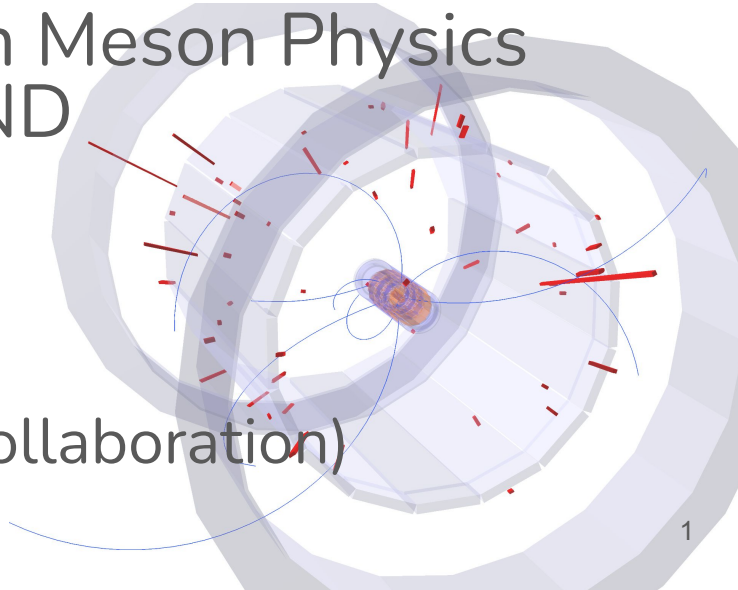
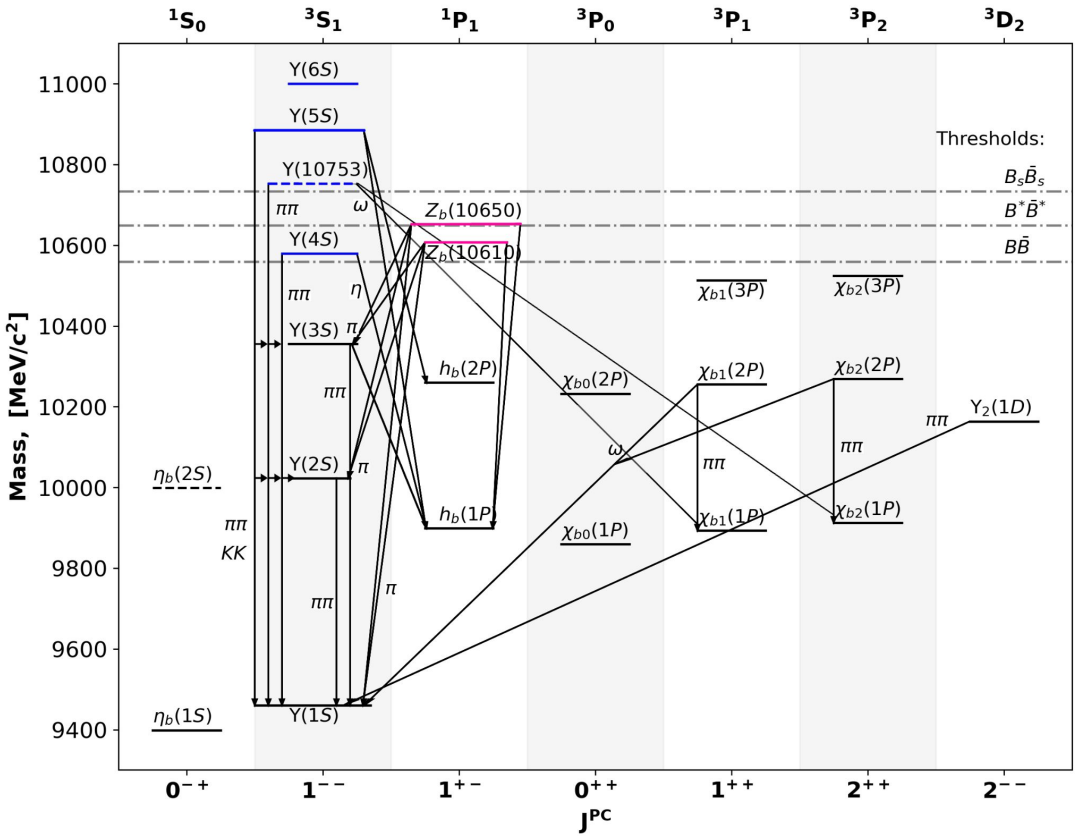
# Quarkonium at Belle II

17th International Workshop on Meson Physics
KRAKÓW, POLAND
22nd - 27th June 2023

Pavel Oskin
(on behalf of the Belle II Collaboration)



# Bottomonium




Two types of states:

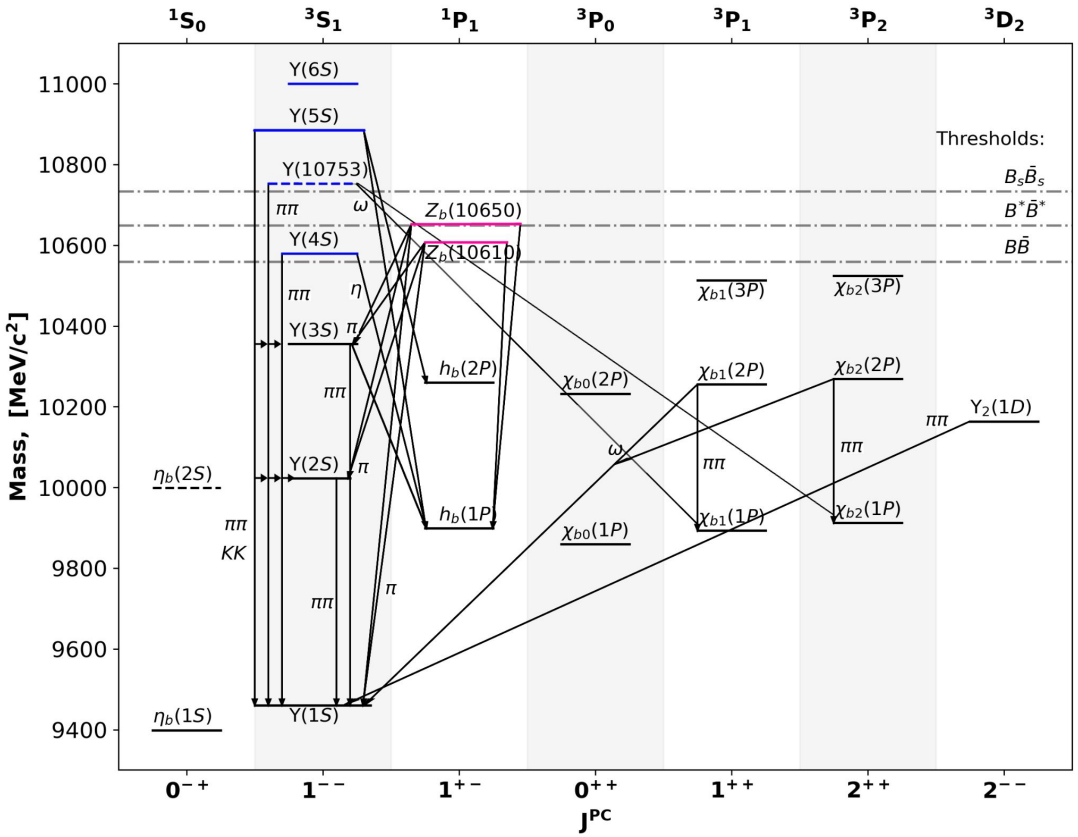
**Below B$\bar{B}$ threshold** states are well described by the potential models;

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

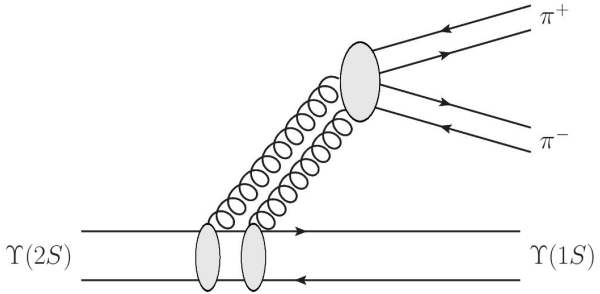
- Hadronic transitions are strongly enhanced (OZI rule violation);
- $\eta$ transitions are not suppressed compare to $\pi^+\pi^-$ transitions (HQSS violation);
- Two charged $Z_b^+$ states are observed;

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

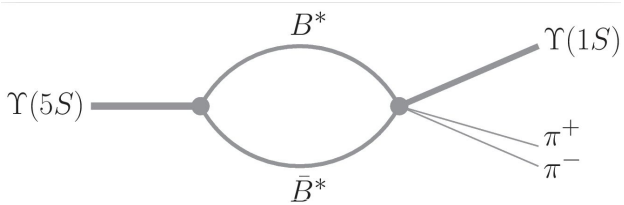
# Bottomonium



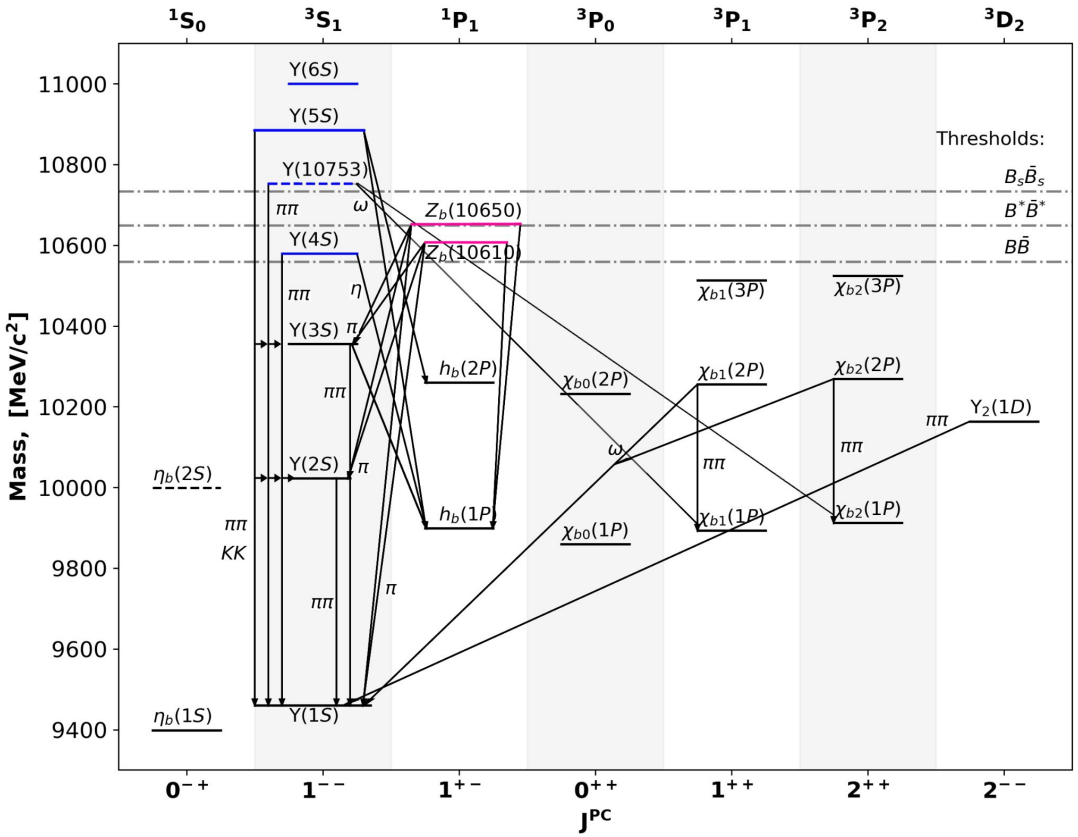

Hadronic transitions from the states **below the $B\bar{B}$ threshold** are described by gluon emission (QCDME):




Hadronic transitions from the states **above the $B\bar{B}$ threshold** can be enhanced due to **$B\bar{B}$ mesons rescattering**:



# Bottomonium




**$Z_b^+$ states** masses coincide with $B\bar{B}^*$ $B^*\bar{B}^*$ thresholds and decays dominantly to constituent mesons:

| $Z_b$ decay mode | Branching fraction |
|---|---|
| $Z_b^+(10610) \to \Upsilon(nS)/h_b(mP)\pi^+$ | $14.4^{+2.5}_{-1.9}\%$ |
| $Z_b^+(10610) \to B^+\bar{B}^{*0}/\bar{B}^0 B^{*+}$ | $85.6^{+2.1}_{-2.9}\%$ |
| $Z_b^+(10650) \to \Upsilon(nS)/h_b(mP)\pi^+$ | $26.6^{+5.0}_{-4.7}\%$ |
| $Z_b^+(10650) \to B^{*+}\bar{B}^{*0}$ | $74^{+4}_{-6}\%$ |

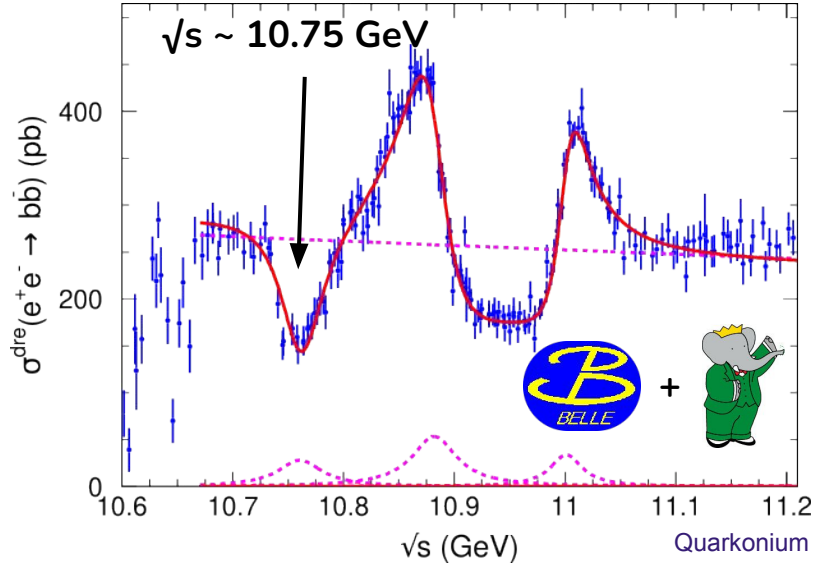
This is a strong indication of the molecular nature of **$Z_b^+$ states**.

PRL, **108**, 122001 (2012)

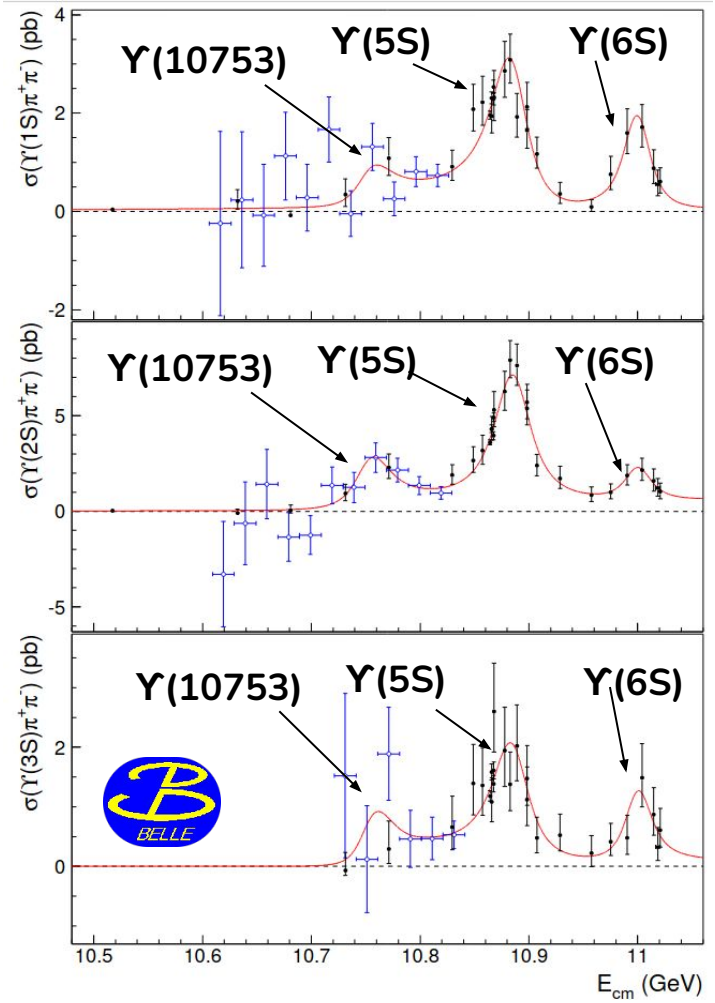
# Discovery of Υ(10753)

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/$c^2$) | $10885.3 \pm 1.5\,^{+2.2}_{-0.9}$ | $11000.0^{+4.0\,+1.0}_{-4.5\,-1.3}$ | $10752.7 \pm 5.9\,^{+0.7}_{-1.1}$ |
| Γ (MeV) | $36.6^{+4.5\,+0.5}_{-3.9\,-1.1}$ | $23.8^{+8.0\,+0.7}_{-6.8\,-1.8}$ | $35.5^{+17.6\,+3.9}_{-11.3\,-3.3}$ |

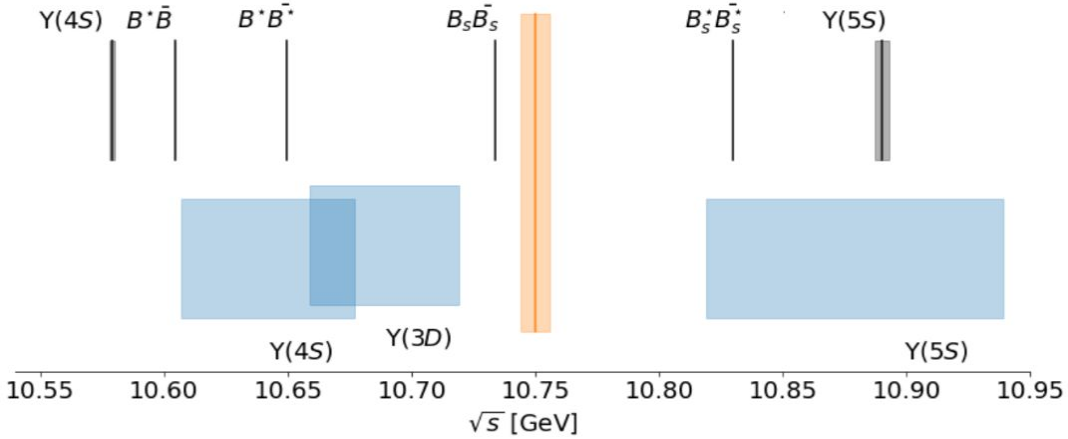



A dip in $\sigma(e^+e^- \to b\bar{b})$ can be described by Υ(10753)
CPC **44**, 8, 083001 (2020)



# What is the nature of Υ(10753)?

- Far from the thresholds;



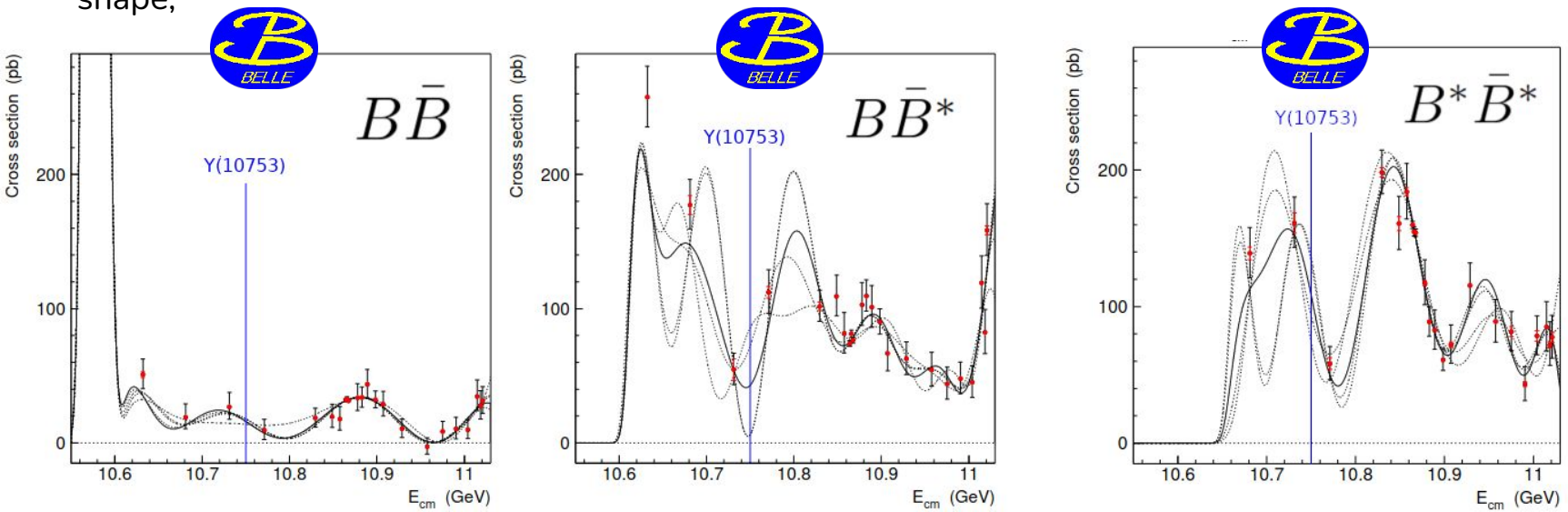

- Mass does not match Υ(3D) theoretical predictions, and D-wave states are not seen in $e^+e^-$ collisions;
- Υ(4S) - Υ(3D) mixing can be enhanced due to hadron loops.

- Tetraquark state:
  CPC **43**, 12, 123102 (2019),
  PLB, **802**, 135217 (2020),
- 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)
  PRD **106**, 094013 (2022)
  EPJC **137**, 357 (2022)

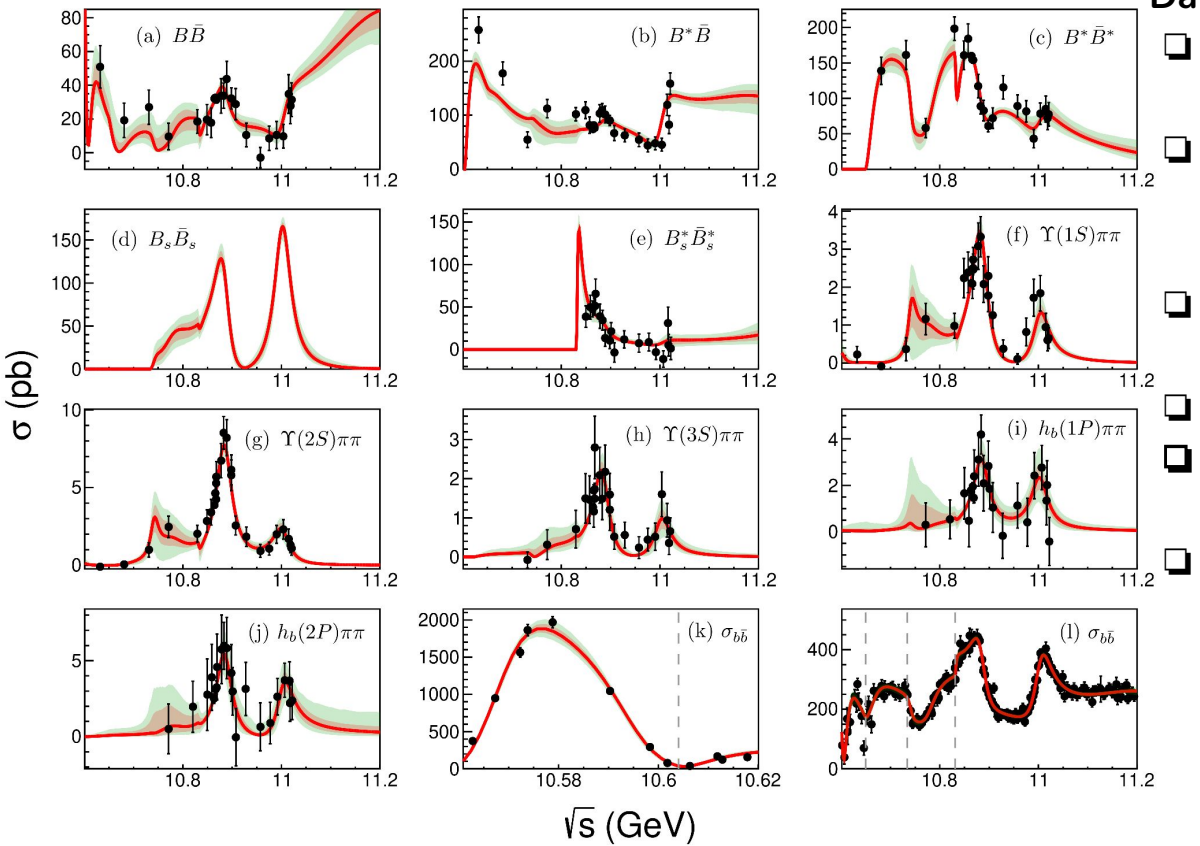
# Study of $e^+e^- \to B^{(*)}\bar{B}^{(*)}$

- $\sigma(e^+e^- \to B^{(*)}\bar{B}^{(*)})$ energy dependence show complicated spectra, that hard to describe with resonance shapes;
- Rescattering and opening of the various $B\bar{B}$ thresholds cause oscillatory behaviour due to the **coupled-channel effect**;
- **Coupled-channel approach** is necessary to study $\sigma(e^+e^- \to B^{(*)}\bar{B}^{(*)})$ shape;

JHEP 06 (2021) 137



# Global phenomenological analysis




**Data:**

- Two-body exclusive cross sections $\sigma(e^+e^- \to B_{(s)}^{(*)}\bar{B}_{(s)}^{(*)})$;
- Three-body exclusive cross sections $\sigma(e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-)$, n = 1,2,3; $\sigma(e^+e^- \to h_b(mP)\,\pi^+\pi^-)$, m = 1,2;
- Combined Belle and BaBar $R_b$ measurement;
- **Use coupled-channel approach.**
- **Poles:** Υ(4S), Υ(10753), Υ(5S) and Υ(6S)
- **Results:** pole positions (mass and width), branching fractions, dependence of scattering amplitudes on energy.

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

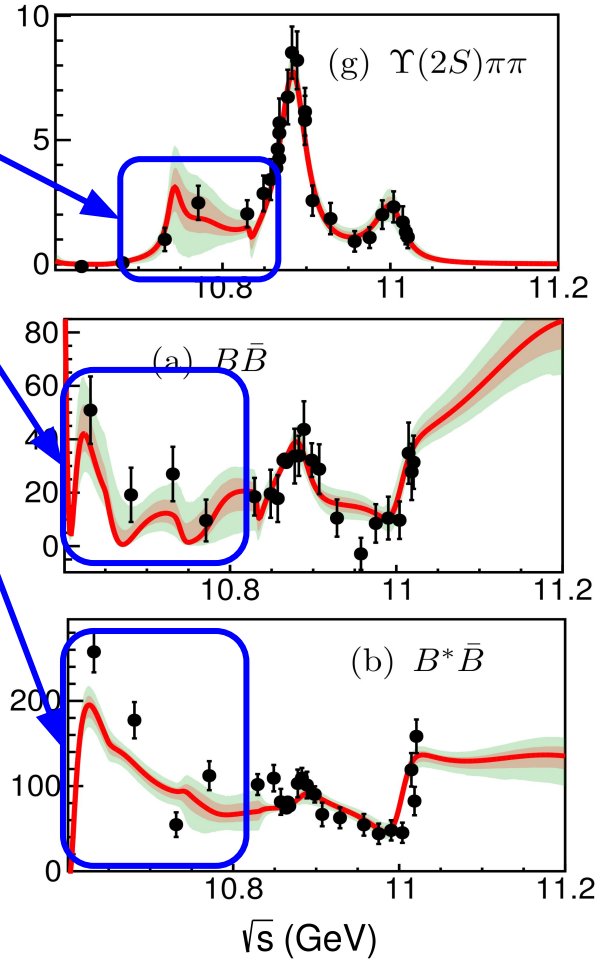
# More data is necessary

- To study Υ(10753) nature;
- Improve accuracy below Υ(5S);

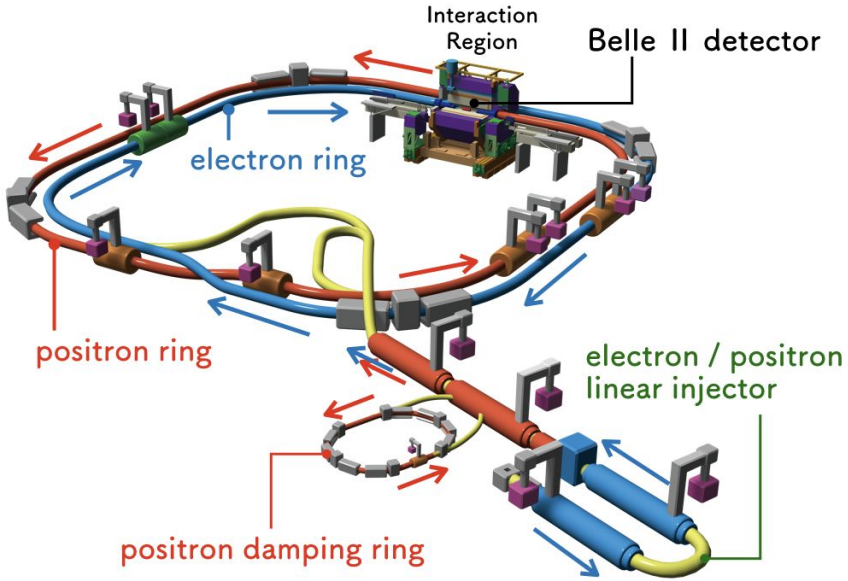
Perform energy scan at the Belle II experiment.

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 $B^*\bar{B}^*$

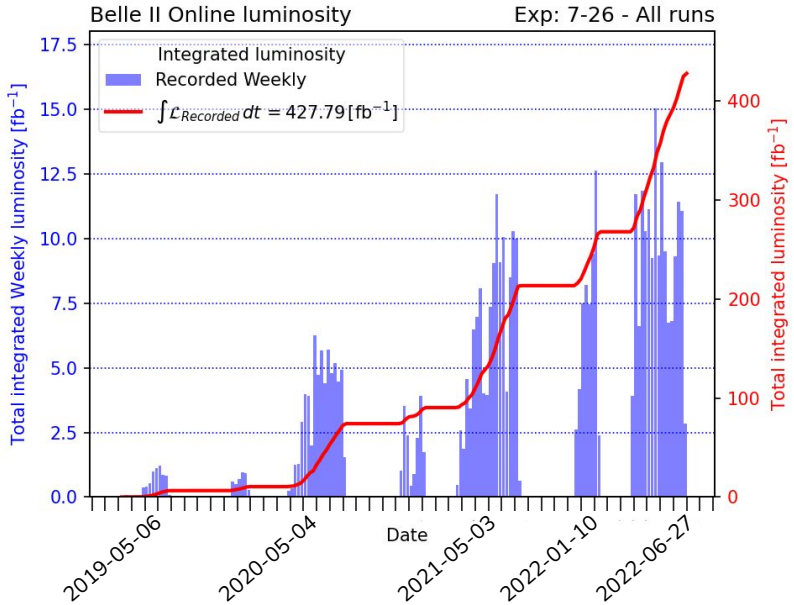


# SuperKEKB and Belle II




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

- Asymmetric $e^+e^-$ collider at KEK (Tsukuba, Japan) provides a unique clean environment;
- Instantaneous luminosity record of 4.7 x $10^{34}$ $cm^{-2}$ $s^{-1}$ (x2 of the Belle peak luminosity, current world record);



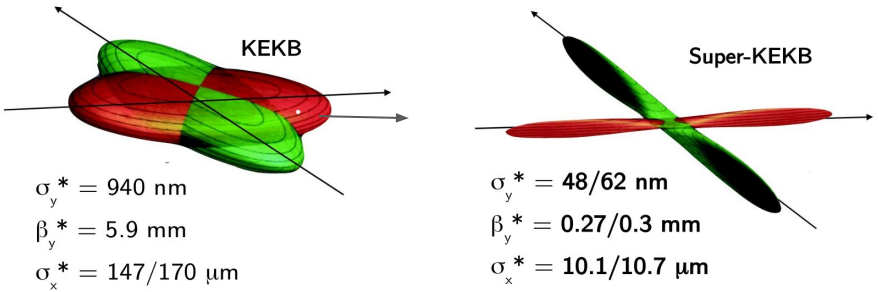
# SuperKEKB and Belle II

Beam current increased by **x1.5**.

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

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

**x30** instantaneous luminosity increase

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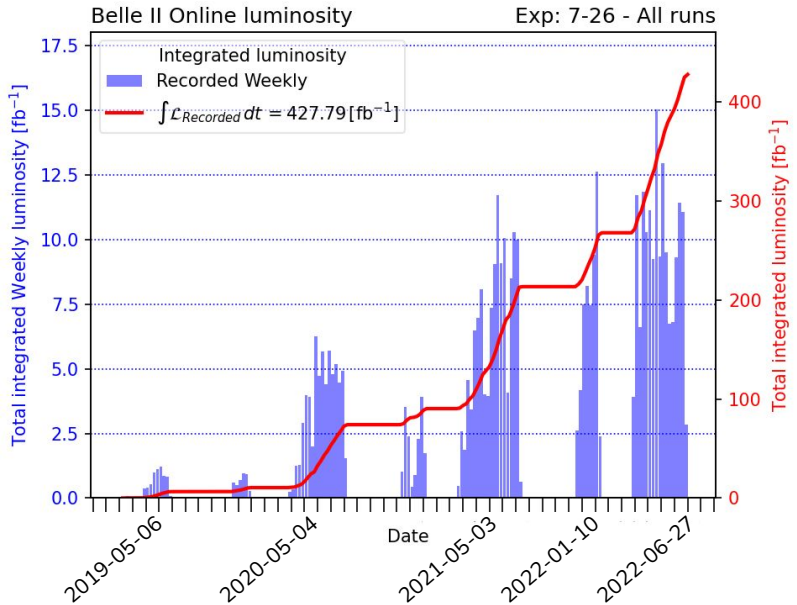
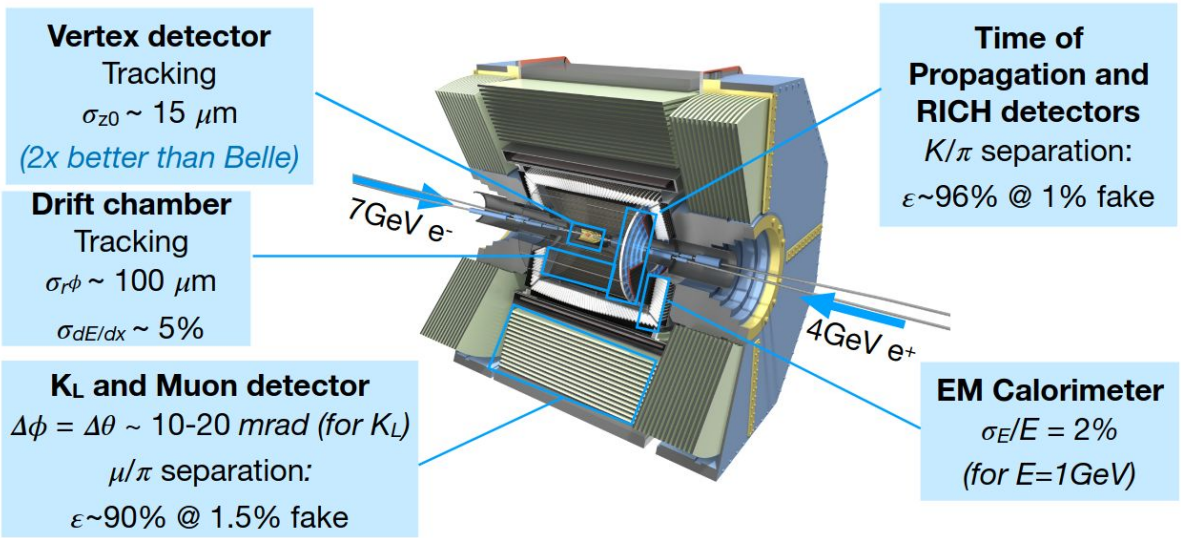


# SuperKEKB and Belle II

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

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

- ❏ Designed to measure CPV in B-mesons decays;
- ❏ Collect the data mostly at Υ(4S);
- ❏ Have a reach physics program beyond CPV;

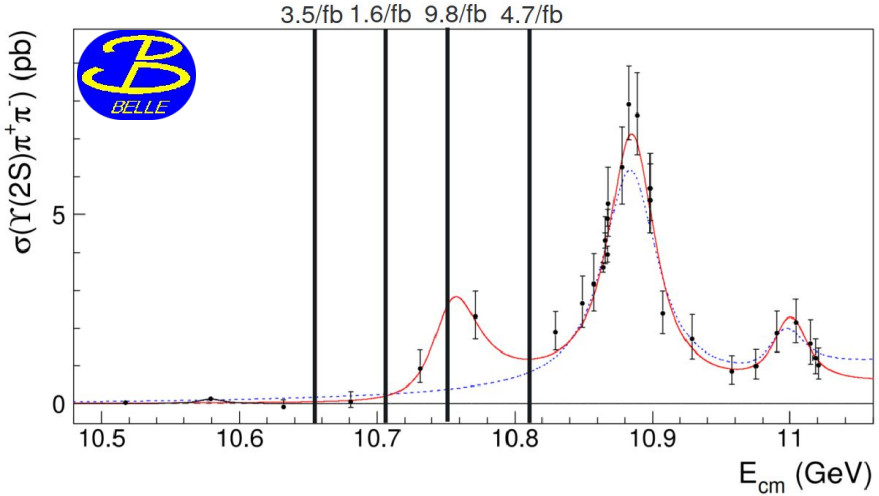


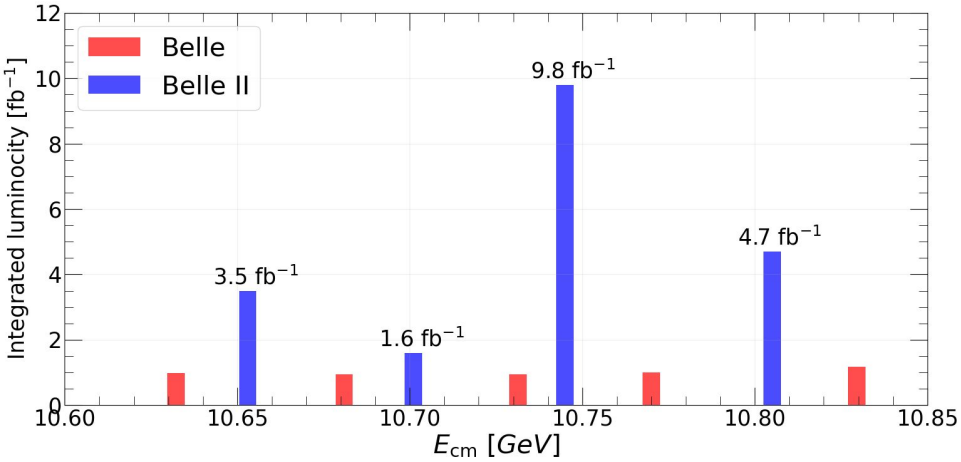

Belle II detector upgrades:

- ❏ 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;
- Belle II collected the data in the gaps between Belle energy scan points;
- The point with highest statistic (9.8 $fb^{-1}$) is near Υ(10753) peak;

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

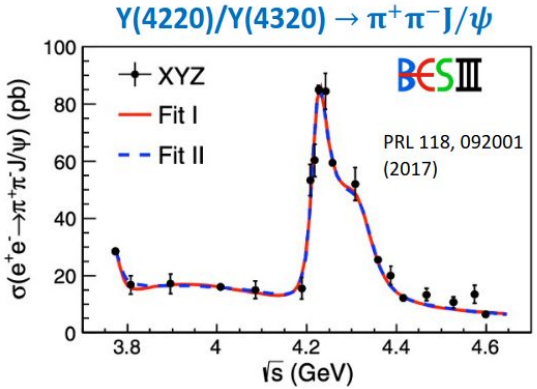
# Motivation to search for $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$

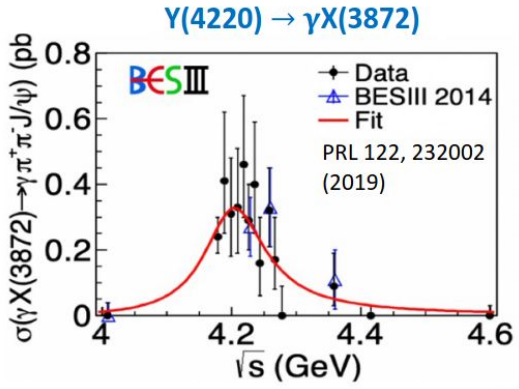
**Theory:**

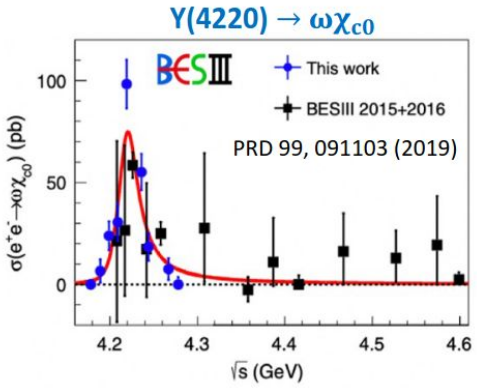
- Mixed $\Upsilon(4S)$ - $\Upsilon(3D)$ state: $\omega\chi_{bJ}$ could be enhanced (PRD **104**, 034036 (2021)).

**Charmonium sector:**

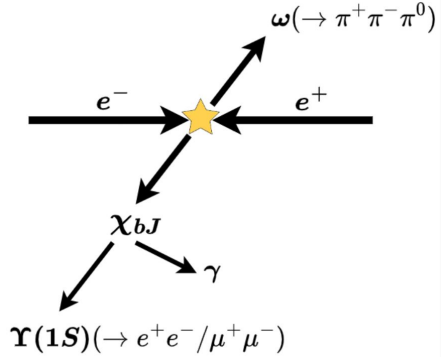
- Similar to $\Upsilon(10753)$ structure $Y(4220)$ was observed in $e^+e^- \to J/\Psi\,\pi^+\pi^-$ cross section dependence by BES III (PRL **118**, 092001 (2017)).
- $Y(4220)$ peak was observed in $\gamma X(3872)$ and $\omega\chi_{c0}$ final states by BES III (PRL, **122**, 232002 (2019), PRD **99**,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



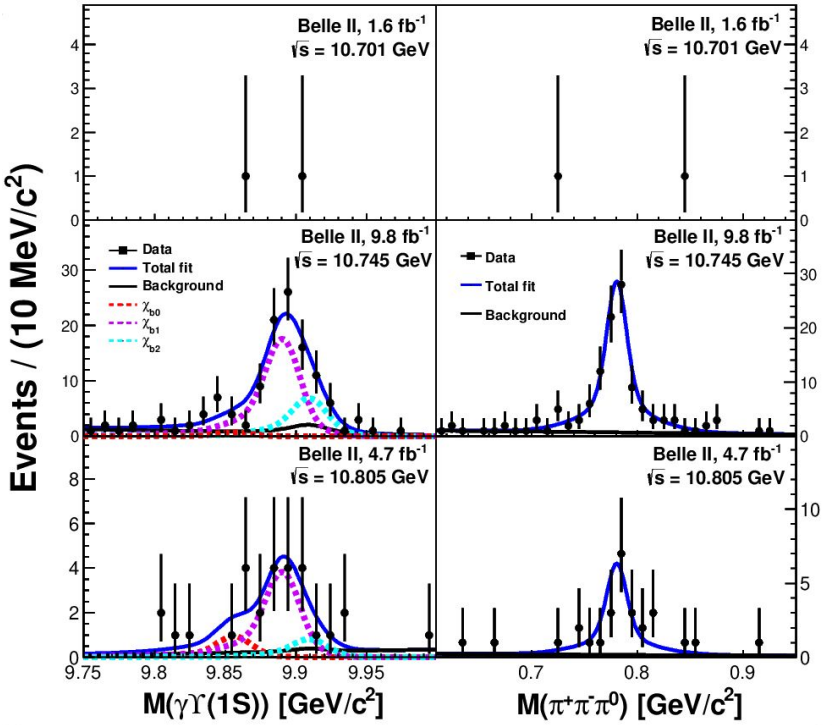

PRL **130**, 091902 (2023)

| Channel | $\sqrt{s}$ (GeV) | $N^{\rm sig}$ | $\Sigma(\sigma)$ | $\sigma_B$ (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 | $< 1.6$ |

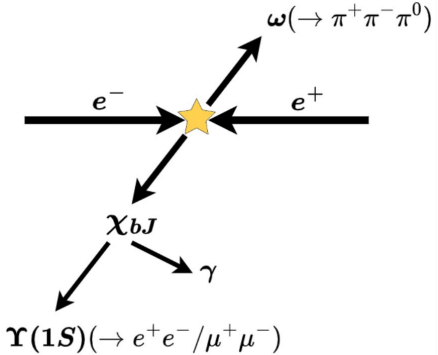
**11 $\sigma$**

**4.5 $\sigma$**

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



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

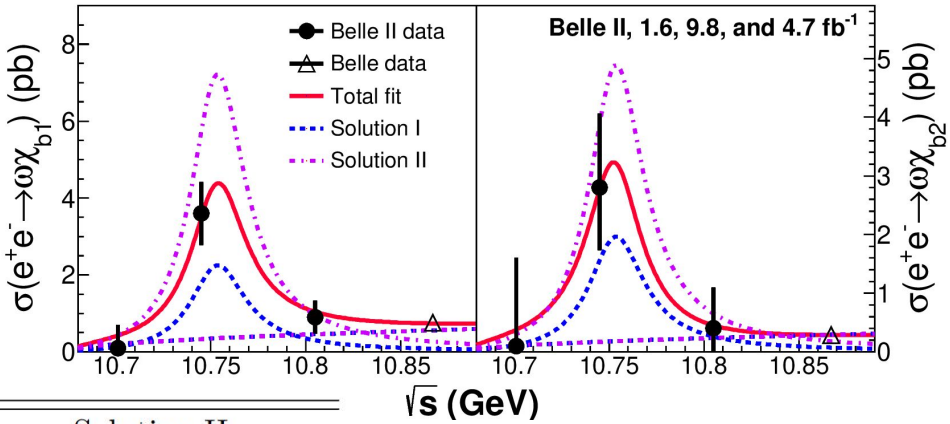



PRL **130**, 091902 (2023)

- Fit with coherent sum of PHSP and BW.

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

- 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 |

# Discussion

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

- Υ(5S) and Υ(10753) have same quantum numbers and similar masses, but there is a difference:

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

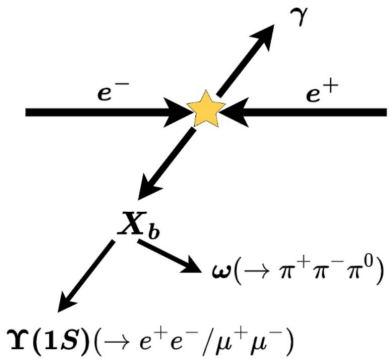
~1.5 at $\sqrt{s}$ = 10.745 GeV

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

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

It indicates the difference in the internal structures of these two states.

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




- No evidence of $X_b$ (partner of X(3872) in bottomonium) signal;
- Only $\omega\chi_{bJ}(1P)$ reflections are seen;

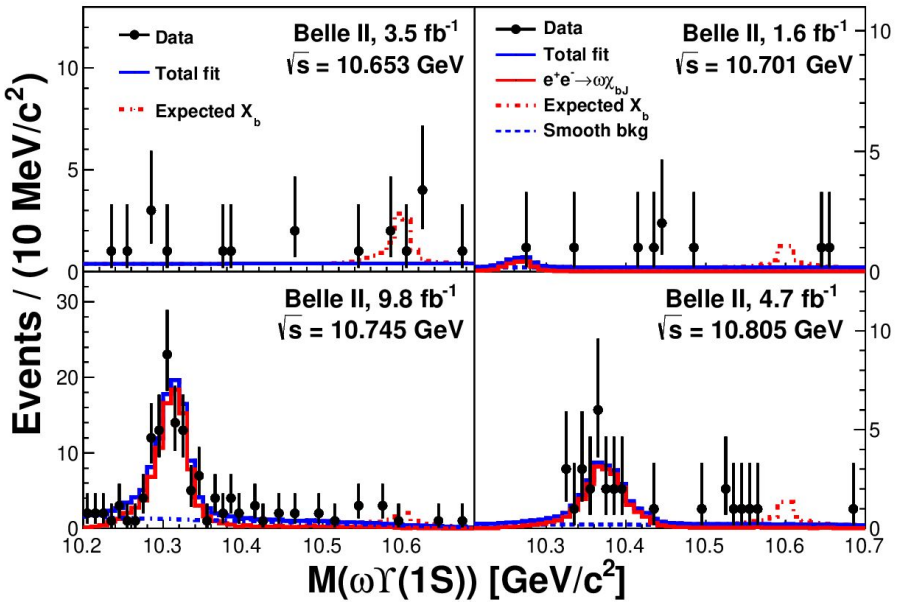
PRL **130**, 091902 (2023)

- 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 | $< 0.47$ |

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



# 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;
- $B^* \to B\gamma$ decays are not reconstructed;

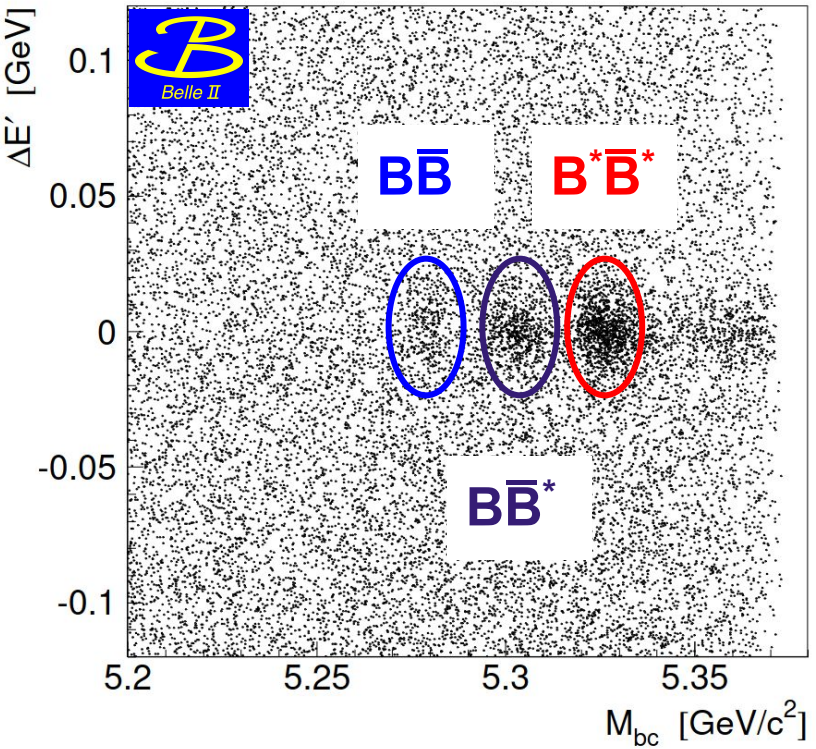
$$\Delta E = E_B - E_{\rm cm}/2$$

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

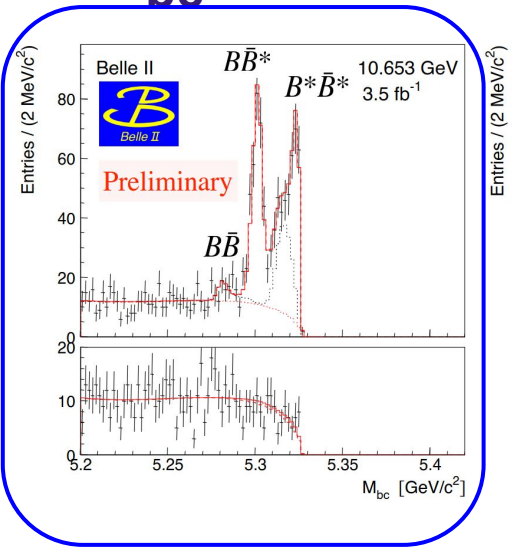
- $|\Delta E'| < 18$ MeV;
- Signal is identified using $M_{bc}$:

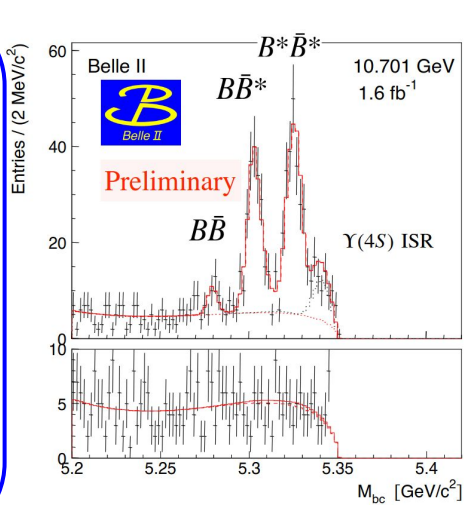
$$M_{\rm bc} = \sqrt{E_{\rm cm}^2/4 - p_B^2}$$

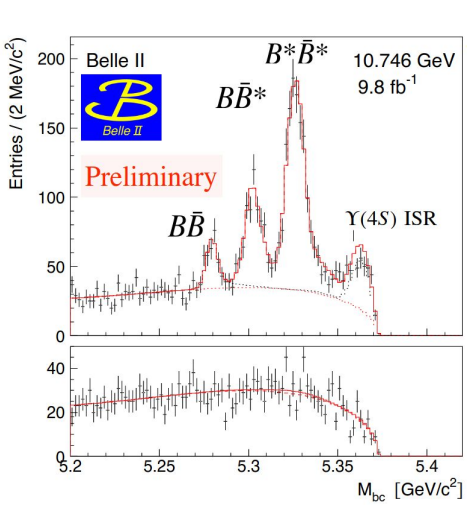
$\Delta E'$ vs $M_{bc}$ at $E_{cm}$ = 10.746 GeV

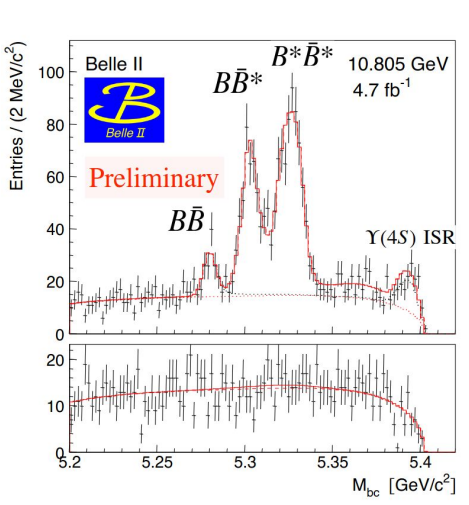


# $M_{bc}$ fit at scan energies



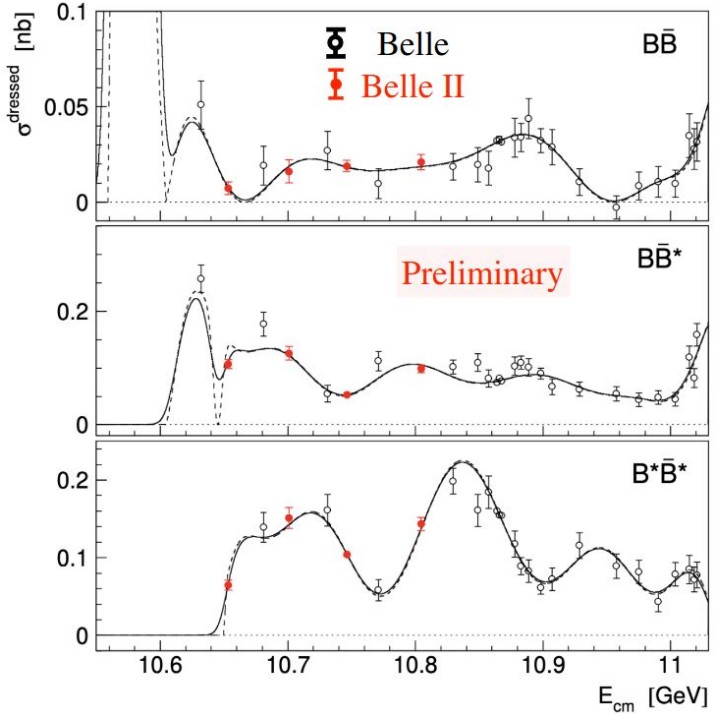




- Good description of the $M_{bc}$ in data;
- Contribution of $\Upsilon(4S)\to B\bar{B}$ production via ISR is visible well described by the fit;
- E=10.653 GeV sharp cut of the data at right edge ⇒ fast rise of $B^*\bar{B}^*$ near threshold;

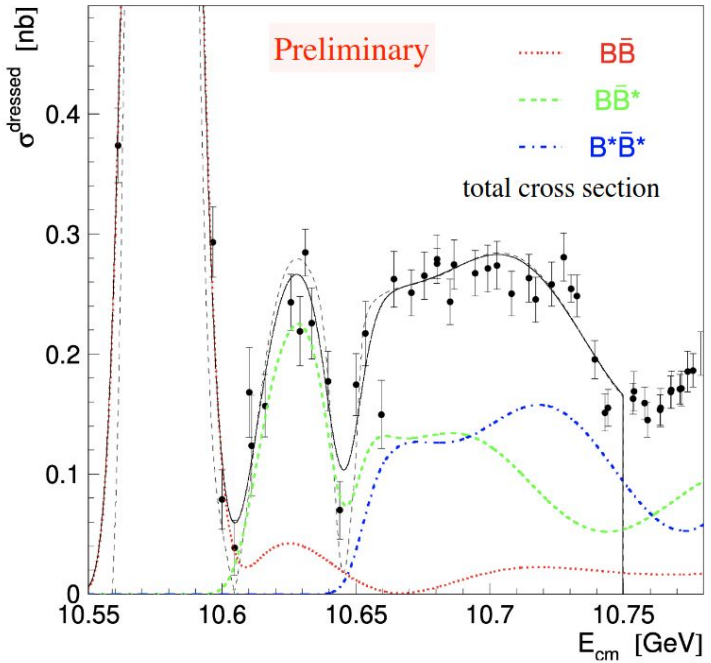
# Energy dependence of the cross sections

Simultaneous fit to:

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

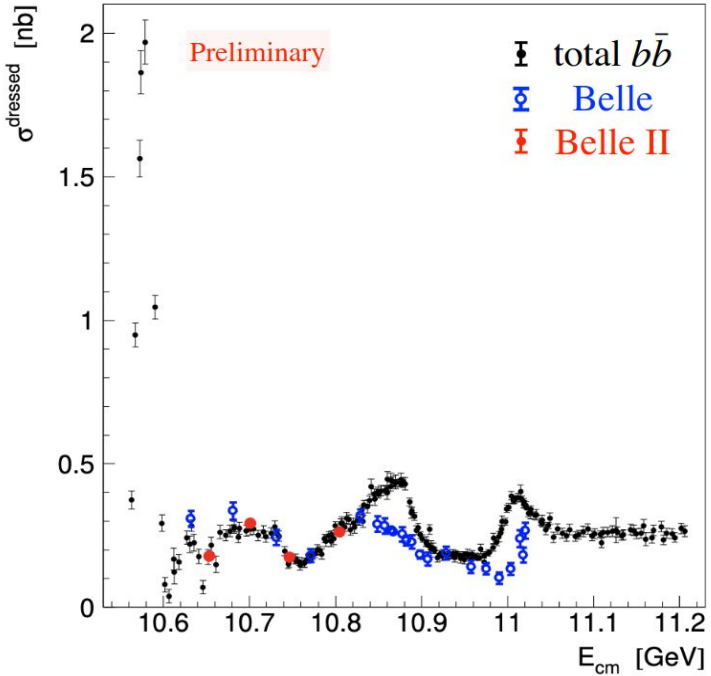


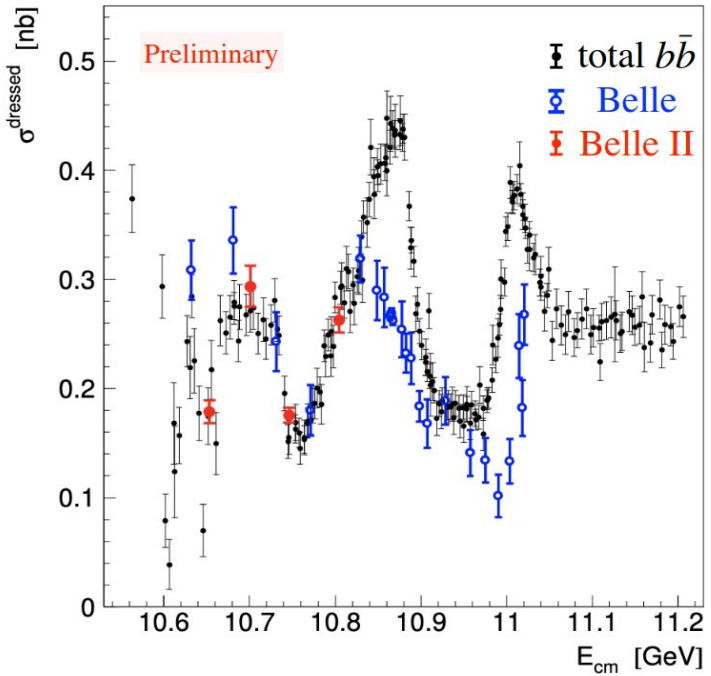

- Total cross section (CPC **44**, 8, 083001 (2020))



# 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 $B_s^{(*)}\bar{B}_s^{(*)}$, multi-body $B^{(*)}\bar{B}^{(*)}\pi(\pi)$ and bottomonia;



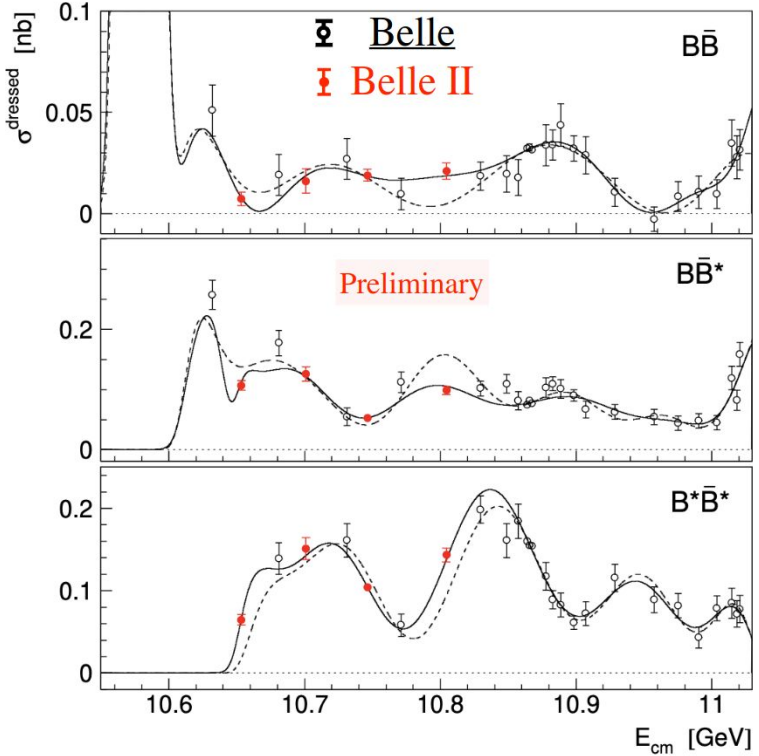
# Discussion

New measurement complements 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 $e^+e^- \to B^*\bar{B}^* \to B\bar{B}^*$;
- $\Upsilon\,\pi^+\pi^-$ and $h_b\eta$ final states could also be enhanced (PRD **87**, 094033 (2013)).



# Conclusion

**Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$ at $\sqrt{s}$ = 10.75 GeV**

- $\sigma[e^+e^- \to \omega\chi_{bJ}(1P)]$ has a peak at 10.75 GeV
- Confirmation of $\Upsilon(10753)$ and observation of its new decay channel;

**Energy dependence of $e^+e^- \to$ $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$**

- Confirmation of "oscillatory" behavior, improvement of the accuracy;
- Rapid rise of $\sigma(e^+e^- \to B^*\bar{B}^*)$ above threshold - signal of molecular $B^*\bar{B}^*$ state?

**Scan above $\Upsilon(4S)$ gives an opportunity for a lot of unique studies:**

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

| Golden Modes |
| --- |
| $e^+e^- \to \pi^+\pi^-\Upsilon(pS)(\to \ell^+\ell^-)$ |
| $B\overline{B}$ decomposition — Preliminary result |
| $\pi^+\pi^-$ 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!**