Carnegie Mellon University

Belle II

Recent quarkonium results from Belle II

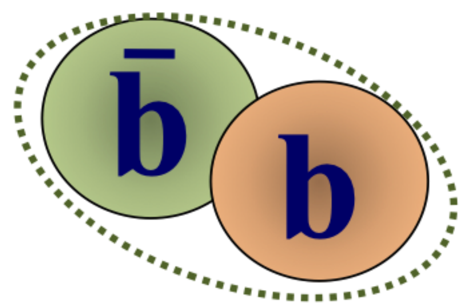
16TH INTERNATIONAL CONFERENCE ON HEAVY QUARKS AND LEPTONS

Renu
On the behalf of Belle II Collaboration

Supported by US DOE funding

28th Nov, 2023 - 2nd Dec, 2023

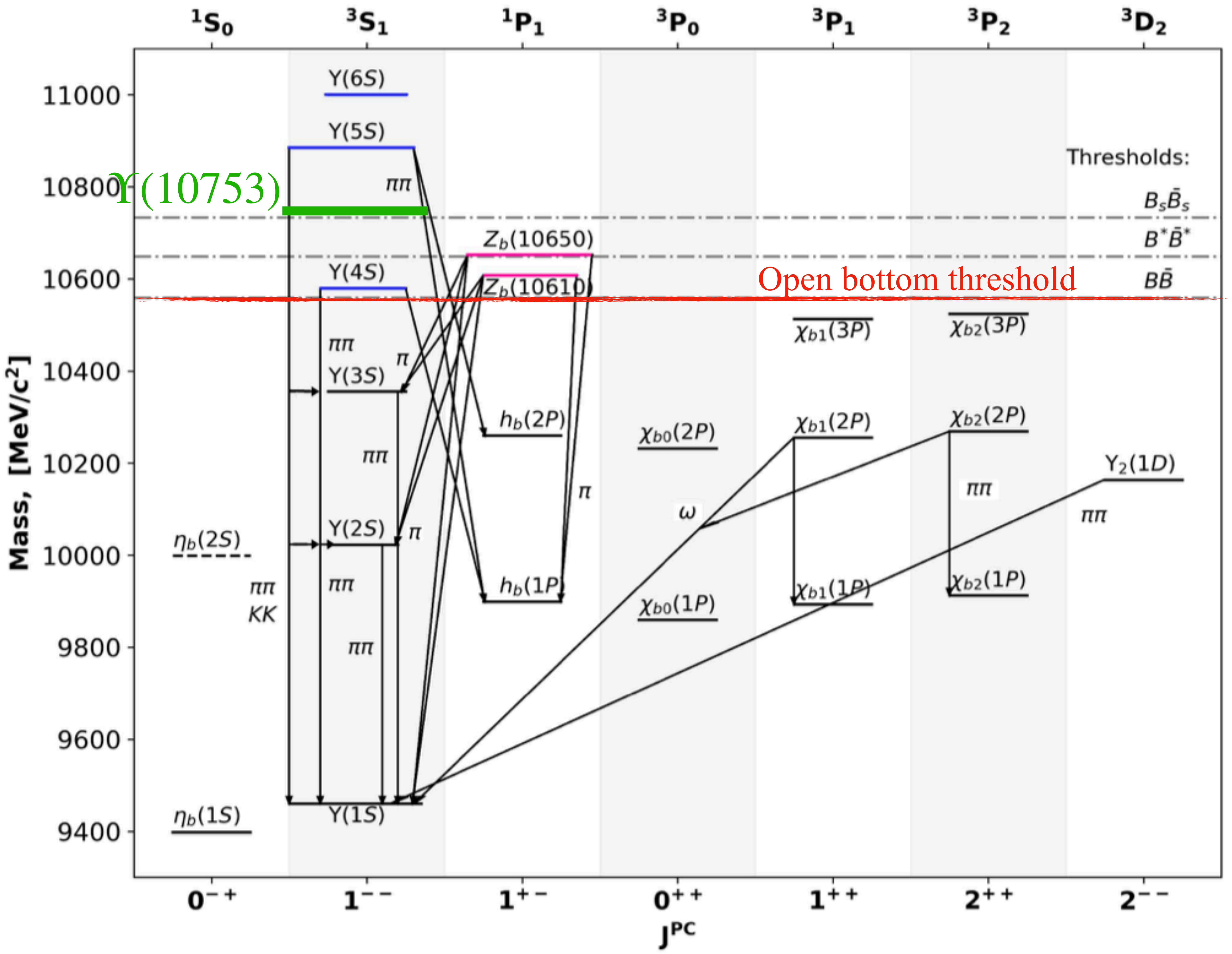
Bottomonium Scheme



- **Below the BB̄ threshold** states are well described by potential models.
- **Above BB̄ threshold states** exhibit unexpected properties:
  - Hadronic transitions to lower bottomonia are strongly enhanced.
  - The η transitions are not suppressed compared to $\pi^+\pi^-$ transitions. Strong violation of Heavy Quark Spin Symmetry.

Exotic admixtures: molecule, compact tetraquark, hybrid.

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



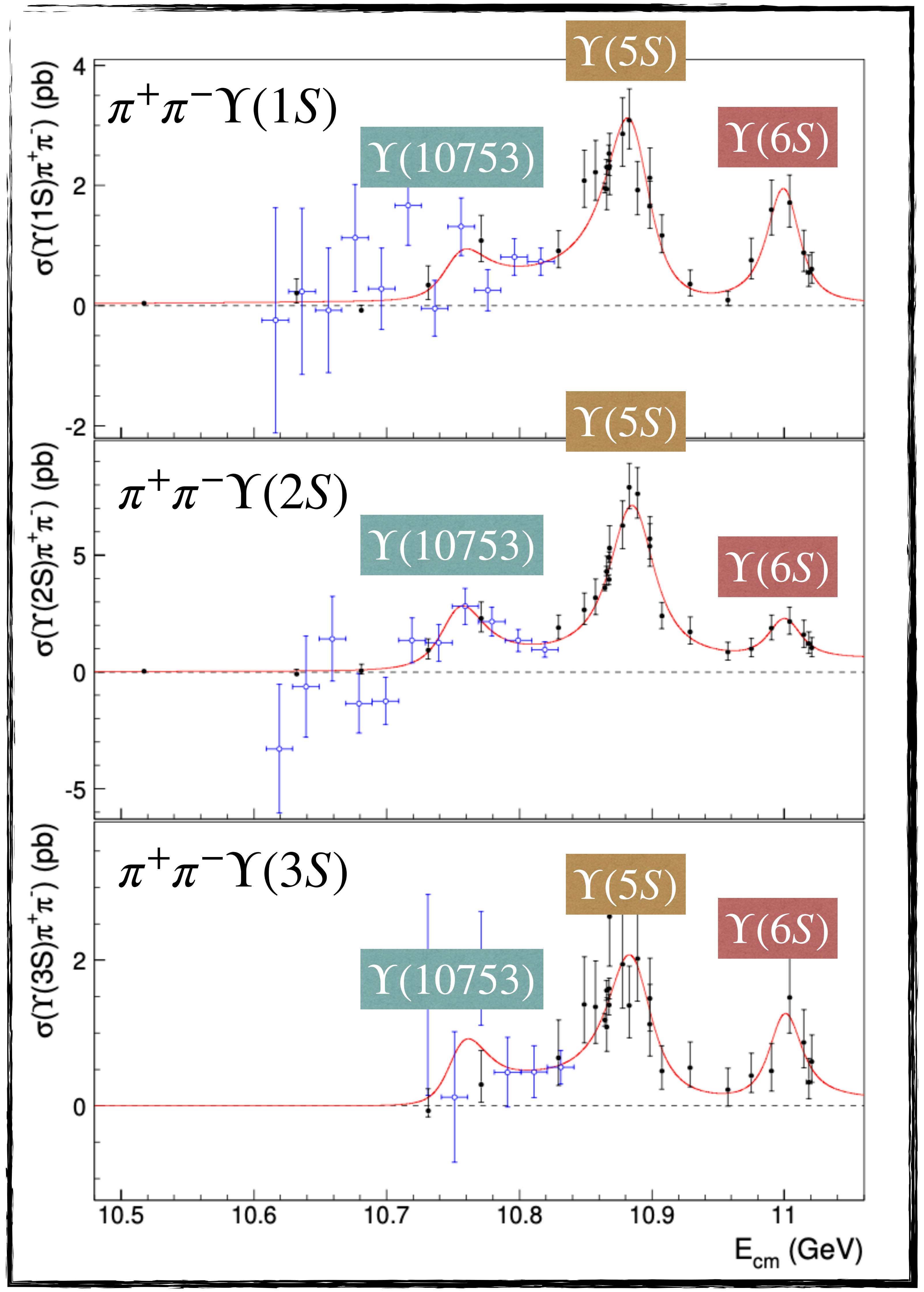
- Conventional bottomonium (pure $b\bar{b}$ state)
- Bottomonium like states (mix of $b\bar{b}$ and $B\bar{B}$)
- Purely exotic states (Z_b)

Discovery of $\Upsilon(10753)$

- $\Upsilon(10753)$ was observed in energy dependence of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1,2,3)$ cross sections by Belle.
- The global significance is 5.2σ

Belle, JHEP 10 (2019) 220

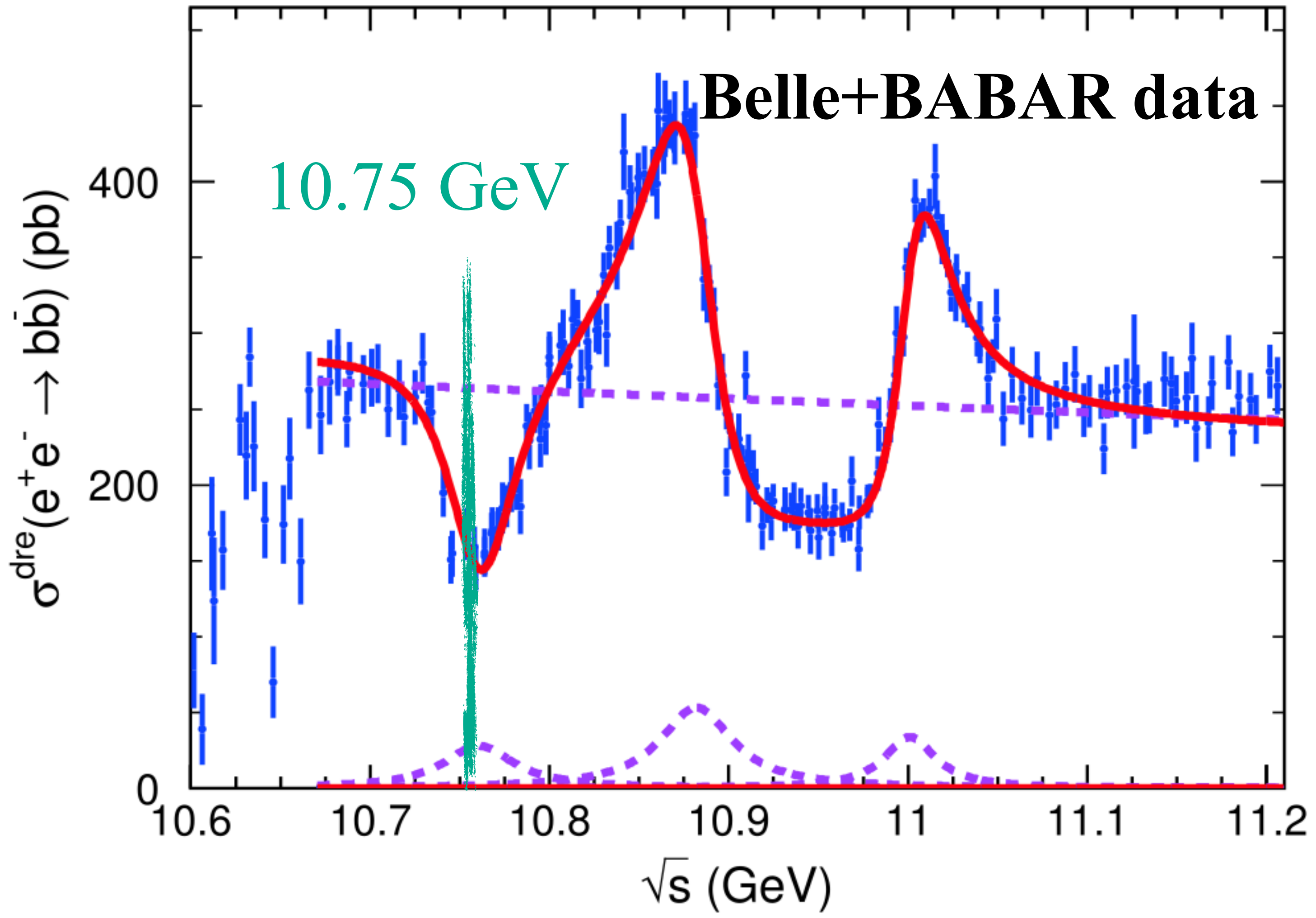
	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5 ^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}{}^{+1.0}_{-1.3}$	$10752.7 \pm 5.9 ^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}{}^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}{}^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}{}^{+3.9}_{-3.3}$



Fit function: 3 BW+smooth component

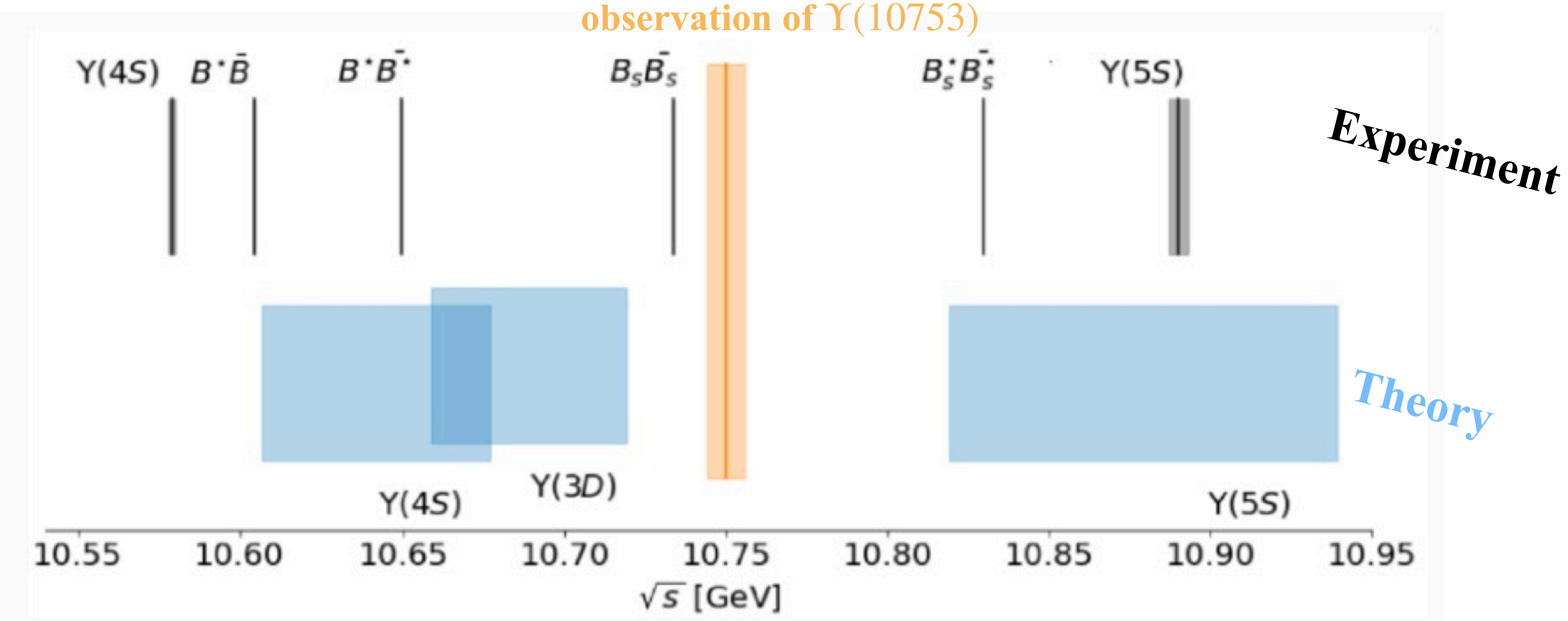
- $e^+e^- \to b\bar{b}$ cross section in bottomonium energy region based on the Belle and BABAR measurement.
  - A dip near 10.75 GeV likely caused by interference between BW and smooth component.

CPC 44, 8, 083001 (2020)



$\Upsilon(10753)$: theoretical interpretation

Experimental observation of $\Upsilon(10753)$



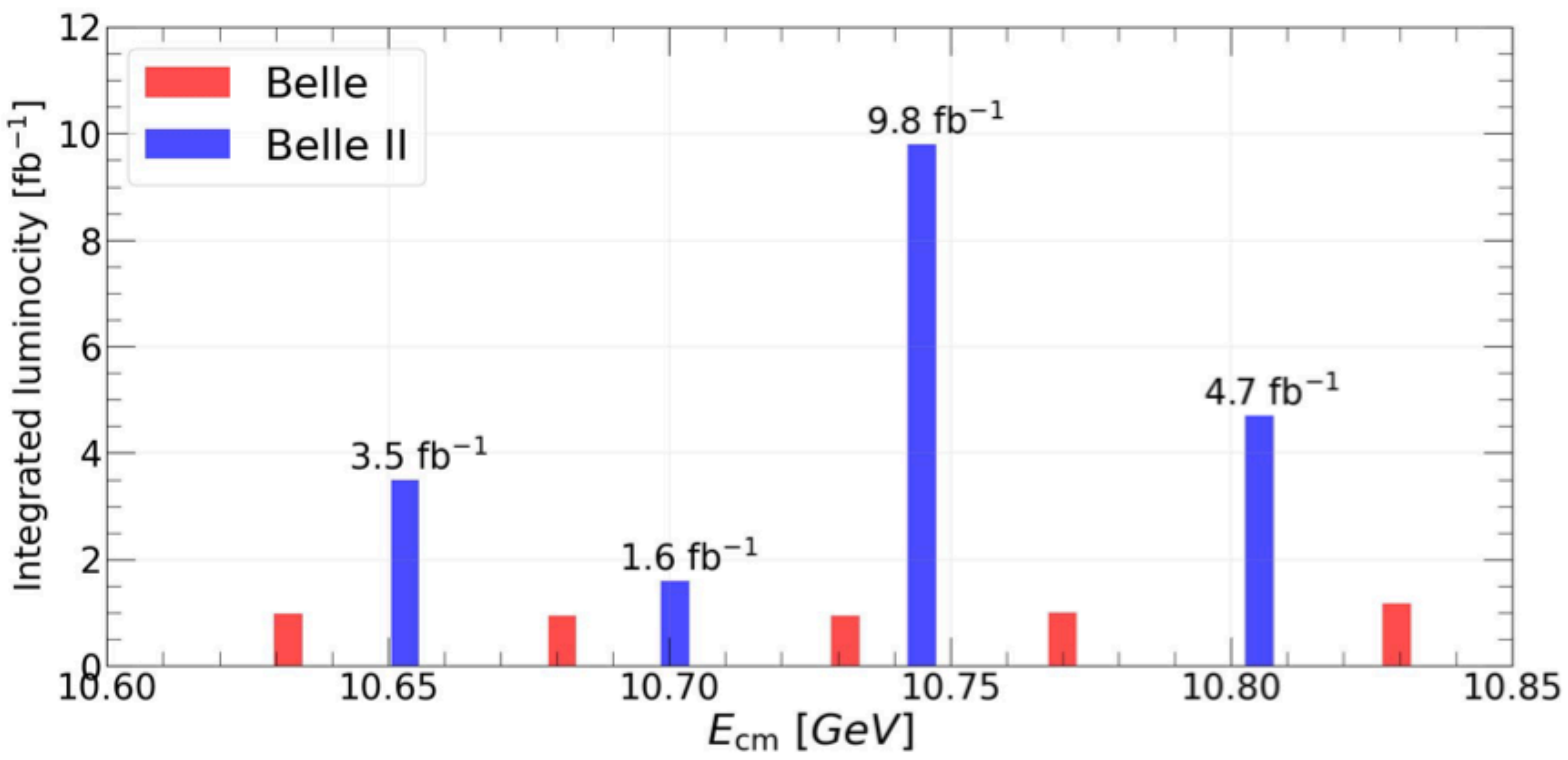
Possible interpretations:

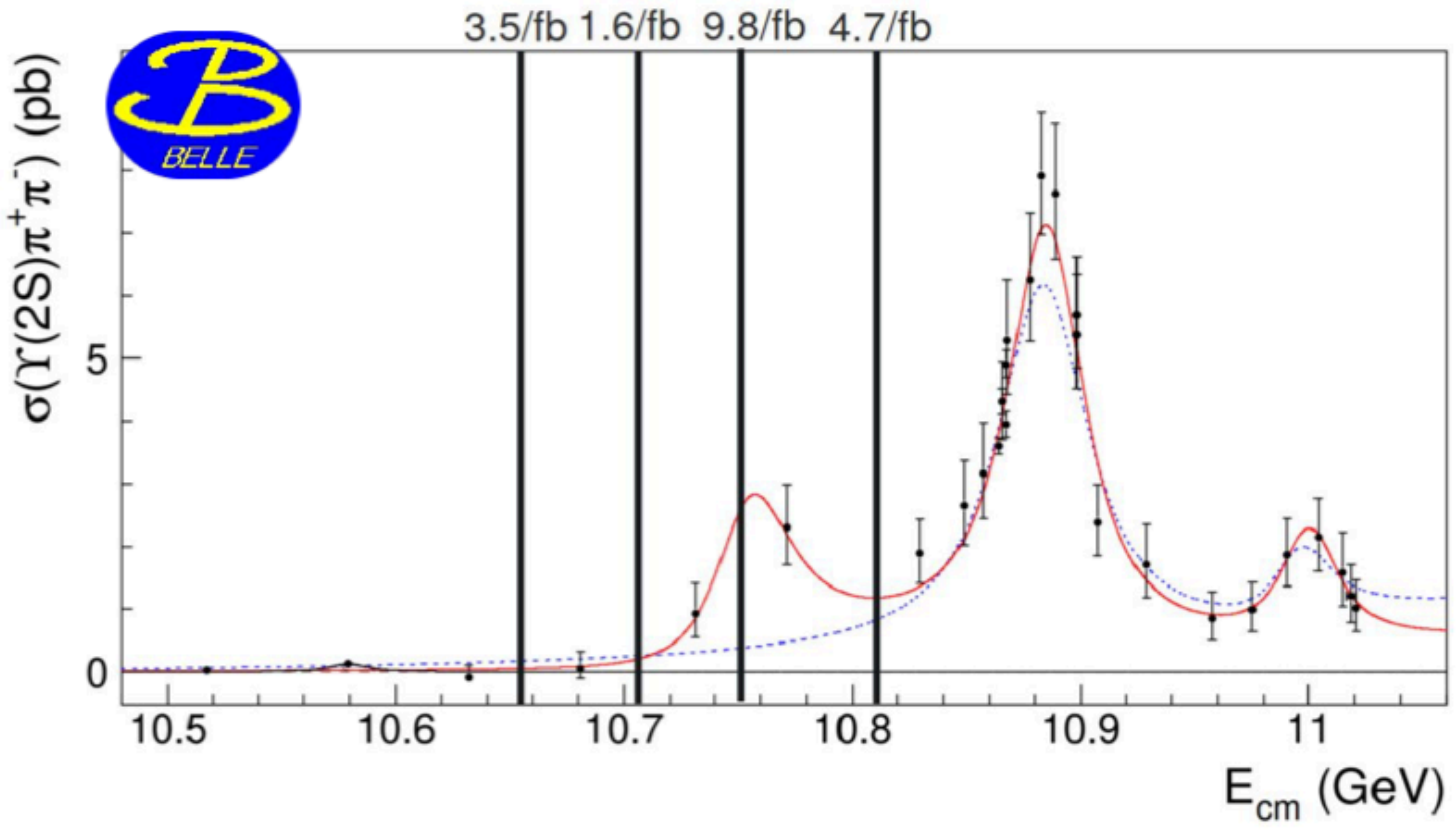
- Conventional bottomonium?
  Phys. Rev. D 105, 114041 (2022)
  Phys. Rev. D 106, 094013 (2022)
  Phys. Rev. D 105, 074007 (2022)
- Hybrid state?
  Phys. Rept. 873, 1 (2020)
  Phys. Rev. D 104, 034019 (2021)
- Tetraquark state?
  Phys. Rev. D 103, 074507 (2021)
  Phys. Rev. D 107, 094515 (2023)
- Hadronic molecule with a small admixture of a bottomonium?

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

Unique scan data near $\sqrt{s} = 10.75$ GeV

- Belle II / SuperKEKB performed an energy scan in November 2021 with a total luminosity of 19 fb^{-1}.
- **Physics Goals:**
  - The main goal was to confirm and study the $\Upsilon(10753)$.
  - Improve the precision of exclusive cross-section below the $\Upsilon(5S)$.



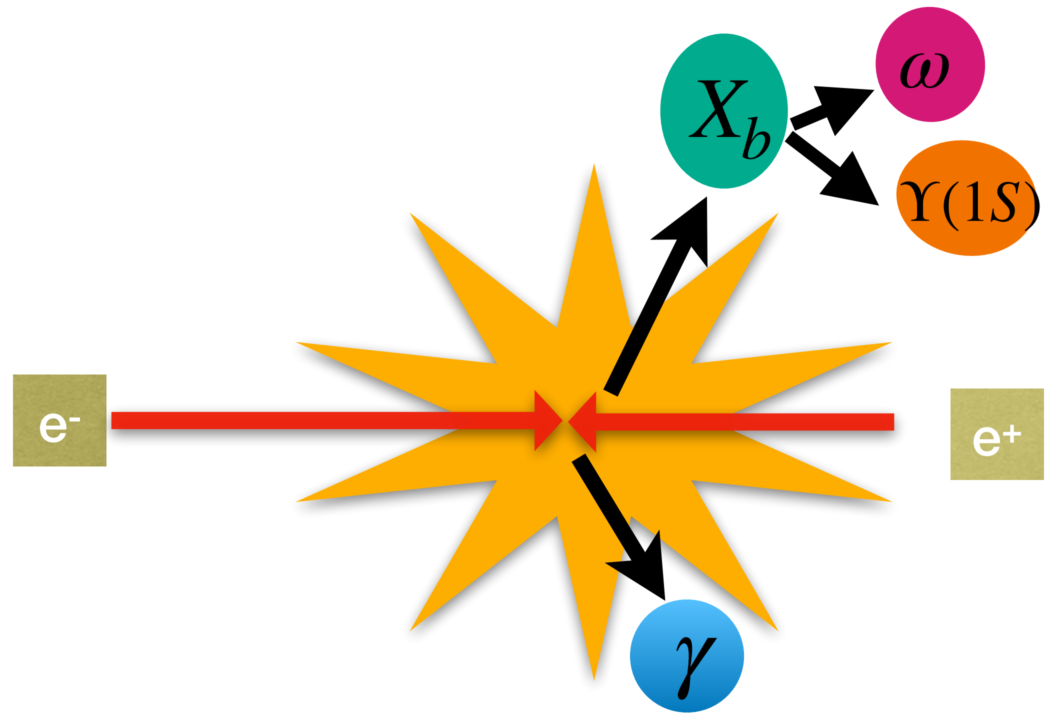


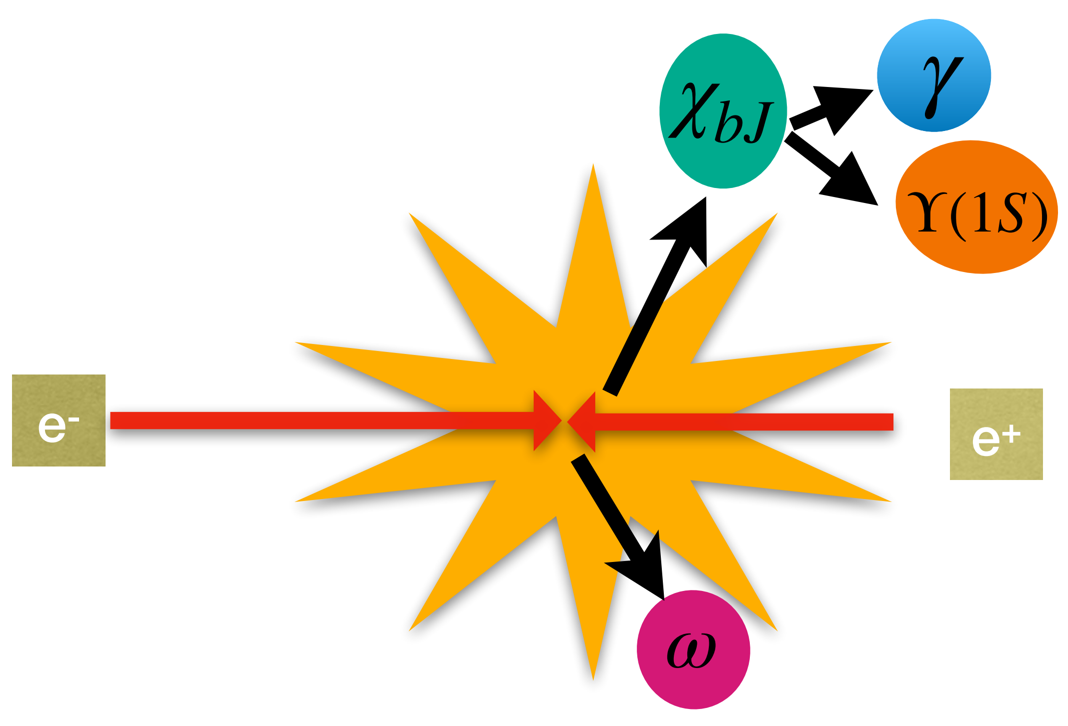
- Belle II collected data in the gaps between the Belle points.
- The point with the highest statistics (9.8 fb^{-1}) is near the $\Upsilon(10753)$ peak.

Study of $\Upsilon(10753) \to (\pi^+\pi^-\pi^0)\ \gamma\ \Upsilon(1S)$

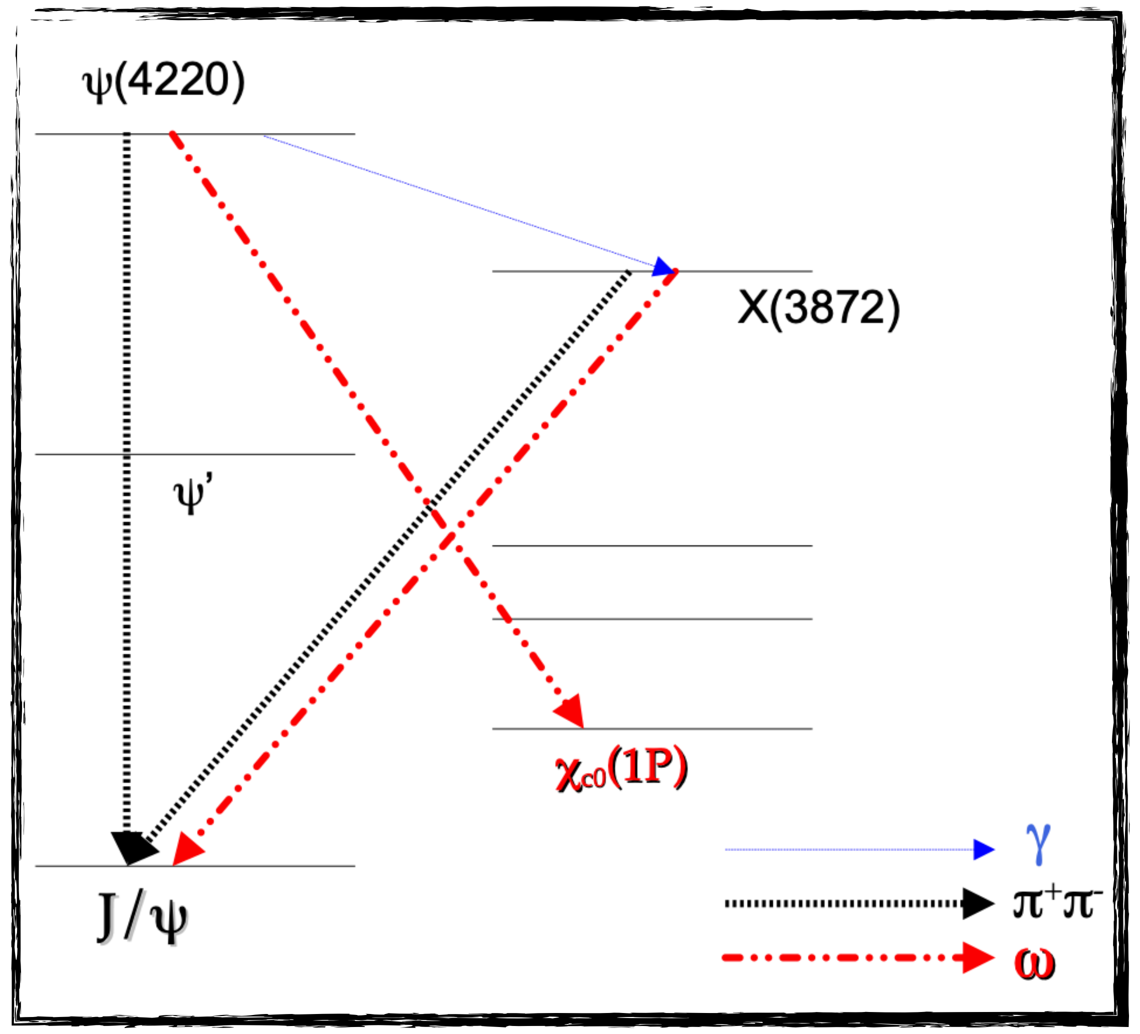
Study of $\Upsilon(10753) \to (\pi^+\pi^-\pi^0)\ \gamma\ \Upsilon(1S)$

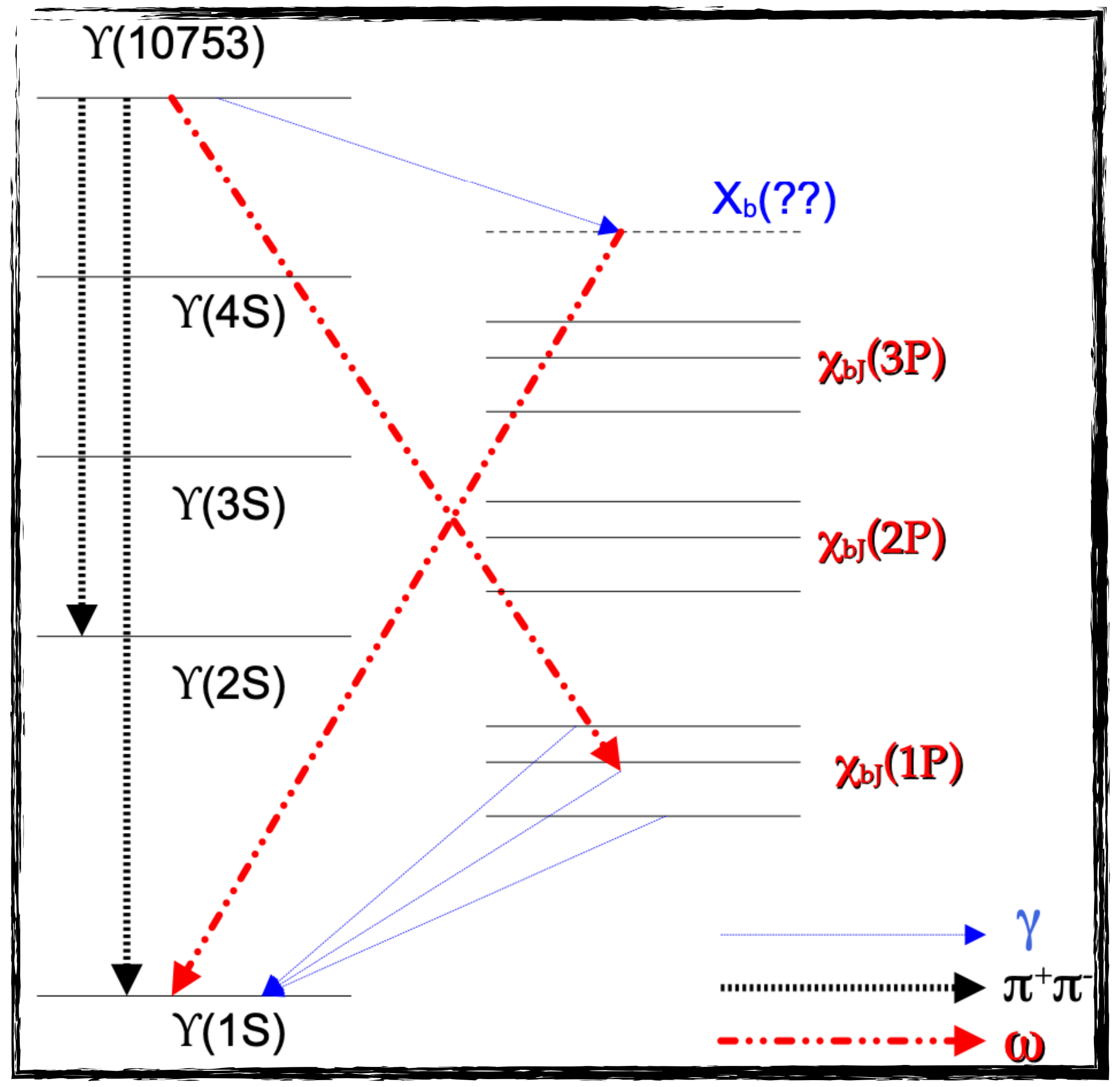
- Theory:
  - Mixed $4S-3D$ model suggests $\Upsilon(10753) \to \chi_{bJ}(1P)\ \omega$ could be enhanced. PRD 104, 034036 (2021)
- Charmonium sector:
  - Similar to $\Upsilon(10753)$ in $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$, $Y(4260)$ was observed in $e^+e^- \to \pi^+\pi^- J/\psi$ cross section by BESIII.
    - Expect similar nature of $\Upsilon(10753)$ and $Y(4260)$.
  - $Y(4260)$ was also observed in $\chi_{c0}(1P)\ \omega$ and $\gamma\ X(3872)$ by BESIII.
  - Inspired by decay modes of $Y(4260)$ charmonium state, we expect
    - $\Upsilon(10753) \to \chi_{bJ}(1P)\ \omega$
    - $\Upsilon(10753) \to \gamma\ X_b$ X_b: bottomonium analogue of X(3872)





Search in $e^+e^- \to (\pi^+\pi^-\pi^0)\ \gamma\ \Upsilon(1S)$ process

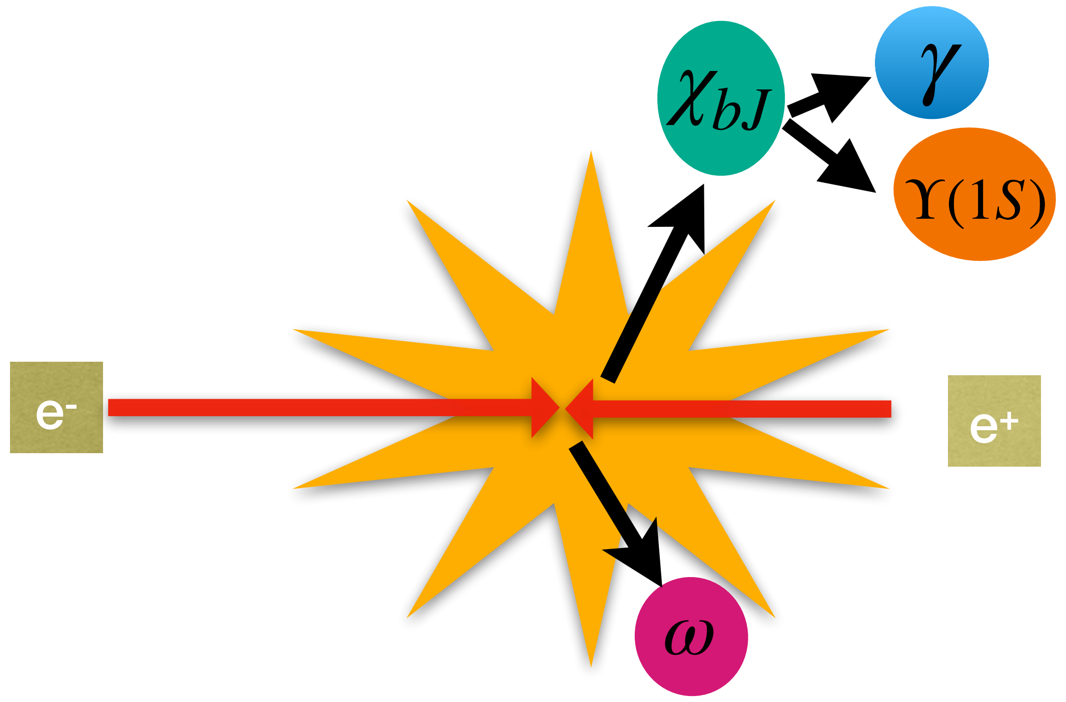


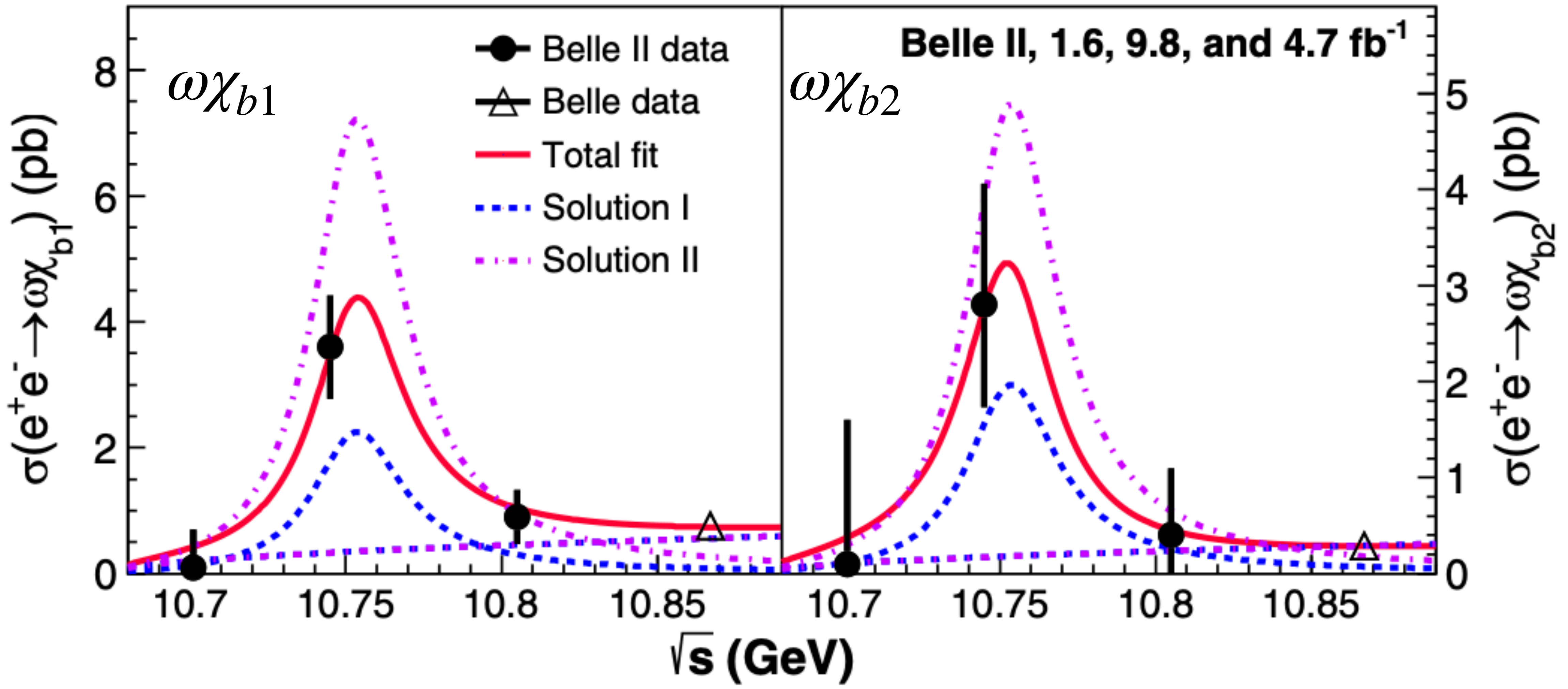


Observation of $\Upsilon(10753) \to \omega\, \chi_{bJ}(1P)$

PRL 130, 091902 (2023)

The $e^+e^- \to \omega\, \chi_{bJ}(1P)$ $(J = 1,2)$ cross sections peak at $\Upsilon(10753)$.





Solution 1: constructive interference

Solution II: destructive interference

- $\dfrac{\sigma(e^+e^- \to \omega\chi_{bJ})}{\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)} \sim$ 1.5 at $\Upsilon(10753)$ GeV; 0.15 at $\Upsilon(5S)$ GeV

$\Longrightarrow$ $\Upsilon(10753)$ and $\Upsilon(5S)$ have different internal structure?

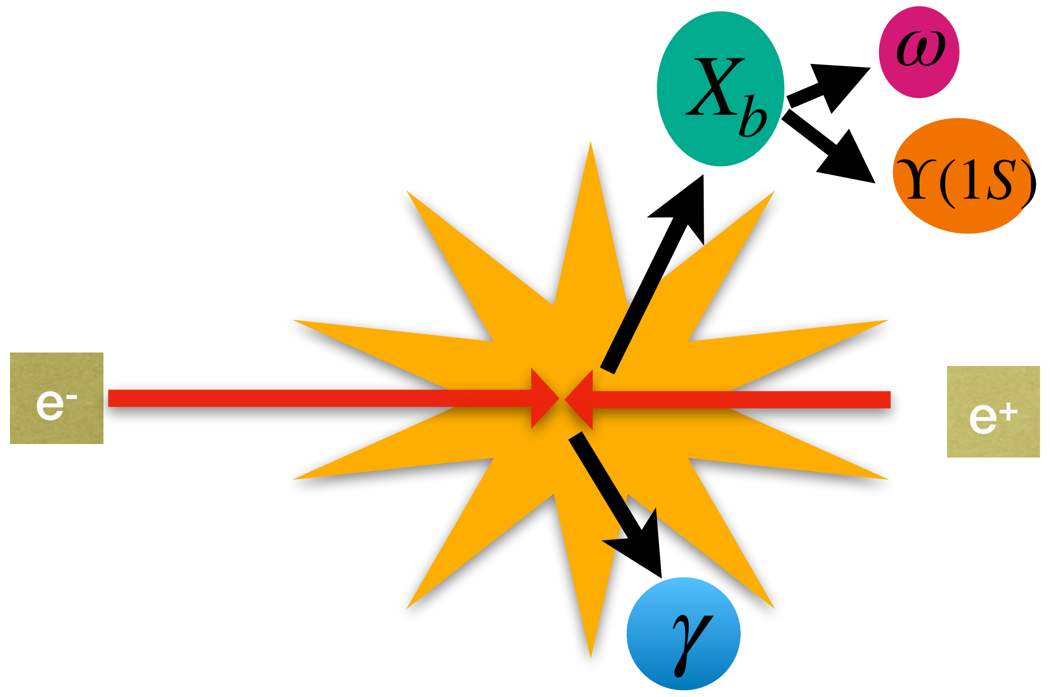
- $\dfrac{\sigma(e^+e^- \to \omega\chi_{b1})}{\sigma(e^+e^- \to \omega\chi_{b2})} = 1.3 \pm 0.6$ at $\sqrt{s} = 10.745$ GeV
  - **Contradicts the expectations for a pure *D*-wave bottomonium state: 15**
  - **An observation of 1.8σ difference with the prediction for a $S - D$ mixed state: 0.2**

Channel	$\sqrt{s}$ (GeV)	N^{sig}	$\sigma_{Born}^{(UL)}$ (pb)
$\omega\chi_{b1}$	10.745	$68.9^{+13.7}_{-13.5}$	$3.6^{+0.7}_{-0.7} \pm 0.4$
$\omega\chi_{b2}$		$27.6^{+11.6}_{-10.0}$	$2.8^{+1.2}_{-1.0} \pm 0.5$
$\omega\chi_{b1}$	10.805	$15.0^{+6.8}_{-6.2}$	1.6 @90% C.L.
$\omega\chi_{b2}$		$3.3^{+5.3}_{-3.8}$	1.5 @90% C.L.

Search for $\Upsilon(10753) \to \gamma X_b$

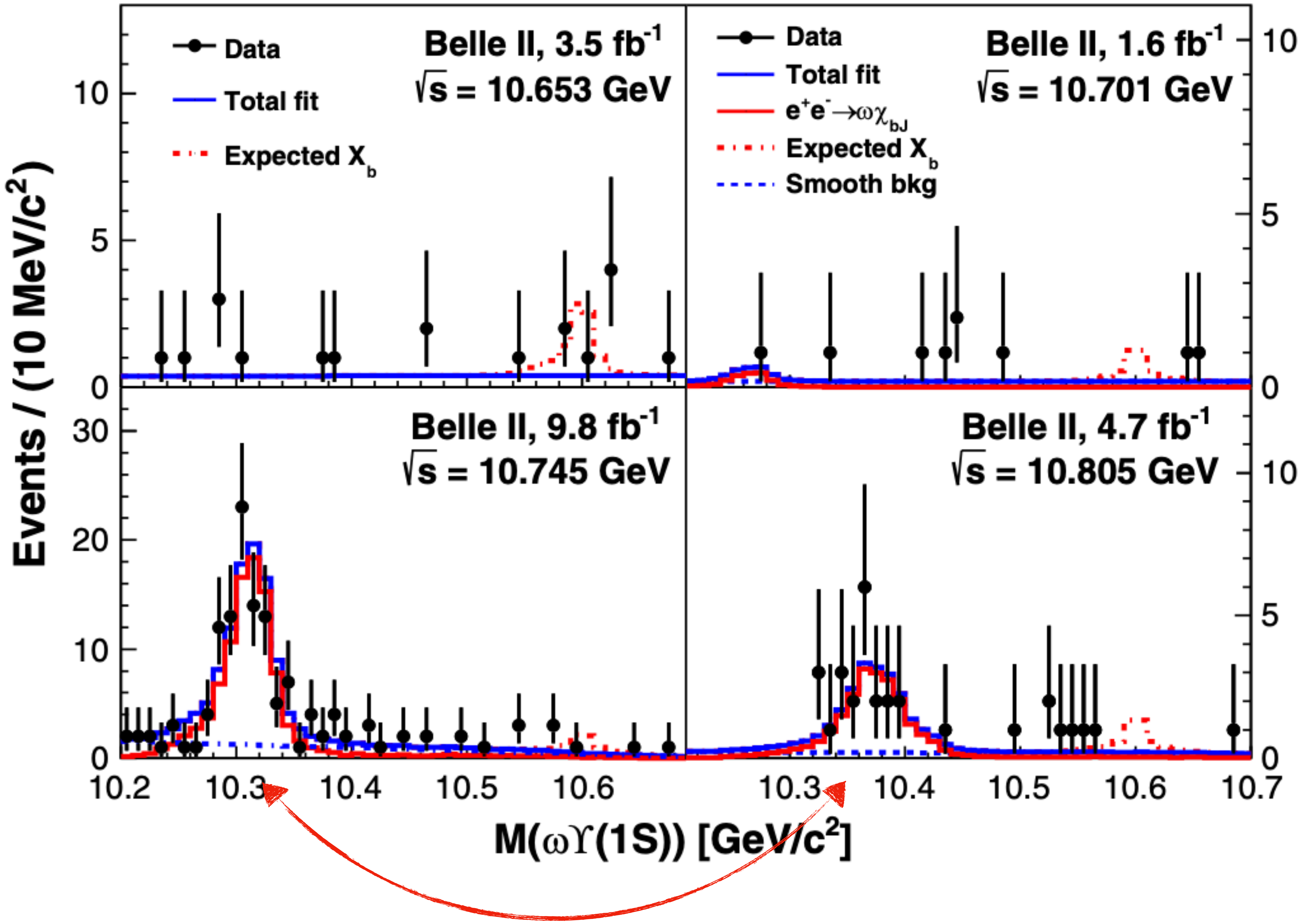
PRL 130, 091902 (2023)

The X_b is posited bottomonium counterpart of X(3872).



- No significant signal of X_b signal is observed.
- Upper limits on cross sections are set for $M(X_b) \in [10.45, 10.65]$ GeV

$\sqrt{s}$ GeV	$\sigma_B(e^+e^- \to \gamma X_b) \times \mathscr{B}(X_b \to \omega\Upsilon(1S))$
10.653	0.14-0.55
10.701	0.25–0.84
10.745	0.06–0.14
10.805	0.08–0.37



Reflection of $e^+e^- \to \omega\chi_{bJ}(1P)$

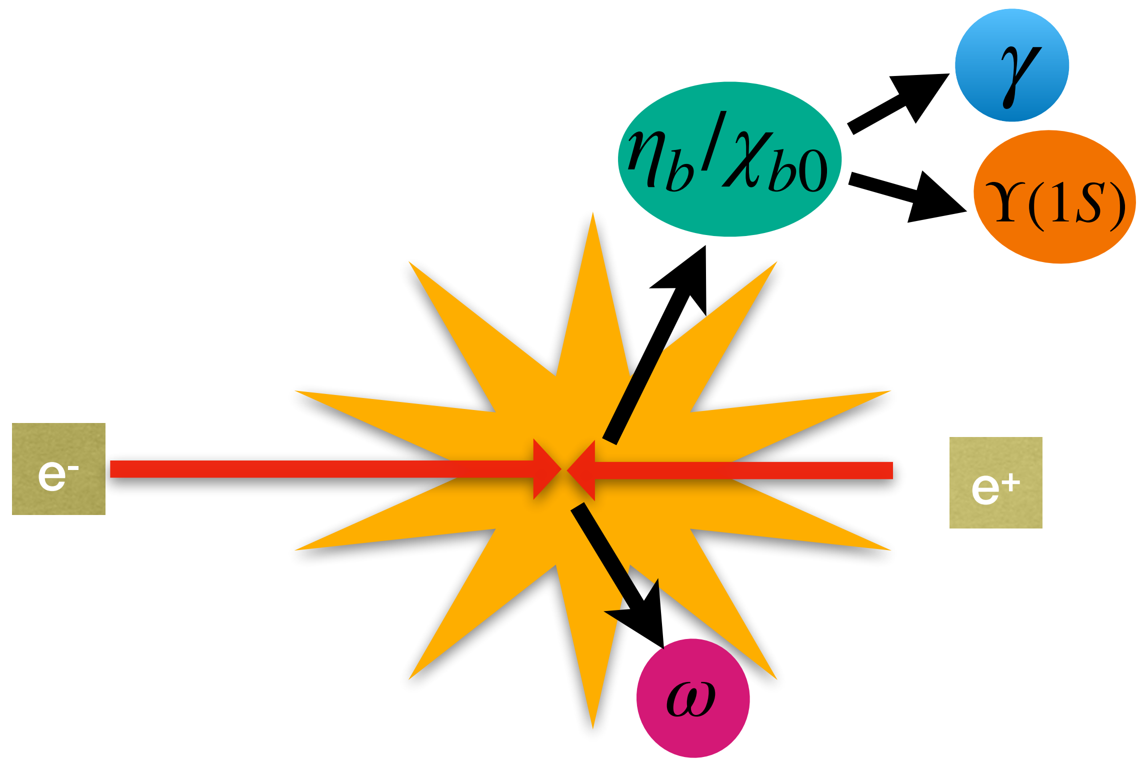
Search for $\Upsilon(10753) \to \omega\chi_{b0}(1P)/\omega\eta_b(1S)$

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

- **Motivation:**
  - $\Upsilon(10753) \to \eta_b(1S)\ \omega$
    - Theoretically, tetraquark interpretation predicts,
      - a strong enhancement of the decay $\eta_b(1S)\ \omega$ compared to $\Upsilon\pi^+\pi^-$

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

CPC 43 (2019) 12, 123102



  - $\Upsilon(10753) \to \chi_{b0}(1S)\omega$
    - In charmonium analogy, $Y(4260) \to \chi_{c0}(1P)\ \omega$ transition is enhanced compared to $Y(4260) \to \chi_{c1,c2}(1P)\ \omega$ PRD 99, 091103(R) (2019)
    - Not observed in full reconstruction analysis of $\Upsilon(10753) \to \chi_{bJ}(1S)\ \omega$ due to small branching fraction

PRL 130 091902 (2023)

- **Strategy**
  - Partial reconstruction:
    - Reconstructed ω meson in $\pi^+\pi^-\pi^0$ and use the recoil mass of ω as signal variable

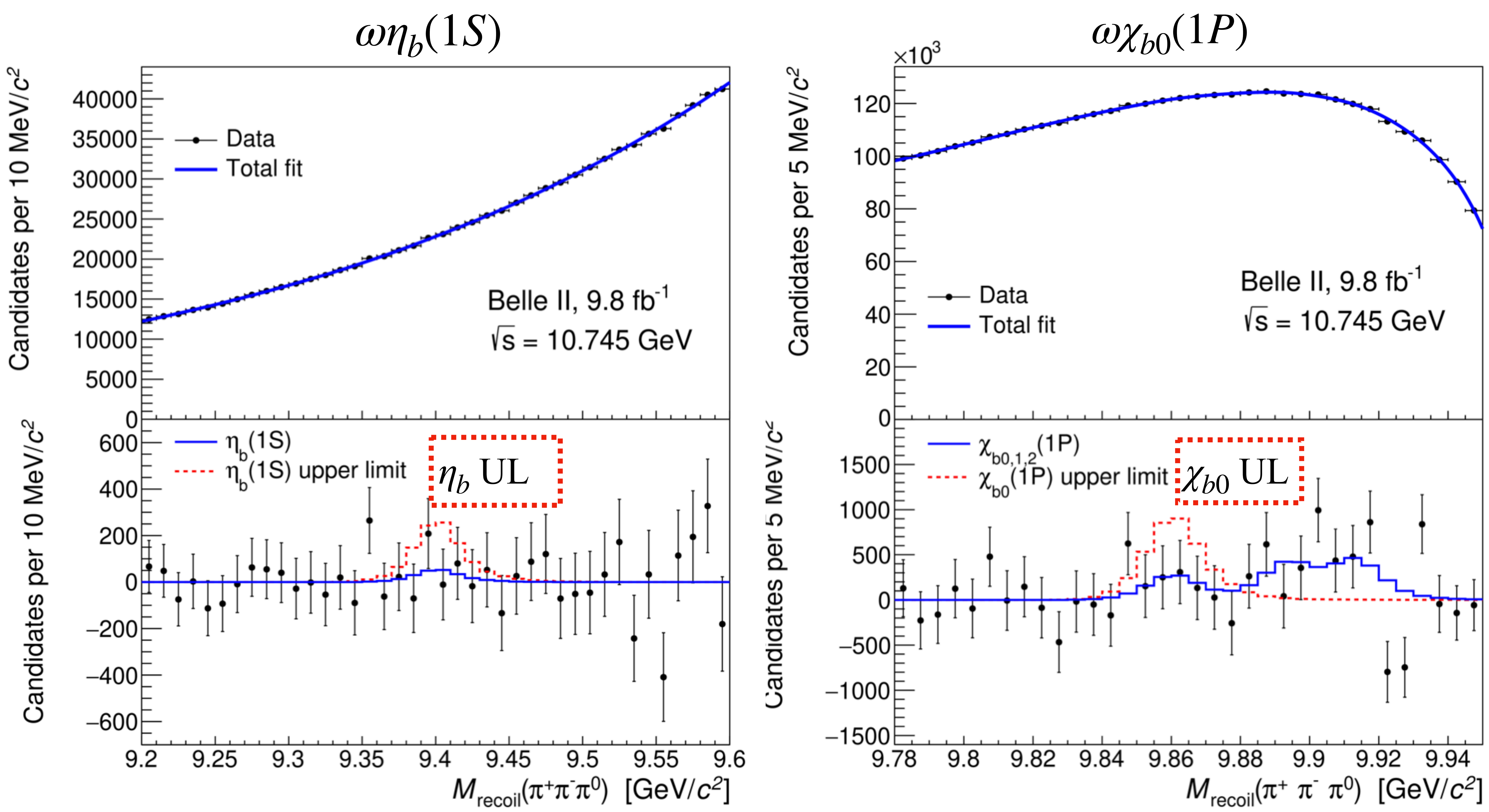
$$M_{\text{recoil}}(\pi^+\pi^-\pi^0) = \sqrt{\left(\frac{\sqrt{s} - E^*}{c^2}\right)^2 - \left(\frac{p^*}{c}\right)^2}$$

Results

- No significant $\omega\ \chi_{b0}(1P)$ and $\omega\ \eta_b(1S)$ signals are observed.
- Upper limits at the 90% C.L. on the Born cross section are set.

$\omega \rightarrow \pi^+\pi^-\pi^0$ recoil mass distributions

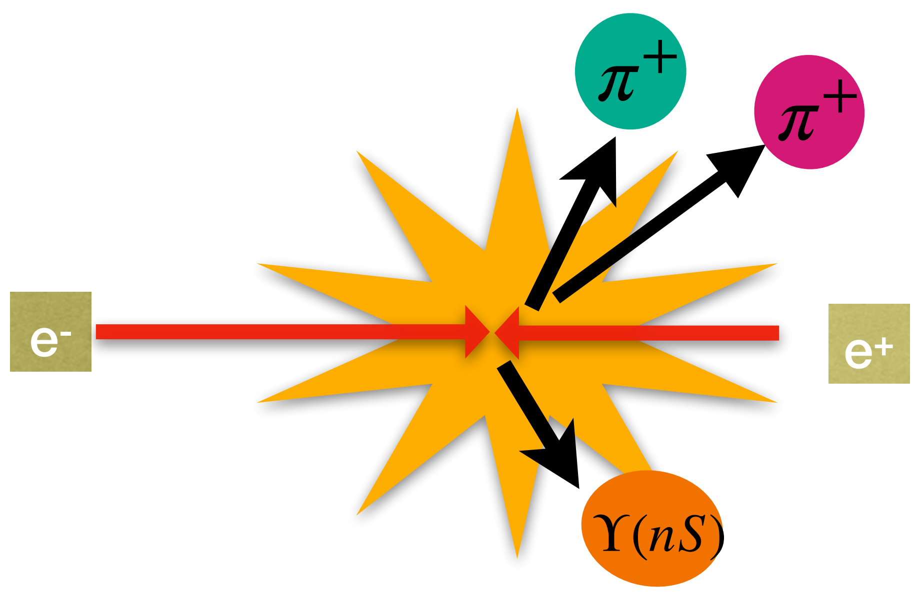
- $\omega\ \eta_b(1S)$:
  - $\sigma(e^+e^- \rightarrow \eta_b(1S)\omega) < 2.5$ pb
  - c.f $\sigma(e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-) \sim 2.0$ pb
  - Evidence against the tetraquark model predictions. CPC 43 (2019) 12, 123102
- $\omega\ \chi_{b0}(1P)$:
  - $\sigma(e^+e^- \rightarrow \chi_{b0}(1S)\omega) < 8.7$ pb
  - Supports the $S - D$ mixing model PRD 104 (2021), 034036

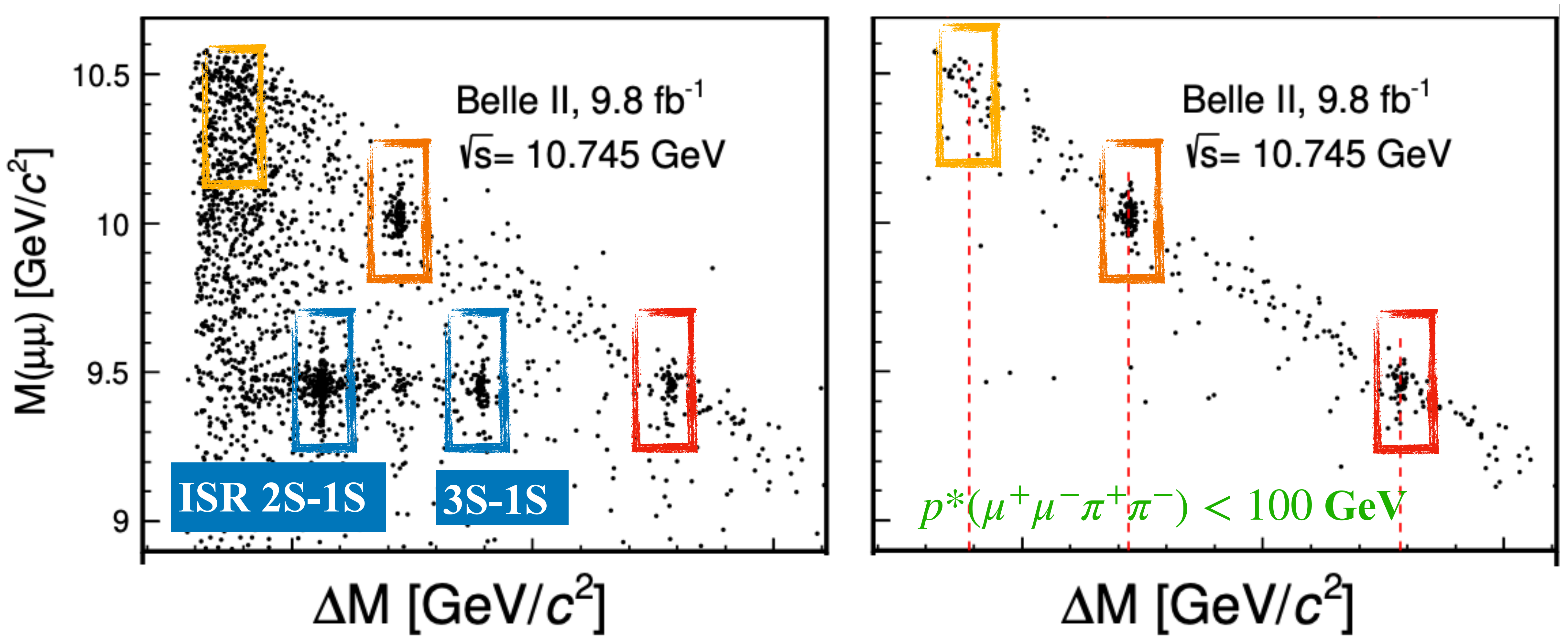


Search for $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$

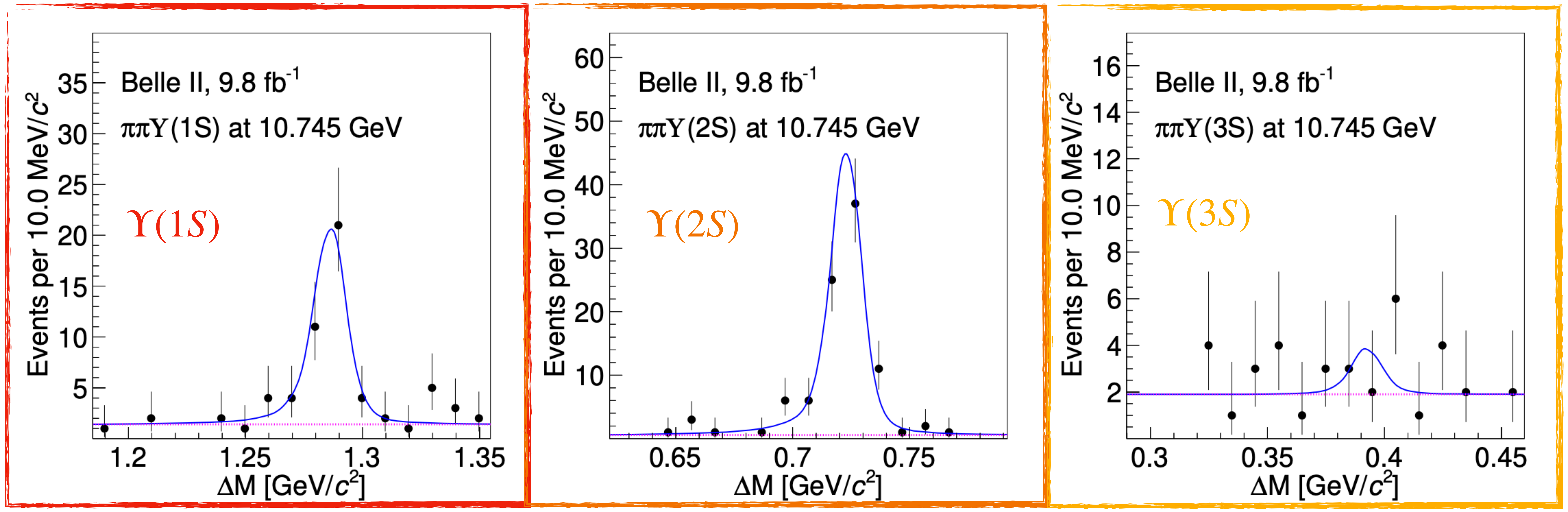
Search for $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$

- Search for $\Upsilon(nS)(\to \mu^+\mu^-)\pi^+\pi^-$ decay mode.
- $p^*(\mu^+\mu^-\pi^+\pi^-) < 100$ MeV/c to reject ISR.





- Clear signal for $\Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(2S)\pi^+\pi^-$ decay mode.
- No evidence of $\Upsilon(3S)\pi^+\pi^-$

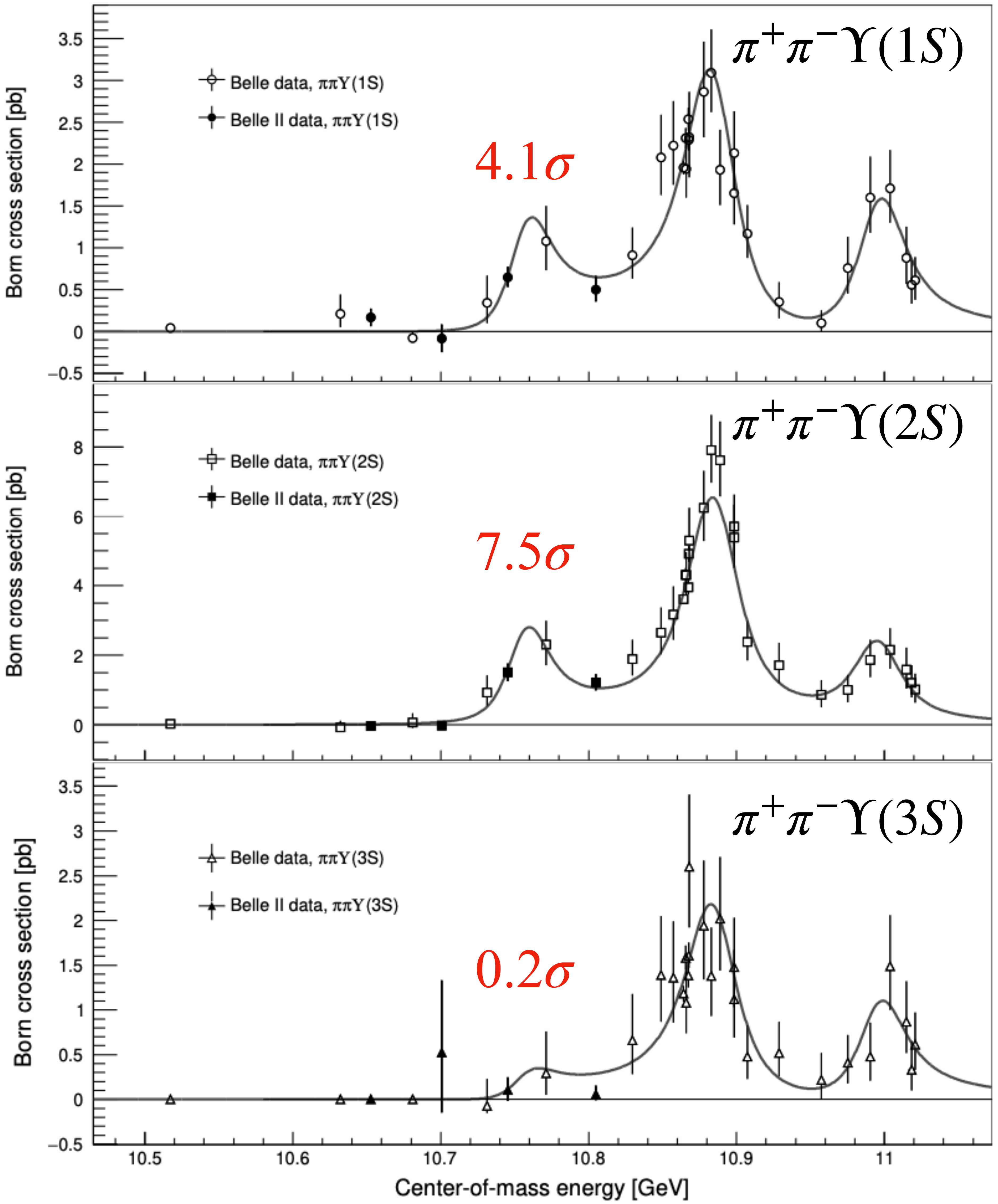


Search for $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$

- New measurement confirms previous Belle result: cross section is peaking near 10.75 GeV.

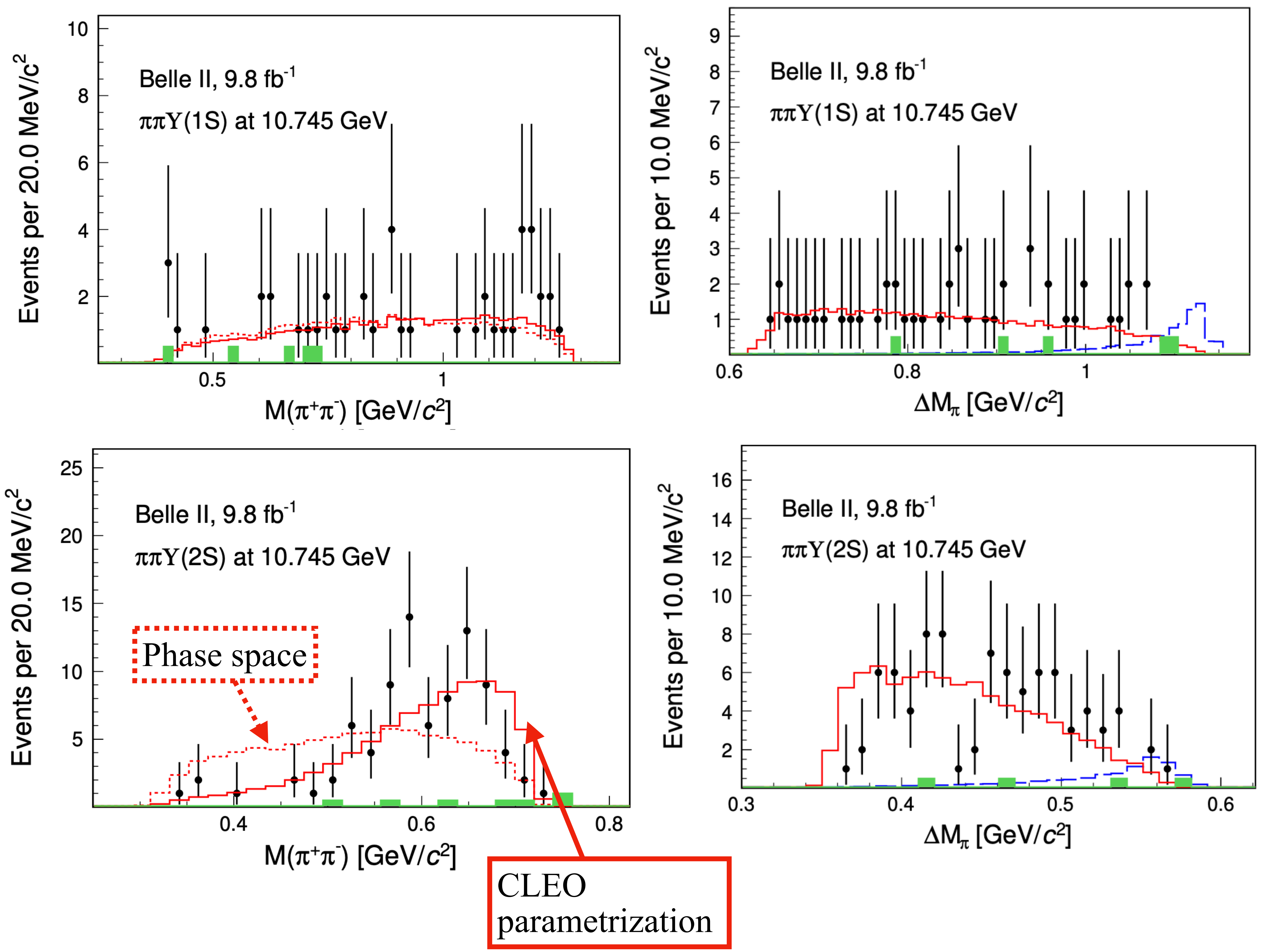
	Belle II	Belle
$M_{\Upsilon(10753)}$	$10756.3 \pm 2.7 \pm 0.6$	$10752.7 \pm 5.9^{+0.7}_{-1.1}$
$\Gamma_{\Upsilon(10753)}$	$29.7 \pm 8.5 \pm 1.1$	$35.5^{+17.6+3.9}_{-11.3-3.3}$

- Results are in consistent with the Belle results.
- Uncertainties are improved by a factor of two from previous Belle results.



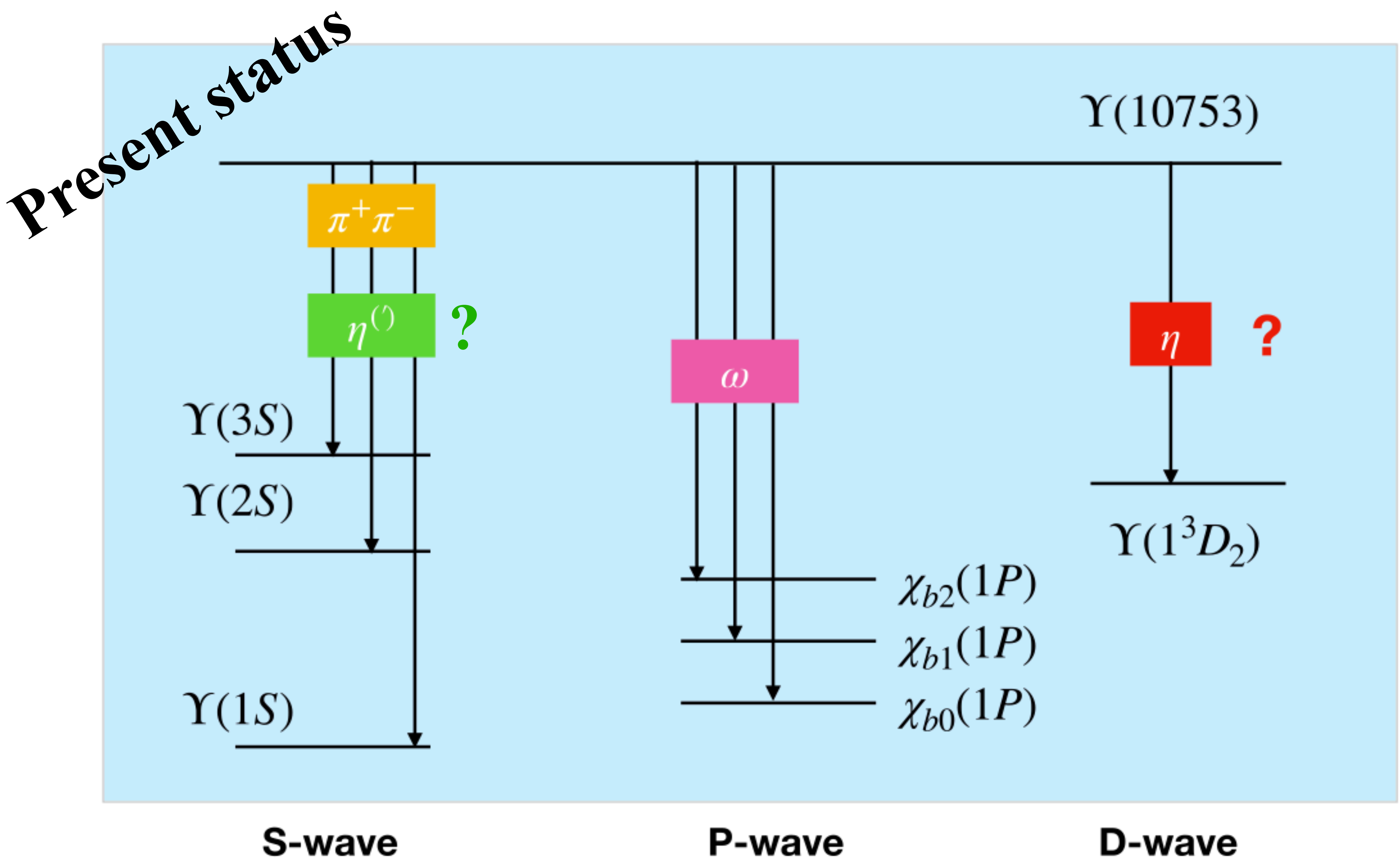
Resonant structure in $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$

- No signal of intermediate $Z_b^+(10610)$ **or** $Z_b^+(10650)$ resonances are observed.
- $\pi^+\pi^-\Upsilon(1S)$: $M(\pi^+\pi^-)$ distribution is consistent with phase space.
- $\pi^+\pi^-\Upsilon(2S)$: larger values of $M(\pi^+\pi^-)$ enhanced (similar to $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ process)



Conclusion on $\Upsilon(10753)$

- New decay modes $\Upsilon(10753) \to \omega\chi_{b1,2}(1P)$ are observed for the first time.
- A stringent upper limit is set for the $\Upsilon(10753) \to \eta_b(1S)\omega$ at $\sqrt{s} = 10.745$ GeV.
- Improved results for mass and width of $\Upsilon(10753)$ using $\Upsilon(10753) \to \Upsilon(nS)\pi^+\pi^-$.
- No signal of intermediate $Z_b^+(10610)$ or $Z_b^+(10650)$ resonances are observed.

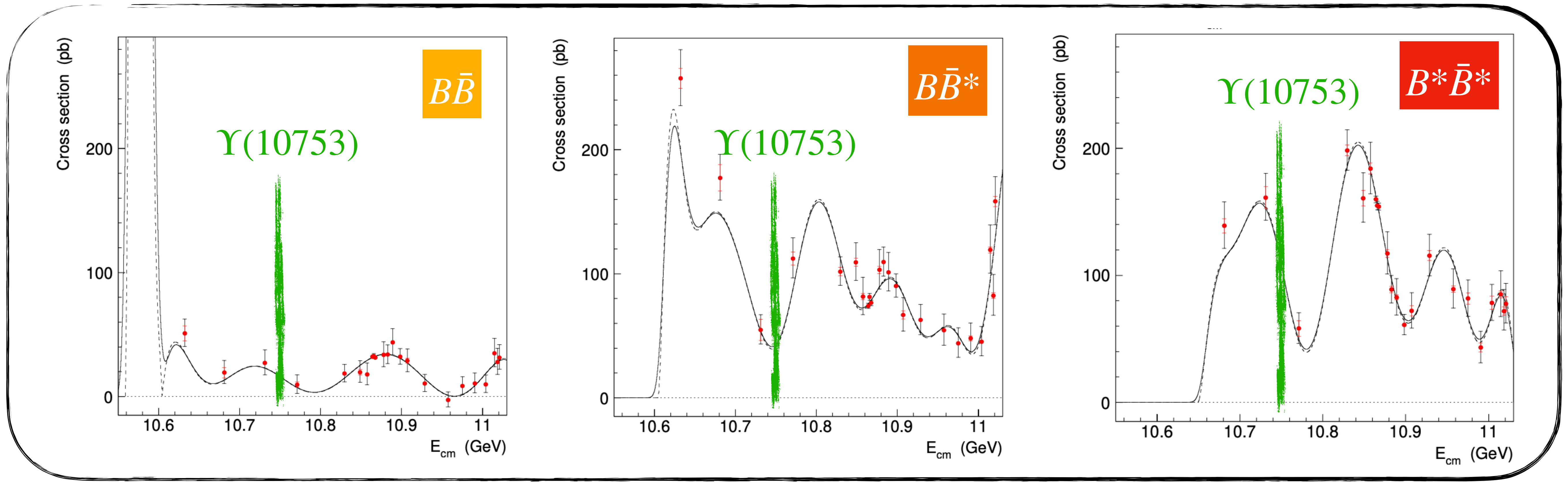


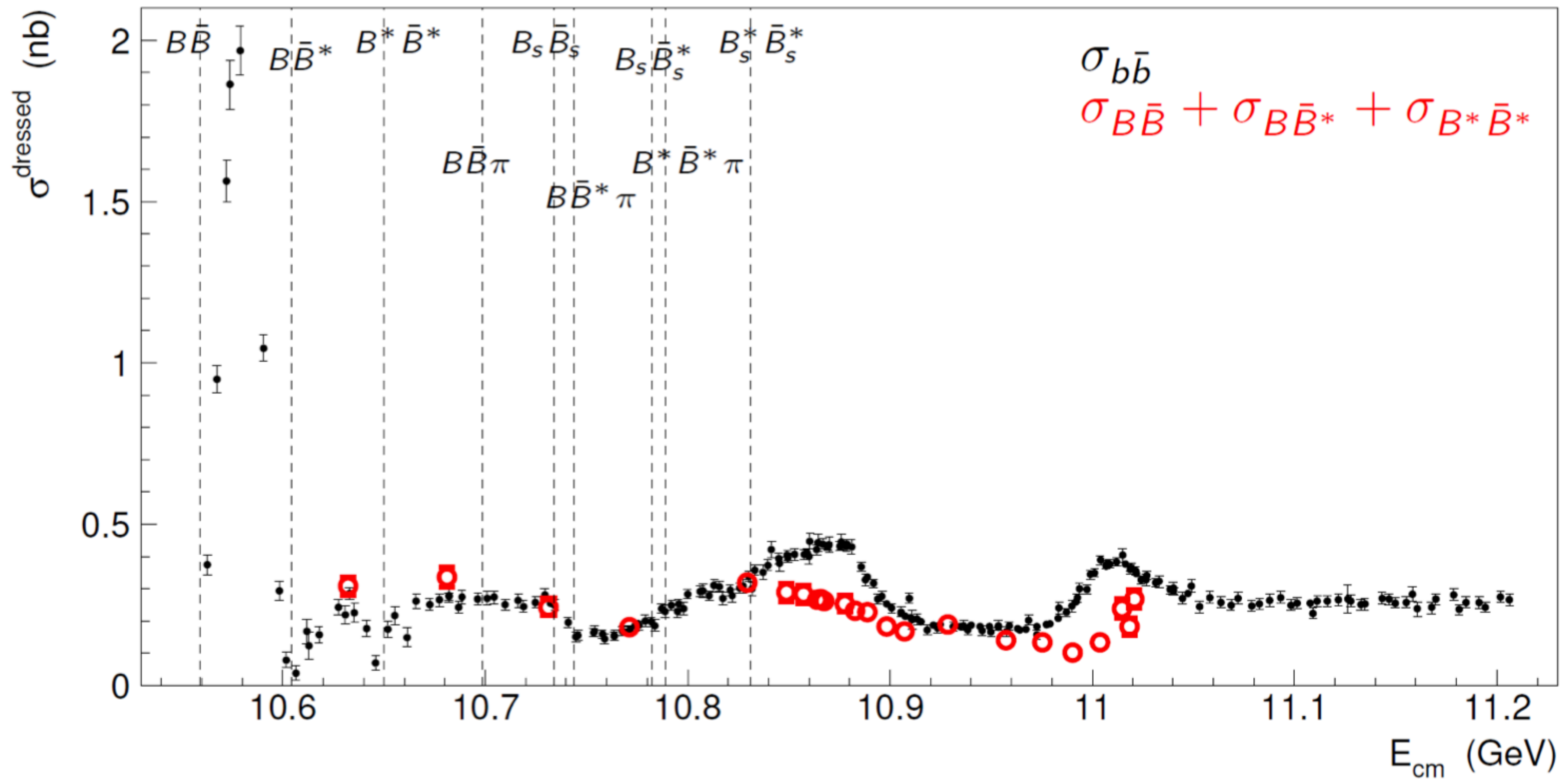
Energy dependence of $e^+e^- \to B^{(*)}\bar{B}^{(*)}$ cross section

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

- **Motivation:**
  - The open flavor final states ($B^{(*)}\bar{B}^{(*)}$) make dominant contribution to $b\bar{b}$ cross-section.
    - Their measurements are critical for understanding the structure of $b\bar{b}$ states.
  - **Belle measured the energy dependencies of $\sigma(e^+e^- \to B^{(*)}\bar{B}^{(*)})$ and observed an oscillatory behavior.**
    - Channels $B^{(*)}\bar{B}^{(*)}$ saturate the cross-section below the $B_s^*\bar{B}_s^*$ threshold.
  - The measured cross sections can be used in the coupled channel analysis of all available scan data to extract the parameters of the Υ states.
  - To improve the accuracy below Y(5S) and understand the nature of $\Upsilon(10753)$, need more data: Belle II

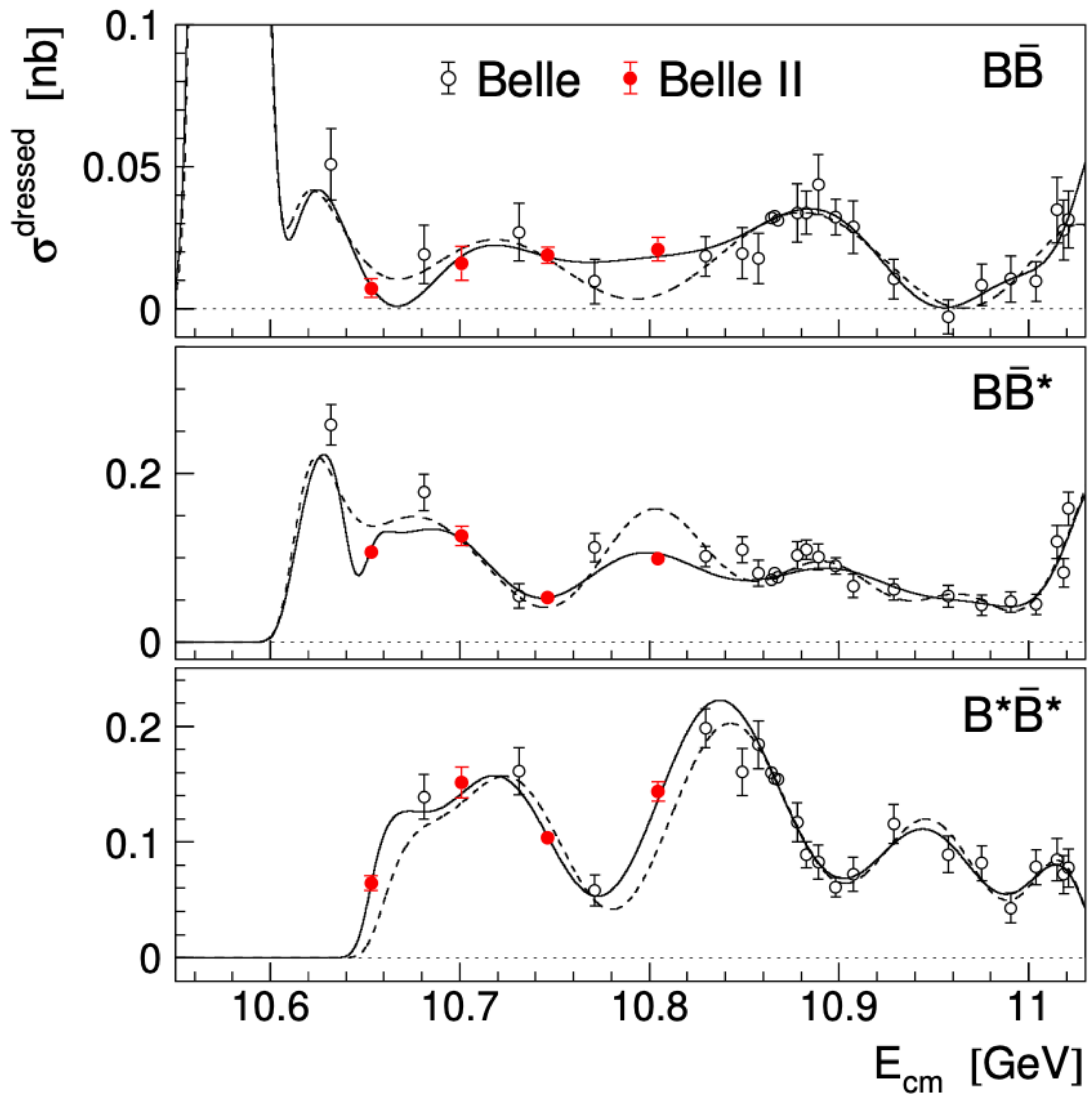
Belle results





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

- The obtained cross sections at four energies are consistent with the Belle results.
- $\sigma(e^+e^- \to B^*\bar{B}^*)$ increases rapidly above $B^*\bar{B}^*$ threshold
  - Similar phenomenon was observed near $D^*\bar{D}^*$ threshold.
  - **Possible interpretation:** resonance or bound state ($B^*\bar{B}^*$ or $b\bar{b}$) near $B^*\bar{B}^*$ threshold
  - Inelastic channels [$\pi^+\pi^-\Upsilon(nS)$ and $h_b(1P)\eta$] could also be enhanced

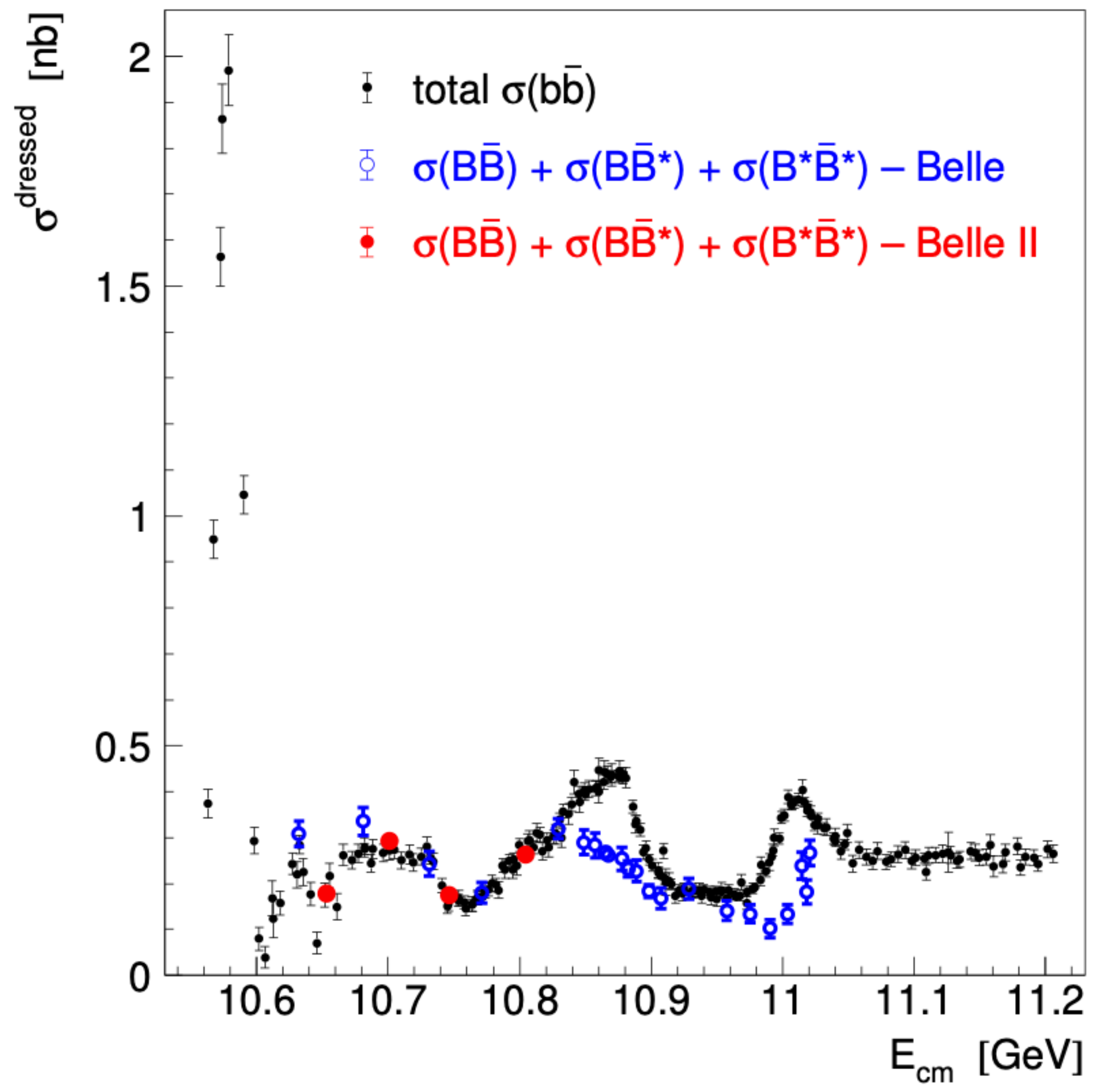


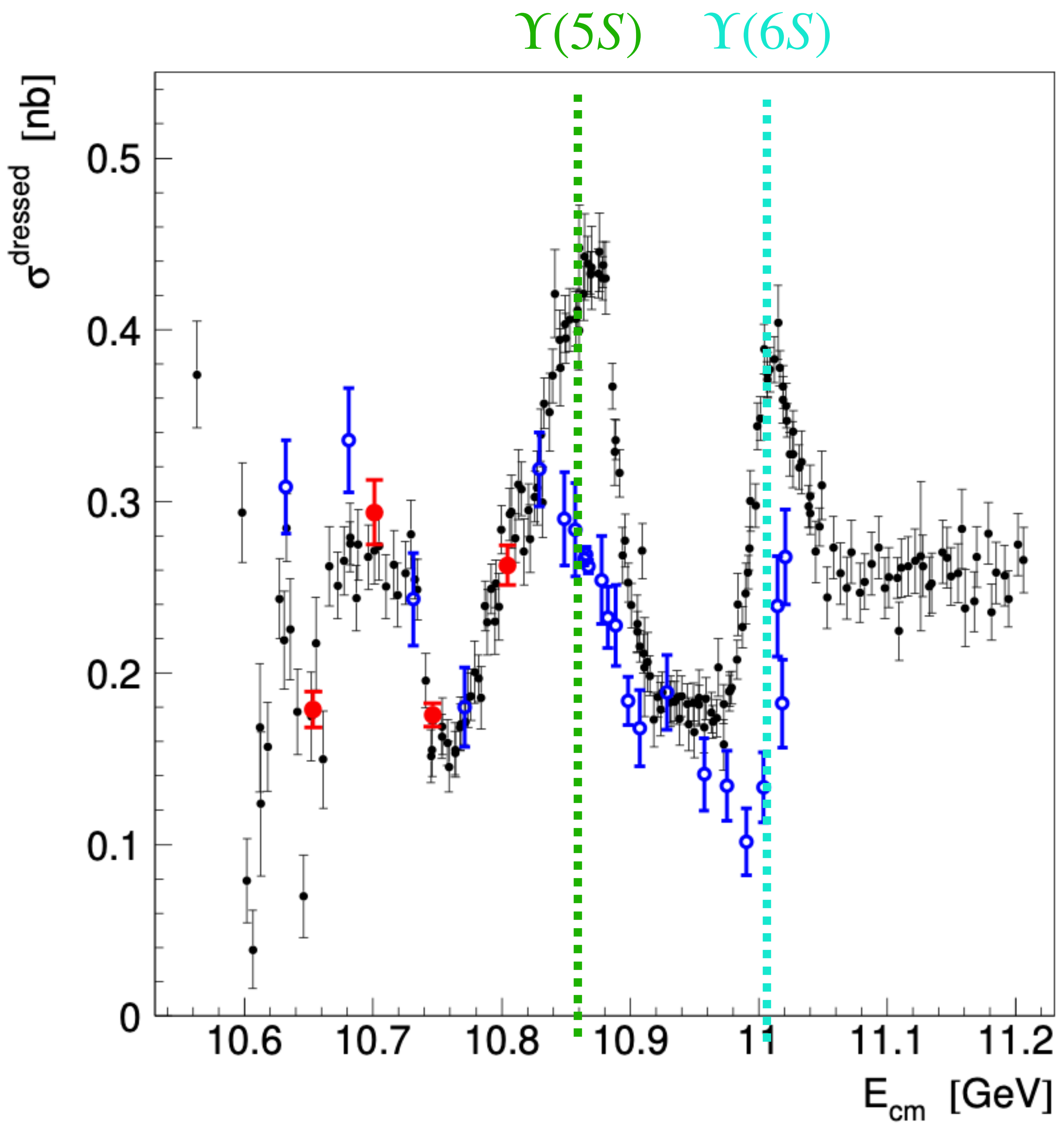
Solid curve – combined Belle + Belle II data fit

Dashed curve – Belle data fit only

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

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





Black dots: Belle + BaBar
[PRL 102, 012001 (2009), PRD 93, 011101 (2016), CPC 44, 083001 (2020)]

Open blue circles: Belle
[JHEP 06, 137 (2021)]

Filled red circles: Belle II
[this work]

- Agreement with $\sigma_{b\bar{b}}$ below the $B_s^{(*)}\bar{B}_s^{(*)}$ threshold.
- Deviation at high energy is presumably due to $B_s^*\bar{B}_s^*$, multi-body $B^{(*)}\bar{B}^{(*)}\pi(\pi)$, etc.

Summary

- We are at the beginning of a long program of quarkonium physics.
- The unique scan data near $\sqrt{s} = 10.75$ GeV at Belle II provides an opportunity
  - To understand the nature of the $\Upsilon(10753)$ energy region,
  - The quarkonium spectroscopy.

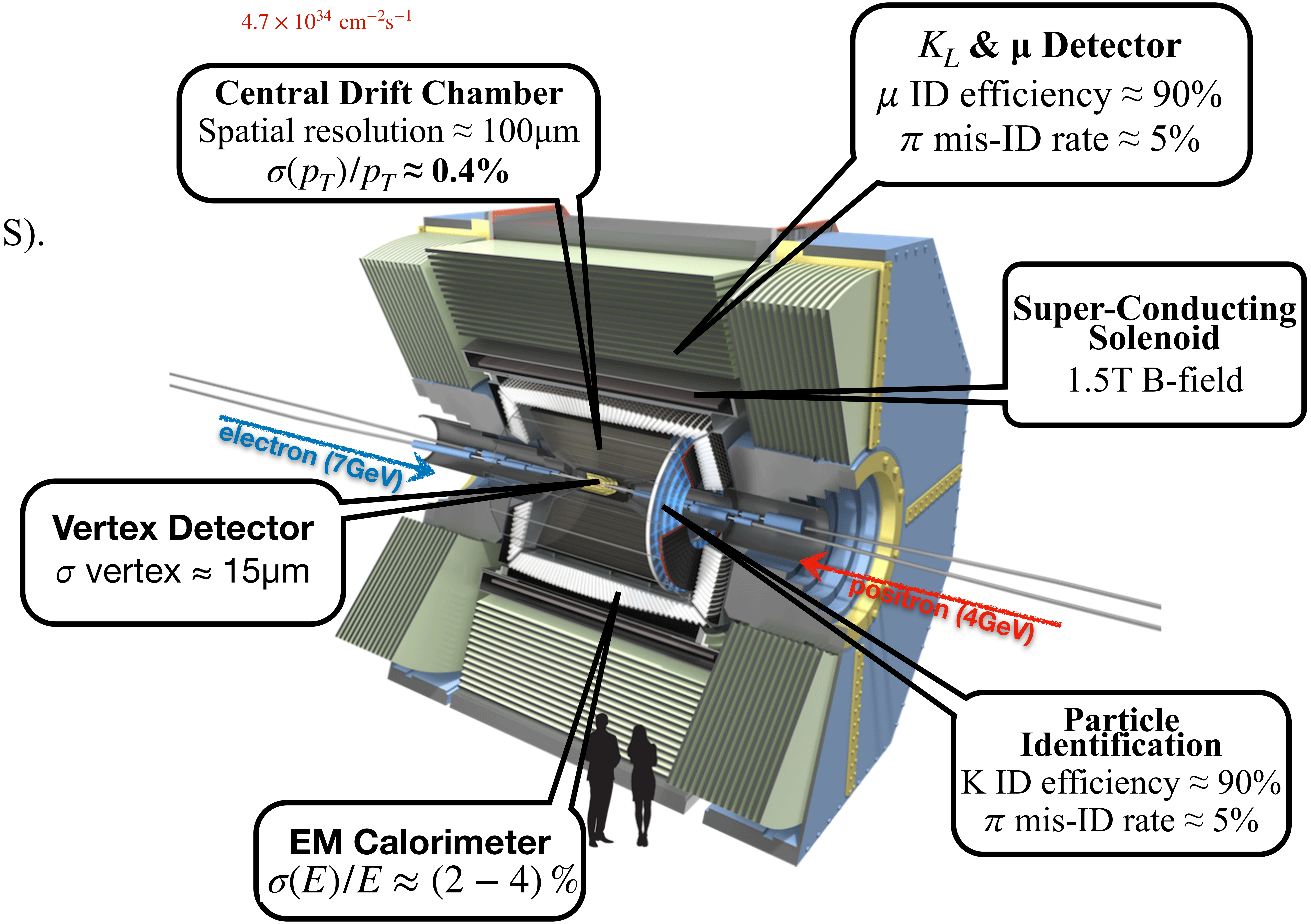

Backup
Ctrl

Belle II detector

- Asymmetric e^+e^- collider
- **Collected data**
  - ~ 362 fb^{-1} at Υ(4S)
  - 42 fb^{-1} off-resonance, 60 MeV below Υ(4S).
  - 19 fb^{-1} energy scan between 10.6 to 10.8 GeV for exotic hadron studies.

Record-breaking instantaneous luminosity:

$4.7 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

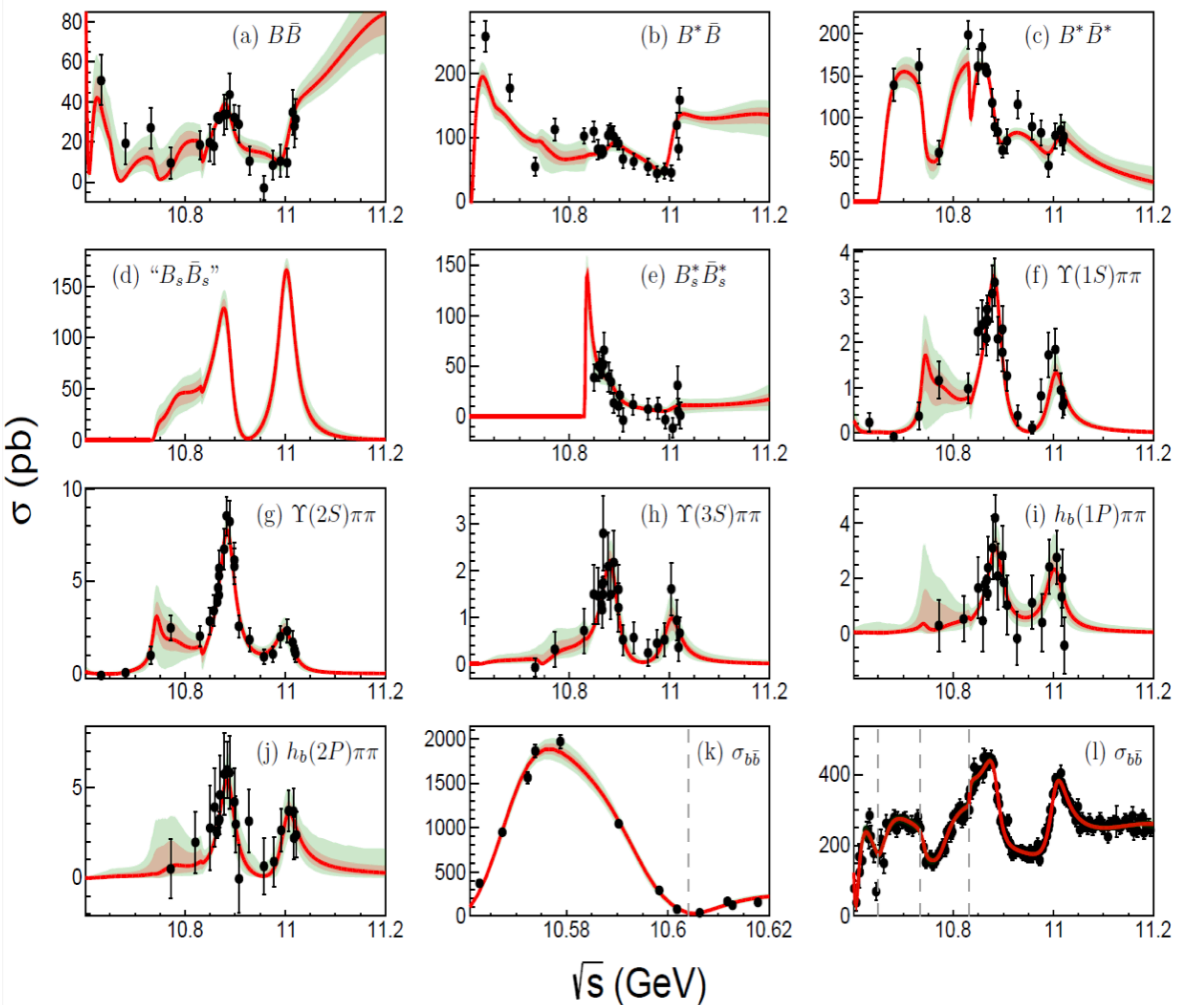


Features:

- Near-hermetic detector
- Excellent vertexing and tracking
- High-efficiency detection of neutrals (γ, π^0, η, η', …)
- Good charged particle reconstruction.

Coupled channel analysis

Hüsken, Mitchell, Swanson, PRD 106, 094013 (2022)



All available scan data

K-matrix: scattering via ϒ(4S), ϒ(10753), ϒ(5S), ϒ(6S) or non-resonantly.

Results:
pole positions,
branching fraction,
energy dependence of scattering amplitudes.

Accuracy above ϒ(6S) and near ϒ(10753) is poor.

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

Decay modes used:

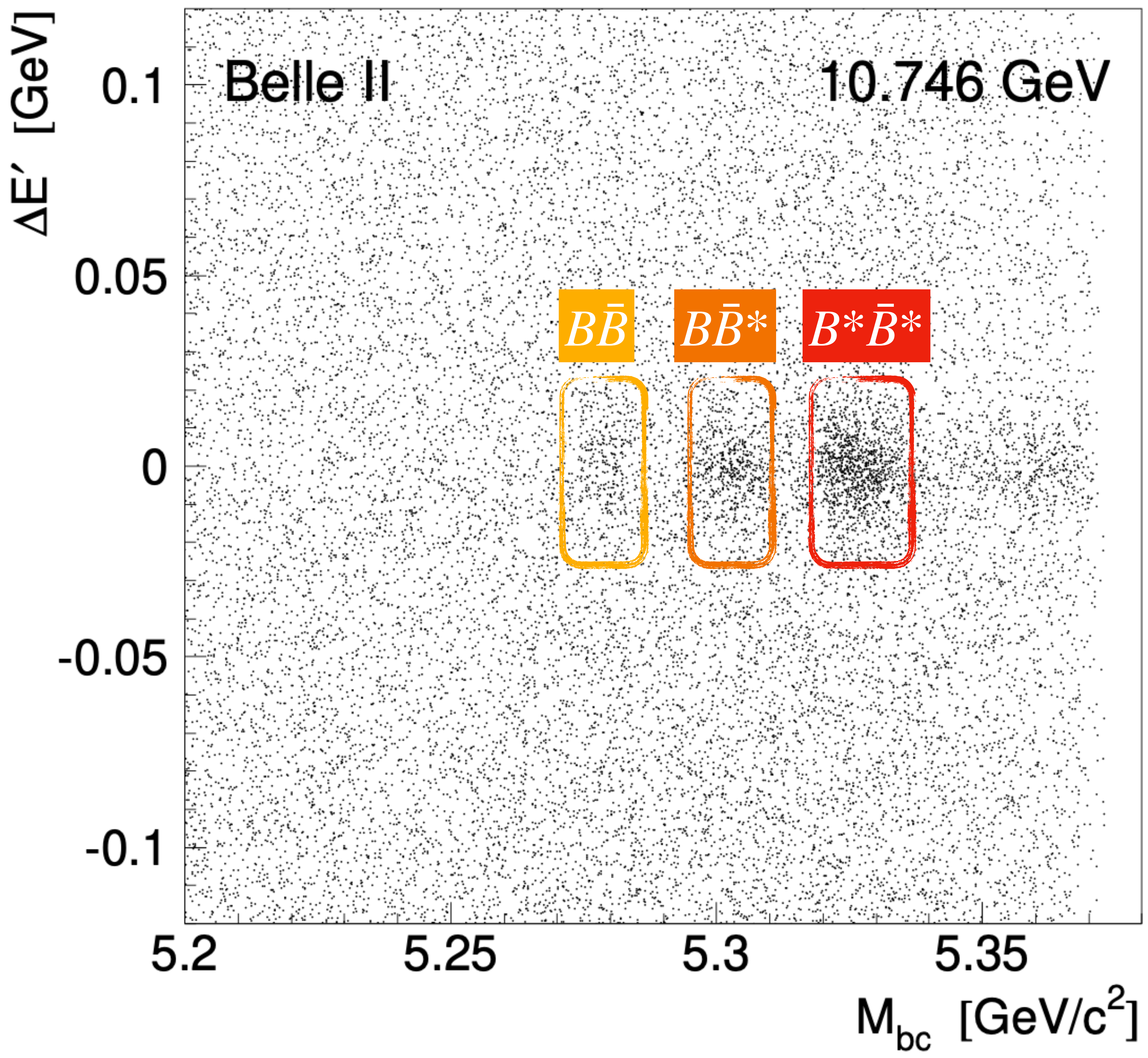
$B^+ \to$	$B^0 \to$
$\bar{D}^0\pi^+$	$D^-\pi^+$
$\bar{D}^0\pi^+\pi^+\pi^-$	$D^-\pi^+\pi^+\pi^-$
$\bar{D}^{*0}\pi^+$	$D^{*-}\pi^+$
$\bar{D}^{*0}\pi^+\pi^+\pi^-$	$D^{*-}\pi^+\pi^+\pi^-$
$D_s^+\bar{D}^0$	$D_s^+D^-$
$D_s^{*+}\bar{D}^0$	$D_s^{*+}D^-$
$D_s^+\bar{D}^{*0}$	$D_s^+D^{*-}$
$D_s^{*+}\bar{D}^{*0}$	$D_s^{*+}D^{*-}$
$J/\psi\, K^+$	$J/\psi\, K_S$
$J/\psi\, K_S\,\pi^+$	$J/\psi\, K^+\pi^-$
$J/\psi\, K^+\pi^+\pi^-$	
$D^-\pi^+\pi^+$	$D^{*-}K^+K^-\pi^+$
$D^{*-}\pi^+\pi^+$	

$D^0 \to$	$D^+ \to$	$D_s^+ \to$
$K^-\pi^+$	$K^-\pi^+\pi^+$	$K^+K^-\pi^+$
$K^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$	K^+K_S
$K^-\pi^+\pi^+\pi^-$	$K_S\,\pi^+$	$K^+K^-\pi^+\pi^0$
$K_S\,\pi^+\pi^-$	$K_S\,\pi^+\pi^0$	$K^+K_S\,\pi^+\pi^-$
$K_S\,\pi^+\pi^-\pi^0$	$K_S\,\pi^+\pi^+\pi^-$	$K^-K_S\,\pi^+\pi^+$
K^+K^-	$K^+K^-\pi^+$	$K^+K^-\pi^+\pi^+\pi^-$
$K^+K^-K_S$		$K^+\pi^+\pi^-$
		$\pi^+\pi^+\pi^-$

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

- **Method:**
  - Reconstruct one B in full hadronic channels.
  - Key variables for analysis are
    - $M_{bc} = \sqrt{(E_{cm}/2)^2 - p_B^2}$
    - $\Delta E' = \Delta E - M_{bc} + M_B$, where $\Delta E = E_B - E_{cm}/2$
  - $\Delta E'$ has improved resolution and allows all desired two-body decays to be selected with a common cut
  - Populations of each can be studied by fitting the projections onto the M_{bc} axis for all energies at which data were accumulated
  - $B^* \to B\gamma$ decays are not reconstructed.

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

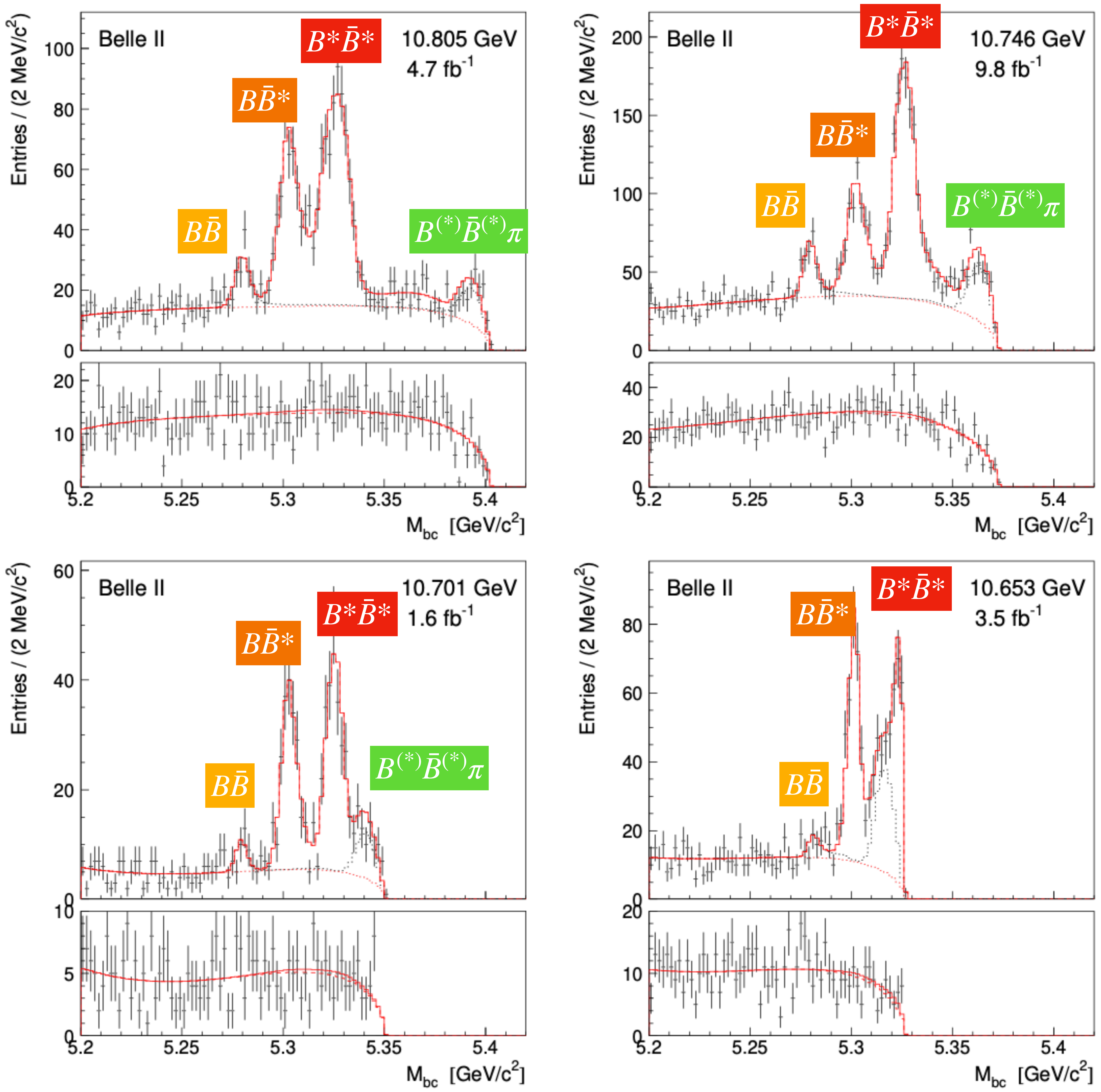


Energy dependence of $e^+e^- \to B^{(*)}\bar{B}^{(*)}$ cross section

M_{bc} fit at scan energies

- M_{bc} fit distribution:
  - ΔE′ signal region (upper)
  - ΔE′ side-bands (lower)

- $e^+e^- \to B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$ signals at $\sqrt{s} \sim 10.75$ GeV can be clearly observed
- Contribution of $\Upsilon(4S) \to B\bar{B}$ production via ISR is visible well (black dotted histograms)
- At $\sqrt{s}$ =10.653 GeV, the sharp cut of the data at right edge is due to threshold effect



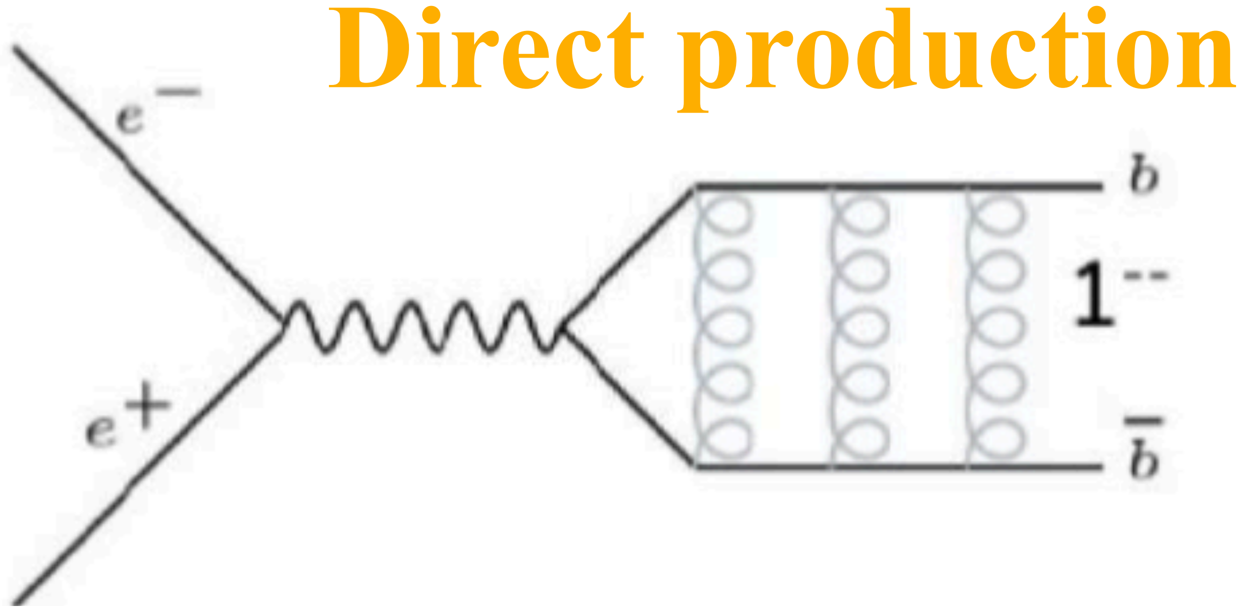
Bottomonium (-like) at Belle II

- **Four ways to access bottomonia:**
  - **Direct production** from e^+e^-: $J^{PC} = 1^{--}$: $\Upsilon(nS)$
  - **ISR production**: $J^{PC} = 1^{--}$: $\Upsilon(nS)$
  - **Hadronic transitions** from $\Upsilon(nS)$ through η, ππ, …

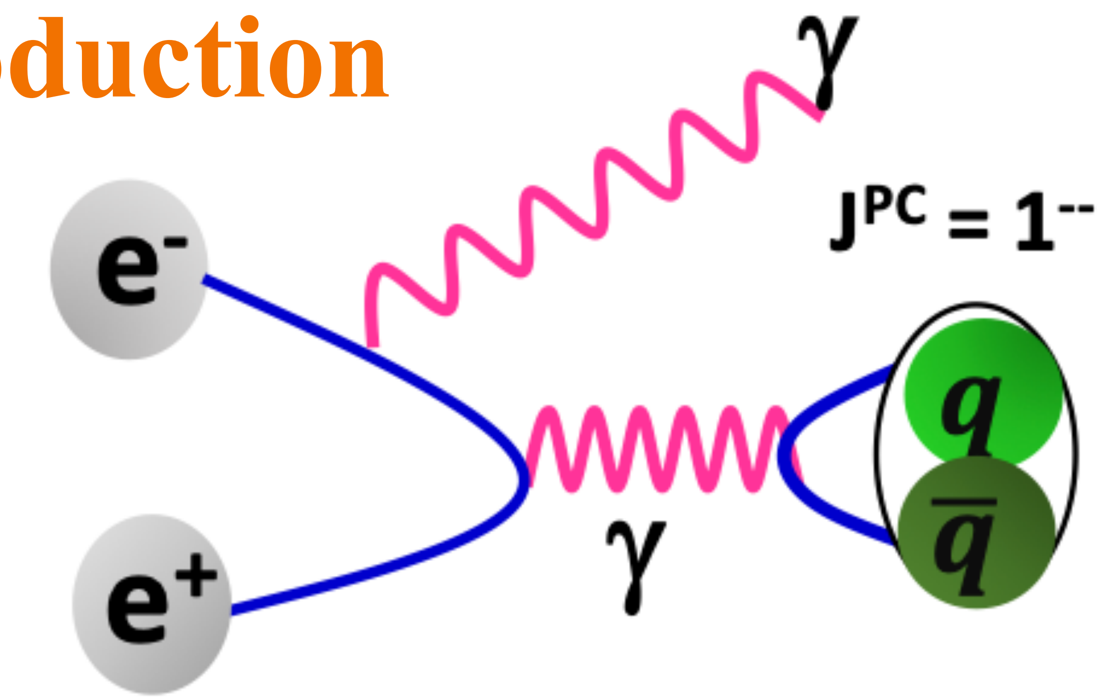
    $J^{PC} = 0^{-+}, 1^{--}, 1^{+-} \ldots : \Upsilon(nS), \eta_b(nS), h_b(nS), \ldots$
  - **Radiative transitions** from $\Upsilon(nS)$

    $J^{PC} = 0^{-+}, 0^{++}, 1^{++}, 2^{++}: \eta_b(nS), \chi_b(nP)$

Direct production



ISR production



Hadronic transitions