International Conference on Particle Physics and Astrophysics,
5 – 10 October 2015, Moscow

Bottomonium-like states at e^+e^- colliders

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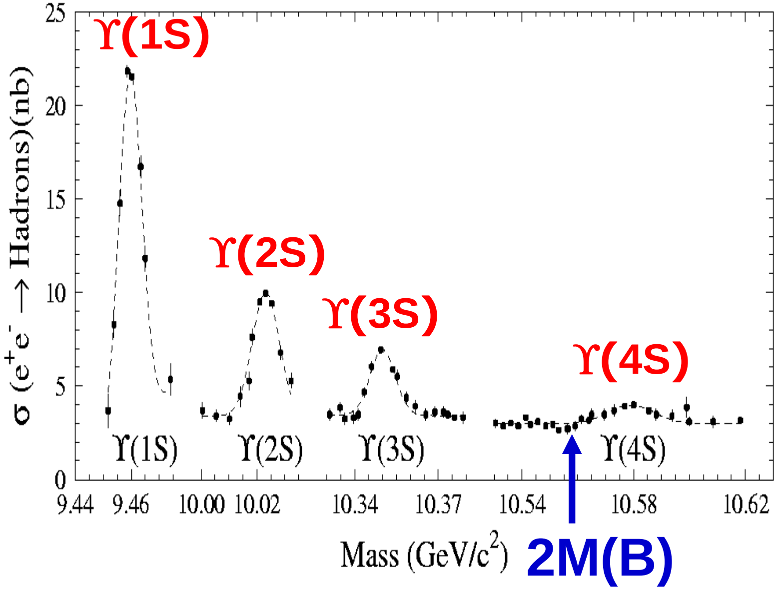
Outline

Charged bottomonium-like states

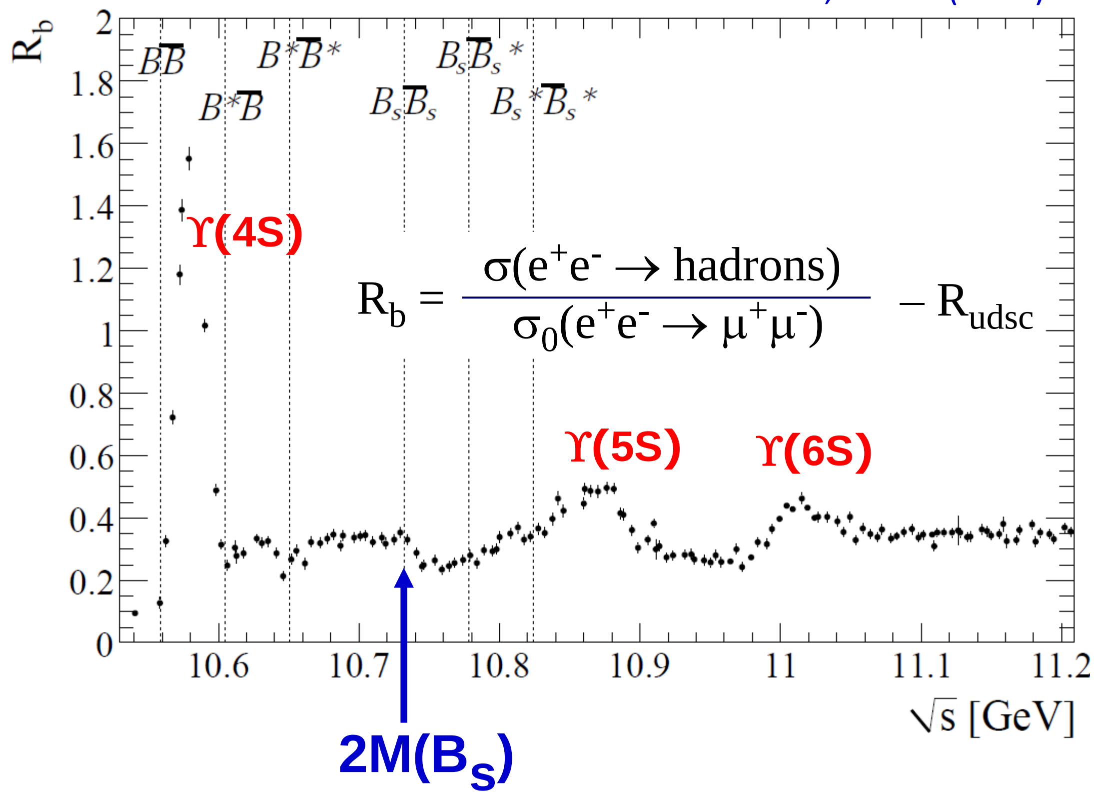
Vector $J^{PC} = 1^{--}$ states

from Belle and BaBar experiments

Cross section $e^+e^- \to$ hadrons



BaBar PRL100,112001(2008)



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

BaBar 433 fb^{-1} + Belle 711 fb^{-1}

$e^+e^- \to b\bar{b}\ (\Upsilon(5S)) \to BB,\ B\bar{B}^*,\ B^*\bar{B}^*,\ B\bar{B}^*\pi,\ B^*\bar{B}^*\pi,\ B_s^{(*)}\bar{B}_s^{(*)},\ \ldots$

Belle 121 fb^{-1}

original motivation

Puzzles of $\Upsilon(5S)$ data

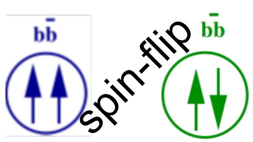
Belle 2007: anomalous production of $\Upsilon(nS)\,\pi^+\pi^-$

PRL100,112001(2008)	$\Gamma(\text{MeV})$
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

10^2

Belle 2011: anomalous production of $h_b(nP)\,\pi^+\pi^-$ PRL108,112001(2012)

$$\frac{\sigma(h_b(nP)\pi^+\pi^-)}{\sigma(\Upsilon(2S)\pi^+\pi^-)} = \begin{cases} 0.46 \pm 0.08^{+0.07}_{-0.12} & n=1 \\ 0.77 \pm 0.08^{+0.22}_{-0.17} & n=2 \end{cases}$$



expect suppression $\sim\Lambda_{QCD}/m_b$

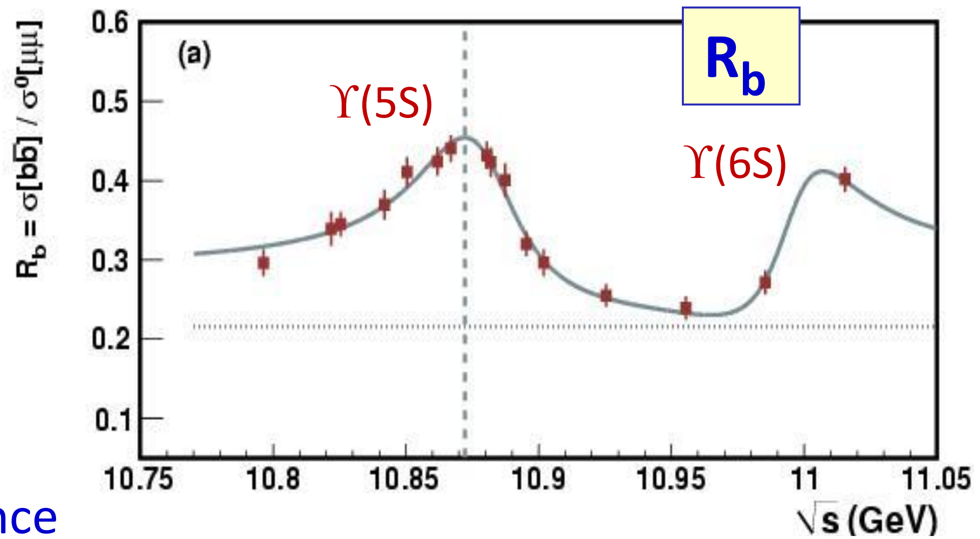
Production mechanism: $\Upsilon(5S)$ resonance or continuum?

PRD82,091106R(2010)

Belle 2007: energy scan

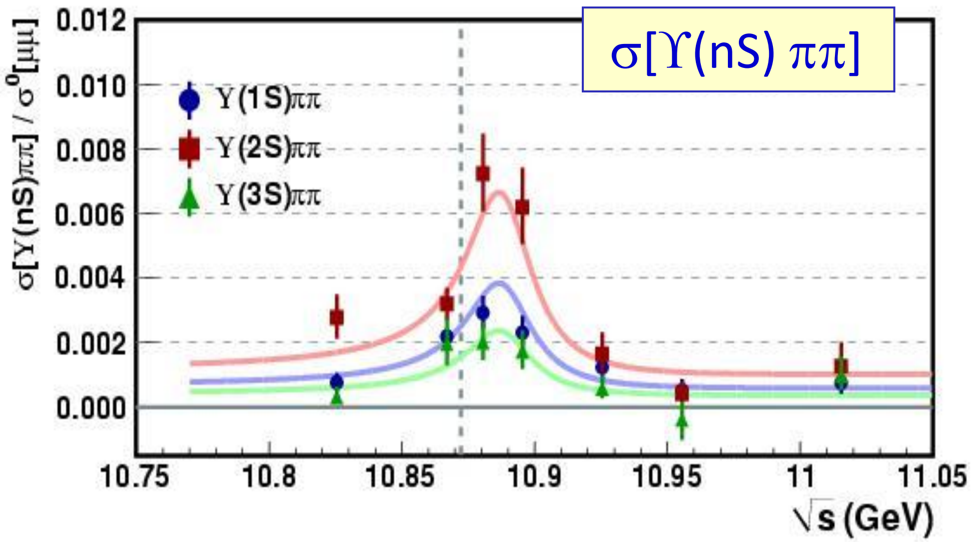
6 points ~1fb^{-1} for $\sigma[\Upsilon(nS)\,\pi\pi]$

9 points 30pb^{-1} for R_b



⇒ Evidence that $\Upsilon(nS)\,\pi\pi$ production is resonant

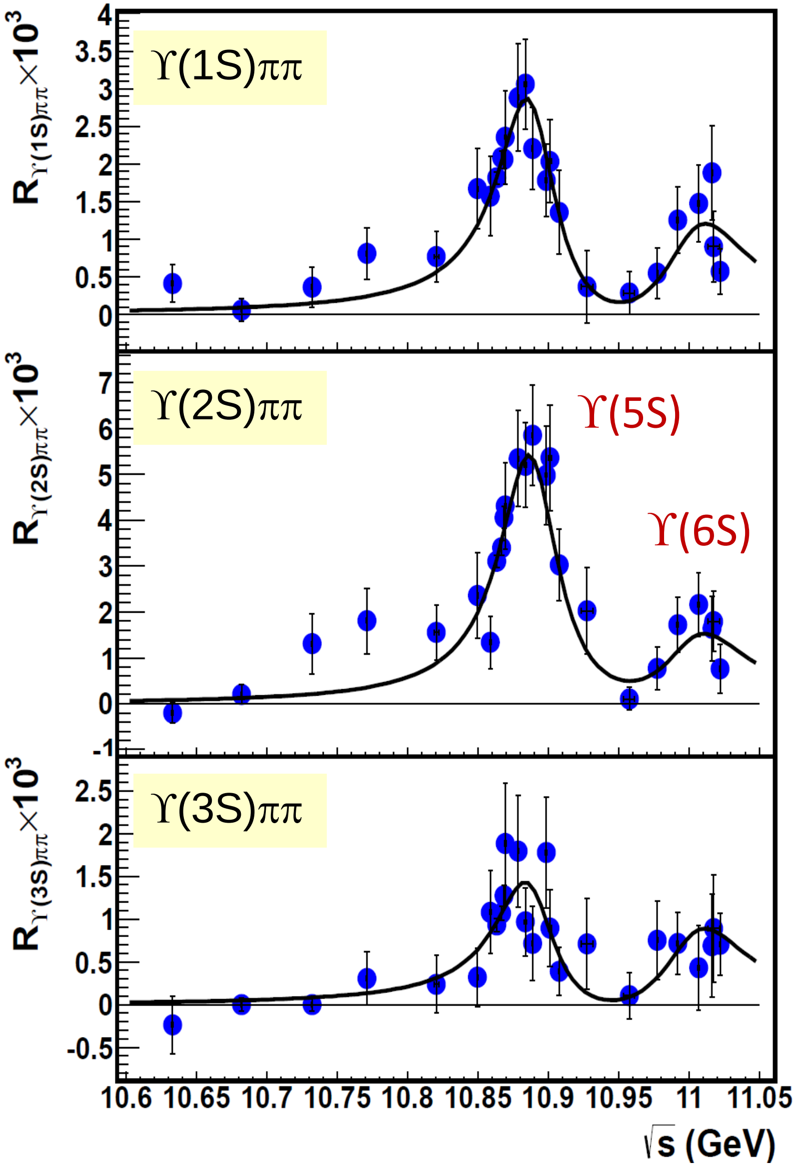
⇒ No clear conclusion if the same resonance is seen in R_b and $\sigma[\Upsilon(nS)\,\pi\pi]$ (2σ mismatch in mass and width)

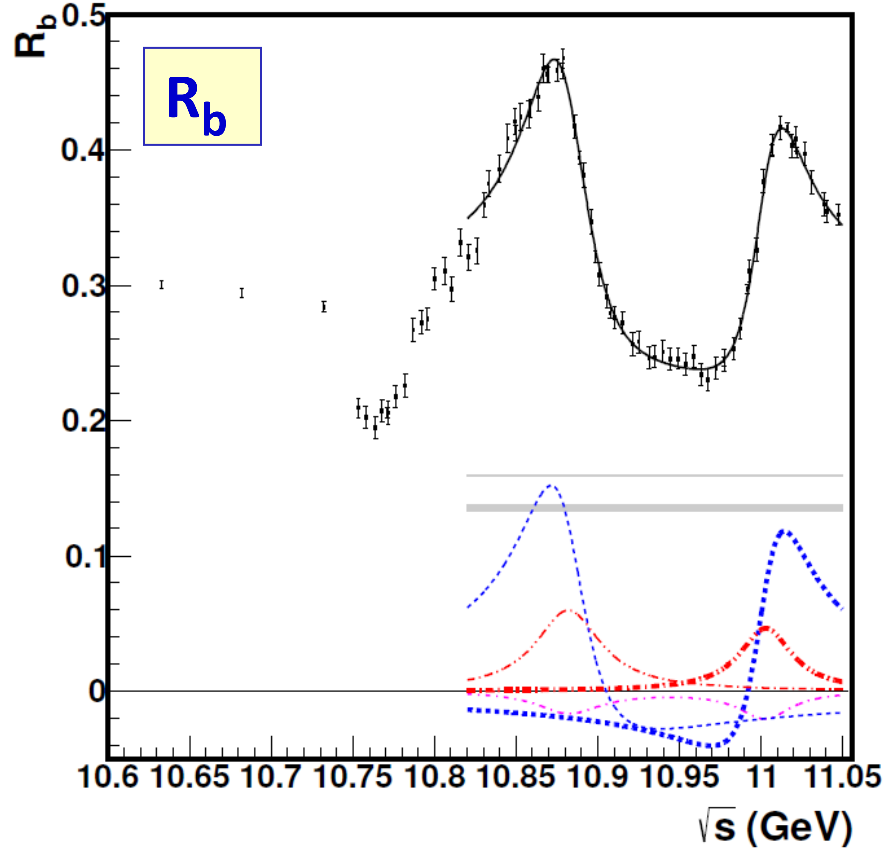


Belle 2010: energy scan

+16 points ~1fb^{-1} for $\sigma[\Upsilon(nS)\,\pi\pi]$

+60 points 50pb^{-1} for R_b





arxiv:1501.01137

⇒ Υ(nS) ππ production is due to Υ(5S) & Υ(6S)

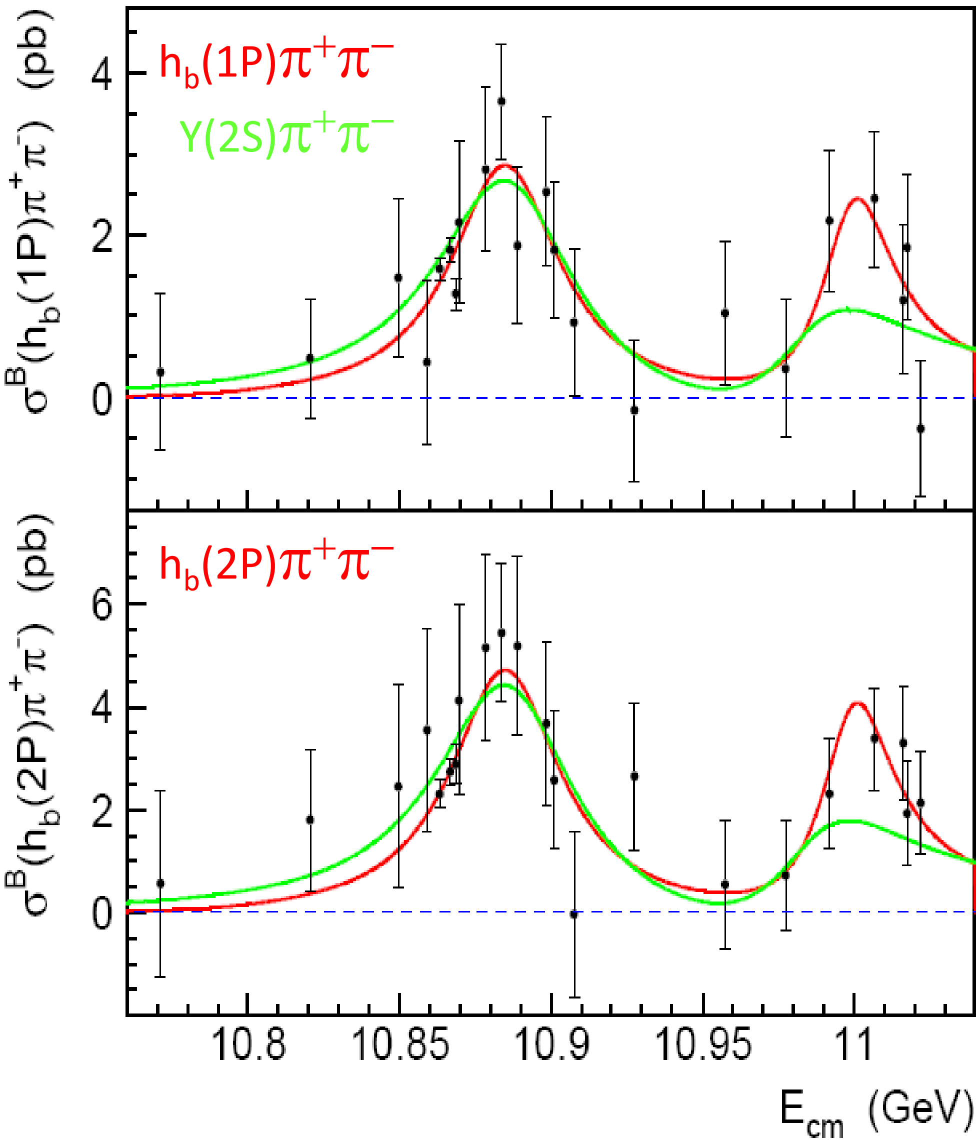
no significant continuum contribution

1st observation of Υ(6S)→Υ(nS)ππ

⇒ No major difference in Υ(5S) & Υ(6S) parameters btw R_b and σ[Υππ].

different from charmonium

Cross section of $e^+e^- \to h_b(1P,2P)\pi^+\pi^-$



arxiv:1508.06562

Resonant behavior of $h_b\pi\pi$ cross sections

- clear $\Upsilon(5S)$ and $\Upsilon(6S)$ signals;
- no continuum contribution.

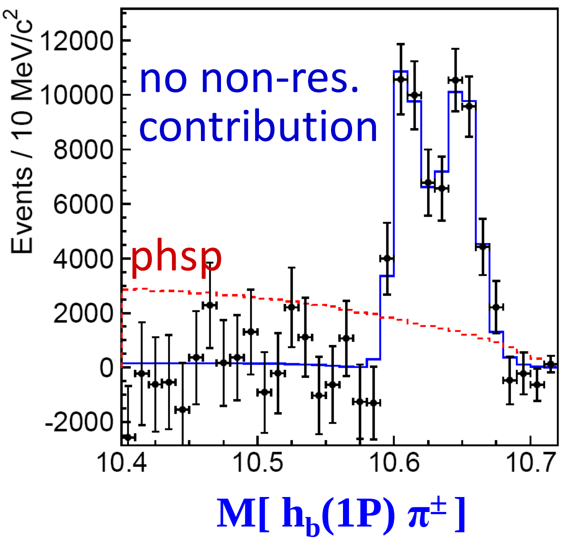
Shapes of $\Upsilon\pi\pi$ and $h_b\pi\pi$ cross sections look very similar.

Anomalous production of $\Upsilon\pi\pi$ and $h_b\pi\pi$ corresponds to $\Upsilon(5S)$, $\Upsilon(6S)$ decays and not to processes in continuum.

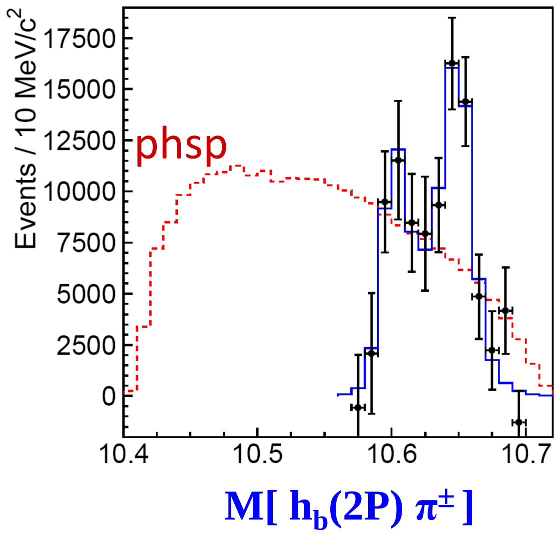
Resonant structure of $\Upsilon(5S) \to (b\bar{b})\,\pi^+\pi^-$

PRL108,122001(2012)

$\Upsilon(5S) \to$ **$h_b(1P)$**$\pi^+\pi^-$



$\Upsilon(5S) \to$ **$h_b(2P)$**$\pi^+\pi^-$



Two peaks in all modes

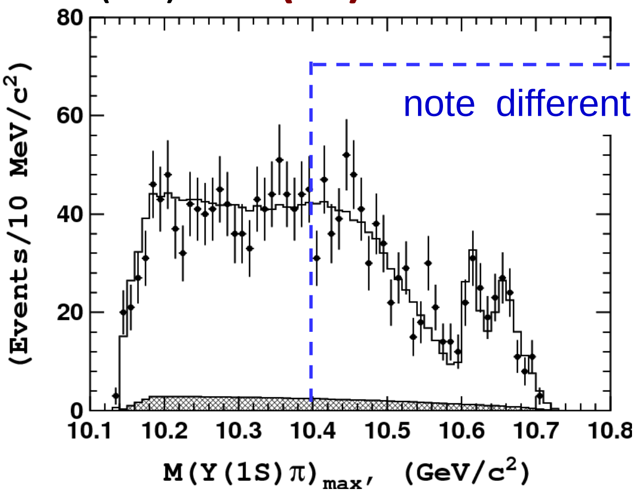
Minimal quark content

$|\, b\bar{b}u\bar{d}\,\rangle$

flavor-exotic states

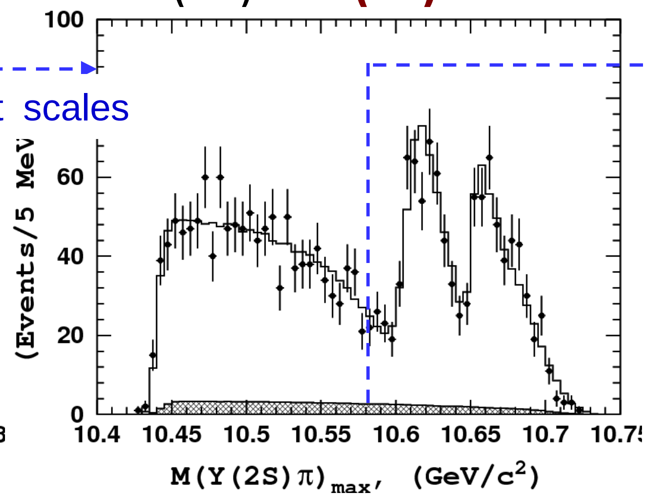
Dalitz plot analysis

$\Upsilon(5S) \to$ **$\Upsilon(1S)$**$\pi^+\pi^-$

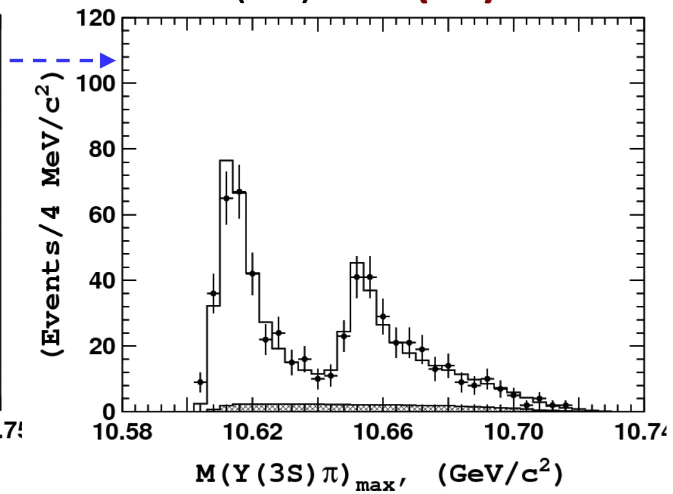


note different scales

$\Upsilon(5S) \to$ **$\Upsilon(2S)$**$\pi^+\pi^-$



$\Upsilon(5S) \to$ **$\Upsilon(3S)$**$\pi^+\pi^-$



Experimental summary on Z_b^+ states

PRL108,122001(2012)

$M_{Zb(10610)} - (M_B + M_{B*}) = +2.6 \pm 2.1$ MeV $\Gamma_{Zb(10610)} = 18.4 \pm 2.4$ MeV

$M_{Zb(10650)} - 2M_{B*} = +1.8 \pm 1.7$ MeV $\Gamma_{Zb(10650)} = 11.5 \pm 2.2$ MeV

arxiv:1209.6450

$J^P = 1^+$

6D amplitude analysis

arxiv:1403.0992

Channel	$\mathcal{B}$ of $Z_b(10610)$	$\mathcal{B}$ of $Z_b(10650)$
$\pi^+\Upsilon(1S)$	$(0.32 \pm 0.09)\%$	$(0.18 \pm 0.05)\%$
$\pi^+\Upsilon(2S)$	$(4.38 \pm 1.21)\%$	$(1.80 \pm 0.47)\%$
$\pi^+\Upsilon(3S)$	$(2.15 \pm 0.56)\%$	$(1.23 \pm 0.30)\%$
$\pi^+h_b(1P)$	$(2.81 \pm 1.10)\%$	$(5.6 \pm 2.0)\%$
$\pi^+h_b(2P)$	$(4.34 \pm 2.07)\%$	$(11.1 \pm 4.7)\%$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$(86.0 \pm 3.6)\%$	$(25 \pm 10)\%$
$B^{*+}\bar{B}^{*0}$	–	$(55.1 \pm 5.3)\%$

suppressed despite larger PHSP

dominant

Assumption:

$|Z_b(10610)\rangle = |B\bar{B}^*\rangle$

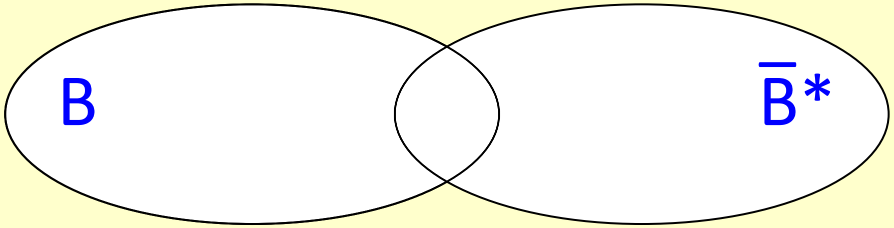
$|Z_b(10650)\rangle = |B^*\bar{B}^*\rangle$

$\delta M \sim 0 \Rightarrow$ loosely bound or virtual

Decays into constituents dominate

$J^P=1^+ \Rightarrow B^{(*)}\bar{B}^*$ in S-wave

Structure of Z_b^+ : molecule



Bondar, Garmash, Milstein, RM, Voloshin,
PRD84,054010(2011)

In the $I^G(J^P) = 1^+(1^+)$ $B^{(*)}\bar{B}^*$ molecule total spin of heavy $b\bar{b}$, S_{bb}, is not definite.

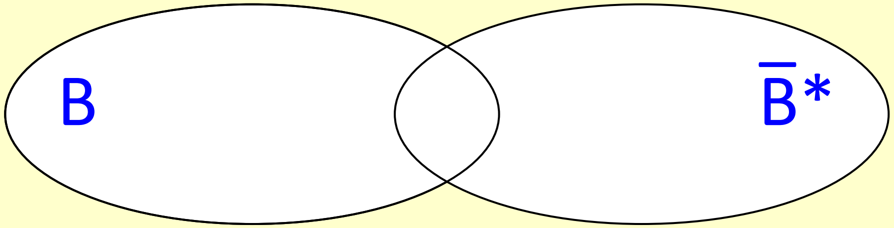
Decomposition in S_{bb} eigenstates $\Rightarrow$

$$|Z_b'\rangle = (0^-_{b\bar{b}} \otimes 1^-_{q\bar{q}} - 1^-_{b\bar{b}} \otimes 0^-_{q\bar{q}})/\sqrt{2}$$

$$|Z_b\rangle = (0^-_{b\bar{b}} \otimes 1^-_{q\bar{q}} + 1^-_{b\bar{b}} \otimes 0^-_{q\bar{q}})/\sqrt{2}$$

$h_b(mP)\pi$ $\Upsilon(nS)\pi$

Structure of Z_b^+ : molecule



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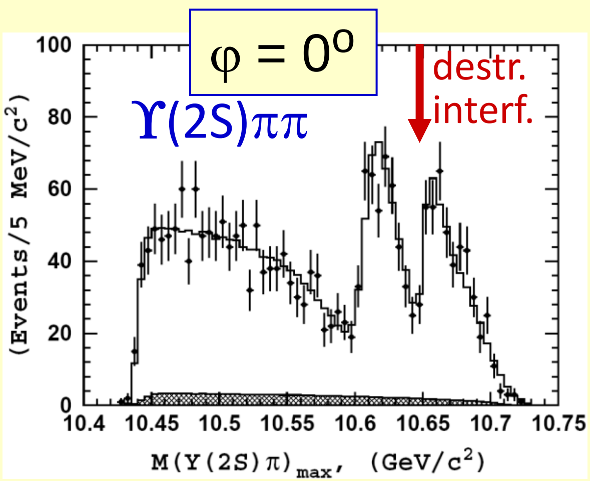
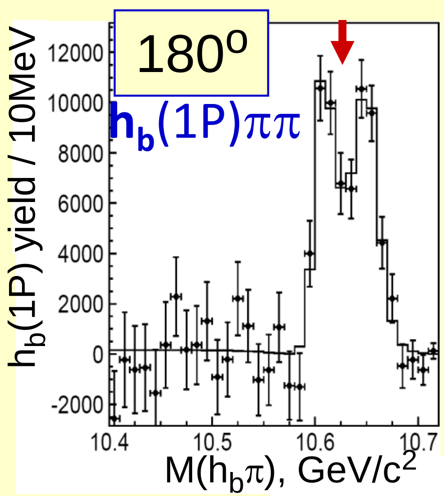
$$|Z_b\rangle = (0^-_{b\bar{b}} \otimes 1^-_{q\bar{q}} + 1^-_{b\bar{b}} \otimes 0^-_{q\bar{q}})/\sqrt{2}$$

$h_b(mP)\pi$ — relative phase — $\Upsilon(nS)\pi$

$$BW(s, M_1, \Gamma_1) + ae^{i\phi}BW(s, M_2, \Gamma_2)$$

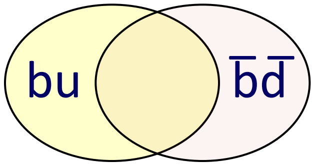




Assumption of molecular structure allows to explain all properties of Z_b states.

Structure of Z_b^+ : diquark-antidiquark

Ali et al, PRD85,054011(2012)



$$|\tilde{Z}_b\rangle = (0_{[bq]} \otimes 1_{[\bar{b}\bar{q}]} - 1_{[bq]} \otimes 0_{[\bar{b}\bar{q}]})/\sqrt{2},$$

$$|\tilde{Z}'_b\rangle = 1_{[bq]} \otimes 1_{[\bar{b}\bar{q}]}.$$

Decomposition:

$$|\tilde{Z}_b\rangle = (-1^-_{b\bar{b}} \otimes 0^-_{q\bar{q}} + 0^-_{b\bar{b}} \otimes 1^-_{q\bar{q}})/\sqrt{2} = 1^-_{b\bar{q}} \otimes 1^-_{q\bar{b}},$$ $B^*\bar{B}^*$

$$|\tilde{Z}'_b\rangle = (1^-_{b\bar{b}} \otimes 0^-_{q\bar{q}} + 0^-_{b\bar{b}} \otimes 1^-_{q\bar{q}})/\sqrt{2}$$

$$= (1^-_{b\bar{q}} \otimes 0^-_{q\bar{b}} + 0^-_{b\bar{q}} \otimes 1^-_{q\bar{b}})/\sqrt{2}.$$ $B\bar{B}^*$

Predictions:

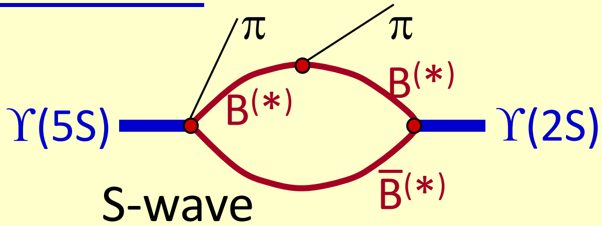
$\Gamma(Z_b \to \Upsilon\pi) \sim \Gamma(Z_b \to h_b\pi) \sim \Gamma(Z_b \to B^{(*)}\bar{B}^*)$ $\Leftarrow$ diquark is destroyed in all cases

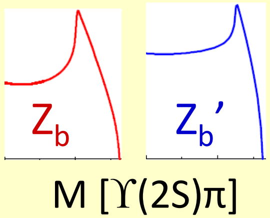
Z_b' decay to $B\ \bar{B}^*$ is not suppressed

Decay pattern of Z_b and Z_b'
disfavors diquark-antidiquark interpretation.

Dynamical model for Z_b states

1. Threshold effect





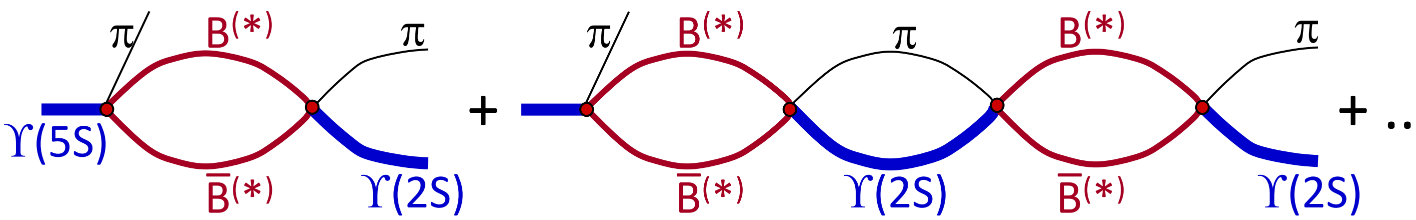
Chen, Liu, PRD84,094003(2011)

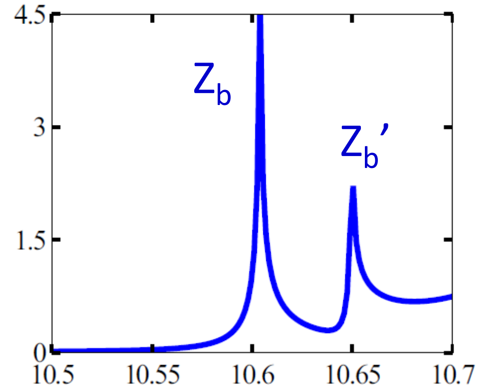
Selfconsistency?

Guo, Hanhart, Wang, Zhao, 1411.5584

Danilkin, Orlovsky, Simonov, PRD85,034012(2012)

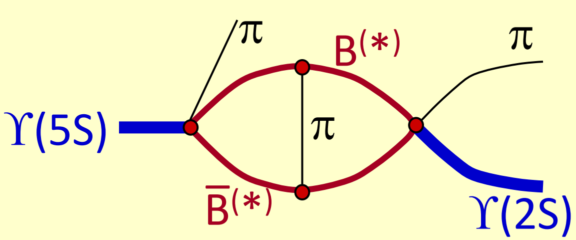
2. Coupled-channels resonance multiple rescattering $\Rightarrow$ pole





3. Deutron-like molecule

π,ρ,ω,σ exchange

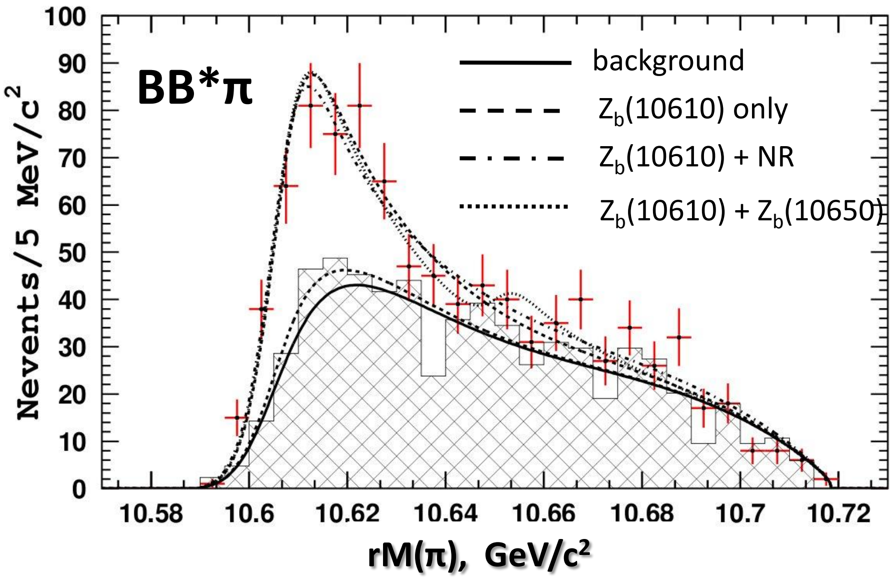


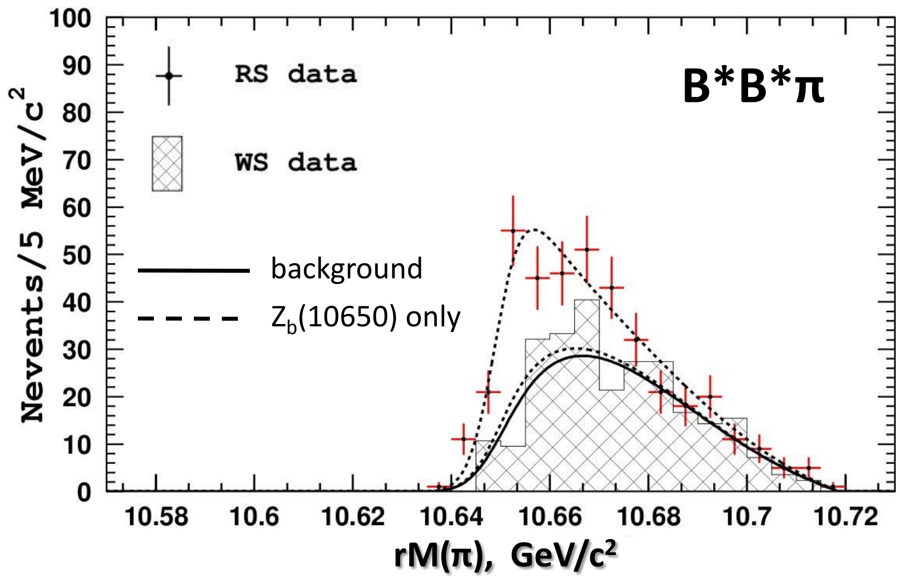
Ohkoda et al. PRD86,014004(2012)

$\Rightarrow$ Predictions to fit data and discriminate models?

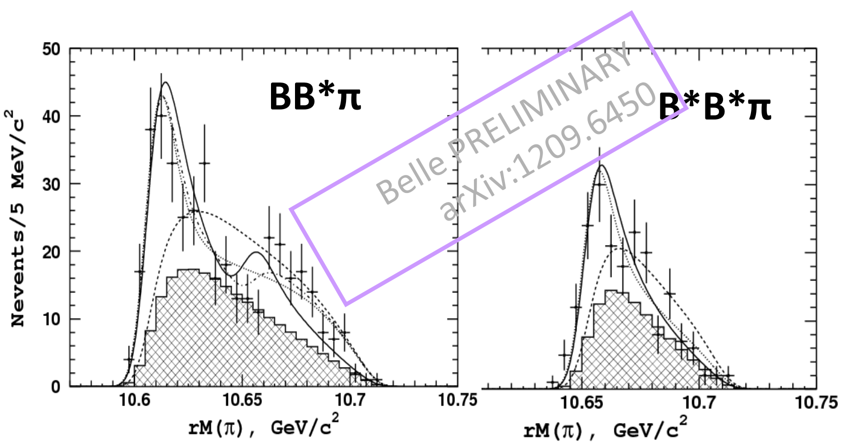
$\Upsilon(5S) \to Z_b \pi^{\pm}$

- For events from 3-body sig. region → recoil mass against primary $\pi^{\pm}$





BB*π and B*B*π data fits well to just $Z_b(10610)$ and $Z_b(10650)$ signal, respectively

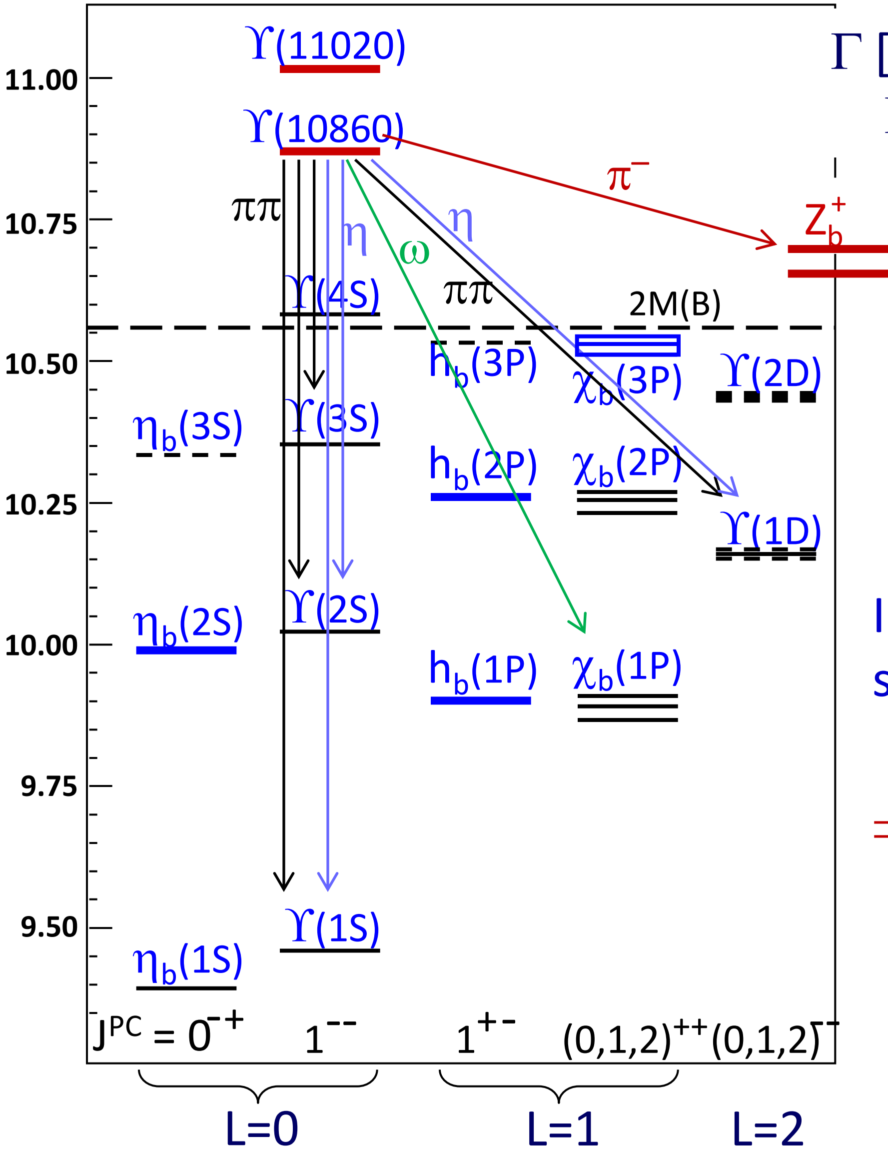


Kinematic cusp effect cannot produce that narrow structures in the elastic channels in contrast to genuine *S*-matrix poles.

Cleven, Guo, Hanhart, Wang, Zhao, arxiv:1510.00854

Transitions from $\Upsilon(5S)$

Partial widths of hadronic transitions from $\Upsilon(5S)$ are anomalously large:



$\Gamma\,[\Upsilon(5S) \to \Upsilon(1S/2S/3S)\pi^+\pi^-] = 260/430/290$ keV

$\Gamma\,[\Upsilon(5S) \to Z_b(10610/10650)^+\pi^-] = 7/3$ MeV

preliminary

$\Gamma\,[\Upsilon(5S) \to \Upsilon(1S/2S)\,\eta] = 40/200$ keV

$\Gamma\,[\Upsilon(5S) \to \Upsilon(1D)\,(\pi^+\pi^-)/\eta] = 60/140$ keV

$\Gamma[\Upsilon(5S) \to \chi_{b1/2}(1P)\,\omega] = 80/30$ keV

$\Gamma\Gamma[\Upsilon(5S)\to\Upsilon(1S)\,K^+K^-] = 30$ keV

PRL113,142001(2014)

In bottomonium hadronic transitions are OZI suppressed: $\Gamma[\Upsilon(3S/2S)\to\Upsilon(1S)\pi\pi] = 1/6$ keV

$\Rightarrow$ Evidence for light d.o.f. inside "$\Upsilon(5S)$":

"$\Upsilon(5S)$" = $|b\bar{b}\rangle + |B\bar{B}\rangle + |b\bar{b}g\rangle + |(bq)(\bar{b}\bar{q})\rangle$...

$\swarrow$ $Z_b\pi$

Production of Z_b – evidence for molecular component inside "$\Upsilon(5S)$"?

Voloshin PRD84, 031502 (2011)

$$|Z_b'\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}} - \frac{1}{\sqrt{2}} 1^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}}$$

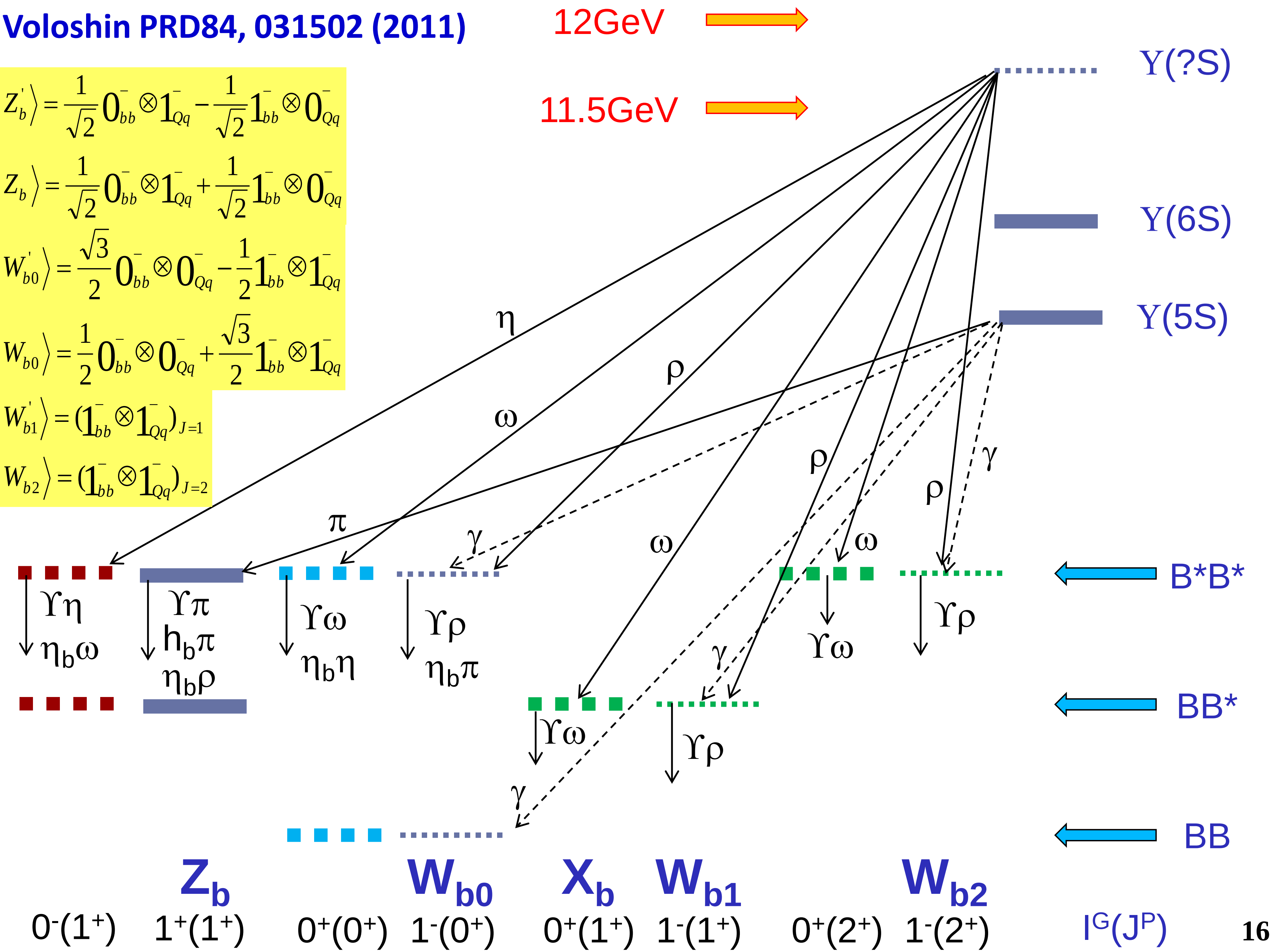
$$|Z_b\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}} + \frac{1}{\sqrt{2}} 1^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}}$$

$$|W_{b0}'\rangle = \frac{\sqrt{3}}{2} 0^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}} - \frac{1}{2} 1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}}$$

$$|W_{b0}\rangle = \frac{1}{2} 0^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}} + \frac{\sqrt{3}}{2} 1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}}$$

$$|W_{b1}'\rangle = (1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}})_{J=1}$$

$$|W_{b2}\rangle = (1^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}})_{J=2}$$



Voloshin PRD84, 031502 (2011)

$$|Z_b'\rangle = \frac{1}{\sqrt{2}} 0^-_{bb} \otimes 1^-_{Qq} - \frac{1}{\sqrt{2}} 1^-_{bb} \otimes 0^-_{Qq}$$

$$|Z_b\rangle = \frac{1}{\sqrt{2}} 0^-_{bb} \otimes 1^-_{Qq} + \frac{1}{\sqrt{2}} 1^-_{bb} \otimes 0^-_{Qq}$$

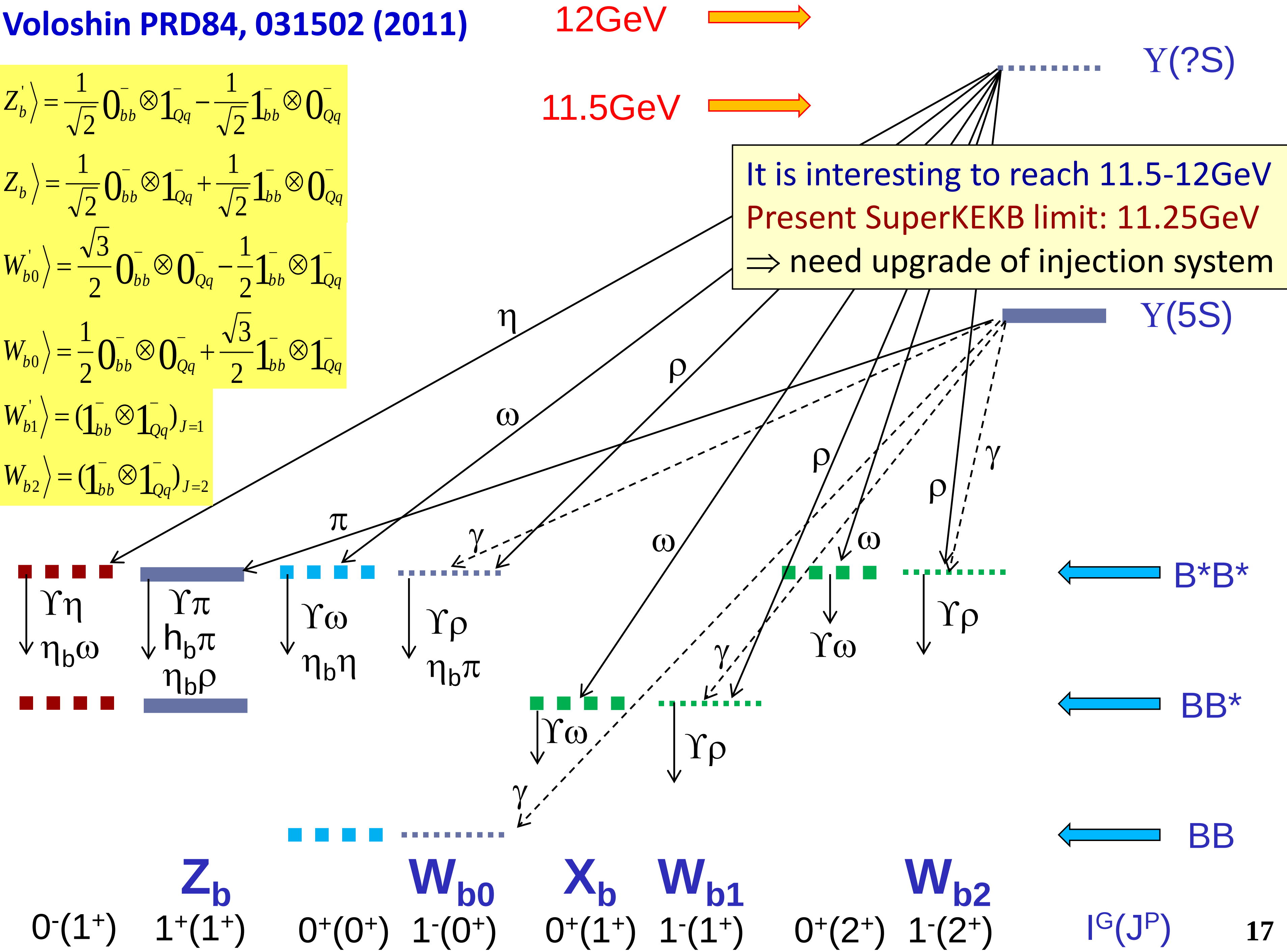
$$|W_{b0}'\rangle = \frac{\sqrt{3}}{2} 0^-_{bb} \otimes 0^-_{Qq} - \frac{1}{2} 1^-_{bb} \otimes 1^-_{Qq}$$

$$|W_{b0}\rangle = \frac{1}{2} 0^-_{bb} \otimes 0^-_{Qq} + \frac{\sqrt{3}}{2} 1^-_{bb} \otimes 1^-_{Qq}$$

$$|W_{b1}'\rangle = (1^-_{bb} \otimes 1^-_{Qq})_{J=1}$$

$$|W_{b2}\rangle = (1^-_{bb} \otimes 1^-_{Qq})_{J=2}$$

It is interesting to reach 11.5-12GeV
Present SuperKEKB limit: 11.25GeV
⇒ need upgrade of injection system



Conclusions

In bottomonium region there are flavor-exotic $| b\bar{b}u\bar{d} \rangle$ states:

$Z_b(10610)^+$ and $Z_b(10650)^+$

their properties $\Rightarrow$ they have molecular structure of $B\bar{B}^*$ and $B^*\bar{B}^*$, respectively, correspond to poles in S-matrix (not kinematic effects).

Properties of vector $\Upsilon(5S)$, $\Upsilon(6S)$ states require that they have 4-quark admixture, likely of molecular structure.

Charmonium sector is very different from bottomonium. Decay pattern is puzzling.

Presence of “short-distance” exotics (diquarks, valence gluons) is an open question.

Further studies: Belle, LHC, Belle-II.