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# $R_b$ measurements

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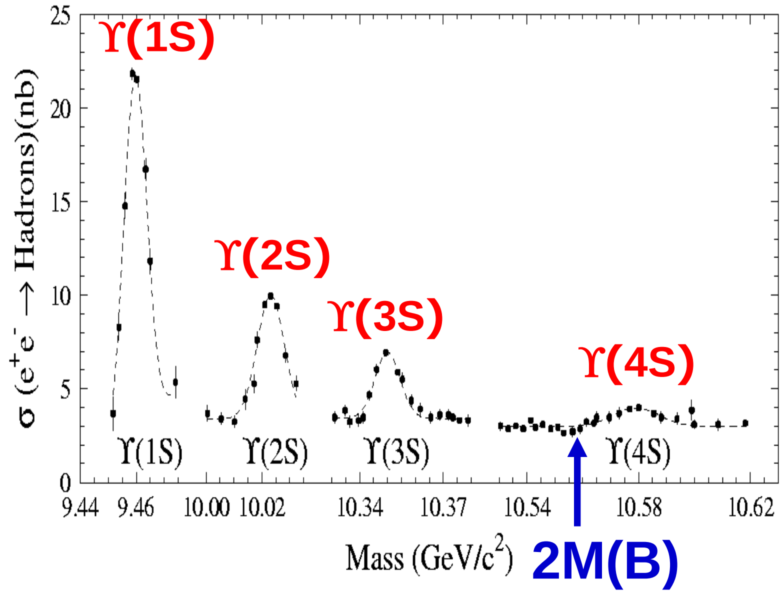
# Outline

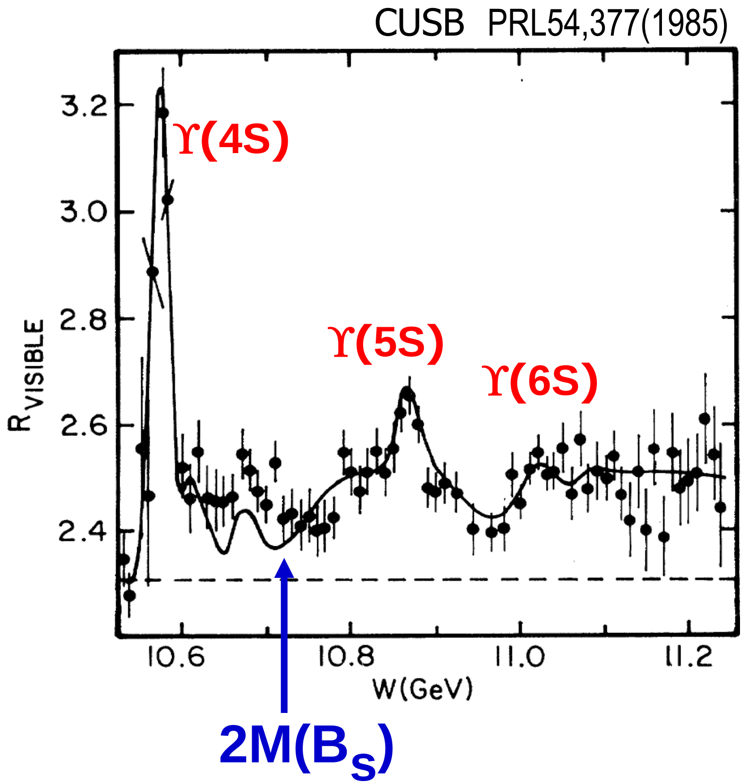
Introduction

$R_b$ and $R_{\Upsilon\pi\pi}$ scans at Belle

Belle / Belle-II plans related to scans

# $e^+e^-$ hadronic cross-section




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

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

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

Belle 121 $fb^{-1}$

original motivation

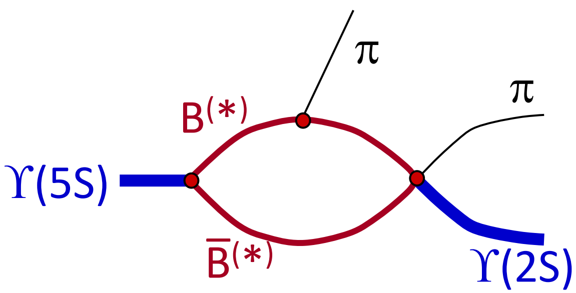
# Puzzle of $\Upsilon(5S)$ decays

Belle 2008: anomalous production of $\Upsilon(nS)\,\pi^+\pi^-$

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

**$10^2$**

1. Rescattering $\Upsilon(5S) \to B^{(*)}B^{(*)} \to \Upsilon(nS)\pi\pi$ ?



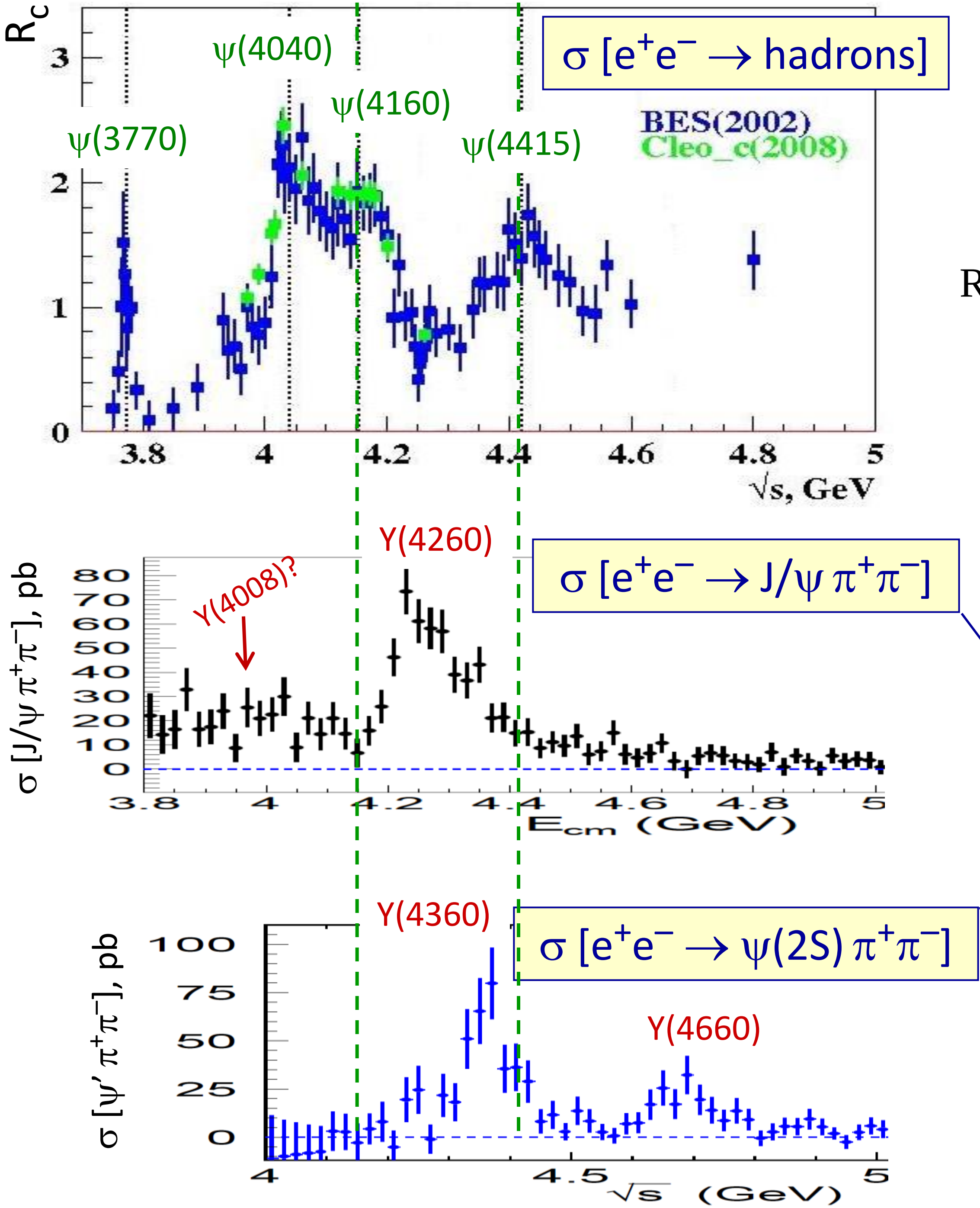

$\Leftarrow$ Enhanced if $B^{(*)}B^{(*)}$ are on-shell

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

2. Not $\Upsilon(5S)$ but some other state ($\equiv Y_b$) decays to $\Upsilon(nS)\pi\pi$ ?

*This is the situation in charmonium* $\Rightarrow$

# Cross-sections in charmonium region




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

using ISR

BaBar PRD86,051102R(2012)
Belle PRL110,252002(2013)
BaBar PRD89,111103(2014)
Belle arxiv:1410.7641

No signals of $\psi$ states

New states:

**Y(4260), Y(4360), Y(4660)**

Y states are not seen in total hadronic cross-section.

# Energy scan by Belle in 2007

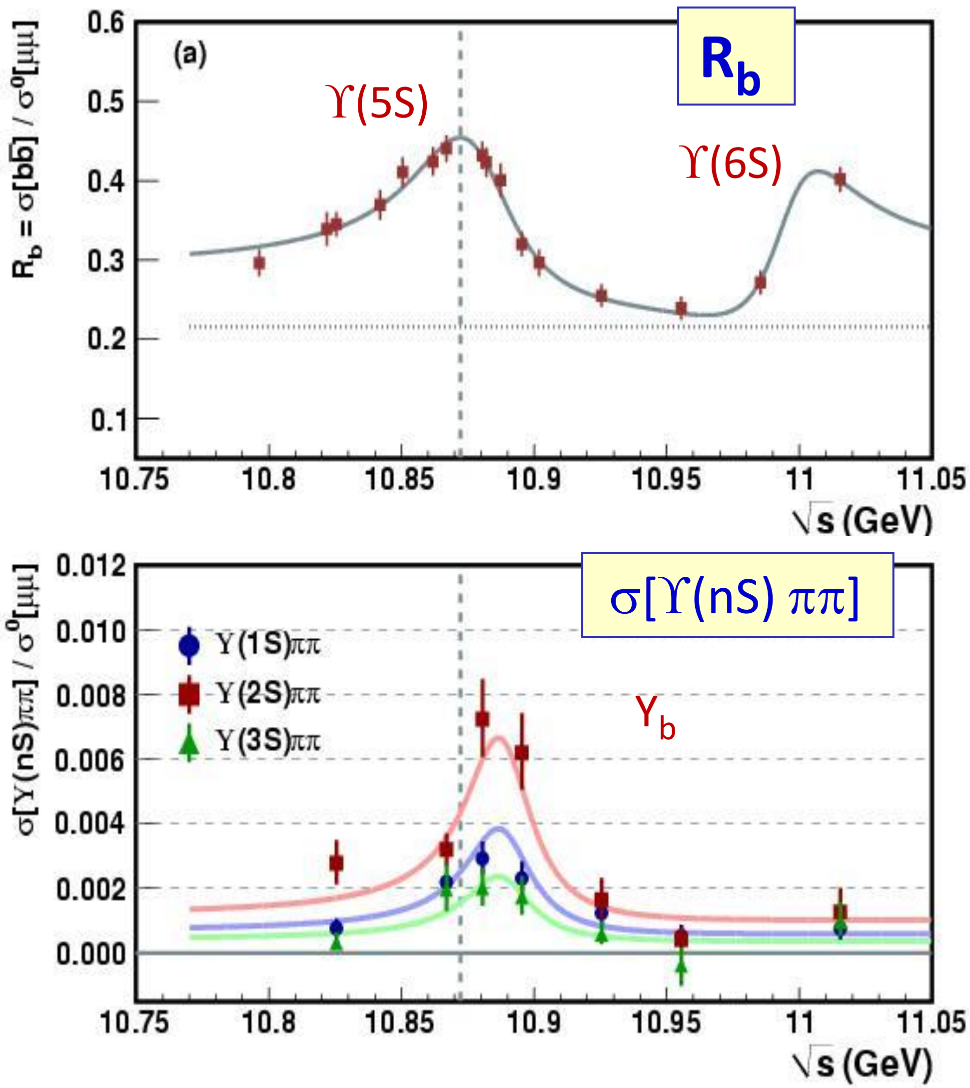
PRD82,091106R(2010)

⇒ Investigate $R_b$ and $\sigma[\Upsilon(nS)\,\pi\pi]$ line shapes

2007 energy scan:

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

9 points $30\,pb^{-1}$ for $R_b$



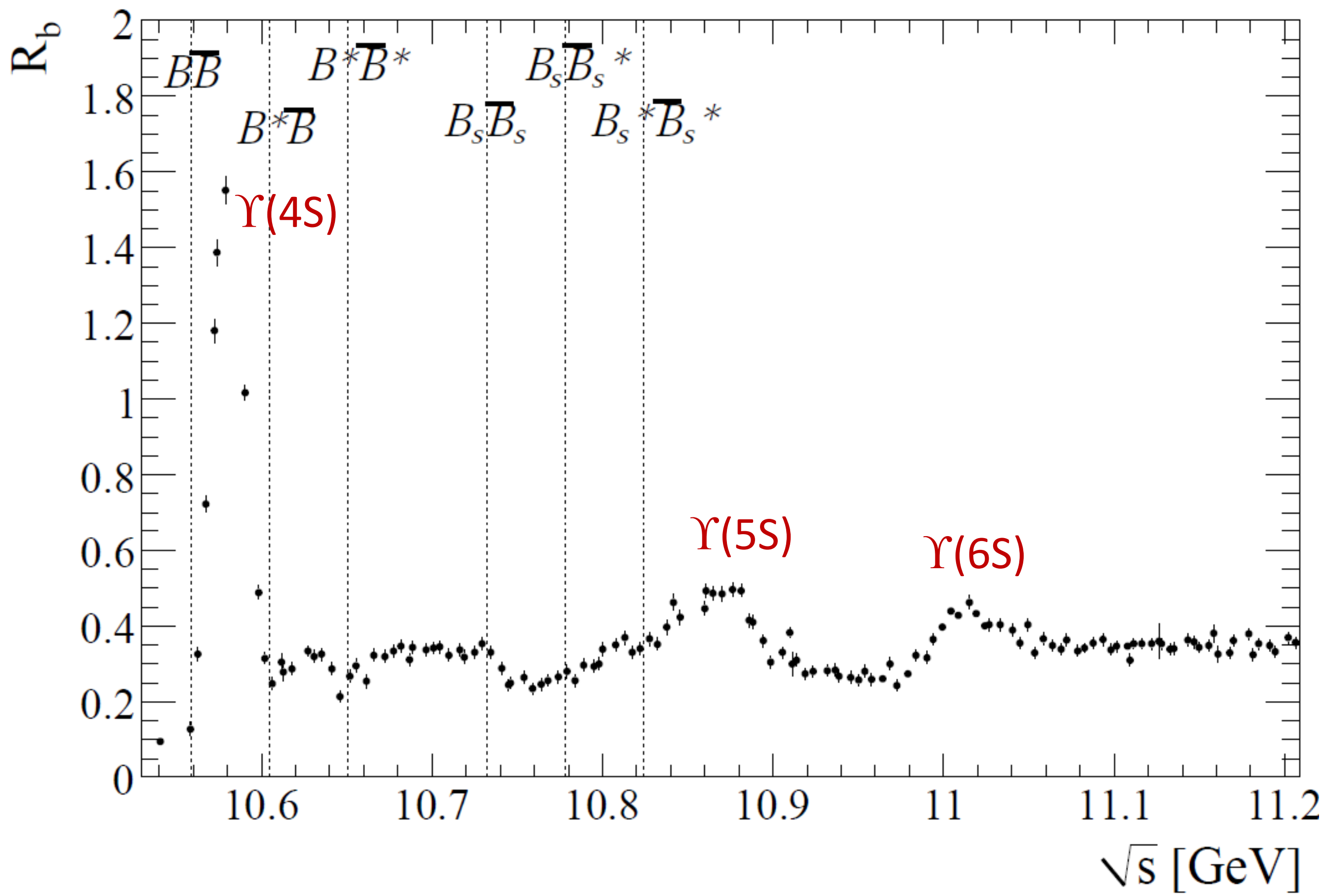

⇒ $R_b$ and $\sigma[\Upsilon(nS)\,\pi\pi]$ shapes disagree, significance is $2\sigma$ only

no evidence for separate $Y_b$ state

# Energy scan by BaBar in 2008

PRL100,112001(2008)

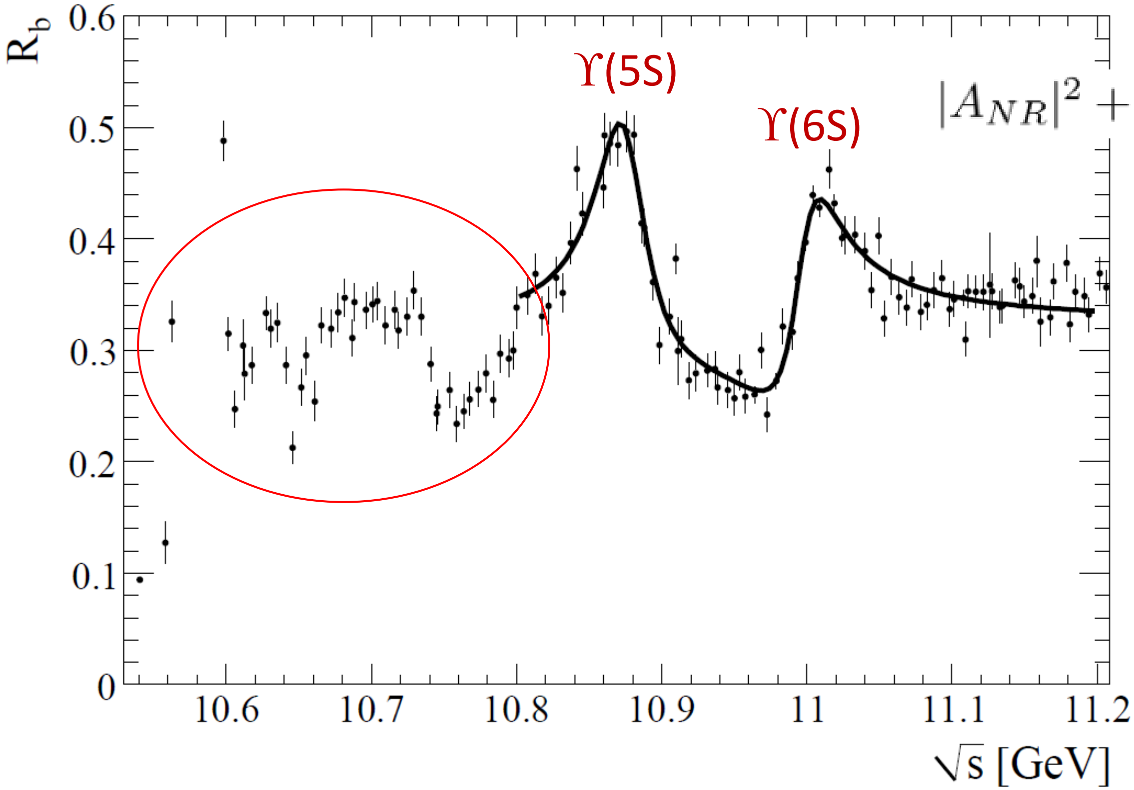
25pb$^{-1}$ per point
also 8 points 600pb$^{-1}$ per points in the $\Upsilon$(6S) region




Radiative corrections are not applied. Visible cross sections.

# Energy scan by BaBar: fit

PRL100,112001(2008)




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

Coupled channel model should provide better description of data.

| | $\Upsilon(10860)$ | $\Upsilon(11020)$ |
|---|---|---|
| mass (GeV) | $10.876 \pm 0.002$ | $10.996 \pm 0.002$ |
| width (MeV) | $43 \pm 4$ | $37 \pm 3$ |
| $\phi$ (rad) | $2.11 \pm 0.12$ | $0.12 \pm 0.07$ |
| PDG mass (GeV) | $10.865 \pm 0.008$ | $11.019 \pm 0.008$ |
| PDG width (MeV) | $110 \pm 13$ | $79 \pm 16$ |

significantly different

No high statistics points to study $\Upsilon(nS)\pi\pi$ final state.

# $R_b$ and $R_{\Upsilon\pi\pi}$ scan by Belle

arxiv:1501.01137
$\rightarrow$ PRL

# Data sets

2010 energy scan:
16 points $1 fb^{-1}$ for $\sigma[\Upsilon(nS)\,\pi\pi]$
61 point $50 pb^{-1}$ 5MeV step for $R_b$
continuum point $1 fb^{-1}$ @ 10.52GeV

Use also:

2007 energy scan: 6 points $\sim 1 fb^{-1}$
$\Upsilon(5S)$ on-resonance point $121 fb^{-1}$

# Energy calibration

$e^+e^- \to \mu^+\mu^-$
Signal shape (including ISR tail) from MC.
Energy scale from high statistics point $\Upsilon(5S) \to \Upsilon(1S,2S,3S)\pi^+\pi^-$
Uncertainty 0.4MeV (0.7MeV) for high (low) statistics points. Scale uncertainty 1MeV.

# Luminosity

Bhabha scattering.
Uncertainty 1.3% (correlated), ~0.3% (uncorrelated).

# Hadronic events selection

≥5 tracks, ≥2 ECL clusters, event vertex close to IP
ECL energy: 0.1 – 0.8 $\sqrt{s}$, total event energy >0.5 $\sqrt{s}$
$R_2<0.2$

**Efficiency** 70-74% (average of highest and lowest among $B_{(s)}^{(*)}B_{(s)}^{(*)}(\pi)$ modes)

# Calculation of $R_b$

$$N_i = \mathcal{L}_i \times \left[\sigma_{b\bar{b},i}\epsilon_{b\bar{b},i} + \sigma_{q\bar{q},i}\epsilon_{q\bar{q},i} + \sum \sigma_{\mathrm{ISR},i}\epsilon_{\mathrm{ISR},i}\right]$$

subtracted using continuum point

rad. return to $\Upsilon$(1S,2S,3S) present at continuum point correction using simulation

Two definitions:

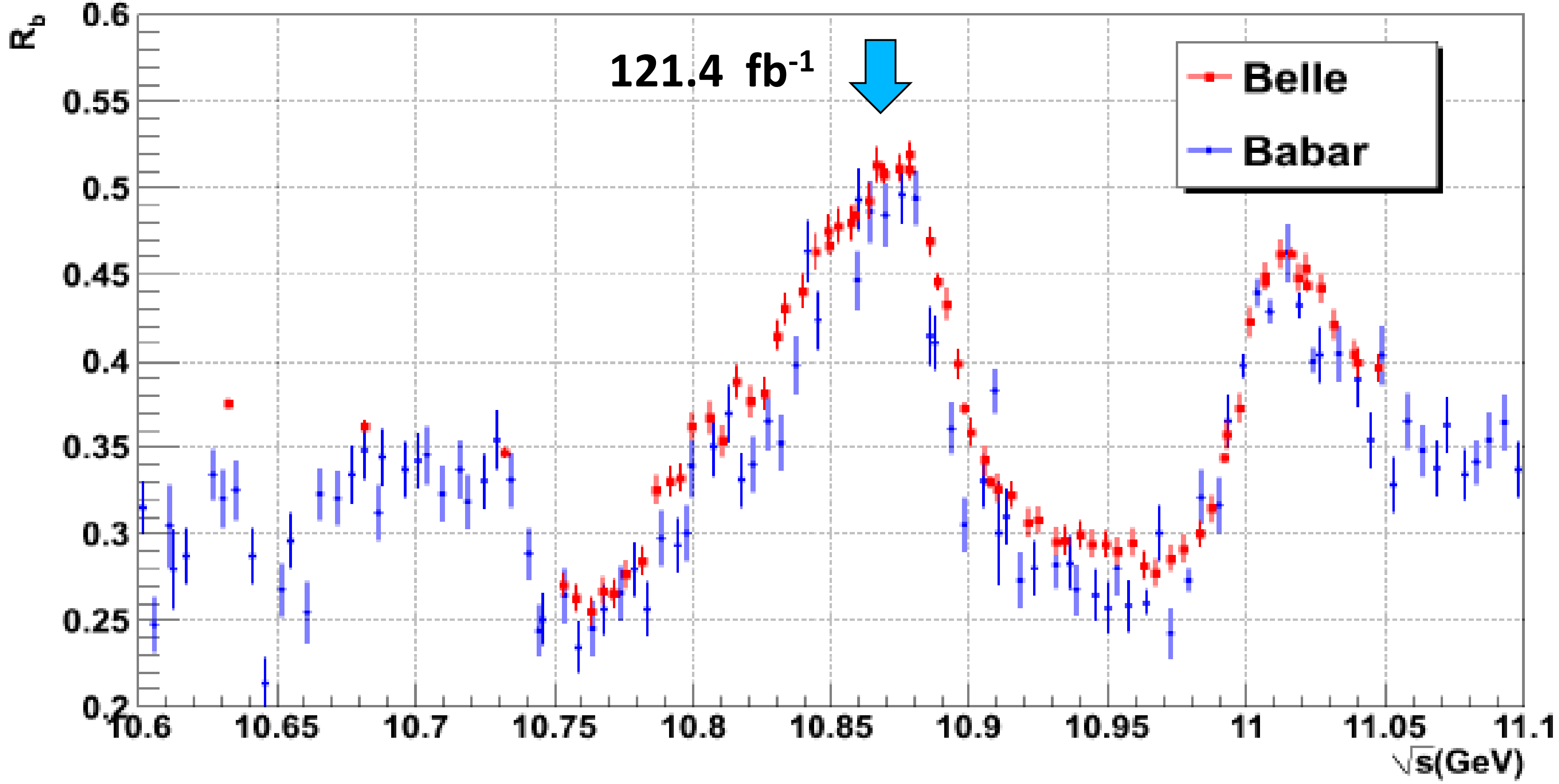
$R_b$ rad. return to $\Upsilon$(1S,2S,3S) is included *comparison with BaBar*

$R'_b$ rad. return to $\Upsilon$(1S,2S,3S) is subtracted *other fits*

N.B.: these are visible cross sections.

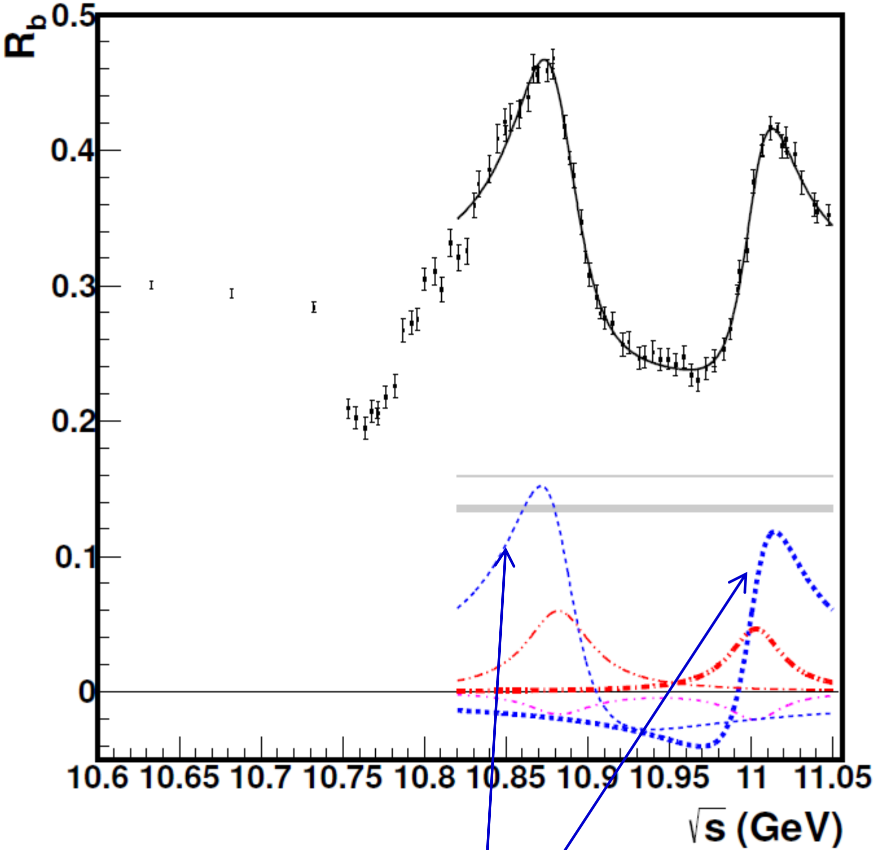
# $R_b$ scan

61 point, 50pb$^{-1}$, step 5MeV




- Better statistical errors, but covers smaller energy range compared to BaBar.
- $R_b$ is slightly higher, by 0.0185.
- No Ali's $Y_b(10900)$ [PLB 684(2010)28], $\Gamma_{ee}$<36eV.

# Fit to $R_b$




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

| | $M_{5S}$ (MeV/$c^2$) | $\Gamma_{5S}$ (MeV) |
|---|---|---|
| $R_b$ | $10881.9 \pm 1.0 \pm 1.2$ | $49.8 \pm 1.9\,^{+2.1}_{-2.8}$ |
| $R_b'$ | $10881.8^{+1.0}_{-1.1} \pm 1.2$ | $48.5^{+1.9}_{-1.8}\,^{+2.0}_{-2.8}$ |

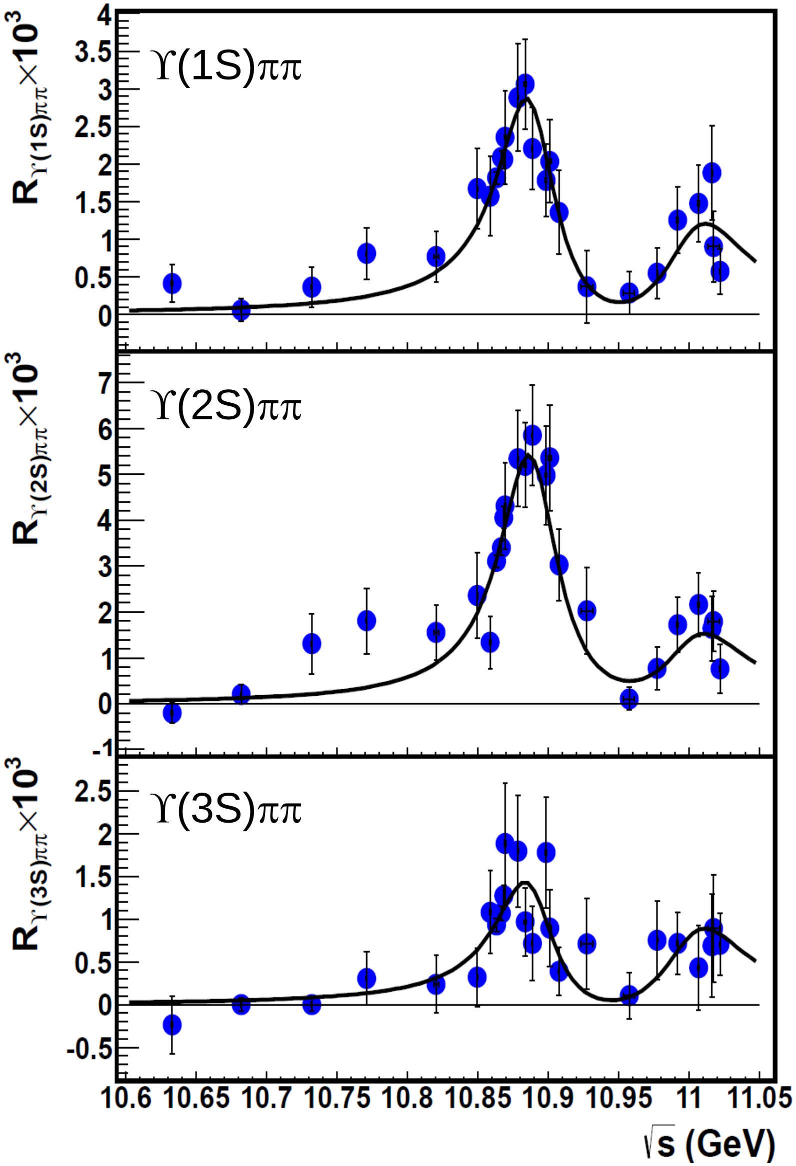
| $M_{6S}$ (MeV/$c^2$) | $\Gamma_{6S}$ (MeV) |
|---|---|
| $11002.9 \pm 1.1\,^{+0.8}_{-0.9}$ | $38.5^{+1.6}_{-1.5}\,^{+1.3}_{-2.4}$ |
| $11003.0 \pm 1.1\,^{+0.9}_{-1.0}$ | $39.3^{+1.7}_{-1.6}\,^{+1.3}_{-2.4}$ |

Strong interference w/ continuum.

In agreement with BaBar:

| | $\Upsilon(10860)$ | $\Upsilon(11020)$ |
|---|---|---|
| mass (GeV) | $10.876 \pm 0.002$ | $10.996 \pm 0.002$ |
| width (MeV) | $43 \pm 4$ | $37 \pm 3$ |

High continuum contribution $\Rightarrow$ uncontrollable systematics due to unknown shape.




# Scan of $R_{\Upsilon(nS)\pi\pi}$

Full reconstruction of $\Upsilon(nS)\pi^+\pi^-$ ⇒ purity ~95%

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

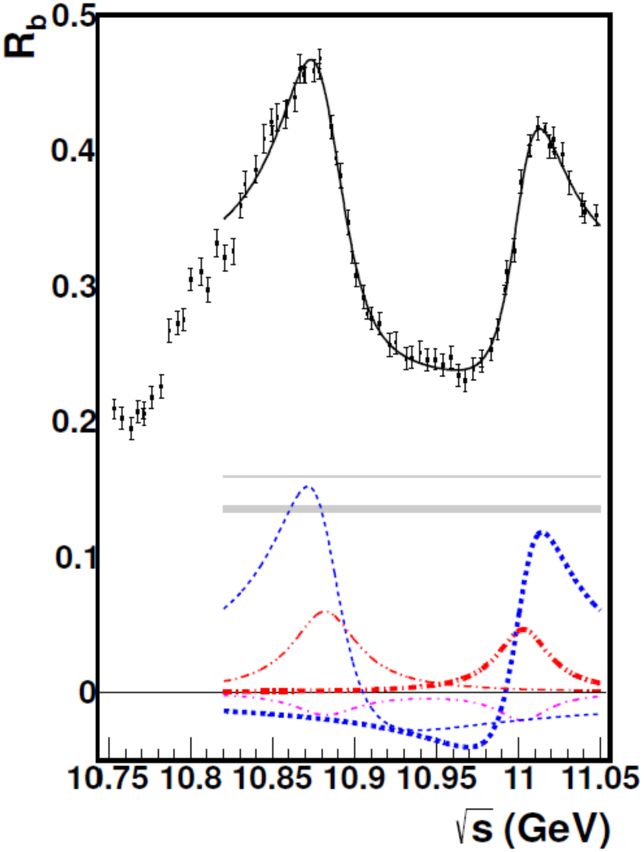
Fit ⇒ $A_{nr}$, $A_r$ consistent with zero; fixed at zero.

No uncontrollable systematics.

| | $M_{5S}$ (MeV/$c^2$) | $\Gamma_{5S}$ (MeV) |
|---|---|---|
| $R'_b$ | $10881.8^{+1.0}_{-1.1} \pm 1.2$ | $48.5^{+1.9}_{-1.8}{}^{+2.0}_{-2.8}$ |
| $R_{\Upsilon(nS)\pi\pi}$ | $10891.1 \pm 3.2^{+0.6}_{-1.7}$ | $53.7^{+7.1}_{-5.6}{}^{+1.3}_{-5.4}$ |
| | $M_{6S}$ (MeV/$c^2$) | $\Gamma_{6S}$ (MeV) |
| | $11003.0 \pm 1.1^{+0.9}_{-1.0}$ | $39.3^{+1.7}_{-1.6}{}^{+1.3}_{-2.4}$ |
| | $10987.5^{+6.4}_{-2.5}{}^{+9.0}_{-2.1}$ | $61^{+9}_{-19}{}^{+2}_{-20}$ |

Consider possible decoherence of Υ(5S,6S) signals due to different resonant structure.

No major difference in Υ(5S) parameters btw $R_b$ and $R_{\Upsilon\pi\pi}$.




# Inconsistency of simple fit model

Based on $|A_{5S} \cdot BW(M_{5S}, \Gamma_{5S})|$ we can estimate BFs of $\Upsilon(5S)$ into various exclusive final states:

| | |
|---|---|
| $\Upsilon(1S,2S,3S)\pi^+\pi^-$ | $17 \pm 2$ % |
| +isospin symmetry | $26 \pm 3$ % |

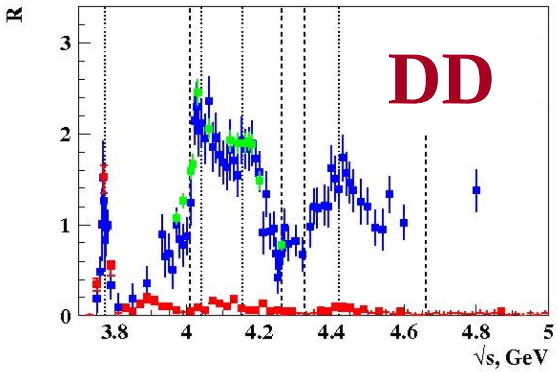
assume Zb states are produced resonantly

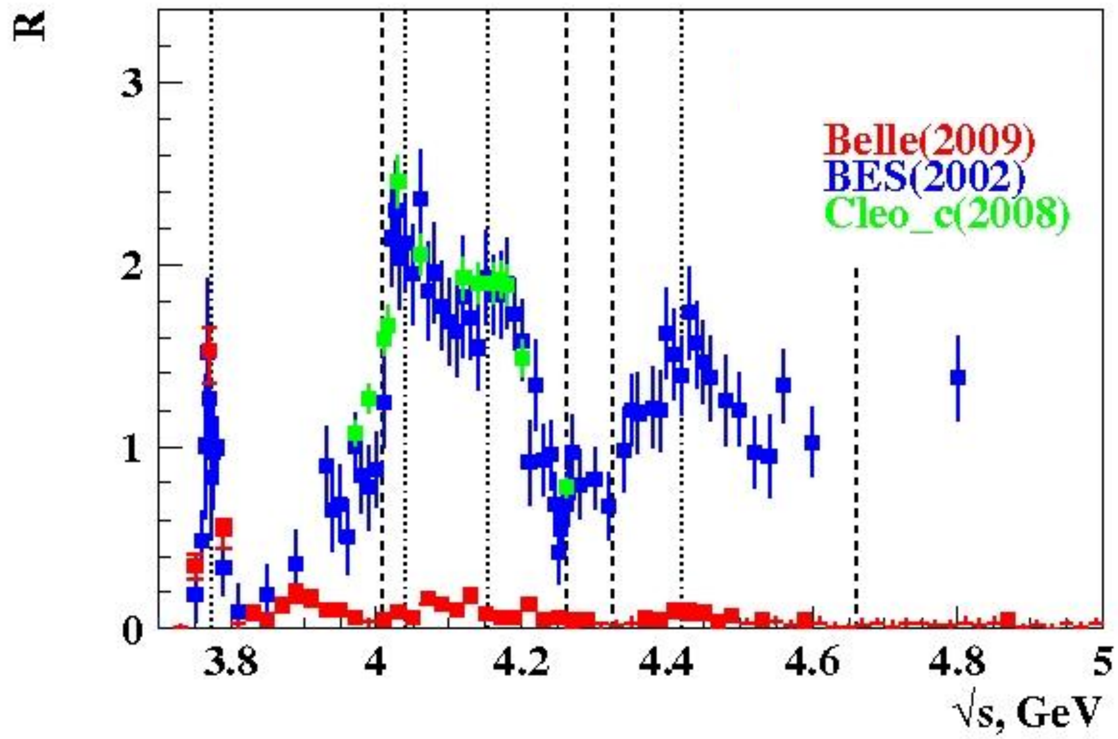
$\Leftarrow$ $Z_b \to \Upsilon(nS)\pi$ , $Z_b \to h_b(nP)\pi$ $\Rightarrow$

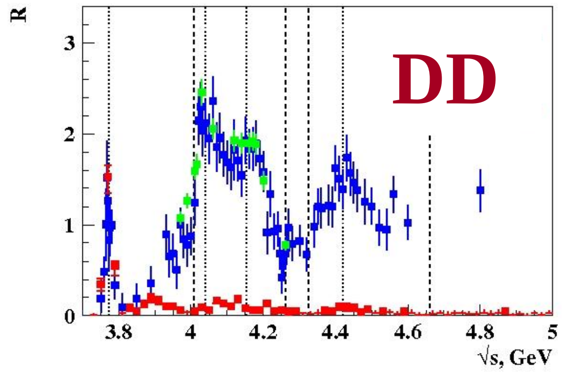
| | |
|---|---|
| $+h_b(1P,2P)\pi\pi$ | $42 \pm 4$ % |
| $+BB^*\pi$, $B^*B^*\pi$ | $109 \pm 15$ % |

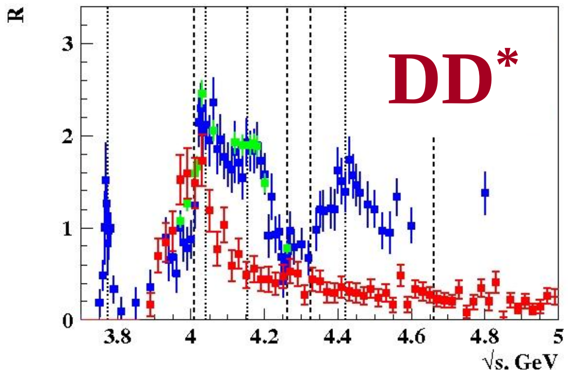
No room for resonant component in $B^{(*)}B^{(*)}$, $Bs^{(*)}Bs^{(*)}$ $\Rightarrow$ Non resonant?
How can interfere resonant and non-resonant components if they are in different channels $\Rightarrow$ inconsistency.

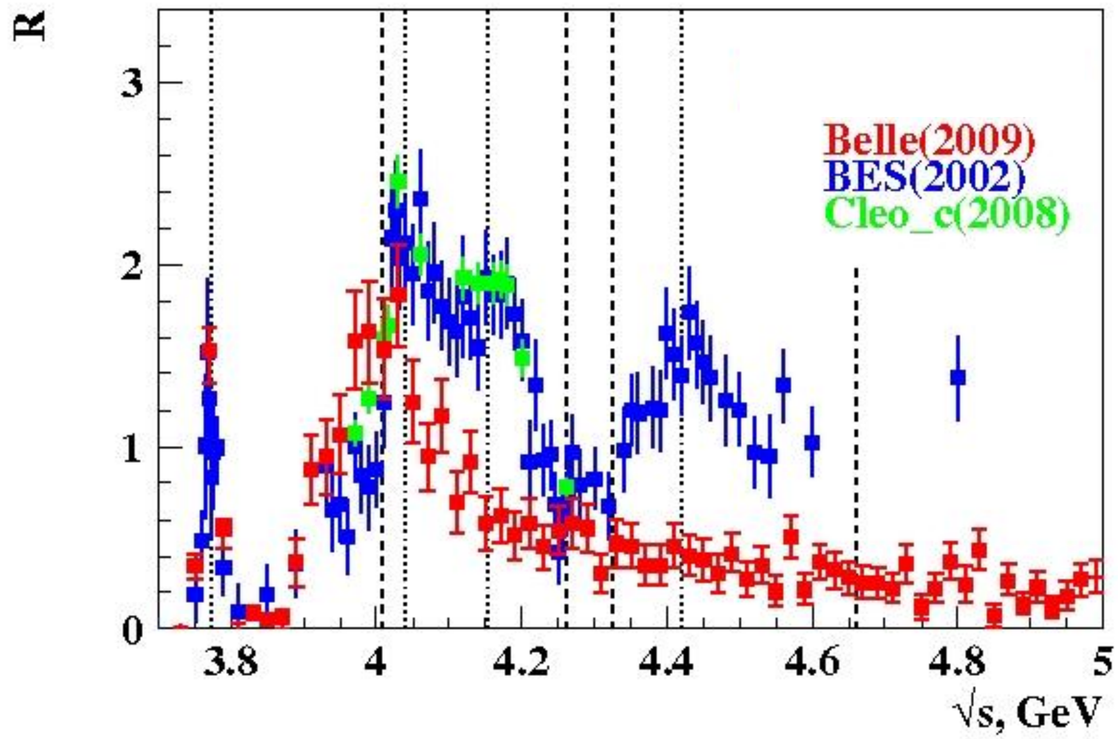
It is useful to decompose $R_b$ into various exclusive channels, like it is done for $R_c$ $\Rightarrow$

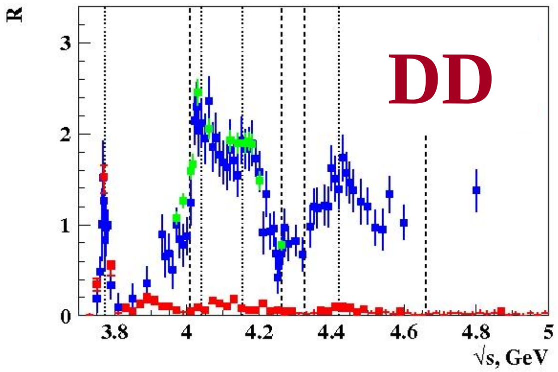

DD
R
3
2
1
0
3.8
4
4.2
4.4
4.6
4.8
5
√s, GeV

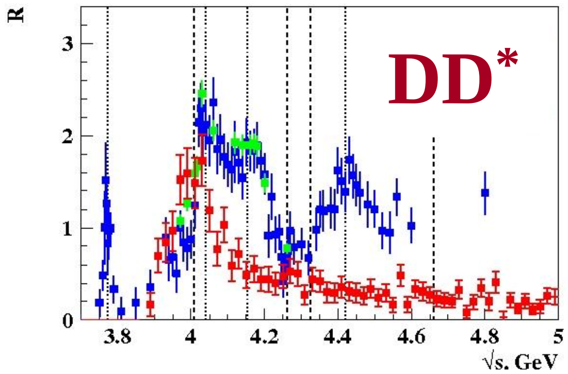

R
Belle(2009)
BES(2002)
Cleo_c(2008)
3
2
1
0
3.8
4
4.2
4.4
4.6
4.8
5
√s, GeV

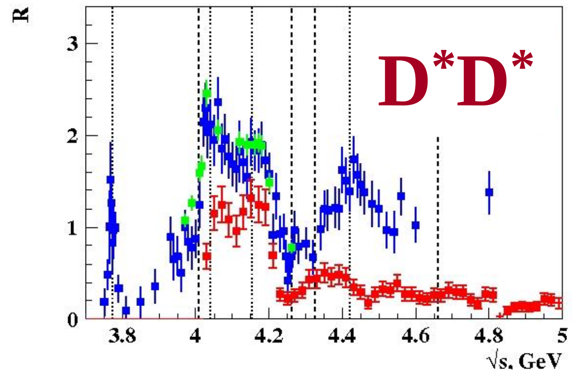

DD
R
0
1
2
3
3.8
4
4.2
4.4
4.6
4.8
5
√s, GeV

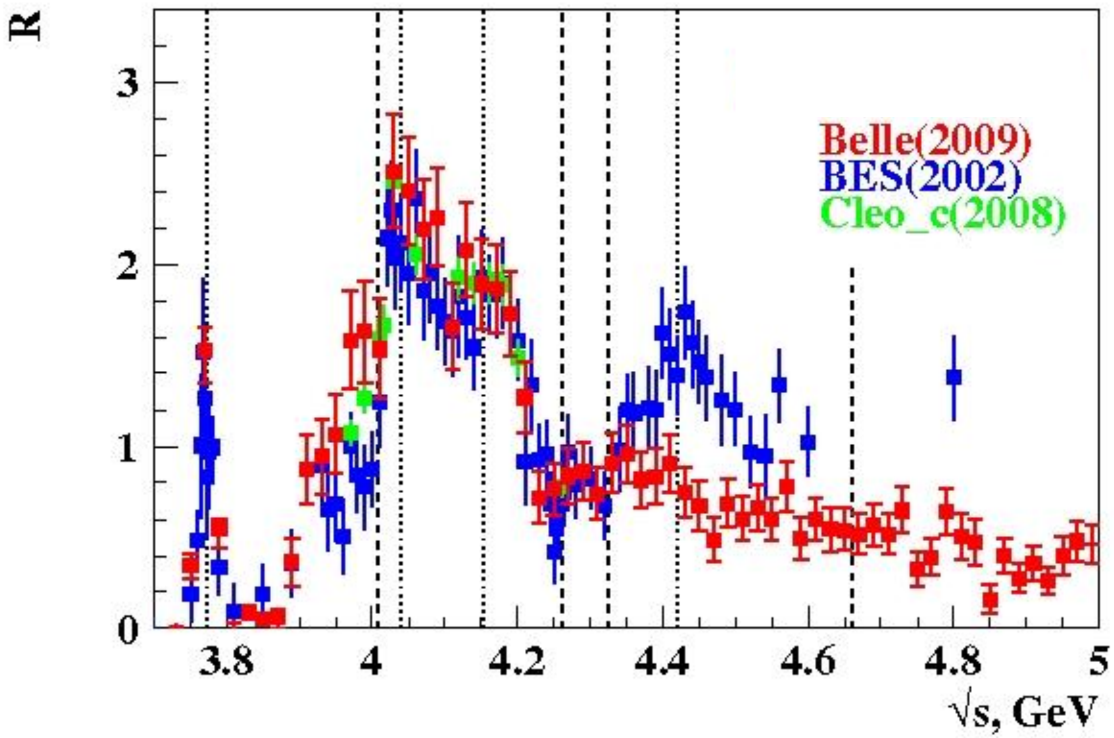

DD*
R
0
1
2
3
3.8
4
4.2
4.4
4.6
4.8
5
√s. GeV

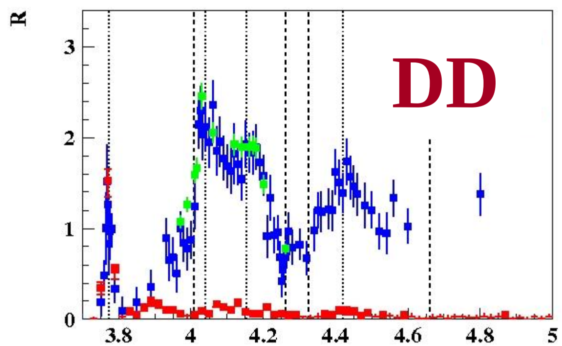

R
0
1
2
3
3.8
4
4.2
4.4
4.6
4.8
5
√s, GeV
Belle(2009)
BES(2002)
Cleo_c(2008)

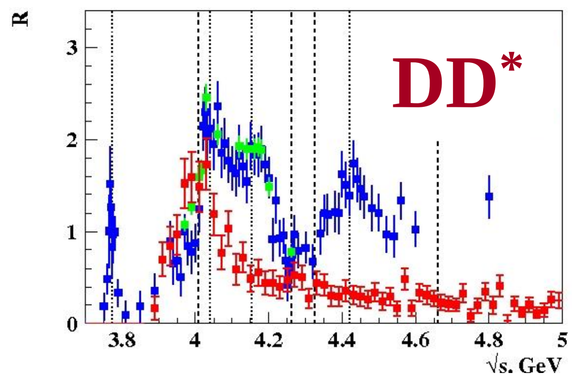

DD
R
√s, GeV

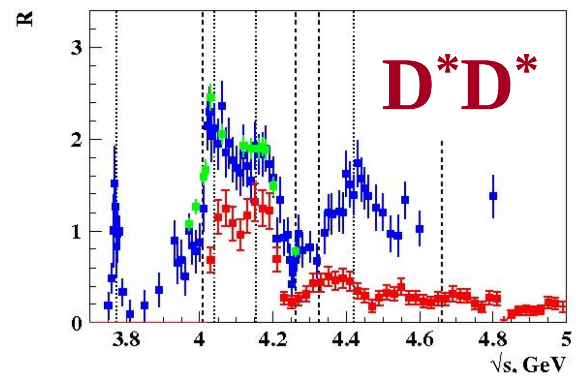

DD*
R
√s, GeV

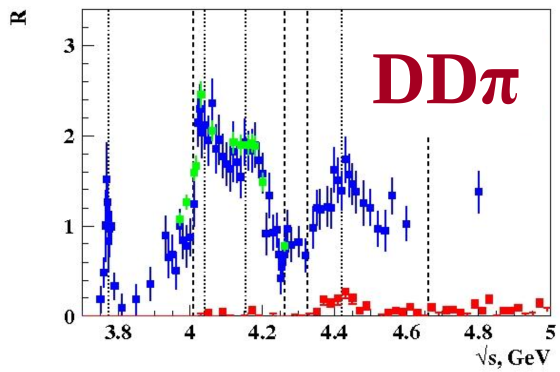

D*D*
R
√s, GeV

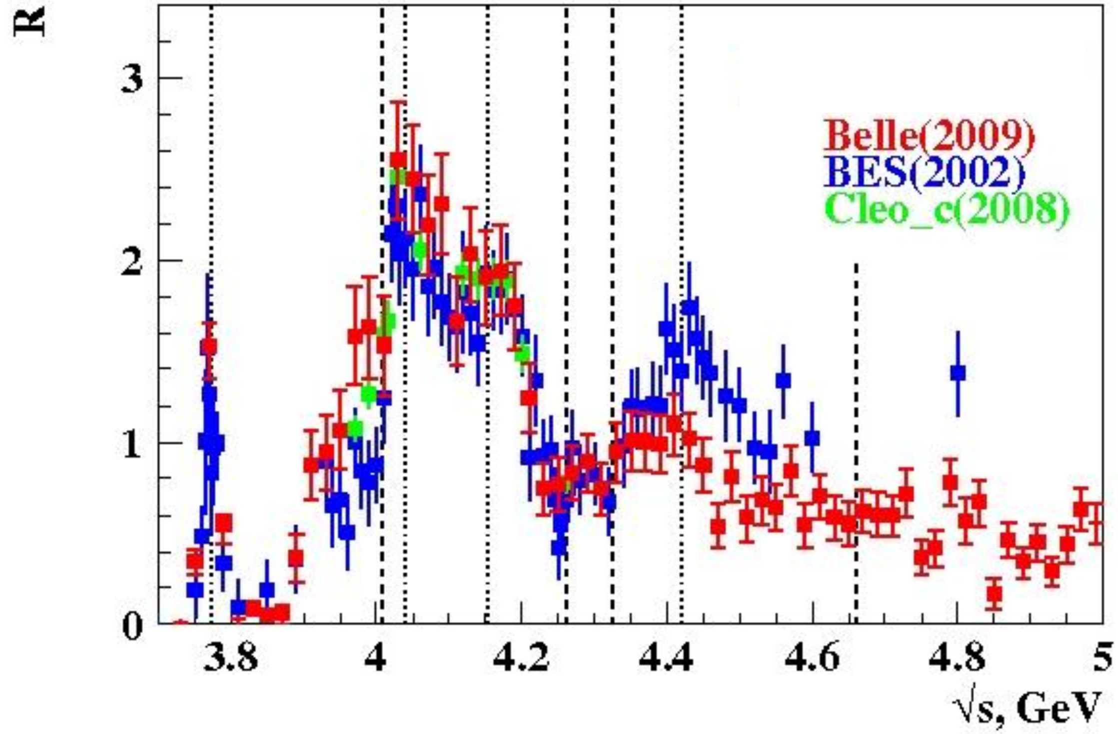

R
Belle(2009)
BES(2002)
Cleo_c(2008)
√s, GeV

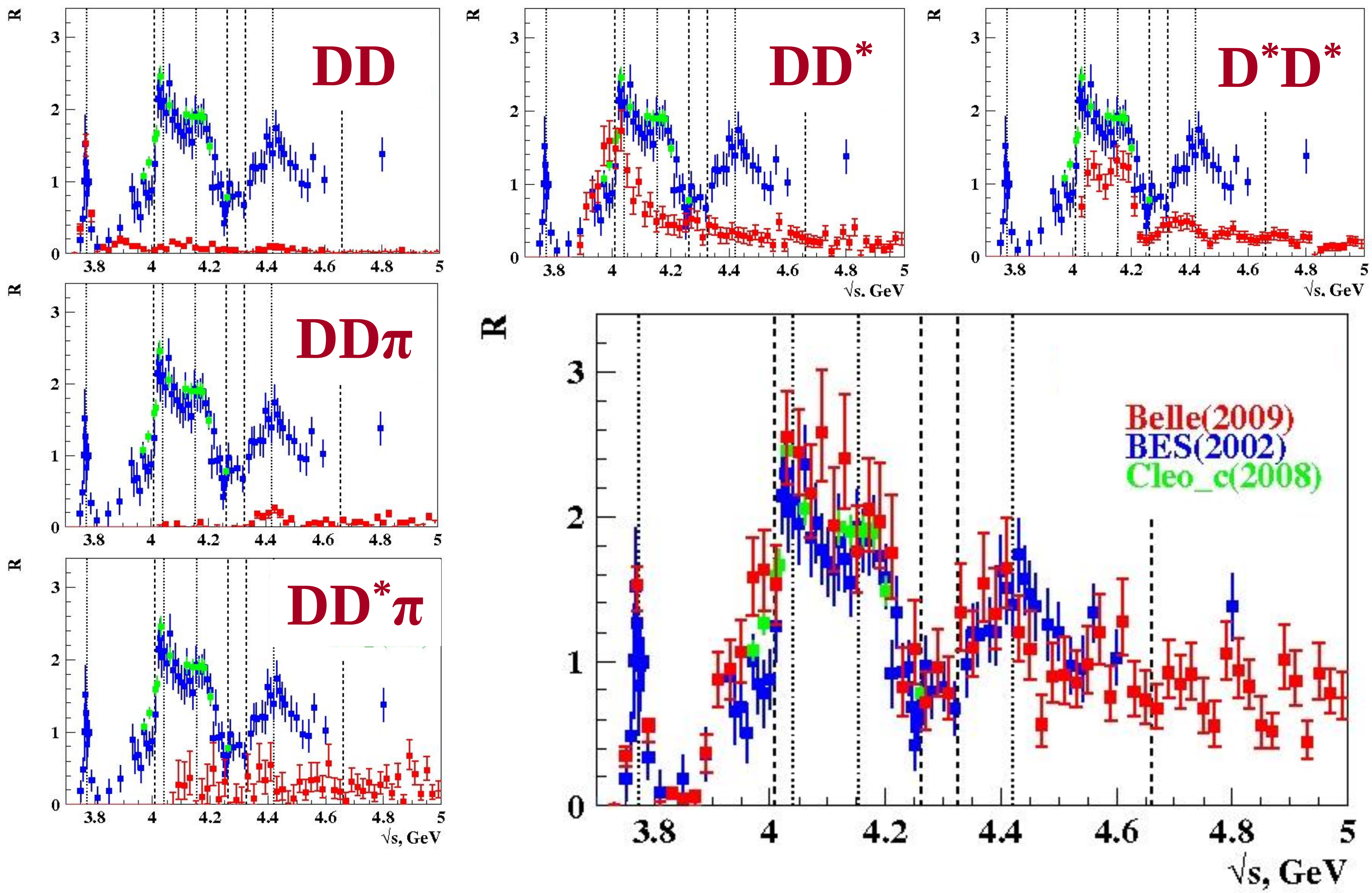

DD
R
√s, GeV

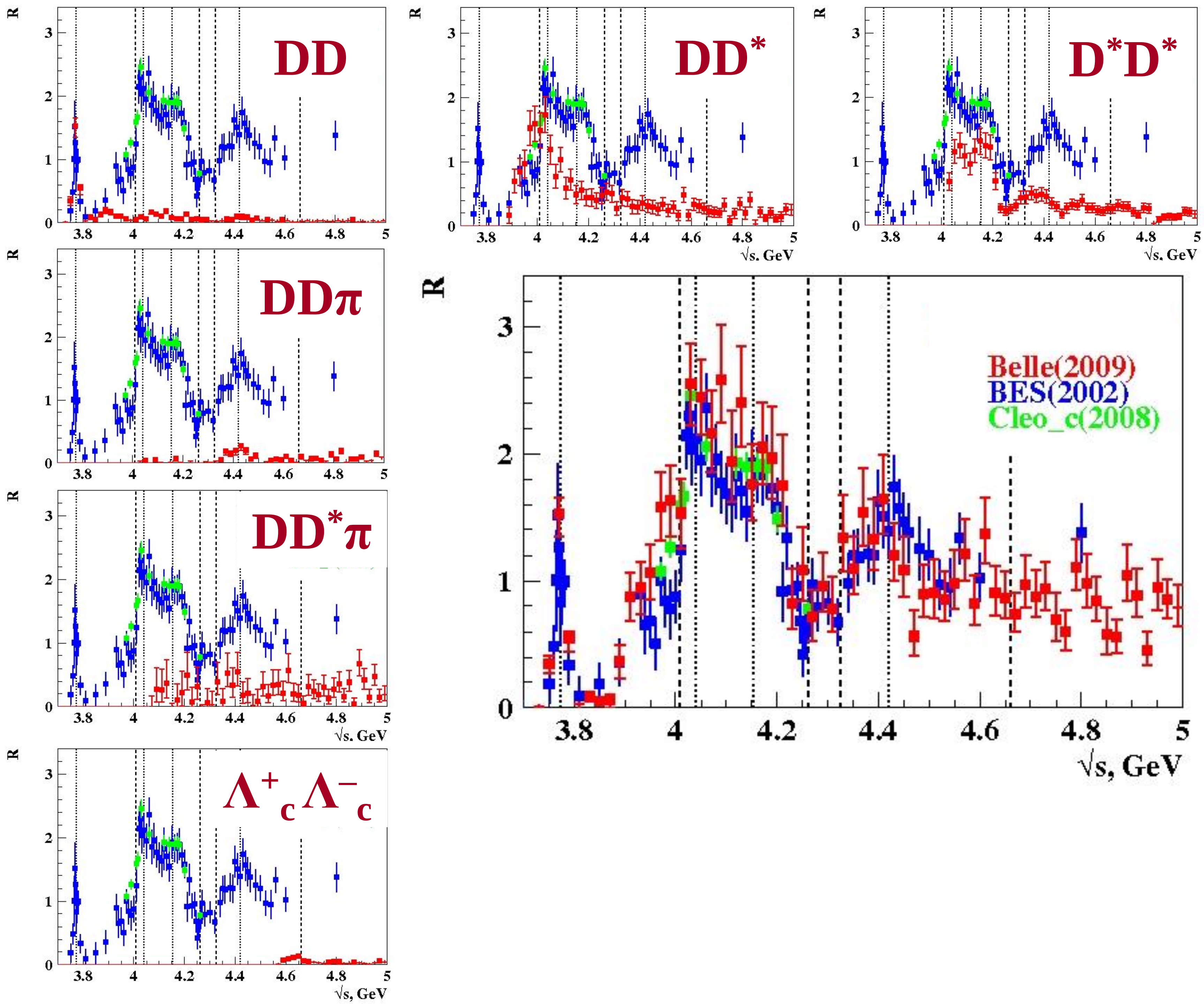

DD*
R
√s. GeV

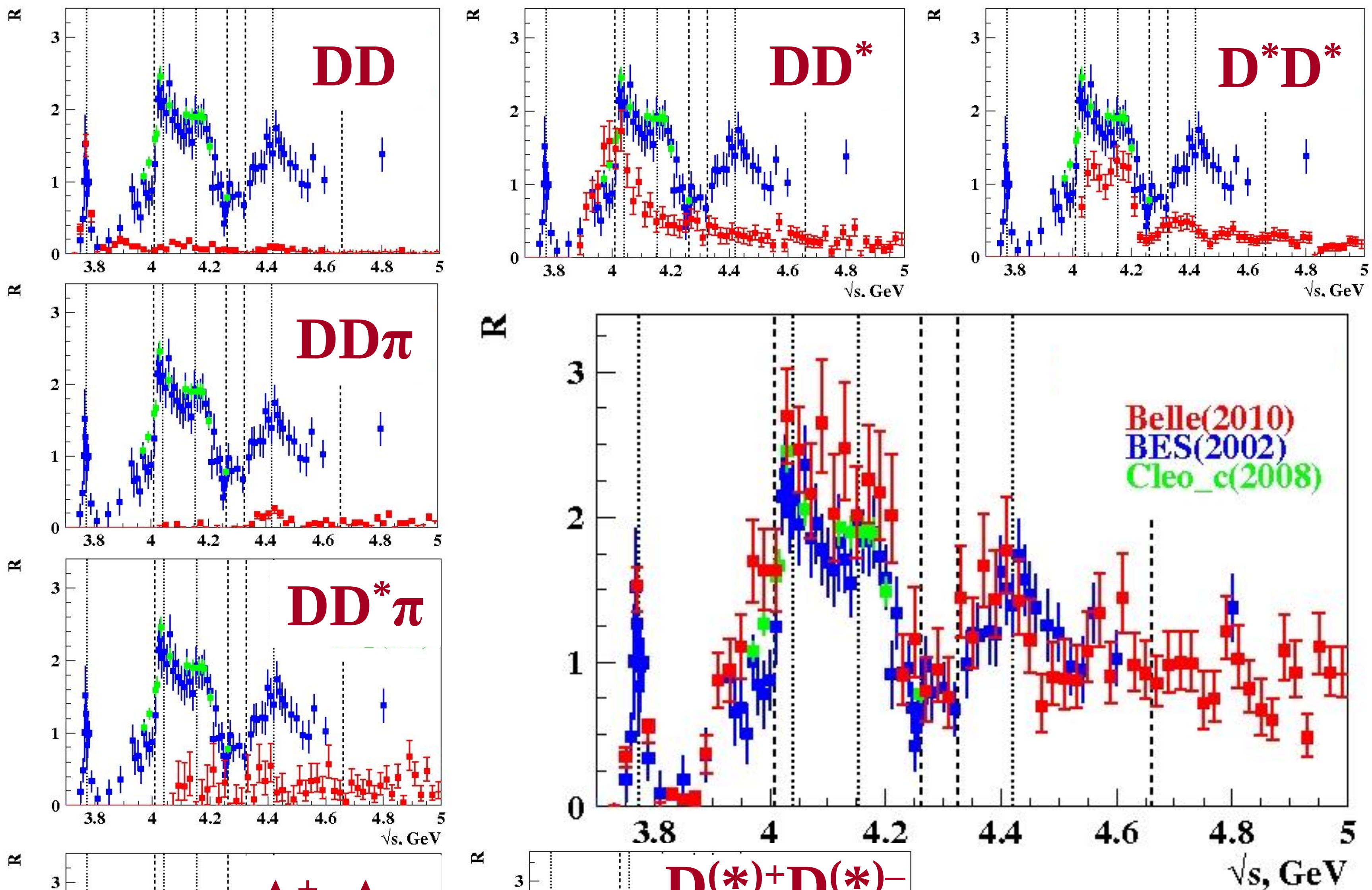

D*D*
R
√s. GeV

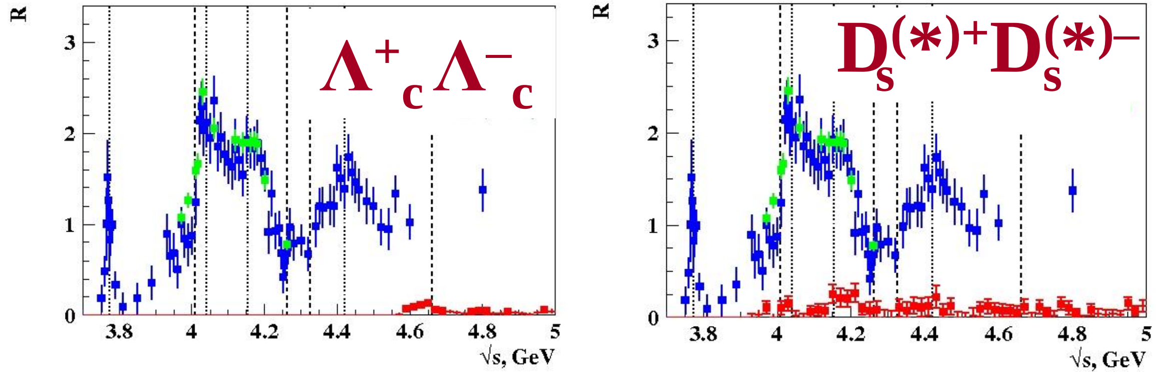

DDπ
R
√s, GeV


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


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


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



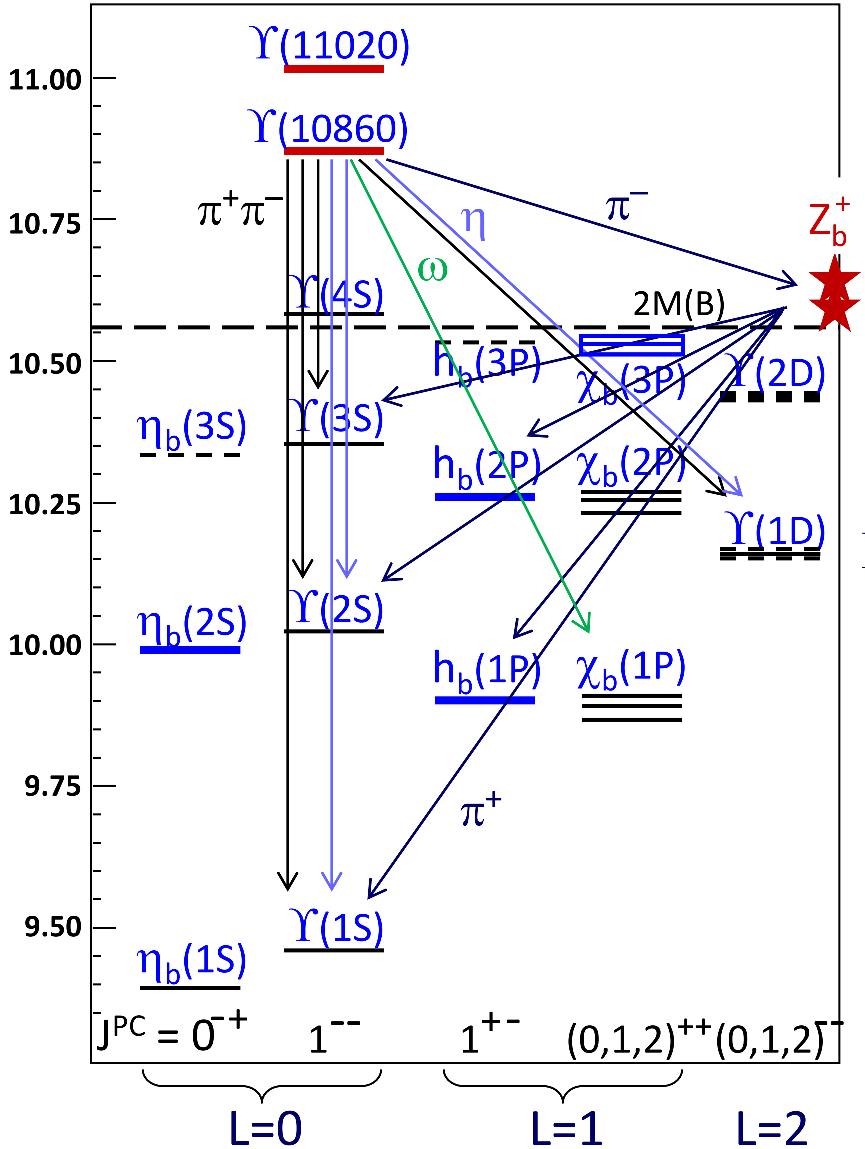




**Total $c\bar{c}$ cross-section is decomposed into open charm channels**

# Belle plans related to scan data

# 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

$\Gamma[\Upsilon(5S)\to h_b(1P/2P)\pi^+\pi^-]$ = 190/330 keV

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

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

$\Gamma[\Upsilon(5S)\to\chi_{b1/2}(1P)\,(\pi^+\pi^-\pi^0)_{non\text{-}res}]$ = 30/30 keV

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

Plans for Belle scan data:

Measure $\sigma\,[h_b\pi\pi]$
Decompose $R_b$ into $B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$, $B^{(*)}\bar{B}^*\pi$ and $B_s^{(*)}\bar{B}_s^{(*)}$

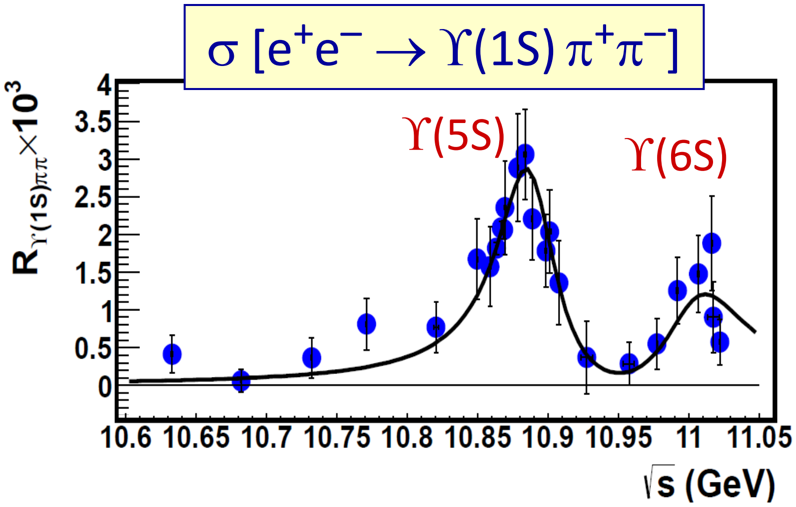
*Statistics are limited ⇒ useful input for Belle-II.*

# Belle-II plans

# First Physics at Belle-II

During 1st year of Belle-II data taking one can expect ~200 $fb^{-1}$.

| | Belle | BaBar |
|---|---|---|
| $\Upsilon(1S)$ | 6 $fb^{-1}$ | – |
| $\Upsilon(2S)$ | 24 $fb^{-1}$ | 14 $fb^{-1}$ |
| $\Upsilon(3S)$ | 3 $fb^{-1}$ | 30 $fb^{-1}$ |
| continuum | 90 $fb^{-1}$ | 54 $fb^{-1}$ |
| $\Upsilon(4S)$ | 711 $fb^{-1}$ | 433 $fb^{-1}$ |
| $\Upsilon(5S)$ | 121 $fb^{-1}$ | – |
| scan | 26 $fb^{-1}$ | 4 $fb^{-1}$ |




almost no data above $\Upsilon(5S)$

Options under discussion:

- ~200 $fb^{-1}$ @ $\Upsilon(3S)$
- Energy scan to search for $\Upsilon(2D)$, total ~10 $fb^{-1}$
- ~100 $fb^{-1}$ @ $\Upsilon(6S)$
- Energy scan in 10.95-11.25GeV region, 10MeV step, 1 $fb^{-1}$ per point.

# Motivation to take data at $\Upsilon(6S)$

Available data: Belle ~5fb$^{-1}$.

1. Clarify structure of $\Upsilon(nS)$ states above $B\bar{B}$ threshold

Unexpected BaBar/Belle results: violation of OZI rule and Heavy Quark Spin Symmetry:

| $\Upsilon(4S) \to$ | $\Gamma$, keV | $\Upsilon(5S) \to$ | $\Gamma$, keV | $\Upsilon(6S) \to$ | $\Gamma$, keV |
|---|---|---|---|---|---|
| $\Upsilon(1S)\pi^+\pi^-$ | 2 | $\Upsilon(1S/2S/3S)\pi^+\pi^-$ | 260/430/290 | – " – | 120/140/200 |
| $\Upsilon(1S)\ \eta$ | 5 | $\Upsilon(1S/2S)\ \eta$ | 40/200 | – " – | ?/? |
| $h_b(1P)\eta$ | 30 | $\Upsilon(1D)\ (\pi^+\pi^-)/\eta$ | 60/140 | – " – | ?/? |
| | | $\chi_{b1/2}(1P)\ \omega$ | 80/30 | – " – | ?/? |
| | | $h_b(1P/2P)\eta$ | 0/0 | – " – | ?/? |

Influence of nearby thresholds? $\Rightarrow$ decay pattern of $\Upsilon(6S)$ should help to clarify.

Closely related: $\Gamma\ [\Upsilon(5S) \to Z_b(10610/10650)^+\pi^-]$ = 7/3 MeV $\Rightarrow$ $\Gamma\ [\Upsilon(6S)]$ = ?/?

2. Search for missing bottomonium states below $B\bar{B}$ threshold

At $\Upsilon(5S)$: $h_b(1P,2P)$, $\eta_b(2S)$ observation, competitive measurement of $\Upsilon(1D)$ mass.

At $\Upsilon(6S)$ the 2D,1F multiplets are available w/ larger phase space.

3. Search for molecular states – partners of $Z_b$

BESIII: $Y(4260) \to X(3872)\gamma$, $Y(4360) \not\to X(3872)\gamma$    Belle: $\Upsilon(5S) \not\to X_b\ \gamma$. $\Upsilon(6S) \to X_b\ \gamma$ ?

Need similar to $\Upsilon(5S)$ data sample ~100fb$^{-1}$.

# Motivation to scan near $\Upsilon$(6S) and above

1. Clarify structure of $\Upsilon$(6S) state

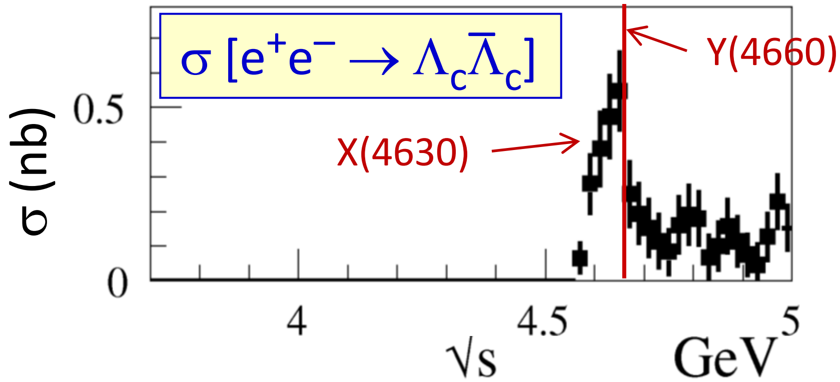
Measure BF[$\Upsilon(6S) \to BB/BB^*/B^*B^*/B^{(*)}B^*\pi/B_s^{(*)}B_s^{(*)}$] $\Rightarrow$ direct info on wave func.
High non-resonant contribution $\Rightarrow$ measurement at $\Upsilon$(6S) peak only is insufficient.

2. Search for new vector bottomonium-like states

BaBar/Belle/BESIII: many structures in $\sigma[e^+e^- \to (\psi/h_c)(\pi\pi/\eta/\omega)]$ scans
$\Rightarrow$ measure $\sigma[e^+e^- \to (\Upsilon/h_b)(\pi\pi/\eta/\omega)]$ vs. c.m. energy.

Belle observed $Y(4660) \to \psi(2S)\pi\pi$ and $X(4630) \to \Lambda_c\bar{\Lambda}_c$ near $\Lambda_c$ threshold
$\Rightarrow$ study $\Lambda_b\bar{\Lambda}_b$ threshold region

$E_{c.m.}$ = 10.24 GeV




Region above $\Upsilon$(5S) is unexplored. Even relatively small amount of data is of interest.

**Voloshin PRD84, 031502 (2011)**

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

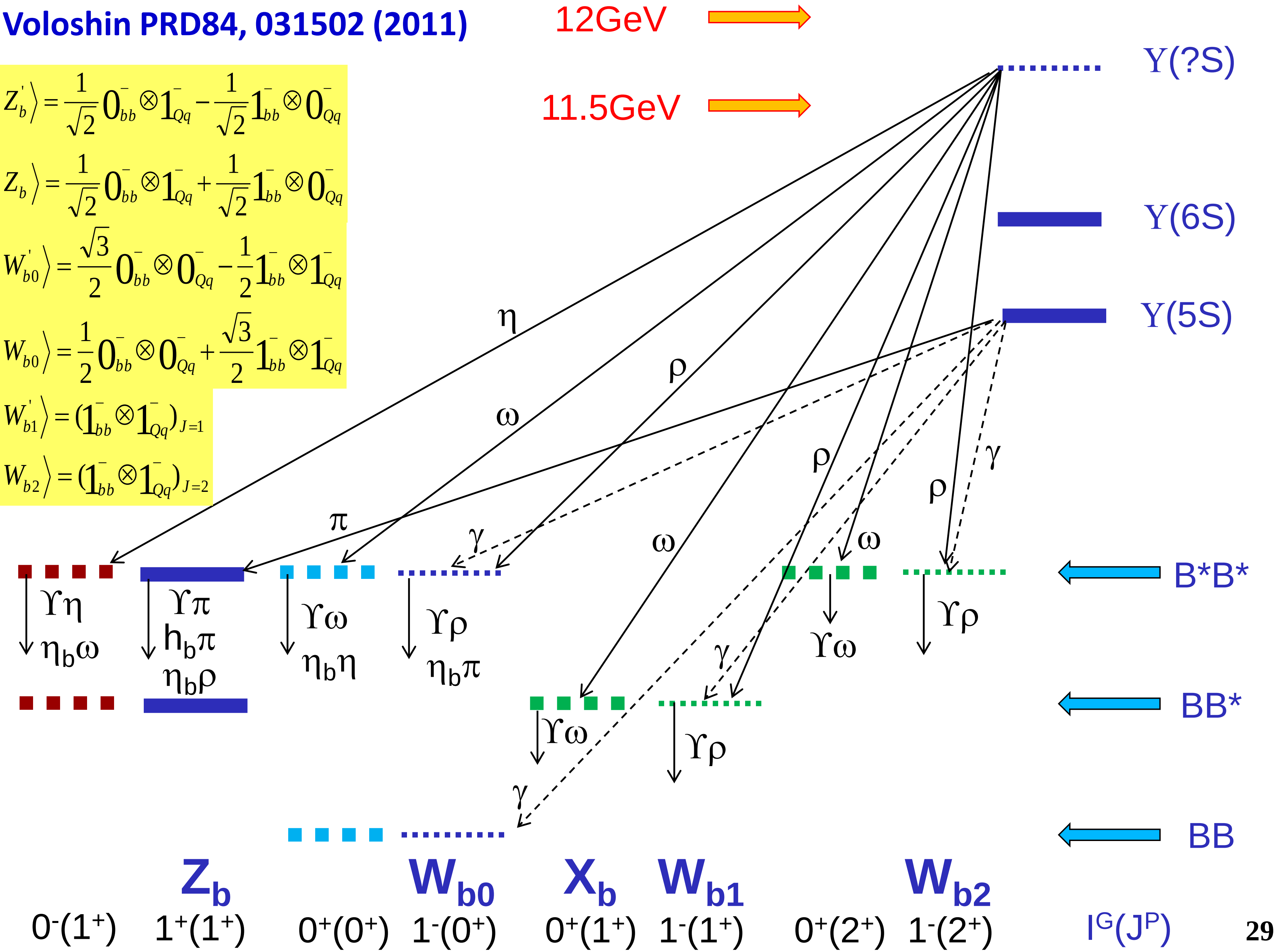
$$\left|Z_b\right\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar b} \otimes 1^-_{Q\bar q} + \frac{1}{\sqrt{2}} 1^-_{b\bar b} \otimes 0^-_{Q\bar q}$$

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

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

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

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



**Voloshin PRD84, 031502 (2011)**

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

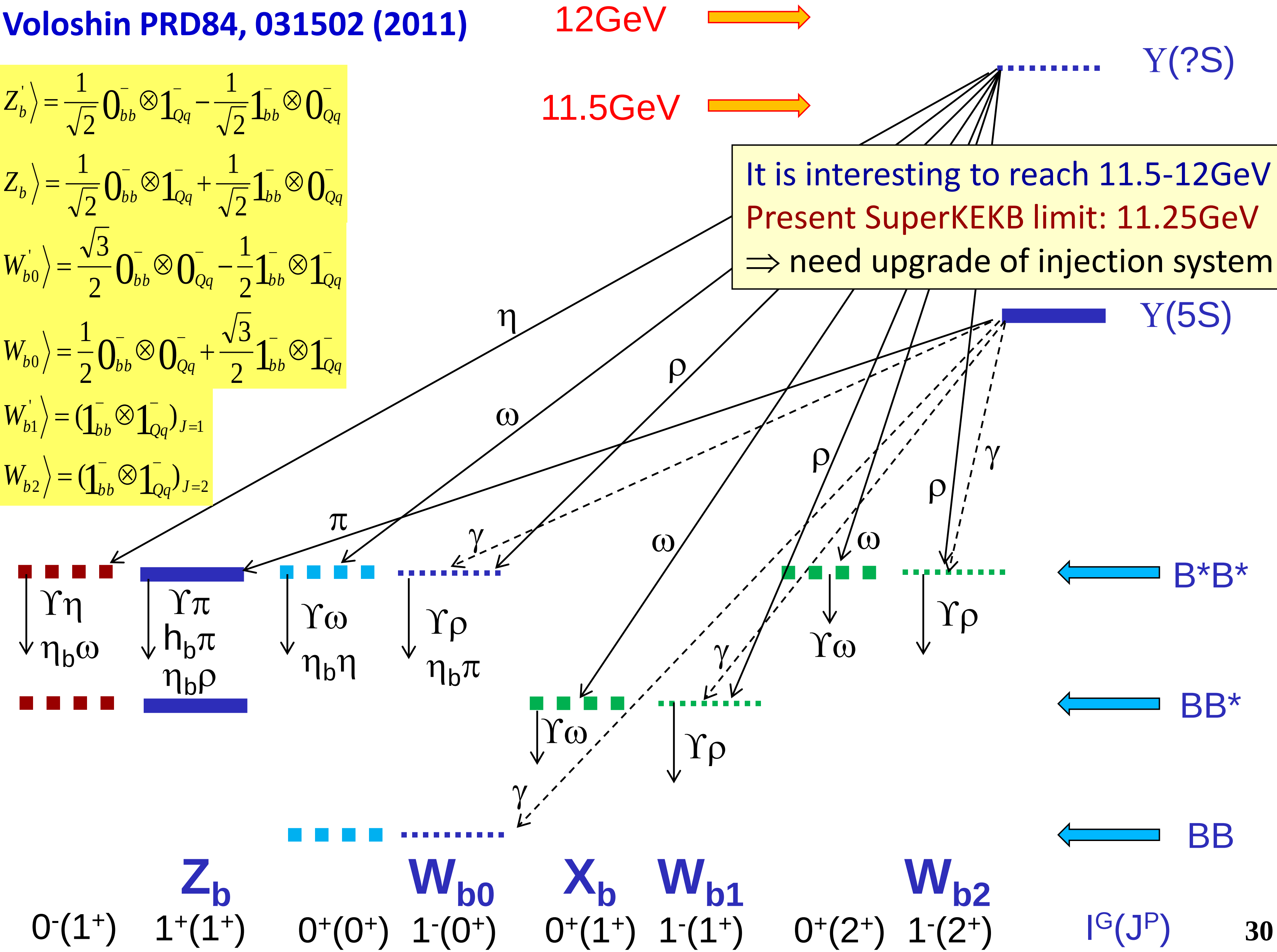
$$|Z_b\rangle = \frac{1}{\sqrt{2}} 0^-_{b\bar{b}} \otimes 1^-_{Q\bar{q}} + \frac{1}{\sqrt{2}} 1^-_{b\bar{b}} \otimes 0^-_{Q\bar{q}}$$

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

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

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

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



# Conclusions

Charmonium: different sets of states in $e^+e^-$ total hadronic cross section ($\psi$ states) and in $\psi\pi^+\pi^-$ total hadronic cross section (Y states).
Belle $\Rightarrow$
Bottomonium: unique set of states ($\Upsilon$ states).

$R_b$ distribution: high non-resonant component $\Rightarrow$ uncontrollable systematics for measurement of $\Upsilon(5S)$ and $\Upsilon(6S)$ parameters. Simple fit model give inconsistent results.

$R_{\Upsilon\pi\pi}$ distribution: ~no non-resonant component $\Rightarrow$ reliable measurement of $\Upsilon(5S)$ and $\Upsilon(6S)$ parameters.

Further studies of Belle scan data are coming:

$e^+e^- \to h_b(nP)\pi^+\pi^-$
Decomposition of $R_b$ into BB, BB*, B*B*, $B^{(*)}B^*\pi$ and $Bs^{(*)}Bs^{(*)}$ components.

More detailed scan is planned at Belle-II.