New and conventional bottomonium states

Jin Li

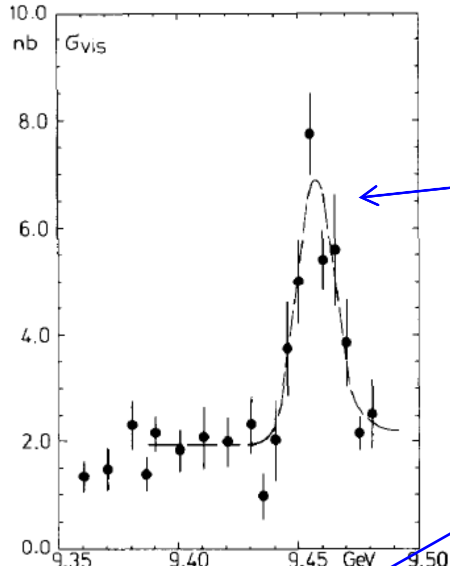
Seoul National University

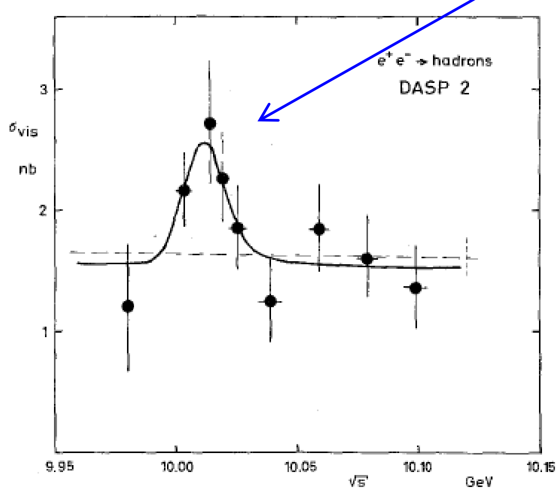
FPCP2012

Υ discovery in 1978

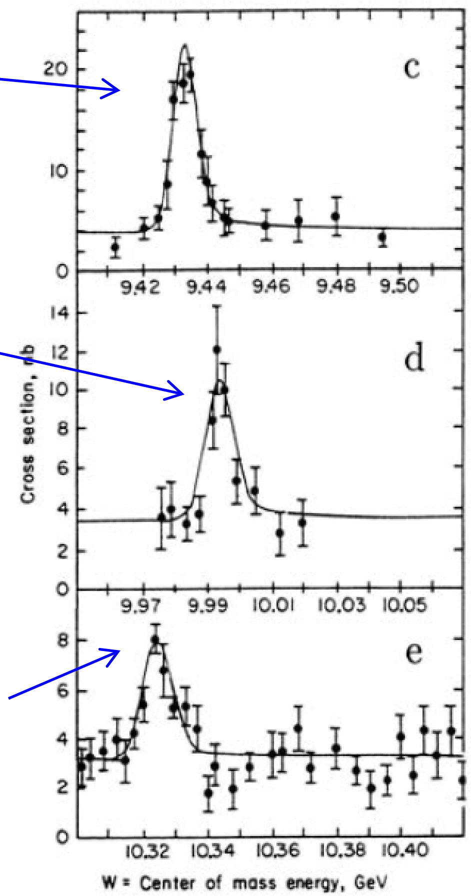
Υ, Υ’ discovered in e^+e^- annihilation.

DORIS ring at DESY





CLEO group at CESR



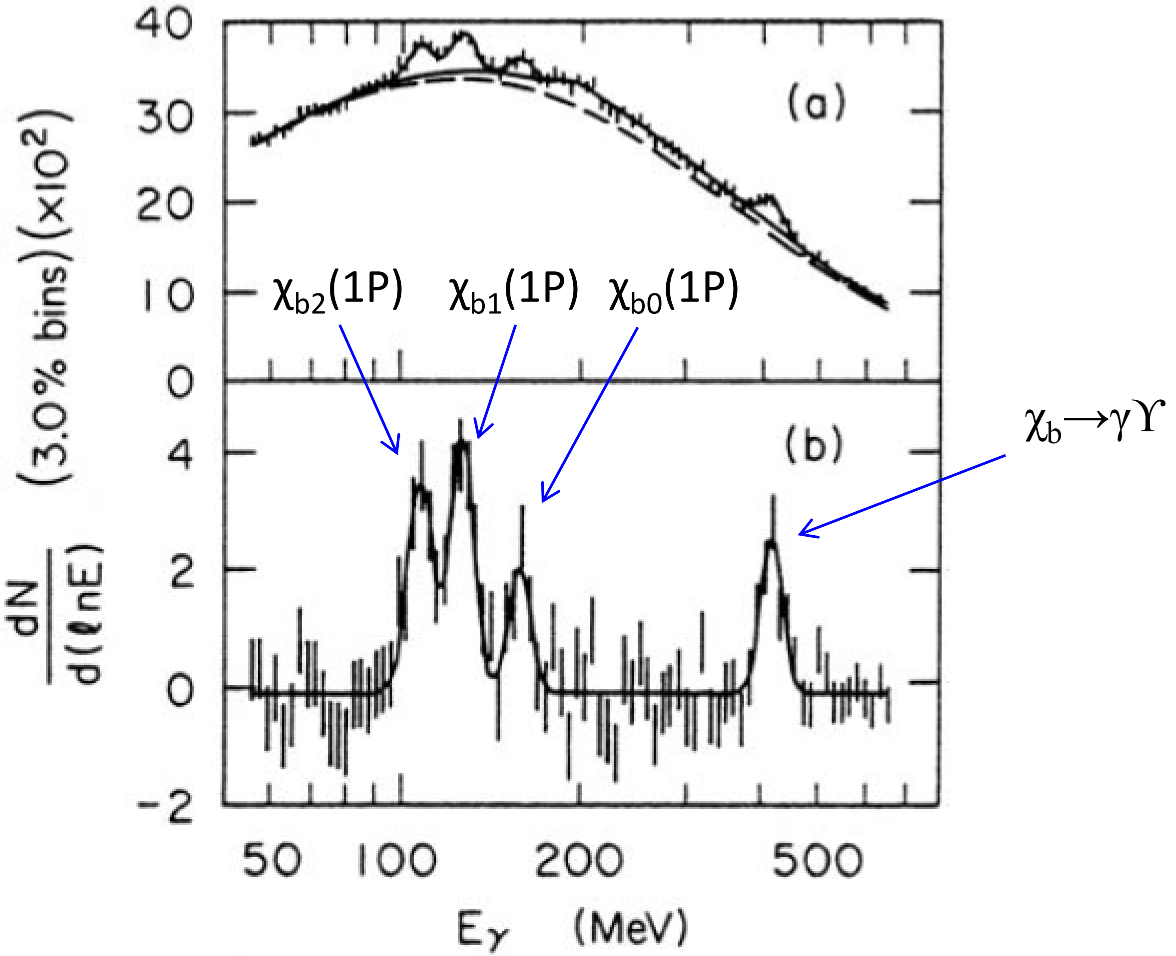
Υ

Υ’

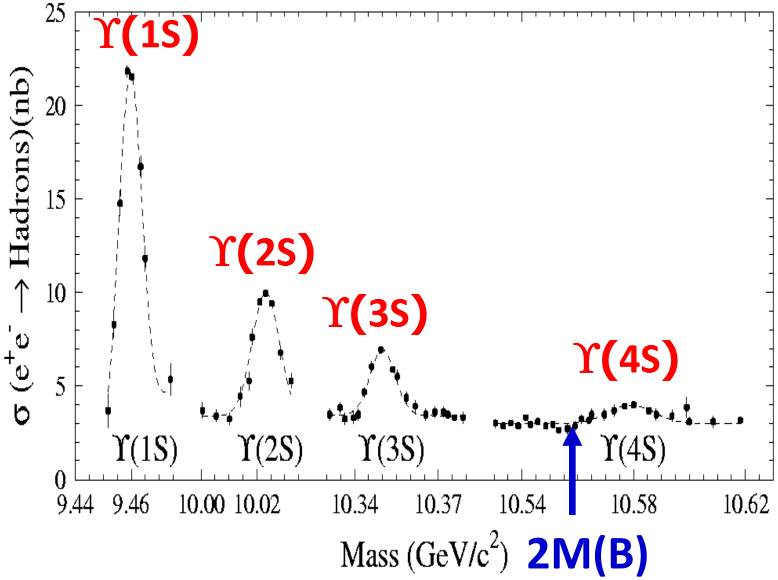
Υ’’

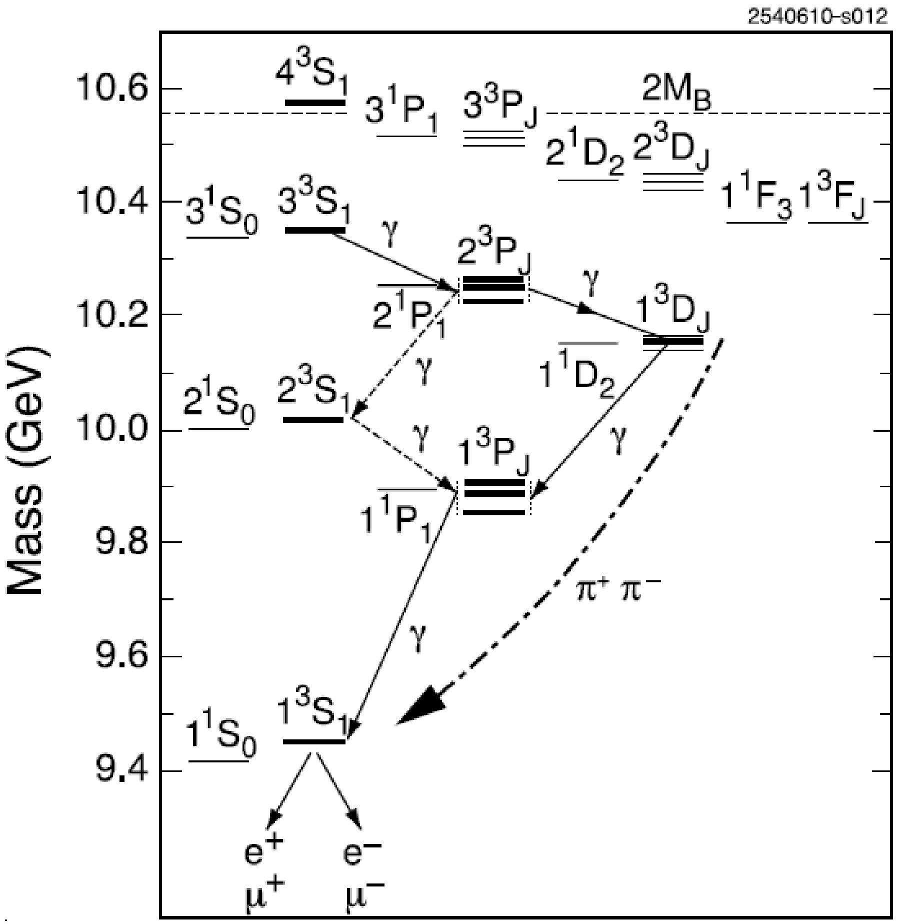
$\chi_b(^3P_{2,1,0})$ observation in 1985

Photon spectrum from ϒ' decays. Crystal Ball Collaboration at DORIS II.



The bottomonium family





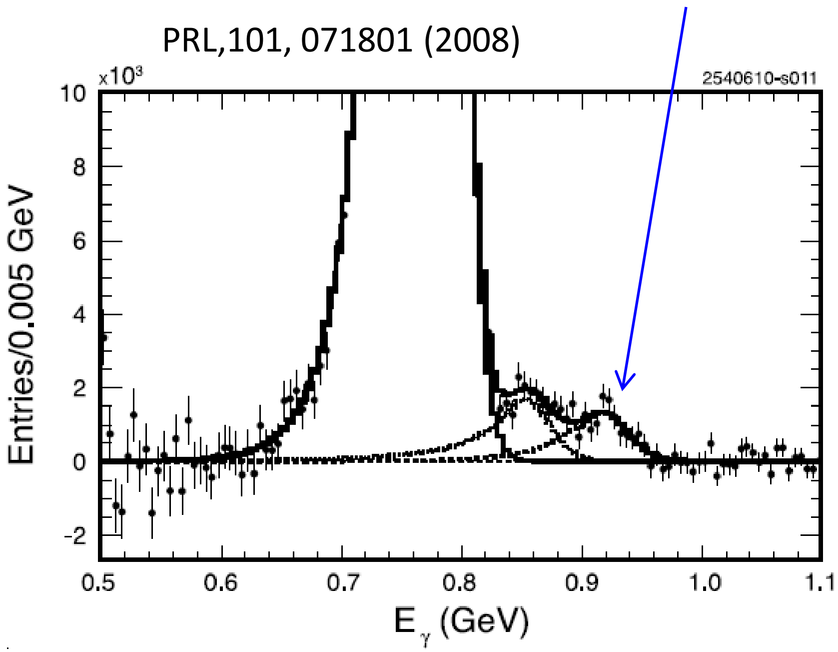
BaBar, CLEO collected large ϒ(3S) data because its rich decay trees.

Old strategy: γ lineshape

BaBar's η_b discovery

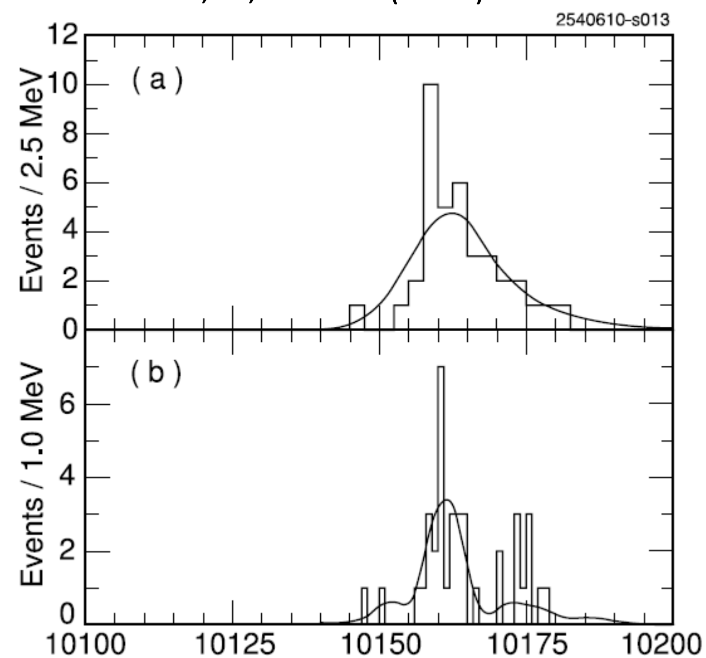
$\Upsilon(3S) \rightarrow \gamma\eta_b$

PRL,101, 071801 (2008)



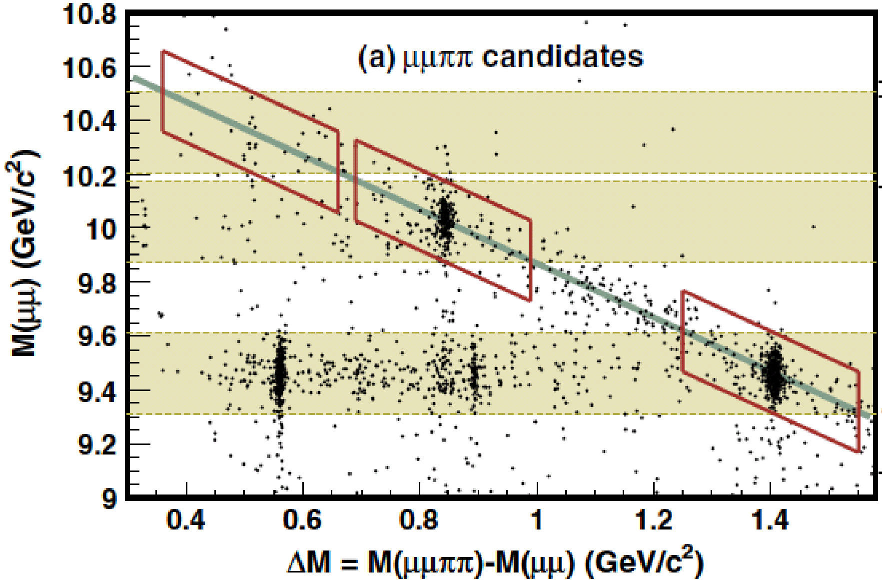
CLEO's Υ(1D) discovery

PRD,70, 032001 (2004)



Recoil mass of two soft γ from the $\Upsilon(3S) \rightarrow \gamma\gamma\gamma\gamma l^+ l^-$ events.

Υ(5S) is just different



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

Process	$\Gamma_{\Upsilon(1S)\pi^+\pi^-}$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060 MeV
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009 MeV
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019 MeV
$\Upsilon(10860) \to \Upsilon(1S)\pi^+\pi^-$	0.59 MeV

~ × 100

Υ(5S) result: (21.7fb^{-1})

Belle, K.F. Chen et al.

PRL 100, 112001 (2008)

Process	σ (pb)	Γ (MeV)
$\Upsilon(1S)\pi^+\pi^-$	$1.61 \pm 0.10 \pm 0.12$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(2S)\pi^+\pi^-$	$2.35 \pm 0.19 \pm 0.32$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(3S)\pi^+\pi^-$	$1.44^{+0.55}_{-0.45} \pm 0.19$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(1S)K^+K^-$	$0.185^{+0.048}_{-0.041} \pm 0.028$	$0.067^{+0.017}_{-0.015} \pm 0.013$

So Belle took large data at **Υ(5S)** resonance. **Now 121.4 fb^{-1} total.**

The $\pi^+\pi^-$ transition of $\Upsilon(5S)$

Missing mass technique ➡ Good for study of unknown particles

Full reconstruction, when the decays of daugher particles are known.

$$\Upsilon(5S) \rightarrow \Upsilon(1S,2S,3S)\ \pi+\pi-$$

$$\Upsilon(nS) \rightarrow \mu + \mu-$$

Missing mass technique:

$$\Upsilon(5S) \rightarrow h_b(nP)\ \pi+\pi-$$

P(5S) from accelerator information

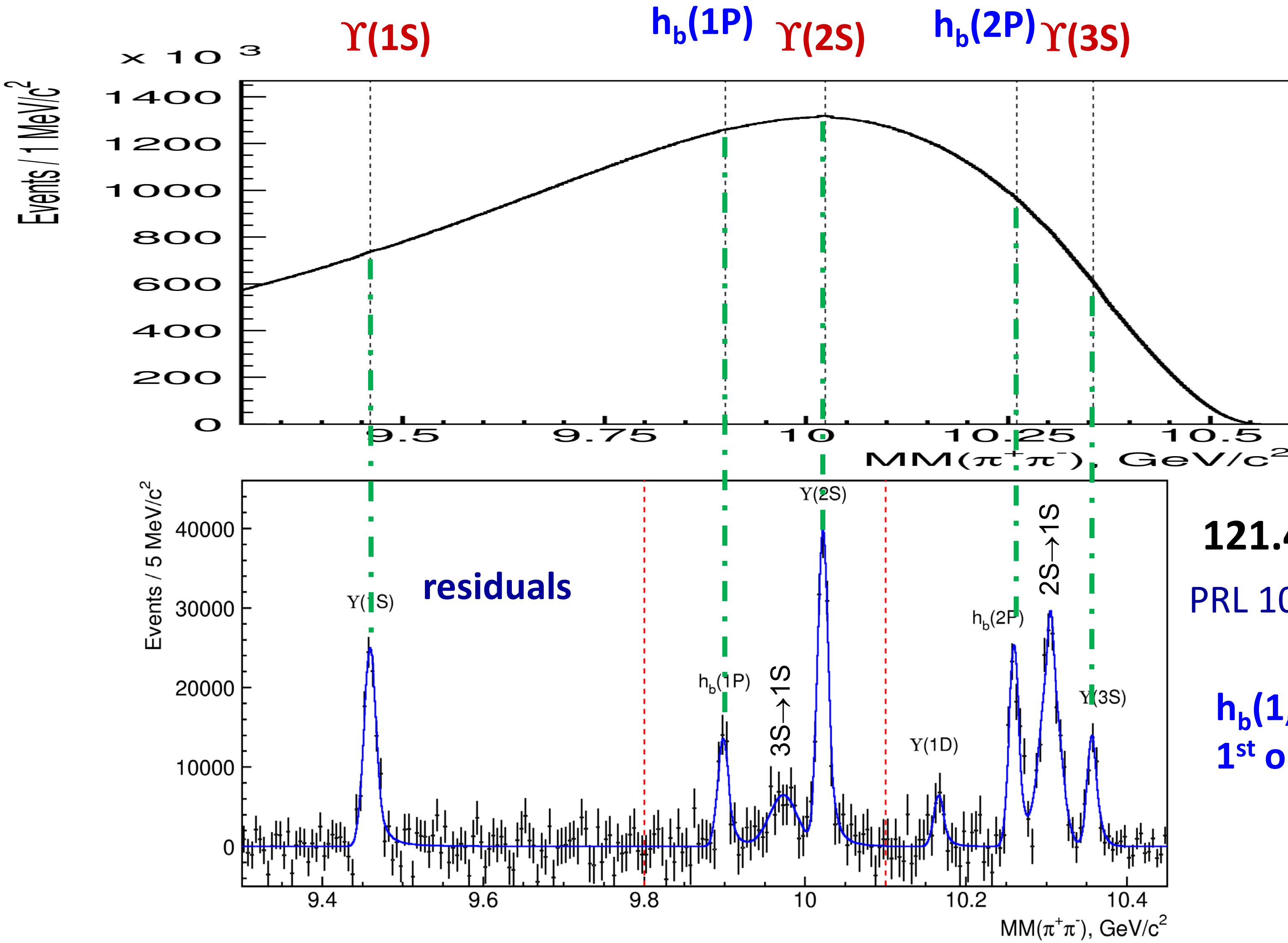
P(ππ) is reconstructed.

$$M(h_b) = \sqrt{(P(5S) - P(\pi^+\pi^-))^2} \equiv MM(\pi^+\pi^-)$$

missing mass of $\pi^+\pi^-$

Since we don't need to reconstruct h_b decays…

Results of $\pi^+\pi^-$ missing mass study



121.4 fb^{-1}

PRL 108 032001

h_b(1,2P) $J^{PC}=1^{+-}$
1st observations

$h_b(1,2P)$ mass

$(b\bar{b})$: S=0 L=1 $J^{PC}=1^{+-}$

Expected mass: center-of-gravity

$\approx (M\chi_{b0} + 3\,M\chi_{b1} + 5\,M\chi_{b2}) / 9$

$\Delta M_{HF} \Rightarrow$ test of hyperfine interaction

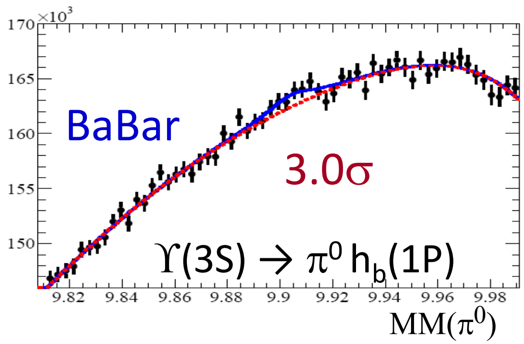
Deviations from expected masses

$h_b(1P)$ (1.7 ± 1.5) MeV/c^2

$h_b(2P)$ $(0.5^{+1.6}_{-1.2})$ MeV/c^2

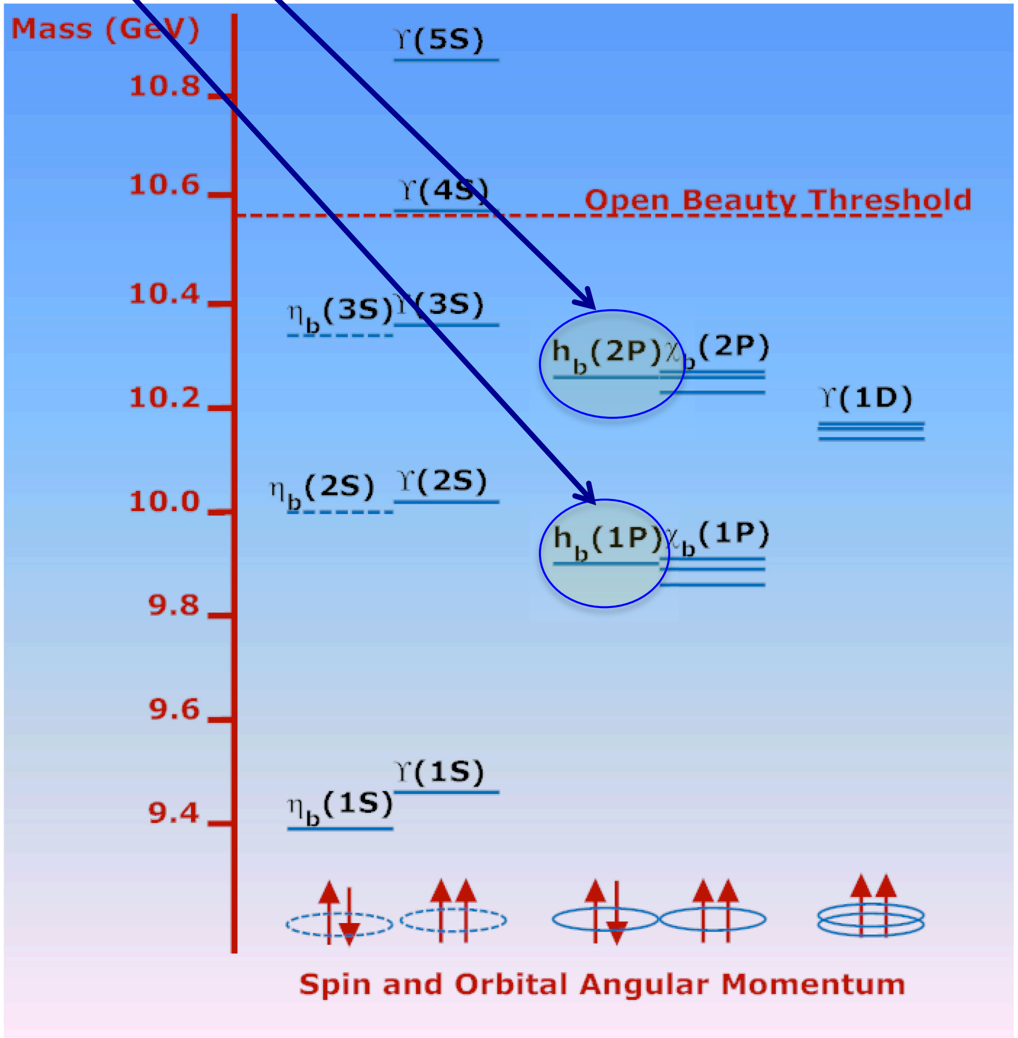
Agrees with expectations

Previous search



arXiv:1102.4565

Belle PRL 108, 032001



Large $\Upsilon(5S) \to h_b(nP)\ \pi^+\pi^-$ rate

S=1 for $\Upsilon(5S)$; S=0 for h_b

Spin-flip

$$\frac{\Gamma(\Upsilon(5S) \to h_b(nP)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)} = \begin{cases} 0.407 \pm 0.079^{+0.043}_{-0.076} & h_b(1P) \\ 0.78 \pm 0.09^{+0.22}_{-0.10} & h_b(2P) \end{cases}$$

No spin-flip

Process with spin-flip of heavy quark is not suppressed

$\Rightarrow$ Mechanism of $\Upsilon(5S) \to h_b(nP)\ \pi^+\pi^-$ decay is exotic

CLEO-c's $e^+e^- \to \pi^+\pi^- h_c$ cross section

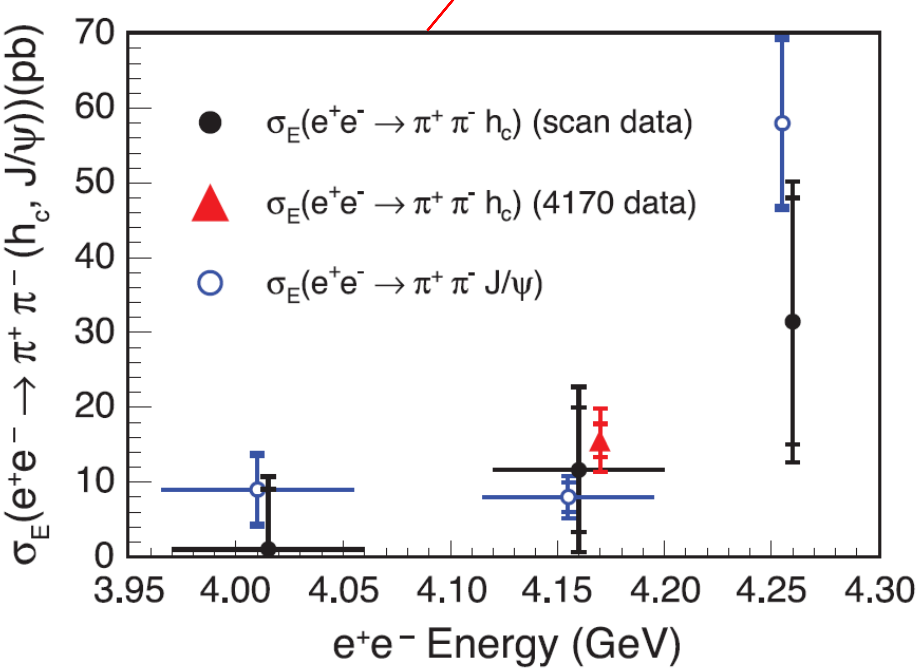
An interesting comparison!

- $\sigma(h_c\,\pi^+\pi^-) \cong \sigma(J/\psi\,\pi^+\pi^-)$
- $\Gamma(Y(4260) \to J/\psi\pi^+\pi^-)$>508 keV@ 90% C.L.

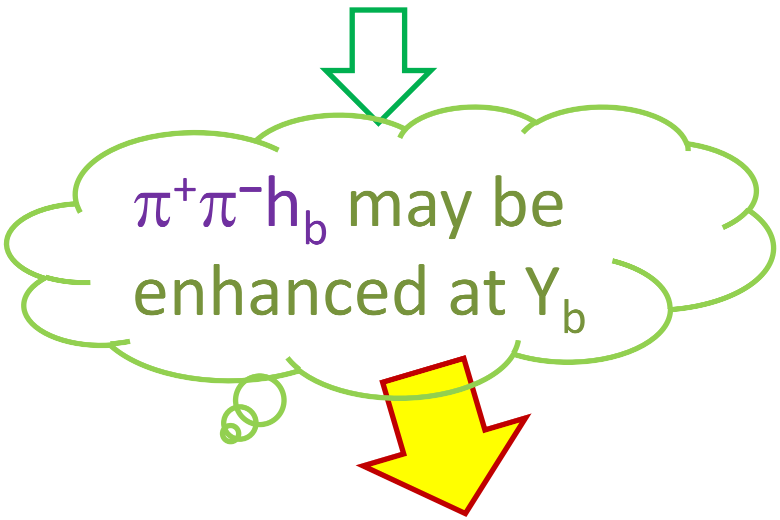
$\Rightarrow$ **Large!!** X. H. Mo et al., Phys. Lett. B 640 (2006) 182

PRL107, 041803 (2011)

arXiv:1102.3424



$\pi^+\pi^- h_c$ production is enhanced at Y(4260)



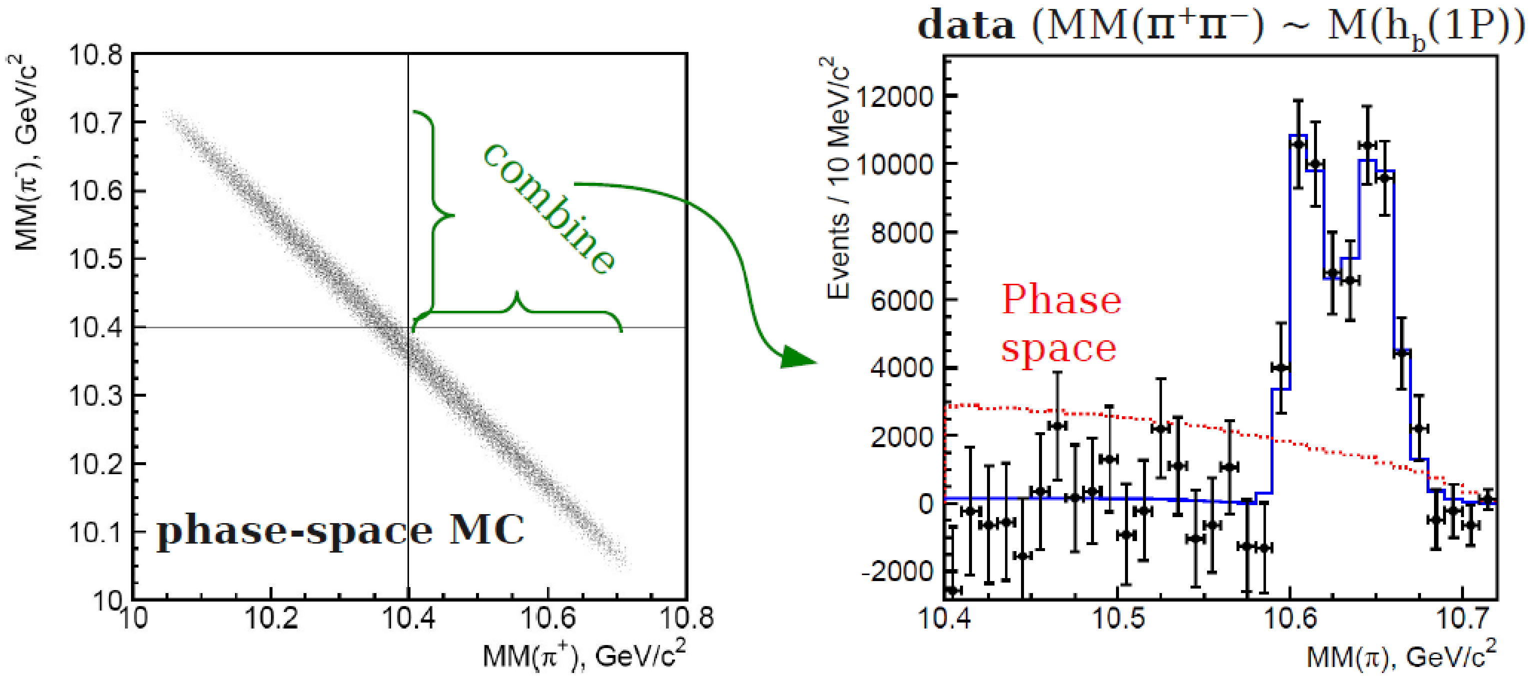
Substructure of $\pi^+\pi^-$ h_c in Y(4260) has **not** been studied.

Substructure of $\pi^+\pi^-$ h_b **:** Enough statistics in Belle's Υ(5S) data.

Original Motivation for h_b search

Resonant substructure of $h_b(nP)\pi^+\pi^-$

Now look at the missing mass of a single pion π^-, then **$MM(\pi^-) = M(h_b\ \pi^+)$**



Fit Function:

$$|\,BW(s,M_1,\Gamma_1)+ae^{i\phi}BW(s,M_2,\Gamma_2)+be^{i\psi}\,|^2\ \frac{qp}{\sqrt{s}}$$

Significances with systematic:

1 resonance v.s. 0: **6.6 σ**

2 resonances v.s. 0: **16 σ**

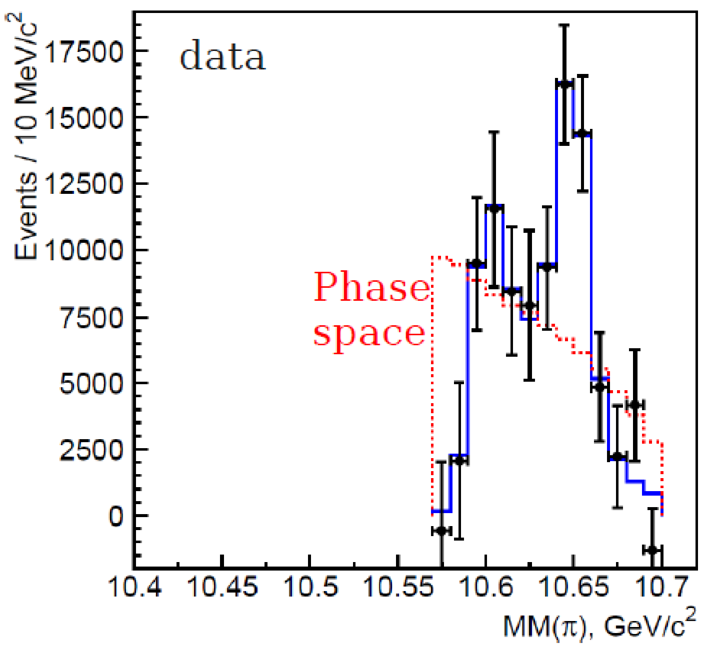
Similar analysis for $h_b(2P)\pi^+\pi^-$

Significances:

For h_b (2P) yields in MM(π^-) bins, the allowed phase space is smaller.

1 resonance v.s. 0: **1.9 σ**

2 resonances v.s. 0: **4.7 σ**



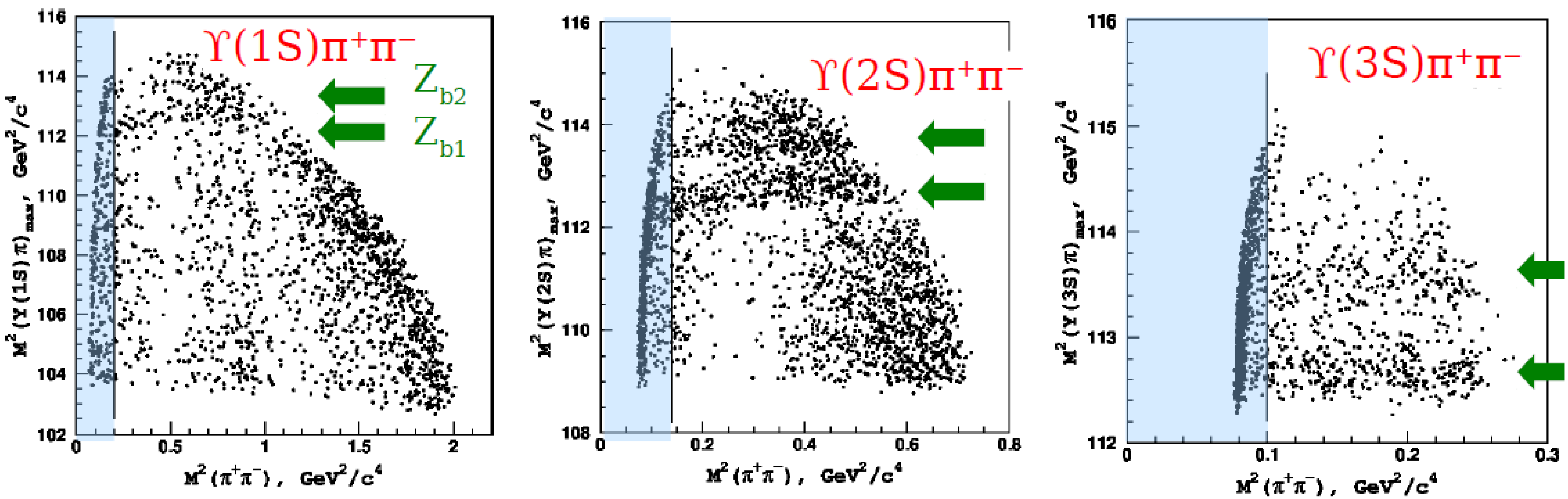
	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M_{Z_{b1}}$	$10605.1 \pm 2.2^{+3.0}_{-1.0}$	$10596 \pm 7^{+5}_{-2}$
$\Gamma_{Z_{b1}}$	$11.4^{+4.5+2.1}_{-3.9-1.2}$	16^{+16+13}_{-10-4}
$M_{Z_{b2}}$	$10654.5 \pm 2.5^{+1.0}_{-1.9}$	$10651 \pm 4 \pm 2$
$\Gamma_{Z_{b2}}$	$11.4^{+5.4+2.1}_{-4.7-5.7}$	$12^{+11+8}_{-9\ -2}$
a	$1.8^{+1.0+0.1}_{-0.7-0.5}$	$1.3^{+3.1+0.4}_{-1.1-0.7}$
ϕ	188^{+44+4}_{-58-9}	$255^{+56+12}_{-72-183}$
NR	~ 0	~ 0

Mass/width in MeV(/c²), phase in degrees

- Good agreement between h_b(1P) and h_b(2P).
- Non resonant part ~ 0: Nearly all produced through

$$\Upsilon(5S) \to Z^{\pm}\pi^{\mp} \to h_b(nP)\pi^{\pm}\pi^{\mp}$$

Dalitz Plots of $\Upsilon(5S)\to\Upsilon(nS)\,\pi^+\pi^-$



Exclude high background from photon conversions

$$S(s_1,s_2) = \left| A_{Z_{b1}} + A_{Z_{b2}} + A_{\mathrm{NR}} + A_{f_0(980)} + A_{f_2(1270)} \right|^2$$

$s_i = M^2_{\Upsilon\pi_i}$

Isospin symmetry

$$A_{Z_{bk}} = a_k e^{i\phi_k}\left(\frac{\sqrt{M_k\Gamma_k}}{M_k^2 - s_1 + iM_k\Gamma_k} + \frac{\sqrt{M_k\Gamma_k}}{M_k^2 - s_2 + iM_k\Gamma_k}\right)$$

$A_{NR} = c_1 + c_2 M^2_{\pi\pi}$

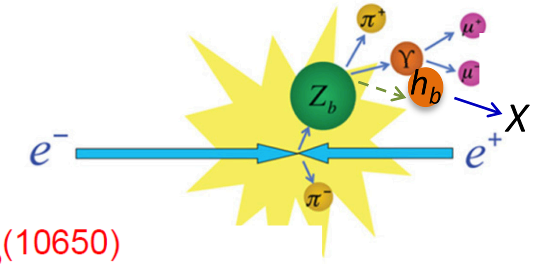
Flatté

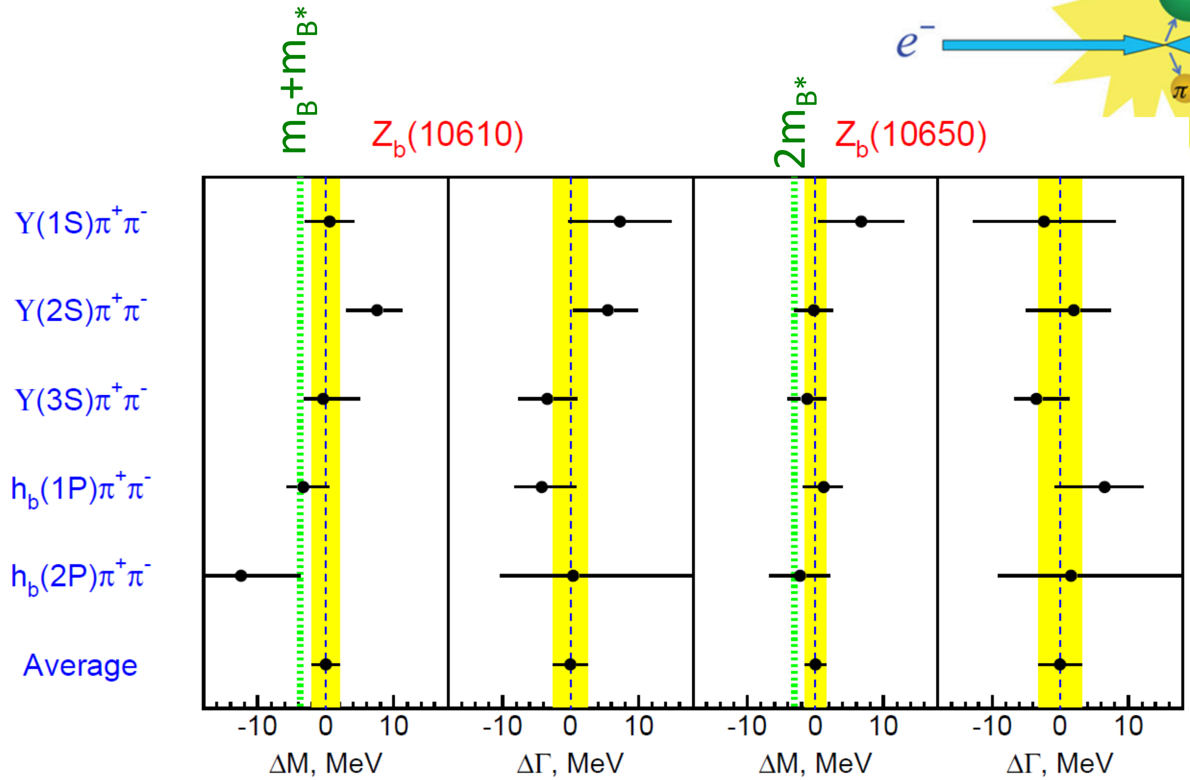
D-Wave Breit-Wigner

A. Voloshin, PRD74,054022 (2006)
Prog. Part. Nucl. Phys. 61,455 (2008)

Summary of parameter measurements

Belle PRL 108, 122001





$Z_b(10610)$

M=10607.2±2.0 MeV

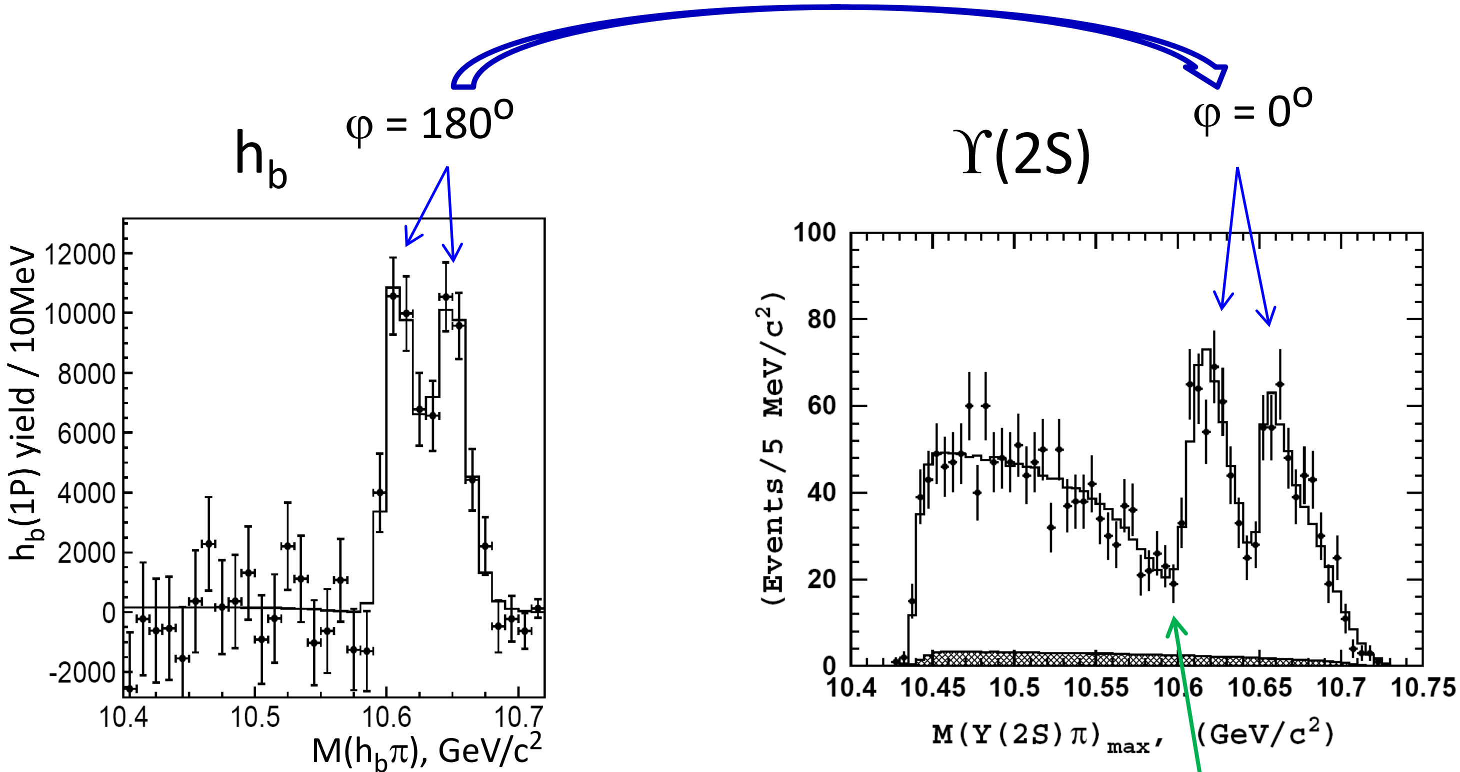
Γ=18.4±2.4 MeV

$Z_b(10650)$

M=10652.2±1.5 MeV

Γ=11.5±2.2 MeV

Projections of $\Upsilon(5S) \to [\Upsilon(nS), h_b]\, \pi^+\pi^-$



Dip due to destructive interference with non-resonant amplitude.
$\Rightarrow$ Information on J^P of Z_b ?

Introduction to η_b

h_b has large expected radiative η_b decay

$h_b(1P) \to ggg$ (57%), $\eta_b(1S)\gamma$ (41%), γgg (2%)   Godfrey & Rosner, PRD66 014012 (2002)

$h_b(2P) \to ggg$ (63%), $\eta_b(1S)\gamma$ (13%), $\eta_b(2S)\gamma$ (19%), γgg (2%)

Large $h_b(mP)$ samples give opportunity to study $\eta_b(nS)$ states.

Reminder: Experimental status of η_b

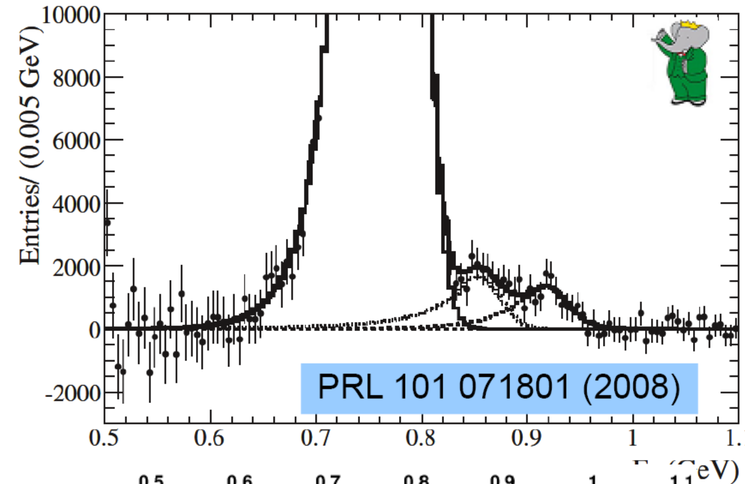
$M[\eta_b(1S)] = 9390.9 \pm 2.8$ MeV (BaBar + CLEO)
$M[\Upsilon(1S)] - M[\eta_b(1S)] = 69.3 \pm 2.8$ MeV

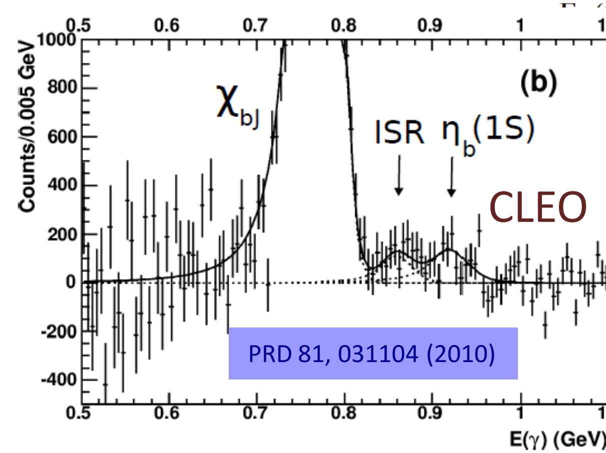
pNRQCD: 41 ± 14 MeV   Lattice: 60 ± 8 MeV

Kniehl et al., PRL92,242001(2004)   Meinel, PRD82,114502(2010)

Width of $\eta_b(1S)$: no information

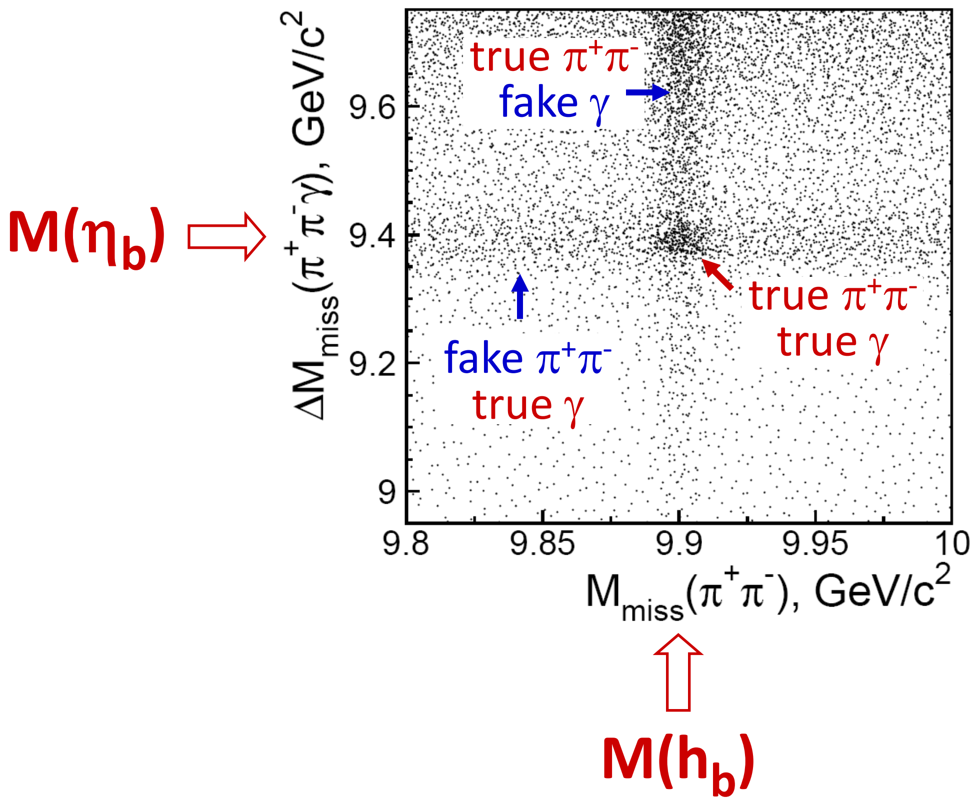
$\Upsilon(3S) \to \eta_b(1S)\,\gamma$





Method of signal extraction

MC simulation



$\Delta M_{miss}(\pi^+\pi^-\gamma) \equiv$

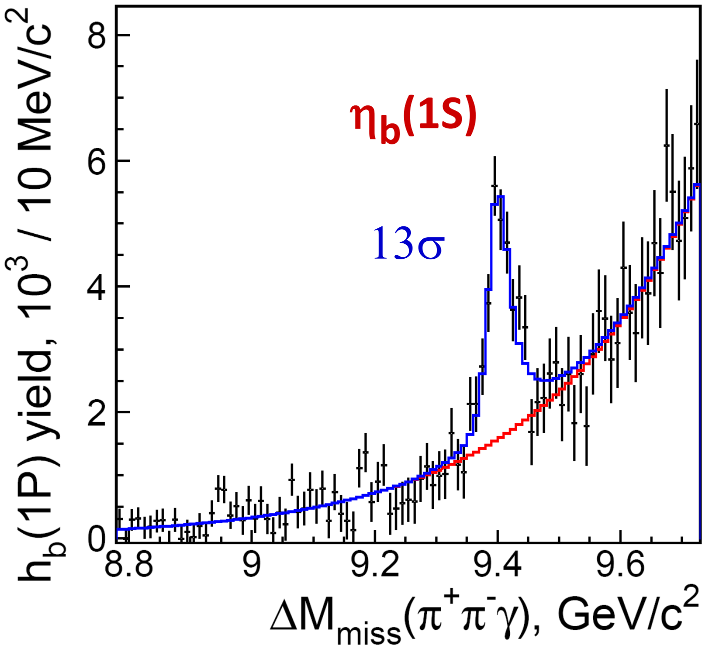
$M_{miss}(\pi^+\pi^-\gamma) - M_{miss}(\pi^+\pi^-) + M[h_b]$

- rectangular bg bands
- no correlation

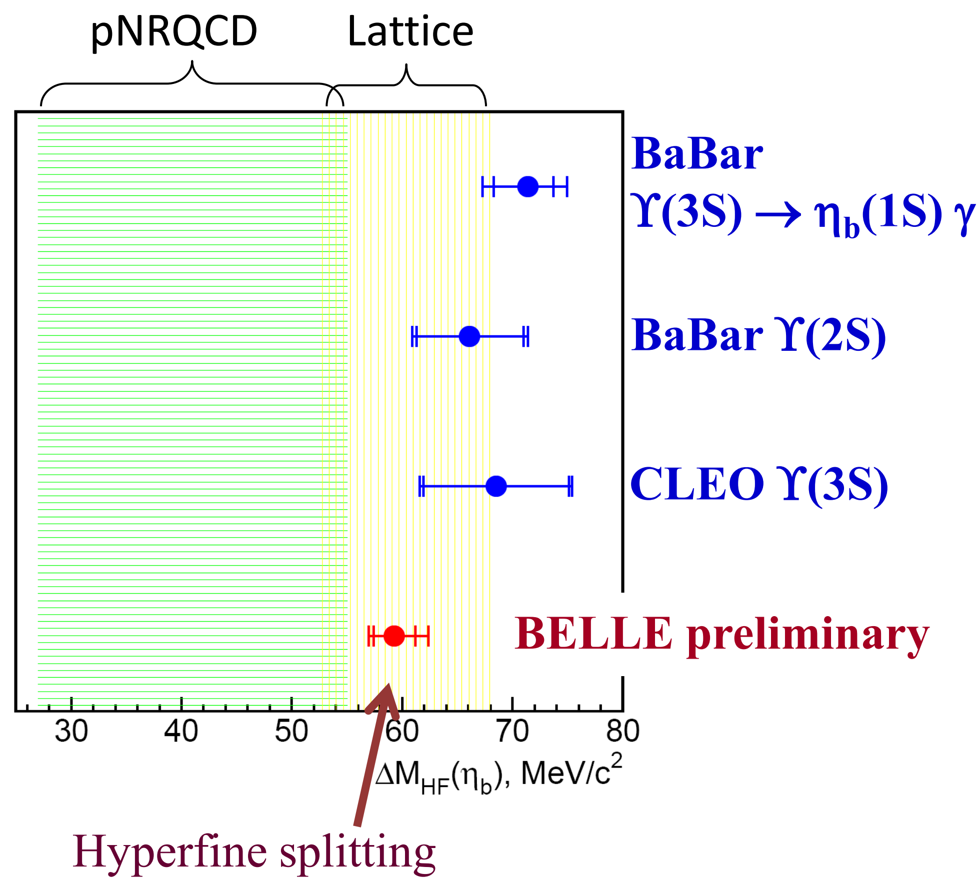
Approach:

fit $M_{miss}(\pi^+\pi^-)$ spectra in $\Delta M_{miss}(\pi^+\pi^-\gamma)$ bins

Observation of $h_b(1P) \to \eta_b(1S)\,\gamma$



N.Brambilla et al., Eur.Phys.J. C71(2011) 1534 (arXiv:1010.5827)



$$N[\eta_b(1S)] \quad (21.9 \pm 2.0^{+5.6}_{-1.7}) \cdot 10^3$$

$$M[\eta_b(1S)] \quad (9401.0 \pm 1.9^{+1.4}_{-2.4})\ \mathrm{MeV}/c^2$$

$$\Gamma[\eta_b(1S)] \quad (12.4^{+5.5+11.5}_{-4.6-3.4})\ \mathrm{MeV}$$

$\Delta M_{HF}[\eta_b(1S)] = 59.3 \pm 1.9^{+2.4}_{-1.4}$ MeV/c^2

Godfrey & Rosner : BF = 41%

$$\mathcal{B}[h_b(1P) \to \eta_b(1S)\gamma] = (49.8 \pm 6.8^{+10.9}_{-5.2})\%$$

First observation of the $\eta_b(2S)$

$h_b(2P) \rightarrow \gamma\eta_b(2S)$: same method

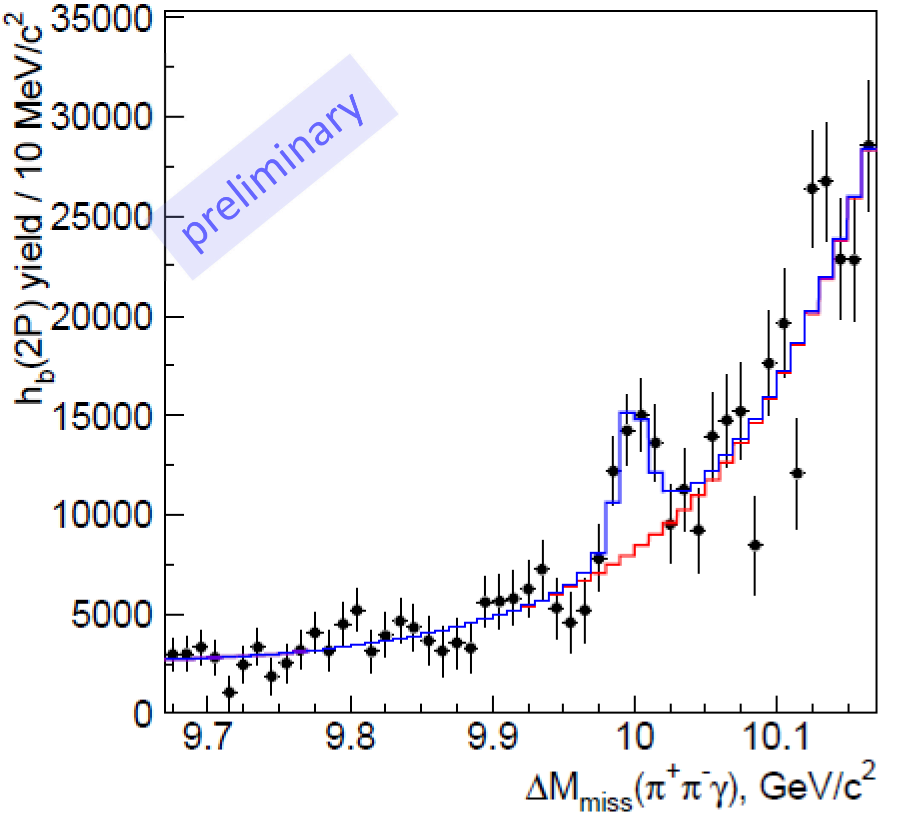
$M[\eta_b(2S)]=9999.0 \pm 3.5^{+2.8}_{-1.9}$ MeV

$Bf[h_b(2P) \rightarrow \gamma\eta_b(2S)]=47.5 \pm 10.5^{+6.8}_{-7.7}$ %

$\Delta M_{hfs}(2S)=24.3 \pm 3.5^{+2.8}_{-1.9}$ MeV

Lattice Meinel PRD82,114502(2010)

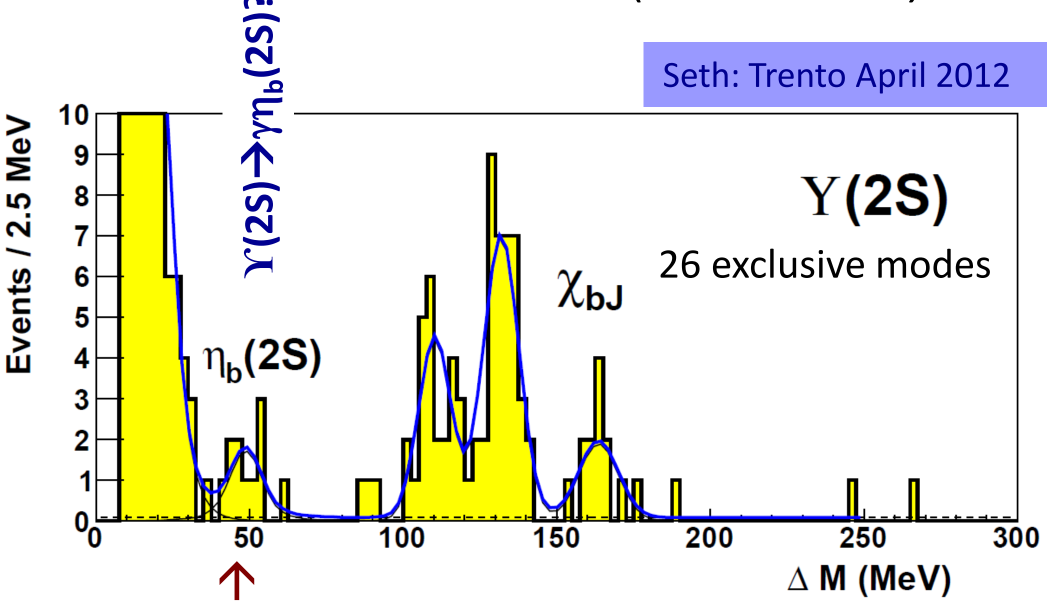
$\Delta M_{HF} = 23.5 \pm 4.7$ MeV



Comparison: $\eta_b(2S)$ "signals"

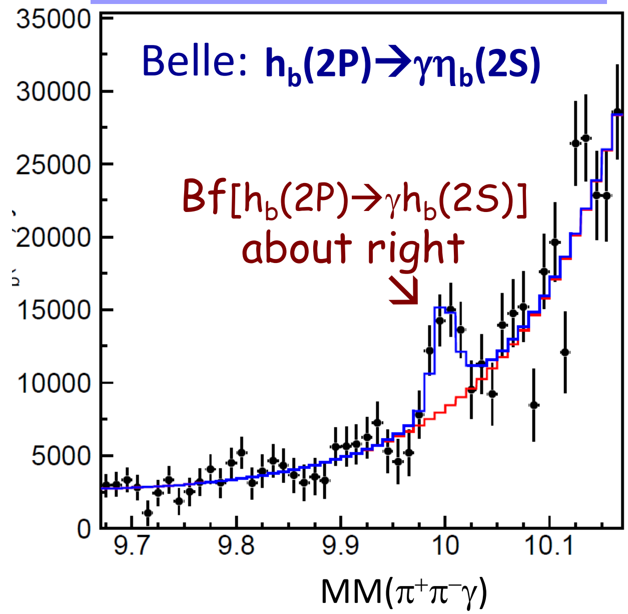
arXiv:1204.4205 (S.Dobbs *et. al)* from CLEO data

Seth: Trento April 2012



anomalously large production rate ($\sim 0.2\times\chi_{b1}$ rate)

Belle: IWHSS'12 April, 2012



Expt	ΔM_{hfs} (2S) (MeV)
S. Dobbs	48.7±2.7
Belle	24.3±4.3

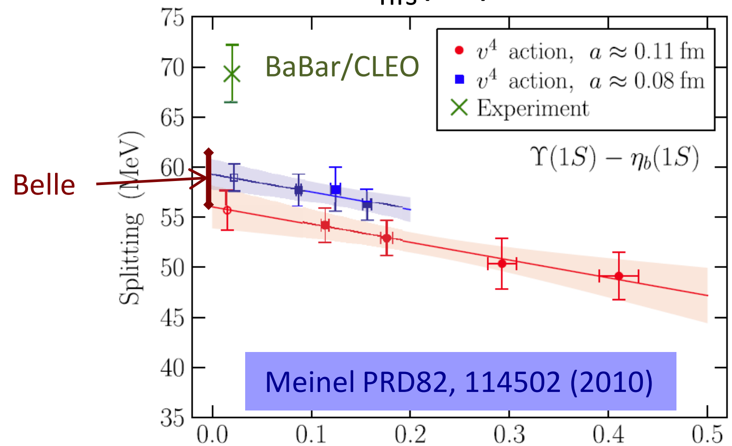
← strong disagreement with theory (S. Dobbs)

← agrees with theory (Belle)

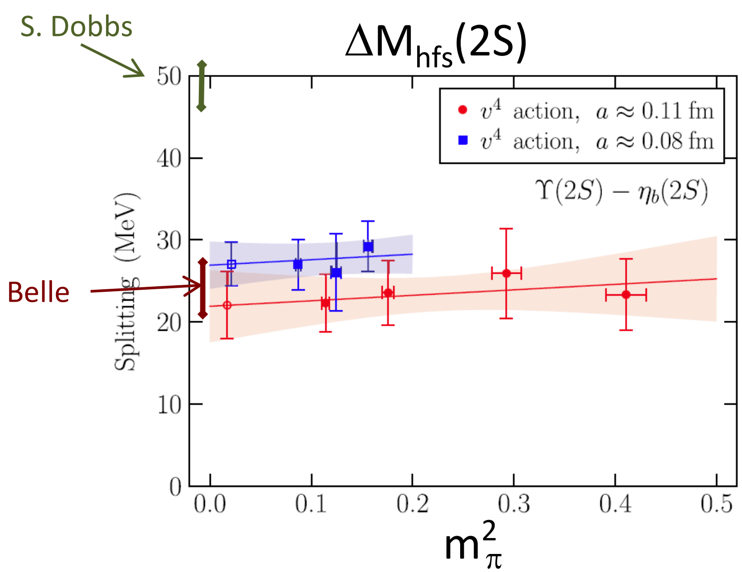
≈5σ discrepancy

LQCD predictions for $\Delta M_{hfs}(1,2S)$

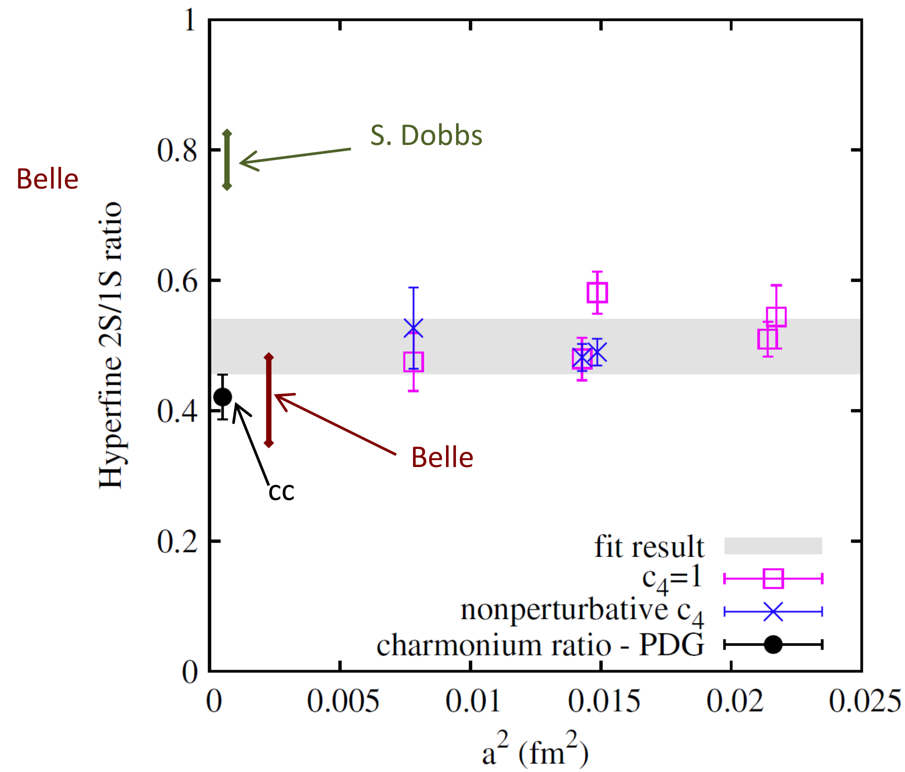
$\Delta M_{hfs}(1S)$



$\Delta M_{hfs}(2S)$



$$\frac{\Delta M_{hfs}(2S)}{\Delta M_{hfs}(1S)}$$



HP-QCD PRD85, 054509 (2012)

Observation of $\chi_b(3P)$

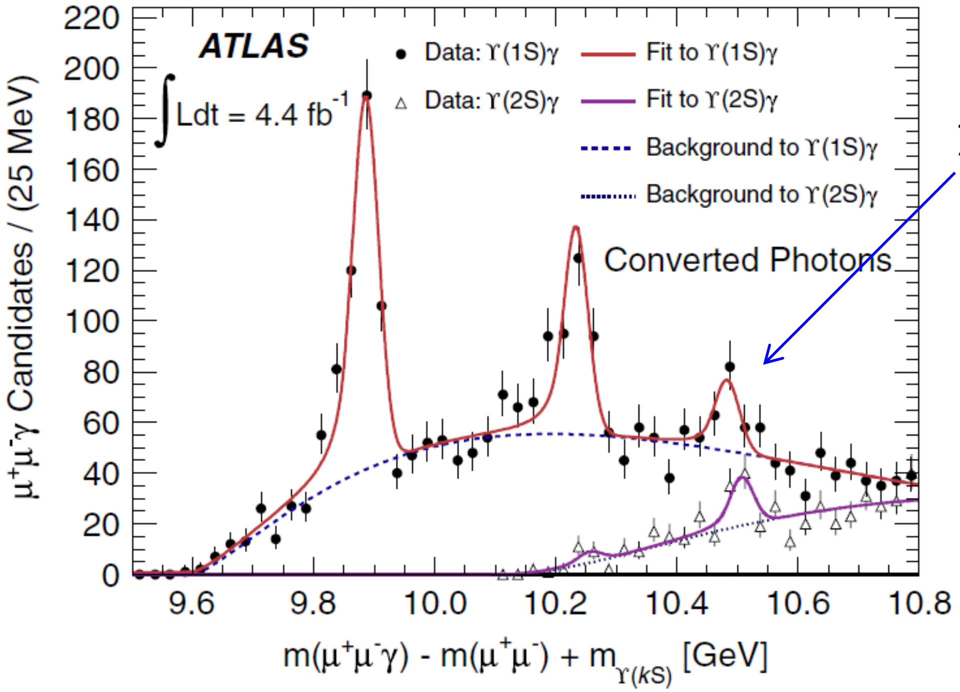
Converted photon is used for mass determination

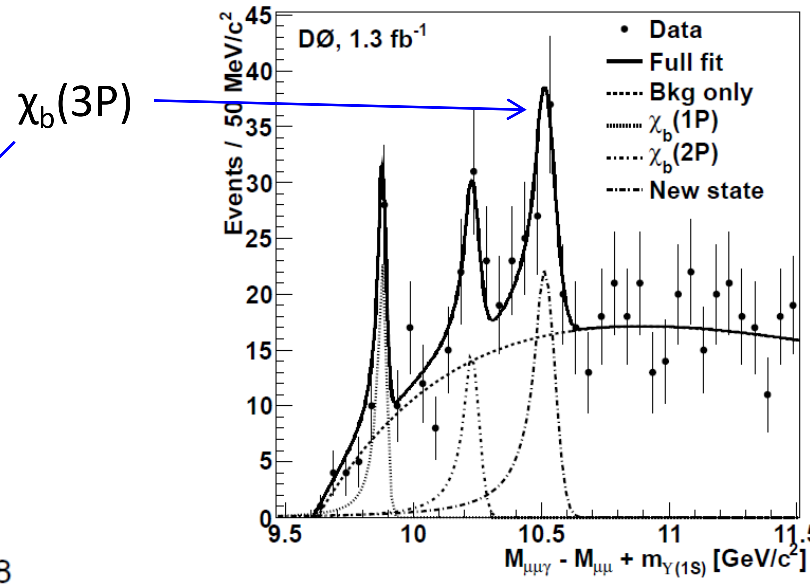
$\chi_b(3P) \rightarrow \Upsilon(1,2S)\gamma$ first by ATLAS:

PRL 108,152001

Confirmed by D0:

arXiv:1203.6034





Spin-weighted mass for $\chi_b(3P)$:

10.530±0.005±0.009 GeV **ATLAS**
10.551±0.014±0.017 GeV **D0**
10.5439 (Potential model, arxiV: 1201.4096)

$\Upsilon(nS) \to \eta \Upsilon(mS)$ Status

$\Upsilon(nS) \to \eta\, \Upsilon(mS)$: E1M2 transition, spin-flip

M. B. Voloshin, Prog. Part. Nucl. Phys. **61**, 455-511 (2008).
Y. -P. Kuang, Front. Phys. China **1**, 19-37 (2006).

QCD multipole formalism:
- spin-flip amplitude scale as $1/m_b$.

Scale from $\psi' \to \eta\, J/\psi$

$B[\Upsilon(2S) \to \Upsilon(1S)\eta] \sim 8 \times 10^{-4}$

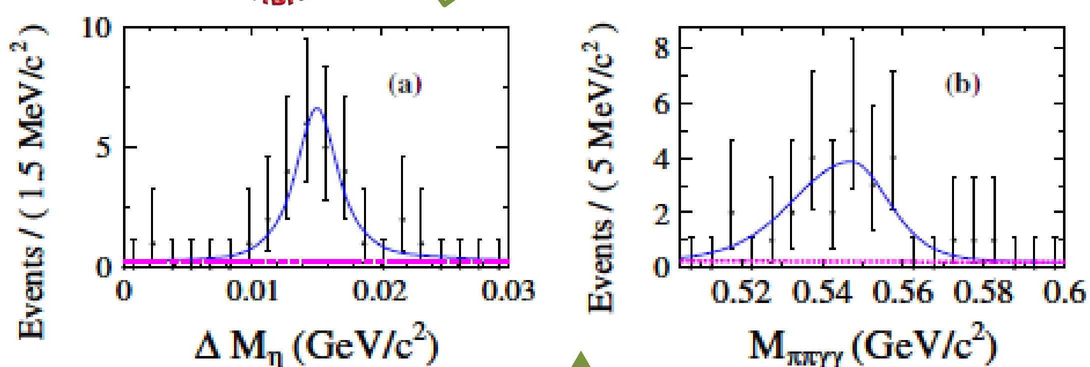
Experiment:

$(2.39 \pm 0.31 \pm 0.14) \times 10^{-4}$

$(2.1 \pm 0.7 \pm 0.4) \times 10^{-4}$
(CLEO, PRL101,192001)

- η transition suppressed compared to $\pi\pi$ transition.

$B[\Upsilon(4S) \to \Upsilon(1S)\eta] \approx 2.5 \times B[\Upsilon(4S) \to \Upsilon(1S)\, \pi^+\pi^-]$
(BaBar, PRD78,112002)



$\eta \to \pi^+\pi^-\pi^0$

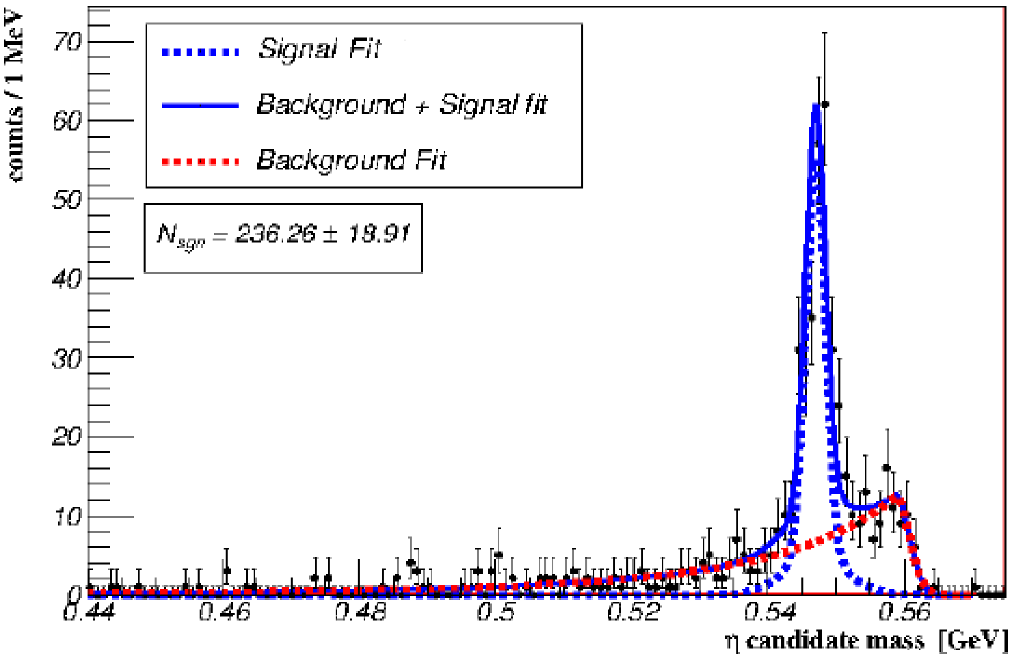
$\eta \to \gamma\gamma$

Phys.Rev.D 84 092003

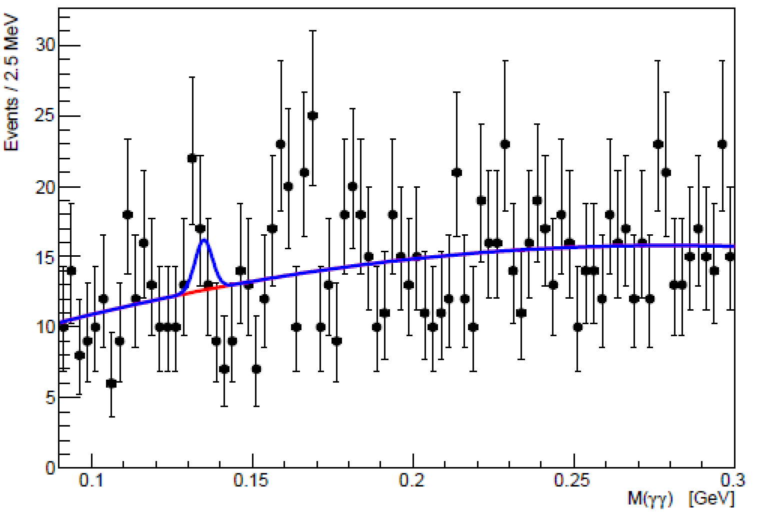
$B[\Upsilon(3S) \to \Upsilon(1S)\eta] < 1.0 \times 10^{-4}$

$\Upsilon(2S) \to \eta, \pi^0 \, \Upsilon(1S)$

Preliminary



- Exclusive analysis
- Normalized to $\Upsilon(2S) \to \pi^+\pi^- \, \Upsilon(1S)$



$$B[\Upsilon(2S) \to \Upsilon(1S)\eta] = (3.41 \pm 0.28 \pm 0.35) \times 10^{-4}$$

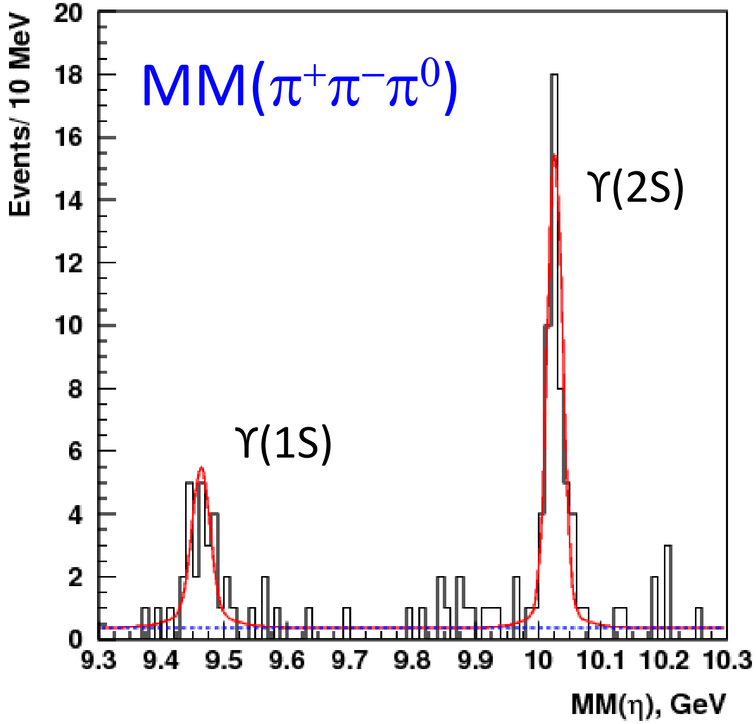
Still < half of theory prediction

$B(\Upsilon(2S) \to \pi^0 \, \Upsilon(1S)) < 0.43 \times 10^{-4}$ (90% CL)

$\sim 6 \times 10^{-4}$(Theory)

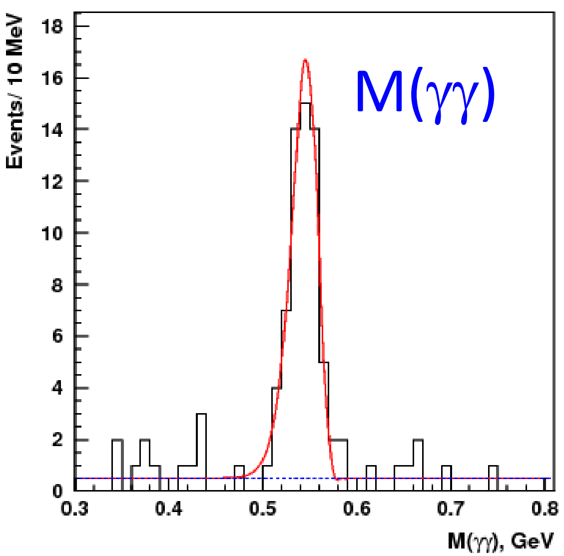
Scale from $\psi' \to \eta \, J/\psi$

Observation of Υ(5S)→Υ(1,2S)η



- Three modes:
  - Υ(1,2S)[$\mu^+\mu^-$] η[$\pi^+\pi^-\pi^0$]
  - Υ(2S)[Υ(1S)$\pi^+\pi^-$] η[γγ]
  - Υ(1S)[$\mu^+\mu^-$] η'[η$\pi^+\pi^-$]

preliminary

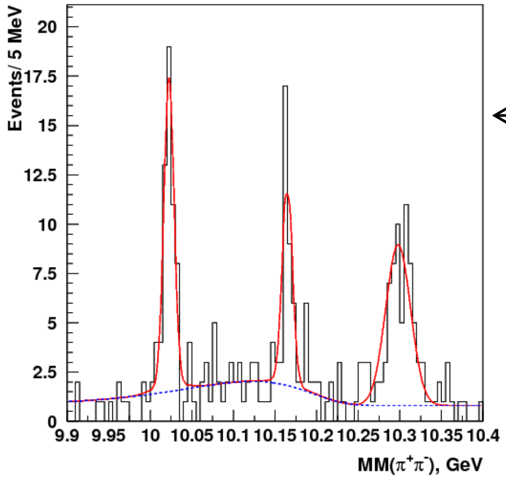


B[Υ(5S)→Υ(1S)η] = $(7.3\pm1.6\pm0.8)\ 10^{-4}$

B[Υ(5S)→Υ(2S)η] = $(38 \pm 4 \pm 5)\ 10^{-4}$

B[Υ(5S)→Υ(1S)η'] < $1.2\ 10^{-4}$

Observation of $\Upsilon(5S)\to\Upsilon(1D)\pi^+\pi^-$

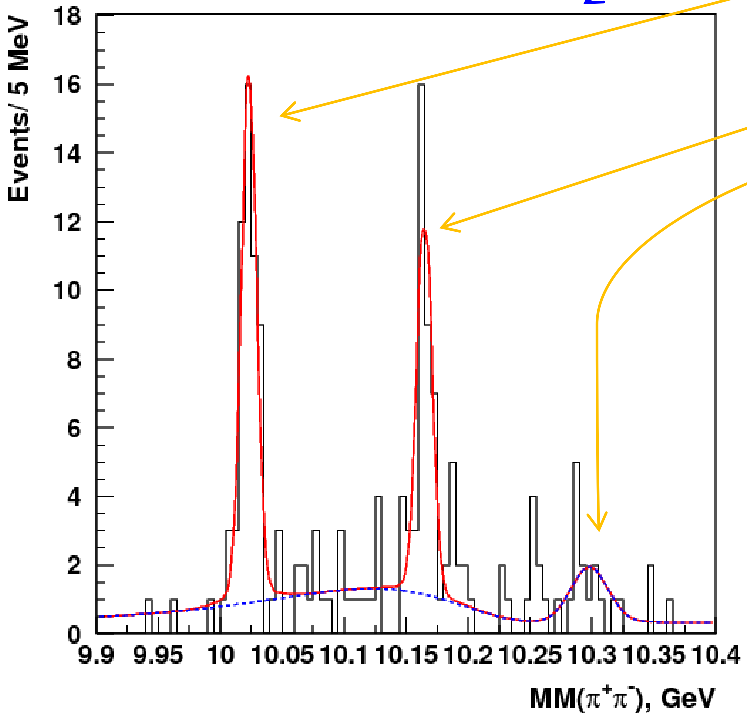


preliminary

- $\Upsilon(1S)[\mu^+\mu^-]\pi^+\pi^-\gamma\gamma$ final state

After $\chi_b(1P)\to\Upsilon\gamma$ selection

- Three peaks in MM($\pi^+\pi^-$):
  - $\Upsilon(2S)\ \pi^+\pi^-$
  - $\Upsilon(1D)\ \pi^+\pi^-$
  - $\Upsilon(2S)[\Upsilon\pi^+\pi^-]\eta[\gamma\gamma]$ reflection



statistical significance 9σ

$B[\Upsilon(5S)\to\Upsilon(2S)\pi^+\pi^-] = (7.5\pm1.1\pm0.8)\ 10^{-3}$ (cross check)

$B[\Upsilon(5S)\to\Upsilon(1D)\pi^+\pi^-]\ B[\Upsilon(1D)\to\chi_b(1P)\gamma\to\Upsilon(1S)\gamma\gamma]$
$= (2.0\pm0.4\pm0.3)\times10^{-4}$

P.S. : An evidence of $\Upsilon(1D)$ was seen in inclusive MM($\pi^+\pi^-$) spectra

Summary

Belle's large Υ(5S) data gives unexpectedly new results.

Inclusive γ,π^0, $\pi^+\pi^-$, spectrum is the main method in discovery of new states.

More results from exclusive reconstruction method.

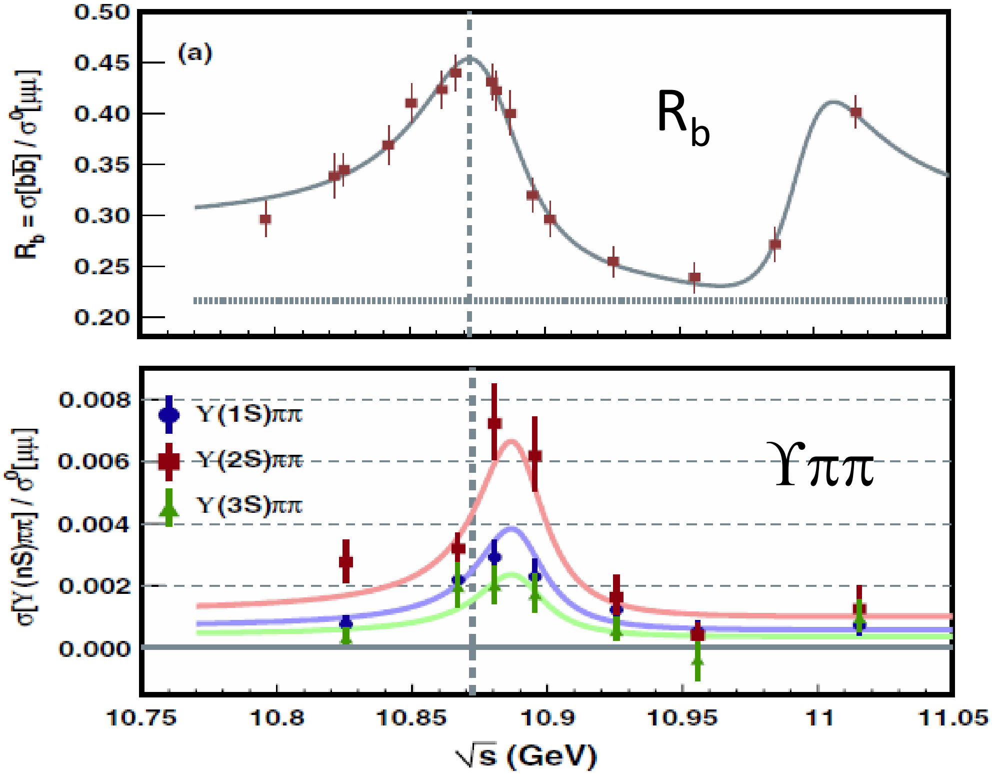
Υ(5S)

BELLE

- Observation of $h_b(1P)$, $h_b(2P)$, Z_{b1}^+, Z_{b2}^+.
    - Exclusive method in final states $\Upsilon(nS)\pi^+\pi^-$.
    - Charm counterpart in Y(4260) decay?
- Observation of $h_b(1P) \rightarrow \eta_b(1S)\gamma$.
- **Observation of of η_b(2S)** from Belle and CLEO (S. Dobbs).
    - Belle: $\Delta M_{hfs}(2S)$ = 24.3±4.3 MeV $Bf[h_b(2P) \rightarrow \gamma\eta_b(2S)]$ = 47±13%
    - S. Dobbs (CLEO): $\Delta M_{hfs}(2S)$ = 48.7±2.7 MeV, no BF info.
    - Disagreement on the $\Delta M_{hfs}(2S)$.
- Observation of $\chi_b(3P)$ from ATLAS and D0.
- Observation of $\Upsilon(5S) \rightarrow \Upsilon(1,2S)\eta$. First measurement.
- Observation of $\Upsilon(5S) \rightarrow \Upsilon(1D)\pi^+\pi^-$. First measurement.
- Measurement of $\Upsilon(2S) \rightarrow \eta\Upsilon(1S)$ from Belle. Still smaller than theory.

BACKUP

(2) $\Upsilon(nS)\pi\pi$ production shape



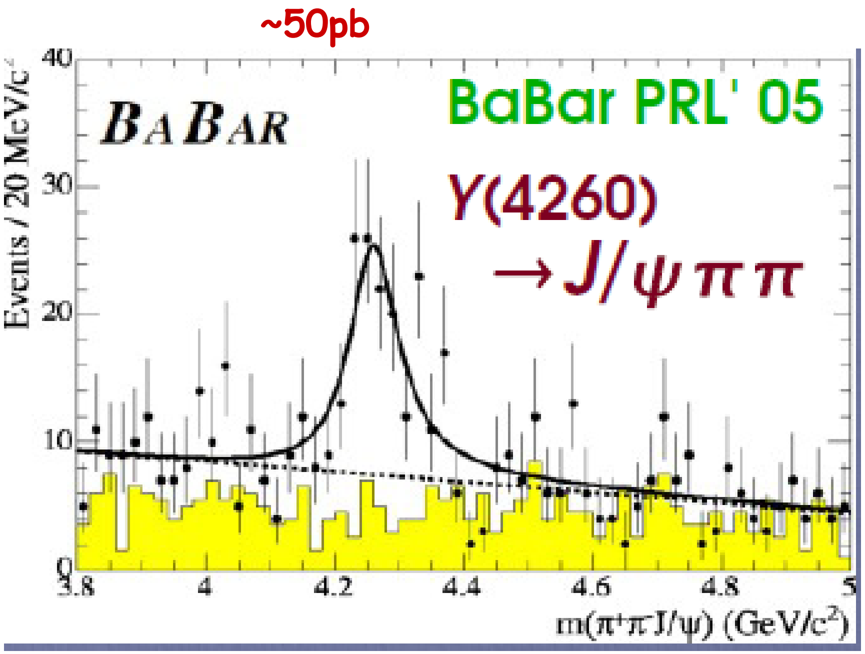
Belle,Phys.Rev.,D82,091106R(2010)

Energy scan ⇒
mean of shapes of $\sigma(\Upsilon\pi\pi)$
and hadronic cross section R_b
shapes differ by 2.0σ

$$\mu_{\Upsilon\pi\pi} - \mu_{10\,860} = 9 \pm 4 \text{ MeV}/c^2$$

$\Upsilon(1S)\pi^+\pi^-\ \sigma_{\text{peak}}$ (pb)	$2.78^{+0.42}_{-0.34} \pm 0.23$
$\Upsilon(2S)\pi^+\pi^-\ \sigma_{\text{peak}}$ (pb)	$4.82^{+0.77}_{-0.62} \pm 0.66$
$\Upsilon(3S)\pi^+\pi^-\ \sigma_{\text{peak}}$ (pb)	$1.71^{+0.35}_{-0.31} \pm 0.24$
μ (MeV/c^2)	$10888.4^{+2.7}_{-2.6} \pm 1.2$
Γ (MeV/c^2)	$30.7^{+8.3}_{-7.0} \pm 3.1$

Reminder of Y(4260)



- Observed from initial state radiation events: e+e→ γJ/ψππ.
- Mass far above $D\bar{D}^{(*)}$ threshold.
- Width ~ 100 MeV (quite narrow).
- $J^{PC} = 1^{--}$ from production mechanism .

$$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$$

↓

BaBar, Phys. Rev. Lett. **95,** 142001 (2005).
arXiv:0808.1543v2.
Belle, Phys. Rev. Lett. **99,** 182004 (2007).

$$e^+e^- \to \pi^+\pi^- J/\psi$$
$$e^+e^- \to \pi^0\pi^0 J/\psi$$

↓

CLEO, Phys. Rev. Lett. **96,**162003 (2006).

Y(4260) notes

- Decay to $D\bar{D}^{(*)}$ not seen.
- Small coupling to e^+e^-,

$BR(J/\psi\pi^+\pi^-) \times \Gamma(e^+e^-)$
$= 7.5\pm0.9\pm0.8$ eV. BaBar, arXiv:0808.1543

- Small coupling to $p\bar{p}$

$BR(Y(4260)\to p\bar{p})/$
$BR(Y(4260) \to J/\psi\pi^+\pi^-)<0.13$.
BaBar, Phys.Rev.D73,012005(2006)

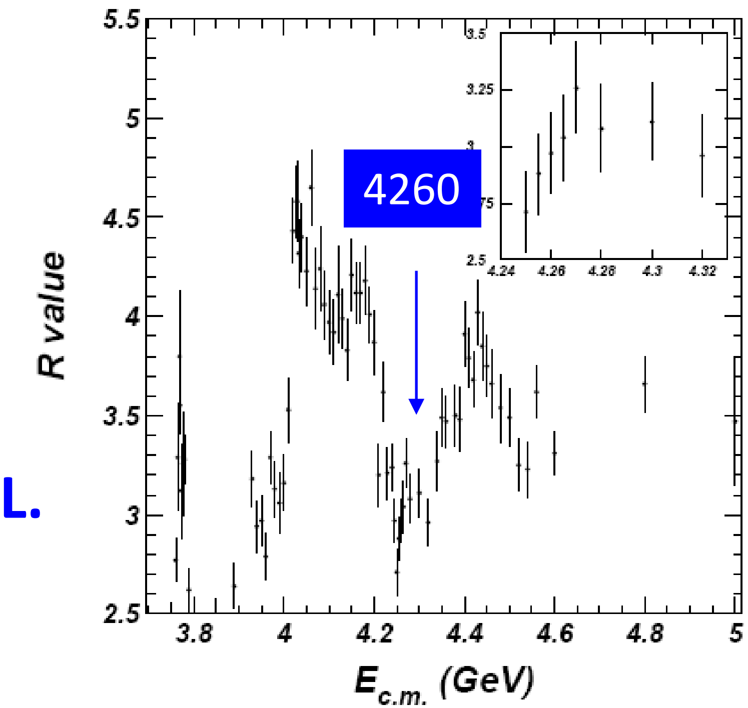
- **$\Gamma(Y \to J/\psi\pi^+\pi^-)>508$ keV @ 90% C.L.**

$\Rightarrow$ Large !!

X. H. Mo et al., Phys. Lett. B 640 (2006) 182

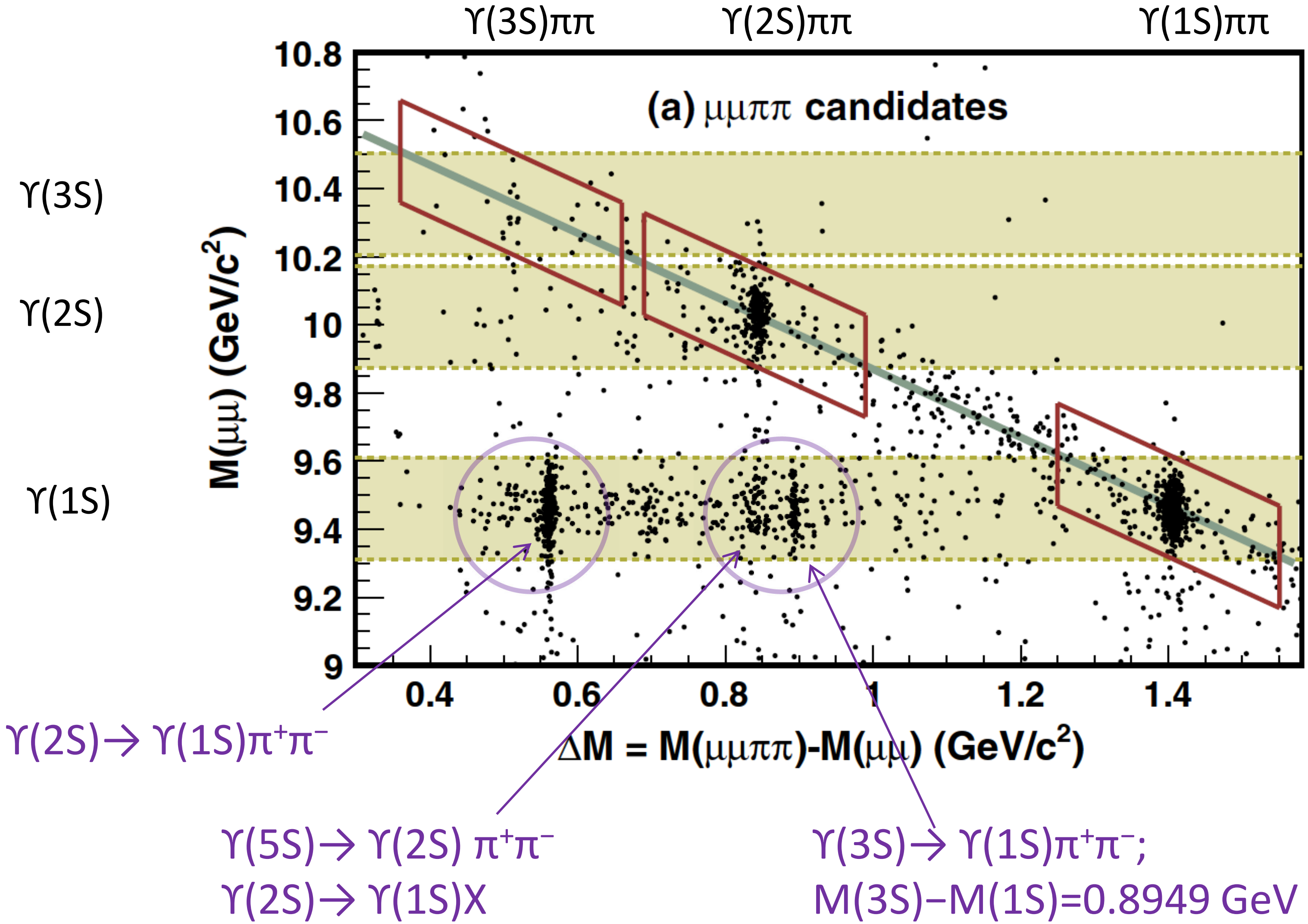
BES,Phys.Rev.Lett.88.101802(2002)

At a dip in $\sigma(e^+e^-)\to$ hadrons)



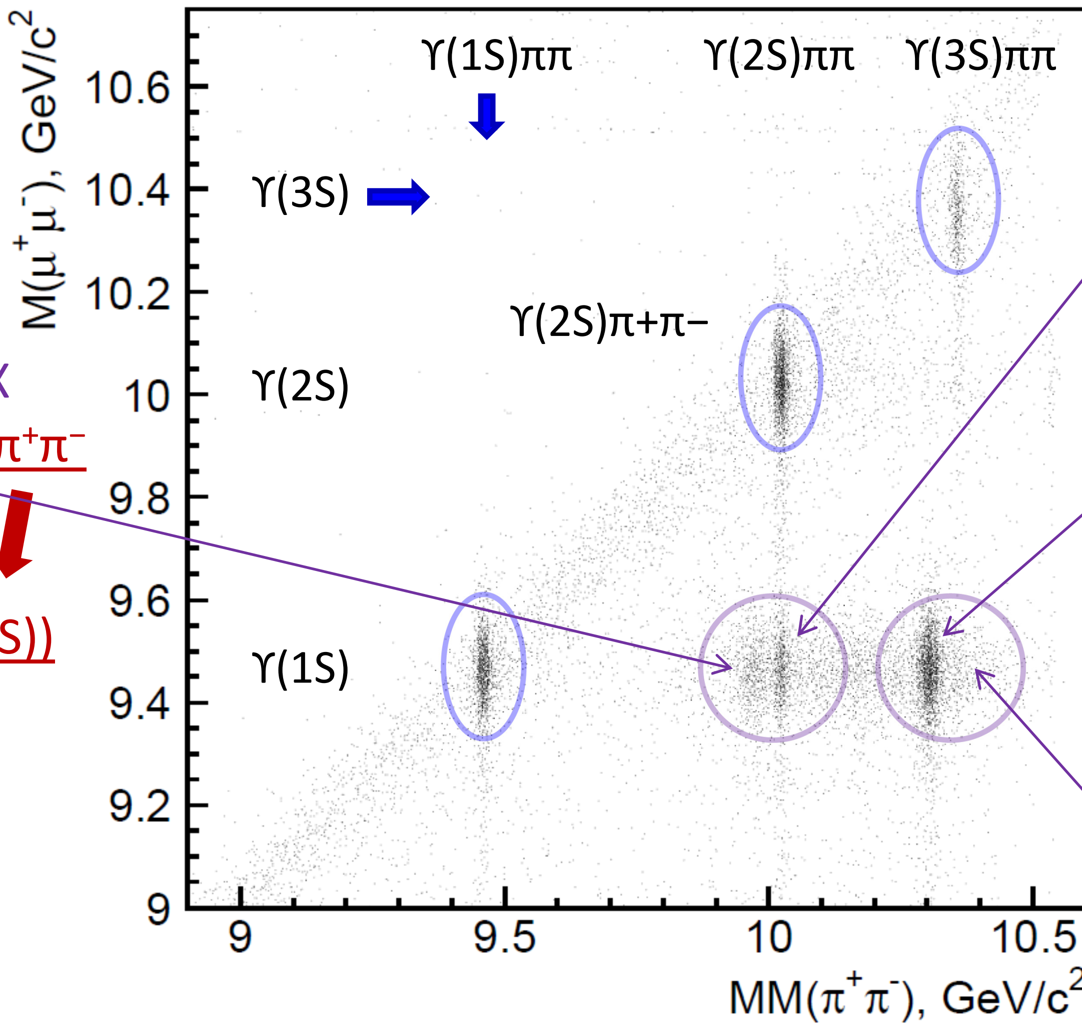
In b-sector, may be there also exists a counterpart Y_b which has also large h_b branching fraction.

Exclusive (full) reconstruction



Missing mass technique: Calibration sources in Υ(5S) events

Reconstruct $\mu^+\mu^-$



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

M(5S)−
(M(3S) − M(1S))
=9.9701 GeV

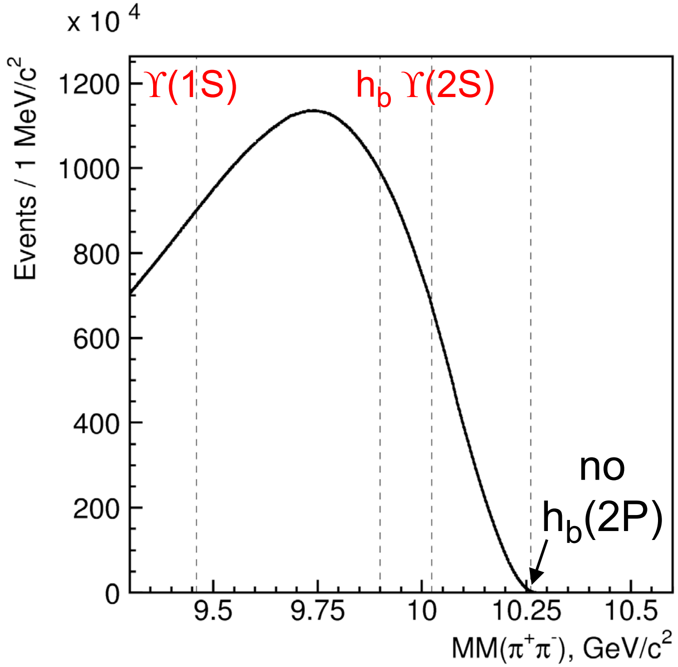
$\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-$
$\Upsilon(2S) \rightarrow \Upsilon(1S)X$

$e^+e^- \rightarrow \Upsilon(2S)X$
$\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$

M(5S)−
(M(2S) − M(1S))
=10.3020 GeV

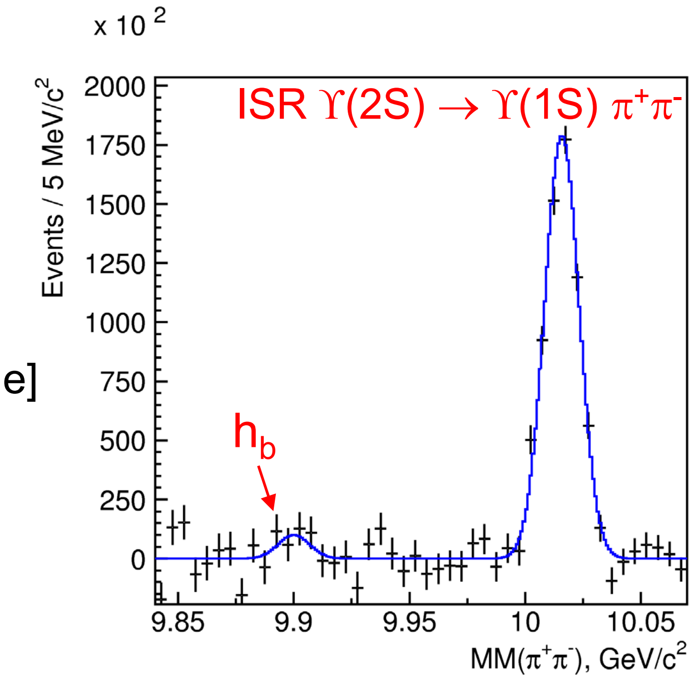
$\Upsilon(5S) \rightarrow \Upsilon(3S)\pi^+\pi^-$
$\Upsilon(3S) \rightarrow \Upsilon(1S)X$

h_b in $\Upsilon(4S)$ data



L = 711fb^{-1}

[×6 $\Upsilon(5S)$ sample]



No significant signal of $h_b(1P)$: $(34 \pm 20) \times 10^3$ (1.7σ)

$$\frac{\sigma[e^+e^- \to h_b(1P)\ \pi^+\pi^-]\ @\ \Upsilon(4S)}{\sigma[e^+e^- \to h_b(1P)\ \pi^+\pi^-]\ @\ \Upsilon(5S)} < 0.28 \text{ at } 90\%\text{C.L.}$$

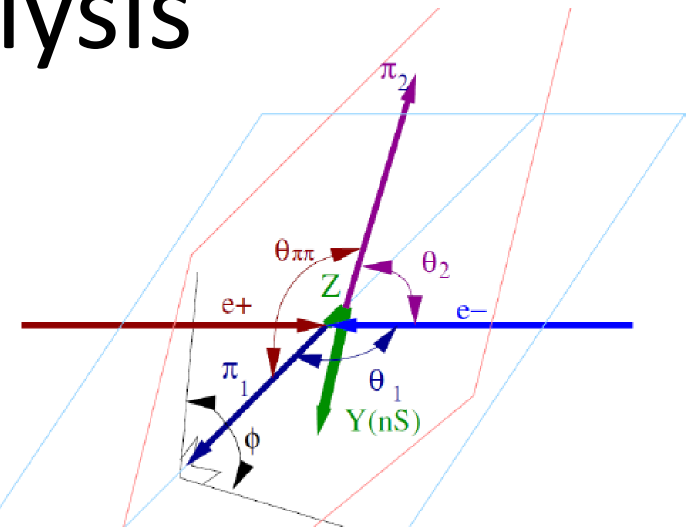
⇒ $\Upsilon(4S)$ does not show anomalous properties

Angular Analysis

Z_b velocity is very small ($\beta<0.02$) $\Rightarrow$ measure all pion momenta in the c.m. frame.

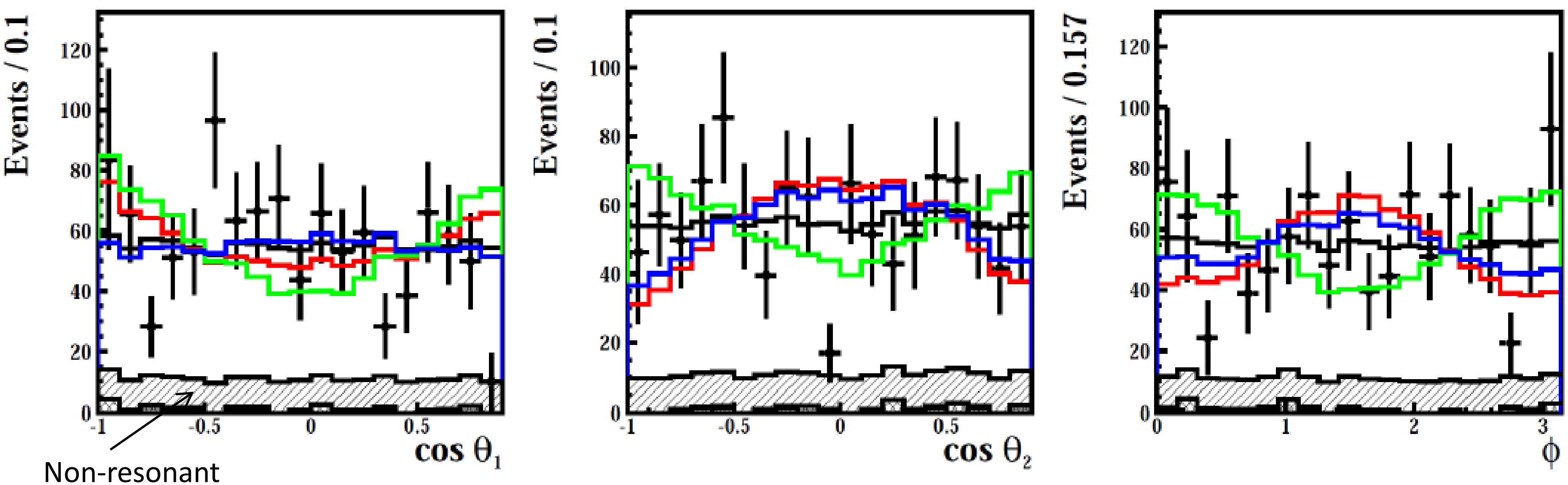
$\Upsilon(5S) \to Z_b(\Upsilon(nS), h_b + \boldsymbol{\pi_1})\boldsymbol{\pi_2}$

$\theta_1 = \angle(\boldsymbol{\pi_1}, e^+)$
$\theta_2 = \angle(\boldsymbol{\pi_2}, e^+)$
$\phi = \angle(\text{plane}(\boldsymbol{\pi_1}, e^+)), \text{plane}(\boldsymbol{\pi_1}, \boldsymbol{\pi_2}))$



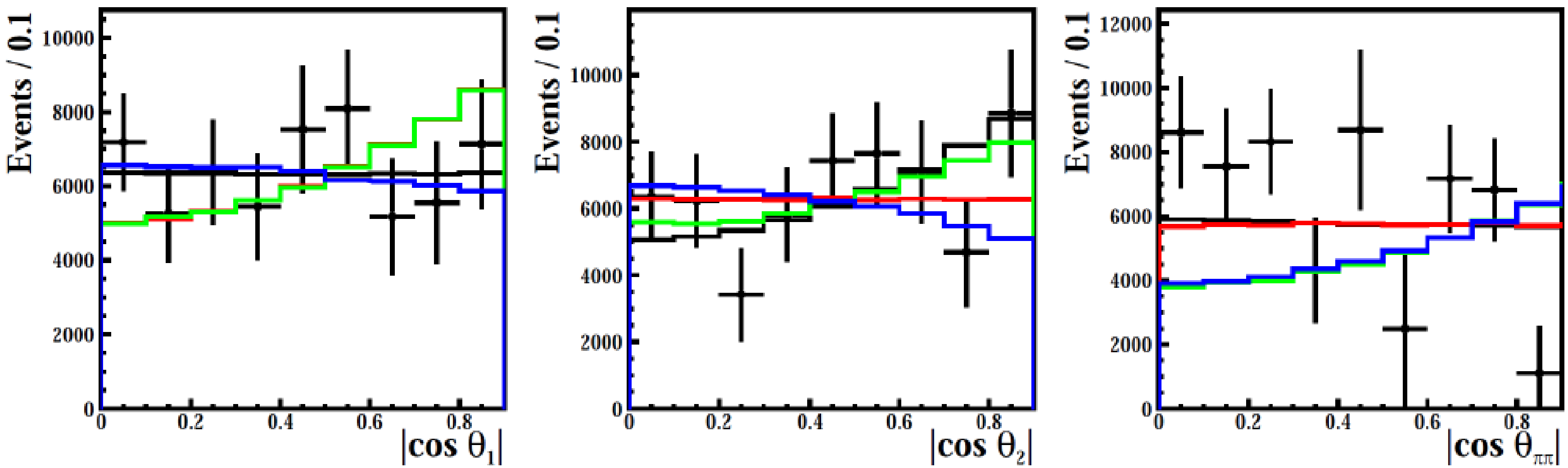
$J^P = 1^+$, 1^-, 2^+, 2^-

Example: $\Upsilon(5S) \to Z_b(10610)\, \boldsymbol{\pi_2} \to \Upsilon(2S)\boldsymbol{\pi_1}\, \boldsymbol{\pi_2}$



Angular Analysis (h_b final state)

J^P = 1$^+$, 1$^-$, 2$^+$, 2$^-$ Example: $\Upsilon(5S) \to Z_b(10610)\,\pi_2 \to h_b(1P)\pi_1\,\pi_2$



Probabilities at which other J^P hypotheses are disfavored with respect to 1$^+$

J^P	$Z_b(10610)$			$Z_b(10650)$		
	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$
1^-	$3.6\,\sigma$	$0.3\,\sigma$	$0.3\,\sigma$	$3.7\,\sigma$	$2.6\,\sigma$	$2.7\,\sigma$
2^+	$4.3\,\sigma$	$3.5\,\sigma$	$4.3\,\sigma$	$4.4\,\sigma$	$2.7\,\sigma$	$2.1\,\sigma$
2^-	$2.7\,\sigma$	$2.8\,\sigma$		$2.9\,\sigma$	$2.6\,\sigma$	

J^P=1$^+$ is favored!

$\Upsilon(5S) \rightarrow \Upsilon(1S)\eta'$