Measurement of the energy dependence of the $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ exclusive cross sections at Belle

new for this conference

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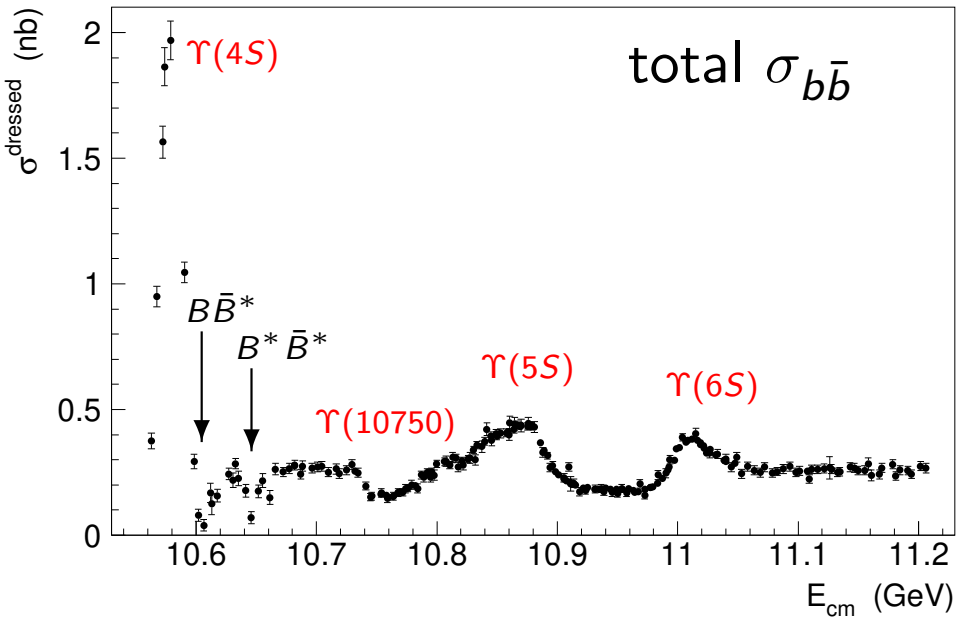
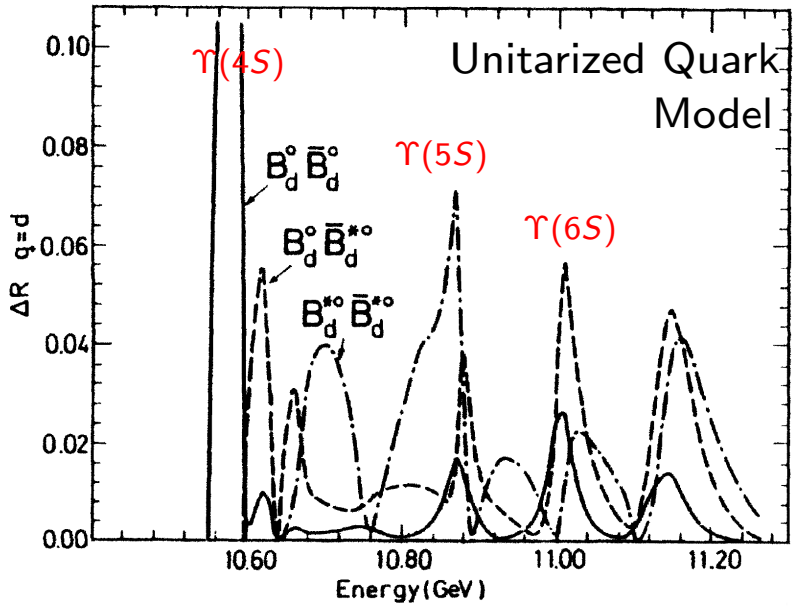
Quarkonium Working Group Meeting, 17 March 2021, UC Davis

Motivation

Dong,Mo,Wang,Yuan CPC**44**, 083001 (2020)



Ono,Sanda,Tornqvist PRD**34**,186(1986)



Total $e^+e^- \to b\bar{b}$: peaks of $\Upsilon(4S)$, $\Upsilon(5S)$ and $\Upsilon(6S)$, dips at $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds and at $\Upsilon(10750)$.

Exclusive cross sections are expected to have more structures. Unitarized Quark Model: minima are due to nodes of the $\Upsilon(4S, 5S, 6S)$ wave functions – information about Υ states.

Overview of the analysis

Identify $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ using $M_{bc} = \sqrt{(E_{\mathrm{cm}}/2)^2 - p_B^2}$, p_B – B meson momentum. Photons from $B^* \to B\gamma$ are not reconstructed $\Rightarrow$ in $\Delta E = E_B - E_{\mathrm{cm}}/2$ the $B^{(*)}\bar{B}^*$ signals are shifted. Rotation: $\Delta E' = \Delta E + M_{bc} - m_B$; all signals peak at zero and have the same shape. Use $\Delta E'$ sidebands to constrain background.

Reconstruct B mesons in a large number of hadronic final states ($\gtrsim 1000$). Use automated procedure from BelleII software that includes machine learning for selection. Advantage: higher flexibility.

Data samples

- scan data: 16 points $1\,\mathrm{fb}^{-1}$ each from 10.63 to $11.02\,\mathrm{GeV}$,
- $\Upsilon(5S)$: $121\,\mathrm{fb}^{-1}$ taken in 3 points separated by $2\,\mathrm{MeV}$,
- $\Upsilon(4S)$ SVD2 configuration: $571\,\mathrm{fb}^{-1}$ – determination of efficiency.

Selection

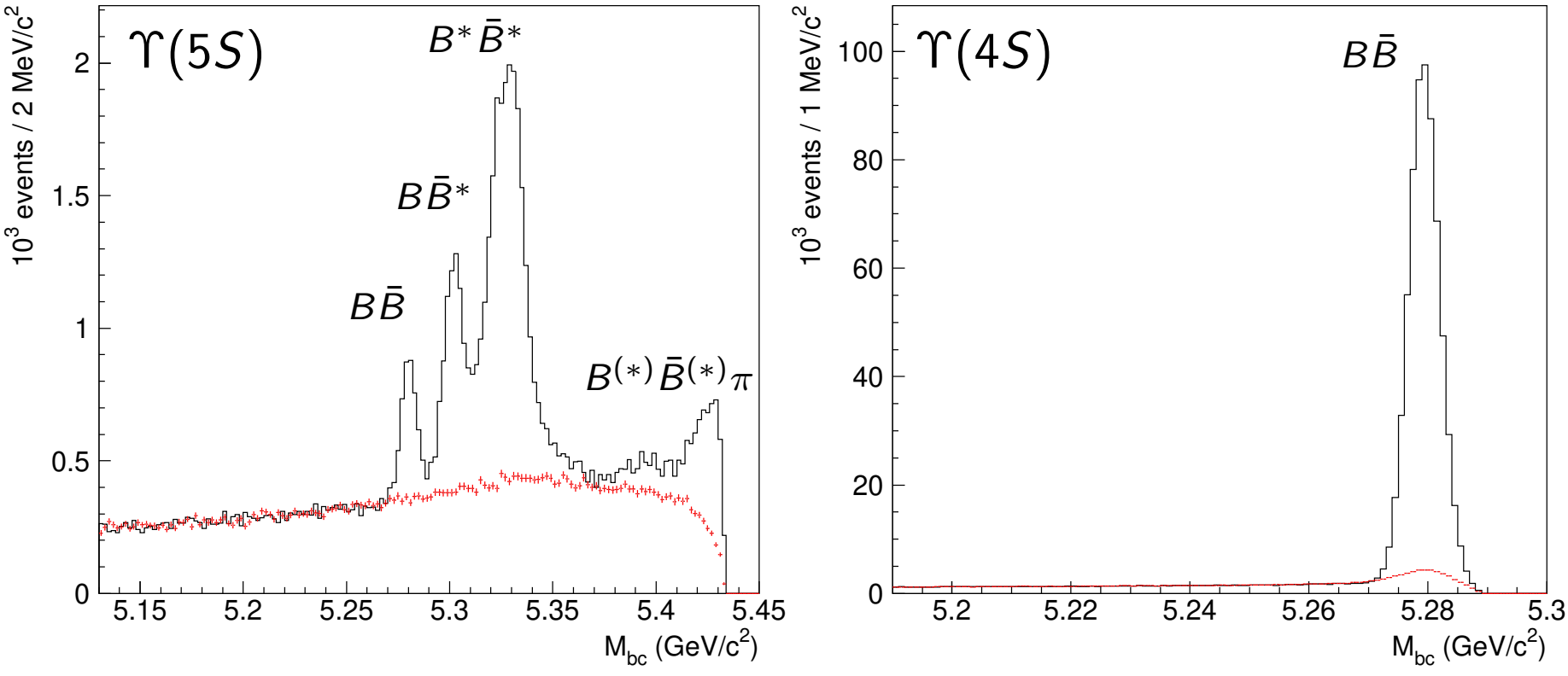
Use B decay channels without π^0 (good E_B resolution):
$B \to D^{(*)}\pi$, $D^{(*)}3\pi$, $D_s^{(*)}\bar{D}^{(*)}$, $J/\psi K$, $J/\psi K\pi(\pi)$.

D^0, D^+ and D_s^+: use 7, 6 and 8 channels, respectively.

Choose MVA input variables that are not correlated with p_B ($\Rightarrow$ efficiency is independent of $E_{\rm cm}$): masses of intermediate long-lived particles and resonances, B- and D-vertex variables, continuum suppression variables (R_2, $\cos\theta_{\rm thrust}$, flag indicating presence of high-momentum lepton).

For each B decay channel apply individual requirements on $|\Delta E'|$ and MVA output to maximize overall $S/\sqrt{S+B}$.

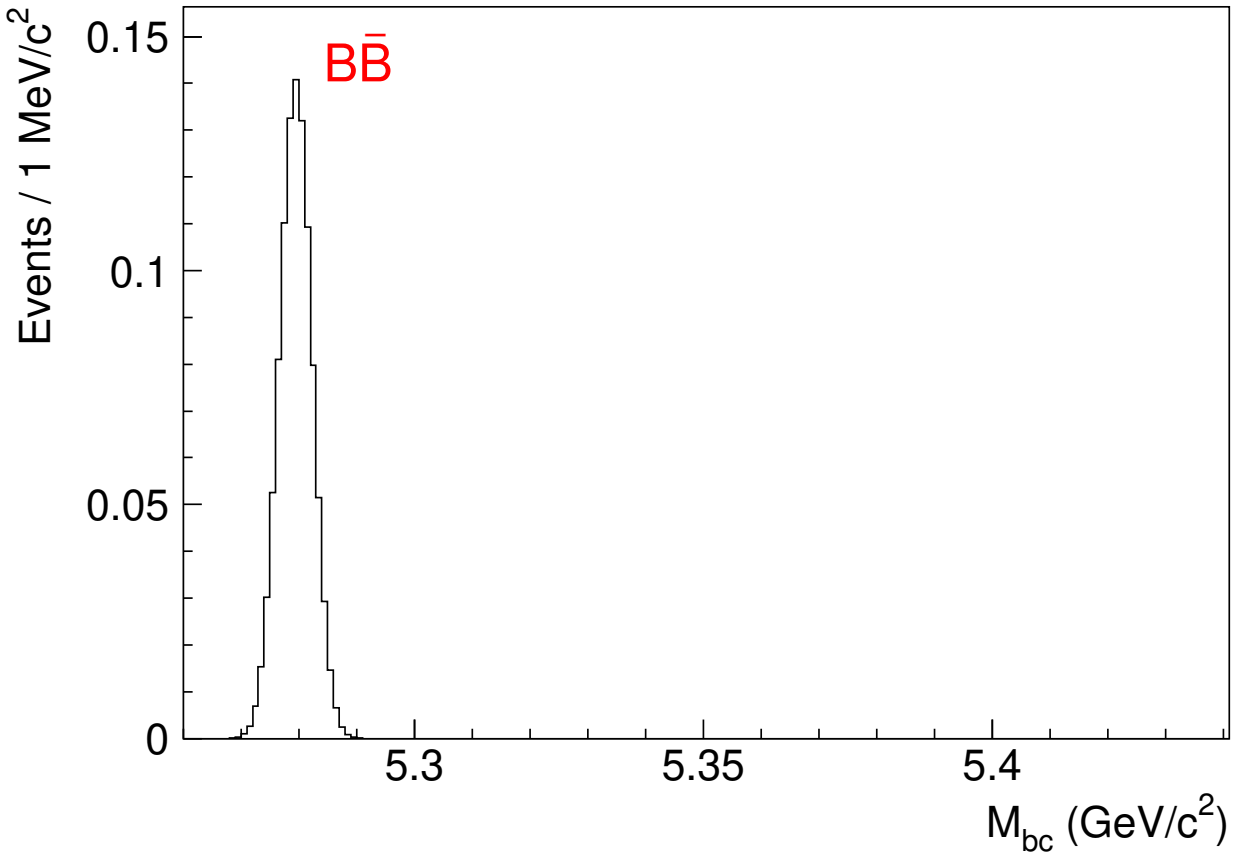
M_{bc} distributions at $\Upsilon(5S)$ and $\Upsilon(4S)$



Clear signals, $\Delta E'$ sidebands describe combinatorial background well, there is a peaking background (soft γ).

M_{bc} fit function

$\Upsilon(5S)$



Fit function is calculated numerically and takes into account: $E_{\rm cm}$ spread, energy dependence of cross section, ISR, momentum resolution and peaking background, kinematics of $B^* \to B\gamma$.

$B^* \to B\gamma$: distribution in helicity angle is $1 + a_{\rm h} \cos^2\theta$.
For $B\bar{B}^*$ expect $a_{\rm h} = 1$, for $B^*\bar{B}^*$ $a_{\rm h}$ is not fixed.

M_{bc} fit function

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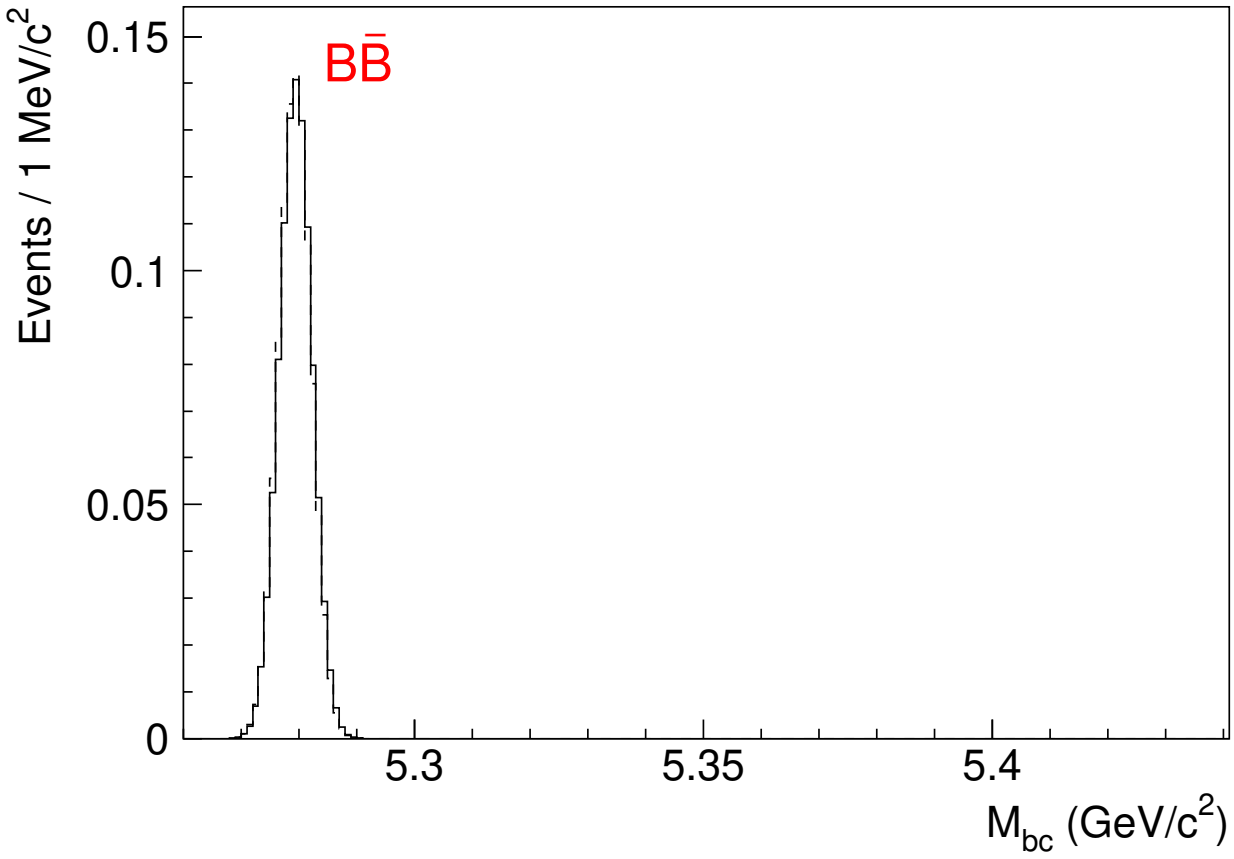

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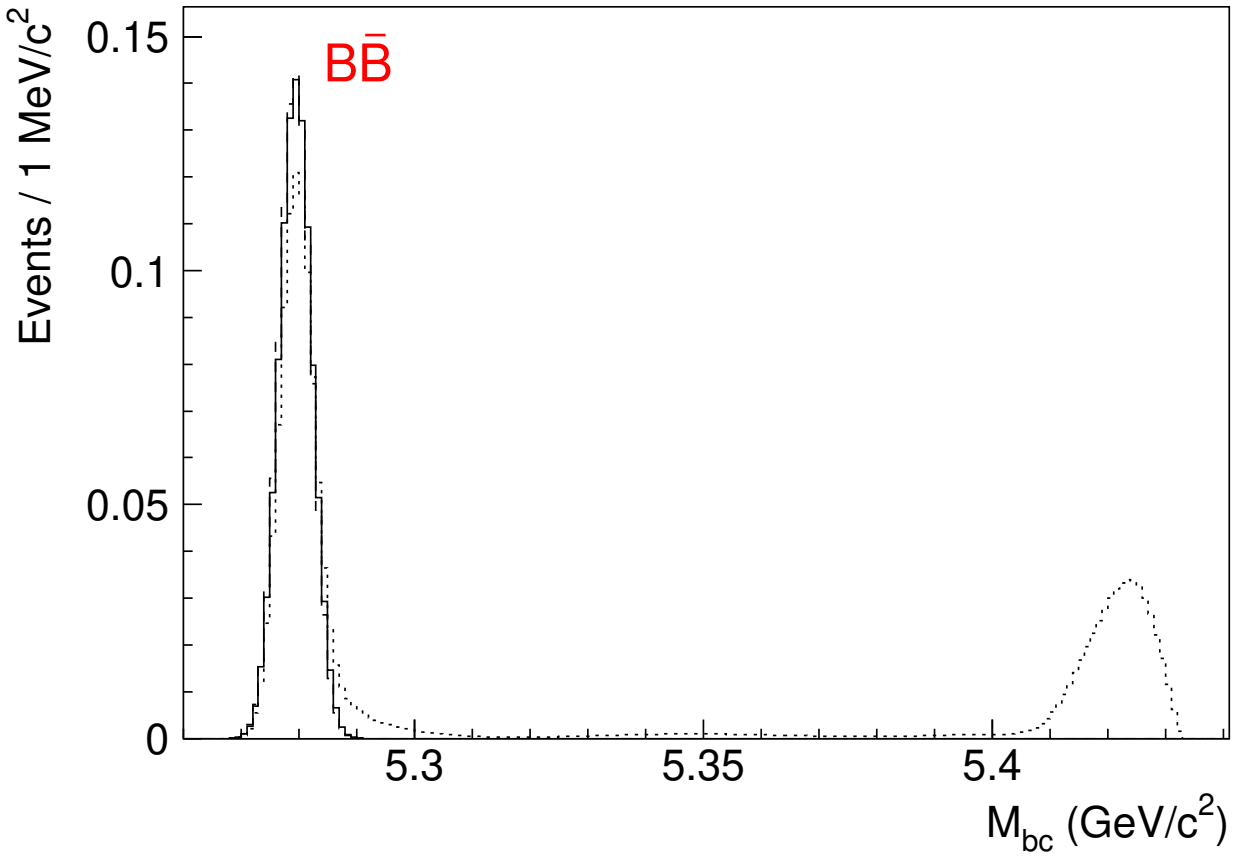

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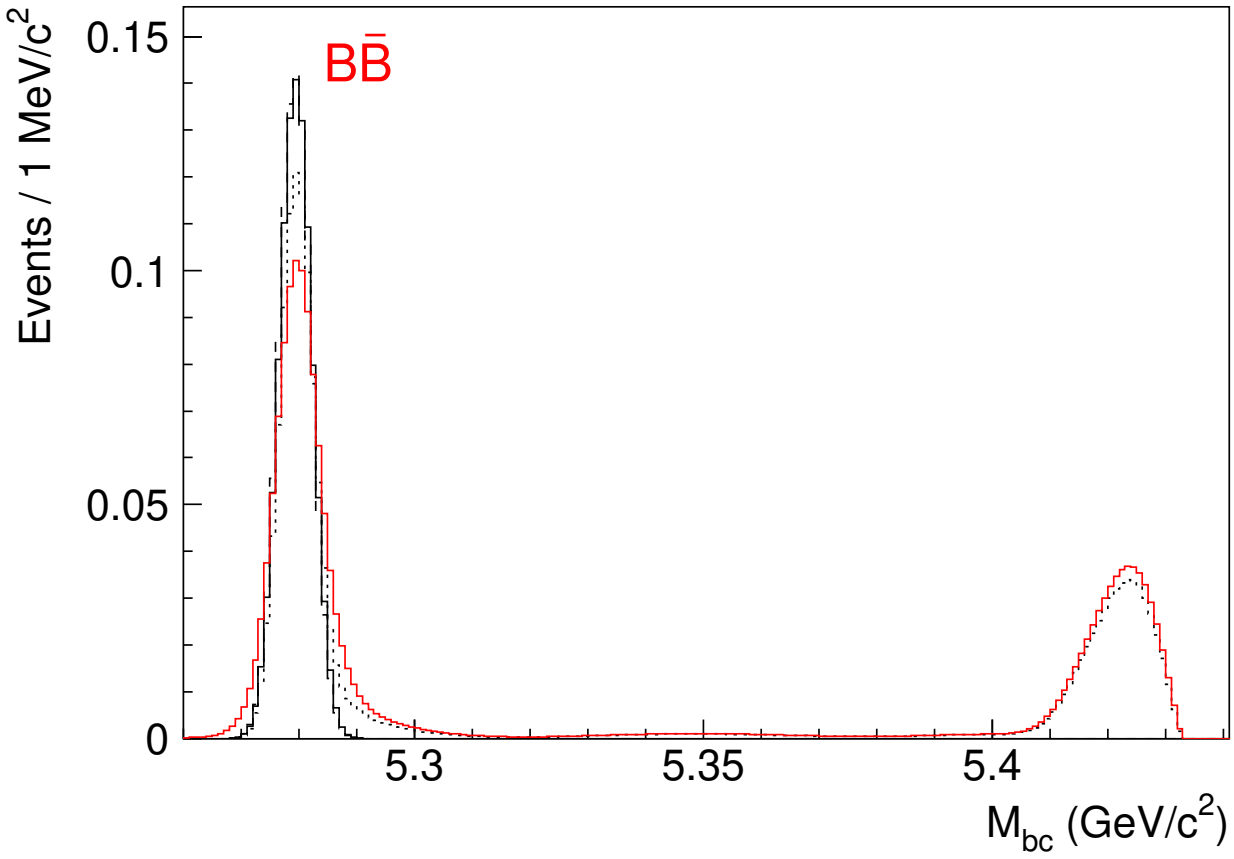

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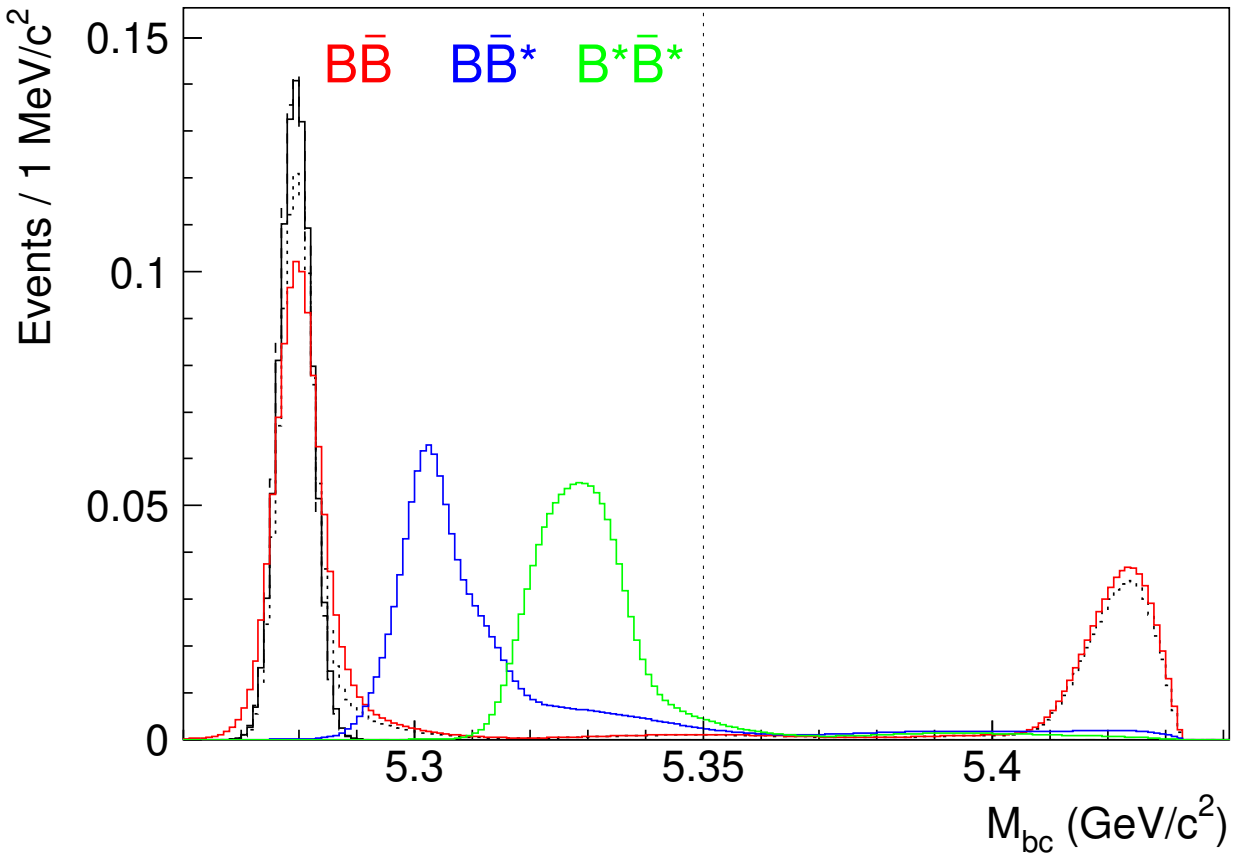

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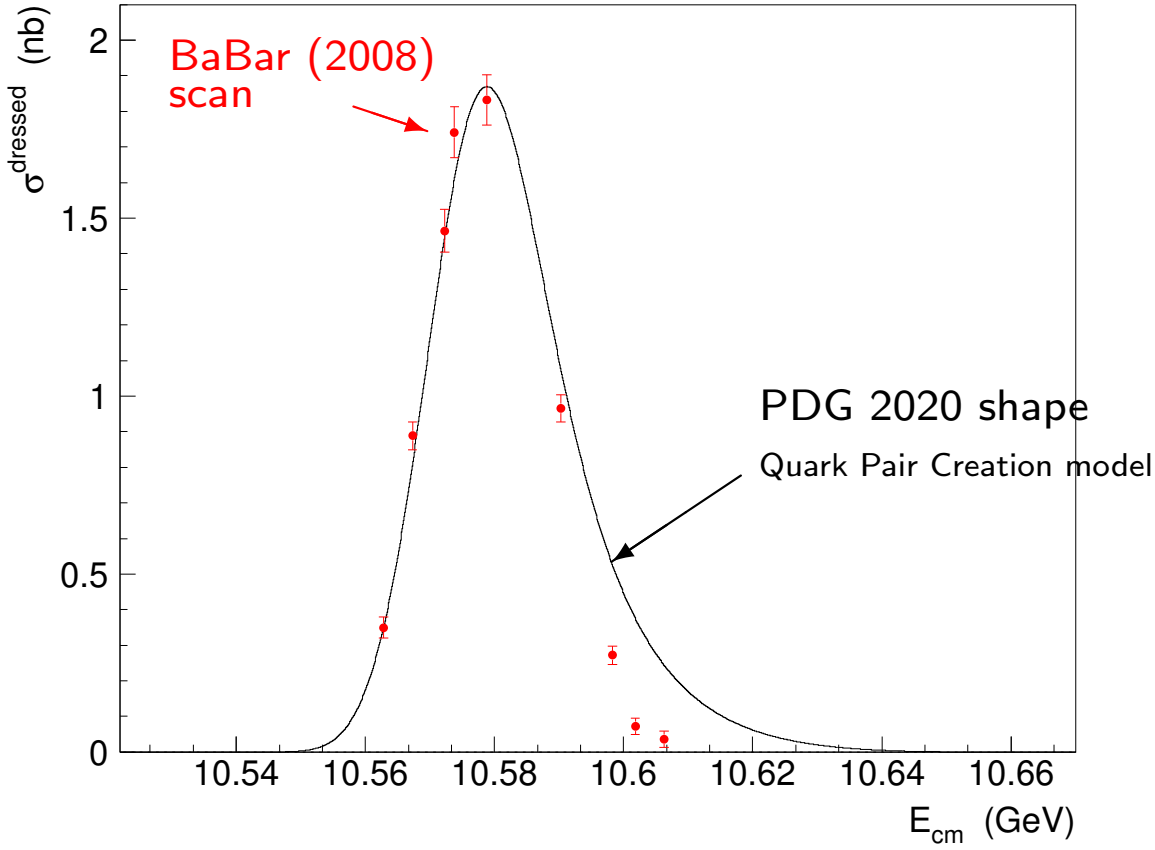
For $B\bar{B}^*$ expect $a_{\rm h} = 1$, for $B^*\bar{B}^*$ $a_{\rm h}$ is not fixed.

$\Upsilon(4S)$ shape

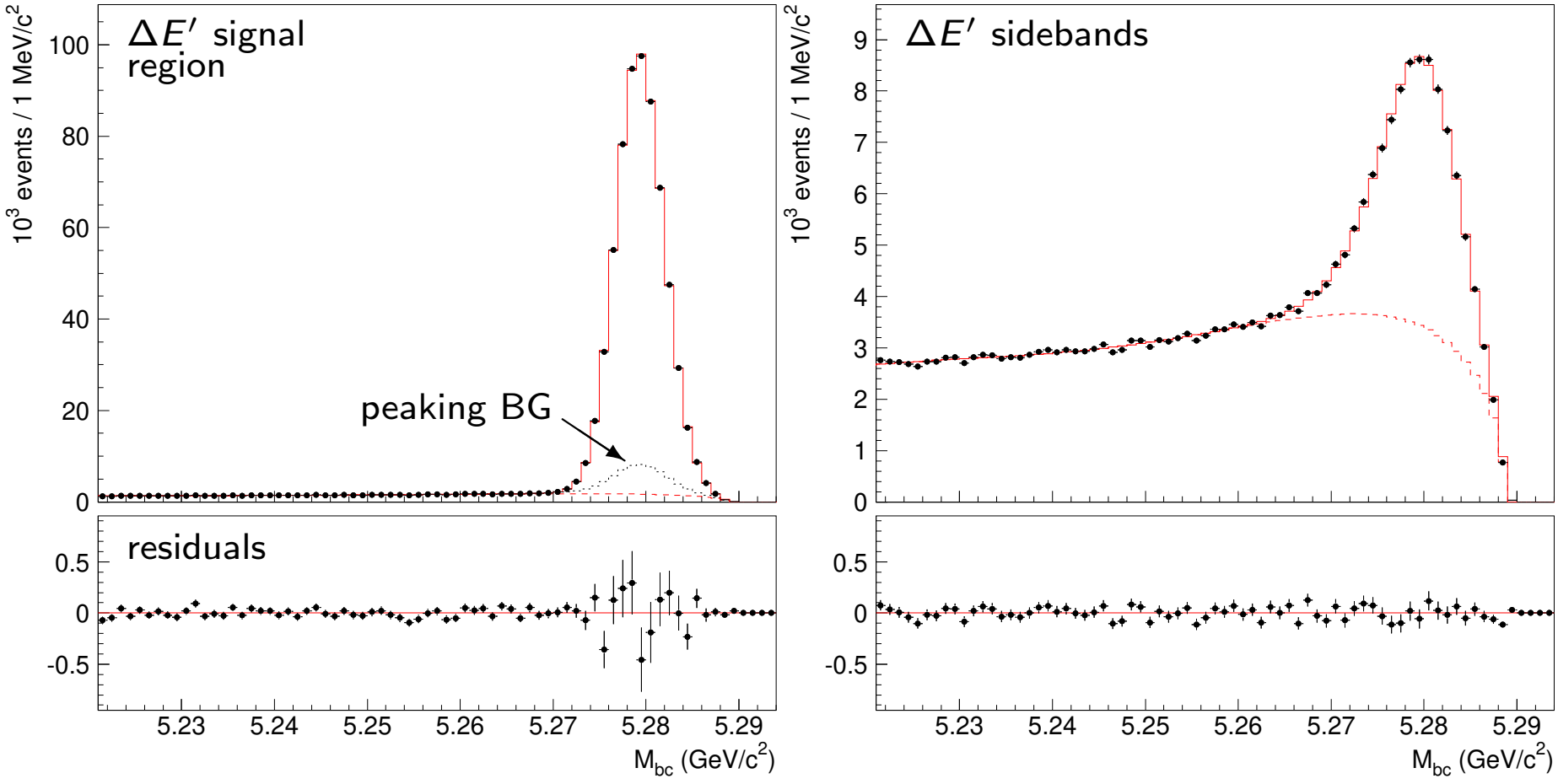


World-average $\Upsilon(4S)$ parameters are dominated by BaBar measurement (2005). In 2008 BaBar performed more precise scan.

Quark Pair Creation model fails to describe 2008 scan data. No suitable phenomenological model to parameterize cross section shape $\Rightarrow$ use high-order Chebyshev polynomials.

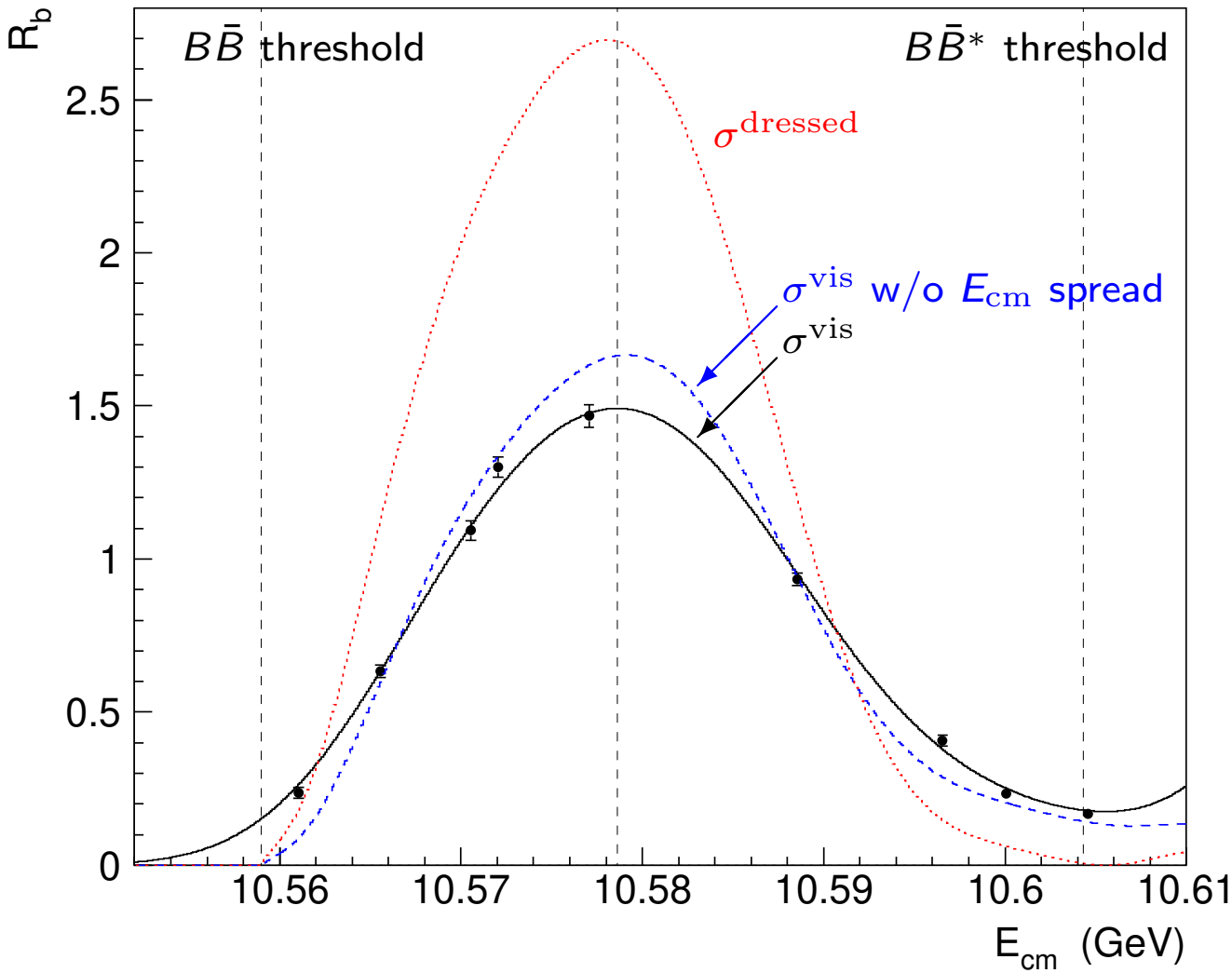
Simultaneous fit to BaBar scan points and Belle M_{bc} distributions.

$\Upsilon(4S)$: simultaneous M_{bc} and cross section fit



Fit describes data well. E_{cm} spread $\sigma_{\mathrm{E}} = (5.38 \pm 0.19)\,\mathrm{MeV}$ is in agreement with measurements at $\Upsilon(1S, 2S, 3S, 5S)$; we find $\sigma_{\mathrm{E}} \propto E_{\mathrm{cm}}$.

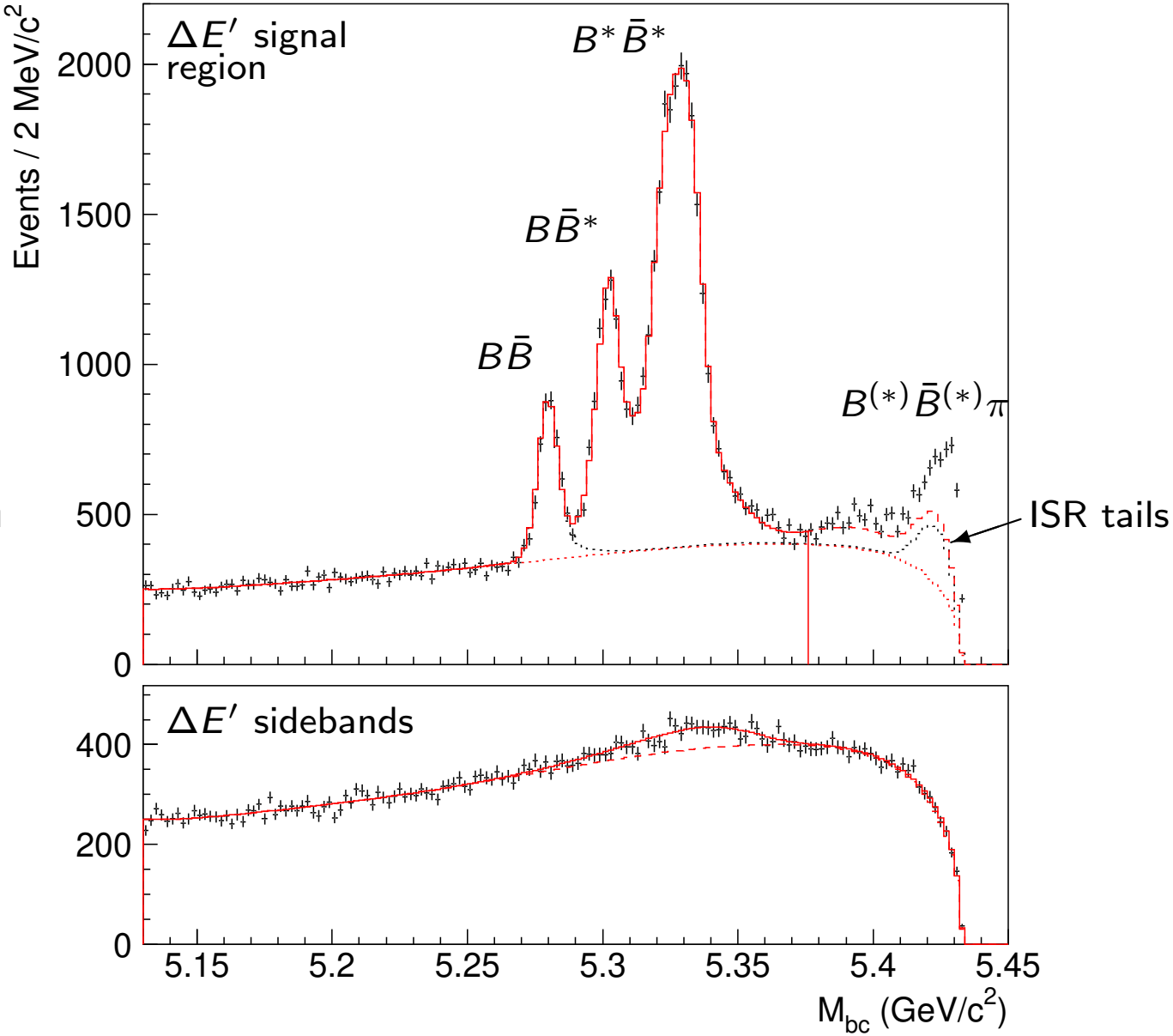
$\Upsilon(4S)$: simultaneous M_{bc} and cross section fit



Fit describes data well. Common shift of points:
$\Delta E_{\rm BaBar} = (-1.75 \pm 0.68)\,{\rm MeV}$.

Fit at $\Upsilon(5S)$

Fit range:
$M_{bc} < 5.375\mathrm{GeV}/c^2$.
Beyond – contribution of $B^{(*)}\bar{B}^{(*)}\pi$.



$B^{(*)}\bar{B}^{(*)}$ cross sections are needed to determine signal shapes $\Rightarrow$ use iterative procedure. Fit describes data well. $a_{\mathrm{h}} = -0.17 \pm 0.07$

Efficiency of B reconstruction

$$\varepsilon_{\Upsilon(4S)} = \frac{N_{\Upsilon(4S)}}{2\, N_{B\bar{B}}(\Upsilon(4S))} = (0.469 \pm 0.008) \times 10^{-3}$$

$N_{B\bar{B}}(\Upsilon(4S))$ – total number of $B\bar{B}$ events, measured using the number of hadronic events and subtracting continuum.

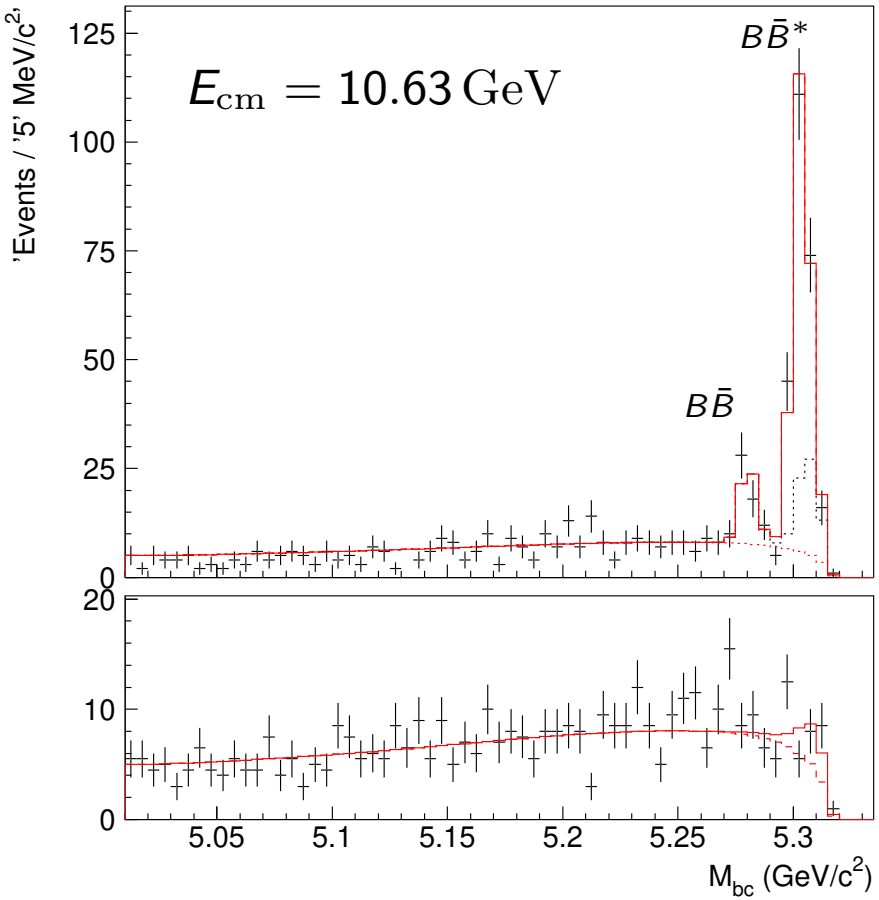
Measure ratio R of B meson numbers in $\Upsilon(5S)$ and $\Upsilon(4S)$ data samples using five low multiplicity final states:
$B^+ \to D^0\pi^+$ ($K^-\pi^+$, $K^-3\pi$), $B^0 \to D^-\pi^+$, $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$.

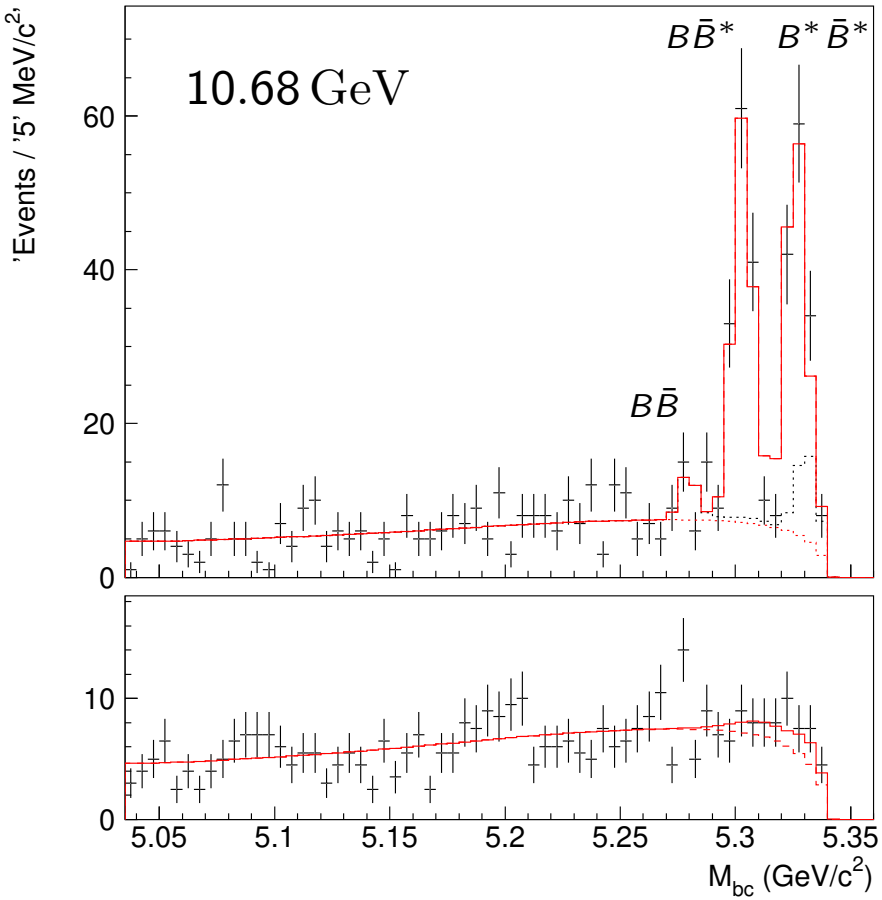
$$\varepsilon_{\Upsilon(5S)} = \frac{N_{\Upsilon(5S)}}{2\, N_{B\bar{B}}(\Upsilon(4S))\, R} = (0.491 \pm 0.017) \times 10^{-3}$$

$\varepsilon_{\Upsilon(5S)}/\varepsilon_{\Upsilon(4S)} = 1.048 \pm 0.032$; MC: 1.028 ± 0.004 – agreement.
Efficiency is almost independent of $E_{\rm cm}$.

M_{bc} fits in scan data

Examples: lowest energies



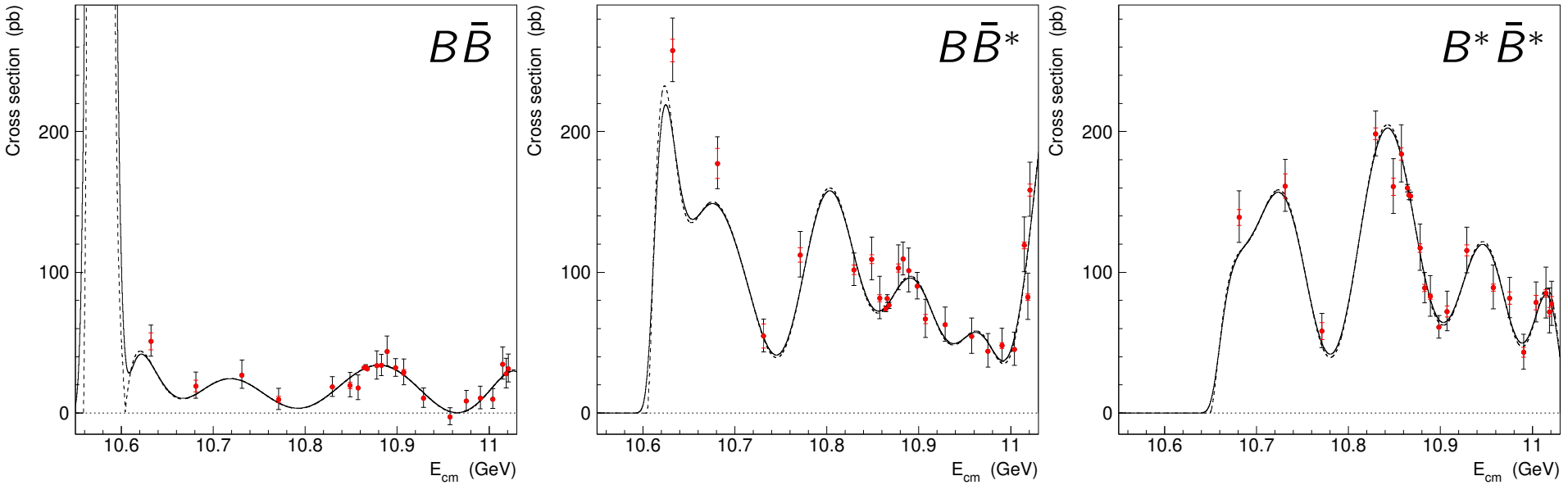


Fit works well at all energies

Dressed cross sections

$$\sigma^{\rm dressed} = \frac{N}{L\,\varepsilon\,(1+\delta_{\rm ISR})}$$

stat., uncorrelated syst. errors



Oscillations.

To calculate M_{bc} fit function and $(1+\delta_{\rm ISR})$ corrections, we need to parameterize the cross section shapes. Use high-order Chebyshev polynomial (orders are 10, 17 and 12).

Systematics: cross section shape (poly orders: ±1, ±2; toy MC) - small.

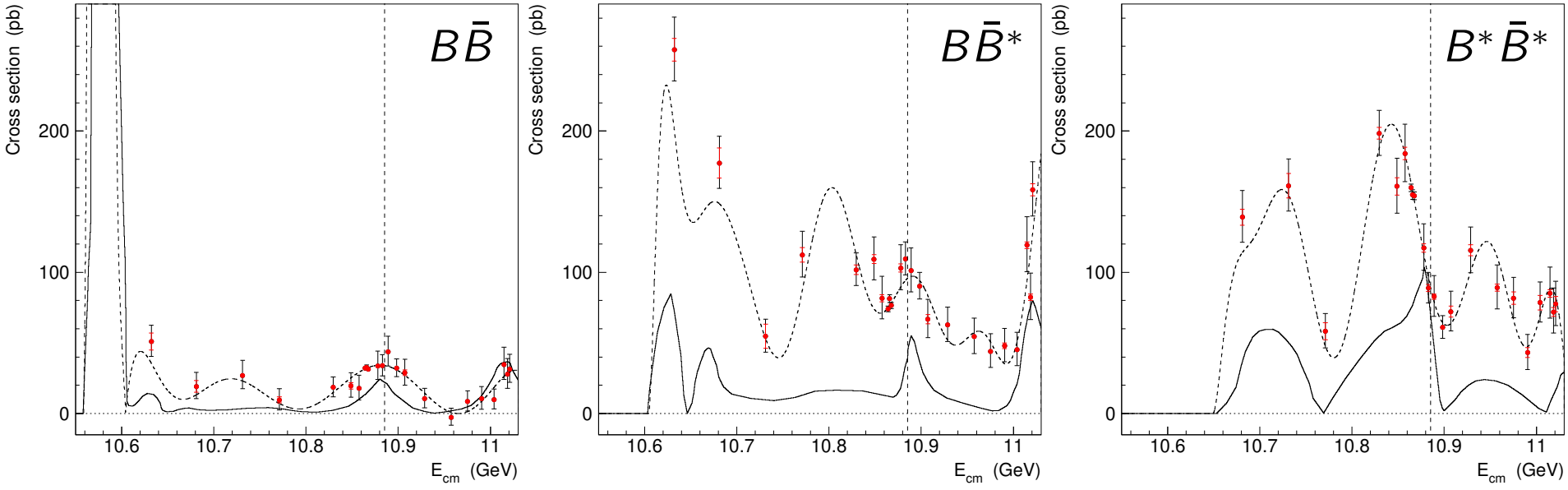
Cross section table

No.	$E_{\rm cm}$	L	$\sigma(B\bar{B})$	$\sigma(B\bar{B}^*)$	$\sigma(B^*\bar{B}^*)$
1	11020.8 ± 1.4	0.982	$31.4 \pm 9.9 \pm 1.2 \pm 1.7$	$158.4 \pm 19.3 \pm 4.2 \pm 7.7$	$77.5 \pm 15.6 \pm 5.4 \pm 3.6$
2	11018.5 ± 2.0	0.859	$27.8 \pm 10.5 \pm 1.0 \pm 1.5$	$82.4 \pm 16.5 \pm 2.3 \pm 4.0$	$71.9 \pm 15.9 \pm 3.1 \pm 3.4$
3	11014.8 ± 1.4	0.771	$34.8 \pm 11.4 \pm 1.2 \pm 1.9$	$119.1 \pm 19.5 \pm 2.4 \pm 5.8$	$85.0 \pm 18.1 \pm 2.7 \pm 3.9$
4	11003.9 ± 1.0	0.976	$9.7 \pm 7.0 \pm 0.3 \pm 0.6$	$45.2 \pm 11.8 \pm 1.3 \pm 2.2$	$78.5 \pm 14.2 \pm 5.1 \pm 3.6$
5	10990.4 ± 1.3	0.985	$10.5 \pm 8.0 \pm 0.4 \pm 0.7$	$48.0 \pm 11.7 \pm 2.0 \pm 2.3$	$43.1 \pm 12.4 \pm 3.5 \pm 2.0$
6	10975.3 ± 1.4	0.999	$8.5 \pm 7.1 \pm 1.2 \pm 0.5$	$44.0 \pm 11.9 \pm 0.8 \pm 2.1$	$81.7 \pm 14.3 \pm 4.5 \pm 3.6$
7	10957.5 ± 1.5	0.969	$-2.9 \pm 6.0 \pm 0.1 \pm 0.3$	$54.5 \pm 12.6 \pm 1.6 \pm 2.5$	$89.2 \pm 15.5 \pm 2.5 \pm 3.8$
8	10928.7 ± 1.6	1.149	$10.5 \pm 6.9 \pm 0.9 \pm 0.6$	$62.7 \pm 12.1 \pm 1.6 \pm 2.7$	$115.6 \pm 16.2 \pm 3.8 \pm 4.7$
9	10907.3 ± 1.1	0.980	$28.8 \pm 9.1 \pm 2.0 \pm 1.4$	$66.7 \pm 13.5 \pm 3.2 \pm 2.8$	$72.1 \pm 14.0 \pm 4.0 \pm 2.8$
10	10898.3 ± 0.7	2.408	$32.2 \pm 6.3 \pm 0.5 \pm 1.4$	$90.2 \pm 9.4 \pm 1.3 \pm 3.7$	$61.0 \pm 8.0 \pm 1.4 \pm 2.3$
11	10888.9 ± 0.8	0.990	$43.7 \pm 10.5 \pm 0.7 \pm 2.0$	$101.2 \pm 15.6 \pm 1.0 \pm 4.1$	$82.8 \pm 14.4 \pm 1.8 \pm 3.1$
12	10882.8 ± 0.7	1.848	$33.8 \pm 7.5 \pm 0.4 \pm 1.5$	$109.5 \pm 11.7 \pm 1.5 \pm 4.4$	$88.9 \pm 10.8 \pm 2.5 \pm 3.3$
13	10877.8 ± 0.8	0.978	$33.7 \pm 10.1 \pm 1.7 \pm 1.5$	$103.1 \pm 16.0 \pm 2.8 \pm 4.1$	$117.3 \pm 16.4 \pm 3.0 \pm 4.3$
14	10867.6 ± 0.2	45.28	$31.3 \pm 1.5 \pm 0.0 \pm 1.3$	$76.5 \pm 2.1 \pm 0.1 \pm 3.2$	$154.1 \pm 2.7 \pm 0.2 \pm 6.2$
15	10865.8 ± 0.3	29.11	$32.6 \pm 1.8 \pm 0.0 \pm 1.4$	$81.3 \pm 2.7 \pm 0.1 \pm 3.4$	$155.0 \pm 3.4 \pm 0.1 \pm 6.2$
16	10864.2 ± 0.3	47.65	$32.1 \pm 1.4 \pm 0.0 \pm 1.4$	$74.2 \pm 2.0 \pm 0.1 \pm 3.1$	$159.9 \pm 2.7 \pm 0.3 \pm 6.4$
17	10857.4 ± 0.9	0.988	$17.8 \pm 8.7 \pm 1.2 \pm 0.8$	$81.5 \pm 15.0 \pm 2.5 \pm 3.2$	$184.2 \pm 20.4 \pm 4.4 \pm 6.5$
18	10848.9 ± 1.0	0.989	$19.6 \pm 8.7 \pm 2.3 \pm 0.9$	$109.3 \pm 15.2 \pm 3.2 \pm 4.1$	$160.8 \pm 19.4 \pm 6.2 \pm 5.6$
19	10829.5 ± 1.2	1.697	$18.5 \pm 7.0 \pm 0.7 \pm 0.8$	$101.8 \pm 11.6 \pm 3.4 \pm 3.7$	$198.4 \pm 16.0 \pm 4.2 \pm 6.6$
20	10771.2 ± 1.0	0.955	$9.6 \pm 7.5 \pm 2.2 \pm 0.5$	$112.2 \pm 16.2 \pm 5.2 \pm 3.6$	$58.2 \pm 12.1 \pm 6.1 \pm 1.7$
21	10731.3 ± 1.5	0.946	$27.0 \pm 10.1 \pm 1.4 \pm 1.0$	$54.7 \pm 11.7 \pm 8.5 \pm 1.6$	$161.3 \pm 18.4 \pm 8.7 \pm 4.2$
22	10681.0 ± 1.4	0.949	$19.2 \pm 9.3 \pm 4.1 \pm 0.7$	$177.3 \pm 18.4 \pm 10.7 \pm 4.5$	$139.0 \pm 18.4 \pm 5.7 \pm 3.1$
23	10632.2 ± 1.5	0.989	$50.9 \pm 11.1 \pm 6.0 \pm 1.4$	$257.6 \pm 22.7 \pm 8.1 \pm 5.6$	—

Table: Dressed cross sections (in pb). The first error is statistical, the second is uncorrelated systematic and the third is correlated systematic.

Data *vs.* Unitarized Quark Model predictions

Ono,Sanda,Tornqvist PRD**34**,186(1986)



UQM predicted successfully

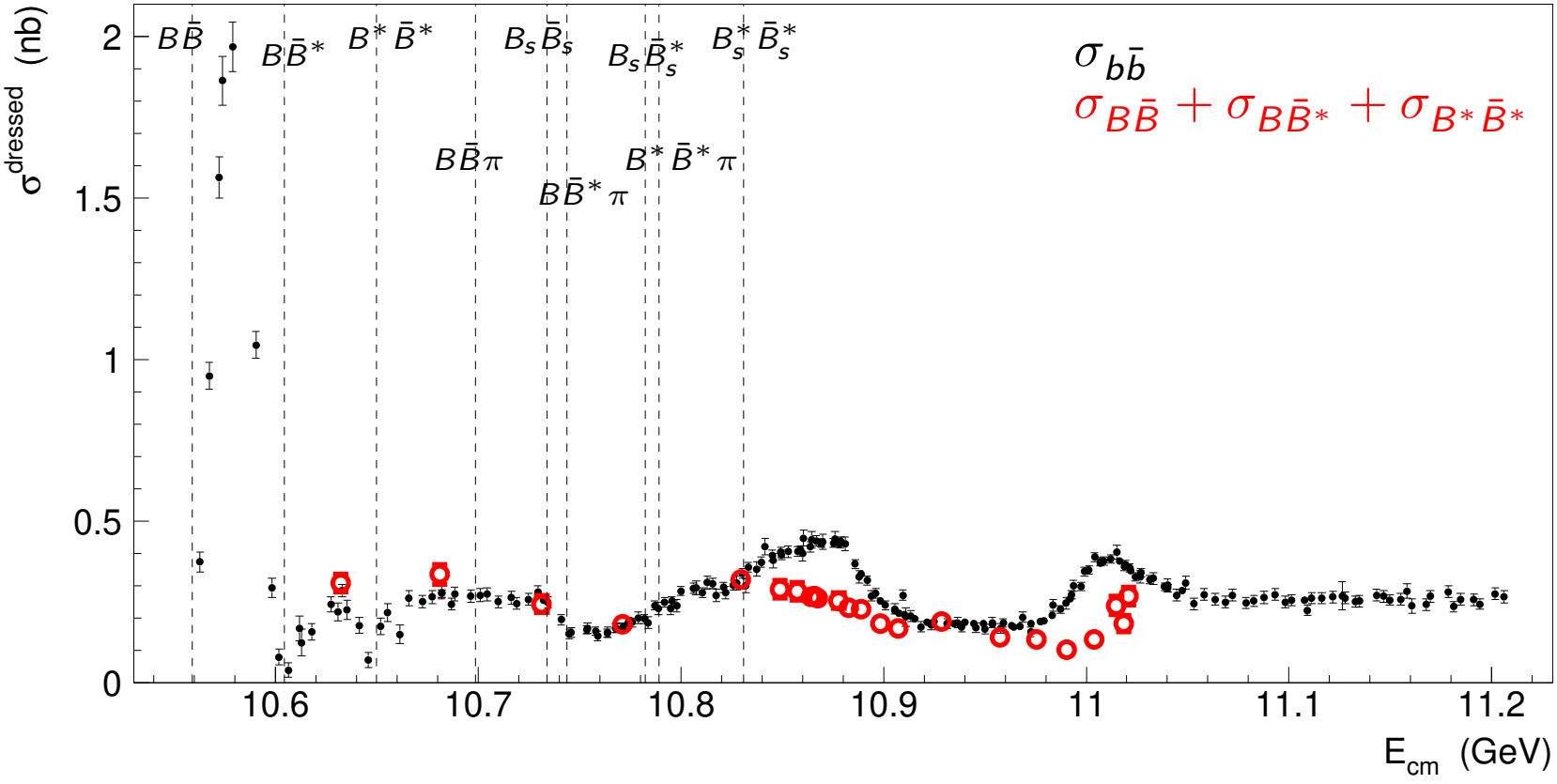
- oscillatory behavior of exclusive cross sections,
- (roughly) positions of minima and maxima.

UQM failed

- to describe non-resonant offset;
- $\sigma_{B^{(*)}\bar{B}^{(*)}}$ do not show obvious signals of $\Upsilon(5S)$.

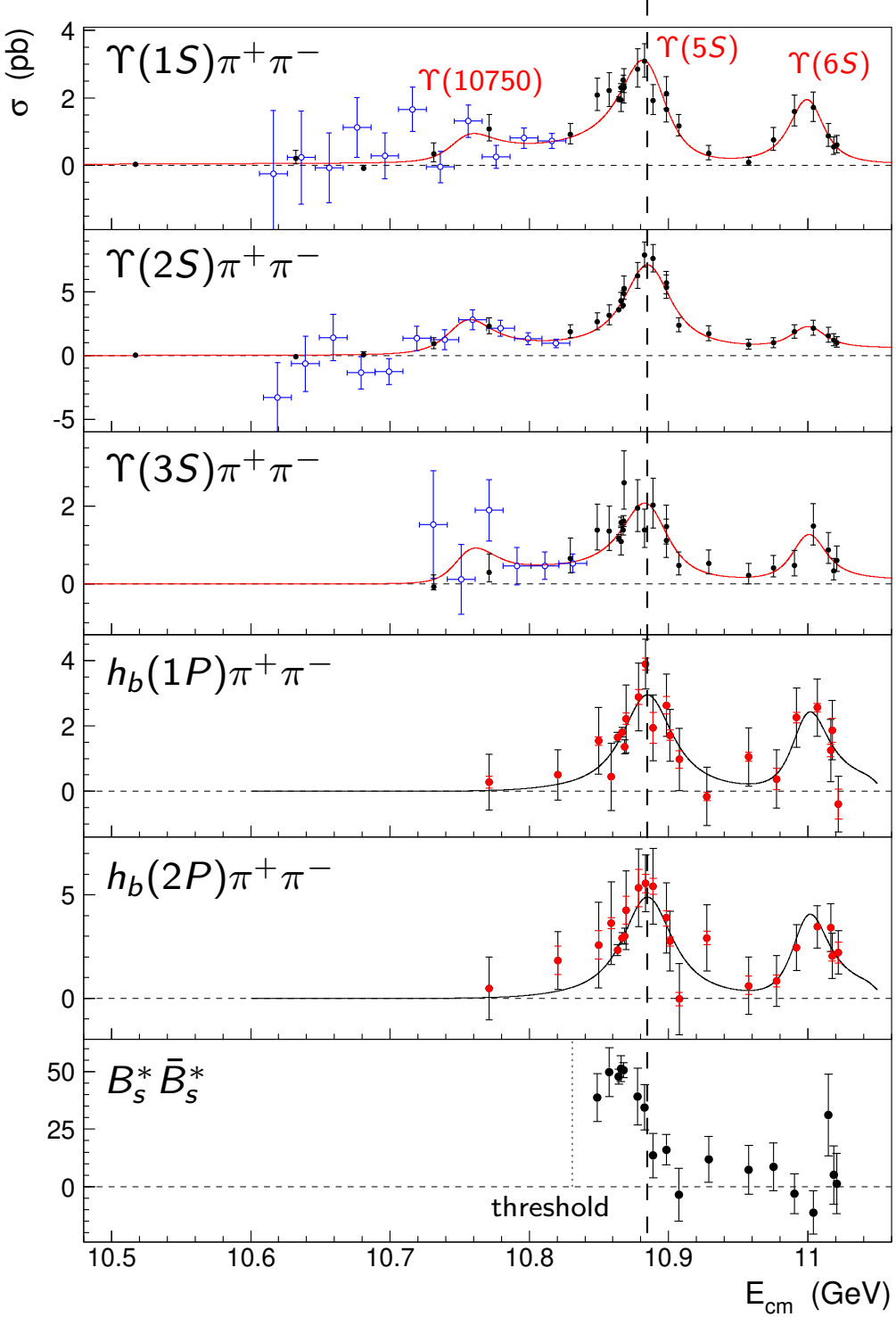
$\sigma_{b\bar{b}}$ vs. $\sigma_{B\bar{B}} + \sigma_{B\bar{B}^*} + \sigma_{B^*\bar{B}^*}$

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



- $\sigma_{b\bar{b}}$ and $\sum \sigma_{B^{(*)}\bar{B}^{(*)}}$ coincide at low E_{cm} – cross check.
- $\Upsilon(5S)$ 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?



$\Upsilon(5S)$: 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? Y_b state?

Need combined analysis of all cross section measurements.

Conclusions

First measurement of exclusive cross sections:

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

in the energy range $10.63 - 11.02\,\mathrm{GeV}$.

- oscillatory behaviour
- no obvious signals of $\Upsilon(5S)$

All results are preliminary.

Of interest to perform combined analysis of available cross sections: $B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$, $B_s^*\bar{B}_s^*$, $\Upsilon(1S, 2S, 3S)\pi^+\pi^-$ and $h_b(1P, 2P)\pi^+\pi^-$.

Perspectives at BelleII - talk by Bryan Fulsom.

Back-up

Energy dependence of the $E_{\rm cm}$ spread

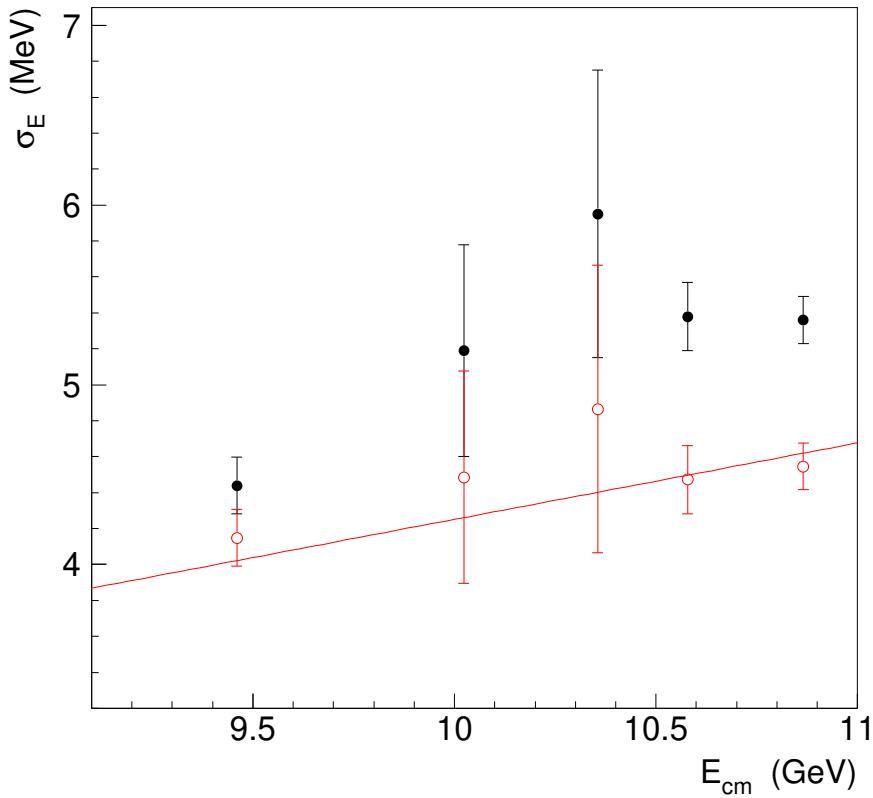


Figure: Energy dependence of the $E_{\rm cm}$ spread. Black dots with error bars are the measurements, red open dots are $\sigma_{\rm E}$ corrected for the microwave instability effect at KEKB, red line is the fit result.

Spread at $\Upsilon(1S, 2S, 3S)$ is found based on visible cross sections. Measurements are consistent with $\sigma_{\rm E} \propto E_{\rm cm}$.

Fit results at $\Upsilon(4S)$

Table: Results of the simultaneous fit to the Belle M_{bc} distribution and the BaBar cross section scan results. The first error is statistical, the second one (if present) is systematic.

N	$(581.2 \pm 1.1 \pm 3.2) \times 10^3$
σ_{E}	$(5.38 \pm 0.11 \pm 0.16)\,\mathrm{MeV}$
$\Delta E_{\mathrm{BaBar}}$	$(-1.75 \pm 0.14 \pm 0.67)\,\mathrm{MeV}$
n	1.16 ± 0.03
s_3	$(-0.2 \pm 0.6)\,\mathrm{MeV}/c$
ϕ_3	1.00 ± 0.02
$r_{\mathrm{s.b.}}$	1.017 ± 0.005

Fit results at $\Upsilon(5S)$

Table: Results of the fit to the M_{bc} distribution at $\Upsilon(5S)$. The errors are statistical.

$N_{\rm total}$	$(23.65 \pm 0.22 \pm 0.34) \times 10^3$
$N_{\rm B\bar{B}} \,/\, N_{\rm total}$	0.1120 ± 0.0030
$N_{\rm B\bar{B}^*} \,/\, N_{\rm total}$	0.3095 ± 0.0045
$N_{\rm B^*\bar{B}^*} \,/\, N_{\rm total}$	0.5785 ± 0.0048
$a_{\rm h}$	-0.17 ± 0.07
s_3	$(-39^{+16}_{-20})\,{\rm MeV}/c$
ϕ_3	$1.42^{+0.59}_{-0.33}$
$r_{\rm s.b.}$	0.998 ± 0.007

Simultaneous fit to the cross section shapes

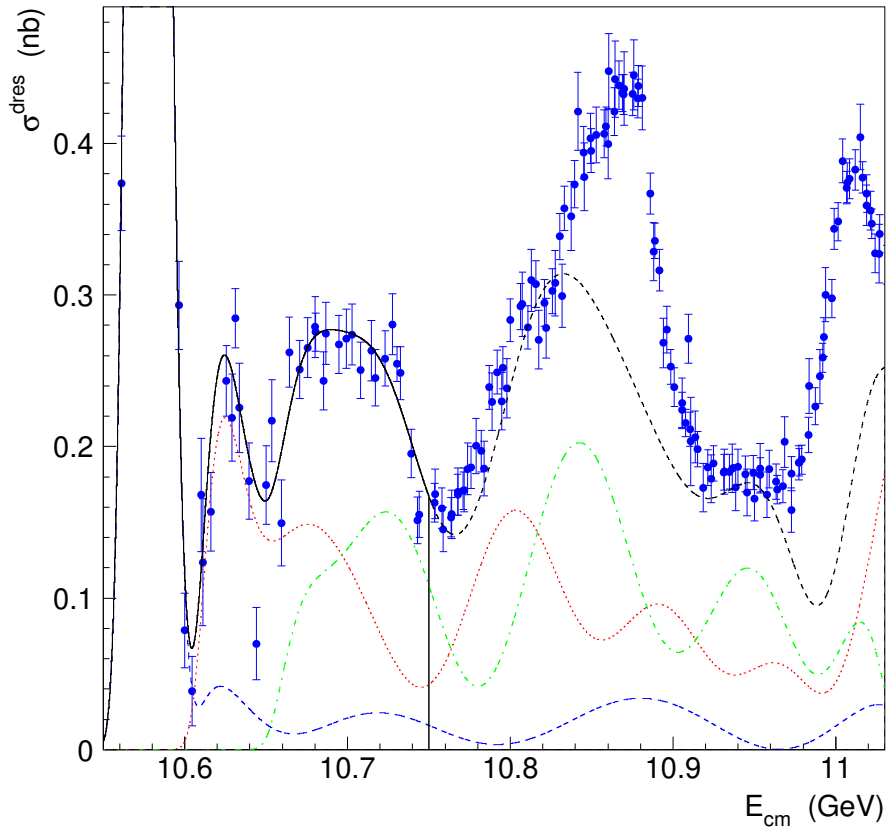


Figure: Energy dependence of the total dressed cross section. Solid black curve is the result of the simultaneous fit to this distribution and the exclusive $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ cross section energy dependence. Also shown are the individual contributions of $B\bar{B}$ (blue dashed curve), $B\bar{B}^*$ (red dotted curve) and $B^*\bar{B}^*$ (green dash-dotted curve).

Systematic uncertainty due to $\sigma^{\rm dressed}$ parameterization

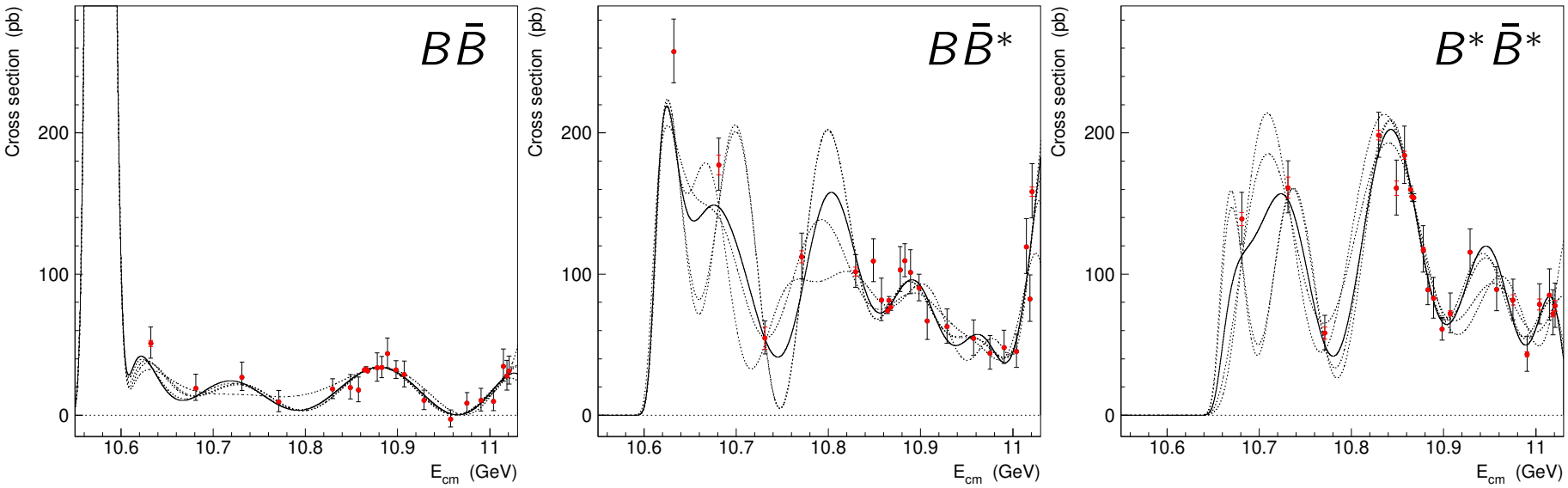


Figure: Measured dressed cross sections for $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$. The outer error bars indicate statistical uncertainties and inner red error bars indicate systematic uncertainties due to the cross section parameterization. Solid curves show the fit results for the default set of polynomial orders. Dotted curves show the fit results for the polynomial orders varied by ± 1 and ± 2.

Cross section table

No.	$E_{\rm cm}$	L	$\sigma(B\bar{B})$	$\sigma(B\bar{B}^*)$	$\sigma(B^*\bar{B}^*)$
1	11020.8 ± 1.4	0.982	$31.4 \pm 9.9 \pm 1.2 \pm 1.7$	$158.4 \pm 19.3 \pm 4.2 \pm 7.7$	$77.5 \pm 15.6 \pm 5.4 \pm 3.6$
2	11018.5 ± 2.0	0.859	$27.8 \pm 10.5 \pm 1.0 \pm 1.5$	$82.4 \pm 16.5 \pm 2.3 \pm 4.0$	$71.9 \pm 15.9 \pm 3.1 \pm 3.4$
3	11014.8 ± 1.4	0.771	$34.8 \pm 11.4 \pm 1.2 \pm 1.9$	$119.1 \pm 19.5 \pm 2.4 \pm 5.8$	$85.0 \pm 18.1 \pm 2.7 \pm 3.9$
4	11003.9 ± 1.0	0.976	$9.7 \pm 7.0 \pm 0.3 \pm 0.6$	$45.2 \pm 11.8 \pm 1.3 \pm 2.2$	$78.5 \pm 14.2 \pm 5.1 \pm 3.6$
5	10990.4 ± 1.3	0.985	$10.5 \pm 8.0 \pm 0.4 \pm 0.7$	$48.0 \pm 11.7 \pm 2.0 \pm 2.3$	$43.1 \pm 12.4 \pm 3.5 \pm 2.0$
6	10975.3 ± 1.4	0.999	$8.5 \pm 7.1 \pm 1.2 \pm 0.5$	$44.0 \pm 11.9 \pm 0.8 \pm 2.1$	$81.7 \pm 14.3 \pm 4.5 \pm 3.6$
7	10957.5 ± 1.5	0.969	$-2.9 \pm 6.0 \pm 0.1 \pm 0.3$	$54.5 \pm 12.6 \pm 1.6 \pm 2.5$	$89.2 \pm 15.5 \pm 2.5 \pm 3.8$
8	10928.7 ± 1.6	1.149	$10.5 \pm 6.9 \pm 0.9 \pm 0.6$	$62.7 \pm 12.1 \pm 1.6 \pm 2.7$	$115.6 \pm 16.2 \pm 3.8 \pm 4.7$
9	10907.3 ± 1.1	0.980	$28.8 \pm 9.1 \pm 2.0 \pm 1.4$	$66.7 \pm 13.5 \pm 3.2 \pm 2.8$	$72.1 \pm 14.0 \pm 4.0 \pm 2.8$
10	10898.3 ± 0.7	2.408	$32.2 \pm 6.3 \pm 0.5 \pm 1.4$	$90.2 \pm 9.4 \pm 1.3 \pm 3.7$	$61.0 \pm 8.0 \pm 1.4 \pm 2.3$
11	10888.9 ± 0.8	0.990	$43.7 \pm 10.5 \pm 0.7 \pm 2.0$	$101.2 \pm 15.6 \pm 1.0 \pm 4.1$	$82.8 \pm 14.4 \pm 1.8 \pm 3.1$
12	10882.8 ± 0.7	1.848	$33.8 \pm 7.5 \pm 0.4 \pm 1.5$	$109.5 \pm 11.7 \pm 1.5 \pm 4.4$	$88.9 \pm 10.8 \pm 2.5 \pm 3.3$
13	10877.8 ± 0.8	0.978	$33.7 \pm 10.1 \pm 1.7 \pm 1.5$	$103.1 \pm 16.0 \pm 2.8 \pm 4.1$	$117.3 \pm 16.4 \pm 3.0 \pm 4.3$
14	10867.6 ± 0.2	45.28	$31.3 \pm 1.5 \pm 0.0 \pm 1.3$	$76.5 \pm 2.1 \pm 0.1 \pm 3.2$	$154.1 \pm 2.7 \pm 0.2 \pm 6.2$
15	10865.8 ± 0.3	29.11	$32.6 \pm 1.8 \pm 0.0 \pm 1.4$	$81.3 \pm 2.7 \pm 0.1 \pm 3.4$	$155.0 \pm 3.4 \pm 0.1 \pm 6.2$
16	10864.2 ± 0.3	47.65	$32.1 \pm 1.4 \pm 0.0 \pm 1.4$	$74.2 \pm 2.0 \pm 0.1 \pm 3.1$	$159.9 \pm 2.7 \pm 0.3 \pm 6.4$
17	10857.4 ± 0.9	0.988	$17.8 \pm 8.7 \pm 1.2 \pm 0.8$	$81.5 \pm 15.0 \pm 2.5 \pm 3.2$	$184.2 \pm 20.4 \pm 4.4 \pm 6.5$
18	10848.9 ± 1.0	0.989	$19.6 \pm 8.7 \pm 2.3 \pm 0.9$	$109.3 \pm 15.2 \pm 3.2 \pm 4.1$	$160.8 \pm 19.4 \pm 6.2 \pm 5.6$
19	10829.5 ± 1.2	1.697	$18.5 \pm 7.0 \pm 0.7 \pm 0.8$	$101.8 \pm 11.6 \pm 3.4 \pm 3.7$	$198.4 \pm 16.0 \pm 4.2 \pm 6.6$
20	10771.2 ± 1.0	0.955	$9.6 \pm 7.5 \pm 2.2 \pm 0.5$	$112.2 \pm 16.2 \pm 5.2 \pm 3.6$	$58.2 \pm 12.1 \pm 6.1 \pm 1.7$
21	10731.3 ± 1.5	0.946	$27.0 \pm 10.1 \pm 1.4 \pm 1.0$	$54.7 \pm 11.7 \pm 8.5 \pm 1.6$	$161.3 \pm 18.4 \pm 8.7 \pm 4.2$
22	10681.0 ± 1.4	0.949	$19.2 \pm 9.3 \pm 4.1 \pm 0.7$	$177.3 \pm 18.4 \pm 10.7 \pm 4.5$	$139.0 \pm 18.4 \pm 5.7 \pm 3.1$
23	10632.2 ± 1.5	0.989	$50.9 \pm 11.1 \pm 6.0 \pm 1.4$	$257.6 \pm 22.7 \pm 8.1 \pm 5.6$	—

Table: Dressed cross sections (in pb). The first error is statistical, the second is uncorrelated systematic and the third is correlated systematic.

Correlated systematic uncertainty at $\Upsilon(5S)$

	$\sigma(B\bar{B})$	$\sigma(B\bar{B}^*)$	$\sigma(B^*\bar{B}^*)$
Cross section shape			
– statistical uncertainty	0.47	1.22	0.79
– parameterization	0.18	1.29	1.48
$E_{\rm cm}$ spread	0.19	0.03	0.06
Yield of peaking background	0.14	0.05	0.05
Shape of peaking background	0.80	0.09	0.20
Efficiency	3.38	3.38	3.38
Luminosity	1.4	1.4	1.4
Total	3.79	4.07	4.03

Visible cross sections and event fractions at $\Upsilon(5S)$

Table: Visible cross sections $\sigma^{\rm vis}$ (in pb) for various processes at $\Upsilon(5S)$ and corresponding $\sigma^{\rm vis}/\sigma_{b\bar{b}}$ fractions (in %). The $B\bar{B}X$ final state includes $B^{(*)}\bar{B}^{(*)}$ and $B^{(*)}\bar{B}^{(*)}\pi(\pi)$. The errors contain the statistical and systematic contributions.

	$\sigma^{\rm vis}$	$\sigma^{\rm vis}/\sigma_{b\bar{b}}$
$e^+e^- \to B\bar{B}X$	255.5 ± 7.9	75.1 ± 4.0
$e^+e^- \to B\bar{B}$	33.3 ± 1.2	9.8 ± 0.5
$e^+e^- \to B\bar{B}^*$	68.0 ± 3.3	20.0 ± 1.3
$e^+e^- \to B^*\bar{B}^*$	124.4 ± 5.3	36.6 ± 2.2

PDG 2020 + isospin relations: $f_{\rm bottomonium} = (4.9^{+5.0}_{-0.6})\%$.

Fraction of $B_s^{(*)}\bar{B}_s^{(*)}$ events $f_s = 1 - f_{B\bar{B}X} - f_{\rm bottomonium} = 0.200^{+0.040}_{-0.064}$.
Consistent with PDG 2020: $f_s = 0.201 \pm 0.031$.