Exotics Workshop, 14 Nov 2023, Nagoya

Belle and Belle II results on exotic hadrons

Roman Mizuk

IJCLab (Orsay) and Paris Saclay University

Contents

Measurement of cross sections

$e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$

$e^+e^- \to \eta_b(1S)\omega\,,\ \chi_{b0}(1P)\omega$ preliminary

$e^+e^- \to B\bar{B}, B\bar{B}^*, B^*\bar{B}^*$ using Belle II energy scan data.

JHEP 08, 131 (2023)

Energy dependence of $\sigma(e^+e^- \to B_s\bar{B}_s\,X)$ at Belle.

$\Rightarrow$ Bottomonium-like states.

Subject appeared in 2008

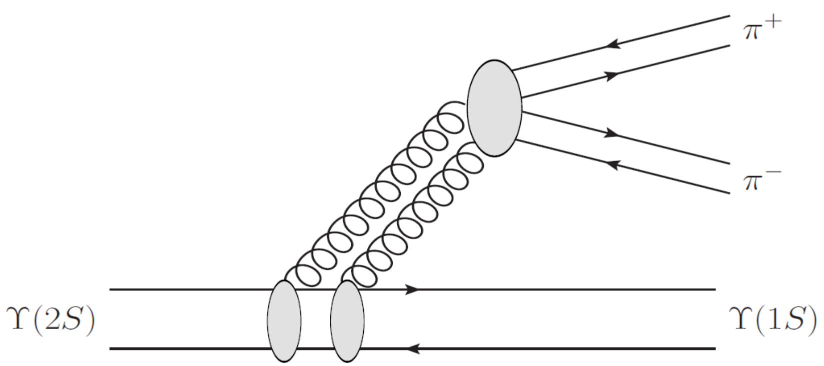
- Belle: PRL 100, 112001 (2008)

$$\Gamma(\Upsilon(5S) \to \Upsilon(1S, 2S, 3S)\ \pi^+\pi^-) \sim 1\ MeV$$

- BaBar: BaBar PRD 78, 112002 (2008)

$$\frac{\Gamma(\Upsilon(4S) \to \Upsilon(1S)\eta)}{\Gamma(\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-)} = 2.4 \pm 0.4$$

Hadronic transitions in bottomonium



$\pi^+\pi^-$: $E1E1$ gluons

$$\Gamma(\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-) = 5.7 \pm 0.5\,\text{keV}$$
$$\Gamma(\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-) = 0.89 \pm 0.08\,\text{keV}$$
$$\Gamma(\Upsilon(3S) \to \Upsilon(2S)\pi^+\pi^-) = 0.57 \pm 0.06\,\text{keV}$$

partial widths are small

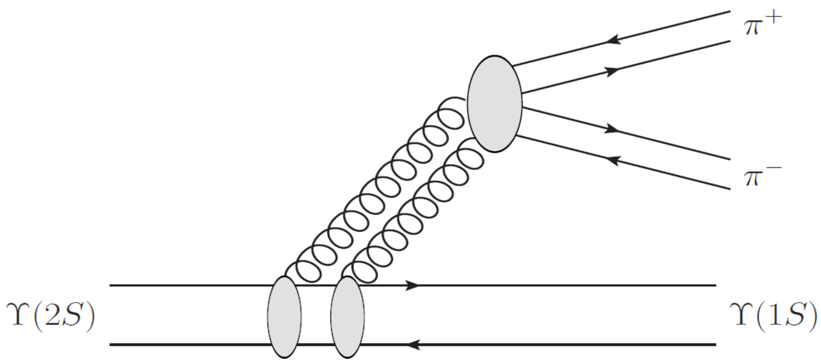
η : $E1M2$ gluons

Amplitude $\propto$ chromomagnetic moment of *b* quark $\propto$ $1/m_b$

$$\Gamma(\Upsilon(2S) \to \Upsilon(1S)\eta) = (9.3 \pm 1.5) \times 10^{-3}\,\text{keV}$$
$$\Gamma(\Upsilon(3S) \to \Upsilon(1S)\eta) < 2 \times 10^{-3}\,\text{keV}$$

additional suppression

Hadronic transitions in bottomonium



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$$\Gamma(\Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-) \sim 1\,MeV$$

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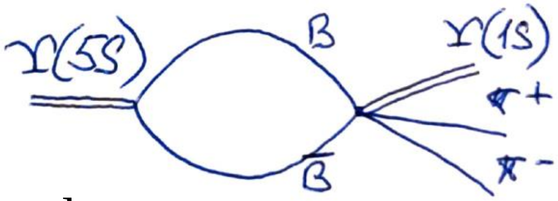
additional suppression

$$\frac{\Gamma(\Upsilon(4S) \to \Upsilon(1S)\,\eta)}{\Gamma(\Upsilon(4S) \to \Upsilon(1S)\,\pi^+\pi^-)} = 2.4 \pm 0.4$$

New decay mechanism: via exotic admixture

Molecular admixture $|B\bar{B}\rangle$



- decay into constituents dominates
- if p_B is high then rescattering is suppressed

$\Upsilon(4S)$ $|B\bar{B}\rangle$ $\Upsilon(5S)$ $|B_s^*\bar{B}_s^*\rangle$ $\Upsilon(6S)$ $|B_1\bar{B}\rangle$

$|B_0\bar{B}^*\rangle$?

Hadroquarkonium $|\Upsilon(2S)\ f_0\rangle$

- decays into bottomonium core

Compact tetraquark $|bq\,\bar{b}\bar{q}\rangle$

- decays into open flavor are not enhanced

Hybrid $|b\bar{b}\ g\rangle$

- $b\bar{b}$ is in spin-singlet state

Angular momentum wave function

Voloshin, PRD 85, 034024 (2012)

$$
\begin{aligned}
|B\bar{B}\rangle \quad &\equiv \quad |S_{b\bar{q}} = 0, L_{b\bar{q}} = 0, S_{\bar{b}q} = 0, L_{\bar{b}q} = 0, L = 1\rangle \\
&= \frac{1}{2\sqrt{3}} \quad |S_{b\bar{b}} = 1, J_{q\bar{q}} = 0\rangle \\
&+ \frac{1}{2} \quad |S_{b\bar{b}} = 1, J_{q\bar{q}} = 1\rangle \\
&+ \frac{\sqrt{5}}{2\sqrt{3}} \quad |S_{b\bar{b}} = 1, J_{q\bar{q}} = 2\rangle \\
&+ \frac{1}{2} \quad |S_{b\bar{b}} = 0, J_{q\bar{q}} = 1\rangle
\end{aligned}
$$

change basis

Angular momentum wave function

Voloshin, PRD 85, 034024 (2012)

$$
\begin{aligned}
|B\bar{B}\rangle &\equiv && |S_{b\bar{q}}=0, L_{b\bar{q}}=0, S_{\bar{b}q}=0, L_{\bar{b}q}=0, L=1\rangle \\
&= && \tfrac{1}{2\sqrt{3}} \; |S_{b\bar{b}}=1, J_{q\bar{q}}=0\rangle \;\rightarrow\; \Upsilon(1S)\,\pi^+\pi^- \text{ in S wave} \\
&+ && \tfrac{1}{2} \; |S_{b\bar{b}}=1, J_{q\bar{q}}=1\rangle \;\rightarrow\; \Upsilon(1S)\,\eta \\
&+ && \tfrac{\sqrt{5}}{2\sqrt{3}} \; |S_{b\bar{b}}=1, J_{q\bar{q}}=2\rangle \;\rightarrow\; \Upsilon(1S)\,\pi^+\pi^- \text{ in D wave} \\
&+ && \tfrac{1}{2} \; |S_{b\bar{b}}=0, J_{q\bar{q}}=1\rangle \;\rightarrow\; h_b(1P)\,\eta
\end{aligned}
$$

Rescattering $\Rightarrow$ many transitions are allowed.

Transition	Partial width (keV)
$\Upsilon(4S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	1.7 ± 0.2
$\Upsilon(1S)\,\eta$	4.0 ± 0.8
$\Upsilon(2S)\,\pi^+\pi^-$	1.8 ± 0.3
$h_b(1P)\,\eta$	45 ± 7
$\Upsilon(5S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	238 ± 41
$\Upsilon(1S)\,\eta$	39 ± 11
$\Upsilon(1S)\,K^+K^-$	33 ± 11
$\Upsilon(2S)\,\pi^+\pi^-$	428 ± 83
$\Upsilon(2S)\,\eta$	204 ± 44
$\Upsilon(3S)\,\pi^+\pi^-$	153 ± 31
$\chi_{b1}(1P)\,\omega$	84 ± 20
$\chi_{b1}(1P)\,(\pi^+\pi^-\pi^0)_{\text{non-}\omega}$	28 ± 11
$\chi_{b2}(1P)\,\omega$	32 ± 15
$\chi_{b2}(1P)\,(\pi^+\pi^-\pi^0)_{\text{non-}\omega}$	33 ± 20
$\Upsilon_J(1D)\,\pi^+\pi^-$	~ 60
$\Upsilon_J(1D)\,\eta$	150 ± 48
$Z_b(10610)^\pm\pi^\mp$	2070 ± 440
$Z_b(10650)^\pm\pi^\mp$	1200 ± 300
$\Upsilon(6S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	137 ± 32
$\Upsilon(2S)\,\pi^+\pi^-$	183 ± 43
$\Upsilon(3S)\,\pi^+\pi^-$	77 ± 28
$Z_b(10610, 10650)^\pm\pi^\mp$	$1300 - 6600$

Bondar, RM, Voloshin MPLA 32, 1750025 (2017)

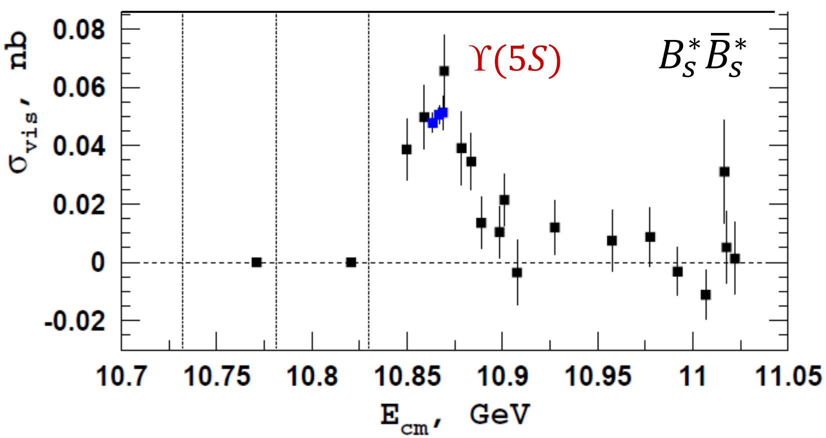
Variety of transitions – support for molecular admixture interpretation.

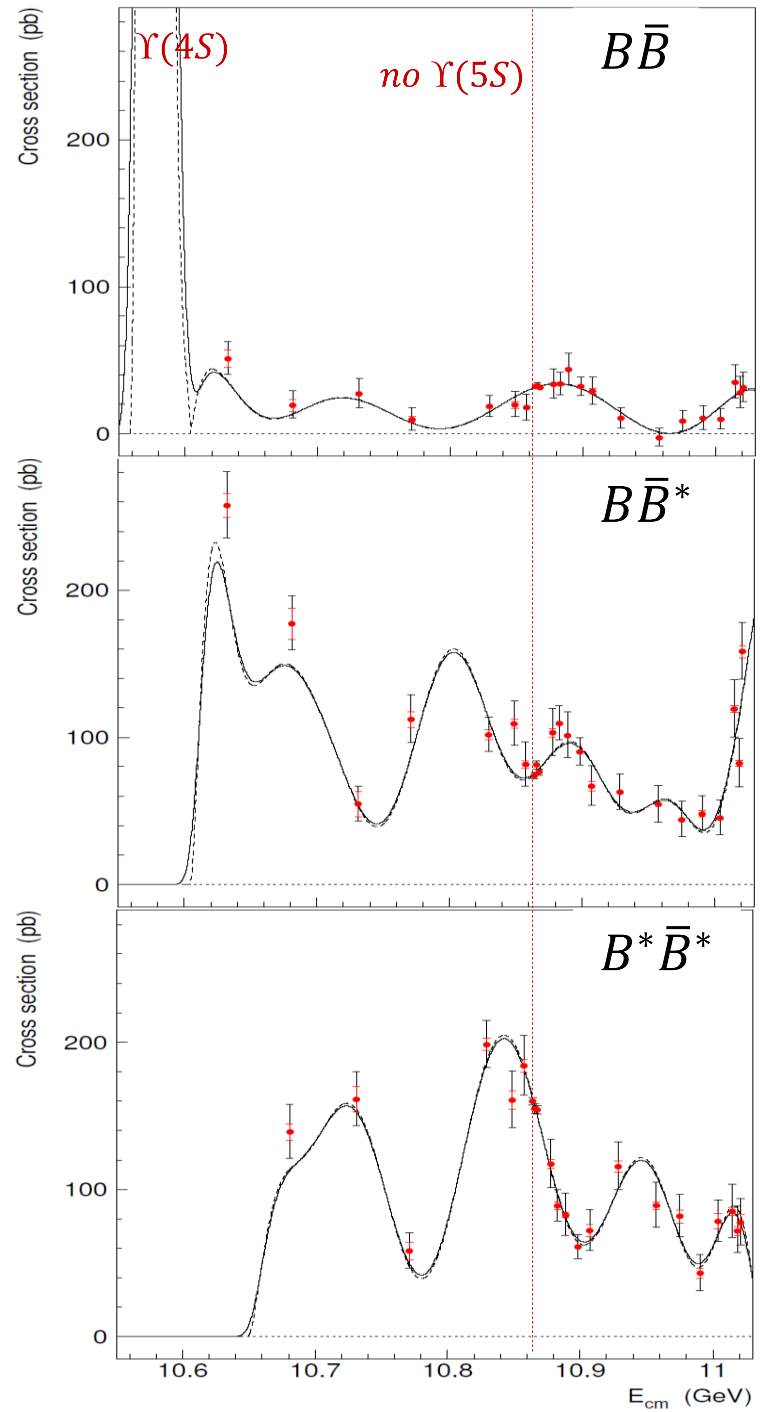
Measurements at a single energy

- non-resonant contributions?
- other resonances?

Need energy scan

Belle arXiv:1609.08749
JHEP 06, 137 (2021)



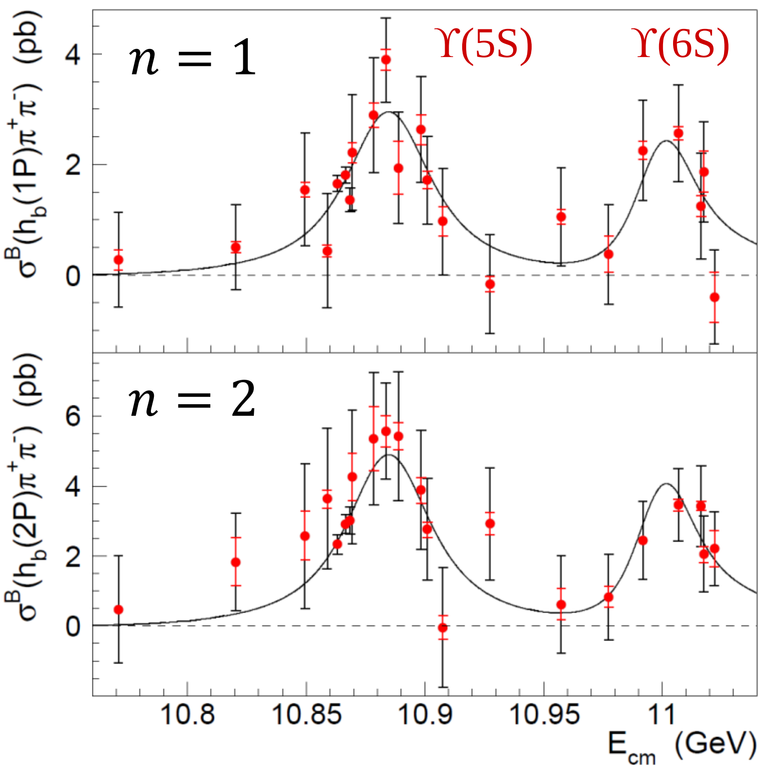


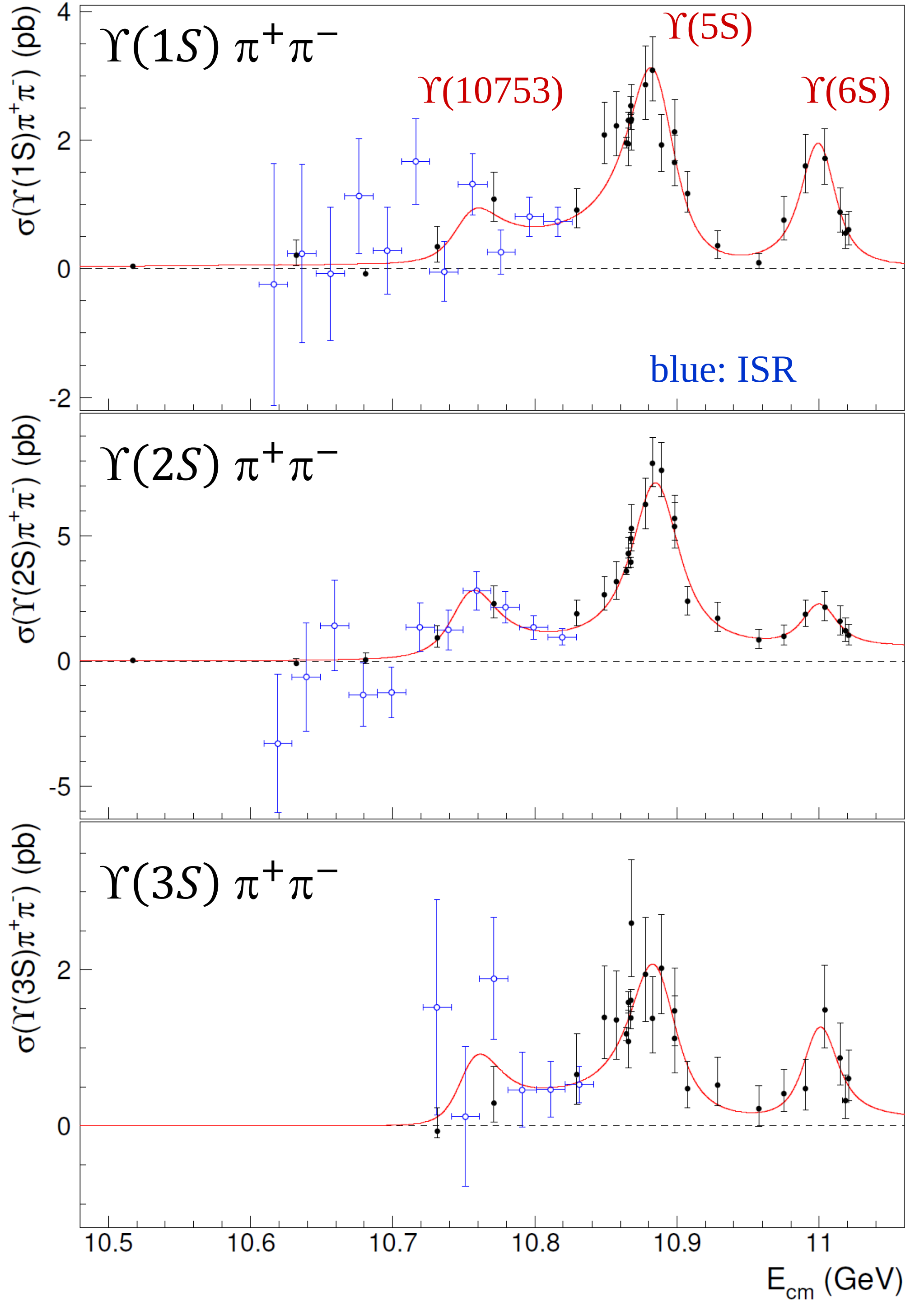
$B_s^* \bar{B}_s^*$ – peak of Υ(5S),
non-resonant contribution is small.

$B^{(*)}\bar{B}^{(*)}$ – no clear Υ(5S) peak,
"oscillatory" non-resonant contribution?

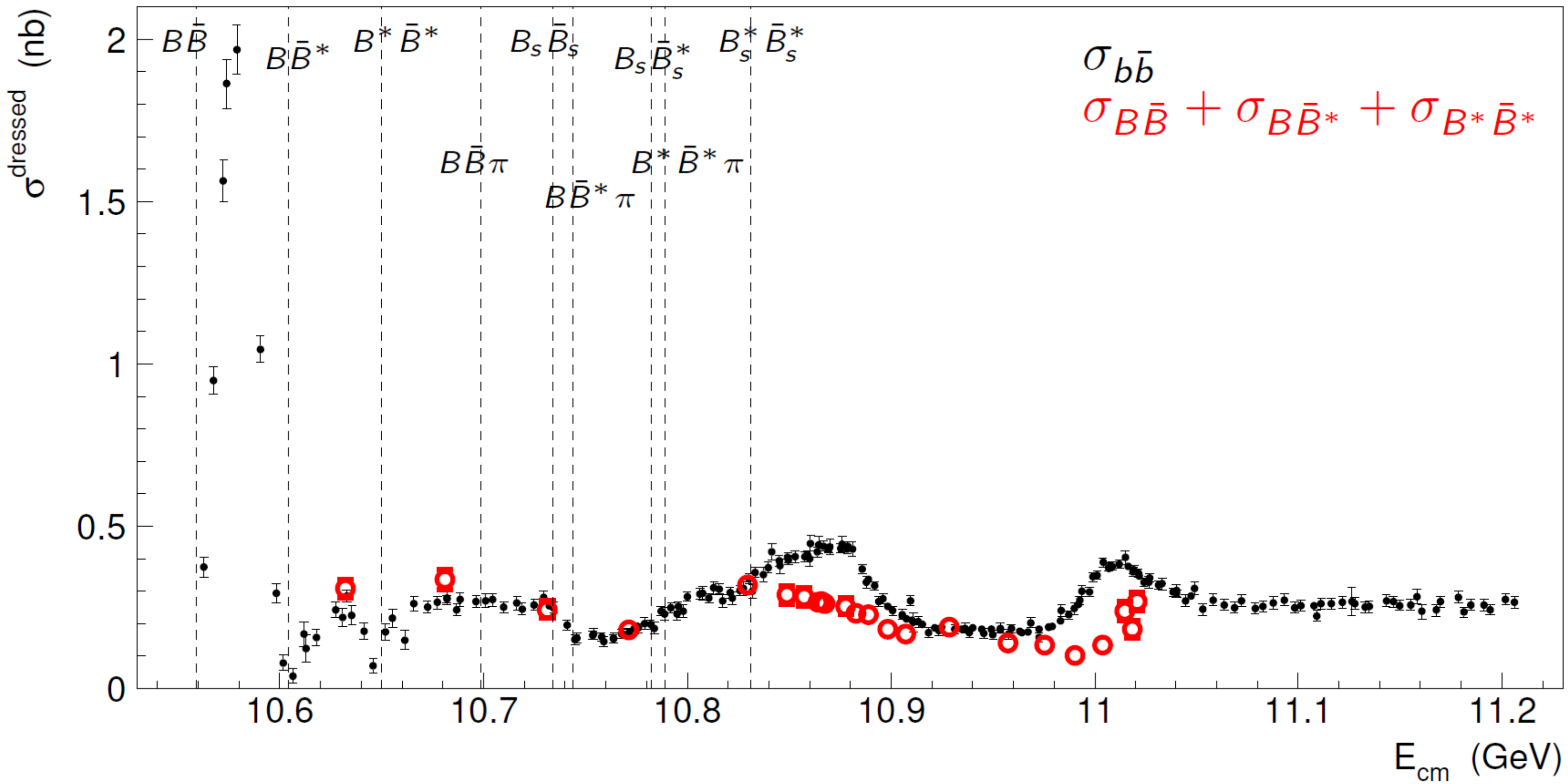
Belle PRL117,142001(2016)
JHEP 10, 220 (2019)

$$Z_b^+\pi^- \rightarrow h_b(nP)\,\pi^+\pi^-$$





Peaks of Υ(5S), Υ(6S)
and new state Υ(10753);
non-resonant contribution is small.



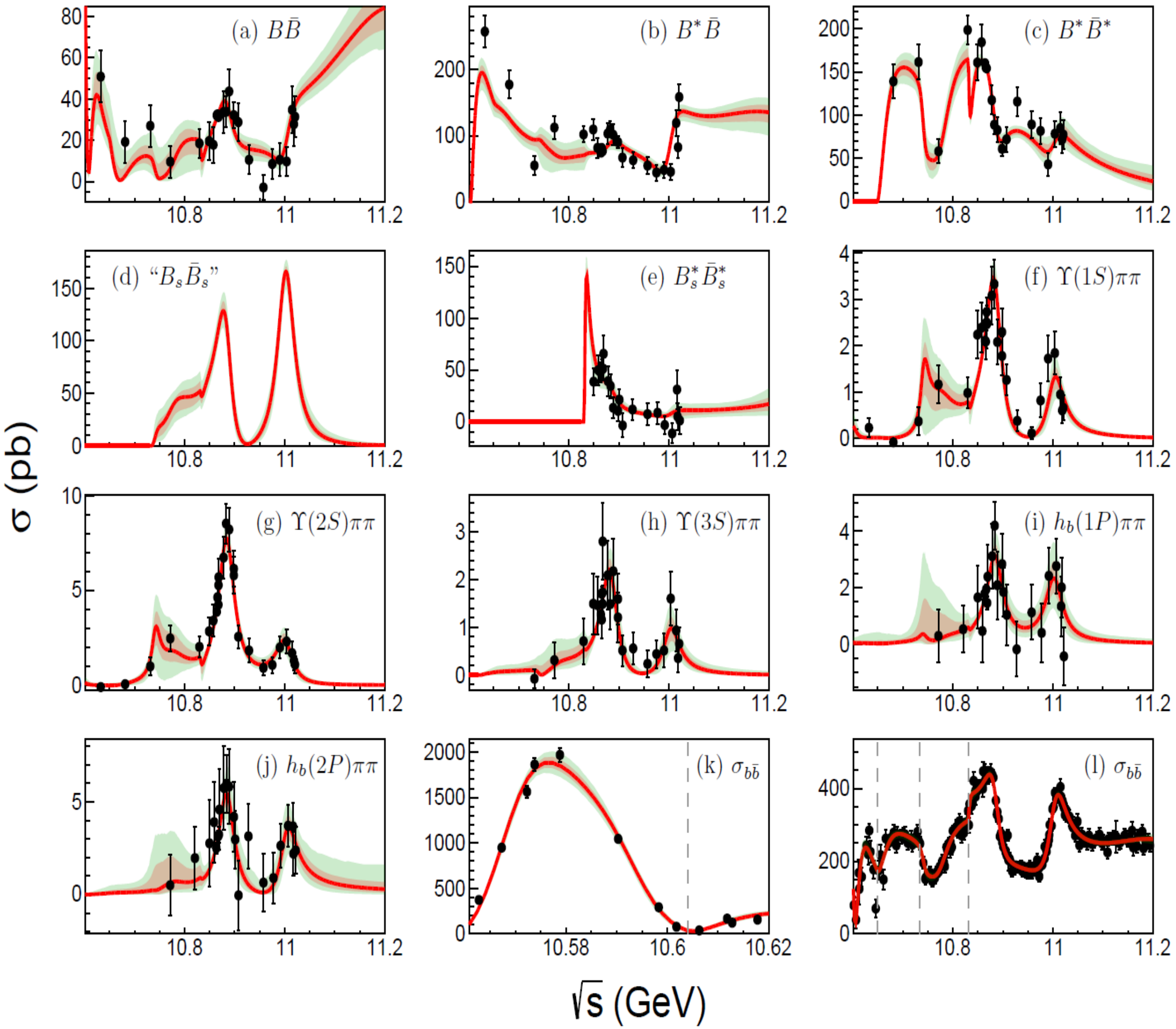
Measured channels: $B^{(*)}\bar{B}^{(*)}$, $B_s^{(*)}\bar{B}_s^{(*)}$, $\Upsilon(nS)\,\pi^+\pi^-$, $h_b(nP)\,\pi^+\pi^-$.

Major unmeasured contribution is $B^{(*)}\bar{B}^{(*)}\pi$ – can be found as a residual between total cross section and the sum of measured contributions.

$\Rightarrow$ Total $b\bar{b}$ cross section is decomposed.

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.

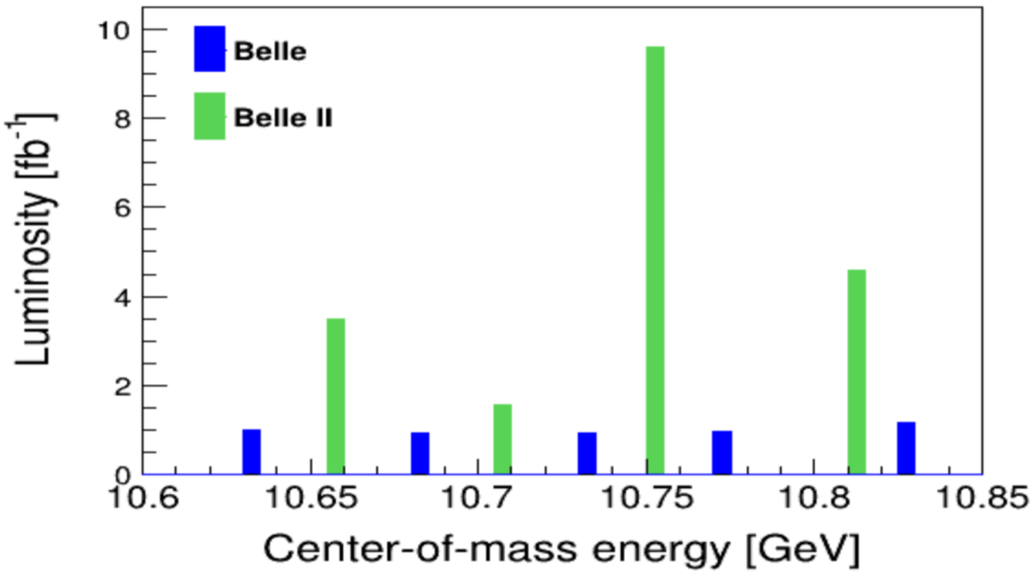
Results:
pole positions,
branching fraction,
energy dependence of scattering amplitudes.

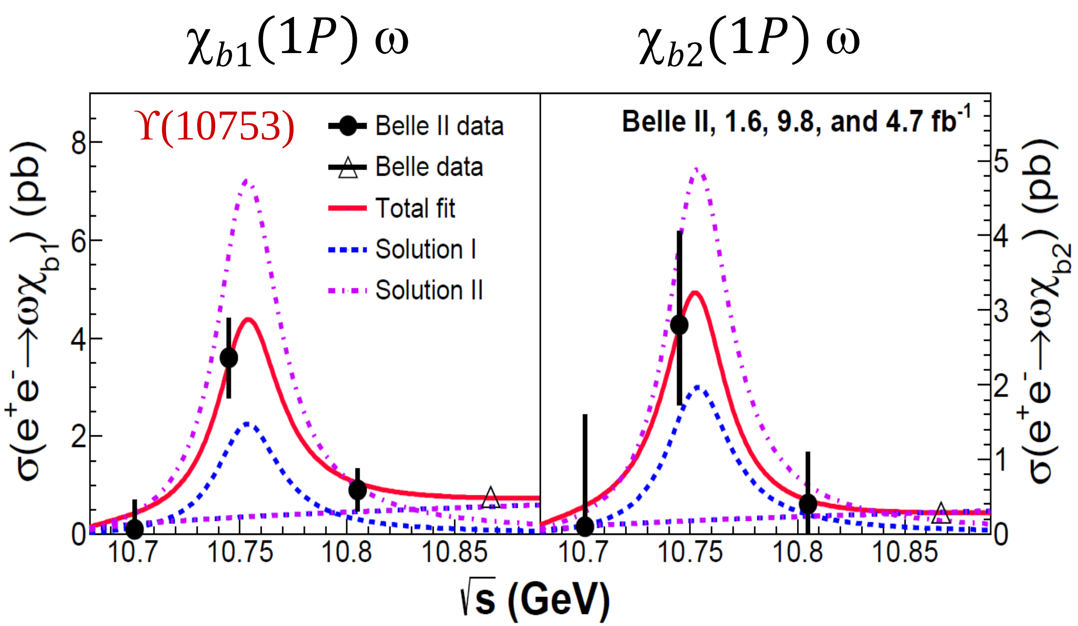
Accuracy above ϒ(6S) and near ϒ(10753) needs improvement.

Belle II energy scan

Nov 2021, L = $20\ fb^{-1}$.

Goal: study $\Upsilon(10753)$ and $B^*\bar{B}^*$ threshold region.





PRL 130, 091902 (2023)

$\sigma(e^+e^-\to\chi_{bJ}(1P)\ \omega)$ are peaking at $\Upsilon(10753)$

$\Upsilon(10753)$ and $\Upsilon(5S)$ have different decay patterns

$\Rightarrow$ Different structures?

Belle II:

preliminary

$$e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$$

$$e^+e^- \to \eta_b(1S)\omega,\ \chi_{b0}(1P)\,\omega$$

$$e^+e^- \to B\bar{B}, B\bar{B}^*, B^*\bar{B}^*$$

$e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$

preliminary

Full reconstruction: $\Upsilon(nS) \to \mu^+\mu^-$

$\Upsilon(10753)$ significance:

	Belle	Belle + Belle II
$\Upsilon(1S)\,\pi^+\pi^-$	2.7σ	4.1σ
$\Upsilon(2S)\,\pi^+\pi^-$	5.4σ	7.5σ

$\Upsilon(10753)$ parameters:

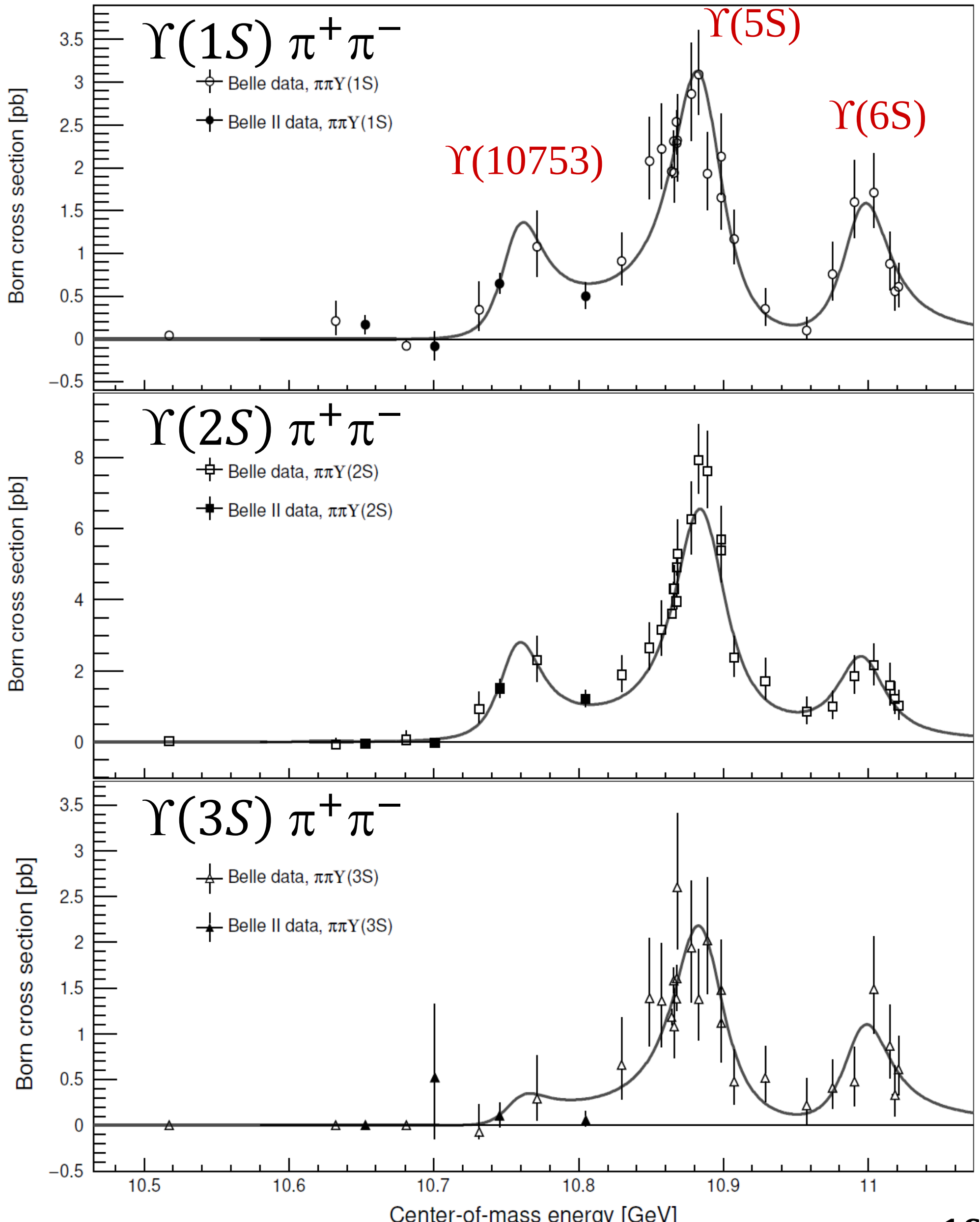
$$M = (10756.3 \pm 2.7 \pm 0.6)\ MeV$$

$$\Gamma = (29.7 \pm 8.5 \pm 1.1)\ MeV$$

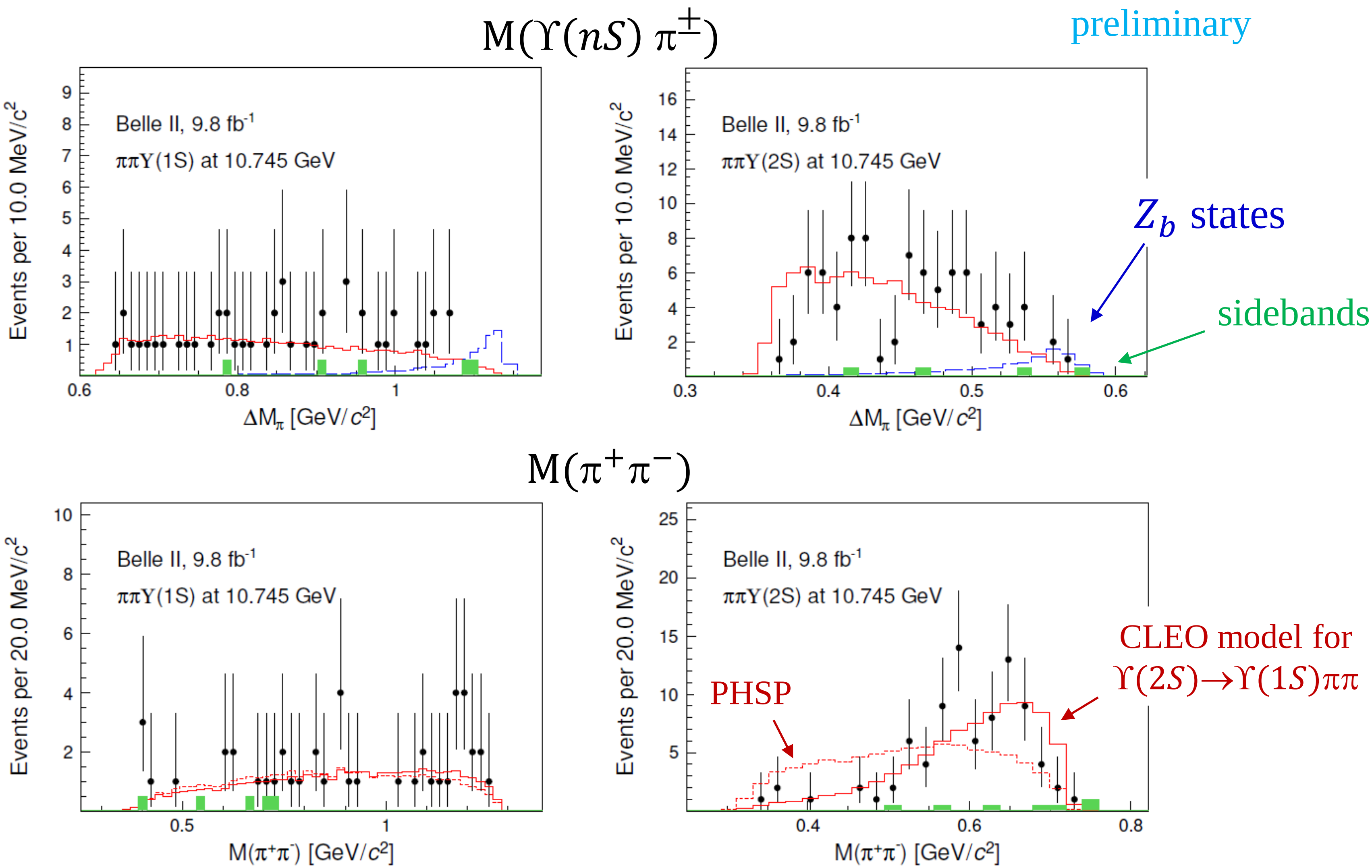
c.f. Belle

$$M = (10752.7 \pm 5.9^{+0.7}_{-1.1})\ MeV$$

$$\Gamma = (35.5^{+17.6}_{-11.3}\ {}^{+3.9}_{-3.3})\ MeV$$



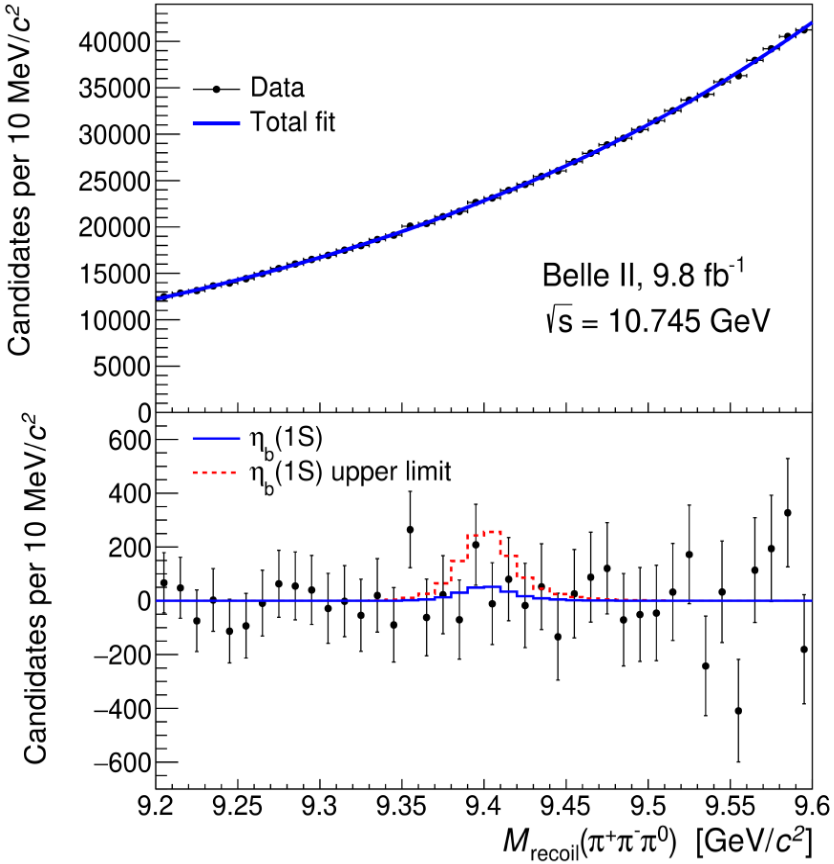
Resonant substructure of $\Upsilon(10753) \to \Upsilon(nS)\,\pi^+\pi^-$



- No Z_b states.
- Large values of $M(\pi^+\pi^-)$ are enhanced in $\Upsilon(2S)\pi^+\pi^-$.

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

preliminary



Reconstruct ω; use recoil mass.

$\sigma(e^+e^- \to \eta_b(1S)\ \omega) < 2.5\ pb$ 90% CL

c.f. $\sigma(e^+e^- \to \Upsilon(1{,}2S)\pi^+\pi^-) = (1-3)\ pb$

CPC 43, 123102 (2019)

Tetraquark model of Υ(10753) predicts that $\eta_b(1S)\ \omega$ is enhanced. Data: no support.

$\sigma(e^+e^- \to \chi_{b0}(1P)\ \omega) < 7.8\ pb$

c.f. $\sigma(\chi_{b1}(1P)\omega\ /\ \chi_{b2}(1P)\omega) = (3.6\ /\ 2.8)\ pb$

Decay of Y(4230) to $\chi_{c0}\ \omega$ is enhanced w.r.t. $\chi_{c1}\omega$ / $\chi_{c2}\omega$. No similar effect for Υ(10753).

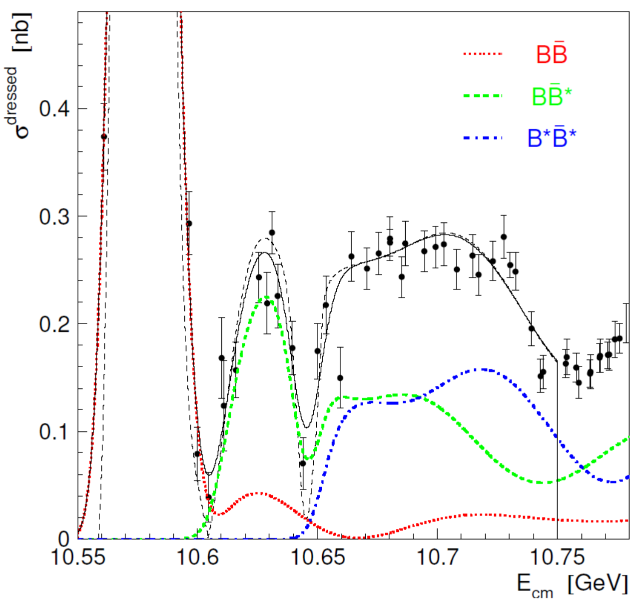
$e^+e^- \to B\bar{B}, B\bar{B}^*, B^*\bar{B}^*$

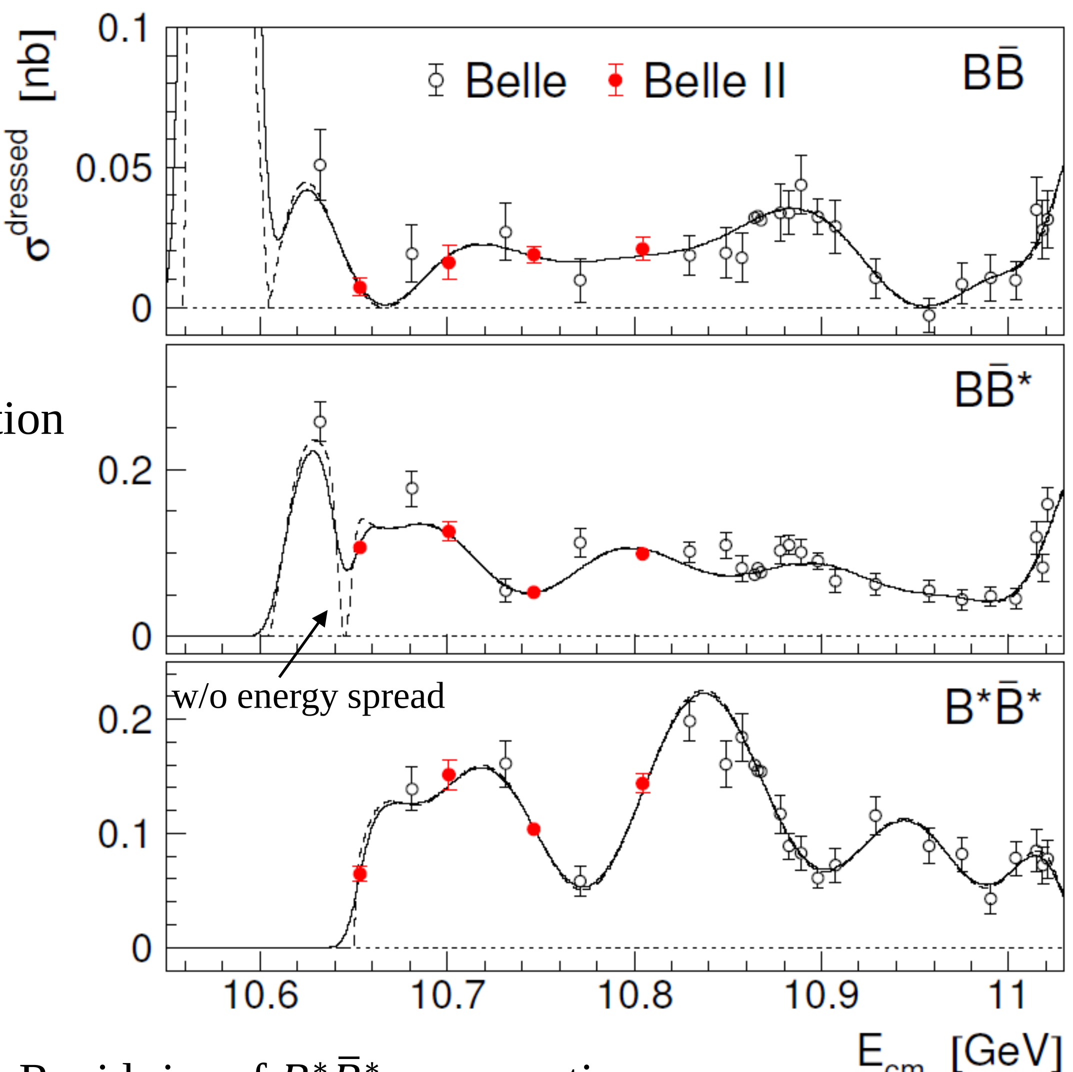
preliminary

Reconstruct one B in ~1000 final states, use its momentum to separate channels.

Belle II data match and significantly supplement the Belle data.

Fit: polynomials; include total cross section to impose zeroth at $B^{(*)}\bar{B}^*$ thresholds.



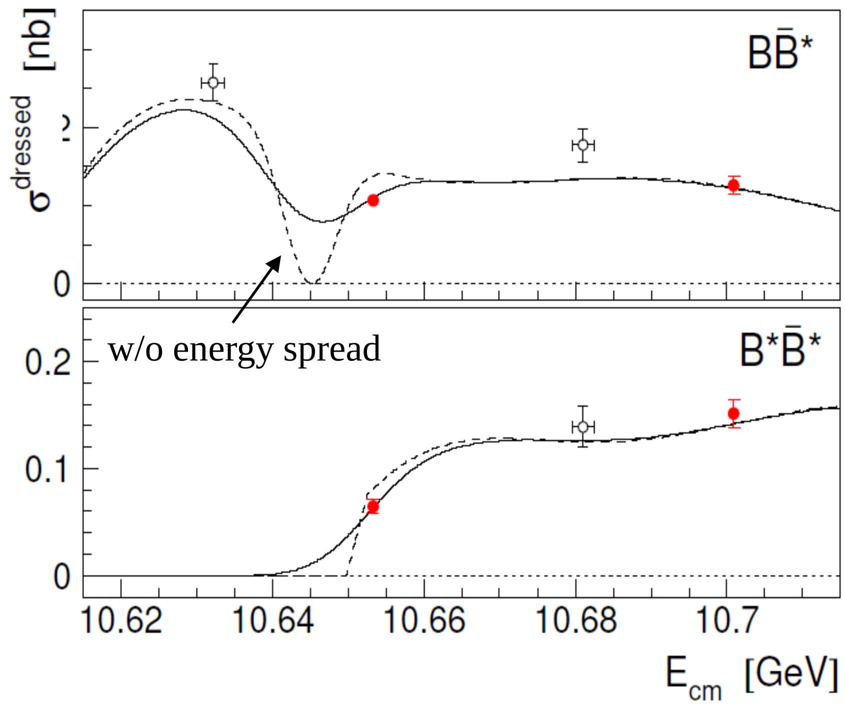


Rapid rise of $B^*\bar{B}^*$ cross section near threshold. Molecular state?

Molecule near $B^*\bar{B}^*$ threshold

preliminary

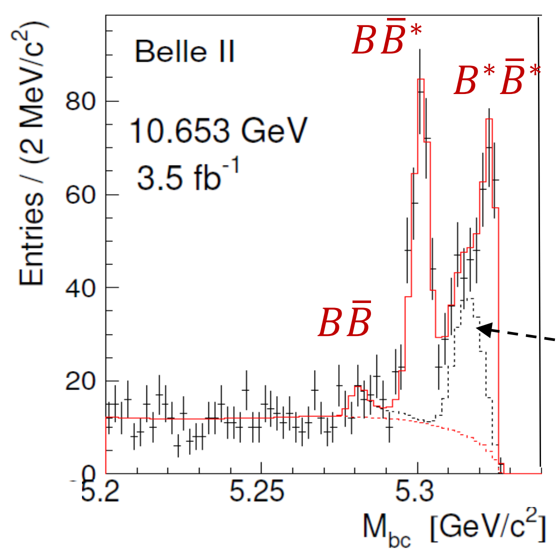
$B^*\bar{B}^*$ are in P-wave $\Rightarrow$ PHSP $\propto p_{B^*}^3$
$\propto (E - E_{thr})^{3/2}$
derivative vanish



Similar phenomenon near $D^*\bar{D}^*$ threshold.
$\Leftarrow$ $D^*\bar{D}^*$ molecular state

Dubynskiy, Voloshin, MPLA 21, 2779 (2006)

$B^*\bar{B}^*$ molecule can explain dip in $\sigma(B\bar{B}^*)$ – destructive interference.
Transitions to bottomonium are expected.



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

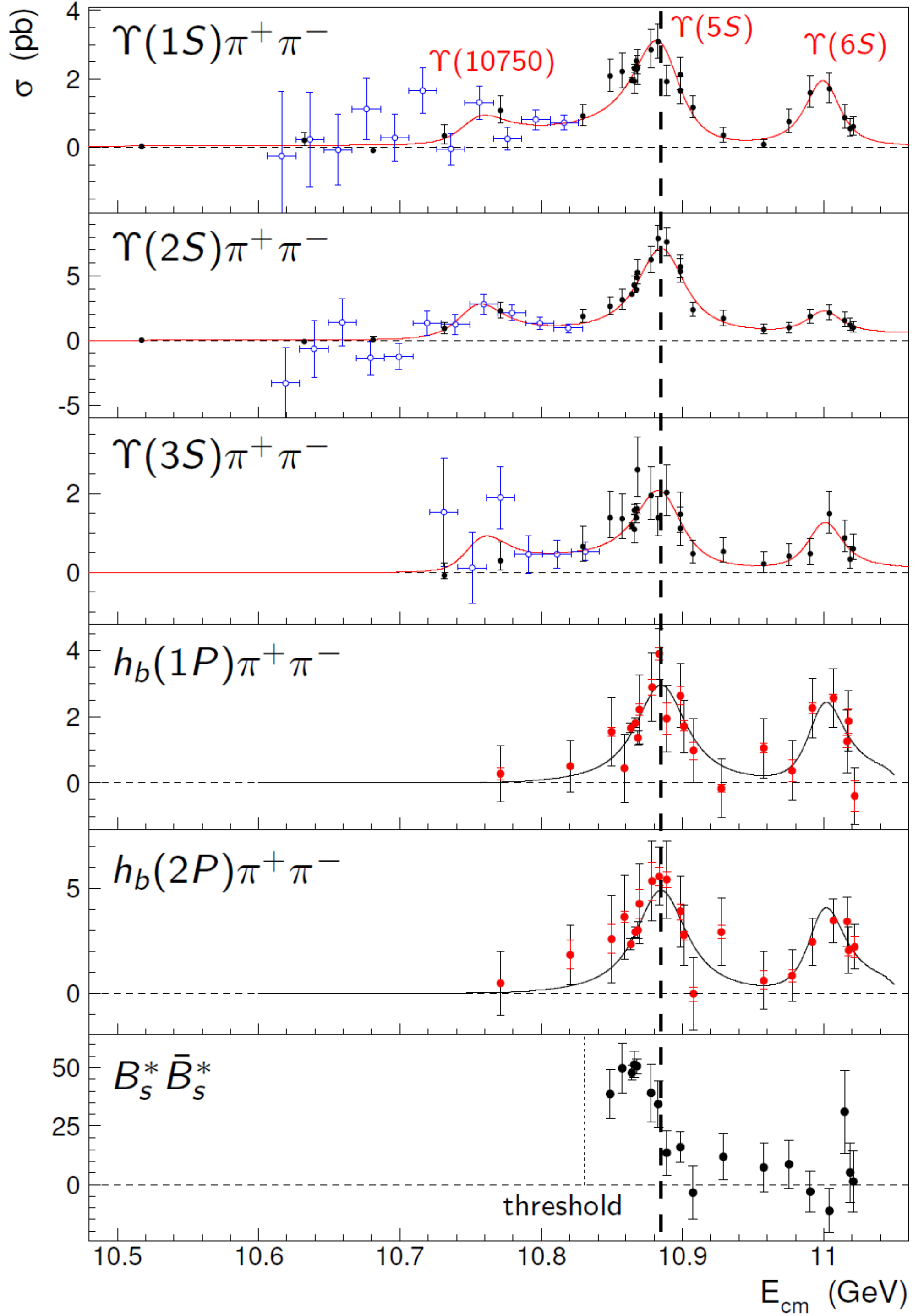
Analysis of preliminary results of this work confirms existence of a $B^*\bar{B}^*$ molecule

Salnikov, Bondar, Milstein, NPA 1041, 122764 (2023)

JHEP 08, 131 (2023)

Belle:

$$e^+e^- \to B_s\bar{B}_s\,X$$



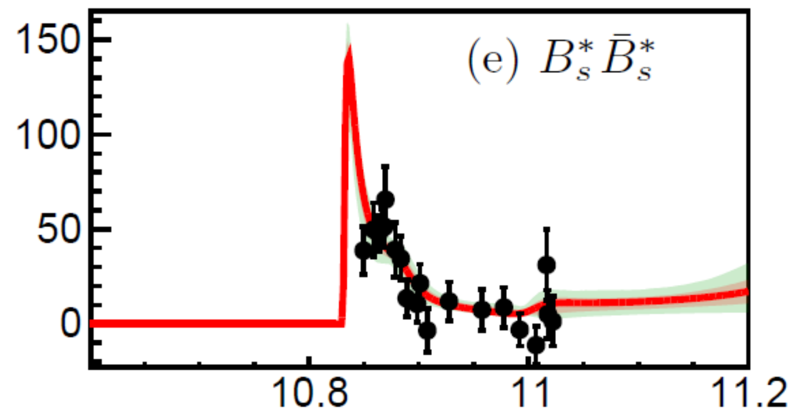
JHEP 10, 220 (2019)
PRL 117, 142001 (2016)
arXiv:1609.08749

$\Upsilon(5S)$ peak in $B_s^* \bar{B}_s^*$ channel is shifted by 20 MeV w.r.t. bottomonium channels.

Two states near $\Upsilon(5S)$?

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

Coupled-channel analysis:



$\Rightarrow$ Improve accuracy in $B_s^* \bar{B}_s^*$

$\sigma(e^+e^- \to B_s\bar{B}_s\, X)$ via inclusive method

JHEP 08, 131 (2023)

Measure (60.2±6.2)% (11.3±0.6)%

$$\sigma(e^+e^- \to b\bar{b} \to D_s\, X) = \sigma(e^+e^- \to B_s\bar{B}_s X)\ 2\ Br(B_s \to D_s\, X) + \sigma(e^+e^- \to B\bar{B}X)\ 2\ Br(B \to D_s X)$$

$$\sigma(e^+e^- \to b\bar{b} \to D^0 X) = \sigma(e^+e^- \to B_s\bar{B}_s X)\ 2\ Br(B_s \to D^0 X) + \sigma(e^+e^- \to B\bar{B}X)\ 2\ Br(B \to D^0 X)$$

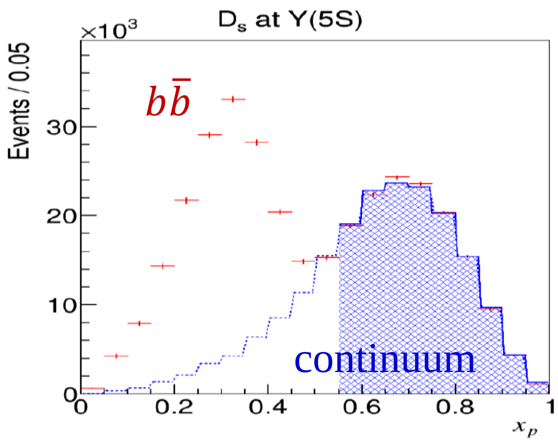
?? (66.7±1.8)%

Using ϒ(5S) data, we measure $\dfrac{Br(B_s \to D^0 X)}{Br(B_s \to D_s\, X)} = 0.415 \pm 0.094$

$\sigma(e^+e^- \to b\bar{b} \to D_s\, X) \Rightarrow$

$$x_p = \frac{p(D)}{p_{max}(D)}$$

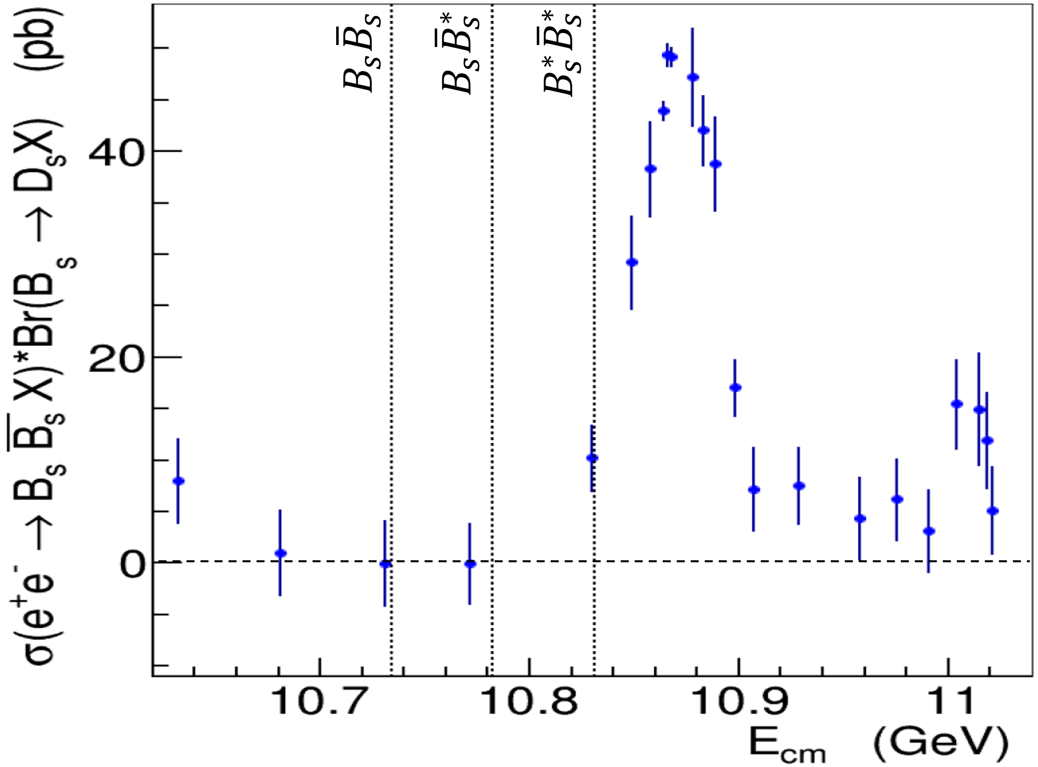
Subtract continuum



Resolve the system w.r.t. $\sigma(B_s\bar{B}_s X)$

$e^+e^- \to B_s\bar{B}_s X$

JHEP 08, 131 (2023)



- Clear peak of ϒ(5S).
- hint of ϒ(6S),
- non-resonant: small.

$\sigma(B_s\bar{B}_s X) = \sigma(B_s^{(*)}\bar{B}_s^{(*)})$ – up to the $B_s\bar{B}_s\pi^0\pi^0$ threshold at 11.004 GeV
– most of the studied energy range.

Conclusions

Belle II performed energy scan from the $B^*\bar{B}^*$ threshold to the onset of $\Upsilon(5S)$.

PRL 130, 091902 (2023)
preliminary

Studied channels: $\chi_{bJ}(1P)\omega$, $\Upsilon(nS)\pi^+\pi^-$, $\eta_b(1S)\omega$, $B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$.

$\Rightarrow$ Confirmation of $\Upsilon(10753)$, observation of its new decay channel.
Hint of a P-wave molecule at the $B^*\bar{B}^*$ threshold?

JHEP 08, 131 (2023)

Belle: $\sigma(B_s^{(*)}\bar{B}_s^{(*)})$ peaks at Υ(5S), possibly at Υ(6S), no non-resonant contribution.

Ongoing analyses: $\eta_b(1S)\phi$, $\Upsilon(nS)\eta$, $\Upsilon(1S)K^+K^-$, $h_b(1P)\pi^+\pi^-$, $h_b(1P)\eta$, $\Upsilon_J(1D)\pi^+\pi^-$, $\Upsilon_J(1D)\eta$.

Belle II plans to collect significant part of data outside of the $\Upsilon(4S)$ peak.