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

arxiv:2104.08371, submitted to JHEP

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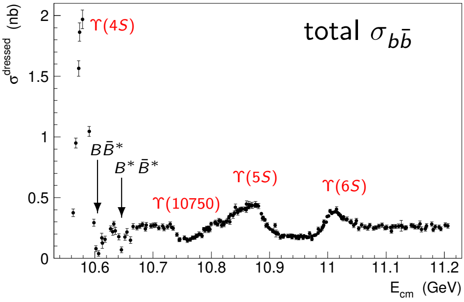
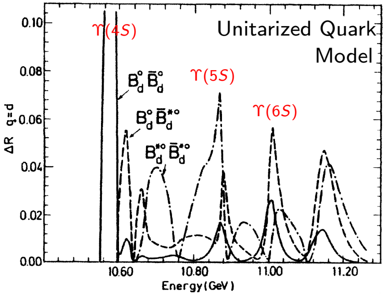
Particle Physics Seminar, 23 April 2021, BINP

Motivation

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



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



$\sigma_{b\bar{b}}$ is not decomposed into exclusive cross sections.

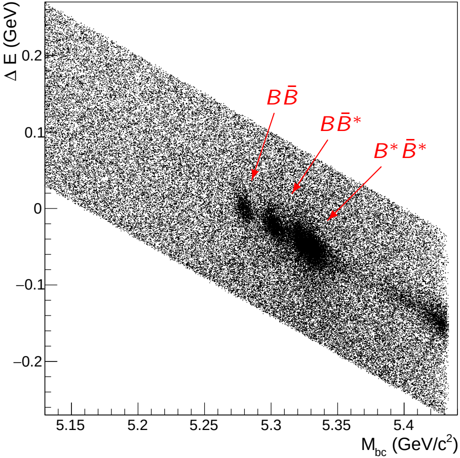
Unitarized Quark Model: minima are due to nodes of the $\Upsilon(4S, 5S, 6S)$ wave functions – information about Υ states.

$\Upsilon(4S, 5S, 6S)$ have anomalous transitions to low bottomonia

Bondar et al. MPLA **32**, 1750025 (2017).

Method

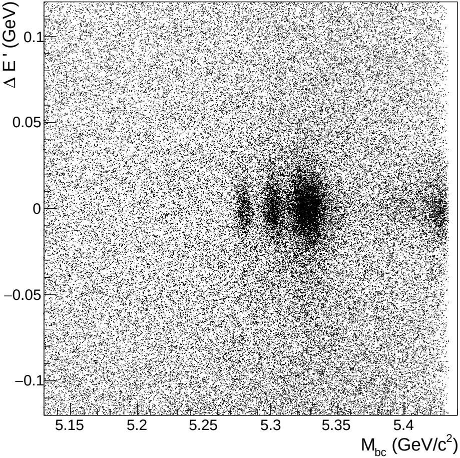
$$M_{bc} = \sqrt{(E_{\mathrm{cm}}/2)^2 - p_B^2} \qquad \Delta E = E_B - E_{\mathrm{cm}}/2$$



$B^* \to B\gamma$, γ is not reconstructed.

Method (II)

$$\Delta E' = \Delta E + M_{bc} - m_B$$



Reconstruct $B \to \textit{hadrons}$ (~1100 final states).

Data samples

- scan data: 22 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.

FEI: B channels

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

FEI: D channels

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

Selection

Use *Full Event Interpretation* package from Belle II software.

Training: variables not correlated with $p_B \Rightarrow$ efficiency is const. in E_{cm}.

$\pi^\pm$, $K^\pm$, $\mu^\pm$, $e^\pm$: PID, p, p_t.

γ: N hits, E_9/E_{25}, E, p_t.

π^0: M, p, decay angle.

K_S: M, detached vertex variables.

D: SignalProbability (classifier output) of each daughter; M; χ^2 of mass-vertex constrained fit; for 3-body decays: masses of all pairs of daughters (ϕ, K^*, ρ).

D^*, J/ψ: SignalProbability of each daughter; M.

Selection (II)

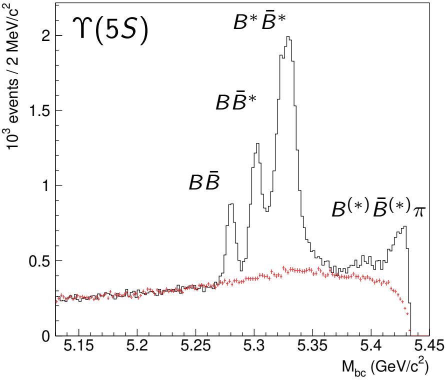
B: SignalProbability of each daughter; χ^2 of B vertex fit; distance between B and D vertices, significance of this distance, cos angle between D momentum and direction from B to D vertices (if D is available); masses of $\rho\,(\to \pi\pi)$ and $a_1(\to 3\pi)$ candidates (if available).

Continuum suppression: R_2, $\cos\theta_{\mathrm{thrust}}$, flag indicating presence of high-momentum lepton.

$\Delta E'$ is not included – use $\Delta E'$ sidebands to constrain background.

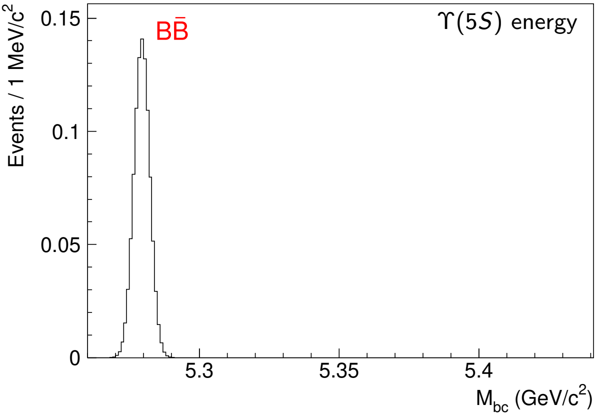
For each B-decay channel apply individual requirements on $|\Delta E'|$ and SignalProbability maximizing overall $S/\sqrt{S+B}$.

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



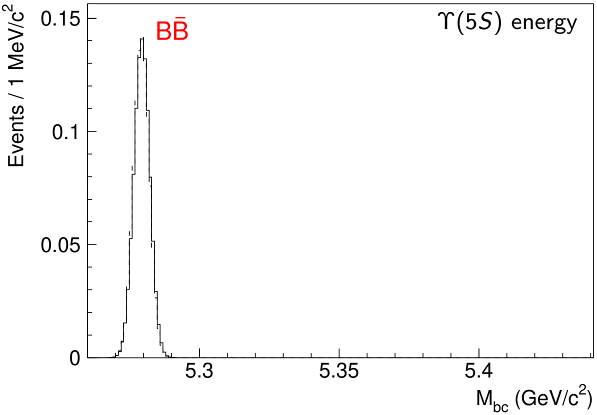
$\Delta E'$ sidebands describe combinatorial background well; there is a peaking background (soft γ).

M_{bc} fit function



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 $B^* \to B\gamma$.

M_{bc} fit function



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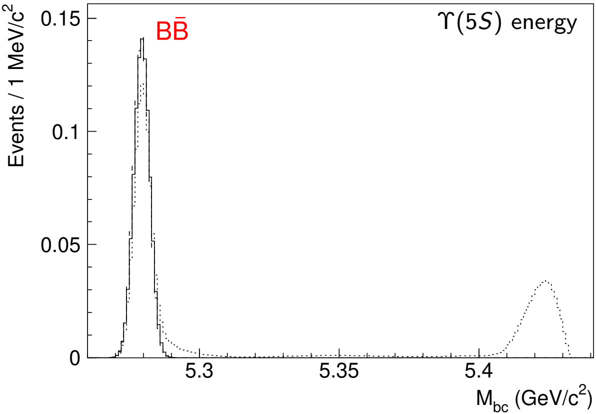

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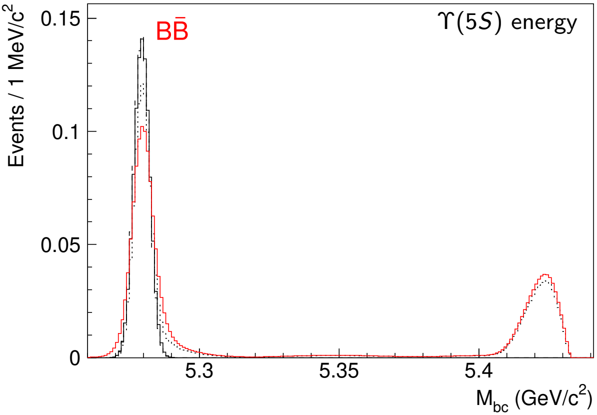

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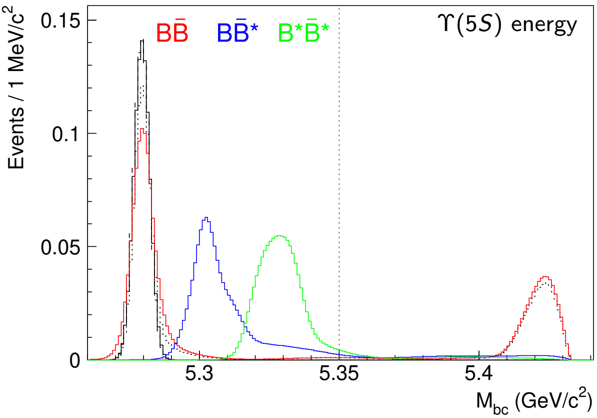
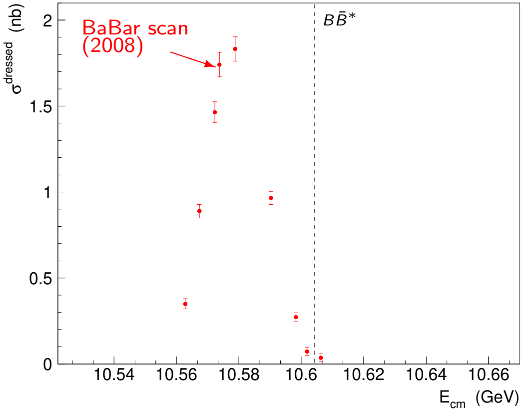
M_{bc} fit function



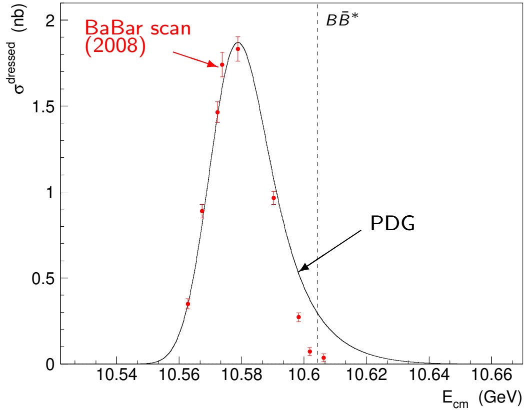
Fit function is calculated numerically and takes into account:
$E_{\rm cm}$ spread, energy dependence of cross section, ISR, momentum resolution and peaking background, kinematics of $B^* \to B\gamma$.

$B^* \to B\gamma$: 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 (A.I. Milstein).

$e^+e^- \to B\bar{B}$ near $\Upsilon(4S)$



$e^+e^- \to B\bar{B}$ near $\Upsilon(4S)$

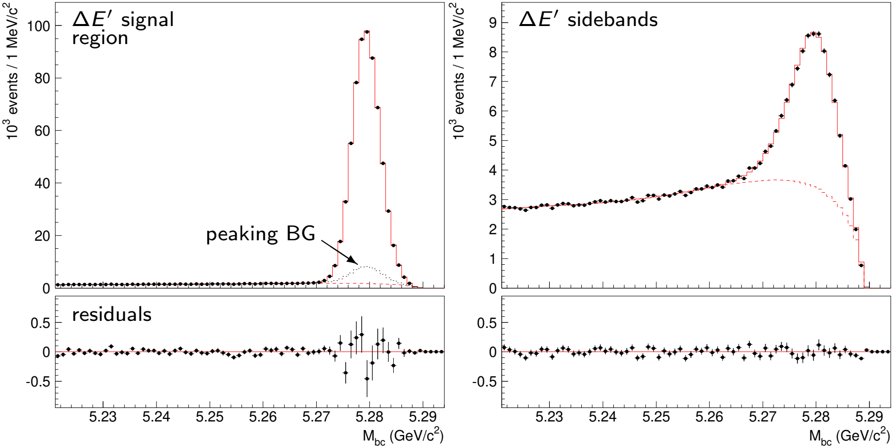


Need phenomenological model to describe cross section shape.

Use high-order Chebyshev polynomial for parameterization.

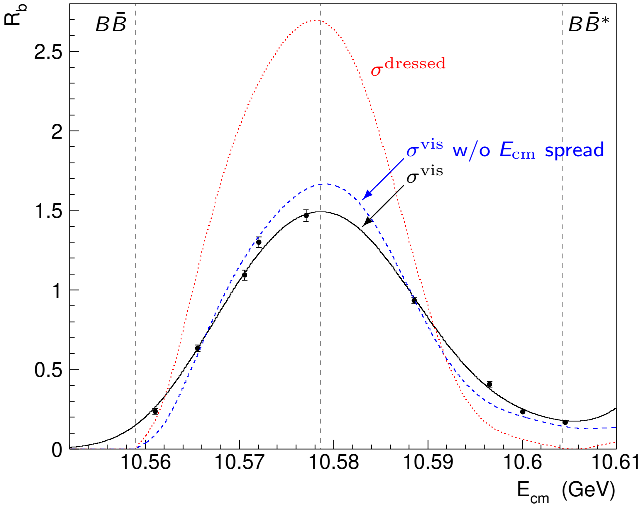
Simultaneous fit to BaBar scan points and Belle M_{bc} distributions.

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



Fit describes data well.

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



Nominal $E_{\rm cm}$ is at the maximum of visible cross section – constraint.
Fit describes data well.

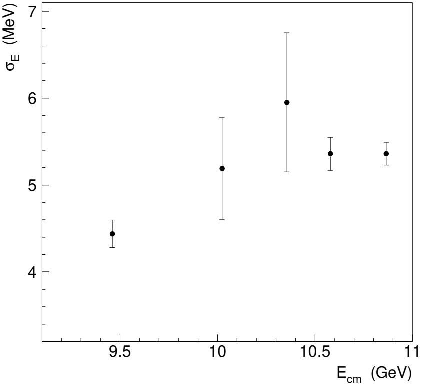
$\Upsilon(4S)$: fit results

N	$(581.2 \pm 1.1 \pm 3.2) \times 10^3$
σ_{E}	$(5.36 \pm 0.11 \pm 0.16)\,\mathrm{MeV}$
$\Delta E_{\mathrm{BaBar}}$	$(-1.75 \pm 0.14 \pm 0.67)\,\mathrm{MeV}$
n	1.16 ± 0.03
s_3	$(-0.2 \pm 0.6)\,\mathrm{MeV}/c$
ϕ_3	1.00 ± 0.02

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

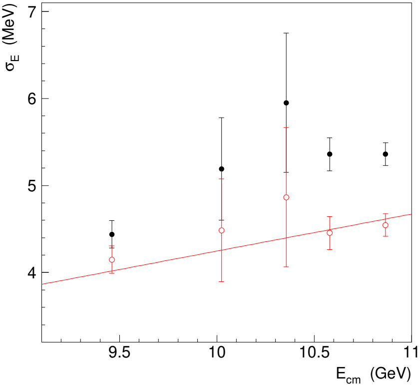
$N_{B\bar{B}} = N_{b\bar{b}}$: number of hadronic events (continuum subtracted)

E_{cm} spread at various E_{cm}



Spread at $\Upsilon(1S, 2S, 3S)$ is found based on visible cross sections.

E_{cm} spread at various E_{cm}

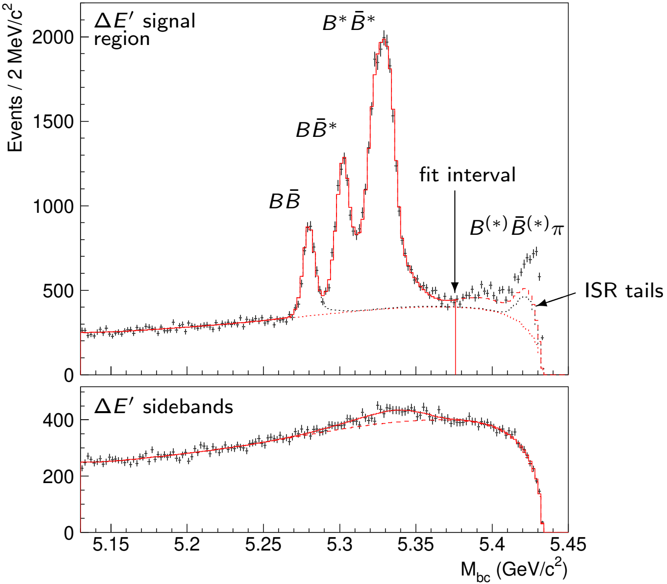


Spread at $\Upsilon(1S, 2S, 3S)$ is found based on visible cross sections.

KEKB: microwave instability at $I^{+}_{\mathrm{bunch}} > 0.5mA$ – increase of spread.

Energy dependence of corrected spread is consistent with proportionality.

Fit at $\Upsilon(5S)$



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

$\Upsilon(5S)$: fit results

N_{total}	$(23.66 \pm 0.22 \pm 0.34) \times 10^3$
$N_{\mathrm{B\bar{B}}}$ / N_{total}	0.1121 ± 0.0030
$N_{\mathrm{B\bar{B}^*}}$ / N_{total}	0.3095 ± 0.0045
$N_{\mathrm{B^*\bar{B}^*}}$ / N_{total}	0.5784 ± 0.0048
a_{h}	-0.18 ± 0.07

$$\varepsilon_{\Upsilon(5S)} = \frac{N_{\mathrm{total}}}{2\, N_{B\bar{B}}[\Upsilon(4S)]\; R} = (0.492 \pm 0.017) \times 10^{-3}$$

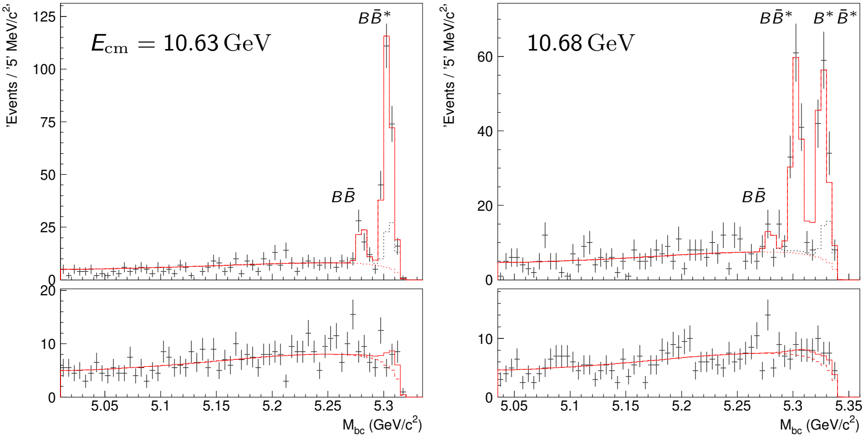
R: ratio of B yields at $\Upsilon(5S)$ and $\Upsilon(4S)$, measured w/ 5 clean channels

$\varepsilon_{\Upsilon(5S)}/\varepsilon_{\Upsilon(4S)} = 1.049 \pm 0.032$, MC: 1.028 ± 0.004 – agreement.

Efficiency at scan energies: linear interpolation.

M_{bc} fits in scan data

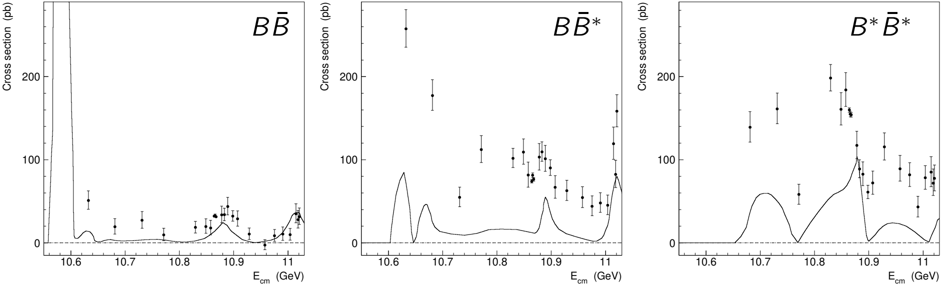
Examples: lowest energies



Fit works well at all energies

Dressed cross sections

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

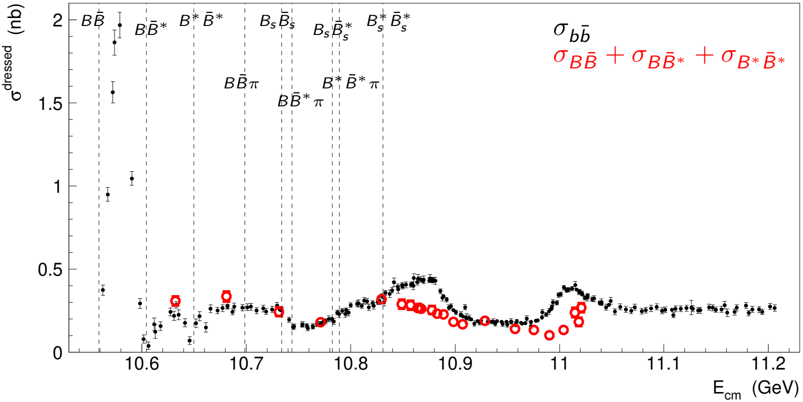


Oscillatory behavior.

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

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

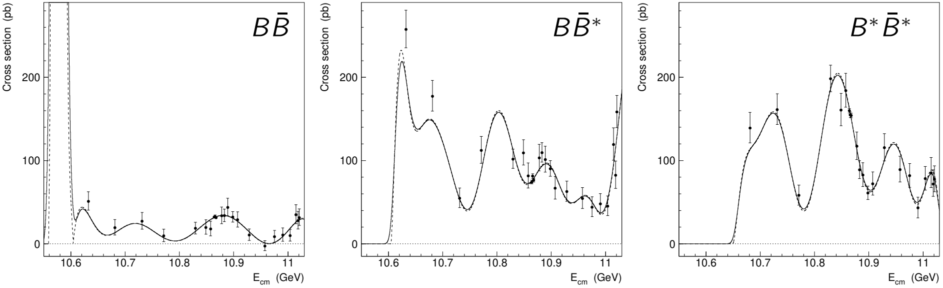
Dong et al. CPC**44**, 083001 (2020)



- $\sigma_{b\bar{b}}$ and $\sum \sigma_{B^{(*)}\bar{B}^{(*)}}$ coincide at low $E_{\rm cm}$ – 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?

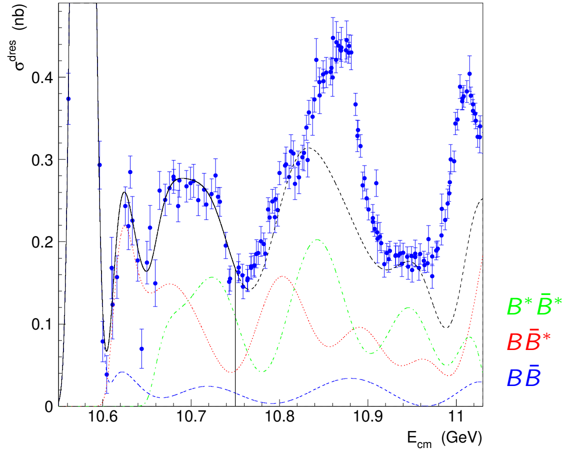
Fit of cross section shapes



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

Use iterative procedure.

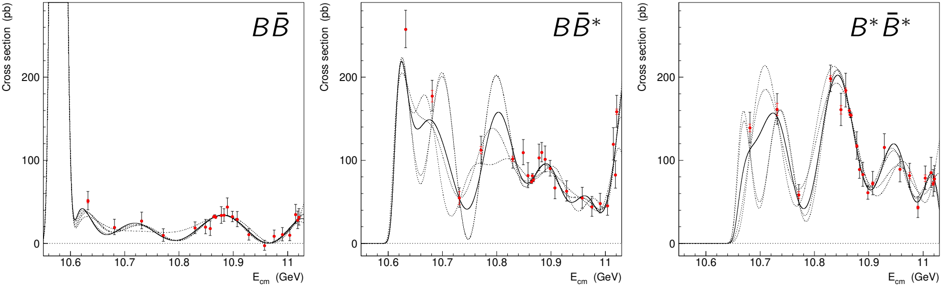
Fit of cross section shapes (II)



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 $E_{\mathrm{cm}} < 10.75\,\mathrm{GeV}$).

Systematics: parameterization of σ vs. $E_{\rm cm}$

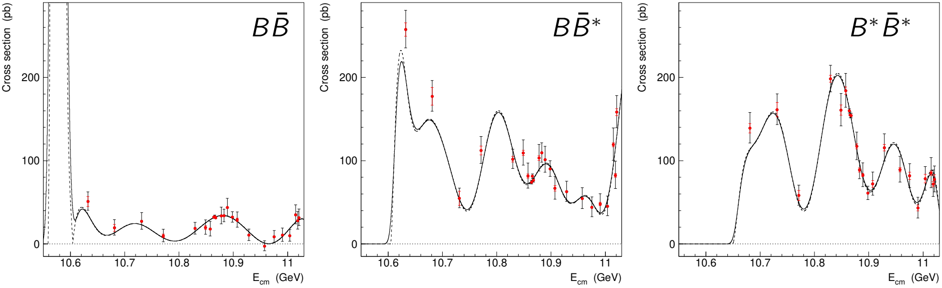
stat. and syst. errors



Systematics: polynomial orders: ±1, ±2.
Shape is not well constraint at low energy where scan step is large.
Systematics is small.

Systematics

stat. and total uncorrelated syst. errors



Uncorrelated syst.: σ parameterization, toy MC, shape of smooth BG.

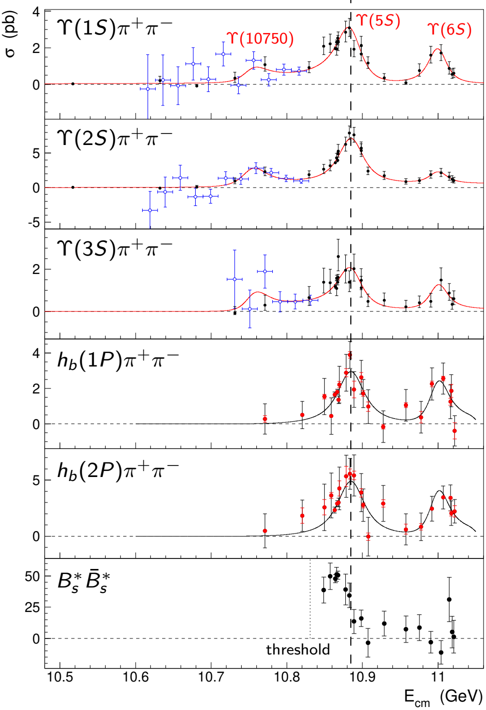
Correlated: $E_{\rm cm}$ spread, peaking BG, efficiency, luminosity.

Systematic uncertainties are 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	$31.5 \pm 9.9 \pm 1.2 \pm 1.7$	$158.4 \pm 19.3 \pm 4.2 \pm 7.7$	$77.6 \pm 15.6 \pm 5.4 \pm 3.6$
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	$34.8 \pm 11.4 \pm 1.2 \pm 1.9$	$119.2 \pm 19.5 \pm 2.4 \pm 5.8$	$85.0 \pm 18.1 \pm 2.7 \pm 3.9$
4	11003.9 ± 1.0	0.976	$9.7 \pm 7.0 \pm 0.3 \pm 0.6$	$45.2 \pm 11.8 \pm 1.3 \pm 2.2$	$78.4 \pm 14.2 \pm 5.1 \pm 3.6$
5	10990.4 ± 1.3	0.985	$10.5 \pm 8.1 \pm 0.4 \pm 0.7$	$47.9 \pm 11.7 \pm 2.0 \pm 2.3$	$43.1 \pm 12.4 \pm 3.5 \pm 2.0$
6	10975.3 ± 1.4	0.999	$8.5 \pm 7.2 \pm 1.2 \pm 0.6$	$44.0 \pm 11.9 \pm 0.8 \pm 2.1$	$81.7 \pm 14.3 \pm 4.5 \pm 3.6$
7	10957.5 ± 1.5	0.969	$-2.8 \pm 6.0 \pm 0.1 \pm 0.3$	$54.5 \pm 12.6 \pm 1.6 \pm 2.5$	$89.2 \pm 15.5 \pm 2.5 \pm 3.8$
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	$28.8 \pm 9.1 \pm 2.0 \pm 1.4$	$66.8 \pm 13.5 \pm 3.2 \pm 2.8$	$72.1 \pm 14.0 \pm 4.0 \pm 2.8$
10	10898.3 ± 0.7	2.408	$32.2 \pm 6.3 \pm 0.5 \pm 1.4$	$90.2 \pm 9.4 \pm 1.3 \pm 3.7$	$61.1 \pm 8.0 \pm 1.4 \pm 2.3$
11	10888.9 ± 0.8	0.990	$43.8 \pm 10.5 \pm 0.7 \pm 2.0$	$101.2 \pm 15.6 \pm 1.0 \pm 4.1$	$82.7 \pm 14.4 \pm 1.8 \pm 3.1$
12	10882.8 ± 0.7	1.848	$33.9 \pm 7.5 \pm 0.4 \pm 1.5$	$109.6 \pm 11.7 \pm 1.5 \pm 4.4$	$88.9 \pm 10.8 \pm 2.5 \pm 3.3$
13	10877.8 ± 0.8	0.978	$33.7 \pm 10.1 \pm 1.7 \pm 1.5$	$103.1 \pm 16.0 \pm 2.8 \pm 4.1$	$117.3 \pm 16.6 \pm 3.0 \pm 4.3$
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	$32.7 \pm 1.9 \pm 0.0 \pm 1.4$	$81.3 \pm 2.7 \pm 0.1 \pm 3.4$	$154.9 \pm 3.4 \pm 0.1 \pm 6.2$
16	10864.2 ± 0.3	47.65	$32.2 \pm 1.4 \pm 0.0 \pm 1.4$	$74.2 \pm 2.0 \pm 0.1 \pm 3.1$	$159.9 \pm 2.7 \pm 0.3 \pm 6.3$
17	10857.4 ± 0.9	0.988	$17.8 \pm 8.8 \pm 1.2 \pm 0.8$	$81.5 \pm 15.0 \pm 2.5 \pm 3.2$	$184.1 \pm 20.4 \pm 4.4 \pm 6.5$
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	$18.6 \pm 7.0 \pm 0.7 \pm 0.8$	$101.8 \pm 11.6 \pm 3.4 \pm 3.7$	$198.4 \pm 16.0 \pm 4.2 \pm 6.6$
20	10771.2 ± 1.0	0.955	$9.7 \pm 7.6 \pm 2.2 \pm 0.5$	$112.2 \pm 16.2 \pm 5.2 \pm 3.6$	$58.2 \pm 12.1 \pm 6.1 \pm 1.7$
21	10731.3 ± 1.5	0.946	$27.0 \pm 10.1 \pm 1.4 \pm 1.0$	$54.7 \pm 11.8 \pm 8.5 \pm 1.6$	$161.3 \pm 18.4 \pm 8.7 \pm 4.2$
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	$51.0 \pm 11.1 \pm 6.0 \pm 1.4$	$257.6 \pm 22.7 \pm 8.1 \pm 5.6$	—

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



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

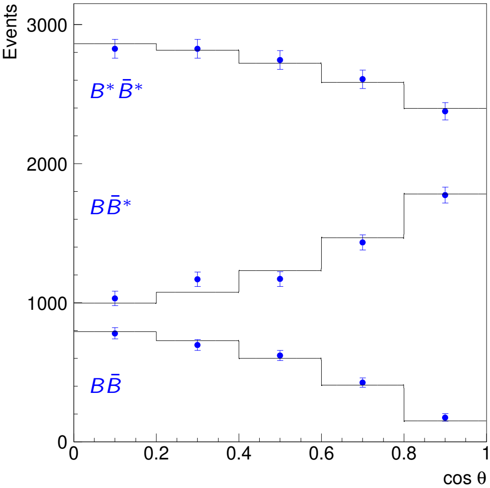
JHEP **10**, 220 (2019)
PRL **117**, 142001 (2016)
arXiv:1609.08749

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.

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 $B^* \to B\gamma$.

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

	σ^{vis} (pb)	$\sigma^{\text{vis}} / \sigma_{b\bar{b}}$ (%)
$e^+e^- \to B\bar{B}X$	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: $f_{\text{bottomonium}} = (4.9^{+5.0}_{-0.6})\%$.

Fraction of $B_s^{(*)}\bar{B}_s^{(*)}$ events $f_s = 1 - f_{B\bar{B}X} - f_{\text{bottomonium}} = (20.0^{+4.0}_{-6.4})\%$.
Consistent with PDG 2020: $f_s = (20.1 \pm 3.1)\%$.

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 GeV.

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

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 $h_b(1P, 2P)\pi^+\pi^-$.

Separation between scan points at low energy is 50 MeV – too big, we miss structures. Belle-II can improve on this.