Carnegie Mellon University

BELLE Belle II

Bottomonium and exotic spectroscopy

22nd Flavor Physics and CP Violation (FPCP)

Renu
On the behalf of Belle II Collaboration
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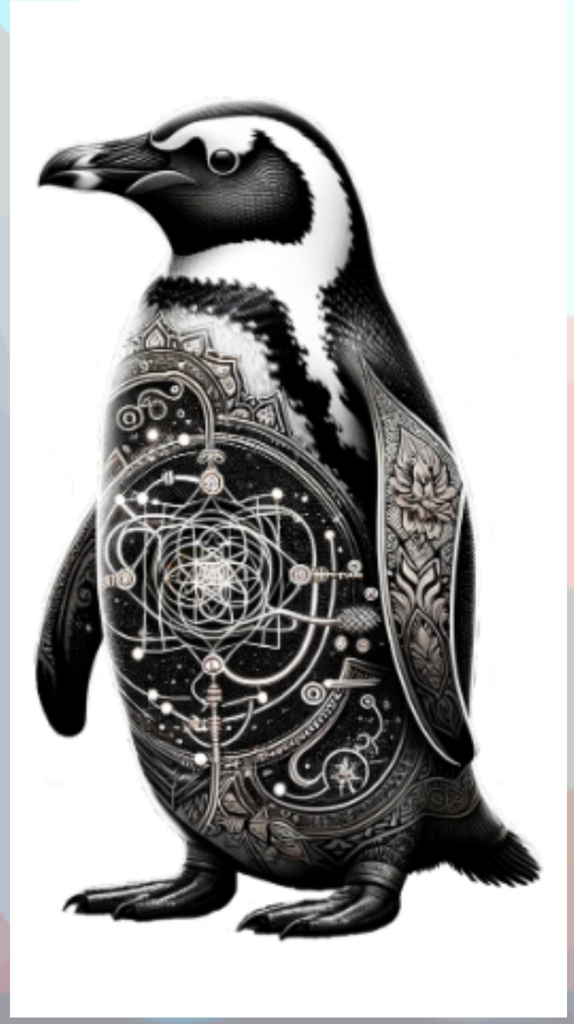
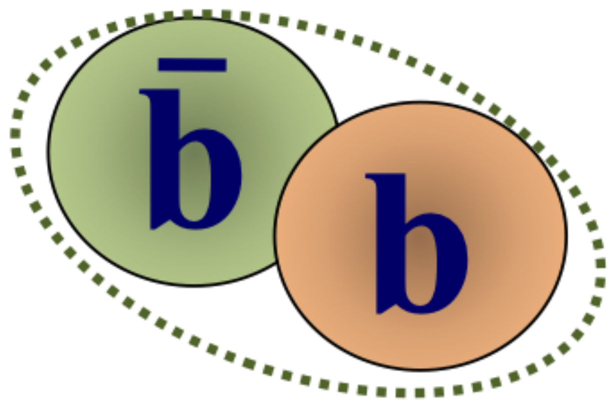
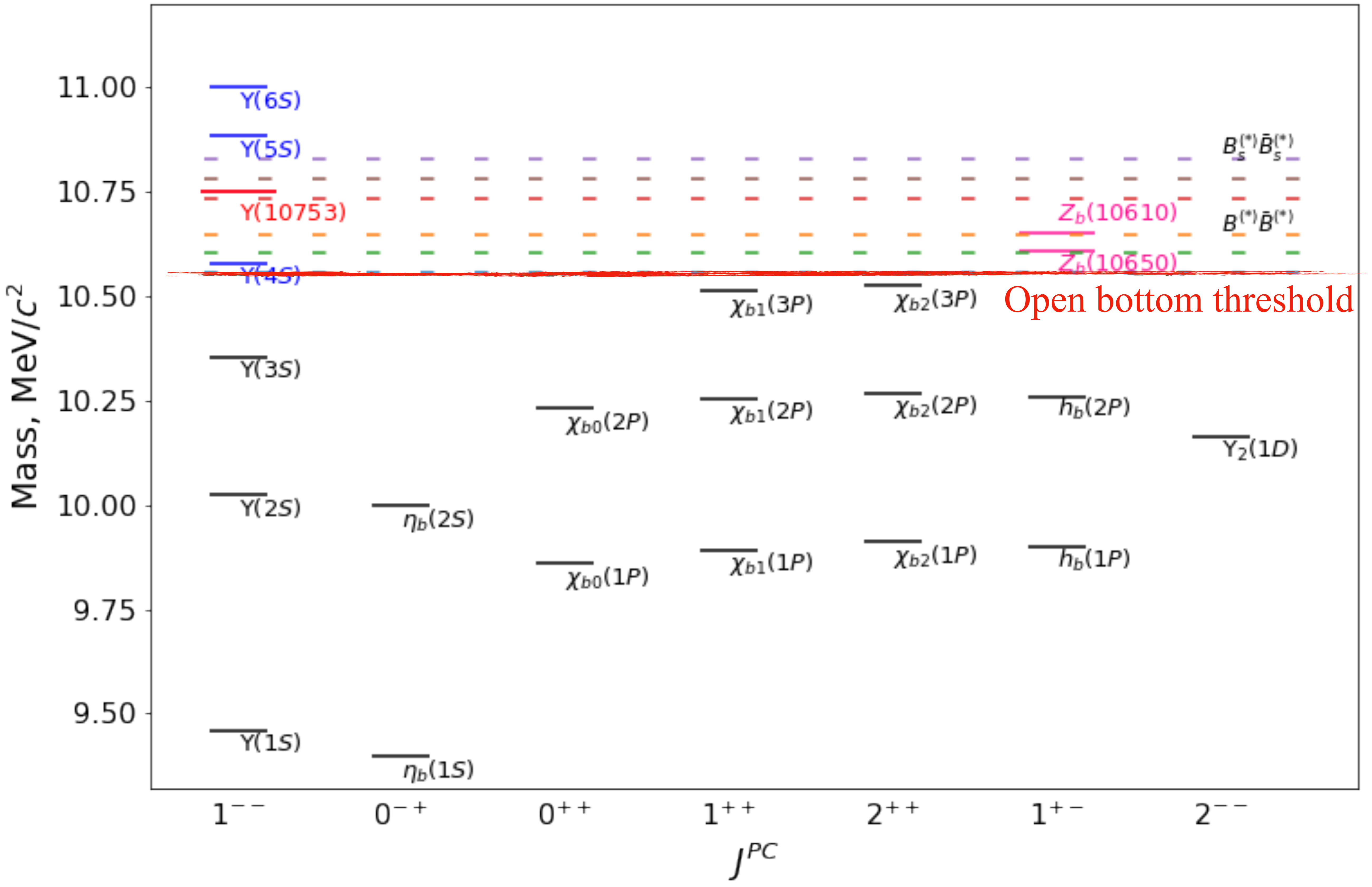


Bottomonium Spectrum



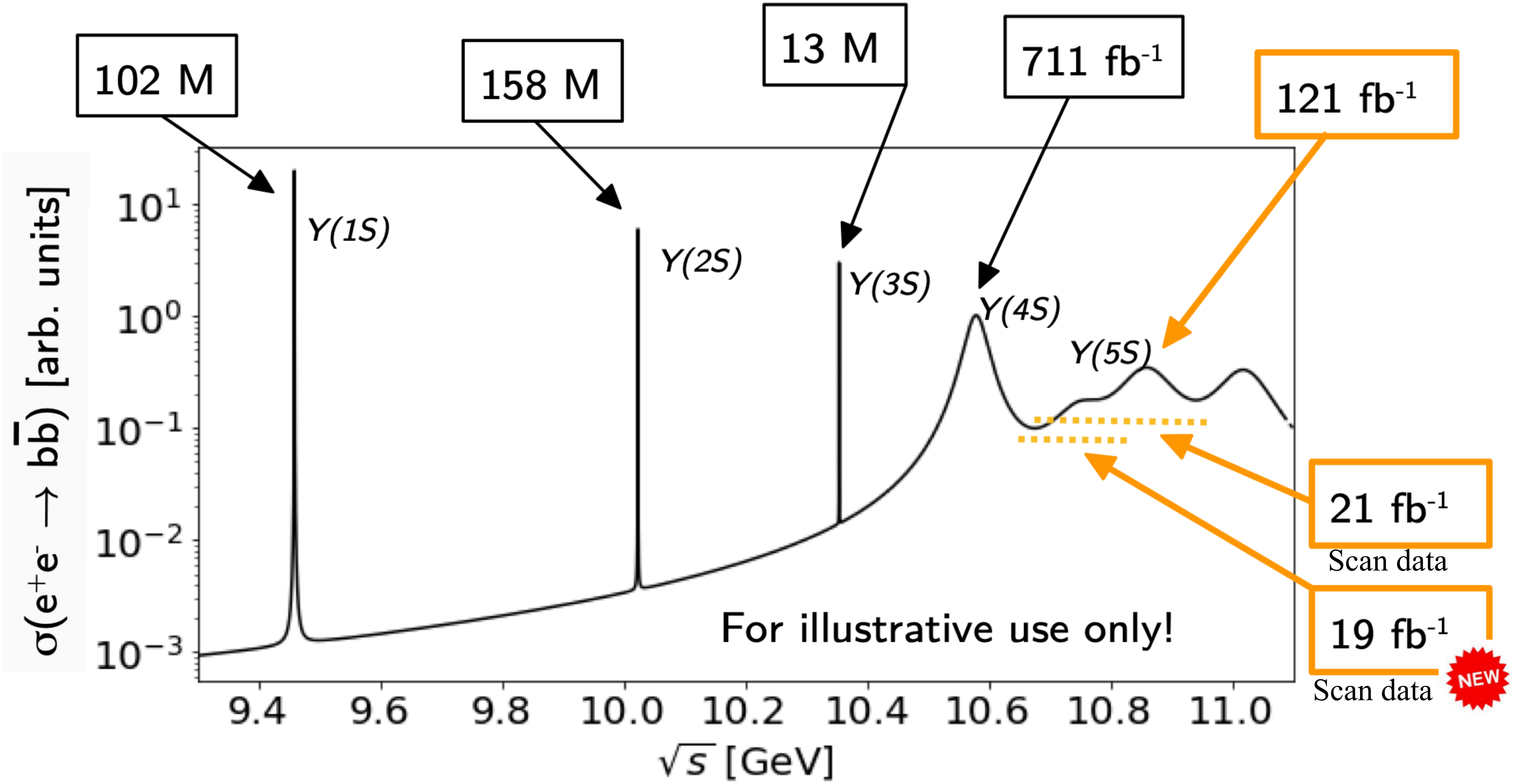
- **Below the $B\bar{B}$ threshold** states are well described by potential models.
- **Above $B\bar{B}$ threshold states** exhibit unexpected properties:
  - Hadronic transitions to lower bottomonia are strongly enhanced.
  - The η transitions are not suppressed compared to $\pi^+\pi^-$ transitions. Strong violation of Heavy Quark Spin Symmetry.
  - $Z_b^+(10610)$ **or** $Z_b^+(10650)$: observed near the $B^{(*)}\bar{B}^*$ thresholds, properties are consistent with $B^{(*)}\bar{B}^*$ molecules.

Exotic admixtures: molecule, compact tetraquark, hybrid.



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

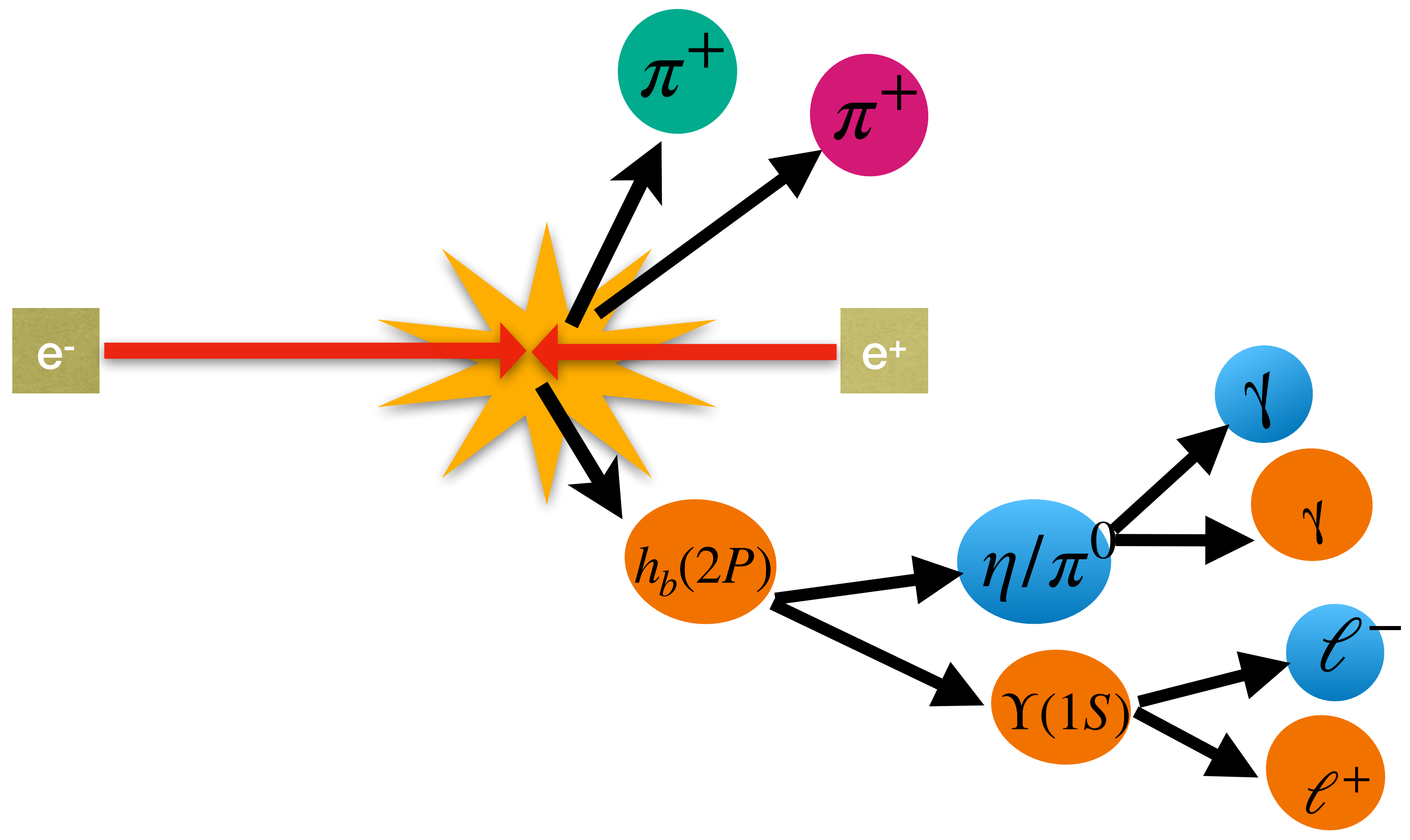
Belle (II) relevant datasets

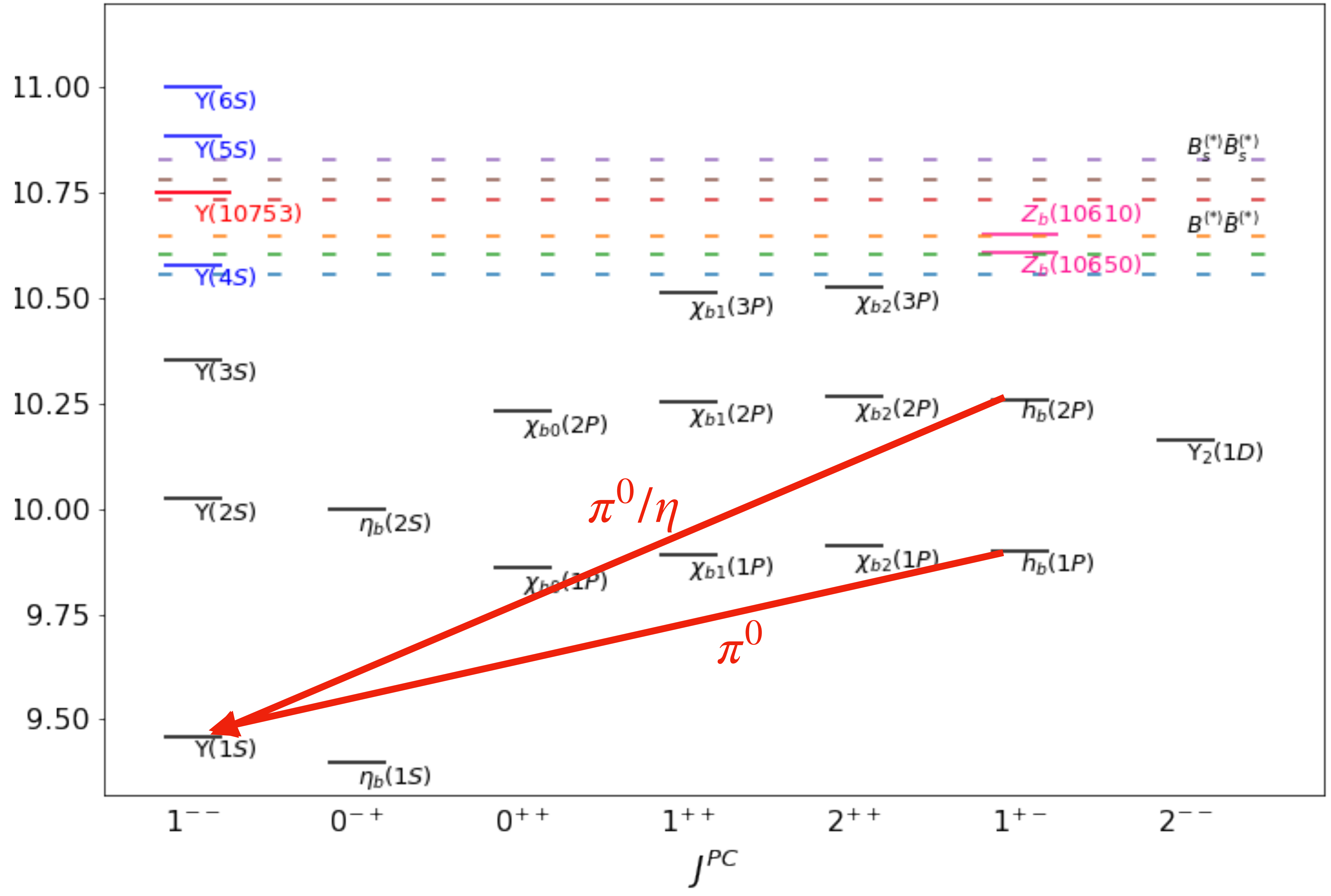


Bottomonium below $B\bar{B}$ threshold

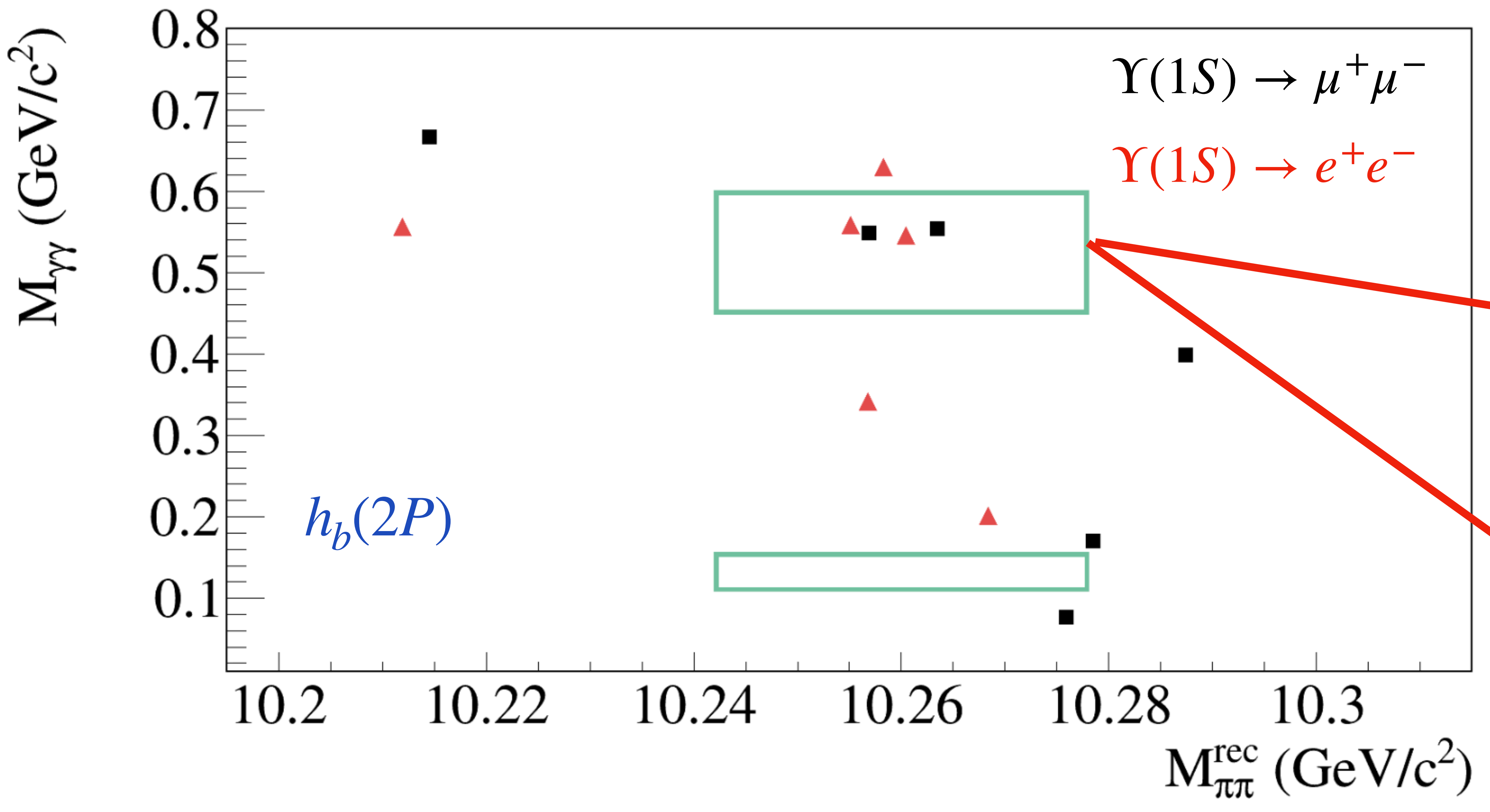
Search for $h_b(2P) \to \Upsilon(1S)\eta$ and $h_b(1P,2P) \to \Upsilon(1S)\pi^0$ at Belle

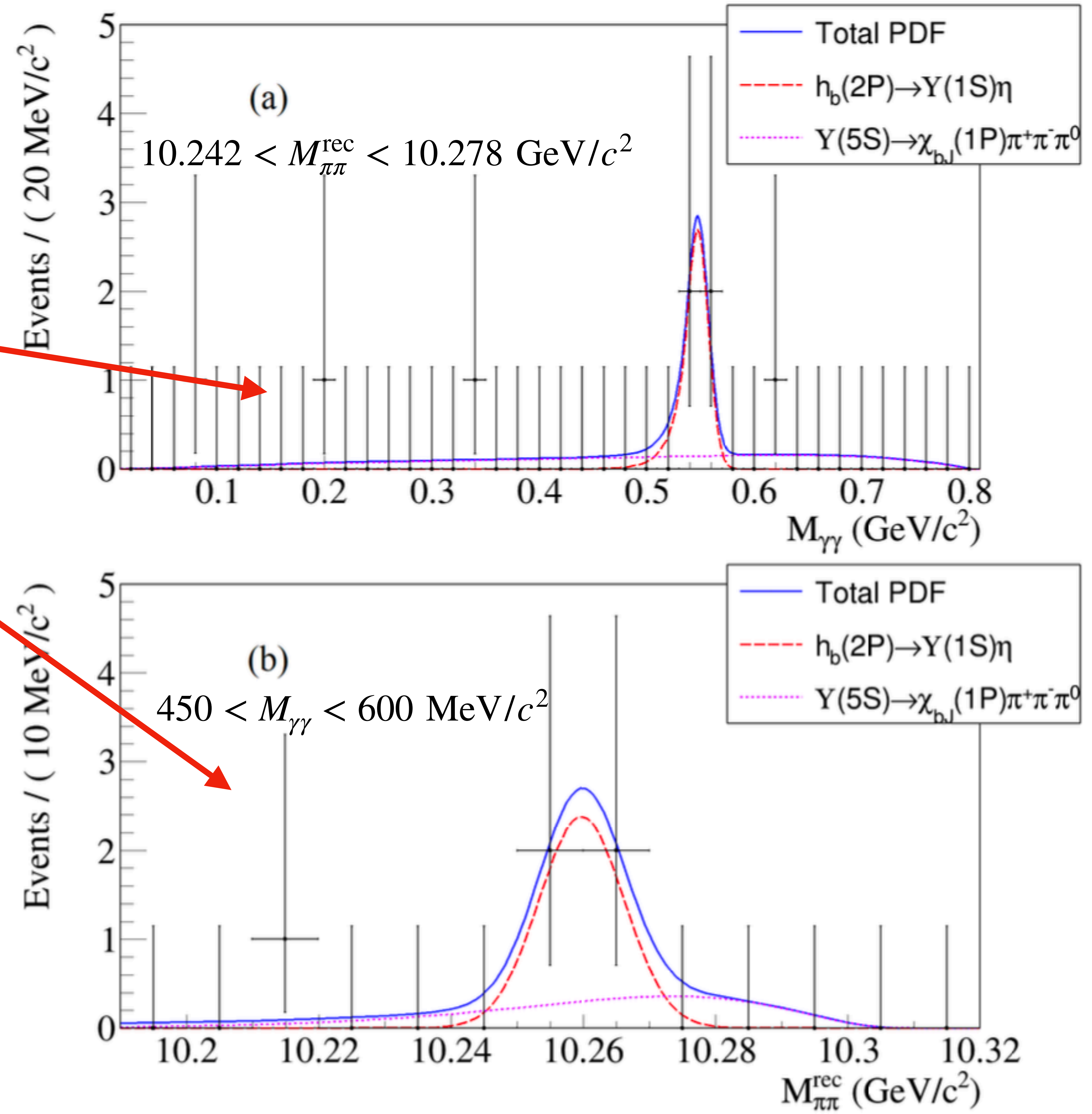
- The properties of spin-singlet $h_b(1P,2P)$ are expected to be similar to spin-triplet partners $\chi_{b1}(1P,2P)$ state.
- **Theoretical prediction:** the ratio of the annihilation rates for the $h_b(1P)$ and $h_b(2P)$ is the same as the corresponding ratio for $\chi_{b1}(1P)$ and $\chi_{b1}(2P)$, $R_{h_b} = R_{\chi_{b1}}$. PRD 86, 094013 (2012)
- Based on current results, the $R_{h_b}/R_{\chi_{b1}} = 0.24^{+0.47}_{-0.24}$ with 3.0σ discrepancy from unity. This discrepancy will increase if the rate of $h_b(2P) \to \Upsilon(1S)\eta$ is as large as 10%





Search for $h_b(2P) \to \Upsilon(1S)\eta$ and $h_b(1P,2P) \to \Upsilon(1S)\pi^0$ at Belle

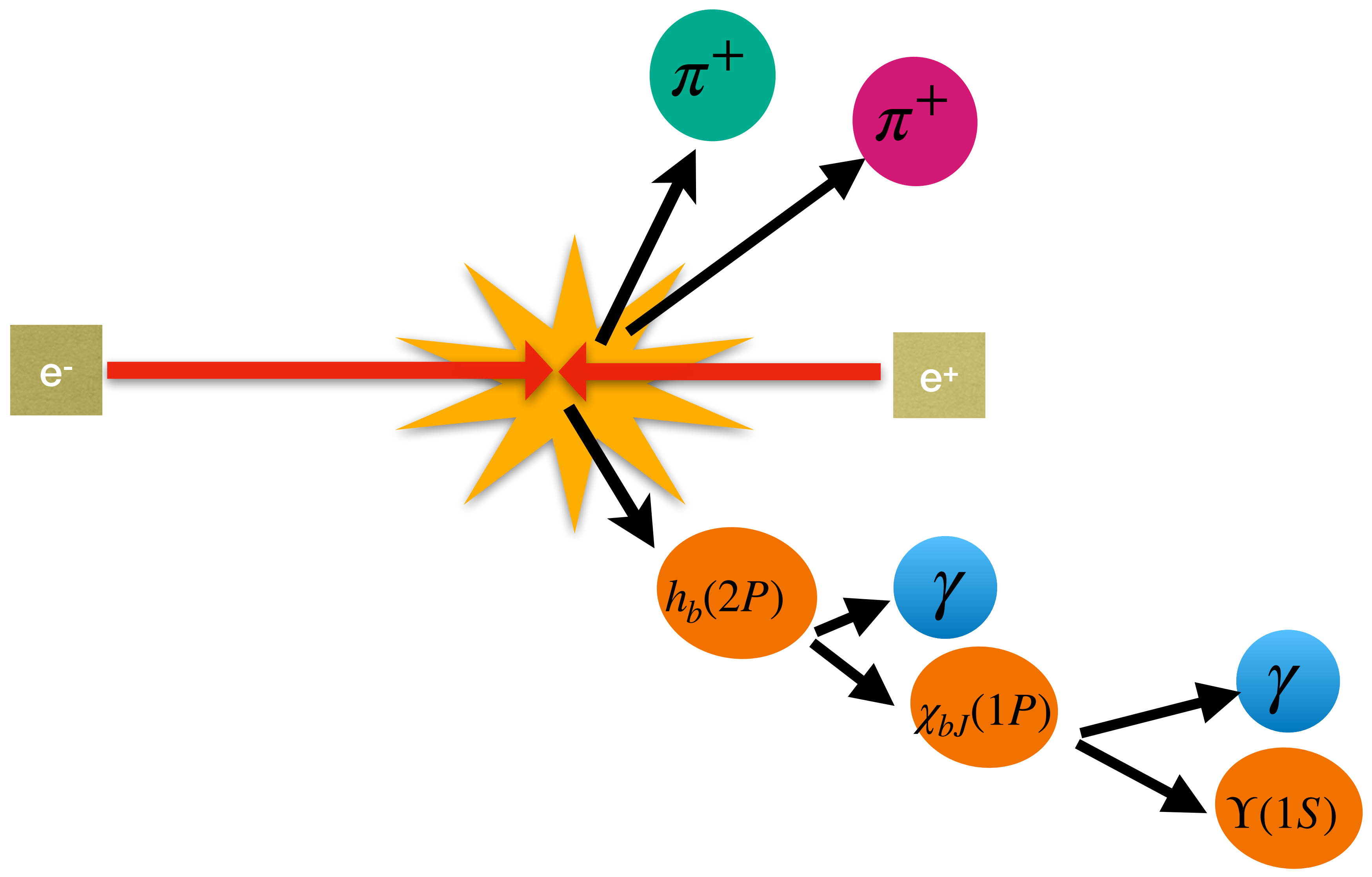


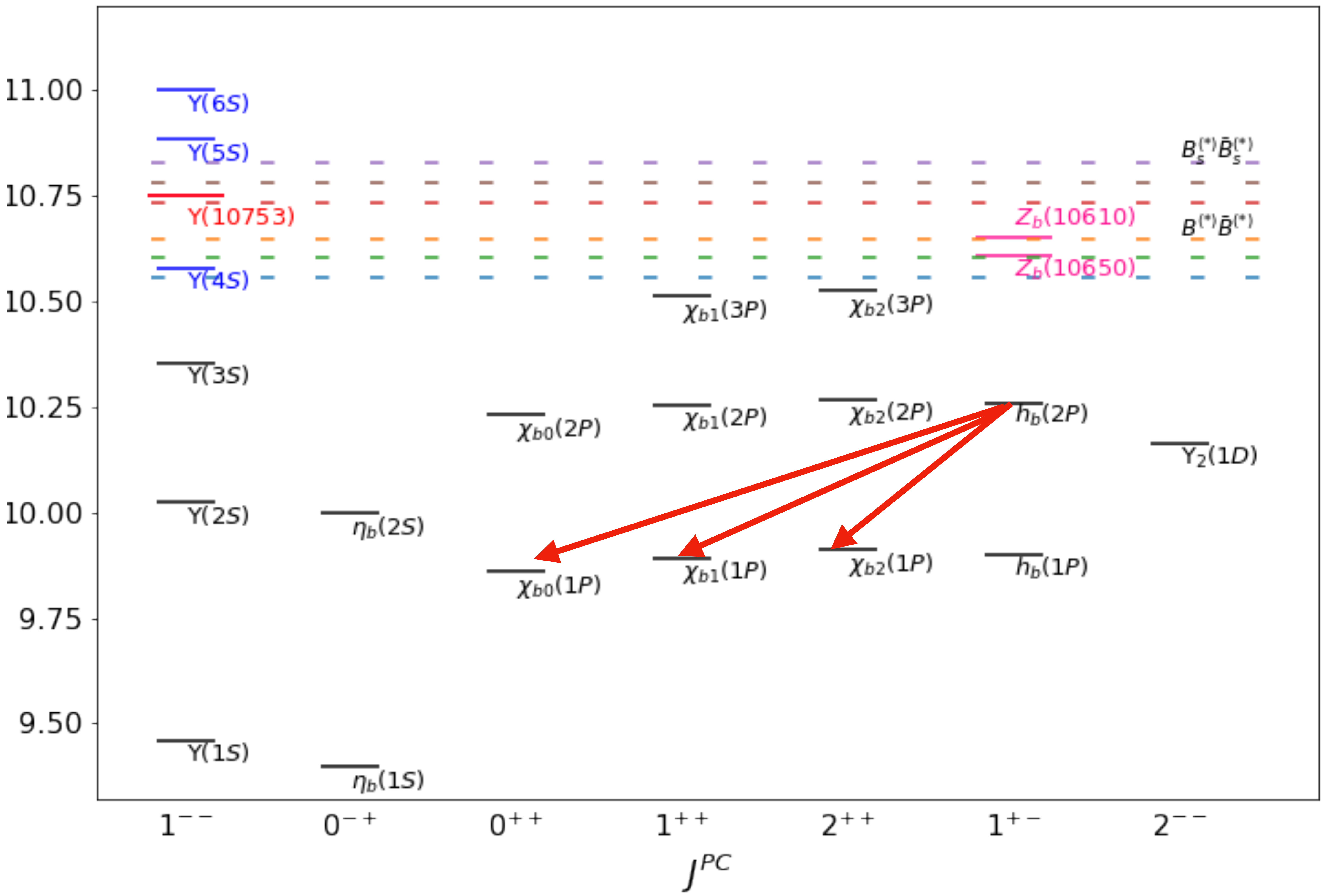


- Evidence for $h_b(2P) \to \Upsilon(1S)\eta$ with 3.5σ significance.
  - $\mathcal{B}(h_b \to \Upsilon(1S)\eta) = (7.1^{+3.5}_{-3.2} \pm 0.8) \times 10^{-3}$
- No significant $h_b(1P, 2P) \to \Upsilon(1S)\pi^0$ signal is observed.
  - Upper limits at the 90% C.L. are set.
  - $\mathcal{B}(h_b(1P,2P) \to \Upsilon(1S)\pi^0) < 1.8 \times 10^{-3}$ at 90% C.L

Search for $h_b(2P) \to \gamma\chi_{bJ}(1P)$ at Belle

- $h_b(2P) \to \gamma\chi_{bJ}(1P)$ is highly suppressed due to heavy quark spin flip.
- Relativized quark model predicts, $\mathscr{B}(h_b(2P) \to \gamma\chi_{bJ}(1P)) = 10^{-6} - 10^{-5}$ PRD 32, 189 (1985)
- According to coupled channel effect, $\mathscr{B}(h_b(2P) \to \gamma\chi_{bJ}(1P)) = 10^{-2} - 10^{-1}$ PLB 760, 417 (2016)
- Experimental results needed !!



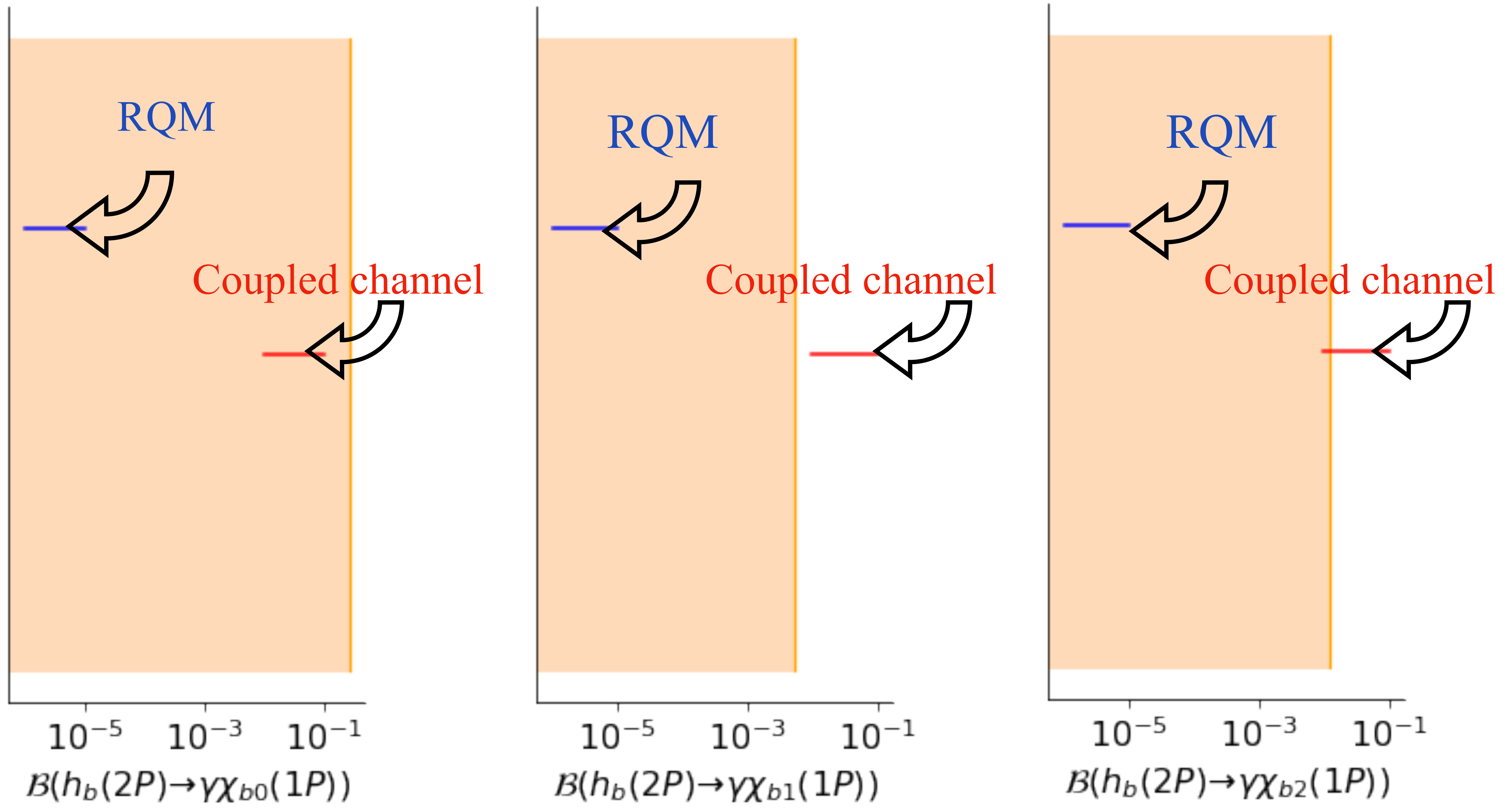


Search for $h_b(2P) \to \gamma\chi_{bJ}(1P)$ at Belle

- No significant $h_b(2P) \to \gamma\chi_{bJ}(1P)$ signal is observed.
- Upper limits at the 90% C.L. are set.

TABLE IV. Observed upper limits at 90% CL for the branching fractions of the investigated transitions.

Channel	$\mathcal{B}$
$h_b(2P) \to \gamma\chi_{b2}(1P)$	$< 1.2 \times 10^{-2}$
$h_b(2P) \to \gamma\chi_{b1}(1P)$	$< 5.4 \times 10^{-3}$
$h_b(2P) \to \gamma\chi_{b0}(1P)$	$< 2.7 \times 10^{-1}$



Results are consistent with the Relativized Quark Model (RQM)

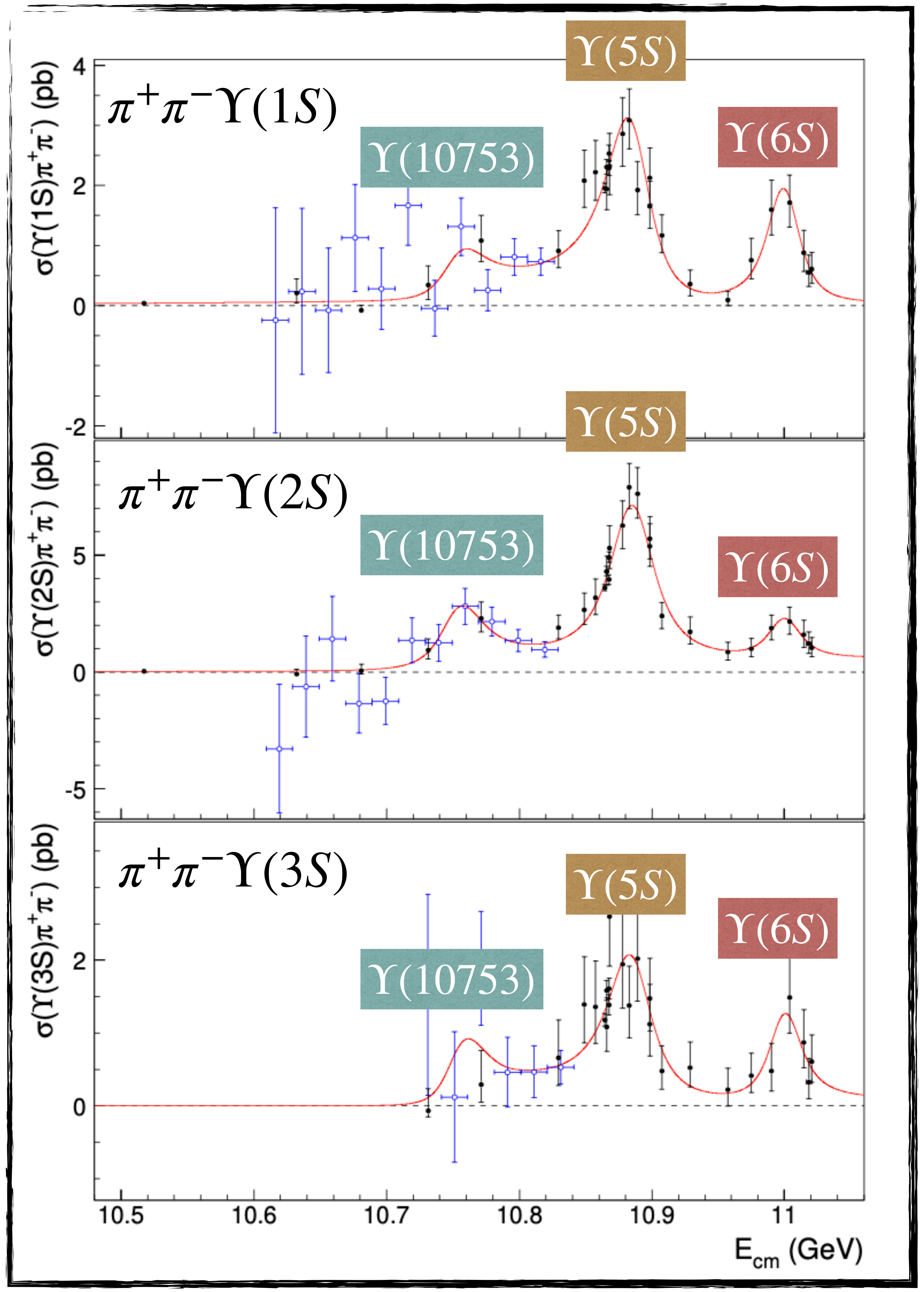
Hidden flavor cross section

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

JHEP 10 (2019) 220

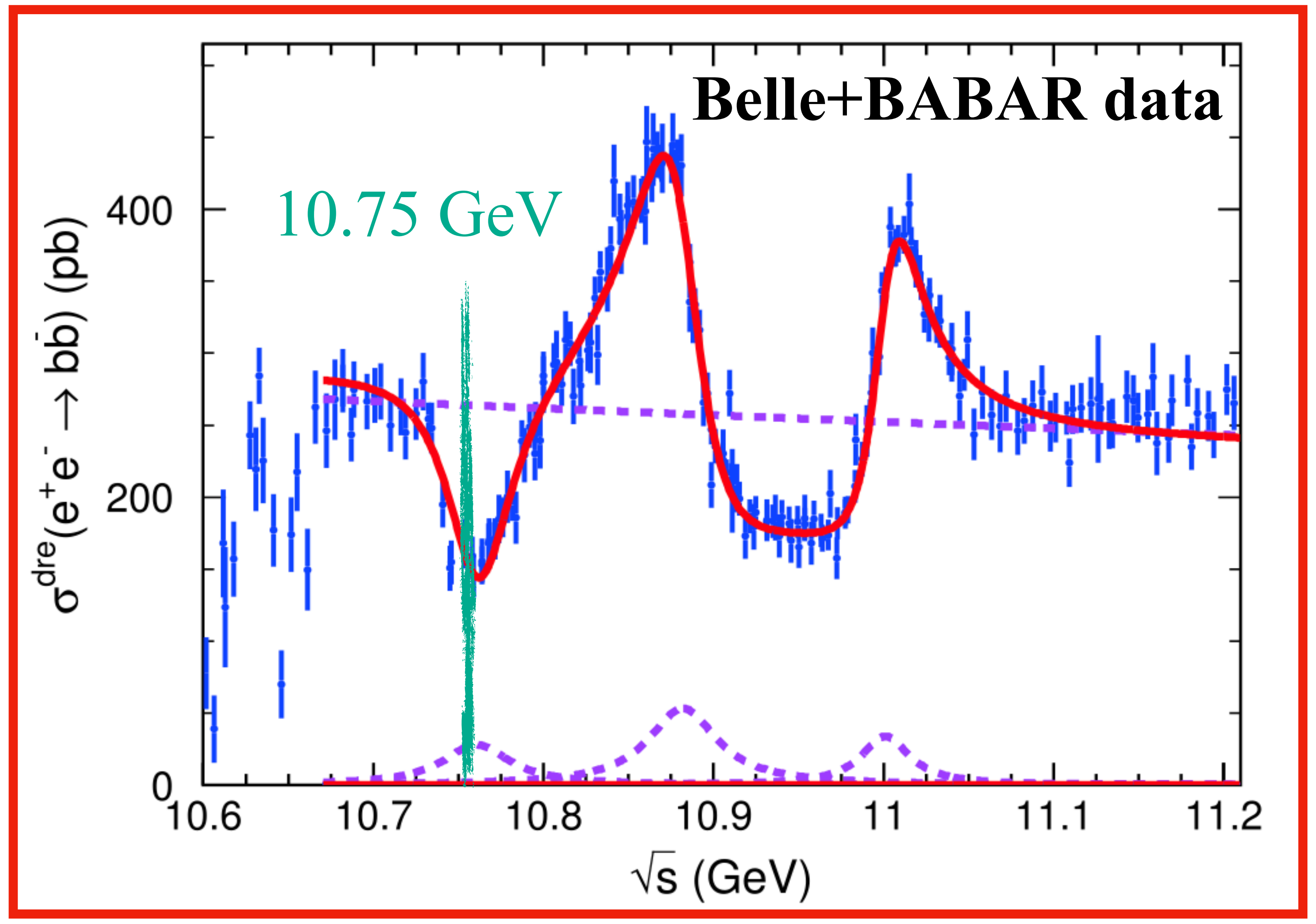
	$\Upsilon(5S)$	$\Upsilon(6S)$	New structure
M (MeV/c²)	$10885.3 \pm 1.5^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}{}^{+1.0}_{-1.3}$	$10752.7 \pm 5.9^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}{}^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}{}^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}{}^{+3.9}_{-3.3}$



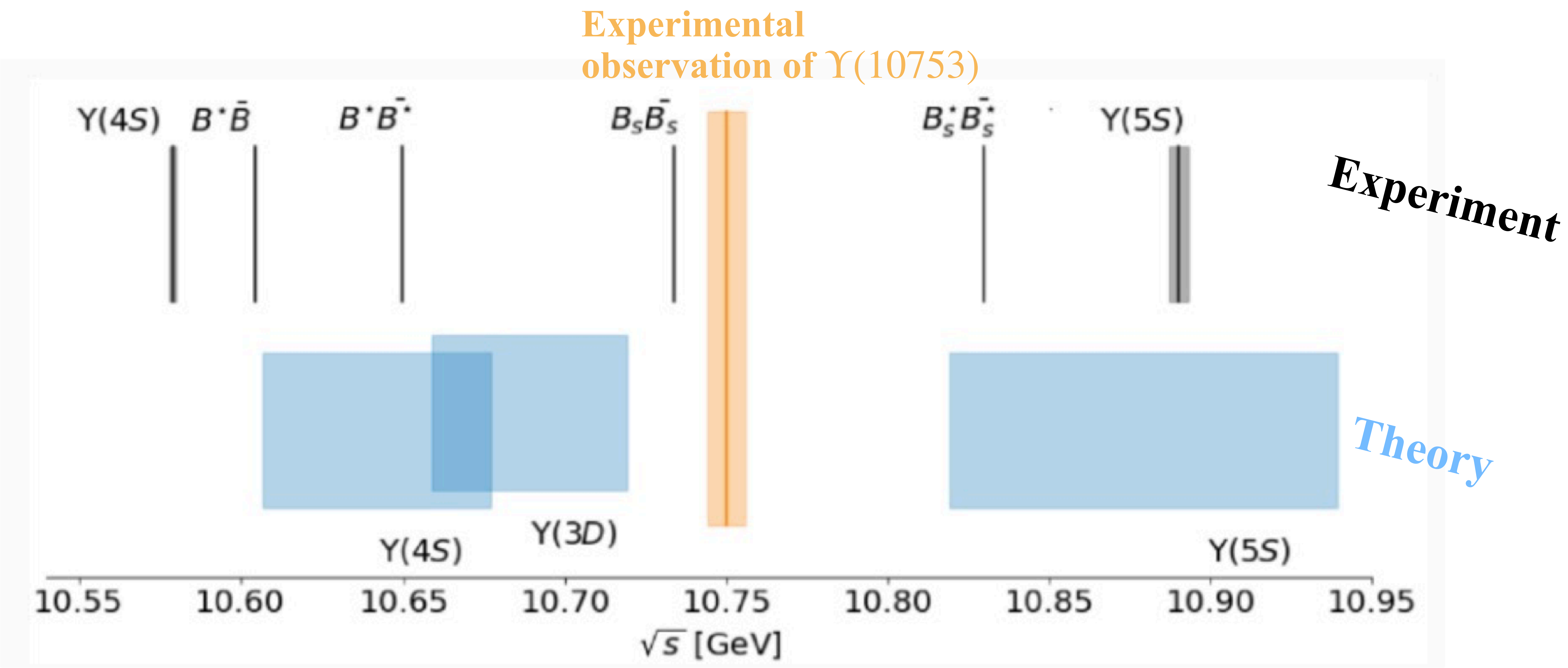
Fit function: 3 BW+smooth component

- $e^+e^- \to b\bar{b}$ 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



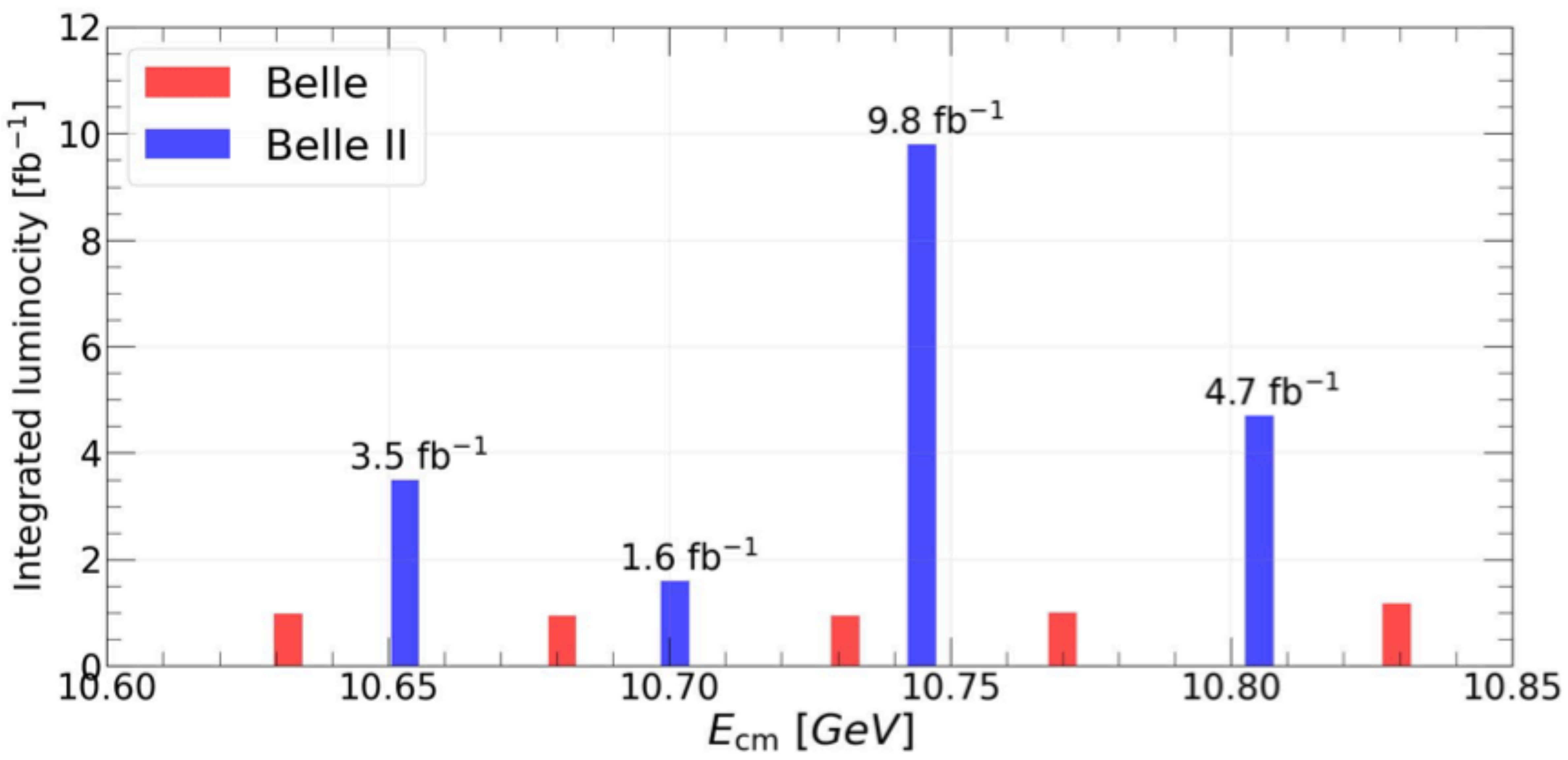
Possible interpretations:

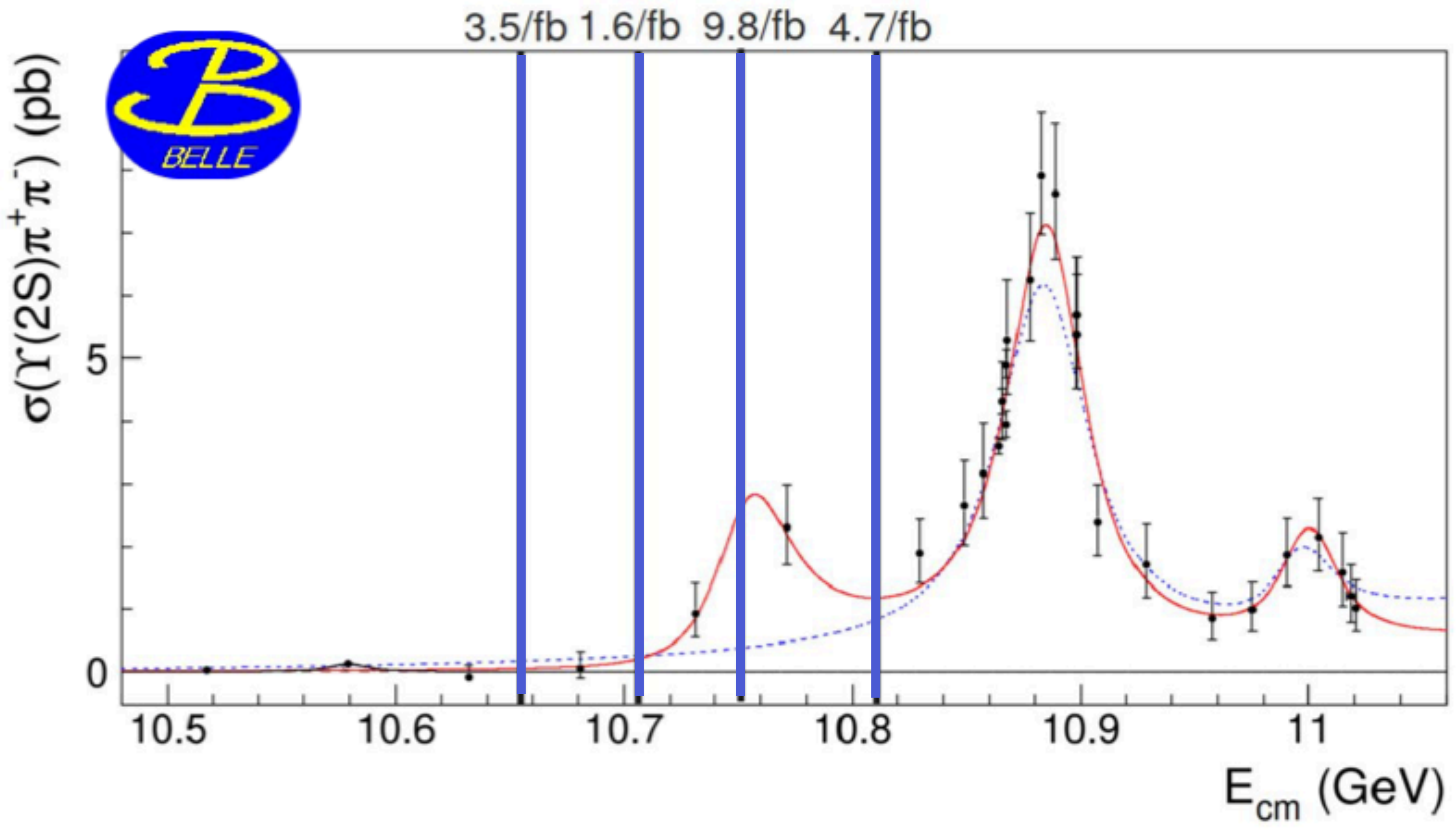
- Conventional bottomonium?
  - **Phys. Rev. D 105, 114041 (2022)**
  - **Phys. Rev. D 106, 094013 (2022)**
  - **Phys. Rev. D 105, 074007 (2022)**
- Hybrid state?
  - **Phys. Rept. 873, 1 (2020)**
  - **Phys. Rev. D 104, 034019 (2021)**
- Tetraquark state?
  - **Phys. Rev. D 103, 074507 (2021)**
  - **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 data with energy scan 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 $\Upsilon(5S)$.

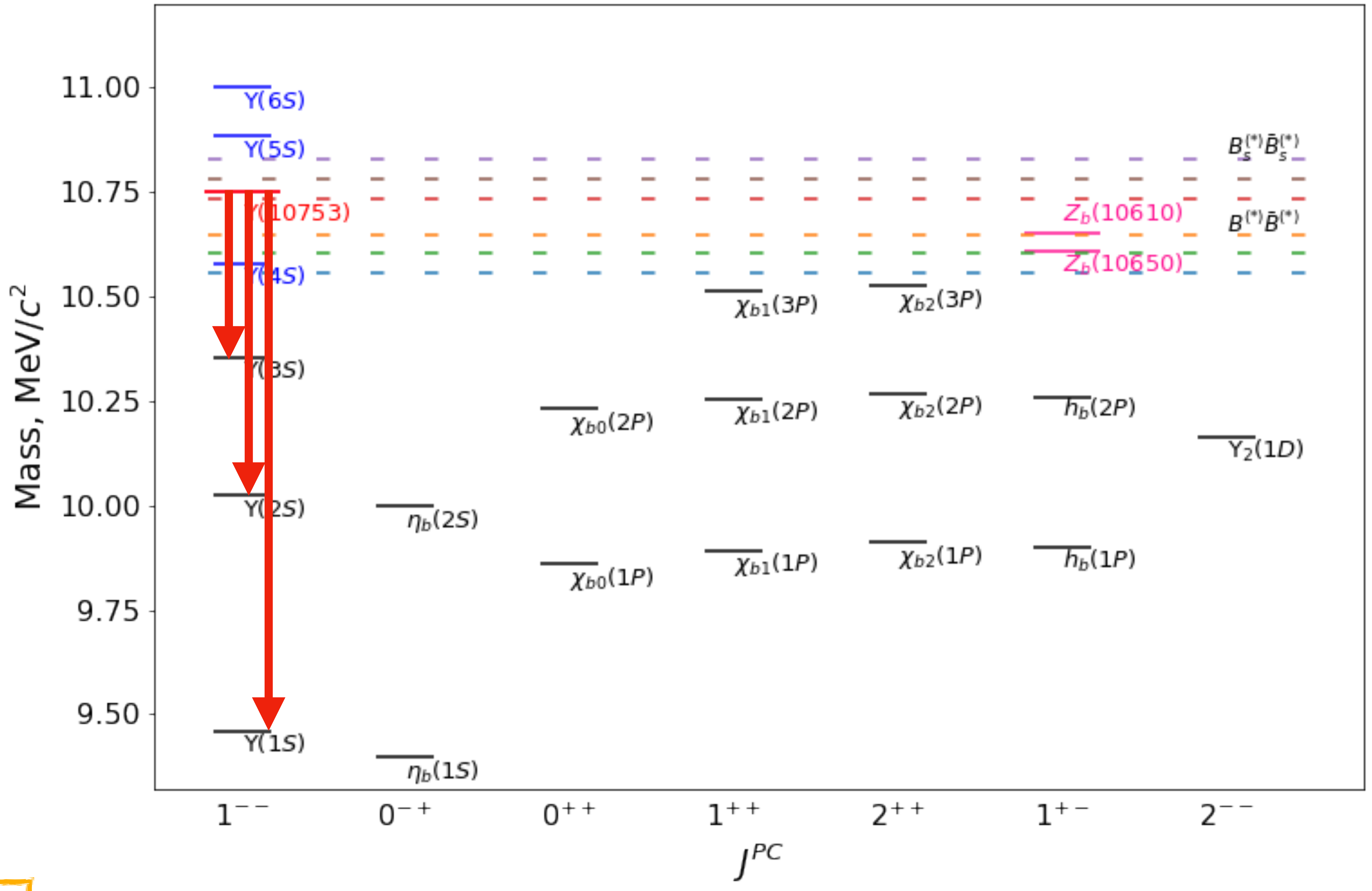




- Belle II collected data in the gaps between the Belle points.
- The point with the highest statistics (9.8 fb^{-1}) is near the $\Upsilon(10753)$ peak.

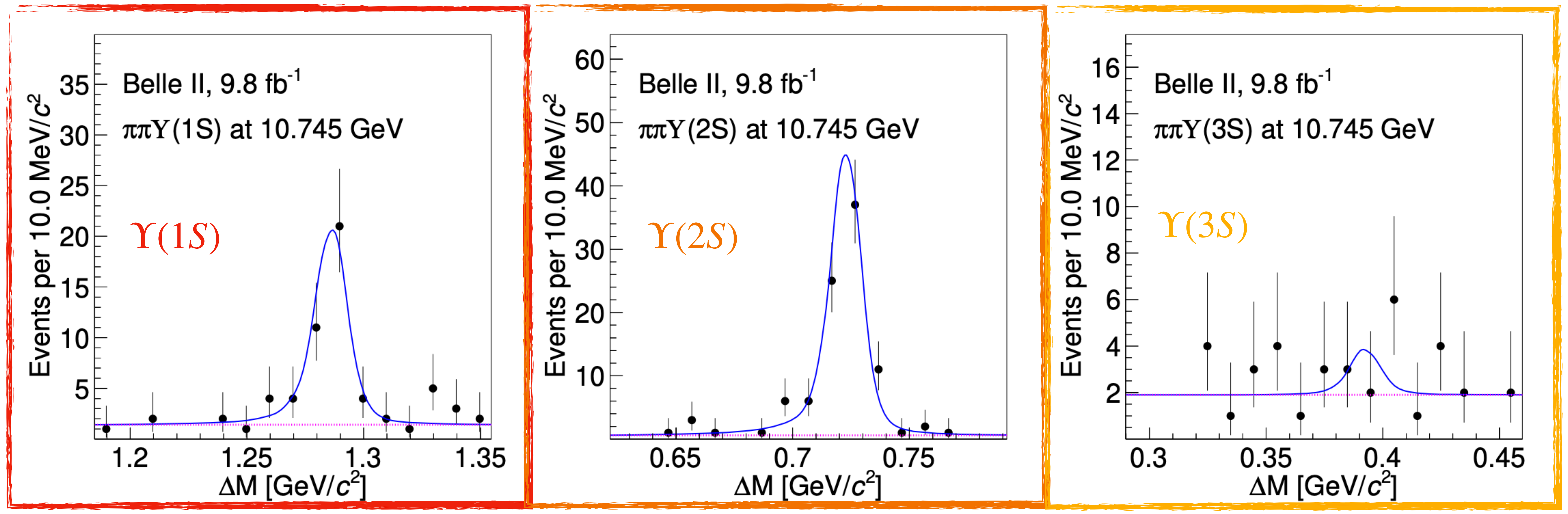
Search for $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$ at Belle II

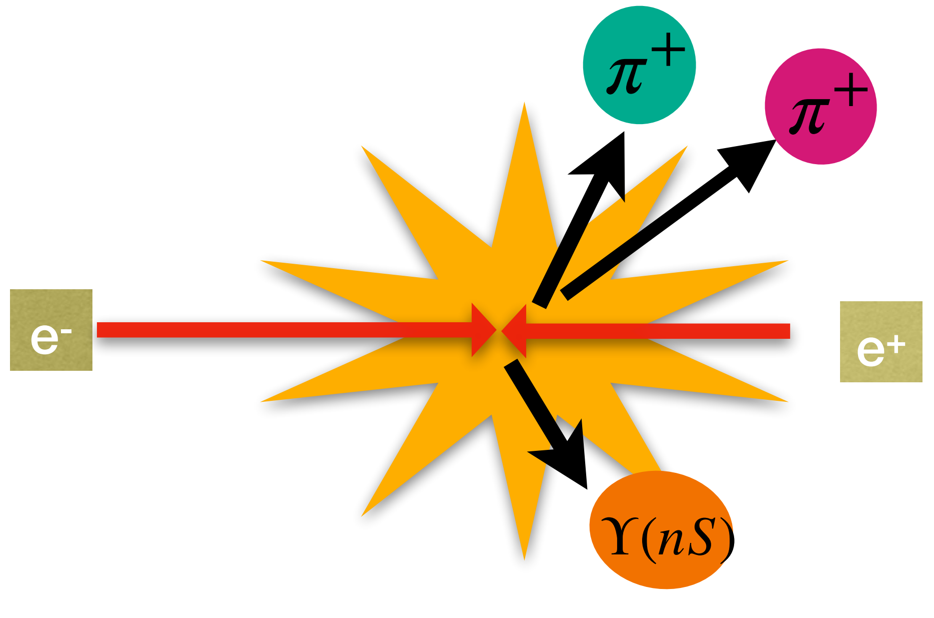
- Discovery mode of the $\Upsilon(10753)$ (Next few slides will cover):
  - Confirm its existence
  - Measure the di-pion spectrum
  - Look for $Z_b^+(10610)$ **or** $Z_b^+(10650)$ intermediate contributions



Confirm $\Upsilon(10753)$ existence

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



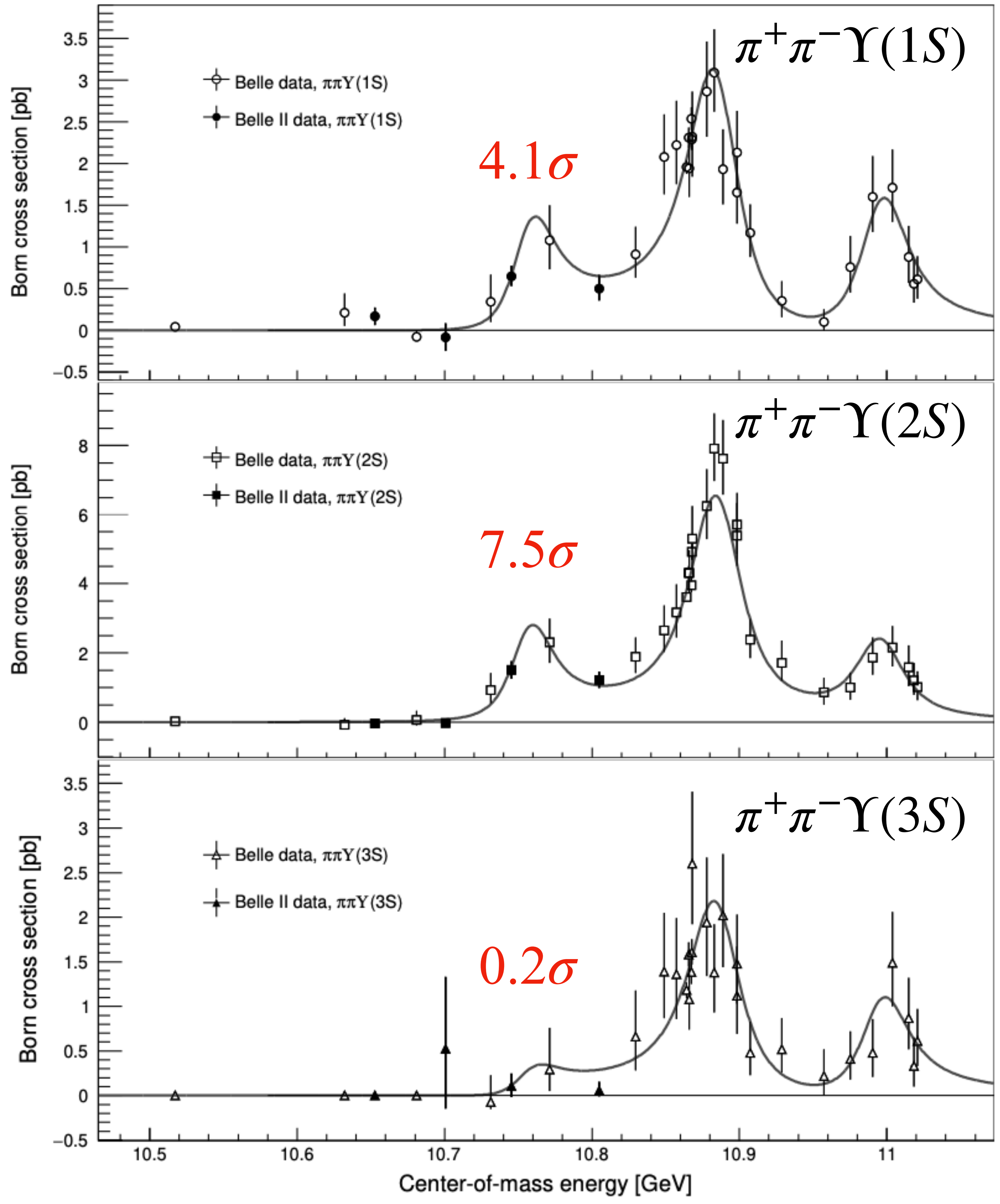


Confirm $\Upsilon(10753)$ existence

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

	Belle + Belle II (MeV)	Belle (MeV)
$M_{\Upsilon(10753)}$	$10756.6 \pm 2.7 \pm 0.9$	$10752.7 \pm 5.9^{+0.7}_{-1.1}$
$\Gamma_{\Upsilon(10753)}$	$29.0 \pm 8.8 \pm 1.2$	$35.5^{+17.6+3.9}_{-11.3-3.3}$

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

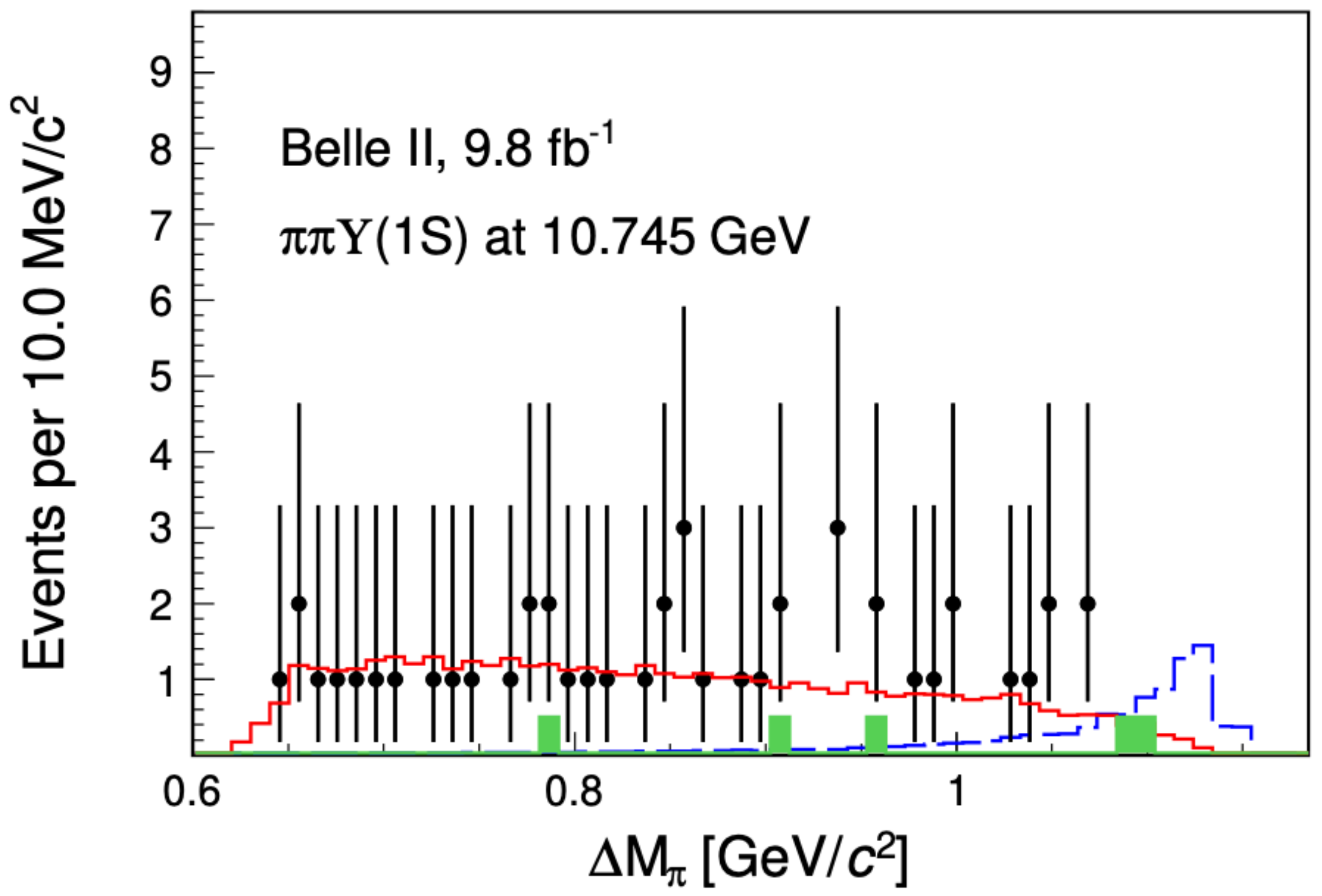


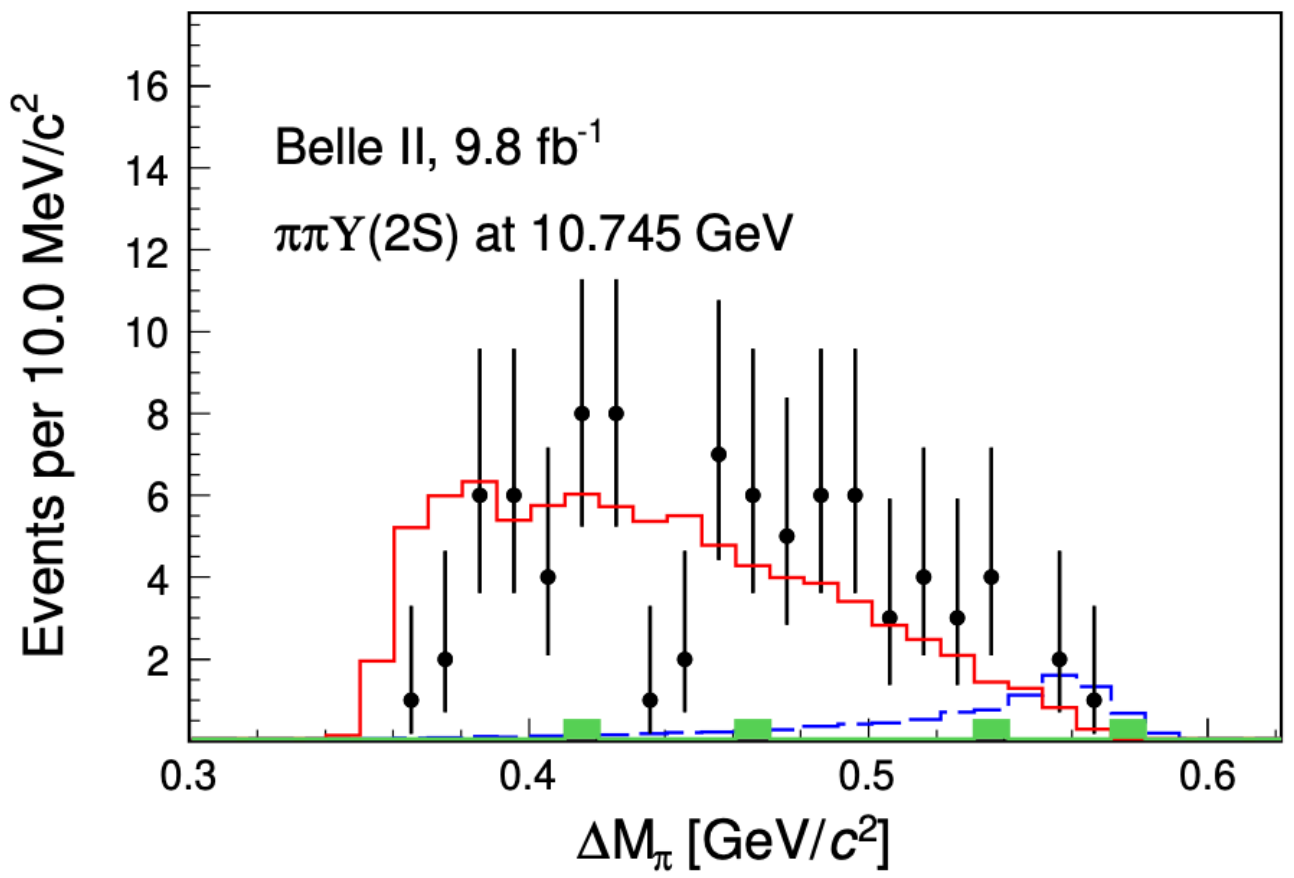
Resonant structure in $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$

$Z_b^+(10610)$ or $Z_b^+(10650)$ intermediate resonances

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

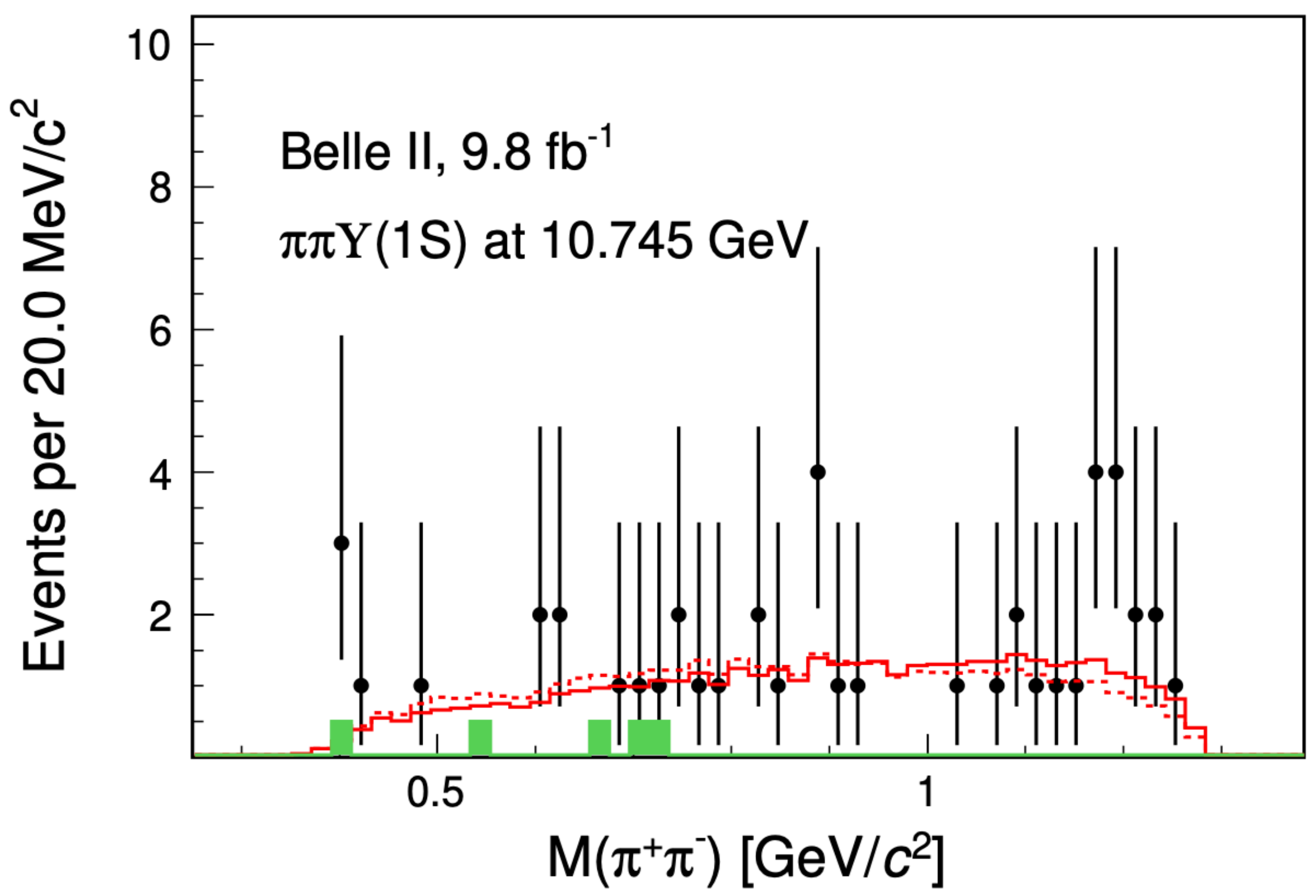
$$\Delta M_\pi = M(\pi^\pm\mu^+\mu^-) - M(\mu^+\mu^-)$$

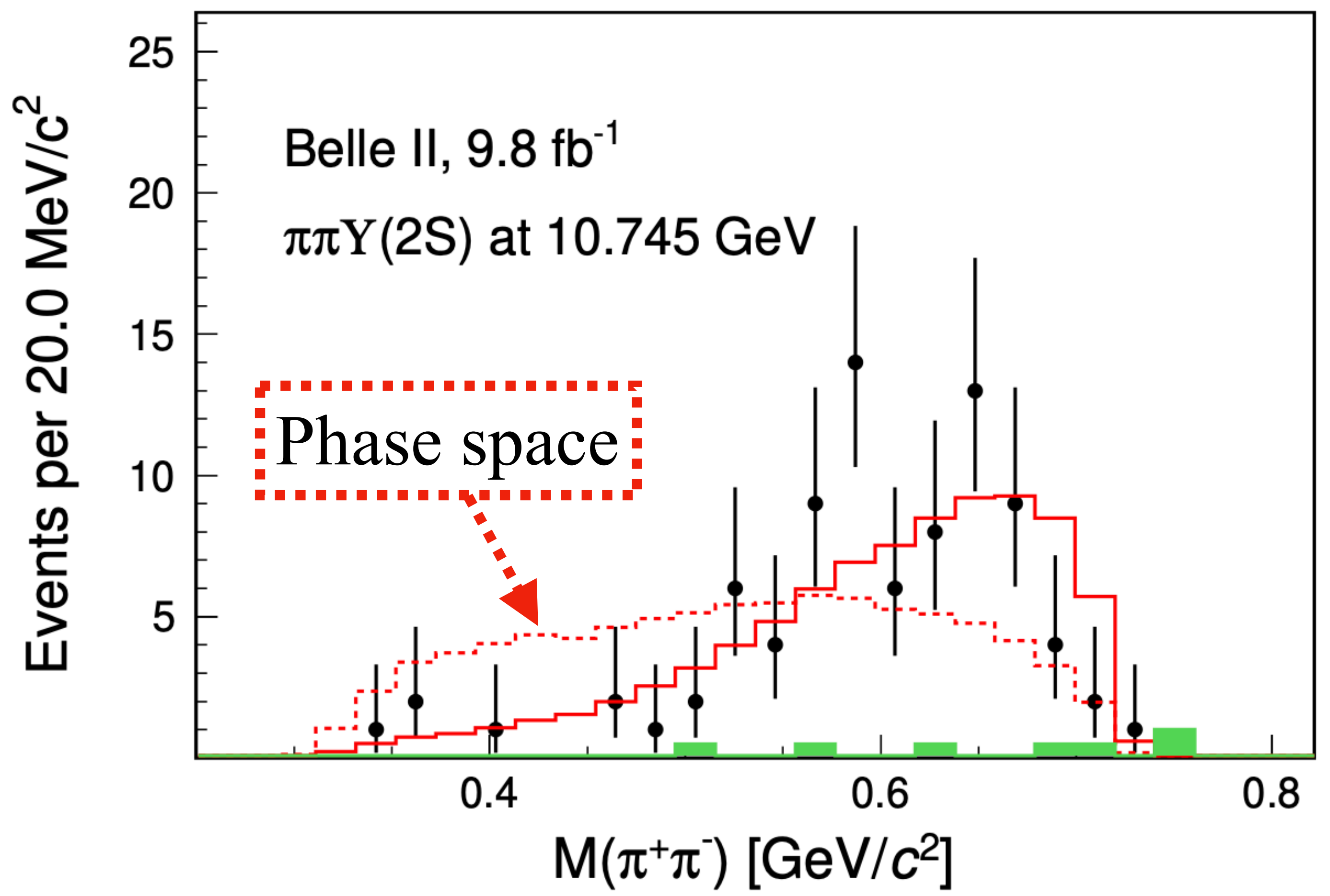




Di-pion spectrum

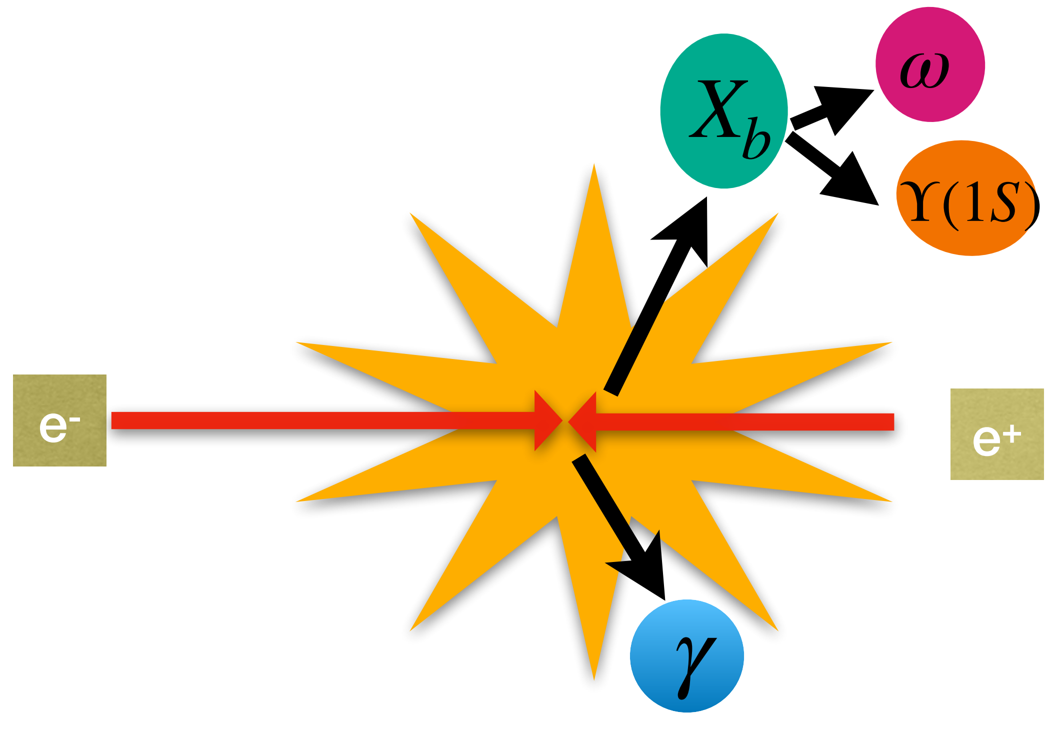
- $\pi^+\pi^-\Upsilon(1S)$: $M(\pi^+\pi^-)$ distribution is consistent with phase space.
- $\pi^+\pi^-\Upsilon(2S)$: larger values of $M(\pi^+\pi^-)$ enhanced (similar to $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ process)

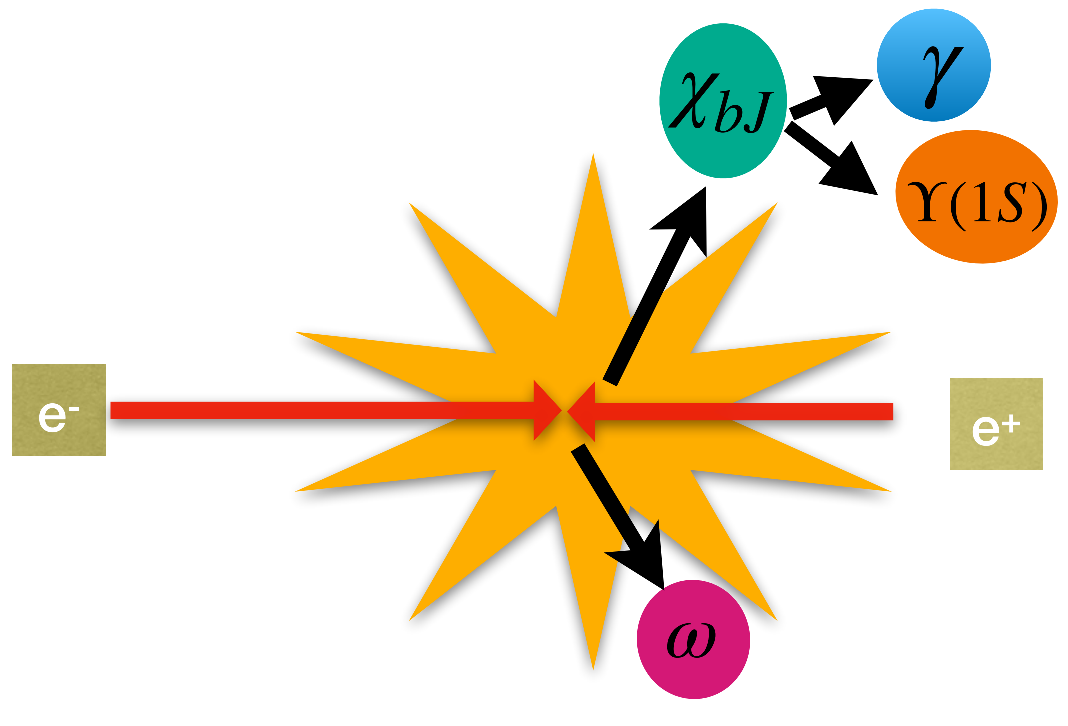




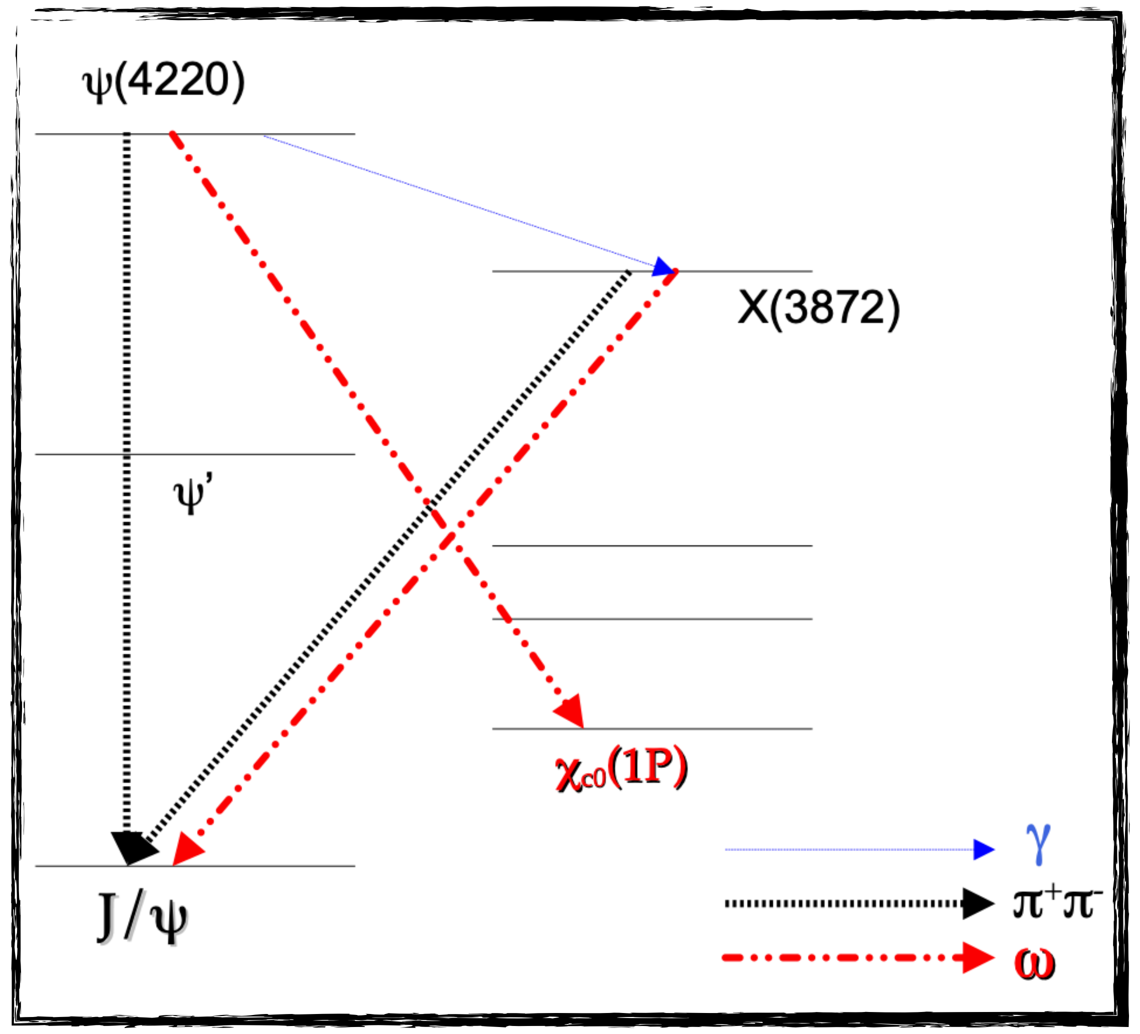
Study of $\Upsilon(10753) \to (\pi^+\pi^-\pi^0)\ \gamma\ \Upsilon(1S)$ at Belle II

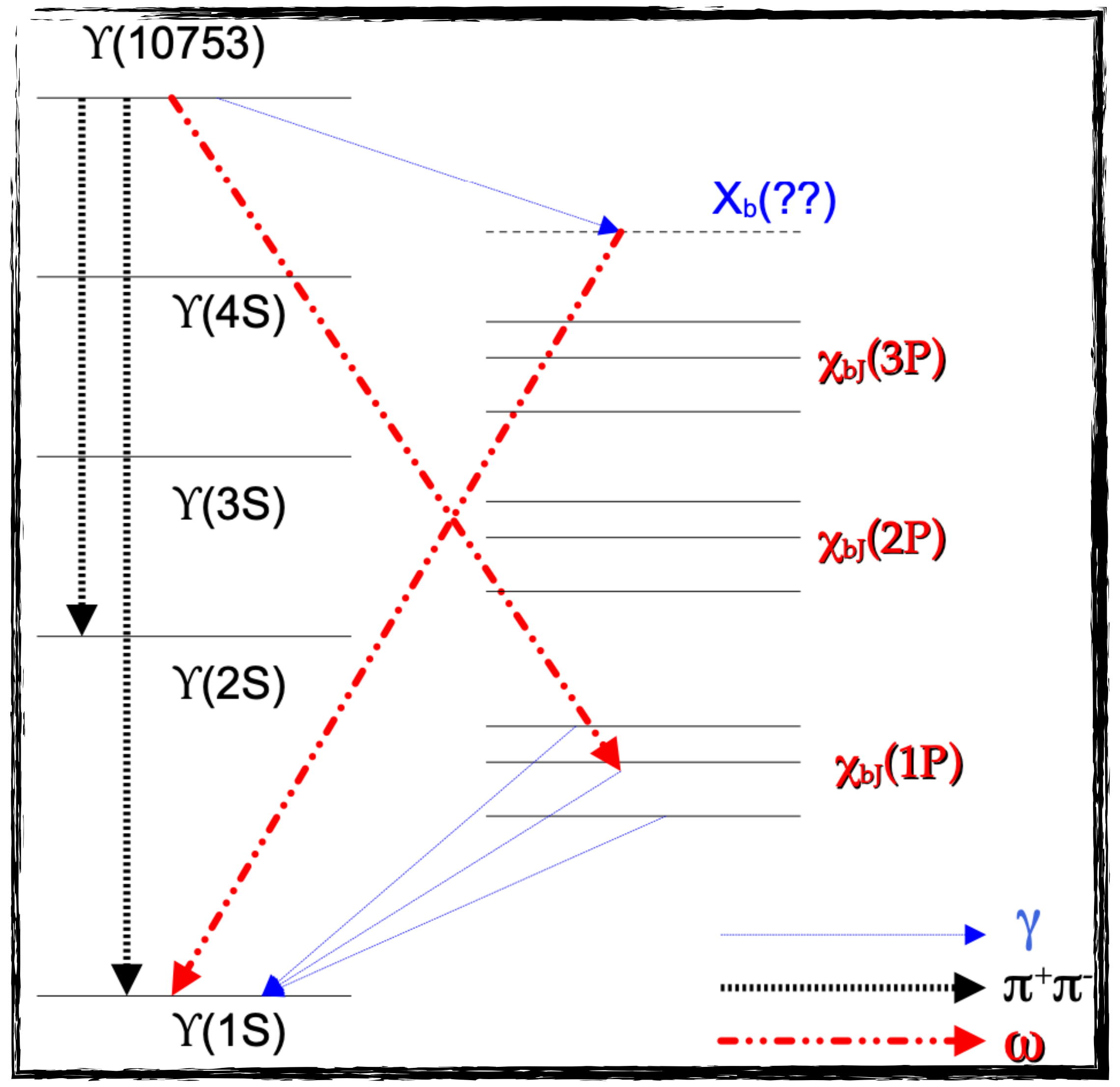
- **Theory**:
  - Mixed $4S - 3D$ model suggests $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$ could be enhanced.
    PRD 104, 034036 (2021)
- **Charmonium sector:**
  - Similar to $\Upsilon(10753)$ in $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$, $Y(4260)$ was observed in $e^+e^- \to \pi^+\pi^- J/\psi$ cross section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





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

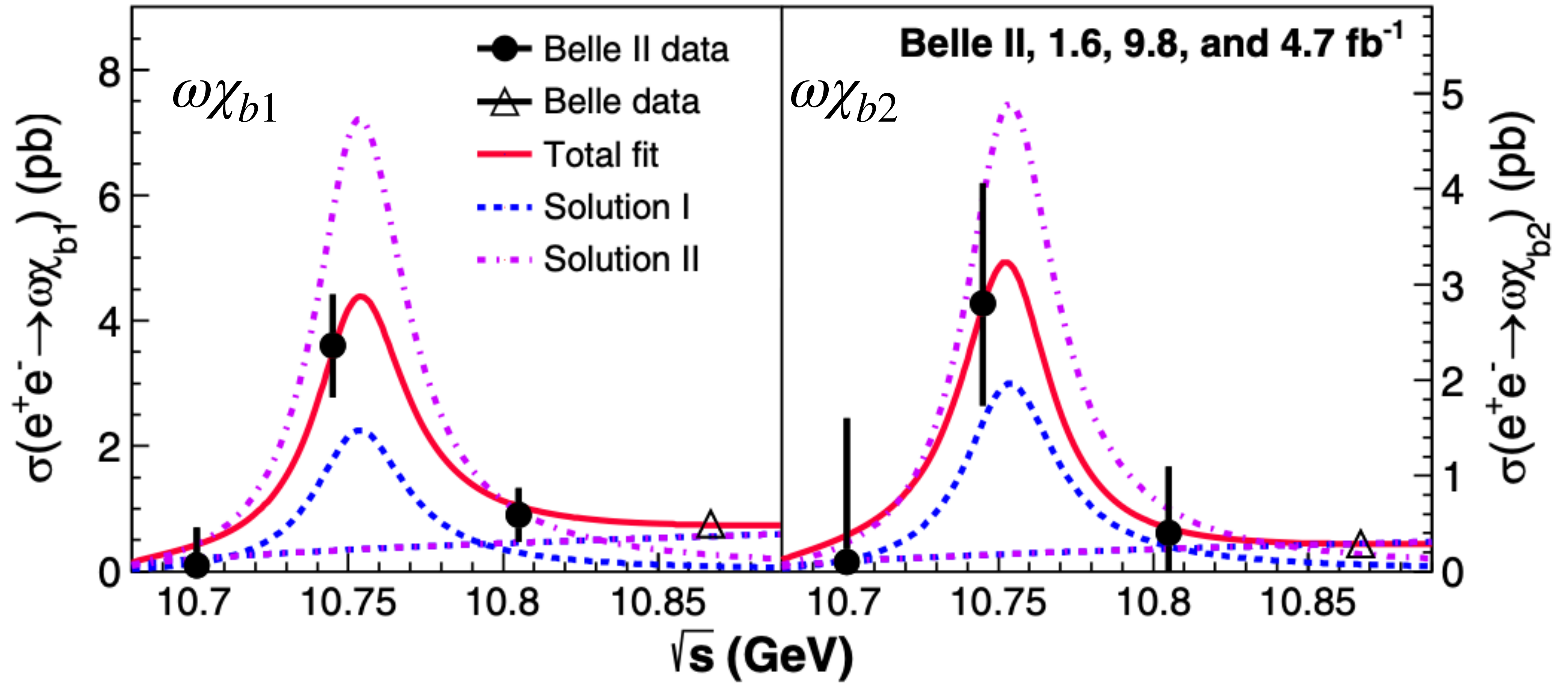




Observation of $\Upsilon(10753) \to \omega\, \chi_{bJ}(1P)$ at Belle II

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

PRL 130, 091902 (2023)



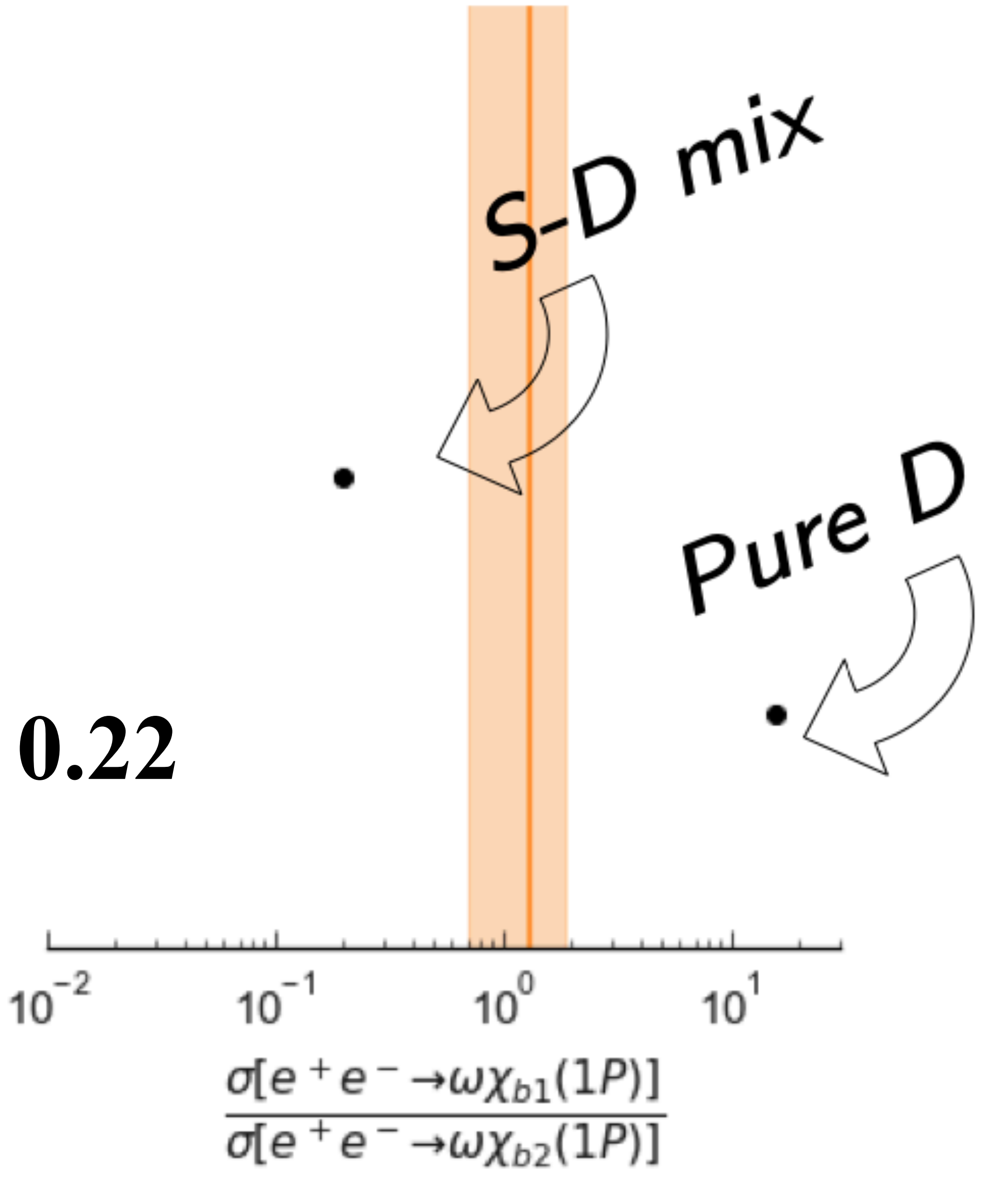
Solution 1: constructive interference

Solution II: destructive interference

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

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

- **Measured ratio:**
  - $$\frac{\sigma(\Upsilon(10753) \to \omega\chi_{b1})}{\sigma(\Upsilon(10753) \to \omega\chi_{b2})} = 1.3 \pm 0.6$$
  - **Prediction for a pure *D*-wave state: 15**
  - **Prediction for a $4S - 3D$ mixed state: 0.18 - 0.22**



Channel	$\sqrt{s}$ (GeV)	N^{sig}	$\sigma^{(UL)}_{Born}$ (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.

Disagreement with both pure *D* and $4S - 3D$ mixed model

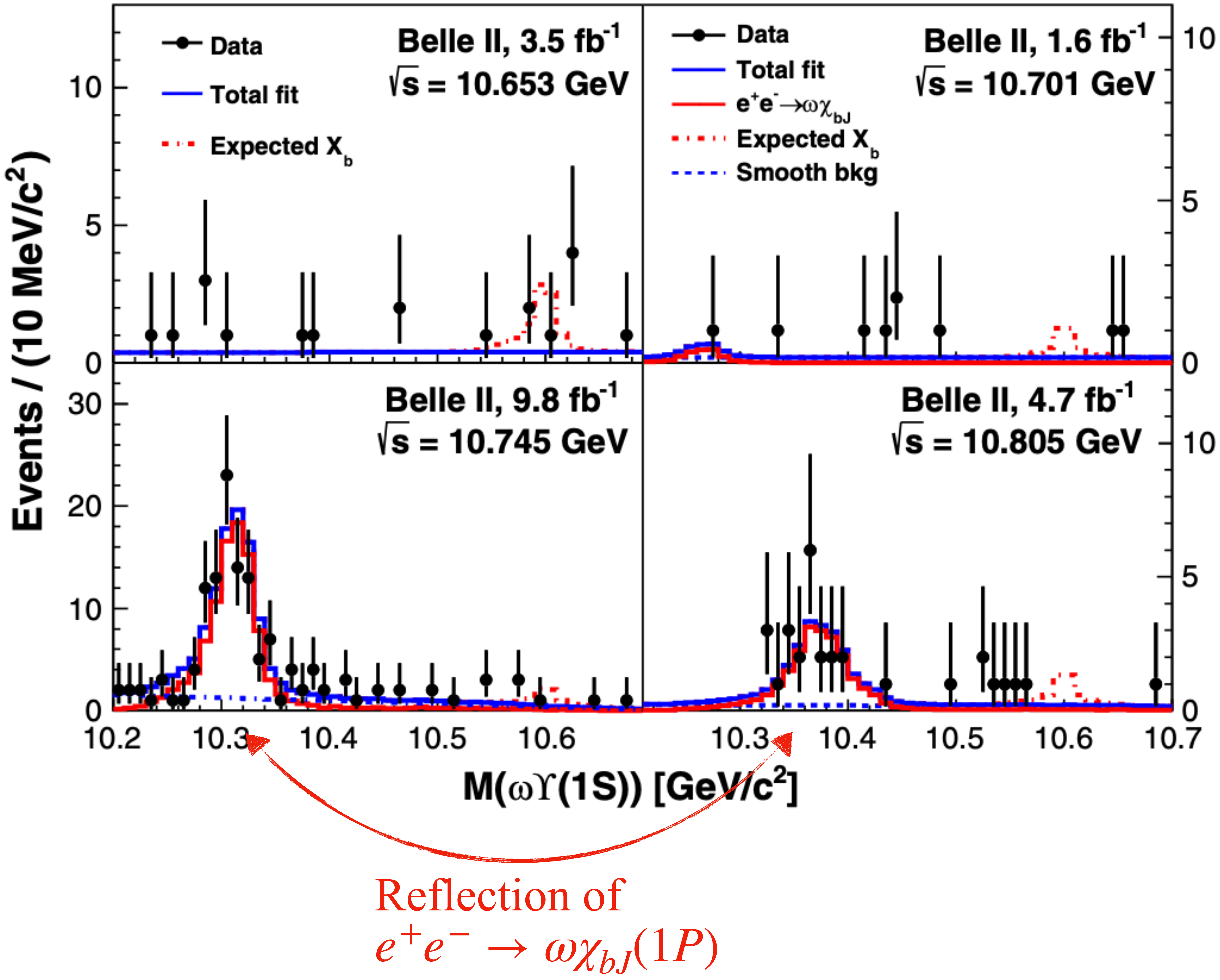
Search for $\Upsilon(10753) \to \gamma X_b$ at Belle II

PRL 130, 091902 (2023)

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

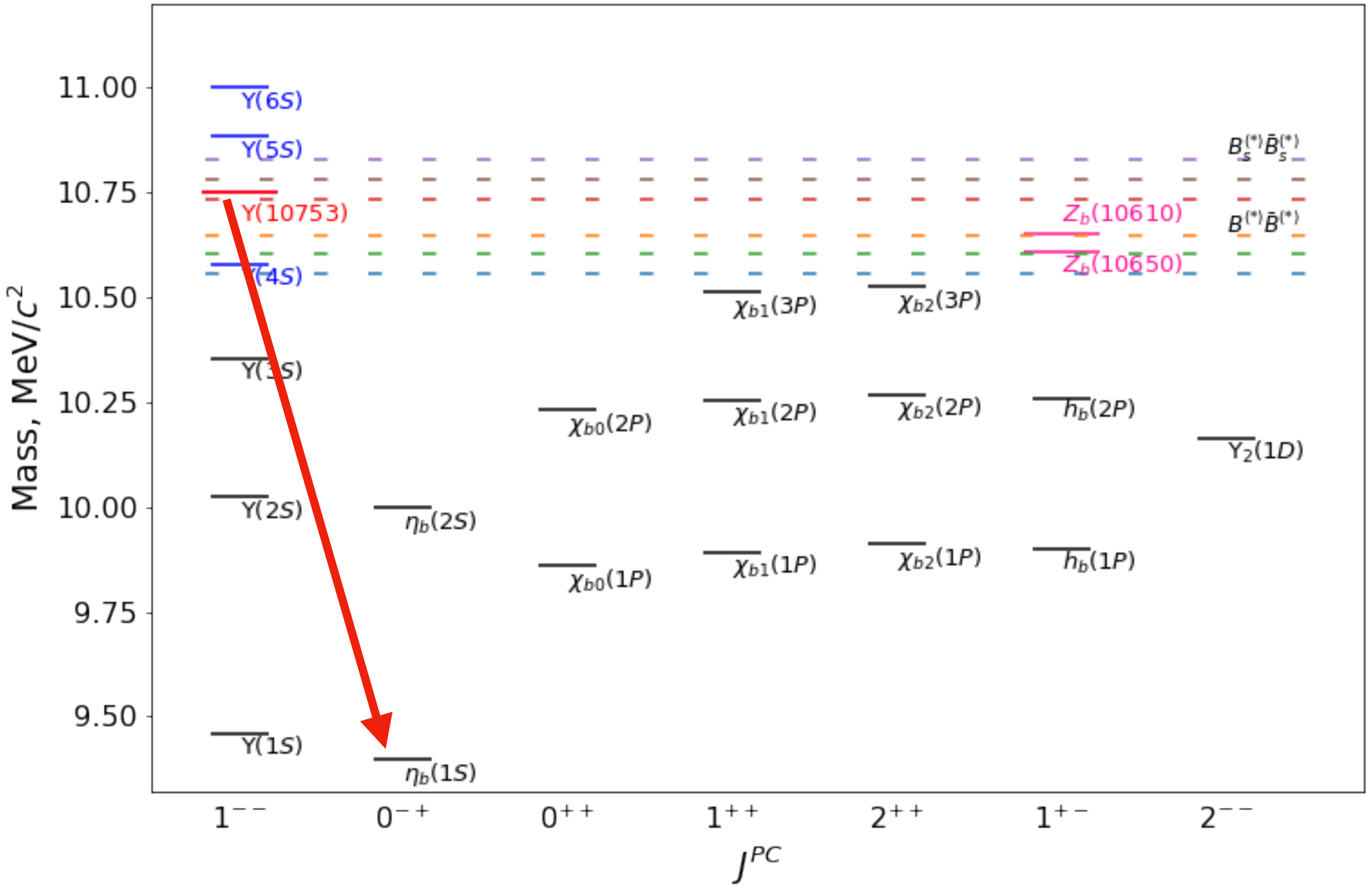
- No significant signal of X_b signal is observed.
- Upper limits on cross sections are set for $M(X_b) \in (10.45 - 10.65)$ GeV

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



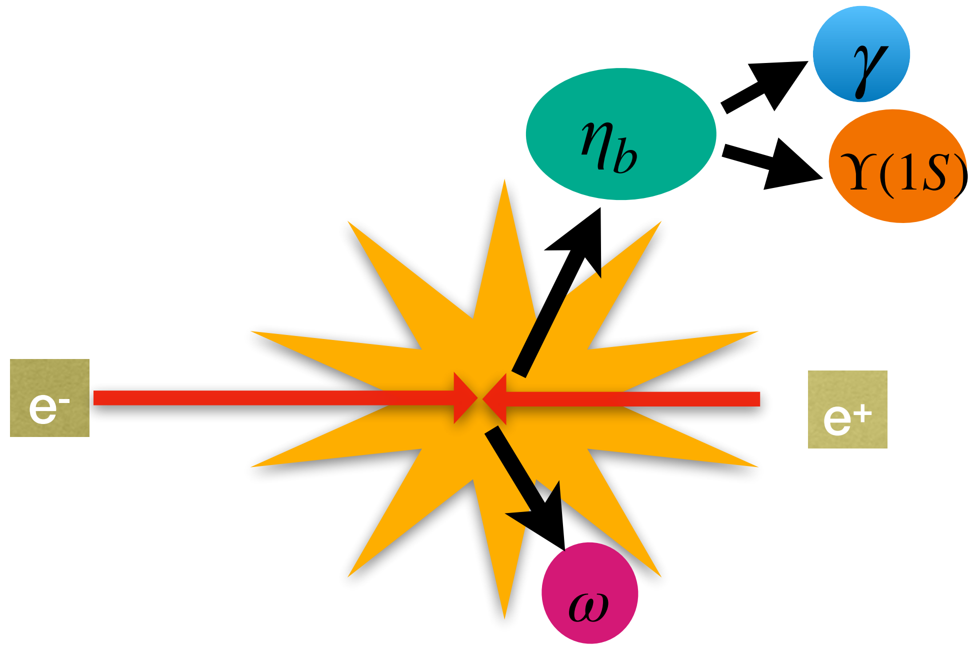
Search for $\Upsilon(10753) \to \omega\eta_b(1S)$ at Belle II

- **Motivation:**
  - Theoretically, tetra-quark interpretation predicts, a strong enhancement of the decay $\omega\ \eta_b(1S)$ compared to $\pi^+\pi^-\Upsilon(nS)$ CPC 43 (2019) 12, 123102
  - $4S-3D$ mixed model predicts that decay rate of $\omega\ \eta_b(1S)$ is smaller than $\pi^+\pi^-\Upsilon(nS)$ by a factor of 0.2-0.4 PRD 109, 014039 (2024)



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

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

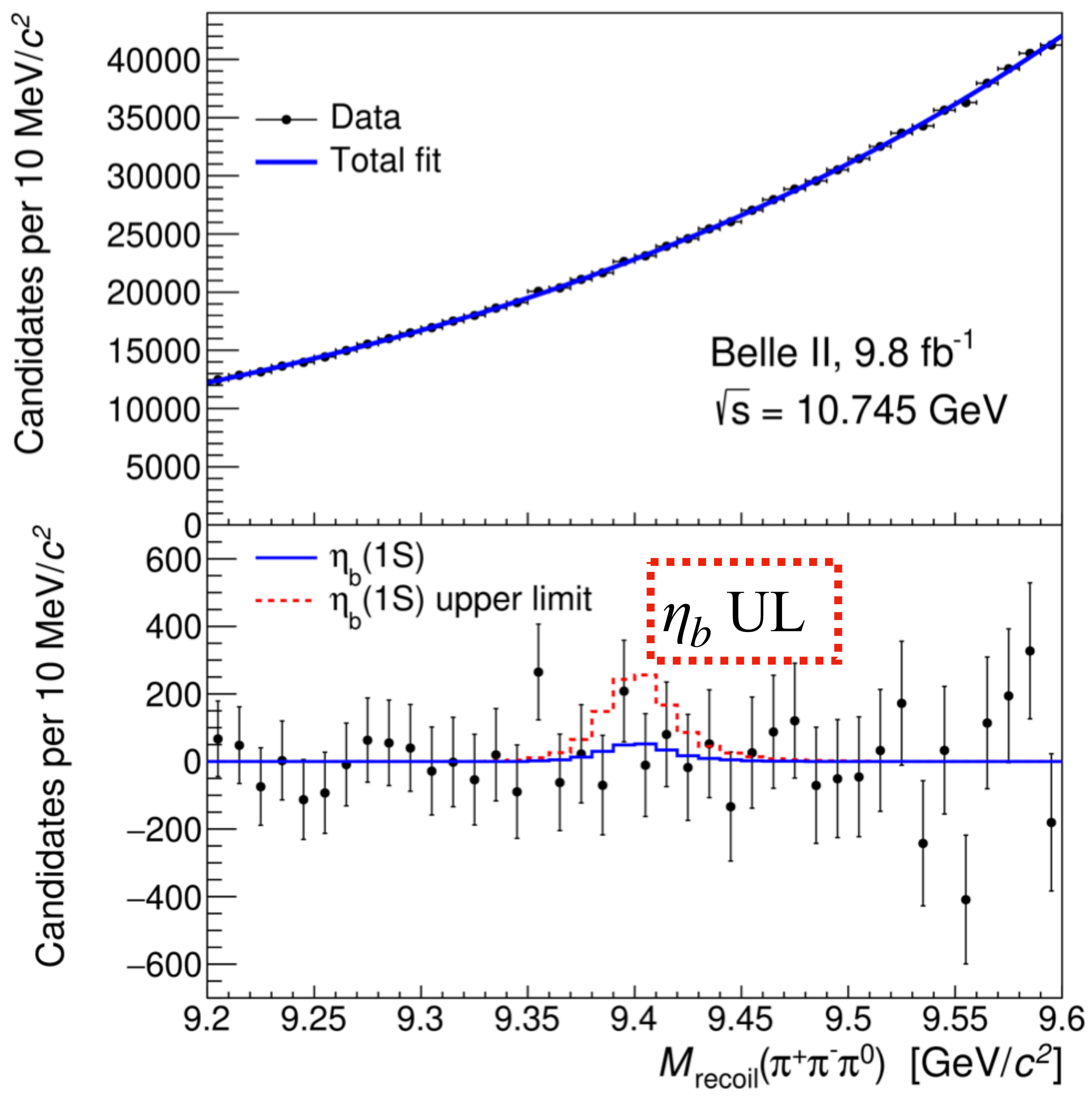


Search for $\Upsilon(10753) \to \omega\eta_b(1S)$ at Belle II

- No significant $\omega\ \eta_b(1S)$ signal is observed.
- Upper limits at the 90% C.L. on the Born cross section are set.
- $\sigma(e^+e^- \to \omega\eta_b(1S)) < 2.5$ pb

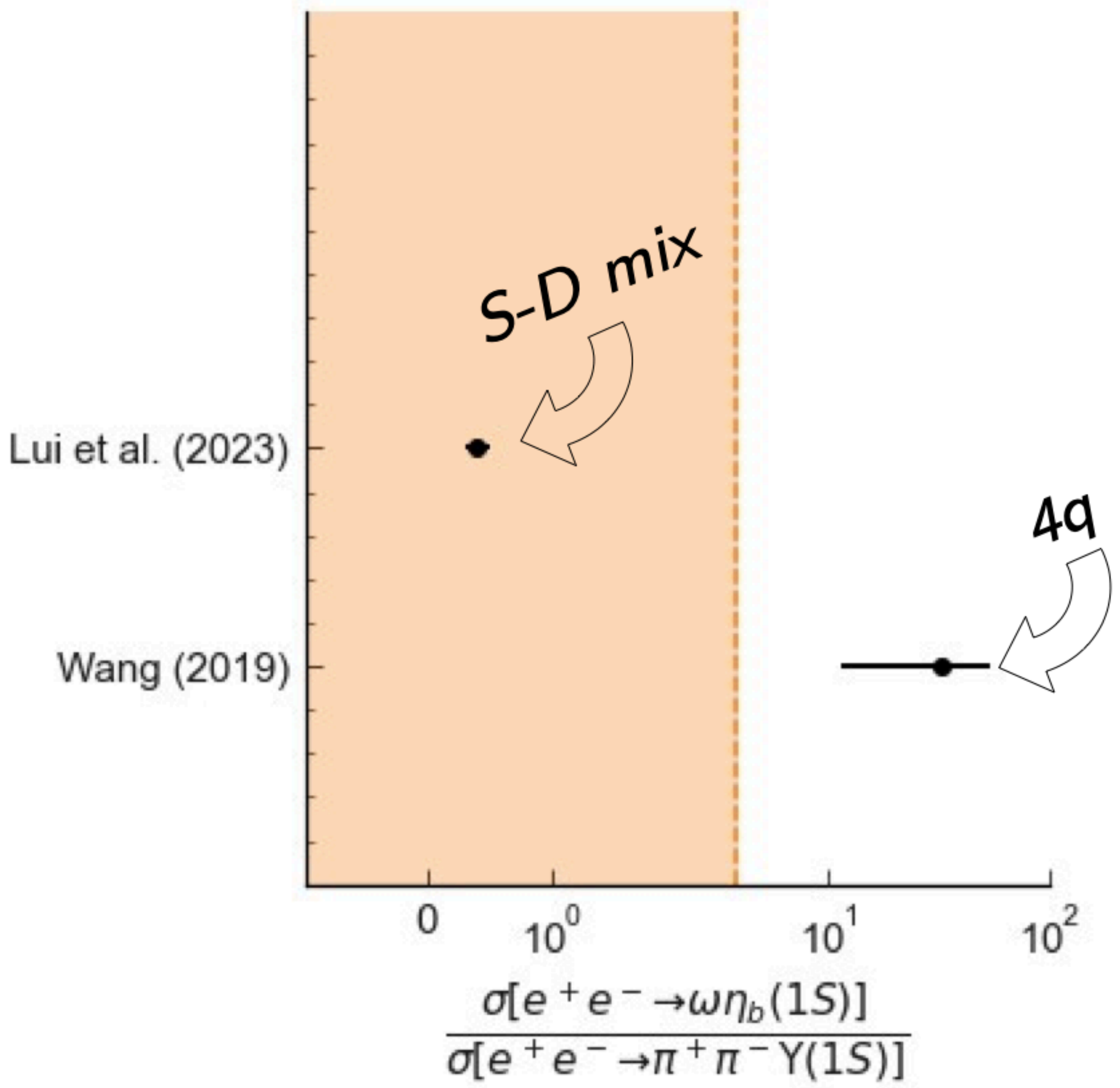
PRD 109, 072013 (2024)

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



Ratio:

- $\dfrac{\sigma(\omega\eta_b)}{\sigma(\pi^+\pi^-\Upsilon(nS))} < 1.25$
- Prediction for a tetra quark model: ~30
- Prediction for a $4S - 3D$ mixed state: 0.2 - 0.4



Evidence against the tetraquark model predictions.

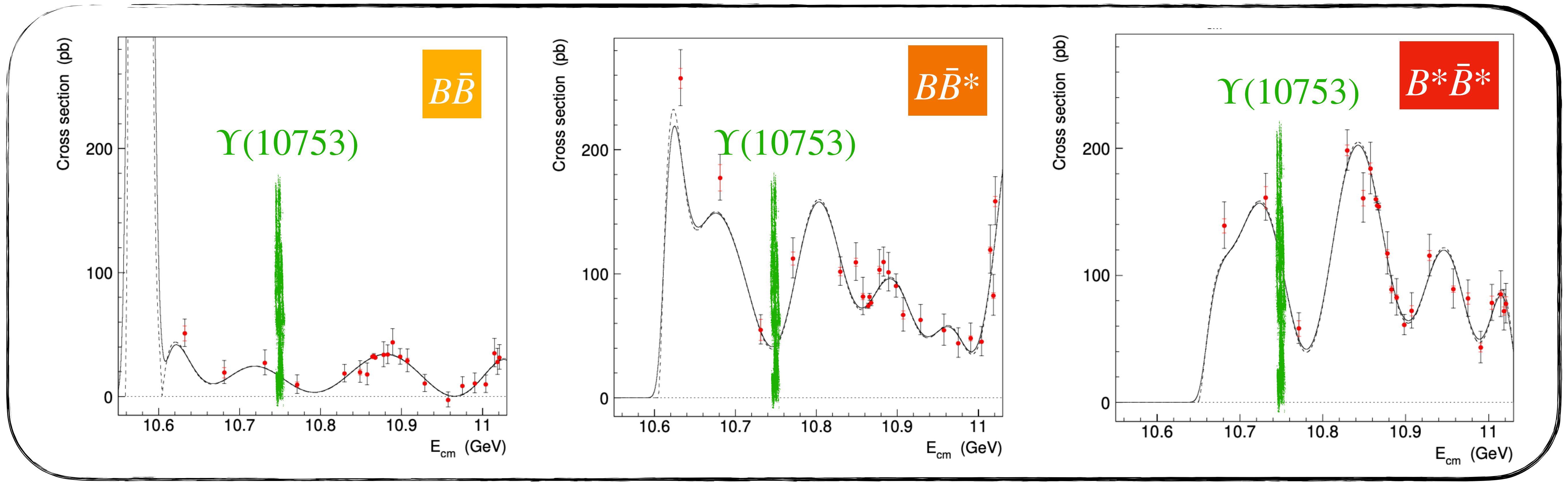
Compatible with $S - D$ mixed model

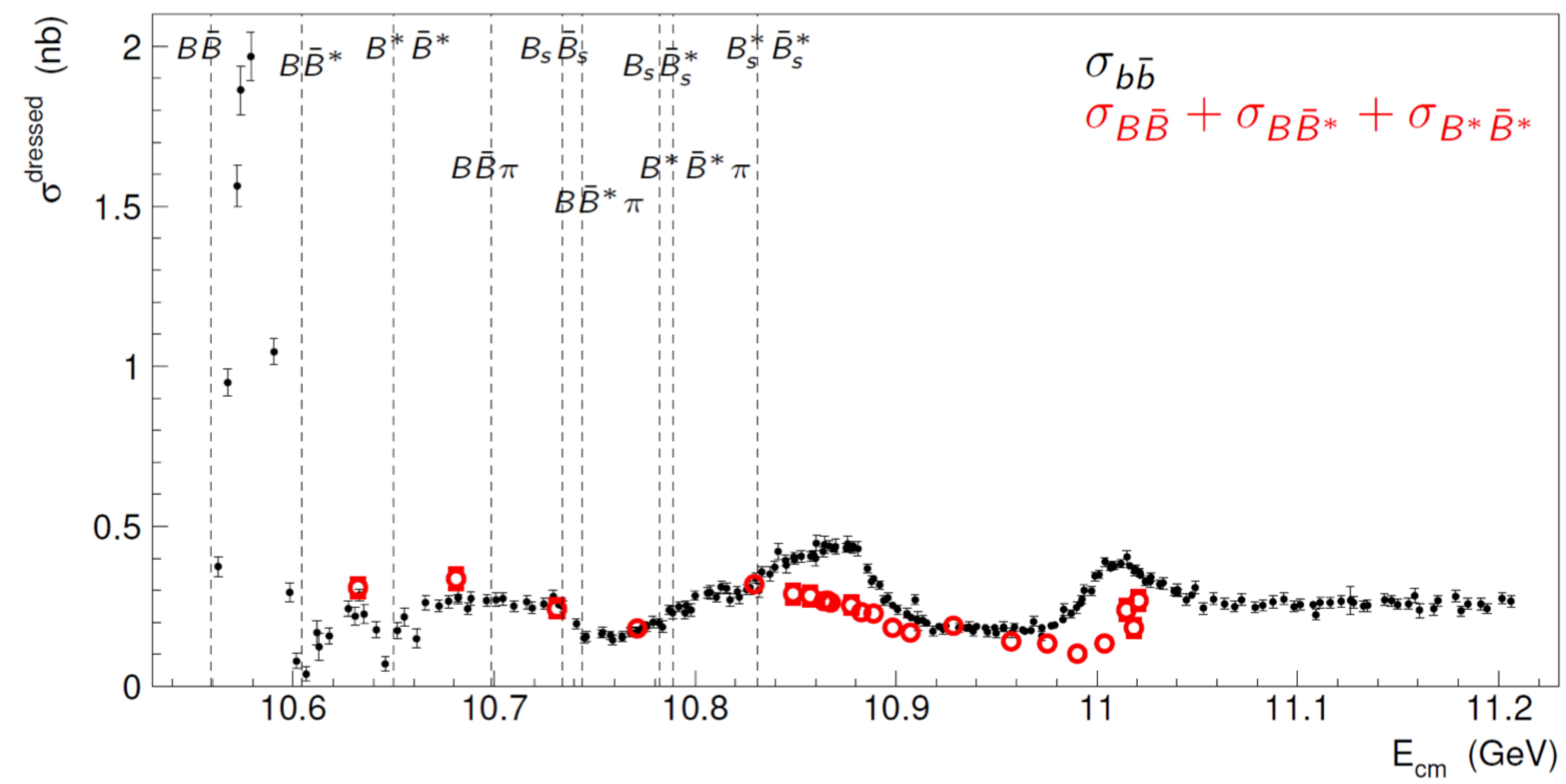
Open flavor cross-section

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

- **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.
  - 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.
  - **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.
  - To improve the accuracy below Υ(5S) and understand the nature of $\Upsilon(10753)$, need more data: Belle II

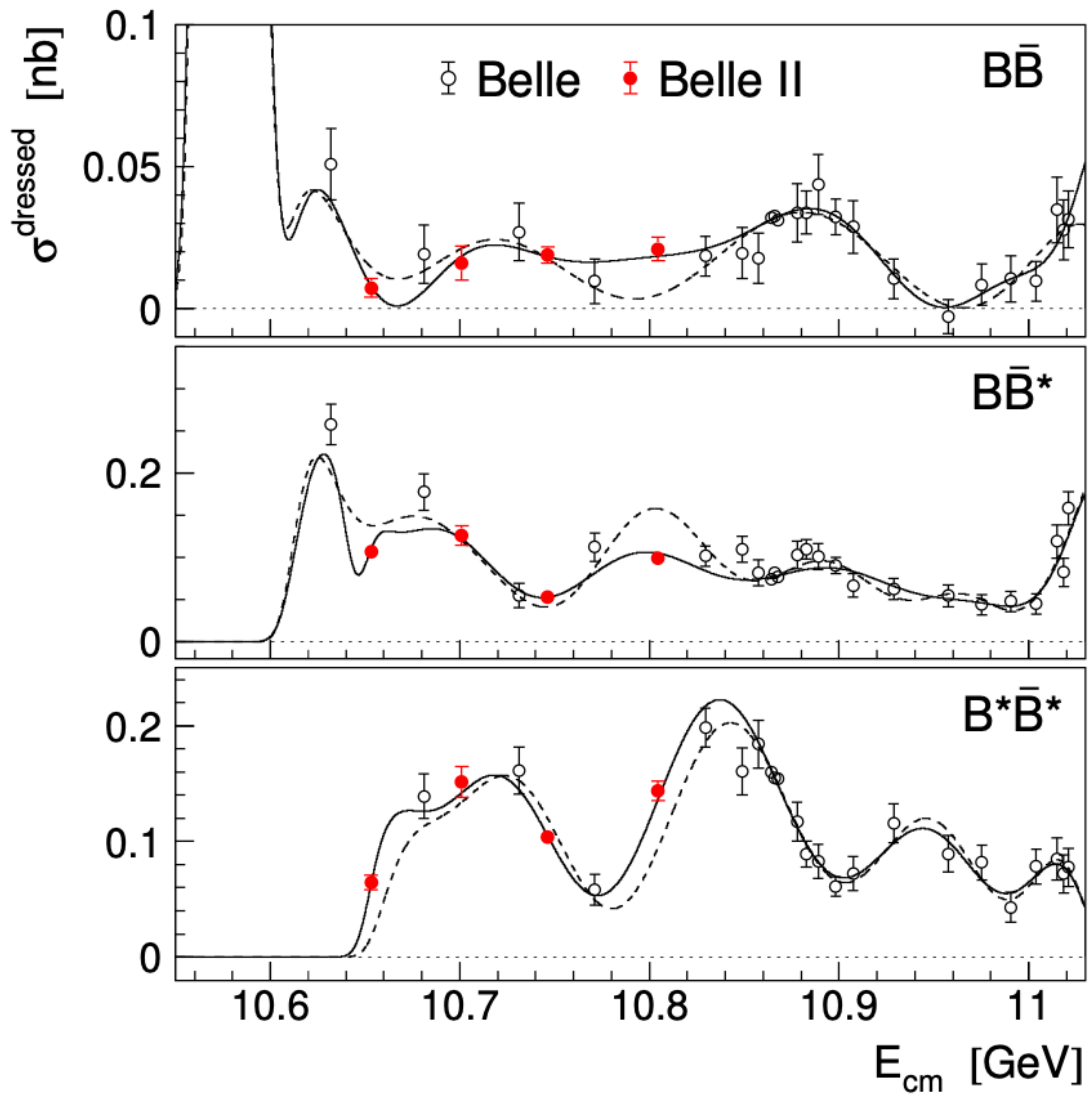
Belle results





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

- 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 $\eta h_b(1P)$] could also be enhanced

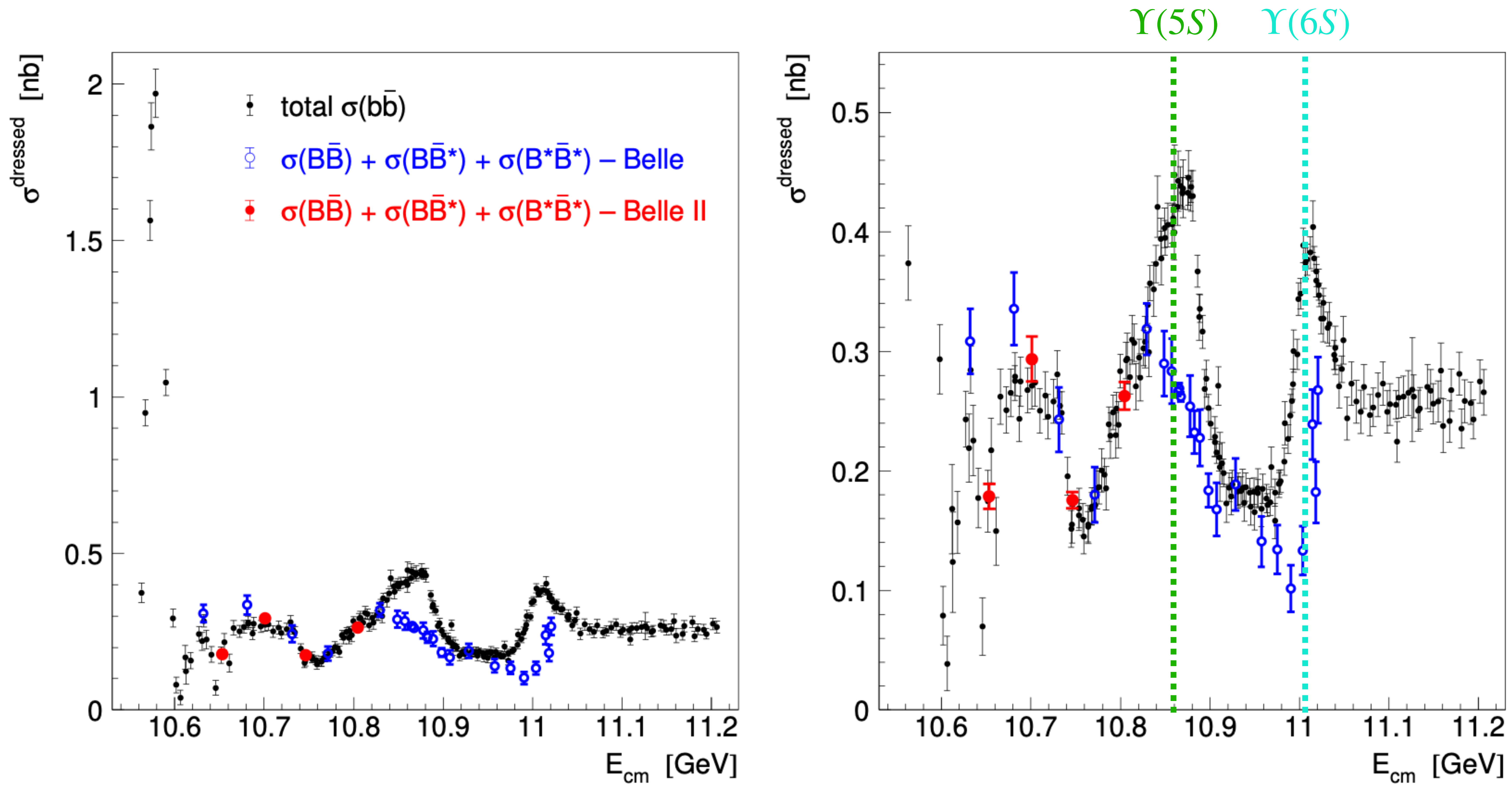


Solid curve – combined Belle + Belle II data fit

Dashed curve – Belle data fit only

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

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)]

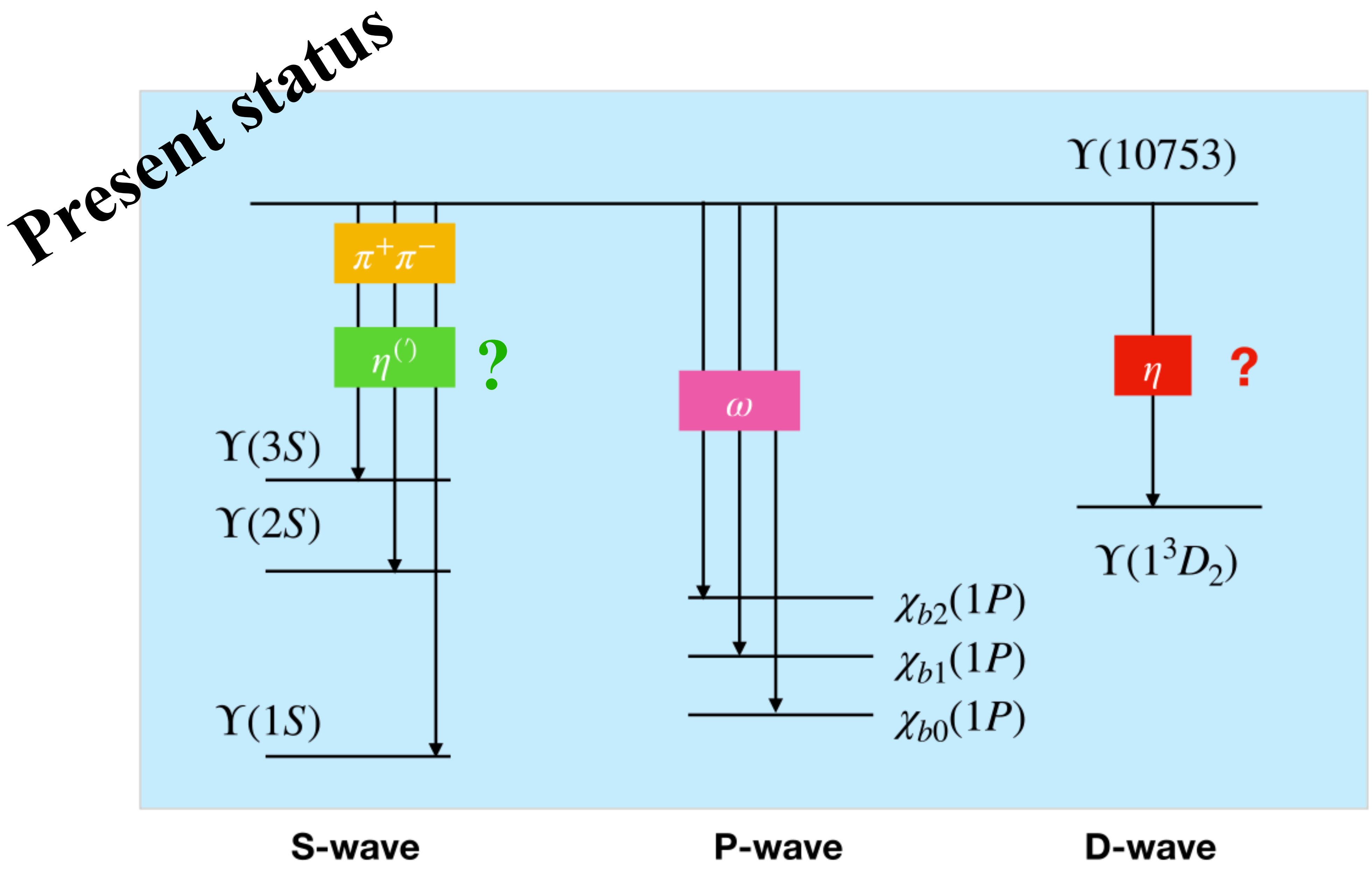
Open blue circles: Belle
[JHEP 06, 137 (2021)]

Filled red circles: Belle II
[this work]

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

Summary

- The understanding of the physics of highly excited heavy bottomonium is very incomplete.
- First energy scan results from Belle II are quite interesting, but not conclusive.
- No clear indication on the nature of $\Upsilon(10753)$.
  - Improved results for mass and width of $\Upsilon(10753)$ using $\Upsilon(10753) \to \Upsilon(nS)\pi^+\pi^-$.
  - $S-D$ model compatible with $\Upsilon(10753) \to \omega\eta_b(1S)$ but not with $\Upsilon(10753) \to \omega\chi_{b1,2}(1P)$.
  - No signal of intermediate $Z_b^+(10610)$ or $Z_b^+(10650)$ resonances are observed.



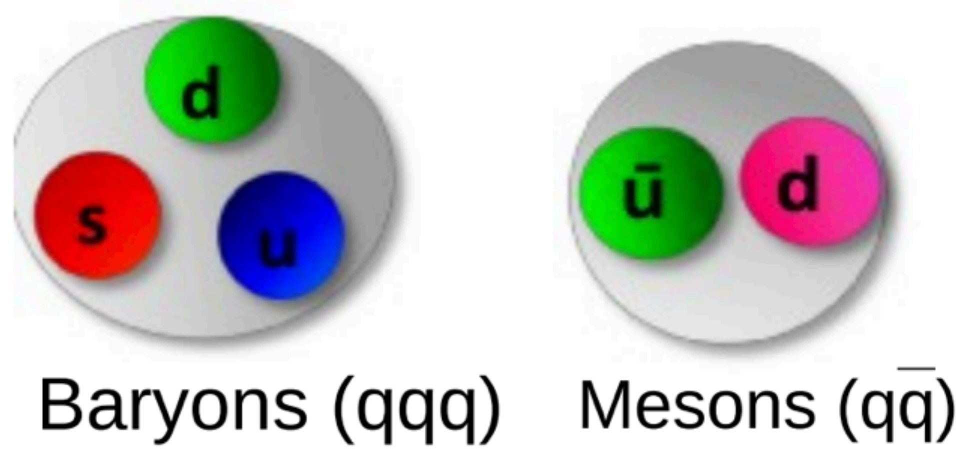
- New data are needed to search for patterns that may indicate possible theoretical solutions.
- Super KEKB is a unique experimental facility in which the phenomena discussed can be studied under well controlled conditions.


Backup
Ctrl

Introduction

Quark model:

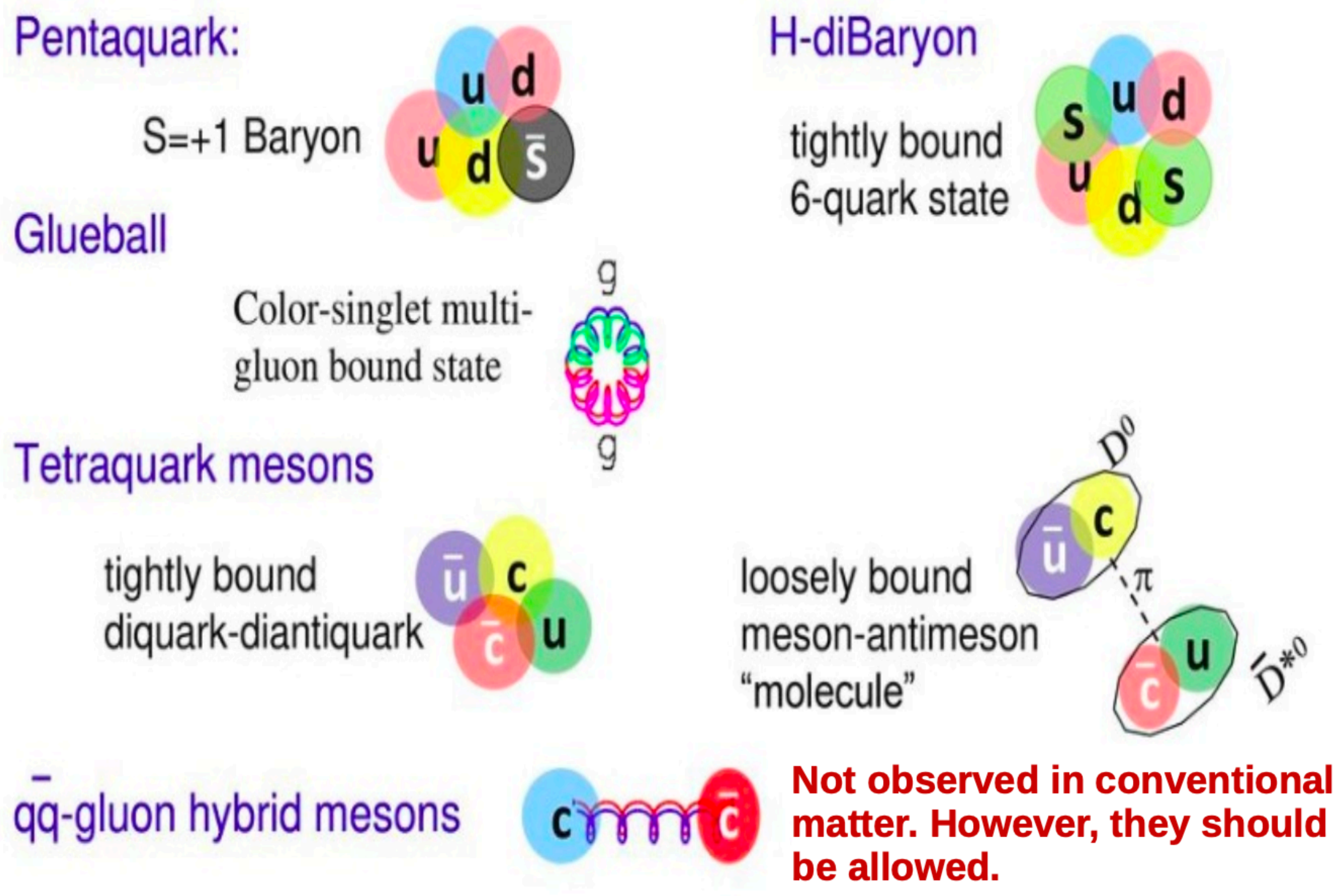
M. Gell-Mann, Phys.Lett. 8, 214 (1964)



Classification scheme for hadrons in terms of valance quarks.

Hadrons are composed of mesons ($q\bar{q}$, $qq\bar{q}\bar{q}$, ...) and baryons (qqq, $qqqq\bar{q}$, ...).

- $q\bar{q}$ spectroscopy with heavy quark (mostly c or b) are best place to study quark model.
- Simple two body system, non-relativistic and narrow (with OZI suppression).
- Further, one can search for exotics with them.

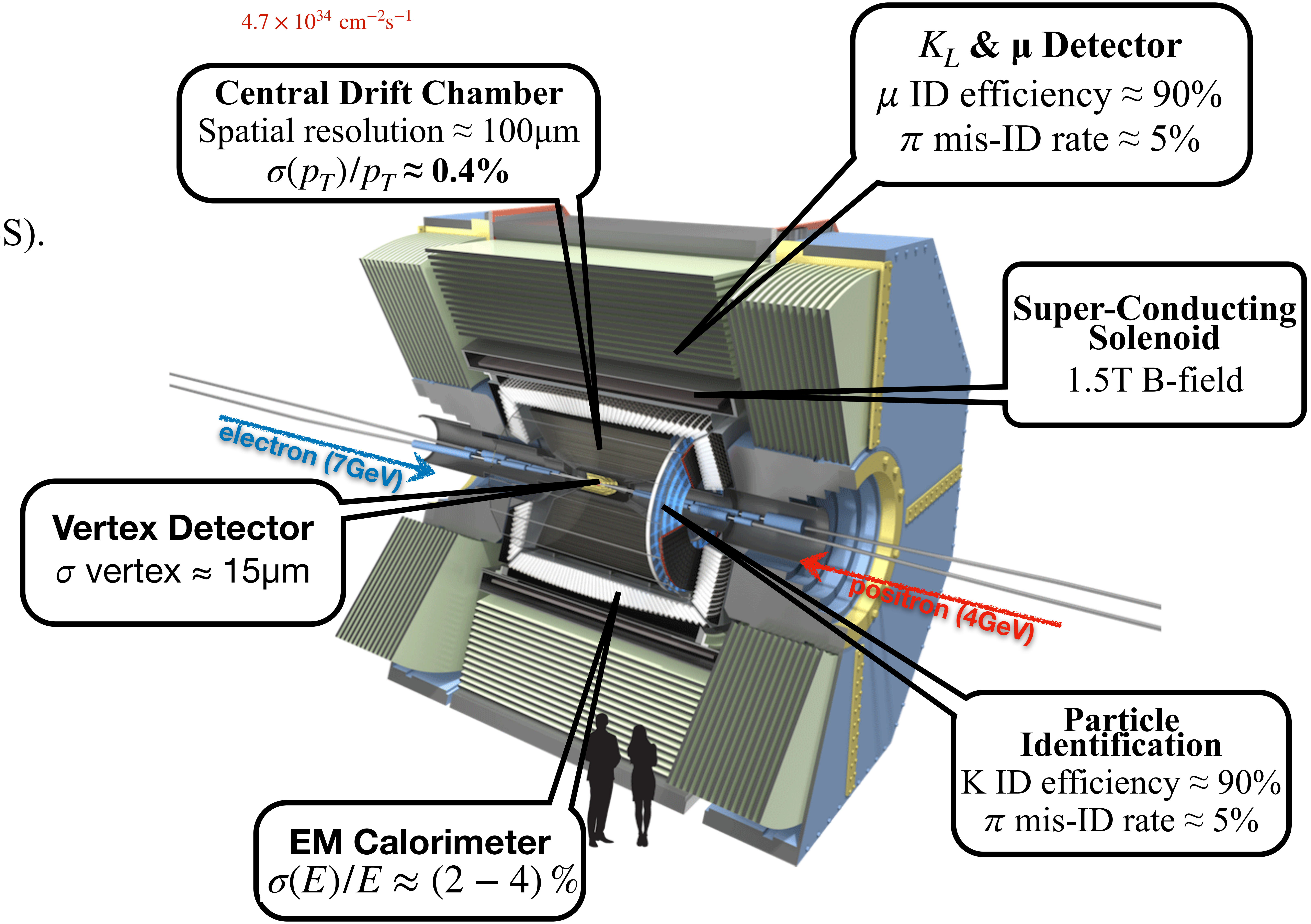


Belle II detector

Record-breaking instantaneous luminosity:

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

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

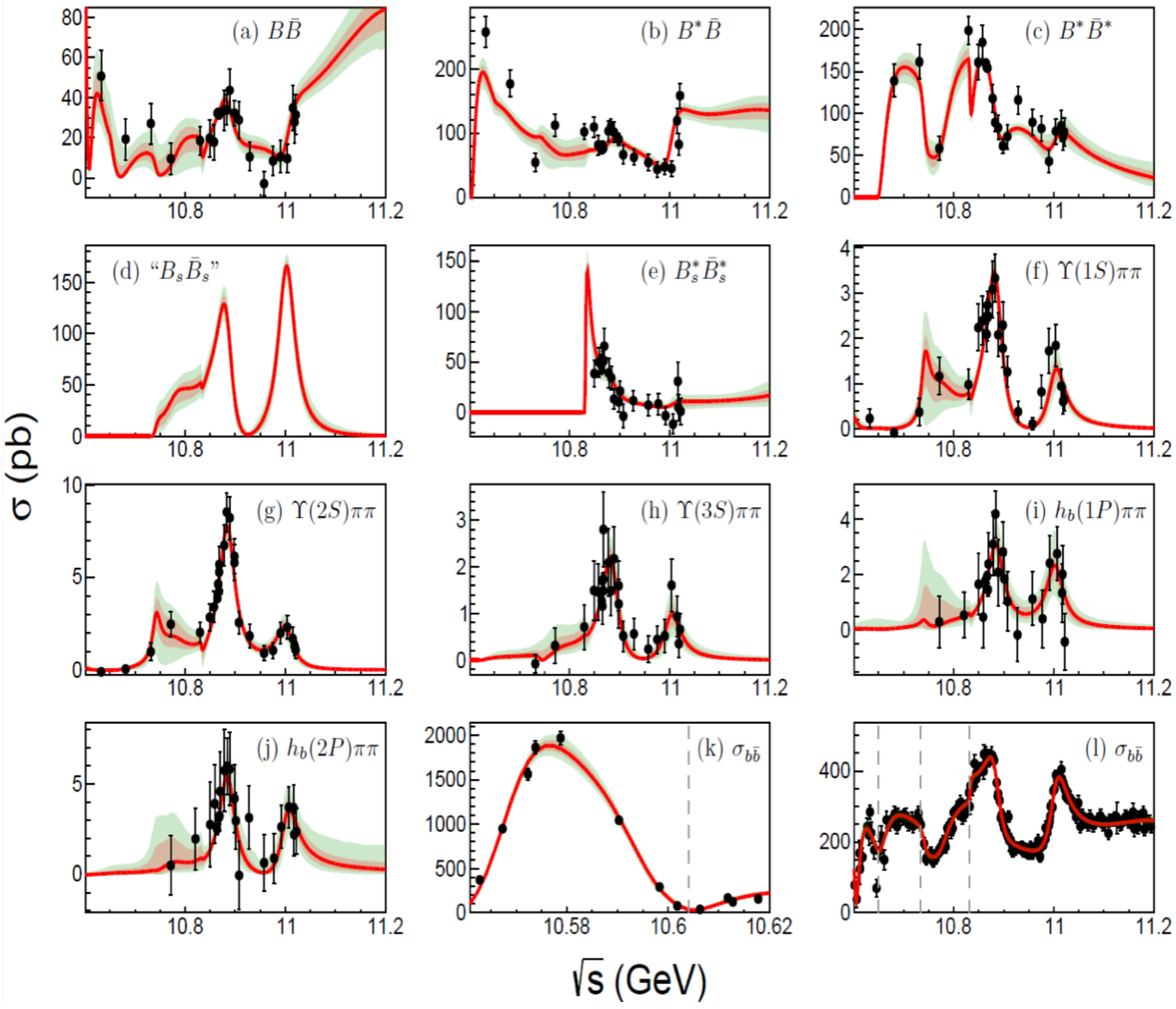


Features:

- 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:

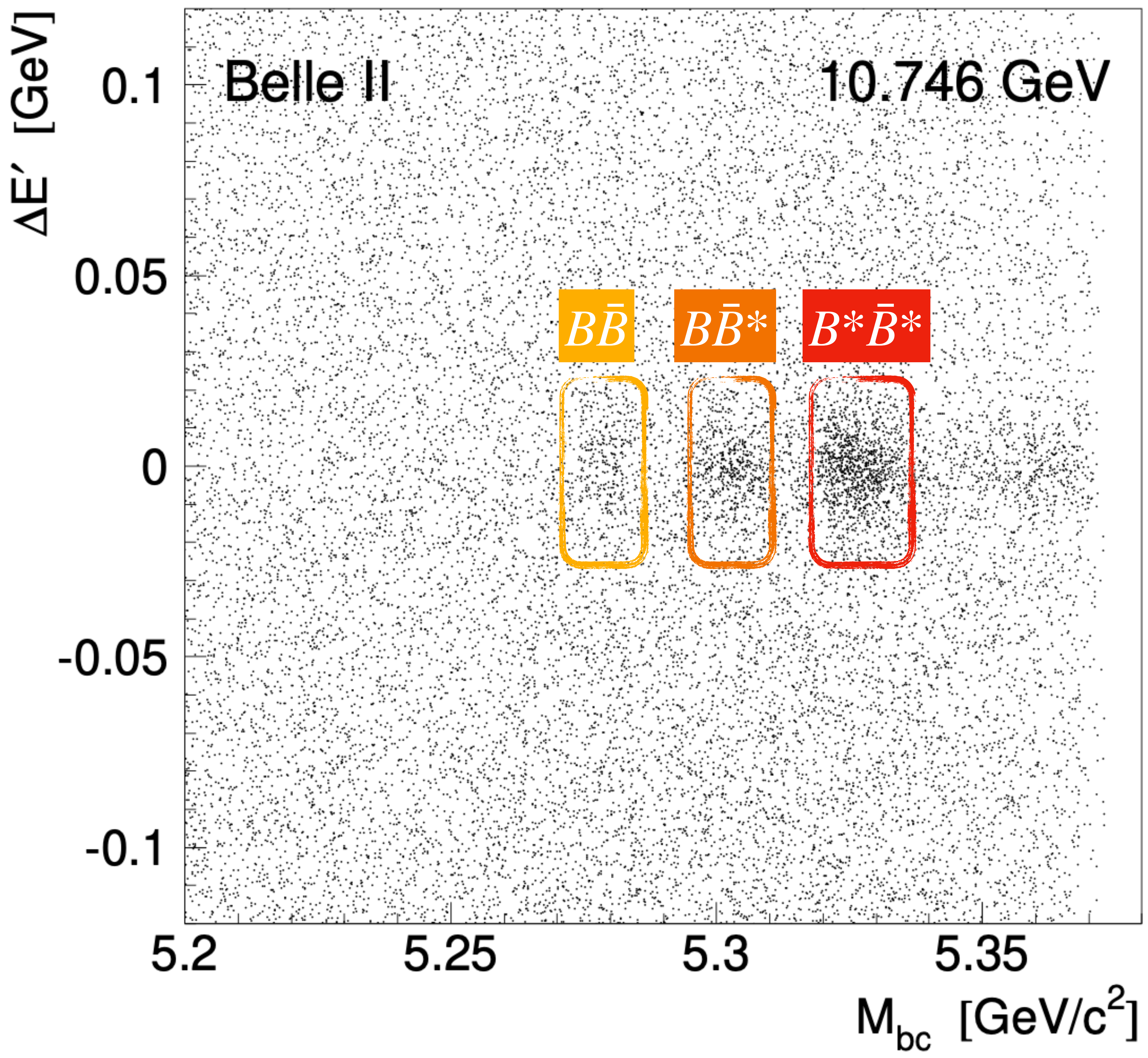
$B^+ \to$	$B^0 \to$
$\bar{D}^0\pi^+$	$D^-\pi^+$
$\bar{D}^0\pi^+\pi^+\pi^-$	$D^-\pi^+\pi^+\pi^-$
$\bar{D}^{*0}\pi^+$	$D^{*-}\pi^+$
$\bar{D}^{*0}\pi^+\pi^+\pi^-$	$D^{*-}\pi^+\pi^+\pi^-$
$D_s^+\bar{D}^0$	$D_s^+D^-$
$D_s^{*+}\bar{D}^0$	$D_s^{*+}D^-$
$D_s^+\bar{D}^{*0}$	$D_s^+D^{*-}$
$D_s^{*+}\bar{D}^{*0}$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

$D^0 \to$	$D^+ \to$	$D_s^+ \to$
$K^-\pi^+$	$K^-\pi^+\pi^+$	$K^+K^-\pi^+$
$K^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$	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
    - $M_{\mathrm{bc}} = \sqrt{(E_{cm}/2)^2 - p_B^2}$
    - $\Delta E' = \Delta E - M_{\mathrm{bc}} + M_B$, where $\Delta E = E_B - E_{\mathrm{cm}}/2$
  - $\Delta E'$ 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

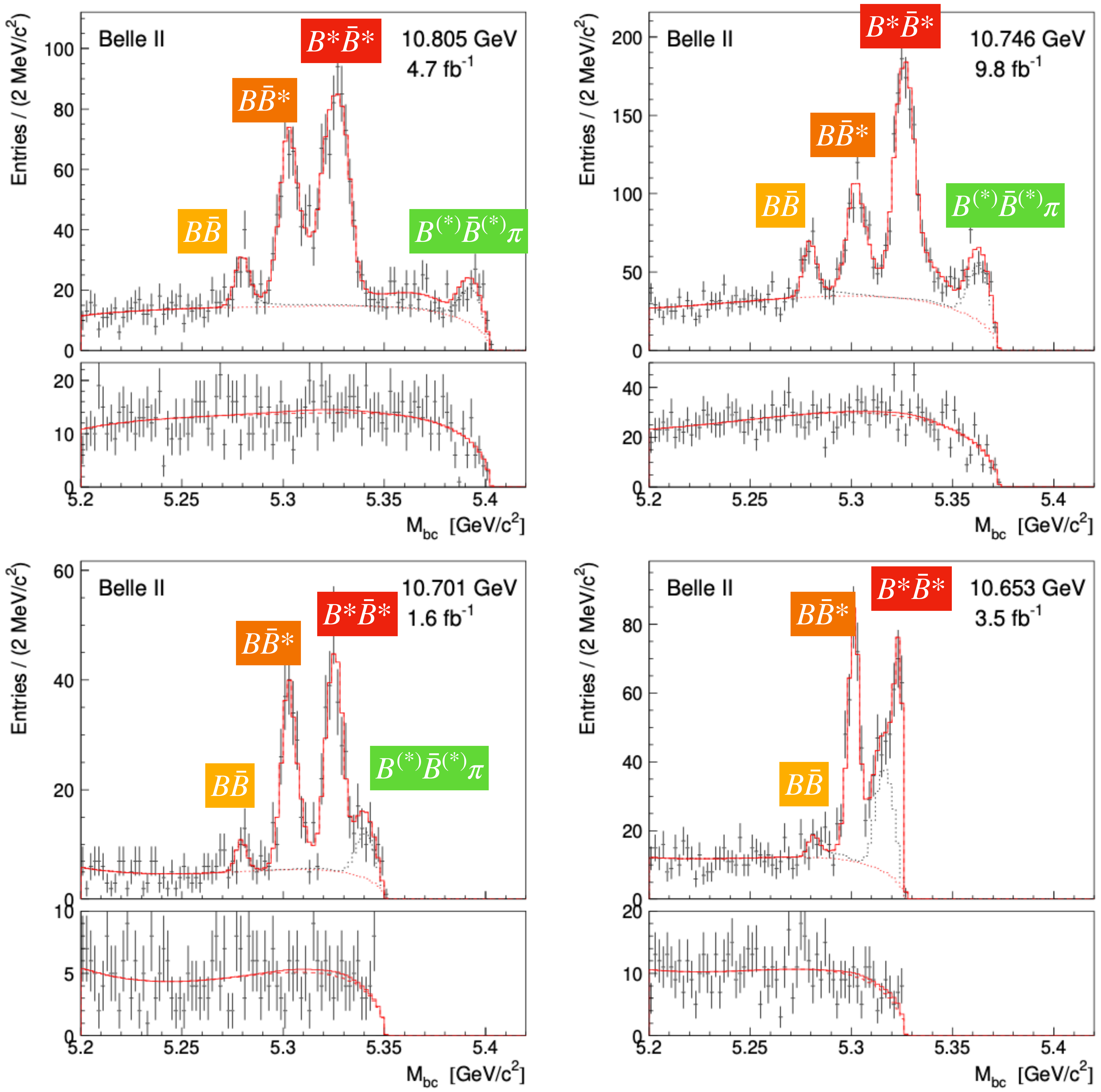


Energy dependence of $e^+e^- \to B^{(*)}\bar{B}^{(*)}$ cross section

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



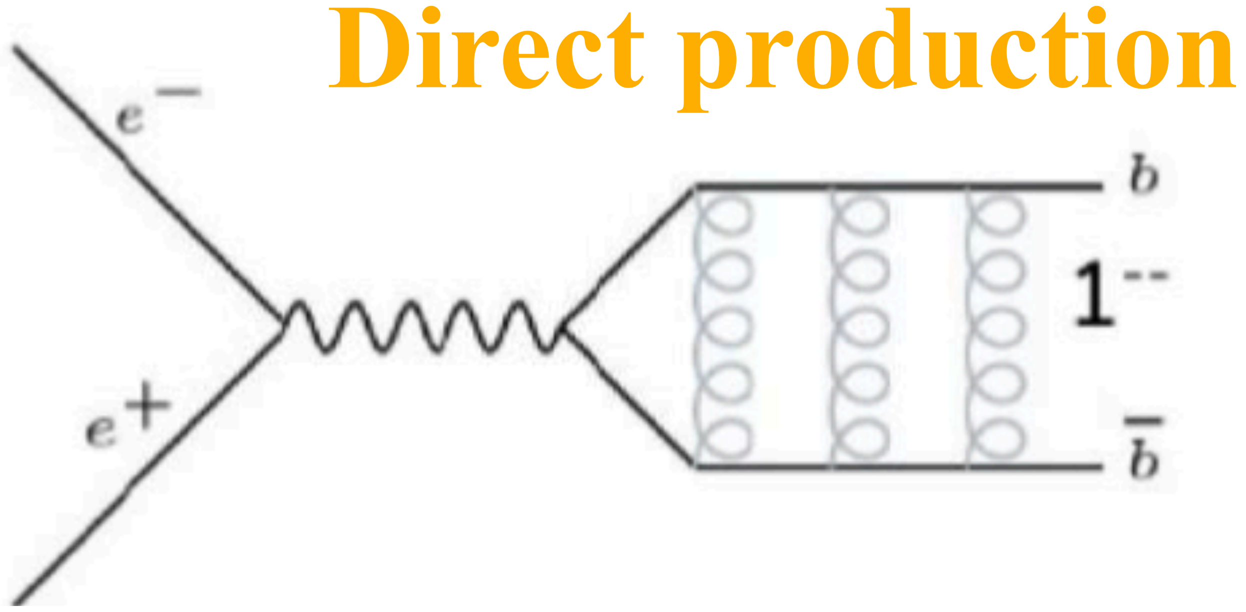
Bottomonium (-like) at Belle II

- **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, …

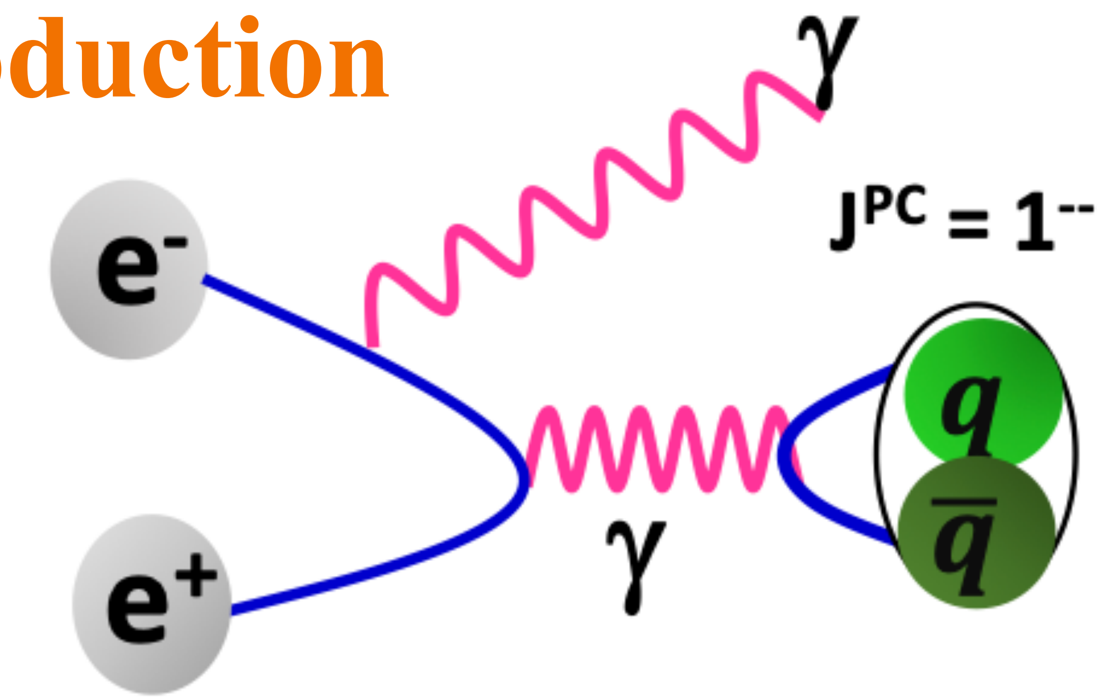
    $J^{PC} = 0^{-+}, 1^{--}, 1^{+-} \ldots : \Upsilon(nS), \eta_b(nS), h_b(nS), \ldots$
  - **Radiative transitions** from $\Upsilon(nS)$

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

Direct production



ISR production



Hadronic transitions