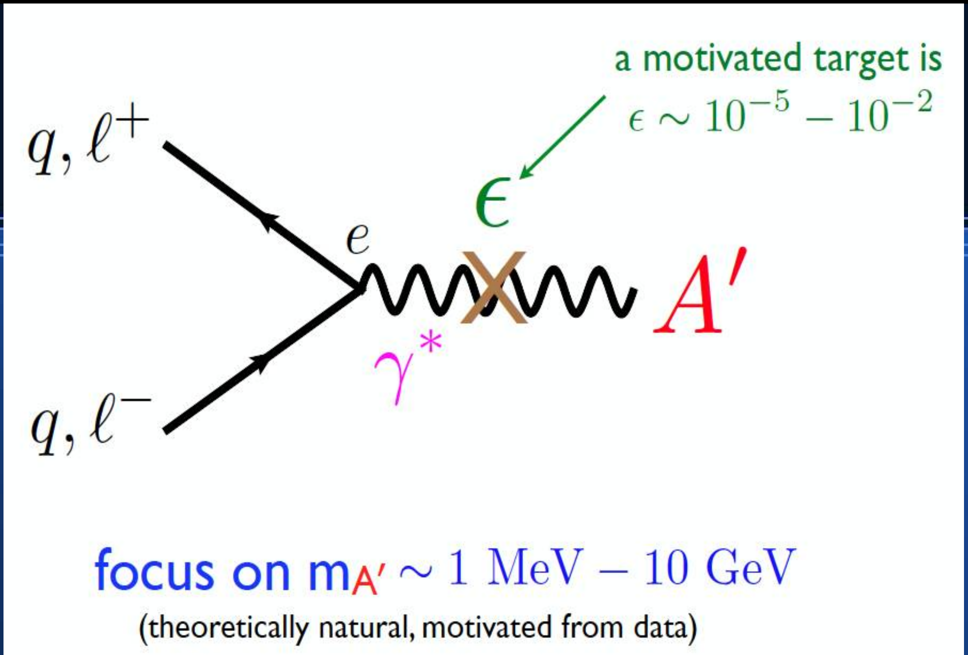
Dark sector and Spectroscopy at Belle-II

- The Dark Sector in continuum
- Heavy onia (S=1 & 0) as portals to DM and light Higgs
- Tagging of invisible bottomonium decays
- Spin effects on hadron masses and widths
- Multiquarks : $Z_{c,b}$ states and Dibaryons

Portals to the "Dark Sector"

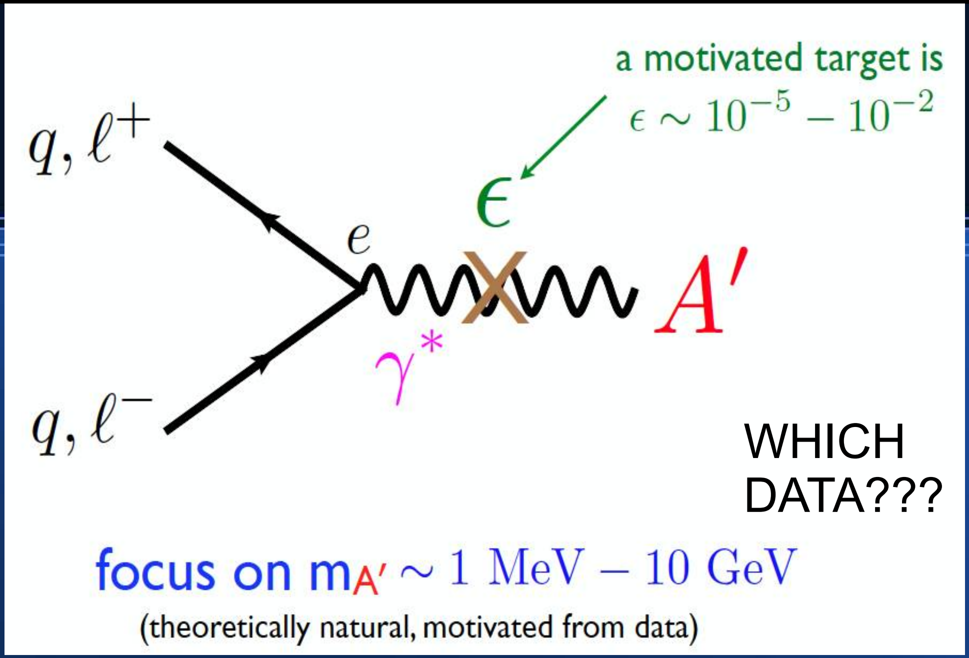
• "Vector"	$\epsilon F^{Y,\mu\nu} F'_{\mu\nu}$	dark photon A'
• "Axion"	$\frac{1}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} a$	axions & axion-like particles (ALPs)
• "Higgs"	$\lambda H^2 S^2 + \mu H^2 S$	exotic Higgs decays?
• "Neutrino"	$\kappa (HL) N$	sterile neutrinos?

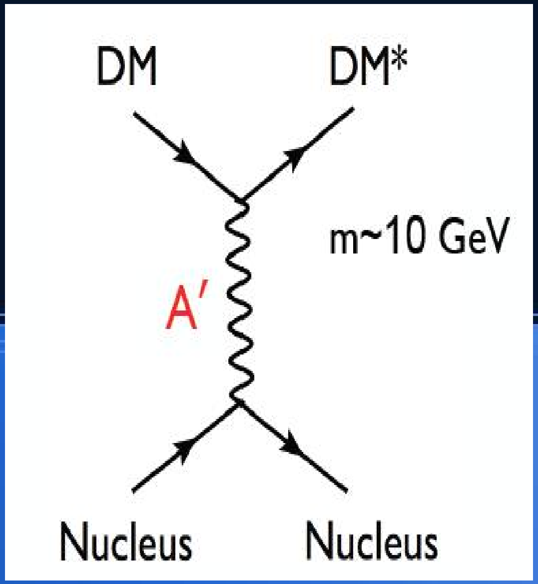
Dark Photon: refugium peccatorum



WHICH DATA???

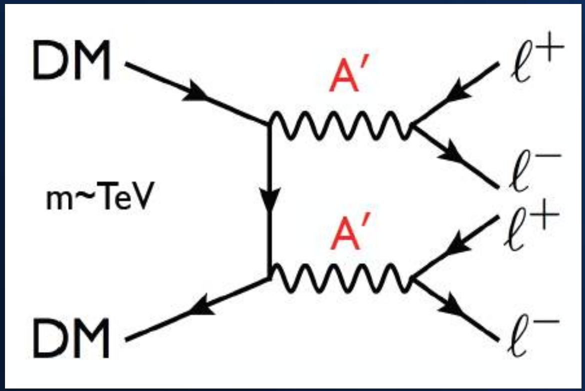
Dark Photon: refugium peccatorum

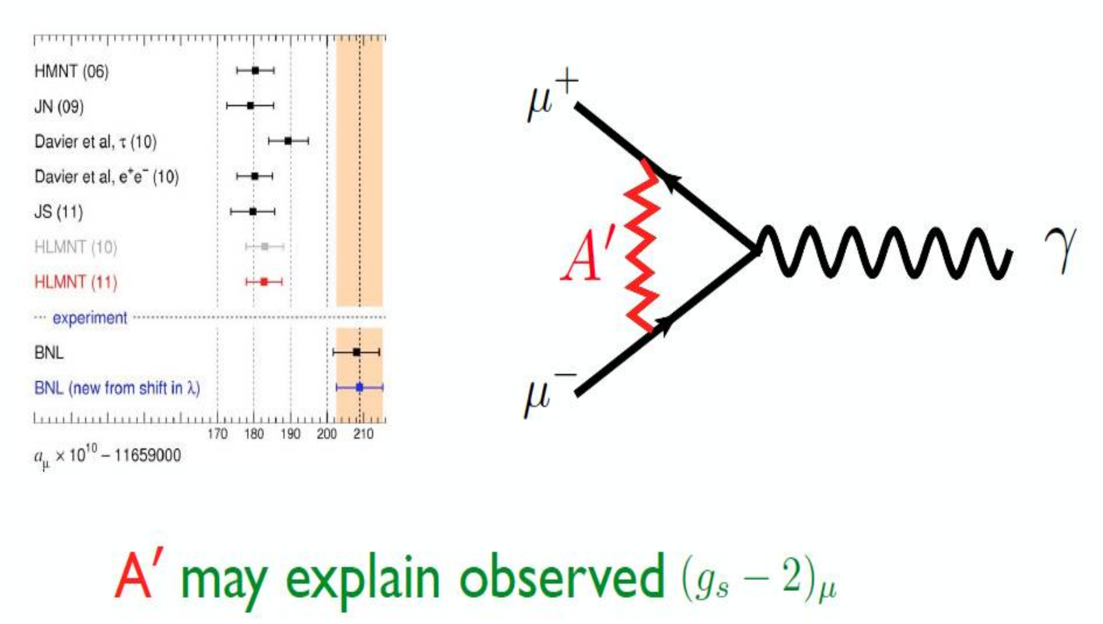




A' may explain the DAMA, CoGENT, CRESST, CDMS-S signals

A' may explain the e+e- excess in Pamela, Fermi, AMS2



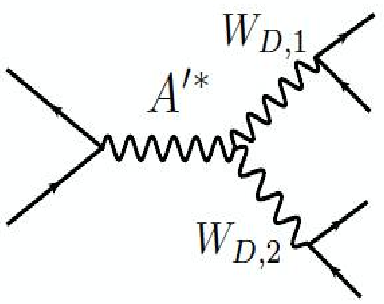


Higher order perversions: "Dark Ws" and "Dark Higgs"

e+e- → 4 leptons

non-Abelian
(many gauge bosons)

0908.2821 (BaBar)

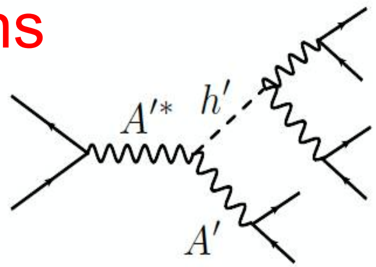


e+e- → 6 leptons

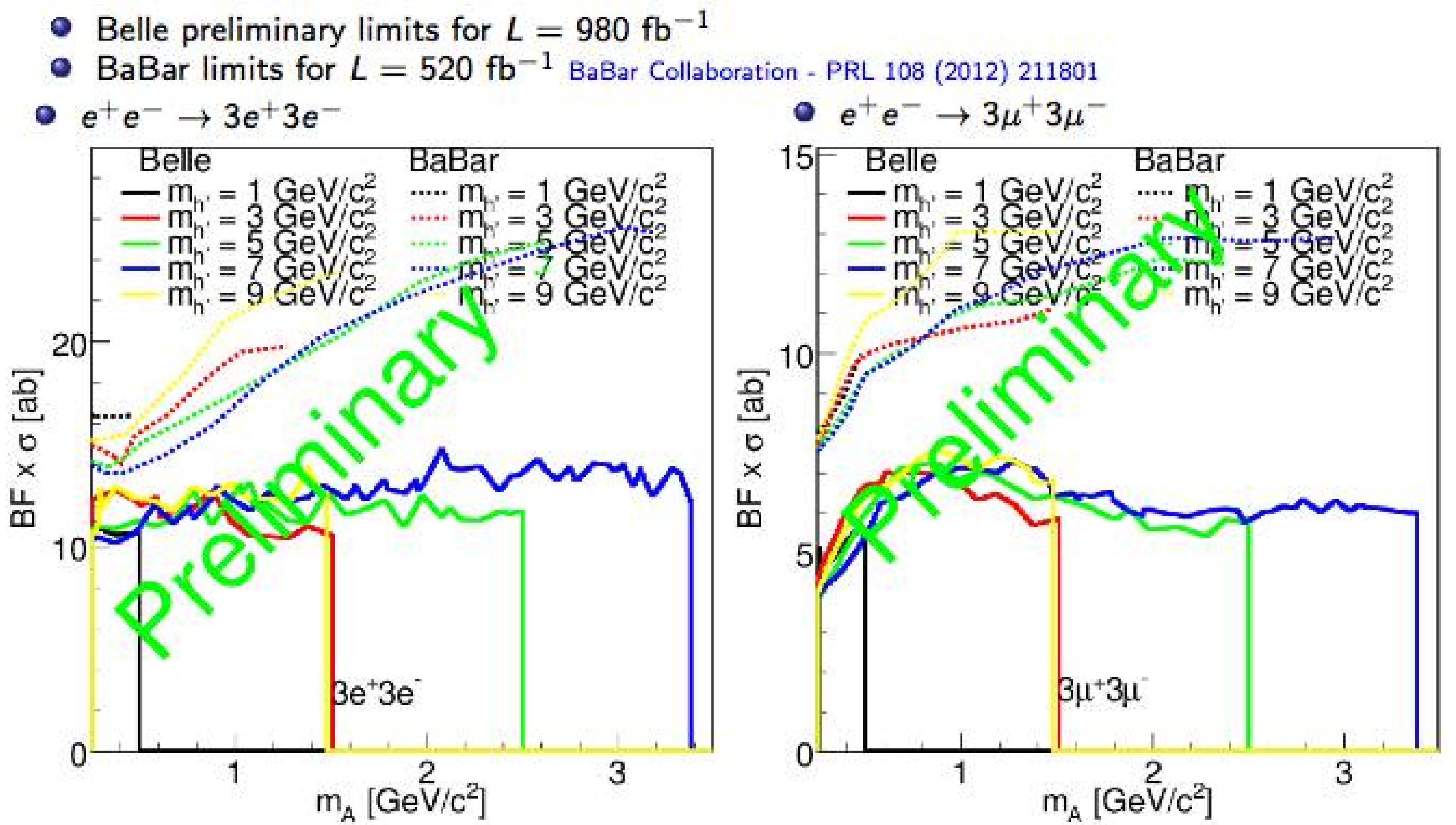
Dark Higgs boson

1202.1313 (BaBar)

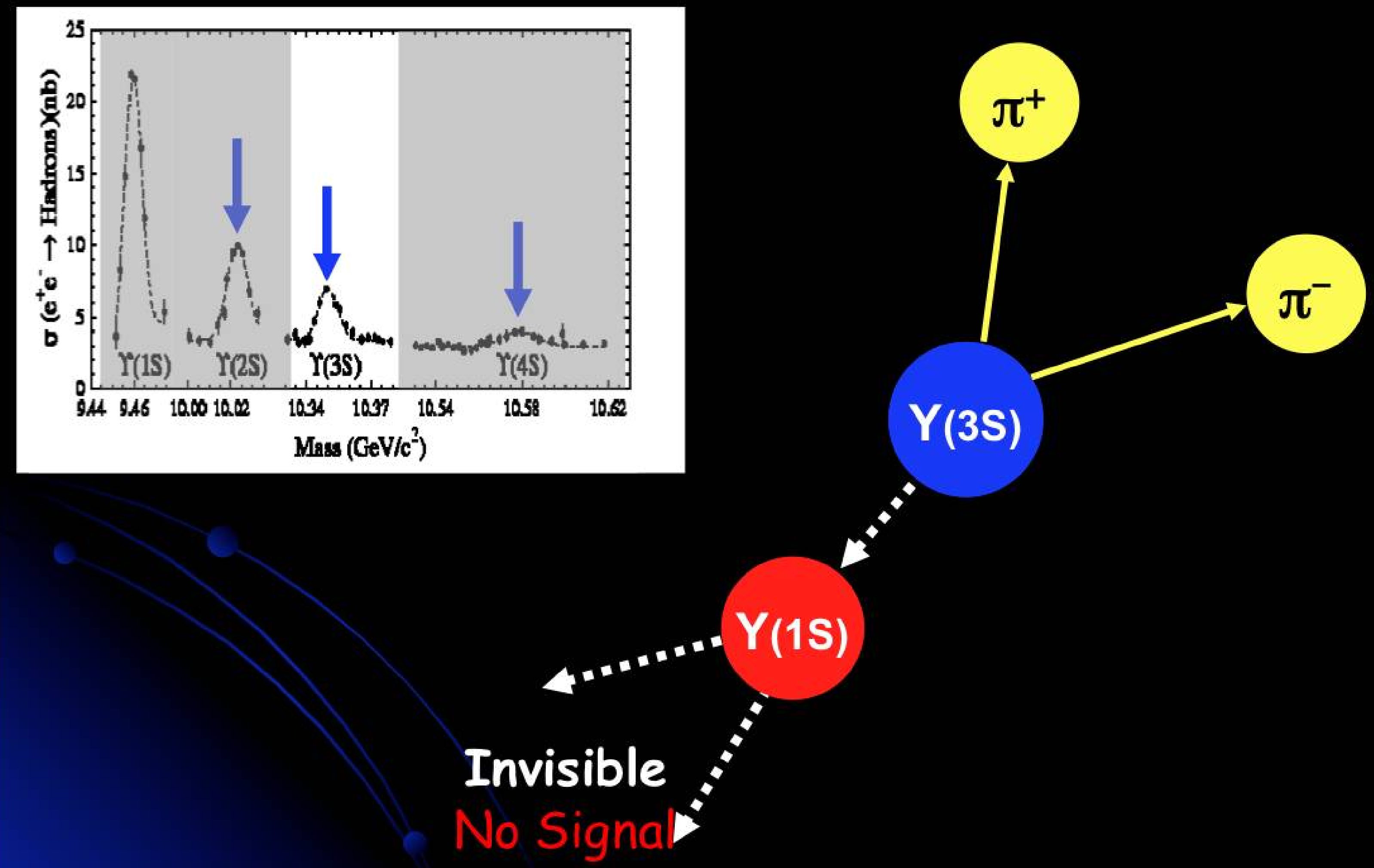
In progress by Belle
(Igal Jaegle)



Last update at DI2014 (Jaegle)



Searches of DM using dipion tagging



Neutralino annihilation to SM particles

Relic density is denoted as follows

$$\Omega h^2 \cong \frac{0.1\ \text{pb} \cdot c}{<\sigma(\chi\chi \rightarrow SM)\ v>}$$

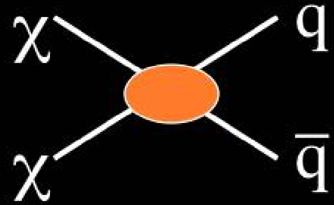
Ω : relic density

h : Hubble constant

v : 1/20 ~ 1/25

$\Omega h^2 = 0.113 \leftarrow$ WMAP

$\sigma(\chi\chi\Diamond SM) \sim 18$ pb



see PDG

SM particles annihilation to neutralinos

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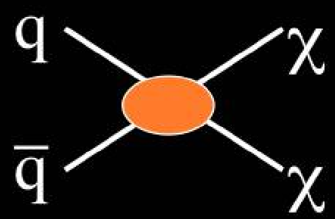


see PDG

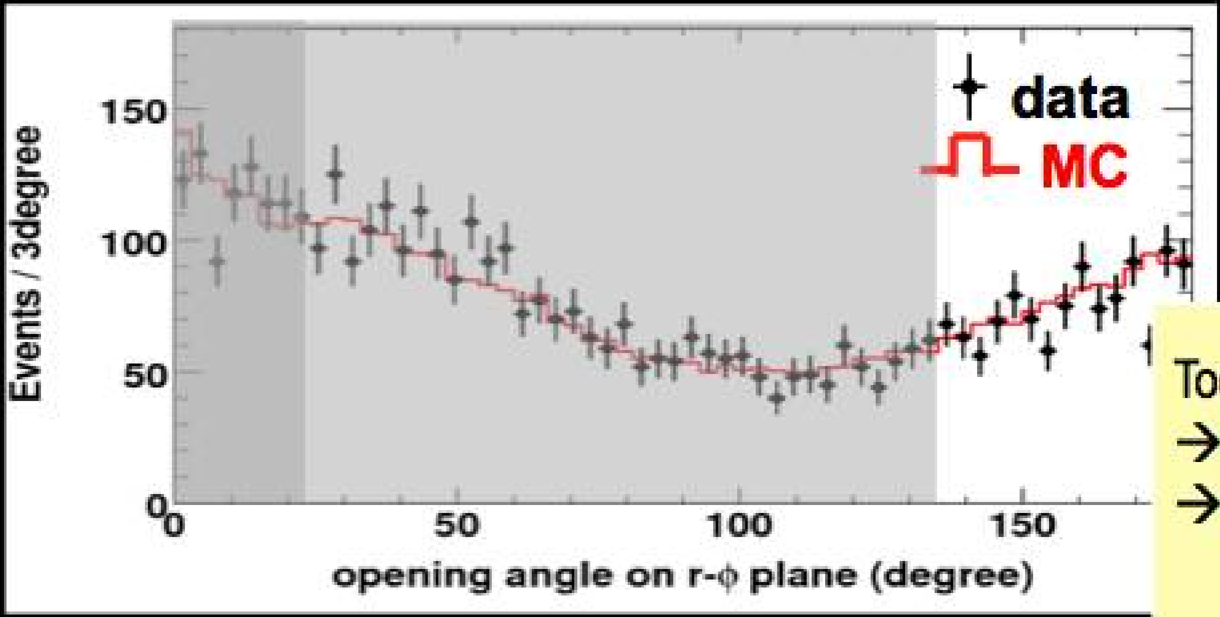
$$\sigma(SM \rightarrow \chi\chi) \cong \sigma(\chi\chi \rightarrow SM),\quad \Gamma(\Upsilon(1S) \rightarrow \chi\chi) = f_\Upsilon^2 M_\Upsilon \sigma(b\bar{b} \rightarrow \chi\chi)$$

$Br(\Upsilon(1S) \rightarrow \chi\chi) \sim 6\text{x}10^{-3}$ ($m_\chi < 4.73\,\text{GeV}/c^2 \sim m_b$)

PRD 72, 103508 (2005) , B.McElrath, "Invisible quarkonium decays as a sensitive probe of dark matter"

Past Best limit < $23\text{x}10^{-3}$ (90% CL) by ARGUS (1986)

Slow dipion trigger for Dark Matter searches

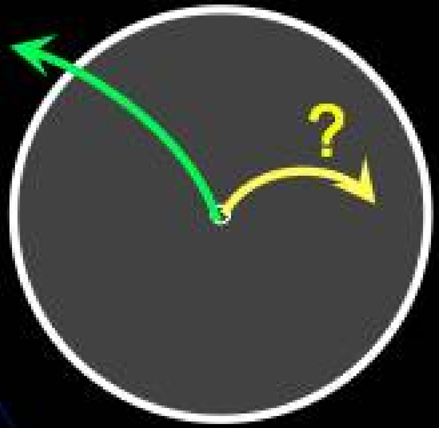


Control sample

$\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$

$\Upsilon(1S) \rightarrow \mu^+\mu^-$

Too low efficiency with usual condition (>135°)
→ Higher efficiency with looser condition
→ Special trigger condition was implemented
(~850 Hz, twice rate as usual)



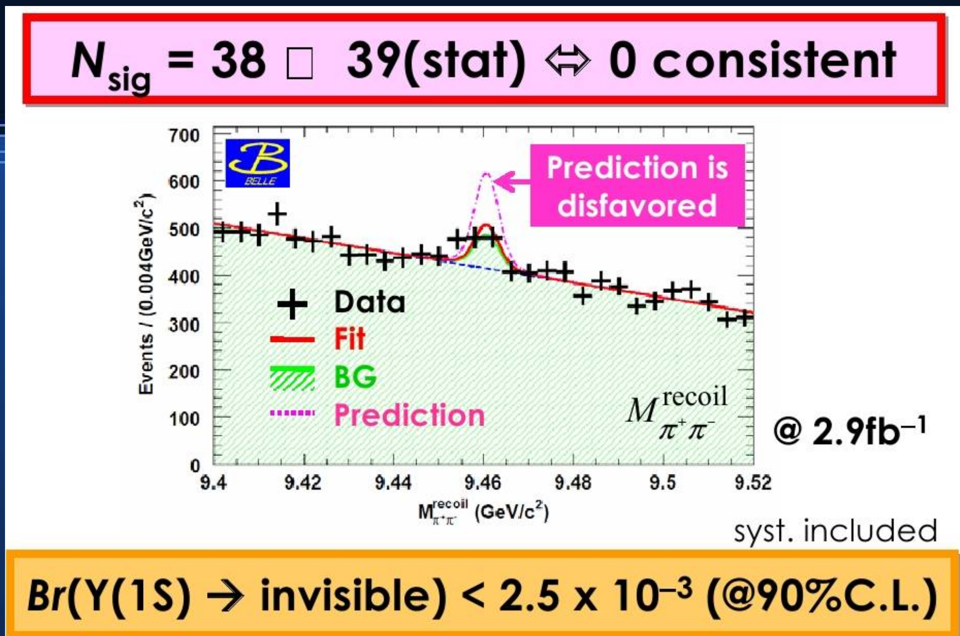
Single track trigger was implemented, too
with 1/500 pre-scale rate (pt>250 MeV/c)

$$\frac{\text{2-track trigger \& 1-track trigger}}{\text{1-track trigger}}$$

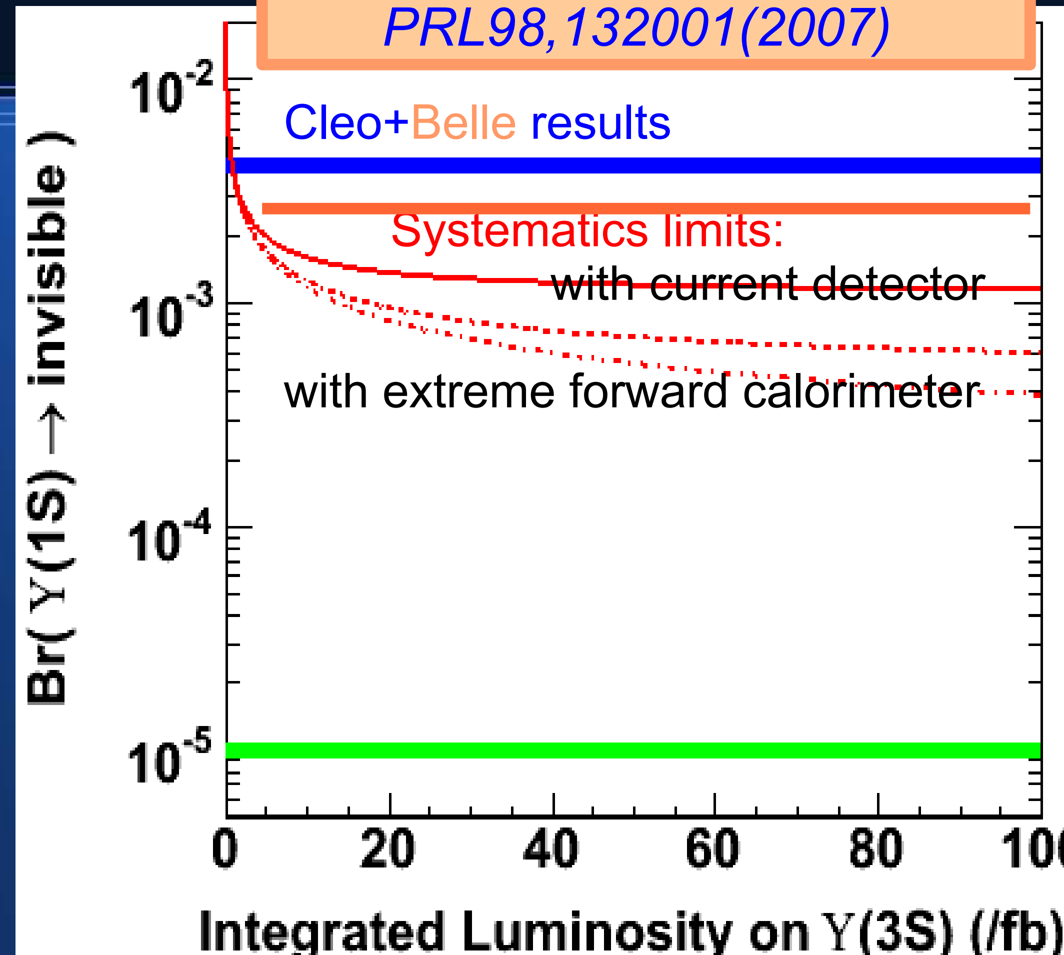
for efficiency monitoring

Dark matter searches in Υ(1S) decays: results

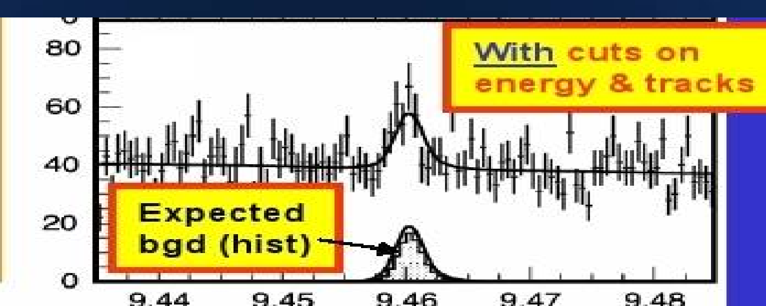
Belle: Υ(3S) → ππ + NOTHING



2.9 fb^{-1}.11 M Υ(3S)
PRL98,132001(2007)



CLEO: Υ(2S) → ππ + NOTHING

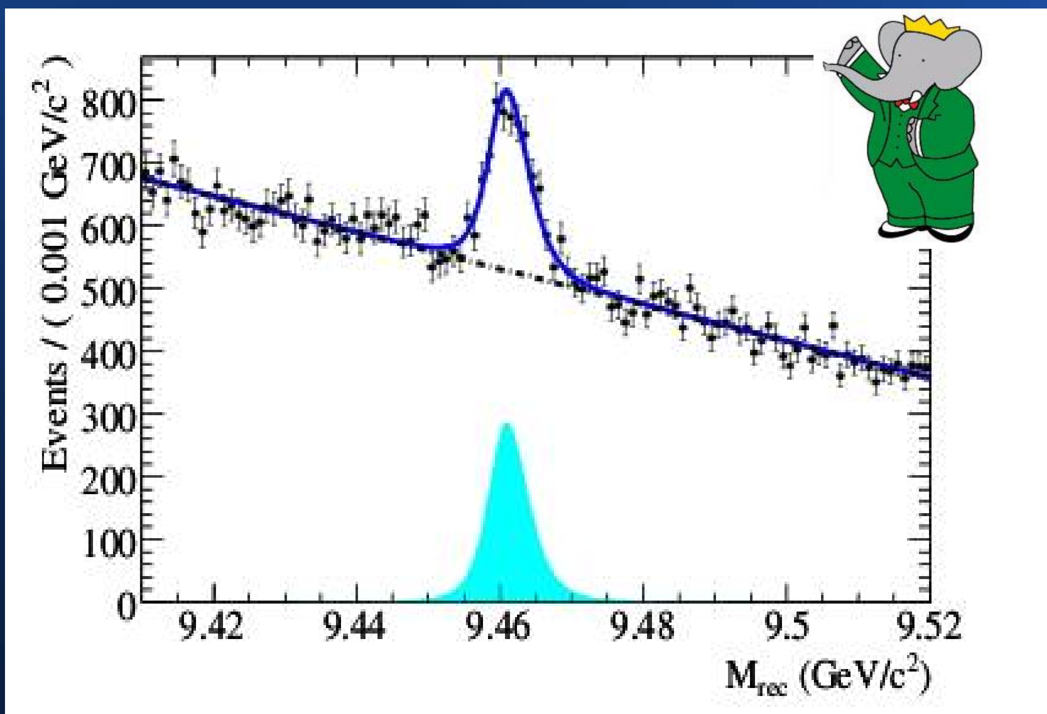


1.46 fb^{-1}, 6M Υ(3S)
PRD75,031104(2007)

BR(Υ(1S) → invisible) < 3.9*10^{-3} (90% CL)

Dark matter searches in Y(nS) decays : results

Babar: Y(3S) → ππ + NOTHING



From MC simulations:

Belle	Babar
50.3	1019 Y(1S) → ee
77.3	1007 Y(1S) → μμ
5.2	92 Y(1S) → ττ
	3 Y(1S) → hadrons
	2122 events tot exp.

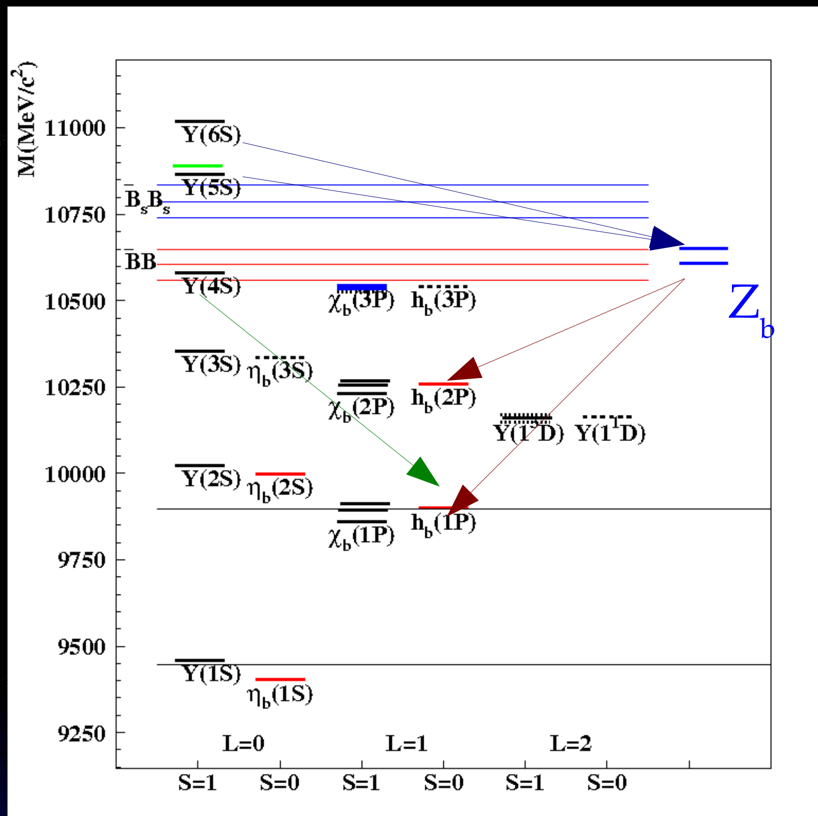
Renormalized from analysis of 3 and 4 track events:

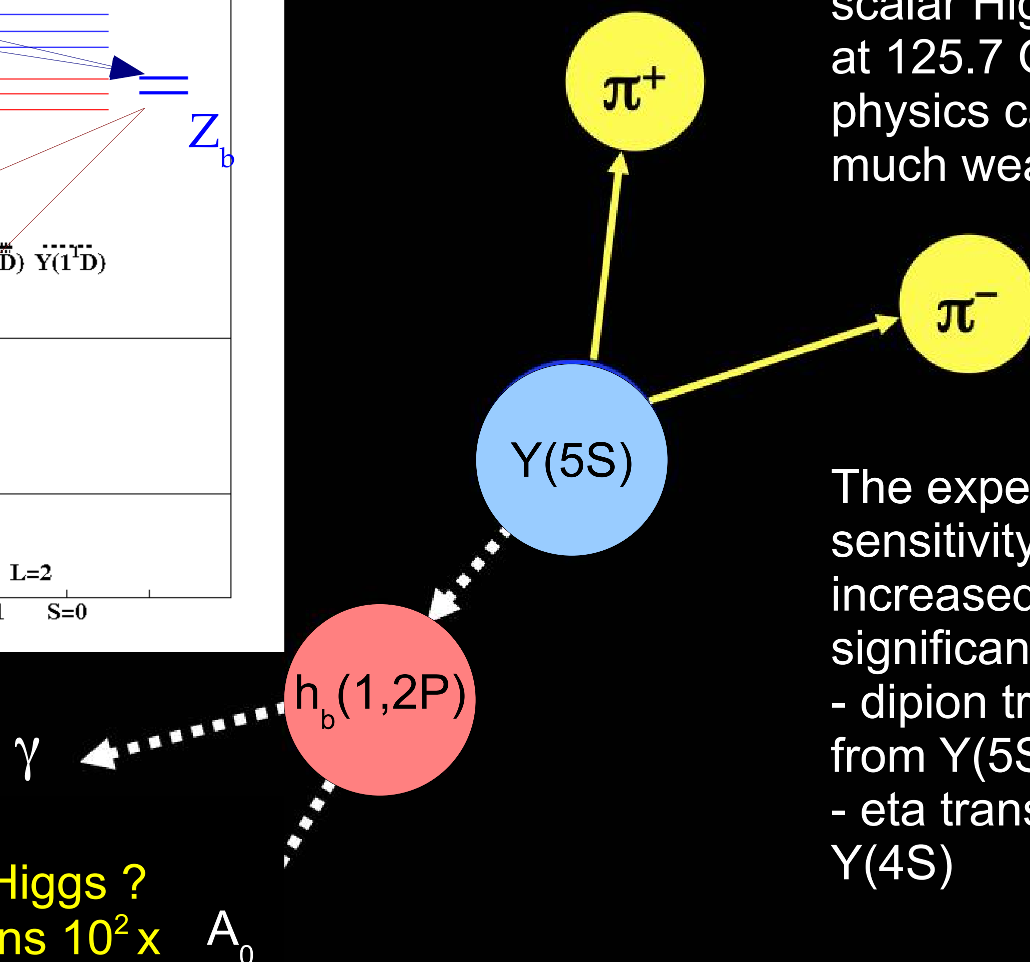
Belle	Babar	
$133.2^{+19.7}_{-14.7}$	2451+/- 38	total exp
38±39	2326+/-105	total obs

BR(Y(1S) → invisible) < $3*10^{-4}$ (90% CL)

BABAR: 30 *fb*$^{-1}$. *91.4M Y(3S)*
Phys.Rev.Lett. 103 (2009) 181801

Further opportunities: dipion + photon tagging of Light Higgs via parabottomonia





1^{+-} decay to CP-odd Higgs ?
M1 Radiative transitions 10^2 x E1 (from Υ)

The search for Light Higgs in Υ decays has been the physics driver for Υ runs at Babar. After the discovery of the scalar Higgs boson at 125.7 GeV the physics case is much weaker, but ...

The experimental sensitivity has increased significantly:
- dipion transitions from Υ(5S)
- eta transitions from Υ(4S)

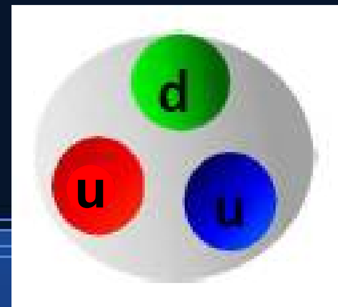
Non-perturbative QCD is the *dark sector* of the Standard Model ....

* 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.

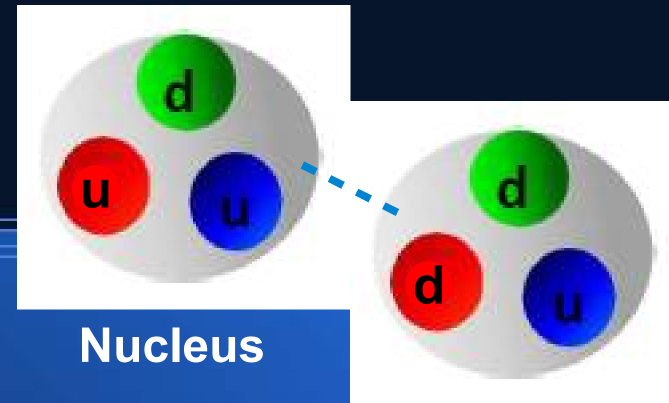
* QCD provides doors towards BSM issues : axions, instantons, strong CP violation, deeply bound multiquarks ... (but also glueballs , hybrids)

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

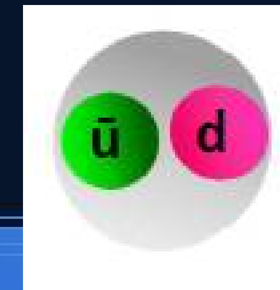
QCD bound states



Nucleon



Nucleus

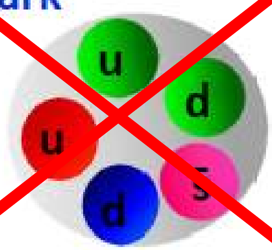


Meson

.... what else?

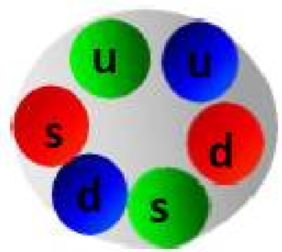
Pentaquark

S= +1
Baryon



H di-Baryon

Tightly bound
6 quark state

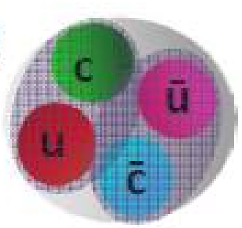


Glueball

Color-singlet multi-
gluon bound state

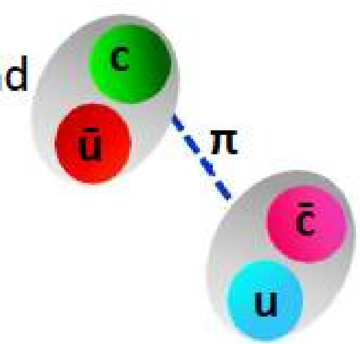
Tetraquark

Tightly bound
diquark &
anti-diquark

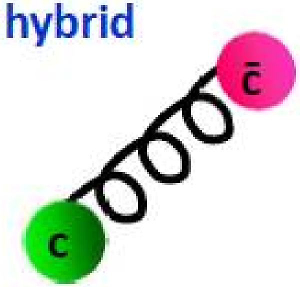


Molecule

loosely bound
meson-
antimeson
"molecule"

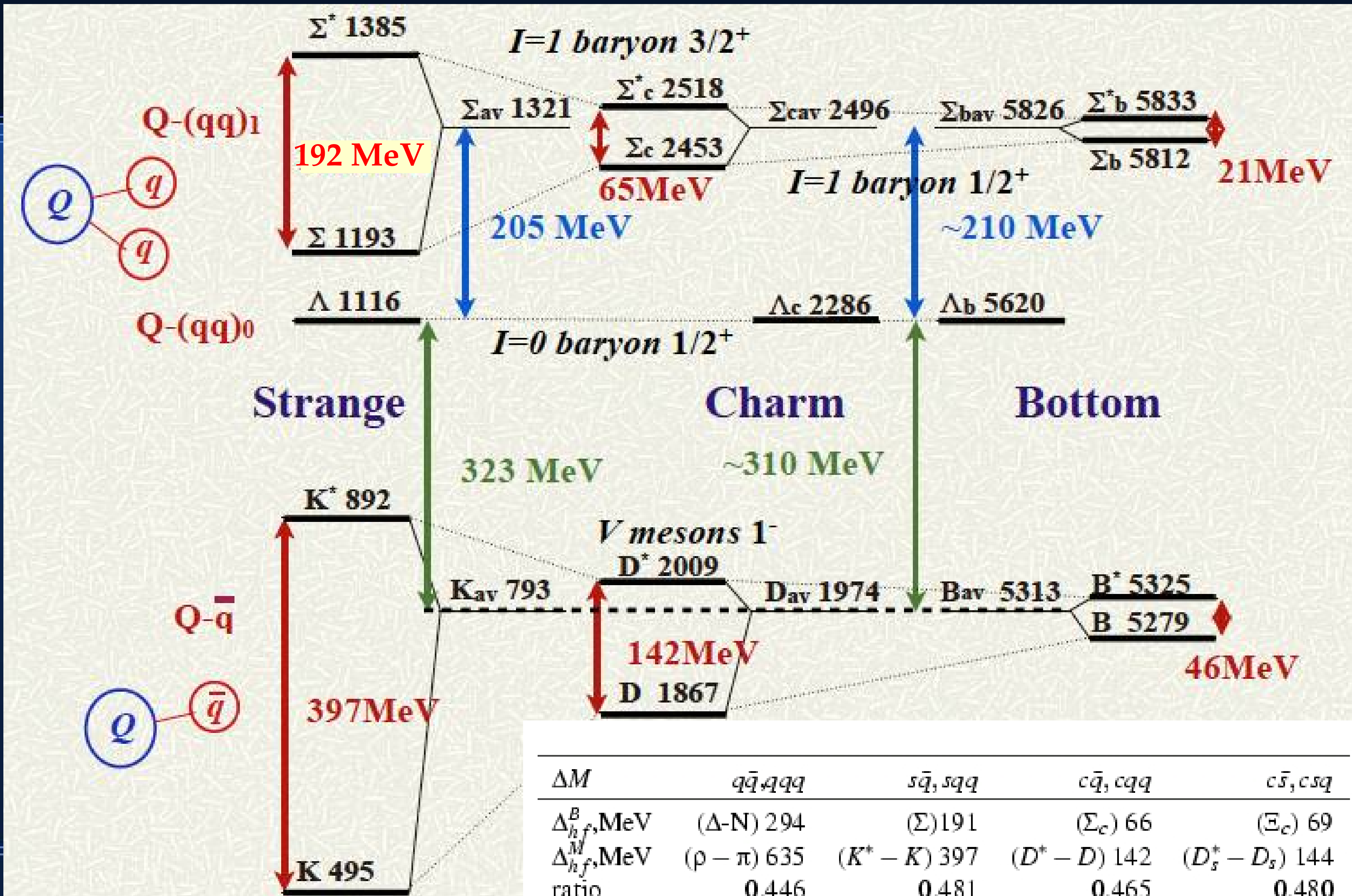


qq̄ -gluon hybrid mesons



But ... why the constituent quark model works so well?

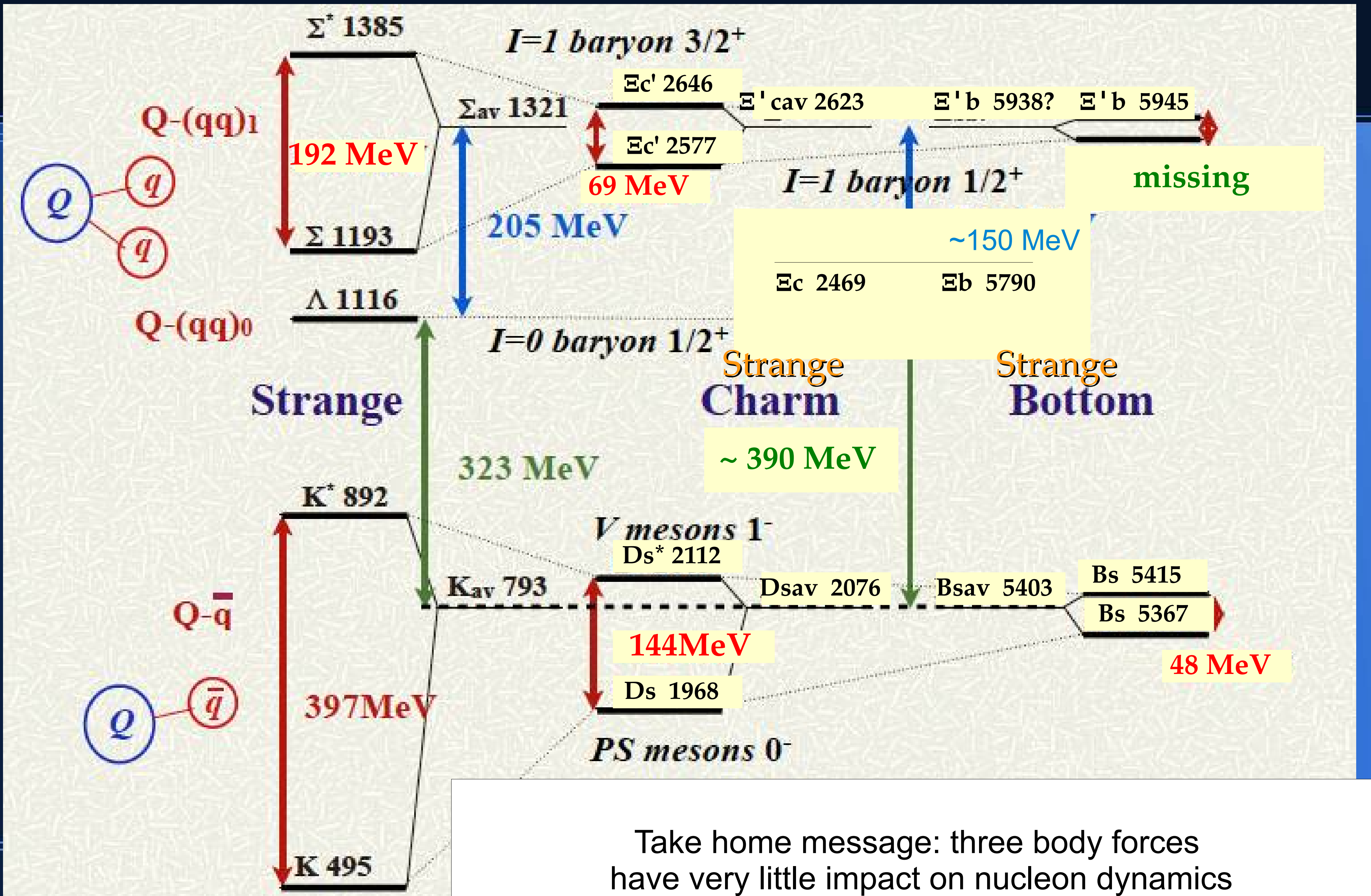
Charmed and Beauty hadron spectra
(from Oka's talk at Hadron 2013)



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

But … why the constituent quark model works so well?

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

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

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

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: can QCD explain it?

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

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

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

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

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

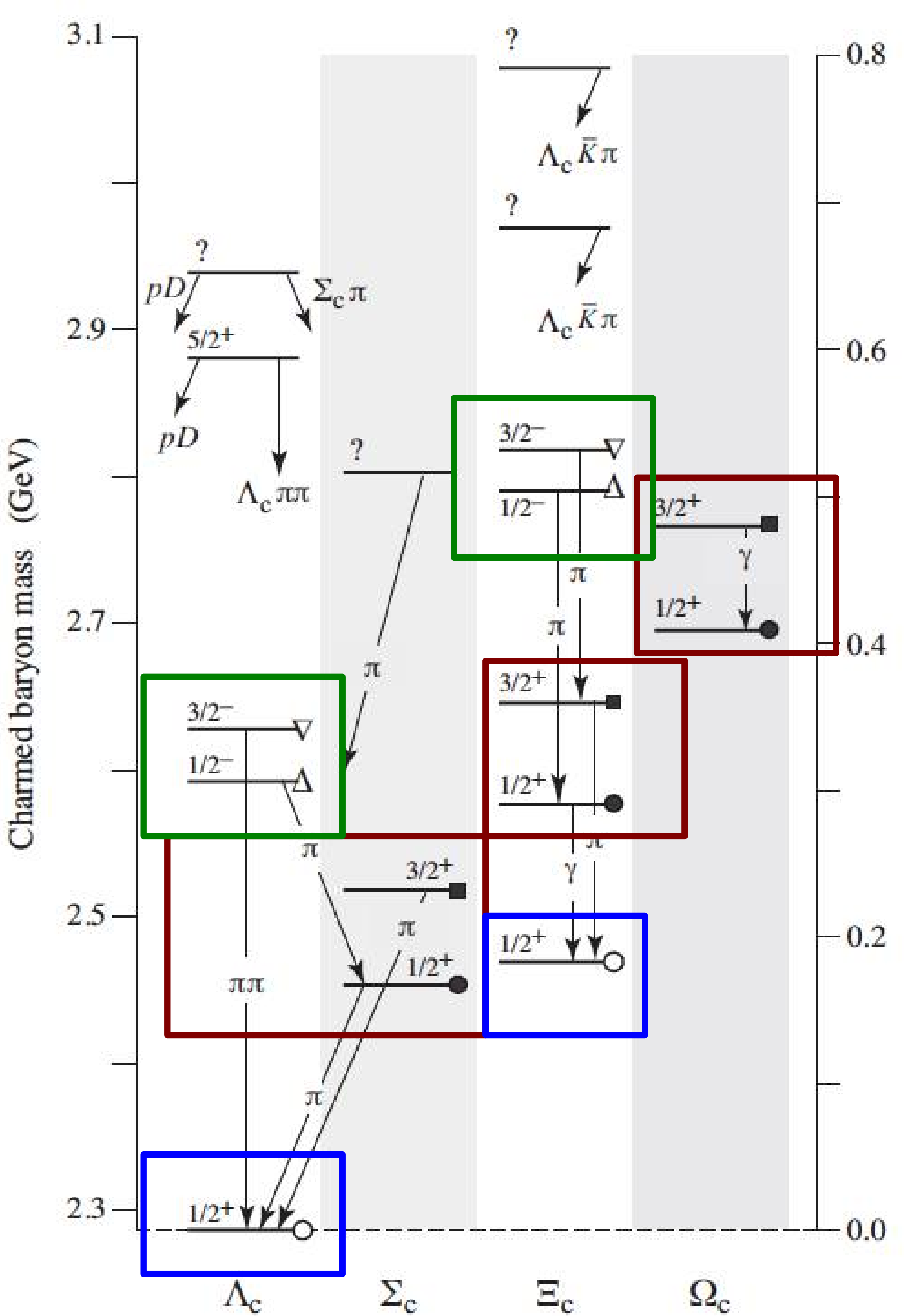
Charmed baryon spectra: P waves

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

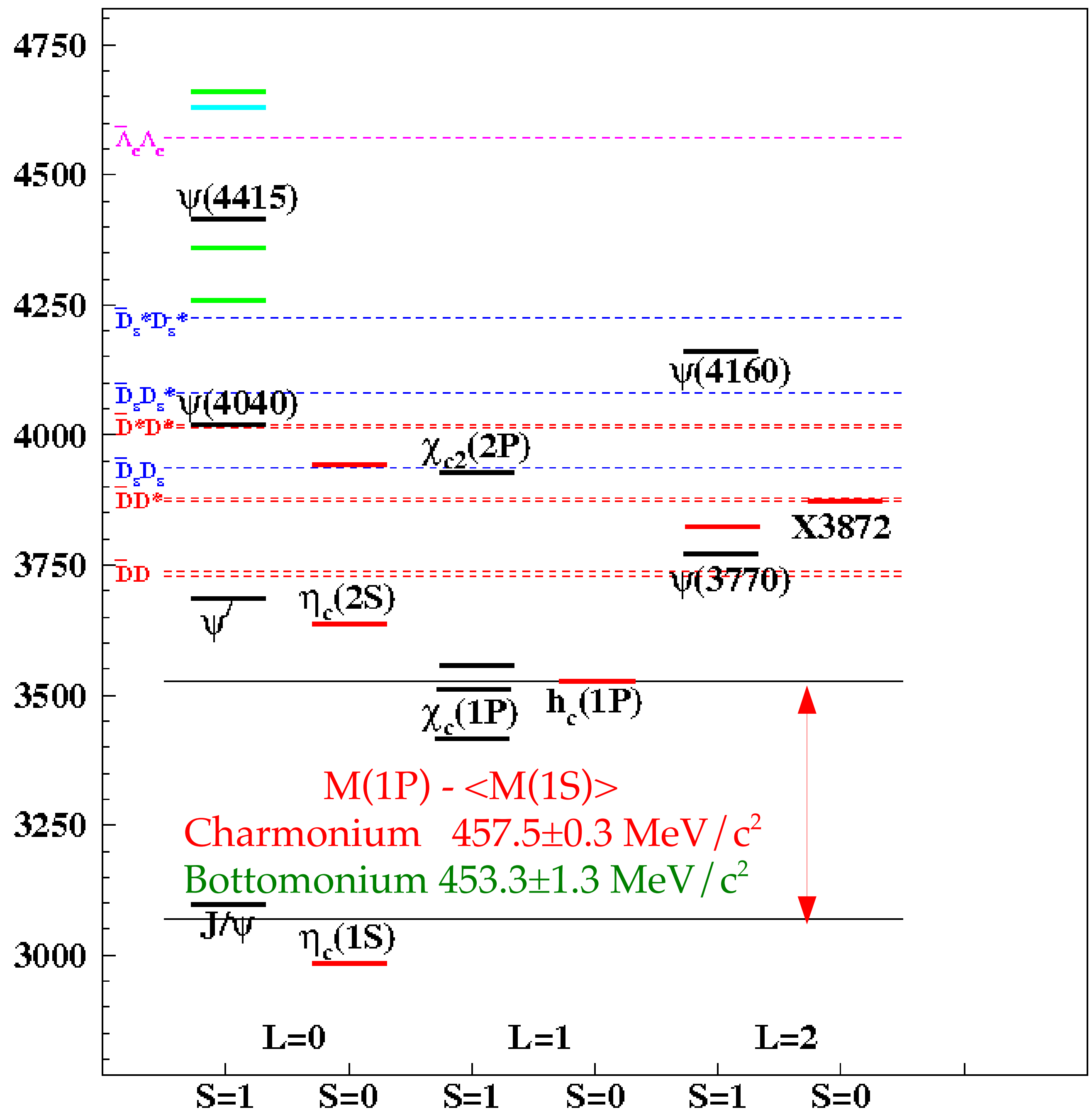
In green: J=0 diquark ; L=1
LS splitting:
[2*M(3/2$^-$)+M(1/2$^-$)]/3-M(1/2$^+$)

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



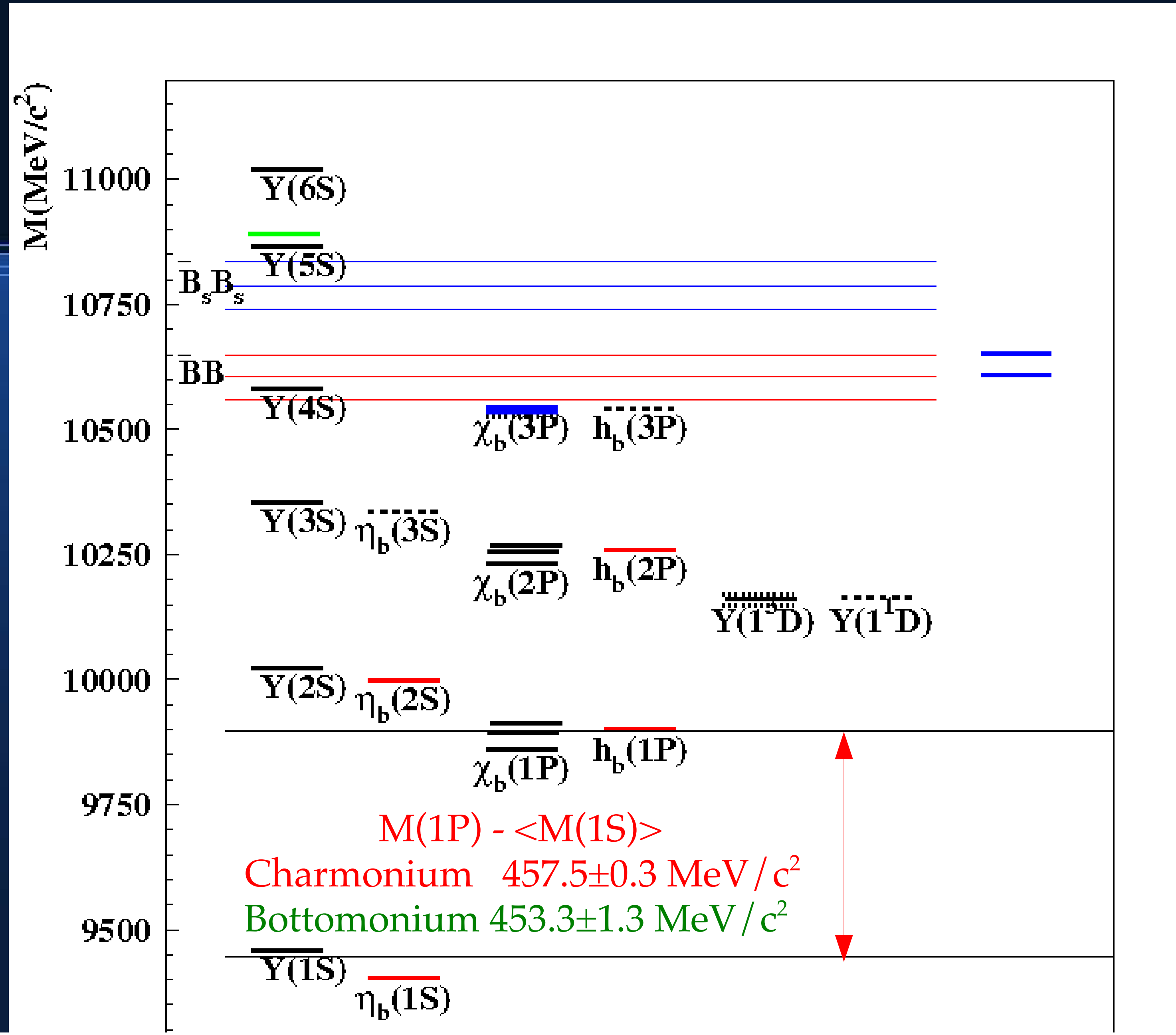
Heavy meson spectra:P waves

Spin averaged 1P-1S splitting seems not to depend on the hard scale: only 1% difference between $b\bar{b}$ and $c\bar{c}$. Why?



Heavy meson spectra:P waves

Spin averaged 1P-1S splitting seems not to depend on the hard scale: only 1% difference between $b\bar{b}$ and $c\bar{c}$.
Why?
The tensor-vector splitting remains constant also in D,Ds. Why?



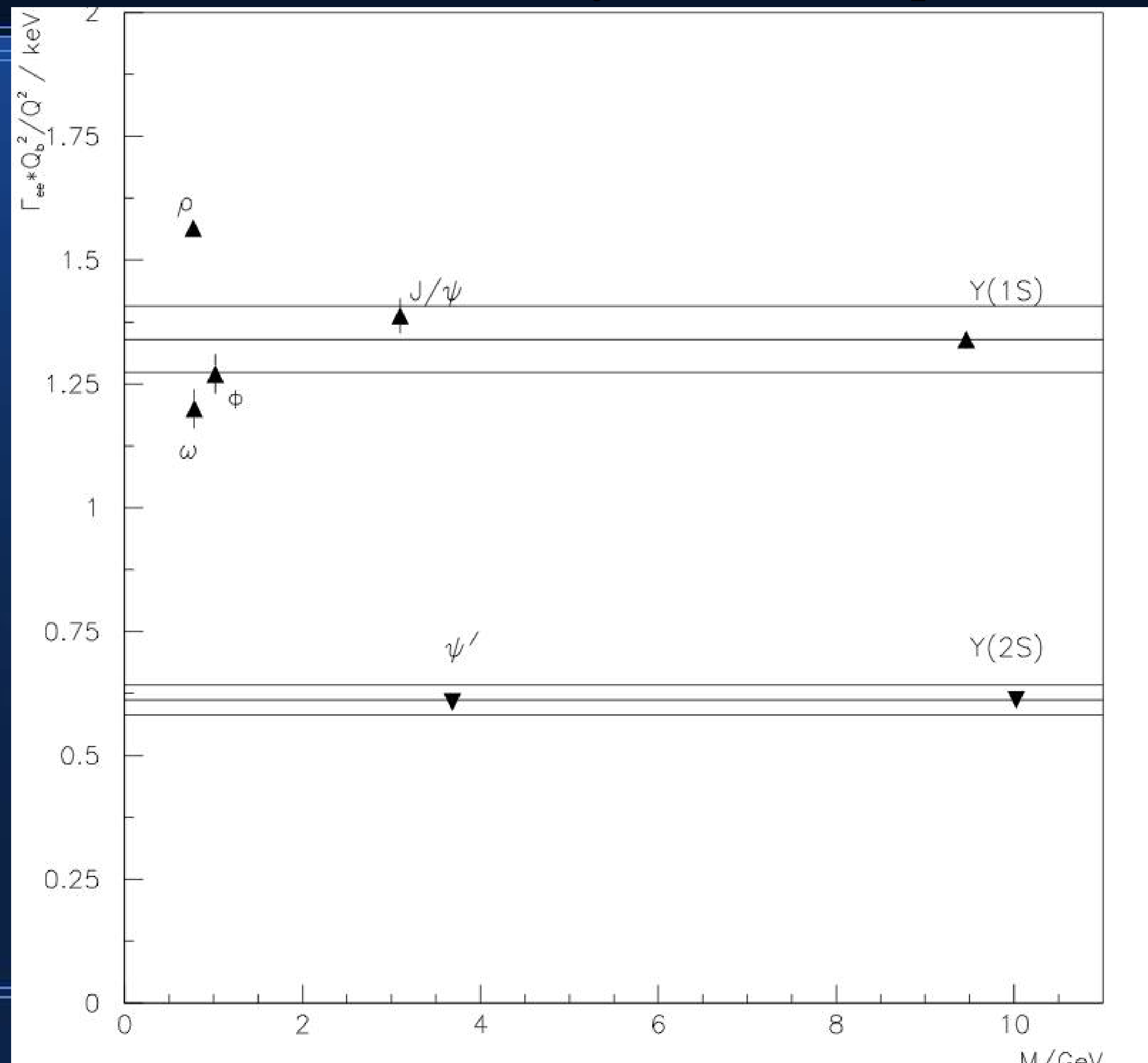
$M(2^+) - M(1^-)$	$c\bar{q}$ 451	$c\bar{s}$ 461	$c\bar{c}$ 458.3
(in MeV/c^2)	$b\bar{q}$ 418	$b\bar{s}$ 425	$b\bar{b}$ 452.3

Leptonic widths

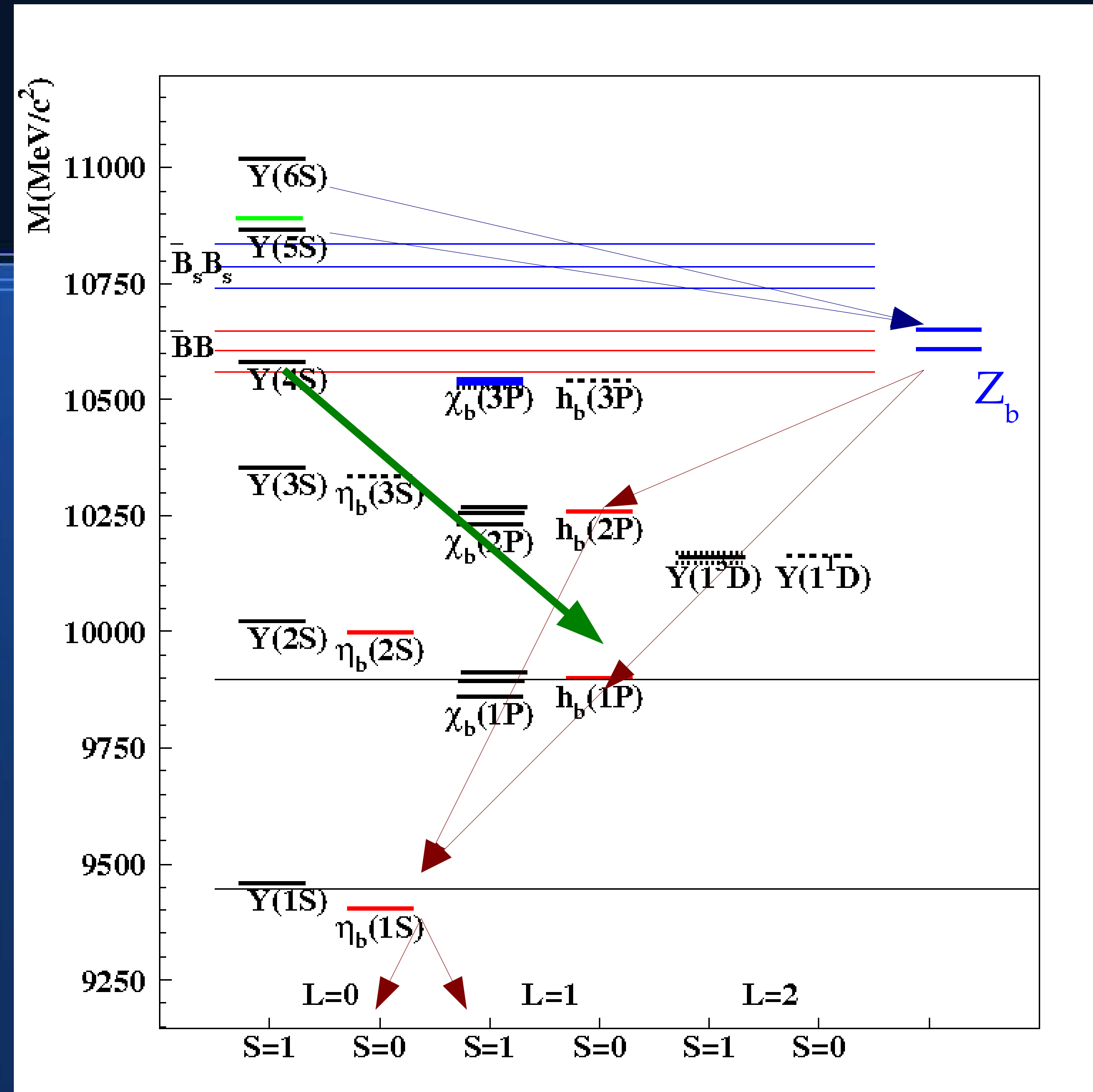
$$\Gamma(V \to e^+e^-) = \frac{16\pi\alpha^2 e_Q^2}{M_V^2} \, |\Psi(0)|^2 \times \left(1 - \frac{16\alpha_s}{3\pi}\right)$$

van Royen-Weisskopf formula

Wavefunction in the origin vs hard mass scale vs α_s running



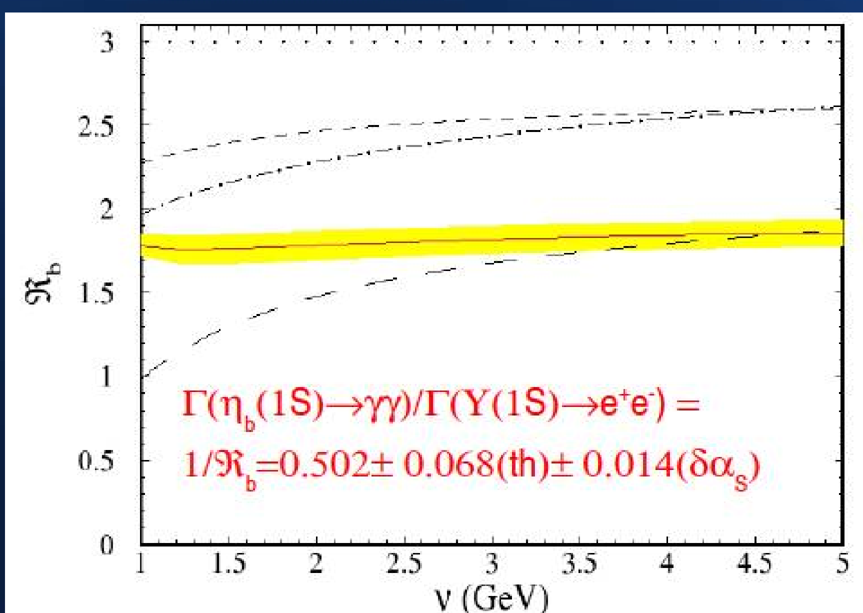
Holy Grail: $\eta_b(1S) \to \gamma\gamma$



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

via two exclusive channel:

- $\pi^+\pi^-\gamma(\gamma\gamma)$, from Υ(5,6S)
- $\gamma\gamma\ \gamma(\gamma\gamma)$, from Υ(4S)



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

$\Gamma(\eta_b(1S) \to \gamma\gamma)$ = 0.66±0.09 keV

$BR(\eta_b(1S) \to \gamma\gamma) = 0.66 \times 10^{-4}$, with $\Gamma(\eta_b)$ = 10 MeV,

Z_b parameters

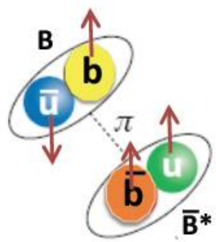
PRL108,122001(2011)

Belle discovered two charged bottomonium-like resonances:

Z(10610)

M=10607.2±2.0 MeV

Γ=18.4±2.4 MeV

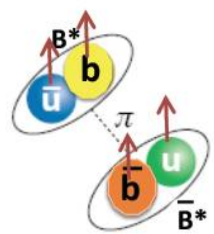


$M_B + M_{B*} = 10604.5 \pm 0.6$ MeV

Z(10650)

M=10652.2±1.5 MeV

Γ=11.5±2.2 MeV

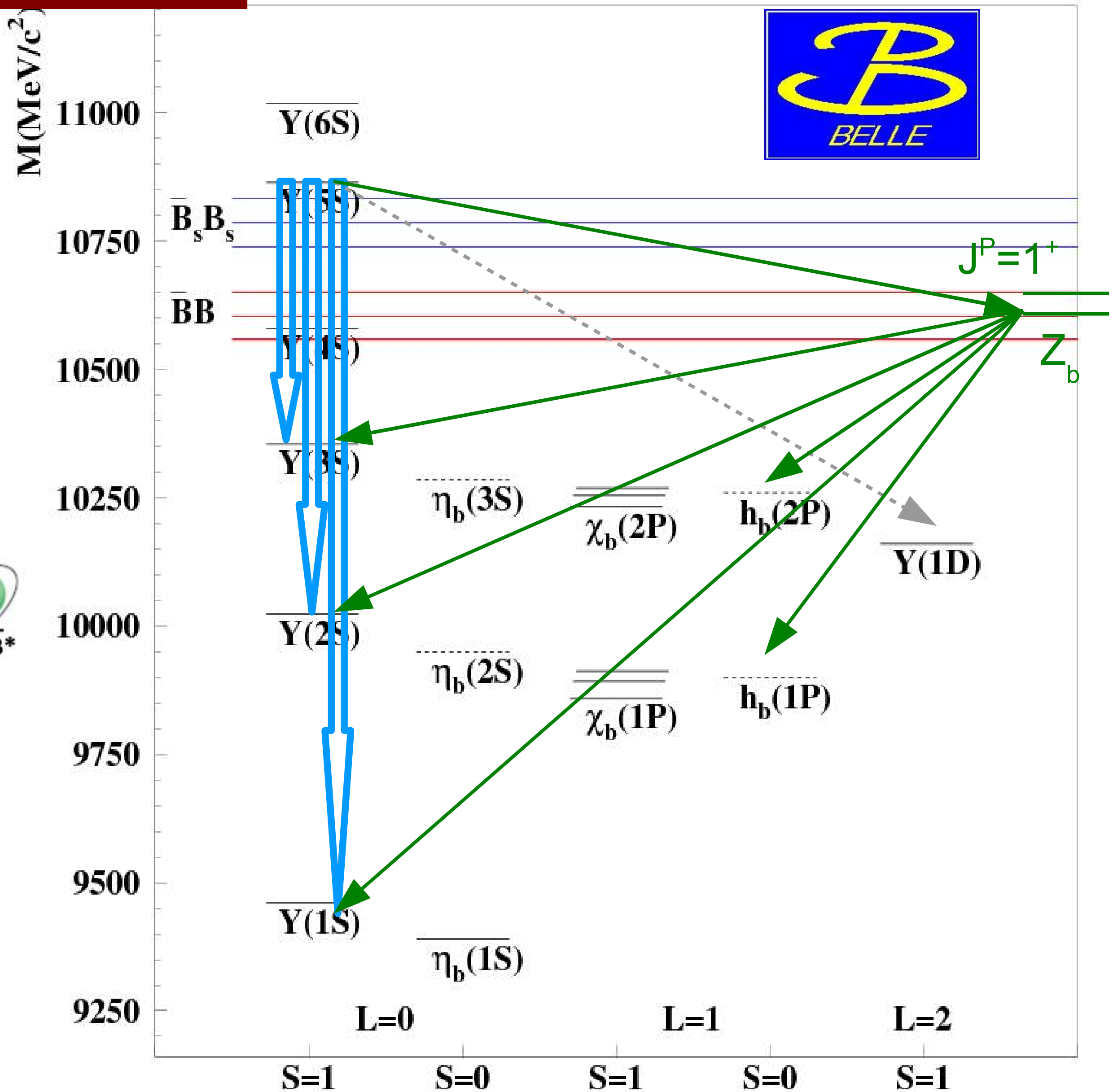


$M_{B*} + M_{B*} = 10650.2 \pm 1.0$ MeV

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)

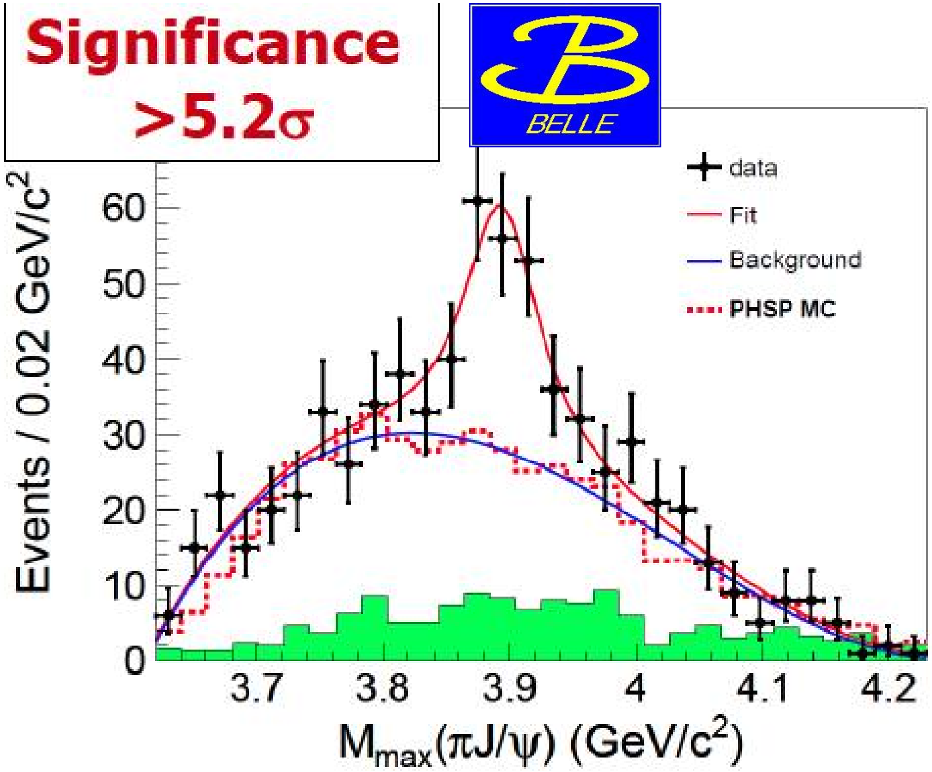
ArXiV:1207.4345:

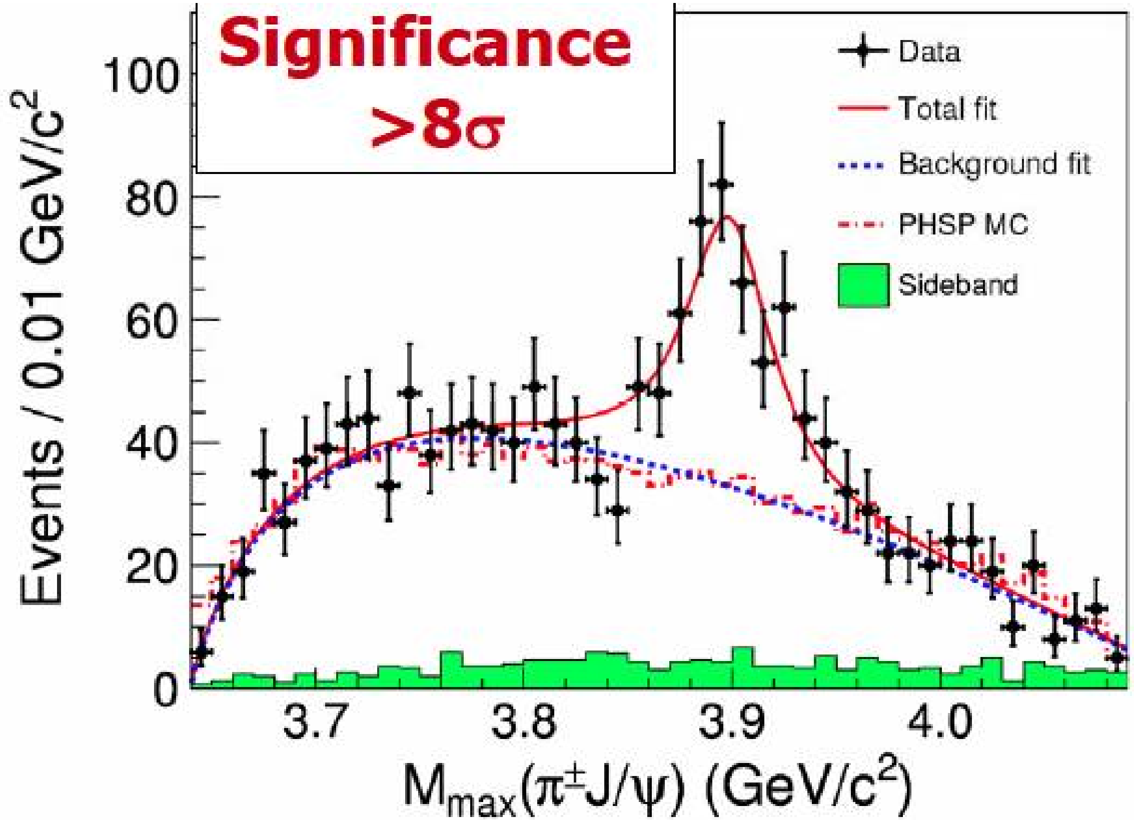
Evidence of neutral partner of lower Zb in $Y\pi^0$ with 4.9 sigma significance



Zc(3900): tetraquarks or meson molecules?

BES-III





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

Phys.Rev.Lett. 110 (2013) 252002

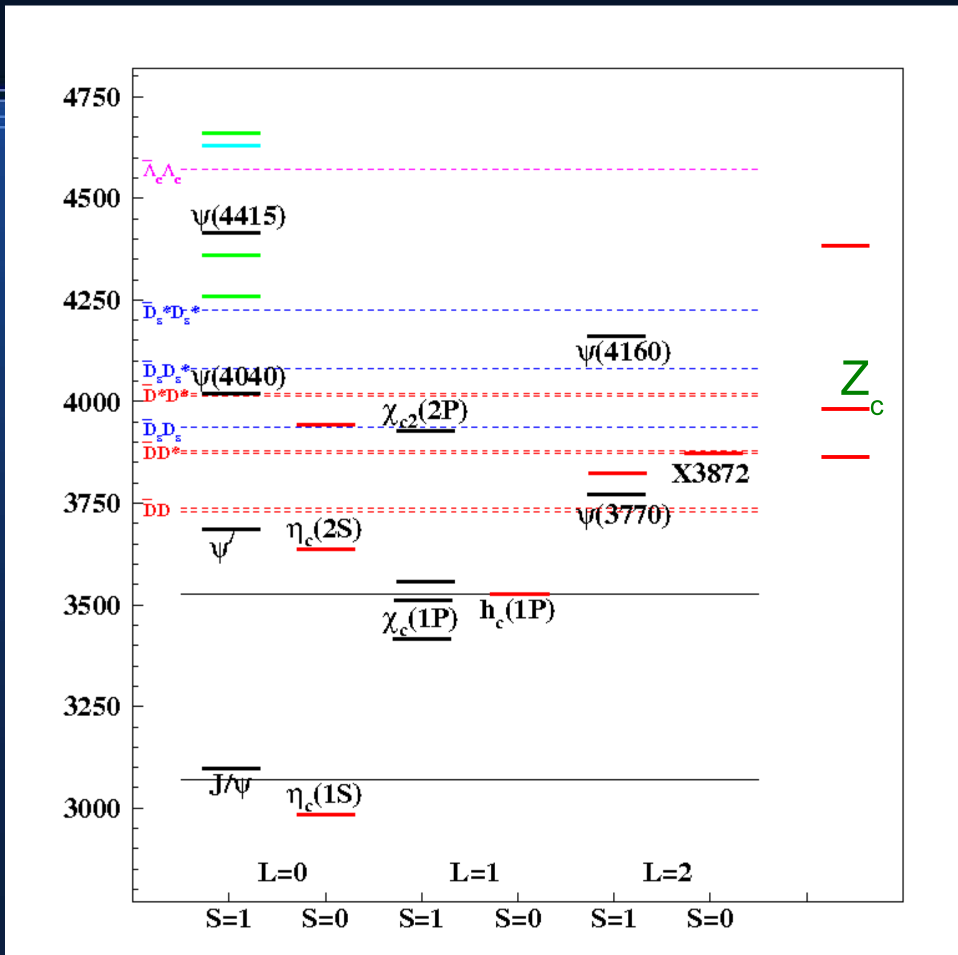
- Mass = (3894.5±6.6±4.5) MeV
- Width = (63±24±26) MeV
- Fraction = (29.0±8.9)% (stat. error only)

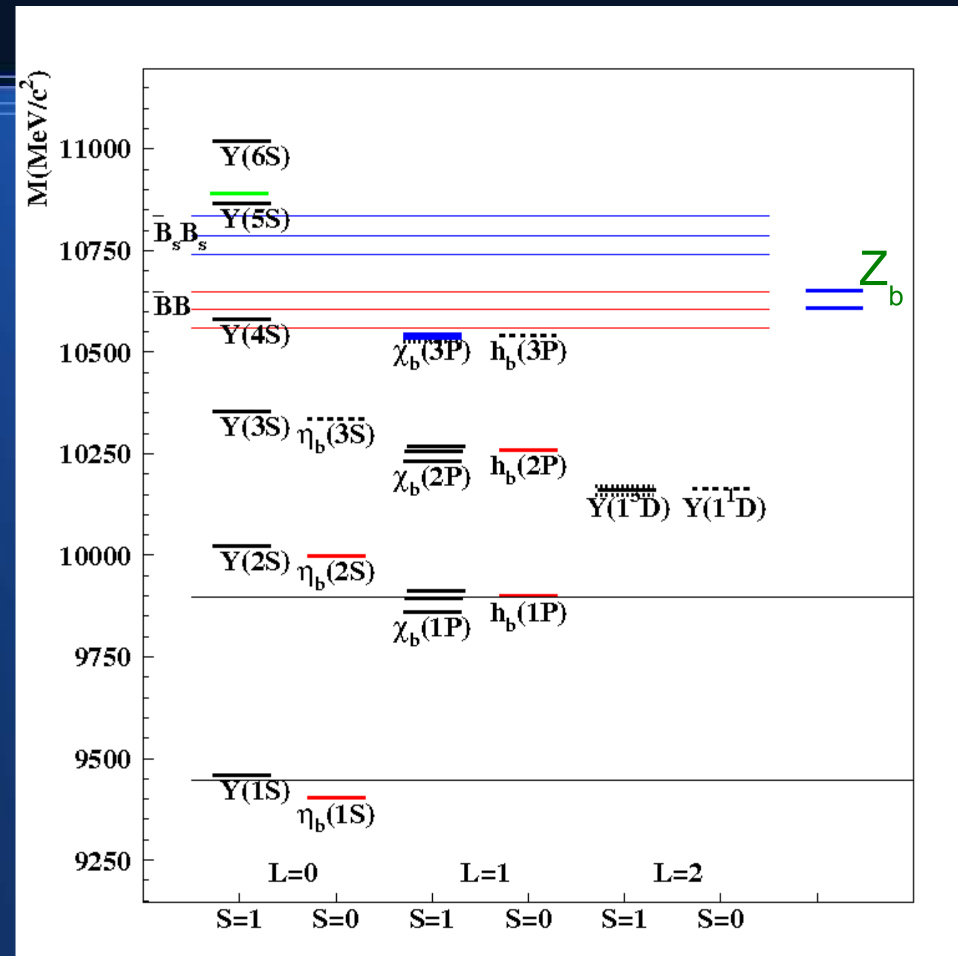
BES-III: 525 pb^{-1} @ Y(4260) peak energy

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? More studies are ongoing to model of these states.

DM candidate from QCD ?

SLAC-PUB-1828
October 1976
(T/E)

PERHAPS A STABLE DIHYPERON*

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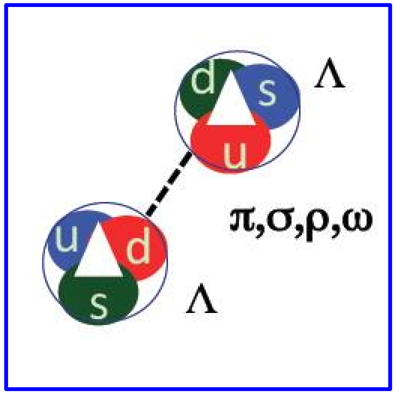
and

Department of Physics and Laboratory of Nuclear Science†
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139



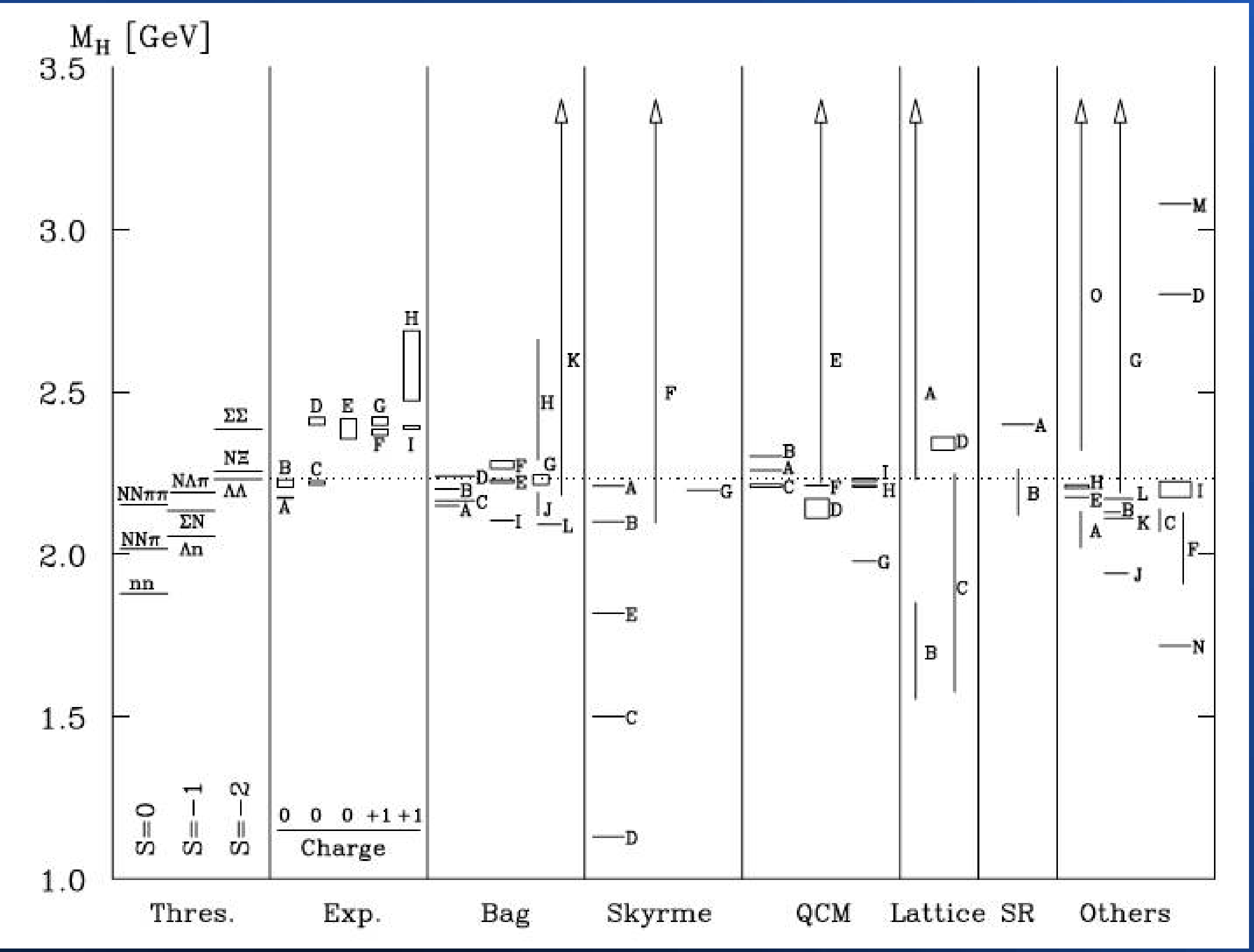
ABSTRACT

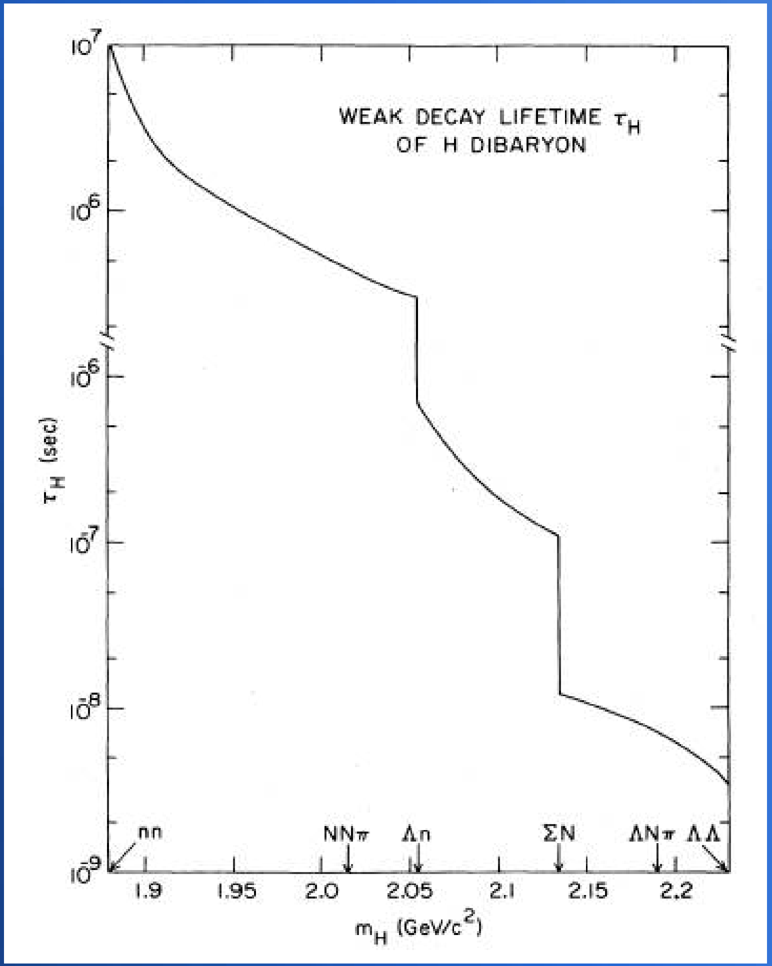
In the quark bag model the same gluon exchange forces which make the proton lighter than the Δ(1236) bind 6 quarks to form a stable, flavor singlet (strangeness −2) $J^P = 0^+$ dihyperon (H) at 2150 MeV. Another isosinglet dihyperon (H*) with $J^P = 1^+$ at 2335 MeV should appear as a bump in ΛΛ invariant mass plots. Production and decay systematics of the H are discussed.

H-dibaryon Mass and Lifetime

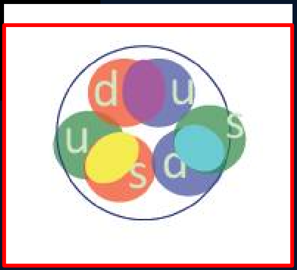
Sakai et al.,Prog.Theor.Phys.Suppl. **137 (2000),121**

Dover et al.,PRC 40 (1989), 115





H-dibaryon as DM?

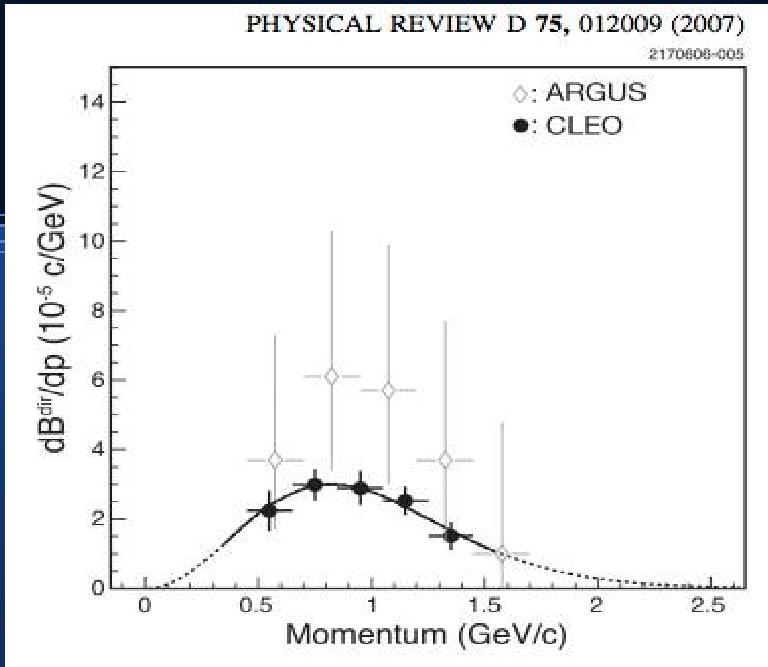


Kochelev 1999: JETP Lett. 70 (1999) 491, hep-ph/9905333
M = 1.7 GeV for QCD induced instanton effects (even LIGHTER than deuteron?)

Farrar-Zaharijas 2003-4: **Int.J.Theor.Phys. 42 (2003) 1211, Phys.Rev. D70 (2004) 014008**
"If very compact ($r_H < r_N/4$) , a H dibaryon would not lead to matter instabilities and maybe candidate for cold dark matter. Data from Uranus internal energy exclude DM made of *equal amounts of H and anti-H dibaryons*."

Shuryak 2005: **J.Phys.Conf.Ser. 9 (2005) 213-217, ArXiV: hep-ph/0505011**
Deeply bound diquarks formed by QCD instantons
"However if one considers the quantum numbers of the famous H dibaryon, one can also make those out of diquarks […] The resulting wave function is overall flavor antisymmetric with all diquarks in S-states. Thus there is no need for P-wave or
tensor diquarks for the H dibaryon. Our schematic model would then lead to a light H never seen"

H-dibaryon in bottomonium decays



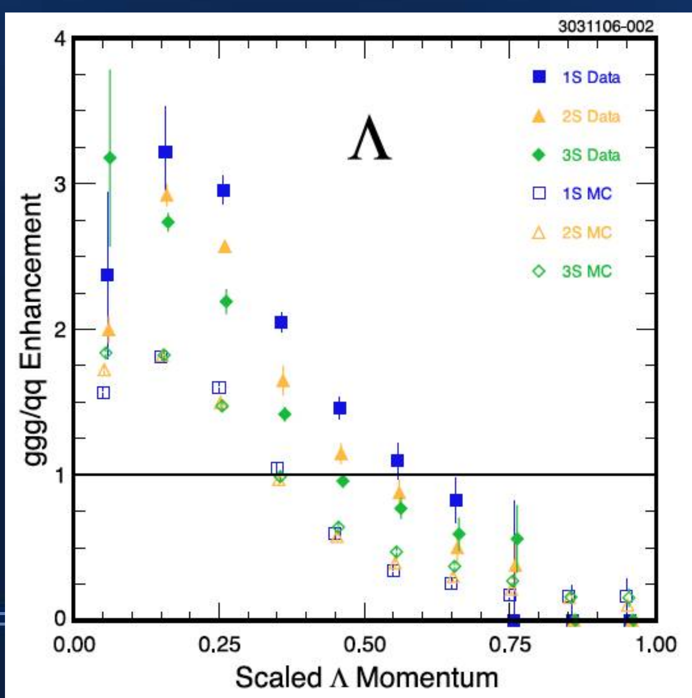
Former observations by ARGUS (**Z.Phys. C39 (1988) 177**) and CLEO (**Phys.Rev. D76 (2007) 012005**)

- Inclusive production of (anti)deuteron in Y(1,2S) decays :

$$\mathcal{B}^{\rm dir}(\Upsilon(1S) \to \bar{d}X) = (3.36 \pm 0.23 \pm 0.25) \times 10^{-5}.$$

$$\mathcal{B}(\Upsilon(2S) \to \bar{d} + X) = (3.37 \pm 0.50 \pm 0.25) \times 10^{-5}.$$

- Enhanced (3x) production of low momentum hyperons in hadronic events from bottomonium decays w/respect to continuum.



BELLE has exploited the Y(1,2S) record samples to search for the long sought H-dibaryon

(Anti)deuterons in Υ decays

CLEO , PRD 75,012009

Υ(1S)	1.2 fb^{-1}	21.95 M
Υ(2S)	0.53 fb^{-1}	3.66 M
Υ(4S)	0.48 fb^{-1}	0.45 M
Continuum	0.67 fb^{-1}	

$$\mathcal{B}^{\rm dir}(\Upsilon(1S) \to \bar{d}X) = (3.36 \pm 0.23 \pm 0.25) \times 10^{-5}$$

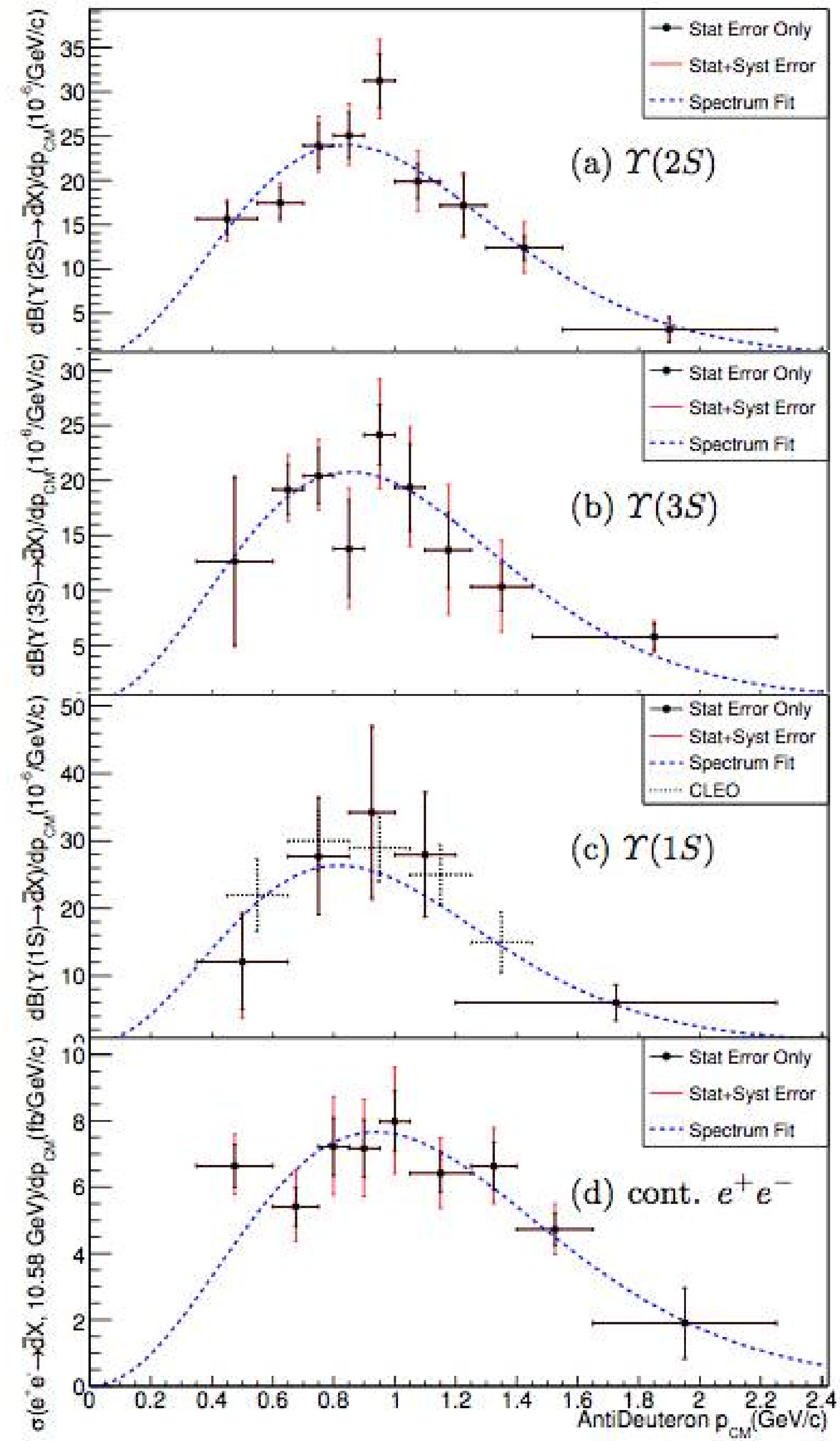
$$\mathcal{B}(\Upsilon(2S) \to \bar{d} + X) = (3.37 \pm 0.50 \pm 0.25) \times 10^{-5}$$

BABAR , 1403.4409

Resonance	Onpeak	# of Υ Decays	Offpeak
$\Upsilon(4S)$	429 fb^{-1}	463×10^6	44.8 fb^{-1}
$\Upsilon(3S)$	28.5 fb^{-1}	116×10^6	2.63 fb^{-1}
$\Upsilon(2S)$	14.4 fb^{-1}	98.3×10^6	1.50 fb^{-1}

Υ(1S) 9.67 M dipion tagged from Υ(2S)

Process	Rate
$\mathcal{B}(\Upsilon(3S) \to \bar{d}X)$	$(2.33 \pm 0.15^{+0.31}_{-0.28}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(2S) \to \bar{d}X)$	$(2.64 \pm 0.11^{+0.26}_{-0.21}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(1S) \to \bar{d}X)$	$(2.81 \pm 0.49^{+0.20}_{-0.24}) \times 10^{-5}$
$\sigma(e^+e^- \to \bar{d}X)$ [$\sqrt{s} \approx 10.58$ GeV]	$(9.63 \pm 0.41^{+1.17}_{-1.01})$ fb
$\dfrac{\sigma(e^+e^- \to \bar{d}X)}{\sigma(e^+e^- \to \text{Hadrons})}$	$(3.01 \pm 0.13^{+0.37}_{-0.31}) \times 10^{-6}$

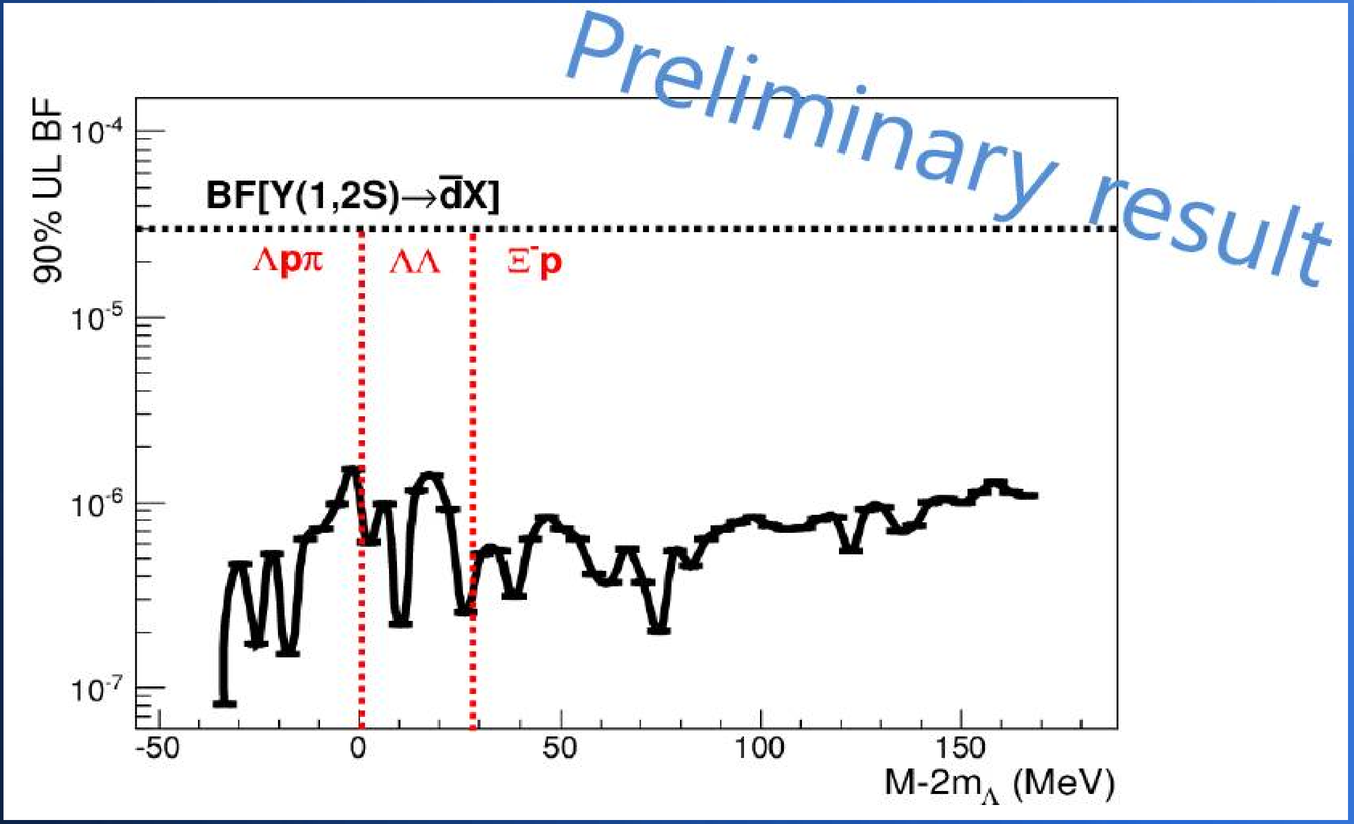


Searches for H-dibaryon at BELLE

Belle has searched for H dibaryon in the folllowing channels:

- $\Lambda\pi p$ (+cc)
- $\Lambda\Lambda$ (+cc)
- Ξ p (+cc) [preliminary]

PRL 110, 222002 (2013)



More to come from Y(1,2,...S) decays (+cont):

- Λp and $\Lambda\Lambda$ (+cc) correlations
- antideuteron spectra (and more)
- antideuteron-deuteron production
- searches for H in missing mass

Summary

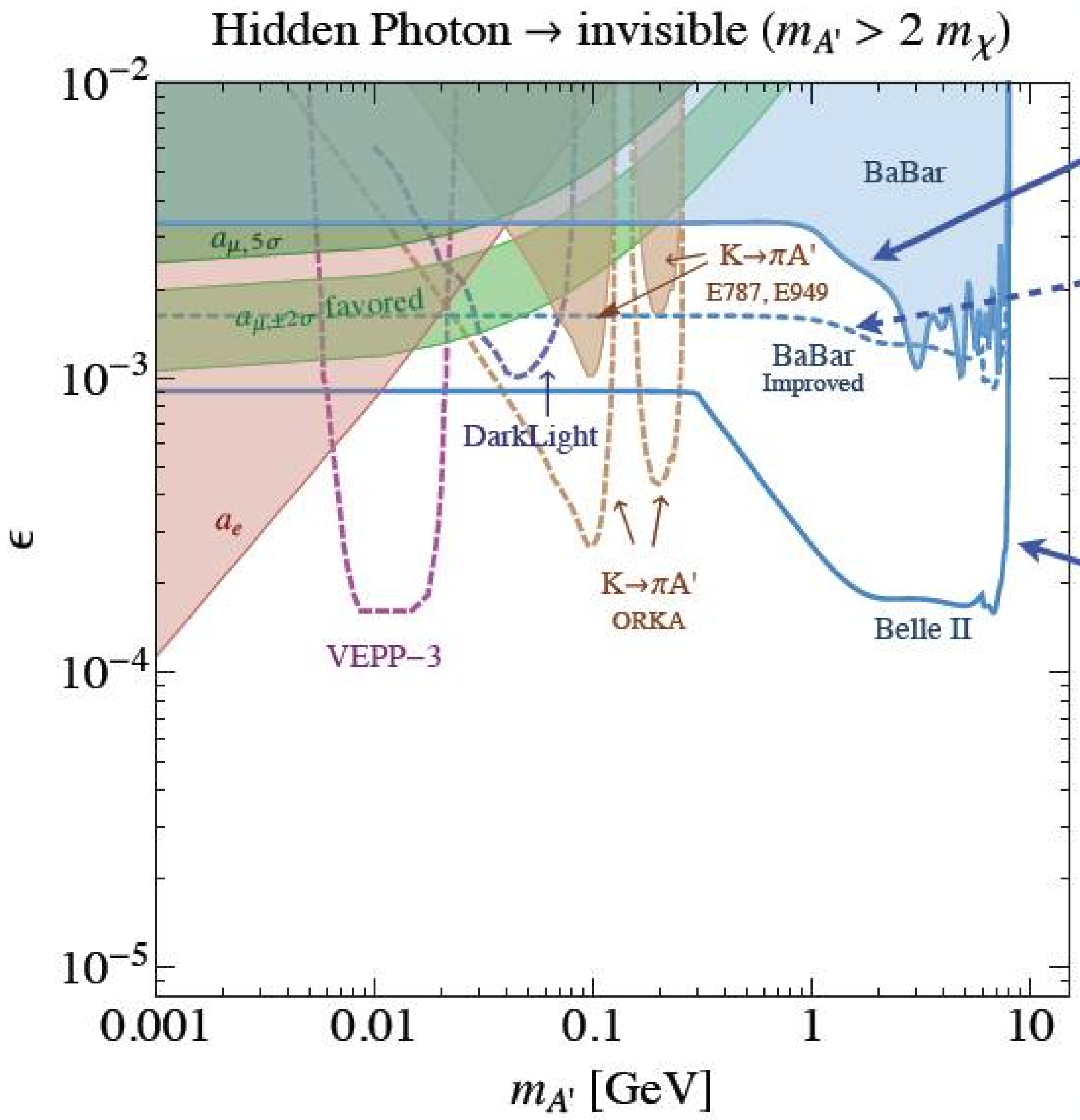
A pretty consistent pattern is emerging in the spectra of heavy baryons, heavy-light mesons, heavy onia, which shows little dependence on the mass scale, and on the running properties of QCD coupling constant. Besides the large developments of QCD based EFTs (NRQCD,HQET, chiral EFT,SCET, and lattice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

Annihilation of the bb pair is still a privileged channel for light higgs or DM particle formation.

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 P and D waves, and multiquark systems, more information can come from the studies of hadronic and radiative transitions of known states.

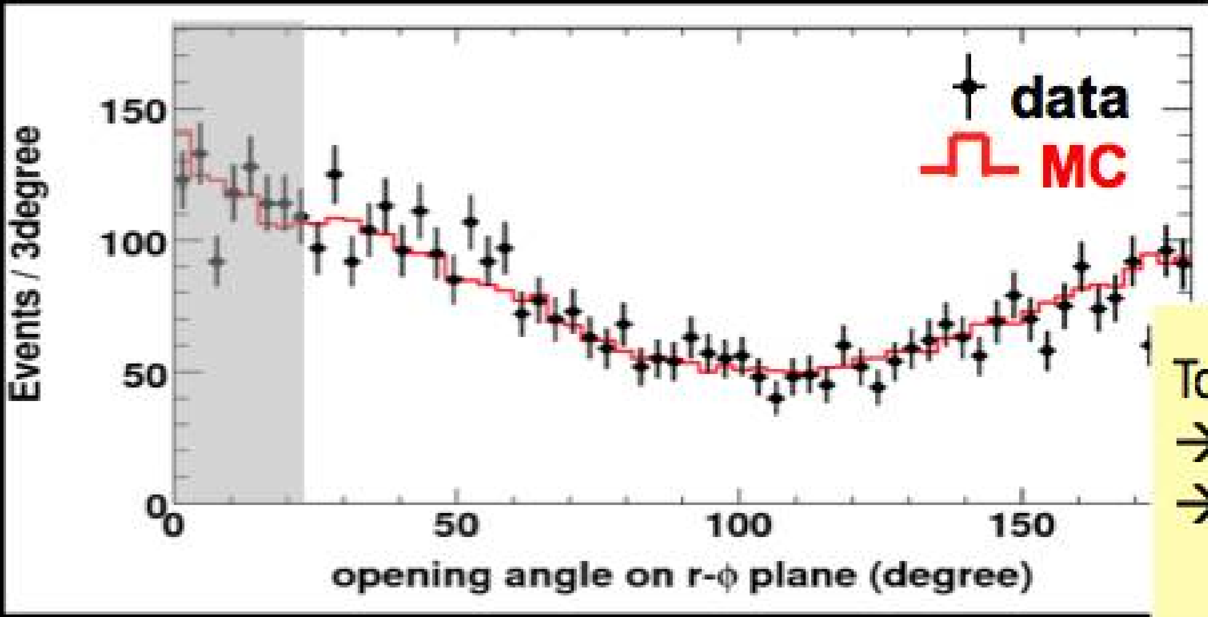
e+e- → γ + A'; A' to invisible



- existing data
- potential improvement from reducing γγ background (private communication)
- projected Belle II
  50/ab + better resolution

Planning single photon trigger at Belle-II (threshold: depends on actual backgrounds)

Slow dipion trigger for Dark Matter searches

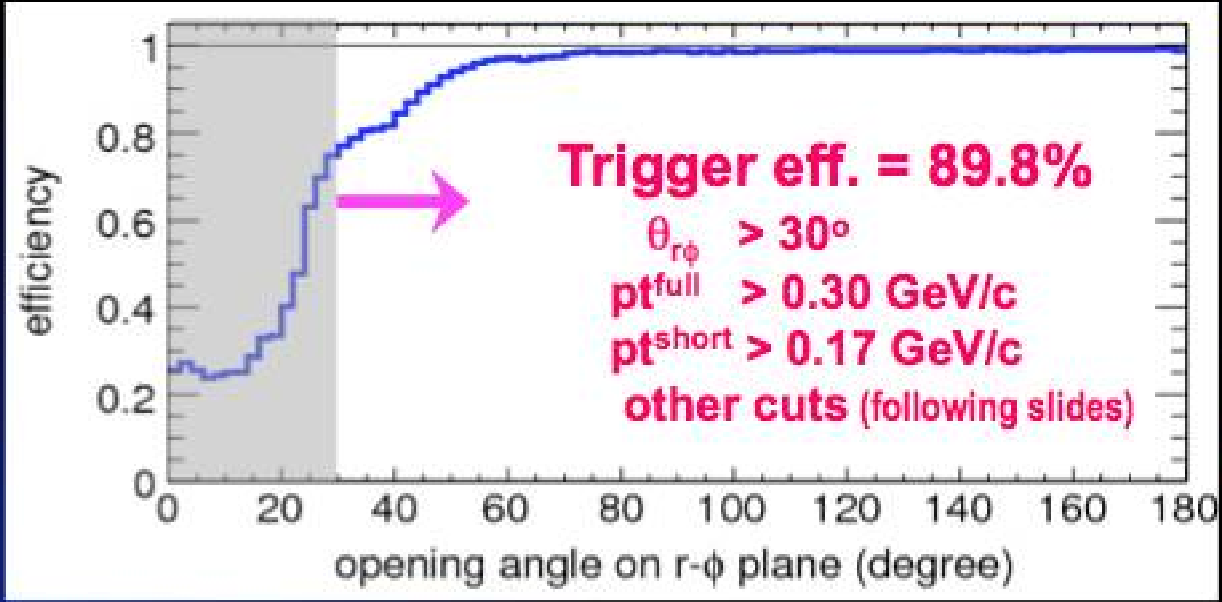


Control sample

$\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$

$\Upsilon(1S) \rightarrow \mu^+\mu^-$

Too low efficiency with usual condition (>135°)
→ Higher efficiency with looser condition
→ Special trigger condition was implemented (~850 Hz, twice as usual condition)



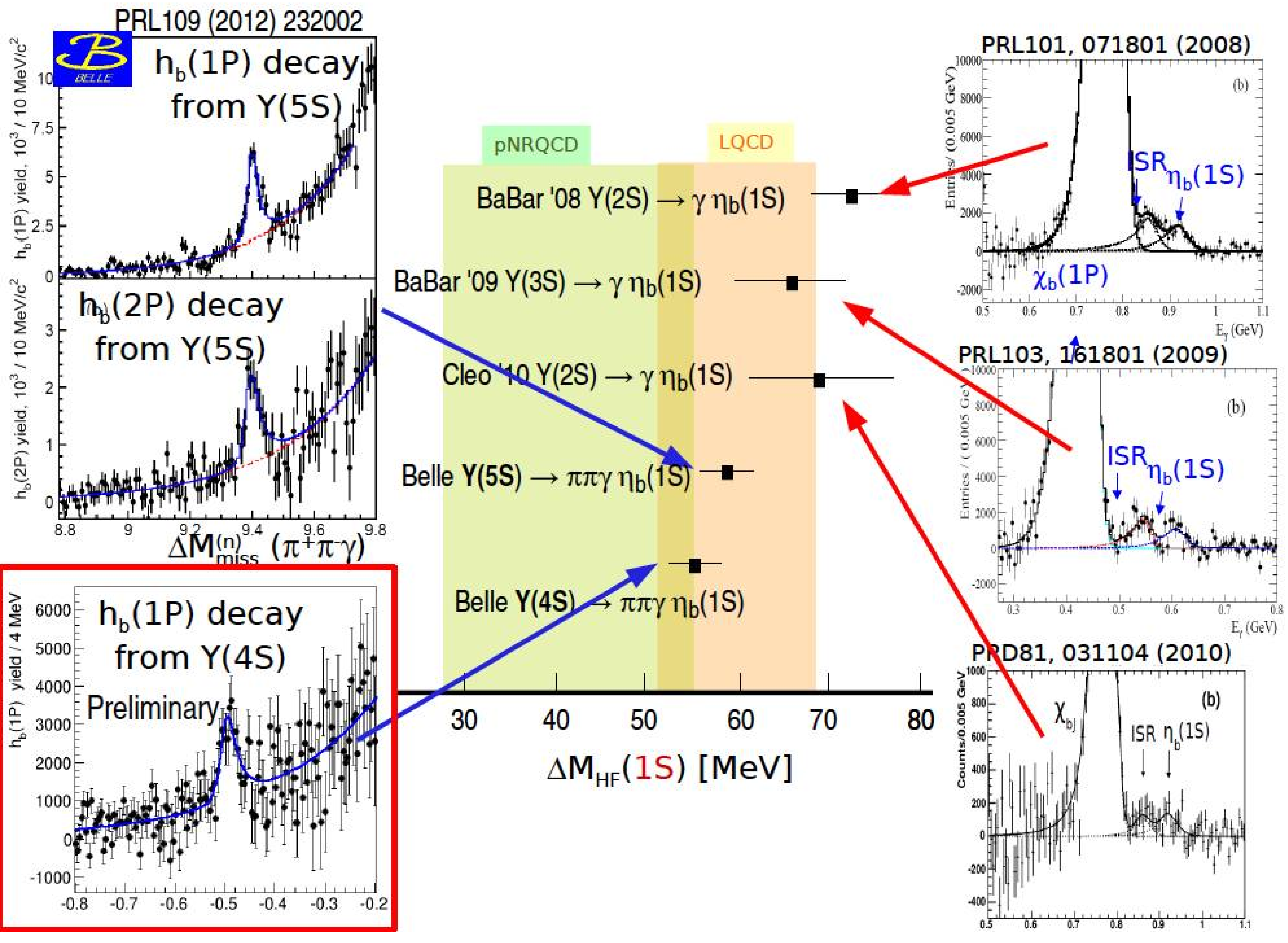
Single track trigger was implemented, too with 1/500 pre-scale rate (pt>250 MeV/c)

$$\frac{\text{2-track trigger \& 1-track trigger}}{\text{1-track trigger}}$$

for efficiency monitoring

244 events predicted

$Br(\Upsilon(1S) \rightarrow \text{invisible}) = 6 \times 10^{-3}$



PRL109 (2012) 232002
BELLE
$h_b(1P)$ decay from Y(5S)
$h_b(2P)$ decay from Y(5S)
$\Delta M_{miss}^{(n)}(\pi^+\pi^-\gamma)$
$h_b(1P)$ decay from Y(4S)
Preliminary
pNRQCD
LQCD
BaBar '08 Y(2S) → γ η_b(1S)
BaBar '09 Y(3S) → γ η_b(1S)
Cleo '10 Y(2S) → γ η_b(1S)
Belle Y(5S) → ππγ η_b(1S)
Belle Y(4S) → ππγ η_b(1S)
ΔM_{HF}(1S) [MeV]
PRL101, 071801 (2008)
PRL103, 161801 (2009)
PRD81, 031104 (2010)
ISR
η_b(1S)
χ_b(1P)
χ_{bJ}

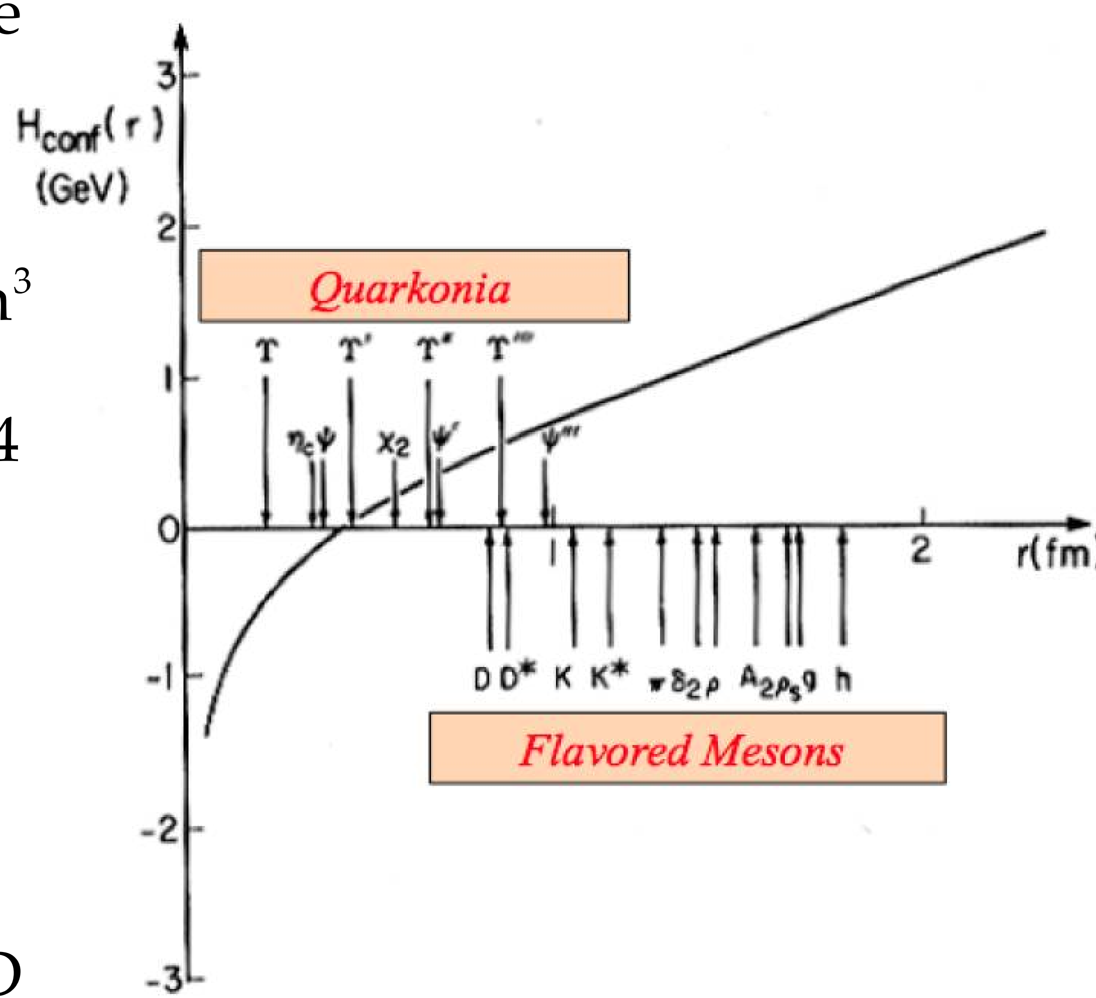
Scales, gluon densities

Low lying bottomonia are the mesons with the highest energy density!
$R = 0.25\text{-}0.5$ fm
$E/(4\pi R^3/3) = 20\text{-}200\ \text{GeV}/\text{fm}^3$

Annihilate to light hadrons (4 flavors: u,d,s,c) via:

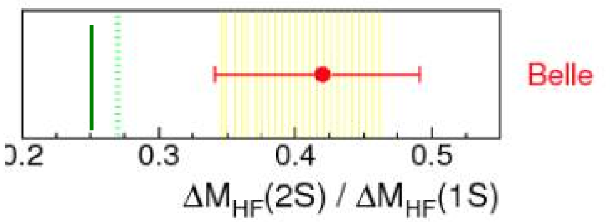
- Y(1,2,3S) $\rightarrow ggg$
  $\rightarrow gg\gamma$
  $\rightarrow \gamma^*$
- $\chi_{b0,2}(1P) \rightarrow gg$
- $\chi_{b1}(1P) \rightarrow gq\bar{q}$

Main backgrounds from QED processes: $ee \rightarrow \gamma^* \rightarrow q\bar{q}$ and radiative corrections (ISR,FSR)



Parabottomonia vs theory

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

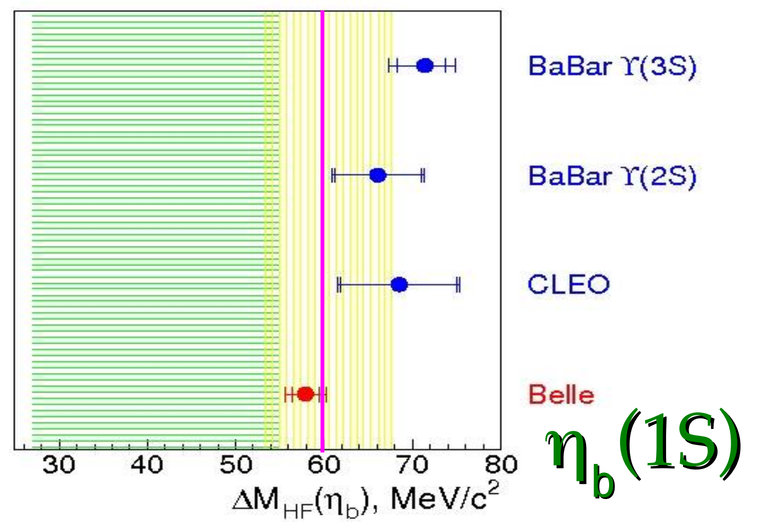


PNRQCD@NLL PRL92,242001(2004)

Lattice QCD PRD82,114502(2010)

Godfrey-Isgur, PRD32,189 (1985)

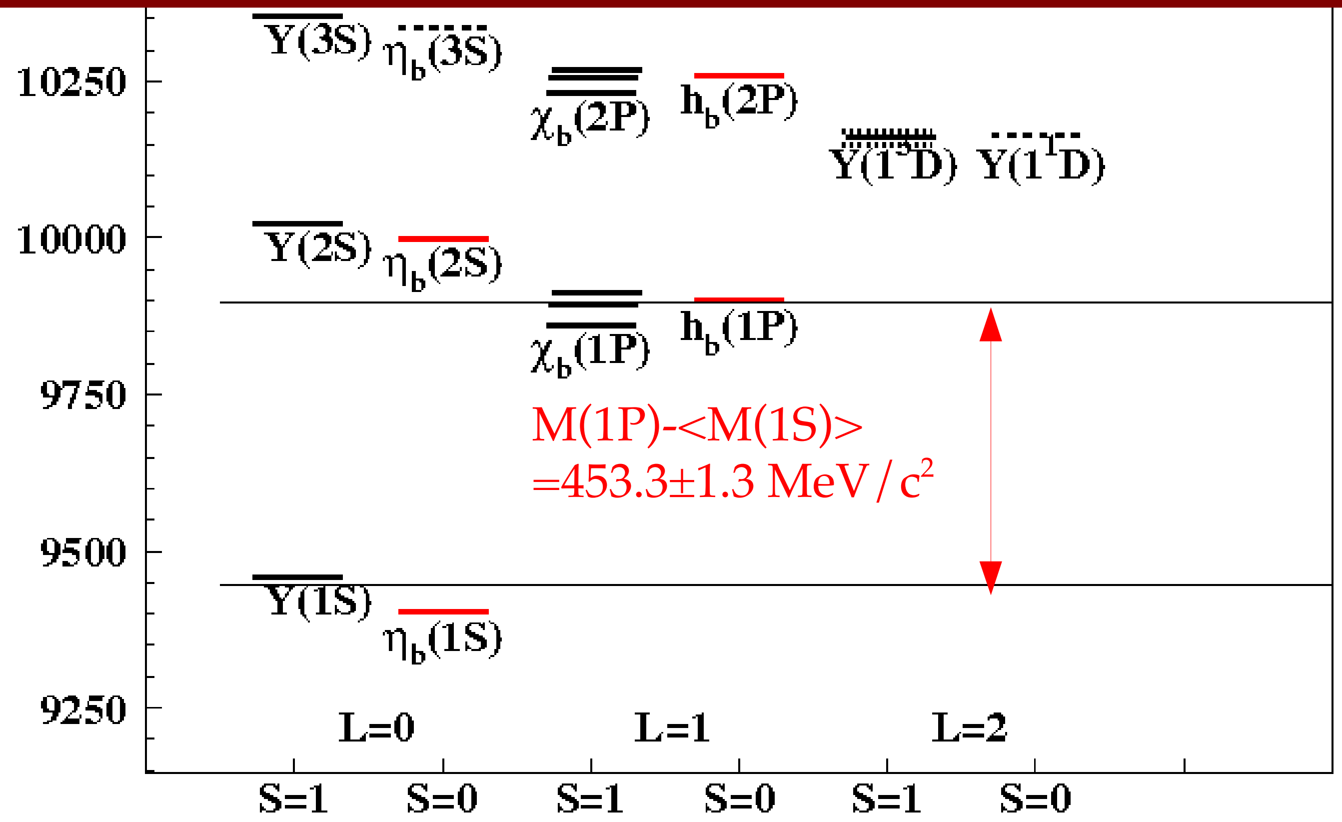
10 MeV discrepancy w/ earlier Babar and CLEO results



$\eta_b(1S)$

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



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

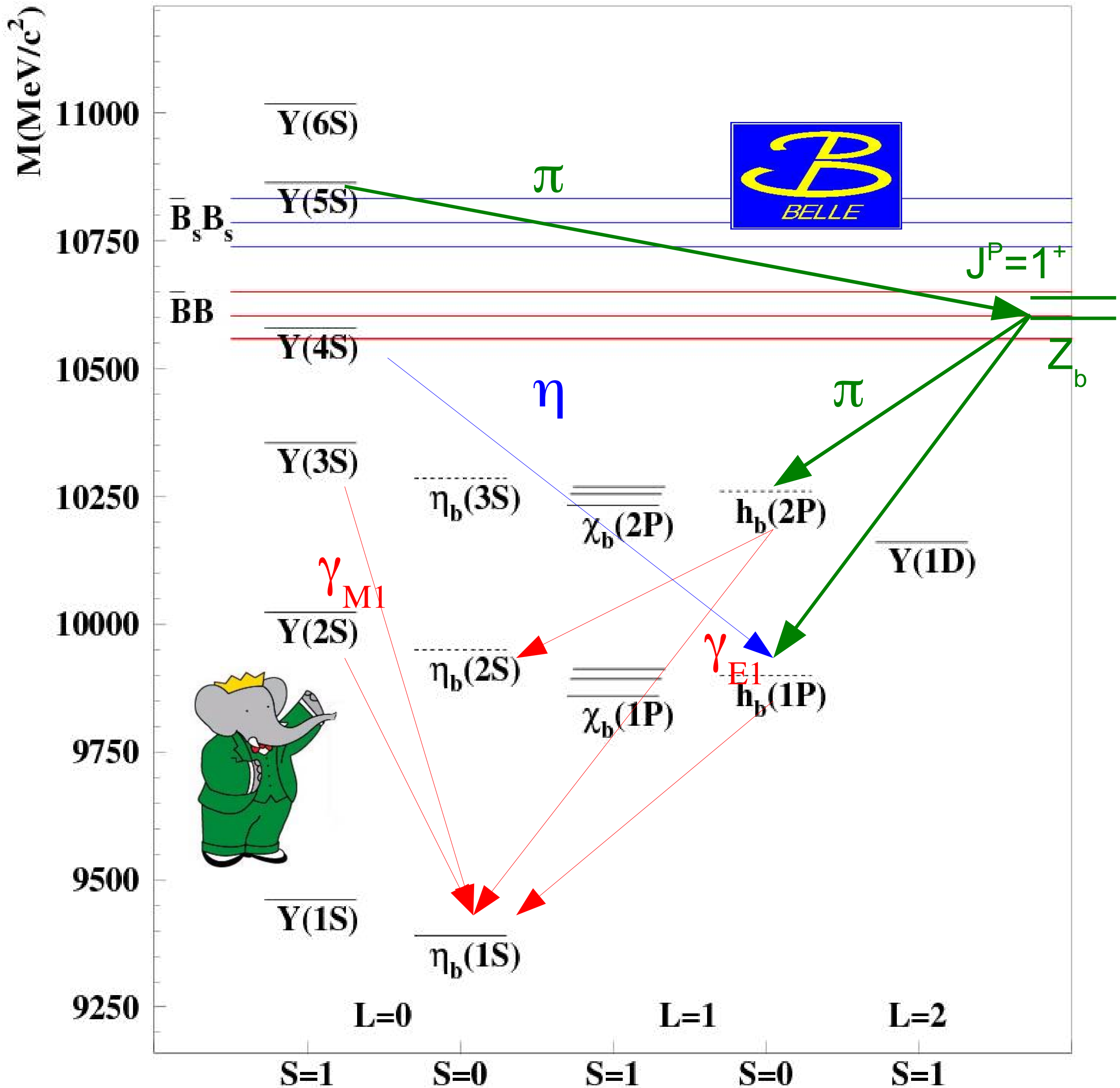
2nd QWG Report :
Eur.Phys.J. C71 (2011) 1534 ,
ArXiv:1010.5827,

The quest for parabottomonia

5 amazing years for bottomonium spectroscopy:

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

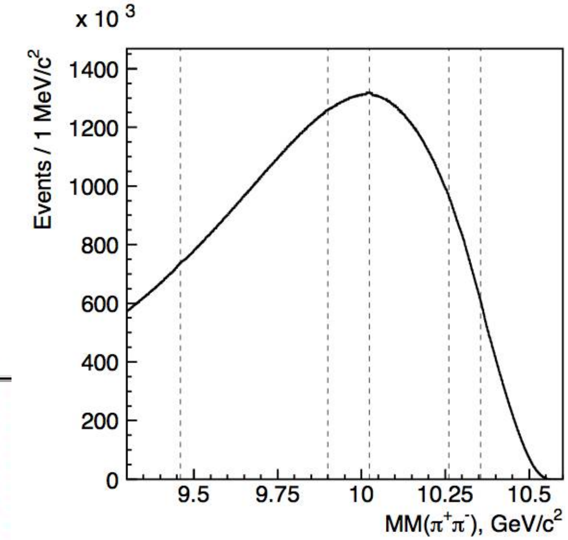
Belle discovers 4 parabottomonia , and 2 4quark states in one shot!

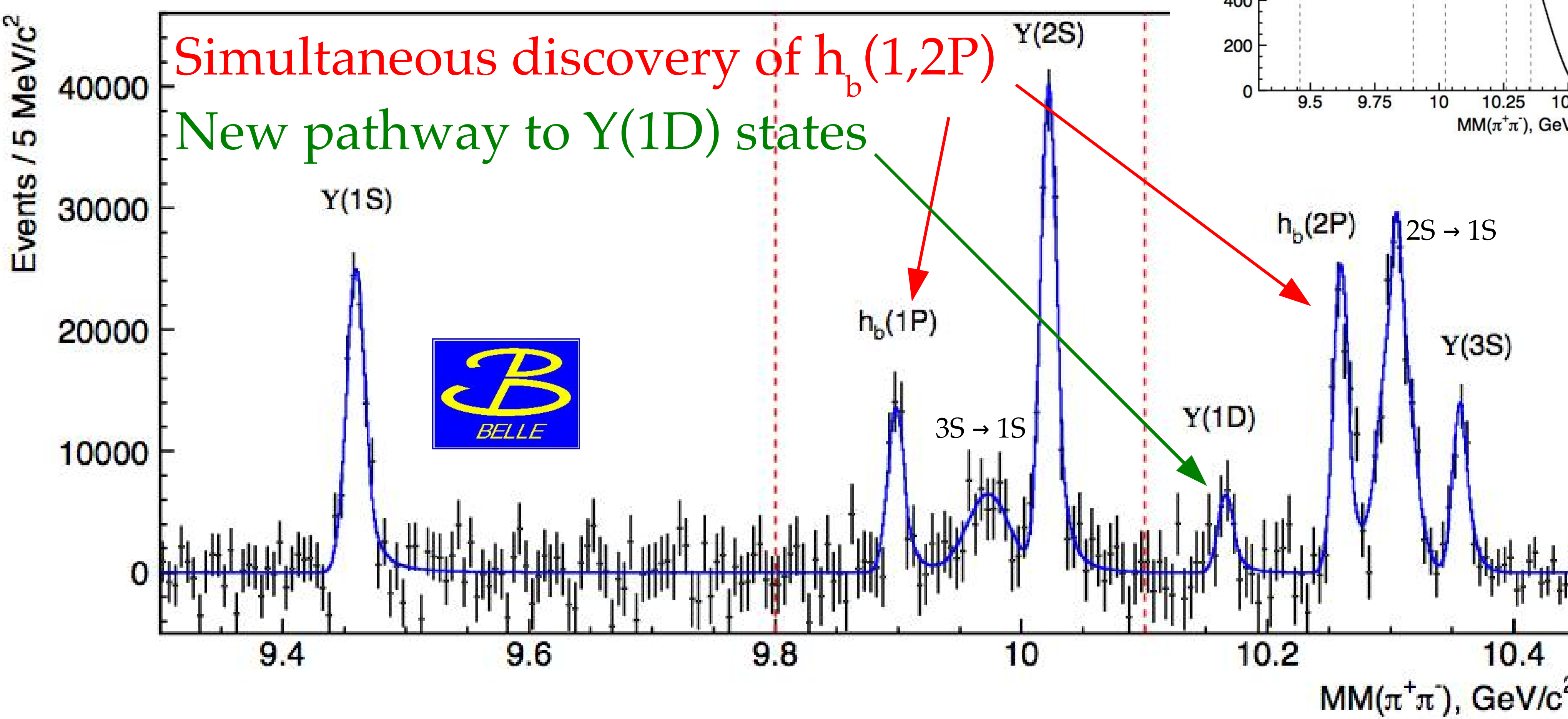


$h_b(1,2P)$ from $\Upsilon(5S)$

PRL108,032001

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

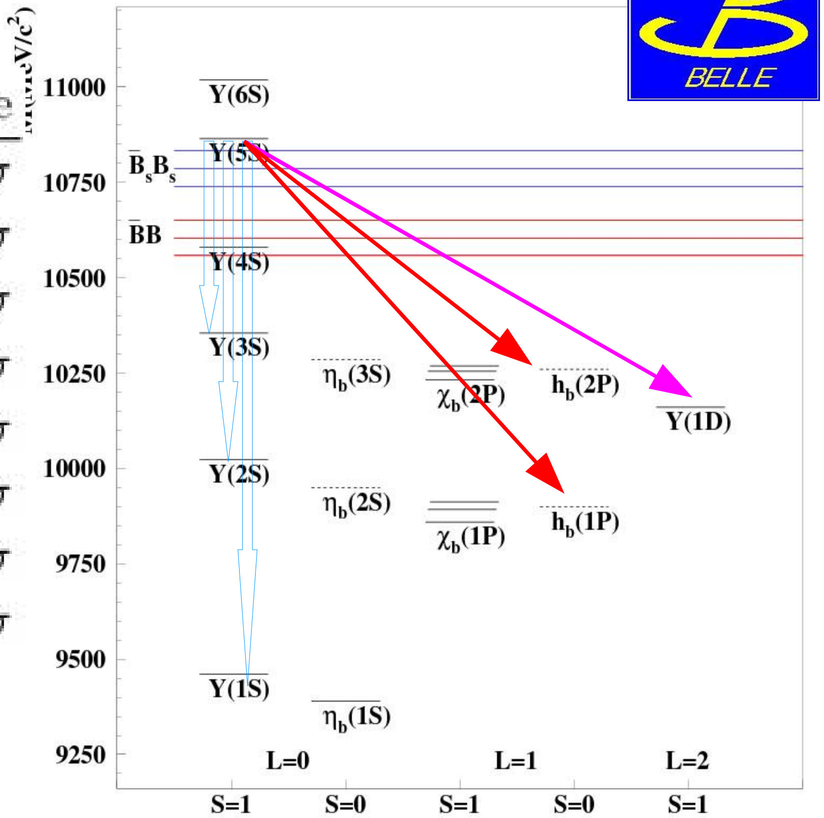




h_b(1,2P) from ϒ(5S)

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	↔	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	↔	$12.4\,\sigma$
$2S \to 1S$	$151.7 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$		$15.7\,\sigma$
$\Upsilon(3S)$	$45.6 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	⇔	$8.5\,\sigma$

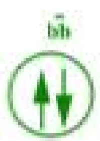


Significance after correcting for systematics effects: $h_b(1P)$ 5.5σ $h_b(2P)$ 11.2σ

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 $\Delta M_{HF}(2P) = 0.5^{+1.6}_{-1.2}$ 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

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)