Exotic Hadrons Workshop, 21-23 August 2017, Crete

Vector bottomonium-like states

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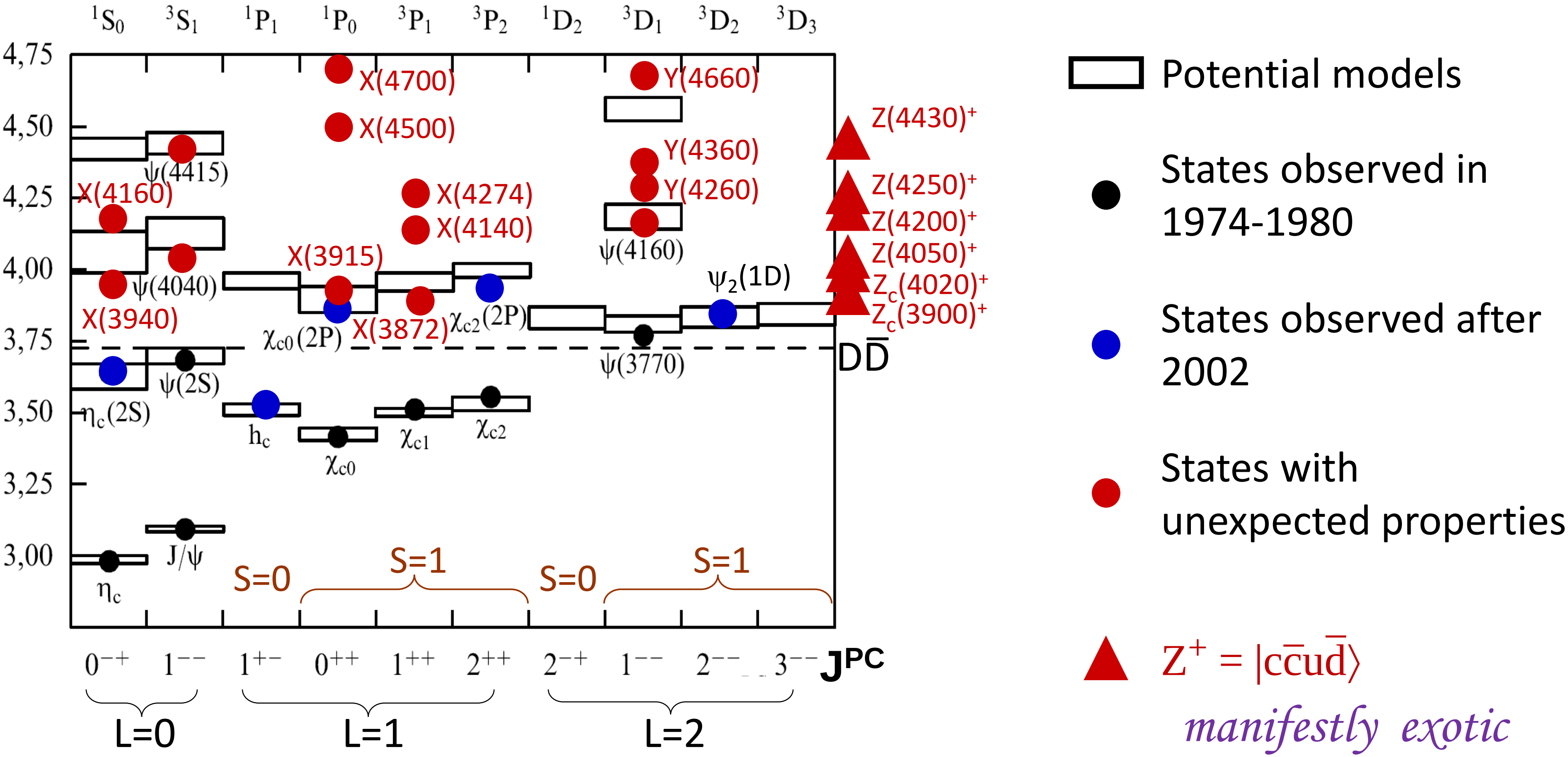
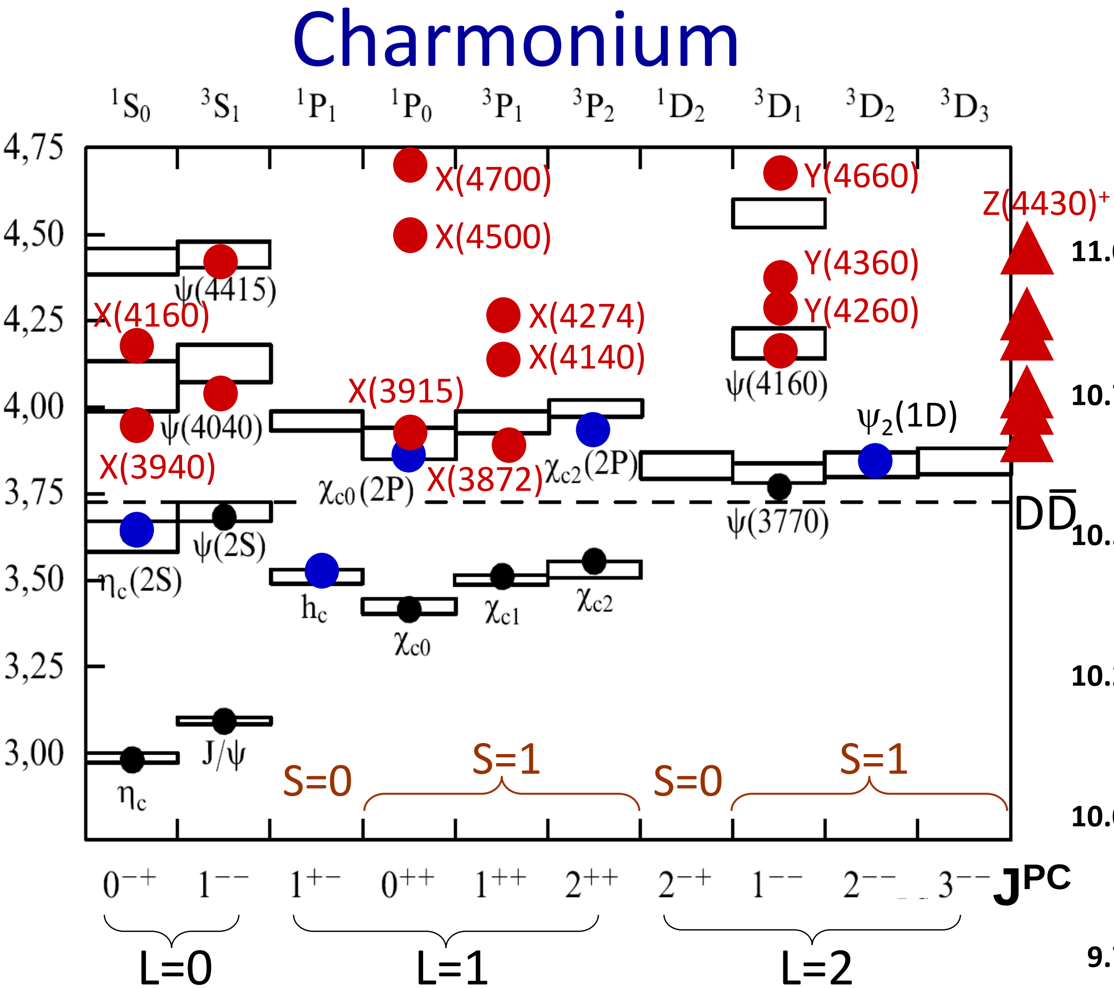
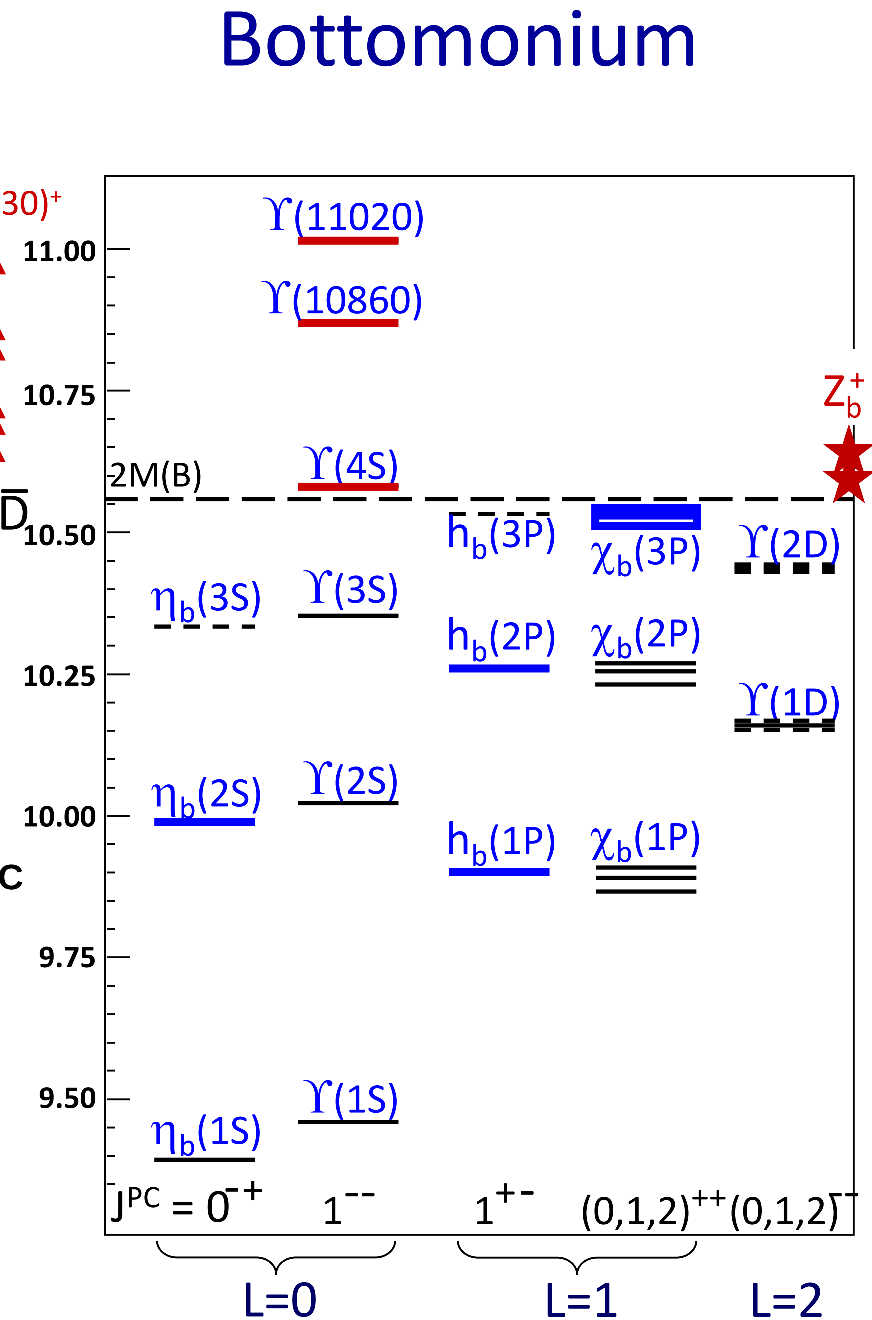
Charmonium table



States below DD̄ threshold are narrow (annihilation or → other charmonia)

States above DD̄ threshold are broad (→ DD̄, DD̄*, ...)



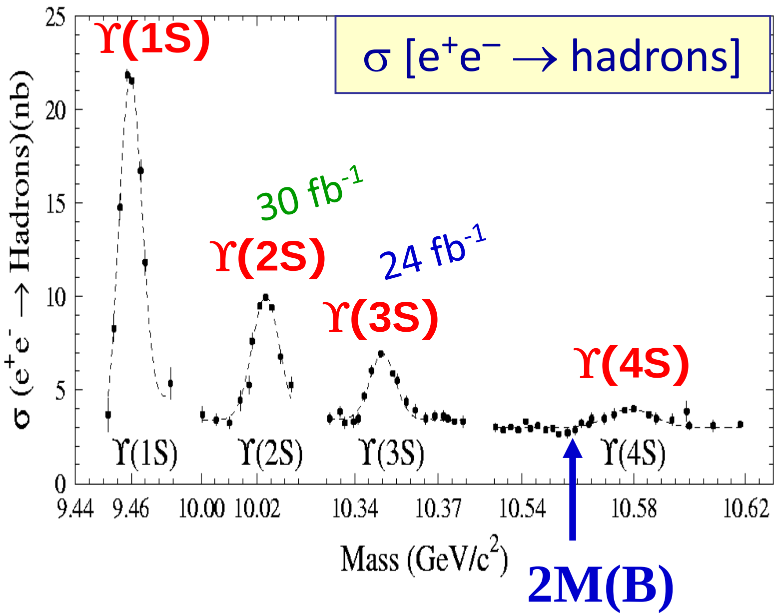


Vector bottomonium states:

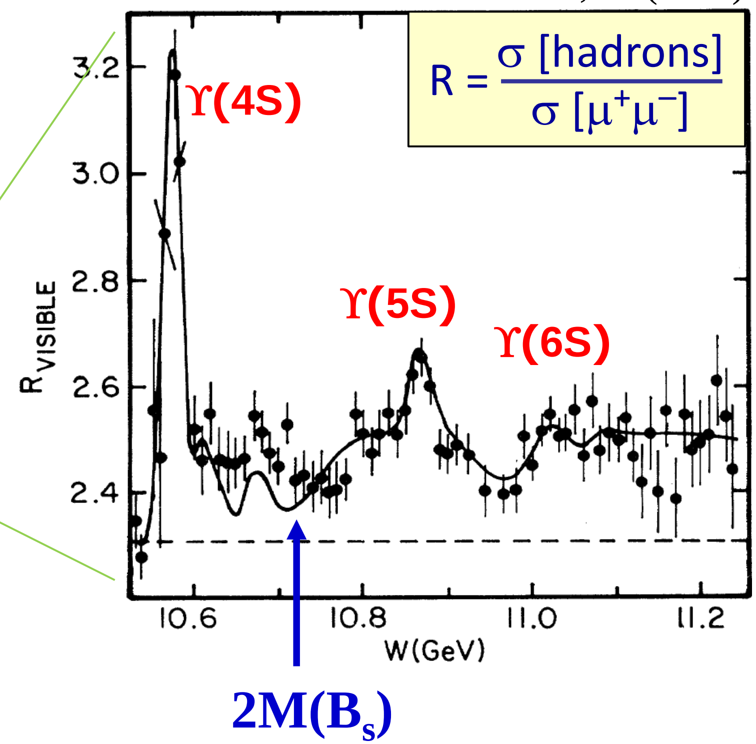
- ϒ(4S)
- ϒ(10860) (or ϒ(5S))
- ϒ(11020) (or ϒ(6S))

This talk: exotic properties, interpretation

Data samples



CUSB PRL54,377(1985)



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

BaBar 433 fb^{-1} + Belle 711 fb^{-1} Study rare B decays and CP violation

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

Belle 121 fb^{-1}

Energy scan: BaBar 4 fb^{-1} + Belle 26 fb^{-1} Study bottomonium

2007: Belle observed $e^+e^- \to \Upsilon(1S,2S,3S)\,\pi^+\pi^-$ at $\Upsilon(5S)$ PRL100,112001(2008)

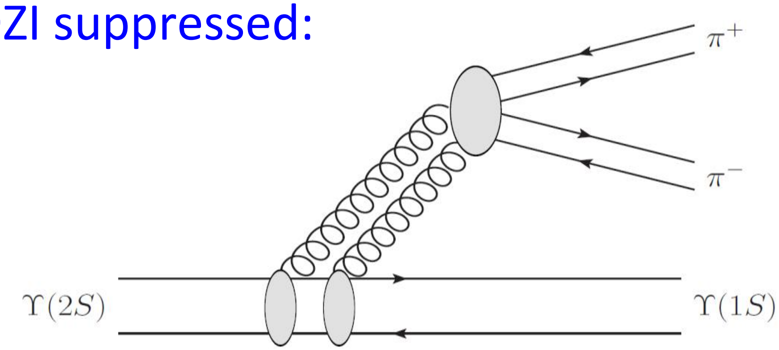
If reactions proceed via $\Upsilon(5S) \Rightarrow$

	Γ(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

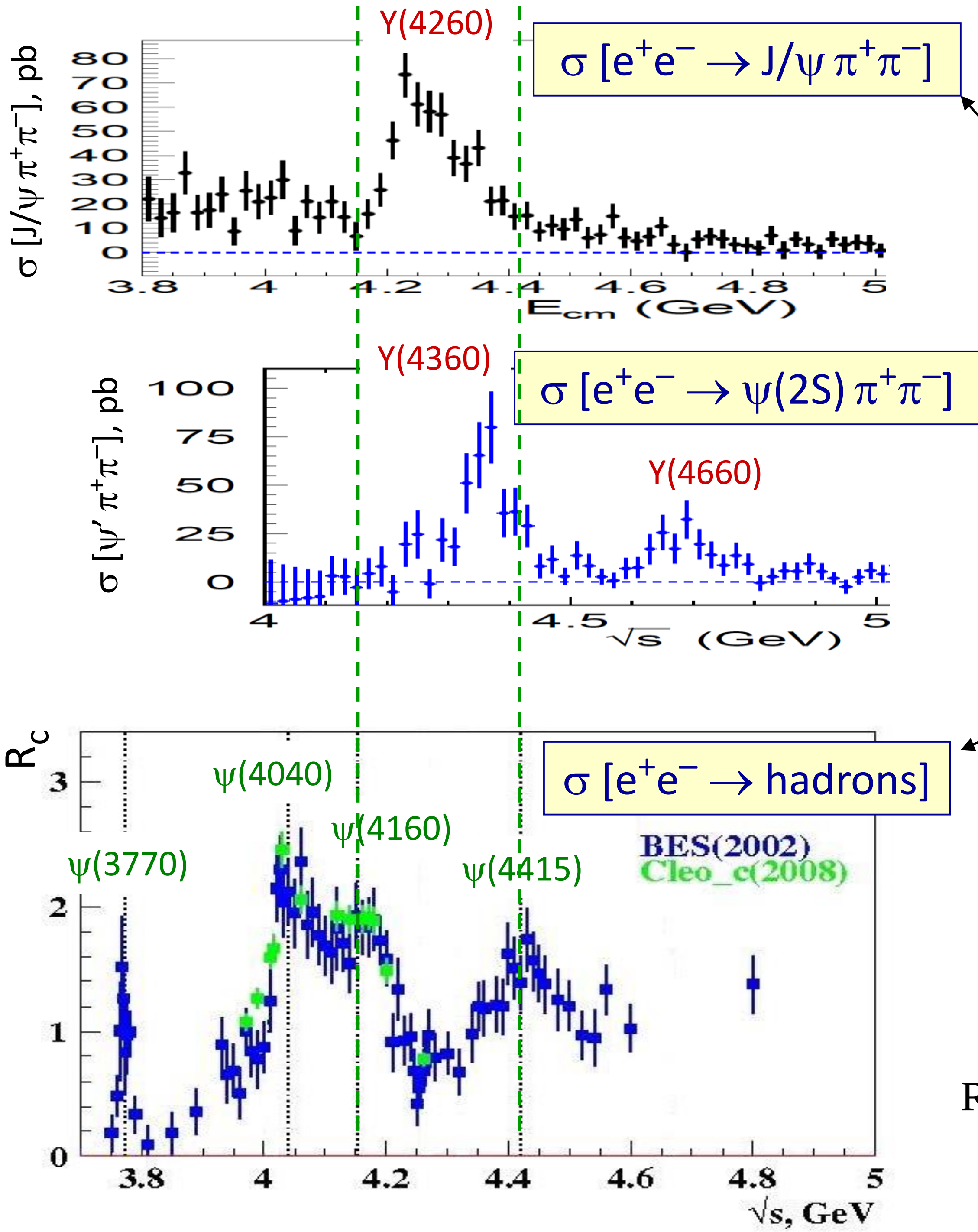
10^2

anomalously high

In bottomonium hadronic transitions are
OZI suppressed:



$\Upsilon(5S)$ – violation of OZI-rule.



Similar phenomena in $c\bar{c}$ region

Proceed via new states
Y(4260), Y(4360), Y(4660)

Y-states are distinct from ψ-states

$$R_c = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma_0(e^+e^- \to \mu^+\mu^-)} - R_{uds}$$

2007: Belle observed $e^+e^- \to \Upsilon(1S,2S,3S)\,\pi^+\pi^-$ at $\Upsilon(5S)$

PRL100,112001(2008)

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anomalously high

10^2

Two possibilities:

1. Reactions proceed via $\Upsilon(5S)$ – then $\Upsilon(5S)$ has exotic properties
2. Reactions proceed via some other state – Y_b, Y_b has exotic properties.

$\Rightarrow$ Measure energy dependence of $\sigma[\Upsilon(nS)\,\pi^+\pi^-]$

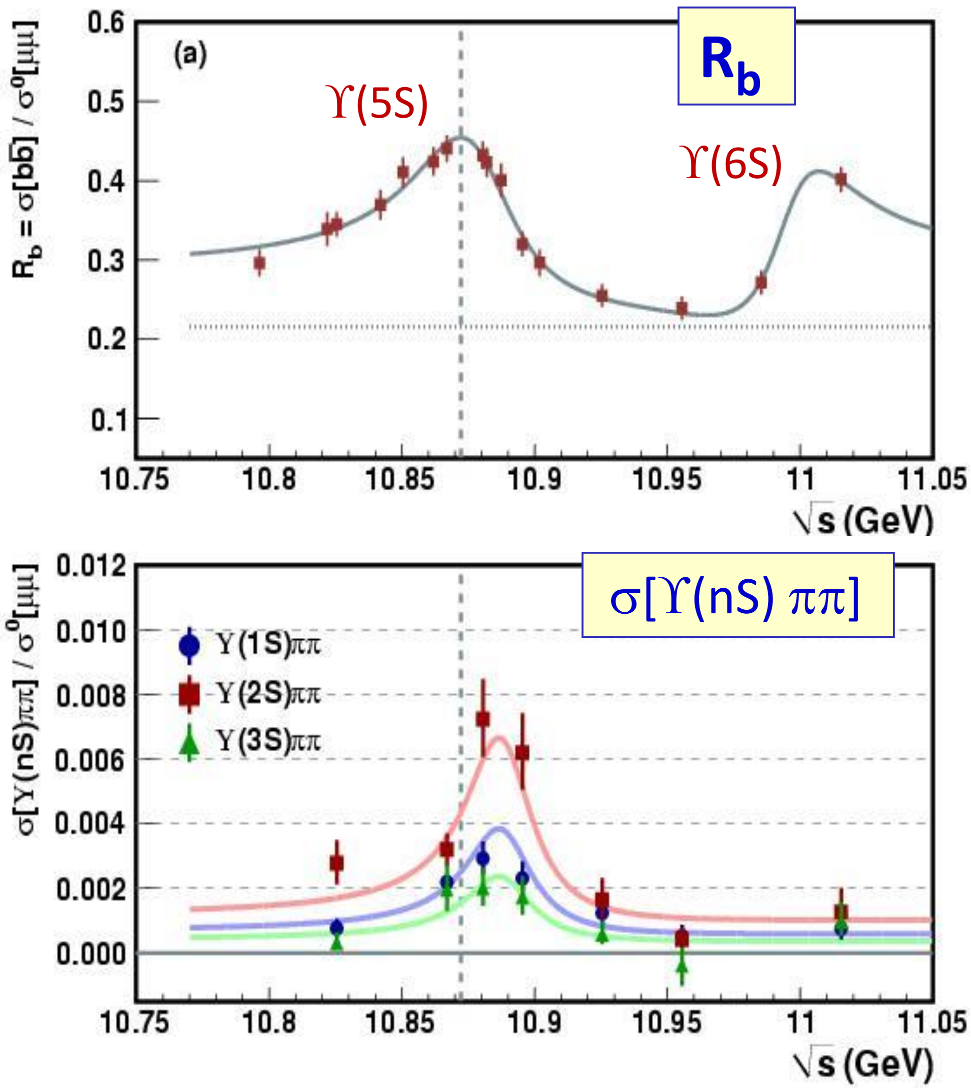
Energy scan by Belle

PRD82,091106R(2010)

2007:

9 points 30pb^{-1} for R_b

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



No evidence for new Y_b state

Energy scan by Belle

2007:

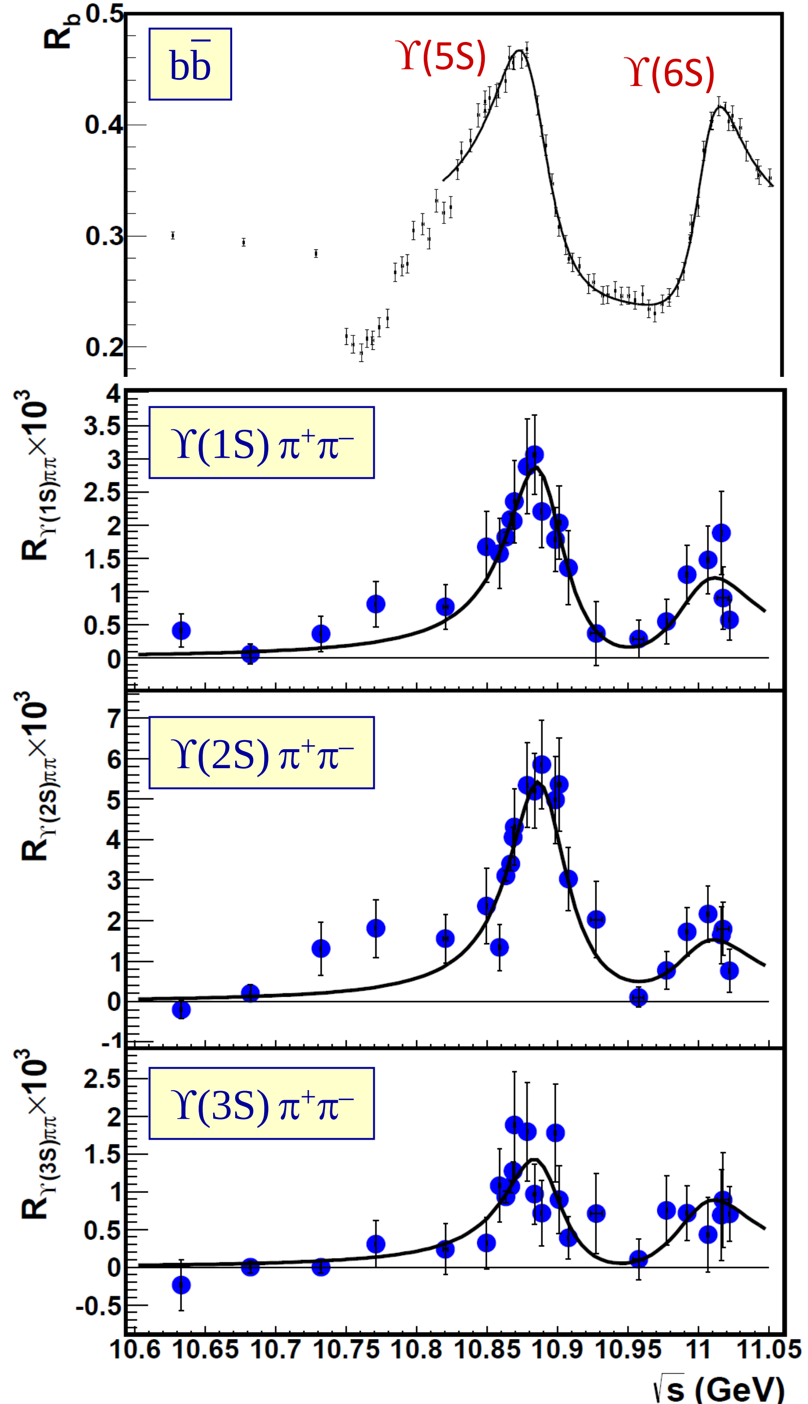
9 points 30pb^{-1} for R_b

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

2010:

61 points 50pb^{-1} for R_b

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



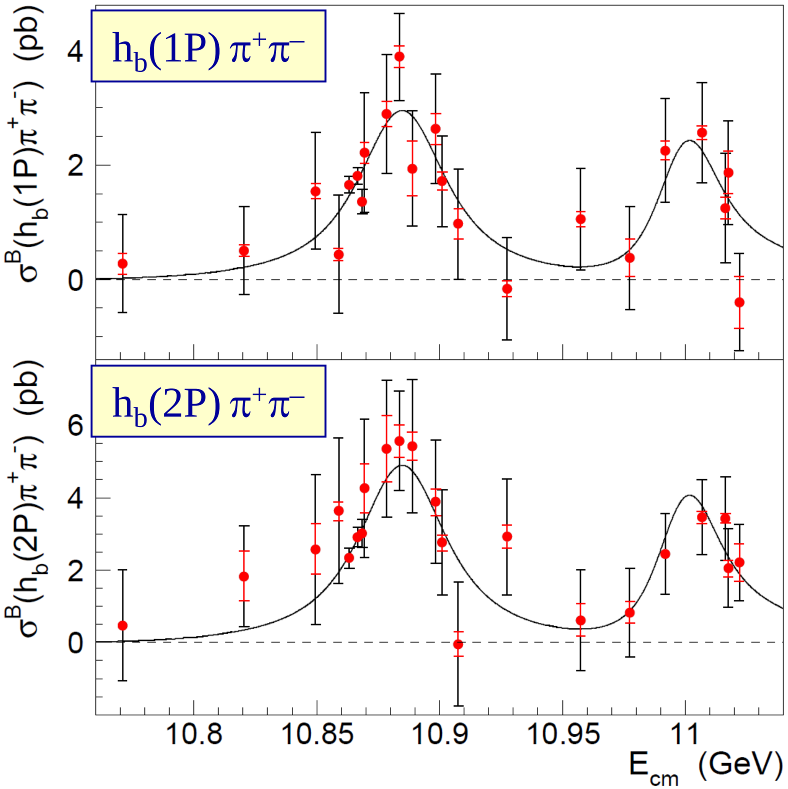
PRD93,011101(2016)

No evidence for new Y_b state

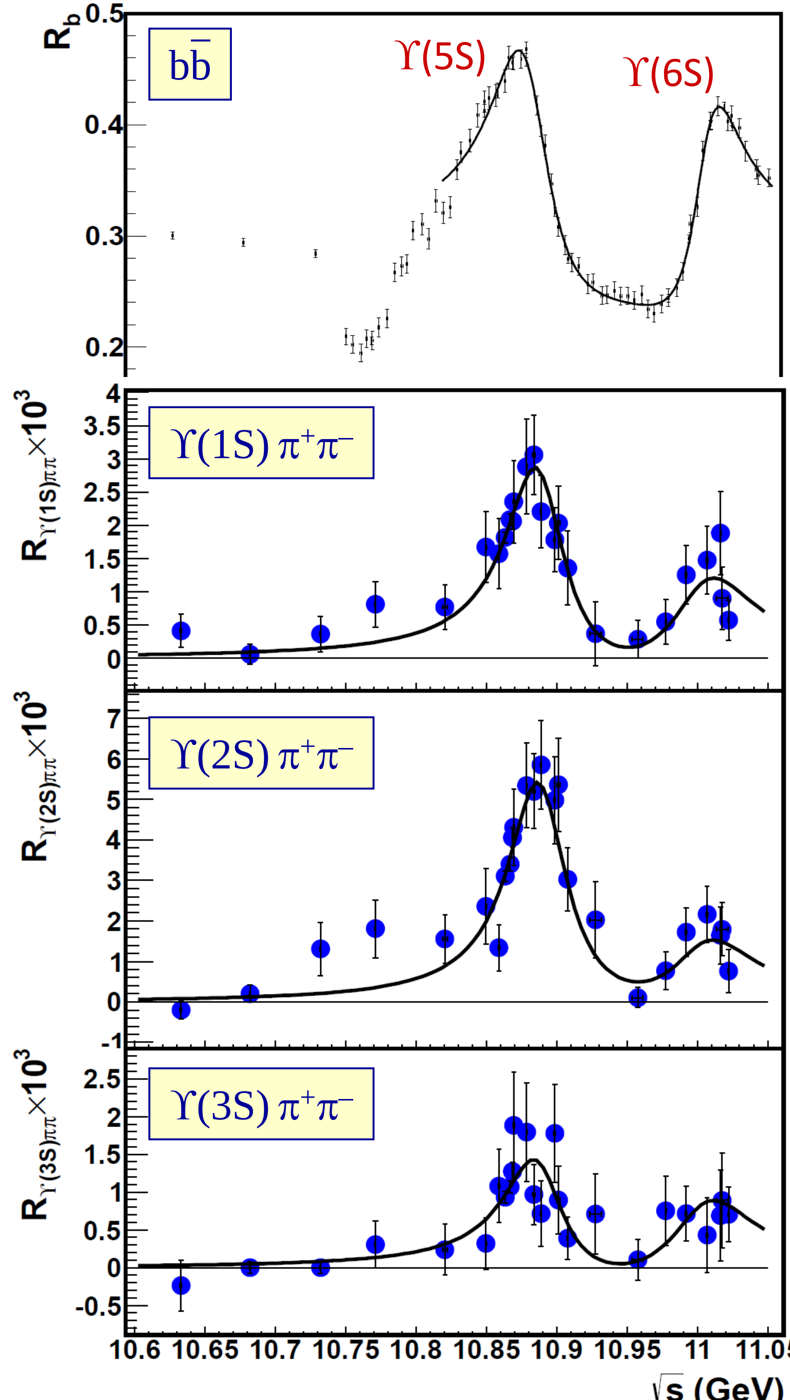
$e^+e^- \to \Upsilon(1S,2S,3S)\,\pi^+\pi^-$

proceed via $\Upsilon(5S)$, $\Upsilon(6S)$

Energy scan by Belle



PRL117,142001(2016)
PRD93,011101(2016)

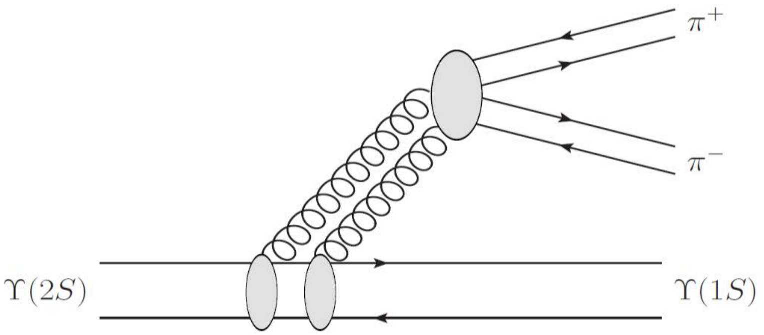


No evidence for new Y_b state

$e^+e^- \to \Upsilon(1S,2S,3S)\,\pi^+\pi^-$ and $h_b(1P,2P)\,\pi^+\pi^-$ proceed via $\Upsilon(5S)$, $\Upsilon(6S)$

Transition	Partial width (keV)
$\Upsilon(2S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	5.7 ± 0.5
$\Upsilon(1S)\,\eta$	$(9.3 \pm 1.5) \times 10^{-3}$
$\Upsilon(3S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	0.89 ± 0.08
$\Upsilon(1S)\,\eta$	$< 2 \times 10^{-3}$
$\Upsilon(2S)\,\pi^+\pi^-$	0.57 ± 0.06
$\Upsilon(4S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	1.7 ± 0.2
$\Upsilon(1S)\,\eta$	4.0 ± 0.8
$\Upsilon(2S)\,\pi^+\pi^-$	1.8 ± 0.3
$h_b(1P)\,\eta$	45 ± 7
$\Upsilon(5S) \to$	
$\Upsilon(1S)\,\pi^+\pi^-$	238 ± 41
$\Upsilon(1S)\,\eta$	39 ± 11
$\Upsilon(1S)\,K^+K^-$	33 ± 11
$\Upsilon(2S)\,\pi^+\pi^-$	428 ± 83
$\Upsilon(2S)\,\eta$	204 ± 44
$\Upsilon(3S)\,\pi^+\pi^-$	153 ± 31
$\chi_{b1}(1P)\,\omega$	84 ± 20
$\chi_{b1}(1P)\,(\pi^+\pi^-\pi^0)_{\text{non-}\omega}$	28 ± 11
$\chi_{b2}(1P)\,\omega$	32 ± 15
$\chi_{b2}(1P)\,(\pi^+\pi^-\pi^0)_{\text{non-}\omega}$	33 ± 20
$\Upsilon_J(1D)\,\pi^+\pi^-$	~ 60
$\Upsilon_J(1D)\,\eta$	150 ± 48
$Z_b(10610)^\pm\pi^\mp$	2070 ± 440
$Z_b(10650)^\pm\pi^\mp$	1200 ± 300

In bottomonium hadronic transitions are OZI suppressed:



Υ(5S), Υ(6S) – violation of OZI-rule.

$\pi^+\pi^-$ transitions: E1E1 gluons,
η transitions: E1M2 gluons
– Heavy Quark Spin Symmetry suppressed

Υ(4S), Υ(5S) – violation of HQSS.

$\Upsilon\eta \,/\, \Upsilon\pi^+\pi^-$, $\chi_{b1}\omega \,/\, \chi_{b2}\omega$

Bondar, RM, Voloshin
MPLA32,1750025(2017)

Comparison with charmonium-like states

	open charm	$J/\psi\, \pi^+\pi^-$	$\psi(2S)\, \pi^+\pi^-$	$J/\psi\, \eta$	$h_c\, \pi^+\pi^-$	$\chi_{c0}\, \omega$	$\chi_{c2}\, \omega$
$\psi(4040)$	+			+		—	—
$\psi(4160)$	+			+		—	—
Y(4220)		+			+	+	—
Y(4340)		+	+				
Y(4390)					+		
$\psi(4415)$	+			+			+
Y(4660)	+		+				

Charmonium-like:

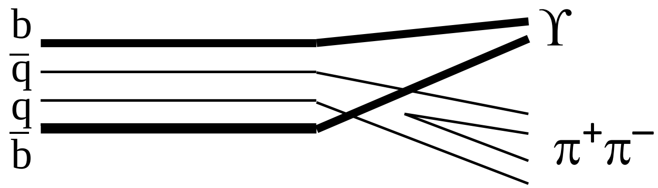
Some states are not seen in hadronic channels? different from bottomonium-like

Some states are seen in one channel only? different from bottomonium-like

Decay patterns for charmonium-like and bottomonium-like states are different.

Interpretation

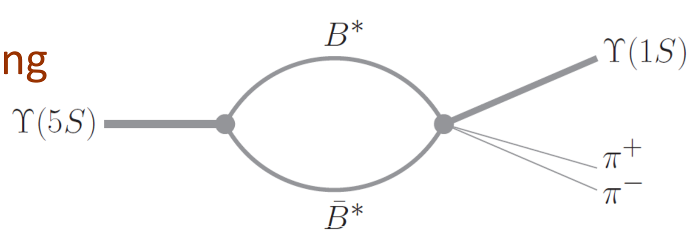
~~OZI~~ ⇒ light d.o.f.



	compact tetraquark $(bq)(\bar{b}\bar{q})$	hadronic admixture $(b\bar{q})(\bar{b}q)$	hadro-quarkonium $(b\bar{b})(q\bar{q})$
Charmonium-like Y-states			
open flavor decays are suppressed*	V	–	V
transition to one charmonium level only*	–	–	V
Bottomonium-like states			
open flavor decays dominate	–	V	–
transition to various bottomonia	V	V	–

* now experimental situation is changing

admixture + rescattering



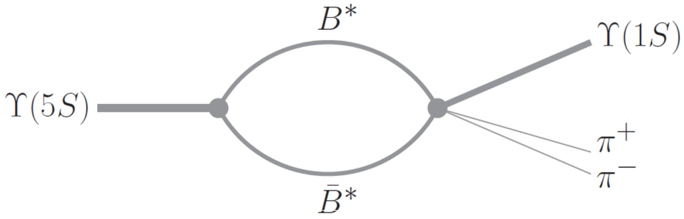
Hadronic admixture

… is very natural:

pure $b\bar{b}$	+	continuum state $B\bar{B}$	+ interaction $\Rightarrow$

physical state = $c_1|b\bar{b}\rangle + c_2|B\bar{B}\rangle$

Hadronic admixture is not an option, but a must.



$\Leftarrow$ Enhanced if $B^{(*)}\bar{B}^{(*)}$ are on-shell

Simonov JETP Lett 87,147(2008)
Meng Chao PRD77,074003(2008)

Hadronic admixture explains ~~OZI~~.
What about ~~HQSS~~ ?

Heavy quark spin structure of hadronic admixture

Reminder

Molecules are ***not*** eigenstates of the total $b\bar{b}$ spin

$$Z_b = B\bar{B}^* \qquad I^G(J^P) = 1^+(1^+)$$
$$Z_b' = B^*\bar{B}^*$$

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

Decomposition ⇒

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

$0^-_{b\bar{b}}$ → $h_b(mP)\pi$ $1^-_{b\bar{b}}$ → $\Upsilon(nS)\pi$

Heavy quark spin structure of hadronic admixture

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$Z_b' = B^*\bar{B}^*$

$I^G(J^P) = 1^+(1^+)$

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Decomposition $\Rightarrow$

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

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

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

Voloshin, PRD85,034024(2012)

Perform decomposition for $B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$ with $I^G(J^P) = 0^-(1^-)$ $\Rightarrow$

Violation of HQSS in $\Upsilon(4S,5S,6S)$

spin of $b\bar{b}$ pair

J of light d.o.f.

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

$$\frac{1}{2\sqrt{3}}\,\psi_{10} + \frac{1}{2}\,\psi_{11} + \frac{\sqrt{5}}{2\sqrt{3}}\,\psi_{12} + \frac{1}{2}\,\psi_{01}$$

Violation of HQSS in $\Upsilon(4S,5S,6S)$

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$$\frac{1}{2\sqrt{3}}\psi_{10} + \frac{1}{2}\psi_{11} + \frac{\sqrt{5}}{2\sqrt{3}}\psi_{12} + \frac{1}{2}\psi_{01}$$

spin of $b\bar{b}$ pair

J of light d.o.f.

$\Upsilon(1S)\pi^+\pi^-$

$\Upsilon(1S)\eta$

$\Upsilon(1S)\,\pi^+\pi^-$ in D-wave

$h_b(1P)\eta$ observed

$\eta_b(1S)\omega$ predicted

Violation of HQSS in $\Upsilon(4S,5S,6S)$

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

$$\frac{1}{2\sqrt{3}}\psi_{10} + \frac{1}{2}\psi_{11} + \frac{\sqrt{5}}{2\sqrt{3}}\psi_{12} + \frac{1}{2}\psi_{01}$$

spin of $b\bar{b}$ pair

J of light d.o.f.

$\Upsilon(1S)\pi^+\pi^-$ ← ψ_{10}

$\Upsilon(1S)\eta$ ← ψ_{11}

$\Upsilon(1S)\,\pi^+\pi^-$ in D-wave ← ψ_{12}

$h_b(1P)\eta$ observed ← ψ_{01}

$\eta_b(1S)\omega$ predicted

$\Upsilon(5S)$:

$(B_s^*\bar{B}_s^*)_{S=2}$

$$\frac{\sqrt{5}}{3}\psi_{10} - \frac{\sqrt{5}}{2\sqrt{3}}\psi_{11} + \frac{1}{6}\psi_{12} \qquad \times 0.82$$

angular ana.

$(B_s^*\bar{B}_s^*)_{S=0}$

$$-\frac{1}{6}\psi_{10} - \frac{1}{2\sqrt{3}}\psi_{11} - \frac{\sqrt{5}}{6}\psi_{12} + \frac{\sqrt{3}}{2}\psi_{01} \qquad \times 0.18$$

$\Upsilon(1S)\eta$ ← ψ_{11}

$\Upsilon(1S)\,K^+K^-$ in D-wave ← ψ_{12}

$h_b(1P)\eta$ ← ψ_{01}

$\eta_b(1S)\phi$ predicted

Violation of HQSS in Υ(4S,5S,6S)

Υ(4S) : $B\bar{B}$

$$\frac{1}{2\sqrt{3}}\psi_{10} + \frac{1}{2}\psi_{11} + \frac{\sqrt{5}}{2\sqrt{3}}\psi_{12} + \frac{1}{2}\psi_{01}$$

spin of $b\bar{b}$ pair

J of light d.o.f.

- $\frac{1}{2\sqrt{3}}\psi_{10}$ → $\Upsilon(1S)\pi^+\pi^-$
- $\frac{1}{2}\psi_{11}$ → $\Upsilon(1S)\eta$
- $\frac{\sqrt{5}}{2\sqrt{3}}\psi_{12}$ → $\Upsilon(1S)\pi^+\pi^-$ in D-wave
- $\frac{1}{2}\psi_{01}$ → $h_b(1P)\eta$ observed; $\eta_b(1S)\omega$ predicted

Υ(5S) :

$(B_s^*\bar{B}_s^*)_{S=2}$: $$\frac{\sqrt{5}}{3}\psi_{10} - \frac{\sqrt{5}}{2\sqrt{3}}\psi_{11} + \frac{1}{6}\psi_{12} \quad \times 0.82$$

$\times$ 0.82 ← angular ana.

$(B_s^*\bar{B}_s^*)_{S=0}$: $$-\frac{1}{6}\psi_{10} - \frac{1}{2\sqrt{3}}\psi_{11} - \frac{\sqrt{5}}{6}\psi_{12} + \frac{\sqrt{3}}{2}\psi_{01} \quad \times 0.18$$

- $\frac{1}{2\sqrt{3}}\psi_{11}$ → $\Upsilon(1S)\eta$
- $\frac{\sqrt{5}}{6}\psi_{12}$ → $\Upsilon(1S)K^+K^-$ in D-wave
- $\frac{\sqrt{3}}{2}\psi_{01}$ → $h_b(1P)\eta$; $\eta_b(1S)\phi$ predicted

Υ(6S) : $B_1\bar{B}$

narrow P-wave excitation

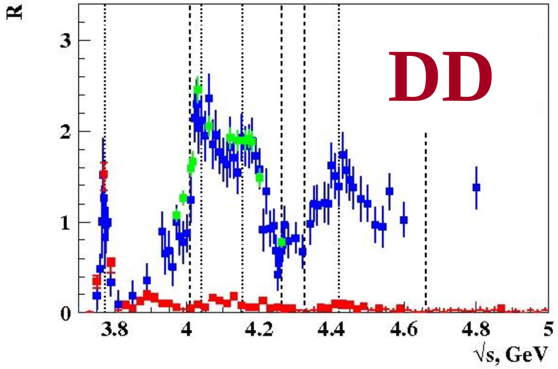
$$\frac{1}{2\sqrt{2}}\psi_{11} + \frac{\sqrt{5}}{2\sqrt{2}}\psi_{12} + \frac{1}{2}\psi_{01}$$

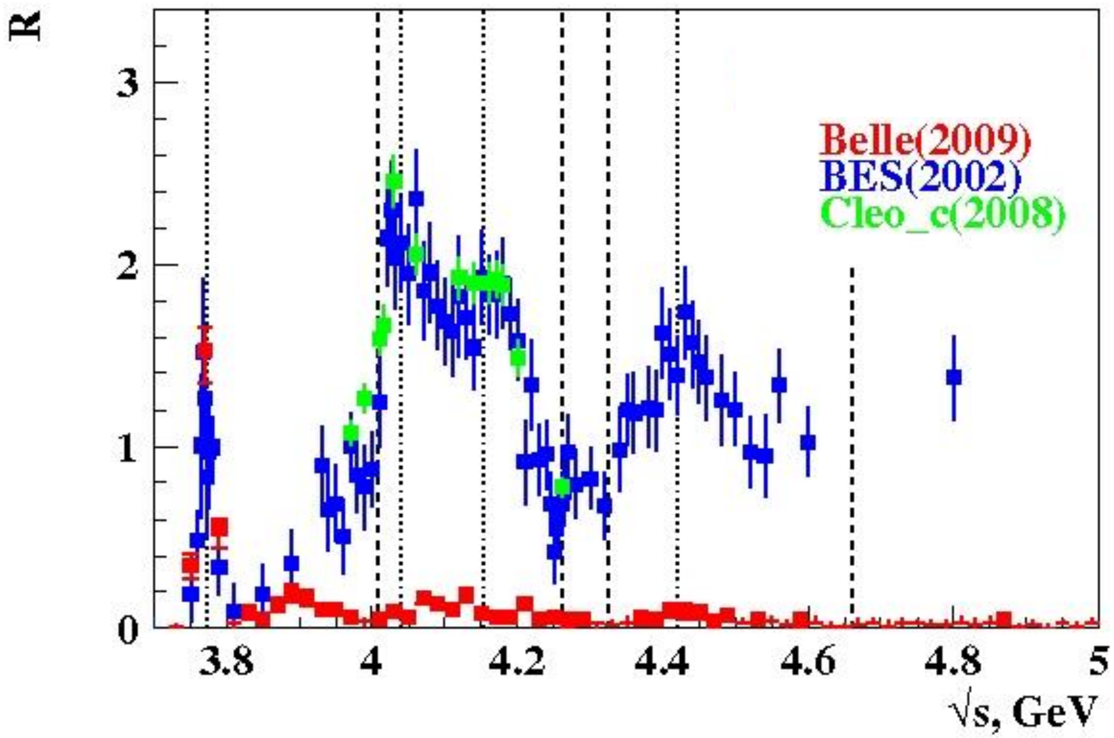
$\Upsilon(1S)\pi^+\pi^-$: S-wave is suppressed only D-wave

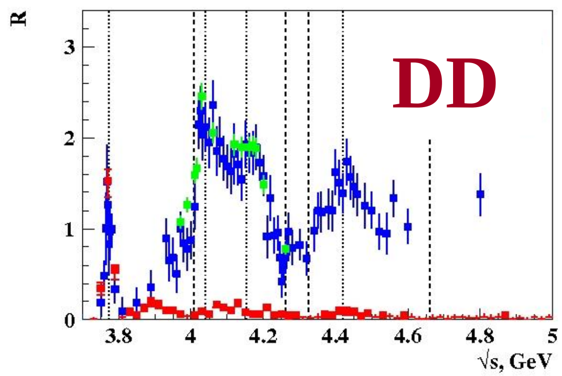
Hadronic admixture can explain ~~HQSS~~

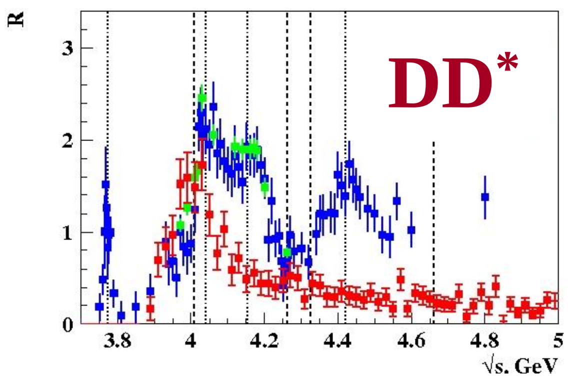
distance to threshold << B*-B mass splitting

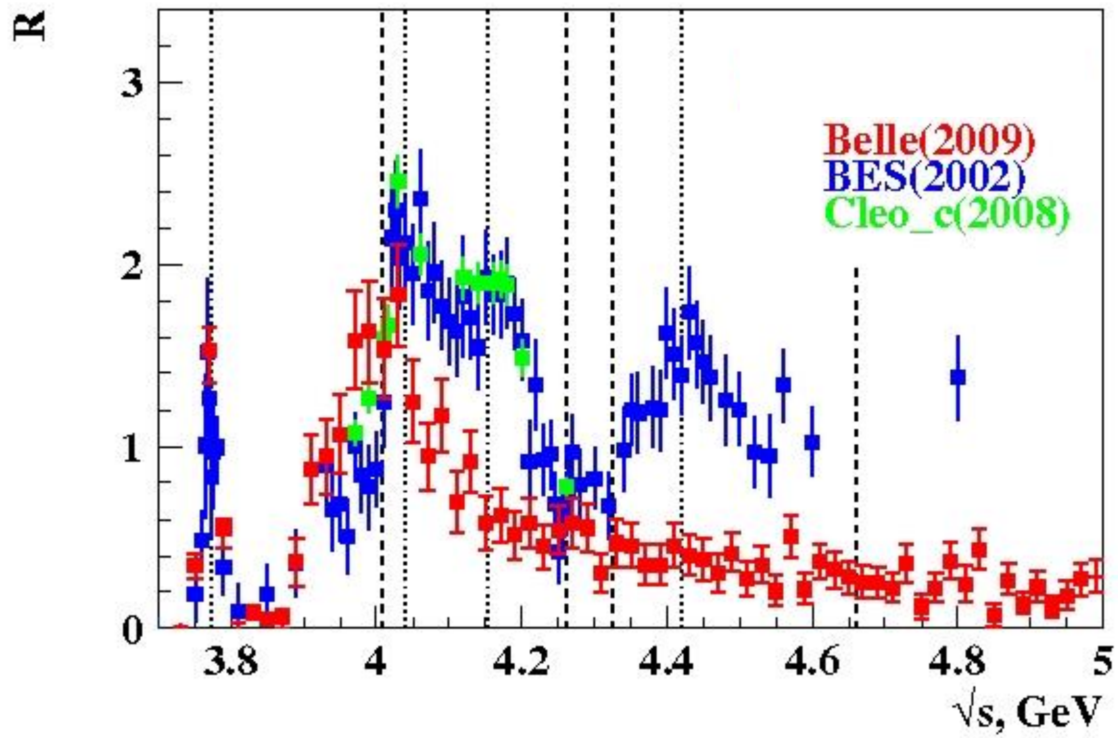
Next steps

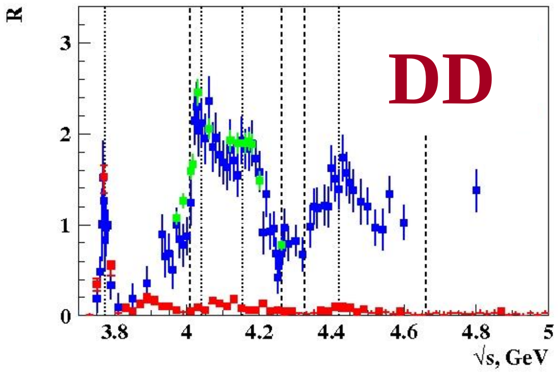

DD
R
√s, GeV

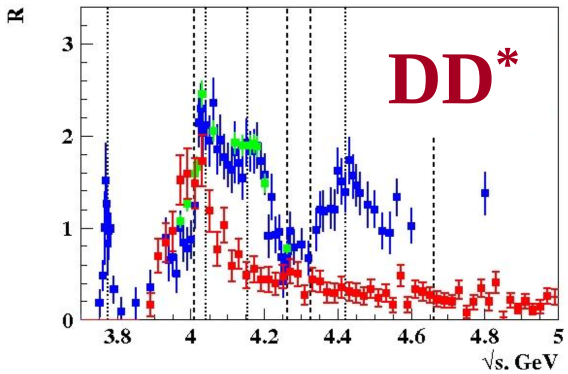

R
Belle(2009)
BES(2002)
Cleo_c(2008)
√s, GeV

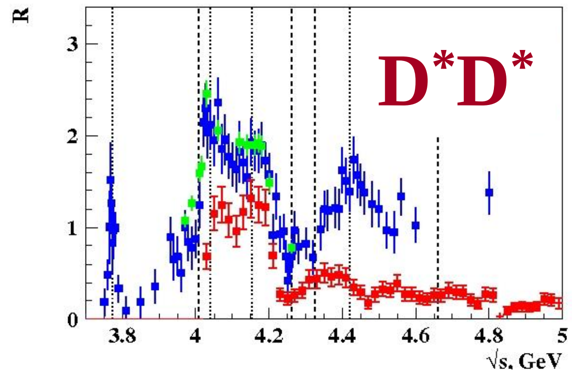

DD
R
√s, GeV

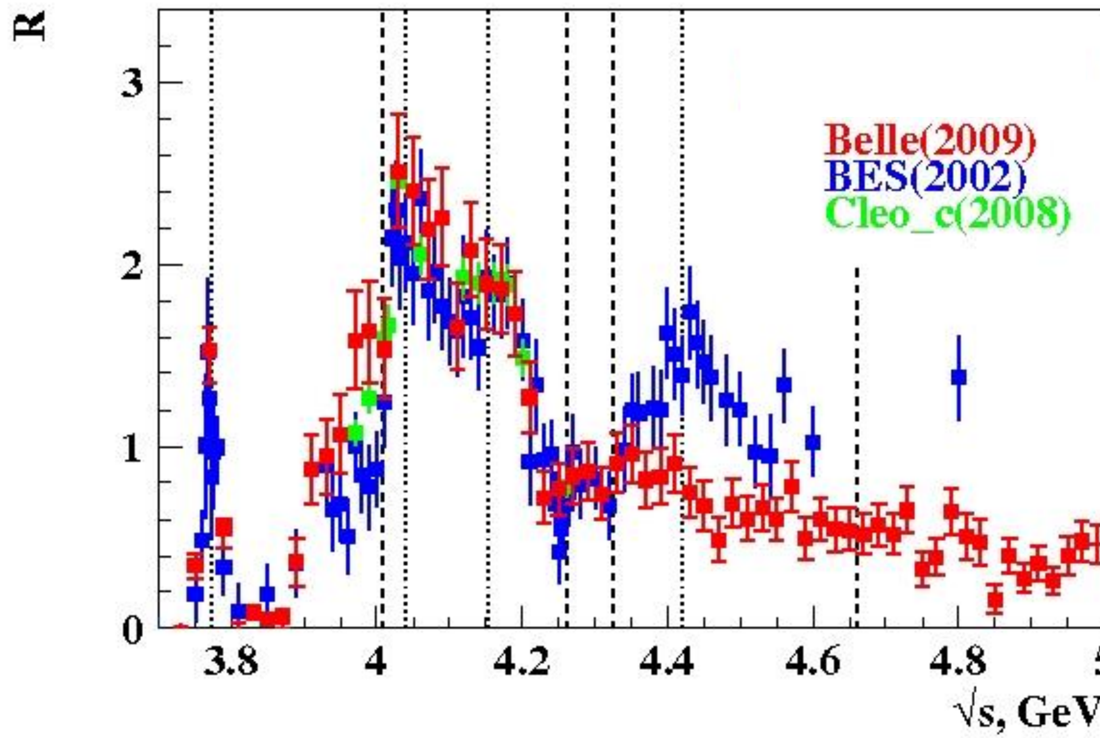

DD*
R
√s. GeV

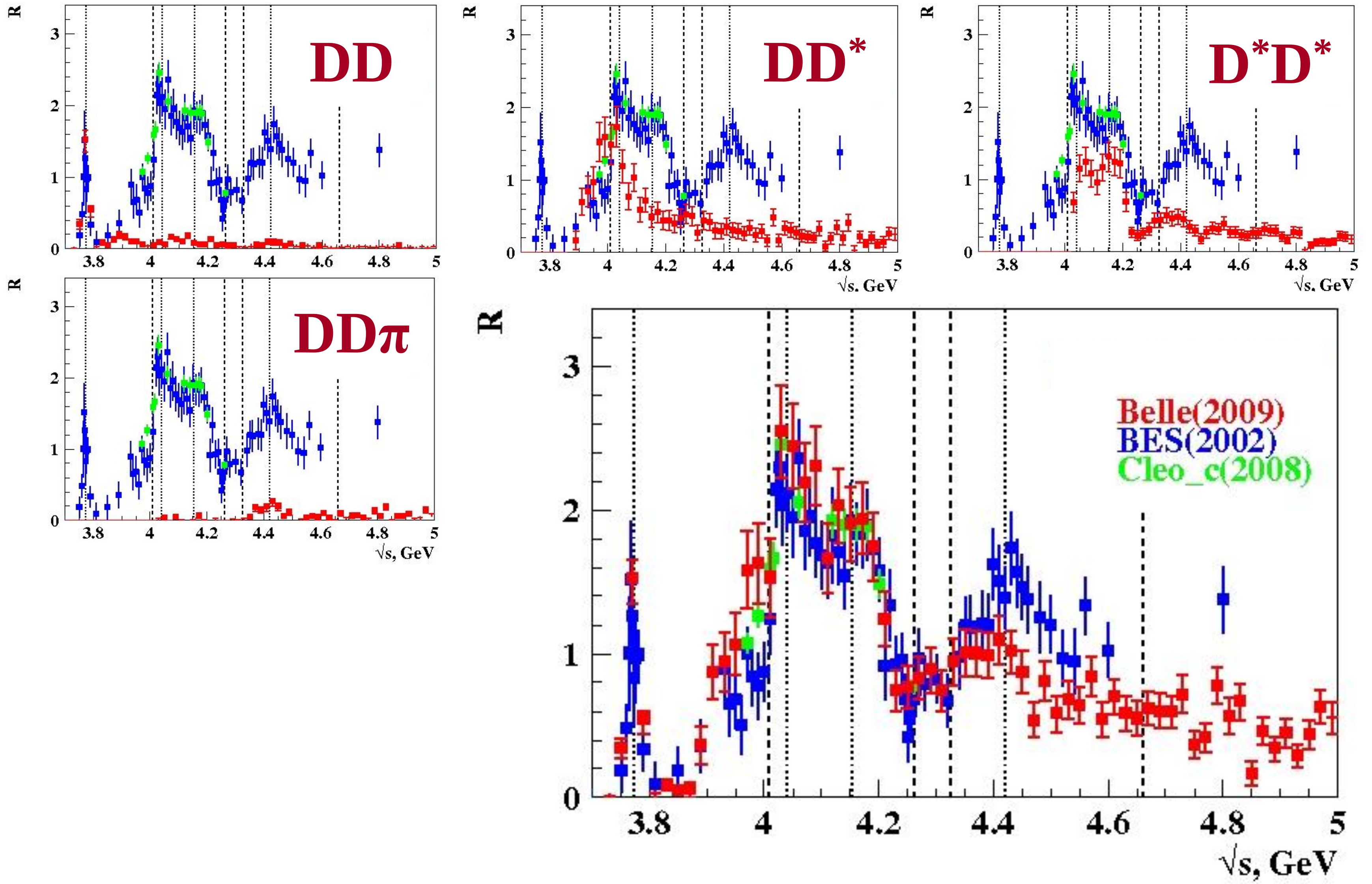

Belle(2009)
BES(2002)
Cleo_c(2008)
R
√s, GeV


DD
R
√s, GeV

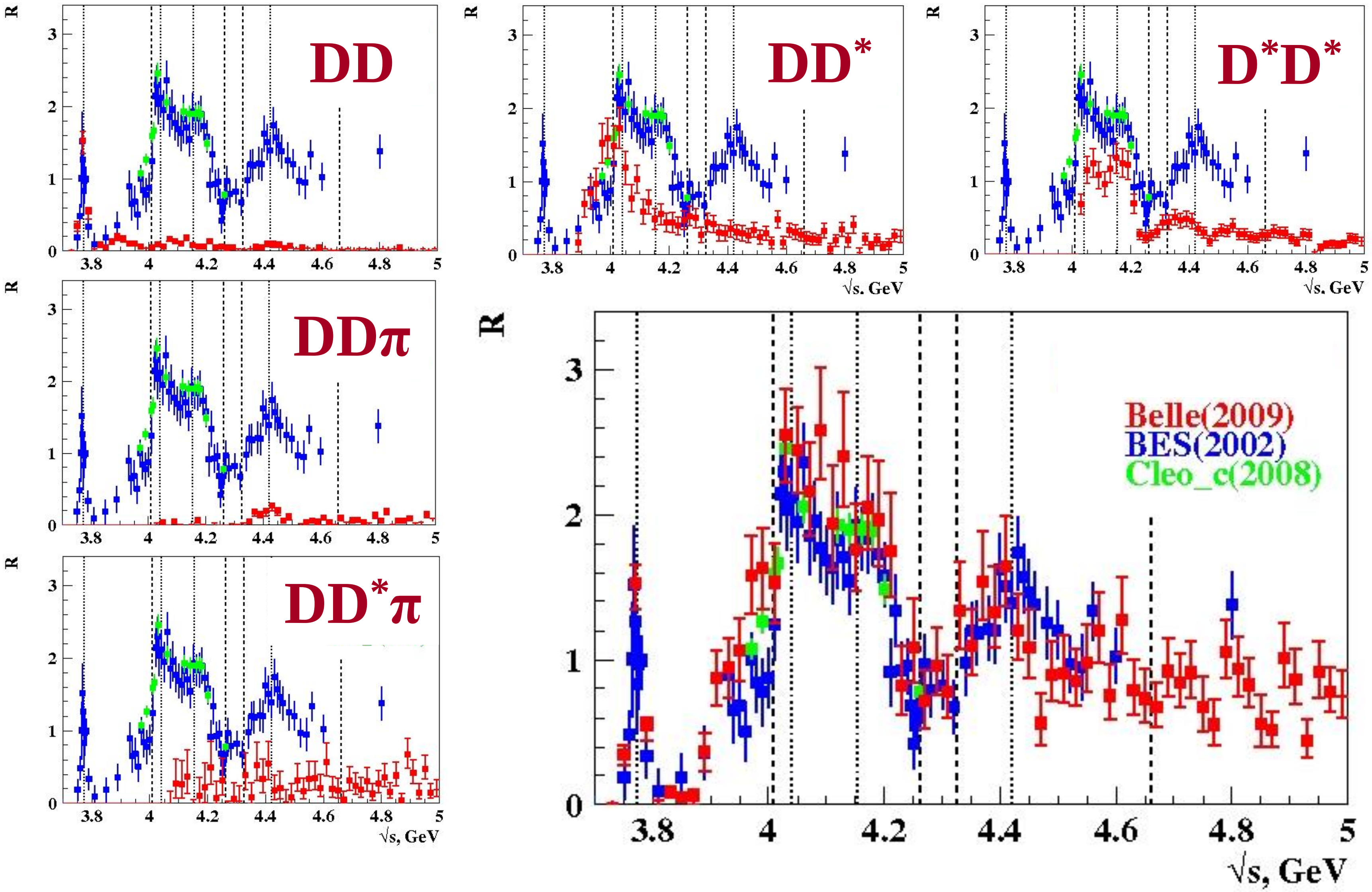

DD*
R
√s. GeV

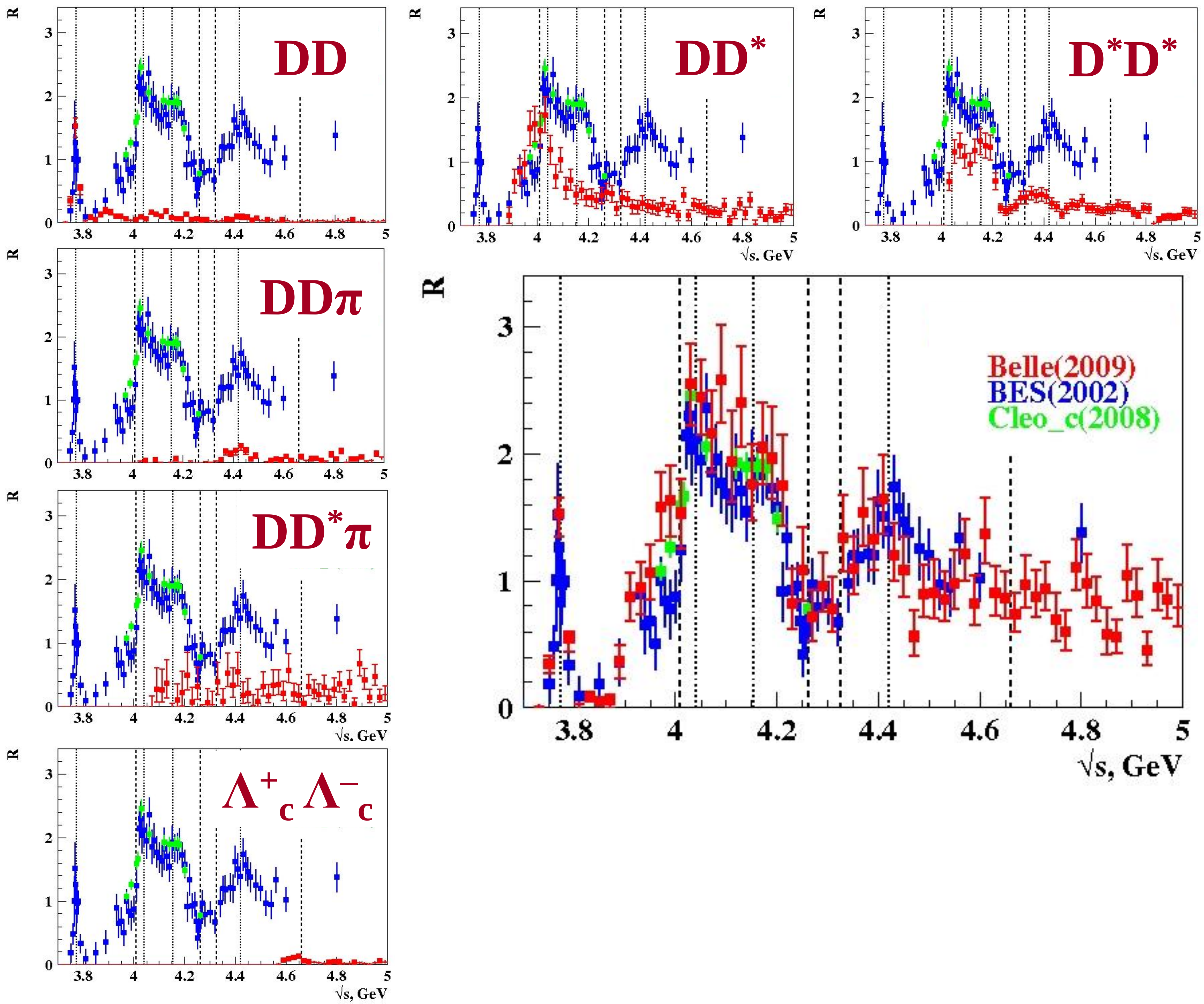

D*D*
R
√s. GeV


R
Belle(2009)
BES(2002)
Cleo_c(2008)
√s, GeV

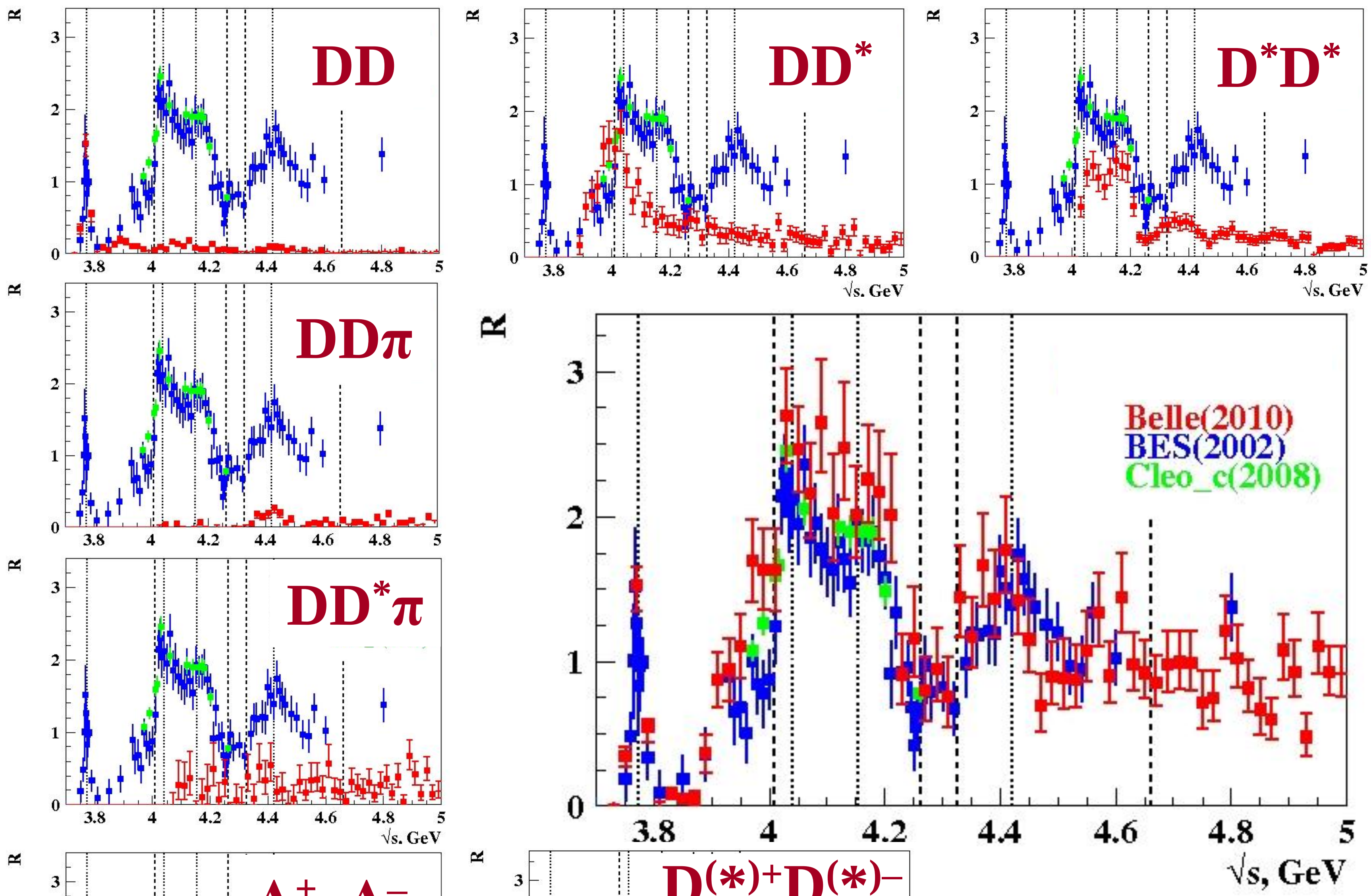

DD
DD*
D*D*
DDπ
Belle(2009)
BES(2002)
Cleo_c(2008)
R
√s, GeV

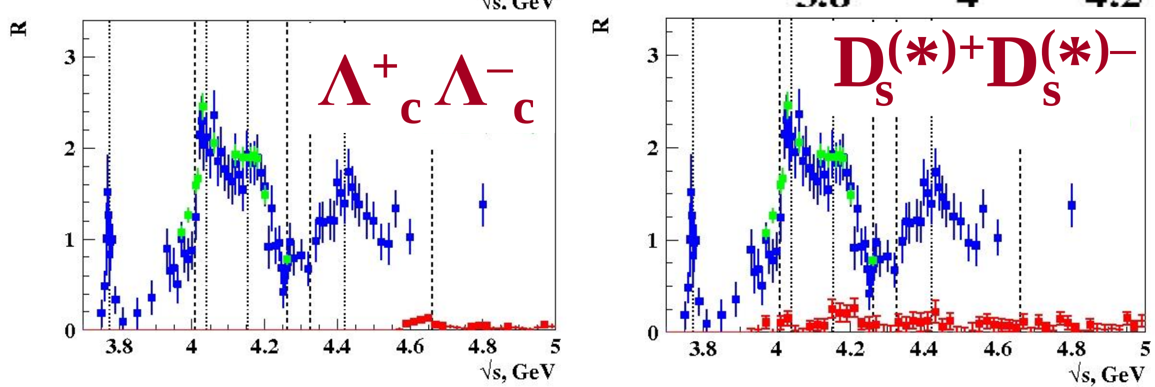
BELLE





DD
DD*
D*D*
DDπ
DD*π
Λ+c Λ−c
R
√s, GeV
Belle(2009)
BES(2002)
Cleo_c(2008)



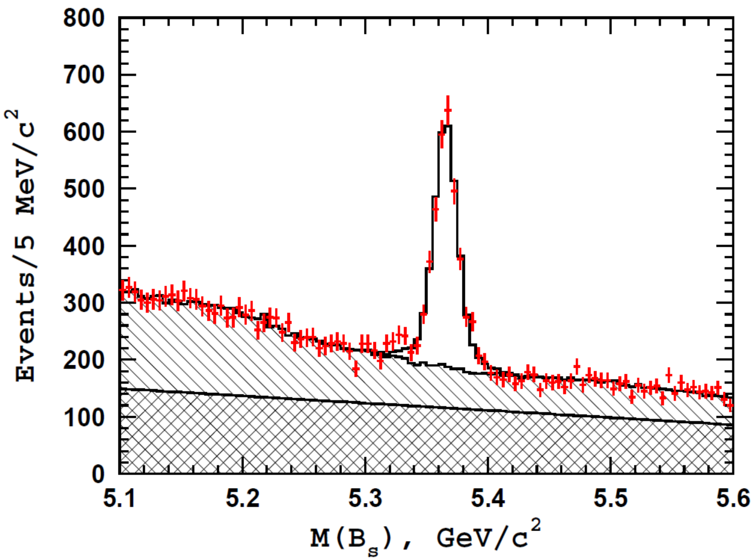


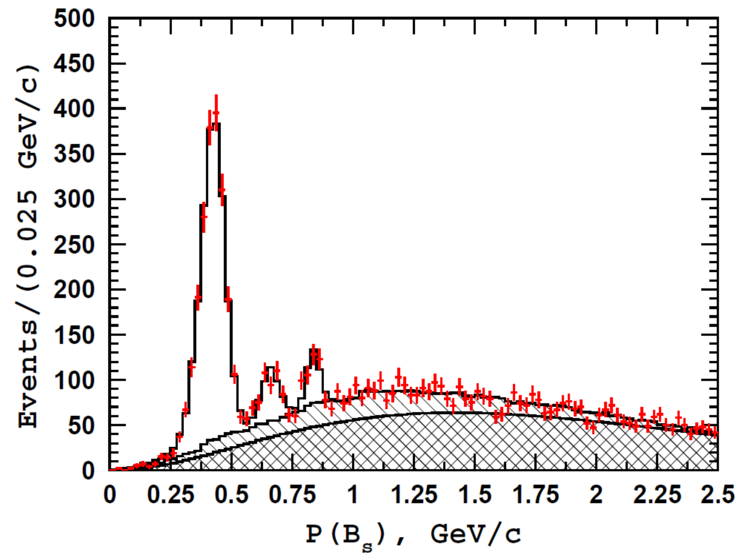
Total $c\bar{c}$ cross-section is decomposed into open charm channels

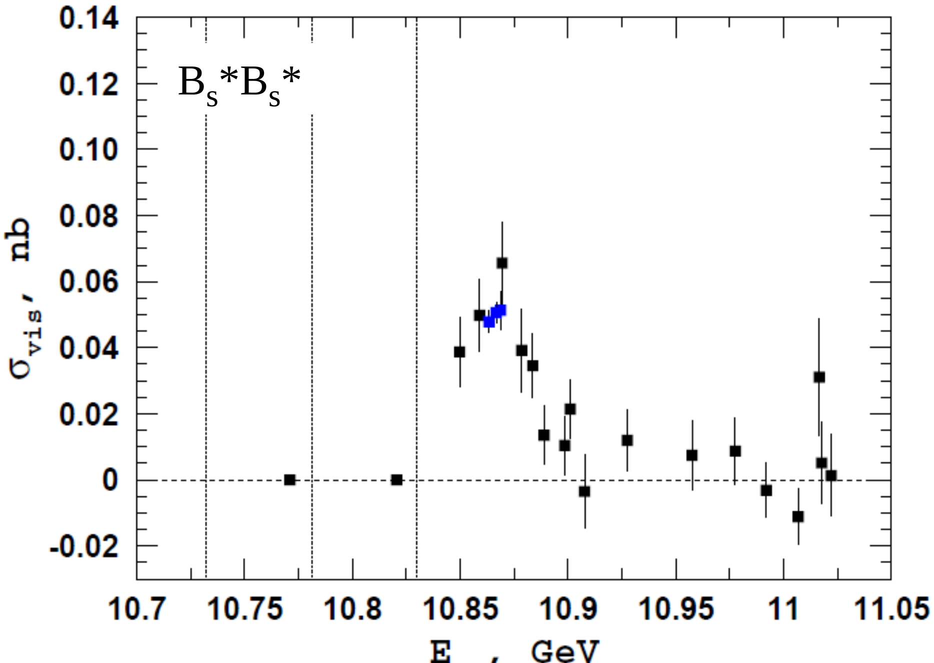
Scan of $e^+e^- \to B_s^{(*)}B_s^{(*)}$

arxiv:1609.08749

Perform full reconstruction of one B_s $\quad D_s^{(*)-}\pi^+,\ J/\psi K^+K^-,\ J/\psi\pi^+\pi^-,\ \psi(2S)K^+K^-$







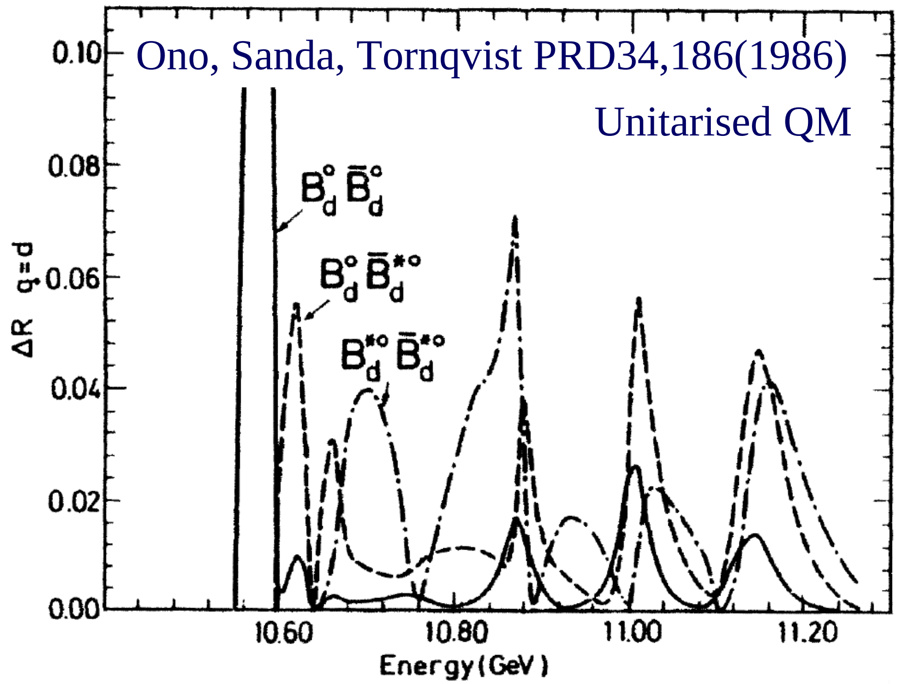
$B_s^*B_s^*$ is peaking at $\Upsilon(5S)$

$B_sB_s^*$ and B_sB_s are consistent with zero

Precision can be improved
by adding more B_s decay channels

Exclusive $e^+e^- \to$ BB, BB*, B*B* cross sections

Prediction



Expect many structures – due to nodes of Υ(5S), Υ(6S) wave functions

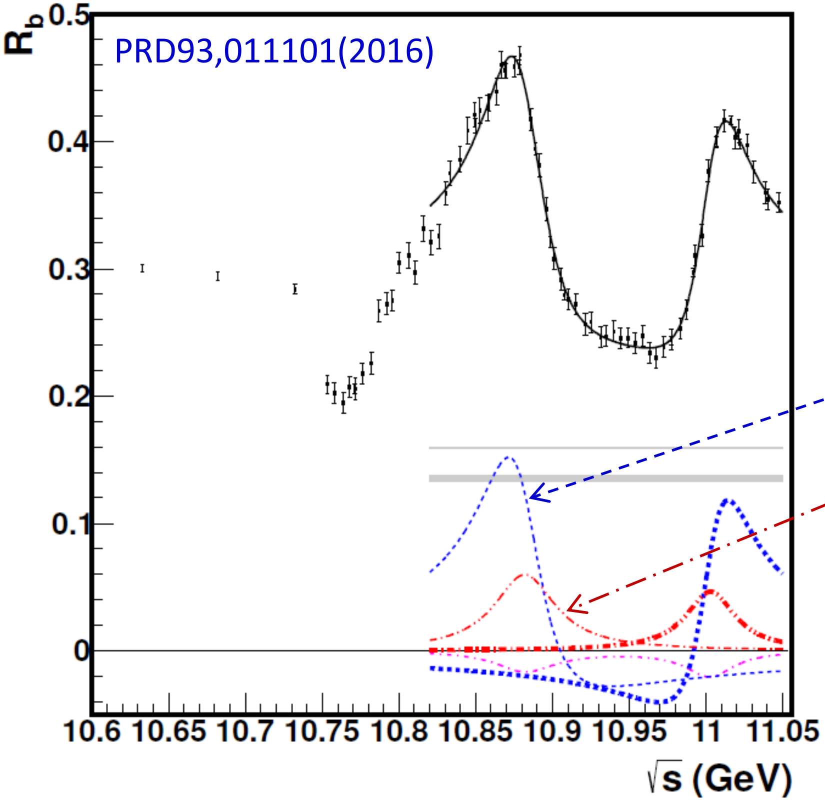
Peaks in different channels are shifted $\Rightarrow$ relatively featureless total cross section

Belle plans to measure this

$\Rightarrow$ Crucial test of hadron admixture interpretation

Deficit of fit to R_b

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



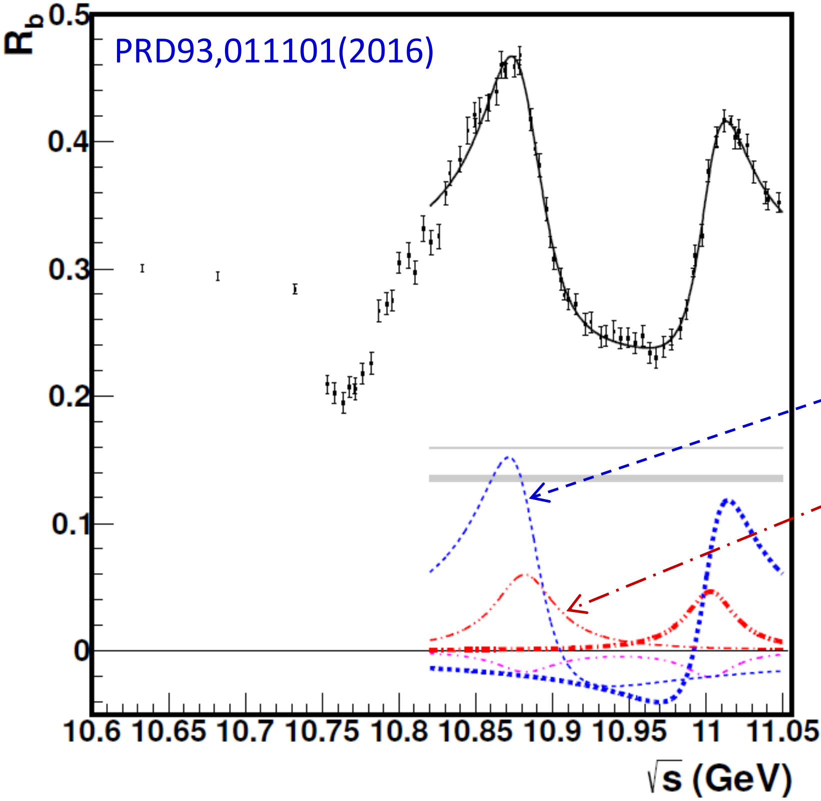
Strong interference btw $\Upsilon(5S)$ & continuum

$\Upsilon(5S)$ peak is saturated by
$B^{(*)}\bar{B}^*\pi$, $\Upsilon(nS)\pi\pi$, $h_b(mP)\pi\pi$

$B\bar{B}/B\bar{B}^*/B^*\bar{B}^*$ do not resonate, continuum

Deficit of fit to R_b

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



inconsistency

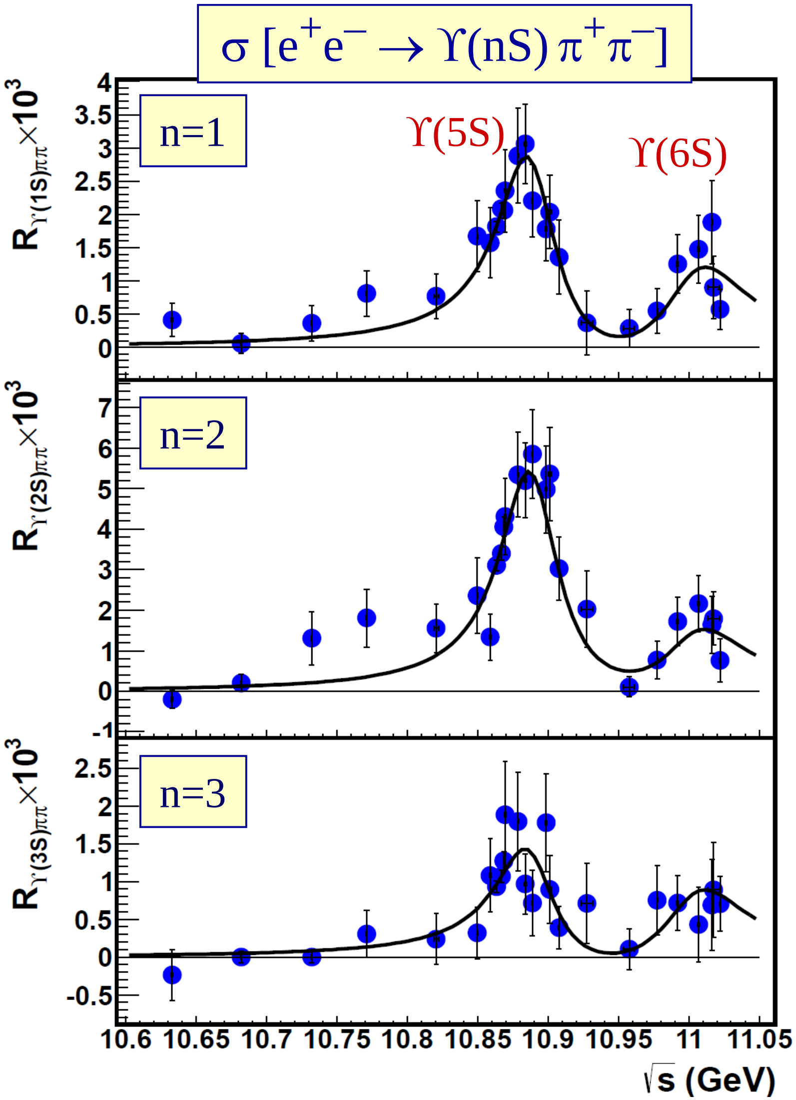
Strong interference btw $\Upsilon(5S)$ & continuum

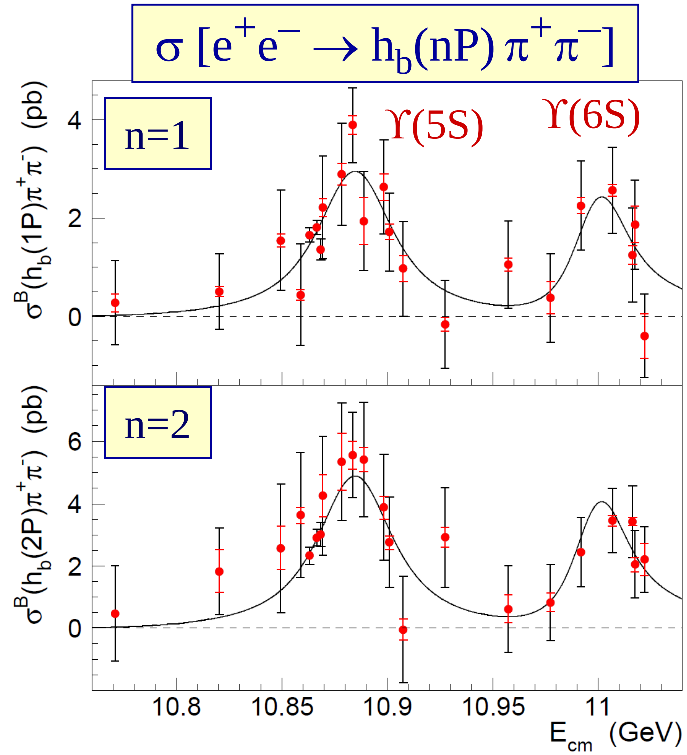
$\Upsilon(5S)$ peak is saturated by

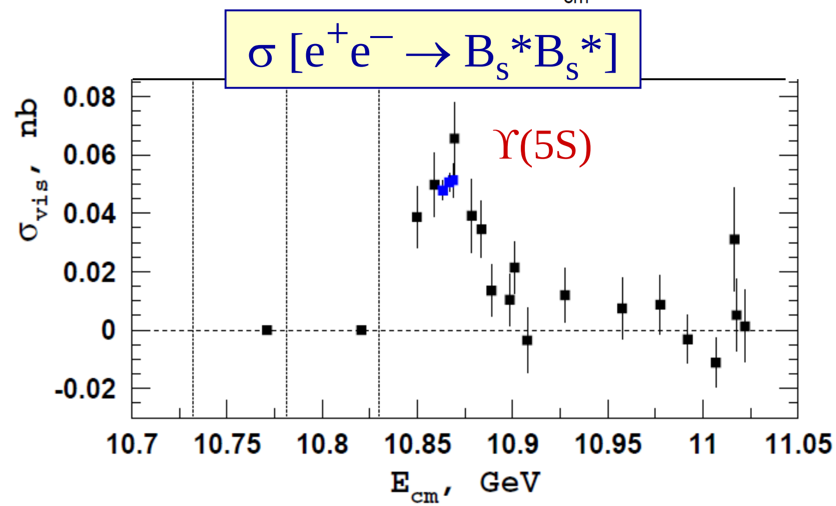
$B^{(*)}\bar{B}^*\pi$, $\Upsilon(nS)\pi\pi$, $h_b(mP)\pi\pi$

$B\bar{B}/B\bar{B}^*/B^*\bar{B}^*$ do not resonate, continuum

Conclusion: simple fit model for R_b should not be used.







Peak positions are slightly different →
Expected in coupled channel approach.
Breit-Wigner M, Γ are channel-dependent.
Universal parameters are pole position and couplings.

Belle-II Prospects

Belle: 1fb^{-1} per point, Belle-II $\to$ 10fb^{-1}. Typical Γ = 50 MeV $\Rightarrow$ step 20 MeV.
Belle: E_{max} = 11.02 GeV, Belle-II : E_{max} = 11.24 GeV.

Exclusive cross sections : complete information about Υ(4S), Υ(5S), Υ(6S) states
Coupled channel analysis: pole positions, couplings to various channels.

Hidden flavor cross sections : search for new states
compact tetraquarks and hadrobottomonia : decays to open flavor are suppressed

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If a new state is found it is of interest to collect a few fb^{-1} at its peak
– detailed study of transitions from this state

– search for missing bottomonia in transitions
spin-singlet members of 3S, 3P, 1D multiplets; complete 2D, 1F, 1G multiplets

– crucial to search for Z_b partners: near-threshold molecular states

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Data around 11.2 GeV are useful to study B_s mesons spectroscopy
are P wave j=1/2 states below BK threshold? narrow similarly to D_{sJ}?
expected to decay to $B_s\pi^0$ or $B_s\gamma$, difficult for LHCb

Promising energy regions

Bondar, RM, Voloshin
MPLA32,1750025(2017)

Molecular states are naturally located near corresponding thresholds:

Particles	Threshold, GeV/c^2
$B^{(*)}\bar{B}^{**}$	$11.00 - 11.07$
$B_s^{(*)}\bar{B}_s^{**}$	$11.13 - 11.26$
$\Lambda_b\bar{\Lambda}_b$	11.24
$B^{**}\bar{B}^{**}$	$11.44 - 11.49$
$B_s^{**}\bar{B}_s^{**}$	$11.48 - 11.68$
$\Lambda_b\bar{\Lambda}_b^{**}$	$11.53 - 11.54$
$\Sigma_b^{(*)}\bar{\Sigma}_b^{(*)}$	$11.62 - 11.67$
$\Lambda_b^{**}\bar{\Lambda}_b^{**}$	$11.82 - 11.84$

Belle-II maximal energy

- Belle-II maximal energy of **11.24 GeV** covers $B_s^{(*)}B_s^{**}$ threshold region.
- Increase to **11.35 GeV** will give information about $\Lambda_b\Lambda_b$ threshold region.
- Increase to **11.5 GeV** is crucial to search for partners of Z_b states.

Conclusions

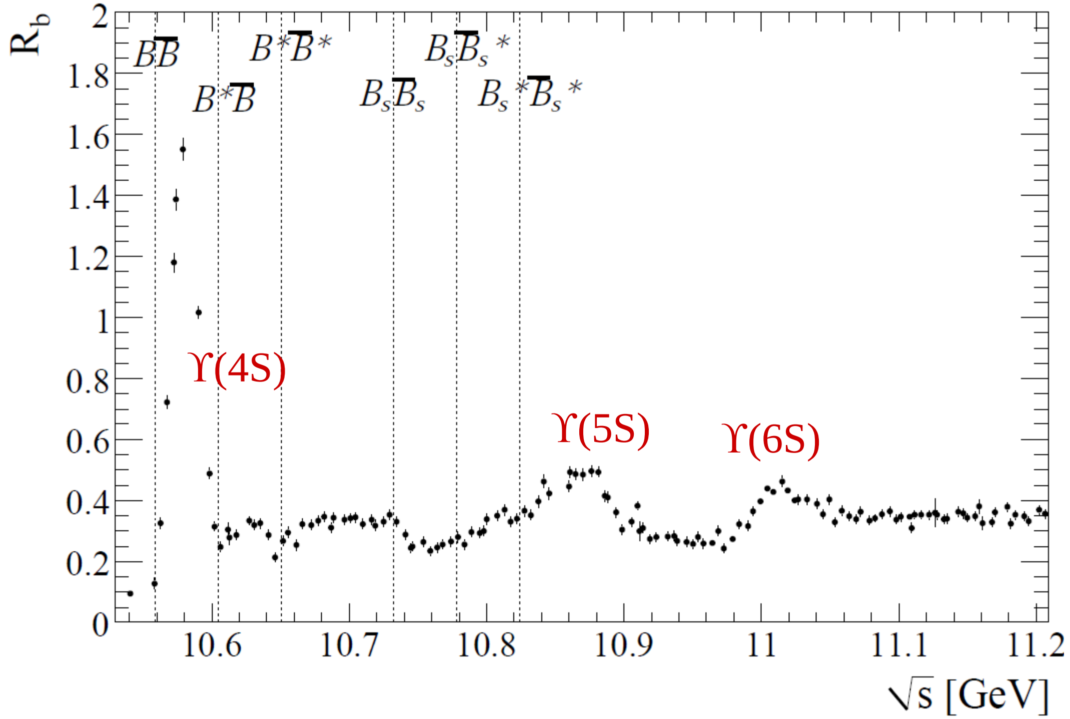
Vector bottomonium-like states:

$$\left.\begin{matrix}\Upsilon(4S)\\ \Upsilon(5S)\\ \Upsilon(6S)\end{matrix}\right. = c_1|b\bar{b}\rangle + c_2|B\bar{B}\rangle + c_3|B\bar{B}^*\rangle + c_4|B^*\bar{B}^*\rangle + \ldots$$

Hadronic admixtures describe existing data.

Belle should measure energy dependence of exclusive open bottom cross sect.

Belle-II: of interest to perform energy scan with 10fb^{-1} per point and to increase maximal energy from 11.24 to 11.5 GeV.



R_b
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10.6
10.7
10.8
10.9
11
11.1
11.2
√s [GeV]
BB̄
B*B̄
B*B̄*
B_sB̄_s
B_sB̄_s*
B_s*B̄_s*
ϒ(4S)
ϒ(5S)
ϒ(6S)