Study of Transitions and Decays of Bottomonia at Belle

Saurabh Sandilya
University of Cincinnati
(On behalf of the Belle Collaboration)

Outline

- Introduction (Bottomonia, KEKB & Belle detector)
- Transitions (hadronic and radiative)
- Decays (light hadrons, baryons)
- Summary

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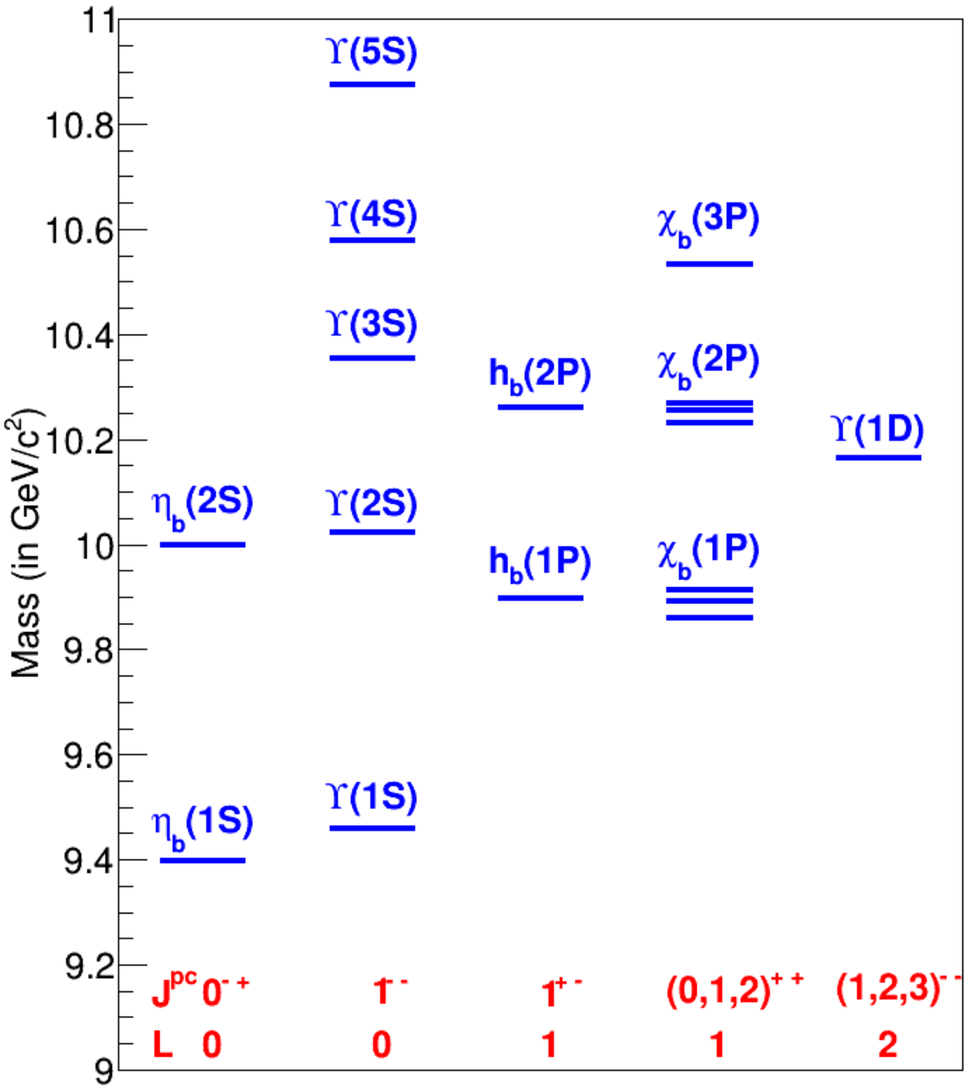
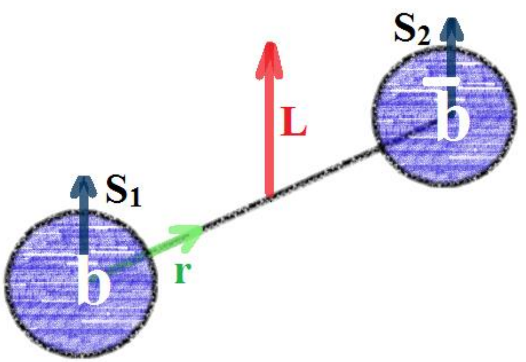
Studies of e+e- processes at and near the Y(10860) at Belle: Todd Pedlar

Study of Charmonia and charmed baryons at Belle: Yuji Kato

Introduction

- "Bottomonia" family - a set of particles that contain a bottom quark (b) and a bottom antiquark ($\bar{b}$) bound together with different energy levels





$$S = S_1 + S_2$$
$$J = L + S$$
$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$

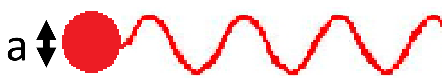
- Bottomonia are the heaviest known quarkonia ($q\bar{q}$) with $m_b \approx 3\, m_c$, which makes the system almost non-relativistic

- Provide a unique laboratory to study the low-energy QCD system

Transitions

Hadronic Transitions: QCD Multi-Pole Expansion (analogous to electrodynamics)

Electrodynamics



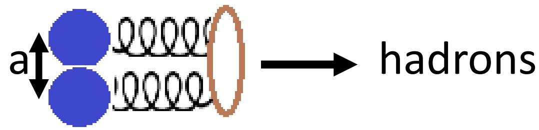
radius of radiating source < wavelength such that,

$a/\lambda \sim ak < 1$

k is momentum of the photon

'ak' can be a good expansion parameter

QCD



'a' $\sim$ 0.1fm

k for hadronic transition $\sim$ few 100 MeV

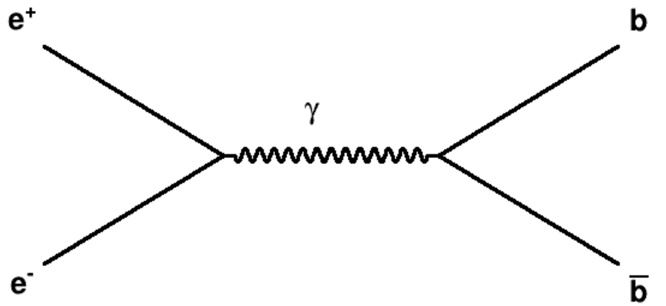
ak $\sim$ 0.1

Thus, Multipole expansion works for quarkonia process

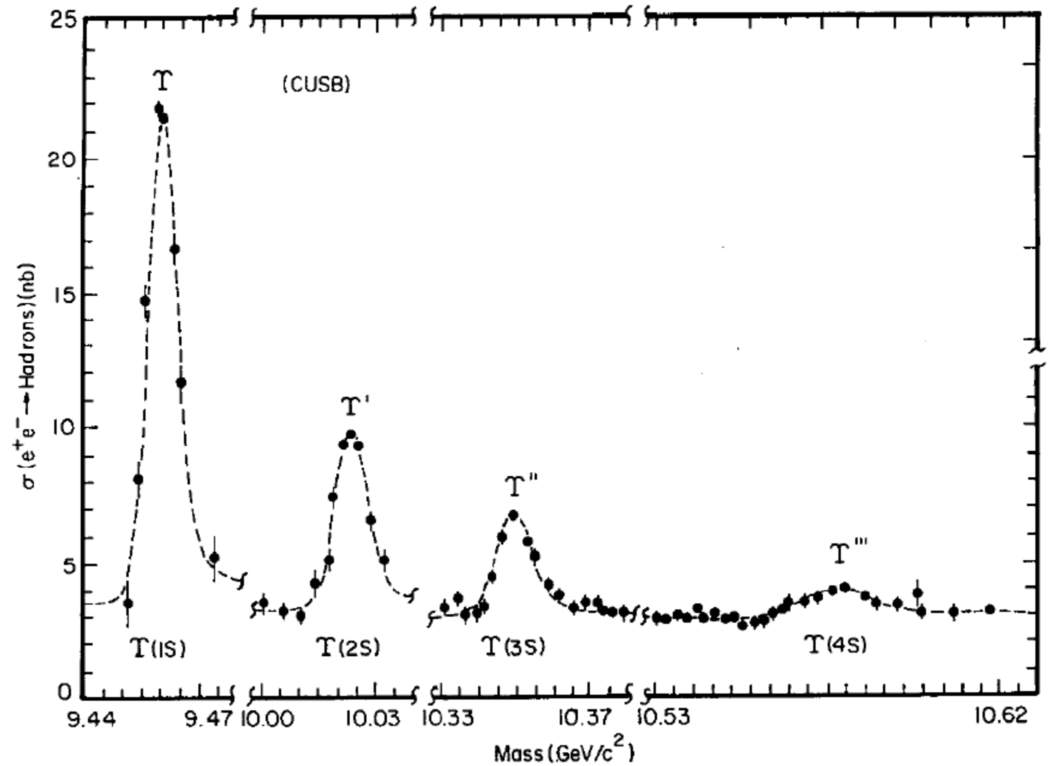
Radiative Transitions:

- Photon wavelength in radiative transitions among $b\bar{b}$ states are larger than or at most comparable to the size of radiating system; thus dipole transitions dominate.
- From the P and C parity,
  - E1 occurs between states with $\Delta S = 0$ and $\Delta L = \pm 1$
  - M1 occurs between states with $\Delta S = \pm 1$ and $\Delta L = 0$
- M1 transitions are expected to be weaker than E1.

Bottomonium Production

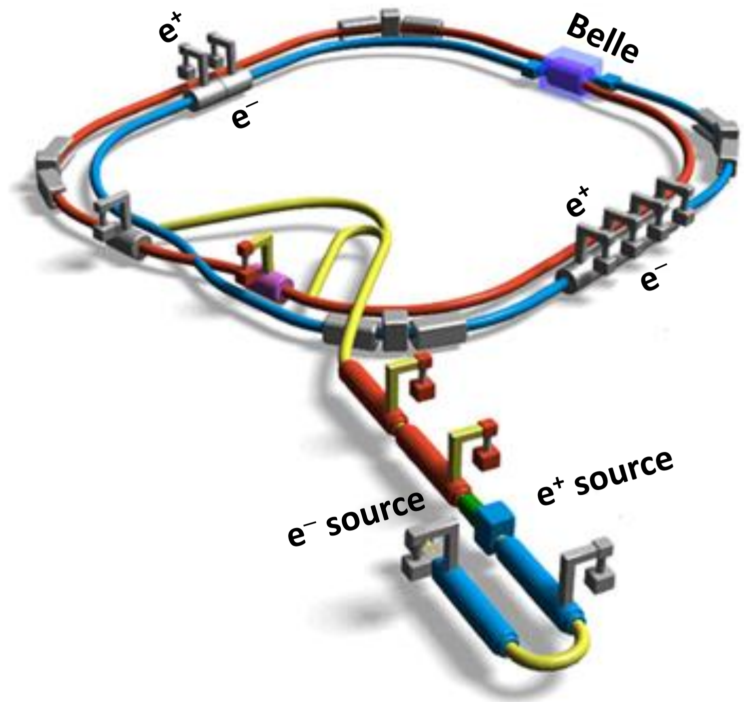


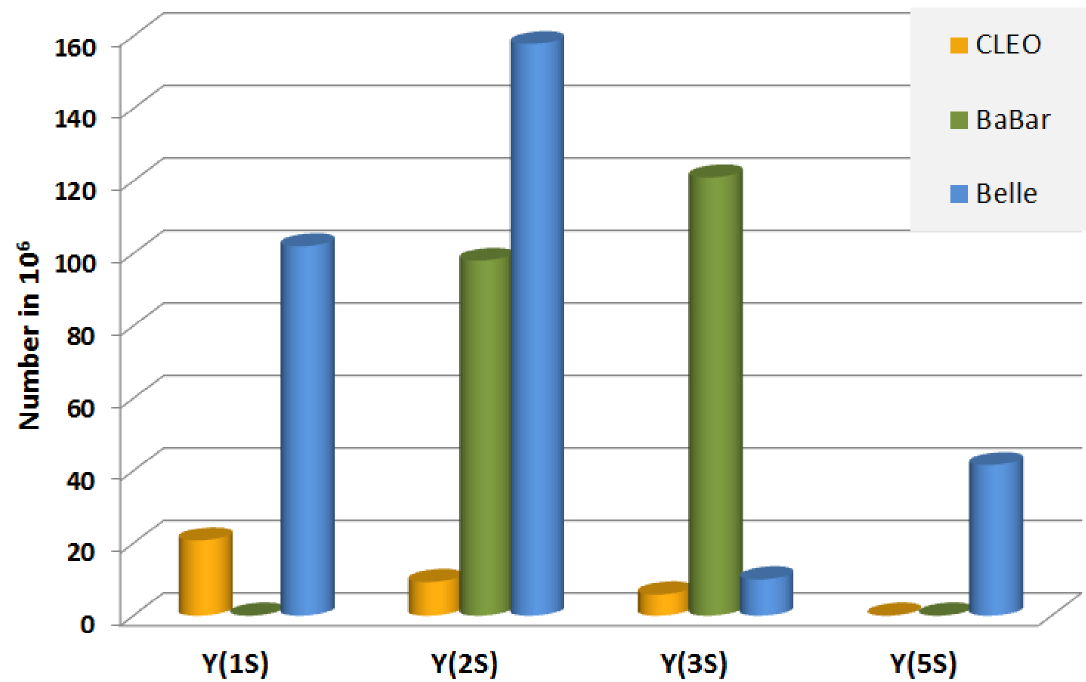
The states must have $J^{PC} = 1^{--}$



- The beam energy is matched to the $\Upsilon(nS)$ resonance mass.
- Entire collision energy of the initial electron and positron turns into the rest mass of the $\Upsilon(nS)$ state.
- No extra beam fragment $\rightarrow$ clean environment
- Other bottomonium states are mainly produced from the $\Upsilon(nS)$ transitions.

KEKB

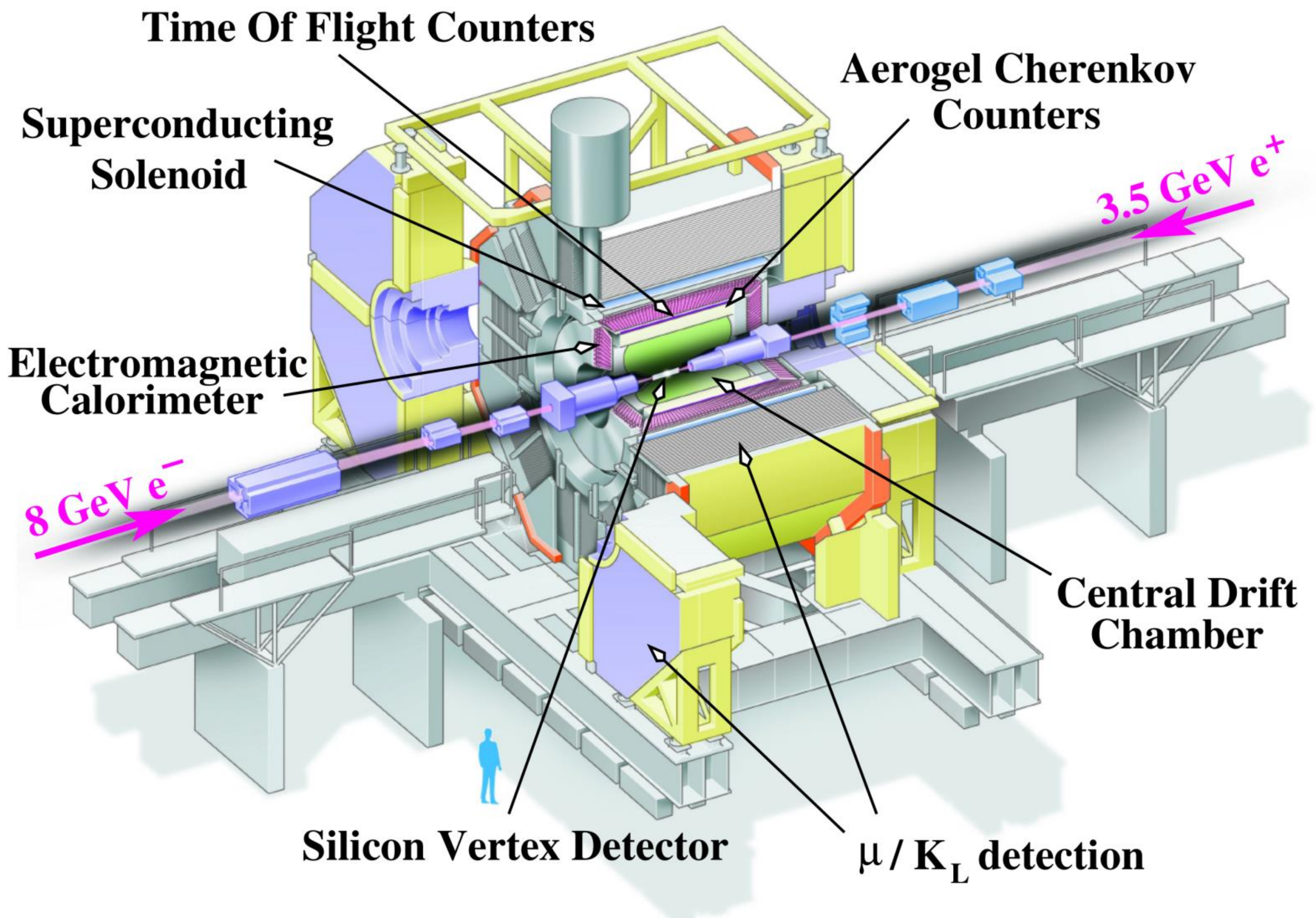




Parameter	LER (e^+)	HER (e^-)
Energy [@$\Upsilon(4S)$]	3.5 GeV	8.0 GeV
Circumference	3.02 km	
Crossing Angle	$\pm$11mrad	
Luminosity	$2 \times 10^{34} cm^{-2}s^{-1}$	

Resonance	Data Collected @ Belle (June 30, 2010)
$\Upsilon(1S)$	6 fb^{-1}
$\Upsilon(2S)$	25 fb^{-1}
$\Upsilon(3S)$	3 fb^{-1}
$\Upsilon(4S)$	711 fb^{-1}
$\Upsilon(5S)$	121 fb^{-1}

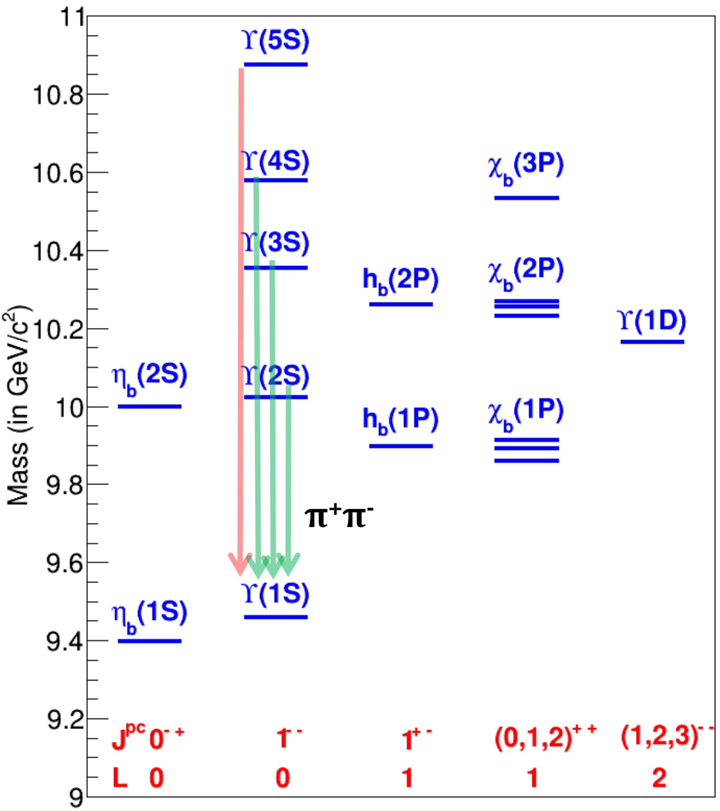
Belle Detector



Tracking : SVD+CDC
Particle Identification: CDC+ACC+TOF
Calorimetry: (CsI(Tl) crystal)

$\pi^+\pi^-$ transitions from $\Upsilon(5S)$

- Dipion transitions between $\Upsilon(nS)$ states below n = 5 have been successfully described in terms of multipole moments of the QCD



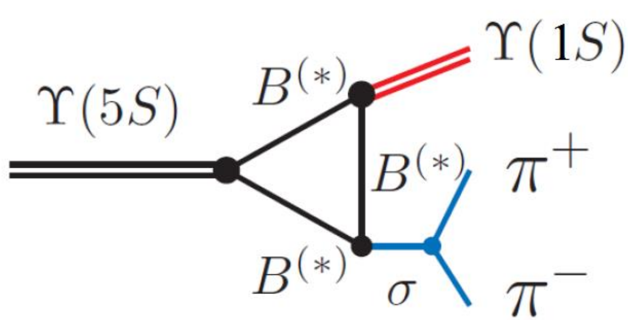
$$\Gamma[\Upsilon(5S) \to \Upsilon(1,2,3S)\pi^+\pi^-] >> \Gamma[\Upsilon(4,3,2S) \to \Upsilon(1S)\pi^+\pi^-]$$

~ 100 times

PRL 100, 112001 (2008)

Process	Γ_{total}	$\Gamma_{e^+e^-}$	$\Gamma_{\Upsilon(1S)\pi^+\pi^-}$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.032 MeV	0.612 keV	0.0060 MeV
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.020 MeV	0.443 keV	0.0009 MeV
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	20.5 MeV	0.272 keV	0.0019 MeV
$\Upsilon(10860) \to \Upsilon(1S)\pi^+\pi^-$	110 MeV	0.31 keV	0.59 MeV

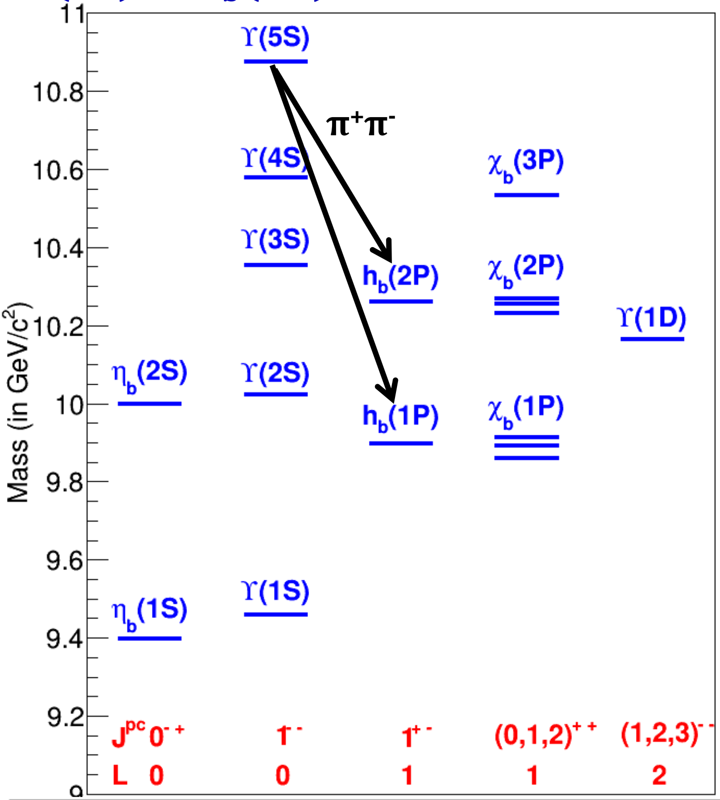
Re scattering of on-shell $B^{(*)}\overline{B}^{(*)}$

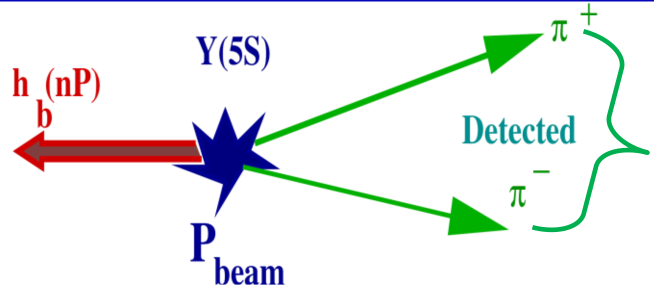


$\pi^+\pi^-$ transitions from $\Upsilon(5S)$

Looking for $h_b(nP)$

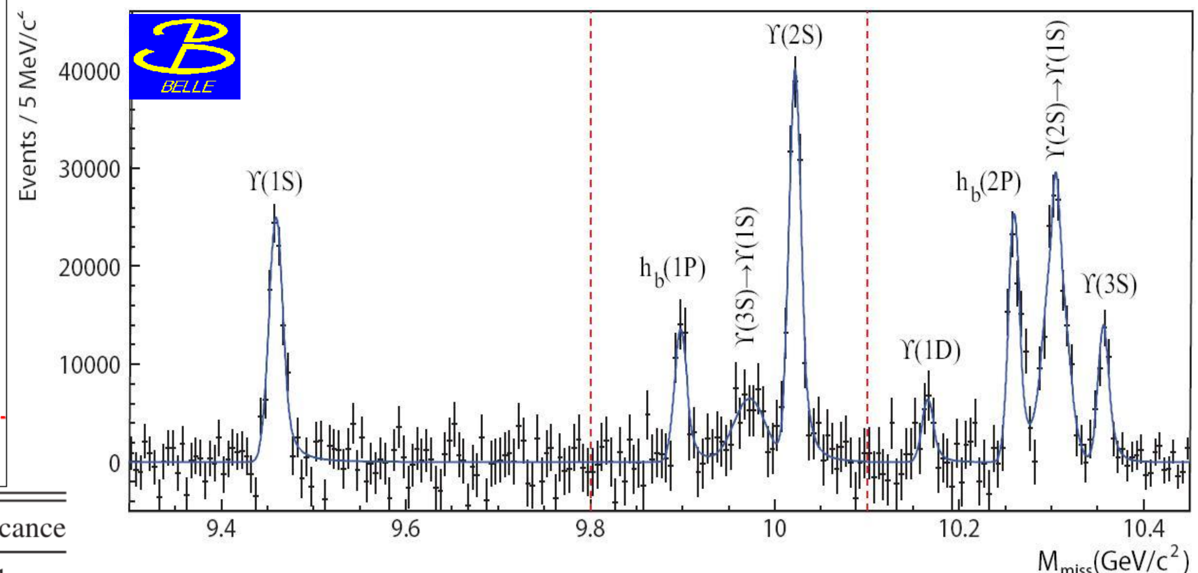
$\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$ reconstruction





Reconstructed, use $M_{miss}(\pi^+\pi^-)$

$$M(h_b) = \sqrt{\left(E_{CM} - E^*_{\pi^+\pi^-}\right)^2 - E^{*\,2}_{\pi^+\pi^-}} \equiv M_{miss}(\pi^+\pi^-)$$



	Yield, 10^3	Mass, MeV/c^2	Significance
$\Upsilon(1S)$	$104.9 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	18.1σ
$h_b(1P)$	$50.0 \pm 7.8^{+4.5}_{-9.1}$	$9898.2^{+1.1+1.0}_{-1.0-1.1}$	6.1σ
$3S \to 1S$	55 ± 19	9973.01	2.9σ
$\Upsilon(2S)$	$143.7 \pm 8.7 \pm 6.8$	$10\,022.2 \pm 0.4 \pm 1.0$	17.1σ
$\Upsilon(1D)$	22.4 ± 7.8	$10\,166.1 \pm 2.6$	2.4σ
$h_b(2P)$	$83.9 \pm 6.8^{+23.}_{-10.}$	$10\,259.8 \pm 0.6^{+1.4}_{-1.0}$	12.3σ
$2S \to 1S$	$151.3 \pm 9.7^{+9.0}_{-20.}$	$10\,304.6 \pm 0.6 \pm 1.0$	15.7σ
$\Upsilon(3S)$	$45.5 \pm 5.2 \pm 5.1$	$10\,356.7 \pm 0.9 \pm 1.1$	8.5σ

$\Delta M_{HF}(1P) = +0.8 \pm 1.1\text{MeV}$
$\Delta M_{HF}(2P) = +0.5 \pm 1.2\text{MeV}$ **consistent with zero, as expected.**

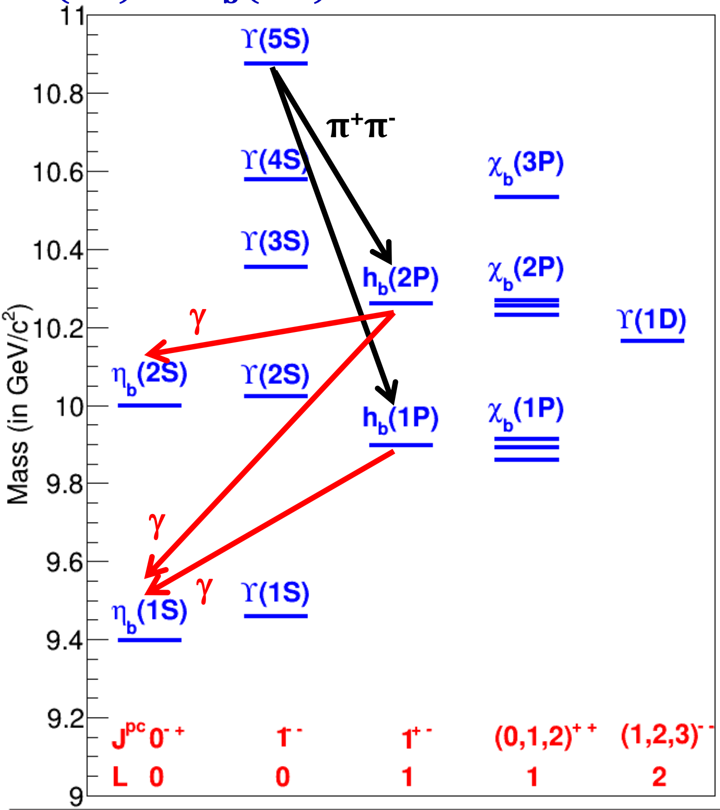
large h_b(1,2P) production rate => Z_b^+ Discovery.

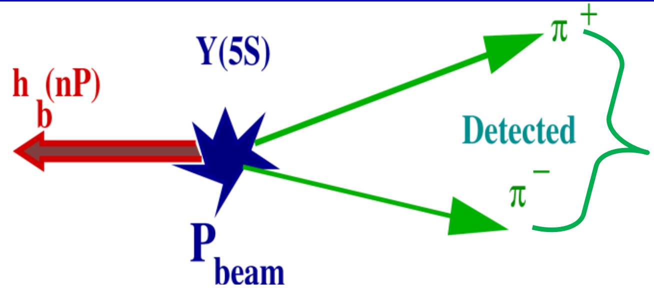
PRL 108, 122001 (2012)

Observation of $h_b(nP)$

Looking for $h_b(nP)$

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





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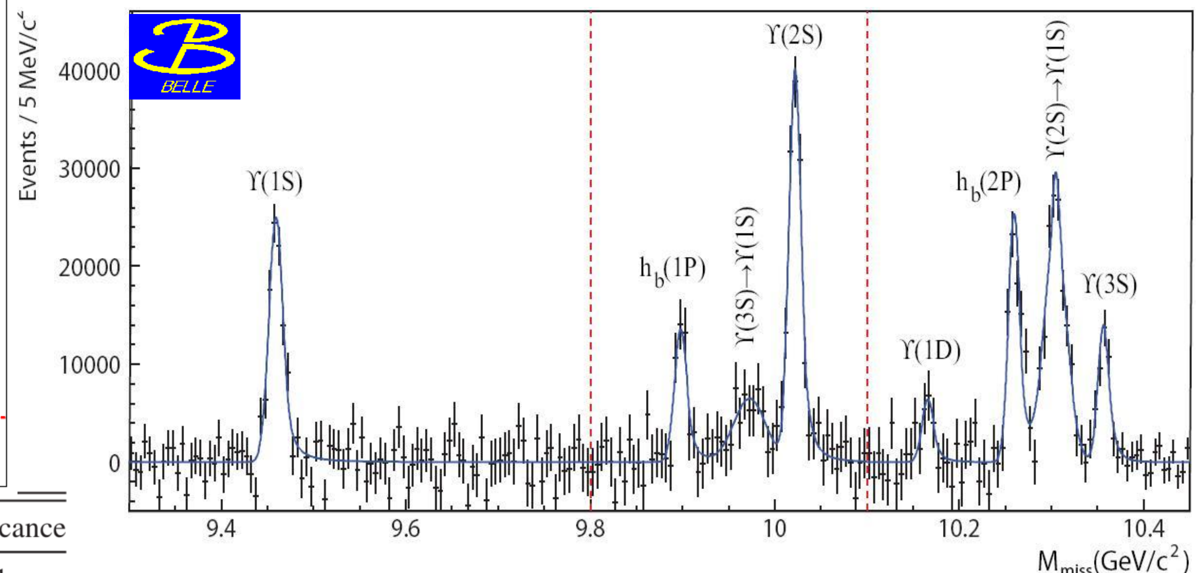

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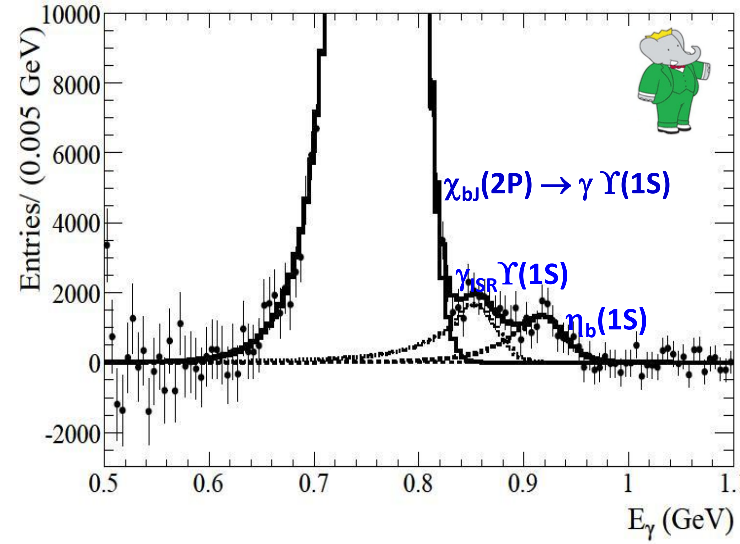
High yield of $h_b(nP)$ opens new perspective to study $\eta_b(mS)$!!

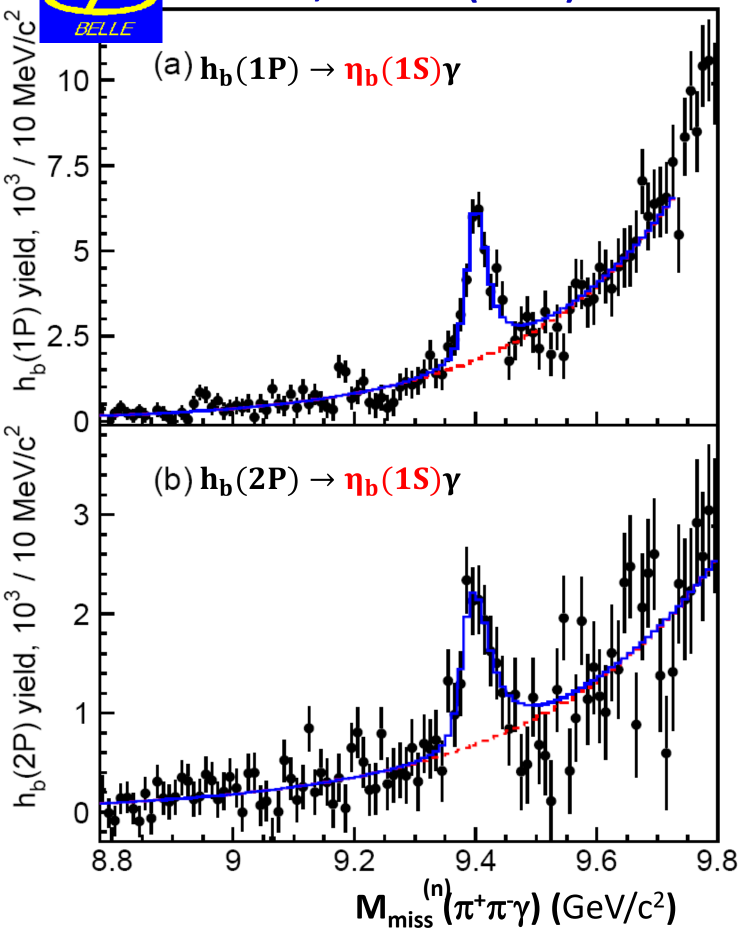
Rad. trans. from $h_b(nP)$: $\eta_b(1S)$

- $\eta_b(1S)$ was discovered by BaBar collaboration in 2008 in radiative decay of $\Upsilon(3S)$.



PRL 101, 071801 (2008)

PRL 109,232002 (2012)



- Re-discovered by Belle collaboration at $\Upsilon(5S)$ resonance in the decay:

$$\Upsilon(5S) \to h_b(1,2P)\,\pi^+\pi^-$$
$$\hookrightarrow \eta_b(1S)\,\gamma$$

reconstruct

$$M_{miss}(X) = \sqrt{(E_{CM} - E_X^*)^2 - p_X^{*2}}$$

$$m_{\eta_b(1S)} = 9402.4 \pm 1.5 \pm 1.8\ \text{MeV/c}^2$$

First measurement of $\Gamma = 10.8^{+4.0}_{-3.7}\,{}^{+4.5}_{-2.0}$ **MeV/c²**

Rad. trans. from $h_b(2P)$: $\eta_b(2S)$

In the same analysis, First evidence of the $\eta_b(2S)$ was found in the decay:

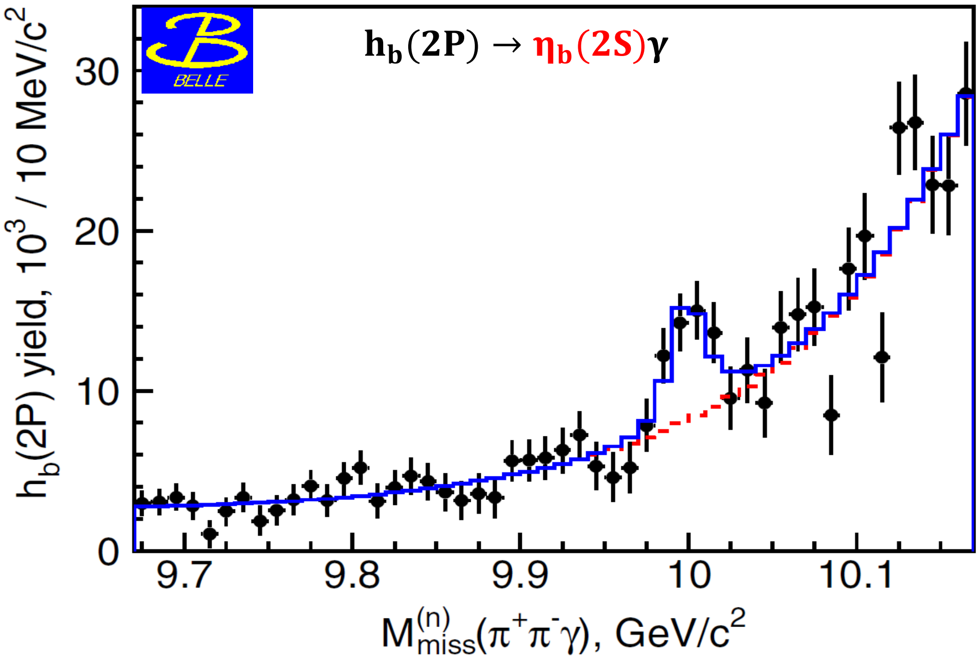
$\Upsilon(5S) \rightarrow h_b\,(2P)\,\pi^+\pi^-$
$\hookrightarrow \eta_b(2S)\,\gamma$

reconstruct

$$\mathbf{M_{miss}(X)} = \sqrt{(\mathbf{E_{CM}} - \mathbf{E_X^*})^2 - \mathbf{p_X^{*2}}}$$

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

PRL 109,232002 (2012)



$$\mathbf{m_{\eta_b(2S)} = 9999.0 \pm 3.5^{+2.8}_{-1.9}\ MeV/c^2}$$

with significance (including sys.)at 4.2σ

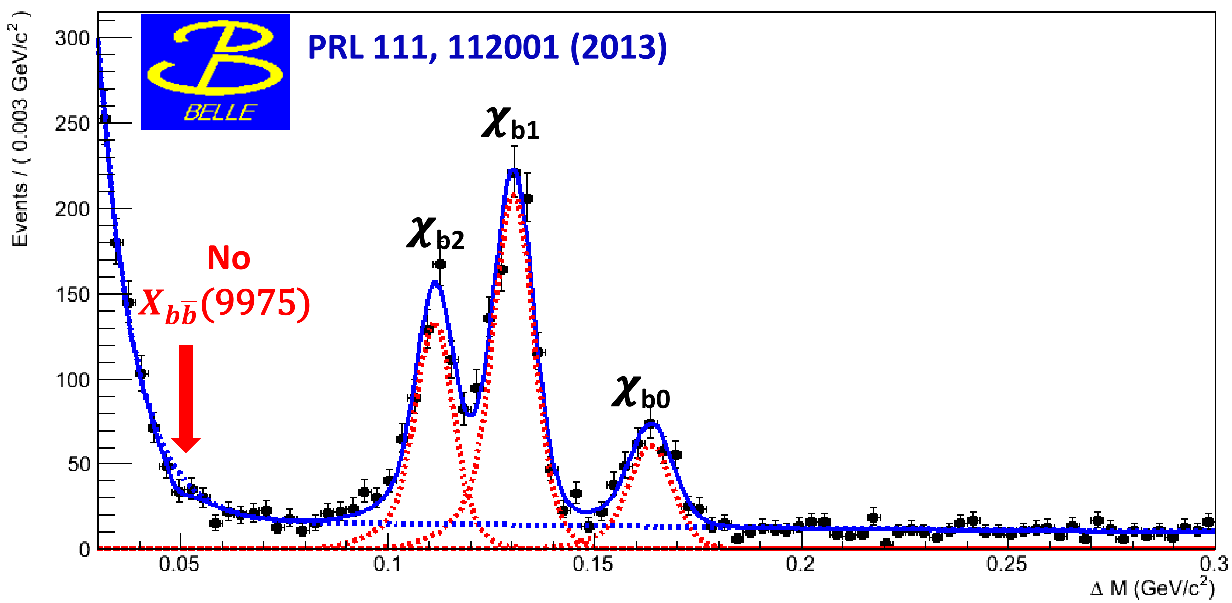
which corresponds to the hyperfine splitting:

$$\Delta M_{HF}\,(2S) = 24.3^{+4.0}_{-4.5}\ \mathrm{MeV/c^2}$$

Rad. trans. from $\Upsilon(2S)$: $\eta_b(2S)$?,$\chi_{bJ}(1P)$

- Analysis based on CLEO III data studied $\Upsilon(2S) \rightarrow \gamma\,(b\bar{b})$,where $(b\bar{b})$ is reconstructed from 26 exclusive hadronic decay modes, comprising charged pions, kaons, protons and K_S^0mesons. **PRL 109, 082001 (2012)**
- Enhancement observed at a ~5σ level at a mass of $9974.6 \pm 2.3 \pm 2.1$MeV was attributed to η_b(2S) [large production rate and large hyperfine splitting ~ 48.7 MeV]
- With 17 times large data, Belle refuted that enhancement .

Sum of 26 hadronic decay modes



$\Delta M \cong (\gamma b\bar{b}) - (b\bar{b})$

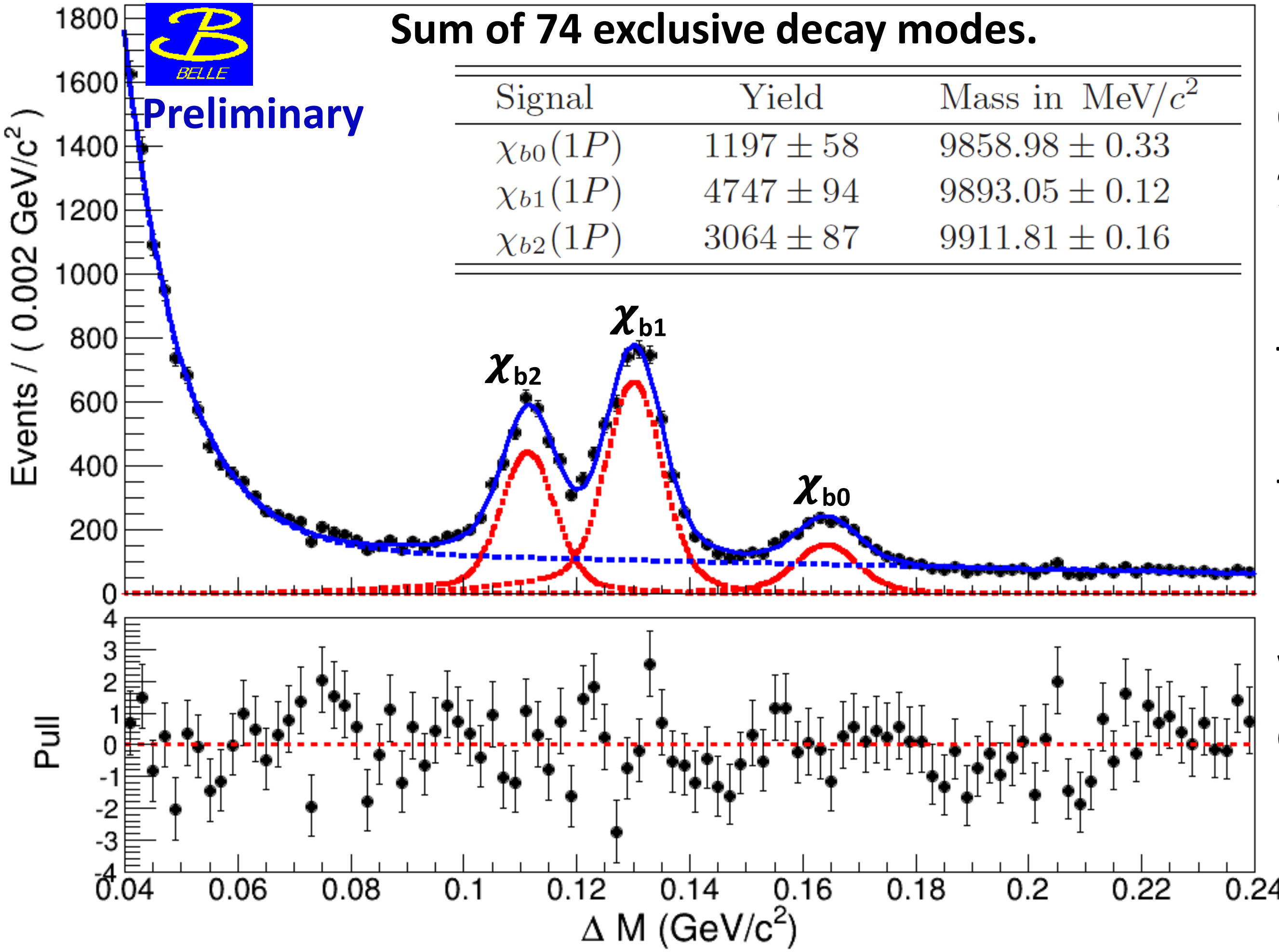
Large statistics of $\chi_{bJ}(1P)$ (300-950 candidates) motivated us further to:

(1) Study the branching fraction of $\chi_{bJ}(1P) \rightarrow$ hadrons (adding more modes with π^0)

(2) Measure the width of $\chi_{b0}(1P)$ (**first time**)

Rad. trans. from $\Upsilon(2S)$: $\chi_{bJ}(1P)$

- In total 74 light hadronic modes are reconstructed for each $\chi_{bJ}(1P)$ states.
- Signal yield is more 5 times more than in our previous analysis.



Signal	Yield	Mass in MeV/c^2
$\chi_{b0}(1P)$	1197 ± 58	9858.98 ± 0.33
$\chi_{b1}(1P)$	4747 ± 94	9893.05 ± 0.12
$\chi_{b2}(1P)$	3064 ± 87	9911.81 ± 0.16

CLEO studied decays of $\chi_{bJ}(1P)$ in light hadrons.
PRD 78, 091103(2008)

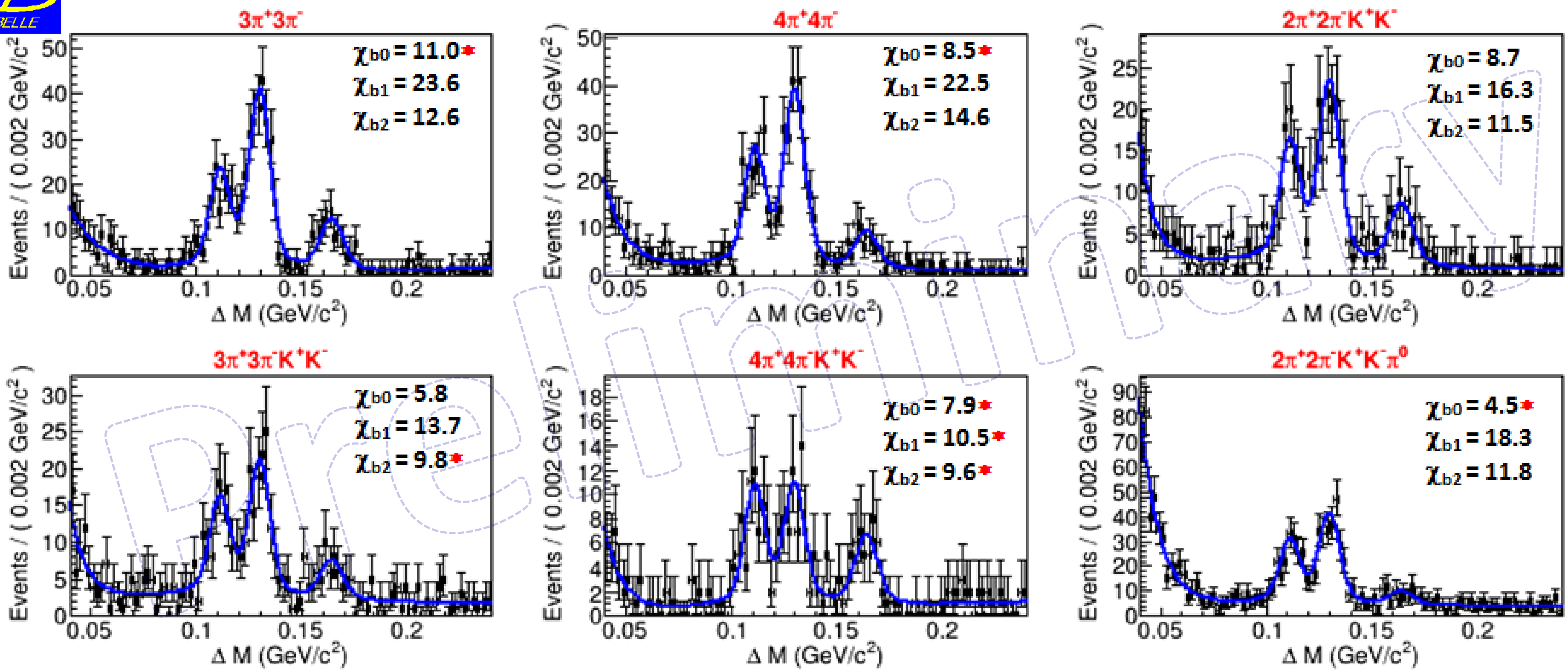
They observed 26 (2+13+11) decay modes for $\chi_{bJ}(1P)$ states (J=0,1,2)

We have 17 time more data at $\Upsilon(2S)$ resonance.

- An opportunity to improve over CLEO's observation of 26 decay modes and potentially uncover many new decay modes.

$\chi_{bJ}(1P)$ decays to light hadrons

- Among the 74 hadronic modes reconstructed for each $\chi_{bJ}(1P)$ states, 41 modes are identified with signal greater than 5σ in any of the $\chi_{bJ}(1P)$.
- CLEO's observation of 26 (= 2+13+11 for J=0,1,2) decay modes are consistent with our result.
- We have observation and evidence signals in total 85 (27+28+30 for J=0,1,2) decay modes. (Plots for all the modes can be found in backup slides)



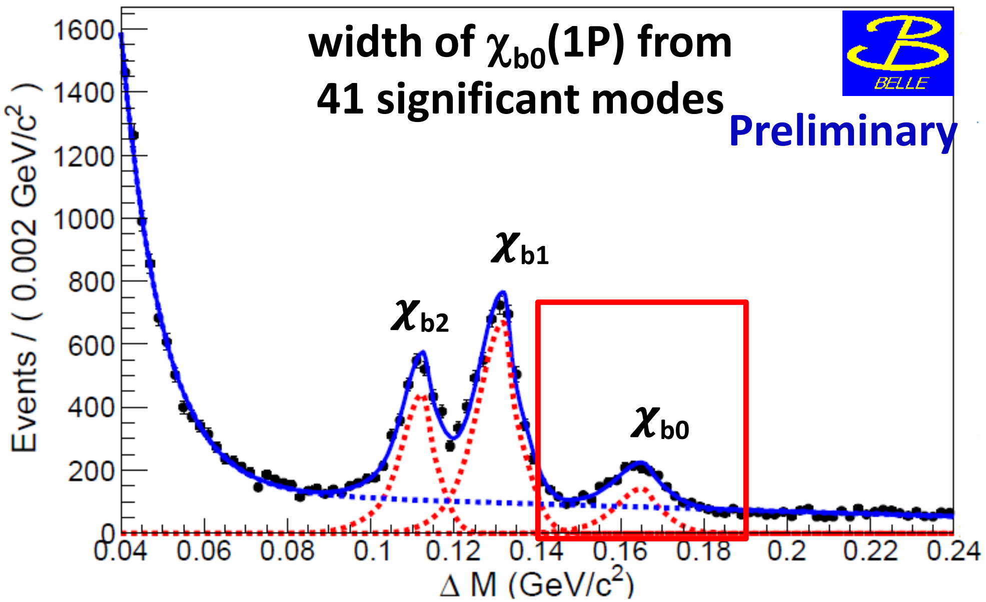
$\chi_{b0}(1P)$ total width

$\Gamma[\chi_{b0}(1P)]$	$\Gamma[\chi_{b2}(1P)]$	Theoretical approach used
431^{+45}_{-49}	214^{+1}_{-0}	Covariant light-front approach
887	220	Relativistic (Salpeter method) corrections
960(2740)	330(250)	Perturbative (nonperturabtive) calculations
653	109	Relativistic quark model
2150(2290)	220(330)	QCD potential (alternative treatment)
672	123	Relativistic quark model

PRD 82, 034021 (2010)

χ_{b0}(1P) is predicted to have width as large as 2.7MeV

- Measured width of χ_{b0}(1P) from the 41 significant modes.
- Detector resolution is modeled with sum of a asymmetric Gaussian and a Gaussian function, which is convolved with a Briet-Wigner function.
- Width of χ_{b0}(1P) is found to be 1.3 ± 0.9 MeV, in the absence of a statistically significant result, a 90% confidence-level upper limit is set on the width at **< 2.4MeV.**



η-transitions

- η transitions are suppressed between Υ-states, as they require a spin flip of the heavy quark.

$$R^{\eta S}_{\pi\pi S}(n, m) = \frac{B[\Upsilon(nS)\to\eta\Upsilon(mS)]}{B[\Upsilon(nS)\to\pi\pi\Upsilon(mS)]} << 1$$

- For low lying states:

$$R^{\eta S}_{\pi\pi S}(2,1) = 1.6 \times 10^{-3} \text{ and } R^{\eta S}_{\pi\pi S}(3,1) < 2.3 \times 10^{-3}$$

CLEO, PRL 101, 192001 (2008) **BaBar, PRD 84, 092003 (2011)** **Belle, PRD 87, 011104 (2013)**

- Above the $B\overline{B}$ threshold, BaBar experiment observed unexpected large ($\sim 2 \times 10^{-4}$) BF for the transition $\Upsilon(4S) \to \eta\ \Upsilon(1S)$, corresponding ratio: **BaBar, PRD 78, 112002 (2008)**

$$R^{\eta S}_{\pi\pi S}(4,1) = 2.41 \pm 0.42$$

- This was explained by the contribution of B meson loops or, equivalently, by the presence of a four-quark $B\overline{B}$ component inside the $\Upsilon(4S)$ wave function.

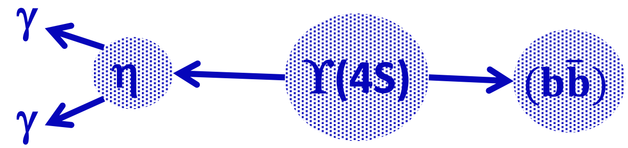
- At $\Upsilon(5S)$ this violation of heavy quark spin symmetry is even more striking (we already saw, previous slides) $\to$ presence of new resonance structures (Z_b)

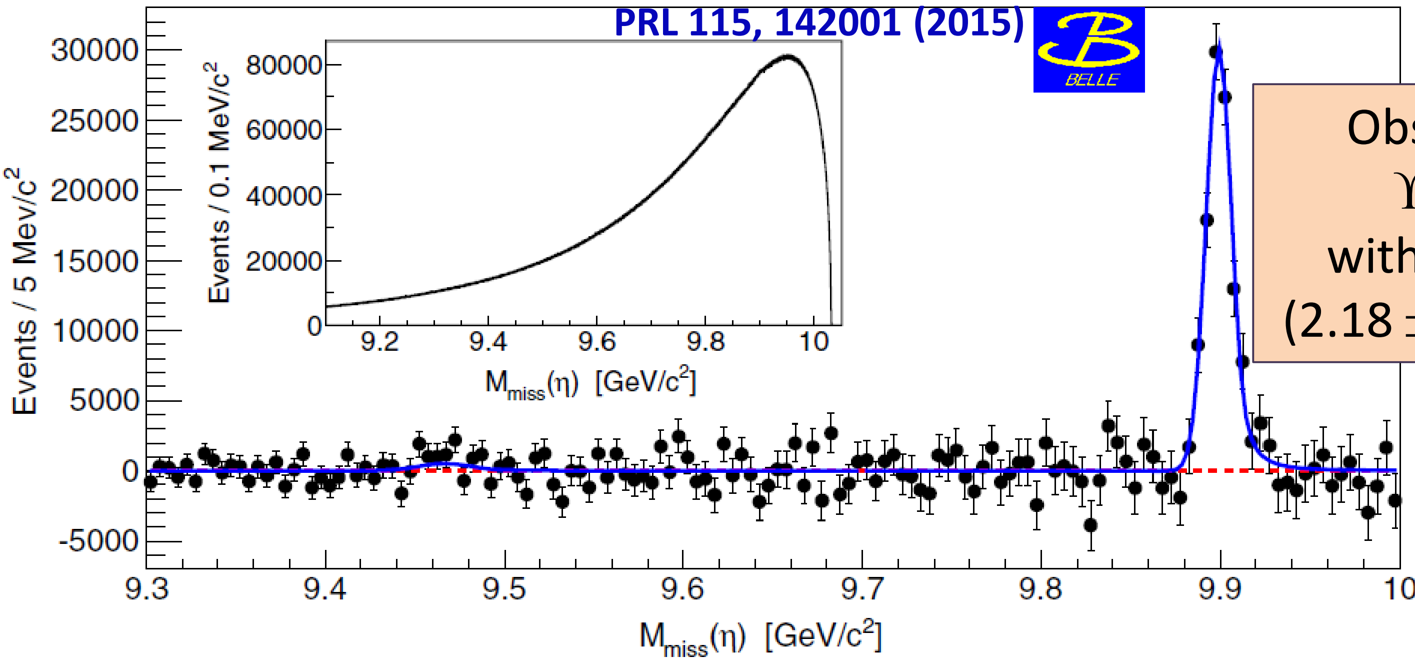
- Further insight into hadronic transition mechanism above threshold can be gained by searching the transition $\Upsilon(4S) \to \eta\ h_b(1P)$, which is predicted to have BF $\sim 10^{-3}$.

PRL 105, 162001 (2010)

η-transitions from ϒ(4S)

We investigated the missing mass spectrum of η mesons in the ϒ(4S) data sample ($711\ fb^{-1}$)





Observed the decay
$\Upsilon(4S) \to \eta h_b(1P)$
with 11 σ significance
$(2.18 \pm 0.11 \pm 0.18) \times 10^{-3}$

$\Gamma_{\eta\Upsilon(1S)} = 4$ KeV

$\Gamma_{\pi\pi\Upsilon(1S)} = 1.7$ KeV

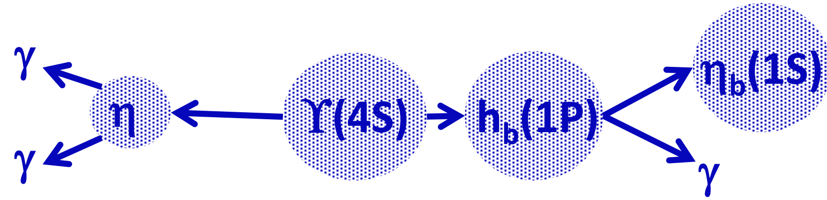
$\Gamma_{\eta h_b(1P)} = 37$ KeV

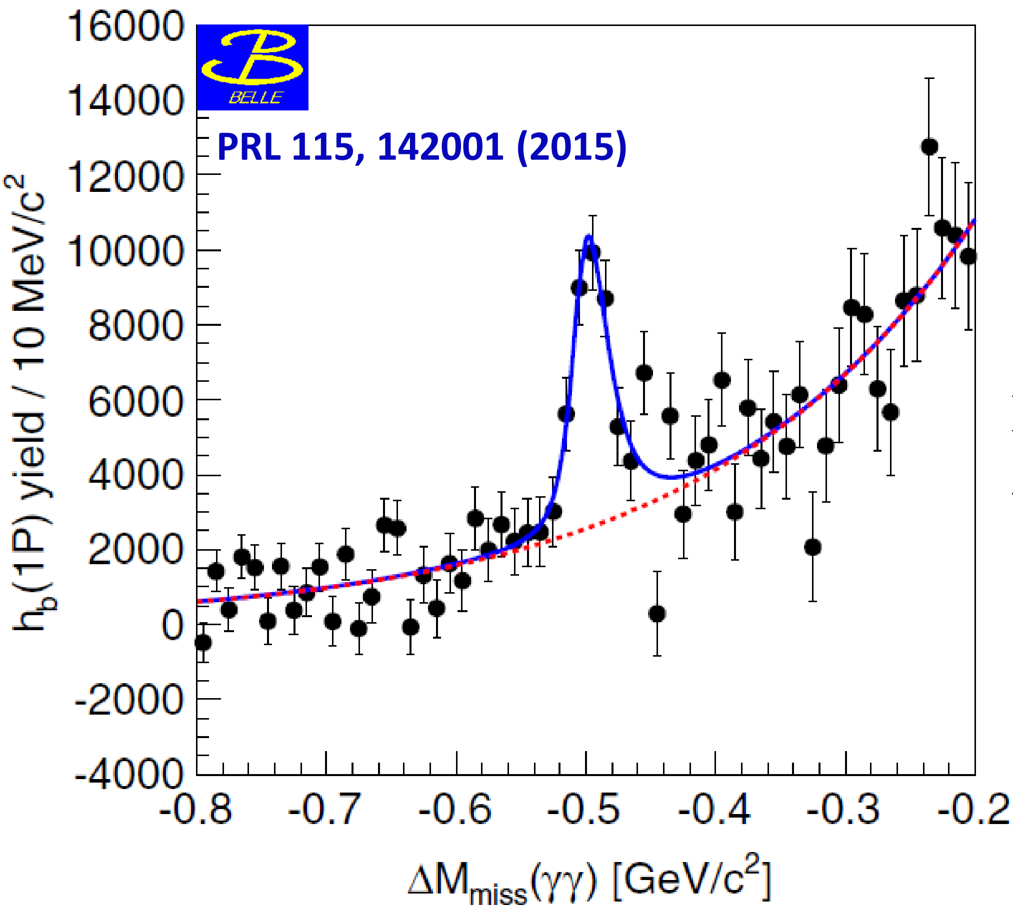
- One order of magnitude larger than any other ϒ(4S) transition.
- Also measured Mass of $h_b(1P) = 9899.3 \pm 0.4 \pm 1.0\ MeV/c^2$.
- Hyperfine splitting, $M[\chi_{bJ}(1P)] - M[h_b(1P)] = 0.6 \pm 0.4 \pm 1.0 MeV/c^2$

Rad. Trans. from $h_b(1P)$: revisit

Large yield of $h_b(1P)$ provided (again) the opportunity to study the radiative transition $h_b(1P) \to \gamma\eta_b(1S)$.

$$\Delta MM(\eta\gamma) = MM(\eta\gamma) - MM(\eta)$$
$$= M(\eta_b) - M(h_b)$$





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

$\Gamma(\eta_b(1S)) = 8^{+6}_{-5} \pm 5$ MeV

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

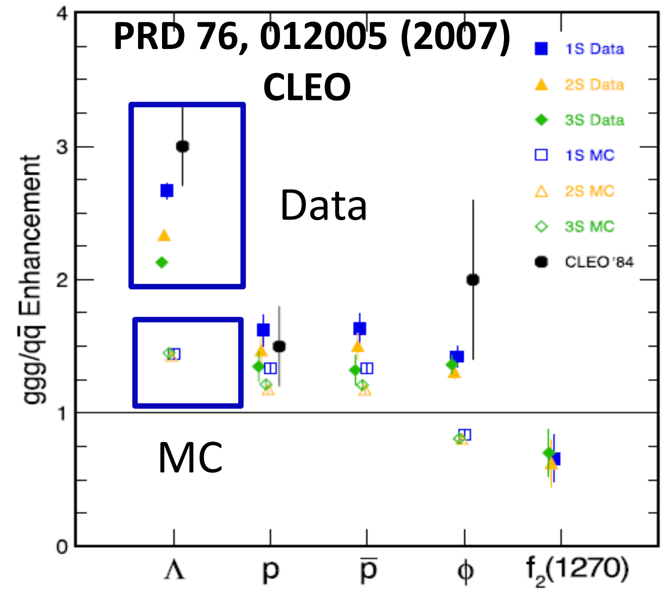
$\Upsilon(1,2S)$ decay to $\Lambda\bar{\Lambda}$

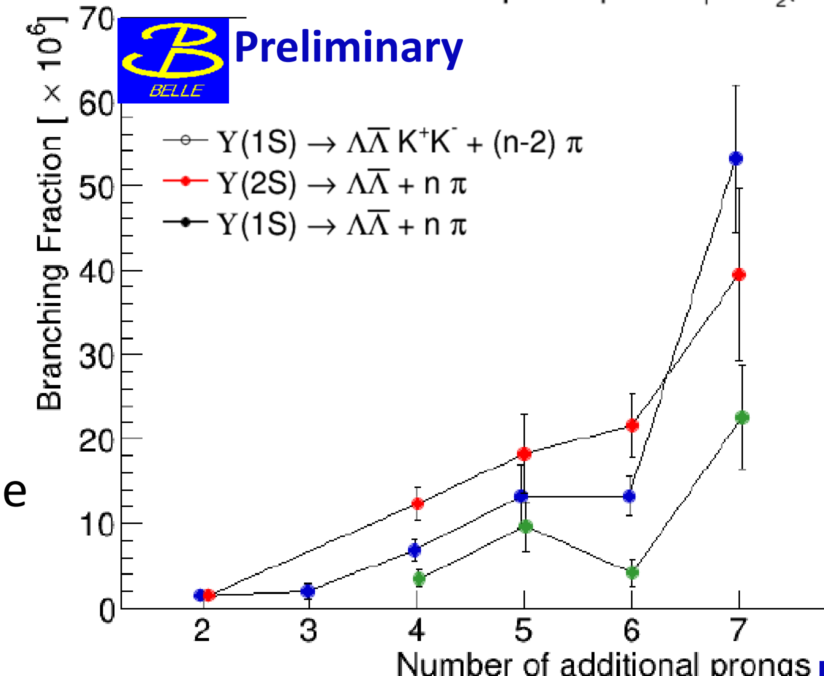
- The inclusive production rate of Λ has been found to be 3 times larger in the $\Upsilon(1S)$ decay with respect to the non resonant $e^+e^- \to q\bar{q}$ at same center of mass energy
- $ggg/q\bar{q}$ enhancement = $\dfrac{\sigma[ee \to \Upsilon(nS) \to \Lambda + X]}{\sigma[ee \to q\bar{q} \to \Lambda + X]}$
- At Belle we reconstructed, 48 modes (X) comprising charged pions and kaons, protons, and a π^0 other than $\Lambda\bar{\Lambda}$ pair

$$\sum_X BF[\Upsilon(1S) \to X] \approx 2 \times 10^{-4}$$

$$\sum_X BF[\Upsilon(2S) \to X] \approx 0.7 \times 10^{-4}$$

- $\Lambda\bar{\Lambda}$ production mostly occurs in an high multiplicity environment.
- a clear multiplicity hierarchy is present: the branching fraction scales with the increasing number of additional particles

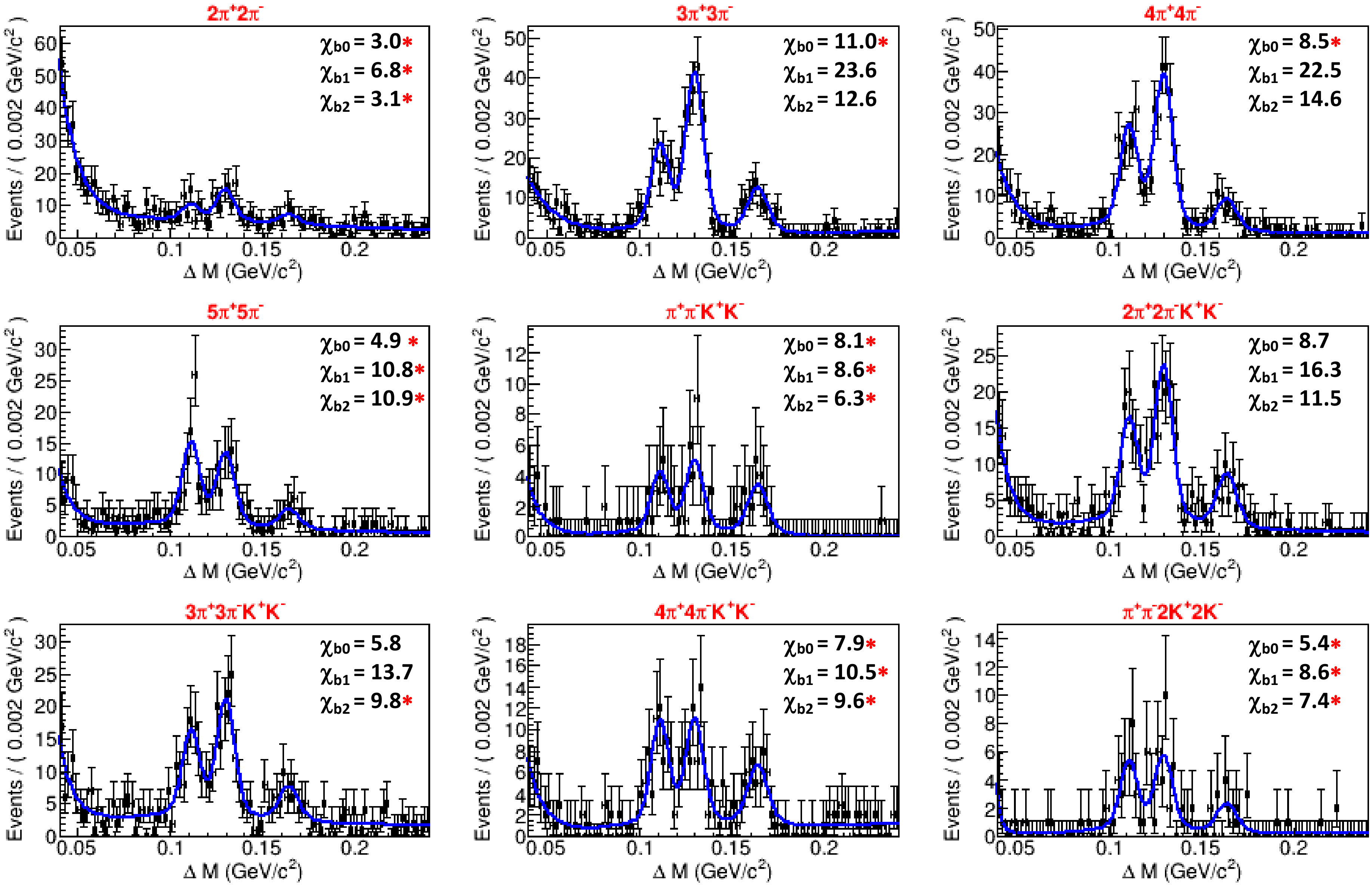




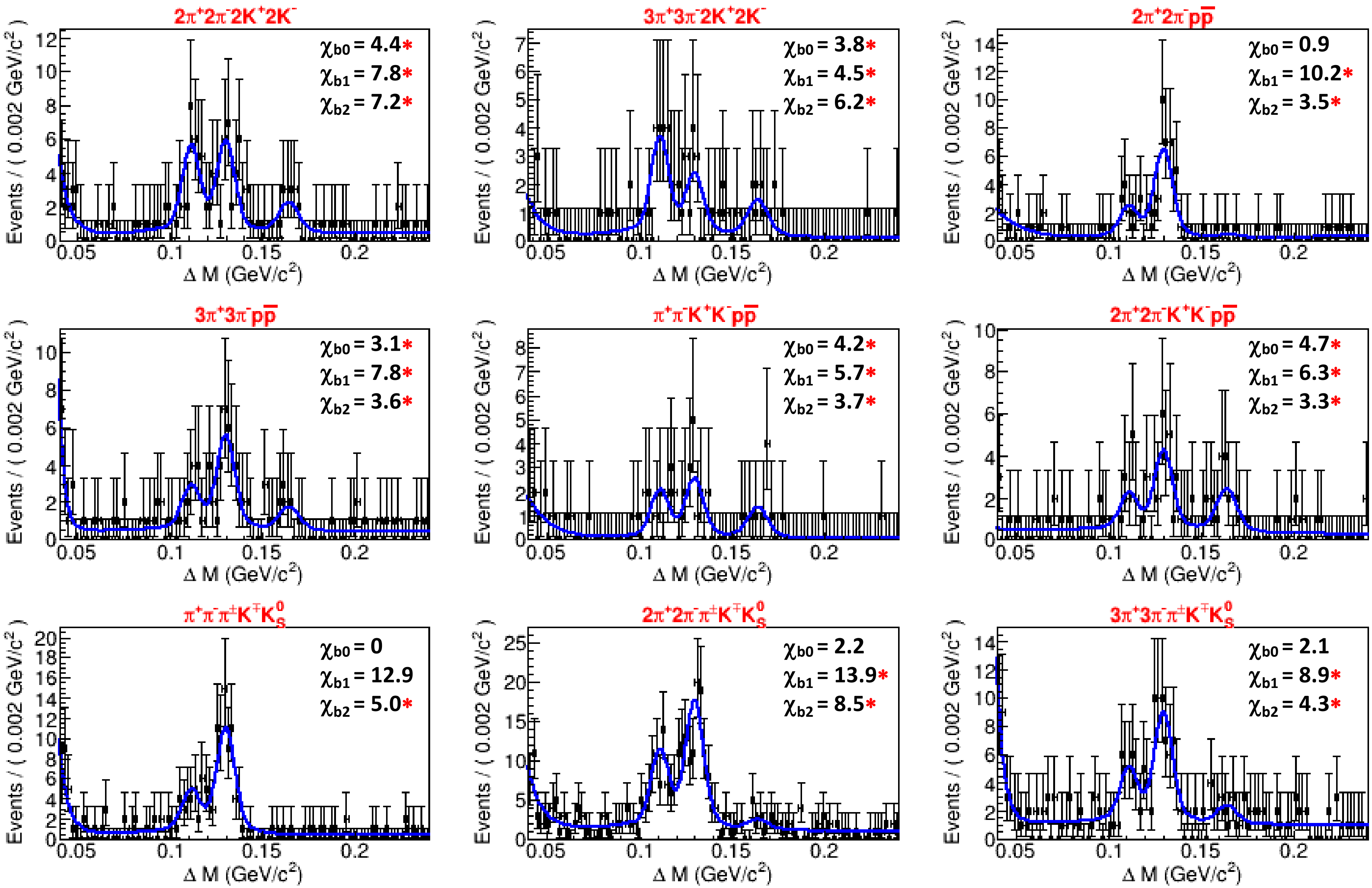
Summary

- $\Gamma[\Upsilon(5S)\rightarrow\Upsilon(1,2S)\pi^+\pi^-] >> \Gamma[\Upsilon(4,3,2S)\rightarrow\Upsilon(1S)\pi^+\pi^-] \sim 100$ times $\rightarrow$ Re-scattering of on-shell $B^{(*)}\overline{B}^{(*)}$ **PRL 100, 112001 (2008)**
- Large yield of $h_b(nP)$ from the $\Upsilon(5S)$ dipion transition $\rightarrow$ Charged Z_b's **PRL 108, 122001 (2012)**
- $h_b(nP)$ opened a new path to study $\eta_b(nS)$ in radiative transition. Studied properties of $\eta_b(1S)$ and first evidence of $\eta_b(2S)$ was reported. **PRL 109,232002 (2012)**
- Radiative population of states from $\Upsilon(2S)$ is also studied. Reconstructed 74 hadronic decay modes of $\chi_{bJ}(1P)$ for each J = 0, 1, and 2. We found observation and evidence of signals in total 85 (27+28+30 for J=0,1,2) decay modes for the first time. **PRELIMINARY**
- Obtained an upper limit on the width of the $\chi_{b0}(1P)$ < 2.4MeV (at 90%CL) **PRELIMINARY**
- $\Upsilon(4S) \rightarrow \eta h_b(1P)$ transition is observed first time with the BF $\sim 2.2 \times 10^{-3}$. **PRL 115,142001 (2015)**
- Studied $\Upsilon(1,2S)$ decay to $\Lambda\overline{\Lambda}$ with other hadrons and found that $\Lambda\overline{\Lambda}$ production mostly occurs in an high multiplicity environment. **PRELIMINARY**

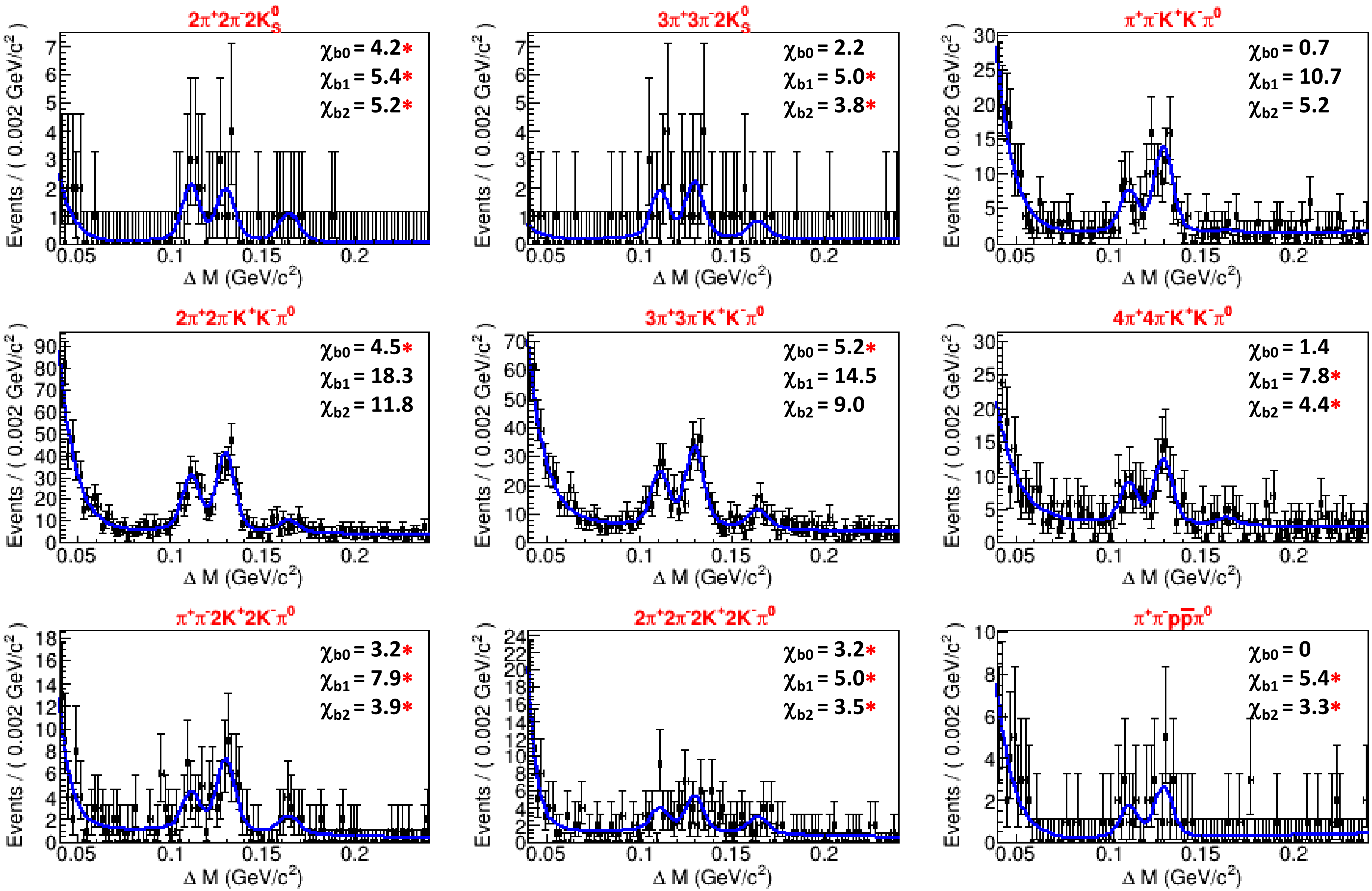
ΔM distribution in each mode



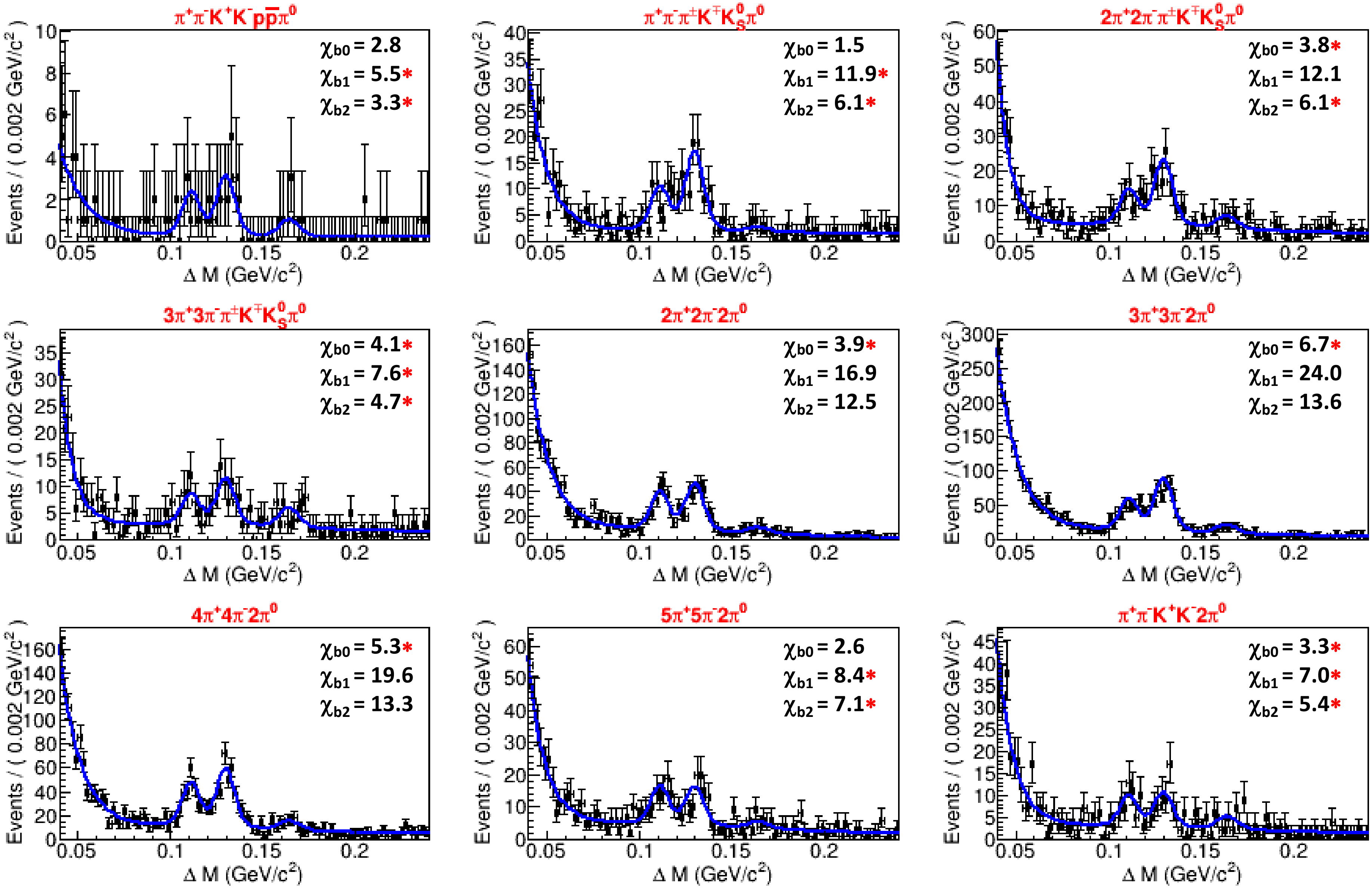
ΔM distribution in each mode



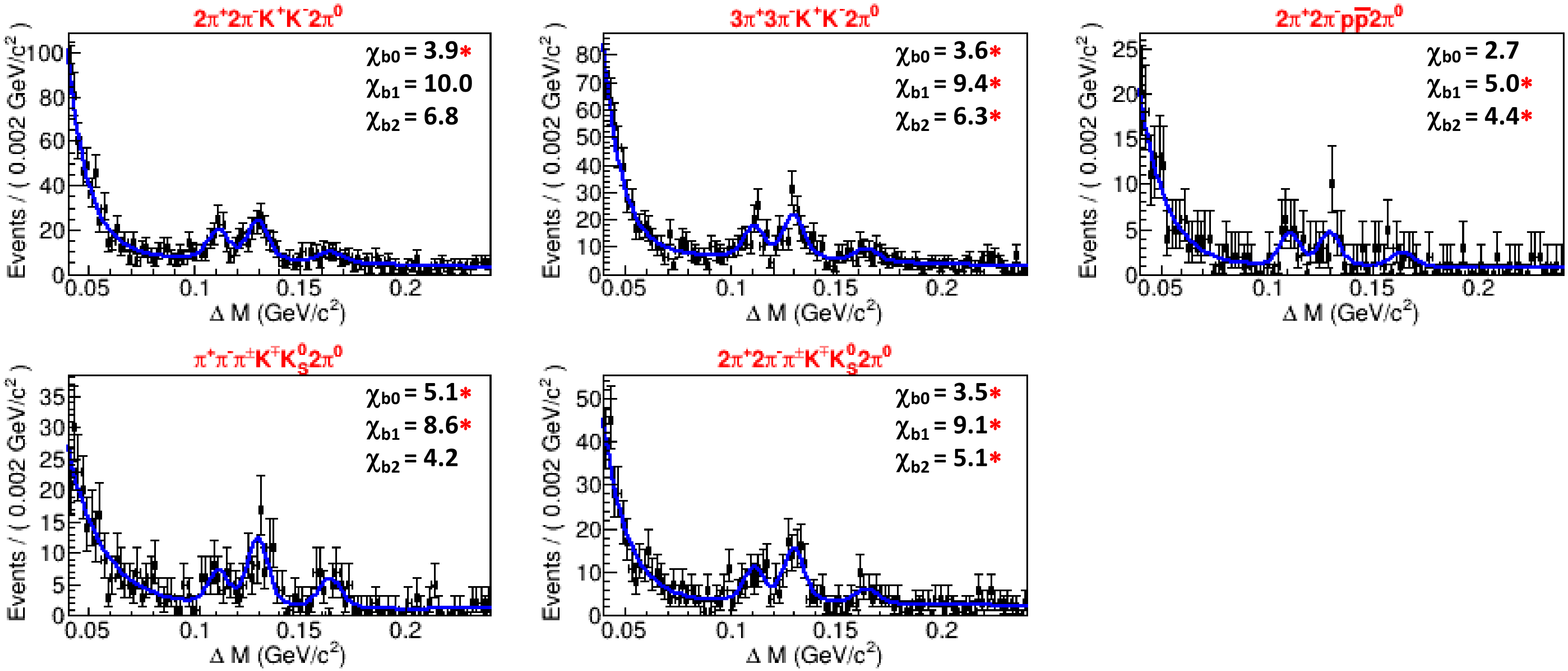
ΔM distribution in each mode



ΔM distribution in each mode



ΔM distribution in each mode



CLEO : $\chi_{bJ}(1P)$ decays to light hadrons

CLEO's study: exclusive decays of $\chi_{bJ}(1P)$