

Production of exotic hadrons and charmonium at e^+e^- B-factories



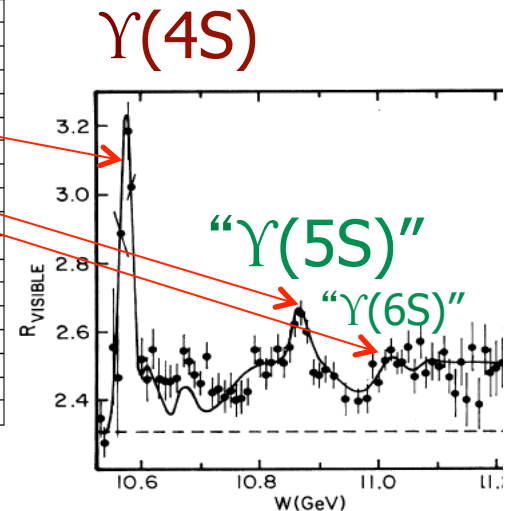
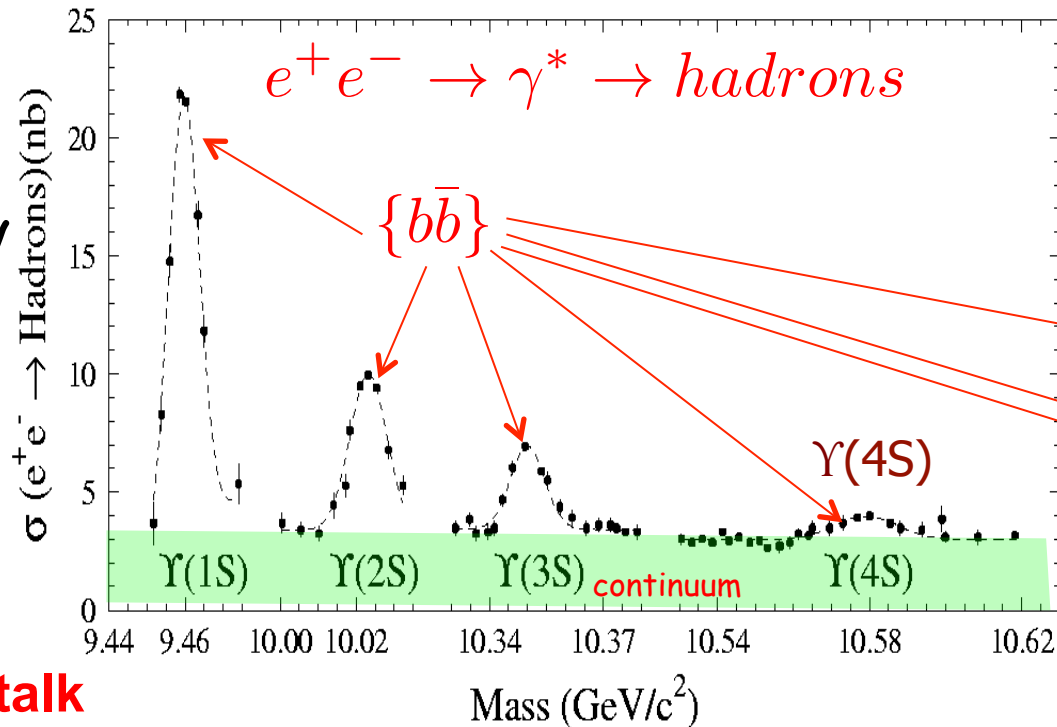
- Studies in the $\Upsilon(5S) - \Upsilon(6S)$ region
At $\Upsilon(5S)$
Energy scan $\Upsilon(5S) \rightarrow \Upsilon(6S)$
- Charmonia in B decays at $\Upsilon(4S)$
- Charmonia in $\Upsilon(1S)$



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e^+e^- B-factories

Upsilon region
~9-11 GeV



Data, this talk

- KEKB/Belle
 - 1999-2010 8.5 GeV e^- + 3.5 GeV e^+
 - 772M $\Upsilon(4S)$ events(B pair), ~37M b-pair@ $\Upsilon(5S)$,
~31 fb^{-1} $\Upsilon(5S)$ scan, 5.7 fb^{-1} $\Upsilon(1S)$
- PEP-II/Babar
 - 1999-2008 9 GeV e^- + 3 GeV e^+
 - 471M $\Upsilon(4S)$

Bottomonia

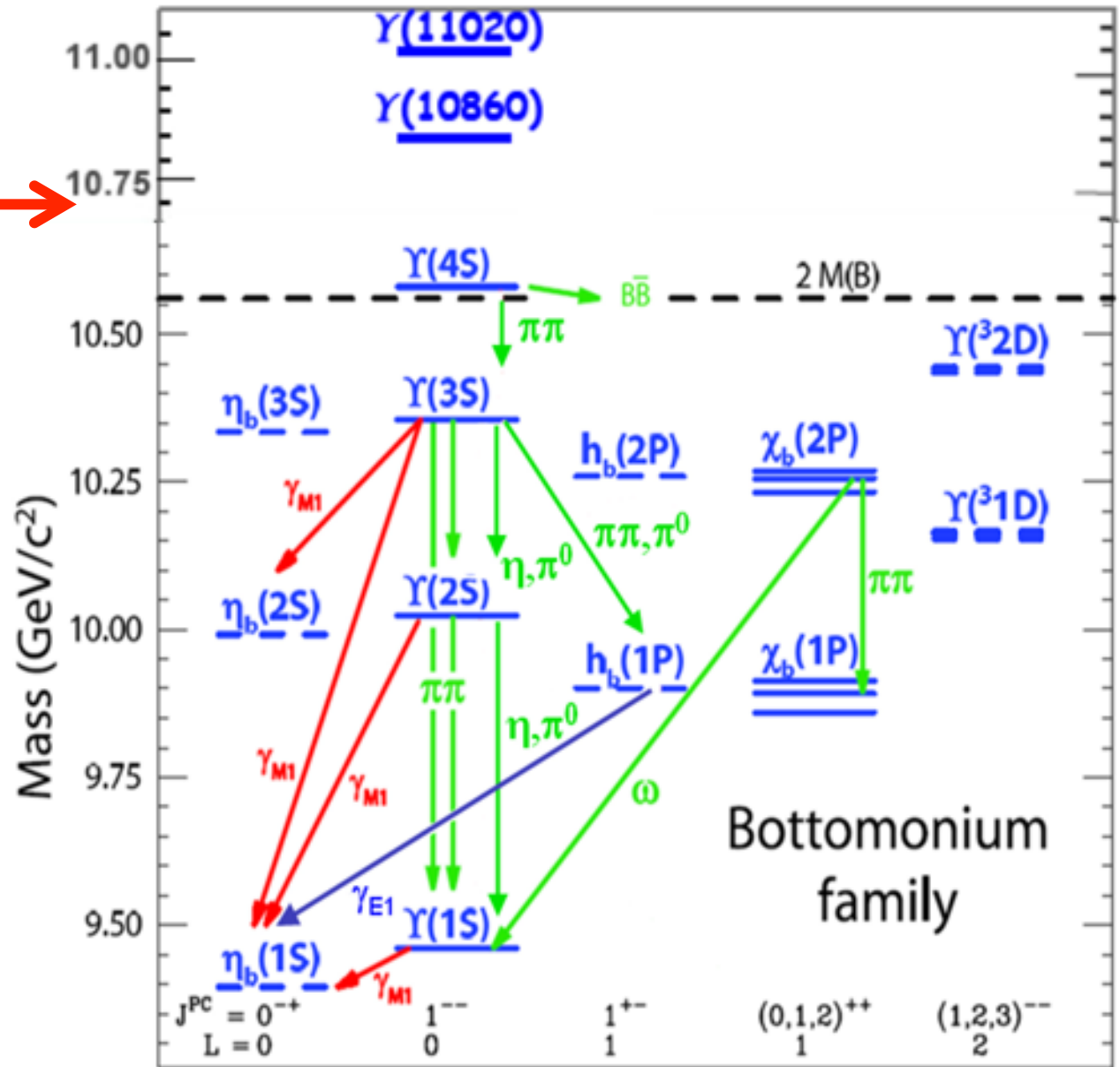


Bottomonium: \longrightarrow

- Atomic-like b-pair bound state

“Bottomonium-like:”

- additional quark pair



History of bottomonium-like states



[Using “Y(5S)”, “Y(6S)” as shorthand for Y(10860), Y(11020)]

- Unexpectedly high rate to $Y(nS)\pi^+\pi^-$ ($n=1,2,3$), $\times 10^2$, at Y(5S)
 - PRL 100, 112001 (2008)
- $\sigma(Y(nS)\pi\pi)$, $\sigma(bb)$ vs CMS energy: “Y(5S)” peaks offset by 9 ± 4 MeV
 - PRD 82, 091106 (2010)
- Bottomonium-like $Z_b^\pm(10610)$, $Z_b^\pm(10650)$ in 5 channels at Y(5S):
 $Y(nS)\pi^\pm$, $h_b(mP)\pi^\pm$ ($m=1,2$)
 - PRL 108, 122001 (2012)
- Neutral Bottomonium-like $Z_b^0(10610)$ to $Y(nS)\pi^0$ at Y(5S)
 - PRD 88, 052016 (2013)
- $Z_b^\pm(10610)$, $Z_b^\pm(10650) \rightarrow Y(nS)\pi^\pm$ amplitude analysis yields $J^P=1^+$
 - PRD 91, 072003 (2015)

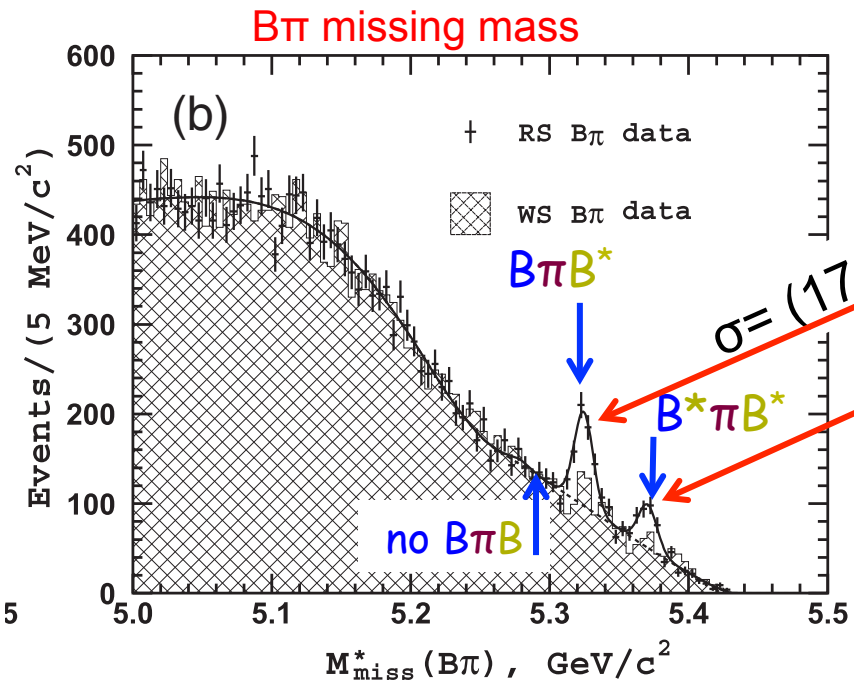
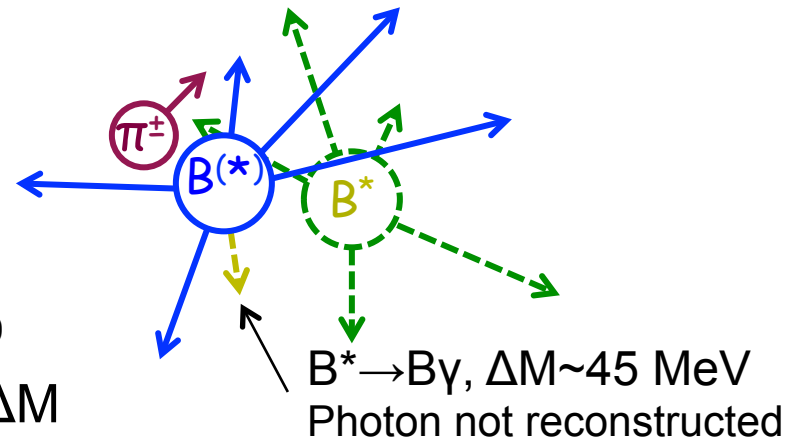
Recent developments on bottomonium-like states



- $Z_b^\pm(10610) \rightarrow B^*B$, $Z_b^\pm(10650) \rightarrow B^*B^*$ observed
 - PRL 116, 212001 (2016)

Exclusive events $B^*B^{(*)}\pi^\pm$

- Fully reconstructed $B^{0/\pm} + \pi^\mp$
- Sign of π^\pm correlates w B flavor
- “wrong sign” – background + mixed B^0
- $B\pi$ missing mass: peaks at M_{B^*} , $M_{B^*} + \Delta M$



Select $B\pi B^*$, $B^*\pi B^*$ events

$\sigma = (17.4 \pm 1.6 \pm 1.9) \text{ pb}$

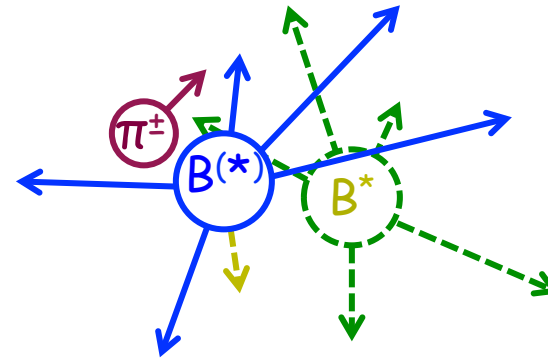
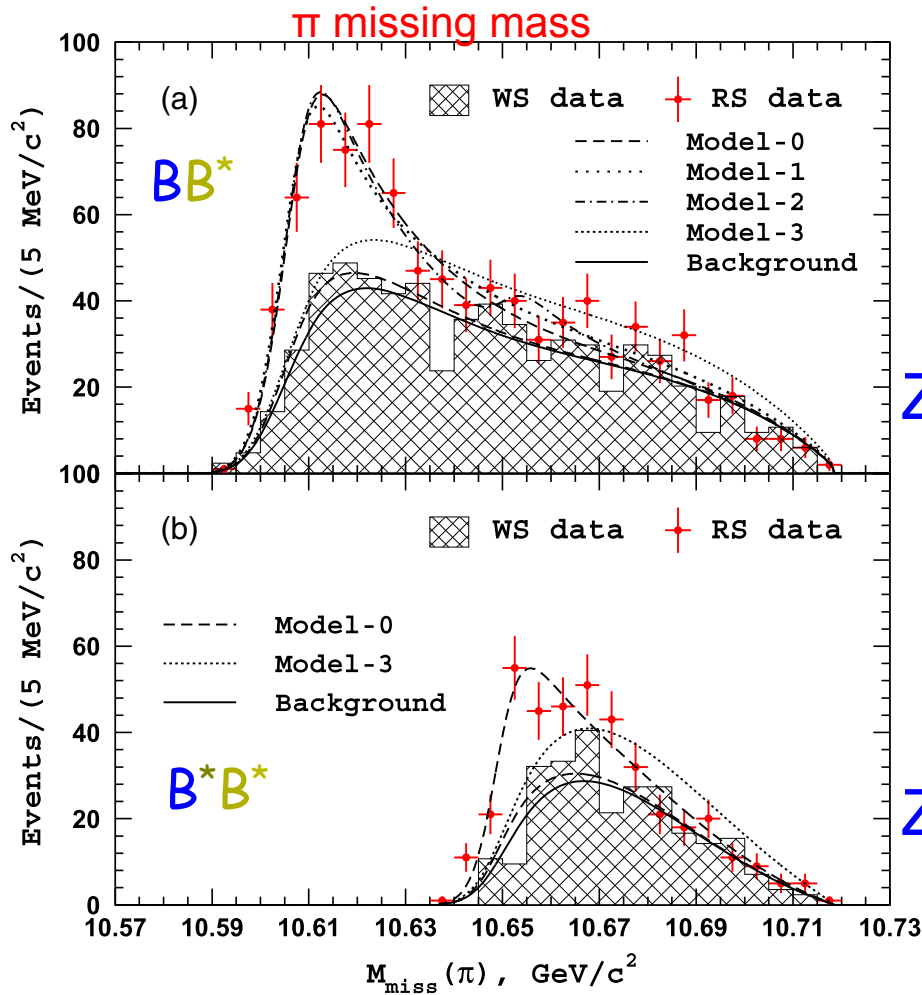
$\sigma = (8.75 \pm 1.15 \pm 1.04) \text{ pb}$

- Probe B^*B^* , $B B^*$ mass through π missing mass \longrightarrow

Recent developments on bottomonium-like states



- $Z_b^\pm(10610) \rightarrow B^*B$, $Z_b^\pm(10650) \rightarrow B^*B^*$ observed
 – PRL 116, 212001 (2016)



$Z_b(10610)$ dominates $B^*B\pi$

$Z_b(10650)$ dominates $B^*B^*\pi$

Recent developments on bottomonium-like states



- $Z_b^\pm(10610) \rightarrow B^*B$, $Z_b^\pm(10650) \rightarrow B^*B^*$ observed
 - PRL 116, 212001 (2016)

$B^*B^{(*)}$ dominate Z_b channels observed so far

| Channel | Fraction, % | |
|-------------------------------------|----------------------------------|----------------------------------|
| | $Z_b(10610)$ | $Z_b(10650)$ |
| $\Upsilon(1S)\pi^+$ | $0.54^{+0.16+0.11}_{-0.13-0.08}$ | $0.17^{+0.07+0.03}_{-0.06-0.02}$ |
| $\Upsilon(2S)\pi^+$ | $3.62^{+0.76+0.79}_{-0.59-0.53}$ | $1.39^{+0.48+0.34}_{-0.38-0.23}$ |
| $\Upsilon(3S)\pi^+$ | $2.15^{+0.55+0.60}_{-0.42-0.43}$ | $1.63^{+0.53+0.39}_{-0.42-0.28}$ |
| $h_b(1P)\pi^+$ | $3.45^{+0.87+0.86}_{-0.71-0.63}$ | $8.41^{+2.43+1.49}_{-2.12-1.06}$ |
| $h_b(2P)\pi^+$ | $4.67^{+1.24+1.18}_{-1.00-0.89}$ | $14.7^{+3.2+2.8}_{-2.8-2.3}$ |
| $B^+\bar{B}^{*0} + \bar{B}^0B^{*+}$ | $85.6^{+1.5+1.5}_{-2.0-2.1}$ | ... |
| $B^{*+}\bar{B}^{*0}$ | ... | $73.7^{+3.4+2.7}_{-4.4-3.5}$ |

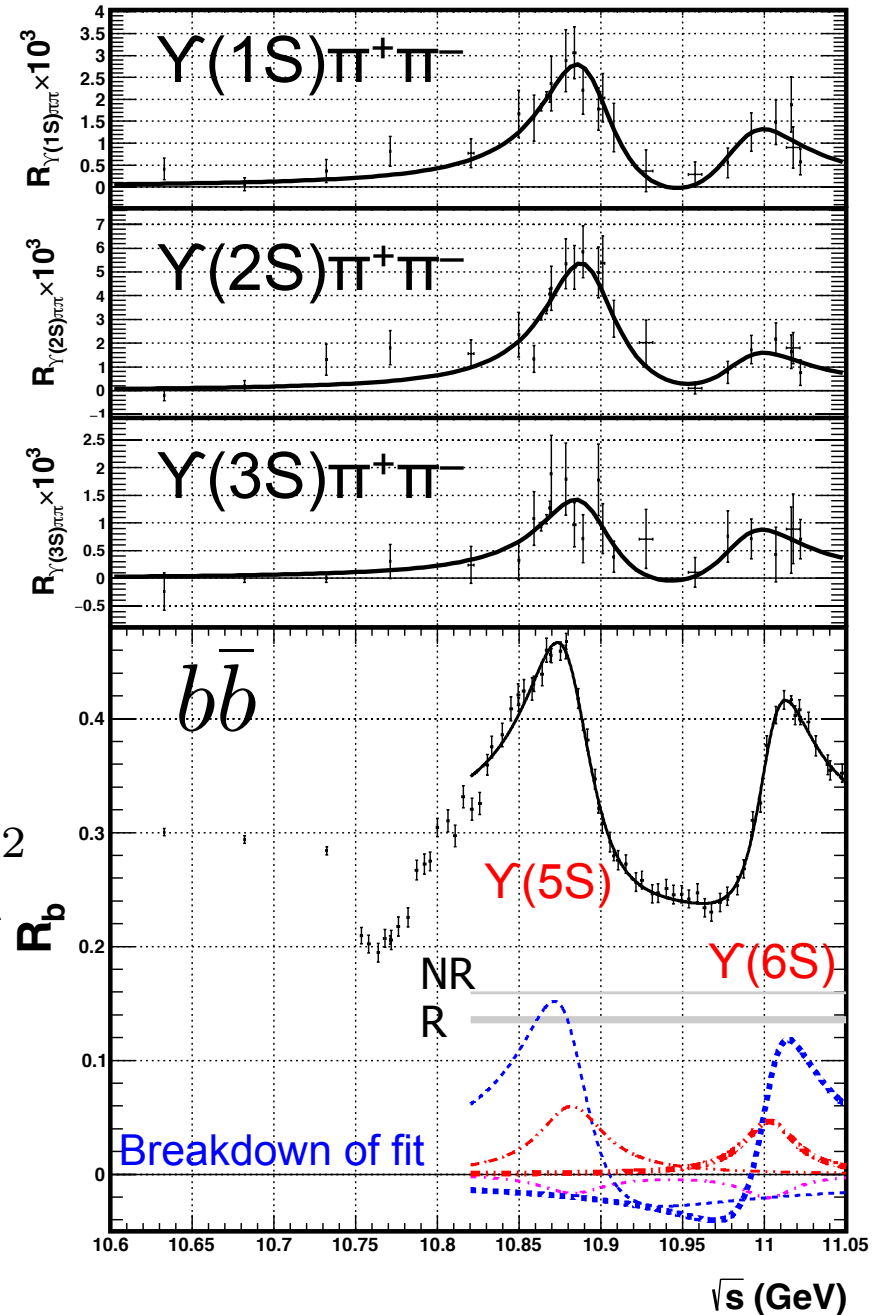
Favors “meson molecule” configuration model
[Voloshin PRD 87, 091501 (2013)]

Recent developments on bottomonium-like states

- $\sigma(Y(nS)\pi\pi)$, $\sigma(bb)$ vs CMS energy redux, additional data (tot 22 points)
 - PRD 93, 011101 (2016)

Fitting Model:
 2 Breit-Wigner+ flat continuum
 (coherent+incoherent)

$$|A_{NR}|^2 + |A_R + A_{5S}e^{i\phi_{5S}} BW(M_{5S}, \Gamma_{5S}) + A_{6S}e^{i\phi_{6S}} BW(M_{6S}, \Gamma_{6S})|^2$$



Recent developments on bottomonium-like states

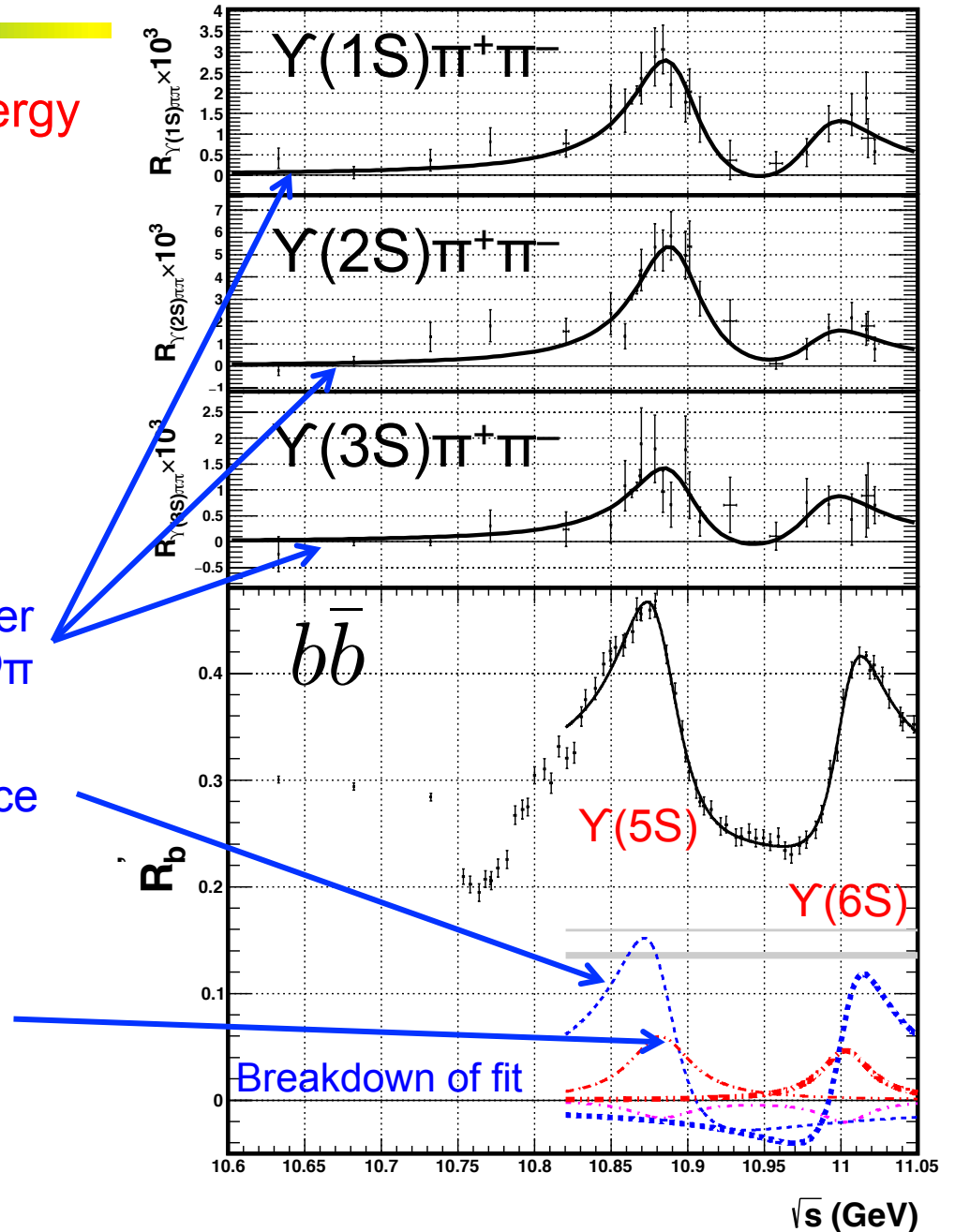
- $\sigma(Y(nS)\pi\pi)$, $\sigma(bb)$ vs CMS energy redux, additional data
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Fitting Model:
 2 Breit-Wigner+ flat continuum
 (coherent+incoherent)

No continuum: expect same for other Z_b -dominated events– $h_b(mP)\pi\pi$, $B^*B^{(*)}\pi$

Large continuum- $Y(5S)$ interference

$Y(nS)\pi\pi+h_b(mP)\pi\pi+BB^*\pi+B^*B^*\pi$
 Saturate “ $Y(5S)$ ”



Recent developments on bottomonium-like states

- $\sigma(Y(nS)\pi\pi), \sigma(bb)$ vs CMS energy redux, additional data
 - PRD 93, 011101 (2016)

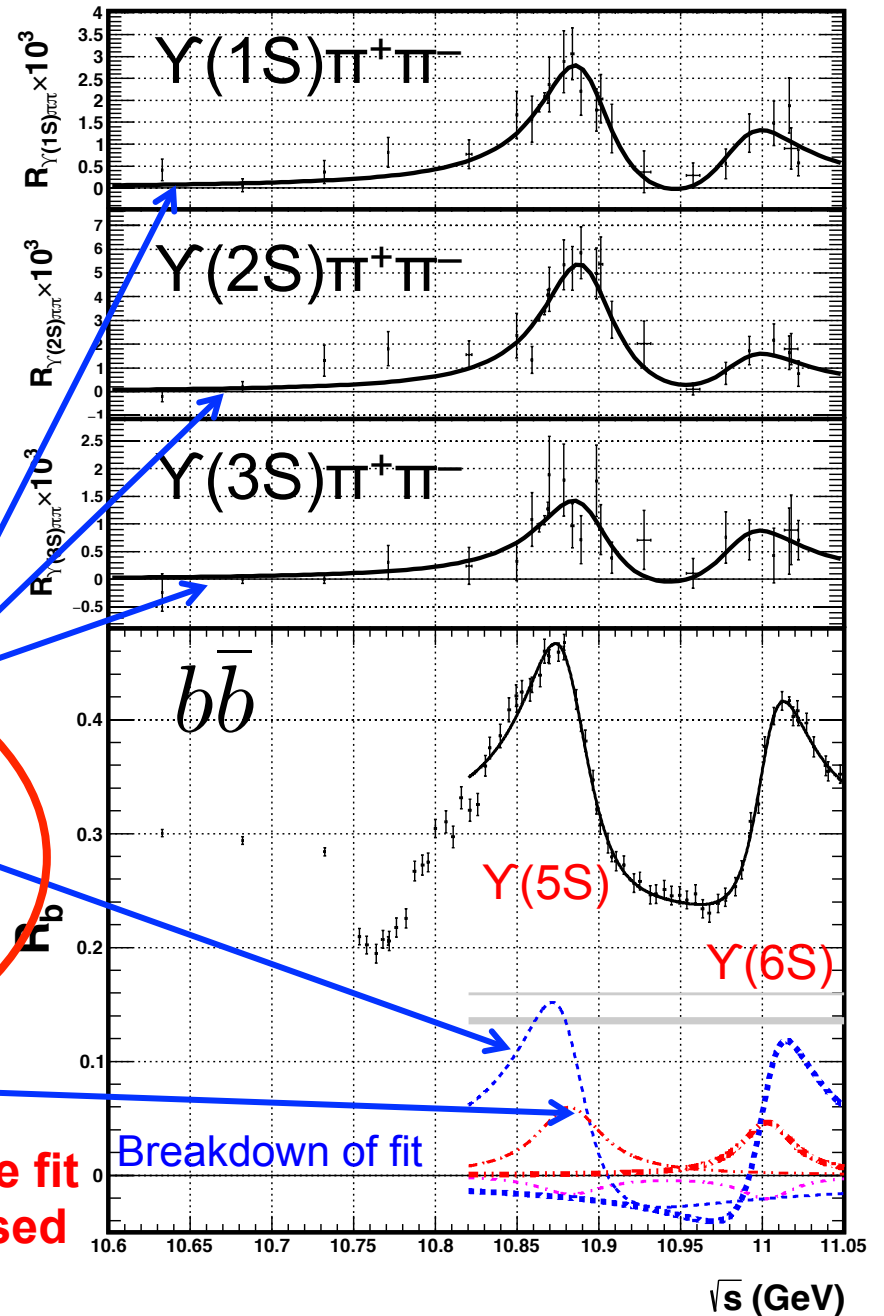
Fitting Model:
 2 Breit-Wigner+ flat continuum
 (coherent+incoherent)

No continuum: expect same for other Z_b dominated events – $h_b(mP)\pi\pi, B^*B^{(*)}\pi$

Large continuum- $Y(5S)$ interference

$Y(nS)\pi\pi+h_b(mP)\pi\pi+BB^*\pi+B^*B^{(*)}\pi$
 Saturate “ $Y(5S)$ ”

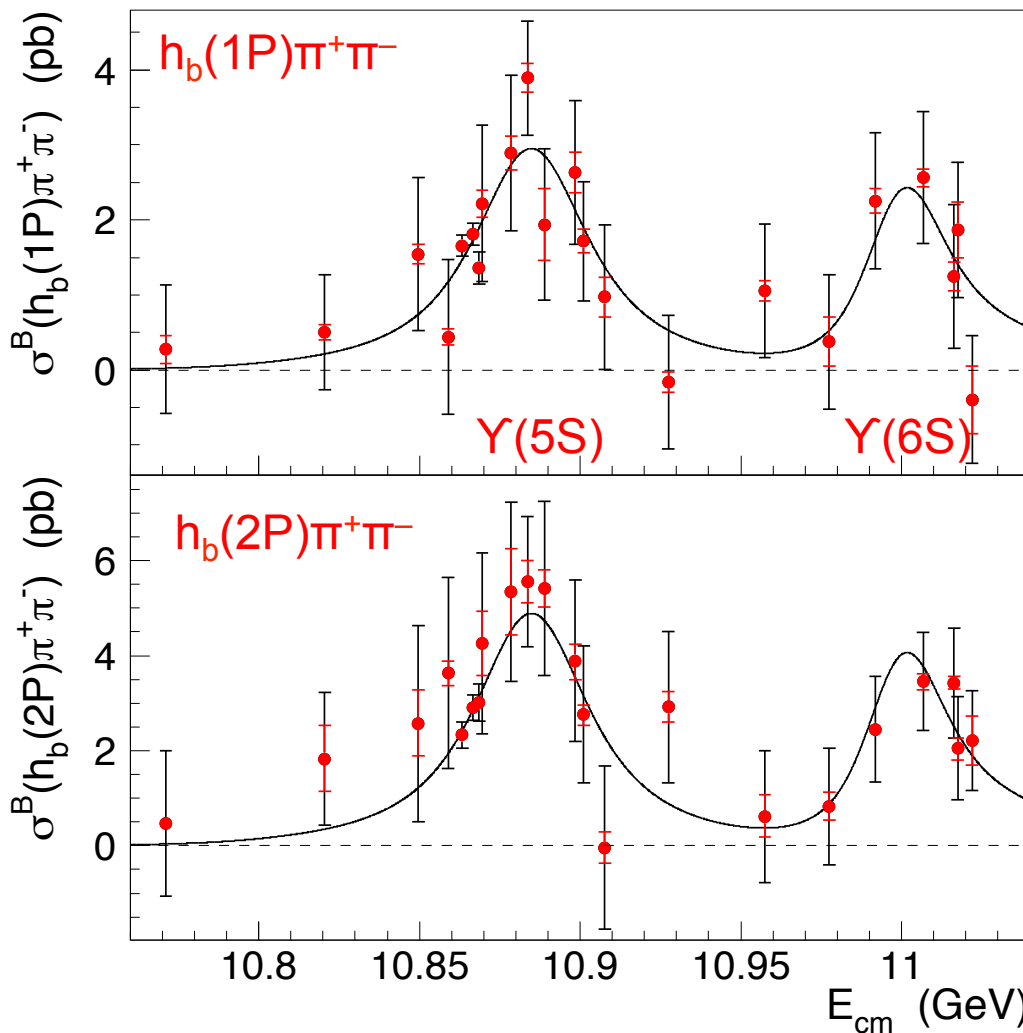
Mutually incompatible \Rightarrow simple fit model for R_b should not be used for $Y(5S)$ mass, width



News on bottomonium-like states



- $h_b(mP)\pi\pi$ vs CMS energy, evidence for Z_b^\pm at $Y(6S)$
 - arXiv:1508.06562



➤ Select $h_b(mP)$ via $\pi^+\pi^-$ missing mass

No continuum
– consistent with expectation from $Y\pi\pi$ scan, $h_b\pi\pi$ at $Y(5S)$

$$M_5 = (10884.7^{+3.6+8.9}_{-3.4-1.0}) \text{ MeV}/c^2,$$

$$\Gamma_5 = (40.6^{+12.7+1.1}_{-8.0-19.1}) \text{ MeV},$$

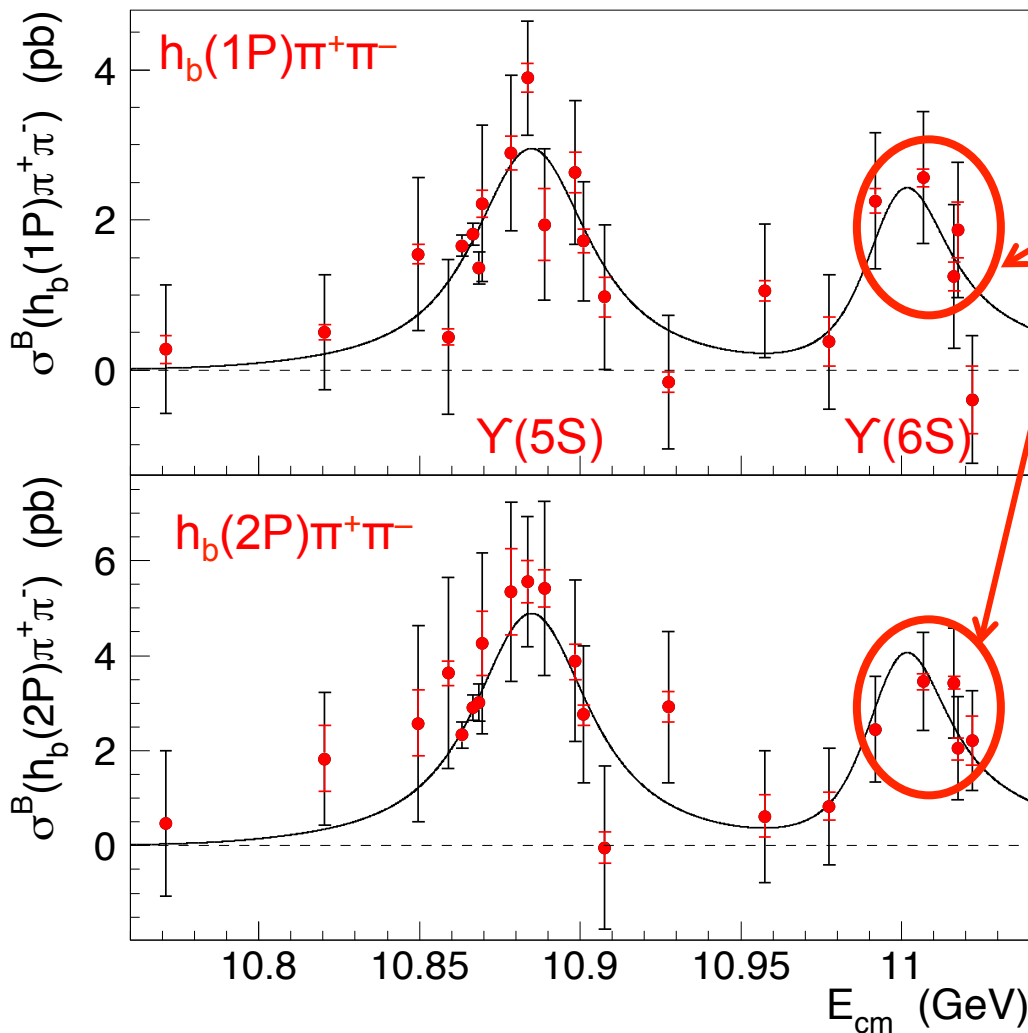
$$M_6 = (10999.0^{+7.3+16.9}_{-7.8-1.0}) \text{ MeV}/c^2,$$

$$\Gamma_6 = (27^{+27+5}_{-11-12}) \text{ MeV},$$

News on bottomonium-like states



- $h_b(mP)\pi\pi$ vs CMS energy, evidence for Z_b^\pm at $Y(6S)$
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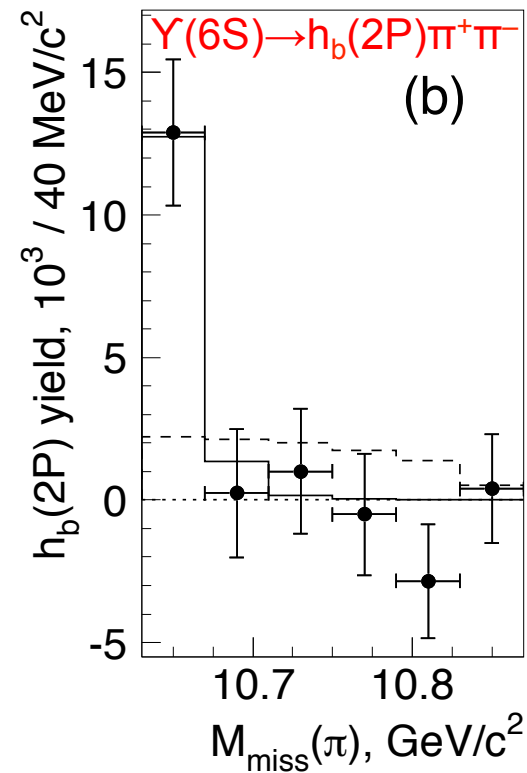
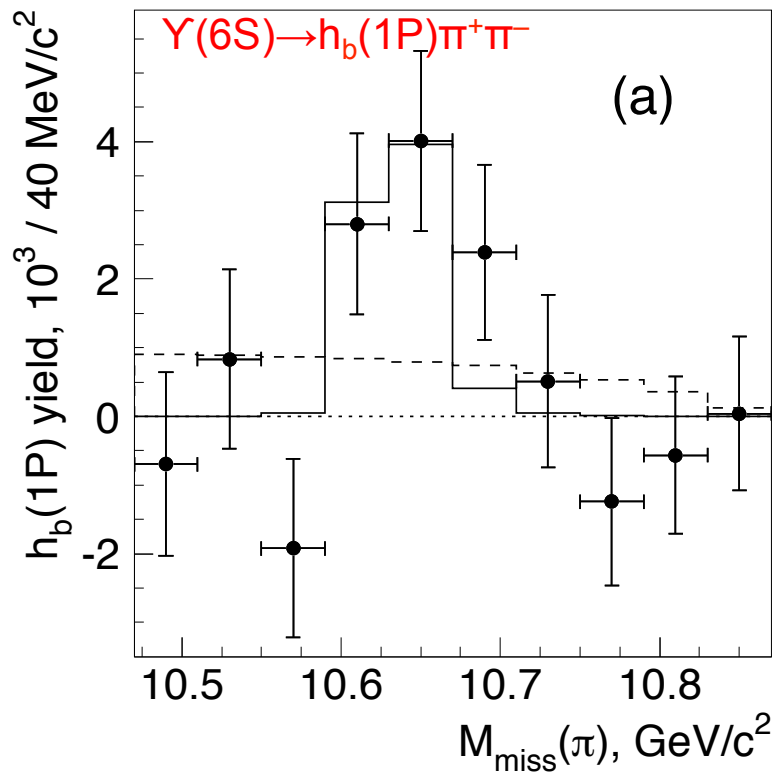
Combine 5 scan points in $Y(6S)$ region

- Significance at $Y(6S)$
 - $h_b(1P)\pi^+\pi^-$ 3.5σ
 - $h_b(2P)\pi^+\pi^-$ 5.3σ
- Search for Z_b^\pm : Plot π^\pm missing mass in $h_b(mP)\pi^+\pi^-$ events →

News on bottomonium-like states



- $h_b(mP)\pi\pi$ vs CMS energy, evidence for Z_b^\pm at $Y(6S)$
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- Events saturated by Z_b^\pm states, no nonresonant contribution
- Relative rates to $Z_b(10610)$, $Z_b(10650)$ loosely constrained;
- Hypothesis of only $Z_b(10610)$ excluded at 3.3σ

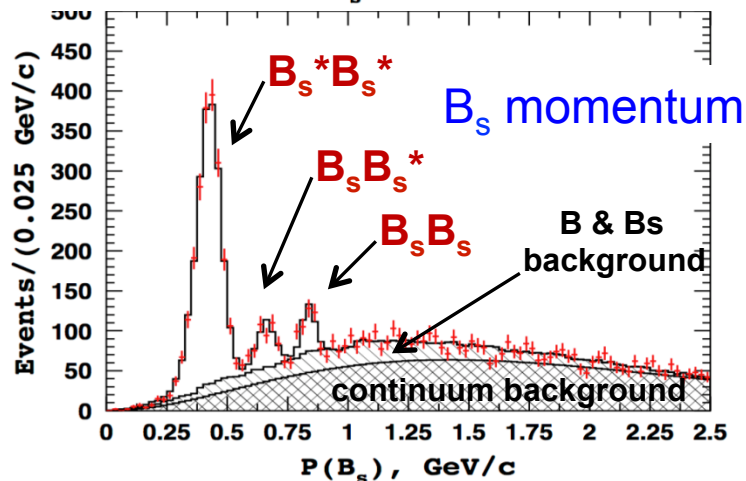
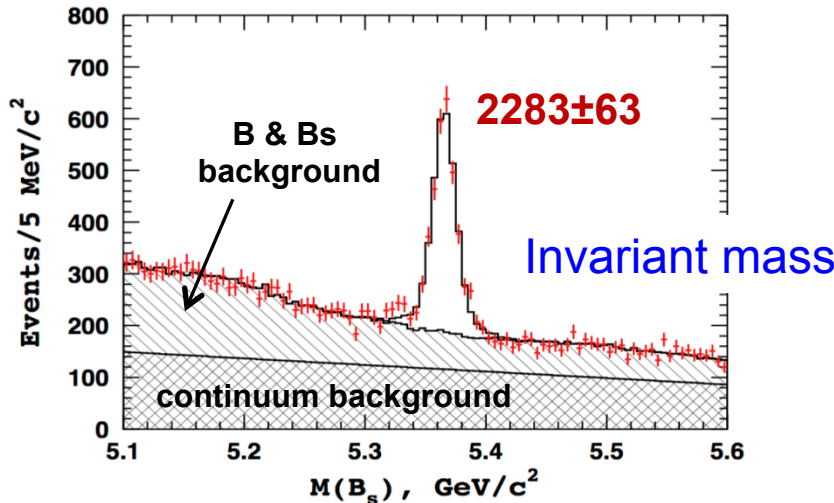
News on bottomonium-like states



NEW PRELIMINARY

- B_s production:
 - BELLE-COEF-1605

121.4 fb⁻¹ at Y(5S)
 Reconstructed B_s modes
 $Ds^{(*)}\mp\pi^\pm$
 $J/\psi K^+K^-$
 $J/\psi\pi^+\pi^-$
 $\psi(2S)K^+K^-$



Relative rates
 $B_s^*B_s^* : B_sB_s^* : B_sB_s$
 $7 : 0.853 \pm 0.106 \pm 0.53 : 0.638 \pm 0.094 \pm 0.033$

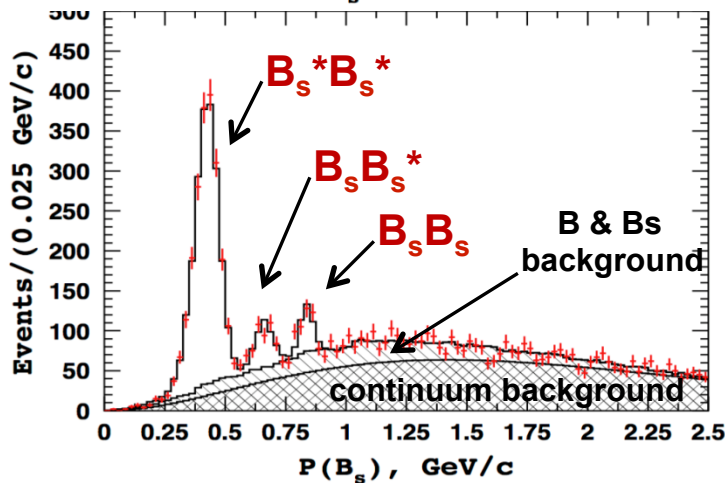
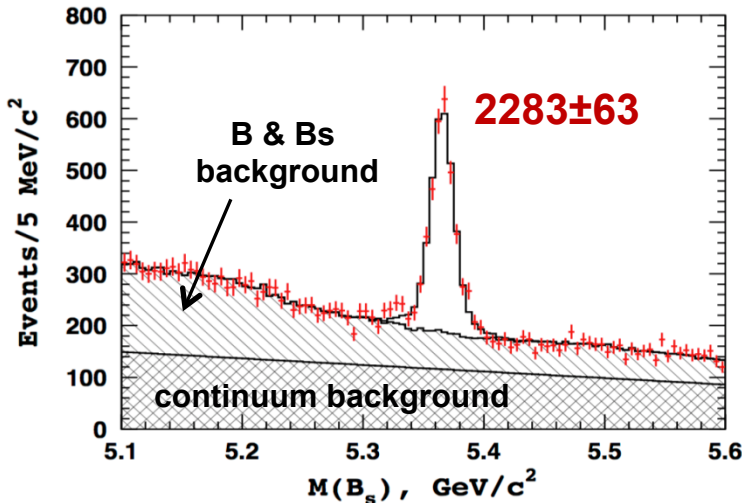
from HQ symmetry
 $7:4:1$
 [PRL 38, 317 (1977); PRD 85, 034024 (2012)]

News on bottomonium-like states



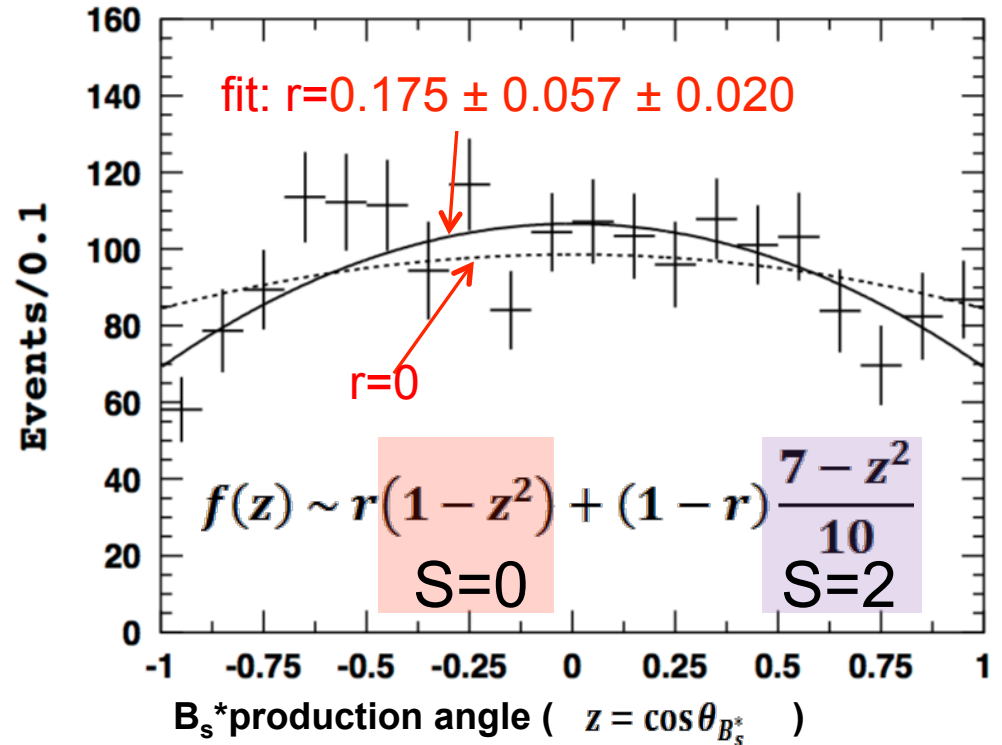
NEW PRELIMINARY

- B_s^* spin analysis
 - BELLE-COEF-1605



B_s^* pair spin analysis

From HQ symmetry
 $r=0.0476$ [PRD 87, 094033 (2013)]

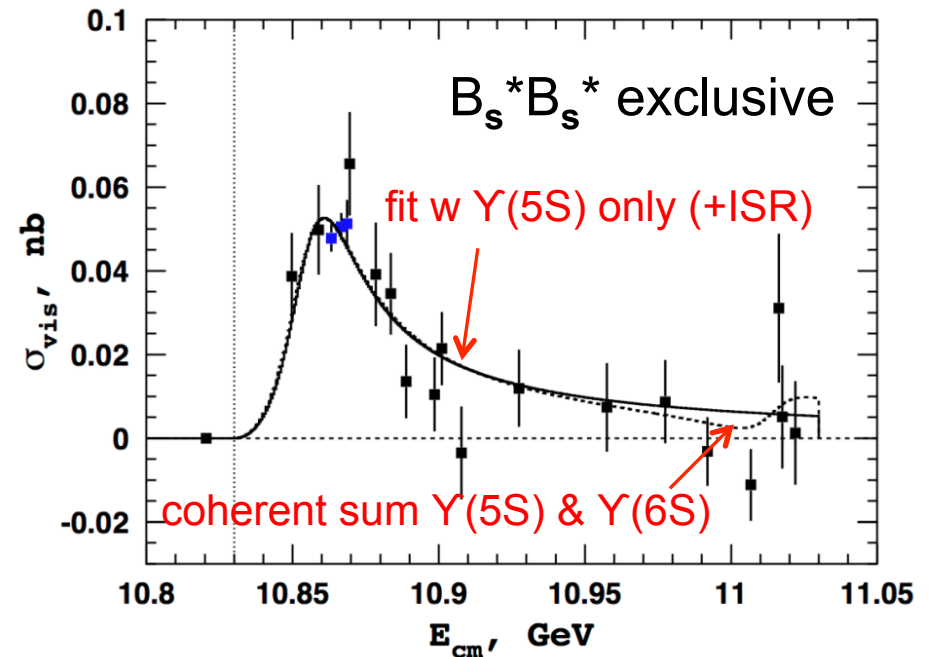
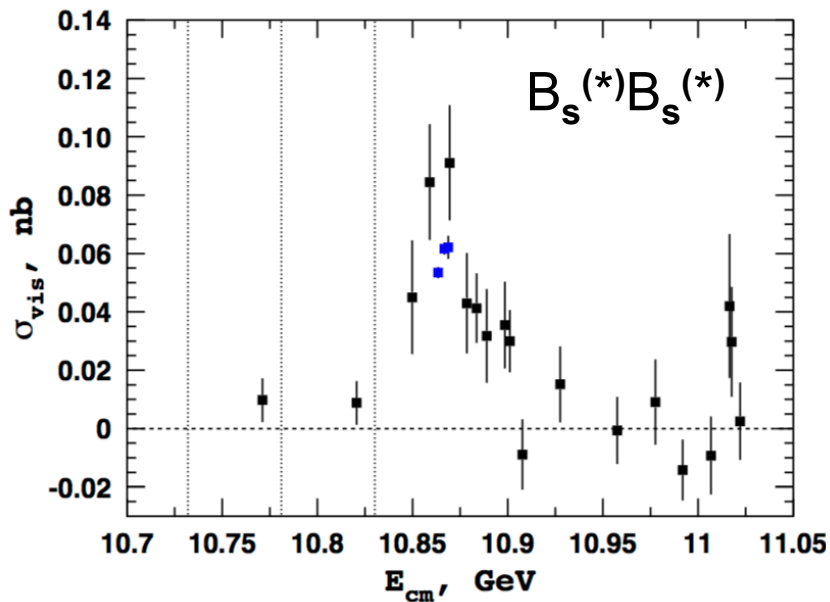


News on bottomonium-like states



- B_s cross section vs CMS energy
— BELLE-CONF-1605

NEW PRELIMINARY



- Consistent with no continuum production
- Clear peak at the $Y(5S)$
- $Y(6S)$ signal is considerably weaker

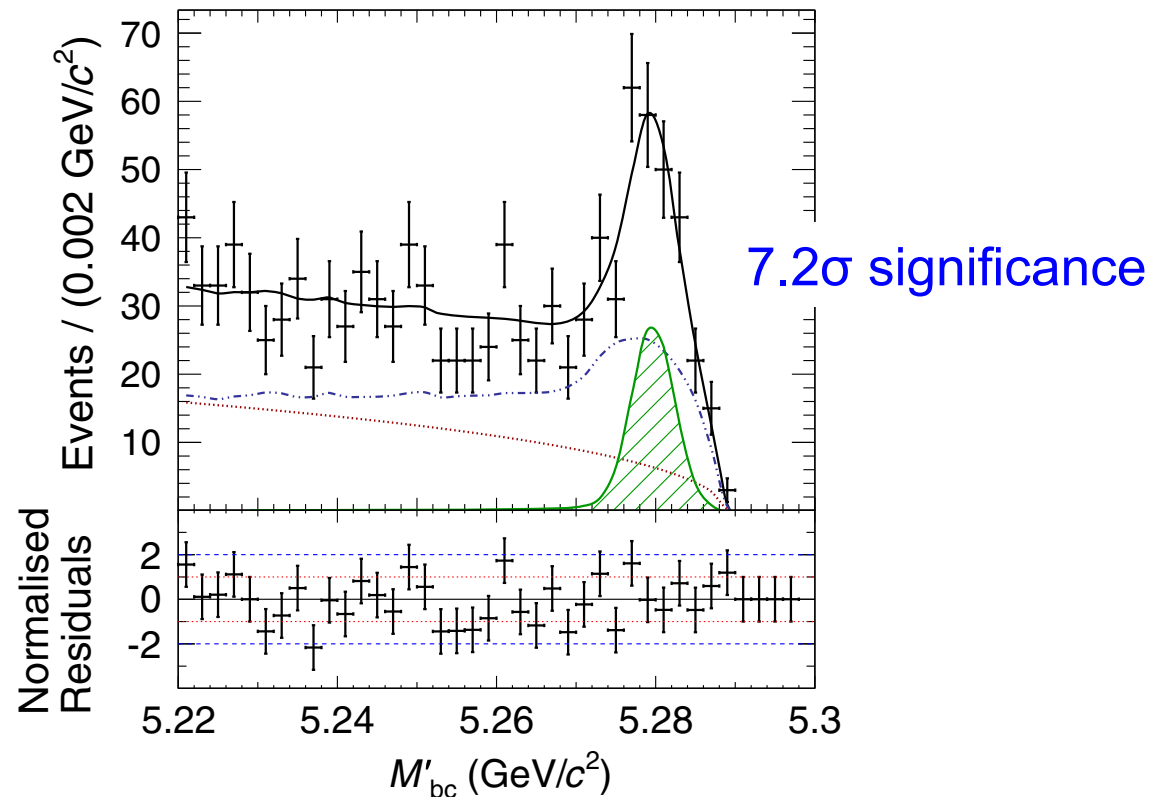
Charmonia in B Decays



- First Observation of $B^0 \rightarrow \psi(2S)\pi^0$
 - PRD 93, 031101 (2016)

$$\psi(2S) \rightarrow \ell^+ \ell^-, J/\psi \pi^+ \pi^- \{ J/\psi \rightarrow \ell^+ \ell^- \} \quad \ell = \mu, e$$

$$\mathcal{B}(B^0 \rightarrow \psi(2S)\pi^0) = (1.17 \pm 0.17 \pm 0.08) \times 10^{-5}$$



Charmonia in B Decays



- Decays to χ_{c1} and χ_{c2}
 - PRD 93, 052016 (2016)

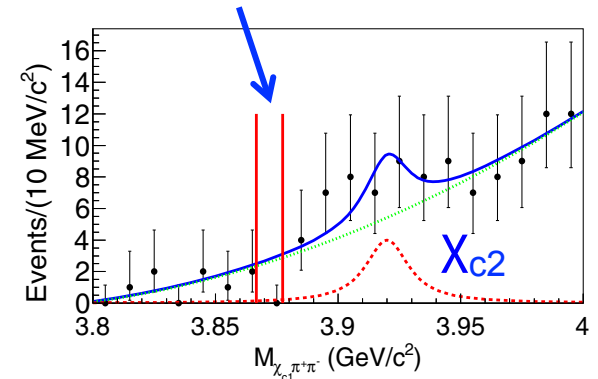
Inclusive $\mathcal{B}(B \rightarrow \chi_{c1} X) = (3.03 \pm 0.05 \pm 0.24) \times 10^{-3}$

$\mathcal{B}(B \rightarrow \chi_{c2} X) = (0.70 \pm 0.06 \pm 0.10) \times 10^{-3}$

Exclusive

| Decay | $\mathcal{B} (10^{-4})$ | $\mathcal{R}_B \chi_{c2}/\chi_{c1}$ |
|---|--------------------------|-------------------------------------|
| $B^0 \rightarrow \chi_{cJ} \pi^- K^+$ | | 0.14 ± 0.02 |
| χ_{c1} | $4.97 \pm 0.12 \pm 0.28$ | |
| χ_{c2} | $0.72 \pm 0.09 \pm 0.05$ | |
| $B^+ \rightarrow \chi_{cJ} \pi^+ K^0$ | | 0.20 ± 0.04 |
| χ_{c1} | $5.75 \pm 0.26 \pm 0.32$ | |
| χ_{c2} | $1.16 \pm 0.22 \pm 0.12$ | |
| $B^+ \rightarrow \chi_{cJ} \pi^0 K^+$ | | < 0.21 |
| χ_{c1} | $3.29 \pm 0.29 \pm 0.19$ | |
| χ_{c2} | < 0.62 | |
| $B^+ \rightarrow \chi_{cJ} \pi^+ \pi^- K^+$ | | 0.36 ± 0.05 |
| χ_{c1} | $3.74 \pm 0.18 \pm 0.24$ | |
| χ_{c2} | $1.34 \pm 0.17 \pm 0.09$ | |
| $B^0 \rightarrow \chi_{cJ} \pi^+ \pi^- K^0$ | | < 0.61 |
| χ_{c1} | $3.16 \pm 0.35 \pm 0.32$ | |
| χ_{c2} | < 1.70 | |
| $B^0 \rightarrow \chi_{cJ} \pi^- \pi^0 K^+$ | | < 0.25 |
| χ_{c1} | $3.52 \pm 0.52 \pm 0.24$ | |
| χ_{c2} | < 0.74 | |

Search for
 $B^\pm \rightarrow X(3872) K^\pm,$
 $X(3872) \rightarrow \chi_{c1} \pi^+ \pi^-$



Charmonia in B Decays (preliminary)



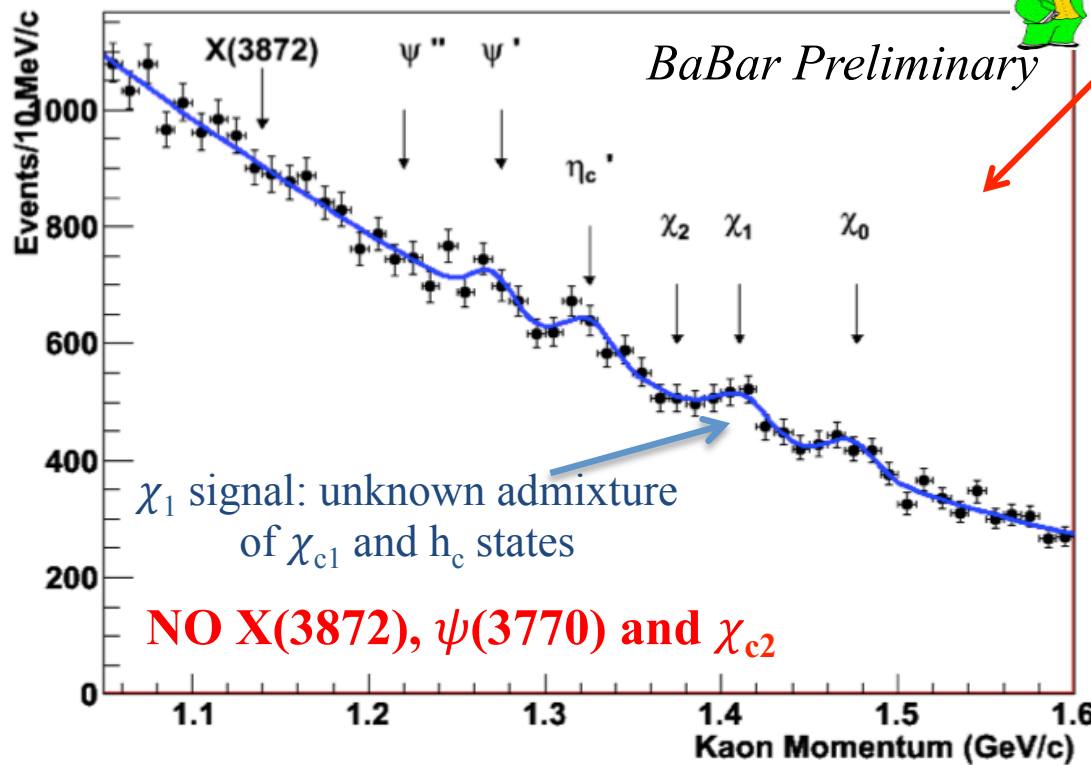
- absolute branching fractions of two-body decays $B \rightarrow KX_{cc}$

$$\Upsilon(4S) \rightarrow B\bar{B}$$

1st B – full reconstruction

2nd B – K from 2-body decay is monoenergetic in CMS

High mass charmonium region



From I. Garzia @Hadron 2015

Branching fractions x 10⁴ Charmonia (neutral)

- X_{c0} 4.4 ± 0.9
- X_{c1} $7.0 \pm 1.3 \pm 1.0$
- X_{c2} < 1.2 (90%CL)
- $\eta_c(2S)$ $6.0 \pm 2.1 \pm 0.4$
- ψ' $6.2 \pm 2.0 \pm 0.6$
- $\psi(3770)$ < 2.0
- $X(3872)$ < 4.4

Charged Charmonium-like

- $Z^\pm(3900)$ < 3 (90%CL)
- $Z^\pm(4050)$ < 3 (90%CL)
- $Z^\pm(4430)$ < 5 (90%CL)

Charmonium-like states



- Search for $Y(1S)$ to XYZ
 - PRD 93, 112013 (2016)

| State | N_{fit} | $\sigma_{\text{syst}}(\%)$ | $\Sigma(\sigma)$ | $\mathcal{B}_R^{\text{prod}}$ |
|--|--------------------|----------------------------|------------------|-------------------------------|
| $X(3872) \rightarrow \pi^+ \pi^- J/\psi$ | 4.8 ± 15.4 | 18.7 | 0.3 | $< 9.5 \times 10^{-6}$ |
| $Y(4260) \rightarrow \pi^+ \pi^- J/\psi$ | -31.1 ± 88.9 | 35.6 | – | $< 3.8 \times 10^{-5}$ |
| $Y(4260) \rightarrow \pi^+ \pi^- \psi(2S)$ | 6.7 ± 29.4 | 35.0 | 0.2 | $< 7.9 \times 10^{-5}$ |
| $Y(4360) \rightarrow \pi^+ \pi^- \psi(2S)$ | -25.4 ± 30.1 | 50.0 | – | $< 5.2 \times 10^{-5}$ |
| $Y(4660) \rightarrow \pi^+ \pi^- \psi(2S)$ | -55.0 ± 26.2 | 40.7 | – | $< 2.2 \times 10^{-5}$ |
| $Y(4260) \rightarrow K^+ K^- J/\psi$ | -13.7 ± 10.9 | 45.8 | – | $< 7.5 \times 10^{-6}$ |
| $Y(4140) \rightarrow \phi J/\psi$ | -0.1 ± 1.2 | 11.0 | – | $< 5.2 \times 10^{-6}$ |
| $X(4350) \rightarrow \phi J/\psi$ | 2.3 ± 2.5 | 10.4 | 1.2 | $< 8.1 \times 10^{-6}$ |
| $Z_c(3900)^\pm \rightarrow \pi^\pm J/\psi$ | -26.5 ± 39.1 | 47.3 | – | $< 1.3 \times 10^{-5}$ |
| $Z_c(4200)^\pm \rightarrow \pi^\pm J/\psi$ | -238.6 ± 154.2 | 48.4 | – | $< 6.0 \times 10^{-5}$ |
| $Z_c(4430)^\pm \rightarrow \pi^\pm J/\psi$ | 94.2 ± 71.4 | 34.4 | 1.2 | $< 4.9 \times 10^{-5}$ |
| $Z_c(4050)^\pm \rightarrow \pi^\pm \psi(2S)$ | 37.0 ± 47.7 | 46.2 | 0.4 | $< 8.8 \times 10^{-5}$ |
| $Z_c(4430)^\pm \rightarrow \pi^\pm \psi(2S)$ | 23.2 ± 42.4 | 47.1 | 0.1 | $< 6.7 \times 10^{-5}$ |
| $Z_{cs}^\pm \rightarrow K^\pm J/\psi$ | -22.2 ± 17.4 | 48.7 | – | $< 5.7 \times 10^{-6}$ |

Summary



from e^+e^- B-factory experiments

- $Y(5S)$: rich in Z_b , observed in 7+ channels
 - Dominant in $B^*B^{(*)}$, favors “meson molecule” model
 - First spin analysis of $B_s^*B_s^*$ events
- Explorations of energy region $Y(5S)$ – $Y(6S)$
 - No continuum w $Y(nS)\pi\pi$, $h_b(mP)\pi\pi$, $Z_b\pi$, $B_s^*B_s^{(*)}$ events
 - Evidence does not support a simple continuum; additional structure probable
- Observations/limits on B decays to charmonium(-like)
- New limits on $Y(1S)$ decays to charmonium-like XYZ