e^+e^- cross section shapes in $\Upsilon(nS)\pi^+\pi^-$ and $B^{(*)}\bar{B}^{(*)}$ channels

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Charmonium *vs.* bottomonium

Vector charmoniumlike states above $D\bar{D}$ threshold: $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4230)$, $\psi(4260)$, $\psi(4360)$, $\psi(4390)$, $\psi(4415)$, $\psi(4660)$.

Bottomonium (until recently): $\Upsilon(4S)$, $\Upsilon(5S)$, $\Upsilon(6S)$.

Why there are less states in bottomonium region?

- phenomenological property of $b\bar{b}$ system
- not all $b\bar{b}$ states are observed

My talk: there is one more (or even two more) $b\bar{b}$ states:

- Observation of $\Upsilon(10750)$.
- $\Upsilon(5S)$: two states?

Observation of $\Upsilon(10750)$

Measurement

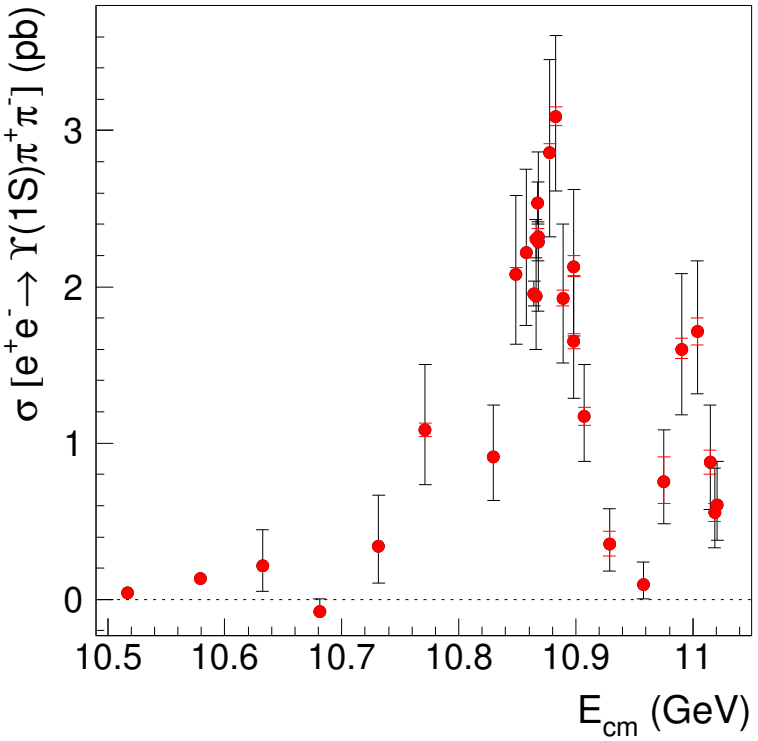
$\Upsilon(10750)$ is observed in energy dependence of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1, 2, 3)$ cross sections

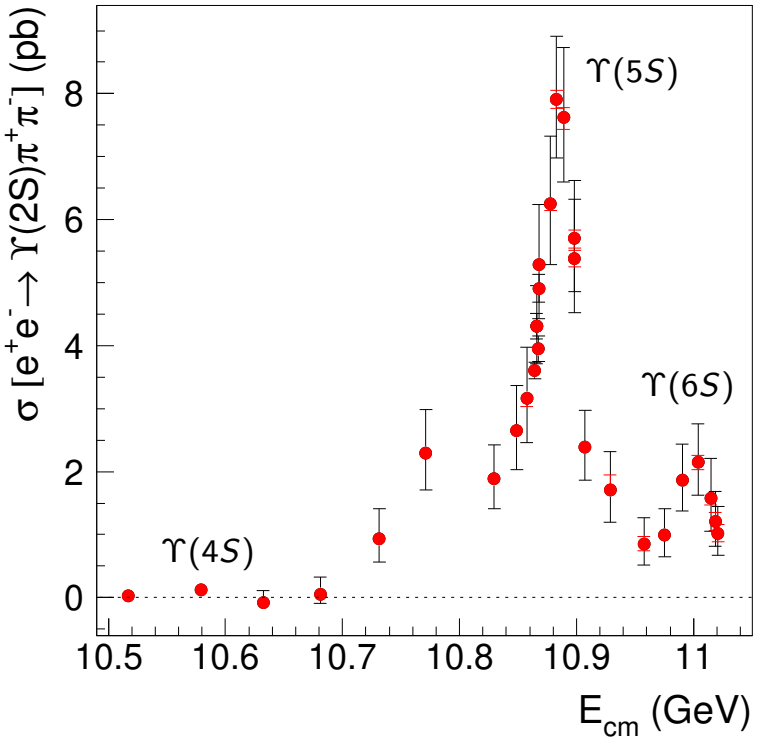
Belle data samples

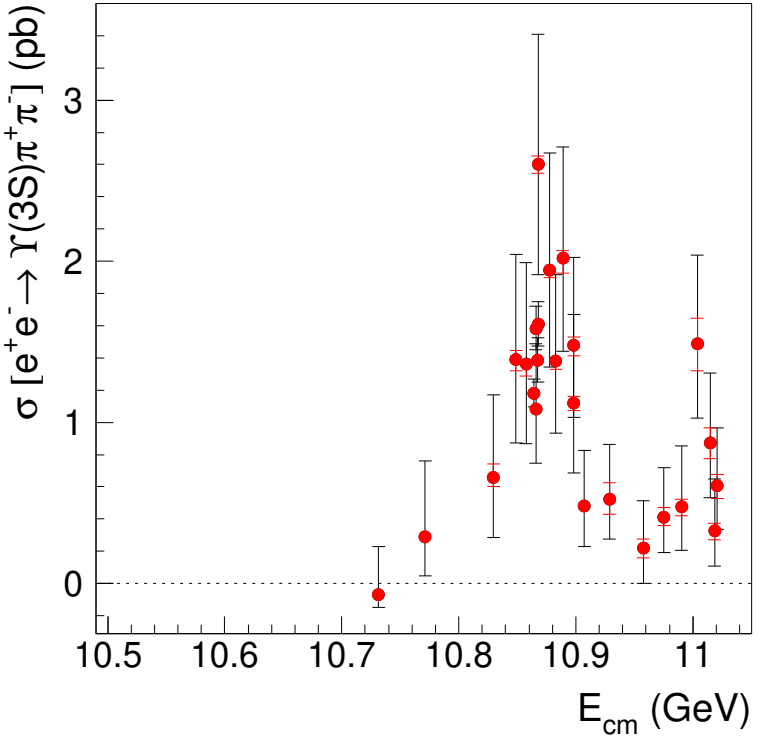
Scan	22 points, each $\sim 1\,\mathrm{fb}^{-1}$, energies between $\Upsilon(4S)$ and $\Upsilon(6S)$
$\Upsilon(5S)$	$121\,\mathrm{fb}^{-1}$
$\Upsilon(4S)$	$711\,\mathrm{fb}^{-1}$
$60\,\mathrm{MeV}$ below $\Upsilon(4S)$	$89\,\mathrm{fb}^{-1}$
$\Upsilon(3S)$	$3\,\mathrm{fb}^{-1}$
$\Upsilon(2S)$	$25\,\mathrm{fb}^{-1}$
$\Upsilon(1S)$	$6\,\mathrm{fb}^{-1}$

Full reconstruction of $\Upsilon(nS)\pi^+\pi^-$ with $\Upsilon(nS) \to \mu^+\mu^-$ and e^+e^-.

Born cross sections







JHEP **10**, 220 (2019)

Clear signals of $\Upsilon(5S)$, $\Upsilon(6S)$.

New structure near 10.77 GeV ?

Bottomonium candidate?

S-wave states are all known: $\Upsilon(4S)$, $\Upsilon(5S)$, $\Upsilon(6S)$.

D-wave states can be produced via $S - D$ mixing, which is strongly suppressed in bottomonium, $\Upsilon(1D)$ is not seen in e^+e^- annihilation.

A. M. Badalian, B. L. G. Bakker and I. V. Danilkin, "Dielectron widths of the S-, D-vector bottomonium states," Phys. Atom. Nucl. **73**, *138 (2010).*

Prediction: above $B\bar{B}$ threshold $S - D$ mixing is significantly enhanced due to B-meson loops.

What we see might be $\Upsilon(3D)$ mixed with $\Upsilon(4S, 5S)$ and "dressed" in a cloud of $B^{(*)}\bar{B}^{(*)}$ pairs.

Cross section via ISR

High-statistics $\Upsilon(5S)$ data are $100\,\mathrm{MeV}$ above the new structure $\Rightarrow$ use ISR at $\Upsilon(5S)$ to measure the cross sections.

Our signal variable is $\pi^+\pi^-$ recoil mass

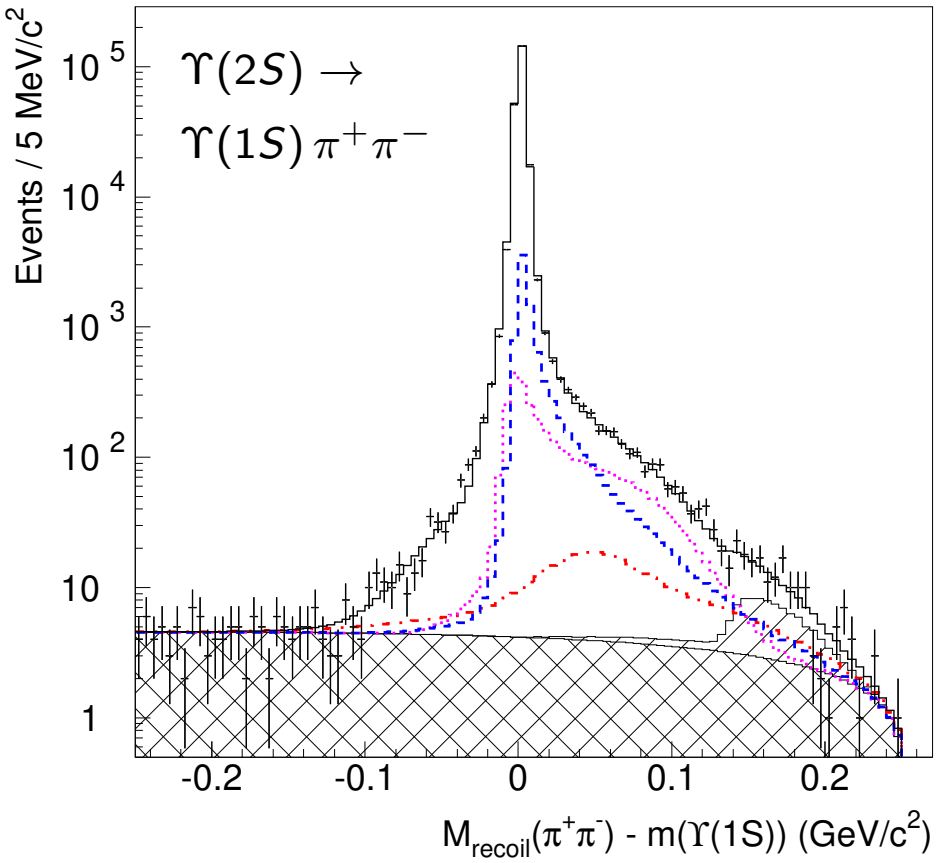
$$M_{\mathrm{recoil}}(\pi^+\pi^-) = \sqrt{(E_{\mathrm{cm}} - E_{\pi^+\pi^-})^2 - p^2_{\pi^+\pi^-}}.$$

ISR tail is on the right-hand side in $M_{\mathrm{recoil}}(\pi^+\pi^-)$.

Shape of ISR tail provides information about the cross sections.

Verification of signal shape

$\Upsilon(2S)$ data

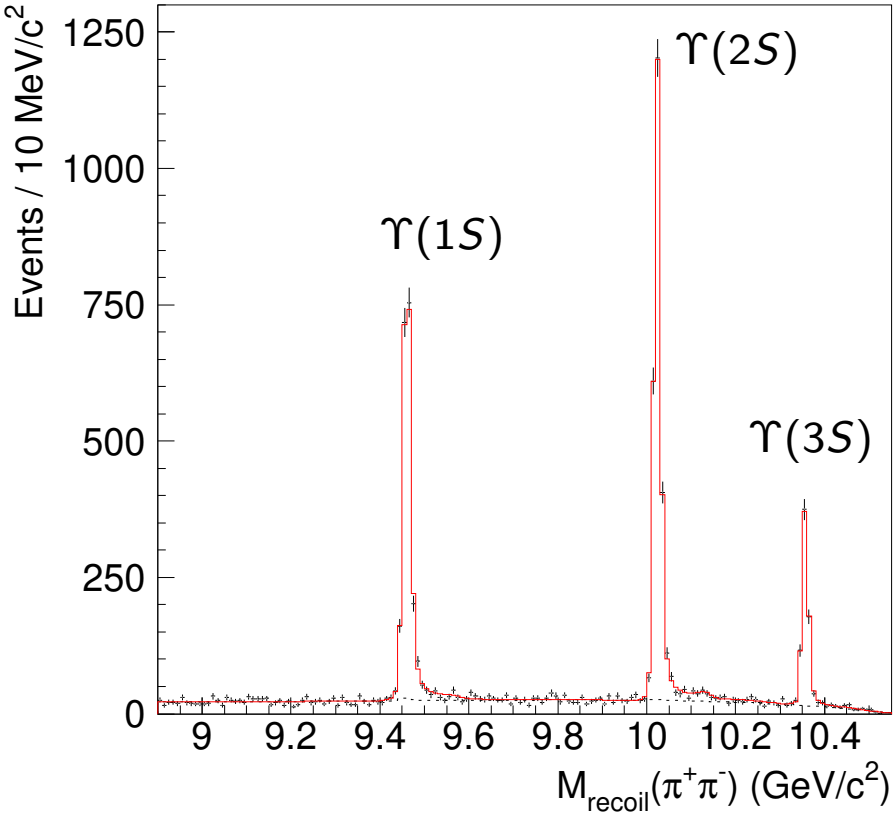


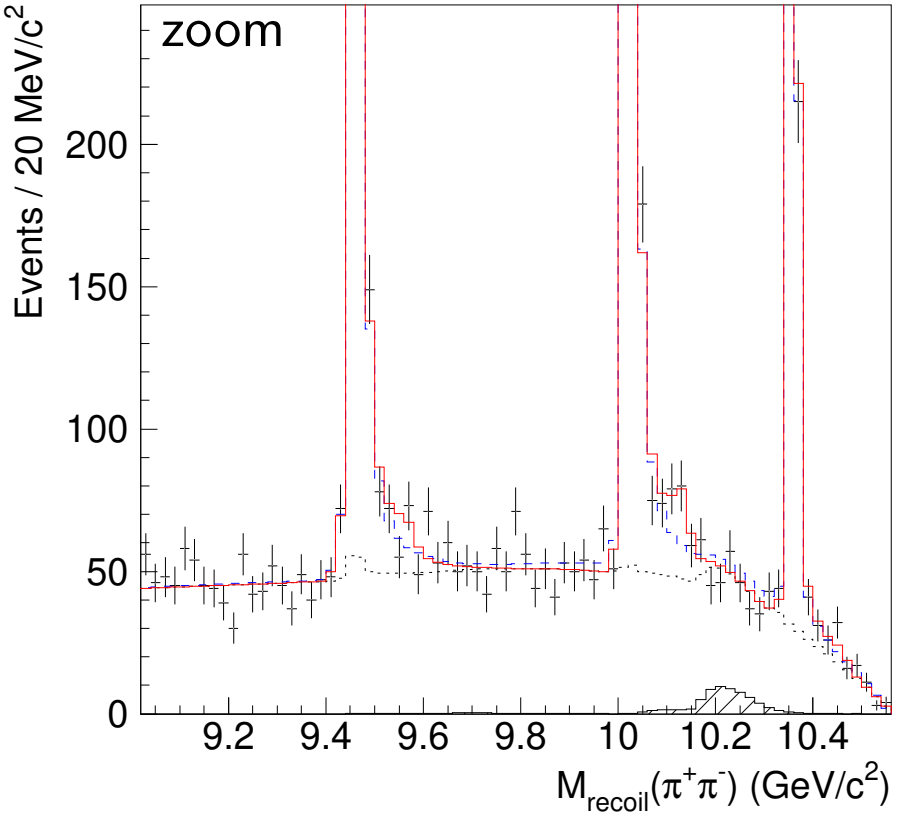
$\Upsilon(2S)$ is narrow $\Rightarrow$
negligible contribution from ISR.

Other processes that produce tail:
- FSR
- decays in flight
- secondary interactions
- $\eta \to \pi^+\pi^-\pi^0$, $\pi^+\pi^-\gamma$

Good description of $\Upsilon(2S, 3S)$ data, reliable modeling of signal.

$M_{\mathrm{recoil}}(\pi^+\pi^-)$ in $\Upsilon(5S)$ data





Simultaneous fit to cross sections at various energies and $M_{\mathrm{recoil}}(\pi^+\pi^-)$.

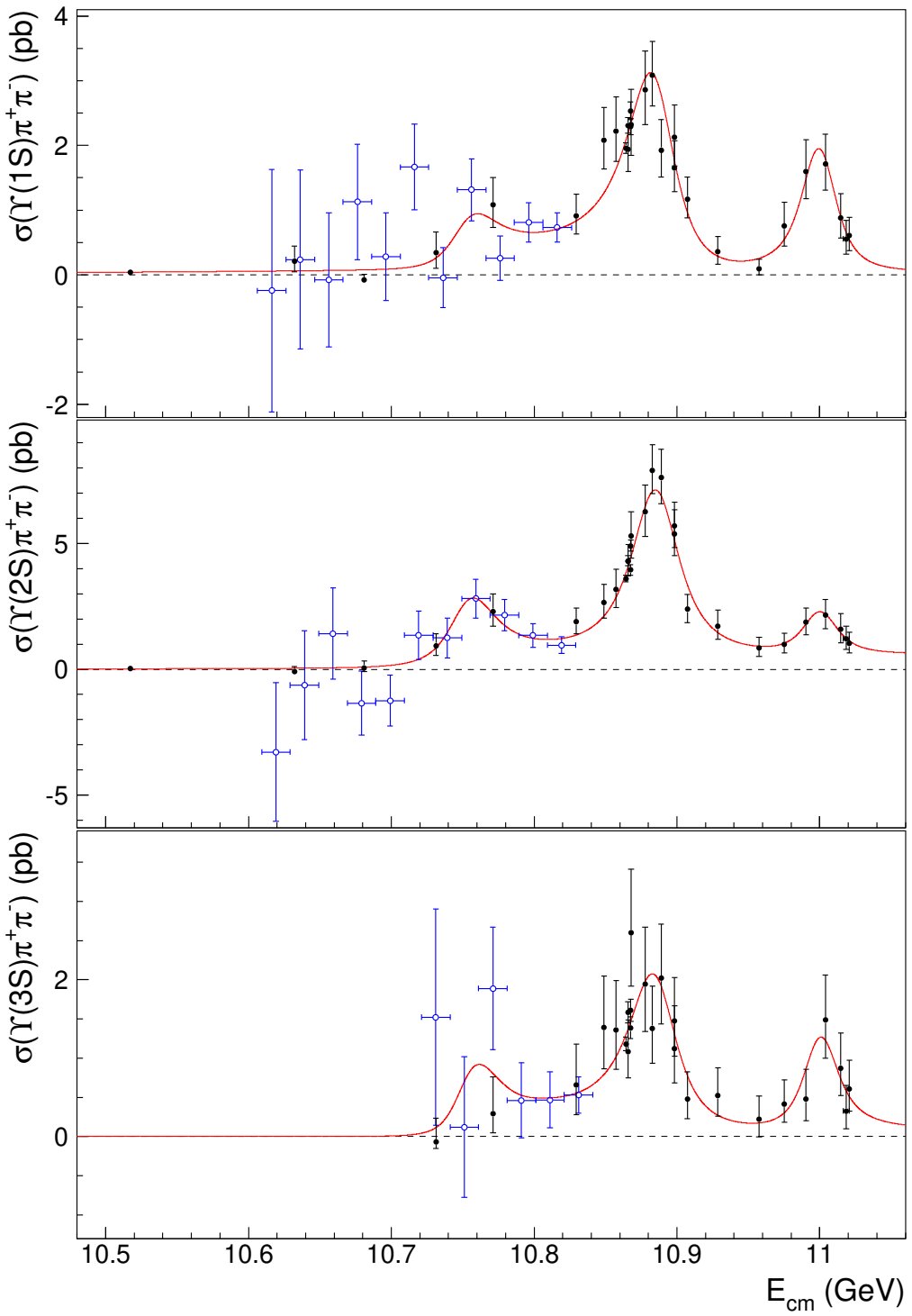
Signal shape in $M_{\mathrm{recoil}}(\pi^+\pi^-)$ is calculated at each fit iteration.

Visualization of fit results

black points: scan results
blue points: cross section via ISR

Parameterization:
sum of BW amplitudes

Global significance of the new structure including syst. uncertainty is $5.2\,\sigma$



Fit results

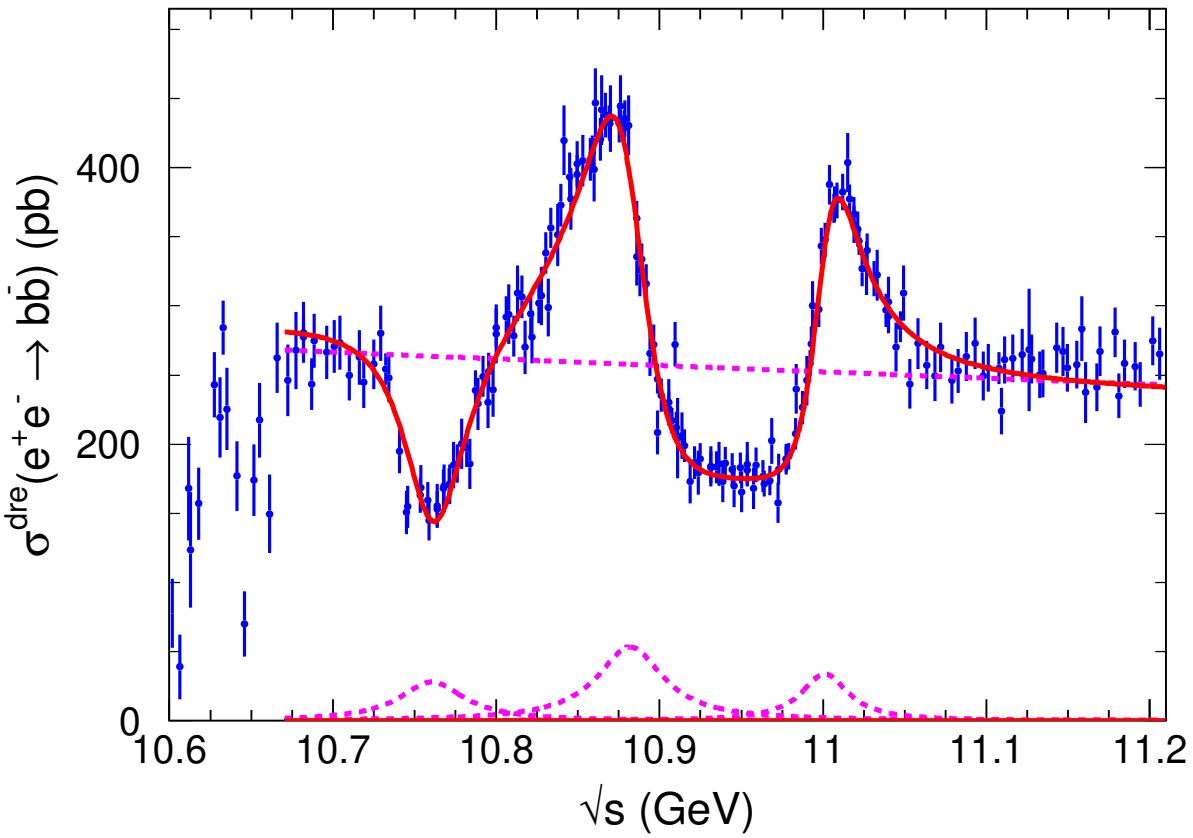
	$\Upsilon(5S)$	$\Upsilon(6S)$	$\Upsilon(10750)$
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0\ +1.0}_{-4.5\ -1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5\ +0.5}_{-3.9\ -1.1}$	$23.8^{+8.0\ +0.7}_{-6.8\ -1.8}$	$35.5^{+17.6\ +3.9}_{-11.3\ -3.3}$

$\Gamma_{\rm ee} \times \mathcal{B}$ in eV (accuracy is poor because of multiple solutions)

	$\Upsilon(5S)$	$\Upsilon(6S)$	$\Upsilon(10750)$
$\Upsilon(1S)\pi^+\pi^-$	$0.75 - 1.43$	$0.38 - 0.54$	$0.12 - 0.47$
$\Upsilon(2S)\pi^+\pi^-$	$1.35 - 3.80$	$0.13 - 1.16$	$0.53 - 1.22$
$\Upsilon(3S)\pi^+\pi^-$	$0.43 - 1.03$	$0.17 - 0.49$	$0.21 - 0.26$

Parameters of $\Upsilon(10750)$ agree with expectation for mixed $\Upsilon(3D)$ state.

Total $e^+e^- \to b\bar{b}$ cross section



There is a dip in total $\sigma_{b\bar{b}}$ near $10.75\,\mathrm{GeV}$. It has been described by destructive interference of $\Upsilon(10750)$.

X. K. Dong, X. H. Mo, P. Wang, C. Z. Yuan, Chin. Phys. C **44**, *083001 (2020).*

Anomalous properties of high Υ states are related to $B^{(*)}\bar{B}^{(*)}$ dynamics. It is crucial to decompose $\sigma_{b\bar{b}}$ into exclusive open flavor cross sections.

Energy dependence of exclusive $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ cross sections

Method

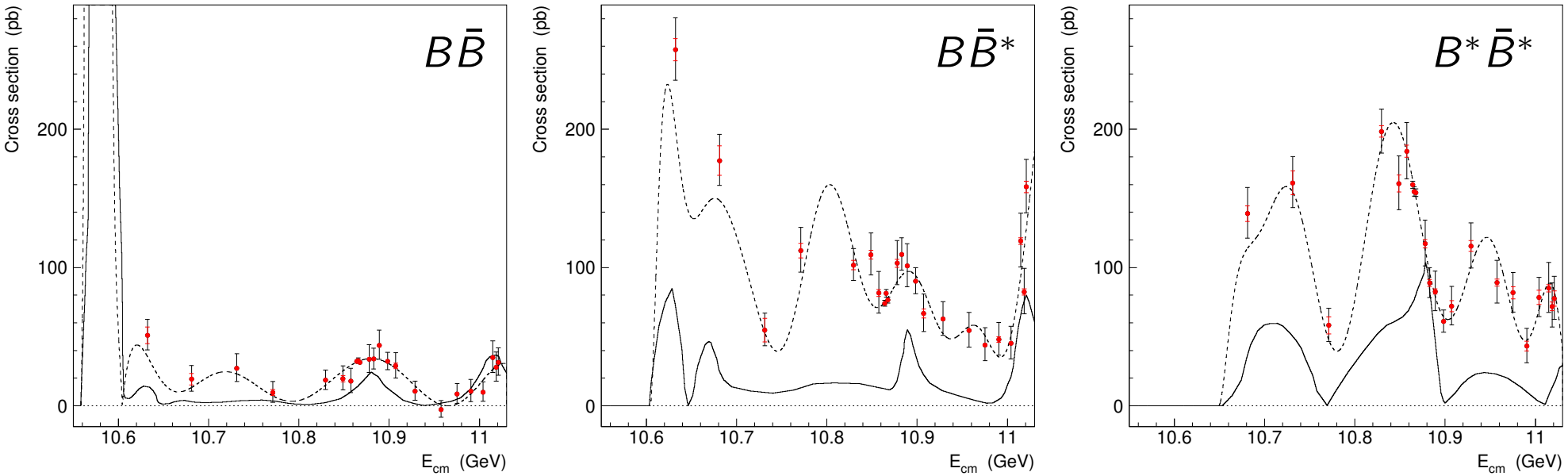
Difficulty: small branching fractions: $BF(B^+ \to \bar{D}^0\pi^+) = 0.47\%$, $BF(D^0 \to K^-\pi^+) = 3.9\%$.

$\Rightarrow$ Consider ~ 1000 final states ($D^{(*)}\pi(2\pi)$, $D^{(*)}\bar{D}_s^{(*)}$, $J/\psi\, K(n\pi)$ etc.), use machine learning in selection.
Reconstruction procedure is automated.

Reconstruct one B meson. To distinguish $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ use its momentum.

Measured $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ cross sections

JHEP **06**, 137 (2021)



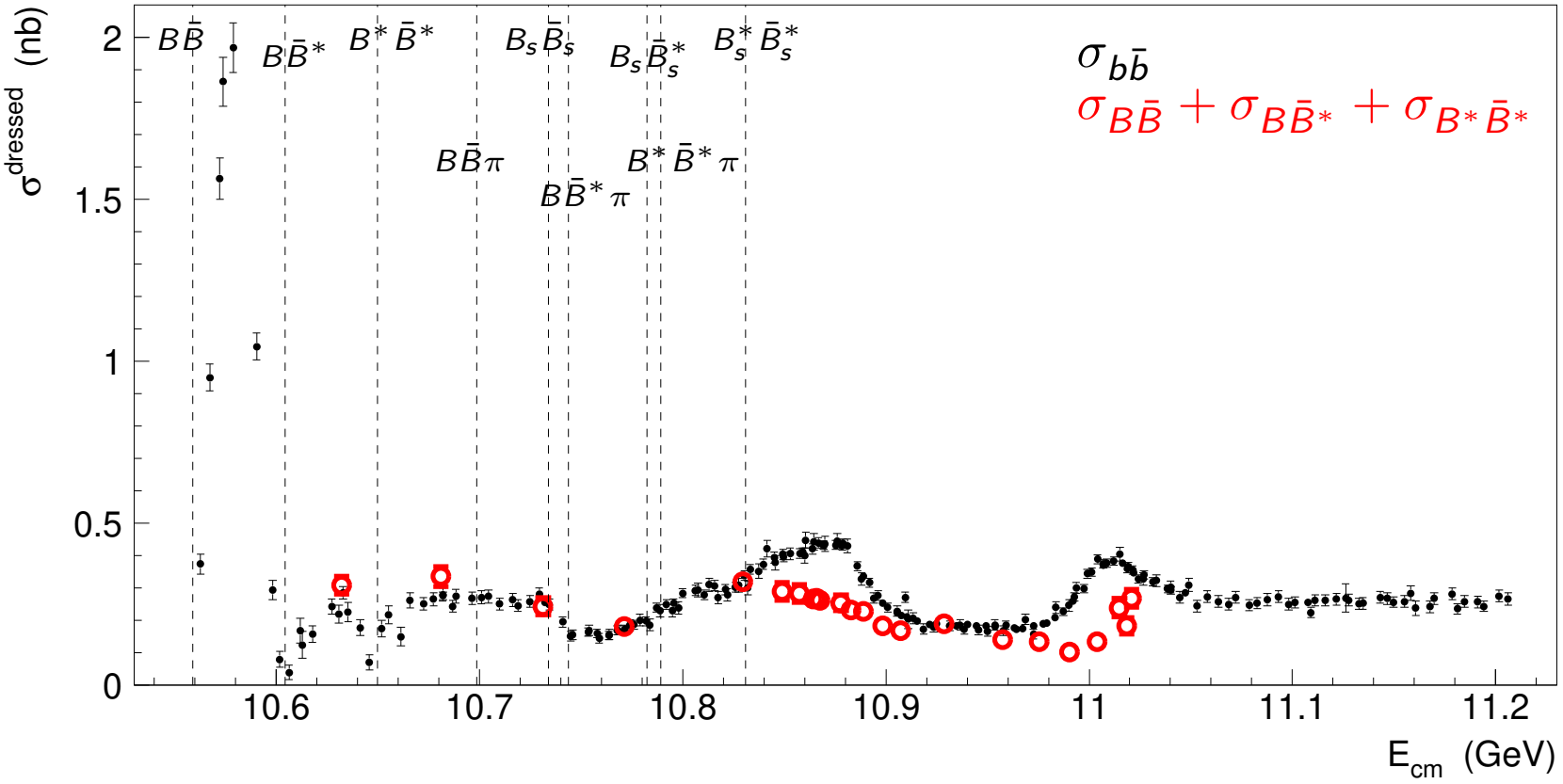
Parameterization: high-order Chebyshev polynomials (10, 17, 12).

Oscillatory behavior. Positions of minima roughly coincide with Unitarized Quark Model prediction: Ono,Sanda,Tornqvist PRD **34**, 186 (1986).

UQM: minima are due to nodes of the $\Upsilon(4S, 5S, 6S)$ wave functions – information about Υ states.

$\sigma_{b\bar{b}}$ vs. $\sigma_{B\bar{B}} + \sigma_{B\bar{B}^*} + \sigma_{B^*\bar{B}^*}$

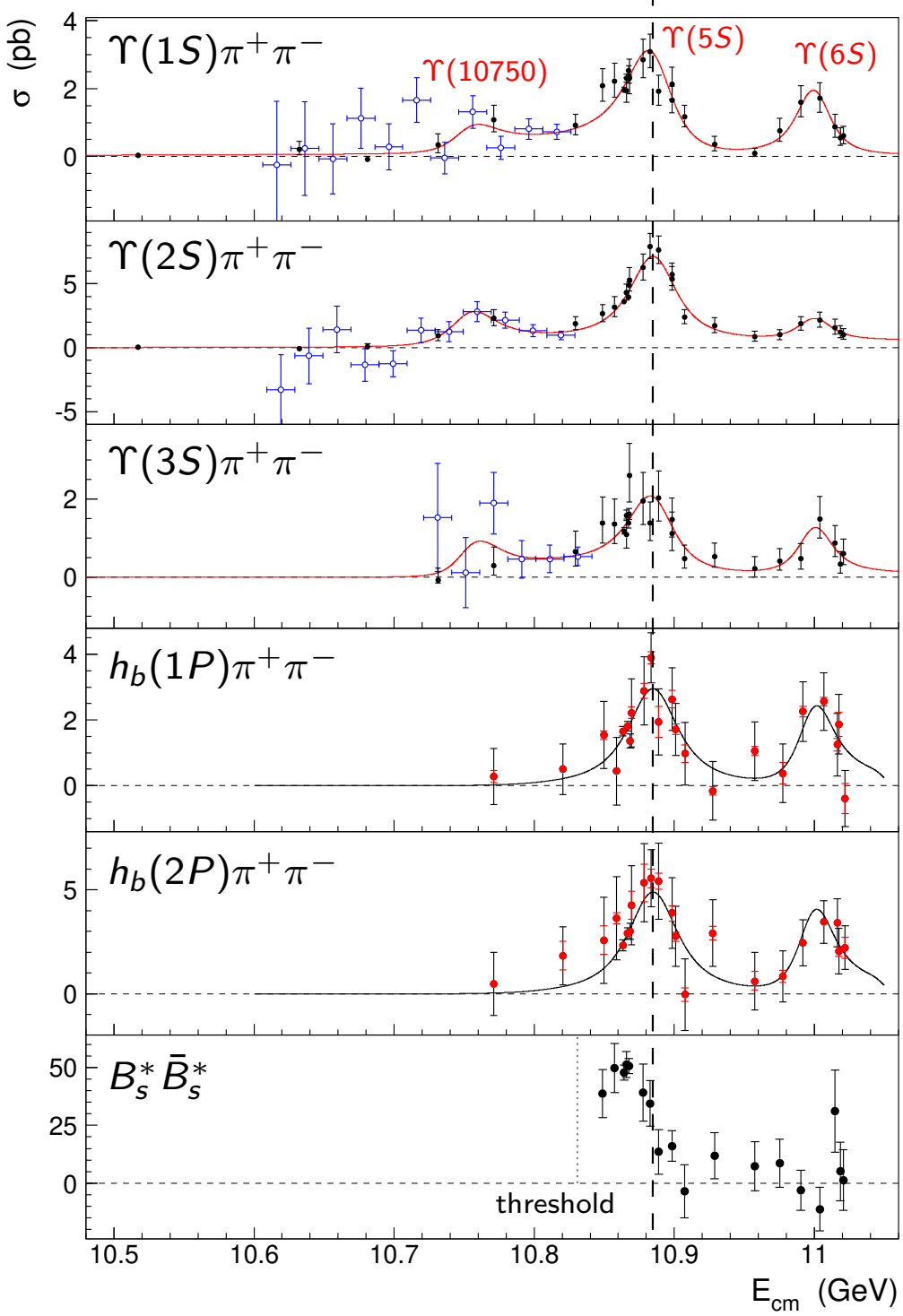
Dong et al. CPC**44**, 083001 (2020)



- $\sigma_{b\bar{b}}$ and $\sum \sigma_{B^{(*)}\bar{B}^{(*)}}$ coincide below $B_s^*\bar{B}_s^*$ threshold.
- $\Upsilon(5S)$ peak is due to $B_s^{(*)}\bar{B}_s^{(*)}$, $B^{(*)}\bar{B}^{(*)}\pi$ and bottomonium channels.

Potential models: $\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}$ dominate – inconsistent w/ data?

$\Upsilon(5S)$: one or two states?



$\Upsilon(5S)$: two states?

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

Peaks in $\Upsilon\pi^+\pi^-$ and $h_b\pi^+\pi^-$ are shifted from peak in $B_s^*\bar{B}_s^*$ by $\sim 20\,\mathrm{MeV}$.

Interference? Two states?

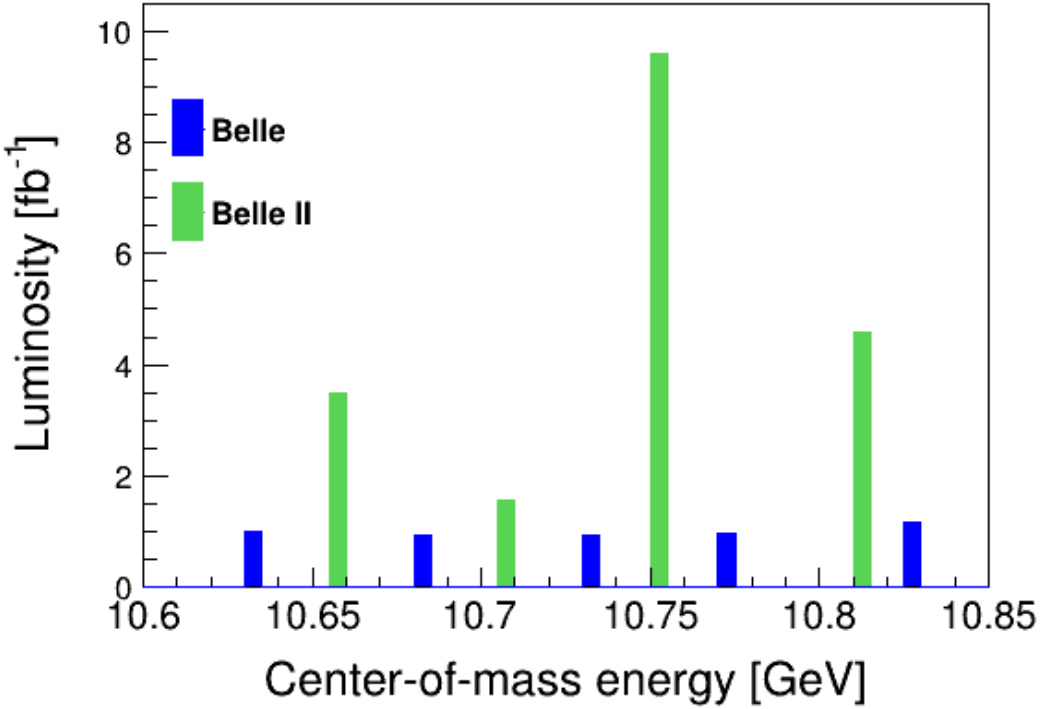
Need combined analysis of all cross section measurements.

Bottomonium at Belle II

Belle II energy scan

Between Nov 12 – 29, 2021 Belle II collected high-energy scan data.

Goal: confirm and explore $\Upsilon(10750)$.



Many analyses started, results expected by QWG meeting in Sep 2022.

Conclusions

$\Upsilon(10750)$ is observed in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$, its $\Gamma \sim 35\,\mathrm{MeV}$. Properties are consistent with expectations for $\Upsilon(3D)$ mixed with $\Upsilon(4S, 5S)$ via B meson loops.

Belle, JHEP **10**, 220 (2019).

First measurement of $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ energy dependence:

- oscillatory behavior – information about Υ wave functions;
- no obvious signal of $\Upsilon(5S)$.

Belle, JHEP **06**, 137 (2021).

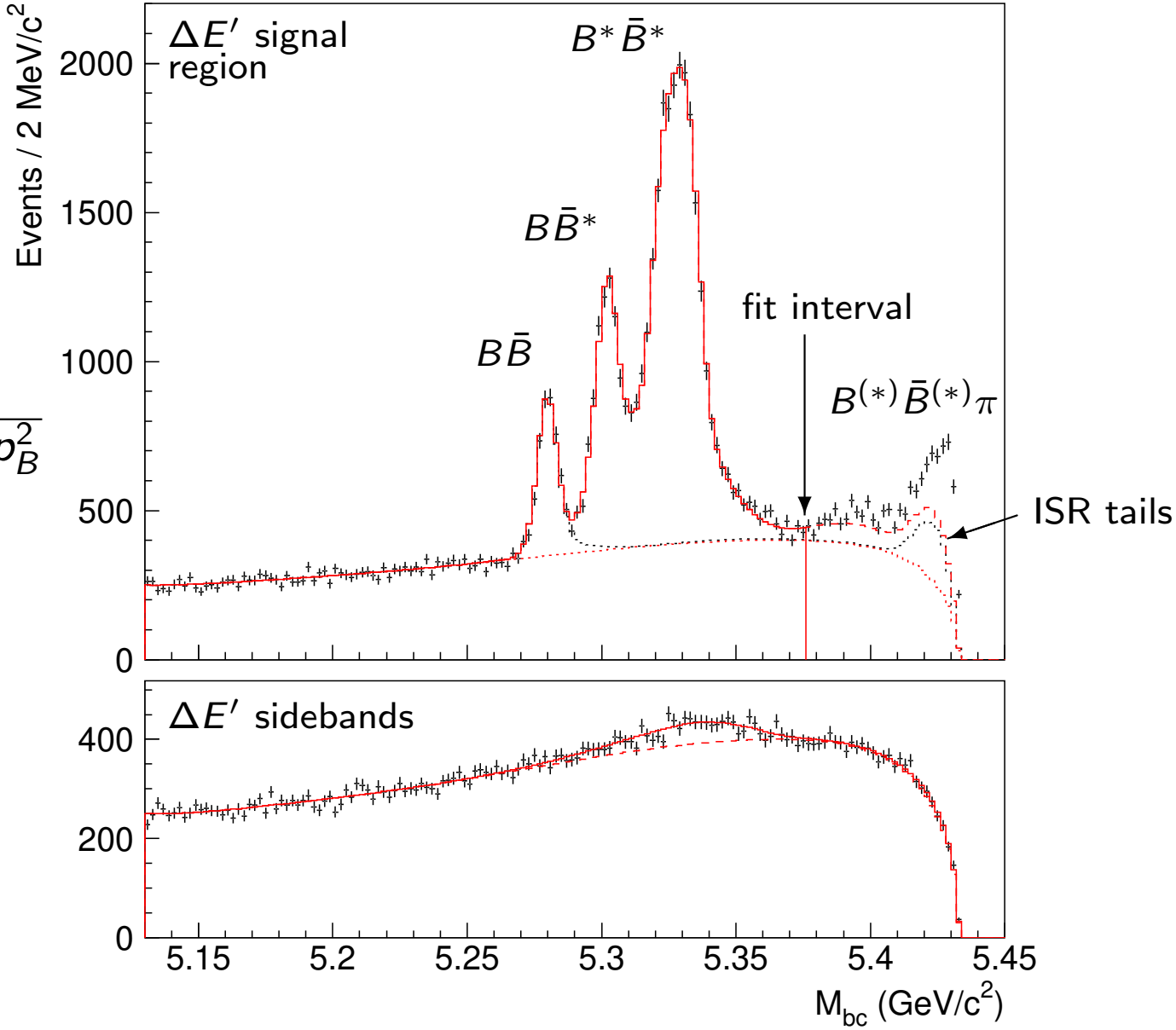
$\Upsilon(5S)$: peak position in $B_s^*\bar{B}_s^*$ is shifted by $20\,\mathrm{MeV}$ compared to $\Upsilon(nS)\pi^+\pi^-$ and $h_b(nP)\pi^+\pi^-$. Two states?

Belle II performed energy scan, results are coming.

Back-up

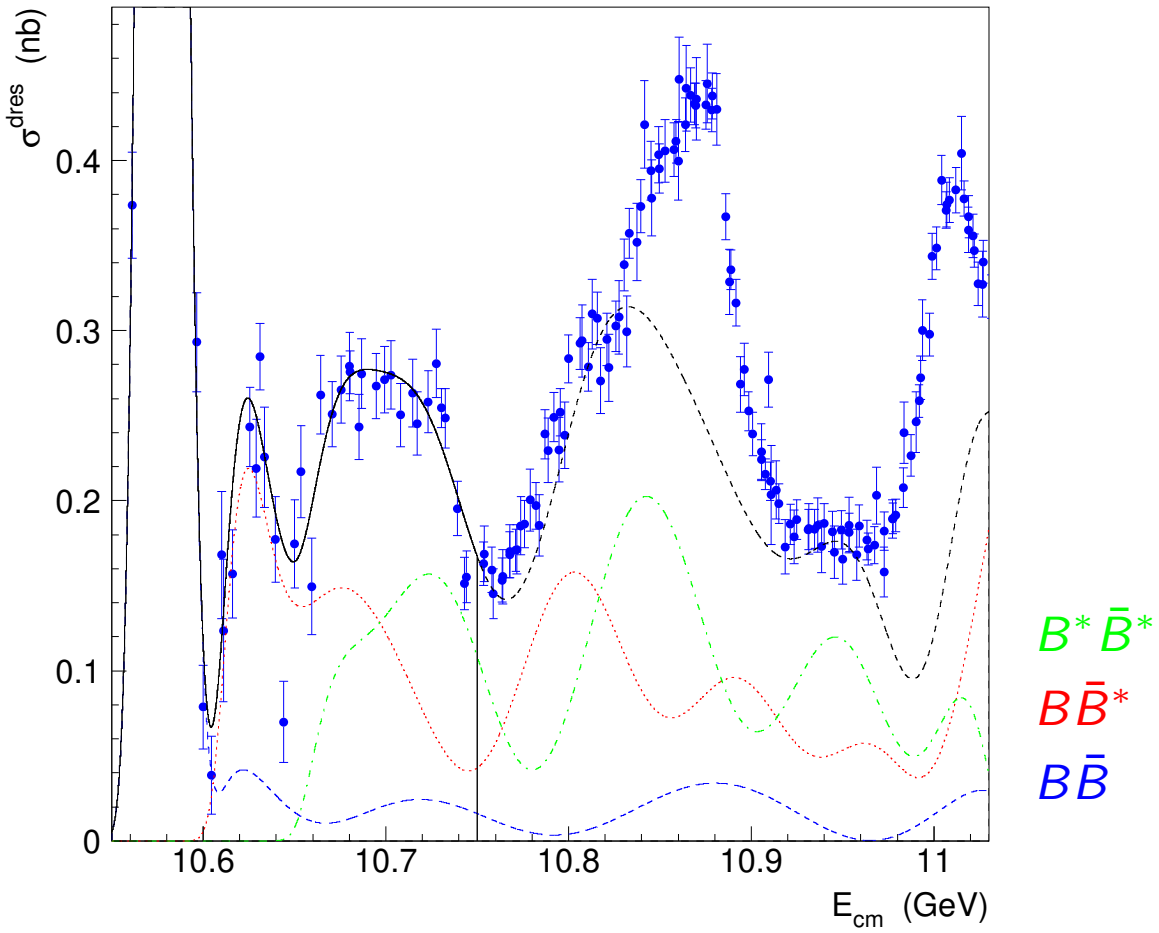
Fit at $\Upsilon(5S)$

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



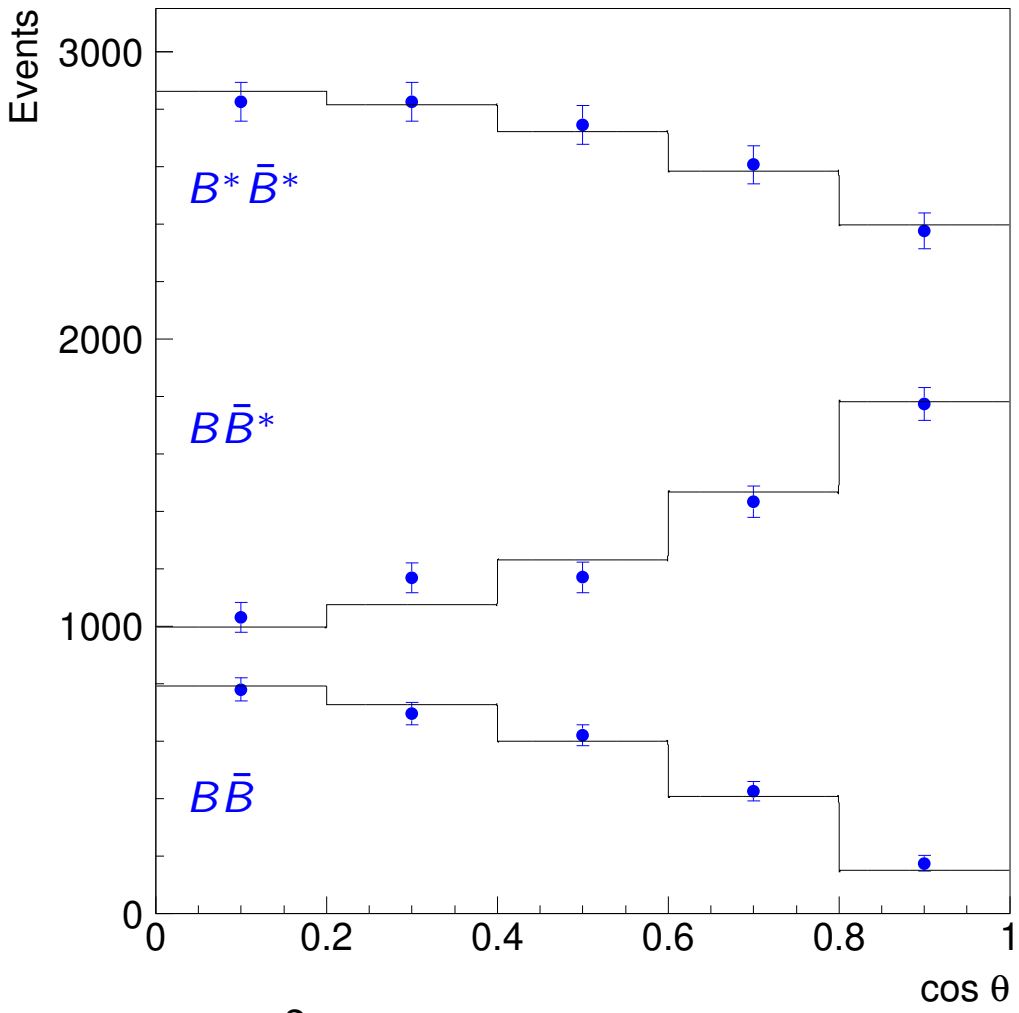
Excess of events near threshold is due to $e^+e^- \to B^{(*)}\bar{B}^{(*)}\pi$.
Fit describes data well.

Fit of cross section shapes



Simultaneous fit of exclusive cross sections $\sigma_{B\bar{B}}$, $\sigma_{B\bar{B}^*}$, $\sigma_{B^*\bar{B}^*}$ and total $\sigma_{b\bar{b}}$ (only for $E_{\mathrm{cm}} < 10.75\,\mathrm{GeV}$).

Angular analysis at $\Upsilon(5S)$



Polar angle distribution: $1 + c\cos^2\theta$.
$B\bar{B}$: $c = -1$, $B\bar{B}^*$: $c = 1$, $B^*\bar{B}^*$: $c = -0.20 \pm 0.03$.

$B^*\bar{B}^*$: three states $L = 1$, $S = 0$; $L = 1$, $S = 2$; $L = 3$, $S = 2$.
Polarization? $\Rightarrow$ reconstruct γ from $B^* \to B\gamma$.