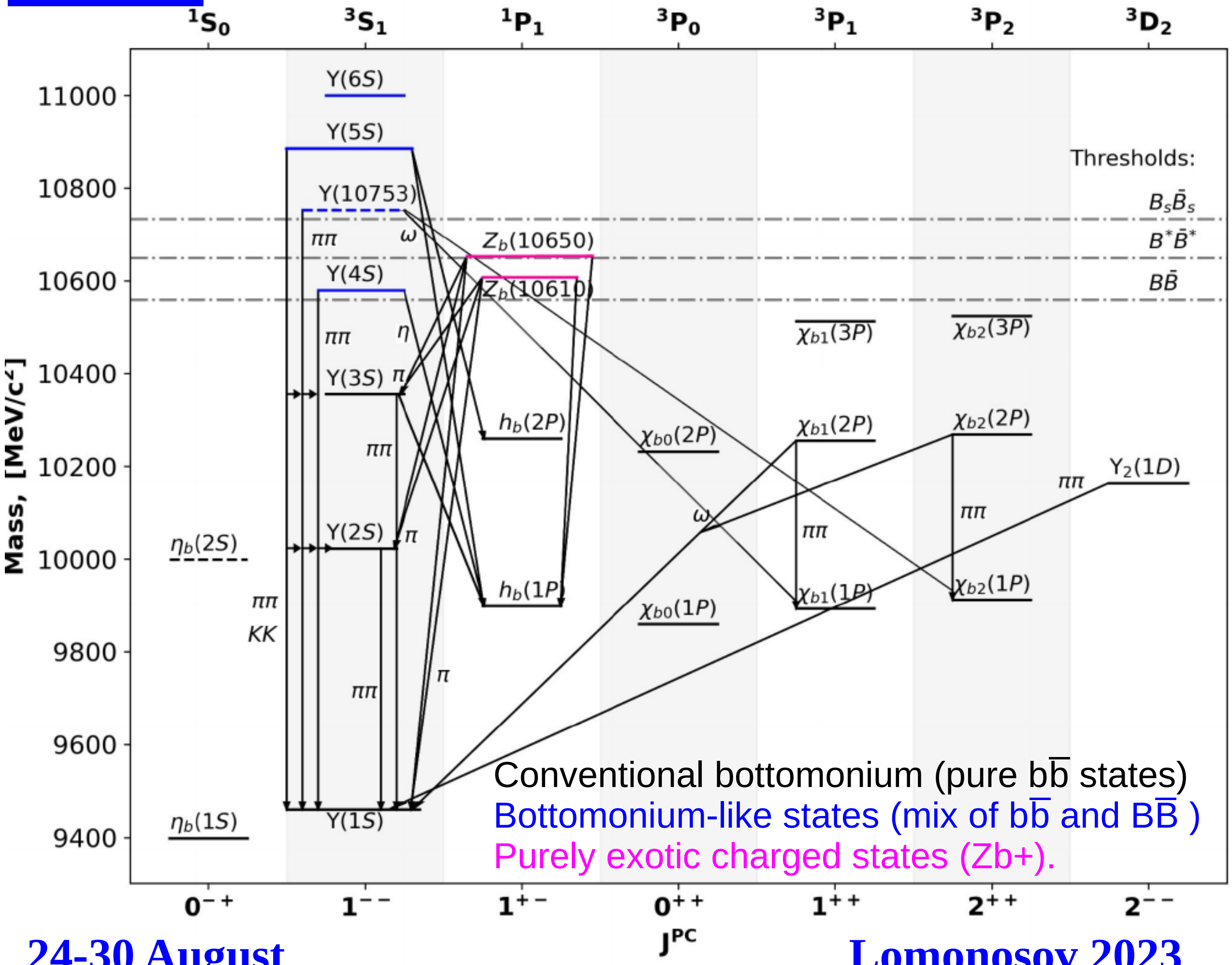
Exotic quarkonium and spectroscopy

Pavel Krokovny
Budker INP
on behalf of Belle II collaboration

- Introduction
- Observation of $Y(10753) \to \omega\chi_{bJ}(1P)$
- $Y(10753) \to \omega\eta_b(1S)$ and $\omega\chi_{b0}(1P)$
- $e^+e^- \to B^{(*)}\bar{B}^{(*)}$
- Summary

Bottomonium states



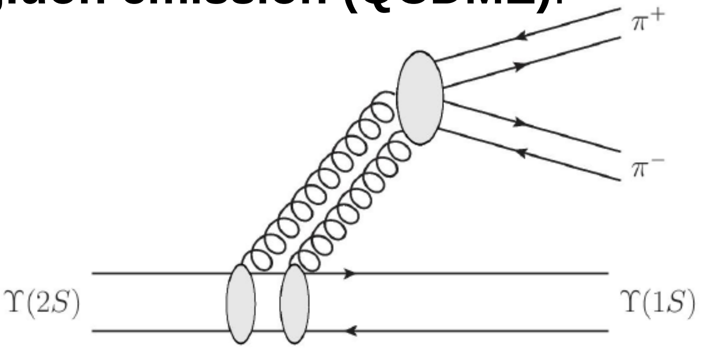
Below $B\bar{B}$ threshold states are well described by the potential models

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

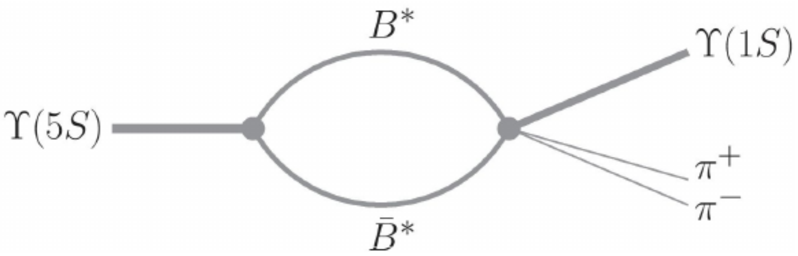
- hadronic transitions are strongly enhanced (OZI rule violation)
- η transitions are not suppressed compare to $\pi^+\pi^-$ transitions (HQSS violation)
- two charged Z_b^+ states are observed

Bottomonium states

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**:



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

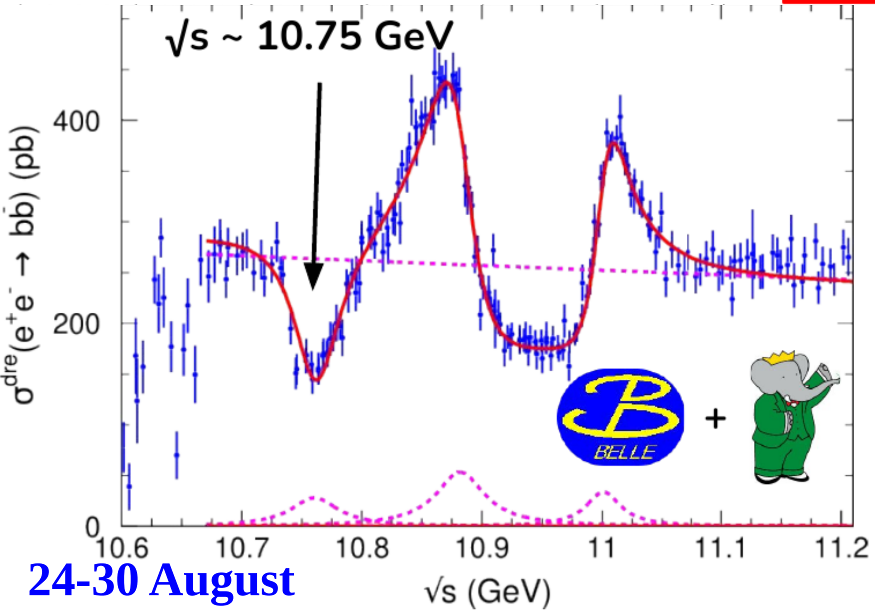
Z_b decay mode	Branching fraction
$Z_b^+(10610) \to \Upsilon(nS)/h_b(mP)\pi^+$	$14.4^{+2.5}_{-1.9}\%$
$Z_b^+(10610) \to B^+\bar{B}^{*0}/\bar{B}^0 B^{*+}$	$85.6^{+2.1}_{-2.9}\%$
$Z_b^+(10650) \to \Upsilon(nS)/h_b(mP)\pi^+$	$26.6^{+5.0}_{-4.7}\%$
$Z_b^+(10650) \to B^{*+}\bar{B}^{*0}$	$74^{+4}_{-6}\%$

This is a strong indication of the molecular nature of Z_b^+ states
PRL, 108, 122001 (2012)

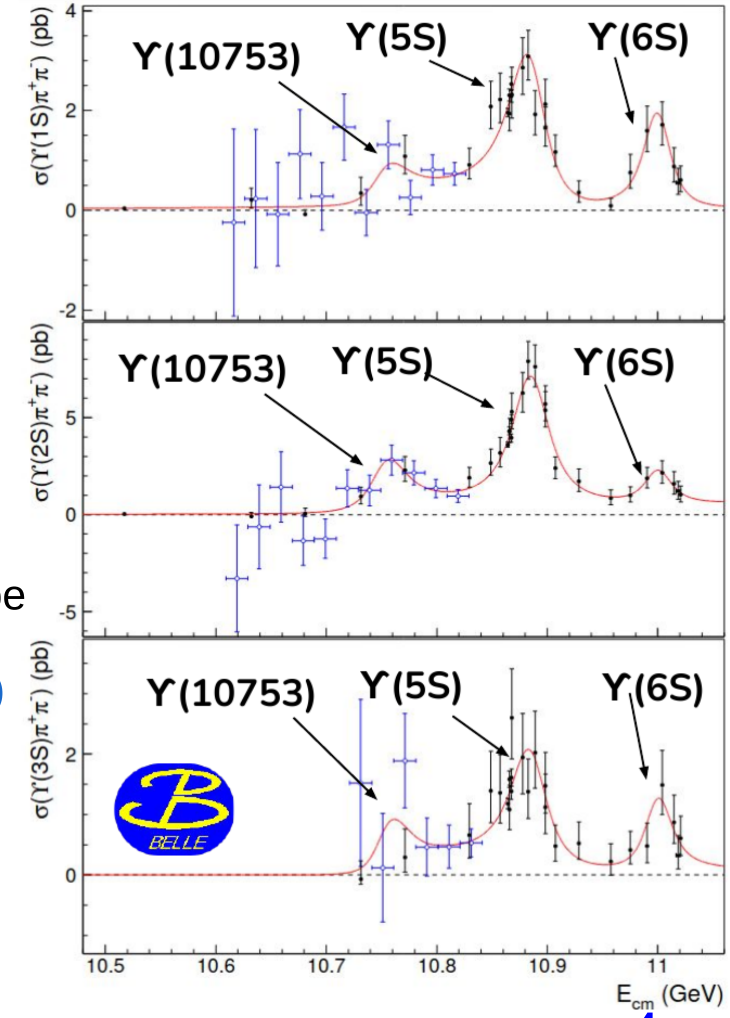
Discovery of Y(10753)

Observed in the $e^+e^- \to Y(nS)\,\pi^+\pi^-$ cross section energy dependence by Belle JHEP 10 (2019) 220

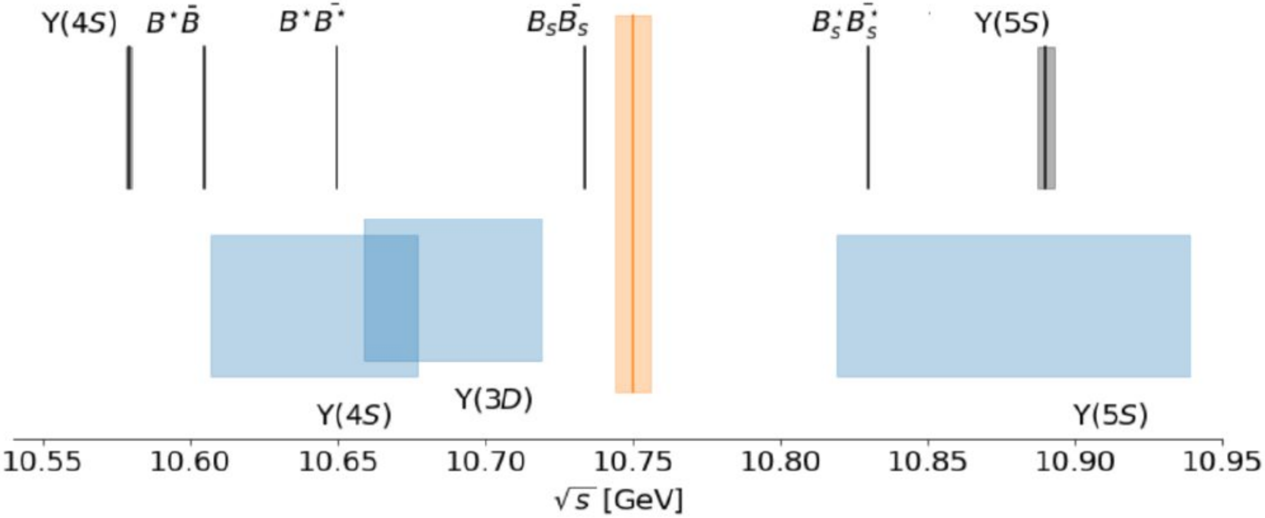
	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}\,^{+1.0}_{-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$



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



What is the nature of Υ(10753)?



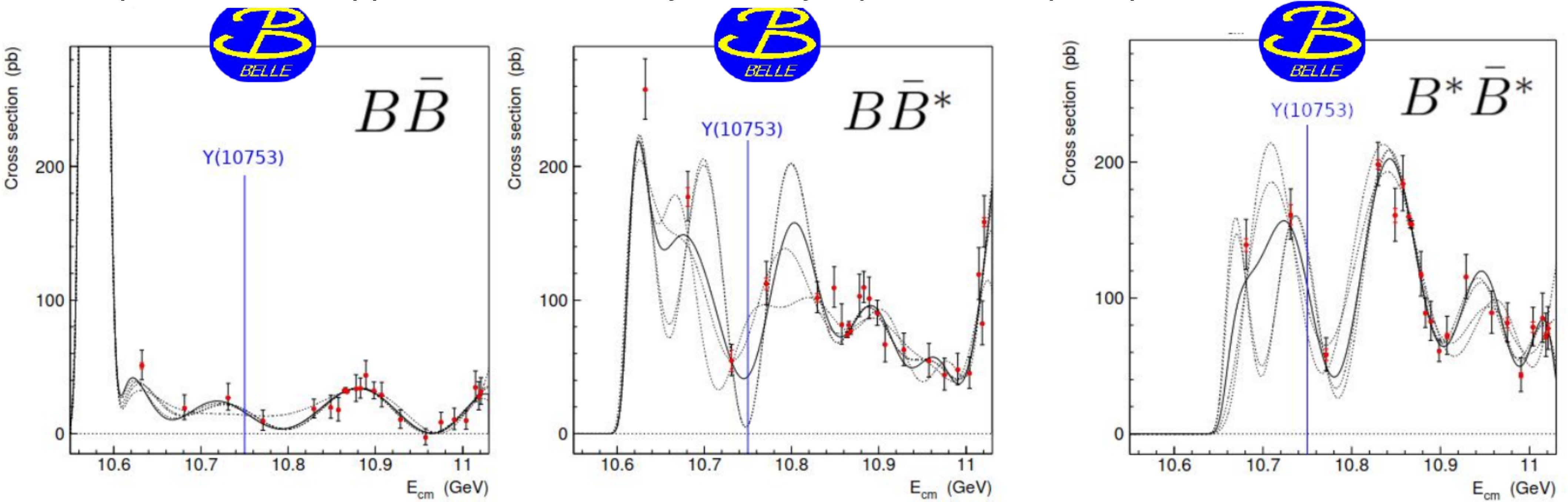
- Far from the thresholds
- Mass does not match Υ(3D) theoretical predictions, and D-wave states are not seen in e^+e^- collisions
- Υ(4S) - Υ(3D) mixing can be enhanced due to hadron loops

- Conventional $b\bar{b}$ state:
  - EPJC 80, 1, 59 (2020)
  - PLB 803, 135340 (2020)
  - PRD 101, 1, 014020 (2020)
  - PRD 102, 1, 014036 (2020)
  - PRD 104, 034036 (2021)
  - PRD 105, 074007 (2022)
  - PRD 106, 094013 (2022)
  - EPJP 137, 357 (2022)
- 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)

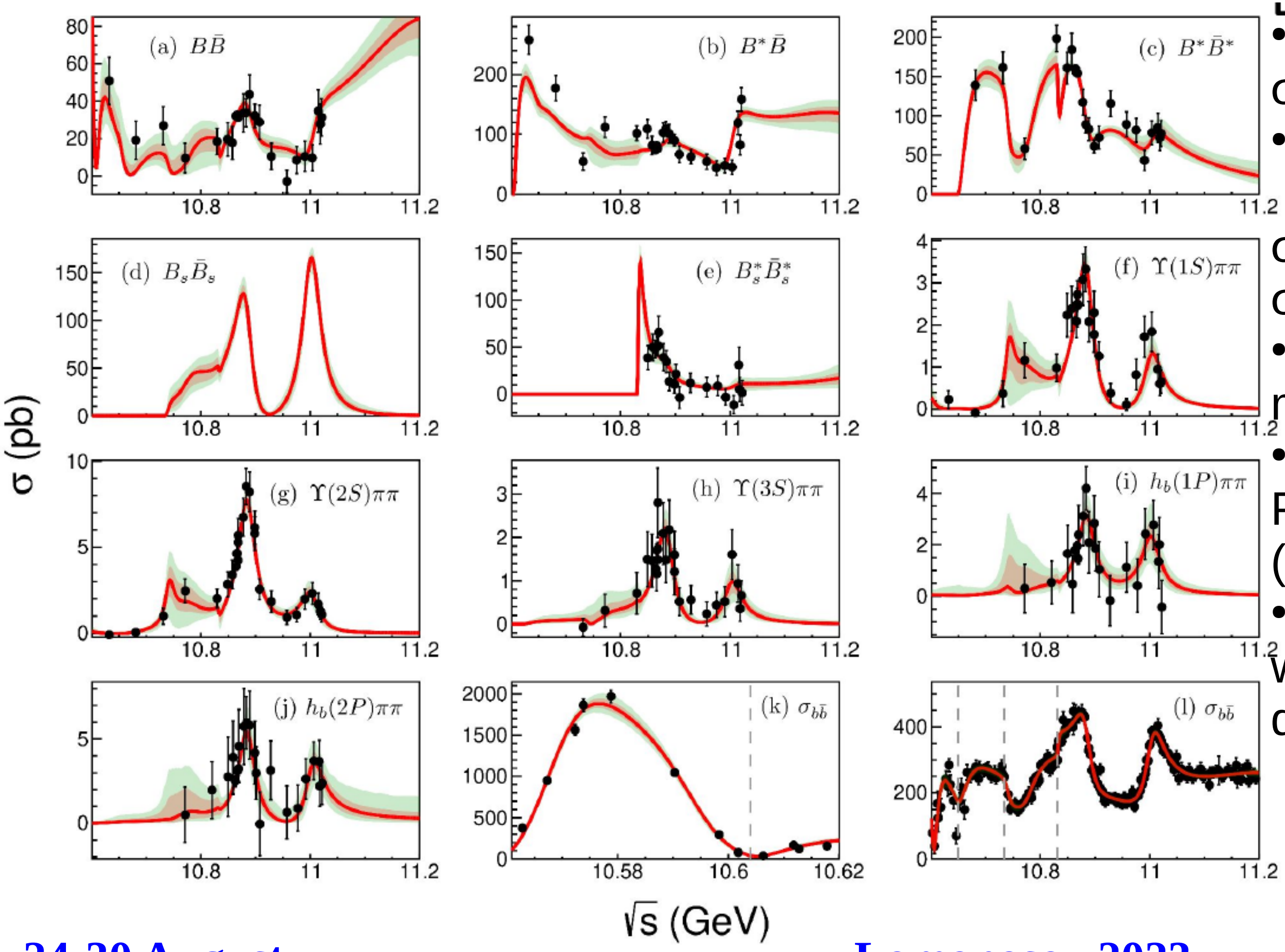
Study of $e^+e^- \to B^{(*)}\bar{B}^{(*)}$

- $\sigma(e^+e^- \to B^{(*)}\bar{B}^{(*)})$ has complicated energy dependence 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
- Using coupled-channel approach.

Poles: Y(4S), Y(10753), Y(5S) and Y (6S)

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

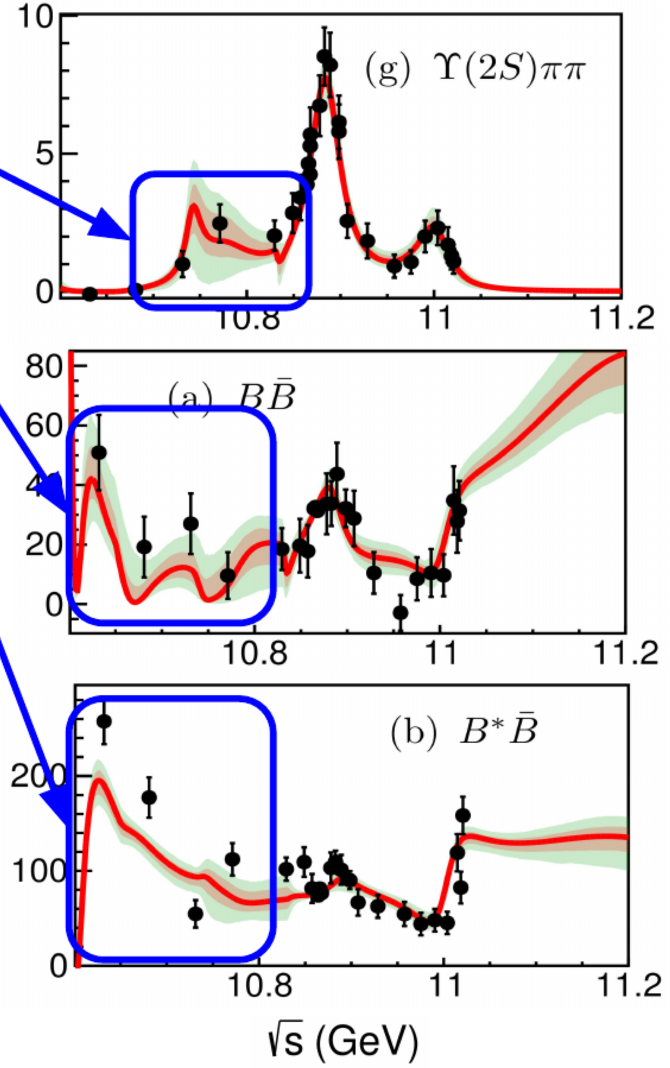
PRD 106 (2022) 9, 094013

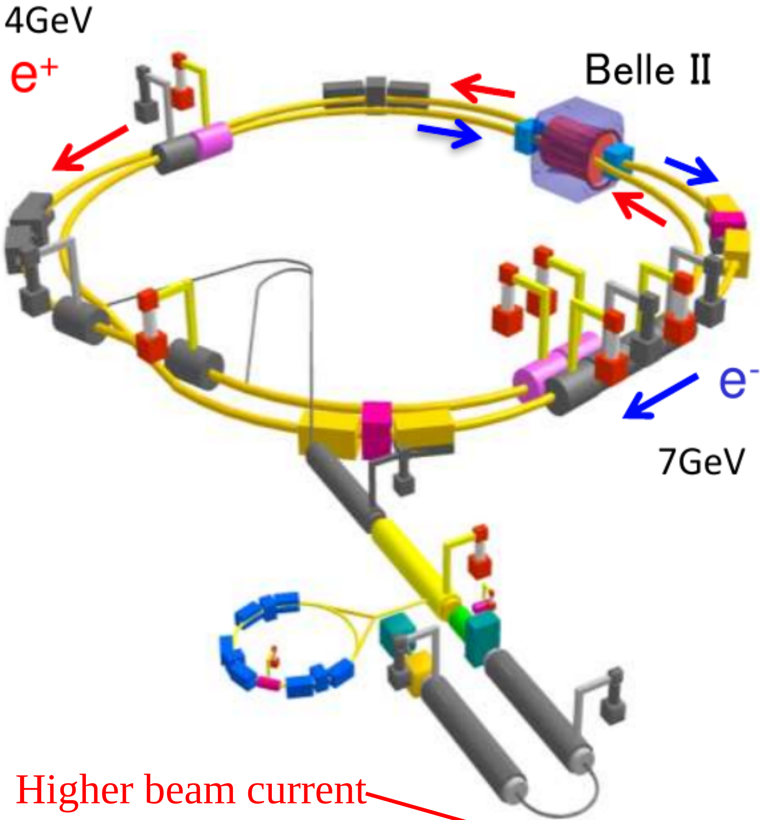
Requesting more data

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

- Perform energy scan at the Belle II experiment

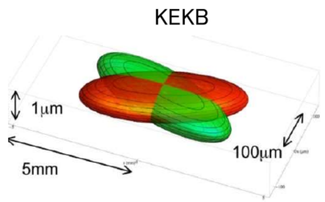
- Two Belle II results will be presented:
  $e^+e^- \to \omega\chi_{bJ}(1P)$ and $\chi_b \to \gamma Y(1S)$
  $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$

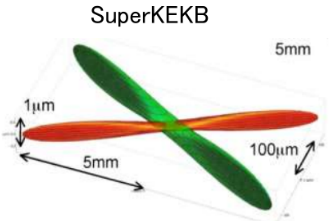




SuperKEKB collider

- Asymmetric e^+e^- collider
- Energy limit 11.02 GeV (up to 11.24)
- Luminosity goal: 6×10^{35} $cm^{-2}s^{-1}$
- Belle II goal: collect 50 ab^{-1}





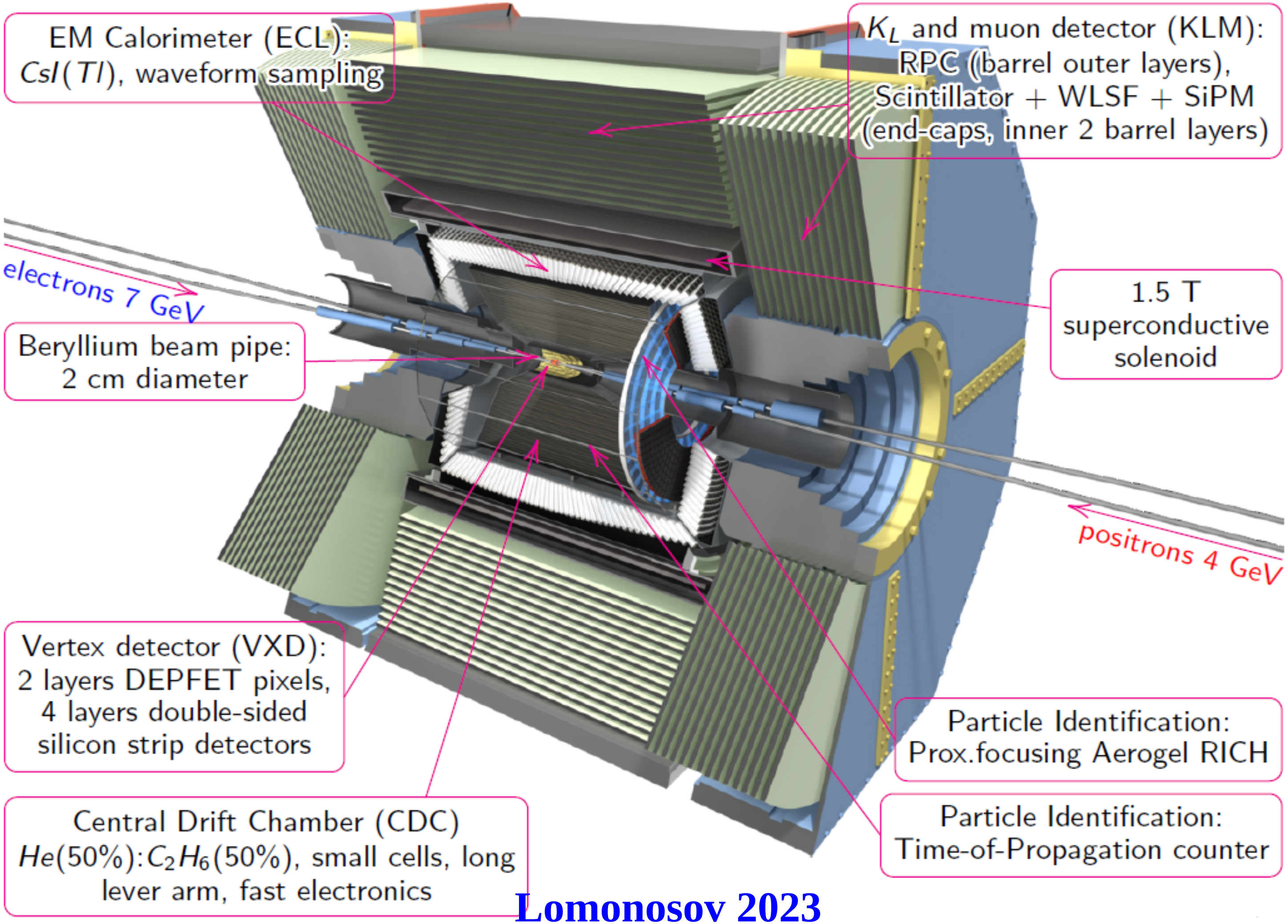
Higher beam current

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

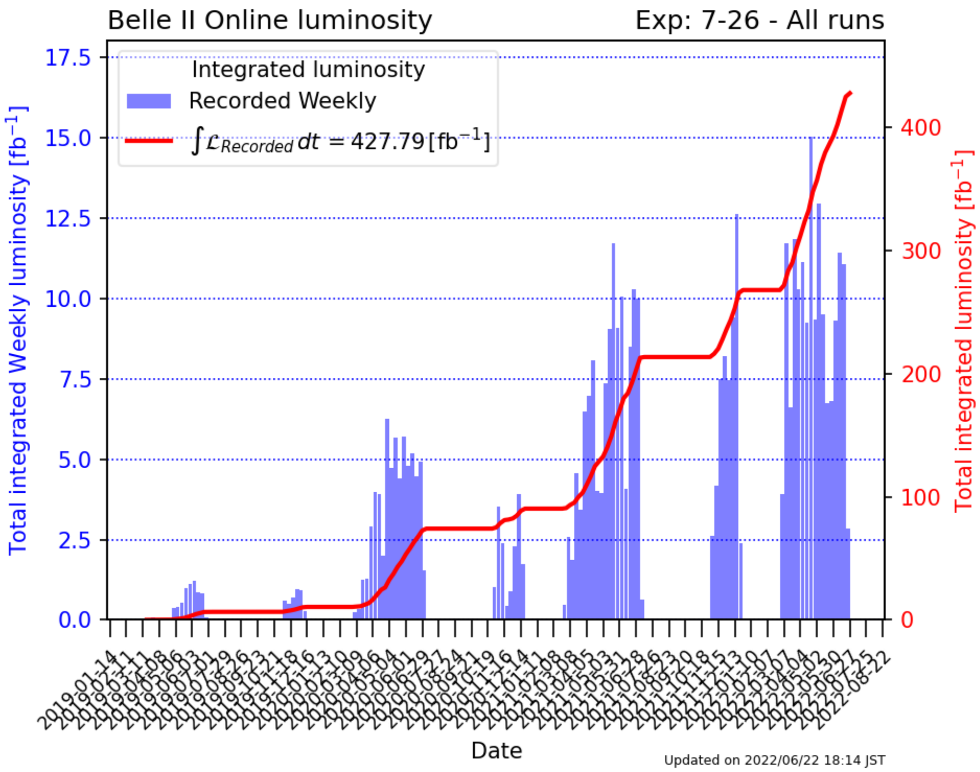
Very strong vertical focusing at the interaction point

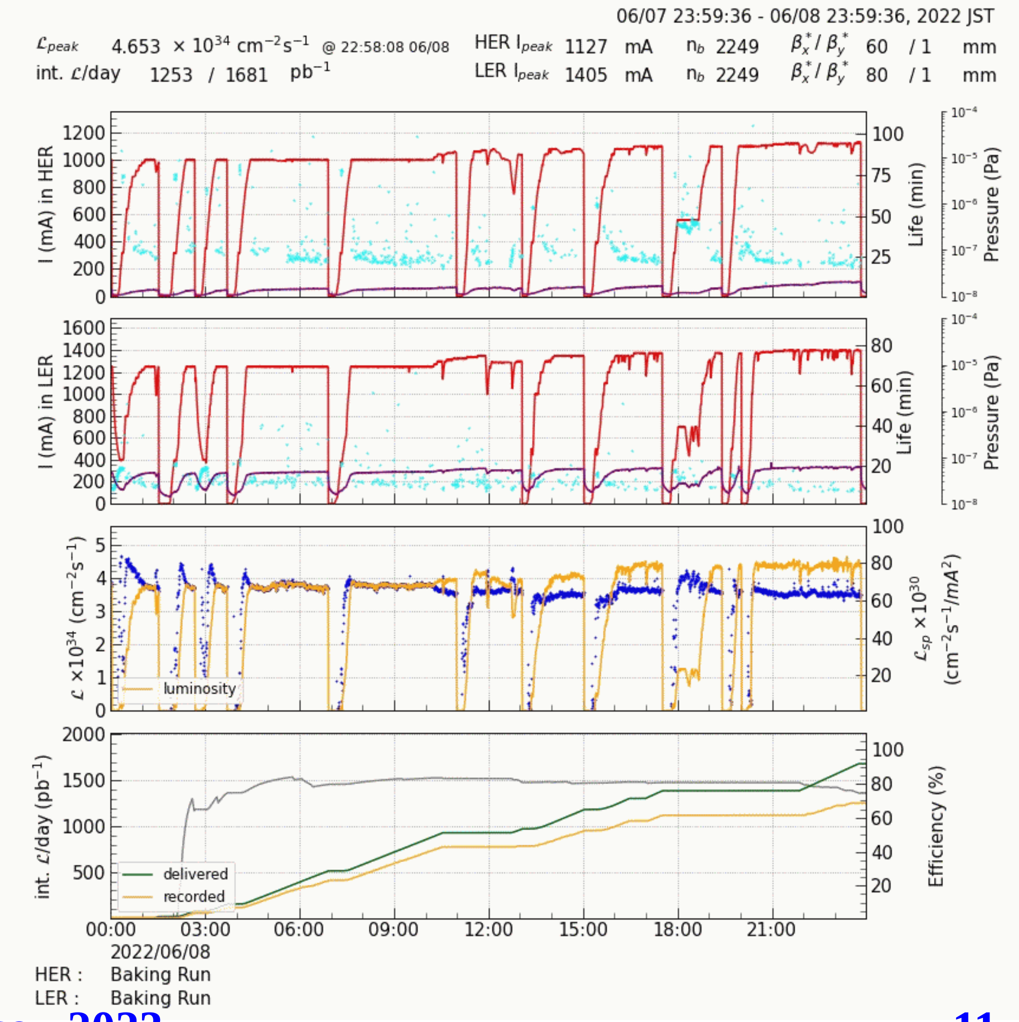
parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7	GeV
bg		0.425		0.28		
Half crossing angle	ϕ	11		41.5		mrad
Beta functions at IP	β_x^*/β_y^*	1200/5.9		x20 → 60/0.3		mm
Beam currents	I_b	1.64	1.19	x1.5 → 2.5	1.8	A
Luminosity	L	2.1 x 10^{34}		6.5 x 10^{35}		$cm^{-2}s^{-1}$

Belle II detector



Data taking status

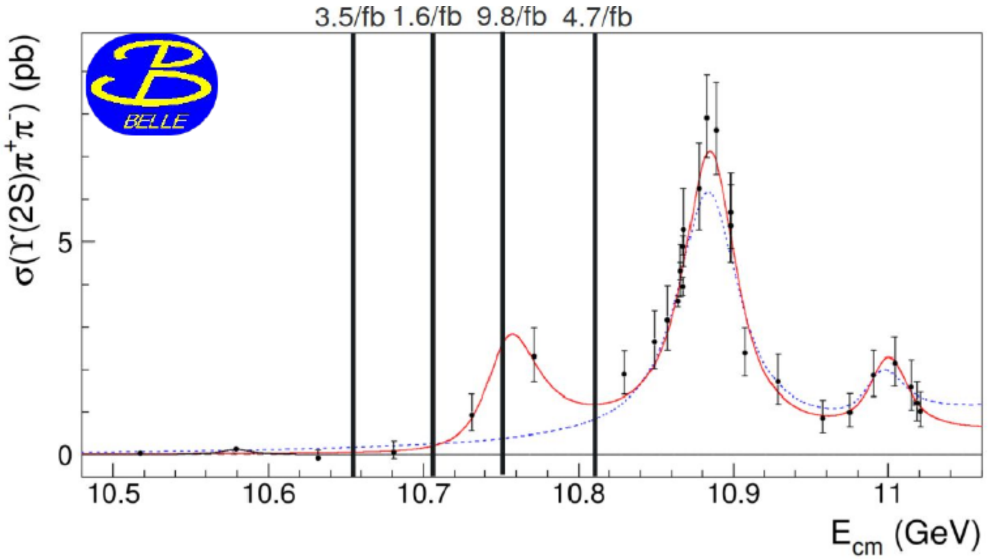


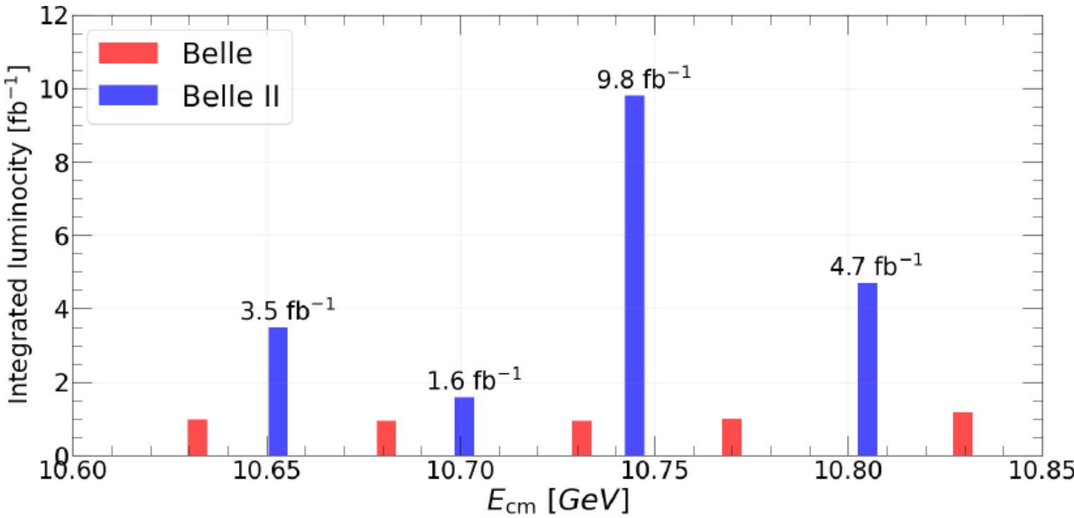


- New luminosity world record $4.65 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
- Data taking efficiency is achieved almost 90%.
- Collected more than $400\ \mathrm{fb}^{-1}$.

Data above Υ(4S)

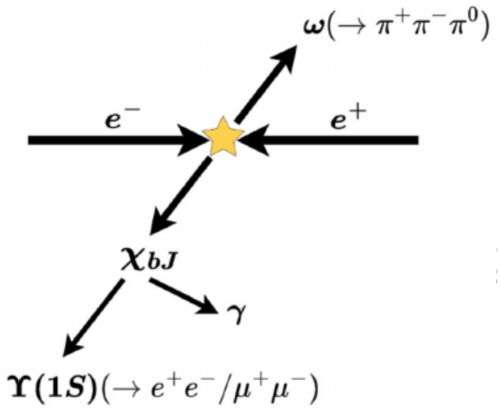
Υ(10753) state was observed by Belle in the analysis of the $e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$ (n = 1,2,3) cross section energy dependence JHEP 10 (2019) 220.

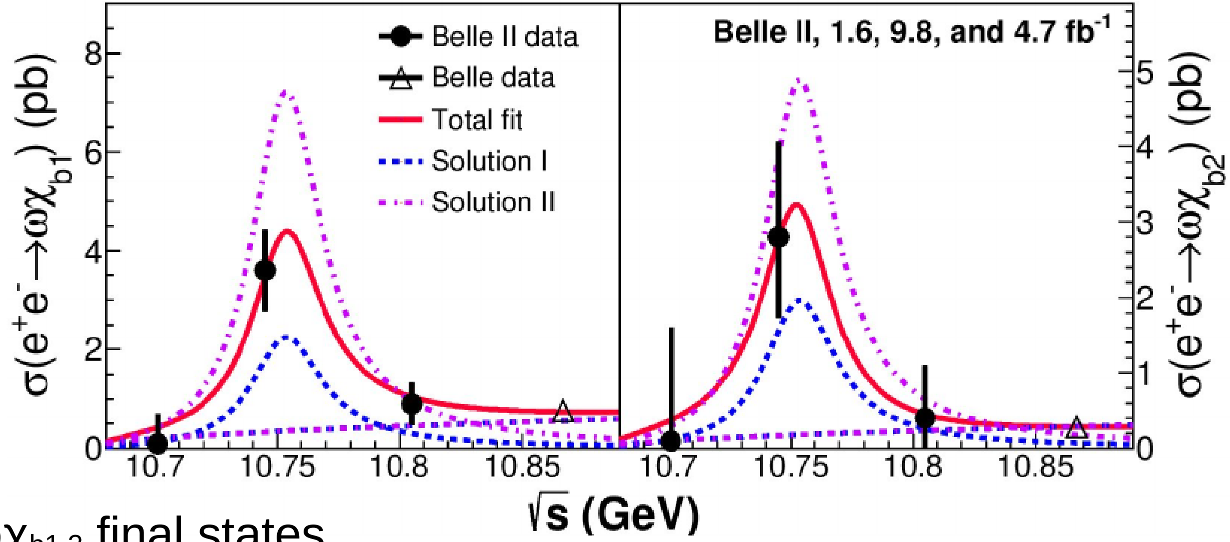




- Belle II collected 19 fb^{-1} around Υ(10753) in the gaps between Belle energy scan points
- 9.8 fb^{-1} is taken near Υ(10753) peak

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





- Significant signals are observed in $\omega\chi_{b1,2}$ final states
- Confirmation of Y(10753) and observation of its new decay channels
- Order of magnitude difference is observed for this ratio at Y(5S) and Y(10753) indicates the difference in the internal structures of these two states:

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

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

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

Motivation for $\Upsilon(10753) \to \omega\eta_b(1S)$ / $\chi_{b0}(1P)$

- Tetraquark (diquark-antidiquark) interpretation of this state predicts enhancement of $\Upsilon(10753) \to \eta_b(1S)\omega$ transition: CPC 43 (2019) 12, 123102

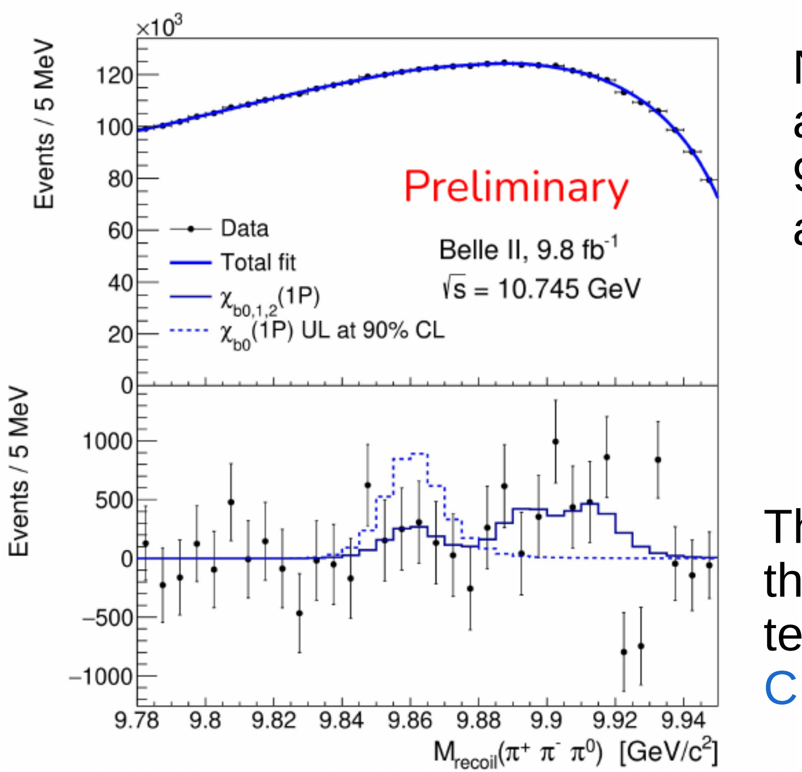
$$\frac{\Gamma(\eta_b\ \omega)}{\Gamma(\Upsilon\ \pi^+\pi^-)} \sim 30$$

- Since $\eta_b(1S)$ does not have easy for reconstruction decay channels, we reconstruct only $\omega \to \pi^+\pi^-\pi^0$ and use its recoil mass to identify the signal:

$$M_{\text{recoil}}(\pi^+\pi^-\pi^0) = \sqrt{\left(\frac{E_{\text{c.m.}} - E^*}{c^2}\right)^2 - \left(\frac{p^*}{c}\right)^2}$$

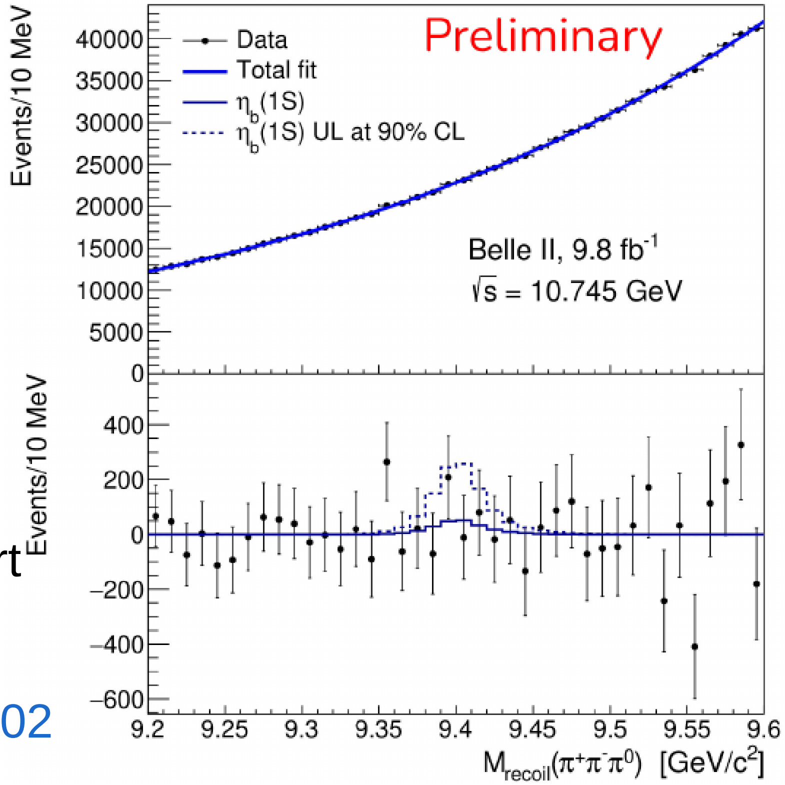
- $e^+e^- \to \omega\chi_{b0}(1P)$ transition was not observed due to $\mathcal{B}[\chi_{b0}(1P) \to \Upsilon(1S)\gamma] = (1.94 \pm 0.27)\%$; In charmonium sector $Y(4220) \to \chi_{c0}\omega$ decay was found to be enhanced compare to $Y(4220) \to \chi_{c1,2}\omega$ by BES III: PRD 99, 091103(R) (2019)

$\Upsilon(10753) \to \omega\eta_b(1S)/\chi_{b0}(1P)$ results



No significant signals are observed, 90% C.L. upper limits are set

This result do not support the prediction within the tetraquark model
CPC 43 (2019) 12, 123102



$\sigma[e^+e^- \to \omega\chi_{b0}(1P)] < 8.7$ pb

$\sigma[e^+e^- \to \omega\eta_b(1S)] < 2.5$ pb

JHEP 10 (2019) 22: $\sigma[e^+e^- \to \Upsilon(nS)\pi^+\pi^-] \sim 2.0$ pb

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

- Previous Belle analysis: JHEP 06 (2021), 137
- One B meson is fully reconstructed using hadronic channels;
- $B^* \to B\gamma$ decays are not reconstructed;

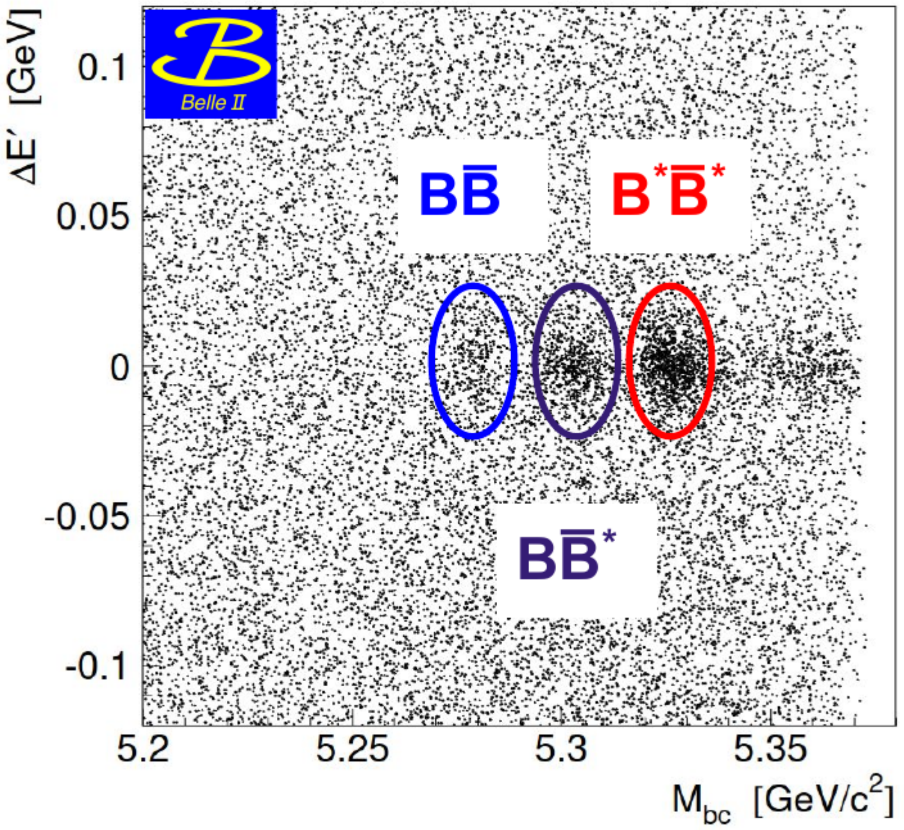
$$\Delta E = E_B - E_{\rm cm}/2$$

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

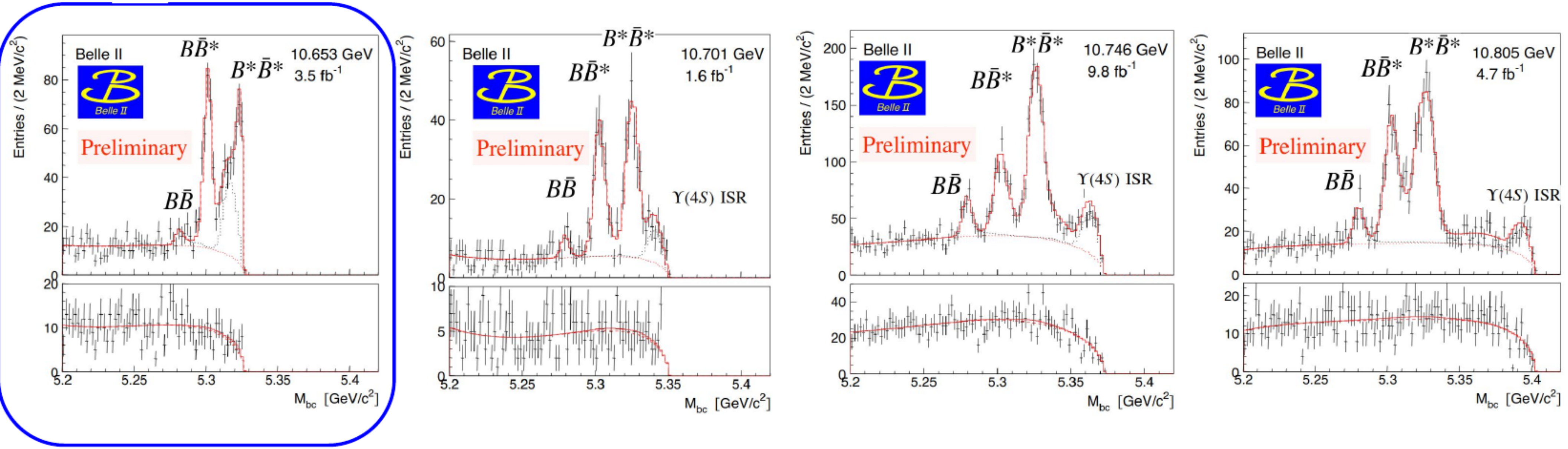
- $|\Delta E'| < 18$ MeV; Signal is identified using beam constrained mass:

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

ΔE' vs M_{bc} at E_{cm} = 10.746 GeV



$e^+e^- \to B^{(*)}\bar{B}^{(*)}$ fit results



- 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 $\Rightarrow$ fast rise of $B^*\bar{B}^*$ near threshold

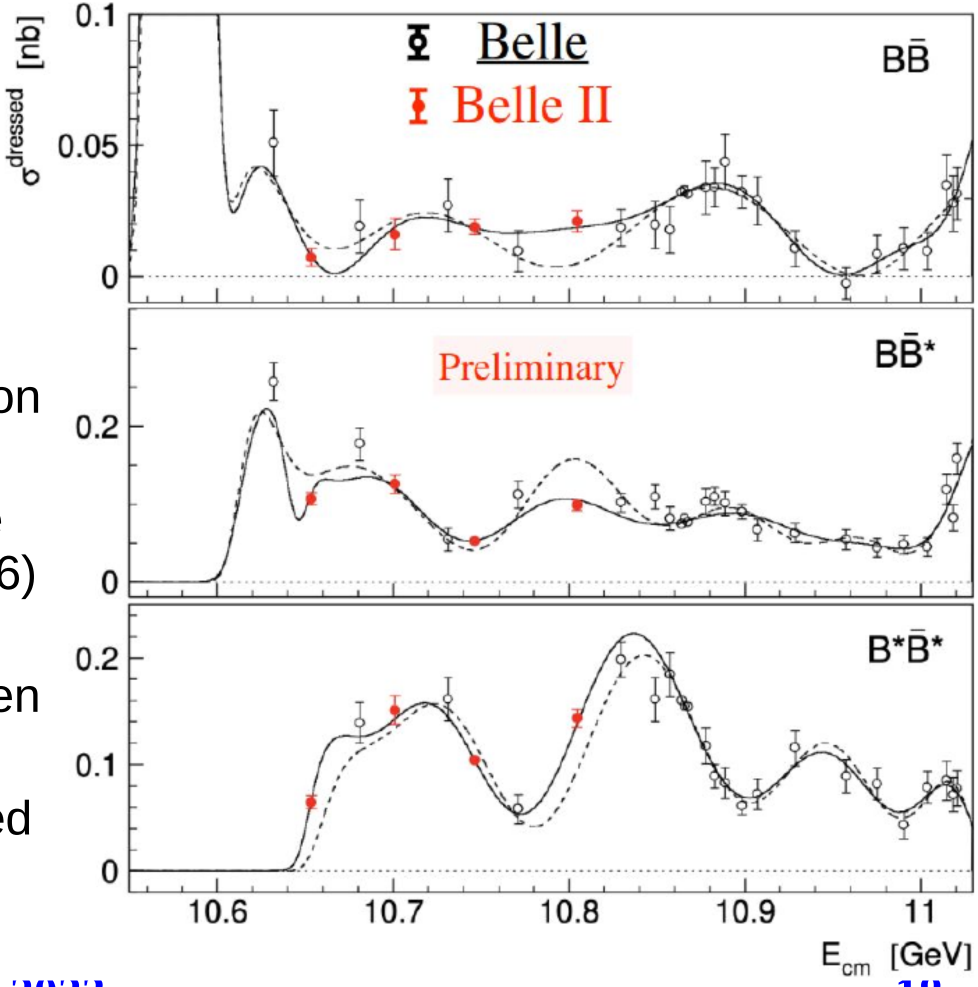
$e^+e^- \to B^{(*)}\bar{B}^{(*)}$ cross section

Confirming 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:

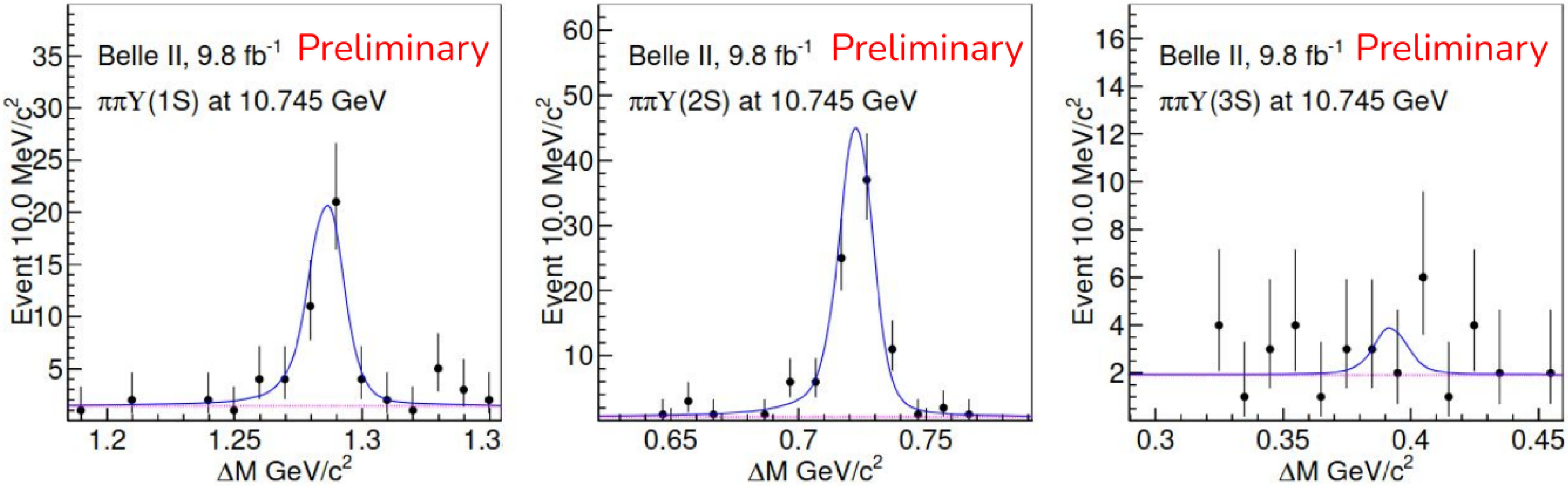
- Similar behaviour was seen for $D^*\bar{D}^*$ cross section PRD 97, 012002 (2018)
- Possible interpretation: resonance or bound state ($b\bar{b}$ or $B^*\bar{B}^*$) near threshold MPL A 21, 2779 (2006)
- Also explains a narrow dip in $\sigma(e^+e^- \to B\bar{B}^*)$ near $B^*\bar{B}^*$ threshold by 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)



Study of $e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$ (n = 1, 2, 3)

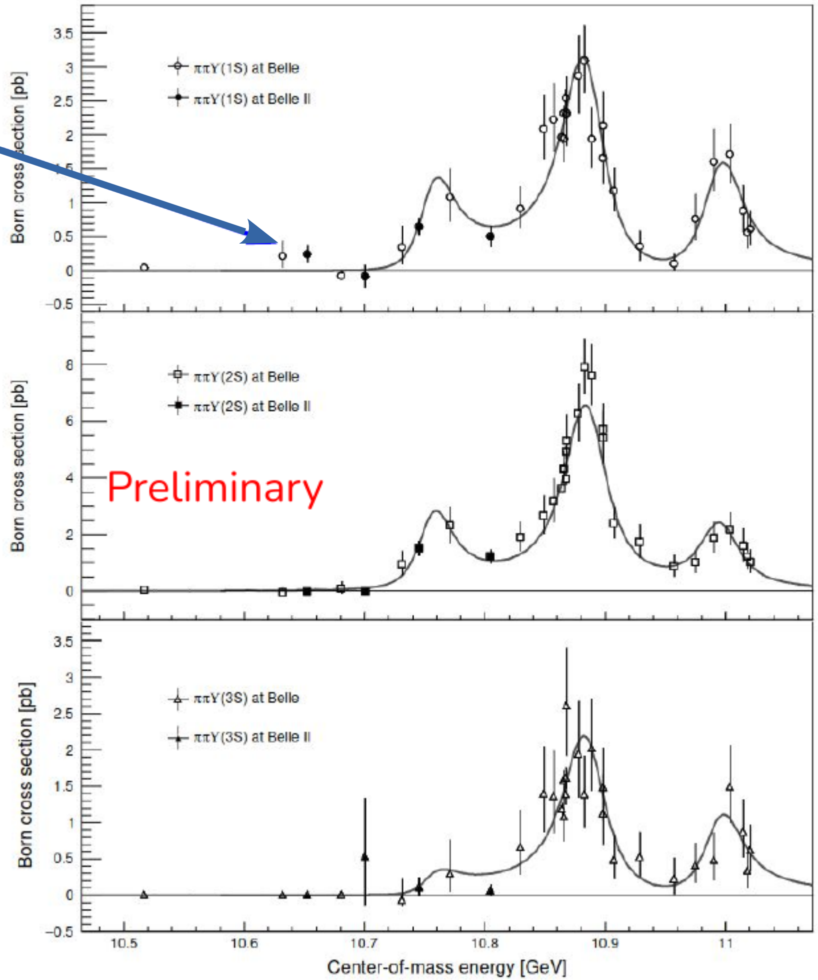
- Previously Belle observed $\Upsilon(10753)$ using combined fit of $e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$ (n = 1,2,3) cross section energy dependencies with 5.2 σ significance JHEP 10 (2019) 220.
- Belle II: $\Upsilon(10753)$ is observed in the Born cross-section of $e^+e \to \Upsilon(1S,2S)\,\pi^+\pi^-$, while no evidence is found in $e^+e^- \to \Upsilon(3S)\,\pi^+\pi^-$ channel.

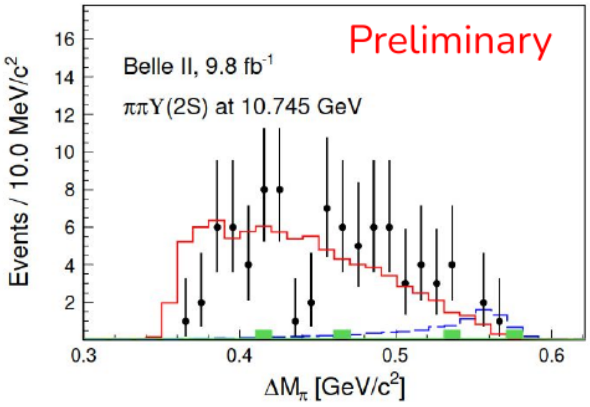
5.8 σ **10 σ** **0.8 σ**

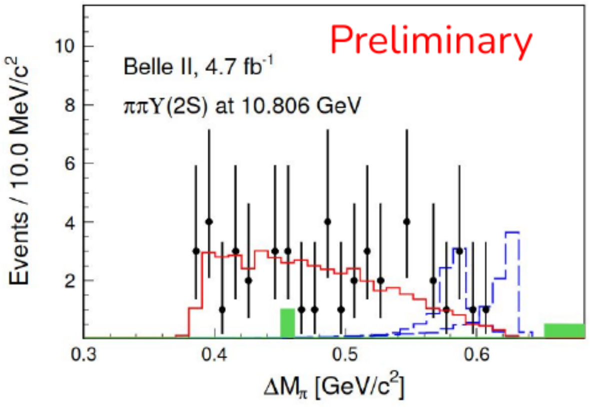


Study of $e^+e^- \rightarrow \Upsilon(nS)\,\pi^+\pi^-$ (n = 1, 2, 3)

- The hint of the $\Upsilon(1S)\,\pi^+\pi^-$ enhancement at the E_{CM} = 10.653 GeV could correspond to the inelastic decay of a molecular ($B^*\bar{B}^*$) state.
- No signals of intermediate $Z_b^+(10610)$ or $Z_b^+(10650)$ resonances are observed.







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 Υ(10753) and observation of its new decay channels

Search for $e^+e^- \to \omega\eta_b(1S)$ / $\chi_{b0}(1P)$ at $\sqrt{s}$ = 10.75 GeV
- No significant signals are observed
- The upper limit on the $\Upsilon(10753) \to \eta_b(1S)\omega$ cross-section contradicts the prediction of the tetraquark model

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 - sign for molecular $B^*\bar{B}^*$ state?

Study of $e^+e^- \to \Upsilon(1S)\pi^+\pi^-$ (n = 1,2,3)
- Υ(10753) signals are observed in Υ(1S,2S) $\pi^+\pi^-$ channels
- No signals of intermediate Z_b resonances are observed
- The hint of the $\Upsilon(1S)\pi^+\pi^-$ enhancement at the E_{CM} =10.653

Golden Modes	
$e^+e^- \to \pi^+\pi^-\Upsilon(pS)(\to \ell^+\ell^-)$	
$B\overline{B}$ decomposition	Preliminary results
$\pi^+\pi^-$ Dalitz	
$Y_b \to \omega\eta_b(1S)$	Preliminary result
$Y_b \to \omega\chi_{bJ}(1P)$	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.)	
...	

Backup