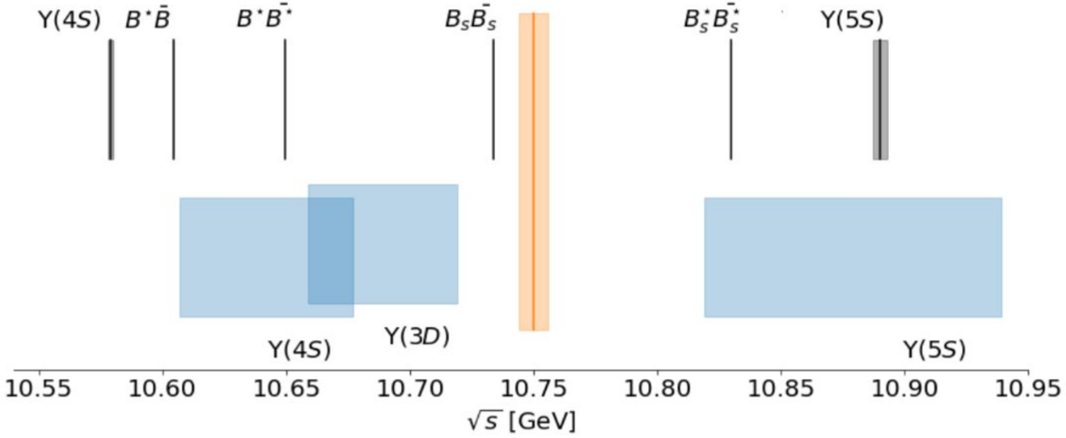
A dip in $\sigma(e^+e^- \to b\bar{b})$ cross section may also correspond to ϒ(10753)

CPC **44**, 8, 083001 (2020)



What is the nature of ϒ(10753)?

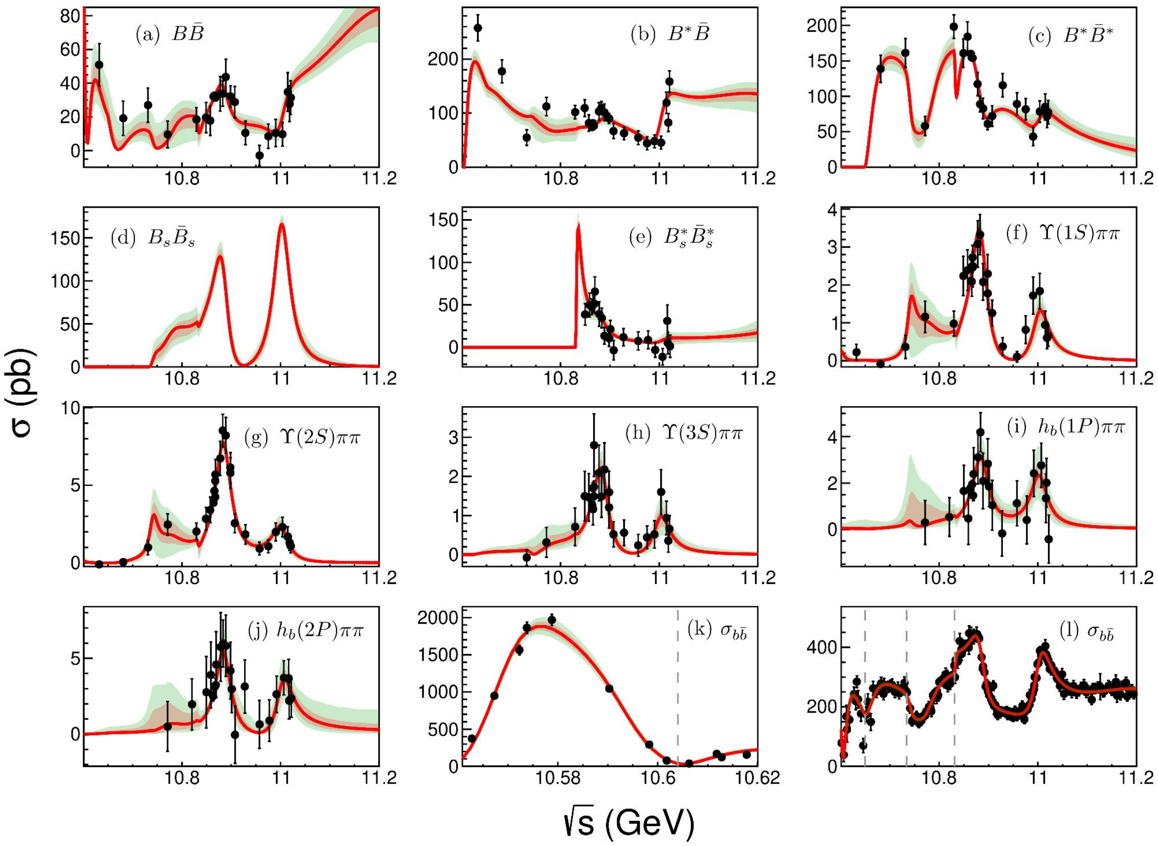
- Far from the thresholds;



- Mass does not match ϒ(3D) theoretical predictions, and D-wave states are not seen in e+ e- collisions;
- ϒ(4S) - ϒ(3D) mixing can be enhanced due to hadron loops:

- Tetraquark state:
  CPC **43**, 12, 123102 (2019),
  PLB, **802**, 135217 (2020),
  PRD, **104**, 3, 034036 (2021).
- Hadronic molecule with a small admixture of a bottomonium:
  PRD **103**, 074507 (2021)
- Hybrid state:
  PRD **99**, 1, 014017 (2019)
- Conventional $b\bar{b}$ state:
  EPJC **80**, 1, 59 (2020)
  PLB **803**, 135340 (2020)
  PRD **102**, 1, 014036 (2020)
  PRD **101**, 1, 014020 (2020)
  PRD **104**, 034036 (2021)
  PRD **105**, 074007 (2022)
  EPJC **137**, 357 (2022)
  PRD **106**, 094013 (2022)

Global phenomenological analysis



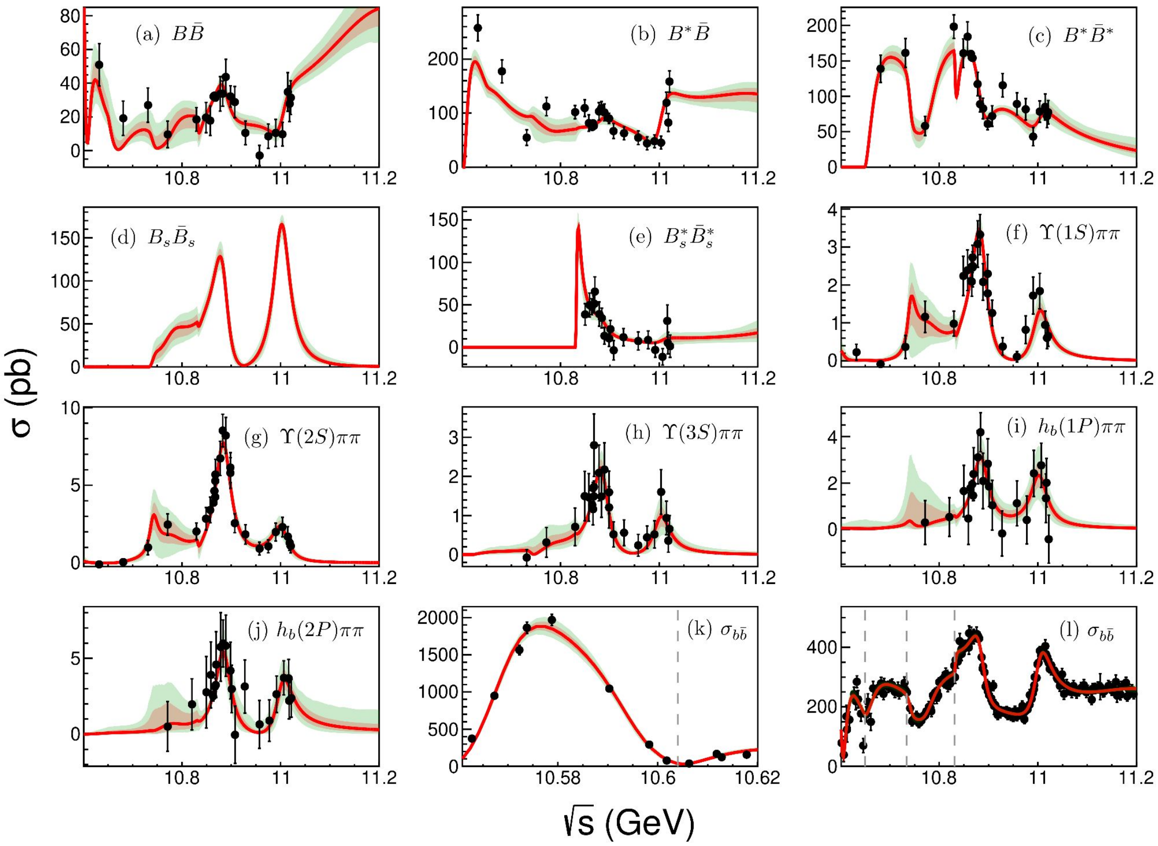
Uses the **coupled-channel approach** to perform a global fit to various cross section energy dependences, taking into account contributions from virtual meson loops and interference between the channels.

Includes ϒ(4S), ϒ(10753), ϒ(5S) and ϒ(6S) poles.

Results: pole positions (mass and width), branching fractions, dependence of scattering amplitudes.

PRD **106** (2022) 9, 094013

Global phenomenological analysis



Uses the data collected by Belle and BaBar experiments:

- Two-body exclusive cross sections $\sigma(e^+e^- \rightarrow B_{(s)}^{(*)}\bar{B}_{(s)}^{(*)})$;
- Three-body exclusive cross sections $\sigma(e^+e^- \rightarrow \Upsilon(nS)/h_b(mP)\,\pi^+\pi^-)$, (n = 1,2,3, m = 1,2);
- Combined R_b measurement;

Inclusion of Υ(10753) pole is necessary to describe the data ⇒ indirect confirmation of Υ(10753)

PRD **106** (2022) 9, 094013

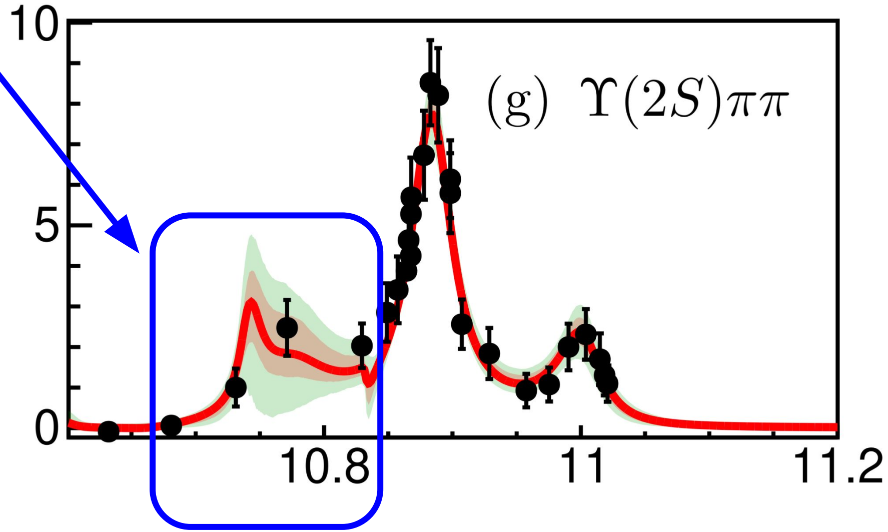
More data is necessary

- To study $\Upsilon(10753)$ nature;
- Improve accuracy below $\Upsilon(5S)$;

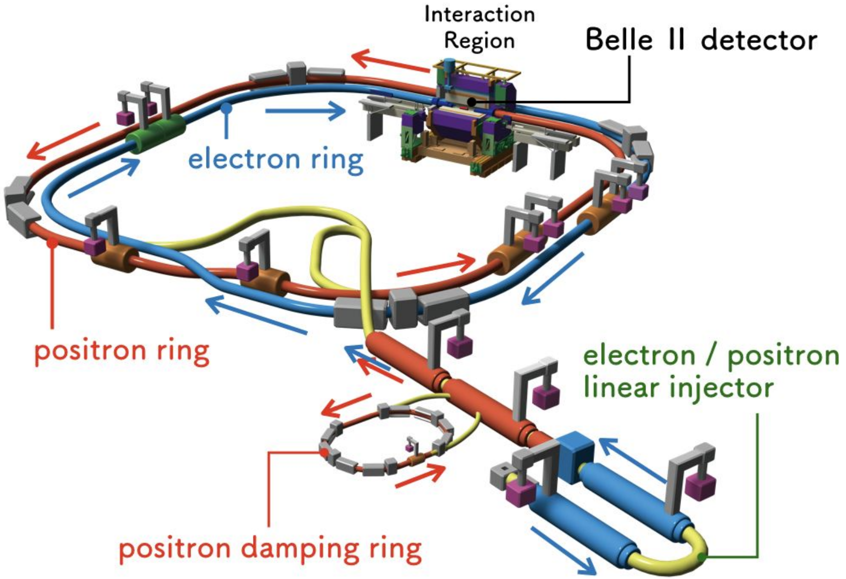
Perform energy scan at the Belle II experiment.

Two Belle II results will be presented:

- $e^+e^- \to \omega\chi_{bJ}(1P)$ and $X_b \to \omega\Upsilon(1S)$
- $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$

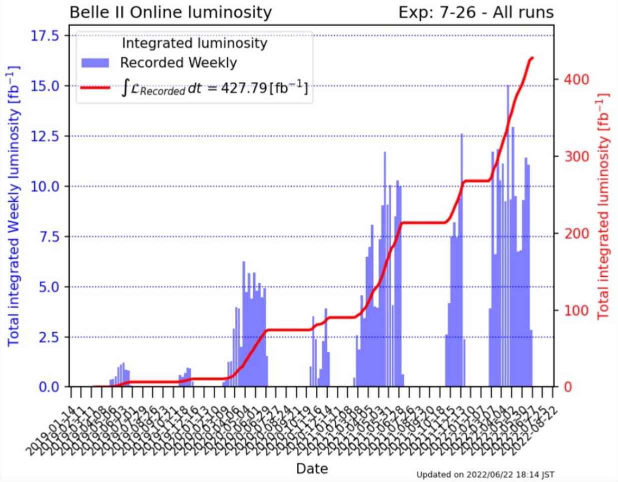


SuperKEKB and Belle II



PTEP **2013**, 03A011 (2013)

- Asymmetric e^+e^- collider at KEK (Tsukuba, Japan) provides unique clean environment;
- Instant luminosity record of 4.7 x 10^{34} cm^{-2} s^{-1} (x2 of the Belle peak luminosity);
- Data is collected with Belle II detector;
- $E_{c.m.}$ is measured with high precision and can be tuned from 9 to 11 GeV;



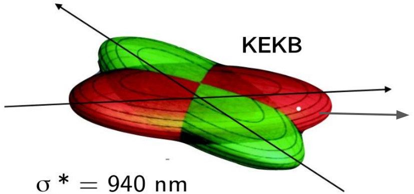
SuperKEKB and Belle II

Beam current increased by **x2.**

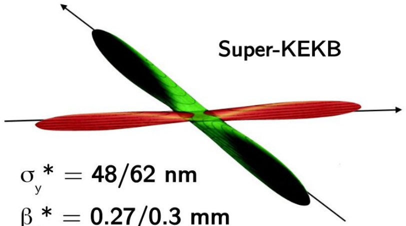
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Vertical beta function at IP reduced by **1/20**
"Nano-beam" scheme.

x40 instant luminosity increase



$\sigma_y{}^* = 940$ 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**

- Asymmetric e^+e^- collider at KEK (Tsukuba, Japan) provides unique clean environment;
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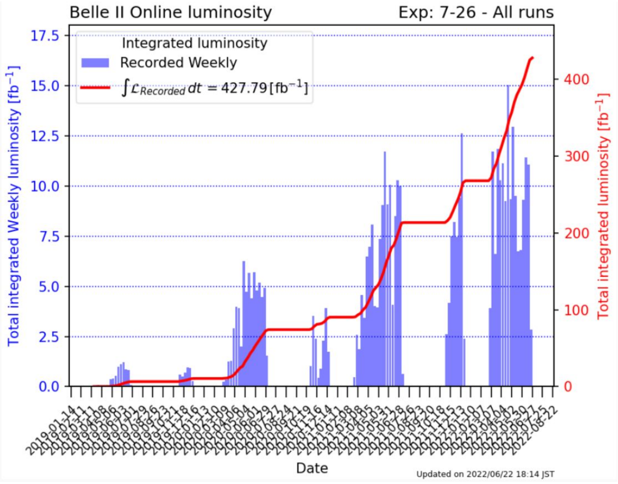
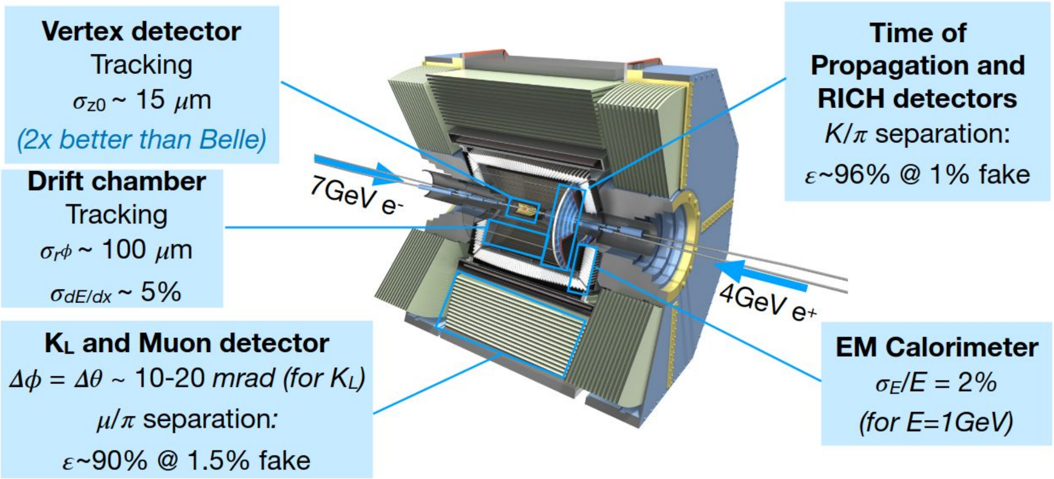


SuperKEKB and Belle II

4π spectrometer with good vertexing, tracking, efficient PID and calorimetry;

PTEP **2020** (2020) 2, 029201

- ❑ Asymmetric e^+e^- collider at KEK (Tsukuba, Japan) provides unique clean environment;
- ❑ Instant luminosity record of 4.7 x 10^{34} cm^{-2} s^{-1} (x2 of the Belle peak luminosity);
- ❑ Data is collected with Belle II detector;
- ❑ $E_{c.m.}$ is measured with high precision and can be tuned from 9 to 11 GeV;

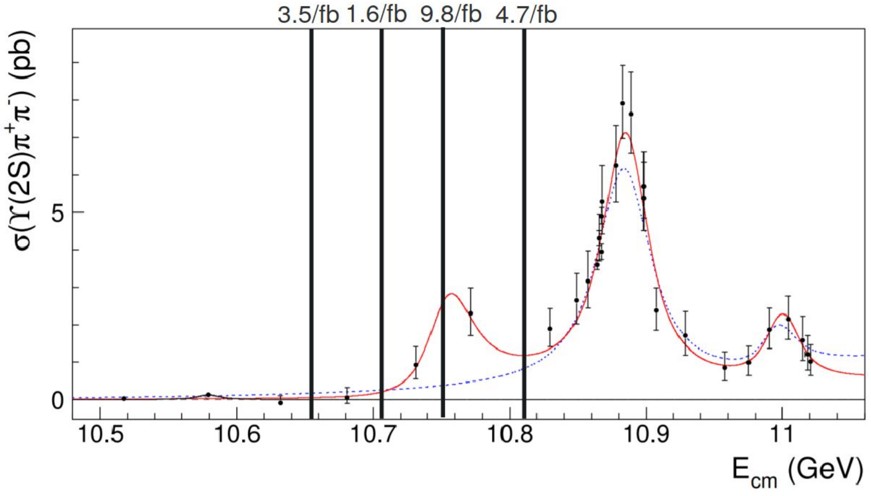


Belle II detector upgrades:

- ❑ Radiation tolerant;
- ❑ Improved vertexing;
- ❑ Better resolution;
- ❑ Faster trigger and DAQ;

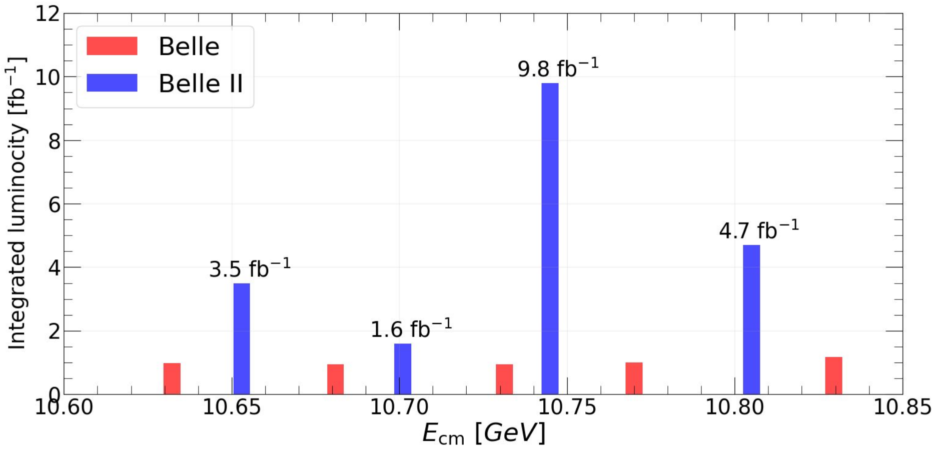
SuperKEKB and Belle II

ϒ(10753) state was observed in the $e^+ e^- \to \Upsilon(nS) \pi^+ \pi^-$ (n = 1,2,3) cross section energy dependence by Belle (JHEP 10 (2019) 220).



- ❑ $19\ fb^{-1}$ scan around ϒ(10753) was collected in November 2021.

- ❑ Asymmetric e^+e^- collider at KEK (Tsukuba, Japan) provides unique clean environment;
- ❑ Instant luminosity record of $4.7 \times 10^{34}\ cm^{-2}\ s^{-1}$ (x2 of the Belle peak luminosity);
- ❑ Data is collected with Belle II detector;
- ❑ $E_{c.m.}$ is measured with high precision and can be tuned from 9 to 11 GeV;



Search for $e^+e^- \to \omega \chi_{bJ}(1P)$ and $X_b \to \omega \Upsilon(1S)$

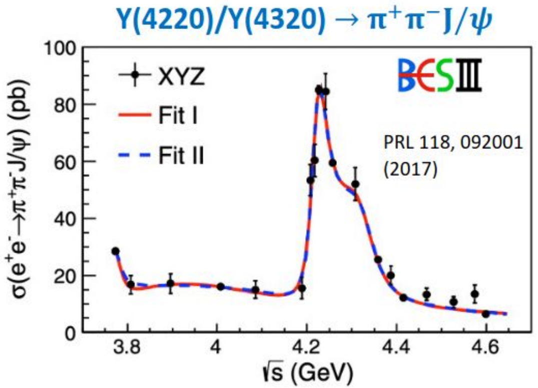
Motivation to search for $\Upsilon(10753)\to\omega\chi_{bJ}(1P)$

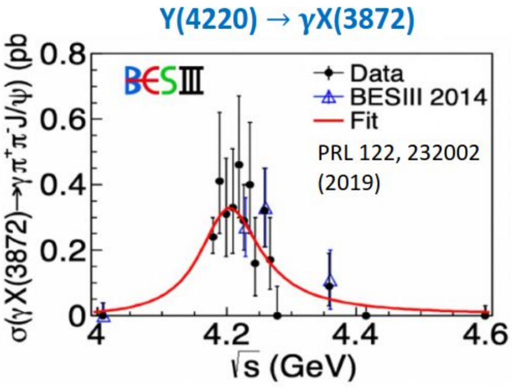
Theory:

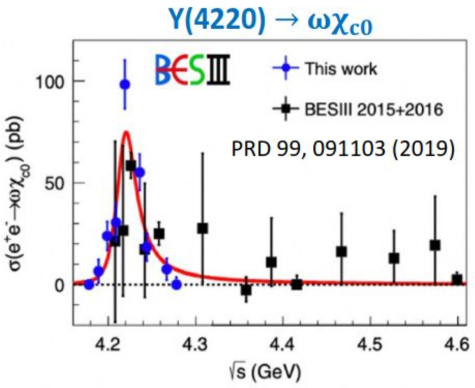
- ❑ Mixed $\Upsilon(4S)$ - $\Upsilon(3D)$ state: $\omega\chi_{bJ}$ could be enhanced (PRD **104**, 034036 (2021)).

Charmonium sector:

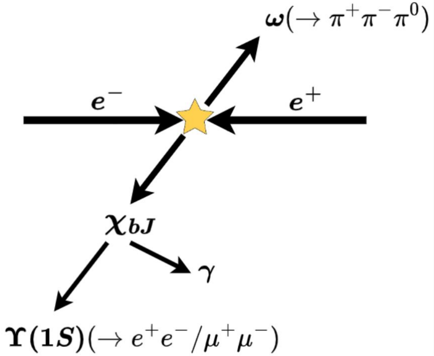
- ❑ Similar to $\Upsilon(10753)$ structure Y(4220) was observed in $e^+e^- \to J/\Psi\, \pi^+\pi^-$ cross section dependence by BES III (PRL **118**, 092001 (2017)).
- ❑ Y(4220) peak was observed in $\gamma X(3872)$ and $\omega\chi_{c0}$ final states by BES III (PRL, **122**, 232002 (2019), PRD **99**, 091103(R) (2019)).
- ❑ We can expect $\Upsilon(10753)$ to decay into $\gamma[X_b\to\omega\Upsilon(1S)]$ and $\omega\chi_{bJ}$ final states.







Observation of $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$



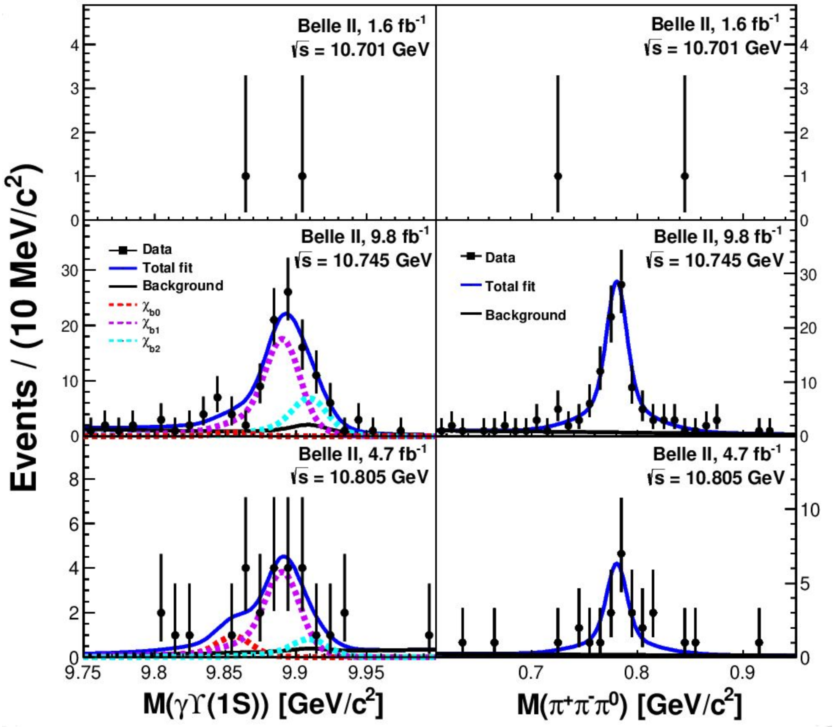
PRL **130**, 091902 (2023)

Channel	$\sqrt{s}$ (GeV)	$N^{\rm sig}$	$\Sigma(\sigma)$	σ_B (pb)
$e^+e^- \to \omega\chi_{b0}$	10.701	< 3.0	-	< 16.6
$e^+e^- \to \omega\chi_{b1}$		< 3.9	-	< 1.2
$e^+e^- \to \omega\chi_{b2}$		< 4.0	-	< 2.5
$e^+e^- \to \omega\chi_{b0}$	10.745	< 12.0	0.5	< 11.3
$e^+e^- \to \omega\chi_{b1}$		$68.9^{+13.7}_{-13.5}$	5.9	$3.6^{+0.7}_{-0.7} \pm 0.5$
$e^+e^- \to \omega\chi_{b2}$		$27.6^{+11.6}_{-10.0}$	3.1	$2.8^{+1.2}_{-1.0} \pm 0.4$
$e^+e^- \to \omega\chi_{b0}$	10.805	< 9.9	1.2	< 11.4
$e^+e^- \to \omega\chi_{b1}$		$15.0^{+6.8}_{-6.2}$	2.7	< 1.7
$e^+e^- \to \omega\chi_{b2}$		$3.3^{+5.3}_{-3.8}$	0.8	< 1.6

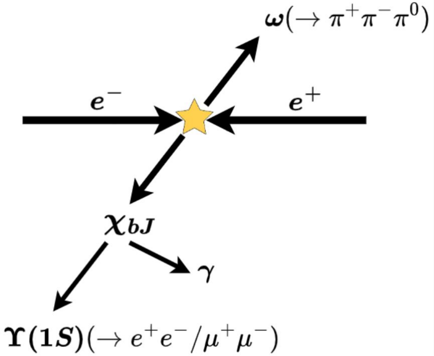
11 σ

4.5 σ

2D fit to $M(\gamma\Upsilon(1S))$ and $M(\pi^+\pi^-\pi^0)$:



Observation of $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$

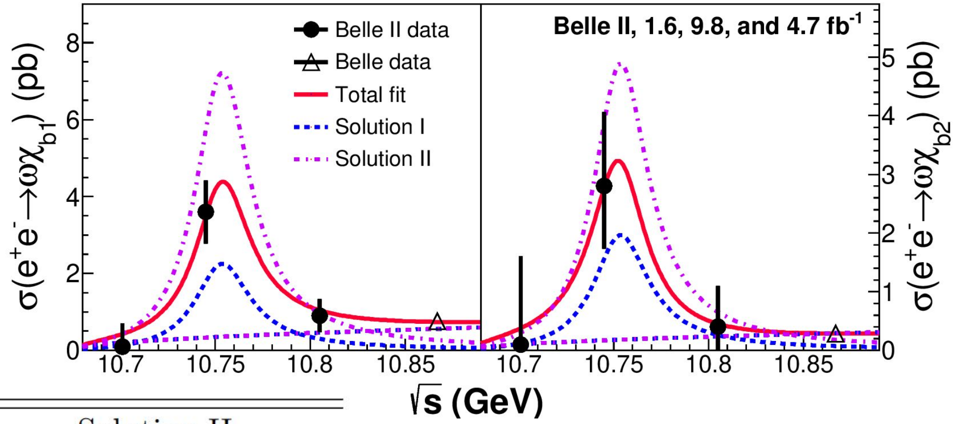


PRL **130**, 091902 (2023)

- Fit with coherent sum of PHSP and BW.

$$\left|\sqrt{\Phi_2(\sqrt{s})} + \frac{\sqrt{12\pi\Gamma_{ee}\mathcal{B}_f\Gamma}}{s - M^2 - iM\Gamma}\sqrt{\frac{\Phi_2(\sqrt{s})}{\Phi_2(M)}}e^{i\phi}\right|^2$$

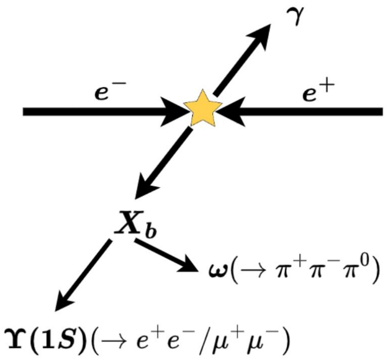
- M and Γ are fixed to 10752.7 MeV and 35.5 MeV



- Confirms Υ(10753) state;
- No peak at Υ(5S);
- $\sigma(\chi_{b1}\omega)/\sigma(\chi_{b2}\omega) \sim 1$;
- $\sigma(\chi_{b1}\omega)/\Upsilon(2S)\pi^+\pi^- \sim 1.5$;

$\Gamma_{ee}\mathcal{B}_f$	Solution I (constructive interference)	Solution II (destructive interference)
$\Gamma_{ee}\mathcal{B}_f(\Upsilon(10753)\to\omega\chi_{b1})$	$(0.63 \pm 0.39 \pm 0.20)$ eV	$(2.01 \pm 0.38 \pm 0.46)$ eV
$\Gamma_{ee}\mathcal{B}_f(\Upsilon(10753)\to\omega\chi_{b2})$	$(0.53 \pm 0.46 \pm 0.15)$ eV	$(1.32 \pm 0.44 \pm 0.55)$ eV

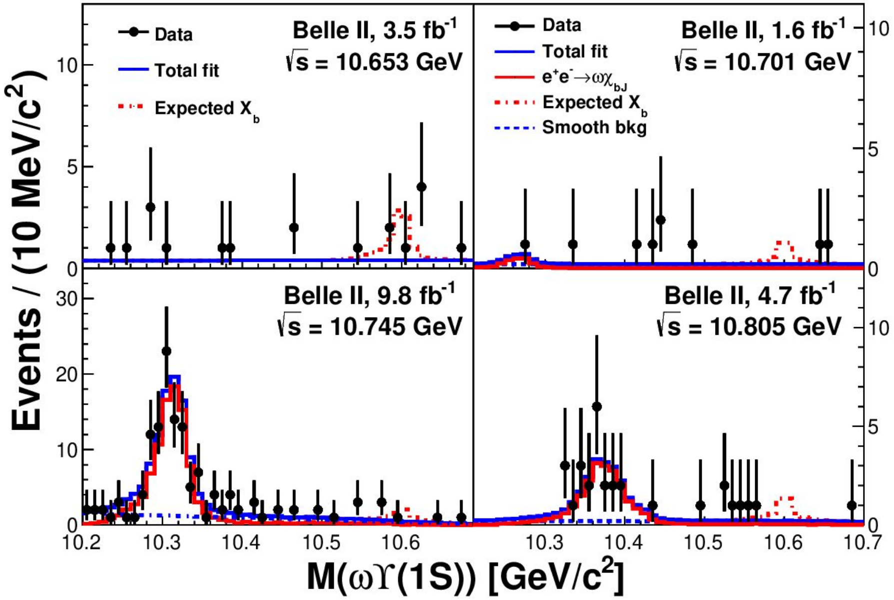
Search for $\Upsilon(10753)\to\gamma X_b[\to\omega\Upsilon(1S)]$



PRL **130**, 091902 (2023)

- ❑ No evidence of X_b signal;
- ❑ Only $\omega\chi_{bJ}(1P)$ reflections are seen;

Fit to $M[\omega\Upsilon(1S)]$



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

$$\sigma^{\rm UL}_{X_b} = \sigma^{\rm UL}_B(e^+e^- \to \gamma X_b)\mathcal{B}(X_b \to \omega\Upsilon(1S))$$

$\sqrt{s}$ (GeV)	M_{X_b} (GeV)	$\sigma^{\rm UL}_{X_b}$ (pb)
10.653	10.59	< 0.55
10.701	10.45	< 0.84
10.745	10.45	< 0.14
10.805	10.53	< 0.47

Discussion

Previously Belle measured $\sigma(e^+e^-\to\chi_{bJ}(1P)\omega)$ at $\sqrt{s}$ = 10.867 GeV (PRL **113** (2014) 14, 142001):

$$\frac{\sigma(e^+e^-\to\chi_{bJ}(1P)\omega)}{\sigma(e^+e^-\to\Upsilon(nS)\pi^+\pi^-)}\sim$$

- ~1.5 at $\sqrt{s}$ = 10.745 GeV
- ~0.15 at $\sqrt{s}$ = 10.867 GeV

❏ Order of magnitude difference is observed for this ratio at Υ(5S) and Υ(10753)

⬇

It may indicate different internal structures for these two states.

Energy dependence of the $e^+e^-\to B^{(*)}\bar{B}^{(*)}$ cross section

Energy dependence of the $e^+e^- \to B^{(*)}\bar{B}^{(*)}$ cross section

Previous Belle analysis: JHEP 06 (2021), 137

- ❑ One B meson is fully reconstructed using hadronic channels (FEI, efficiency ~ 0.6%);
- ❑ $B^* \to B\gamma$ decays are not reconstructed;

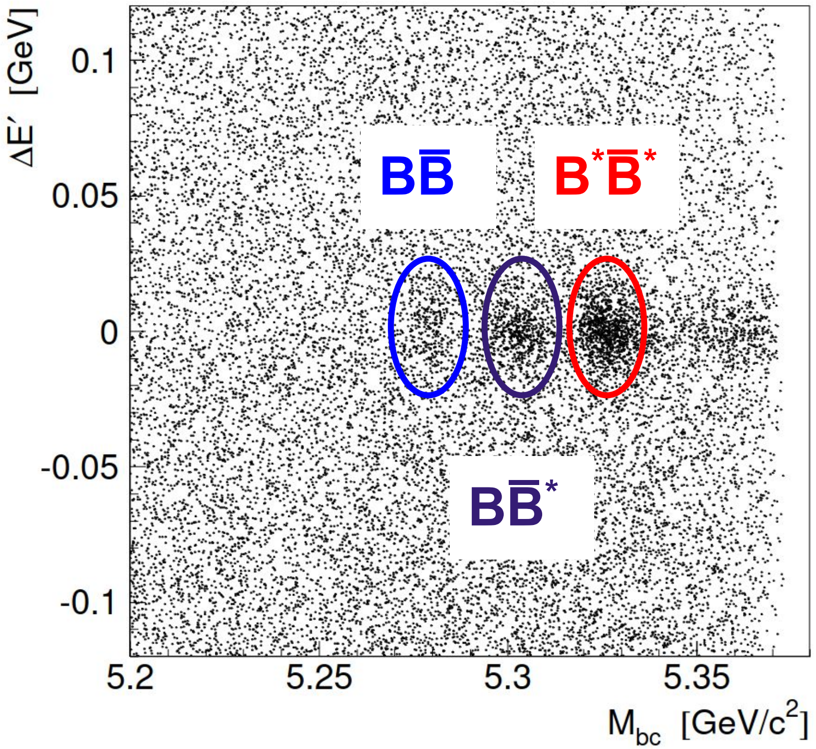
$$\Delta E = E_B - E_{\rm cm}/2$$

$$\Delta E' = \Delta E + M_{\rm bc} - m_B$$

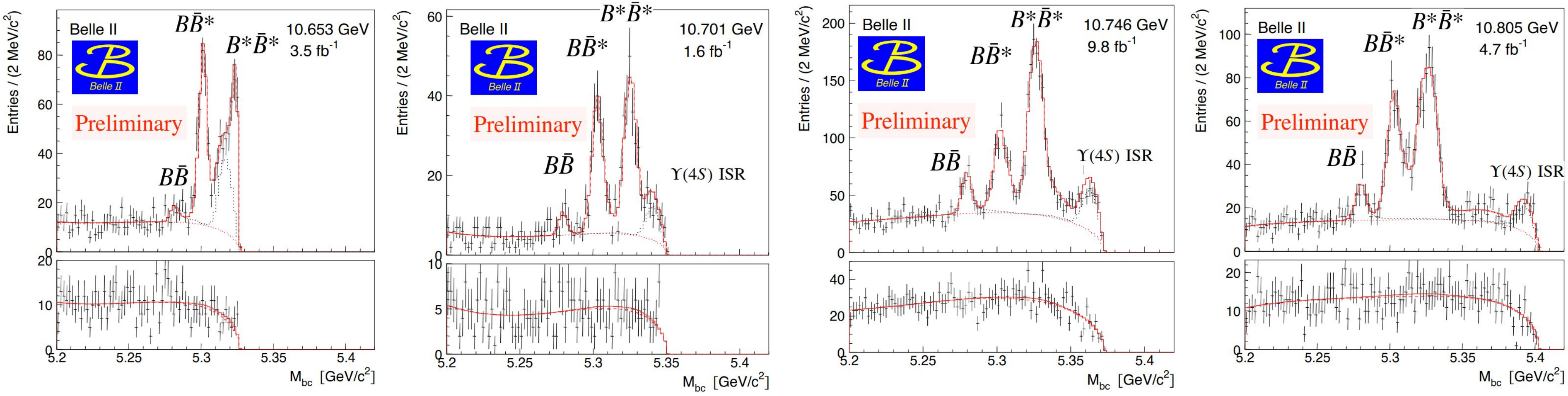
- ❑ $|\Delta E'| < 18$ MeV;
- ❑ Signal is identified using M_{bc}:

$$M_{\rm bc} = \sqrt{E_{\rm cm}^2/4 - p_B^2}$$

$\Delta E'$ vs M_{bc} at E_{cm} = 10.746 GeV



M_{bc} fit at scan energies

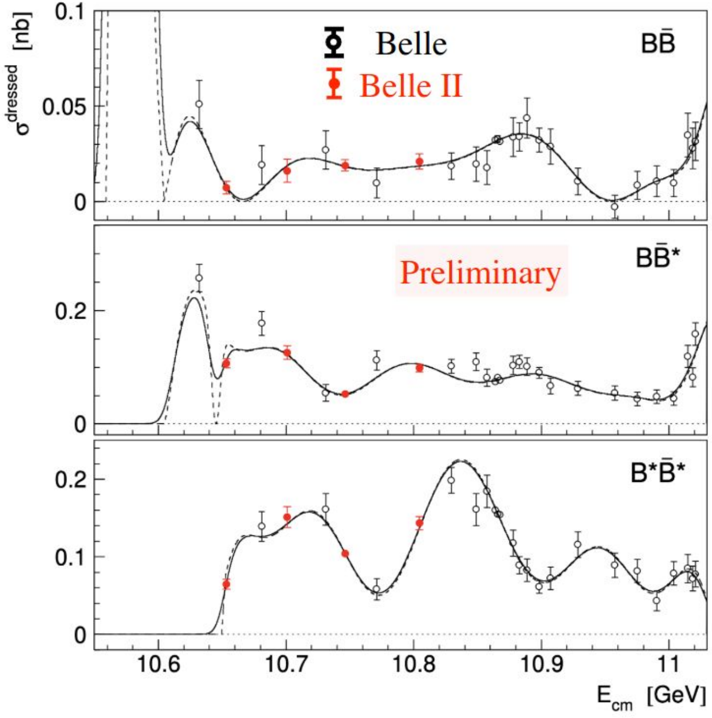


- ❑ Good description of the M_{bc} in data;
- ❑ Contribution of $\Upsilon(4S)\rightarrow B\bar{B}$ production via ISR is visible well described by the fit;
- ❑ Sharp cut of the data at right edge for E=10.653 GeV ⇒ fast rise of $B^*\bar{B}^*$ near threshold;

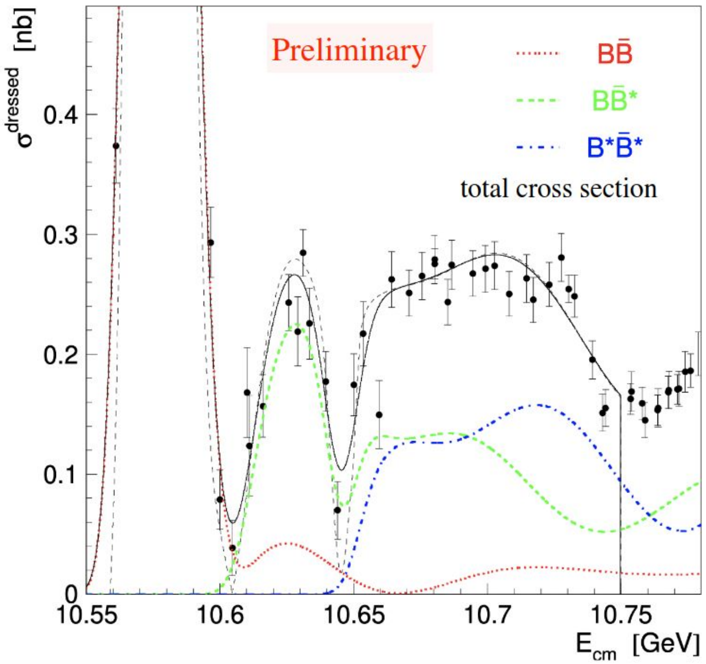
Energy dependence of the cross sections

Simultaneous fit to:

- ❏ Exclusive cross sections measured by in this work and previous Belle study (JHEP 06 (2021), 137);

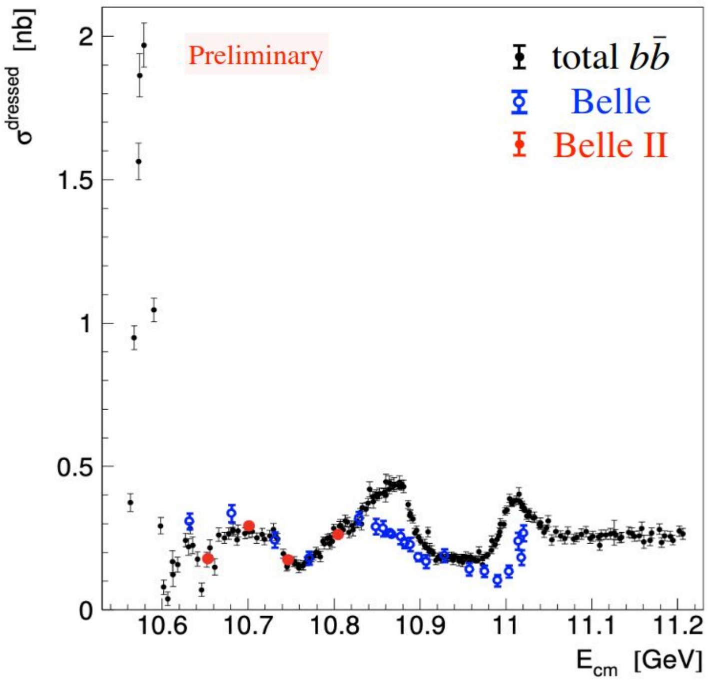


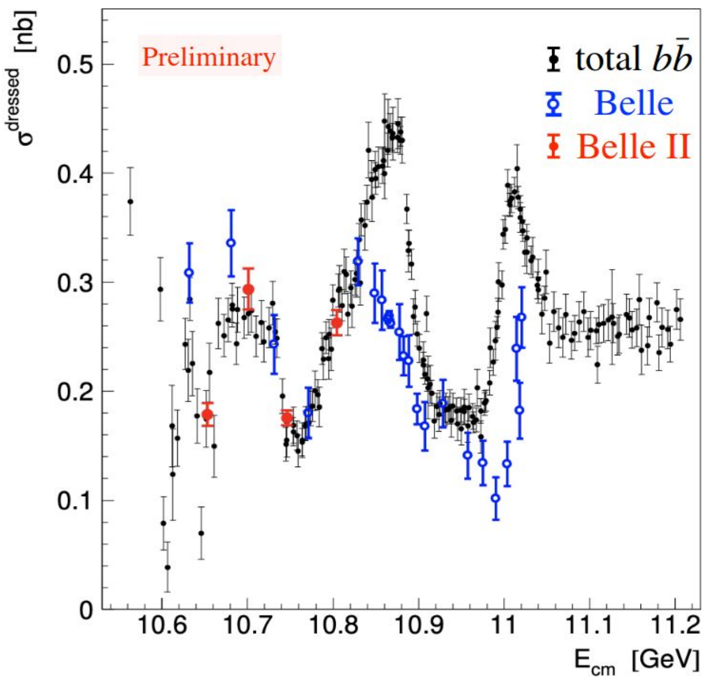
- ❏ Total cross section (CPC **44**, 8, 083001 (2020))



Comparison of $\sigma_{b\bar{b}}$ and $\sigma_{B\bar{B}} + \sigma_{B\bar{B}^*} + \sigma_{B^*\bar{B}^*}$

- Good agreement at low energies;
- Difference at higher energy is due to $B_s^{(*)}$, multi-body $B^{(*)}\bar{B}^{(*)}\pi(\pi)$ and bottomonia;





Discussion

New measurement significantly improves previous Belle result:

- ❑ Solid curve – combined Belle + Belle II data fit
- ❑ Dashed curve – Belle data fit only

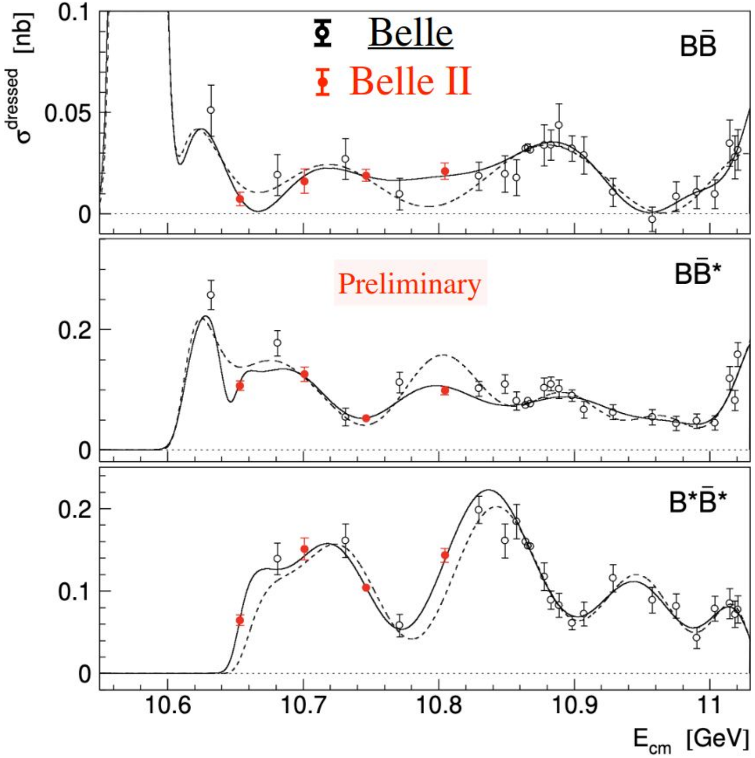
$\sigma(e^+e^- \to B^*\bar{B}^*)$ rises rapidly above $B^*\bar{B}^*$ threshold:

- ❑ Similar behaviour was seen for $D^*\bar{D}^*$ cross section (PRD **97**, 012002 (2018));

- ❑ **Possible interpretation:** resonance or bound state ($b\bar{b}$ or $B^*\bar{B}^*$) near threshold (MPL A 21, 2779 (2006));

- ❑ Also explains a narrow dip in $\sigma(e^+e^- \to B\bar{B}^*)$ near $B^*\bar{B}^*$ threshold by destructive interference between $e^+e^- \to B\bar{B}^*$ and $e^+e^- \to B^*\bar{B}^* \to B\bar{B}^*$

- ❑ Could also enhance and $\Upsilon\,\pi^+\pi^-$ and $h_b\eta$ final states.



Conclusion

Scan above Υ(4S) gives an opportunity for a lot of unique studies:

- ❏ Υ(10753) decays to different final states. Study of its properties;
- ❏ Energy dependence of the various final states production;

Wide range of long-term non-Υ(4S) possibilities:

- ❏ Increase the above-Υ(4S) scan statistics;
- ❏ Υ(6S) region study with high statistics;
- ❏ Study of the threshold regions;

Golden Modes
$e^+e^- \to \pi^+\pi^-\Upsilon(pS)(\to \ell^+\ell^-)$
$B\overline{B}$ decomposition
$\pi^+\pi^-$ Dalitz
$Y_b \to \omega\eta_b(1S)$
$Y_b \to \omega\chi_{bJ}(1P)$ PRL **130**, 091902 (2023)
Silver Modes
$Y_b \to \pi^+\pi^- X$ (inclusive)
$Y_b \to \eta X$ (inclusive)
$Y_b \to \eta\Upsilon(1S,2S)(\to \ell^+\ell^-)$
$Y_b \to \eta'\Upsilon(1S)(\to \ell^+\ell^-)$
$Y_b \to \Upsilon(1S)$ (inclusive)
Bronze Modes
$Y_b \to \gamma X_b$
$Y_b \to \pi^0\pi^0\Upsilon(pS)(\to \ell^+\ell^-)$
$Y_b \to KK(\phi)\Upsilon(pS)(\to \ell^+\ell^-)$
$Y_b \to \pi^0\pi^0 X$ (inclusive)
$Y_b \to \pi^0 X$ (incl. or excl.)
...

Thank you!