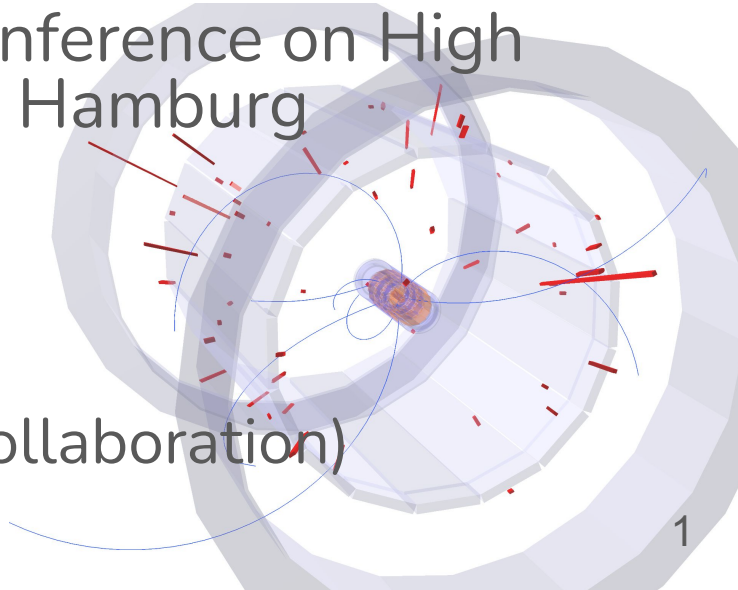
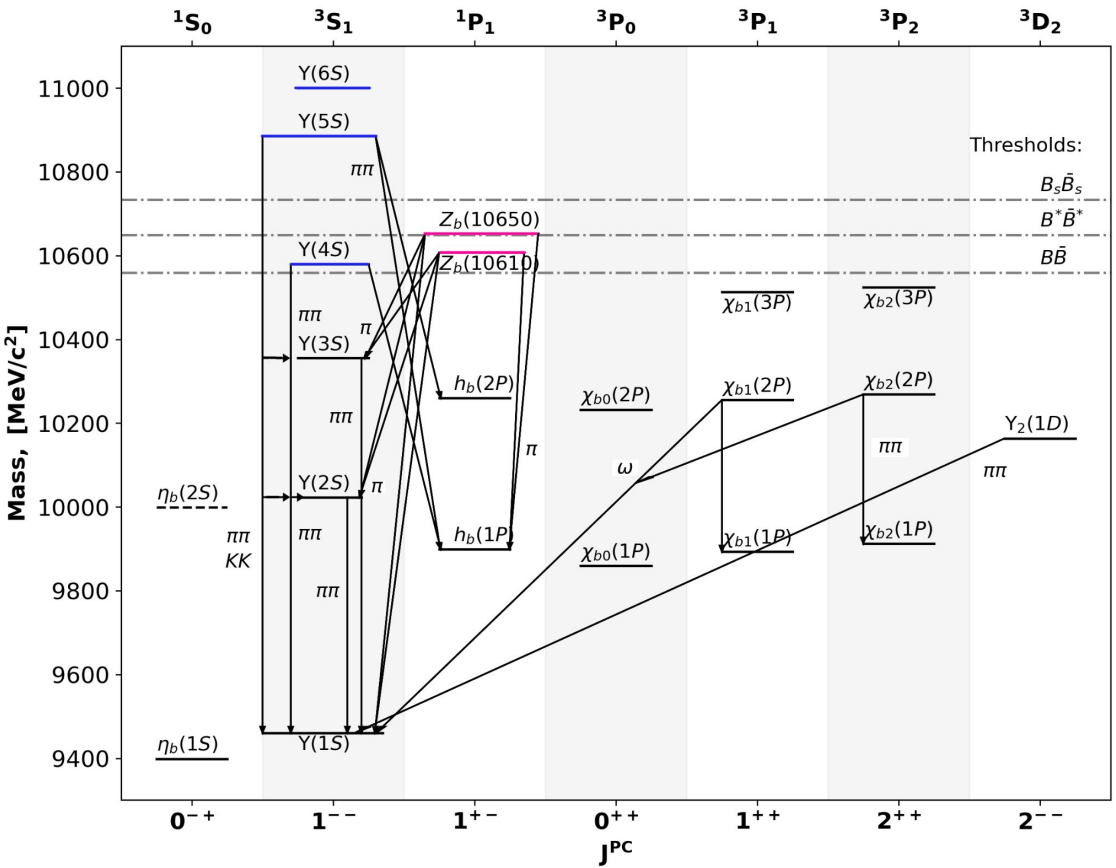
Recent quarkonium results at Belle II

The European Physical Society Conference on High Energy Physics (EPS-HEP), Hamburg
21st - 25th August 2023



Pavel Oskin
(on behalf of the Belle II Collaboration)

Bottomonium scheme



States **below the $B\bar{B}$ threshold** are well described by potential models.

Above the $B\bar{B}$ threshold: $\Upsilon(4S)$, $\Upsilon(5S)$ and $\Upsilon(6S)$. Unexpected properties:

- ❏ Hadronic transitions to lower bottomonia are strongly enhanced.
- ❏ Strong violation of Heavy Quark Spin Symmetry.

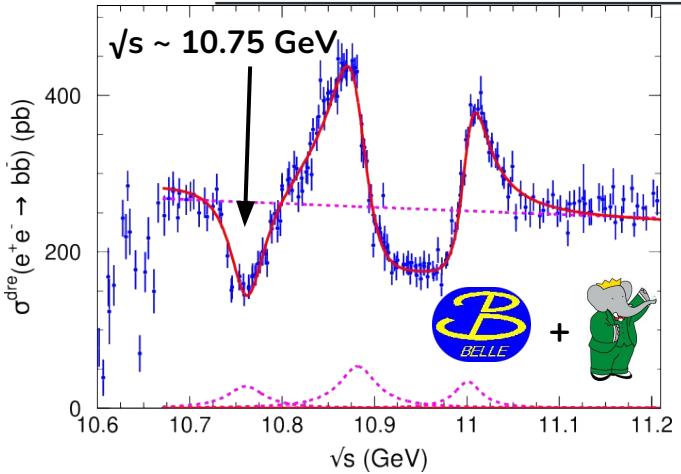
Exotic admixtures: molecule, compact tetraquark, hybrid.

$Z_b^+(10610)$ and $Z_b^+(10650)$: observed near the $B^{(*)}\bar{B}^*$ **thresholds**, properties are consistent with $B^{(*)}\bar{B}^*$ molecules.

Discovery of Υ(10753)

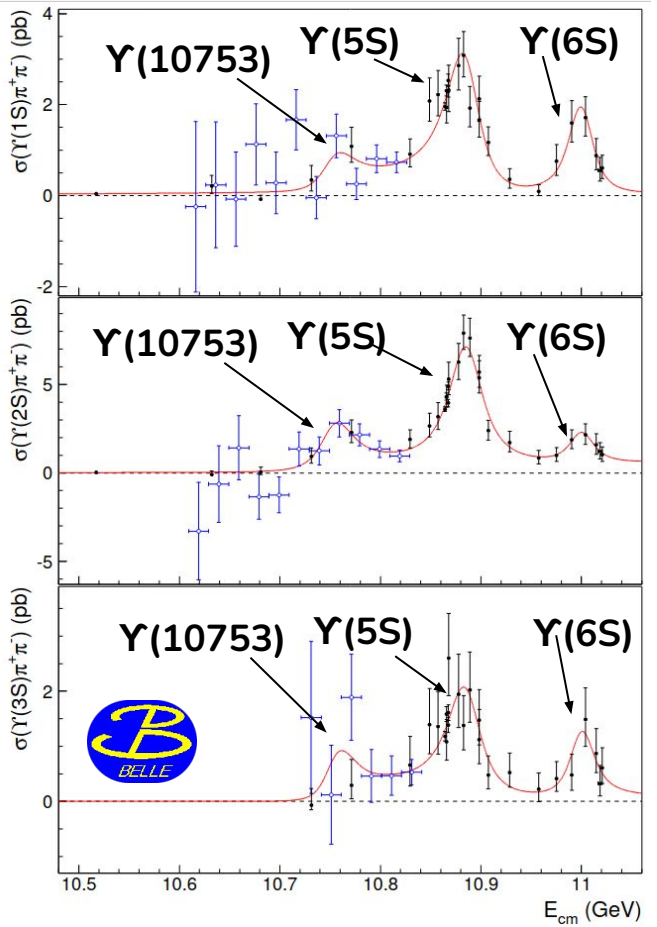
Observed in the $e^+ e^- \to \Upsilon(nS)\, \pi^+ \pi^-$ (n = 1,2,3) cross section energy dependence by Belle (JHEP 10 (2019) 220) with **5.2σ** significance:

	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)	$36.6^{+4.5\ +0.5}_{-3.9\ -1.1}$	$23.8^{+8.0\ +0.7}_{-6.8\ -1.8}$	$35.5^{+17.6\ +3.9}_{-11.3\ -3.3}$



Υ(10753) can describe a dip in $\sigma(e^+e^- \to b\bar{b})$

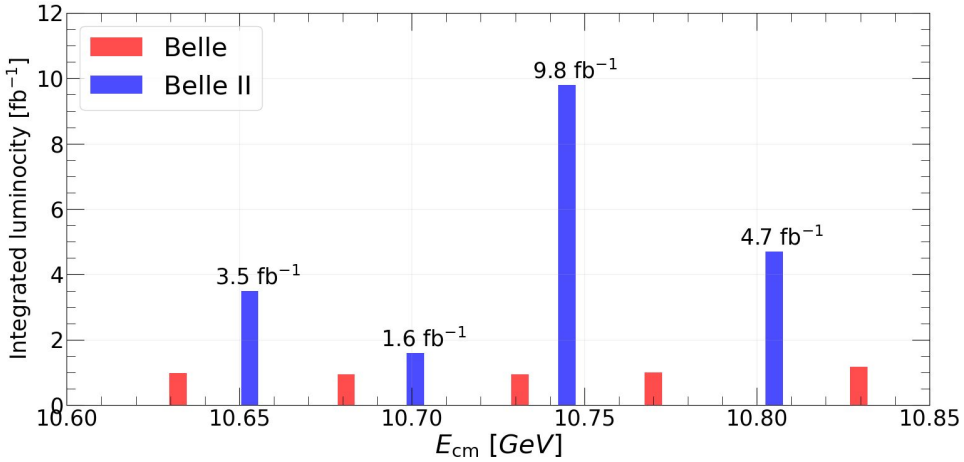
CPC **44**, 8, 083001 (2020)

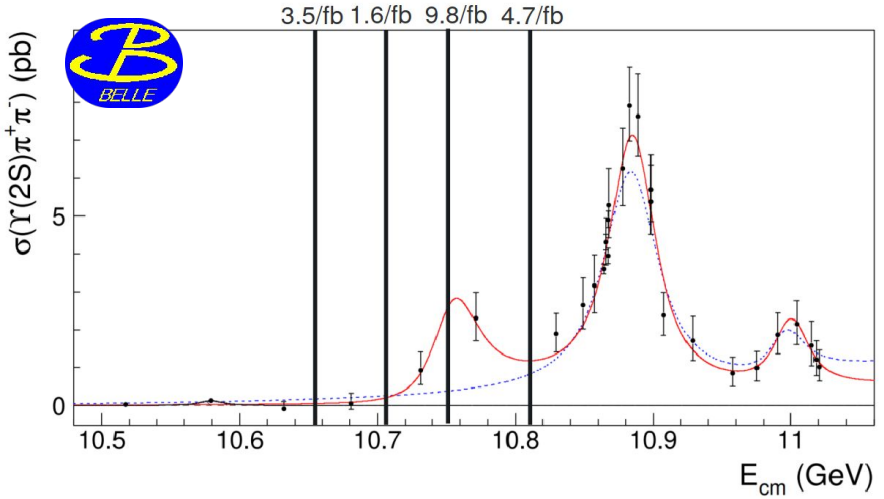


Interpretation: Y(3D) or Y(4D) state with S-D mixing enhanced due to hadron loops or exotic state.

Energy scan by Belle II

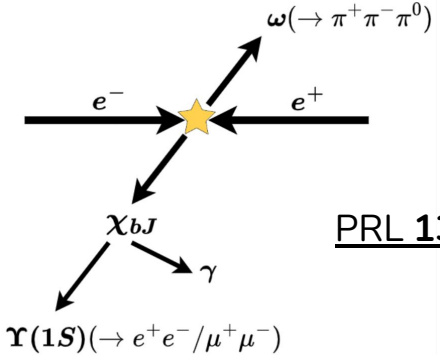
Belle II / SuperKEKB performed an energy scan in November 2021 with a total luminosity of 19 fb^{-1}. The main goal was to confirm and study $\Upsilon(10753)$.



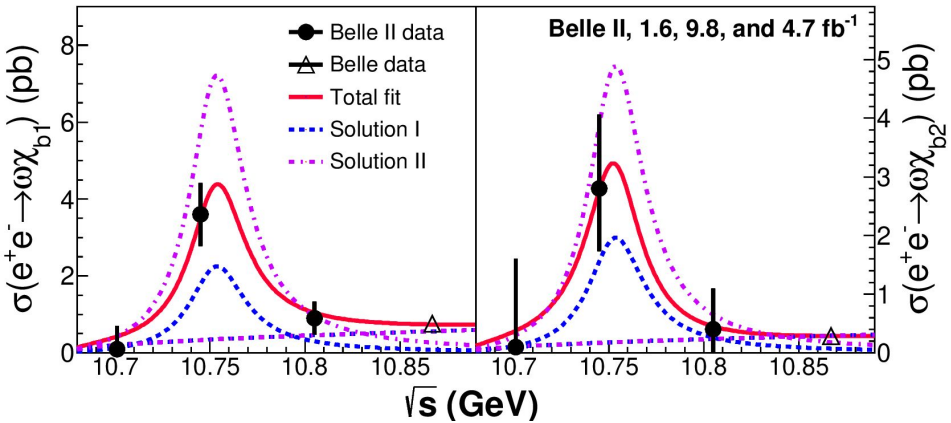


- Belle II collected data in the gaps between the Belle points.
- The point with the highest statistic (9.8 fb^{-1}) is near the $\Upsilon(10753)$ peak.

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



PRL **130**, 091902 (2023)



- Cross sections show a peak in the $\Upsilon(10753)$ region $\Rightarrow$ confirmation of $\Upsilon(10753)$ and observation of its new decay channels.
- No peak in the $\Upsilon(5S)$ region:

$$\frac{\sigma(e^+e^- \to \chi_{bJ}(1P)\omega)}{\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)} \sim \begin{matrix} 1.5 \text{ at } \Upsilon(10753) \\ 0.15 \text{ at } \Upsilon(5S) \end{matrix}$$

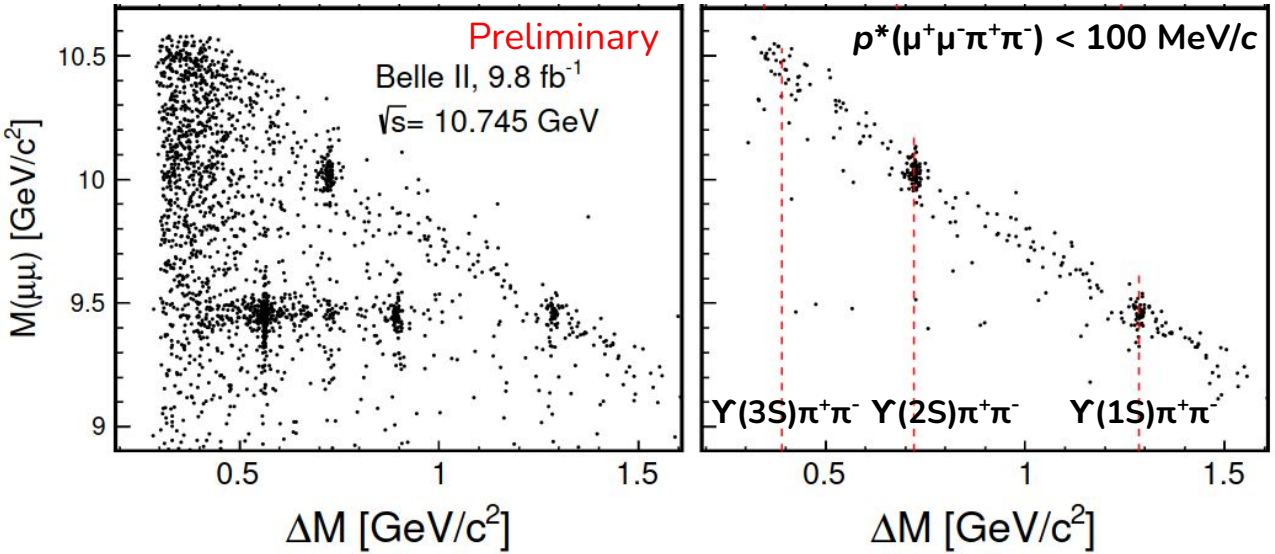
$\Rightarrow$ $\Upsilon(10753)$ and $\Upsilon(5S)$ have different structures.

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

Selection criteria

- The full reconstruction is used: $e^+e^- \to [\Upsilon(nS) \to \mu^+\mu^-]\pi^+\pi^-$.

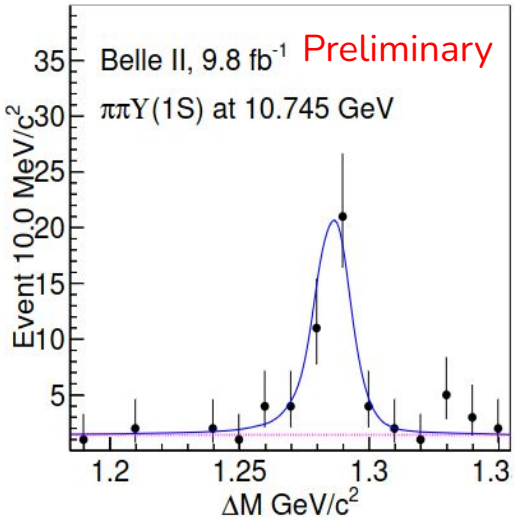
- Plot $\Delta M = M(\pi^+\pi^-\mu^+\mu^-) - M(\mu^+\mu^-)$ vs. $M(\mu^+\mu^-)$: clear signals of $\Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(2S)\pi^+\pi^-$, no signal of $\Upsilon(3S)\pi^+\pi^-$.

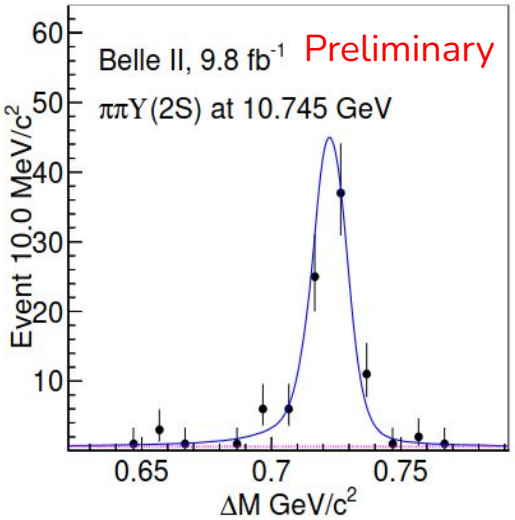


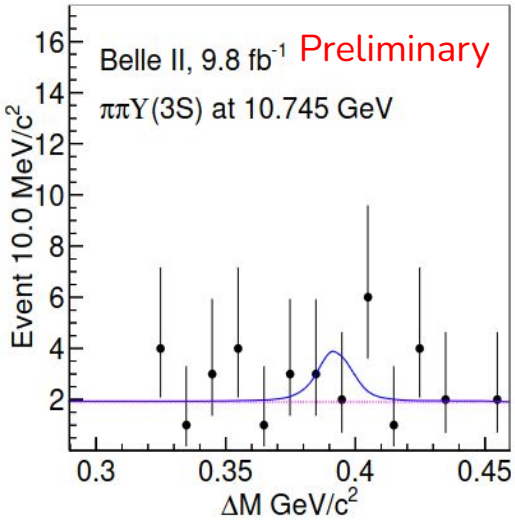
Fits to ΔM distributions

- The signal shapes are obtained using MC taking into account beam energy spread, ISR and cross section energy dependence.

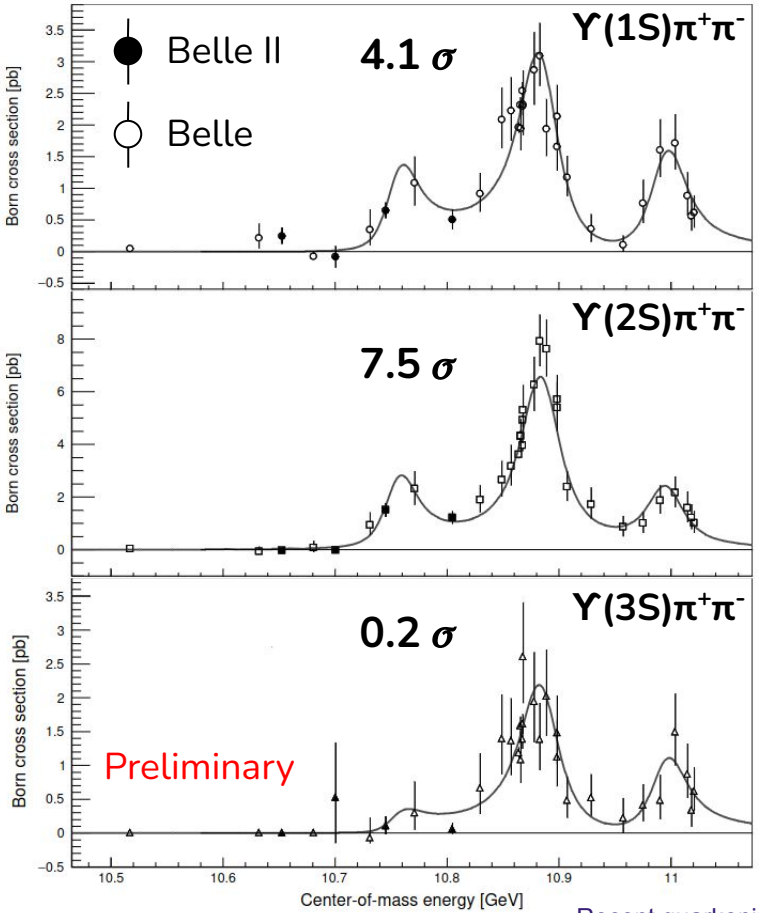
- Good description of the ΔM distributions in data.







Energy dependence of $e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$ cross section



- New measurement **confirms previous Belle result**: cross section is peaking near 10.75 GeV.
- Fit: use sum of Breit-Wigner amplitudes; convolve with a Gaussian to account for the energy spread.

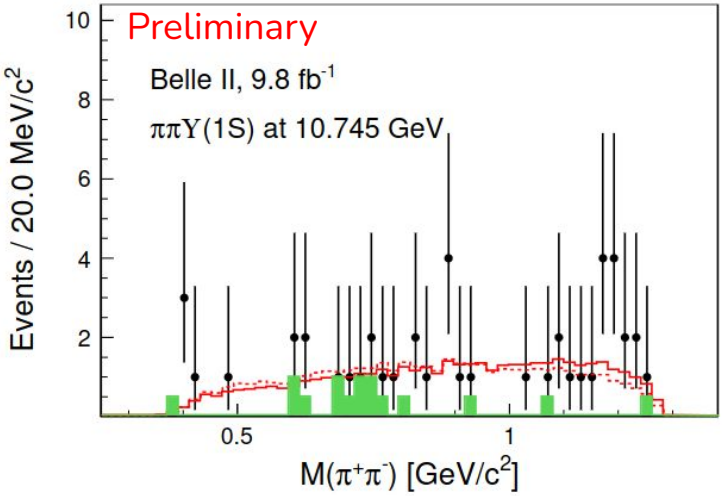
$$M_{\Upsilon(10753)} = (10756.3 \pm 2.7_{(stat)} \pm 0.6_{(syst)})\ \text{MeV}/c^2$$
$$\Gamma_{\Upsilon(10753)} = (29.7 \pm 8.5_{(stat)} \pm 1.1_{(syst)})\ \text{MeV}$$

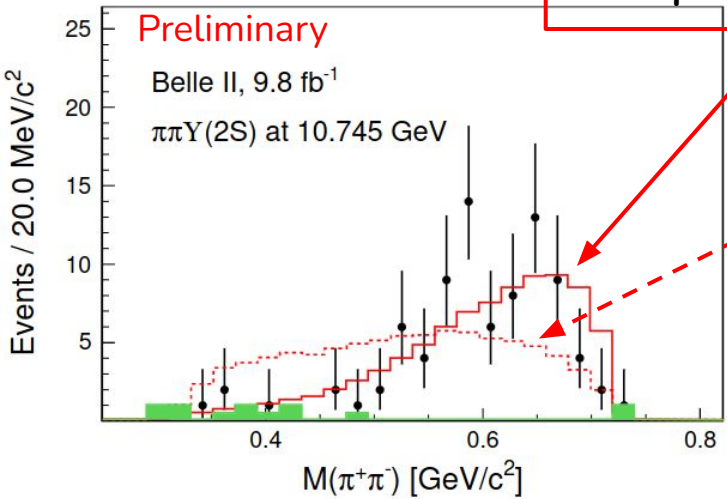
In agreement with the Belle measurement.

Resonant structure in $\Upsilon(nS)\pi^+\pi^-$

- **No signals** of intermediate $Z_b^+(10610)$ **or** $Z_b^+(10650)$ resonances are observed.

- $\Upsilon(1S)\pi^+\pi^-$: $M(\pi^+\pi^-)$ distribution is consistent with phase space.
- $\Upsilon(2S)\pi^+\pi^-$: large values of $M(\pi^+\pi^-)$ are enhanced (similarly to $\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-$).





CLEO parameterization

phase space

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

Motivation

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

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

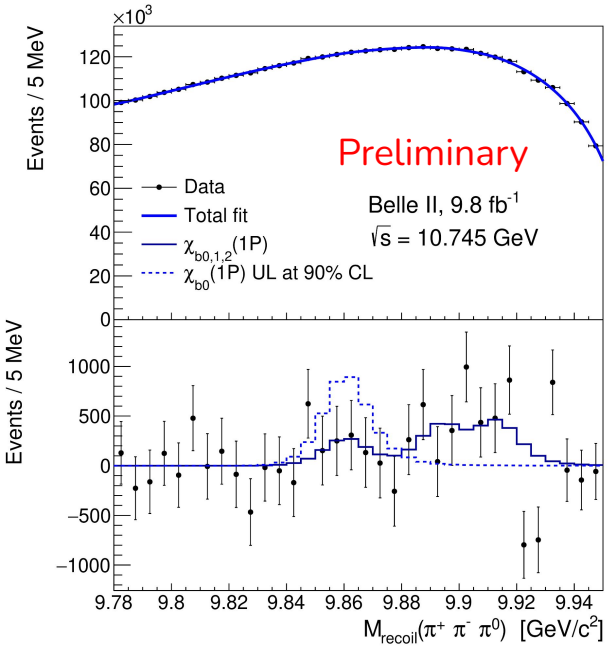
- Since $\eta_b(1S)$ does not have convenient for reconstruction decay channels, we reconstruct only $\omega \to \pi^+\pi^-\pi^0$ and use its recoil mass to identify the signal:

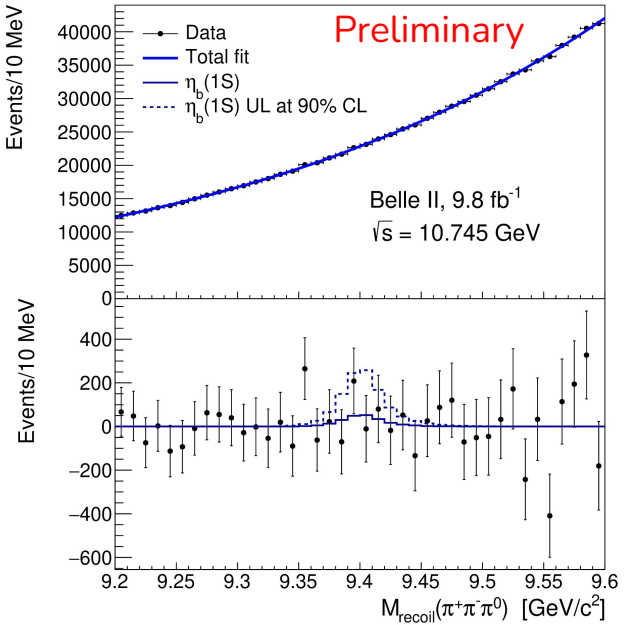
$$M_{\text{recoil}}(\pi^+\pi^-\pi^0) = \sqrt{\left(\frac{E_{\text{c.m.}} - E^*}{c^2}\right)^2 - \left(\frac{p^*}{c}\right)^2}$$

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

Fit to $M_{recoil}(\pi^+\pi^-\pi^0)$

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





- $\sigma[e^+e^- \to \omega\chi_{b0}(1S)] < 8.7$ pb
- $\sigma[e^+e^- \to \omega\eta_b(1S)] < 2.5$ pb
- c.f. $\sigma[e^+e^- \to \Upsilon(nS)\pi^+\pi^-] \sim 2.0$ pb (JHEP 10 (2019) 220)

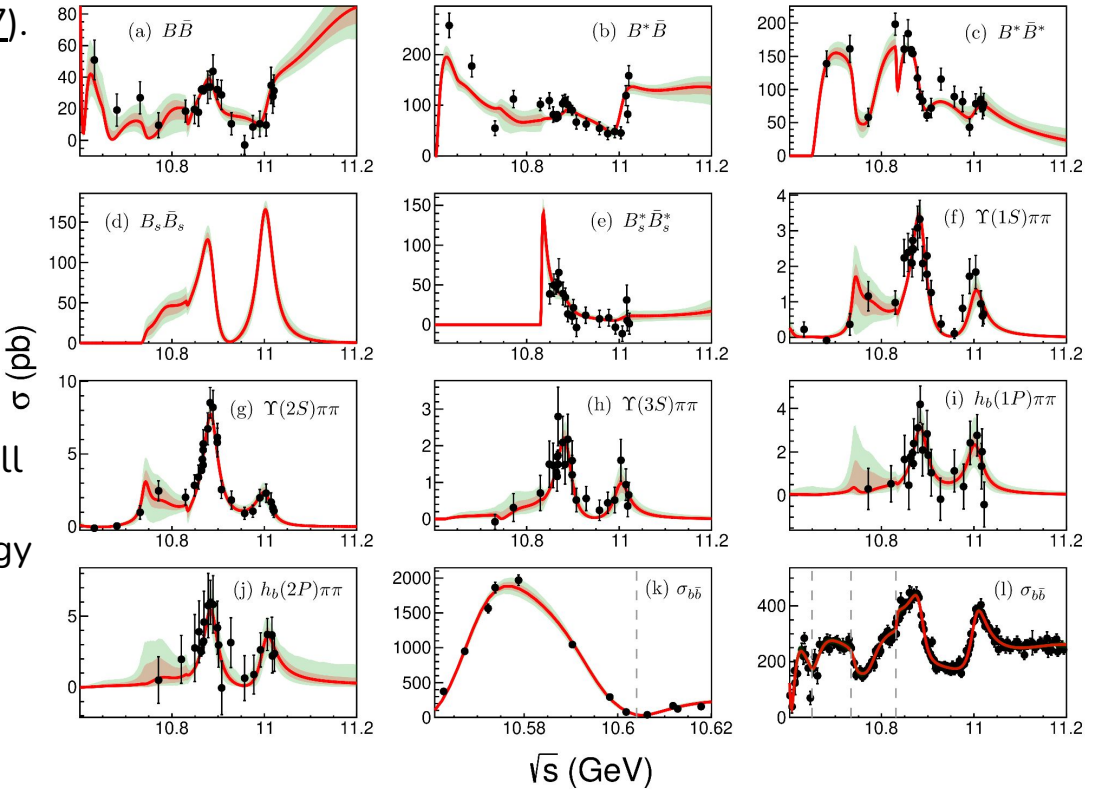
This result does not support the prediction of the tetraquark model in CPC 43 (2019) 12, 123102

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

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

- Belle measured the energy dependencies of $\sigma(e^+e^- \to B^{(*)}\bar{B}^{(*)})$ and observed an oscillatory behavior (JHEP 06 (2021), 137).
- Rescattering, opening of new channels,..
- $e^+e^- \to B^{(*)}\bar{B}^{(*)}$ make dominant contribution to the total $b\bar{b}$ cross section.
- Combined **coupled-channel analysis** of all available energy scan results.
  Results: parameters of the Υ states, energy dependence of various scattering amplitudes.
- It is of interest to improve the accuracy in cross sections in the region below $\Upsilon(5S)$.

PRD **106** (2022) 9, 094013 (does not include Belle II results)



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.

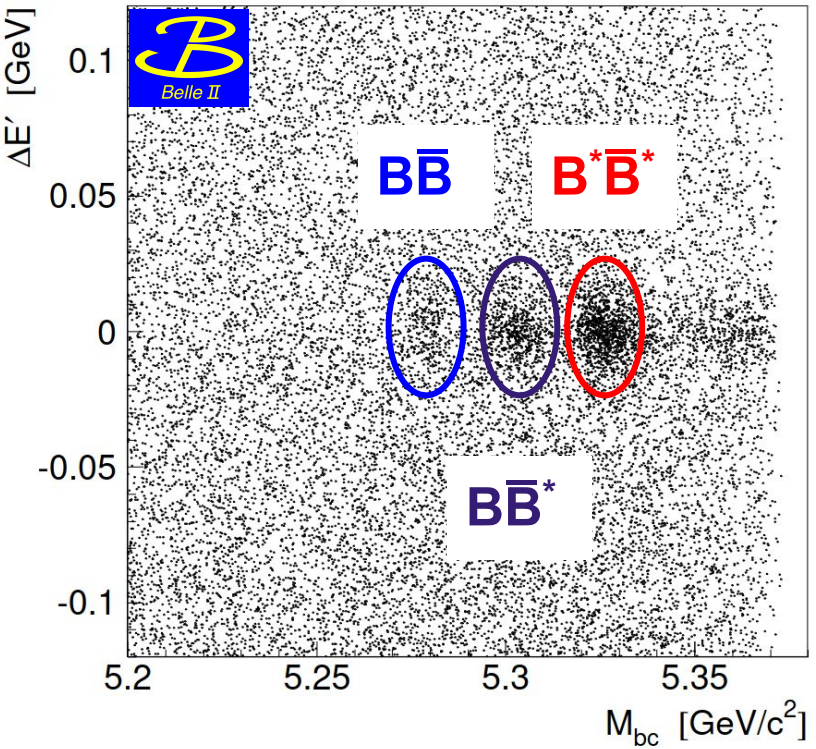
$$\Delta E = E_B - E_{\rm cm}/2$$

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

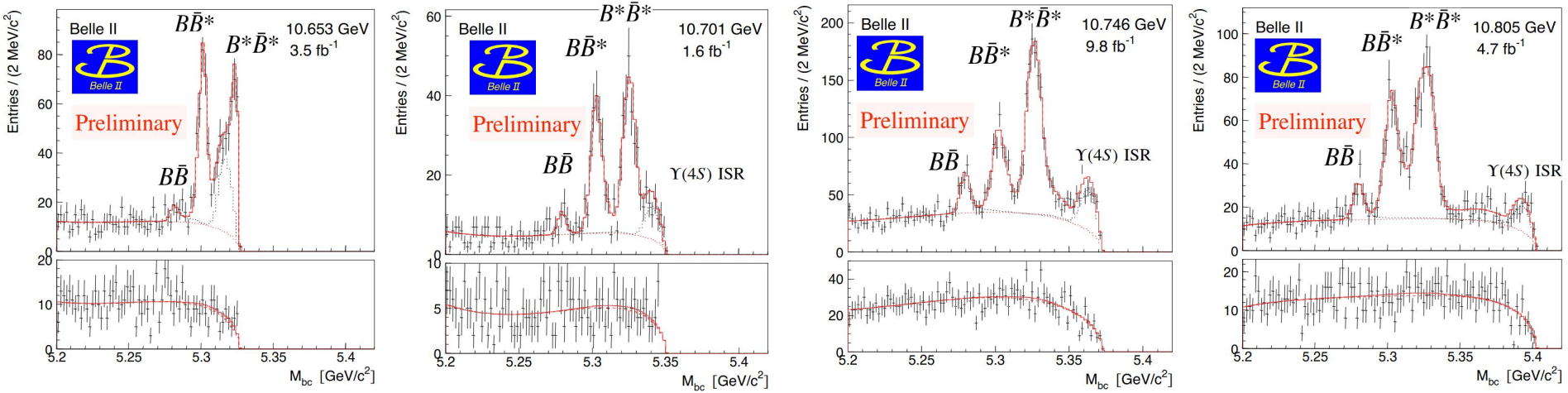
- $|\Delta E'| < 18$ MeV.
- Signal is identified using M_{bc}:

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

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

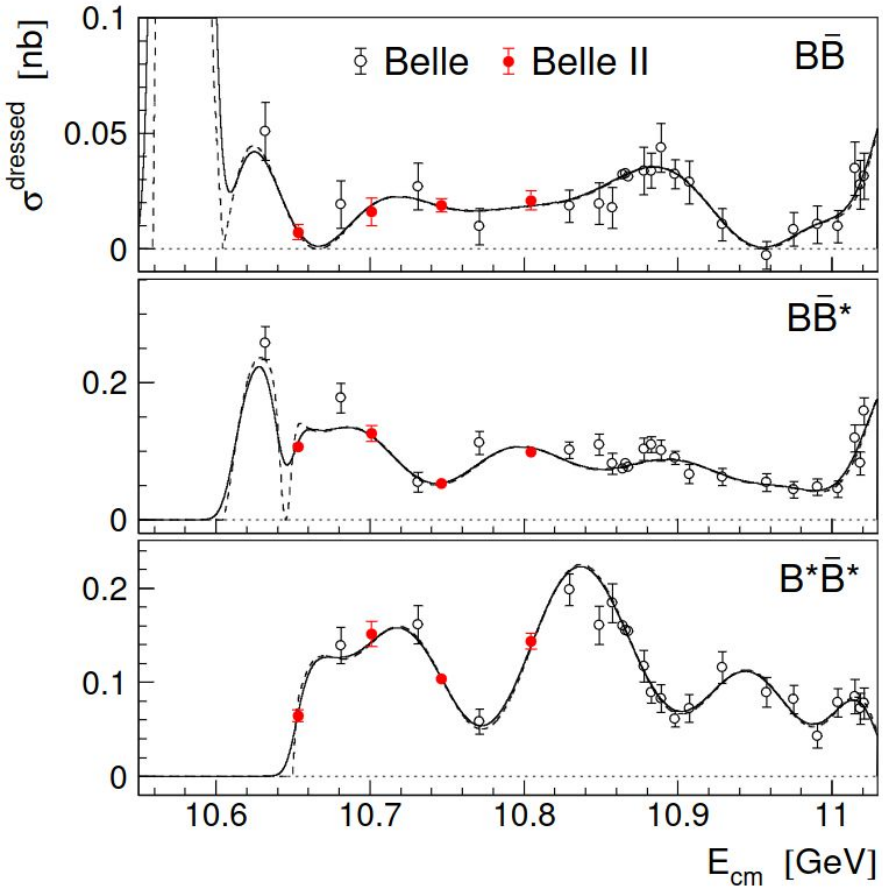


M_{bc} fit at scan energies



- 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.

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



New measurement confirms oscillatory behavior of cross sections and significantly supplements the previous Belle result.

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

- Similar behaviour was seen for $D^*\bar{D}^*$ cross section; possible interpretation: P-wave $D^*\bar{D}^*$ molecule near threshold.
- There could be a $B^*\bar{B}^*$ molecule near the $B^*\bar{B}^*$ threshold?
- 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 $e^+e^- \to B^*\bar{B}^* \to B\bar{B}^*$.

Conclusion

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

- $\Upsilon(10753)$ signals are observed in $\Upsilon(1S,2S)\,\pi^+\pi^-$ channels.
- The $M(\pi^+\pi^-)$ in $\Upsilon(1S)\pi^+\pi^-$ is consistent with PHSP while in $\Upsilon(2S)\pi^+\pi^-$ large $M(\pi^+\pi^-)$ is enhanced.
- No signals of intermediate Z_b resonances are observed.

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

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

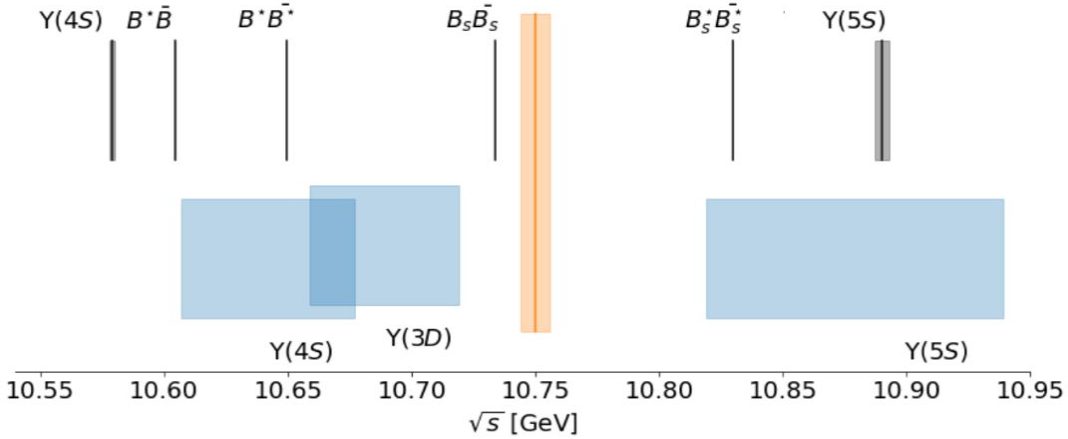
- Confirmation of “oscillatory” behavior, improvement of accuracy.
- Rapid rise of $\sigma(e^+e^- \to B^*\bar{B}^*)$ above threshold - signal of molecular $B^*\bar{B}^*$ state?

Thank you!

BACKUP

What is the nature of Υ(10753)?

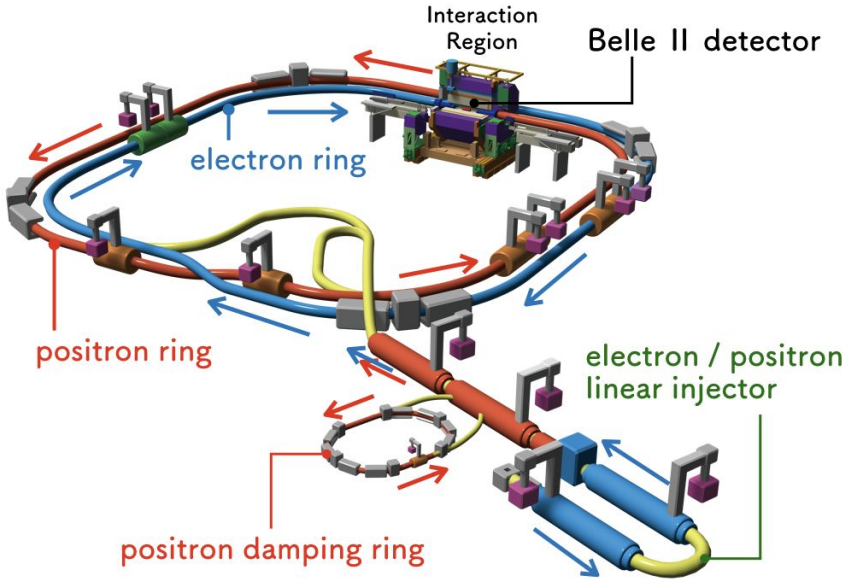
- Far from the thresholds;



- 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.

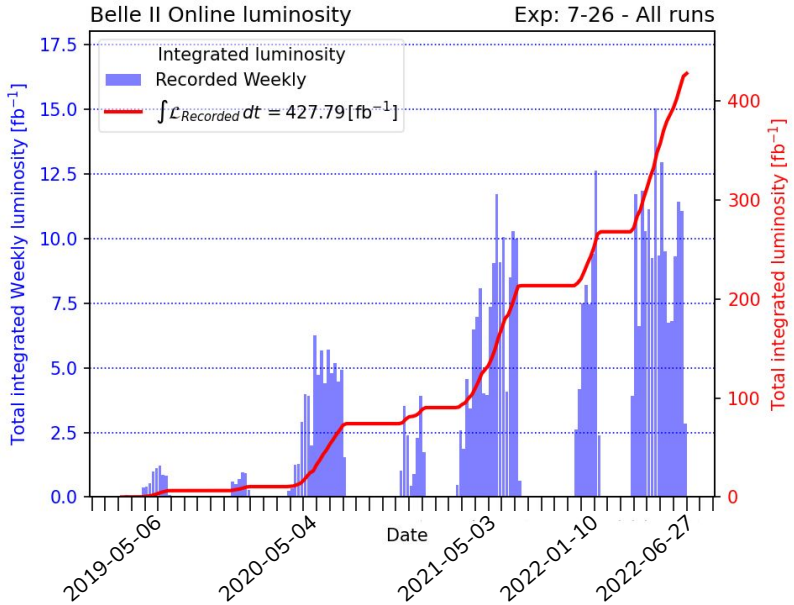
- Tetraquark state:
  CPC **43**, 12, 123102 (2019),
  PLB, **802**, 135217 (2020),
  PRD, **104**, 3, 034036 (2021).
- Hadronic molecule with a small admixture of a bottomonium:
  PRD **103**, 074507 (2021)
- Hybrid state:
  PRD **99**, 1, 014017 (2019)
- Conventional $b\bar{b}$ state:
  EPJC **80**, 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)

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);



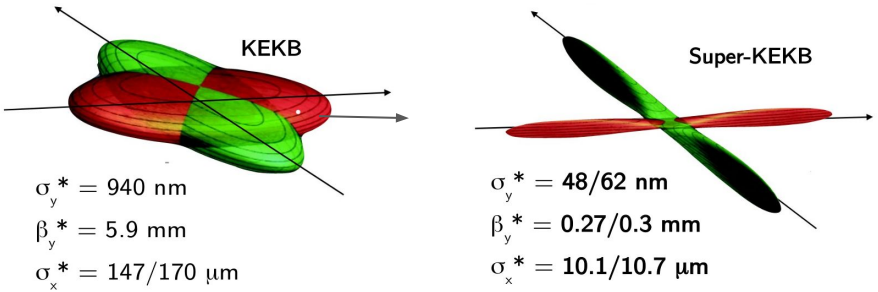
SuperKEKB and Belle II

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

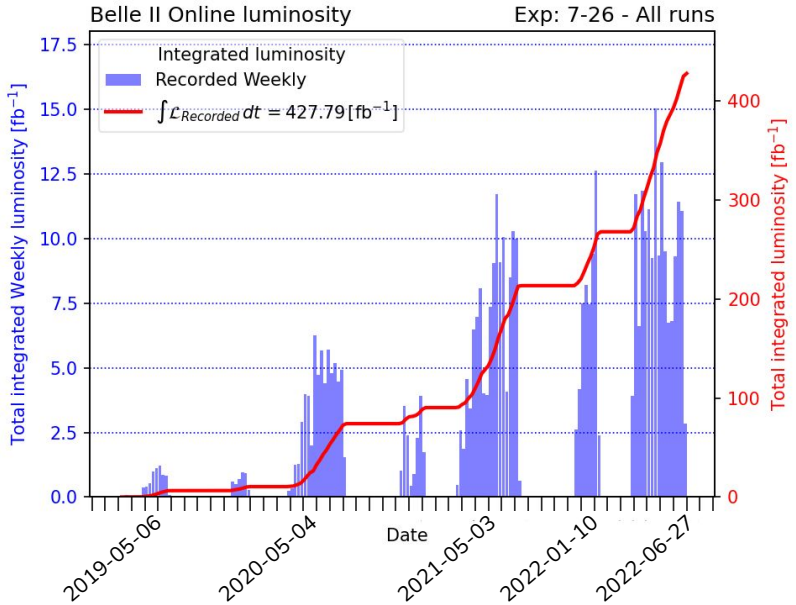
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

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

x30 instant luminosity increase



- 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);

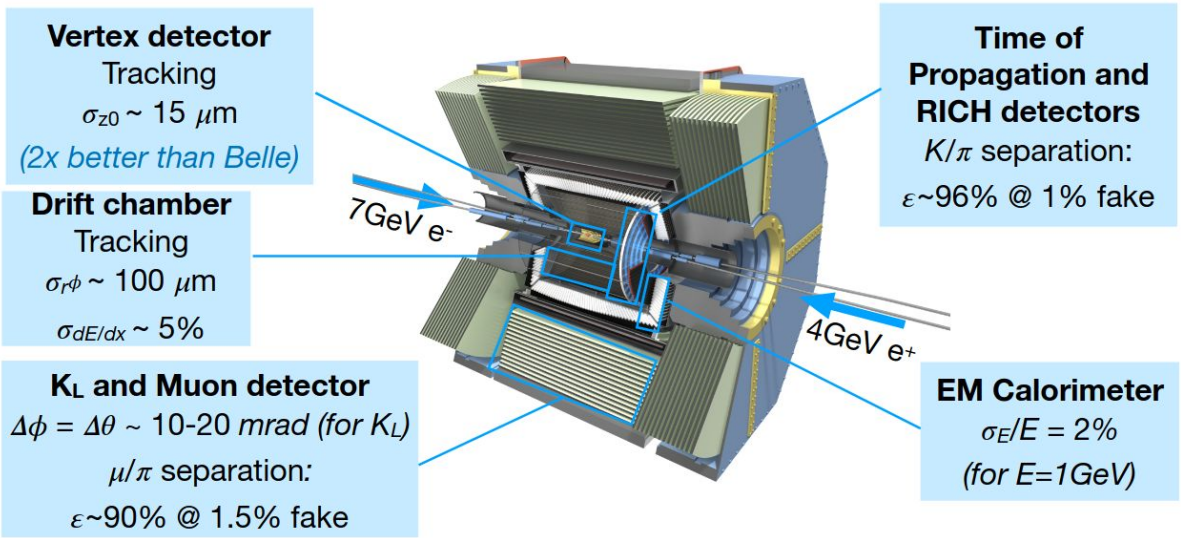


SuperKEKB and Belle II

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;

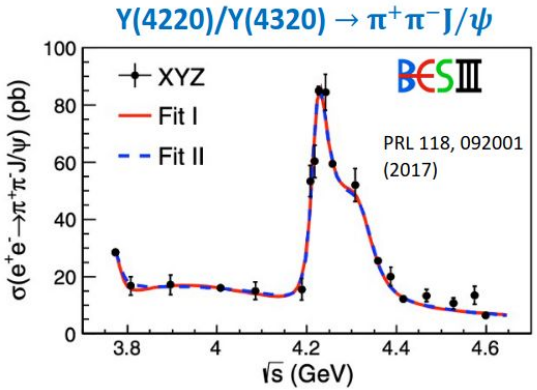
Motivation to search for $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$

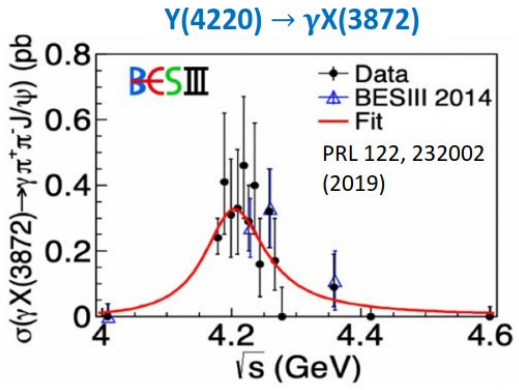
Theory:

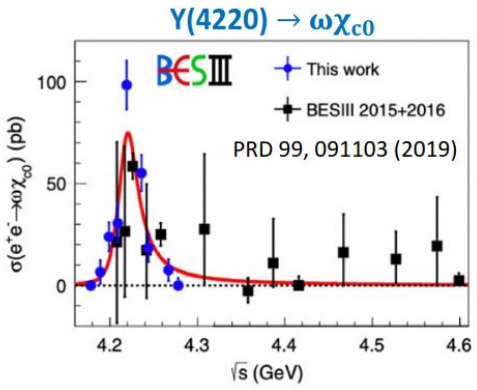
- Mixed $\Upsilon(4S)$ - $\Upsilon(3D)$ state: $\omega\chi_{bJ}$ could be enhanced (PRD **104**, 034036 (2021)).

Charmonium sector:

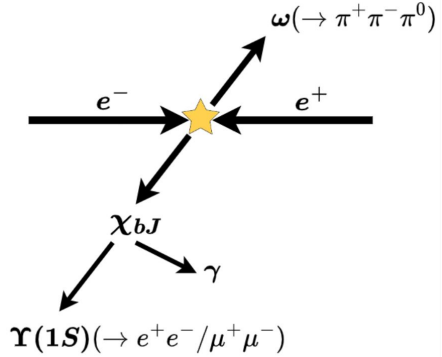
- Similar to $\Upsilon(10753)$ structure $Y(4220)$ was observed in $e^+e^- \to J/\Psi\,\pi^+\pi^-$ cross section dependence by BES III (PRL **118**, 092001 (2017)).
- $Y(4220)$ peak was observed in $\gamma X(3872)$ and $\omega\chi_{c0}$ final states by BES III (PRL, **122**, 232002 (2019), PRD **99**,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



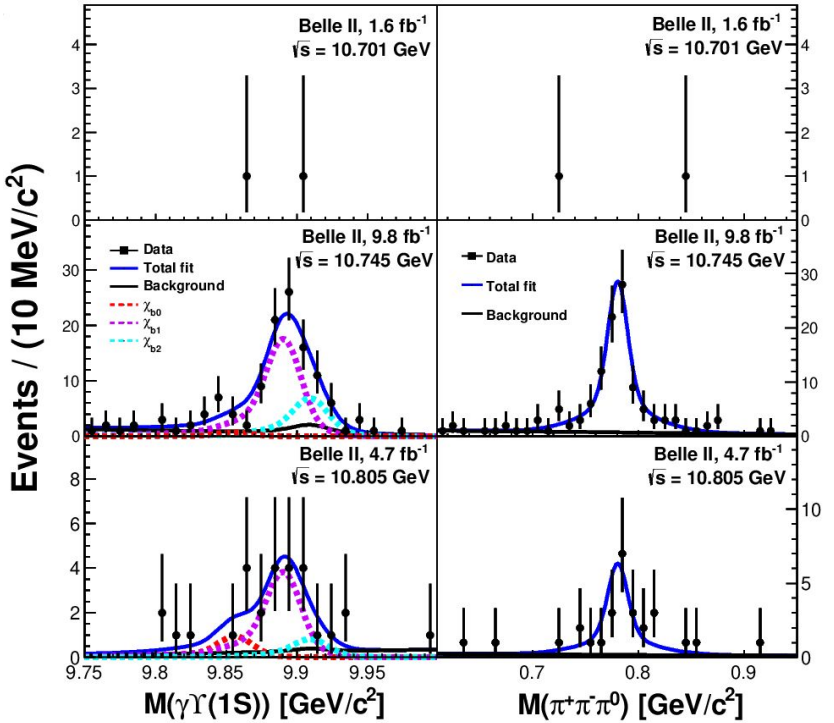
PRL **130**, 091902 (2023)

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

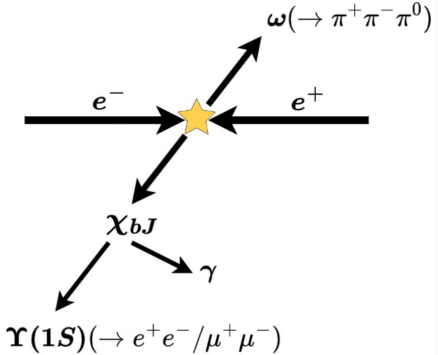
11 σ

4.5 σ

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



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

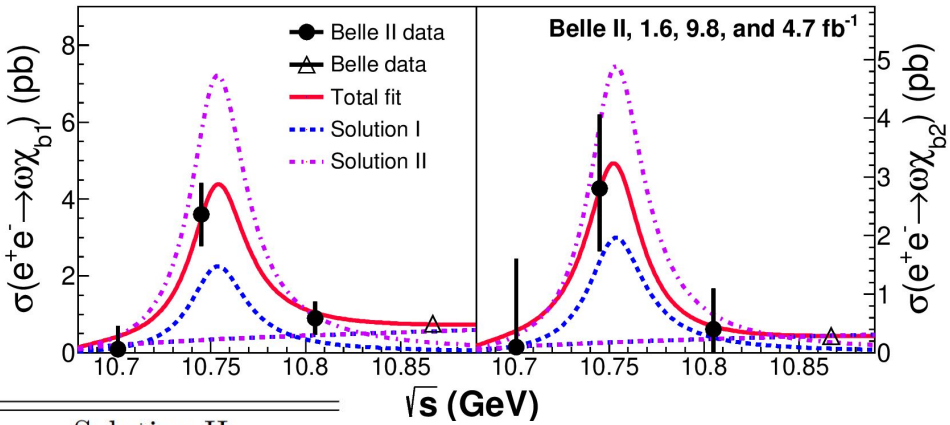


PRL **130**, 091902 (2023)

- Fit with coherent sum of PHSP and BW.

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

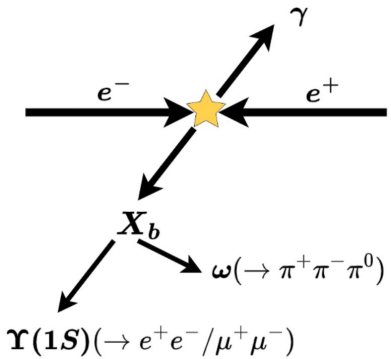
- M and Γ are fixed to 10752.7 MeV and 35.5 MeV



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



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

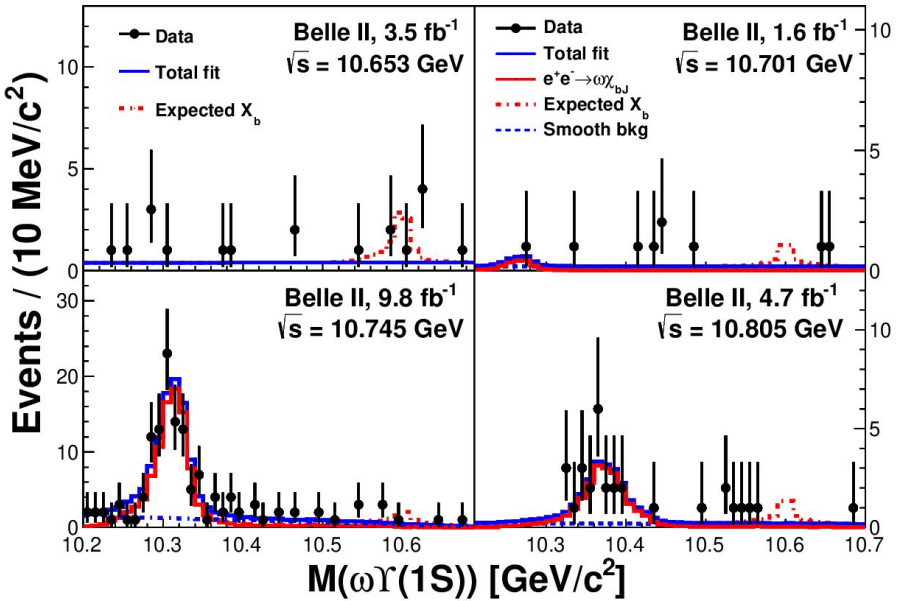
PRL **130**, 091902 (2023)

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

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

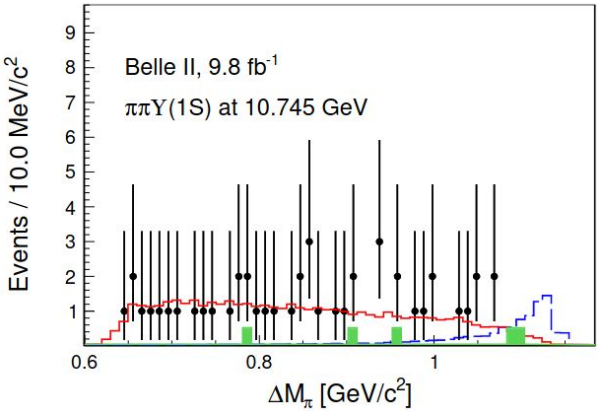
$\sqrt{s}$ (GeV)	M_{X_b} (GeV)	$\sigma^{\mathrm{UL}}_{X_b}$ (pb)
10.653	10.59	< 0.55
10.701	10.45	< 0.84
10.745	10.45	< 0.14
10.805	10.53	< 0.47

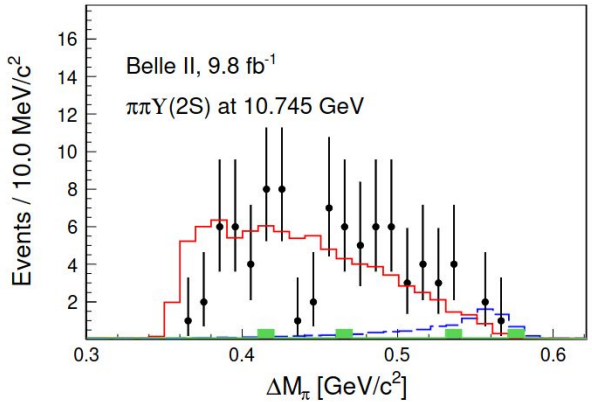
Fit to $M[\omega\Upsilon(1S)]$

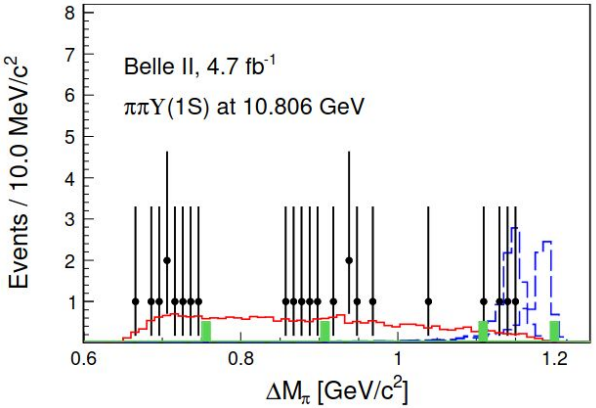


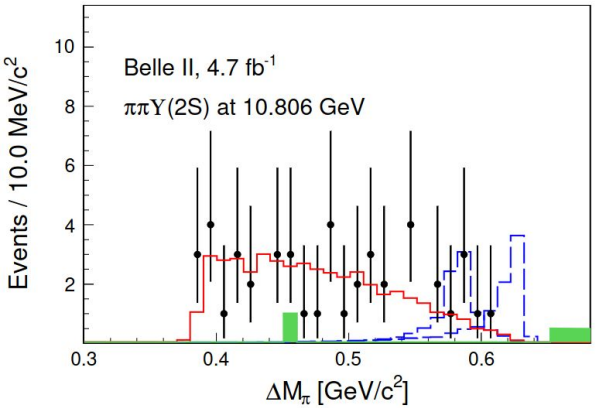
Resonant structure in $\Upsilon(nS)\pi^+\pi^-$

- No signals of intermediate $Z_b^+(10610)$ or $Z_b^+(10650)$ resonances are observed



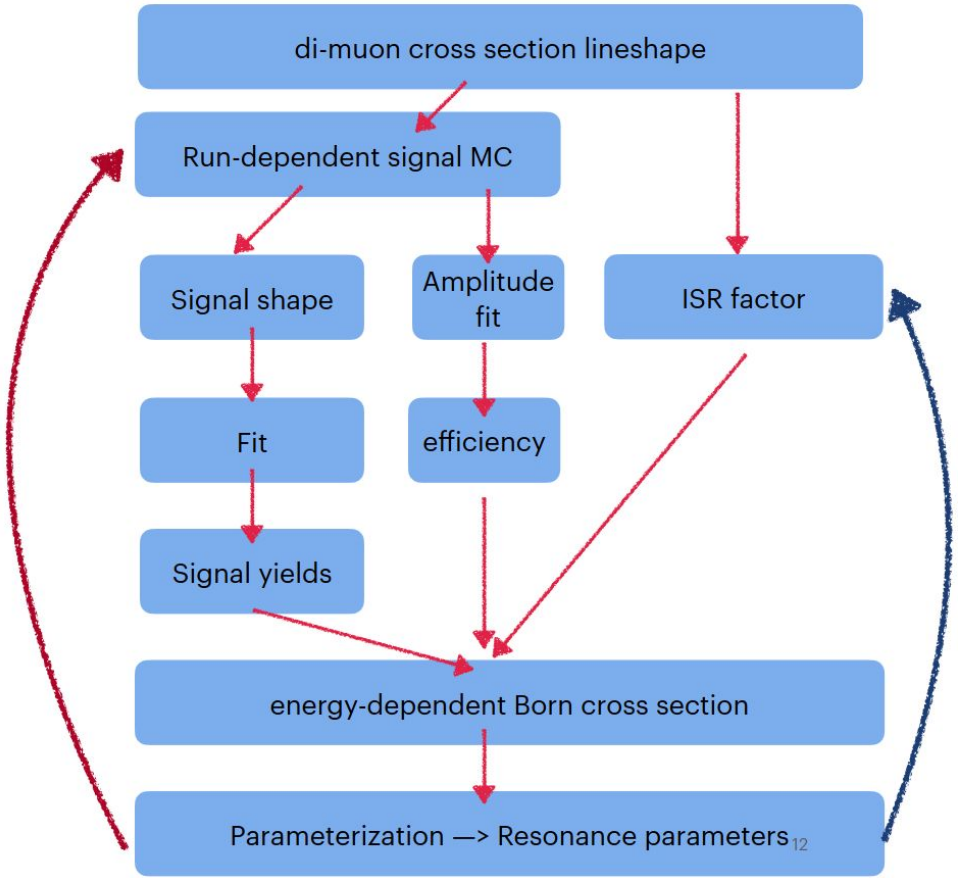






$\Upsilon(nS)\pi^+\pi^-$ signal yields & Cross sections — Iterative approach

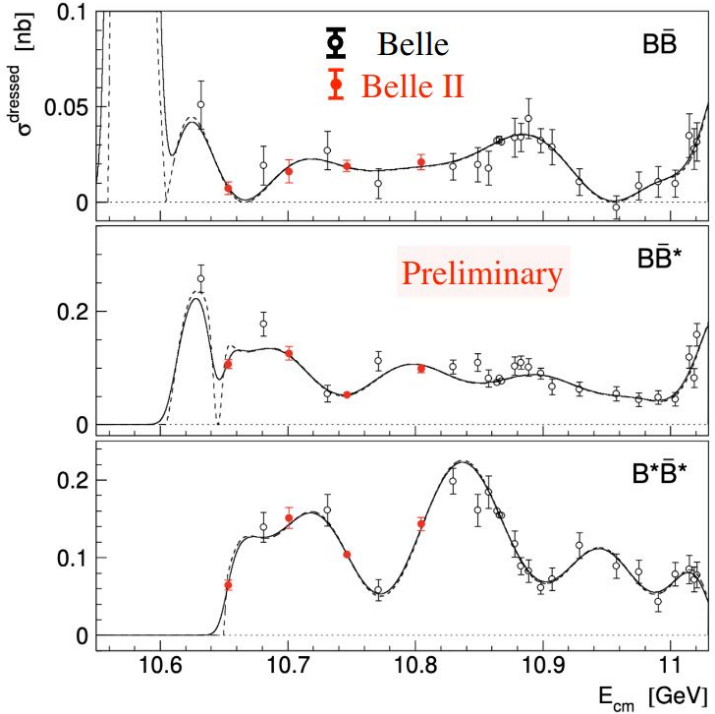
re-Weight Until parameters are consistent with previous result



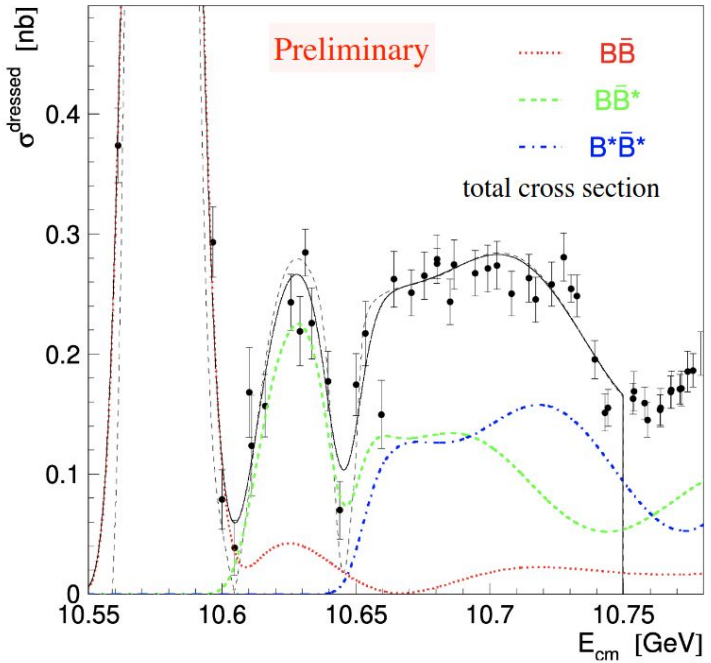
Energy dependence of the cross sections

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;