Hadron Spectroscopy

Roberto Mussa
INFN Torino

* heavy baryons
* heavy-light mesons
* heavy quarkonia

* running coupling constant?

* 'old' exotics
* new exotics on thresholds
* Bc

What Next , LTS1, la Biodola 22/5/2014

Why hadron spectroscopy ?

* Quark-hadron duality :
investigate the role of spin and quark masses on : hadron masses , hadron magnetic moments.

* Non perturbative QCD: this is what explains most of baryon matter. Infrared slavery is a theoretical limit, which prevents to do predictions on an amazing set of measurable quantities. Asymptotic freedom is nice, but being able to cope with infrared slavery is crucial, to deeply test our understanding of the nature of matter.

* QCD provides doors towards BSM issues : axions, instantons, strong CP violation ... (but also glueballs , hybrids , multiquarks)

* Last 15 years taught us that all hints of new physics in the quark sector (and not only : See L2L in g-2) could be explained as unexpected effects of strong interactions: badly known form factors, final state interactions, SU(3) breaking effects ...

QED example n.1: hydrogen atom

Proton-electron bound state
Non relativistic system
velocity ~ β ~ n α_{QED}

Mp / Me = 938/0.511 = 1836

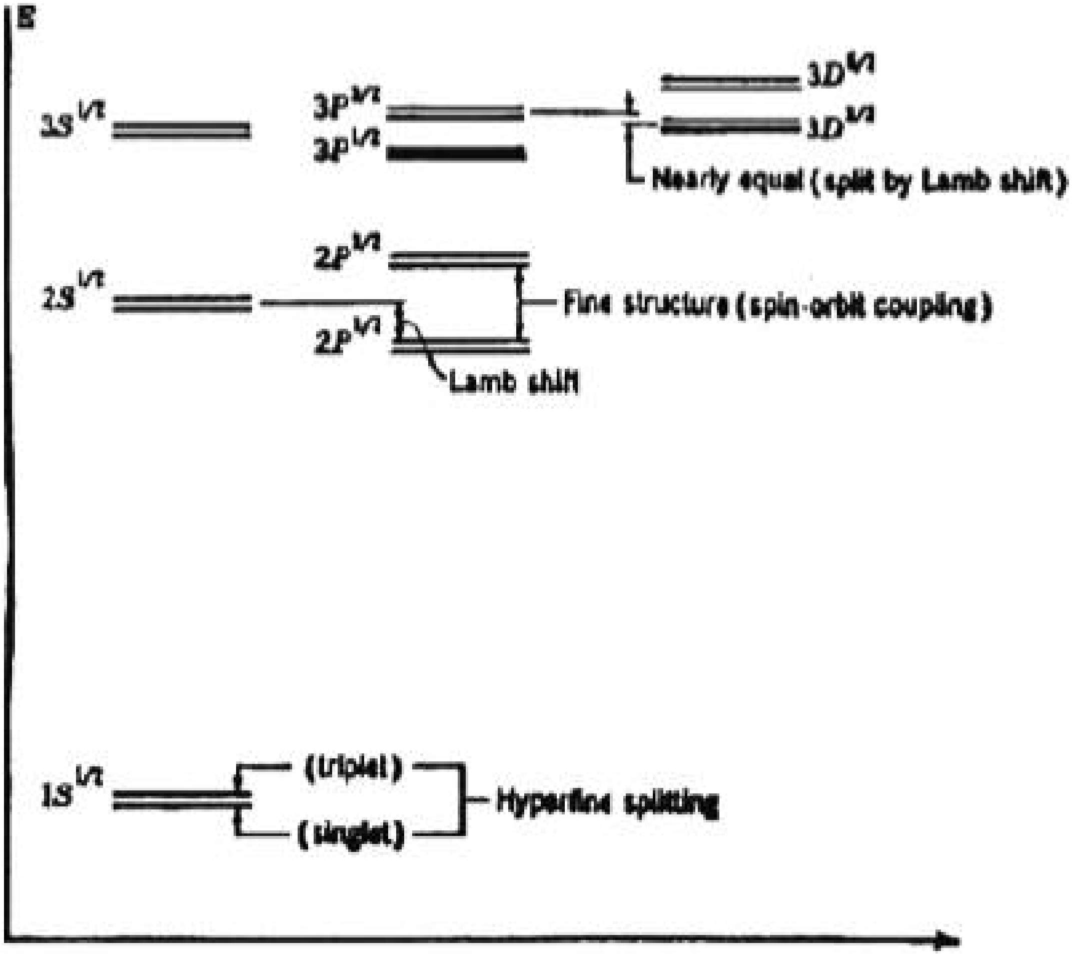
EM Transitions between energy levels
Stable ground state

2S-1S splitting ~ 10 eV

Fine Splitting : 45 μeV(2P)

Hyperfine Splitting : 5.9 μeV(1S)
0.7 μeV(2S), 0.2 μeV(2P)

2S-2P degeneration broken by
Lamb Shift : $\Delta m \sim m_e a^5_{QED}$ ~ 4.4 μeV(1S)



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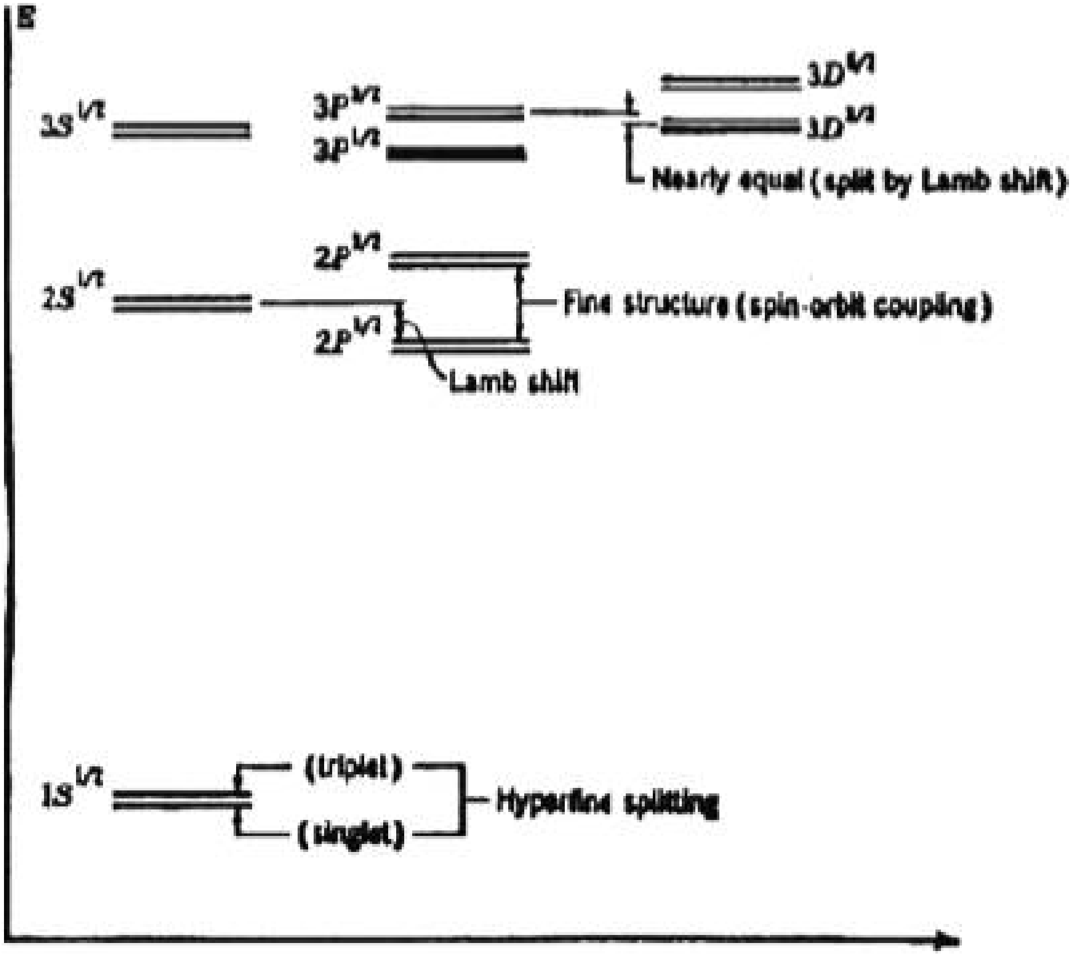


2S-2P degeneration broken by
Lamb Shift : $\Delta m \sim m_e a^5_{QED} \sim 4.4$ μeV(1S)

In QCD :
heavy light
mesons+
baryons

QED example n.2: positronium

Bound state e+e-
Non relativistic system
velocity ~ β ~ α_{QED}

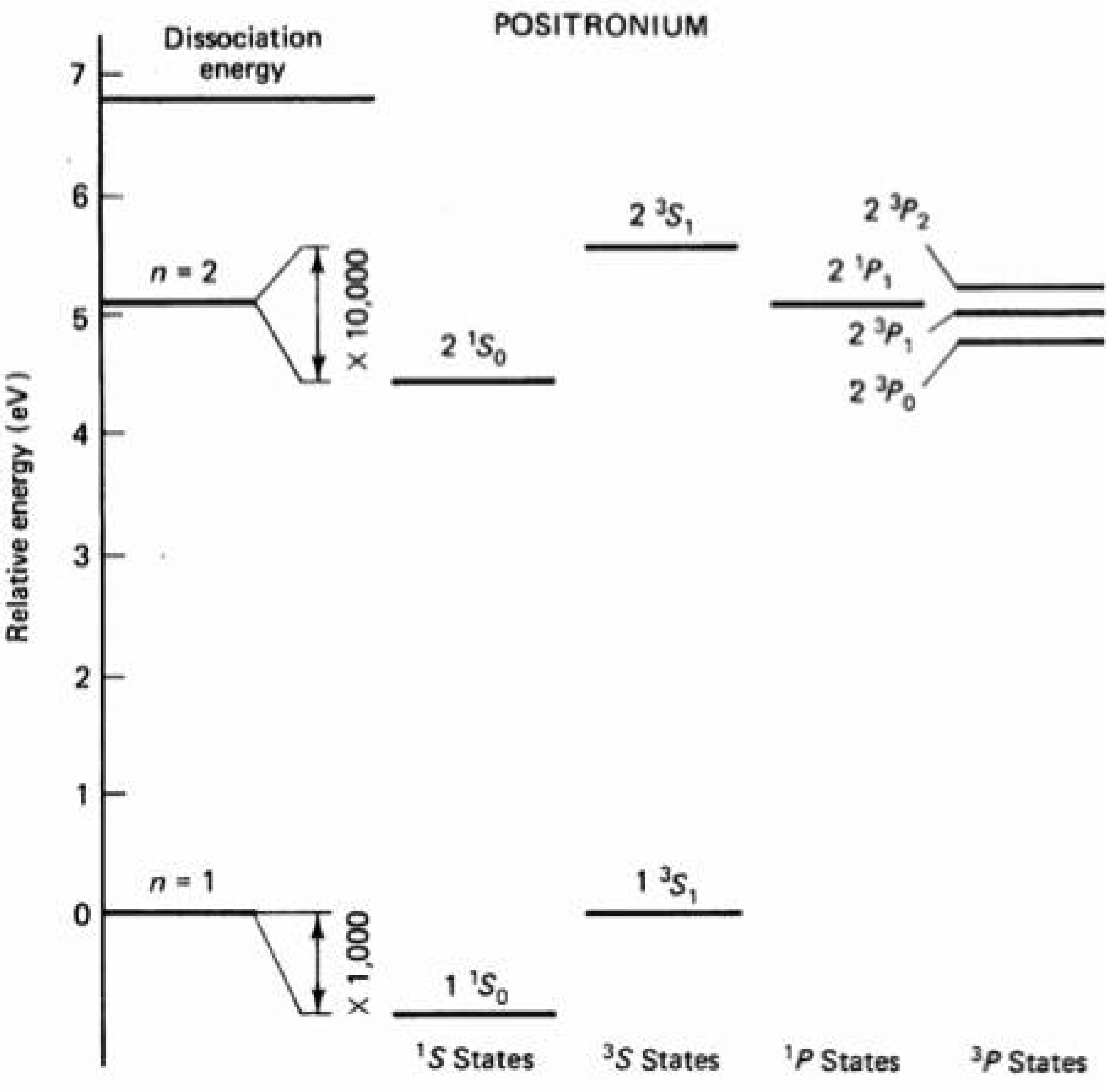
J,L,S are good quantum numbers

S=0 : *para*positronium
Decays to 2 photons
short lifetime

S=1 : *orto*positronium
Decays to 3 photons
long lifetime

2S-2P degeneration

Hyperfine Splitting : 1 meV (1S)
0.1 meV (2S)
Fine Splitting: 0.03 meV (2P)



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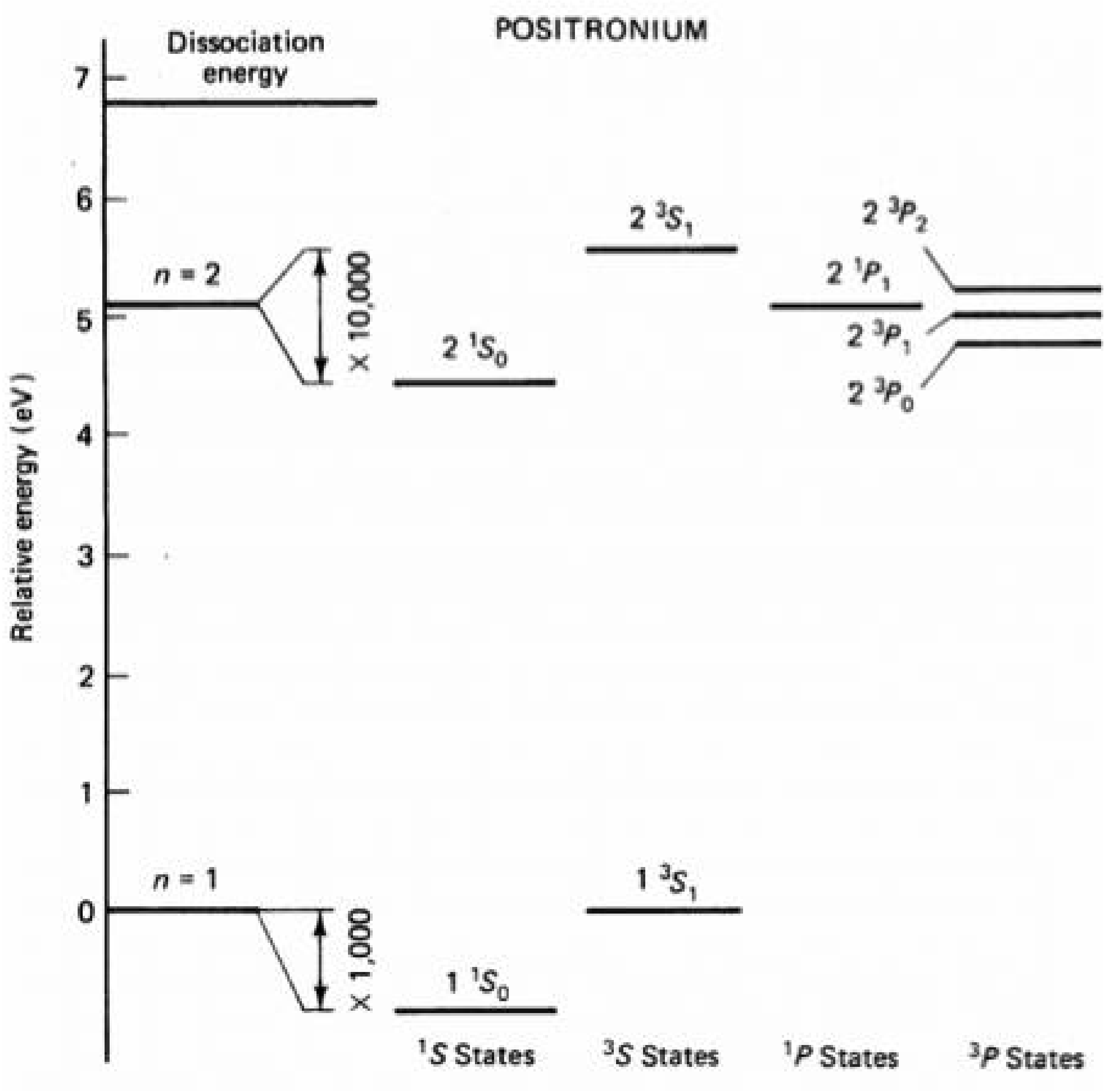
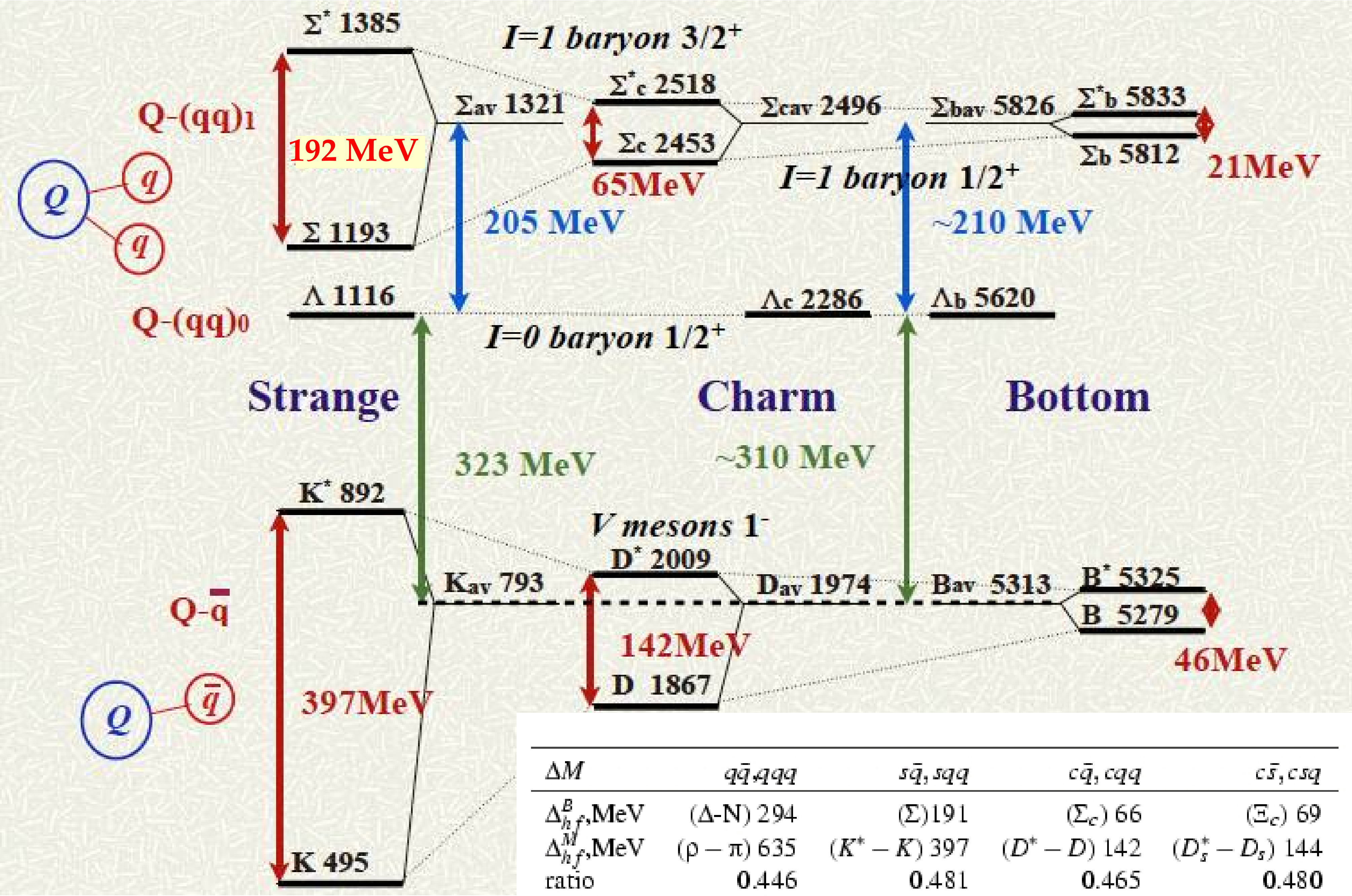


In QCD : Quarkonium

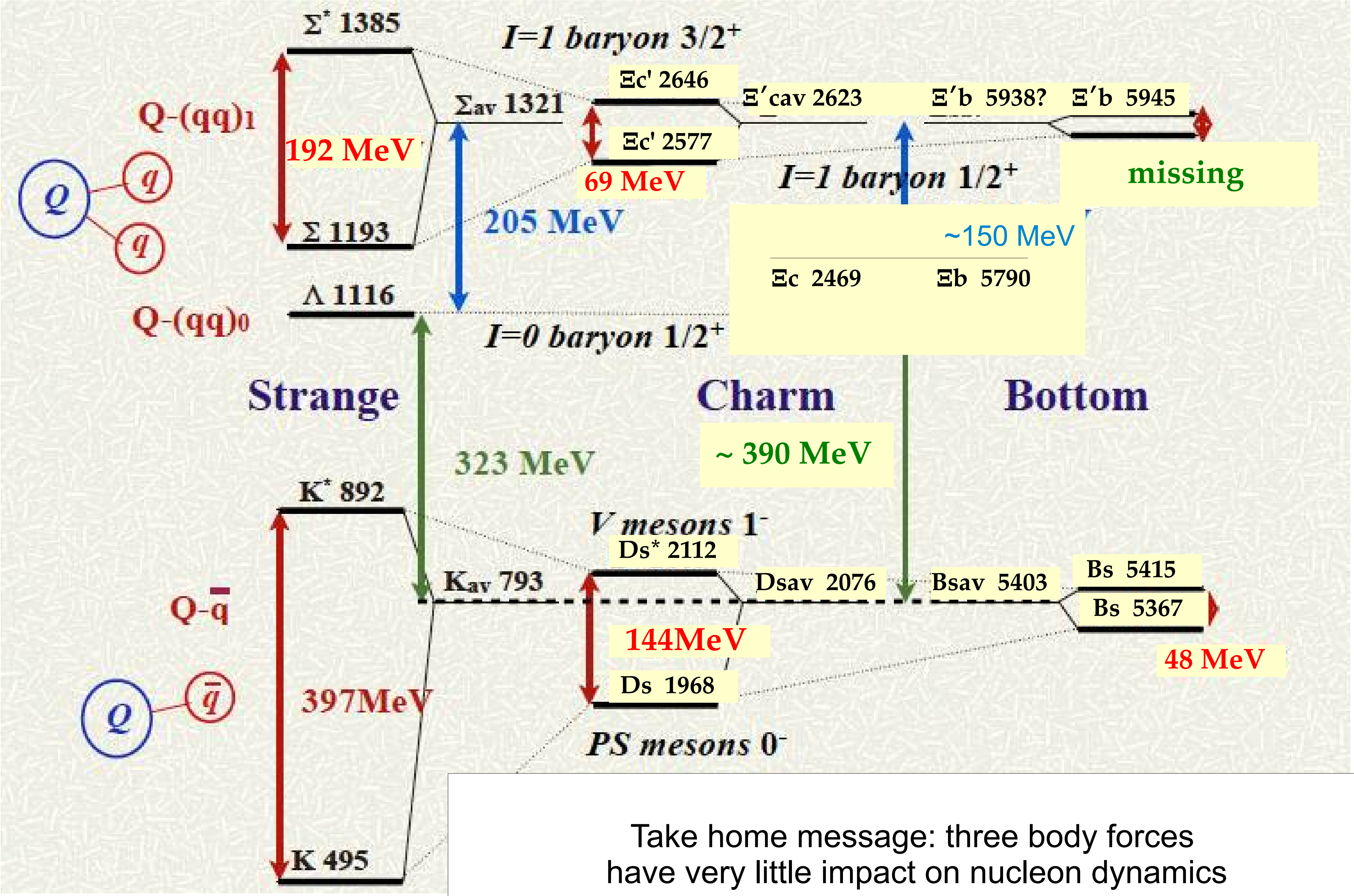
Charmed and Beauty hadron spectra

From Oka's talk
at Hadron 2013



ΔM	$q\bar{q}, qqq$	$s\bar{q}, sqq$	$c\bar{q}, cqq$	$c\bar{s}, csq$
Δ^B_{hf},MeV	(Δ-N) 294	(Σ)191	(Σ_c) 66	(Ξ_c) 69
Δ^M_{hf},MeV	($\rho - \pi$) 635	($K^* - K$) 397	($D^* - D$) 142	($D_s^* - D_s$) 144
ratio	0.446	0.481	0.465	0.480

Strange Charmed and Beauty hadron spectra



Take home message: three body forces
have very little impact on nucleon dynamics

The unexpected success of constituent quark model

Using a very simple mass formula for the ground states , Karliner and Lipkin (hep-ph/0307243) calculated constituent quark mass differences and ratios in baryons and mesons with 2-3% differences: why such a precision?

$$M = \sum_i m_i + \sum_{i>j} \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i \cdot m_j} \cdot v_{IE}^{hyp}$$

Ya.B. Zeldovich and A.D. Sakharov, Yad. Fiz 4(1966)395;

$$\langle m_s - m_u \rangle_{Bar} = M_{sud} - M_{uud} = M_\Lambda - M_N = 177\,\mathrm{MeV}$$

$$\langle m_s - m_u \rangle_{Mes} = \frac{3(M_{\mathcal{V}_{s\bar{d}}} - M_{\mathcal{V}_{u\bar{d}}}) + (M_{\mathcal{P}_{s\bar{d}}} - M_{\mathcal{P}_{u\bar{d}}})}{4} = \frac{3(M_{K^*} - M_\rho) + M_K - M_\pi}{4} = 179\,\mathrm{MeV}$$

$$\left(\frac{m_c}{m_s}\right)_{Bar} = \frac{M_{\Sigma^*} - M_\Sigma}{M_{\Sigma_c^*} - M_{\Sigma_c}} = 2.84 = \left(\frac{m_c}{m_s}\right)_{Mes} = \frac{M_{K^*} - M_K}{M_{D^*} - M_D} = 2.81$$

$$\left(\frac{m_c}{m_u}\right)_{Bar} = \frac{M_\Delta - M_p}{M_{\Sigma_c^*} - M_{\Sigma_c}} = 4.36 = \left(\frac{m_c}{m_u}\right)_{Mes} = \frac{M_\rho - M_\pi}{M_{D^*} - M_D} = 4.46$$

$$\left(\frac{\frac{1}{m_u^2} - \frac{1}{m_u m_c}}{\frac{1}{m_u^2} - \frac{1}{m_u m_s}}\right)_{Bar} = \frac{M_{\Sigma_c} - M_{\Lambda_c}}{M_\Sigma - M_\Lambda} = 2.16 \approx \left(\frac{\frac{1}{m_u^2} - \frac{1}{m_u m_c}}{\frac{1}{m_u^2} - \frac{1}{m_u m_s}}\right)_{Mes} = \frac{(M_\rho - M_\pi) - (M_{D^*} - M_D)}{(M_\rho - M_\pi) - (M_{K^*} - M_K)} = 2.10$$

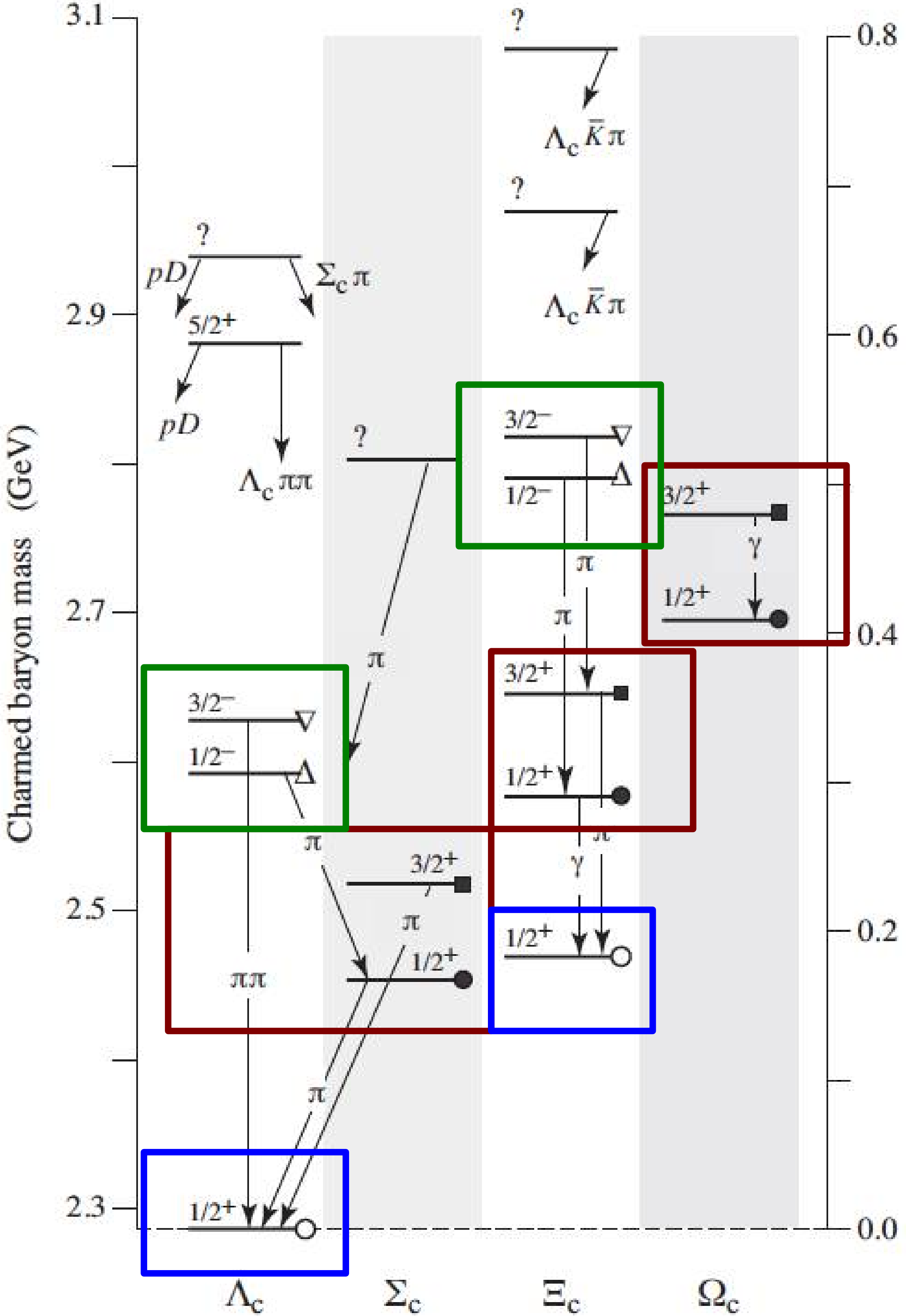
Charmed baryon spectra: P waves

In blue: J=0 diquark ; L=0

In red: J=1 diquark ; L = 0
HF splitting:
$M(3/2^+)-M(1/2^+)$
[ud]c = 65 MeV
[qs]c = 69 MeV
[ss]c = 71 MeV

In green: J=0 diquark ; L=1
LS splitting:
$[2*M(3/2^-)+M(1/2^-)]/3-M(1/2^+)$

[ud]s = 366.3 MeV
[ud]c = 329.7MeV
[qs]c = 339.8 MeV
[ud]b = 297.8 MeV



Quarkonium working group

www.qwg.to.infn.it

QWG Workshops on Heavy Quarkonium:

QWG1: CERN, November 8 to 10, 2002

QWG2: Fermilab, September 20 to 22, 2003

QWG3: Beijing, October 12 to 15, 2004

QWG4: Brookhaven, June 27 to 30, 2006

QWG5: DESY Hamburg, October 12 to 15, 2007

QWG6: Nara Women's University, December 2 to 5, 2008

QWG7: Ferrmilab, May 18 to 21, 2010

QWG8: GSI Darmstadt, October 3 to 7, 2011

QWG9: IHEP Beijing, April 22 to 26, 2013

QWG10: CERN, November 10 to 14, 2014

YELLOW REPORT :
CERN-2005-005,
ArXiv: hep-ph/0412158

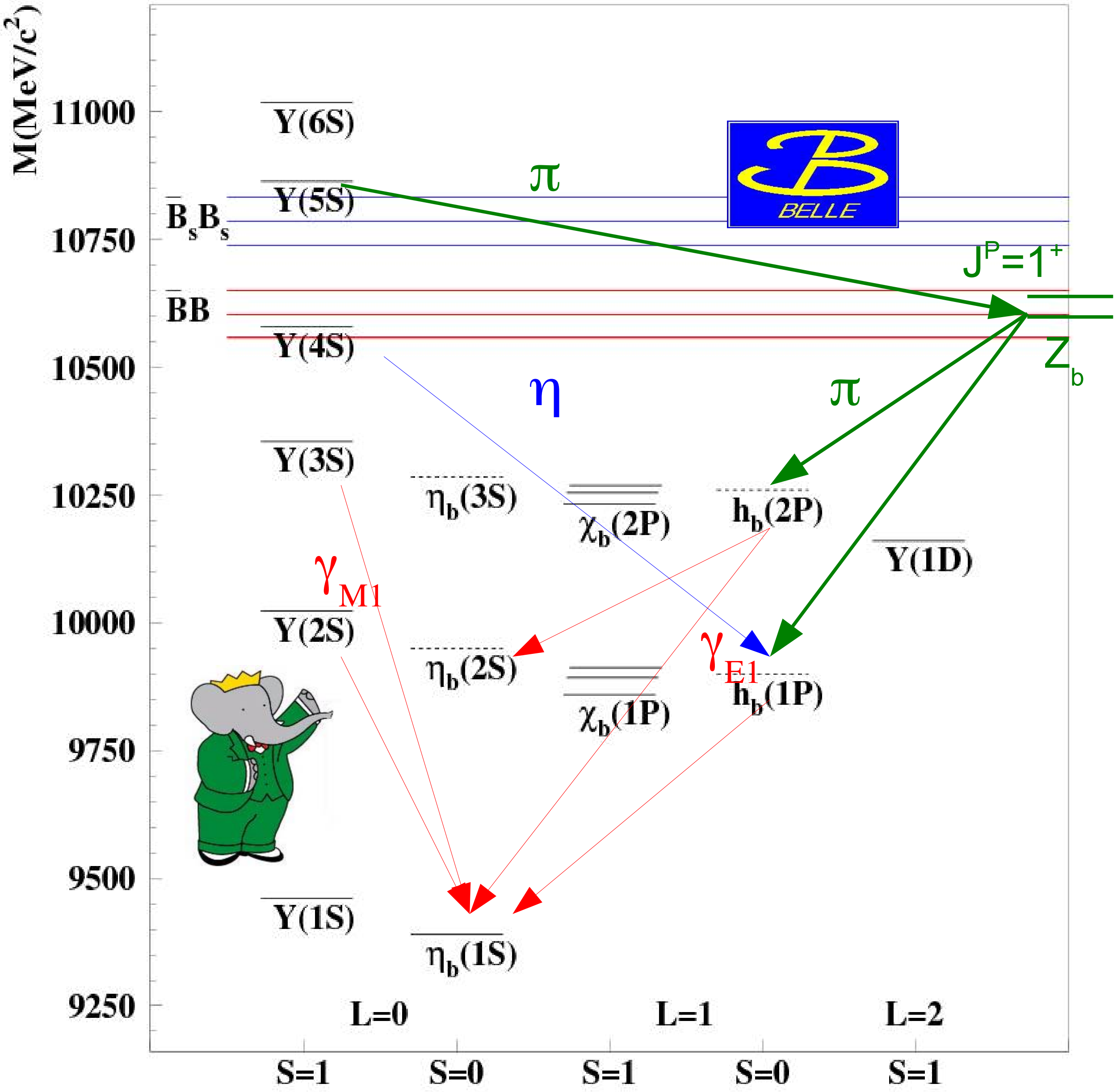
2nd QWG Report :
Eur.Phys.J. C71 (2011) 1534 ,
ArXiv:1010.5827,

The quest for parabottomonia

5 amazing years for bottomonium spectroscopy:

- Y_b / Y(5S):observation of large dipion transitions to Y(1,2,3S) from 20 MeV above 5S peak
- 2008 Discovery of η_b(Babar)
- 2011-2:Discovery of the triple cascade $Y_b \to Z_b \to h_b \to \eta_b$

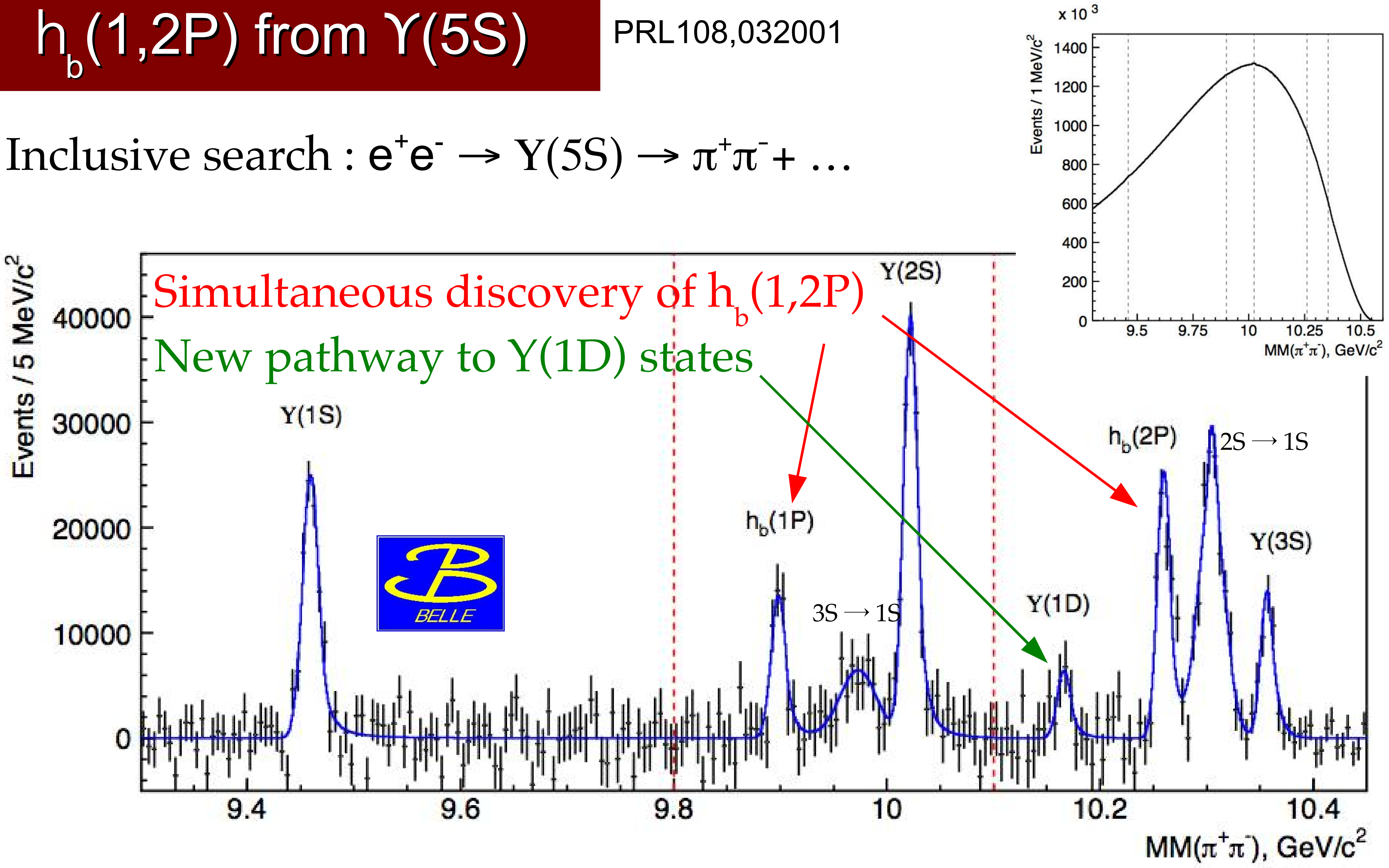
Belle discovers 4 parabottomonia , and 2 4quark states in one shot!



$h_b(1,2P)$ from $\Upsilon(5S)$

PRL108,032001

Inclusive search : $e^+e^- \rightarrow \Upsilon(5S) \rightarrow \pi^+\pi^- + \ldots$



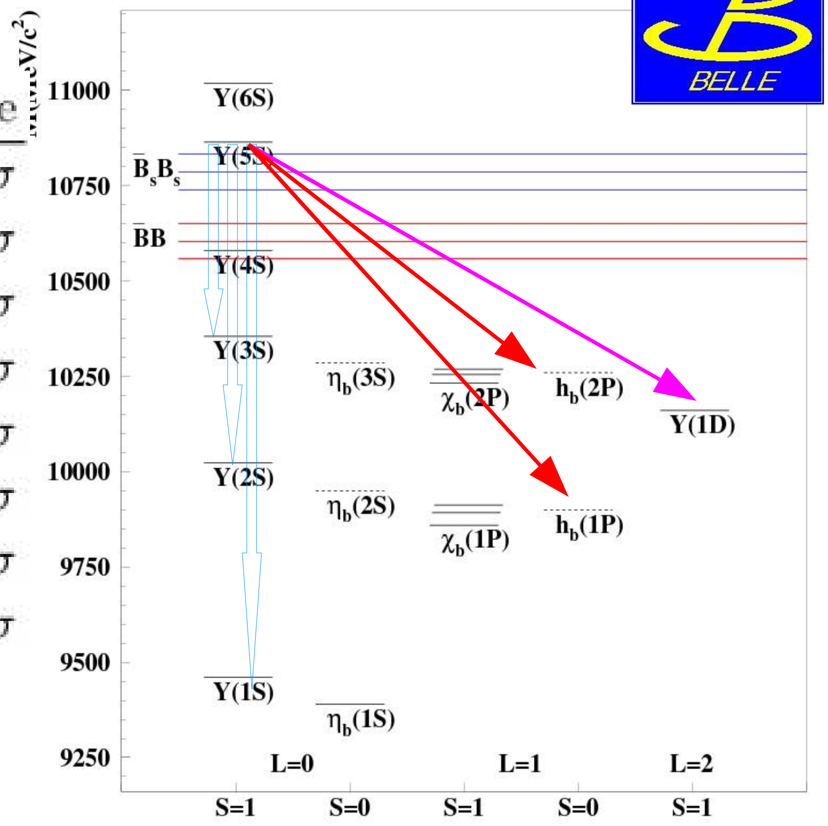
Simultaneous discovery of $h_b(1,2P)$

New pathway to $\Upsilon(1D)$ states

h_b(1,2P) from Υ(5S)

PRL108,032001

	Yield, 10^3	Mass, MeV$/c^2$		Significance
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	⇔	$18.2\,\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.3 \pm 1.1^{+1.0}_{-1.1}$	↔	$6.2\,\sigma$
$3S \to 1S$	56 ± 19	9973.01		$2.9\,\sigma$
$\Upsilon(2S)$	$143.5 \pm 8.7 \pm 6.8$	$10022.3 \pm 0.4 \pm 1.0$	⇔	$16.6\,\sigma$
$\Upsilon(1D)$	22.0 ± 7.8	10166.2 ± 2.6	↔	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	↔	$12.4\,\sigma$
$2S \to 1S$	$151.7 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$		$15.7\,\sigma$
$\Upsilon(3S)$	$45.6 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	⇔	$8.5\,\sigma$



Significance after correcting for systematics effects:

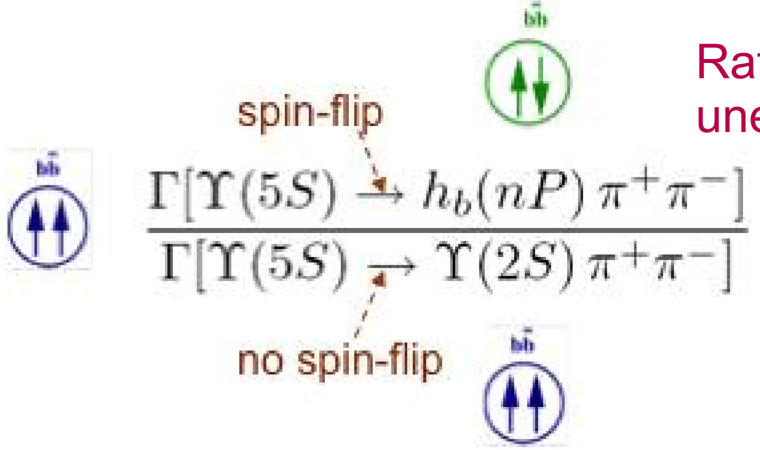
$h_b(1P)$ 5.5σ

$h_b(2P)$ 11.2σ

Masses very close to the state COG of χ states, as expected from theory.

$\Delta M_{HF}(1P) = 1.6 \pm 1.5$ MeV/c^2 $\quad \Delta M_{HF}(2P) = 0.5^{+1.6}_{-1.2}$ MeV/c^2

Ratio of spin flip vs noflip dipion transitions totally unexpected from theory....



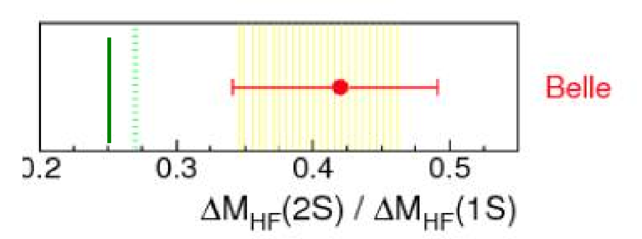
spin-flip

$$\frac{\Gamma[\Upsilon(5S) \to h_b(nP)\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-]} = \begin{cases} 0.46 \pm 0.08^{+0.07}_{-0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08^{+0.22}_{-0.17} & \text{for } h_b(2P) \end{cases}$$

no spin-flip

Parabottomonia vs theory

$\eta_b(2S)$ vs $\eta_b(1S)$

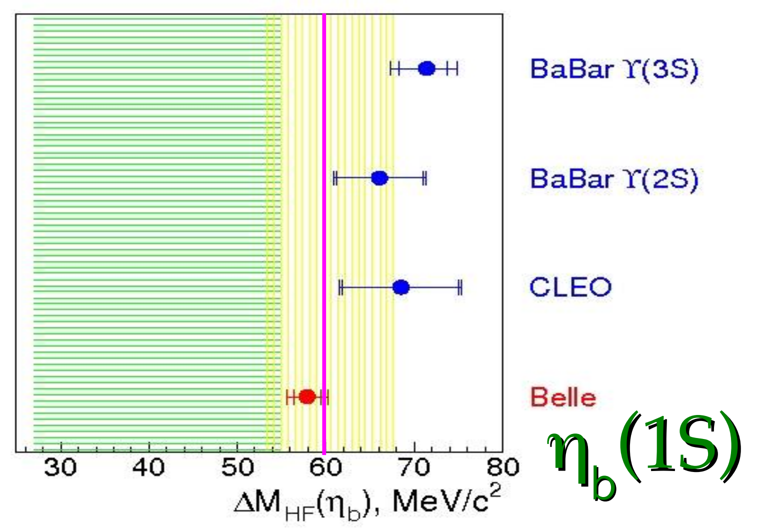


🟩 PNRQCD@NLL
PRL92,242001(2004)

🟨 Lattice QCD
PRD82,114502(2010)

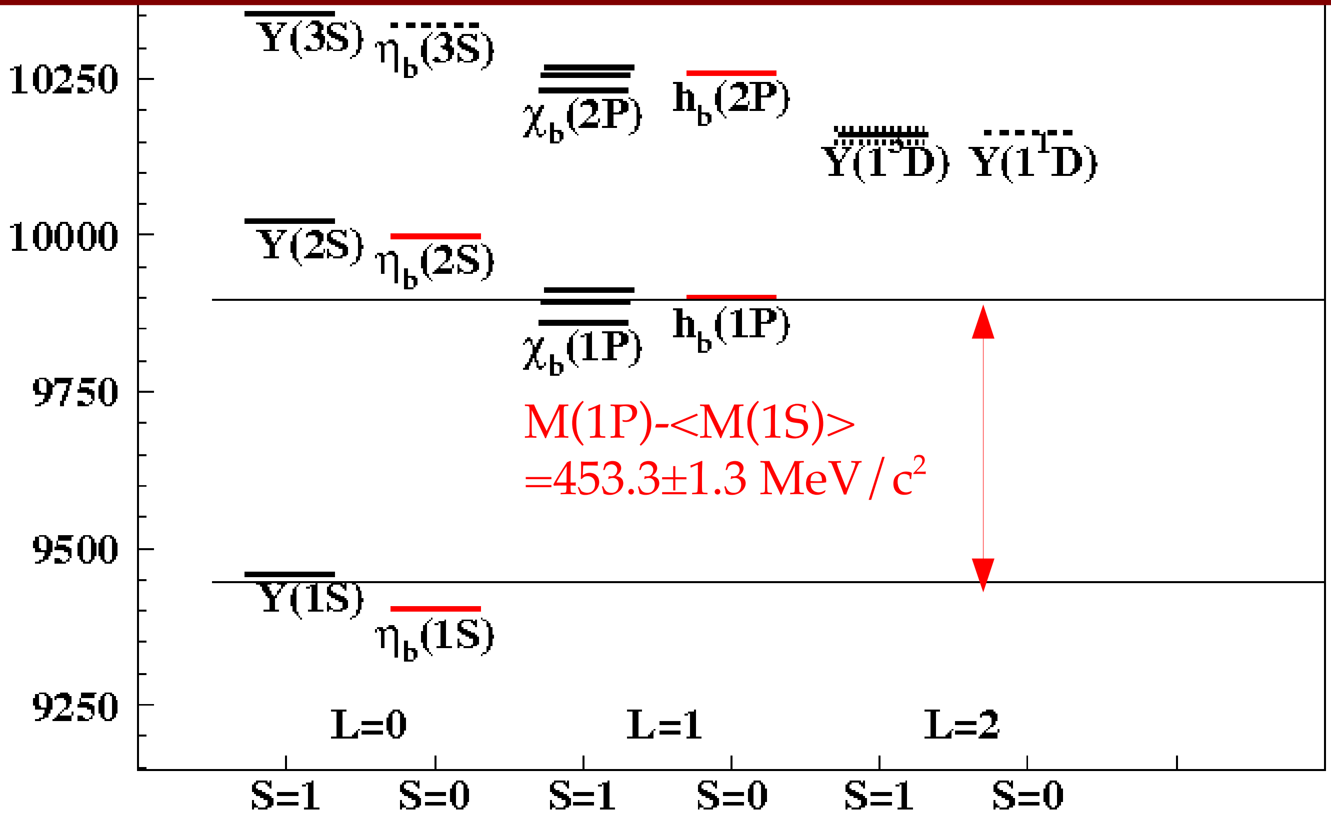
🟪 Godfrey-Isgur,
PRD32,189 (1985)

10 MeV discrepancy w/ earlier Babar and CLEO results



Some tension with the most accurate NRQCD prediction , but very close to lattice QCD (Meinel) predictions.

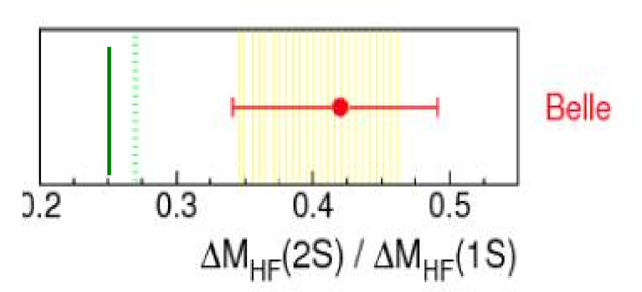
Spin averaged 1P-1S splitting seems not to depend on scale



M(1P)-<M(1S)>
=453.3±1.3 MeV/c^2

Parabottomonia vs theory

$\eta_b(2S)$ vs $\eta_b(1S)$



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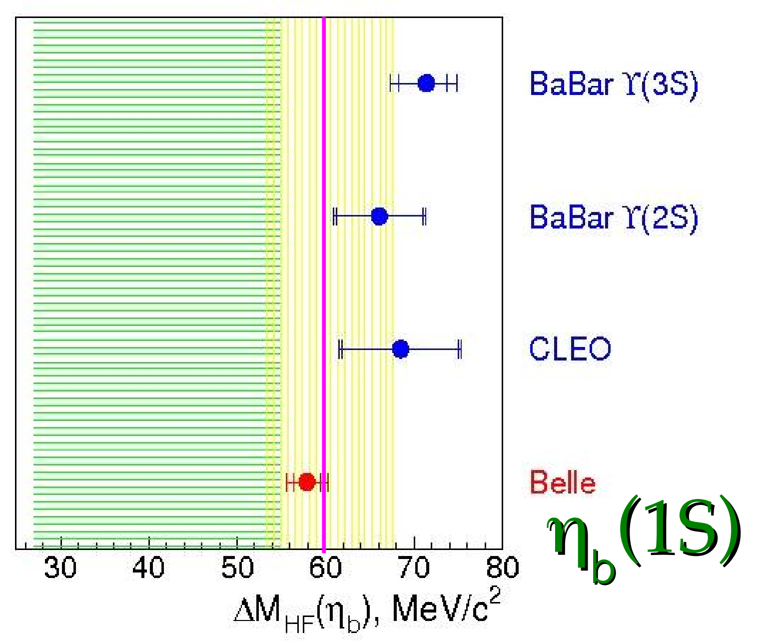
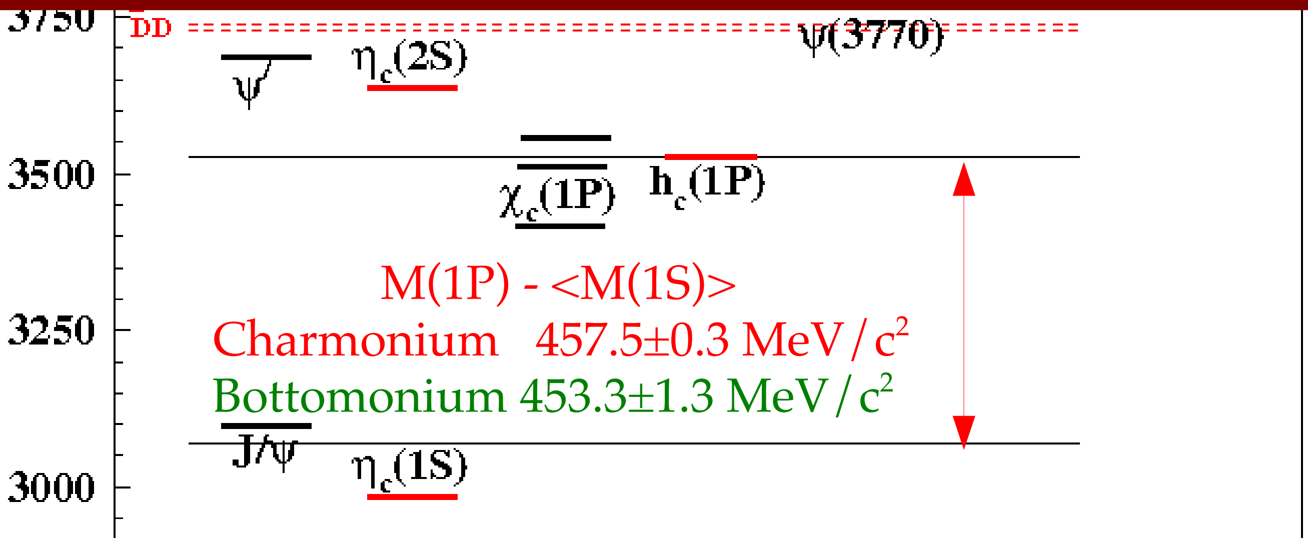
10 MeV discrepancy w/ earlier Babar and CLEO results: Skewed lineshape as in charmonium?



Spin averaged 1P-1S splitting seems not to depend on scale: only 1% difference with charmonium: similarly, the tensor-vector splitting remains constant also in D,Ds.



$M(1P) - \langle M(1S) \rangle$

Charmonium 457.5±0.3 MeV/c^2

Bottomonium 453.3±1.3 MeV/c^2

	$c\bar{u}$	$c\bar{d}$	$c\bar{s}$	$c\bar{c}$	$b\bar{b}$
$M(2^+)-M(1^-)$, in MeV/c^2	452 ± 2	449±4	461±2	458.3±0.1	452.3±0.6

Holy Grail: $\eta_b(1S) \rightarrow \gamma\gamma$

Search for $\eta_b(1S) \rightarrow \gamma\gamma$

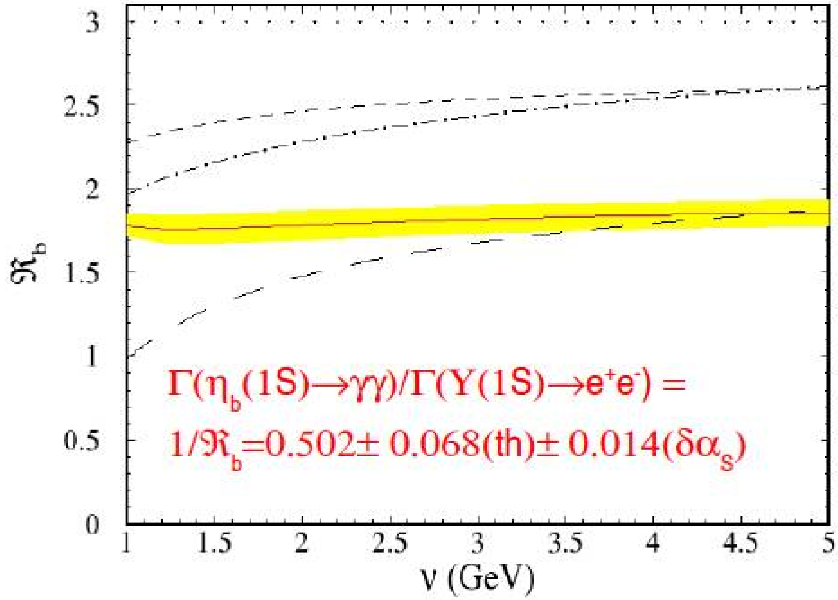
via exclusive channel: $\pi^+\pi^-\gamma(\gamma\gamma)$!!

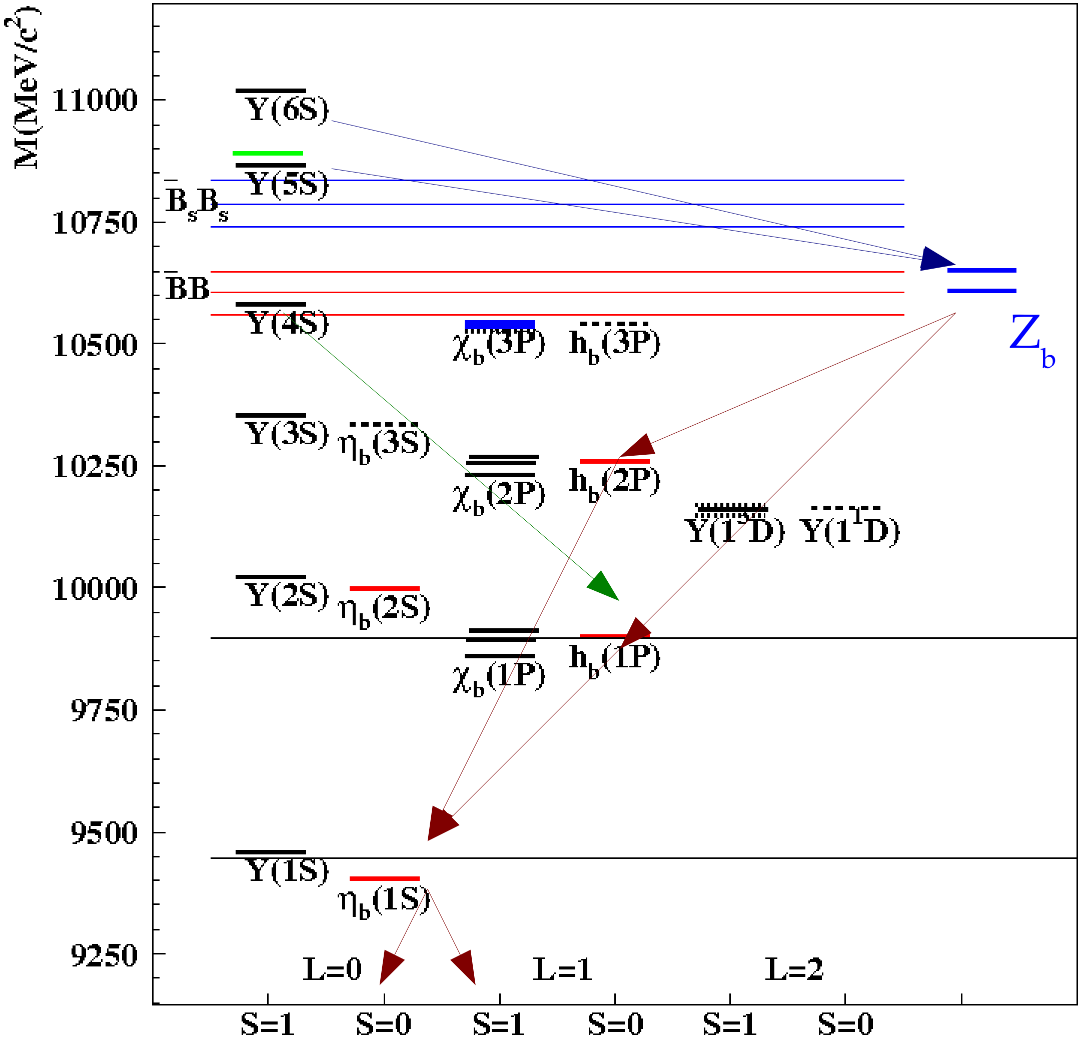
NRQCD NNLL prediction:
Penin et al., NP B699(2004),183

$\Gamma(\eta_b(1S) \rightarrow \gamma\gamma) = 0.66 \pm 0.09$ keV

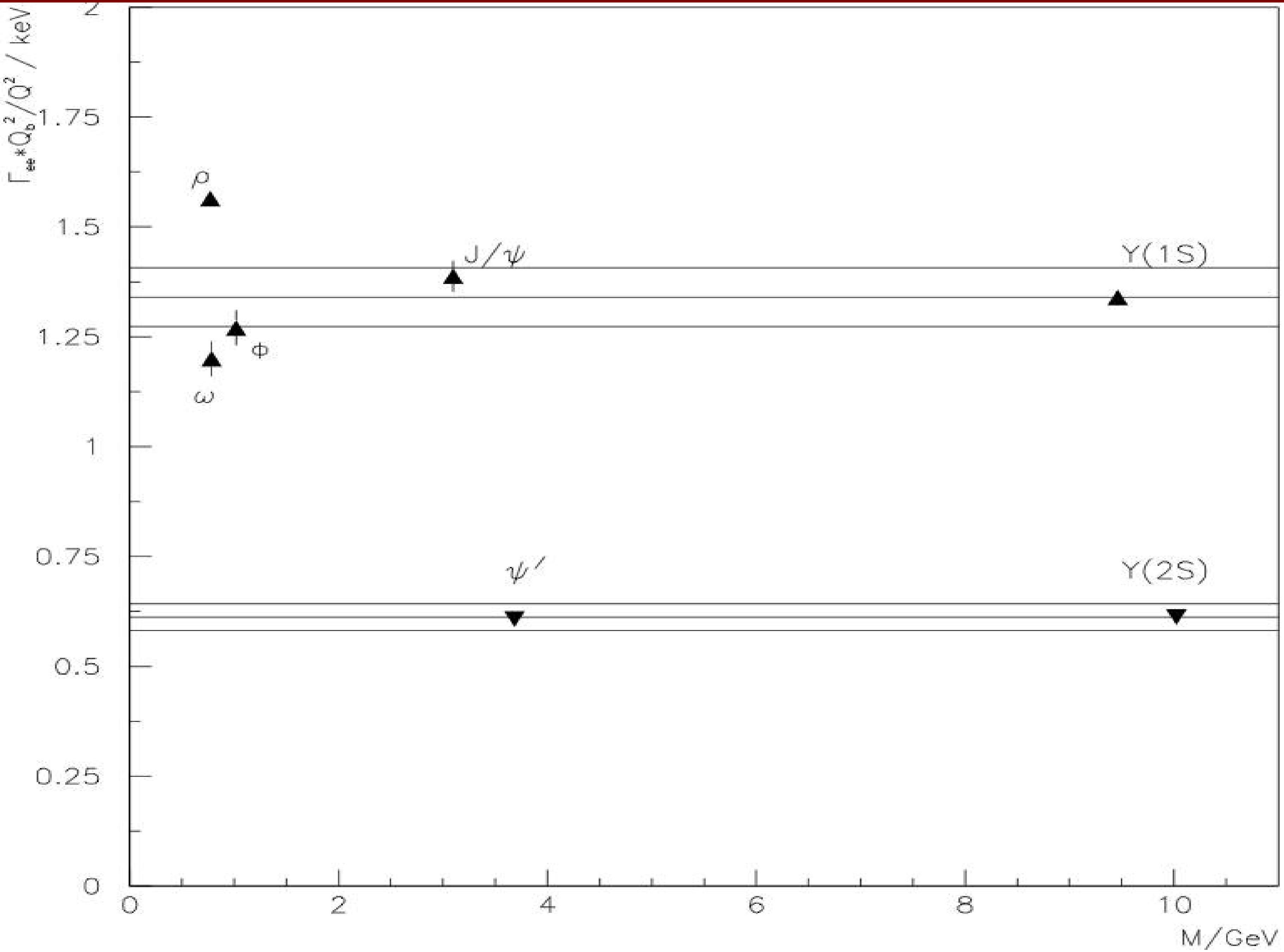
With $\Gamma(\eta_b) = 10$ MeV,

$BR(\eta_b(1S) \rightarrow \gamma\gamma) = 0.66 \cdot 10^{-4}$

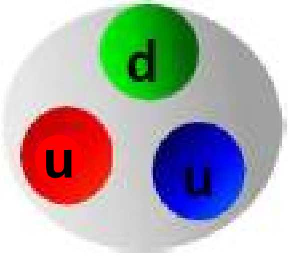




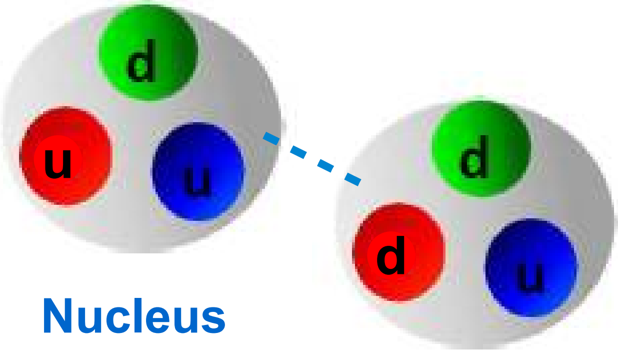
Why the van Royen-Weisskopf formula works so well?



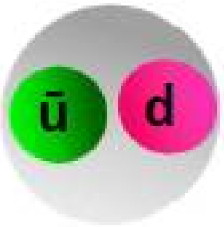
Bound states in QCD



Nucleon



Nucleus

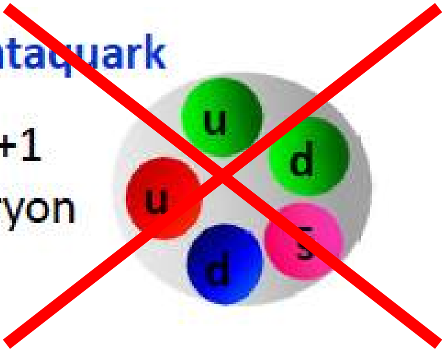


Meson

…. what else?

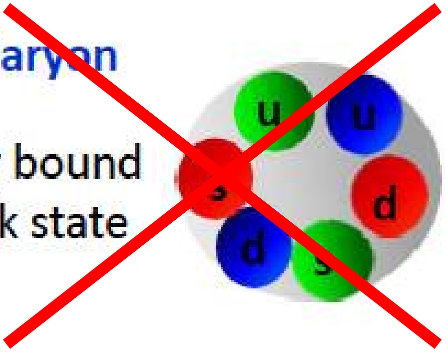
Pentaquark

S= +1
Baryon



H di-Baryon

Tightly bound
6 quark state



Glueball

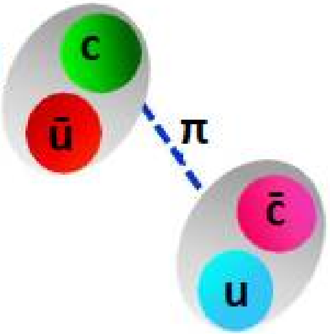
Color-singlet multi-
gluon bound state

Tetraquark

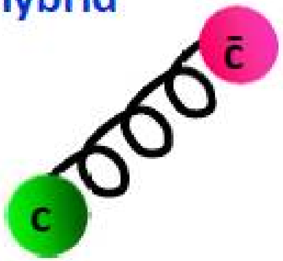
Tightly bound
diquark &
anti-diquark

Molecule

loosely bound
meson-
antimeson
“molecule”



$q\bar{q}$ -gluon hybrid
mesons

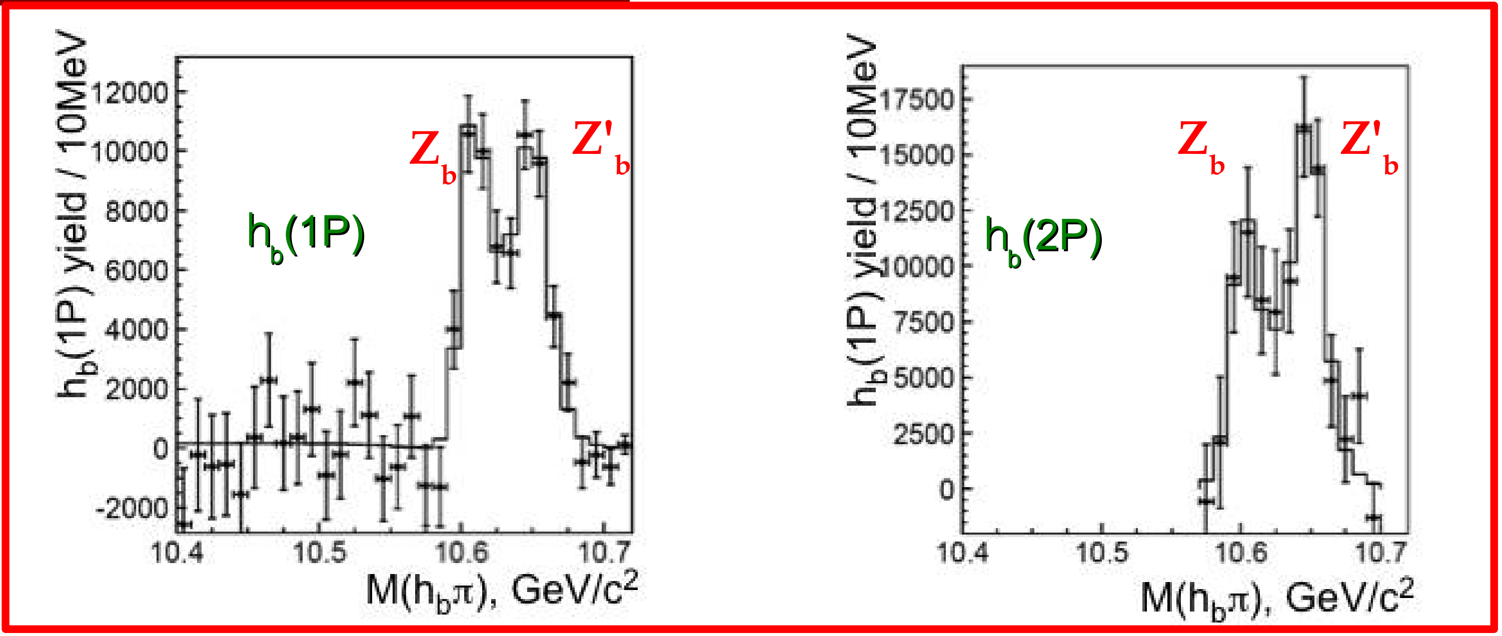


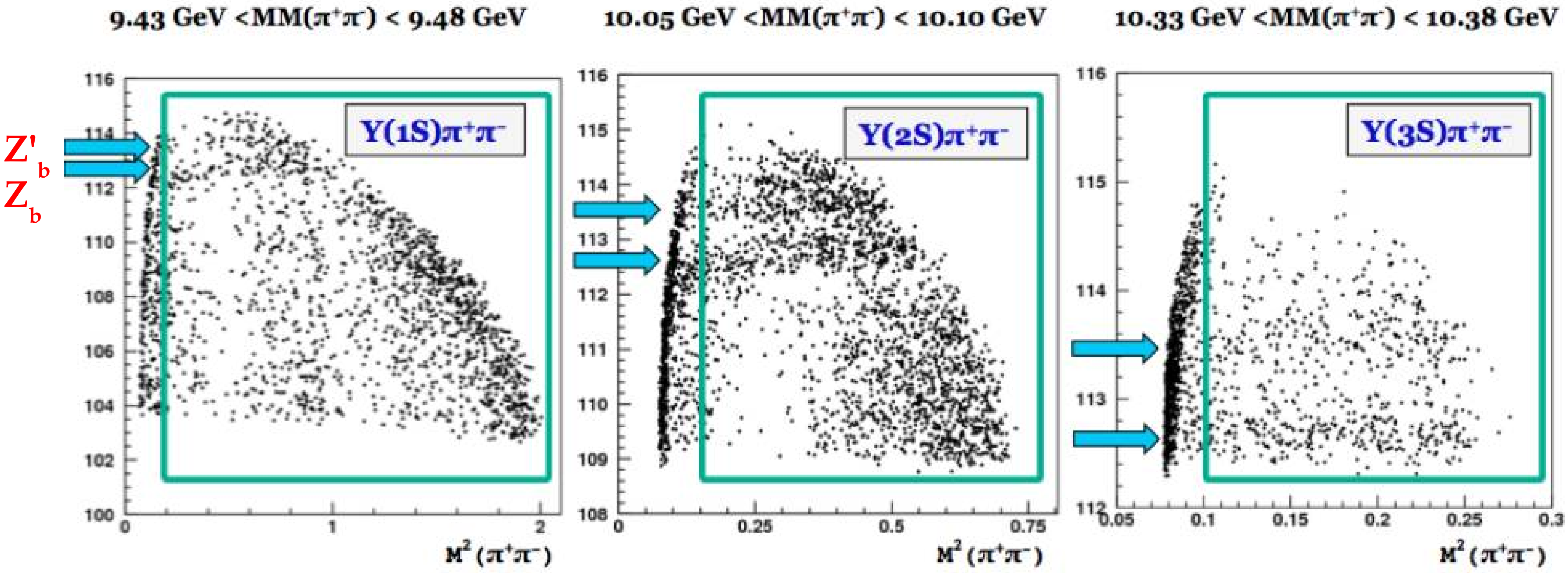
Charged Bottomonia : Z_b's

The two charged bottomonium states are observed in single pion recoil in 5 processes:

- inclusive Υ(5S) decays to h_b(1,2P)

- Dalitz plot of exclusive Υ(5S) dipion transitions to Υ(1,2,3S)




9.43 GeV <MM($\pi^+\pi^-$) < 9.48 GeV

10.05 GeV <MM($\pi^+\pi^-$) < 10.10 GeV

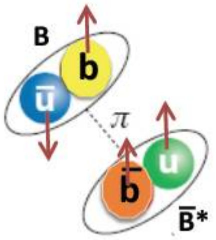
10.33 GeV <MM($\pi^+\pi^-$) < 10.38 GeV

Z_b parameters

PRL108,122001(2011)

Belle discovered two charged bottomonium-like resonances:

Z(10610)

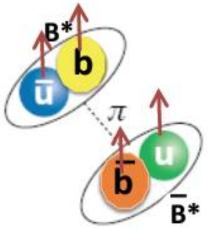


M=10607.2±2.0 MeV

Γ=18.4±2.4 MeV

$M_B + M_{B*} = 10604.5 \pm 0.6$ MeV

Z(10650)



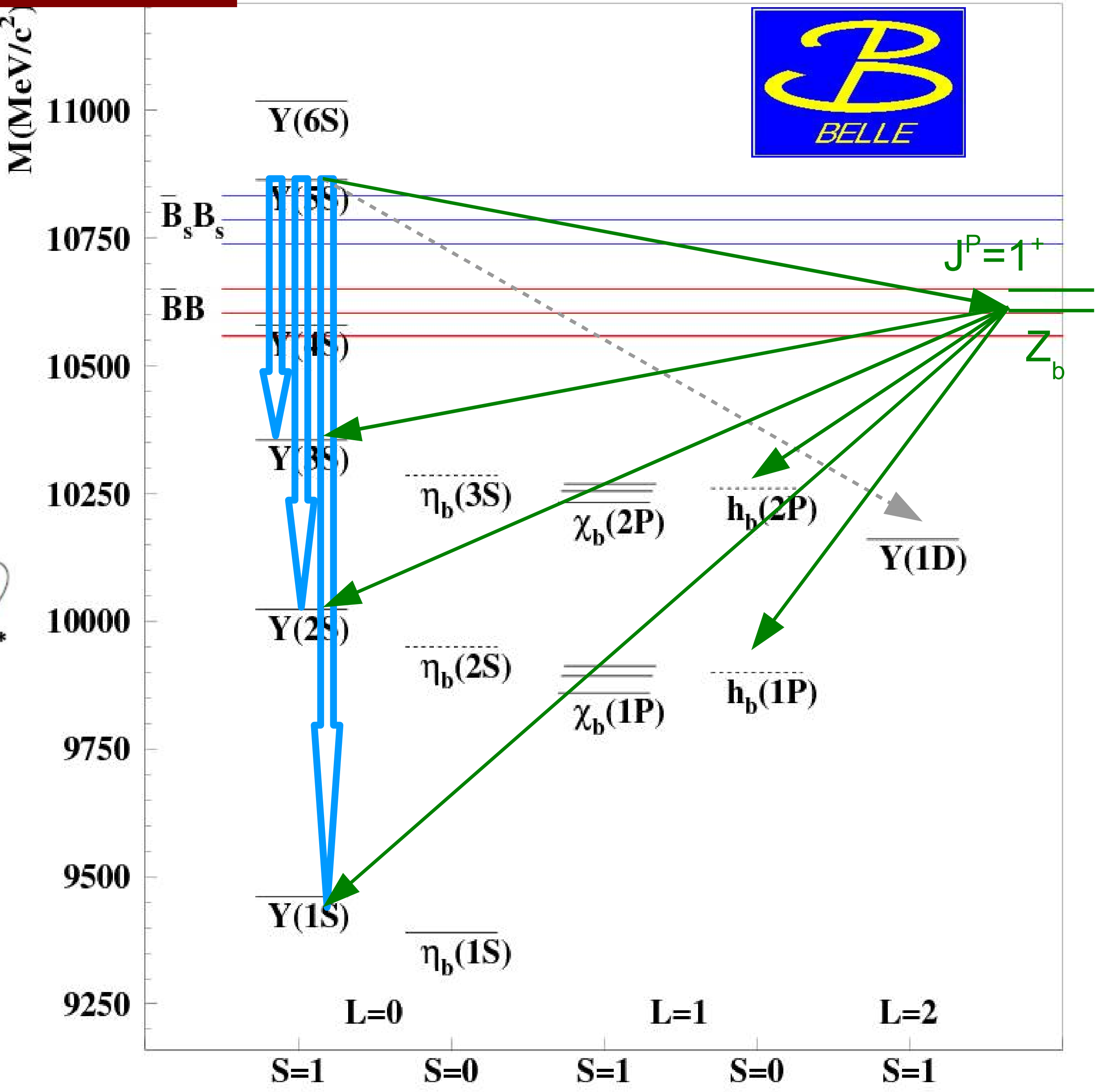
M=10652.2±1.5 MeV

Γ=11.5±2.2 MeV

$M_{B*} + M_{B*} = 10650.2 \pm 1.0$ MeV

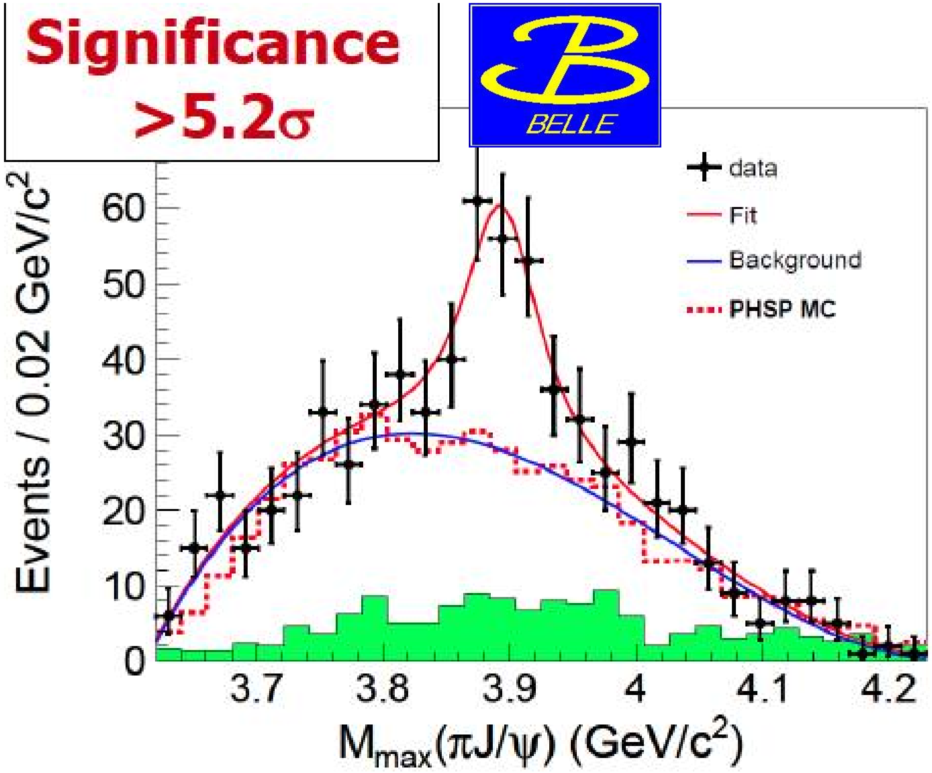
Analysis of angular distributions suggests $J^P=1^+$ for both these states. Observation of Zb decays to BB* and B*B* is consistent with molecular nature of the charged bottomonia. (Voloshin, Bondar, et al)

ArXiV:1207.4345:
Evidence of neutral partner of lower Zb in Yπ^0 with 4.9 sigma significance

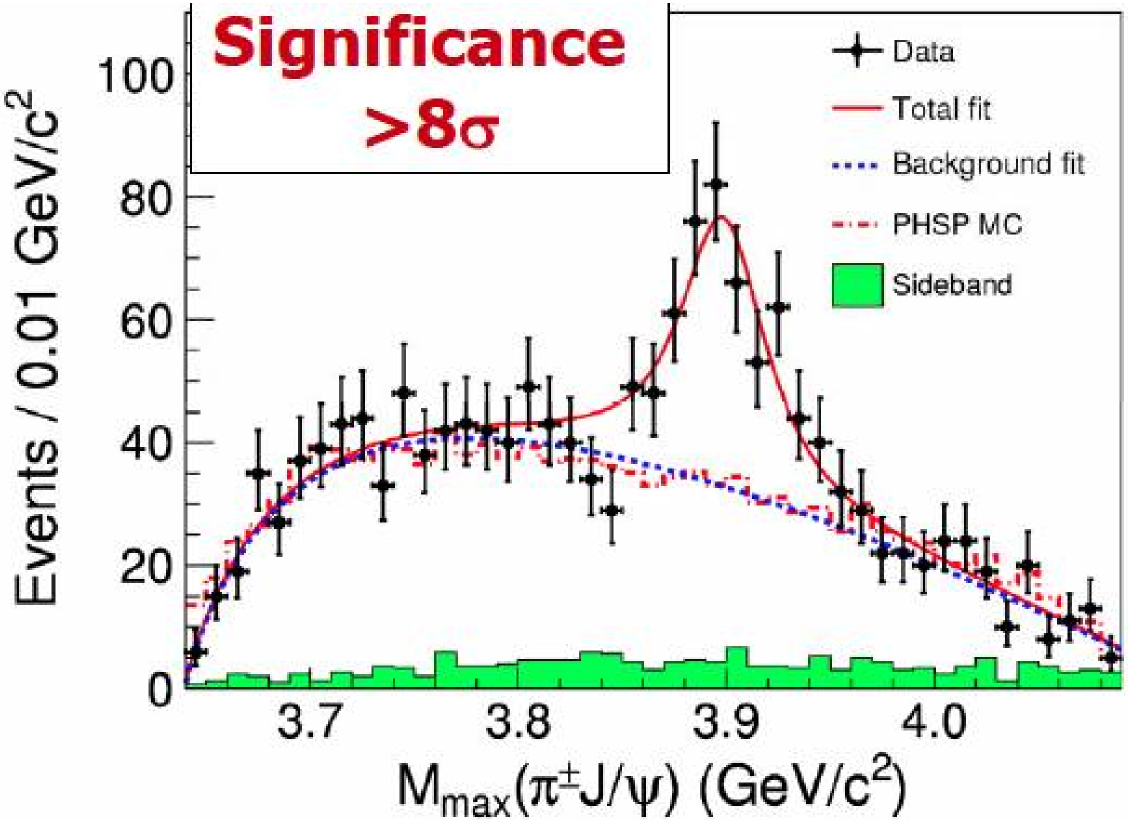


Zc(3900): tetraquarks or meson molecules?

BES-III



Significance
>5.2σ



Significance
>8σ

Belle: 927 fb^{-1} of ISR data at ϒ(nS) energy

BES-III: 525 pb^{-1} @ Y(4260) peak energy

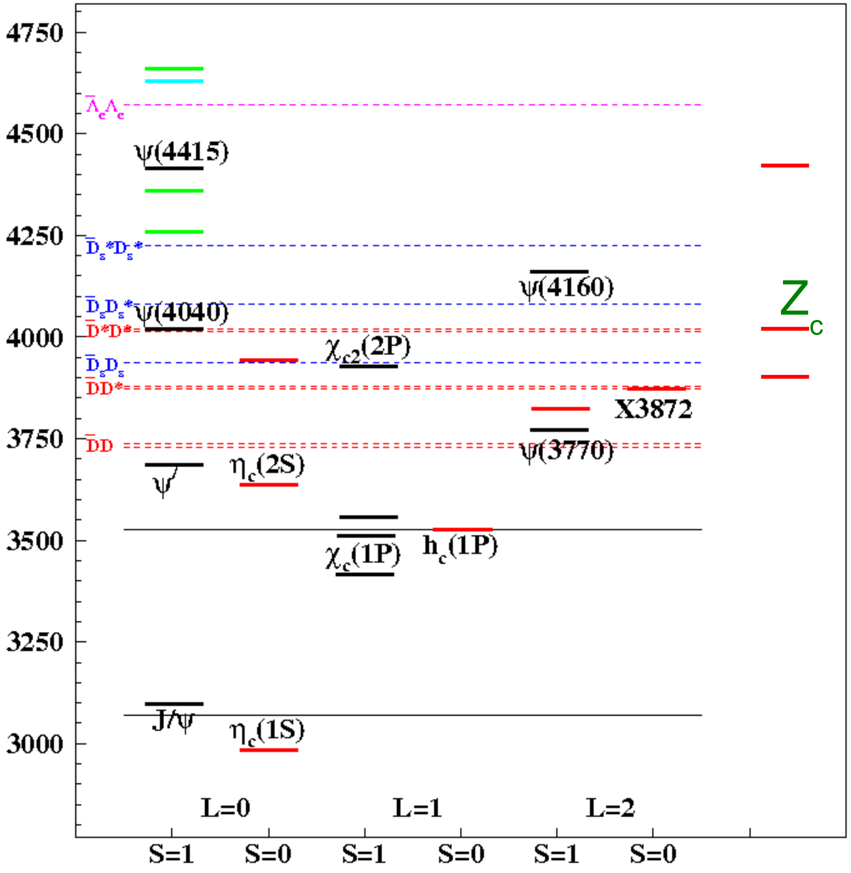
Phys.Rev.Lett. 110 (2013) 252002

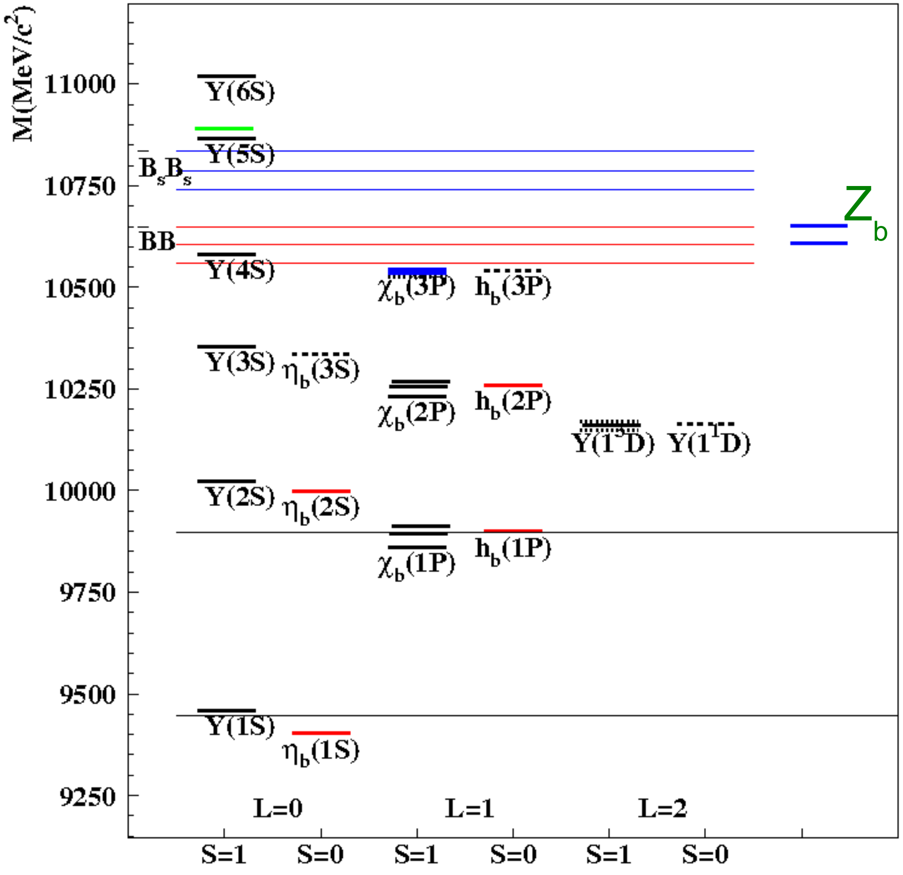
- Mass = (3894.5±6.6±4.5) MeV
- Width = (63±24±26) MeV
- Fraction = (29.0±8.9)% (stat. error only)

Phys.Rev.Lett. 110 (2013) 252001

- Mass = (3899.0±3.6±4.9) MeV
- Width = (46±10±20) MeV
- Fraction = (21.5±3.3±7.5)%

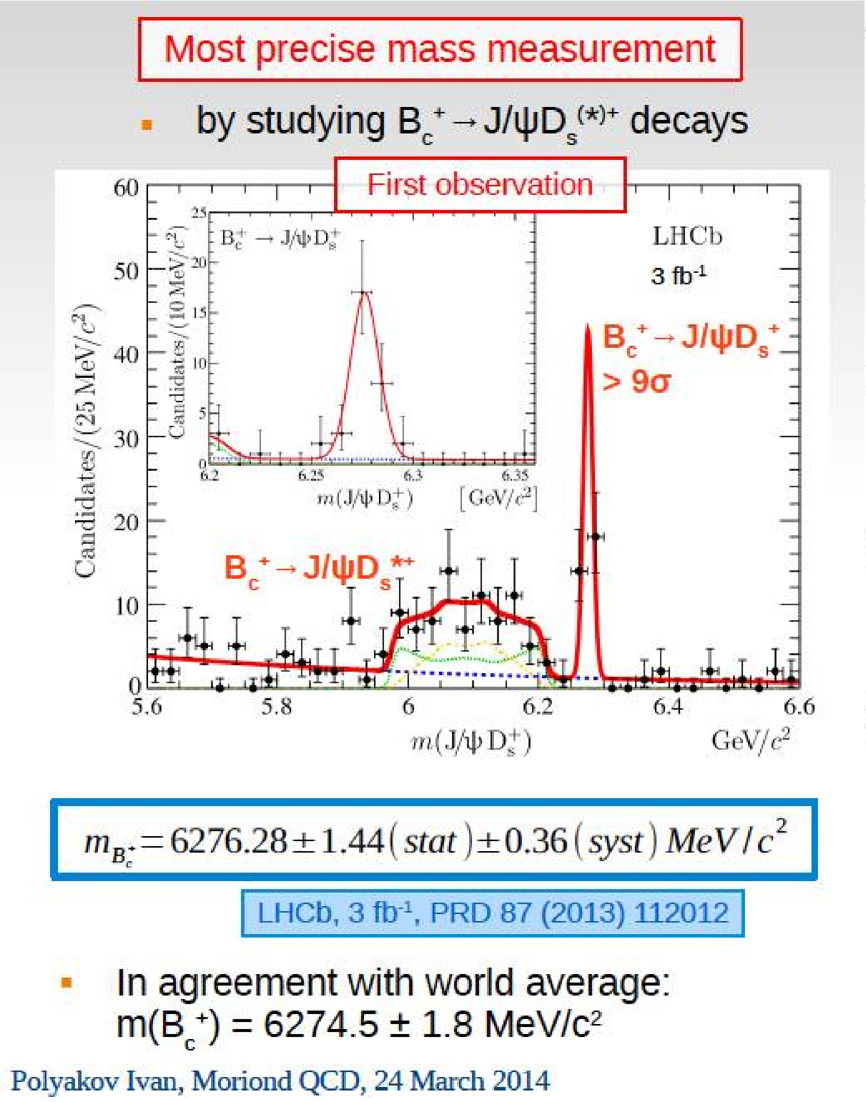
Charged heavy quarkonia





In the last years , 2 (+3 in B decays) Zc states and 2 Zb states were observed: their nature is still uncertain : tetraquark or molecules? Further studies are needed to build a model of these states.

Future: Bc spectroscopy



Most precise mass measurement

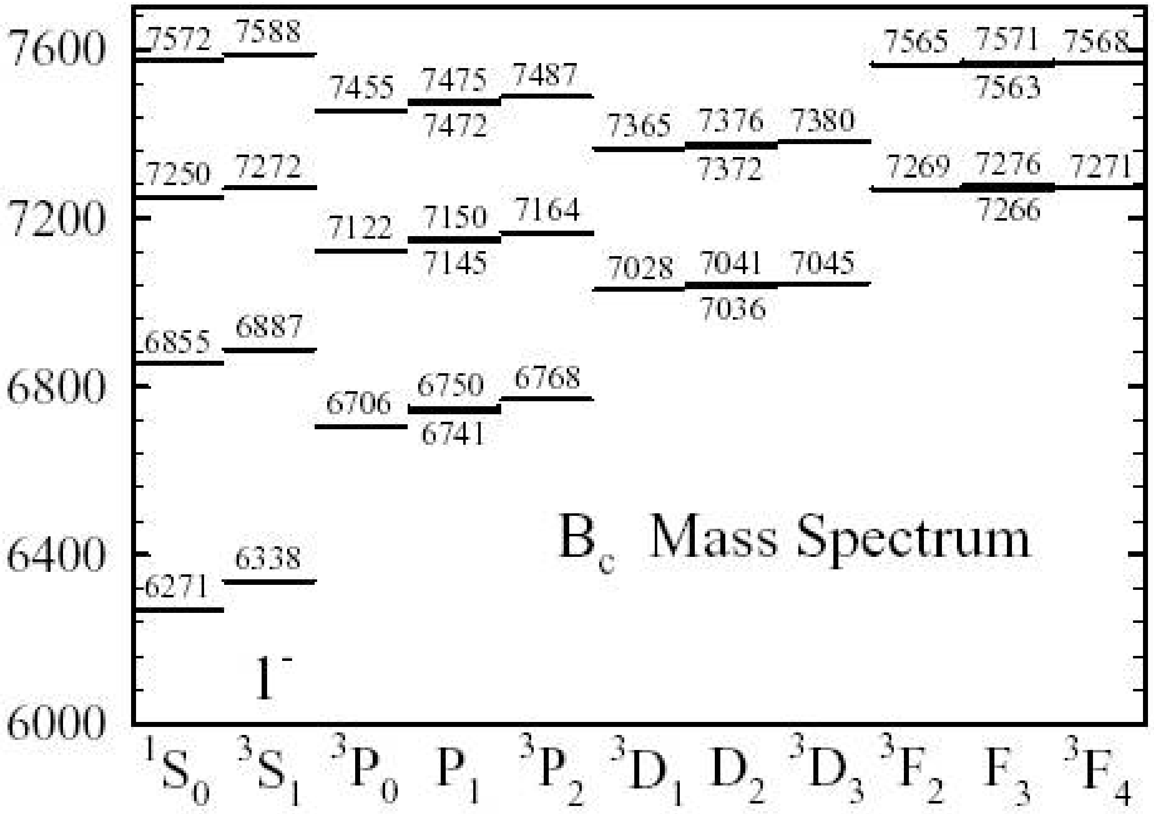
- by studying $B_c^+ \to J/\psi D_s^{(*)+}$ decays

$$m_{B_c^+} = 6276.28 \pm 1.44(stat) \pm 0.36(syst)\, MeV/c^2$$

LHCb, 3 fb^{-1}, PRD 87 (2013) 112012

- In agreement with world average: $m(B_c^+) = 6274.5 \pm 1.8$ MeV/c^2

Polyakov Ivan, Moriond QCD, 24 March 2014



Photon and dipion transitions to study the Bc spectrum : a great opportunity for LHCB!

Summary

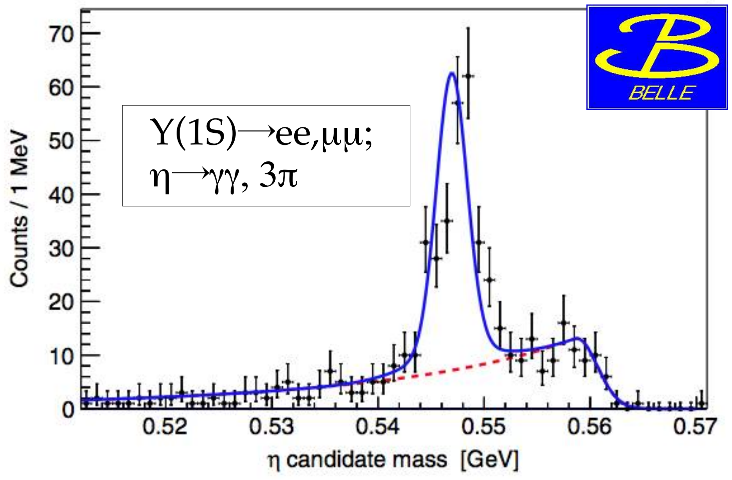
A pretty consistent pattern is emerging in the spectra of heavy baryons, heavy-light mesons, heavy onia, which shows little dependence on the mass scale, and on the running properties of QCD coupling constant. Besides the large developments of QCD based EFTs (NRQCD,HQET, chiral EFT,SCET, and lattice QCD) the success of constituent quark model is hard to be explained from first principles. Are we overlooking some hidden symmetry?

Spin anomalies in hadron transition amplitudes has led to nice surprises in the recent years of heavy quarkonium spectroscopy, and may need to further interesting developments.

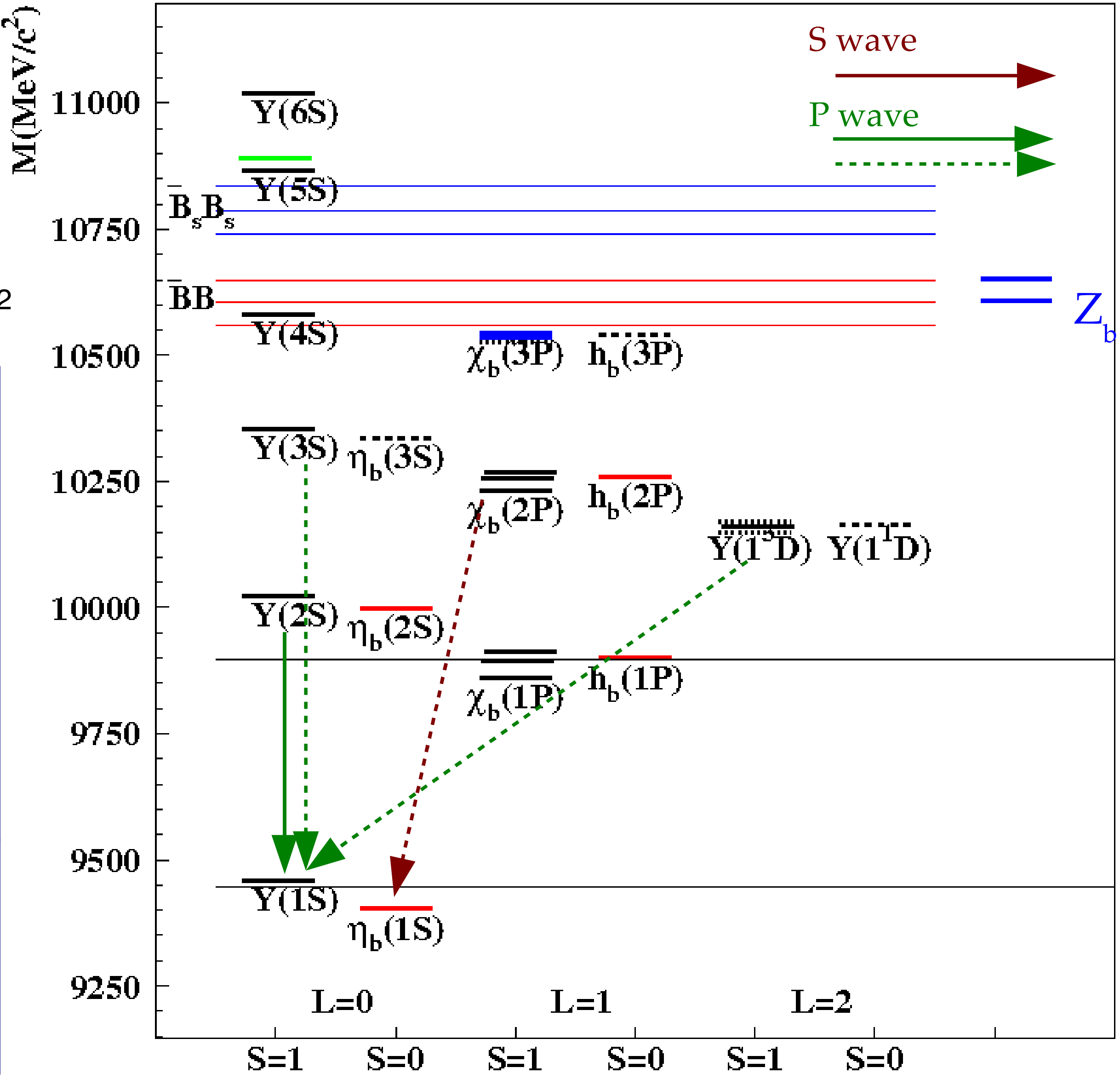
While future spectroscopy studies will focus on Bc , P waves, and multiquark systems, more information can come from the studies of hadronic and radiative transitions of known states.

The η transitions

Testing QCD multipole expansion
In low mass region:
Υ' → ηΥ : M2*E1+M1*M1
Υ' → ππΥ : E1*E1
(Υ' → ηΥ)/(Υ' → ππΥ) ~ $(\Lambda_{QCD}/m_b)^2$



B(Υ(2S) → ηΥ(1S))	theory(*): ~4× 10^{-4}
CLEO PRL101,192001	(2.10±0.70±0.40)× 10^{-4}
BaBar PRD84,42003(2011)	(2.39 ± 0.31 ±0.14)×10^{-4}
Belle PRD87,011104(R) (2013)	(3.41± 0.28± 0.35)×10^{-4}



(*)Most theory papers are in the range 7-16x10^{-4}. Voloshin, Prog.Part.Nucl.Phys.61,455(2008), predicts 4.3× 10^{-4}

- The process Υ(1D) → ηΥ(1S) should be enhanced with respect to Υ(1D) → ππΥ(1S) because of Triangle anomaly in QCD Voloshin: PLB 562, 68(2003) Work in progress at Belle

The η transitions

QCDME does not apply on higher states: coupled channel effects proposed, need more crosschecks.

Babar *PRD78,112002 (2008)*

B(Υ(4S) ⟶ ηΥ(1S))

= (1.96±0.06±0.09)× 10^{-4}

= 2.5 x B(Υ(4S) ⟶ ππΥ(1S))

Belle

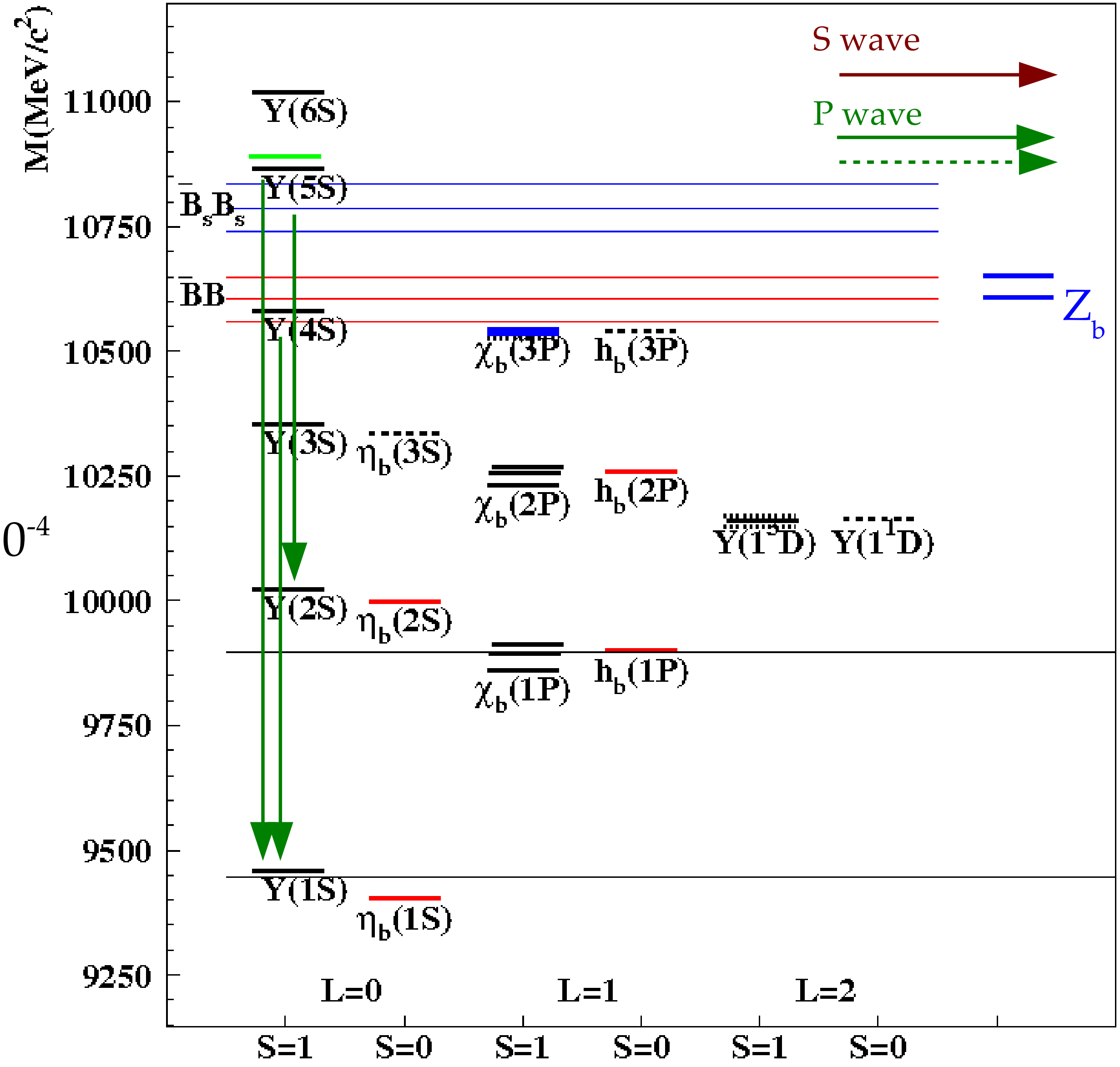
B(Υ(5S) ⟶ ηΥ(1S))=(7.3±1.6±0.8)× 10^{-4}

= 0.25 x B(Υ(5S) ⟶ ππΥ(1S))

B(Υ(5S) ⟶ ηΥ(2S))=(38±4±5) × 10^{-4}

= B(Υ(5S) ⟶ ππΥ(2S))

All measured η transitions are P-wave.



The η transitions

QCDME does not apply on higher states: coupled channel effects proposed, need more crosschecks.

Babar *PRD78,112002 (2008)*

$B(\Upsilon(4S) \rightarrow \eta\Upsilon(1S))$

$= (1.96\pm0.06\pm0.09)\times 10^{-4}$

$= 2.5 \times B(\Upsilon(4S) \rightarrow \pi\pi\Upsilon(1S))$

Belle

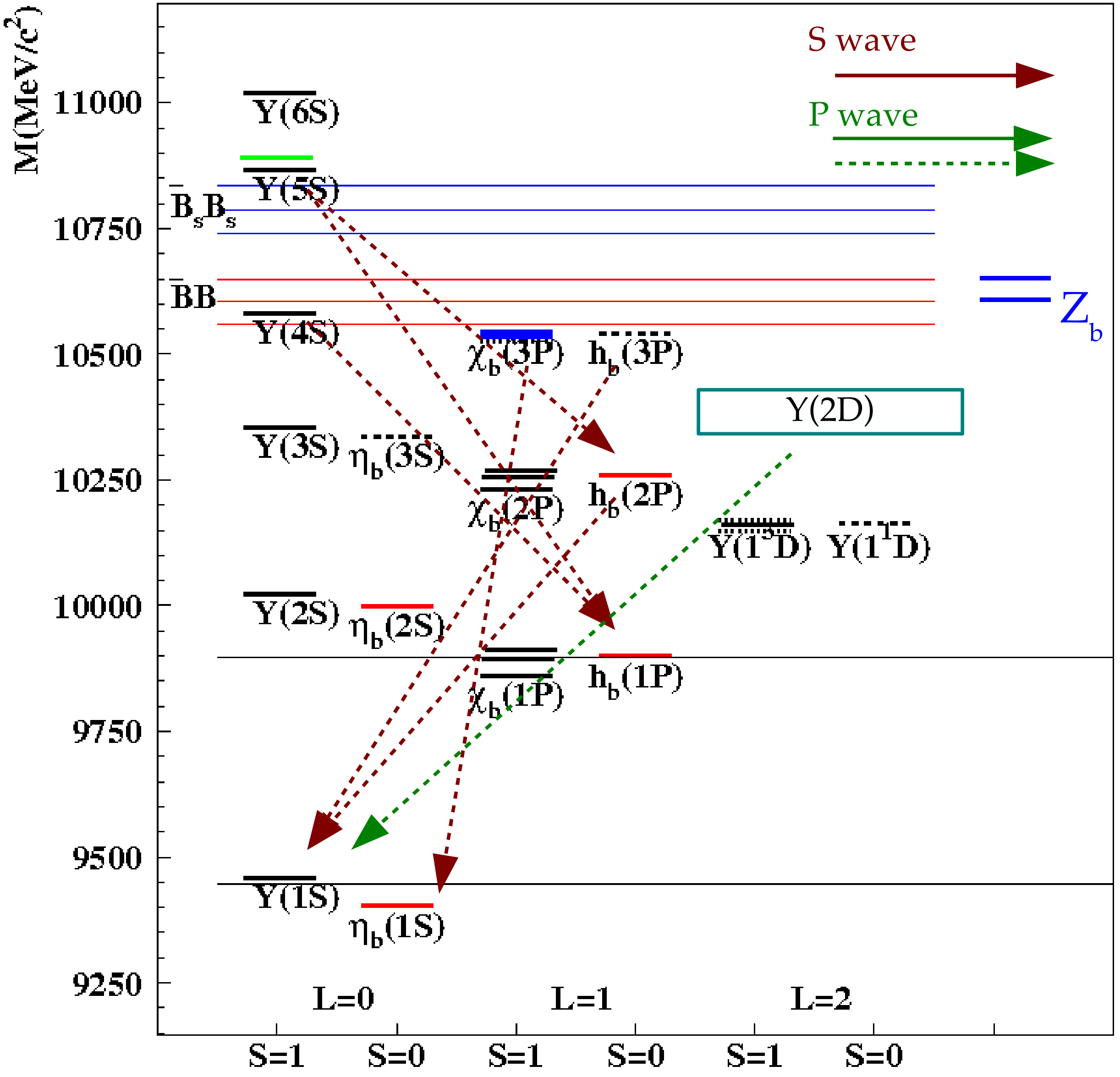
$B(\Upsilon(5S) \rightarrow \eta\Upsilon(1S)) = (7.3\pm1.6\pm0.8)\times$ 1(

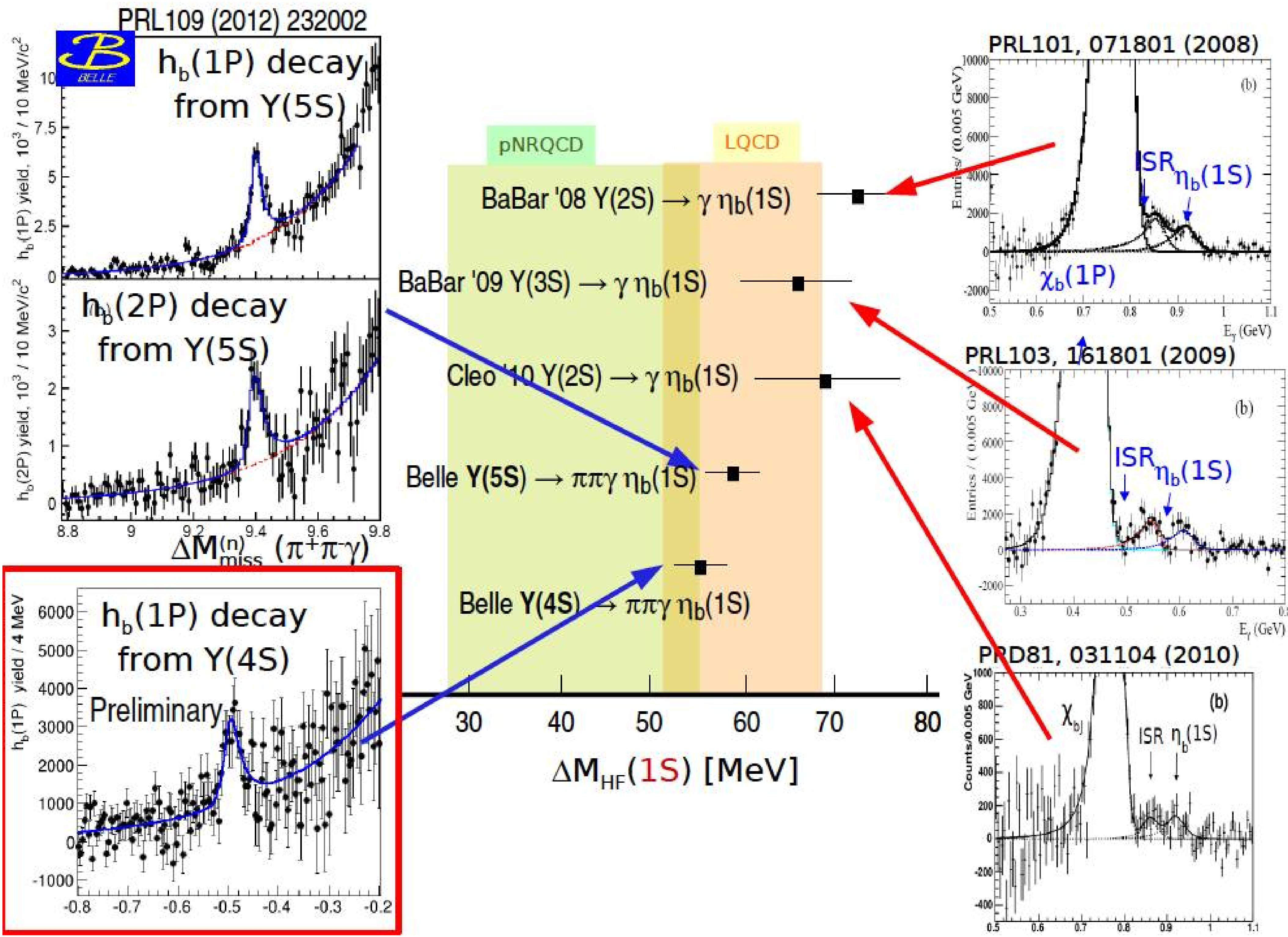
$= 0.25 \times B(\Upsilon(5S) \rightarrow \pi\pi\Upsilon(1S))$

$B(\Upsilon(5S) \rightarrow \eta\Upsilon(2S)) = (38\pm4\pm5)\times 10^{-4}$

$= B(\Upsilon(5S) \rightarrow \pi\pi\Upsilon(2S))$

All measured η transitions are P-wave.
Belle is now searching for all missing S-wave transitions





PRL109 (2012) 232002

PRL101, 071801 (2008)

PRL103, 161801 (2009)

PRD81, 031104 (2010)