Bottomonium physics at Y(4S,5S,6S) with Belle

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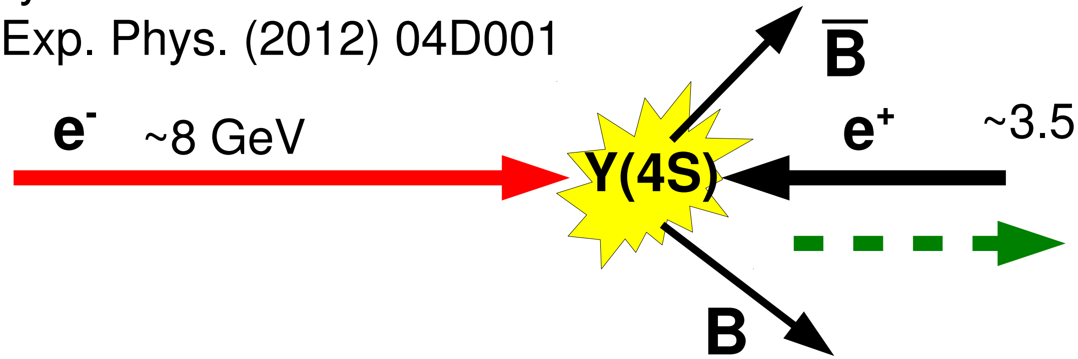
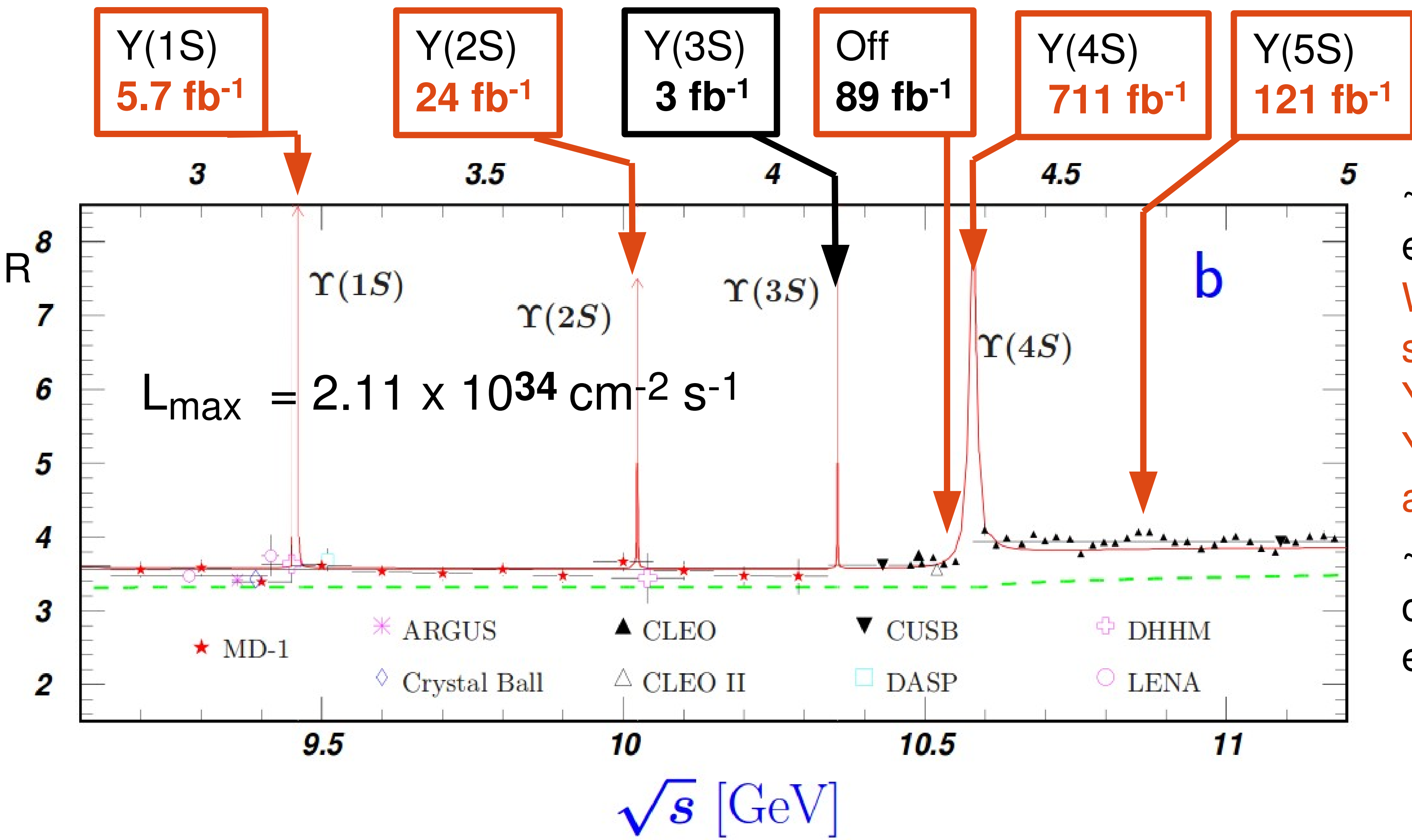
Fairness 2016
Garmisch-Partenkirchen, 02/15/2016

The KEKB complex

For a summary of Belle's resuts:
Prog. Theor. Exp. Phys. (2012) 04D001



LAB to CM boost
Complete knowledge of initial state

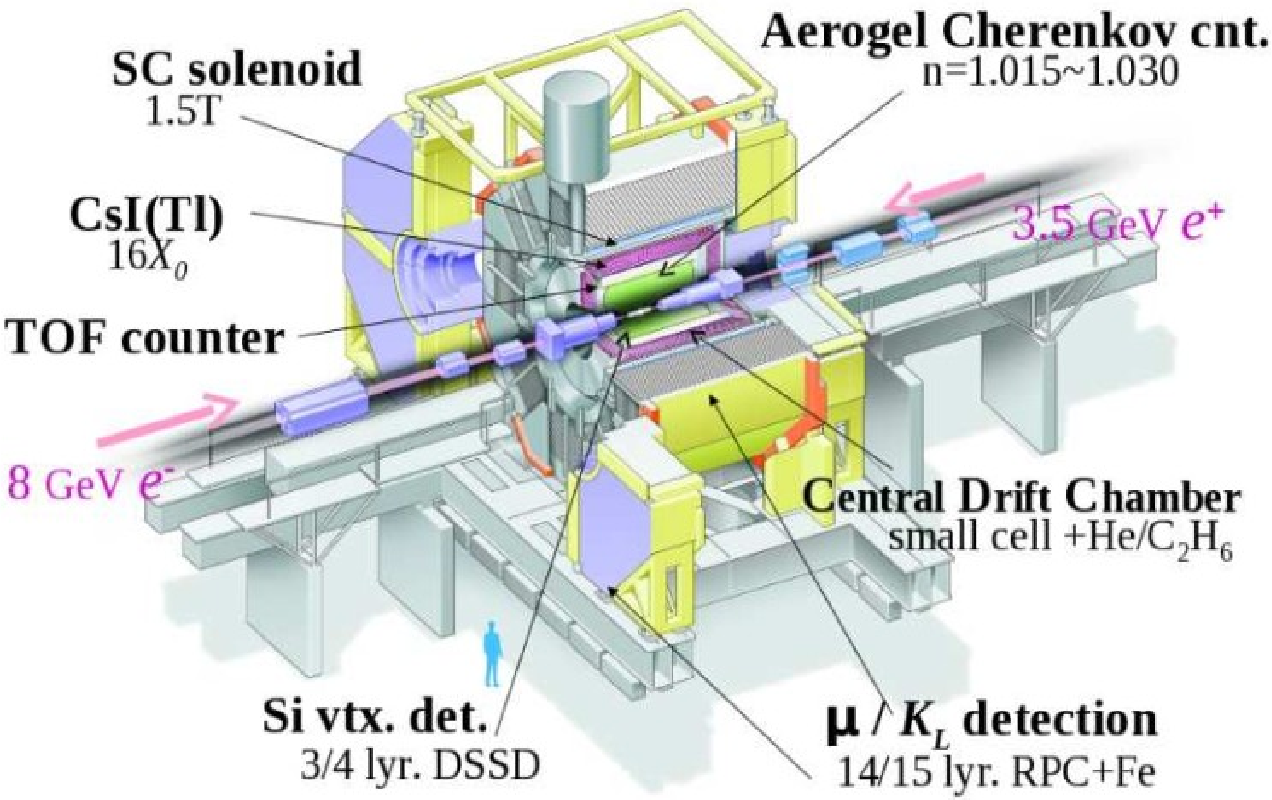


~ 1 ab of e+e- events

World largest samples of Y(1S), Y(2S), Y(4S), Y(5S) and off-resonance

~ 770 M of of Y(4S) → BB events

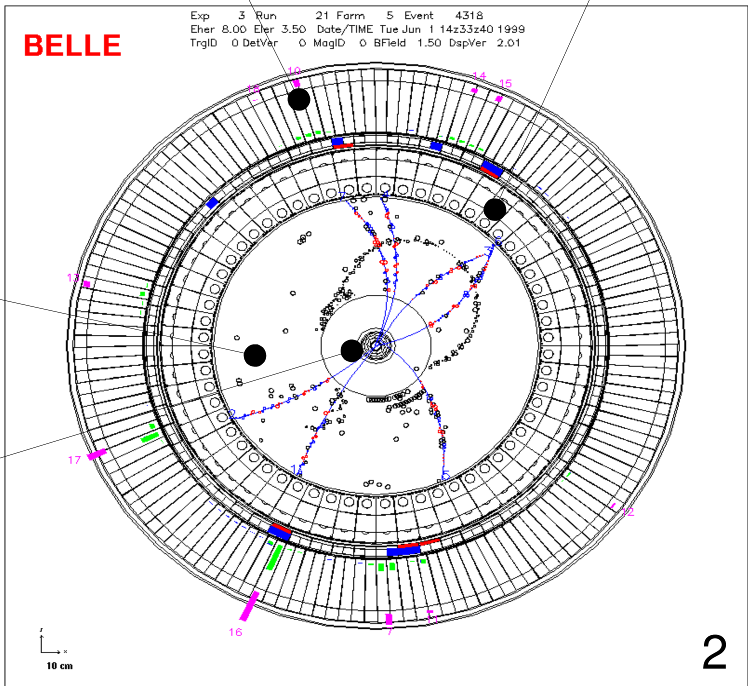
The Belle detector



Inner tracking:
3-4 layers of Double Sided Silicon Strip
Drift chamber (traking + dE/dx)

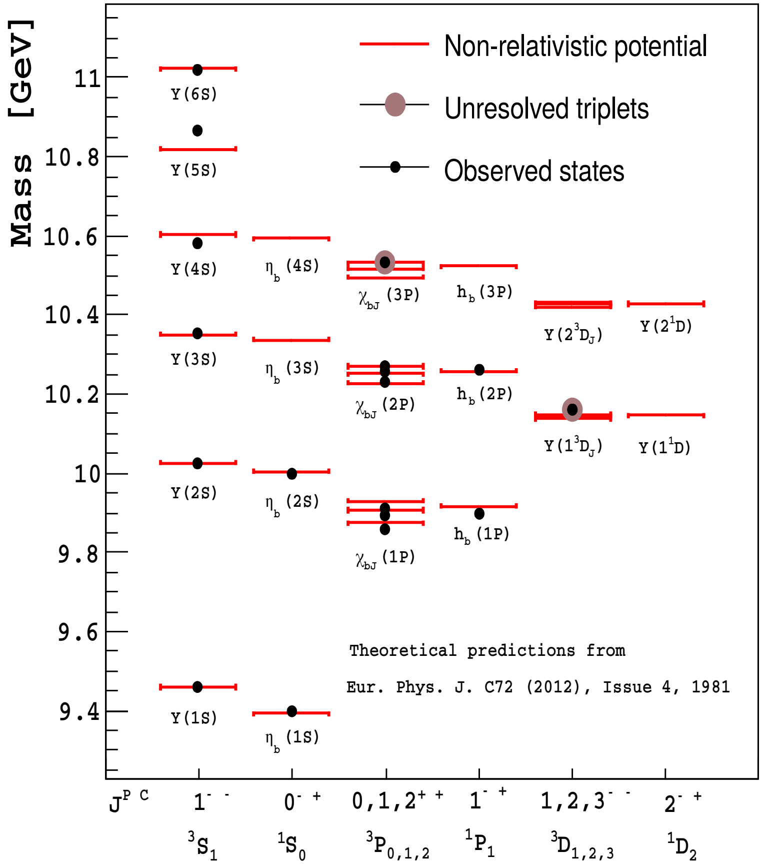
Particle Identification:
Time of flight (TOF)
Threshold Cherenkov counter

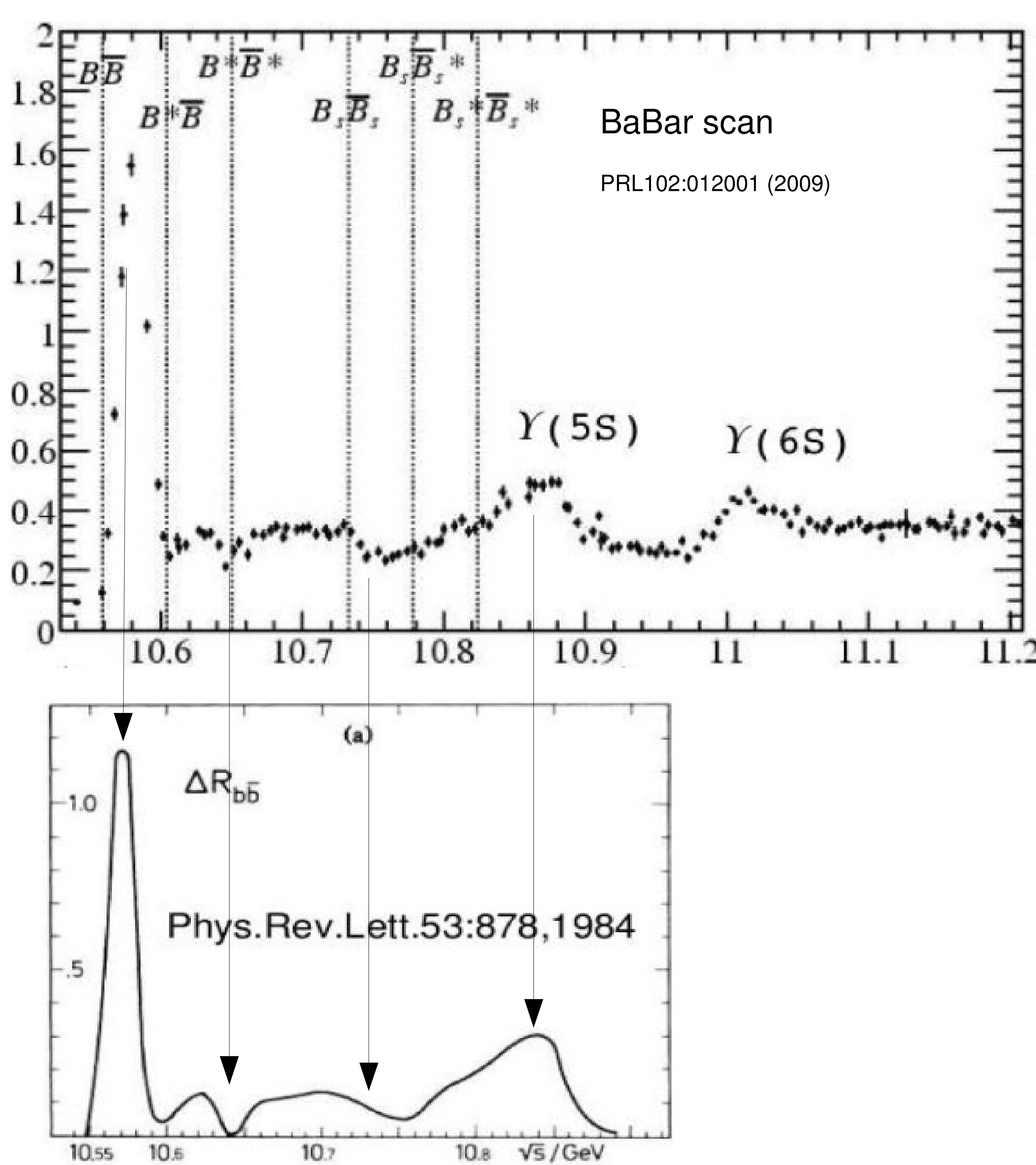
Neutrals:
NaI(TI) calorimeter
RPC + Fe for K_L conversions



Part I – Energy scans

Threshold structure in bottomonium





Bottomonium is intrinsically non relativistic

→ no mixing

→ simpler than charmonium

→ good description of the cross section sin terms of Rb

$$\textbf{Rb} = \frac{\sigma[e^+e^- \to b\bar{b} \to \text{hadrons}]}{\sigma[e^+e^- \to \mu^+\mu^-]}$$

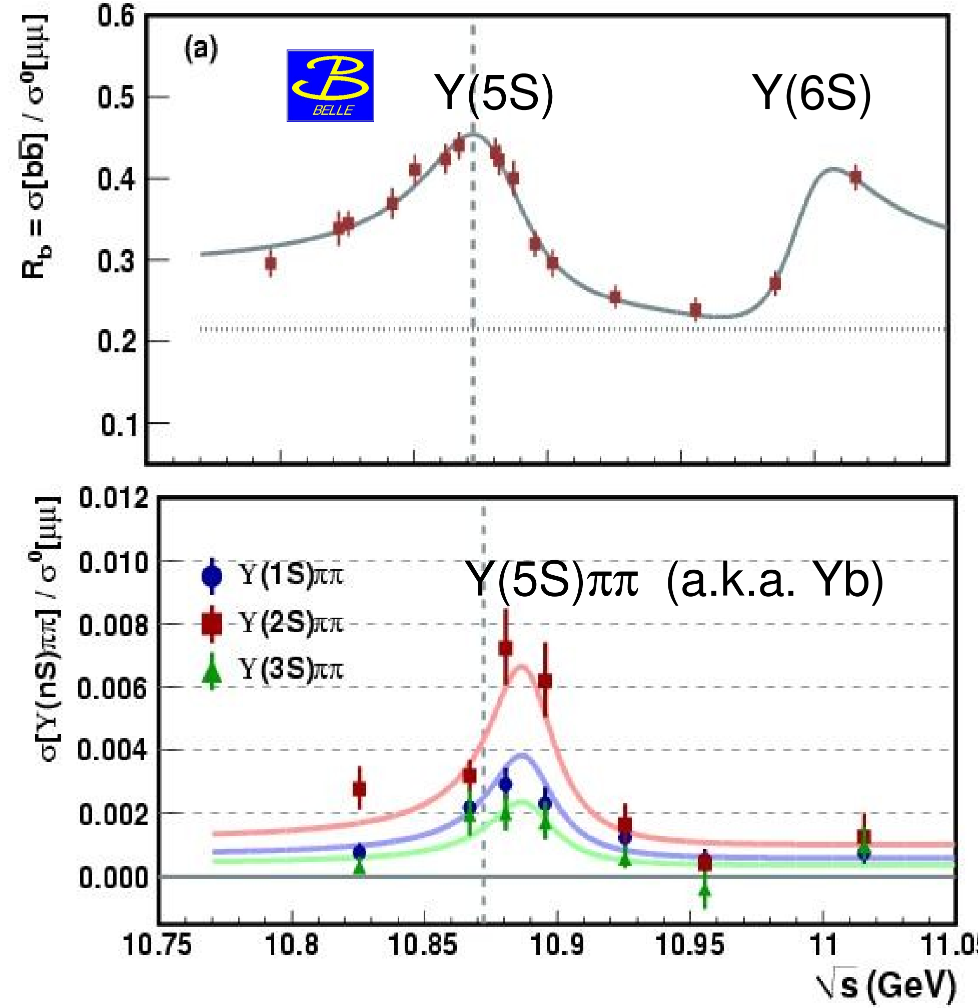
Y(5S) lineshape history

Both open and close

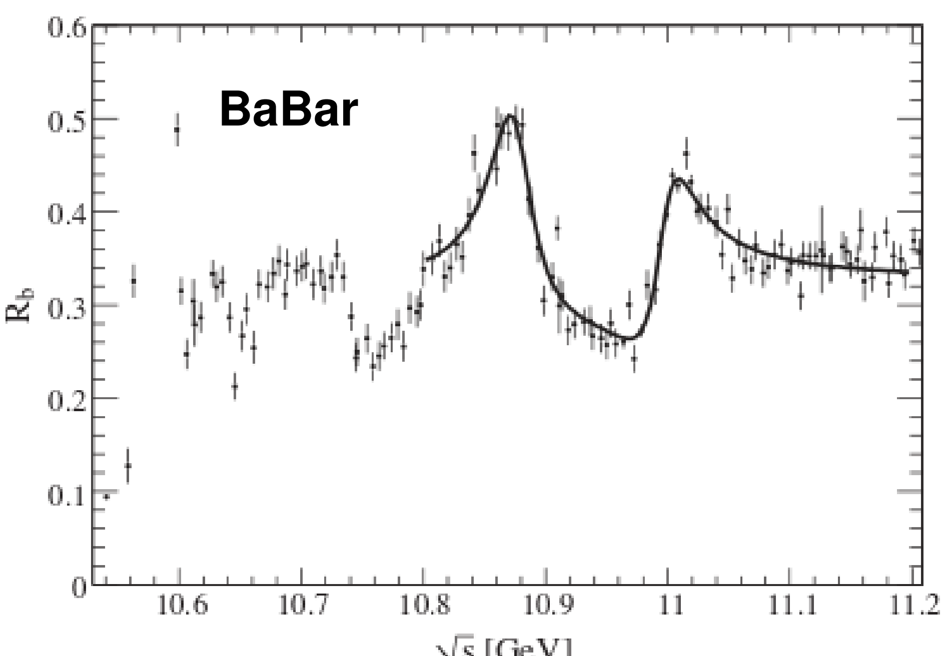
$$R_b = \frac{\sigma[e^+e^- \to b\bar{b} \to \text{hadrons}]}{\sigma[e^+e^- \to \mu^+\mu^-]}$$

$$R_{\pi\pi} = \frac{\sigma[e^+e^- \to \pi\pi Y(nS)]}{\sigma[e^+e^- \to \mu^+\mu^-]}$$

PRD 89, 091106 **(2010)** ~1 fb^{-1}/point SCAN



PRL 102, 012001 **(2009)**



Belle 2010

$M(5S)b\bar{b}$ = **10869 ± 2 MeV**

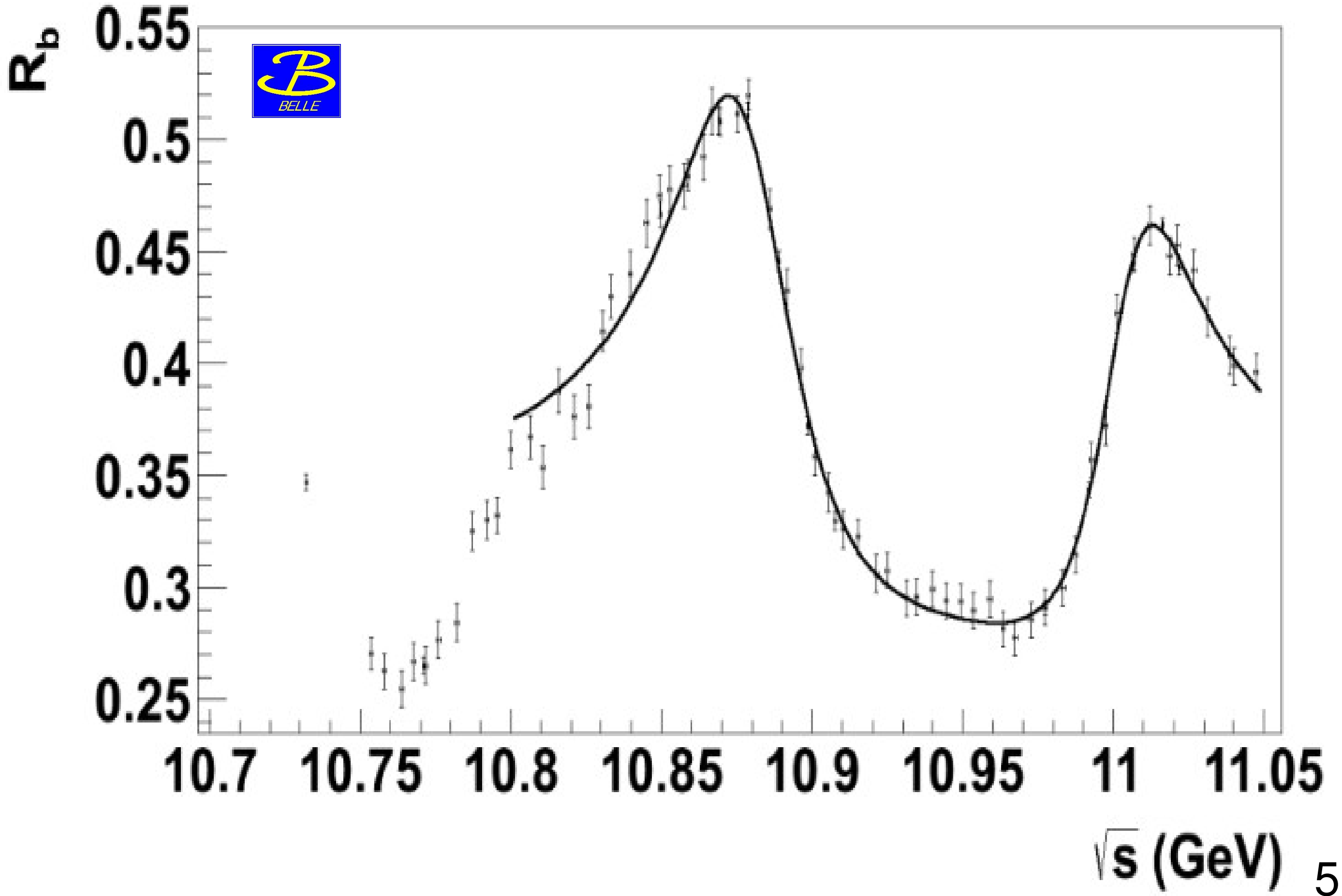
$M(5S)\pi\pi$ = **10888.4 ± 2.7 ± 1.2 MeV**

$M(5S) - M(5S)\pi\pi$ = -9 ± 4 MeV

New Belle Υ(5S) scan

Full Belle scan
For Rb: 61 points (50/pb each) every 5 MeV
For Rππ: 22 points (1/fb each)

According to PRL 102, 012001 **(2009)** cross sections are **visible ones**, not Born



New Belle Υ(5S) scan

Same as PRL 102,012001 **(2009)**

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

Incoherent continuum Amplitude

Coherent continuum Amplitude

Υ(5S) relativistic Breit-Wigner

Υ(6S) relativistic Breit-Wigner

According to BaBar's analysis, **continuum is assumed to be flat**

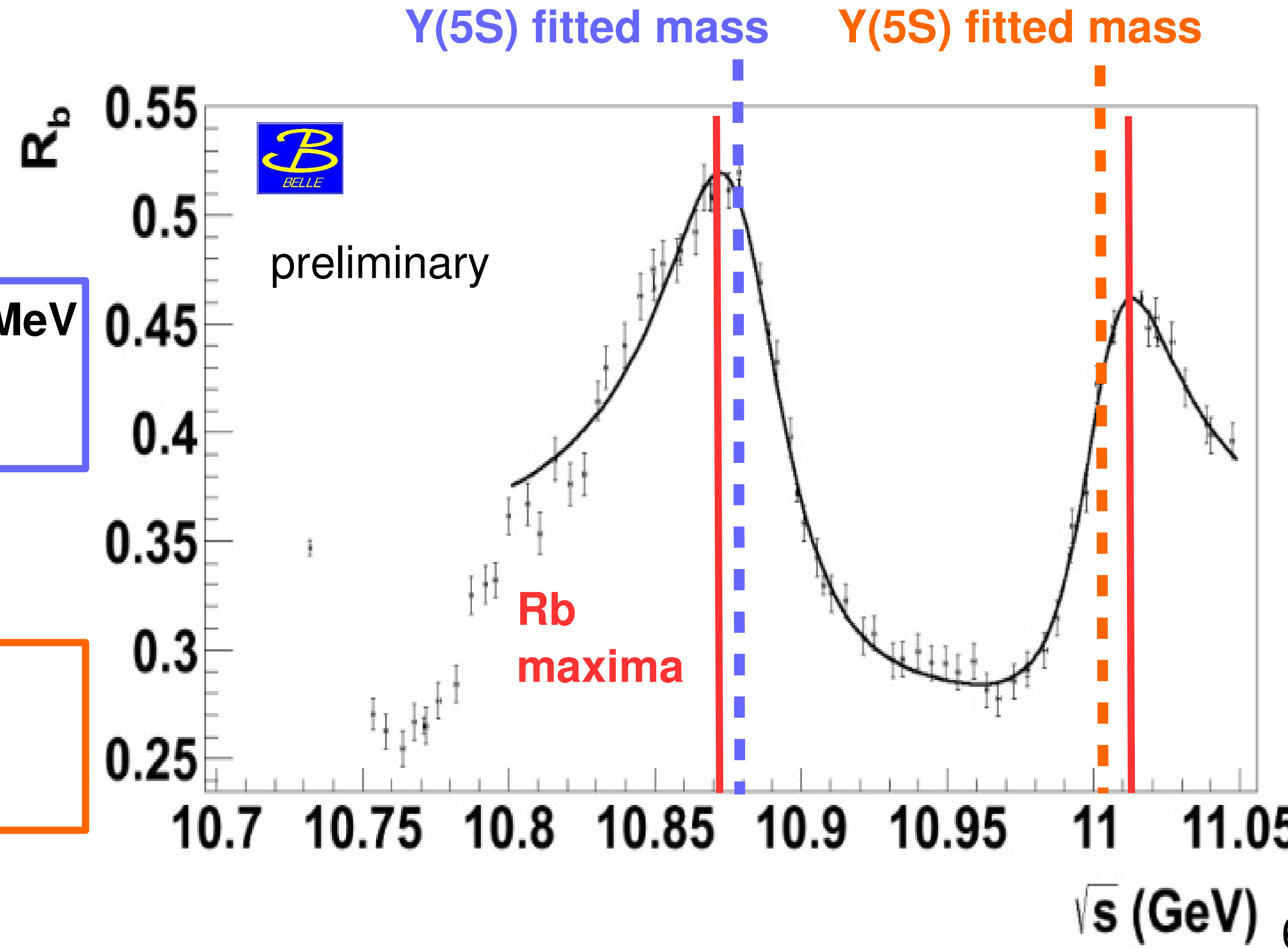
$M(5S)b\bar{b}$ = **10880.2 ± 0.9 ± 1.4 MeV**

$\Gamma(5S)b\bar{b}$ = **51 ± 2 MeV**

BaBar, same fit
$M(5S)b\bar{b}$ = 10879 ± 3 MeV

$M(6S)b\bar{b}$ = **11004 ± 1 ± 3 MeV**

$\Gamma(6S)b\bar{b}$ = **40 ± 2 MeV**

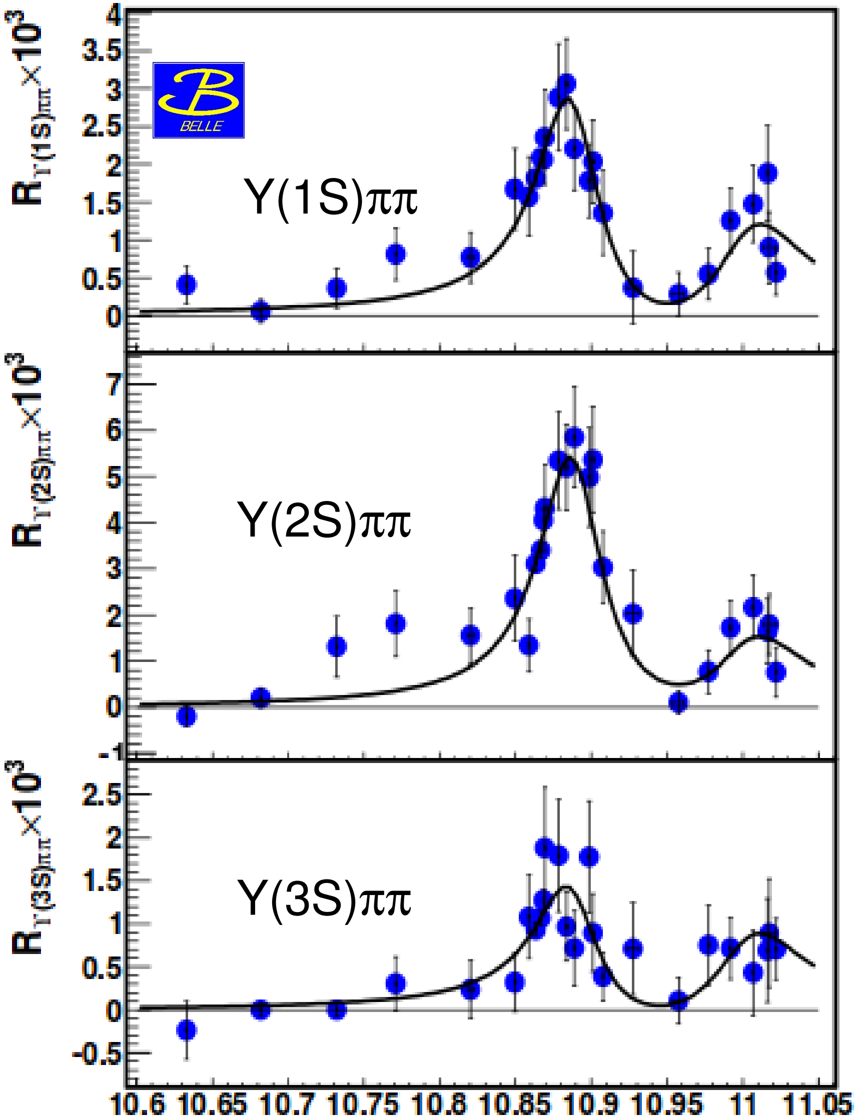


$R\pi\pi$ at Belle

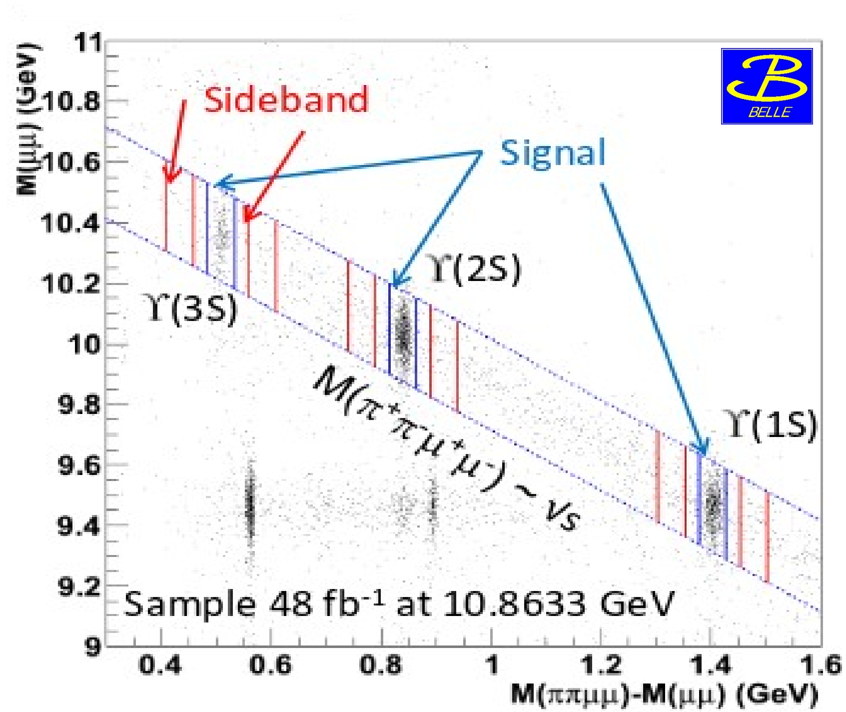
ArXiv:1501.01137

$$R\pi\pi = \frac{\sigma[e^+e^- \to \pi\pi\Upsilon(nS)]}{\sigma[e^+e^- \to \mu^+\mu^-]}$$

Full reconstruction of $\Upsilon \to \mu\mu$
No continuum background



$e^+e^- \to \mu^+\mu^-\gamma$ suppression: sidebands



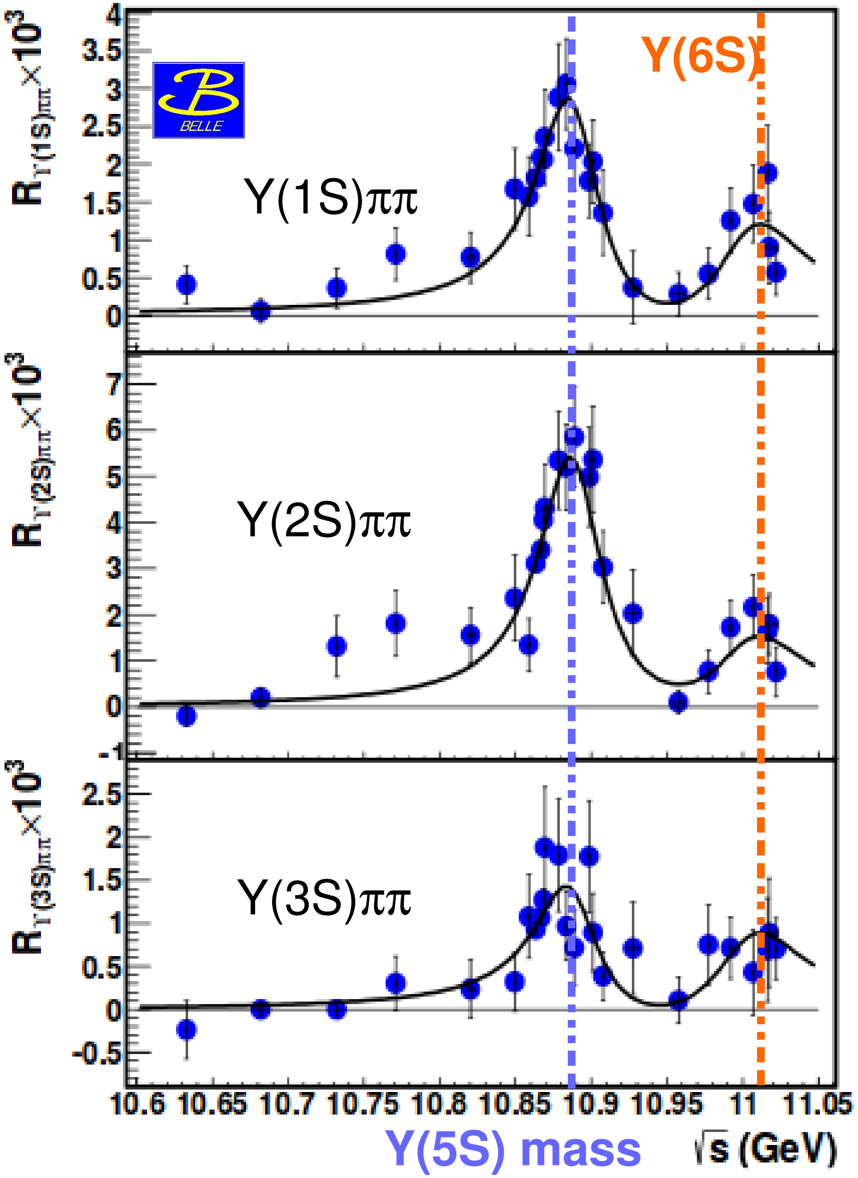
$R\pi\pi$ at Belle

ArXiv:1501.01137

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

No continuum contribution is visible

Fixed by Rb



Υ(6S) → ππ Υ(1,2,3S)

→ First Evidence

M(5S)ππ = **10884.6 ± 1.4 ± 1.2 MeV**

Γ(5S)$b\bar{b}$ = **51 ± 5 ± 5 MeV**

M(5S)ππ – M(5S)$b\bar{b}$ = 4.4 ± 2.5 MeV (1.8σ)

Γ(5S)ππ – Γ(5S)$b\bar{b}$ = 0 ± 8 MeV

The discrepancy between Rb and Rππ is not striking

Rππ seems to be more reliable

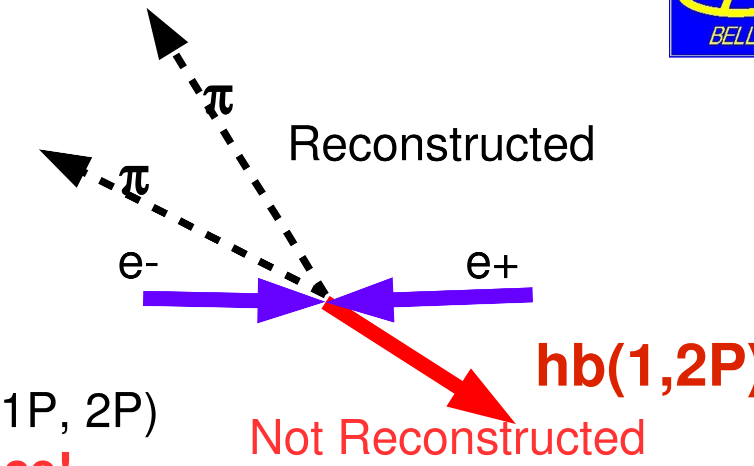
$R\pi\pi$ with $h_b(1,2P)$

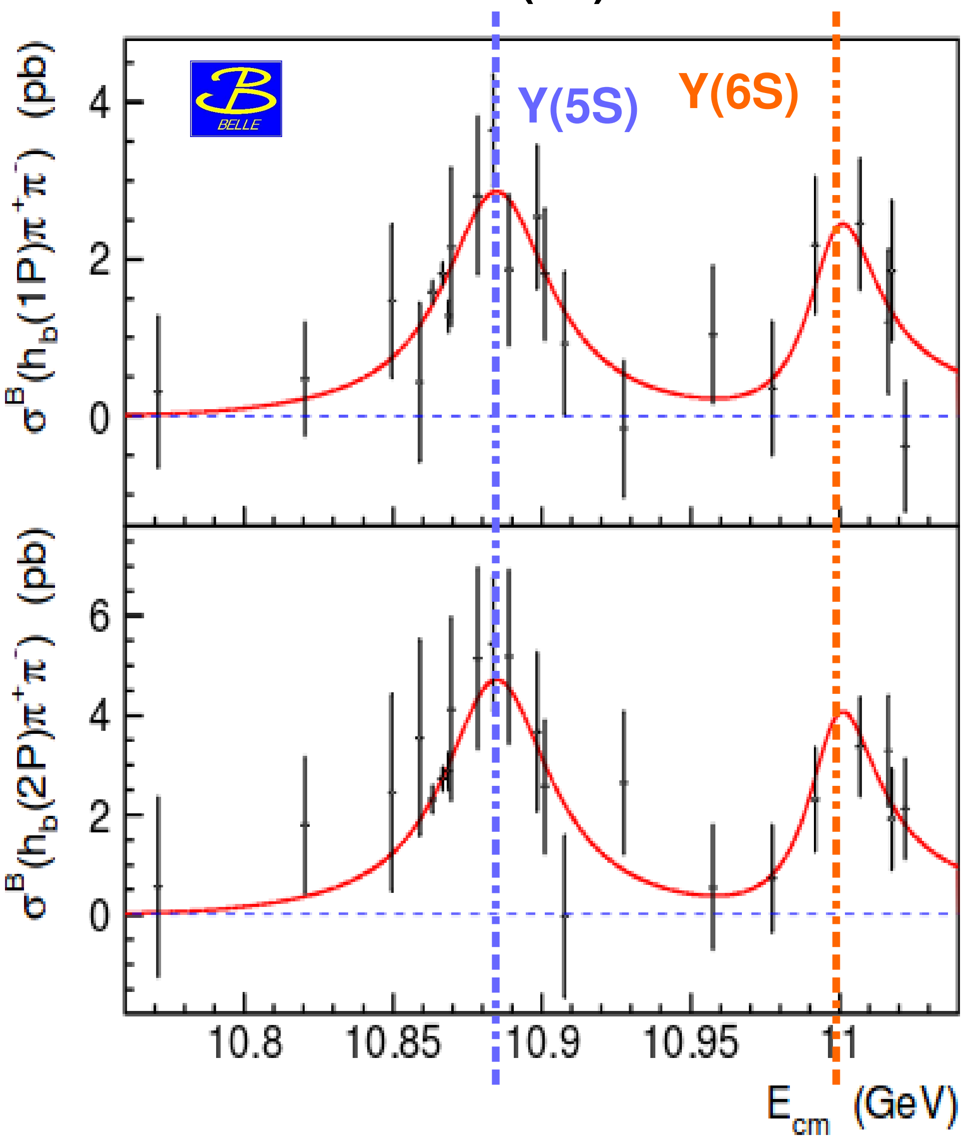
ArXiv:1508.06562

Y(5S) → ππ h_b(1P) was observed.

→ does it behave like ππY(nS)?

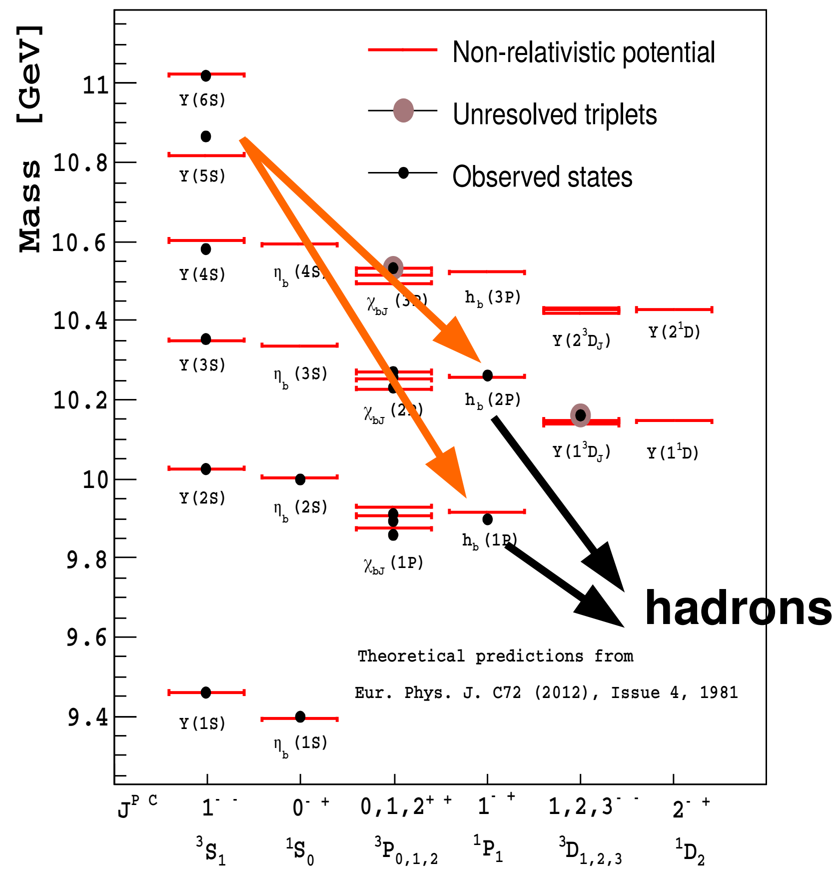
→ what about the Y(6S)?





Y(6S) → ππ hb(1P, 2P)

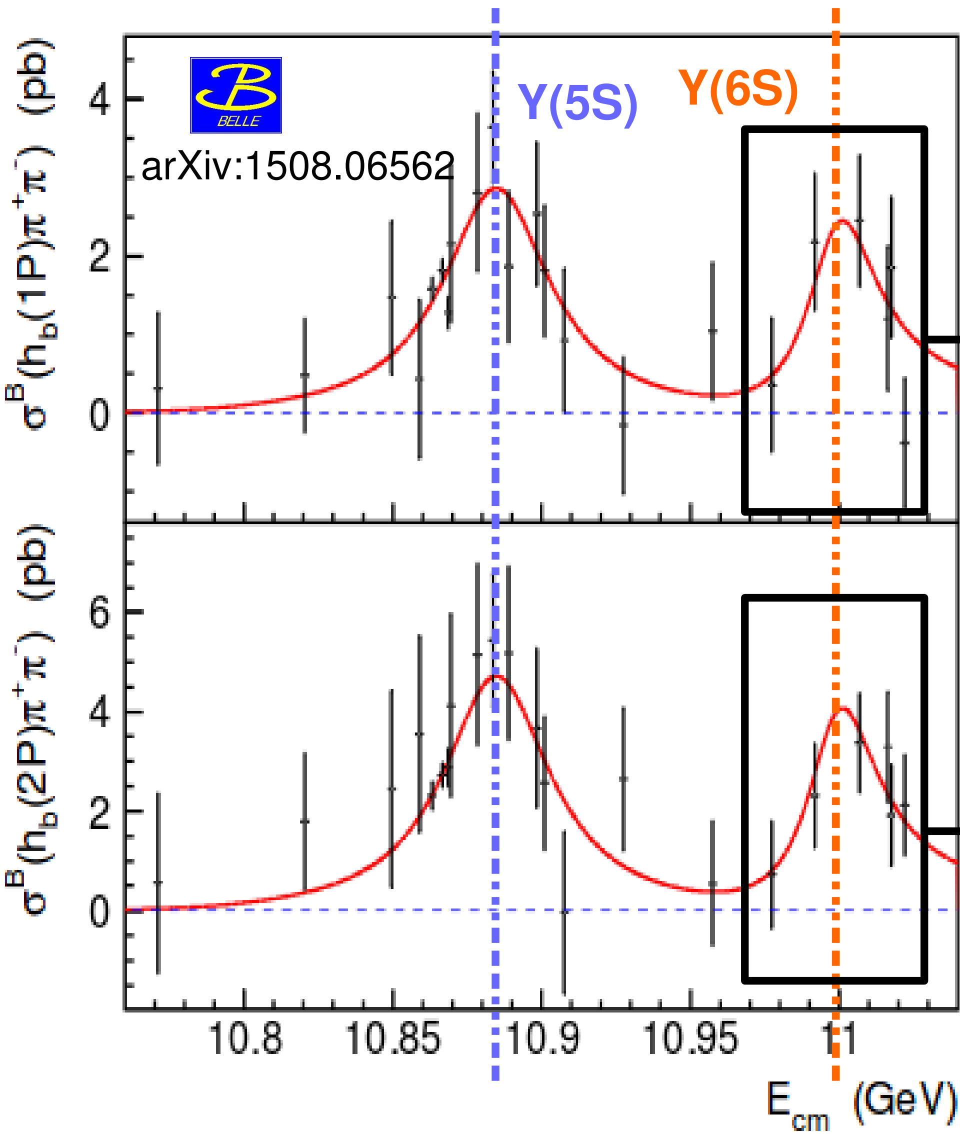
→ First Evidence!

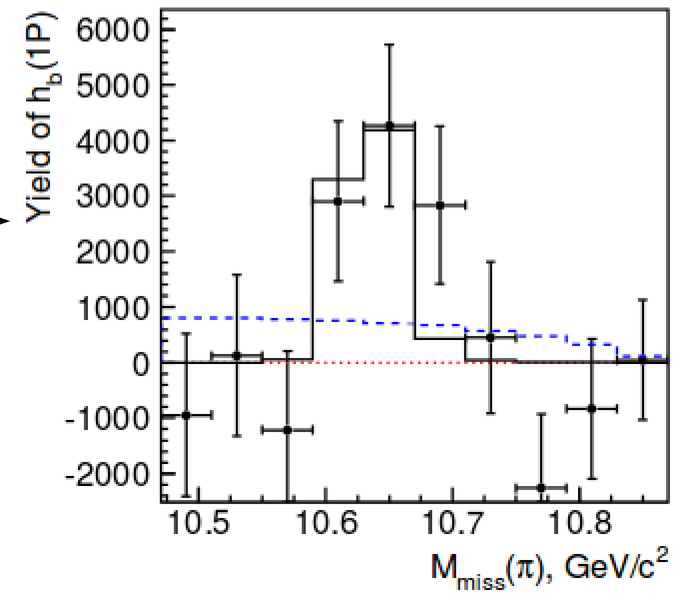


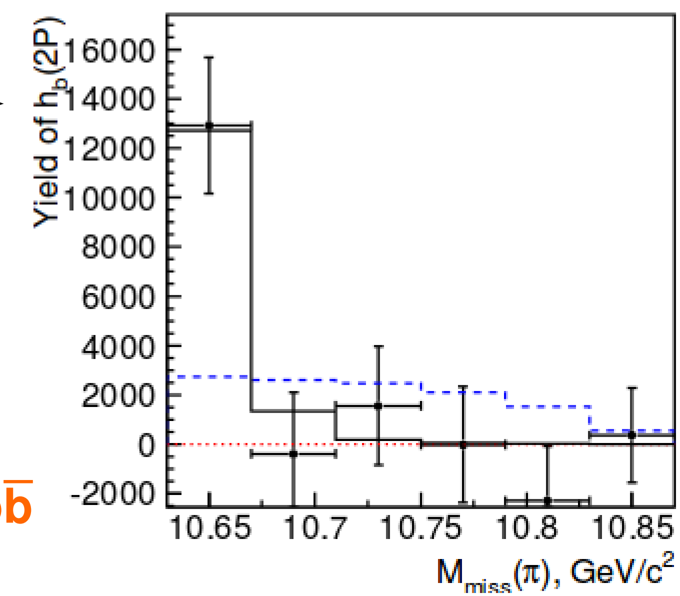
$R\pi\pi$ with h_b(1,2P)

Is there any Zb signal?

→ single pion recoil mass







First evidence of resonant structures in Y(6S) → pp $b\bar{b}$

Transition dominated by the Zb contributions

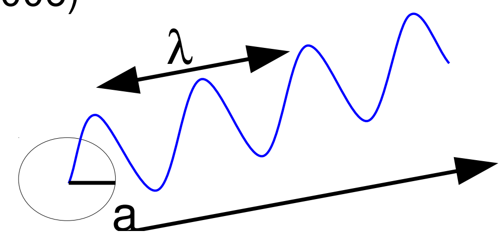
Part II – New transitions

Hadronic transitions: lower states

Kuang, Front.Phys.China 1, 19 (2006)

QED multipole expansion

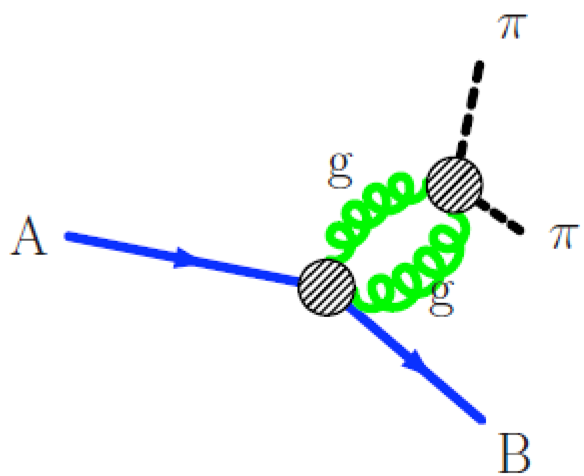
$a/\lambda \sim ak < 1$



In quarkonia:

$r \sim 0.1$ fm $\qquad rk < 1$

$k \sim 100$ MeV



Two-step process with emission of gluon pairs

→ **Chromo-electric** gluons (no spin-flipping)

→ **Chromo-magnetic** gluons (spin-flipping)

Color octet, Intermediate states can be factorized

A potential model may enter here

$$\mathcal{A}_{E1E1} = i\frac{g_E^2}{6}\sum_{K,L}\frac{<\Phi_I|\vec{x}_k|K,L><K,L|\vec{x}_l|\Phi_f>}{E_I - E_{KL}} < \pi\pi|E_k E_l|0>$$

First gluon emission

QQg hybrid states

Second gluon emission

Gluons → hadrons

HQSS above the threshold

Heavy Quark Spin Symmetry predicts:

b quark spin flip

$$\frac{\Gamma[Y(nS)\rightarrow\eta\,Y(mS)]}{\Gamma[Y(nS)\rightarrow\pi\pi\,Y(mS)]}\ll 1$$

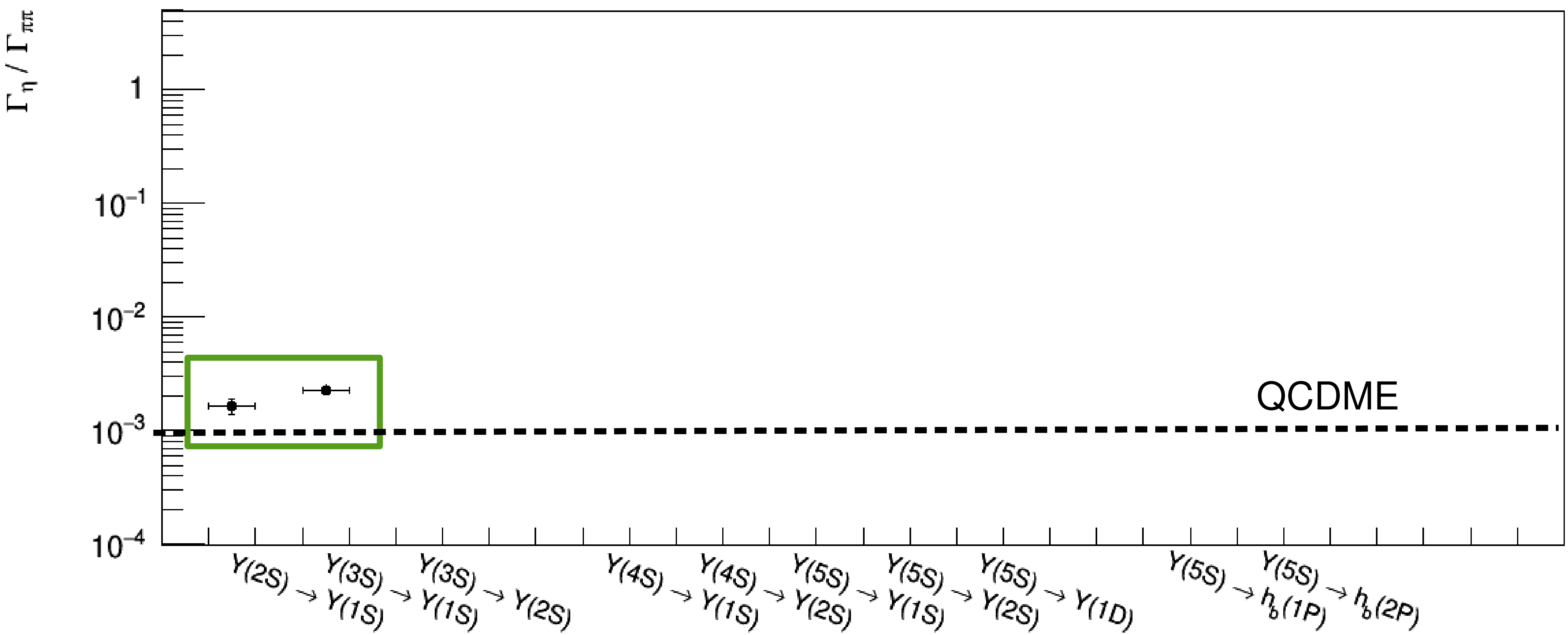
no b quark spin flip

$$\frac{\Gamma[Y(nS)\rightarrow\pi\pi\,h_b(mP)]}{\Gamma[Y(nS)\rightarrow\pi\pi\,Y(mS)]}\ll 1$$

Below threshold ~ OK

$$\frac{B[Y(3S)\rightarrow\eta\,Y(1S)]}{B[Y(3S)\rightarrow\pi\pi\,Y(1S)]}<2.2\times10^{-3}$$

$$\frac{B[Y(2S)\rightarrow\eta\,Y(1S)]}{B[Y(2S)\rightarrow\pi\pi\,Y(1S)]}=(1.64\pm0.25)\times10^{-3}$$



HQSS above the threshold

Heavy Quark Spin Symmetry predicts:

b quark spin flip:

$$\frac{\Gamma[Y(nS)\to\eta Y(mS)]}{\Gamma[Y(nS)\to\pi\pi Y(mS)]}\ll 1$$

no b quark spin flip:

$$\frac{\Gamma[Y(nS)\to\pi\pi h_b(mP)]}{\Gamma[Y(nS)\to\pi\pi Y(mS)]}\ll 1$$

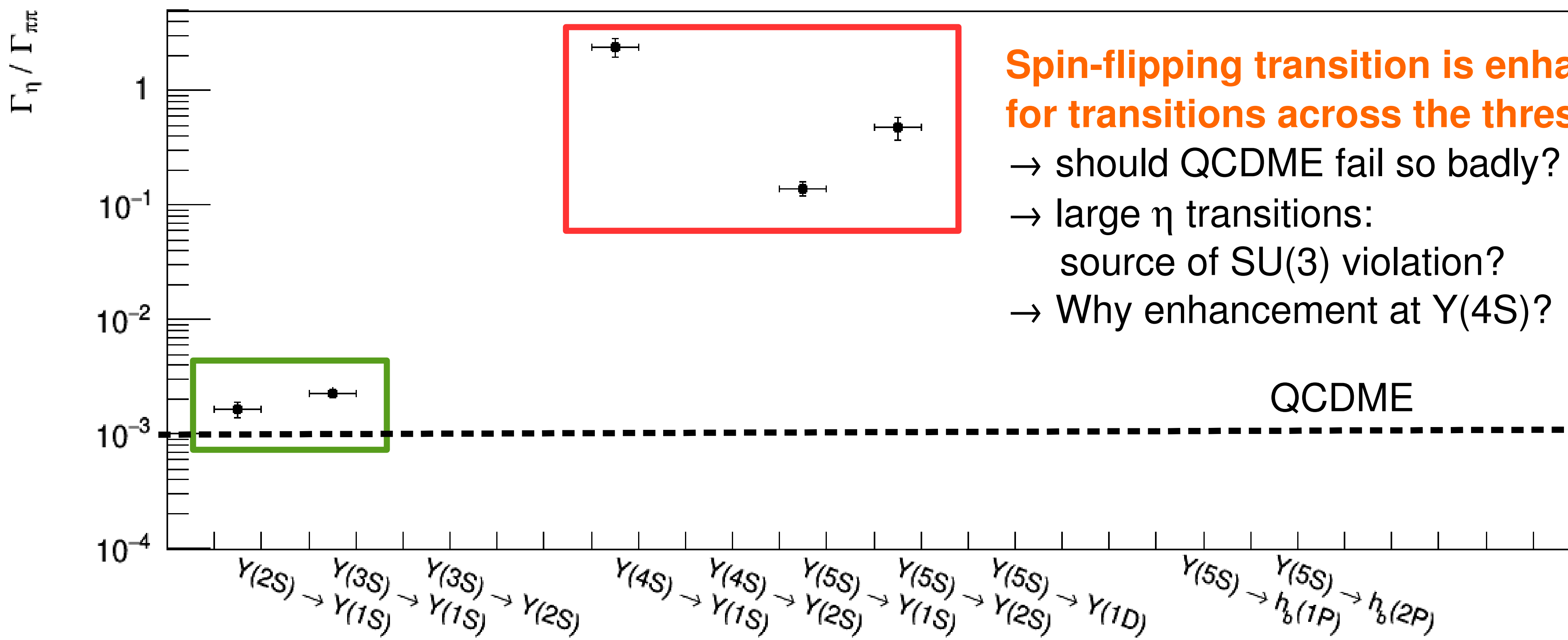
$$\frac{\Gamma[Y(5S)\to\eta Y(1S)]}{\Gamma[Y(5S)\to\pi\pi Y(1S)]}=0.16$$

$$\frac{\Gamma[Y(5S)\to\eta Y(2S)]}{\Gamma[Y(5S)\to\pi\pi Y(2S)]}=0.48$$

Belle preliminary

$$\frac{\Gamma[Y(4S)\to\eta Y(1S)]}{\Gamma[Y(4S)\to\pi\pi Y(1S)]}=2.41\pm0.40\pm0.20$$

PRD 78, 112002



Spin-flipping transition is enhanced for transitions across the threshold

→ should QCDME fail so badly?

→ large η transitions: source of SU(3) violation?

→ Why enhancement at Y(4S)?

Missing transitions

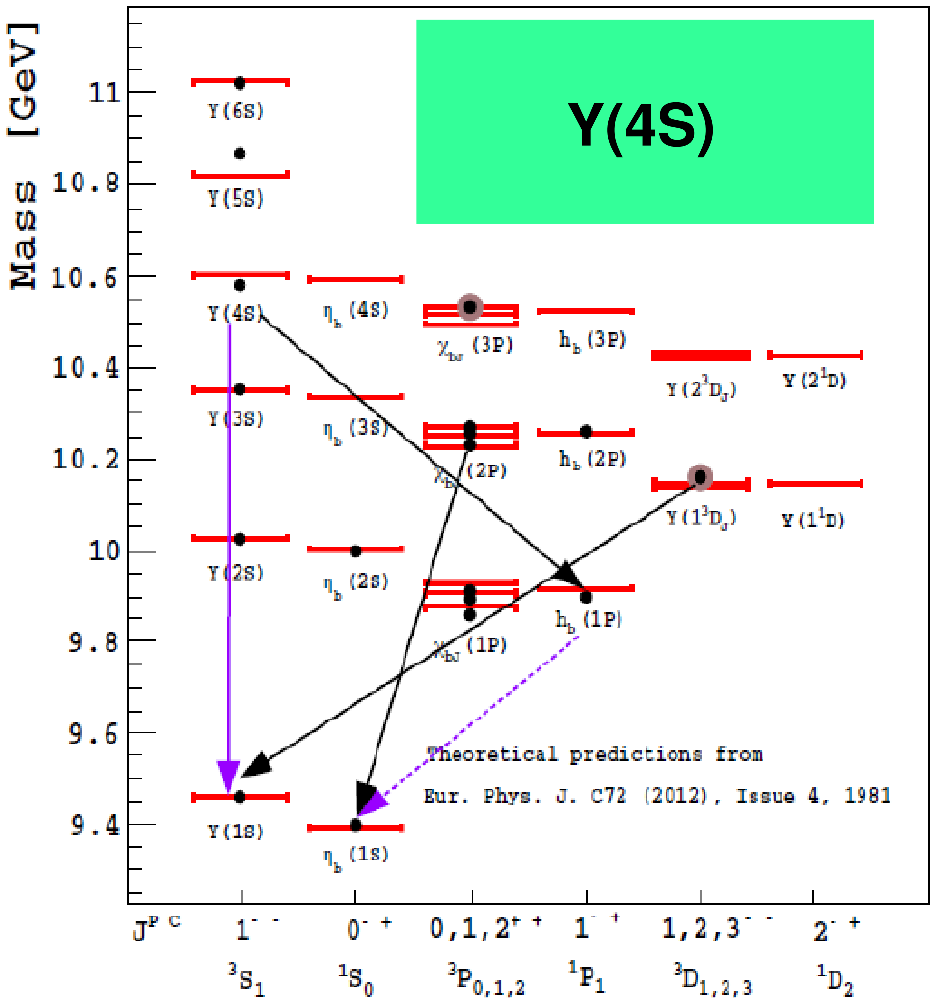
$\pi\pi$ transitions from Υ(5S) have been widely studied

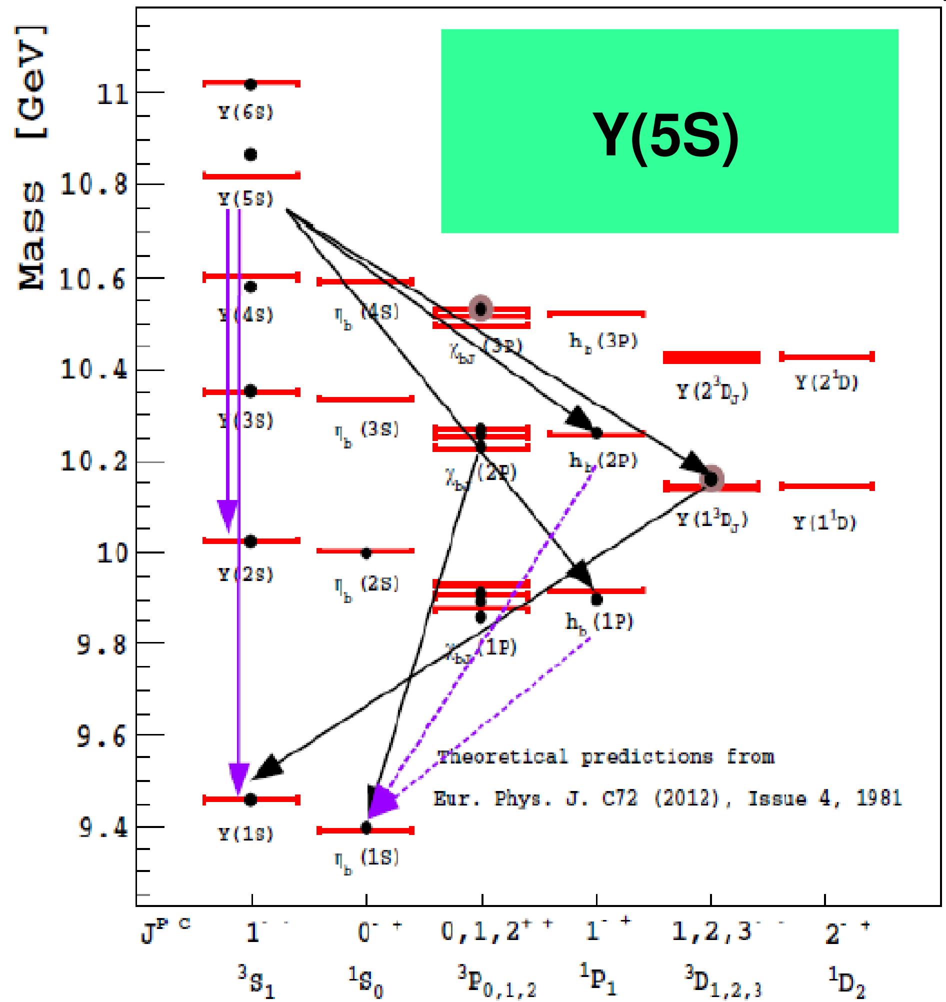
Unknown η

Known η

Known γ

η transitions to spin singlet states are still not studied





Υ(4S) → η h_b(1P) predicted to have BF ~ 10^{-3} **Possible new gateway to η_b(1S)**

Υ(5S) → η h_b(2P) can give indications on the HQSS breaking mechanism

$\Upsilon(4S) \to \eta\, b\bar{b}$

BF[Υ(4S)→η h_b(1P)] = (2.18 ± 0.11 ± 0.18)x10^{-3}

First **single meson**, $^3S \to {}^1P$

BF[Υ(4S)→η Υ(1S)] < 2.7 x 10^{-4}

In agreement with previous results and simulation

M(h_b(1P) = (9899.3 ± 0.4 ± 0.9) MeV/c^2

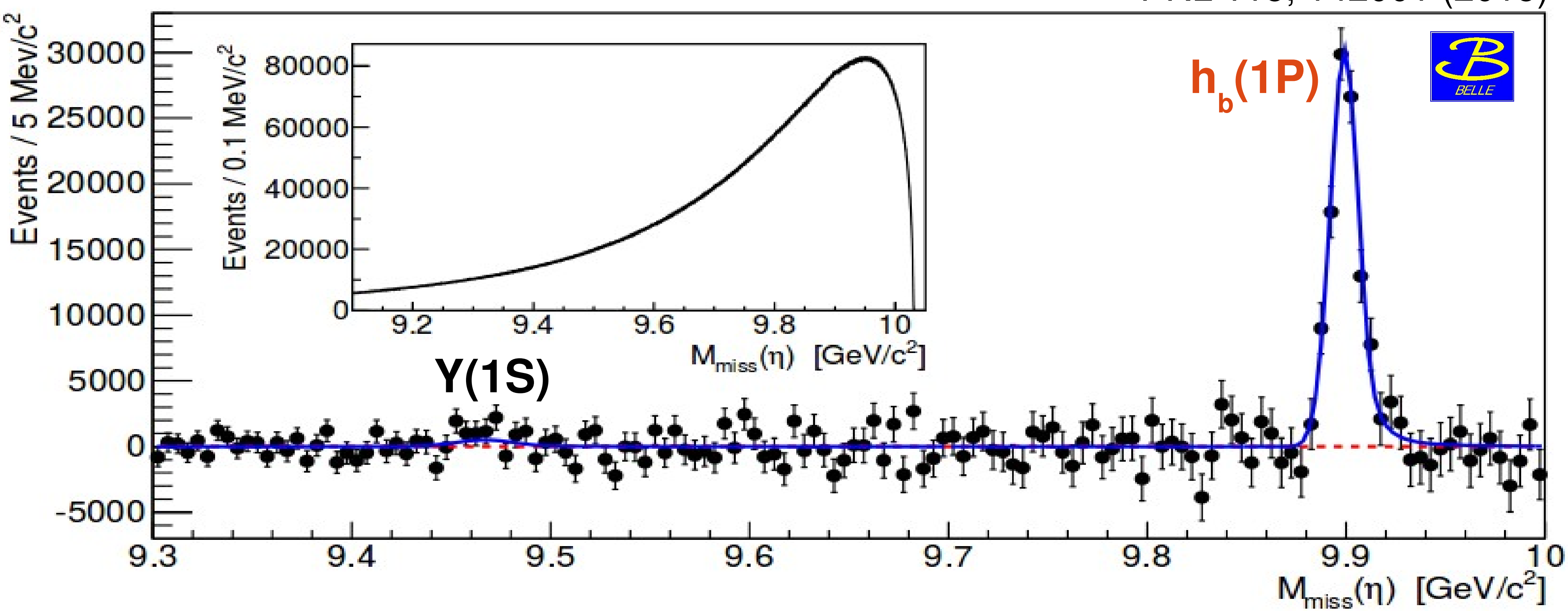
In agreement with previous measurement

M(h_b(1P) = (9899.1 ± 0.4 ± 1.0) MeV/c^2

Systematic uncertainties

Source	$N_{h_b(1P)}$	$N_{\Upsilon(1S)}$	$M_{h_b(1P)}$
Background order and range	±2.4	±7.1	±0.1
Bin width	±2.5	±2.4	±0.1
ISR modeling	±2.8	±2.6	±0.7
γ energy calibration	±1.2	±1.4	±0.3
Peaking backgrounds	±0.5	-	±0.4
Reconstruction efficiency	±6.6	±8.2	-
$N_{\Upsilon(4S)}$	±1.4	±1.4	-
Beam energy calibration	±0.0	±0.0	±0.4
$\mathcal{B}[\eta \to \gamma\gamma]$	±0.5	±0.5	-
Total	±8.2	±11.6	±1.0

PRL 115, 142001 (2015)



Results: $\Upsilon(5S) \to \eta\, b\bar{b}$

Assuming $\sigma(e^+e^- \to \Upsilon(5S))$ = (0.340 ± 0.016) nb

BF[$\Upsilon(5S) \to \eta\, \Upsilon(2S)$]=(2.1 ± 0.7 ± 0.3) x 10^{-3}

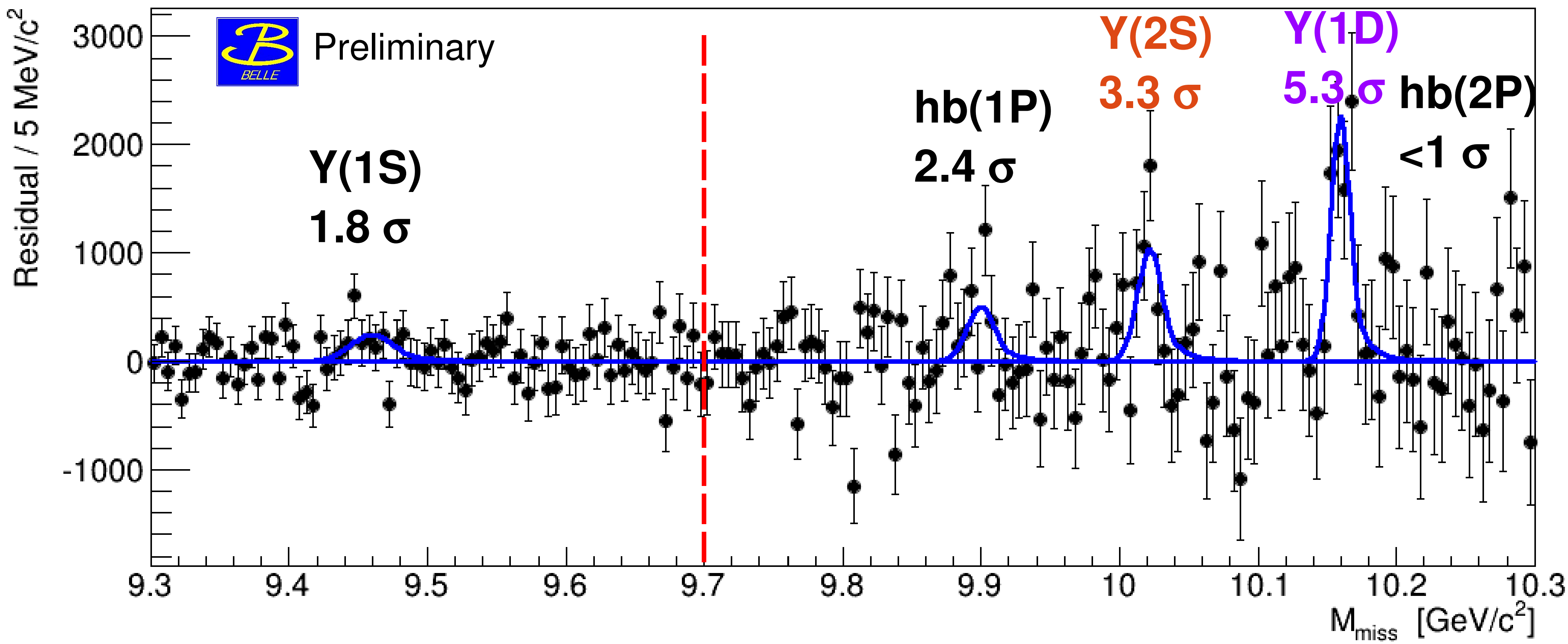
BF[$\Upsilon(5S) \to \eta\, \Upsilon(1D)$]=(2.8 ± 0.7 ± 0.4) x 10^{-3}

BF[$\Upsilon(5S) \to \eta\, h_b(1P)$] < 3.3 x 10^{-3} (90% CL)

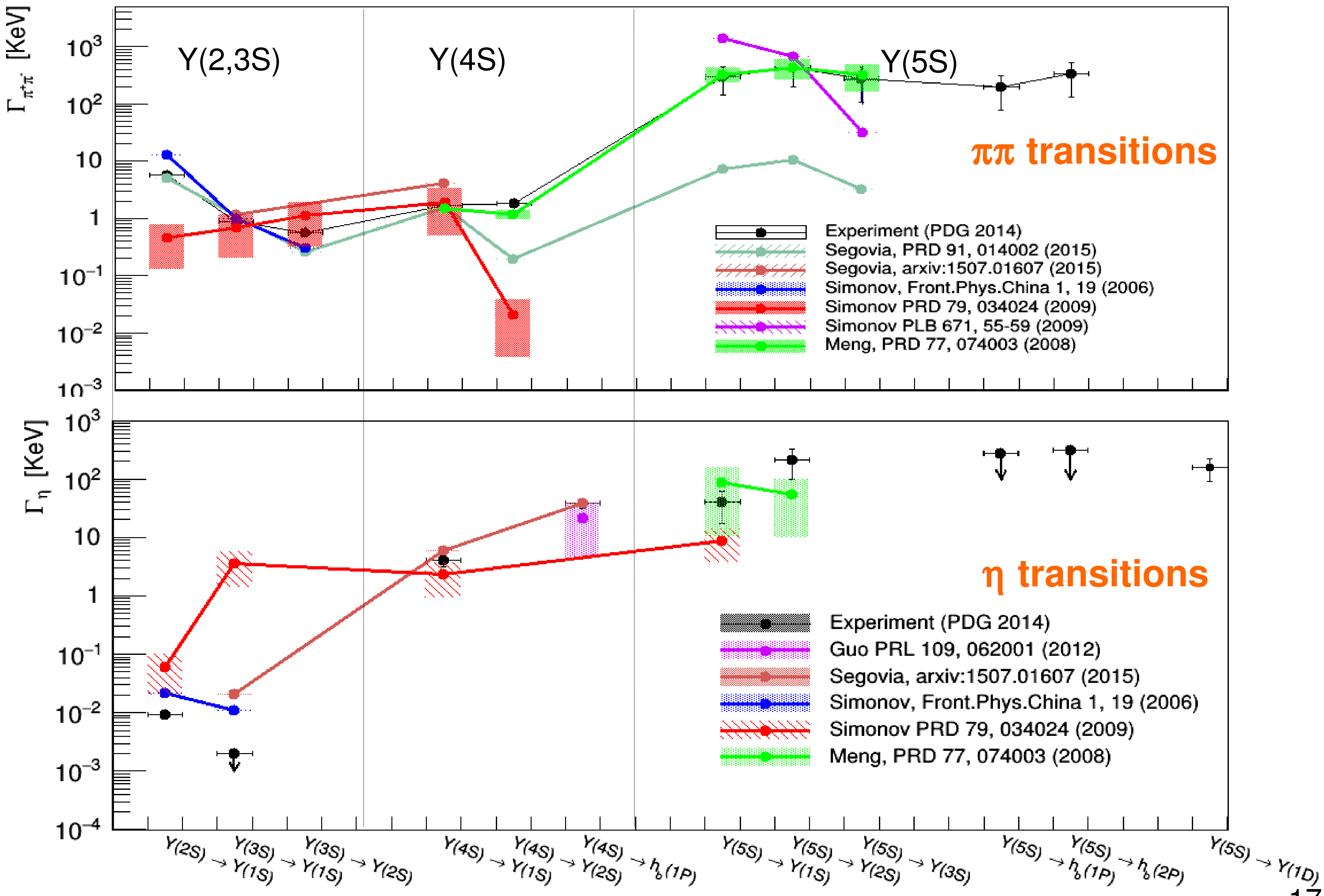
BF[$\Upsilon(5S) \to \eta\, h_b(2P)$] < 3.7 x 10^{-3} (90% CL)

Systematic uncertainties

Source	$\eta\Upsilon(1S)$	$\eta\Upsilon(2S)$	$\eta\Upsilon(1D)$	$\eta h_b(1P)$	$\eta h_b(2P)$
$N_{\Upsilon(5S)}$	±4.9%	±4.9%	±4.9%	±4.9%	±4.9%
γ reconstruction	±4.0%	±4.0%	±4.0%	±4.0%	±4.0%
Fit range	±4.0%	±6.0%	±3.5%	±9.0%	±10%
Bin width	±7.1%	±1.0%	±3.5%	±15%	±20%
Polynomial order	±9.0%	±7.3%	±1.1%	±10%	±9.0%
Signal resolution	±7.0%	±12%	±1.0%		
Floating masses	±5.0%	±7.2%	±1.7%		
Peaking backgrounds			±0.3%		
Total	±16.2%	±18.1%	±8.3%	±21.0%	±25.0%



ππ/η transitions: Th. VS Exp



$\pi\pi/\eta$ transitions: HQSS

$$\frac{\Gamma[\Upsilon(4S)\to\eta h_b(1P)]}{\Gamma[\Upsilon(4S)\to\pi\pi h_b(1P)]}>5.4$$

Assuming BF[Y(4S)→ππ h_b(1P)] =< 0.4 x10^{-3}

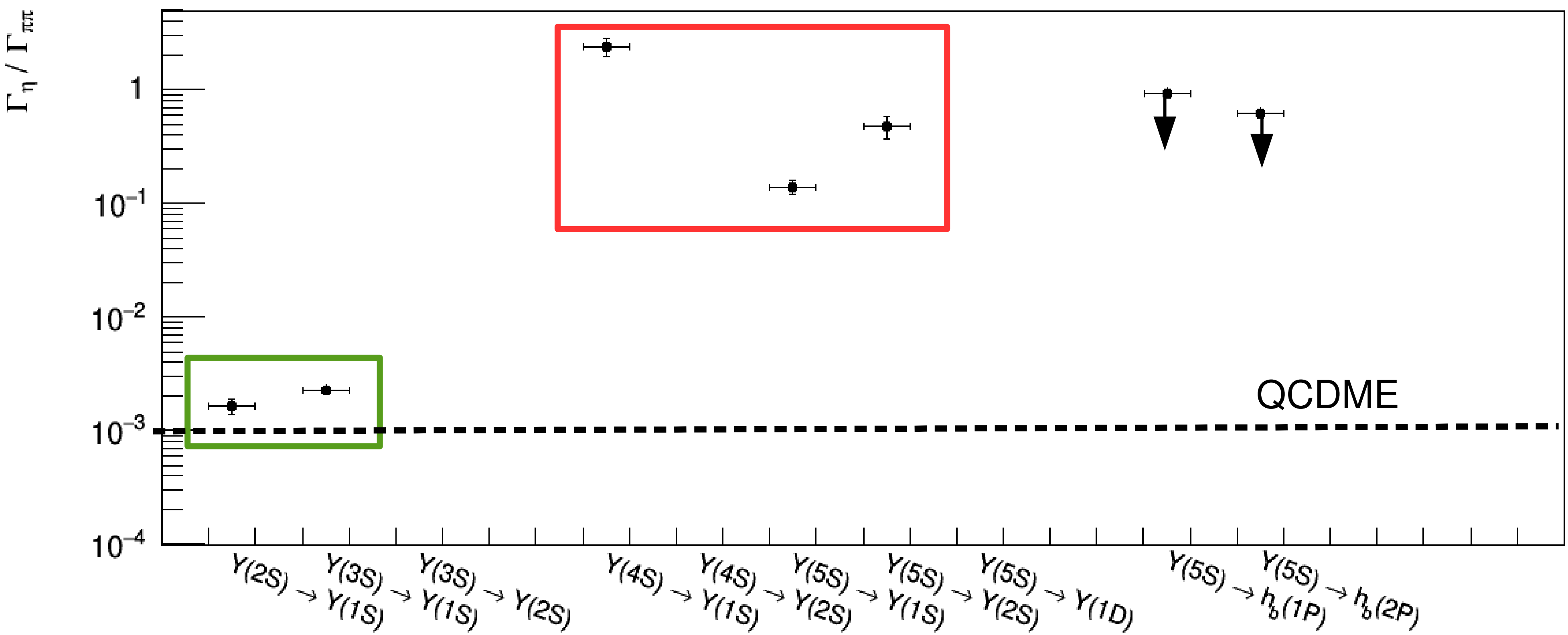
Same behavior as in the Y(4S) → Y(1S) transitions

$$\frac{\Gamma[\Upsilon(5S)\to\eta h_b(1P)]}{\Gamma[\Upsilon(5S)\to\pi\pi h_b(1P)]}<0.94$$

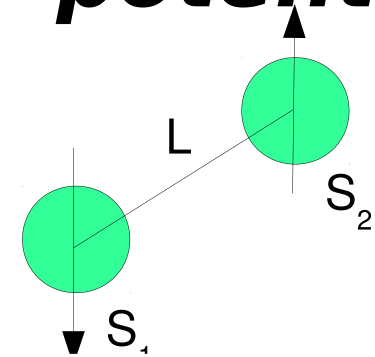
$$\frac{\Gamma[\Upsilon(5S)\to\eta h_b(2P)]}{\Gamma[\Upsilon(5S)\to\pi\pi h_b(2P)]}<0.62$$

Spin flip / spin flip ratios

No theoretical predictions



Investigations on the static potential



Eichten and Feinberg, PRD23, 2724 (1981)

Spin-dependent potential as function of **long range** and **short rage** potentials

$$V_{LS}(\vec{r}) = \frac{1}{2m_b^2 r}\left(3\frac{dV_V}{dr} - \frac{dV_S}{dr}\right),$$

$$V_T(\vec{r}) = \frac{1}{6m_b^2}\left(\frac{d^2V_V}{dr^2} - \frac{1}{r}\frac{dV_S}{dr}\right),$$

$$V_{SS}(\vec{r}) = \frac{1}{3m_b^2}\nabla^2 V_V$$

P wave → Odd ψ(r) → |ψ(0)|² = 0

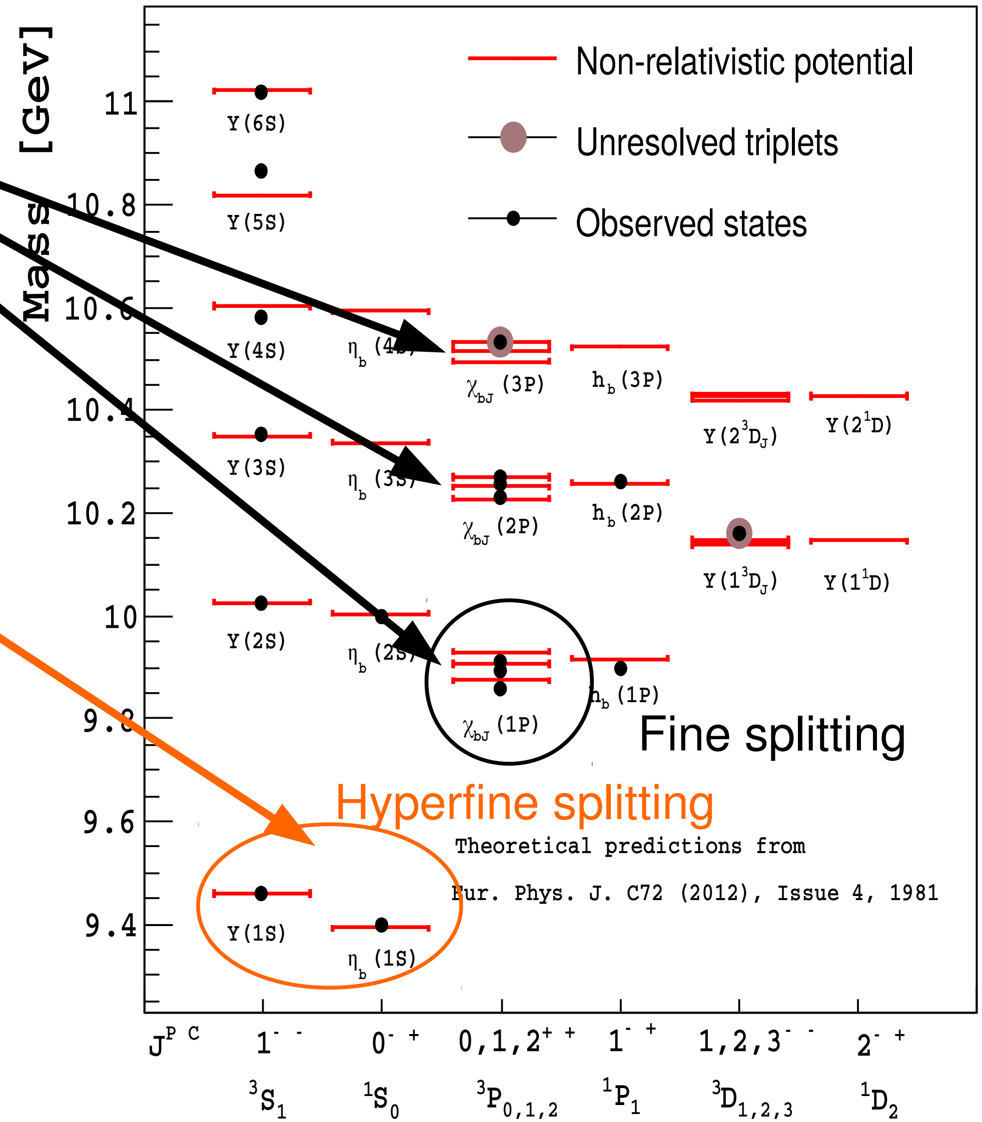
$\Delta M_{HF}(1P)$ = +0.8 ± 1.1 MeV/c² PDG

$\Delta M_{HF}(1P)$ = +0.6 ± 1.1 MeV/c² This work

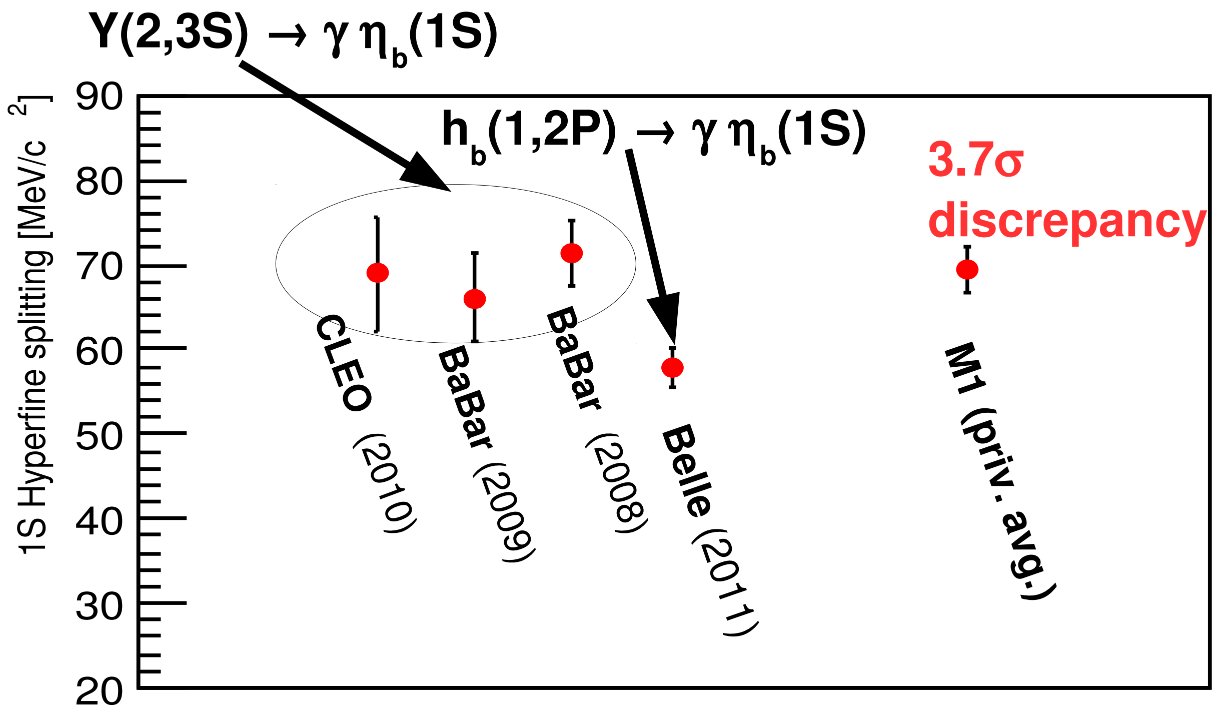
$\Delta M_{HF}(2P)$ = +0.5 ± 1.2 MeV/c² PDG

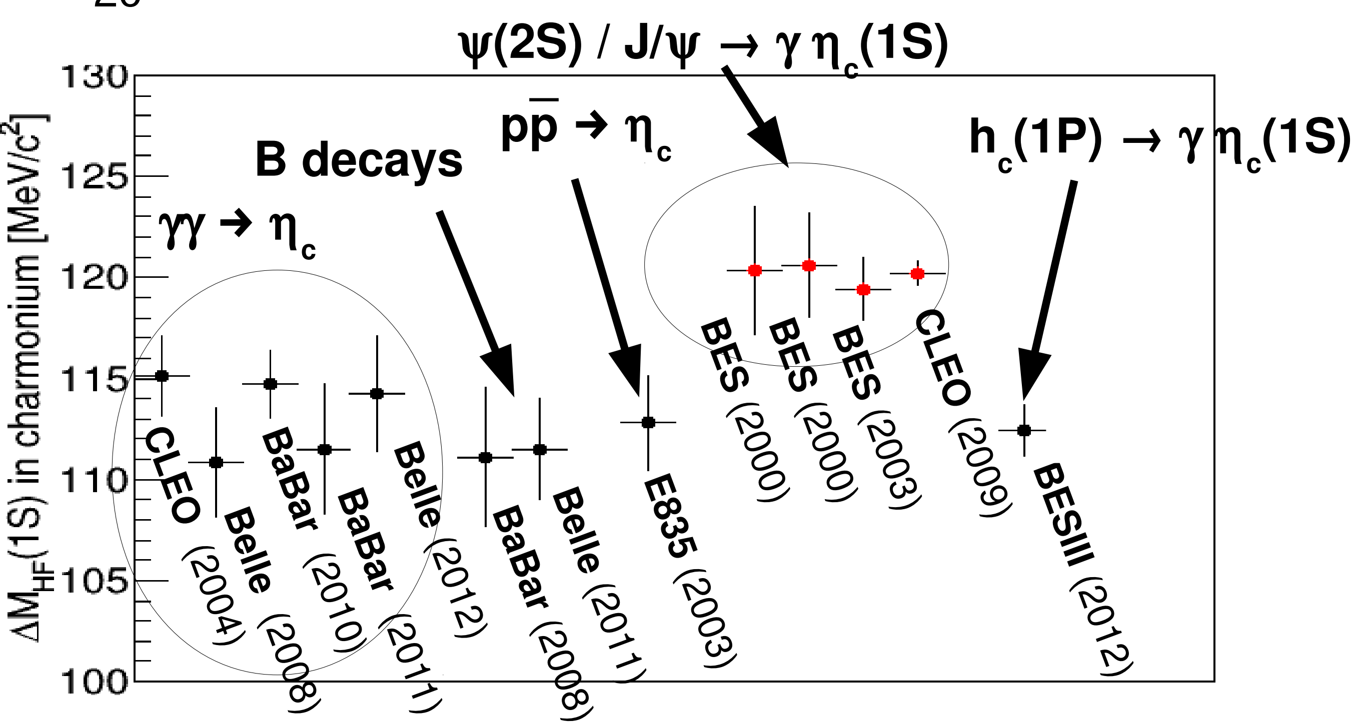
S wave → Even ψ(r) → |ψ(0)|² ≠0

$\Delta M_{HF}(1S)$ = 69.3 ± 2.8 MeV/c² PDG



1S HF puzzles



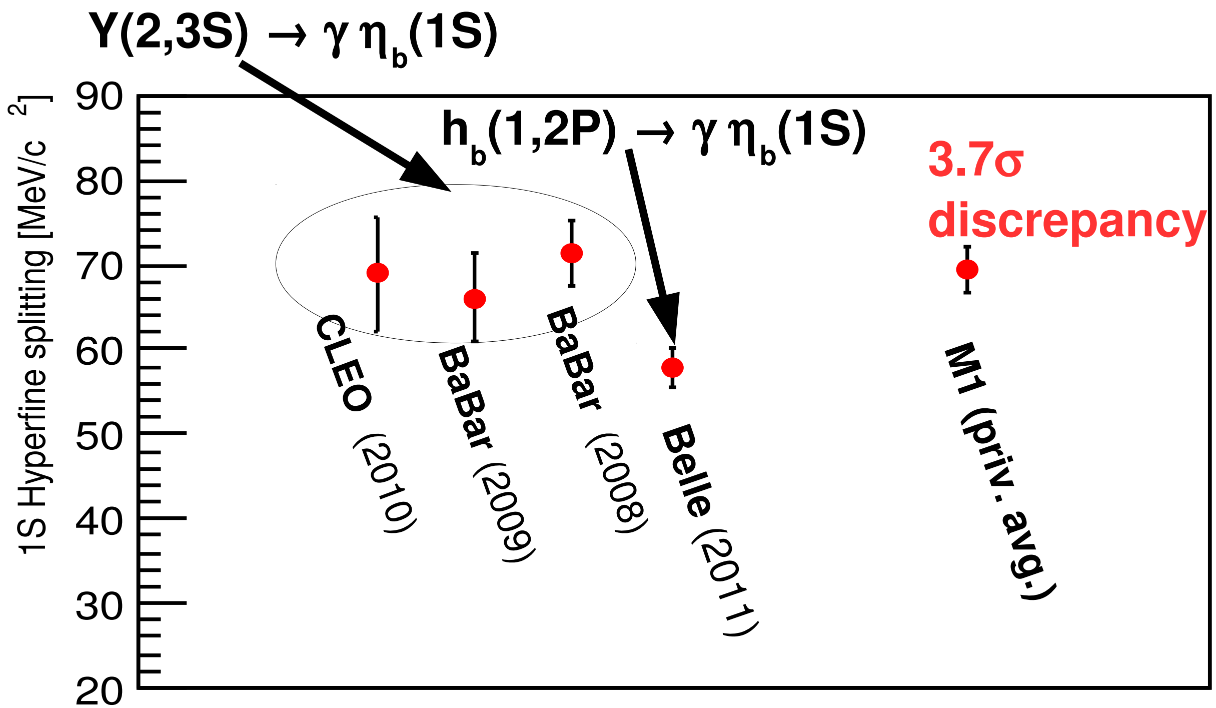


Measurements of the ground state HF in different channels gave different results

$M(\eta_b)_{M1} - M(\eta_b)_{E1} = -12 \pm 3$ MeV

$M(\eta_c)_{M1} - M(\eta_c)_{E1} = -7.7 \pm 1.4$ MeV

1S HF puzzles



In charmonium, the discrepancy is corrected introducing a form factor for the M1 transitions

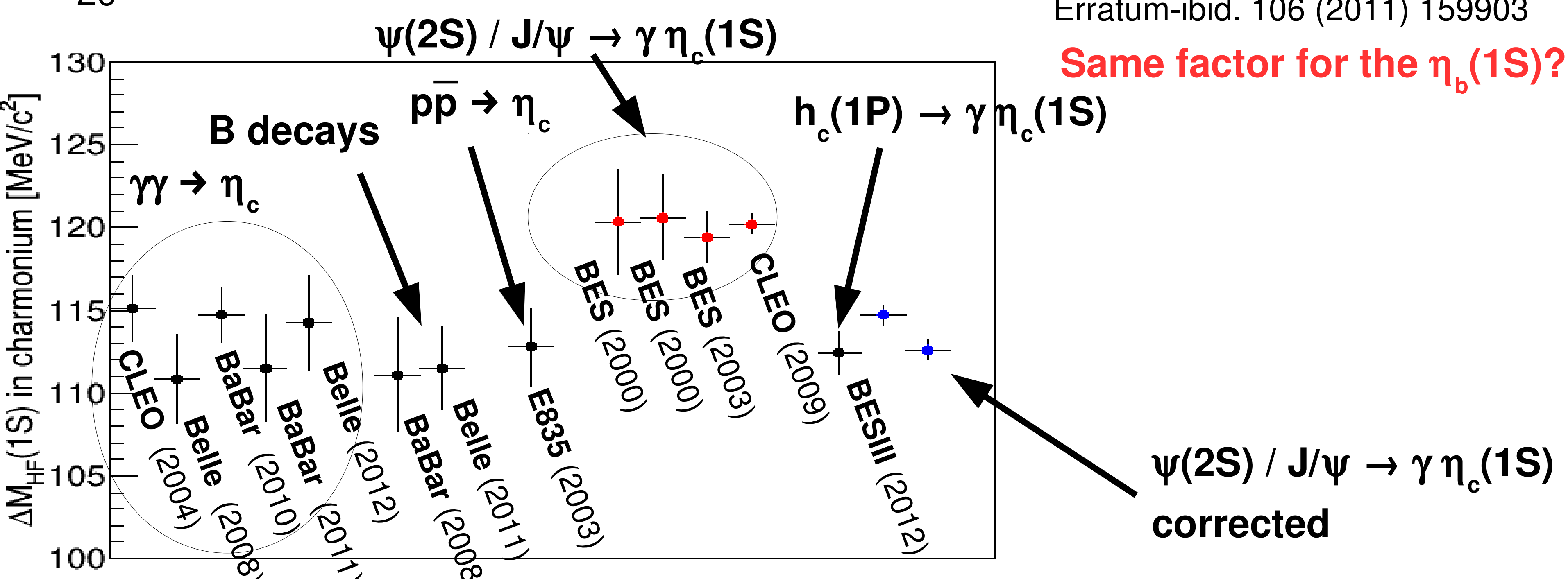
M(η_c)line shape factor:

$$E_\gamma^3 \exp\left(E_\gamma^{-2}/(8\beta^2)\right)$$

$\beta = 65 \pm 2.5$ MeV

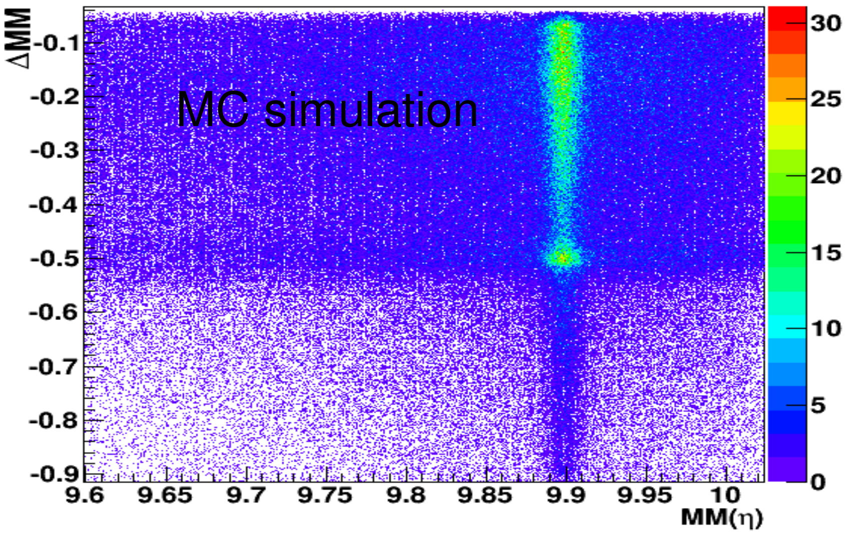
PRL 102 (2009) 011801,
Erratum-ibid. 106 (2011) 159903

Same factor for the $\eta_b(1S)$?



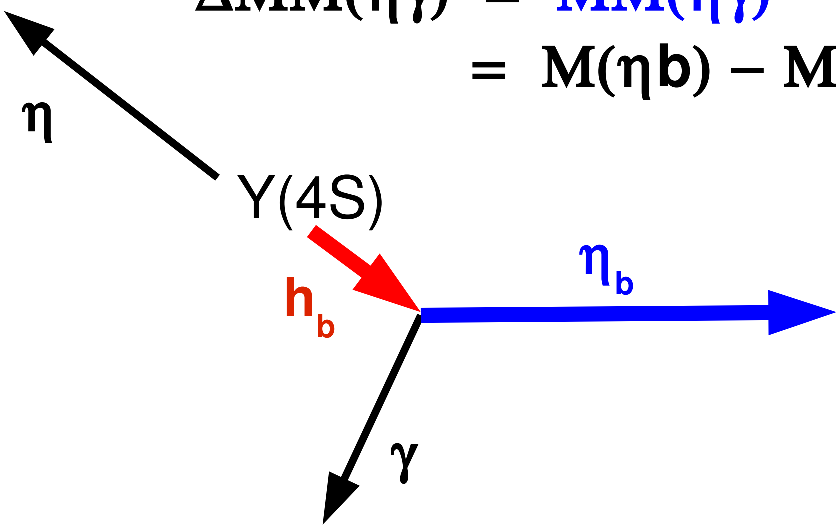
$\Upsilon(4S) \rightarrow \eta\, h_b(1P) \rightarrow \eta\, \gamma\, \eta_b(1S)$

arXiv:1506.08914

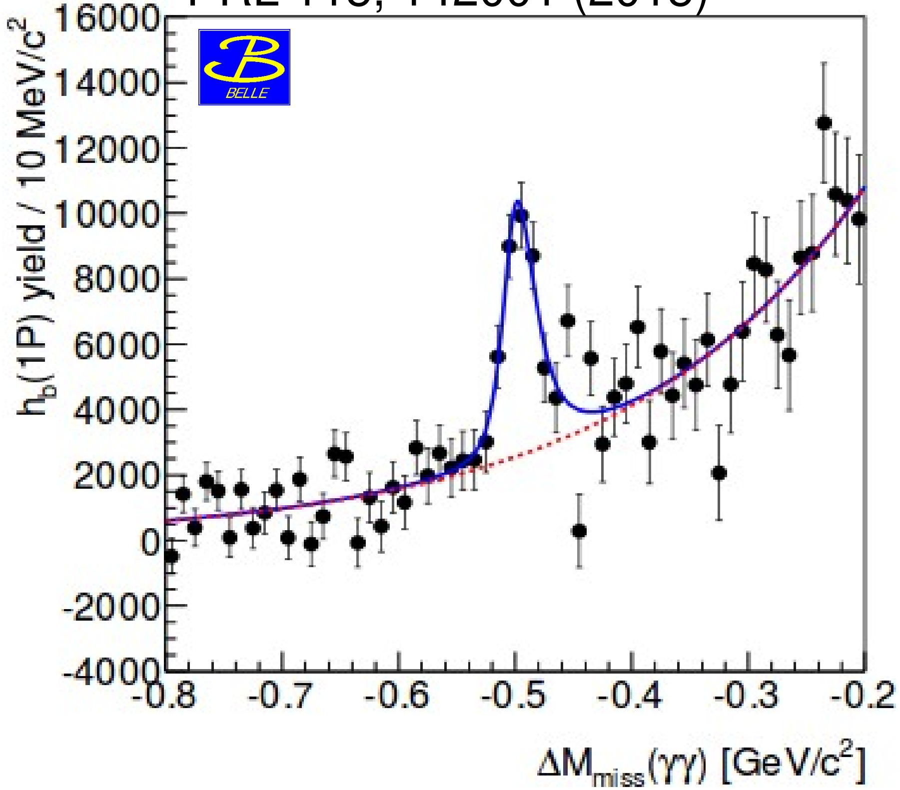


$\Delta MM(\eta\gamma) = MM(\eta\gamma) - MM(\eta)$

$= M(\eta b) - M(hb)$



PRL 115, 142001 (2015)



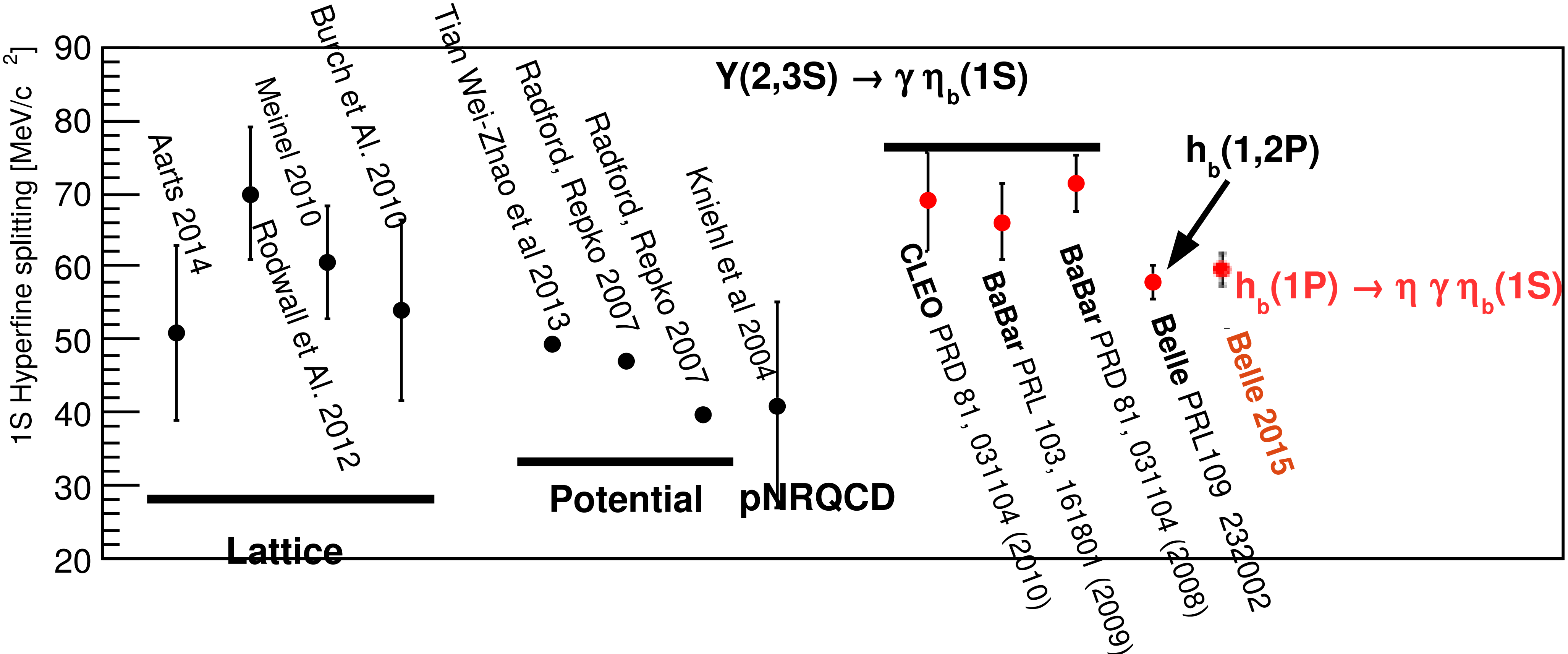
$M[\eta_b(1S)] - M[h_b(1S)] = (-498.6 \pm 1.7 \pm 1.2)$ MeV

$M[\eta_b(1S)] = (9400.7 \pm 1.7 \pm 1.6)$ MeV

$\Gamma[\eta b(1S)] = (8\,^{+6}_{-5} \pm 5)$ MeV

$BF[h_b(1P) \rightarrow \gamma\, \eta b(1S)] = (56 \pm 8 \pm 4)$ %

1S HF splitting theory VS experiment



Belle Υ(4S):

$\Delta M_{HF}(1S)$ = (+59.6 ± 1.7 ± 1.6) MeV

$\Delta M_{HF}(1P)$ = (+0.6 ± 0.4 ± 1.0) MeV

Belle Υ(5S):

$\Delta M_{HF}(1S)$ = (+57.9 ± 2.3) MeV

$\Delta M_{HF}(1P)$ = (+0.8 ± 1.1) MeV

Summary

First observation of Υ(4S) → η h_b(1P)

First study of Υ(5S) → η h_b(1P) **Preliminary**

→ No evidences, but upper limits allows to increase our knowledge of the spin flipping transitions pattern

Updated parameters of η_b(1S)

→ Line shape factor as in charmonium?

Fine-graned R_b and $R_{\pi\pi}$ scan

→ Evidence of Υ(6S) → ππ Υ(nS)

→ Can Υ(5S) – Yb difference be due to interference with non-flat continuum ?

Rππ scan with ππhb(nP)

→ First evidence of Υ(6S) → ππ hb(1P,2P)

BelleII

50 ab^{-1} Υ(4S) → ~ 100 millions h_b(1P) via η transitions (untagged)

Backup

Heavy quark spin symmetry tests

η/ππ transitions to spin singlets (first study)

$$\frac{\Gamma[Y(5S)\to\eta h_b(1P)]}{\Gamma[Y(5S)\to\pi\pi h_b(1P)]}<0.94$$

$$\frac{\Gamma[Y(5S)\to\eta h_b(2P)]}{\Gamma[Y(5S)\to\pi\pi h_b(2P)]}<0.62$$

Spin flip / spin flip ratios
No theoretical predictions

Results on transition
Y(5S) → ππ Y(1D)
is **estimated** on published data

$$\frac{\Gamma[Y(4S)\to\eta h_b(1P)]}{\Gamma[Y(4S)\to\pi\pi h_b(1P)]}>5.4$$

Assuming BF[Y(4S)→ππ h_b(1P)] =< 0.4 x10^{-3}
Same behavior as in the Y(4S) → Y(1S) transitions

η/η and ππ/ππ ratios compared

$$\frac{\Gamma[Y(5S)\to\eta Y(1D)]}{\Gamma[Y(5S)\to\eta h_b(1P)]}>0.92$$

$$\frac{\Gamma[Y(5S)\to\eta Y(1D)]}{\Gamma[Y(5S)\to\eta h_b(2P)]}>0.78$$

$$\frac{\Gamma[Y(5S)\to\eta Y(1D)]}{\Gamma[Y(5S)\to\eta Y(2S)]}=1.6\pm0.7$$

Spin flip / spin flip. Theory?

Non spin flip / spin flip

$$\frac{\Gamma[Y(5S)\to\pi\pi Y(1D)]}{\Gamma[Y(5S)\to\pi\pi h_b(1P)]}\approx0.5$$

$$\frac{\Gamma[Y(5S)\to\pi\pi Y(1D)]}{\Gamma[Y(5S)\to\pi\pi h_b(2P)]}\approx0.3$$

Expected to be small in HQSS

$$\frac{\Gamma[Y(5S)\to\pi\pi Y(1D)]}{\Gamma[Y(5S)\to\pi\pi Y(2S)]}\approx0.3$$

Non spin flip / non spin flip

Opposite behavior between ππ and η

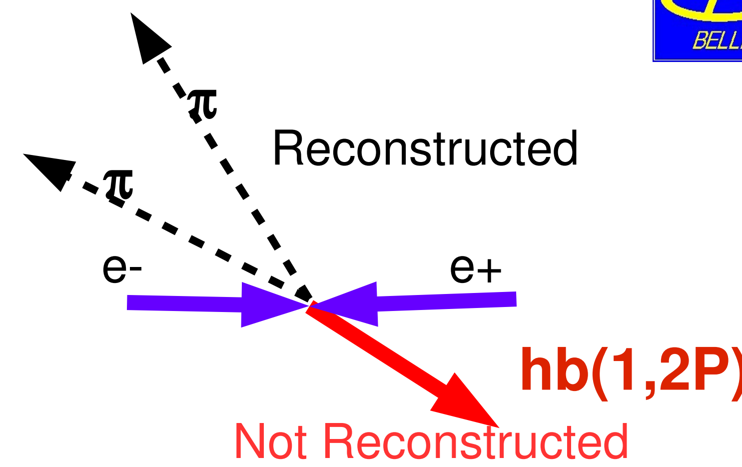
Rππ with hb(1,2P)

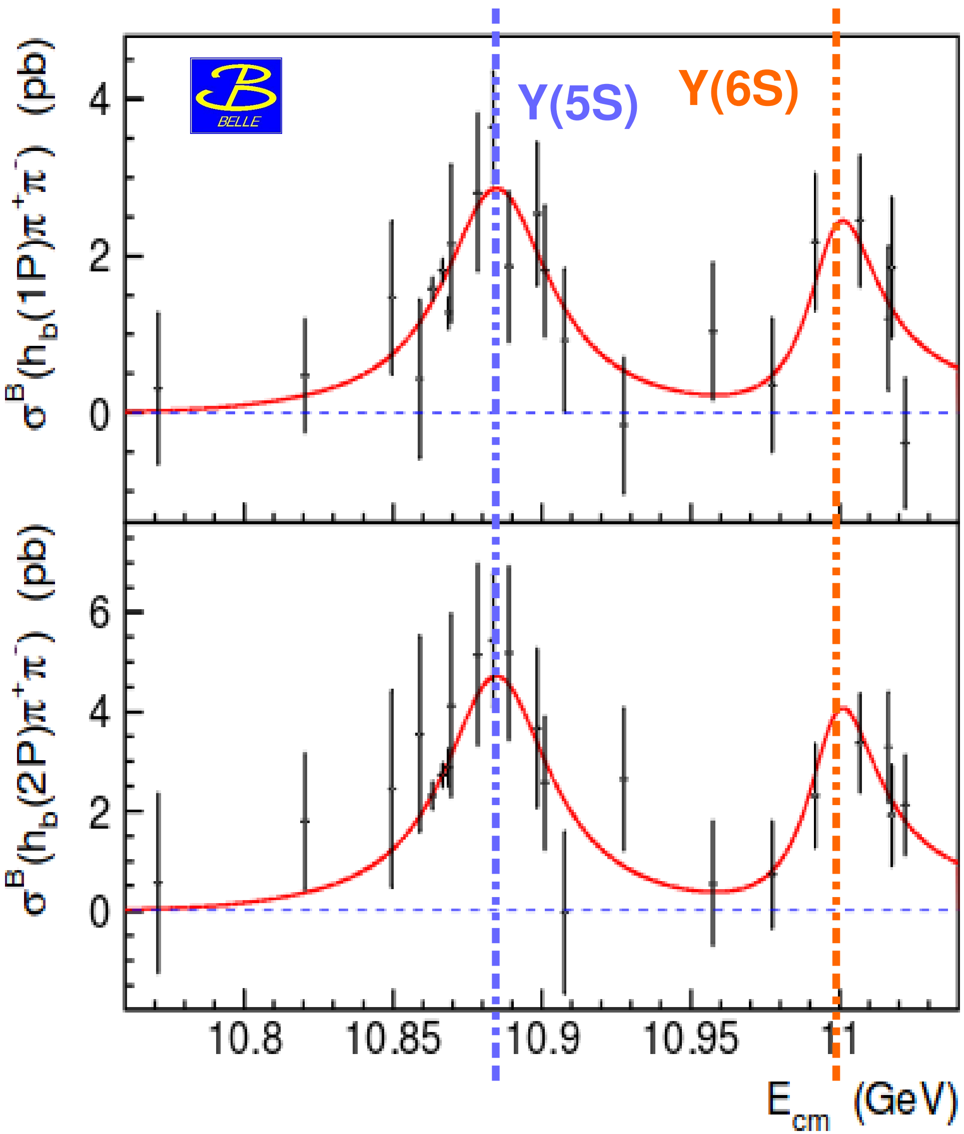
ArXiv:1508.06562

Y(5S) → ππ hb(1P) was observed.

→ does it behave like ππY(nS)?

→ what about the Y(6S)?





Y(6S) → ππ hb(1P, 2P)

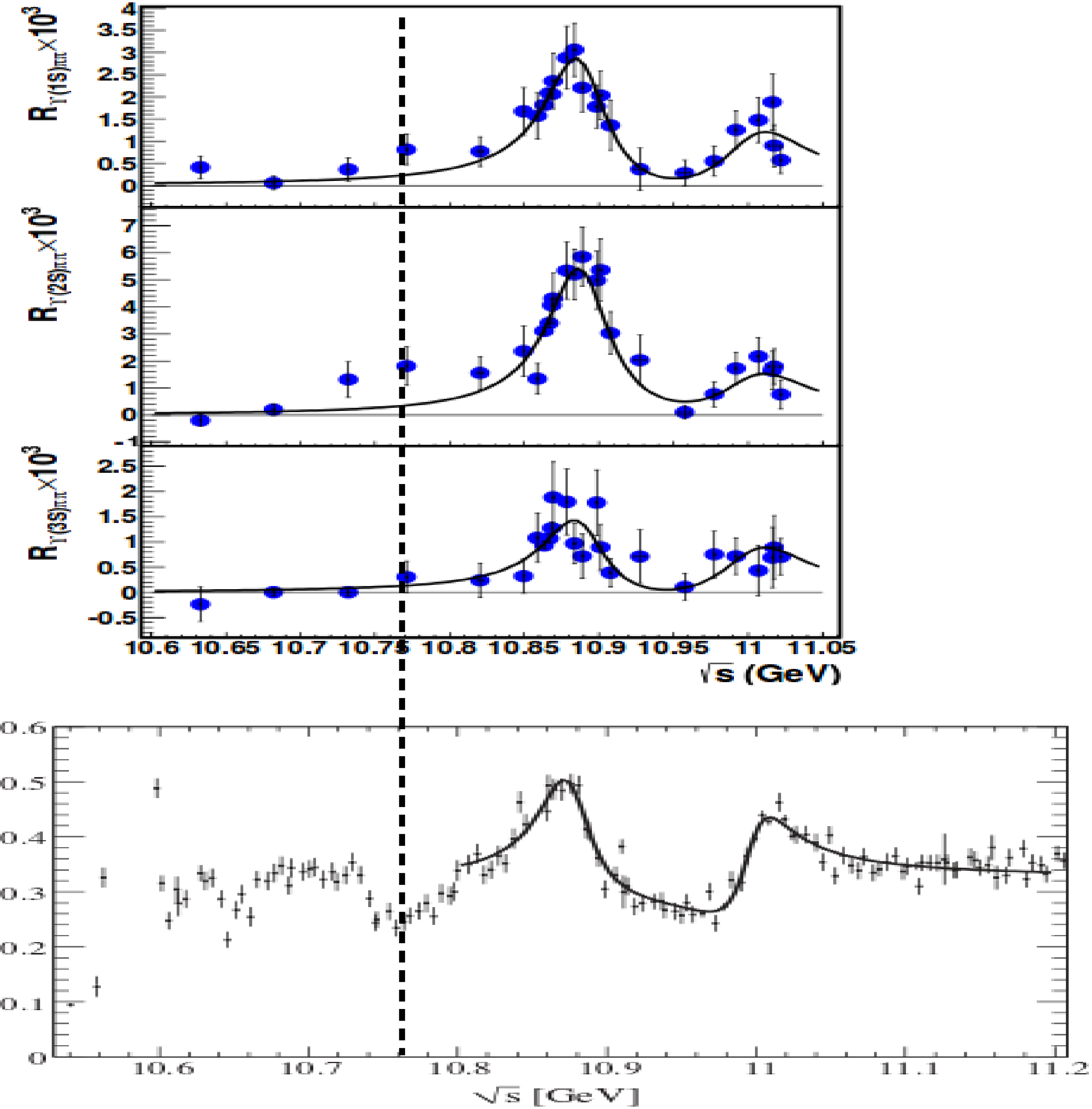
→ First Evidence!

Fit model:

$$A_n\ f(s)\ |BW(s, M_5, \Gamma_5) + a\, e^{i\,\phi} BW(s, M_6, \Gamma_6) + b\, e^{i\,\delta}|^2$$

Parameter	Default model	$\Upsilon(nS)\pi^+\pi^-$ analysis
M_5 , MeV$/c^2$	$10884.7^{+3.2\,+8.6}_{-2.9\,-0.6}$	$10891.1 \pm 3.2^{+0.5}_{-1.5}$
Γ_5 , MeV	$44.2^{+11.9\,+2.2}_{-7.8\,\ -15.8}$	$53.7^{+7.1\,+0.9}_{-5.6\,-5.4}$
M_6 , MeV$/c^2$	$10998.6 \pm 6.1^{+16.1}_{-1.1}$	$10987.5^{+6.4\,+9.0}_{-2.5\,-2.1}$
Γ_6 , MeV	$29^{+20\,+2}_{-12\,-7}$	$61^{+9\ \,+2}_{-19\,-20}$
$A_1/10^3$	$4.8^{+2.7}_{-0.8}$	
$A_2/10^3$	$8.0^{+4.6}_{-1.3}$	
a	$0.64^{+0.37\,+0.13}_{-0.11\,-0}$	
(ϕ/π)	$0.1^{+0.3}_{-0.5}$	
$\sigma^B(h_b(1P))$, fb	$1606 \pm 90 \pm 95$	
$\sigma^B(h_b(2P))$, fb	$2605 \pm 164^{+169}_{-193}$	

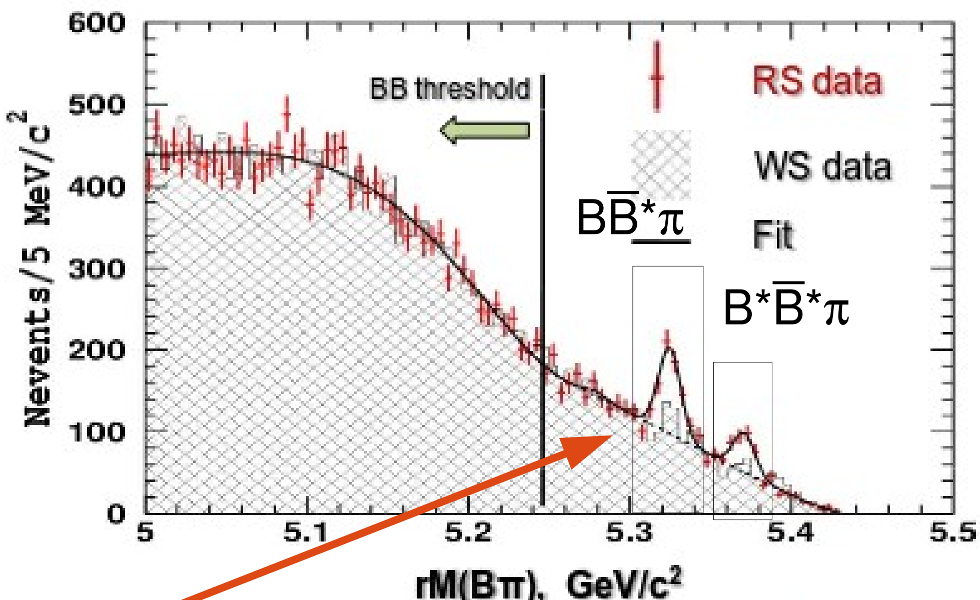
$R\pi\pi$ VS Rb

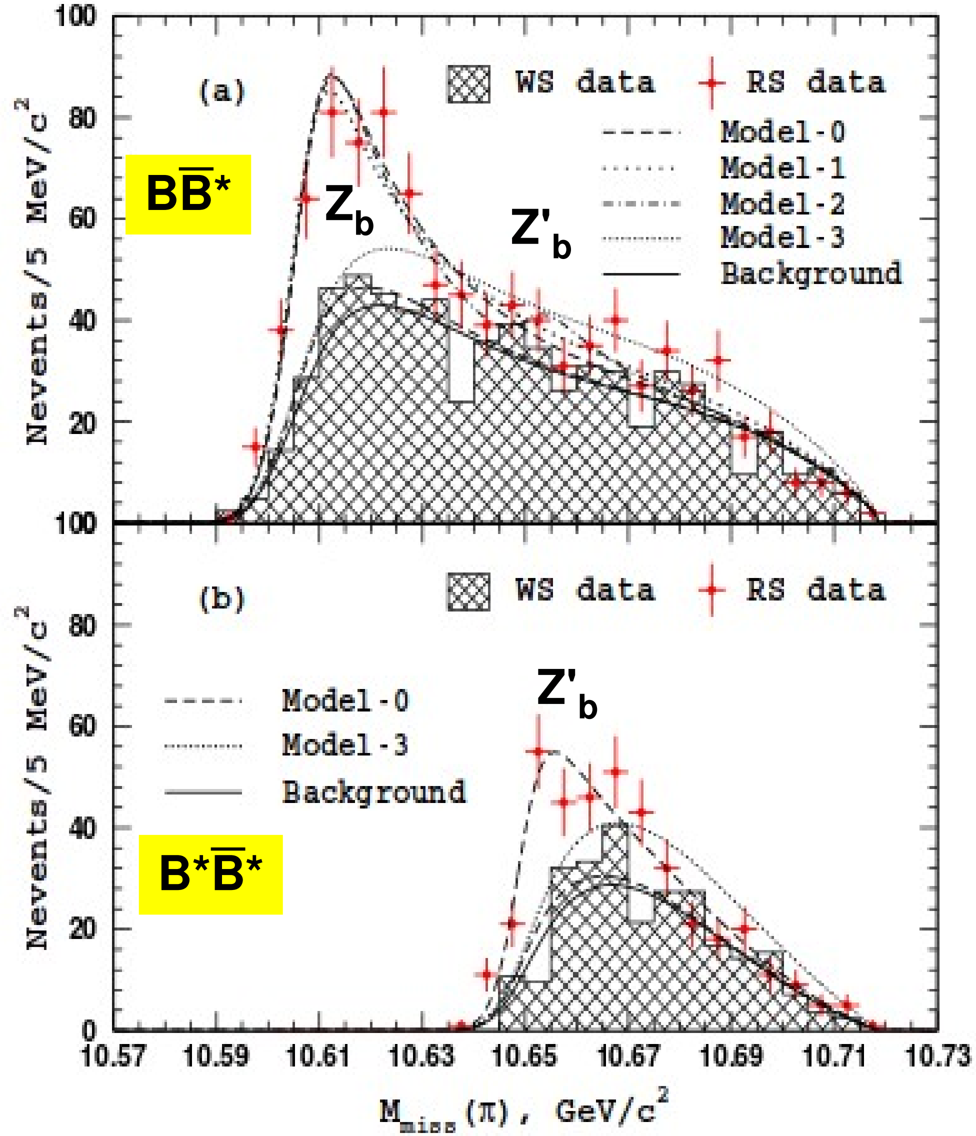


$R_{\Upsilon(1S)\pi\pi} \times 10^3$
$R_{\Upsilon(2S)\pi\pi} \times 10^3$
$R_{\Upsilon(3S)\pi\pi} \times 10^3$
10.6 10.65 10.7 10.75 10.8 10.85 10.9 10.95 11 11.05
$\sqrt{s}$ (GeV)
10.6 10.7 10.8 10.9 11 11.1 11.2
$\sqrt{s}$ [GeV]

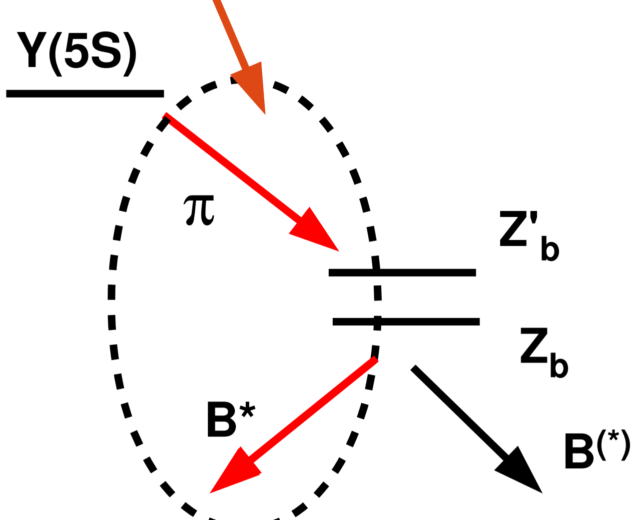
Z_b decay modes

Preliminary





Recoil mass from $B^*\pi$ system tags the other B

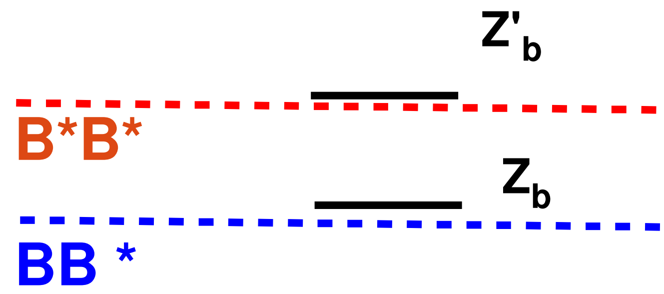


Z_b decay modes

preliminary

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.60 \pm 0.17 \pm 0.07$	$0.17 \pm 0.06 \pm 0.02$
$\Upsilon(2S)\pi^+$	$4.05 \pm 0.81 \pm 0.58$	$1.38 \pm 0.45 \pm 0.21$
$\Upsilon(3S)\pi^+$	$2.40 \pm 0.58 \pm 0.36$	$1.62 \pm 0.50 \pm 0.24$
$h_b(1P)\pi^+$	$4.26 \pm 1.28 \pm 1.10$	$9.23 \pm 2.88 \pm 2.28$
$h_b(2P)\pi^+$	$6.08 \pm 2.15 \pm 1.63$	$17.0 \pm 3.74 \pm 4.1$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$82.6 \pm 2.9 \pm 2.3$	–
$B^{*+}\bar{B}^{*0}$	–	$70.6 \pm 4.9 \pm 4.4$

From inclusive Y(5S) → $\pi^+\pi^-$ +X decays



Kinematically favoured but absent

Why Z_b(10650) should not decay in BB* ?

Molecular Model

Z_b ~ | BB *>

Z'_b ~ |B*B* > with negligible |BB*> component

Proximity to open threshold ✓

Γ(open flavour) >> Γ(narrow quarkonium) ✓

HQSS above the threshold

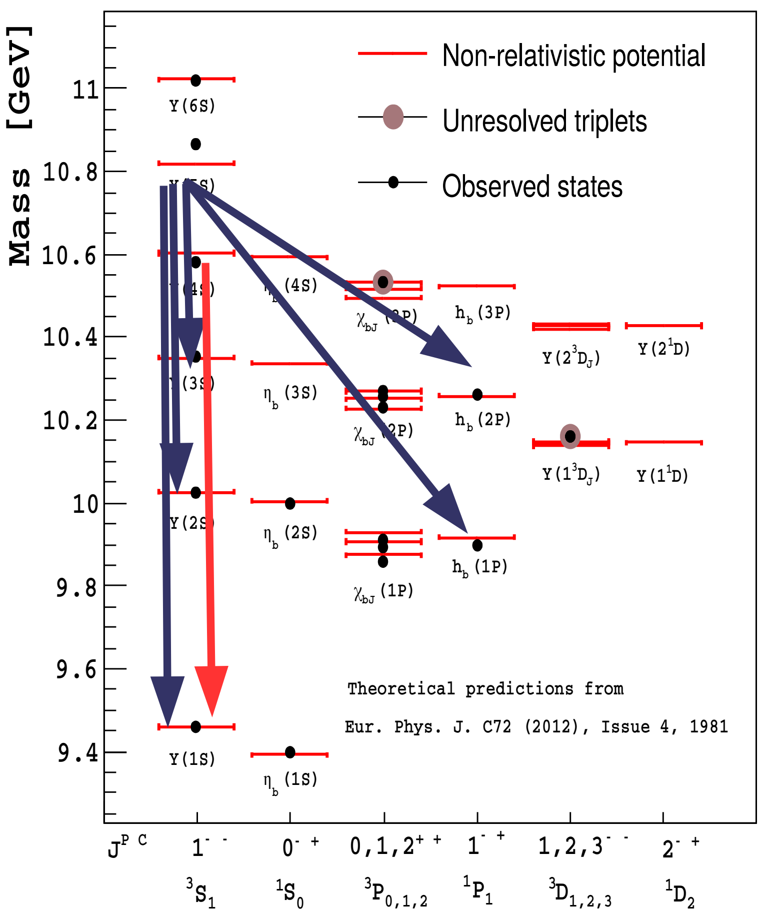
Heavy Quark Spin Symmetry predicts:

b quark spin flip

$$\frac{\Gamma[Y(nS)\to\eta Y(mS)]}{\Gamma[Y(nS)\to\pi\pi Y(mS)]}\ll 1$$

no b quark spin flip

$$\frac{\Gamma[Y(nS)\to\pi\pi h_b(mP)]}{\Gamma[Y(nS)\to\pi\pi Y(mS)]}\ll 1$$



Y(5S): no spin flip suppression

$$\frac{\Gamma[Y(5S)\to\pi\pi h_b(2P)]}{\Gamma[Y(5S)\to\pi\pi Y(2S)]}=0.77\pm0.08^{+0.22}_{-0.17}$$

$$\frac{\Gamma[Y(5S)\to\pi\pi h_b(1P)]}{\Gamma[Y(5S)\to\pi\pi Y(2S)]}=0.46\pm0.08^{+0.07}_{-0.12}$$

PRL108, 122001

$$\frac{\Gamma[Y(5S)\to\eta Y(1S)]}{\Gamma[Y(5S)\to\pi\pi Y(1S)]}=0.16$$

$$\frac{\Gamma[Y(5S)\to\eta Y(2S)]}{\Gamma[Y(5S)\to\pi\pi Y(2S)]}=0.48$$

Belle preliminary

Y(4S): spin flip enhancement

$$\frac{\Gamma[Y(4S)\to\eta Y(1S)]}{\Gamma[Y(4S)\to\pi\pi Y(1S)]}=2.41\pm0.40\pm0.20$$

PRD 78, 112002

Spin-flipping transition is enhanced for transitions across the threshold

→ should QCDME fail so badly?

→ large η transitions:
  source of SU(3) violation?

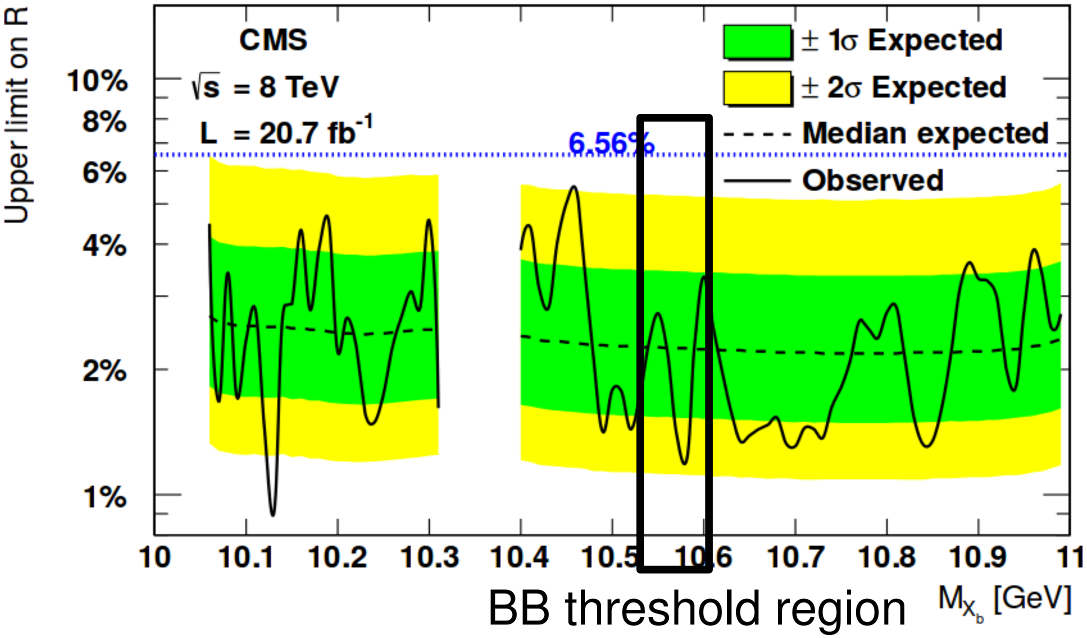
→ Why enhancement at Y(4S)?

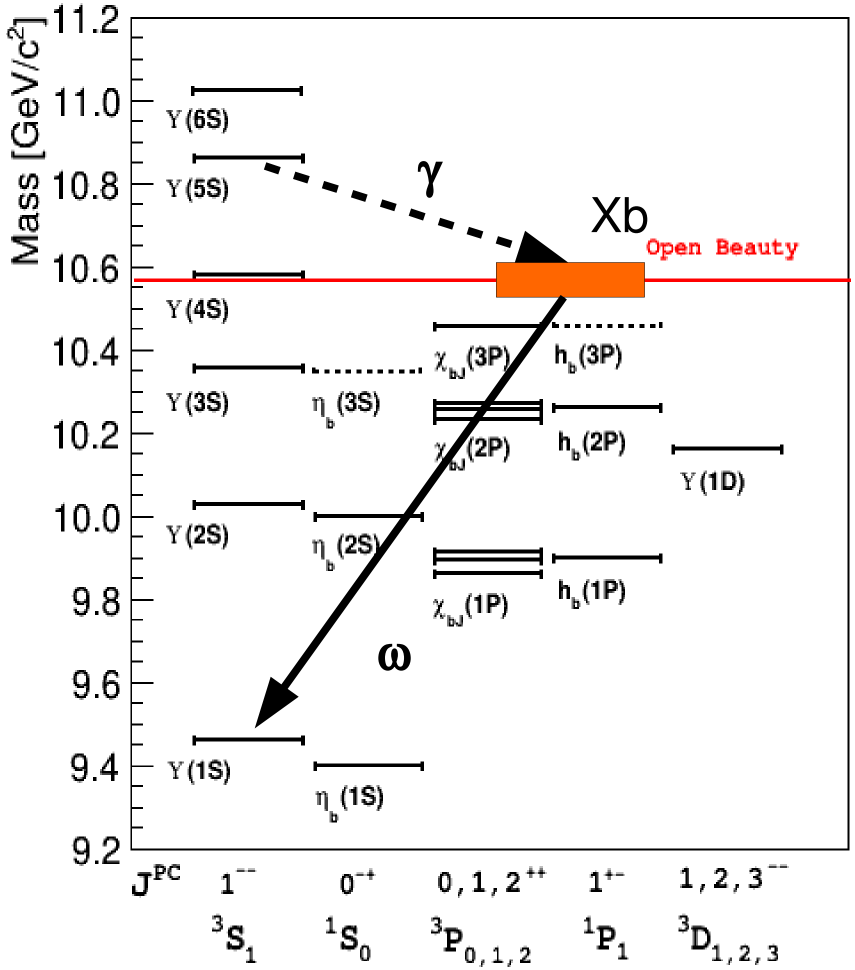
Other exotics in Y(5S) transitions?

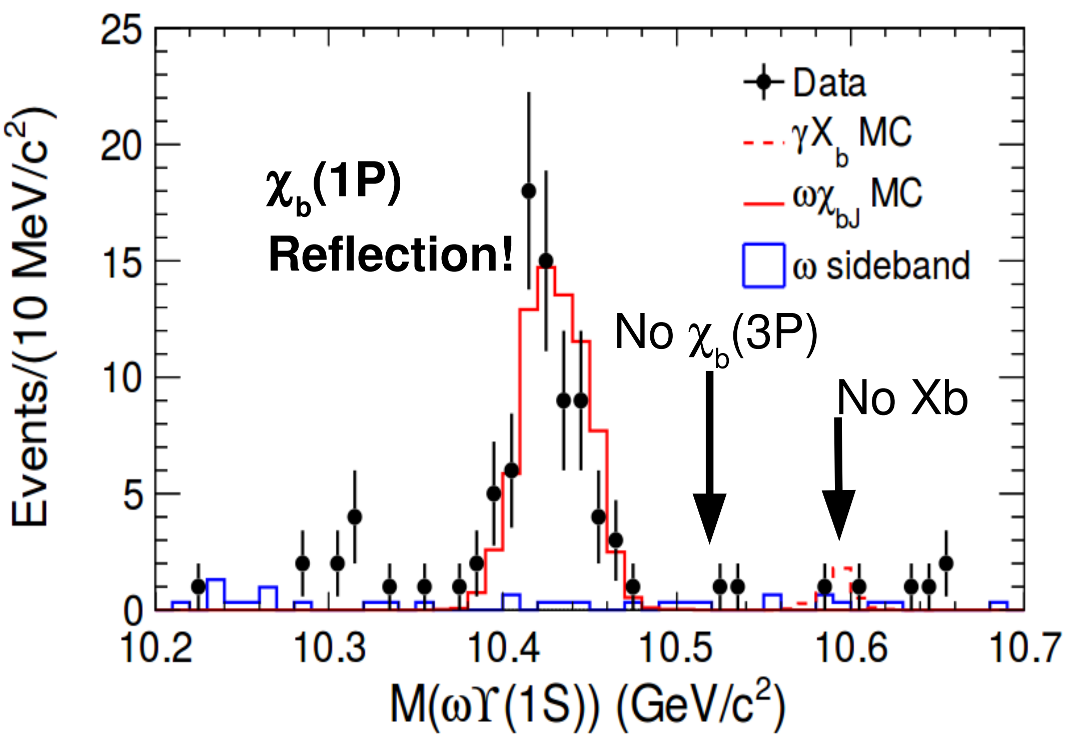
Bottomonium equivalent of X(3872)

CMS: inclusive search for PLB 727 (2013) 57
Xb → ππ Y(1S) in pp collisions

Belle: exclusive Y(5S) decay
Y(5S) → γ Xb → γ ω Y(1S) arXiv:1408.0504







$\Upsilon(5S) \to \omega\, \chi_b(1P)$

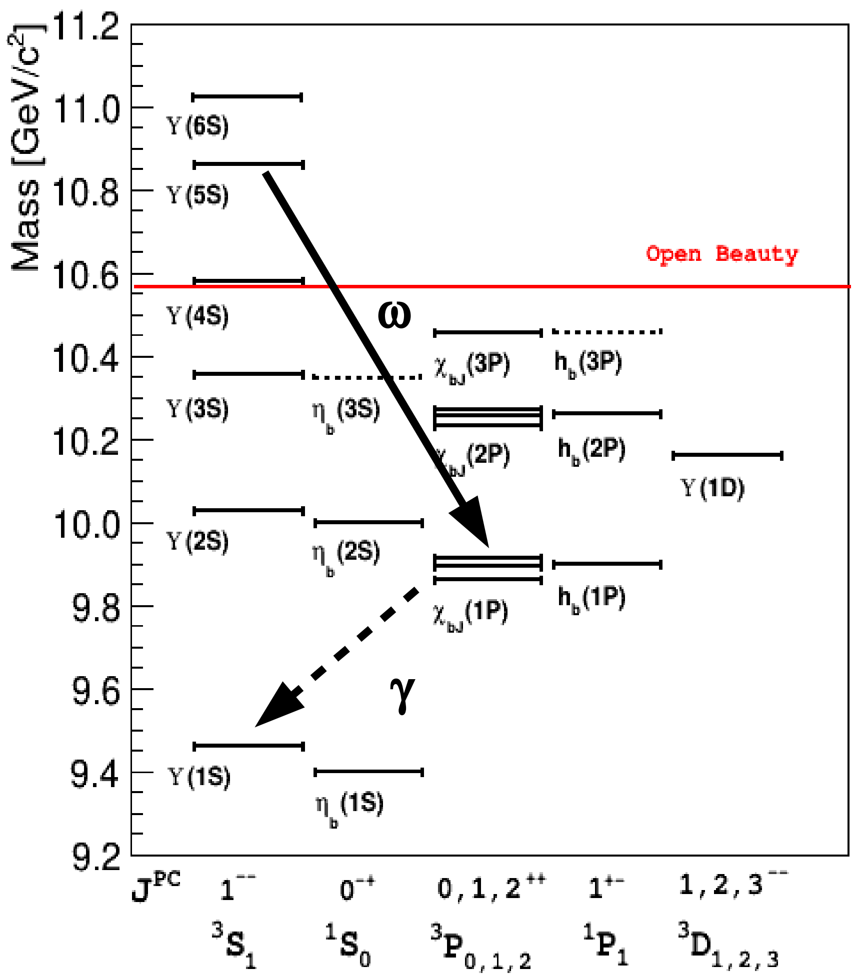
arXiv:1408.0504

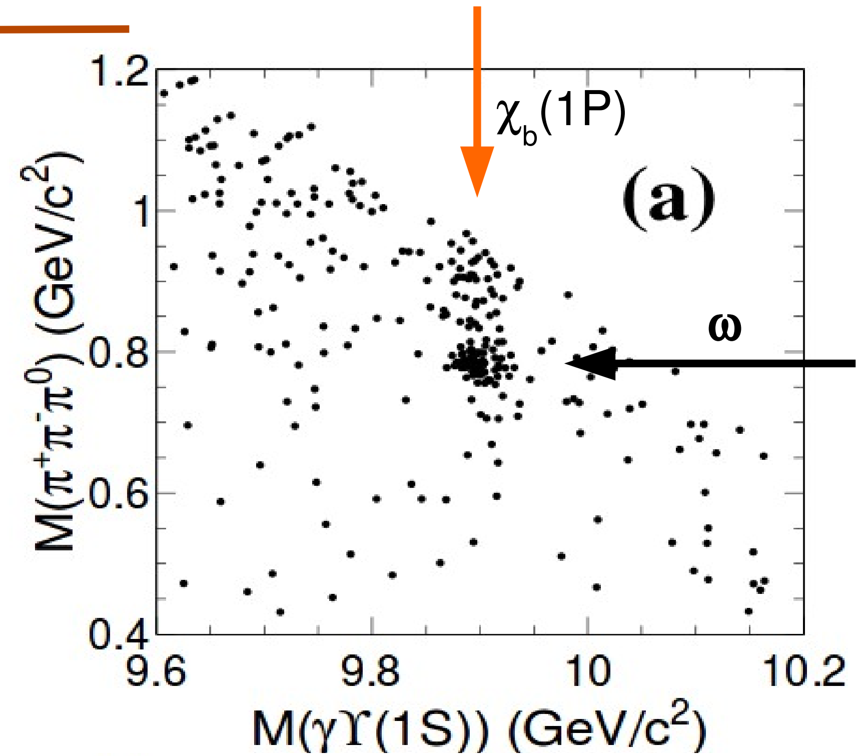
$B[\Upsilon(5S) \to \omega\, \chi_{b0}(1P)] < 3.9 \times 10^{-3}$

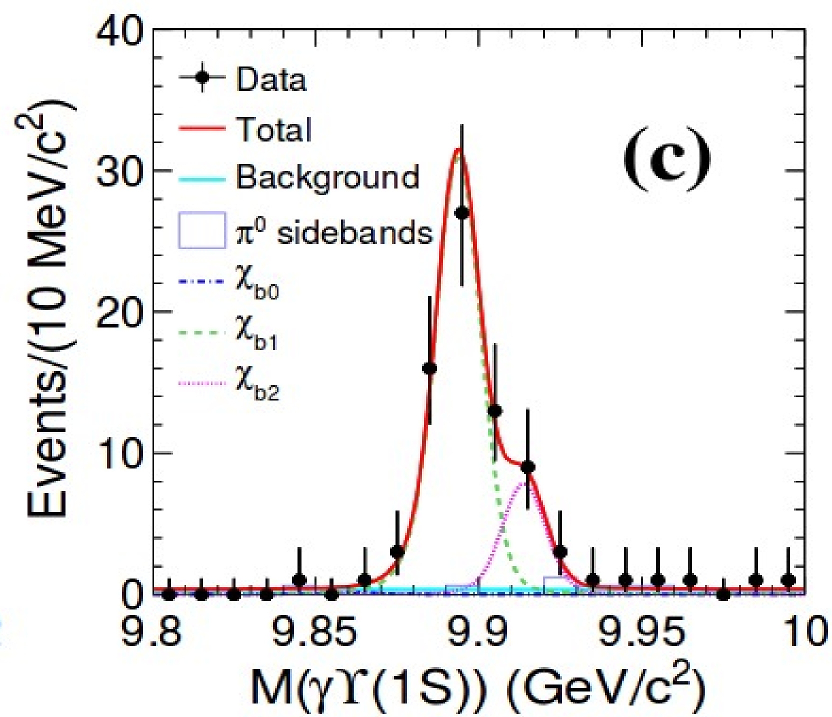
$B[\Upsilon(5S) \to \omega\, \chi_{b1}(1P)] = 1.57 \pm 0.22 \pm 0.21 \times 10^{-3}$

$B[\Upsilon(5S) \to \omega\, \chi_{b2}(1P)] = 0.60 \pm 0.23 \pm 0.15 \times 10^{-3}$

$B[\Upsilon(5S) \to \gamma X_b \to \gamma\omega\, \Upsilon(1S)] < 2.6 - 3.8 \times 10^{-5}$







Rb versus $R\pi\pi$

Rb an $R\pi\pi$ are not independent
→ Rb includes contribution form $\pi\pi Y(nS)$
→ Rb includes contribution form $\pi\pi h_b(nP)$

$Pb = |A_{5S}(b\bar{b}) \times BW(5S)|^2$ — **$b\bar{b}$ contribution**

$P(\pi^+\pi^-\ nS) = PHSP \times |A_{5S}(nS) \times BW(5S)|^2$ — **$Y(nS)\pi\pi$ contribution**

From $R\pi\pi$: $\sum P(\pi^+\pi^-\ nS) = (20 \pm 6)$ % of Pb

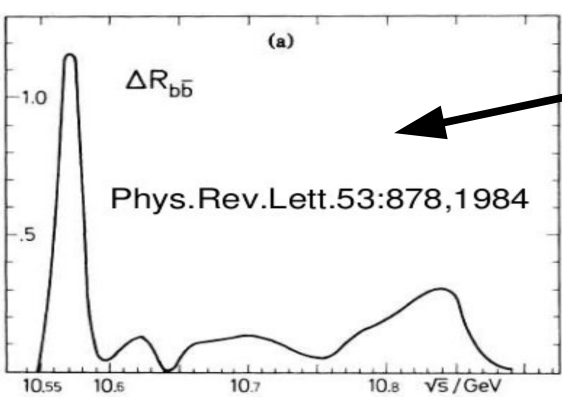
Adding $Y(5S) \to \pi\pi\ h_b(1,2P)$: $\sum P(\pi^+\pi^-\ b\bar{b}) = (33 \pm 7.5)$ % of Pb

Assuming Isospin simmetry: $\sum P(\pi\pi\ b\bar{b}) = (50 \pm 14)$ % of Pb

Adding $Z_b \to \pi B^{(*)}\bar{B}^{(*)}$: $\sum P(\pi\pi\ b\bar{b} + \pi Zb) = (132 \pm 36)$ % of Pb

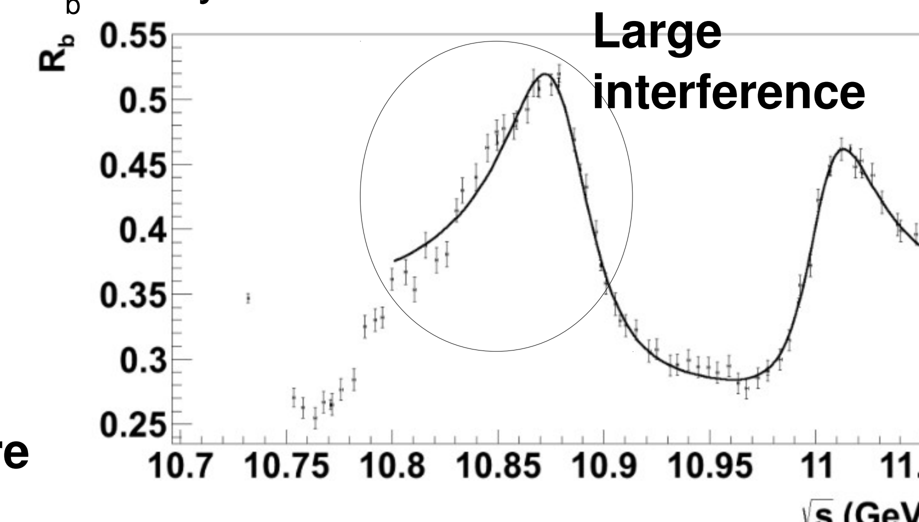
No or little room for $Y(5S) \to BB^*$, BB, B^*B^*, B_sB_s direct decays

→ these events come either from continuum, or from Z_b decay
→ **Small interference between Y(5S) and continuum (different final states)**

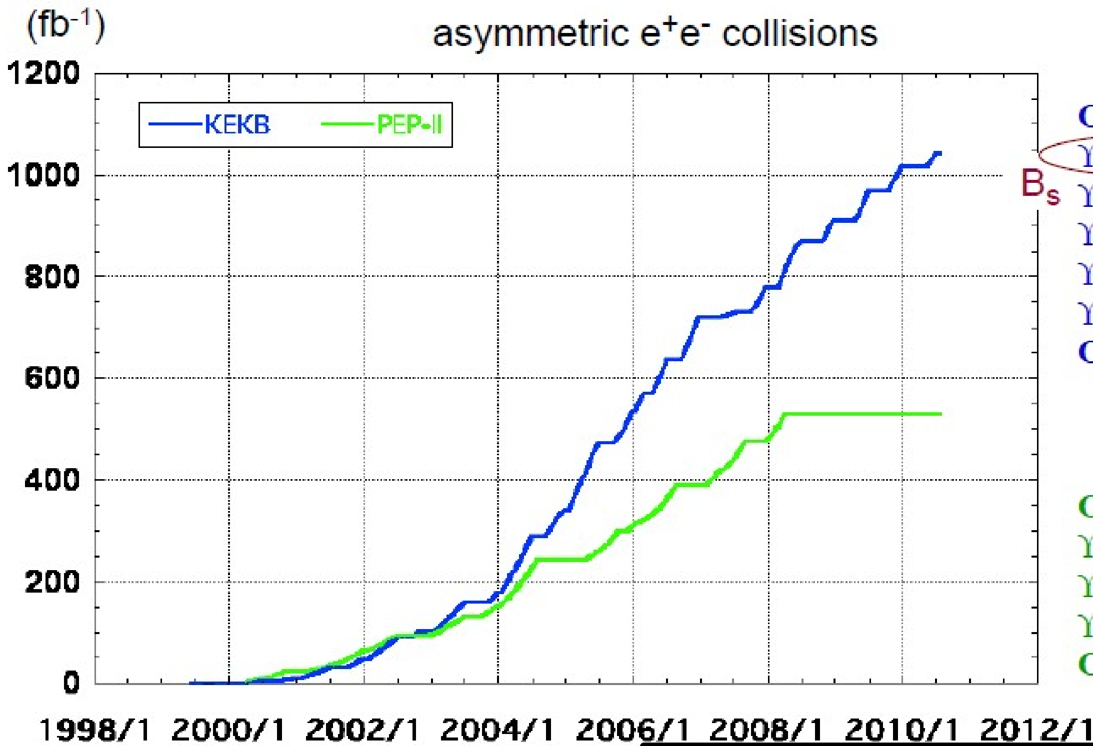


Flat continuum is a crude approximation

Resonance parameters from $R\pi\pi$ are likely more reliable



The first B-Factory generation



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 24 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan :

~100 fb-1

530 fb^{-1}

On resonance:

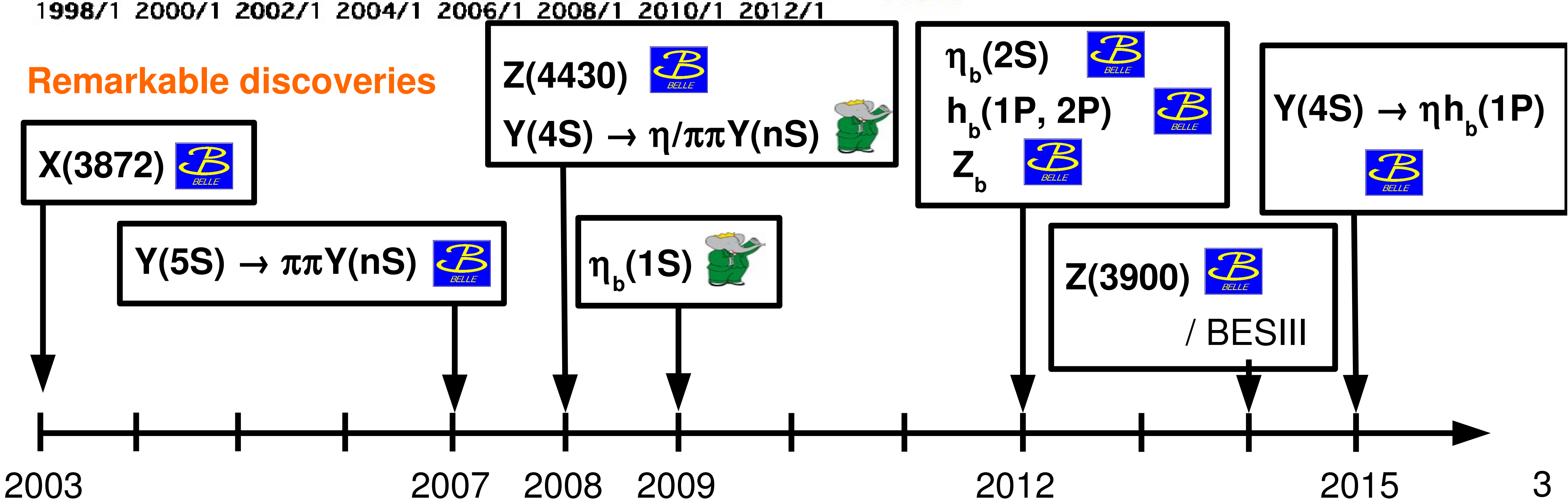
$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off reson./scan :

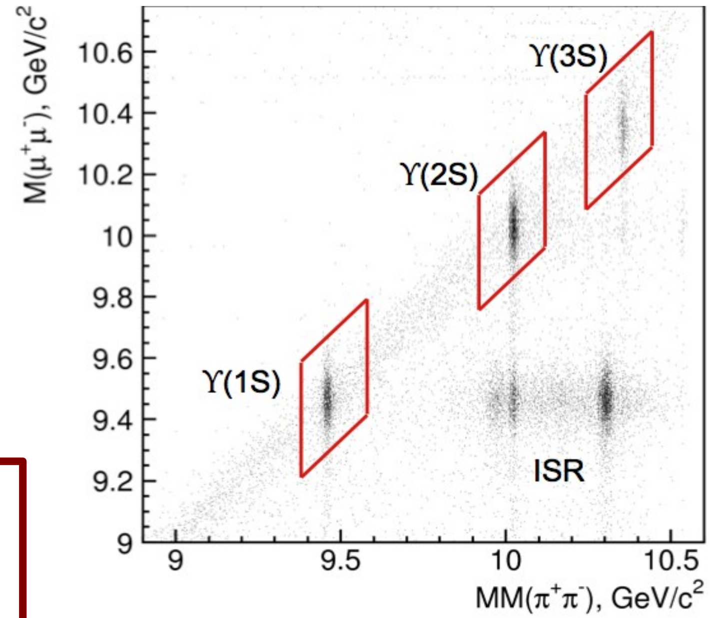
~54 fb-1

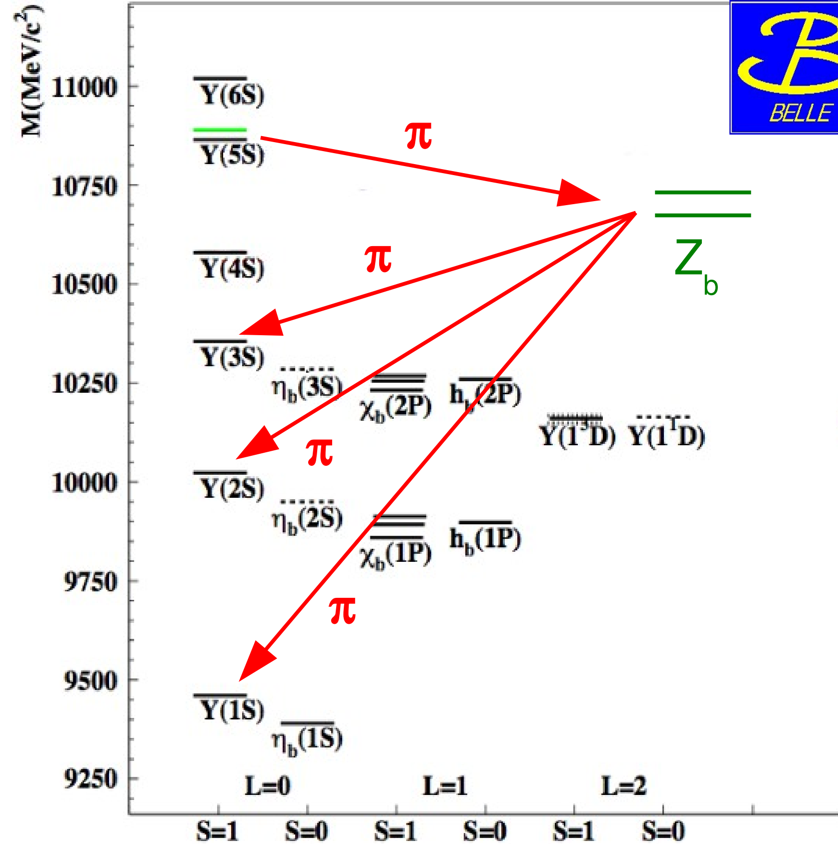


Z_b in $\Upsilon(nS)$ final states

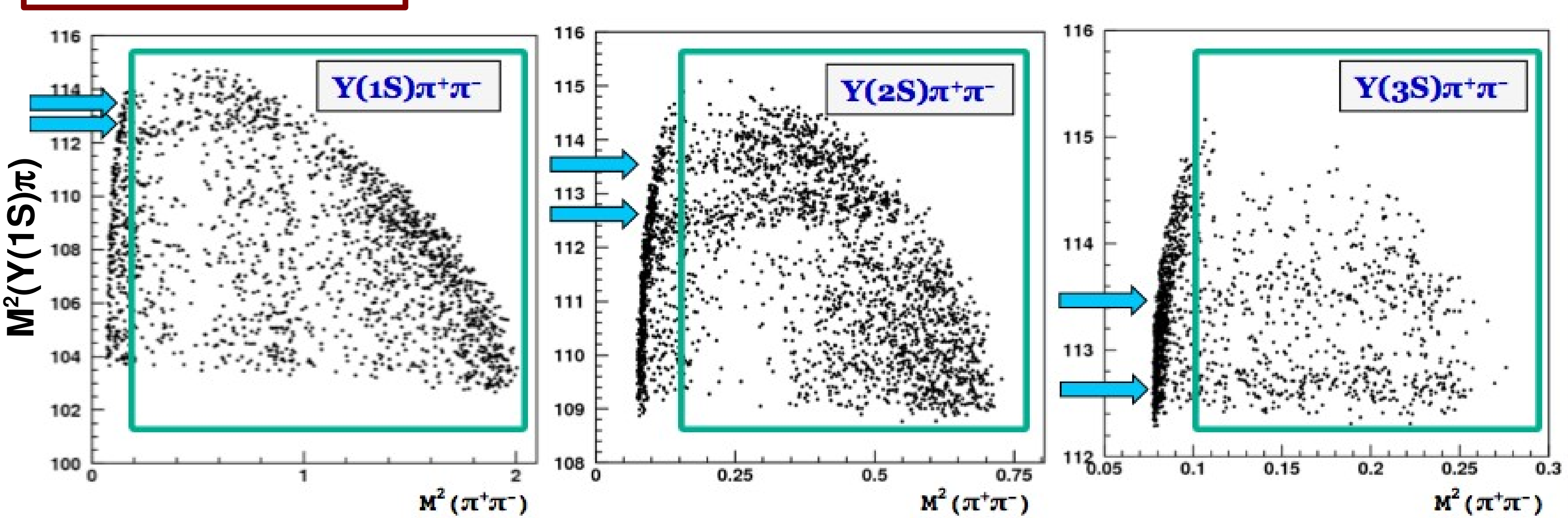
PRL108,122001

$\Upsilon(nS) \rightarrow \mu^+\mu^-$
- Clean final state
- Pure $\Upsilon(nS)$ sample
- $\pi^+\pi^-$ recoil tag



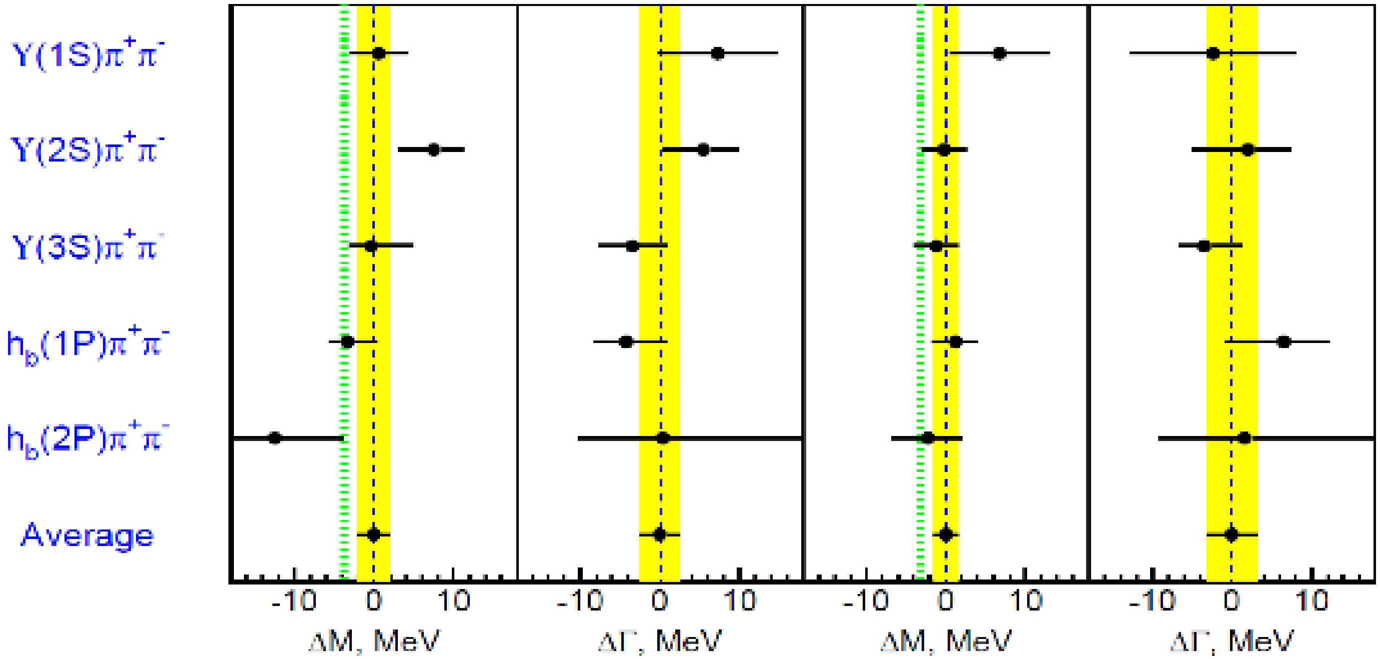


3 other observation of Z_b's !



Z_b Summary

PRL108,122001



Mass and Γ measured in 5 different final states agree

Angular analysis suggests $\mathbf{J^P = 1^+}$

Z_b(10610)
M = 10608 pm 2.0 MeV
Γ = 15.6 pm 2.5 MeV
Z_b(10650)
M = 10653 pm 1.5 MeV
Γ = 14.4 pm 3.2 MeV

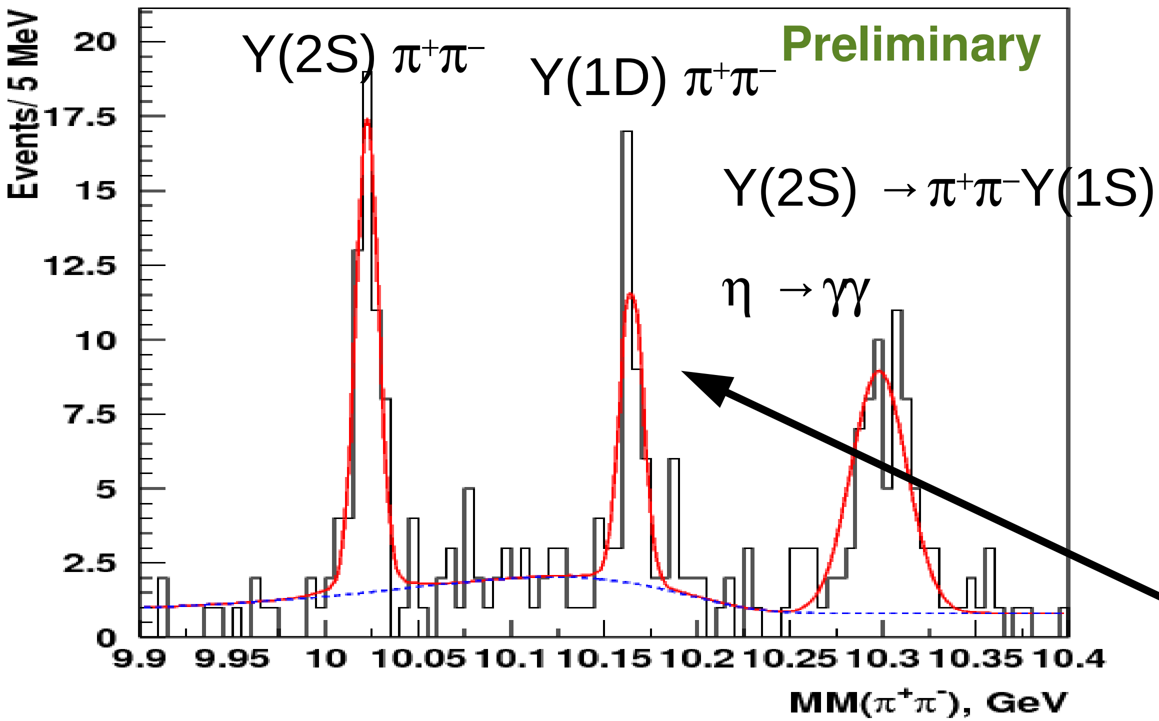
The Di Pion transitions from the Y(5S) proceed via the intermediate charged state Z_b

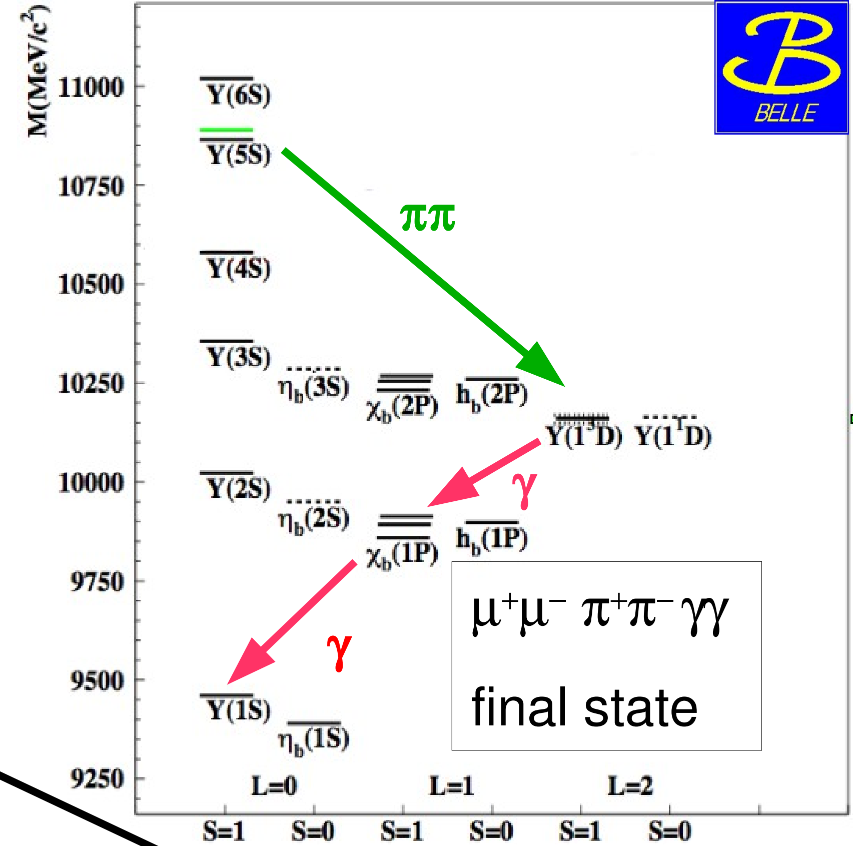
The transition does not imply spin flip

Masses are close to B*B and B*B* theresholds
Molecules?

The Y(5S) is an unexpected source of h_b

Υ(5S)→Υ(1D)$\pi^+\pi^-$

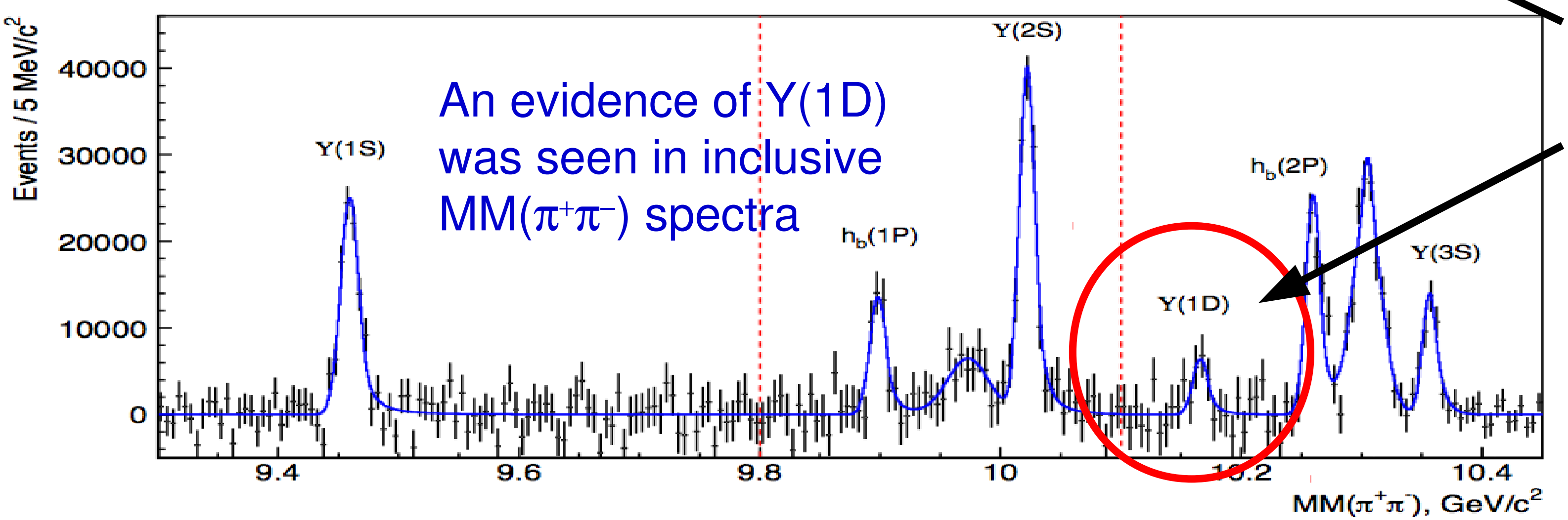




$\mu^+\mu^-$ $\pi^+\pi^-$ γγ final state

Significance 9 σ

Significance 2.9σ



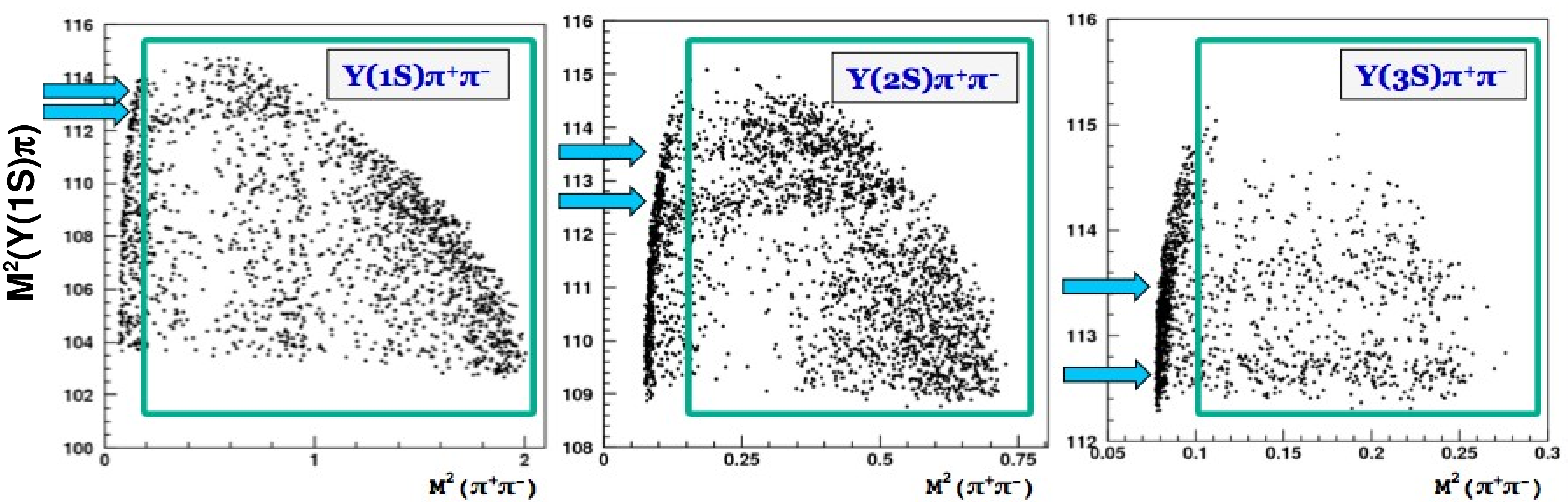
An evidence of Υ(1D) was seen in inclusive MM($\pi^+\pi^-$) spectra

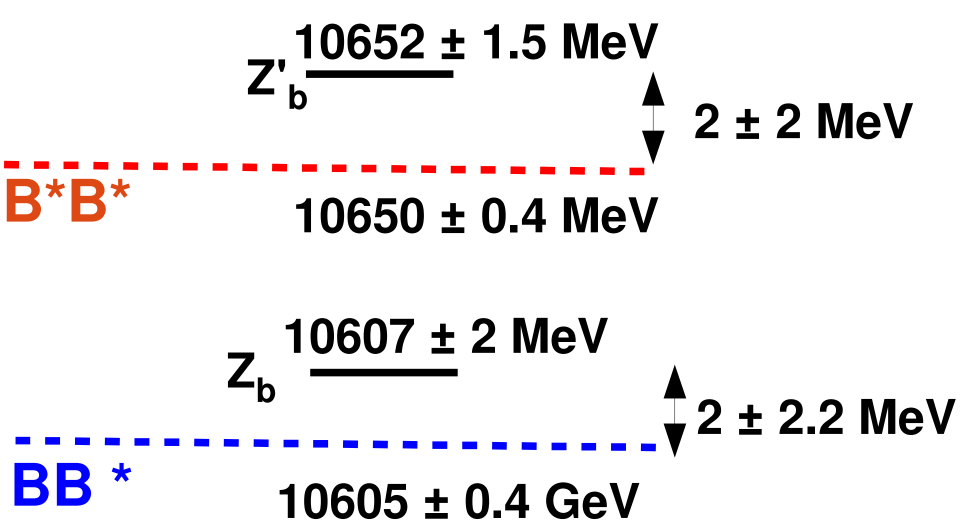
B[Υ(5S)→Υ(1D)$\pi^+\pi^-$] B[Υ(1D)→χ_b(1P)γ →Υ(1S)γγ] = (2.0±0.4±0.3) 10^{-4}

$\Upsilon(5S) \rightarrow \pi\pi\ (b\bar{b})$: the Zb

PRL108,122001

Dalitz analysis of $\Upsilon(5S) \rightarrow \pi\pi\ \Upsilon(nS)\ (\rightarrow \mu\mu)$





Open questions about Zb

→ charged (minumum 4 quark content)

→ close to B*B* an BB* thresholds

Open questions about $\Upsilon(5S)$

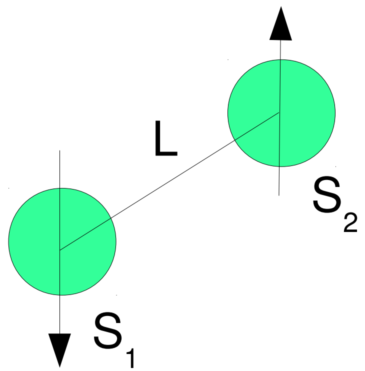
→ Two peaks?

→ Narrow state at

→ Spin flipping amplitudes: η transitions?

Quarkonium: the general picture

Bound state of **two heavy quarks**



Non relativistic regime
$\langle v^2(c)\rangle \sim 0.3\ c^2$
$\langle v^2(b)\rangle \sim 0.1\ c^2$

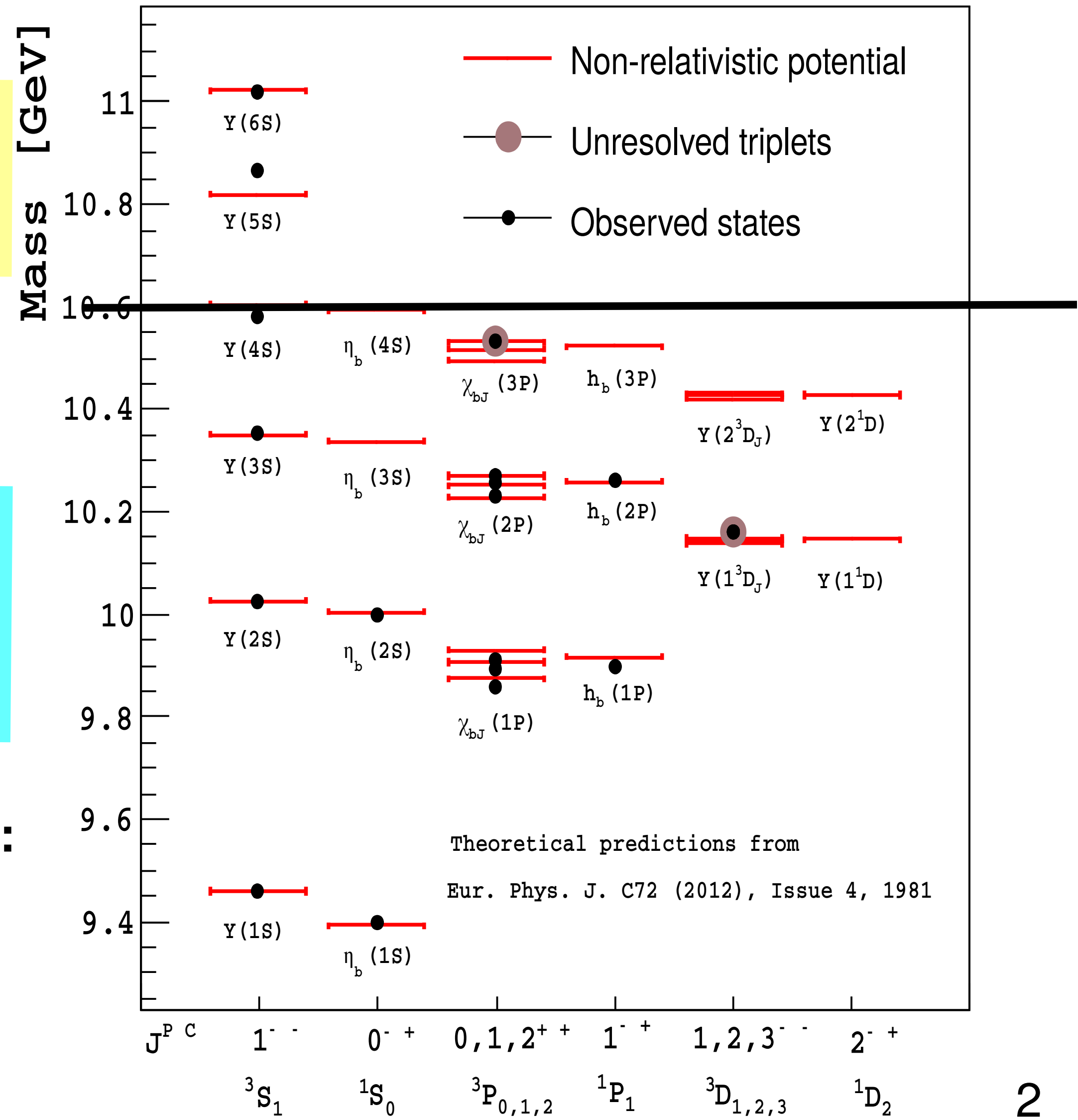
$$V = -\frac{4}{3}\frac{\alpha_s(r)}{r} + br$$

1-gluon exchange (the $-\frac{4}{3}\frac{\alpha_s(r)}{r}$ term)

Confinement (the br term)

Broad states: decay into "open flavor" ~ 100%

Narrow states: decay with transitions or annihilations in light hadrons



"Classic" rules about hadronic transitions:

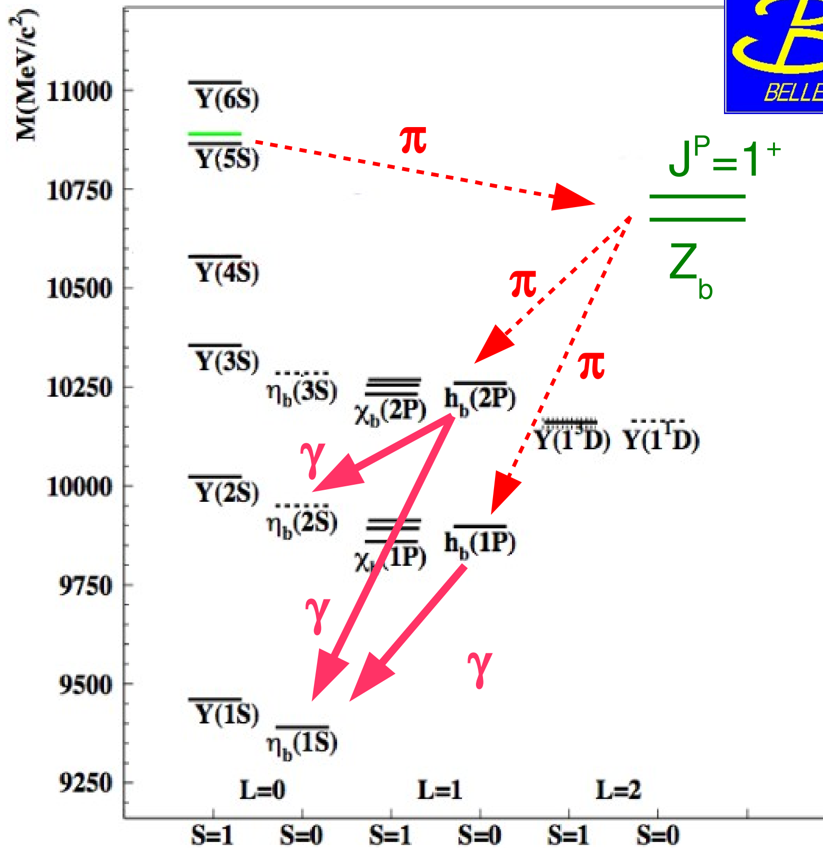
→ Transitions across the BB threshold are suppressed (OZI rule)

→ Heavy Quark Spin Symmetry (HQSS) is preserved

h_b (1P,2P)→ $\gamma\, \eta_b$ (1S,2S)

PRL109 (2012) 232002

h_b(1,2P) is predicted to have large BF for radiative decays to η_b



BF[h_b(1P) → $\gamma\, \eta_b$(1S)] = **41%**

BF[h_b(2P) → $\gamma\, \eta_b$(1S)] = **63%**

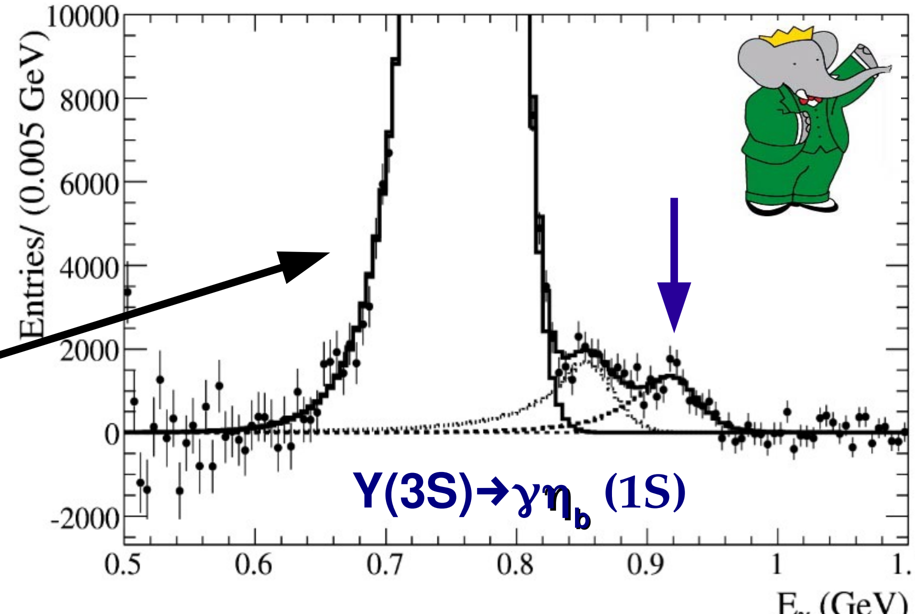
BF[h_b(2P) → $\gamma\, \eta_b$(2S)] = **13%**

O(**10**^{4}) larger than in the Y(nS) system

Clean experimental signature with the h_b(1,2P) and Z_b tagging

Means

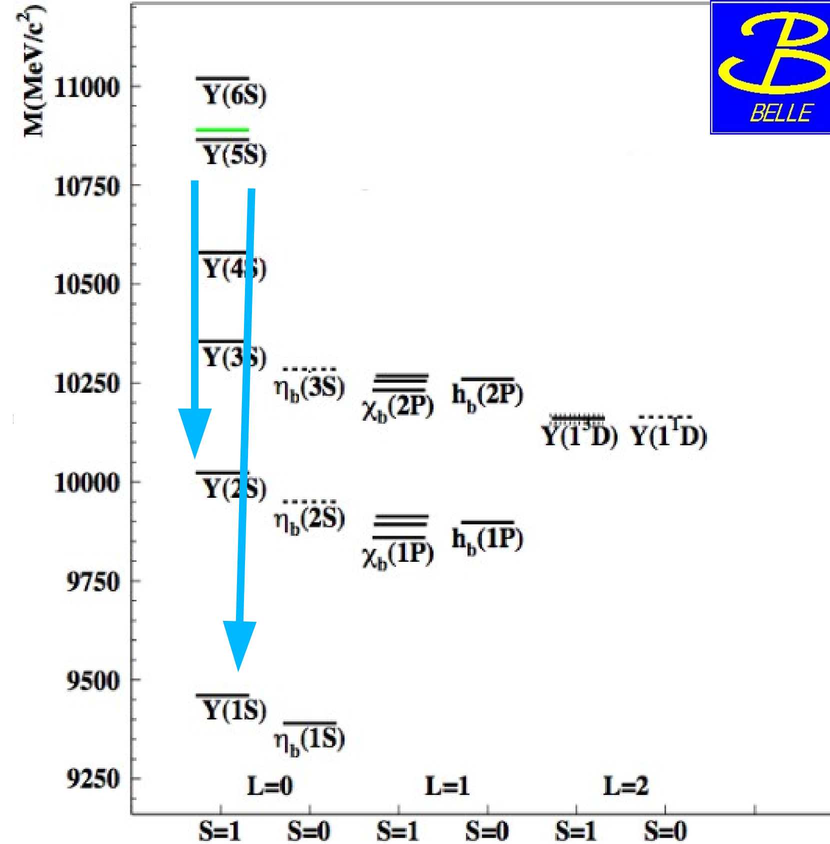
Less background than in the inclusive searches from Y(2,3S)



$\Upsilon(5S) \to \eta\, \Upsilon(1,2S)$

Exclusive reconstruction

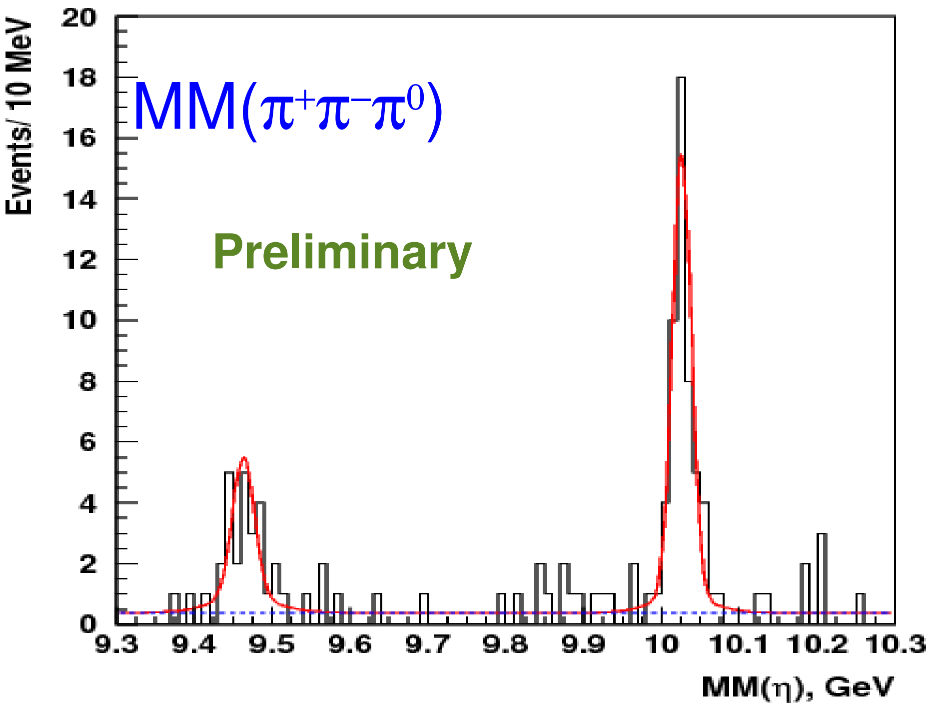
- $\Upsilon(1,2S) \to \mu^+\mu^- + \eta \to \pi^+\pi^-\pi^0$
- $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^- + \eta \to \gamma\gamma$

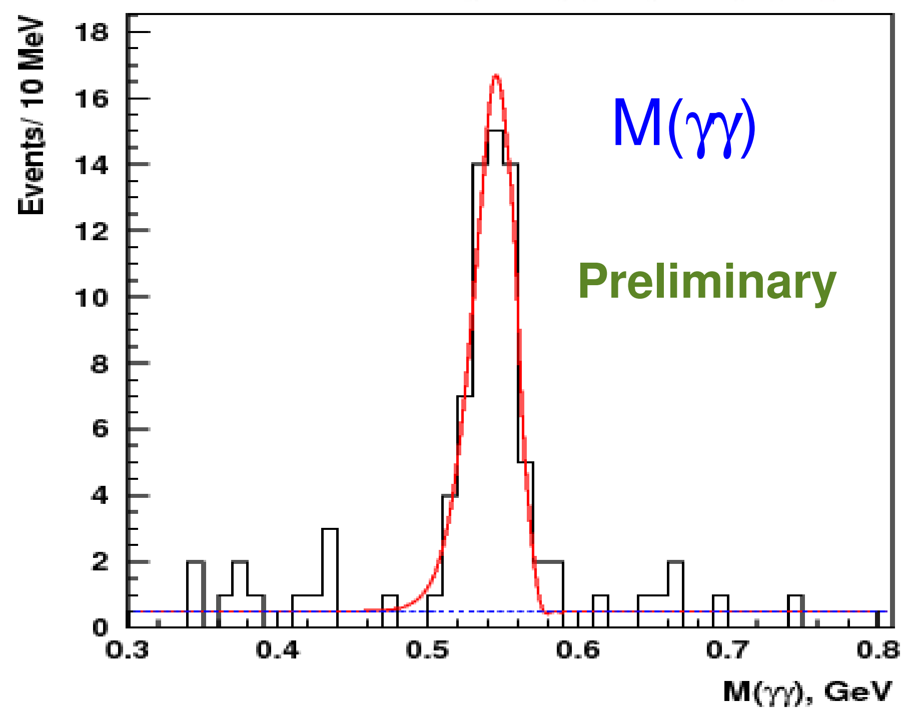


$B[\Upsilon(5S) \to \Upsilon(1S)\eta] = (7.3 \pm 1.6 \pm 0.8)\, 10^{-4}$

$B[\Upsilon(5S) \to \Upsilon(2S)\eta] = (38 \pm 4 \pm 5)\, 10^{-4}$

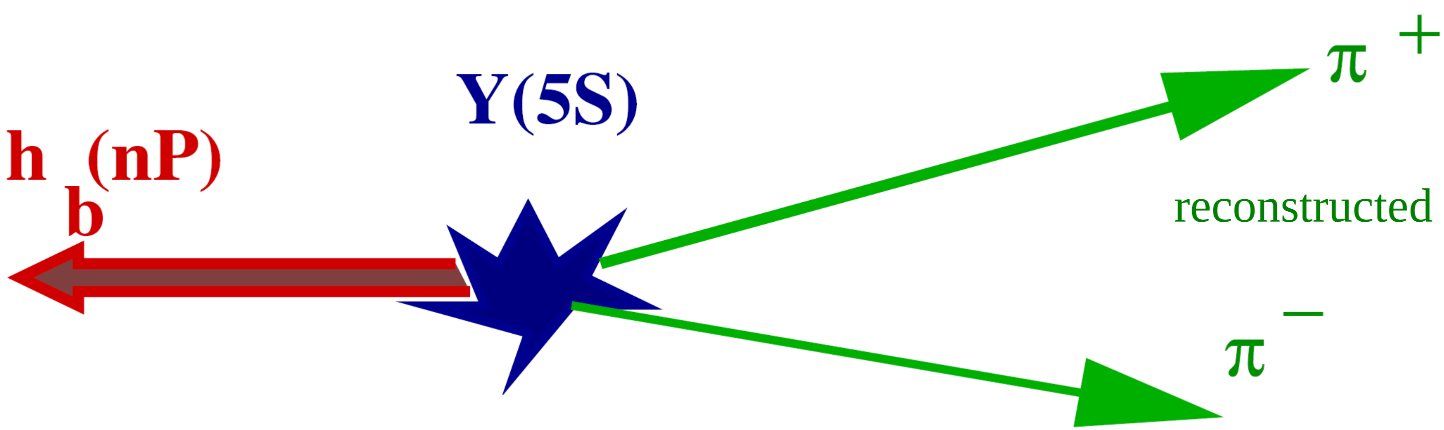
Preliminary





Missing Mass technique

Y(5S) produced <u>at rest</u> in the colliding e$^+$e$^-$ frame



$$M(h_b) = \sqrt{(E_{c.m.} - E^*_{\pi^+\pi^-})^2 - p^2_{\pi^+\pi^-}} \equiv M_{miss}(\pi^+\pi^-)$$

Known — $E_{c.m.}$

Measured — $E^*_{\pi^+\pi^-}$, $p_{\pi^+\pi^-}$

Belle Υ(5S) scan

Full Belle scan
For Rb: 61 points (50/pb each) every 5 MeV
For Rππ: 22 points (1/fb each)

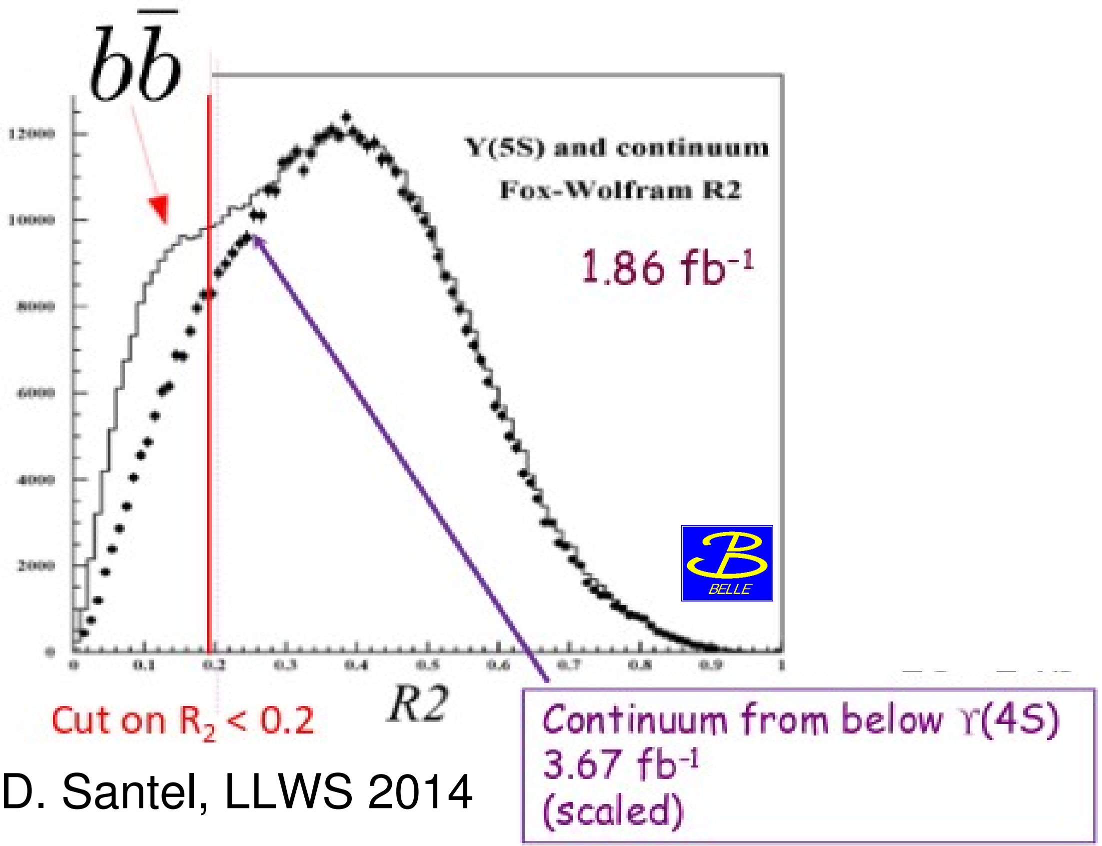
According to PRL 102, 012001 **(2009)** cross sections are **visible ones**, not Born

Both open and close

$$\mathbf{Rb} = \frac{\sigma[e^+e^- \to b\bar{b} \to \text{hadrons}]}{\sigma[e^+e^- \to \mu^+\mu^-]}$$

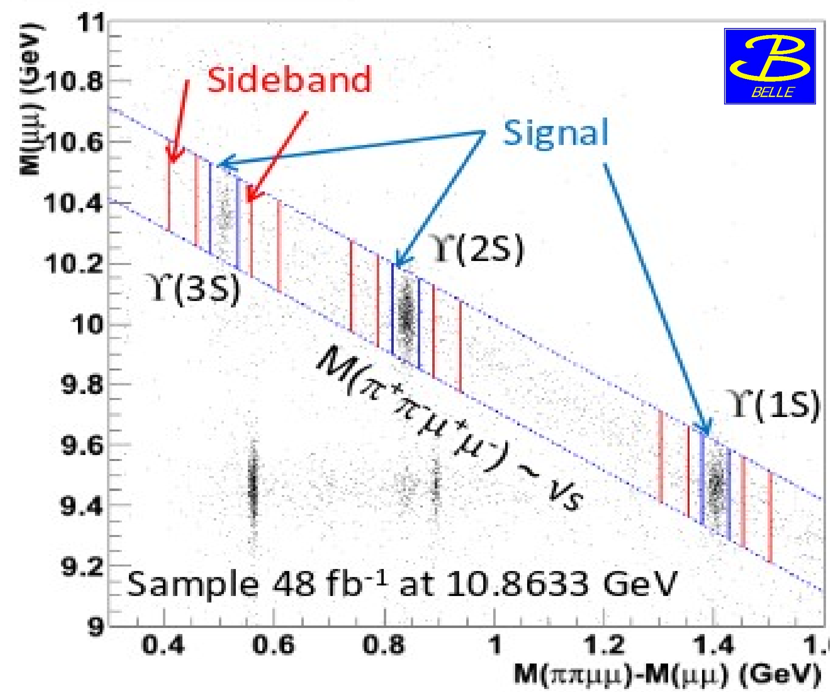
$$\mathbf{R\pi\pi} = \frac{\sigma[e^+e^- \to \pi\pi\Upsilon(nS)]}{\sigma[e^+e^- \to \mu^+\mu^-]}$$

$e^+e^- \to q\bar{q}$ suppression: R2



D. Santel, LLWS 2014

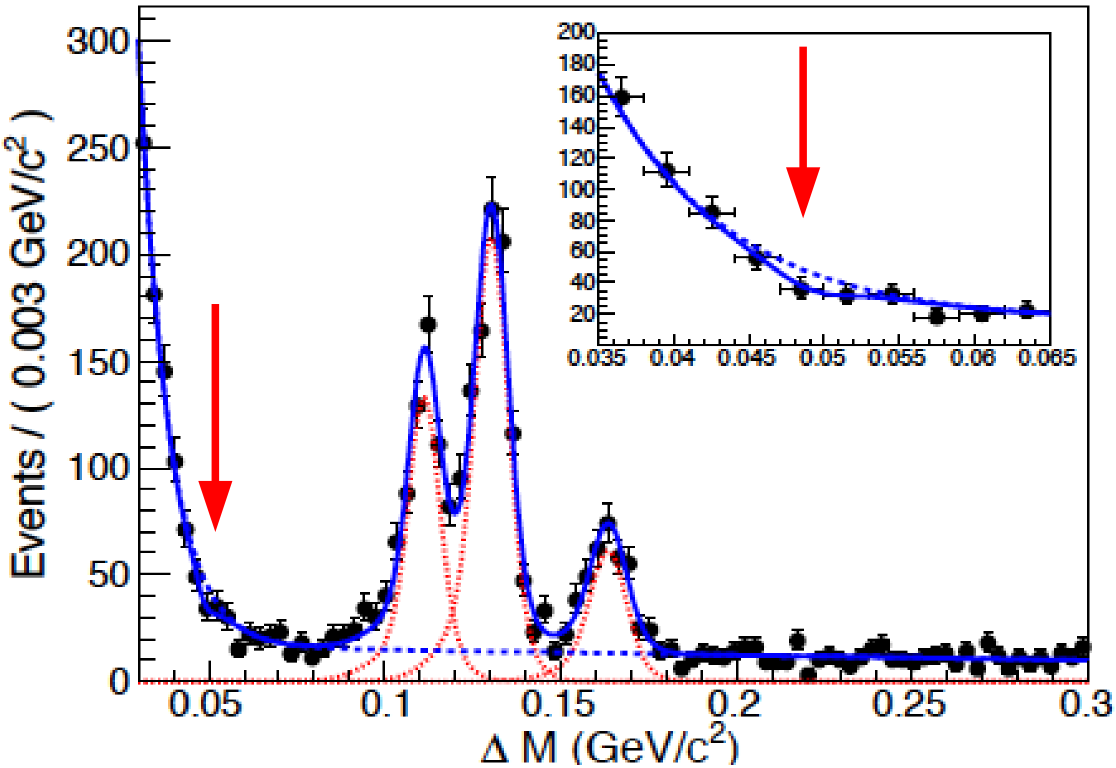
$e^+e^- \to \mu^+\mu^-\gamma$ suppression: sidebands



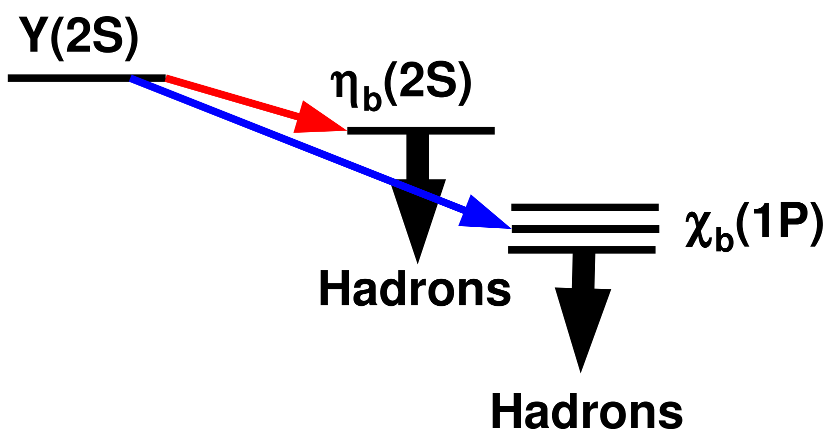
D. Santel, LLWS 2014

Exclusive $\eta_b(2S)$ at Belle

arXiv:1306.6212



Identical reconstruction modes



25 fb^{-1} at Υ(2S) energy
(158 M Υ(2S) decays, **16x CLEO)**

η_b**(2S) claim by Dobbs et Al. is disconfirmed by Belle.**

87 fb^{-1} below Υ(4S) energy
for the study of the contiuum background study

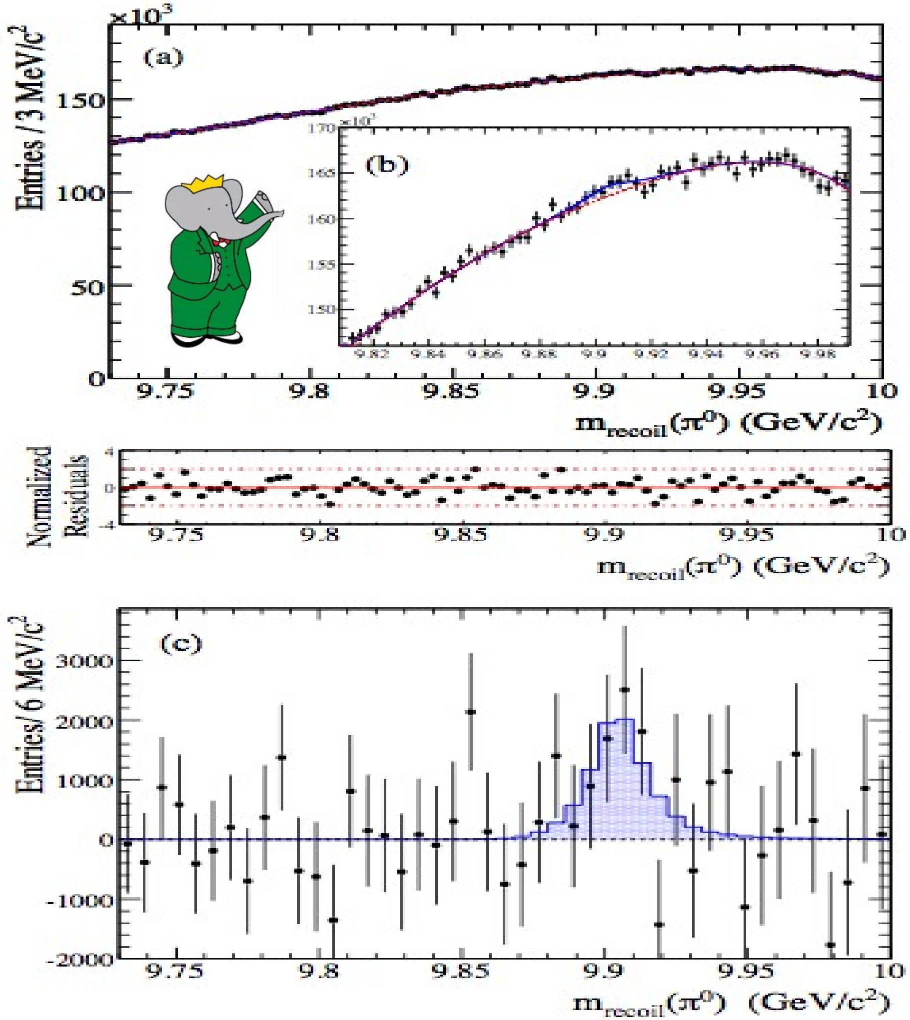
BF[Υ(2S) → γη_b(2S)] x BF[γη_b(2S) → had] < 4.9 x 10^{-6}

~ one order of magnitude below the claim by Dobbs et at

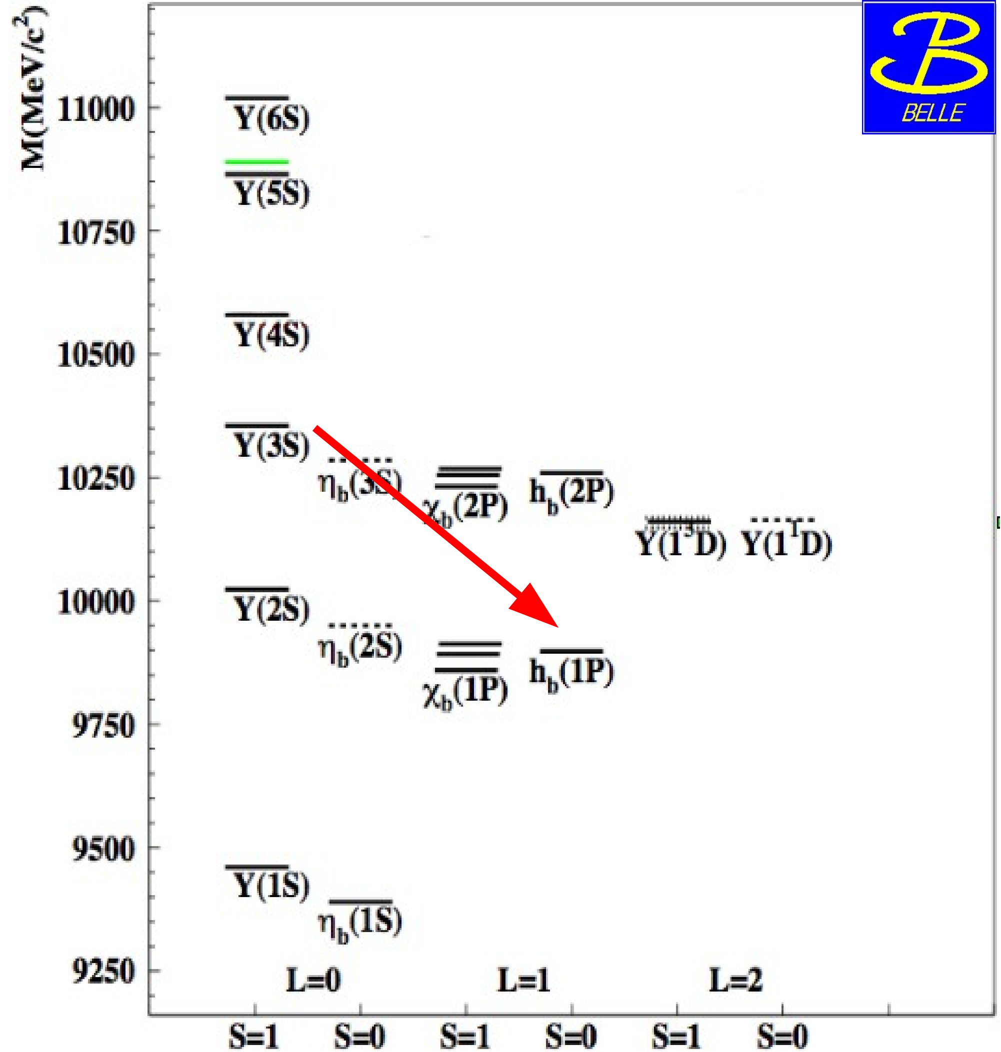
$h_b(1P)$ at BaBar

3 sigma evidence:

$e^+e^- \rightarrow \Upsilon(3S) \rightarrow \pi^0 h_b$



π⁰ recoil mass (GeV/c²)



Phys.Rev.D 84 091101(R)

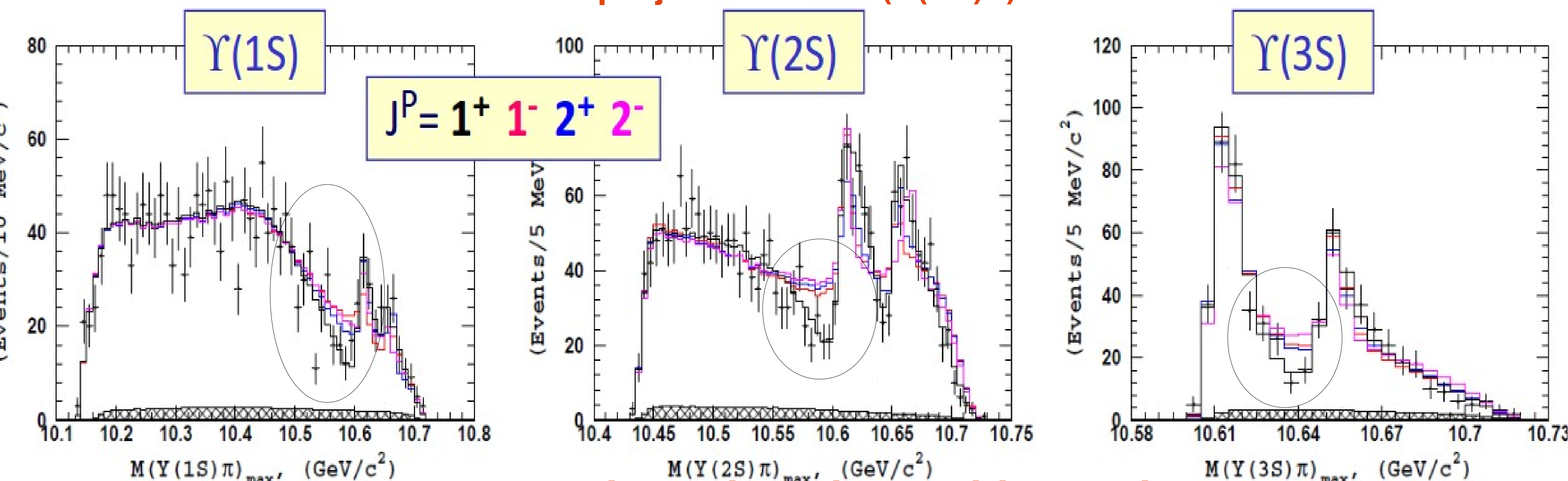
Spin-parity of the Z_b

New study of spin parity with a **6-D fit** that includes contributions from non-resonant S and D waves:

$$S(s1,s2) = A(Z_b) + A(Z'_b) + A(f_0(980)) + A(f_2(1275)) + A(NR) + A(\sigma)$$

- $A(Z_b)$, $A(Z'_b)$: Breit-Wigner
- $A(f_0(980))$: Flatte
- $A(f_2(1275))$: Breit-Wigner
- $A(NR)$: $c_1 + c_2 M^2(\pi\pi)$
- $A(\sigma)$: Breit-Wigner

Fit projections in $M(\Upsilon(nS)\pi)$

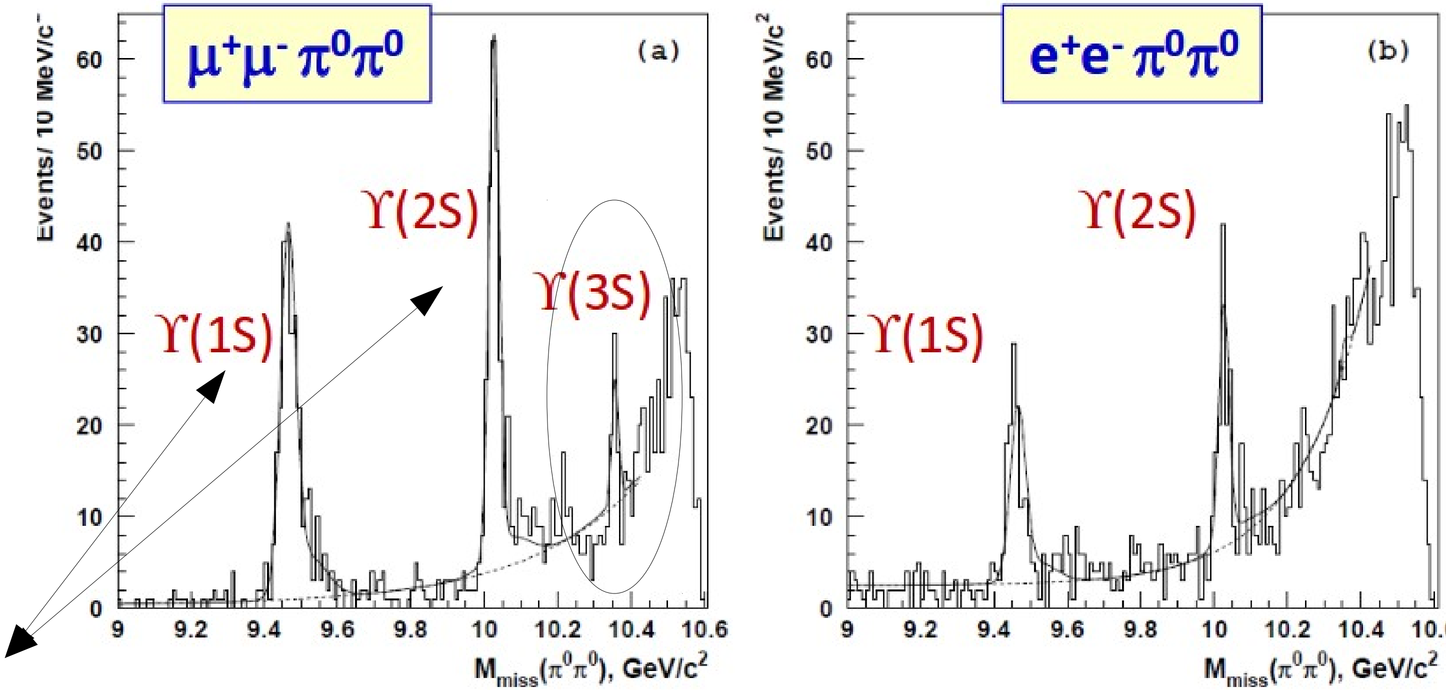


1^+ is assigned unambiguously

Search for Z_b^0

arXiv:1318.2648

$\Upsilon(5S) \to \pi^0\pi^0$ $\Upsilon(nS)$ ⟶ e^+e^-, $\mu^+\mu^-$



BF[$\Upsilon(5S) \to \pi^0\pi^0\ \Upsilon(1S)$] = $(2.25 \pm 0.11 \pm 0.20) \times 10^{-3}$ BF[$\pi^+\pi^-$] = $(4.45 \pm 0.16 \pm 0.35) \times 10^{-3}$

BF[$\Upsilon(5S) \to \pi^0\pi^0\ \Upsilon(2S)$] = $(3.79 \pm 0.24 \pm 0.49) \times 10^{-3}$ BF[$\pi^+\pi^-$] = $(7.97 \pm 0.31 \pm 0.96) \times 10^{-3}$

BF[$\Upsilon(5S) \to \pi^0\pi^0\ \Upsilon(3S)$] = $(2.09 \pm 0.51 \pm 0.34) \times 10^{-3}$ BF[$\pi^+\pi^-$] = $(2.88 \pm 0.19 \pm 0.36) \times 10^{-3}$

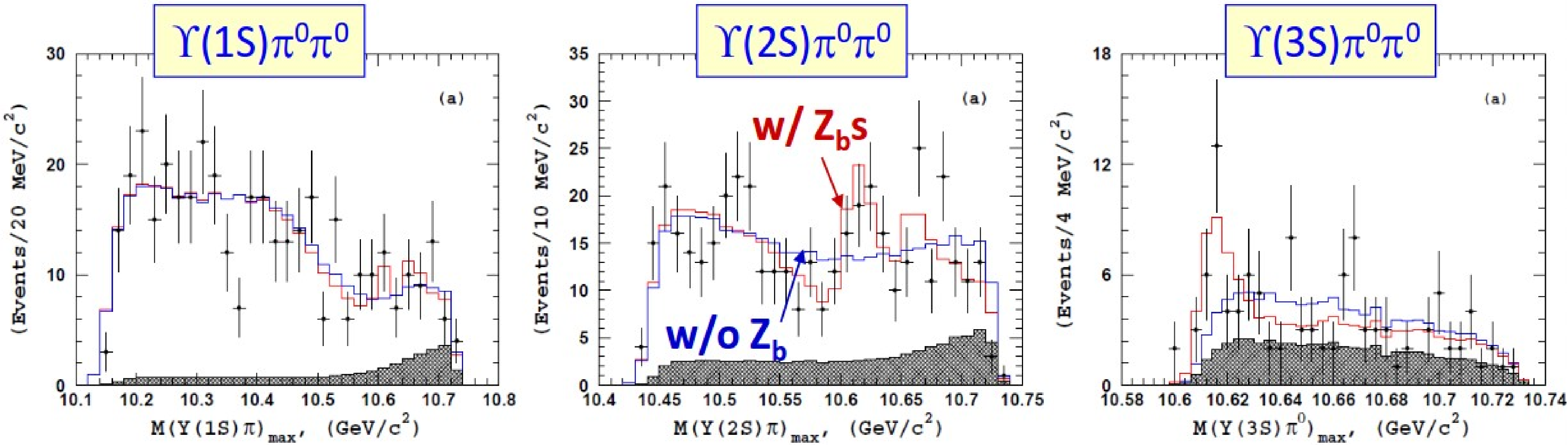
Isospin symmetry : BF[$\pi^+\pi^-$] = 2x BF[$\pi^0\pi^0$] OK

Search for Z_b^0

arXiv:1318.2648

Again multidimensional fit that includes contributions from non resonant S and D wave

$$S(s1,s2) = A(Z_b) + A(Z'_b) + A(f_0(980)) + A(f_2(1275)) + A(NR)$$

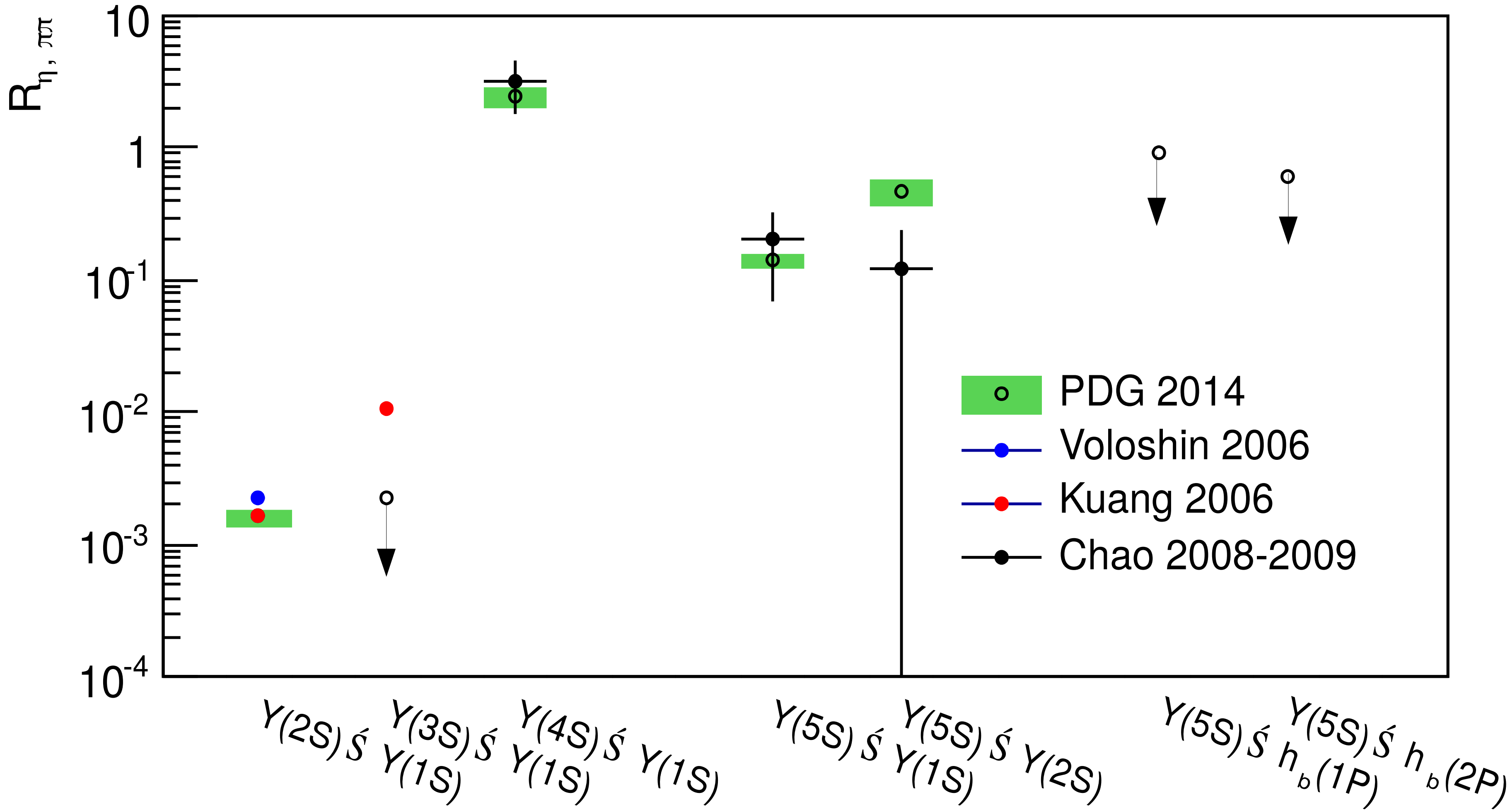


Significance is calculated from the Multi-dimensional fit

Z^0_b(10610): 6.5 σ [4.9σ from Y(2S) + 4.3σ from Y(3S)] Observed

Z^0_b(10650): not observed but not excluded either

$\eta/\pi\pi$ ratio

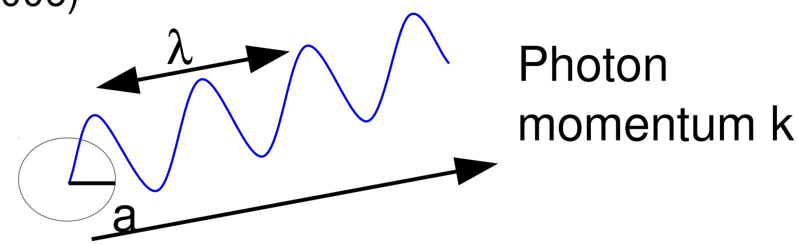


Hadronic transitions: lower states

Kuang, Front.Phys.China 1, 19 (2006)

QED multipole expansion

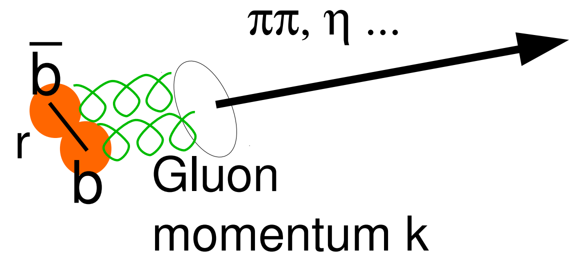
$a/\lambda \sim ak < 1$



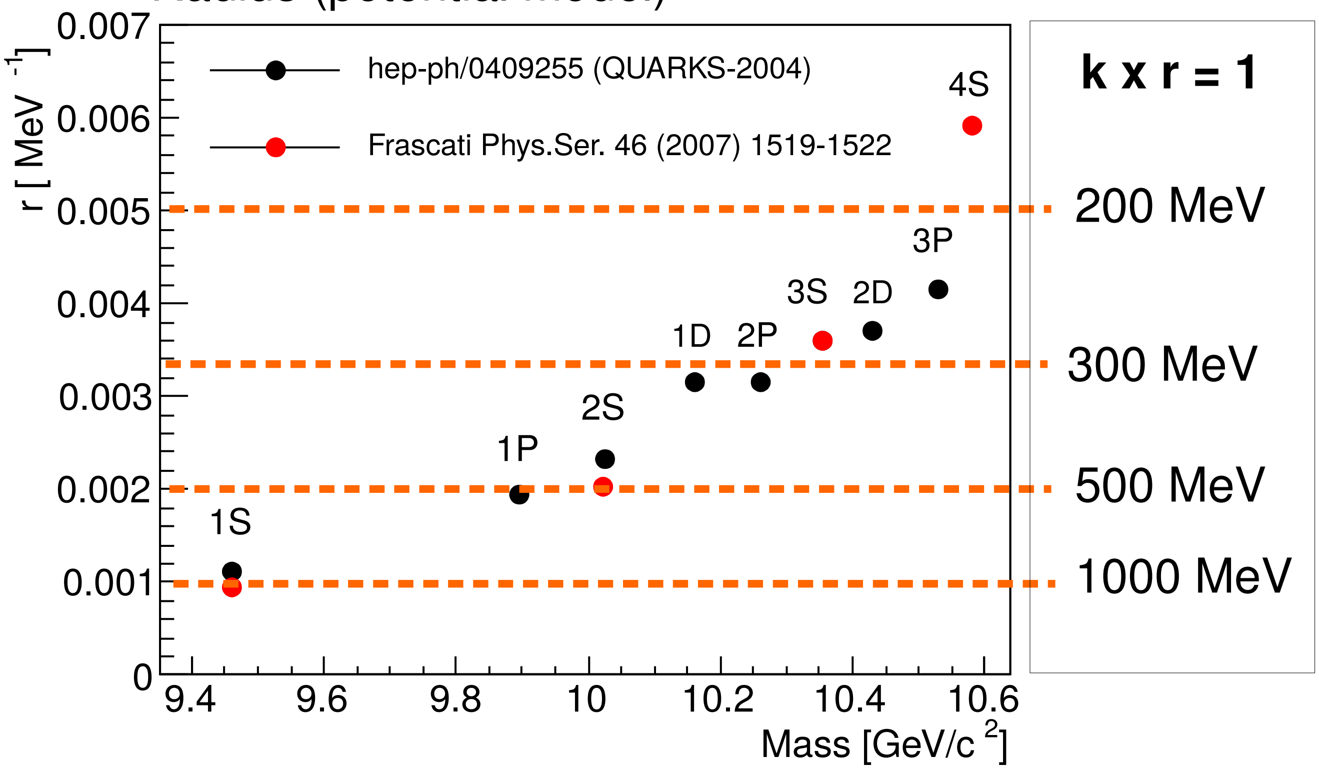
In quarkonia:

r ~ 0.1 fm rk < 1

k ~ 100 MeV



Radius (potential model)



Heavy quark spin symmetry:
Transitions involving spin flipping amplitudes are suppressed

QCDME natural limitations
Power expansion breaks with increasing mass
→ what happens above the threshold?