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Bottomonium(-like) / Charmonium(-like) Transitions

G. TATISHVILI
Pacific Northwest National Laboratory

Quarkonium 2014

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Outline

- Search for X_b
- Observation of $e^+e^- \rightarrow \pi^+\pi^-\pi^0 \chi_{bJ}$
  - $\omega \chi_{bJ}$
  - $(\pi^+\pi^-\pi^0)_{\text{non-}\omega} \chi_{bJ}$
- Belle: Recent Hadronic Transition Results
- Observation of $B \rightarrow J/\psi \eta K$
- Search for charmonium(-like) state in the $J/\psi \eta$ final state

Bottomonium and Charmonium Family Resemblance

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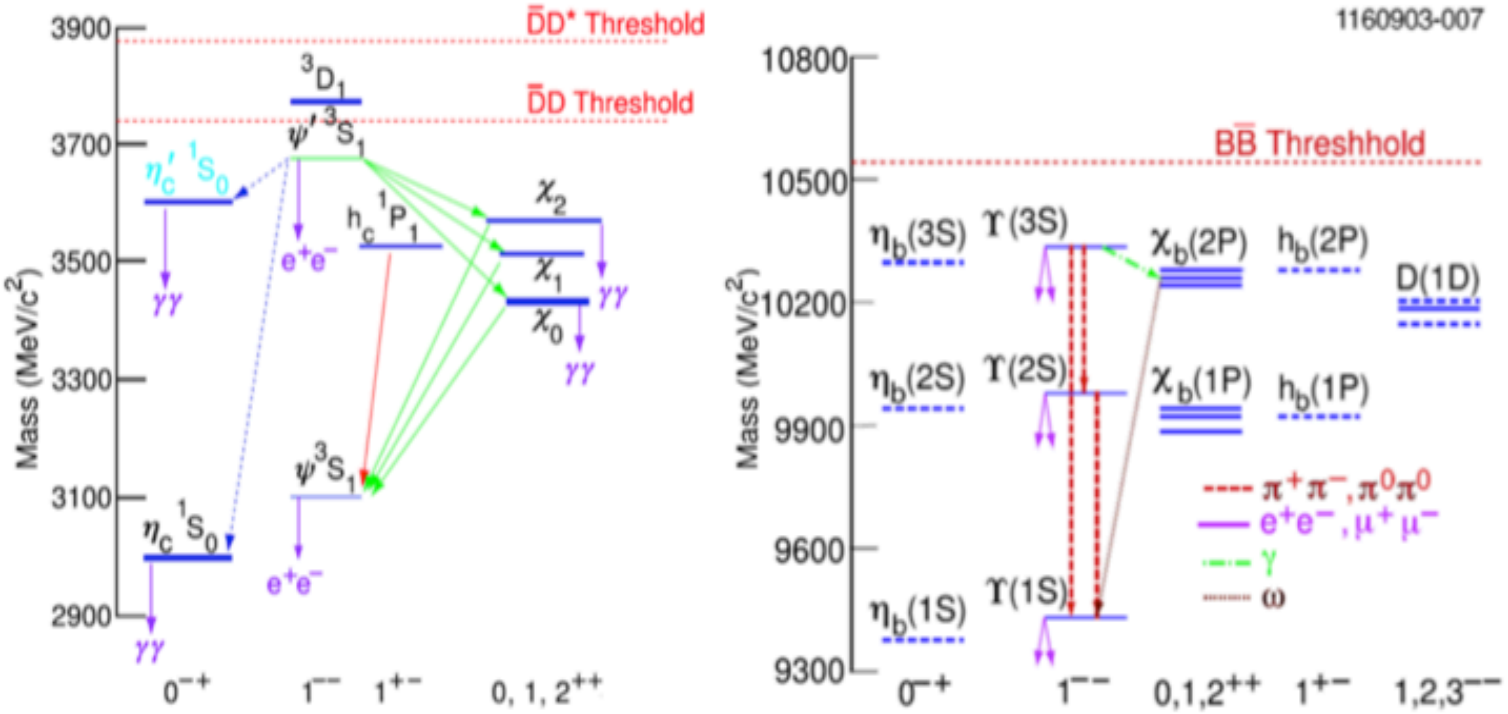
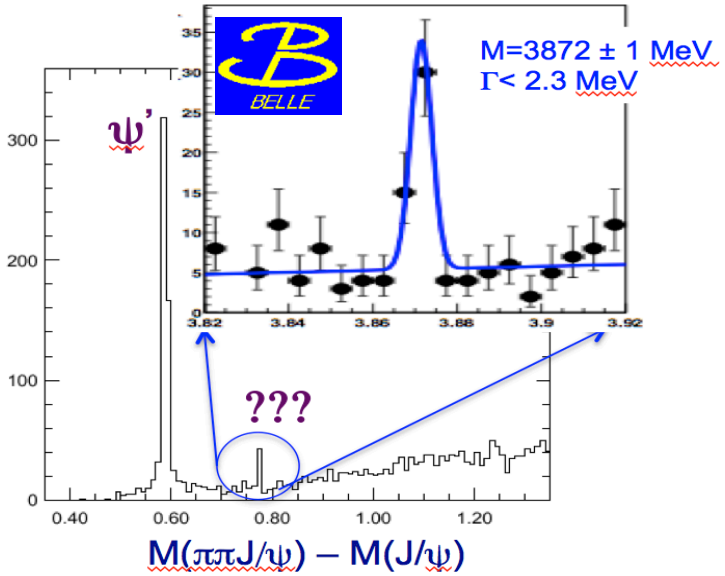
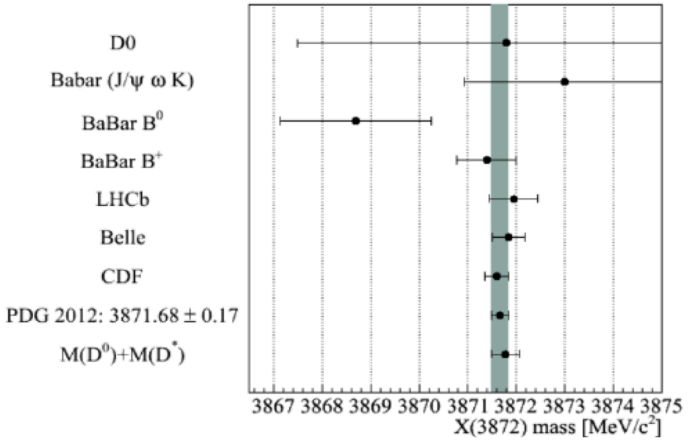


The b quark mass is ~3 times the c quark mass but the spacing of the main energy levels are much the same. The strong interaction is flavor blind…

The rich spectra of these states offer MANY opportunities for discovery and refinement of our understanding of the strong interaction and strongly interacting systems.

Search for X_b





The observation of a new charmonium-like resonance, X(3872), in the $\pi^+\pi^- J/\psi$ final state by the Belle collaboration opened a new era in the spectroscopy of charmonium and charmonium-like exotic states.
S.-K. Choi, S.Olsen et al. (Belle) PRL 91, 262001

X(3872) - mixture of a P-wave charmonium $\chi_{c1}(2P)$ level of spin 1 and an S-wave molecule of $D^0\bar{D}^{*0}$ +c.c. (arXiv:1410.7729)

A similar behavior in the bottomonium system could lead to resonant effects near $B\bar{B}^*$ + c.c. thresholds. (arXiv:0802.0649)

A predicted mass of X_b:
$M(X_b) = 10562$ MeV/c^2 (arXiv:0802.0649)
for a $B\bar{B}^*$ +c.c. state of $J^{PC} = 1^{++}$.
Close to the observed P-wave $b\bar{b}$ excitation $\chi_{b1}(3P)$

$M(X_b) = 10585$ MeV/c^2 (arXiv:1304.0345)
based on the expected binding energy of a $B\bar{B}^*$

CMS: Search for X_b

CMS: Search for $X_b \rightarrow \Upsilon(1S)\pi+\pi-$ (Phys. Lett. B 727, 57 (2013)).

Motivation: the seemingly analogous decay $X(3872) \rightarrow J/\psi\ \pi^+\pi^-$.

A sample of pp collisions at an integrated luminosity of 20.7 fb^{-1}.

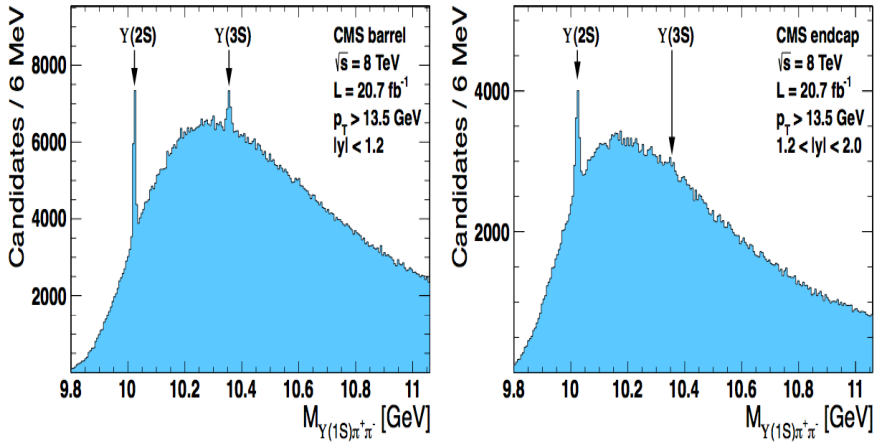
The search for the X_b was performed in the mass regions
$10.06 < M(\Upsilon(1S)\pi+\pi-) < 10.31$ GeV/c^2 and
$10.40 < M(\Upsilon(1S)\pi+\pi-) < 10.99$ GeV/c^2

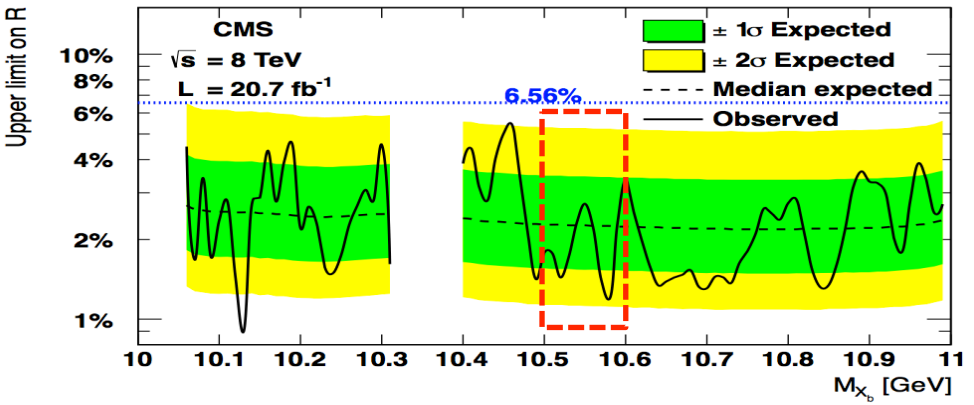
Mass intervals around the $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances were excluded.

$$R = \frac{\sigma(pp \rightarrow X_b \rightarrow \Upsilon(1S)\pi^+\pi^-)}{\sigma(pp \rightarrow \Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-)}$$

R: 95% confidence level upper limit: Depending on the assumed X_b mass.

CMS





No evidence of X_b signal is observed

ATLAS: Search for X_b

A search for a hodden-beauty analogue of the X(3872) was performed by reconstructing $\pi^+\pi^-\Upsilon(1S) \rightarrow \mu^+\mu^-$ in 16.2fb^{-1} of pp collision by ATLAS. (arXiv:1410.4409).

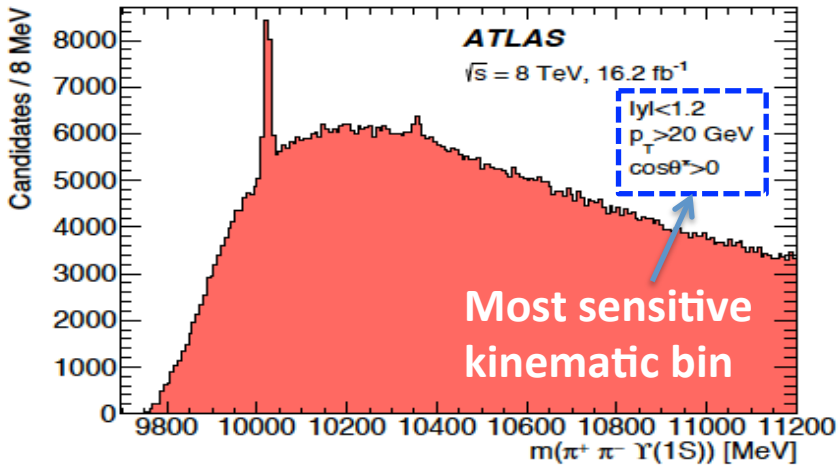
The search for the X_b was performed in the mass regions
$10.05 < M(\Upsilon(1S)\pi^+\pi^-) < 10.31$ GeV/c^2 and
$10.40 < M(\Upsilon(1S)\pi^+\pi^-) < 11.00$ GeV/c^2

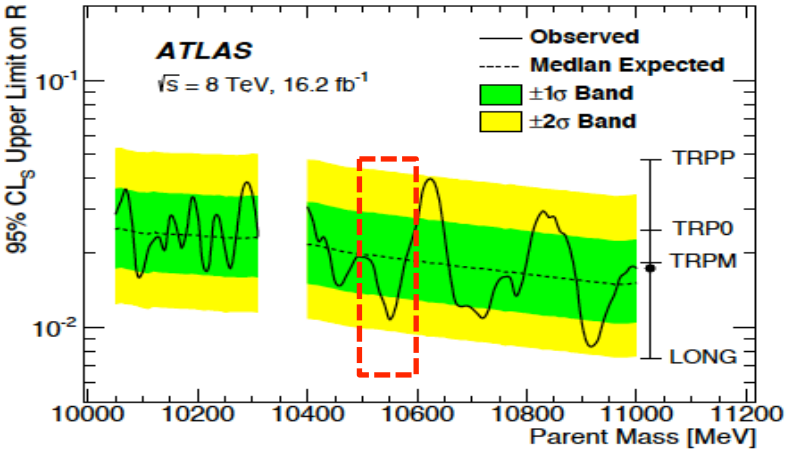
Mass intervals around the $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances were excluded.

Upper limits are set on the ratio:

$$R = \frac{\sigma(pp \rightarrow X_b) \times Br(X_b \rightarrow \Upsilon(1S)\pi^+\pi^-)}{\sigma(pp \rightarrow \Upsilon(2S)) \times Br(\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-)}$$

R: 95% confidence level upper limit is from 0.8% to 4.0% depending on the assumed X_b mass.





No evidence of X_b signal is observed

Interpretation of X_b Search Results

For an isoscalar with $J^{PC} = 1^{++}$ such a decay is forbidden by G-parity conservation.

How X(3872) with the same $J^{PC} = 1^{++}$ does decay into $J/\psi\,\pi^+\pi^-$? (arXiv:1410.7729).

Charm Sector	Bottom Sector
$MD^+ - MD^0 = 4.76$ MeV/c^2 – Isospin is broken	$MB^0 - MB^+ = 0.32$ MeV/c^2 – Isospin is conserved
X(3872) decays brake isospin	Isospin is conserved in the decays of X_b
$X(3872) \rightarrow J/\psi\,\pi^+\pi^-$ is allowed	$X_b \rightarrow \Upsilon(1S)\pi^+\pi-$ is forbidden

X_b should be reconstructed in the $\gamma\Upsilon(nS)$ (n=1,2,3), $\Upsilon(1S)\pi^+\pi-\pi^0$, or $\chi_{bJ}\pi^+\pi-$ instead of the $\Upsilon(nS)\pi^+\pi-$ final states – analogous of $X(3872) \rightarrow J/\psi\,\pi^+\pi^-$ (arXiv:1402.6236).

M. Karliner and J. Rosner (arXiv:1410.7729) suggested the following decay channels to search for X_b state:

A. $X_b \rightarrow \Upsilon(1S, 2S)\omega = \Upsilon(1S, 2S)\pi^+\pi-\pi^0$

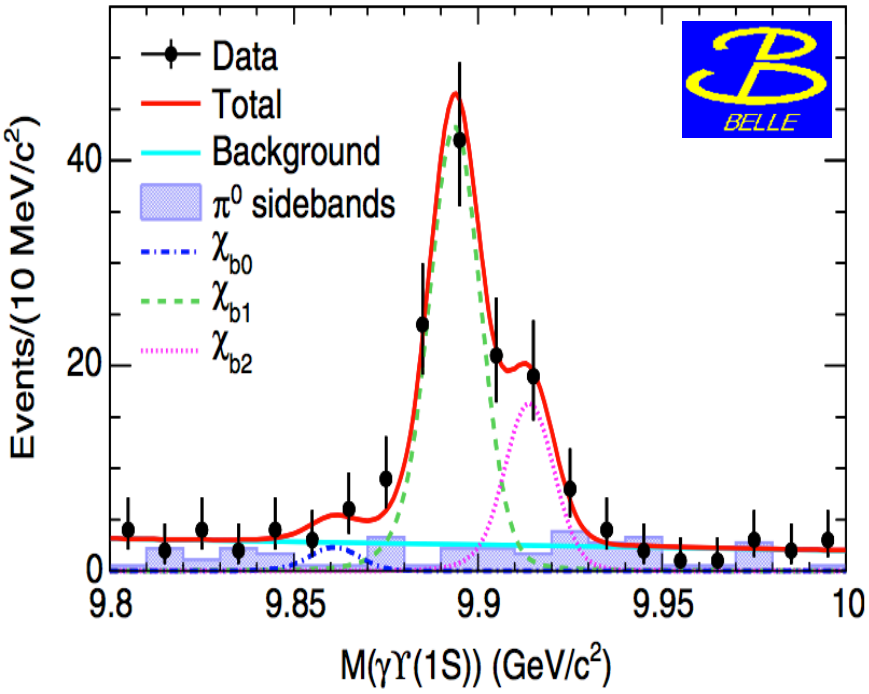
B. $X_b \rightarrow \chi_{b1}(1P)\,\pi^+\pi-$

C. $X_b \rightarrow \Upsilon(3S)\gamma$

Experiment Belle presented results of $\Upsilon(1S)\omega$ analysis

Study of the e+e- → $\pi^+\pi^-\pi^0\chi_{bJ}$ processes with subsequent $\chi_{bJ} \to \gamma\Upsilon(1S)$

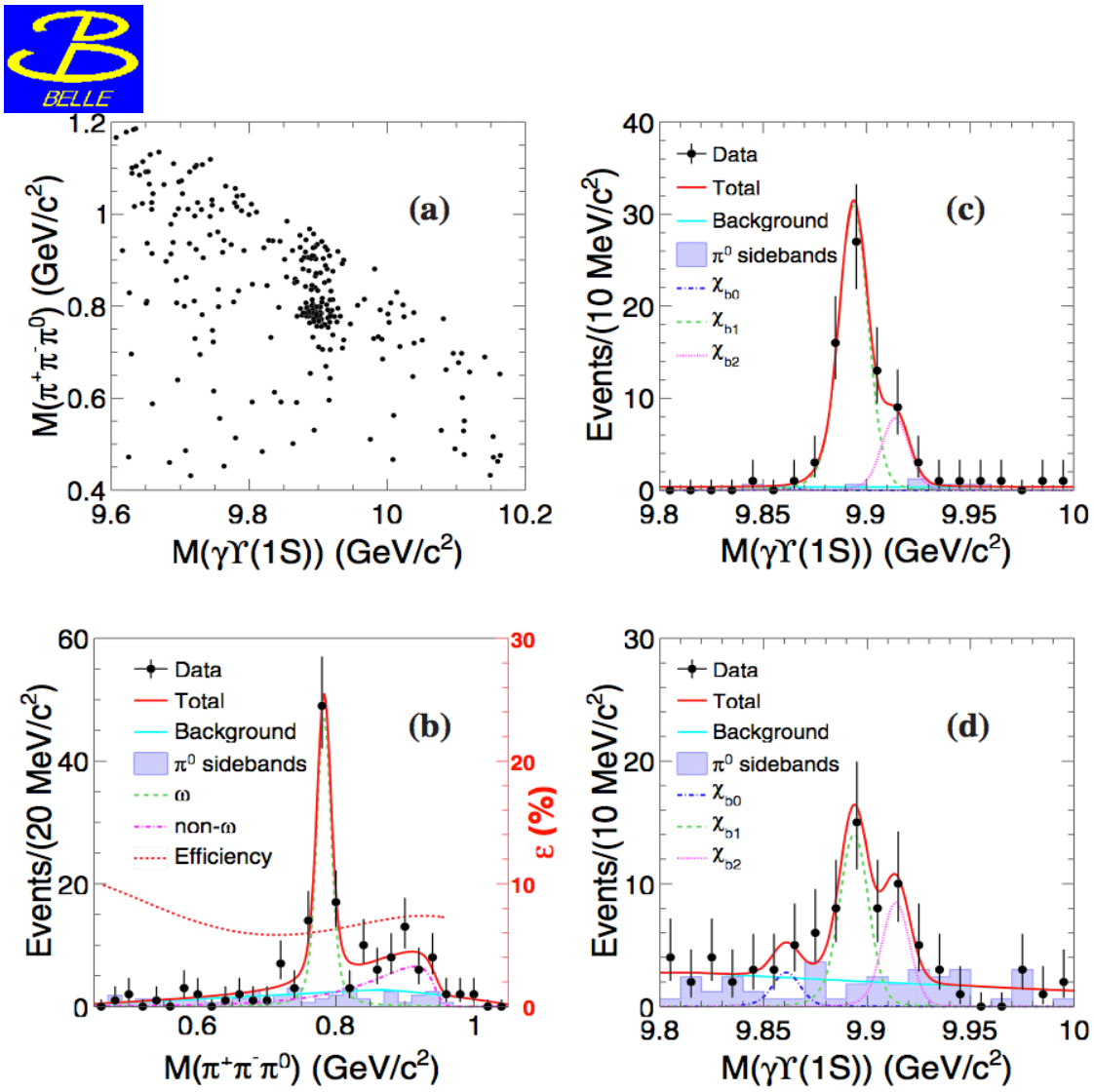
At a center-of-mass energy of 10.867 GeV using a 118 fb^{-1} experiment Belle studied The e+e- → $\pi^+\pi^-\pi^0\chi_{bJ}$(J=0,1,2) processes with subsequent $\chi_{bJ} \to \gamma\Upsilon(1S)$, $\Upsilon(1S) \to l^+l^-$ (l = e or μ) decays. PRL 113, 142001 (2014).



Clear peaking signals of χ_{b1} and χ_{b2} are observed.

the signal significances of χ_{b1} and χ_{b2} are 12σ and 5.9σ with systematic uncertainties included, while for the χ_{b0} the signal significance is only 1.0σ.

$\Upsilon(5S) \rightarrow \omega \chi_b(1P)$



(a) $M(\pi^+\pi^-\pi^0)$ vs $M(\gamma\Upsilon(1S))$. In addition to the clear ω signal in the χ_{bJ} mass region, there is an obvious accumulation of events above the ω mass region.

(b) projections to $M(\pi^+\pi^-\pi^0)$ for 9.8 GeV/c^2 < $M(\gamma\Upsilon(1S))$ < 10 GeV/c^2, where the dashed and dash-dotted curves represent the ω and ($\pi^+\pi^-\pi^0$)non-ω events;

(c) $M(\gamma\Upsilon(1S))$ in the ω signal region.

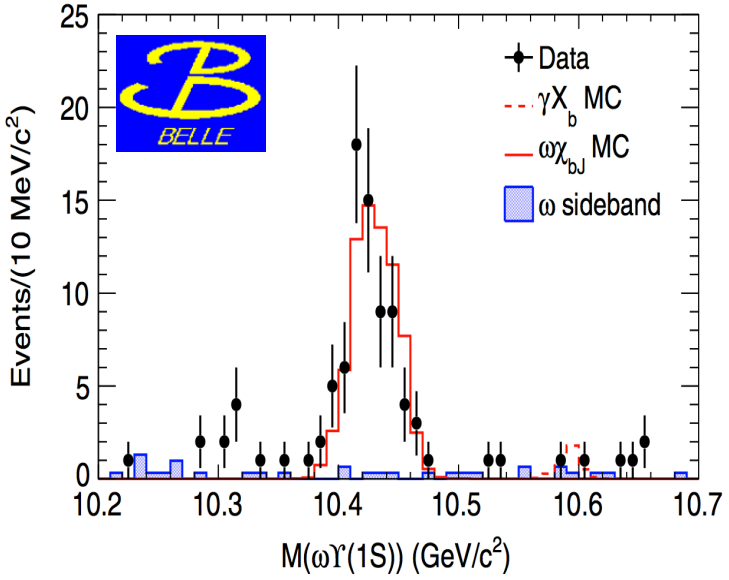
(d) $M(\gamma\Upsilon(1S))$ outside of the ω signal region.

Search for $X_b \to \omega\Upsilon(1S)$

Mode	Yield	Σ (σ)	ε (%)	σ_B (pb)	$\mathcal{B}$ (10^{-3})
$\pi^+\pi^-\pi^0\chi_{b0}$	< 13.6	1.0	6.43	< 3.1	< 6.3
$\pi^+\pi^-\pi^0\chi_{b1}$	80.1 ± 9.9	12	6.61	$0.90 \pm 0.11 \pm 0.13$	$1.85 \pm 0.23 \pm 0.23$
$\pi^+\pi^-\pi^0\chi_{b2}$	28.6 ± 6.5	5.9	6.65	$0.57 \pm 0.13 \pm 0.08$	$1.17 \pm 0.27 \pm 0.14$
$\omega\chi_{b0}$	< 7.5	0.5	6.35	< 1.9	< 3.9
$\omega\chi_{b1}$	59.9 ± 8.3	12	6.53	$0.76 \pm 0.11 \pm 0.11$	$1.57 \pm 0.22 \pm 0.21$
$\omega\chi_{b2}$	12.9 ± 4.8	3.5	6.56	$0.29 \pm 0.11 \pm 0.08$	$0.60 \pm 0.23 \pm 0.15$
$(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\chi_{b0}$	< 10.7	0.4	6.68	< 2.3	< 4.8
$(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\chi_{b1}$	23.6 ± 6.4	4.9	6.88	$0.25 \pm 0.07 \pm 0.06$	$0.52 \pm 0.15 \pm 0.11$
$(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\chi_{b2}$	15.6 ± 5.4	3.1	6.91	$0.30 \pm 0.11 \pm 0.14$	$0.61 \pm 0.22 \pm 0.28$

$$R = \frac{\sigma(e+e- \to \omega\chi_{b2})}{\sigma(e+e- \to \omega\chi_{b1})} = 0.38 \pm 0.16(stat.) \pm 0.09(syst.)$$

$$R = \frac{\sigma(e+e- \to (\pi^+\pi^-\pi^0)_{non-\omega}\chi_{b2})}{\sigma(e+e- \to (\pi^+\pi^-\pi^0)_{non-\omega}\chi_{b1})} = 1.20 \pm 0.55(stat.) \pm 0.65(syst.)$$



Belle also searched for an X(3872)-like state X_b decaying to $\omega\Upsilon(1S)$ with $\omega \to \pi^+\pi-\pi^0$ in $e+e- \to \gamma X_b$ at higher energies.

No obvious X_b signal is observed after applying all the event selection criteria.

Belle obtained the product branching fraction $Br(\Upsilon(10860) \to \gamma X_b)(Br(X_b \to \omega\Upsilon(1S)) < 2.9 \times 10^{-5}$ at 90% C.L.

Belle: Recent Hadronic Transition Results

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For η transition results obtained by Belle collaboration
See U. Tamponi's Presentation at this workshop.

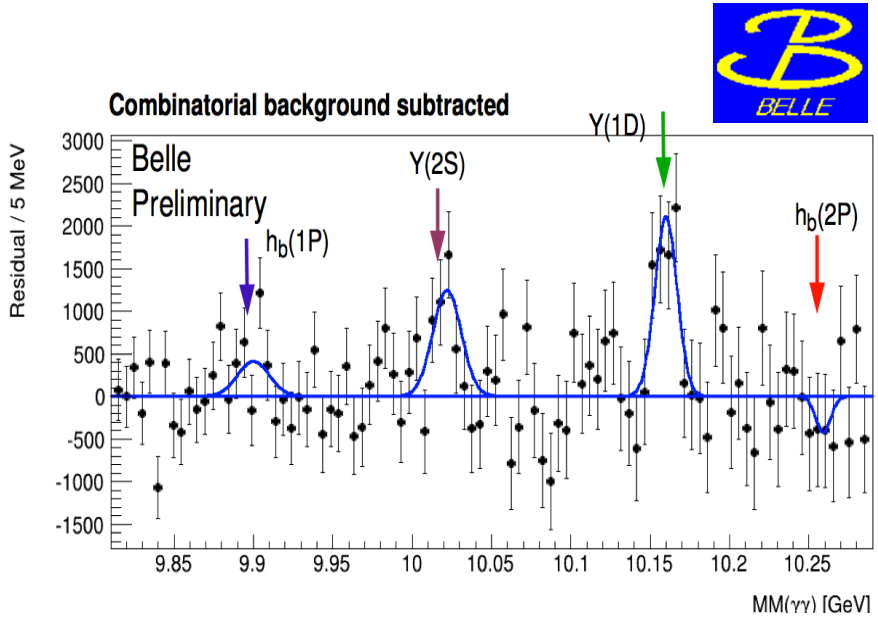
$Y(5S) \to \eta\, b\bar{b}$

- BF[Y(5S) → η Y(2S)] = (2.1 ± 0.7 ± 0.3) x 10^{-3}
- BF[Y(5S) → η Y(1D)] = (2.8 ± 0.7 ± 0.4) x 10^{-3}

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

- BF[Y(5S) → η hb(1P)] = < 3.3 x 10^{-3} (90% CL)
- BF[Y(5S) → η hb(2P)] = < 3.7 x 10^{-3} (90% CL)

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



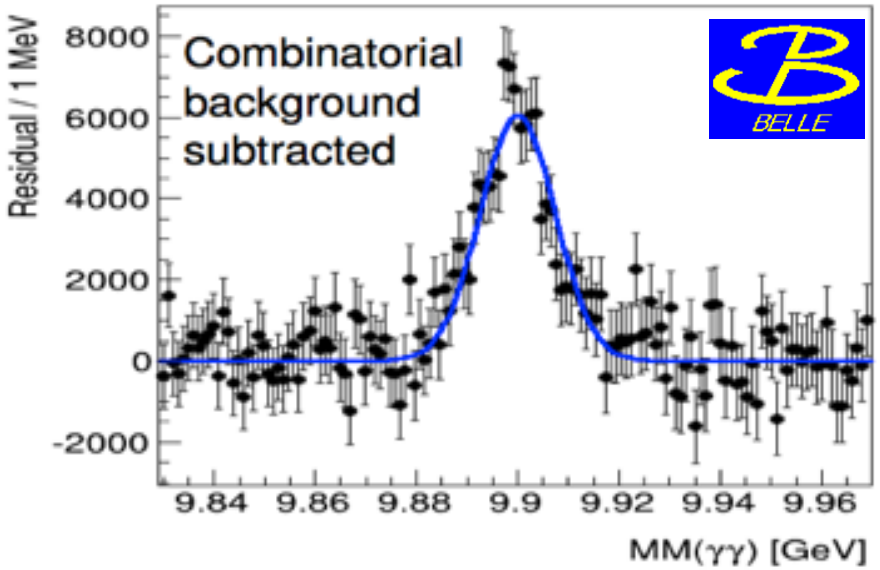
$Y(4S) \to \eta\, b\bar{b}$

First **single meson**, $^3S \to {}^1P$ transition observed with > 5 σ

BF[Y(4S)→η hb(1P)] = (1.83 ± 0.16 ± 0.17)x10^{-3}

$\Gamma_{\eta Y(1S)}$ = 4 KeV
$\Gamma_{\pi\pi Y(1S)}$ = 1.7 KeV
$\Gamma_{\eta hb(1P)}$ = 37 KeV

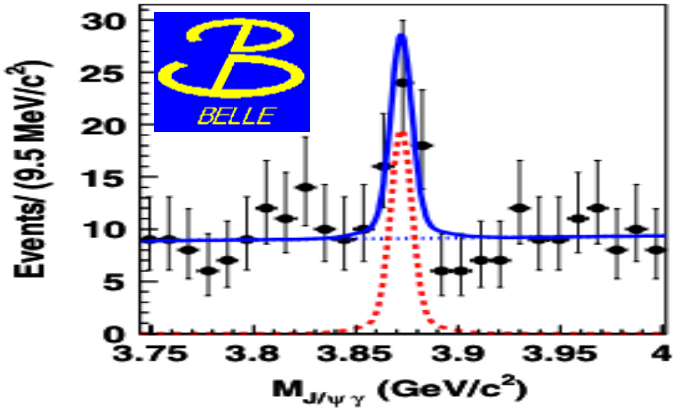
One order of magnitude larger than any other Y(4S) transition



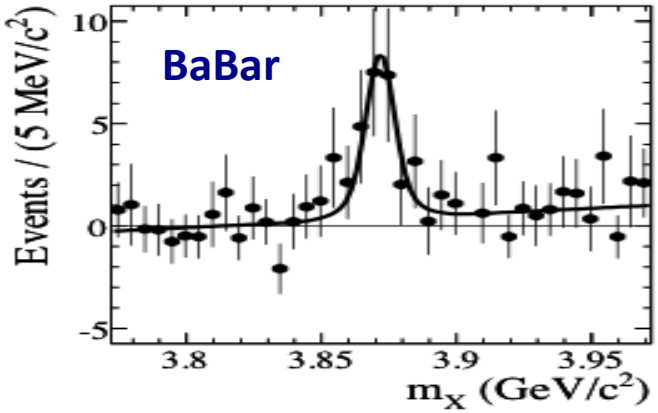
B→ J/ψ η K

The X(3872) was discovered by the Belle experiment in $\pi^+\pi^-$ J/ψ recoiling against K^+ from B^+ decay.

PRL 107, 091803 (2011)



PRL 102, 132001 (2009)

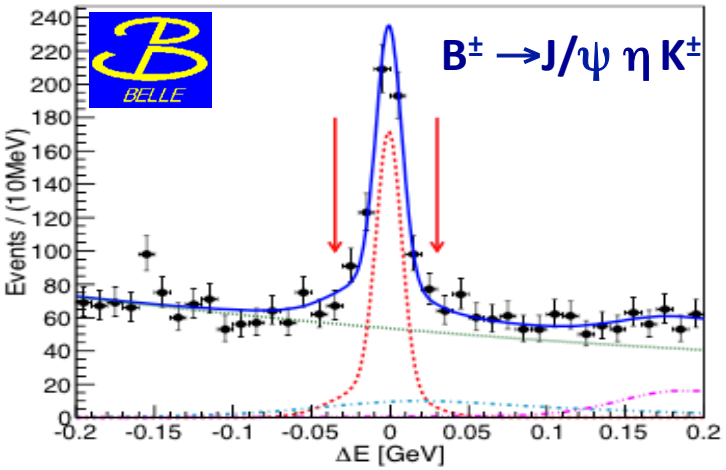


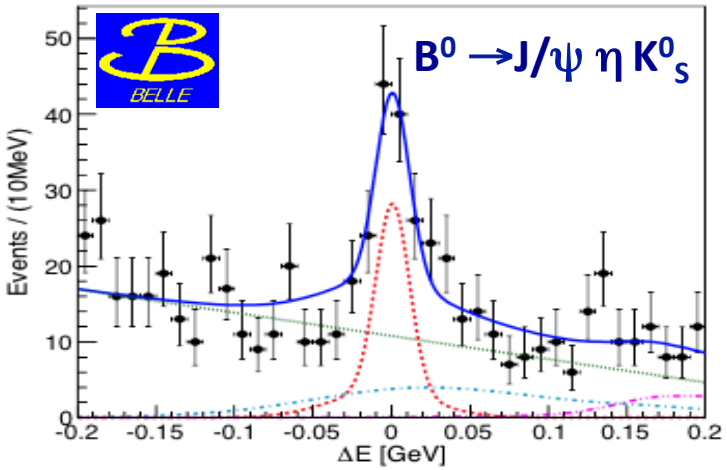
Observation of the X(3872) → J/ψ γ mode by belle and BaBar confirmed that its C-parity is even.

The J/ψ η system in the three-body B→ J/ψ η K decay is a suitable final state to search for a missing C-odd partner of the X(3872) and yet-unseen charmonium(-like) resonances.

The Belle experiment performed a study of the B→ J/ψ η $\bar{K}$ decays based on a data sample of 772x10^6 B$\bar{B}$ events collected at the Υ(4S) resonance (PTEP 2014, 043C01)

Br(B→ J/ψ η K) Measurements





$\Delta E = E^{*}_{B} - E^{*}_{beam}$ $M_{bc} > 5.27\ GeV/c^2$

Decay mode	$\epsilon(\%)$	N_{sig}	$\mathcal{B}$
$B^{\pm} \to J/\psi\eta K^{\pm}$	9.37	428±37	$(1.27\pm0.11\pm0.11)\times10^{-4}$
$B^{0} \to J/\psi\eta K^{0}_{S}$	7.23	94±14	$(5.22\pm0.78\pm0.49)\times10^{-5}$

Search for a Narrow Resonance in the J/ψ η Final State

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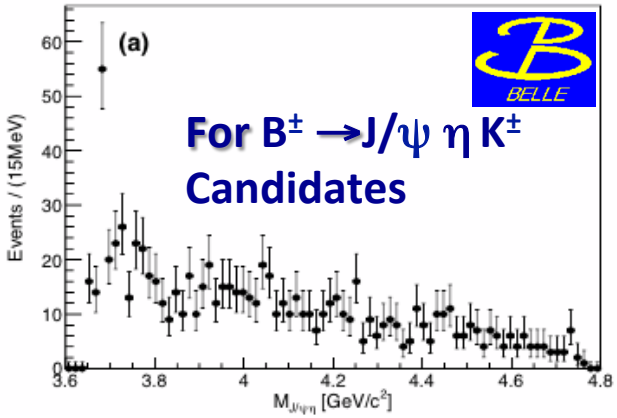
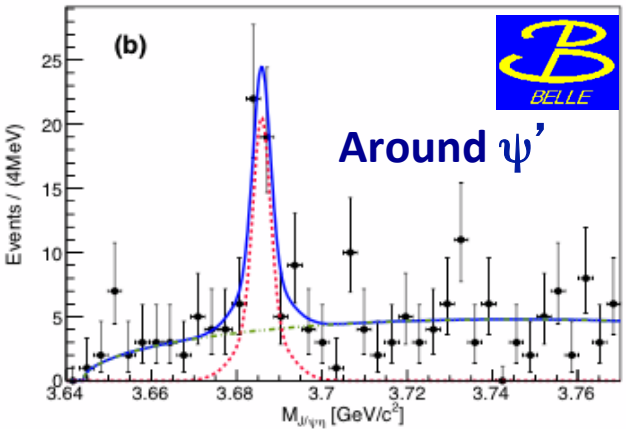
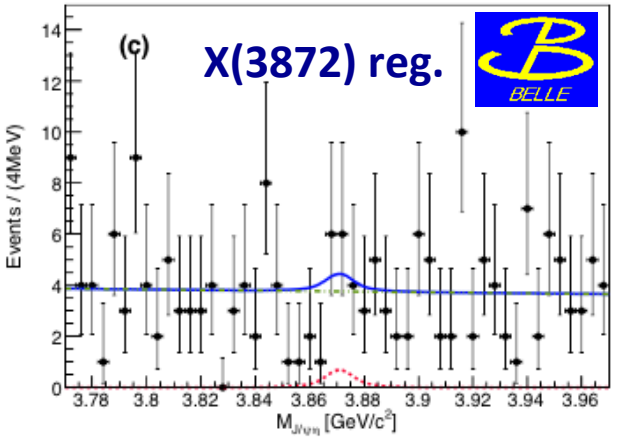
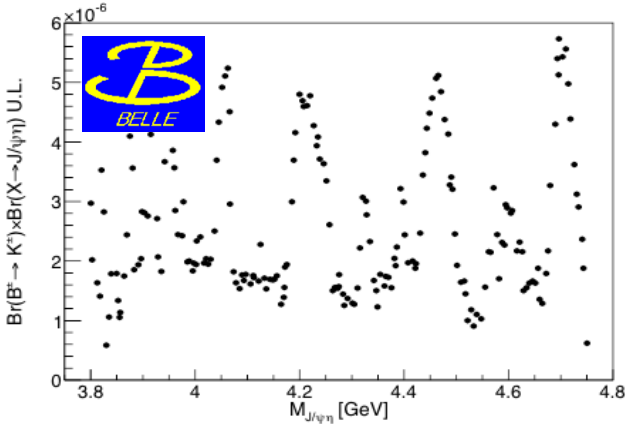






$$B(B^{\pm} \to \psi' K^{\pm}) B(\psi' \to J/\psi\eta) = (0.15 \pm 0.03(stat.) \pm 0.01(syst.)) \times 10^{-4}$$



90% CL upper limit of

$$B(B^{\pm} \to XK^{\pm}) B(X \to J/\psi\eta)$$

The Belle experiment observed the $B^{\pm} \to J/\psi\,\eta\,K^{\pm}$ and $B^{0} \to J/\psi\,\eta\,K^{0}_{S}$ decay modes and obtained the branching fractions.

No signal is seen in M(J/ψ η).

U.L. on the product branching fractions was obtained

$$B(B^{\pm} \to X^{C-odd} K^{\pm}) B(X^{C-odd} \to J/\psi\eta) < 3.8 \times 10^{-6}$$

at 90% C.L.

Summary

- Belle observed clear $\pi^+\pi^-\pi^0$ χ_{bJ} (J=1,2) signals at a center-of-mass energy 10.867 GeV.
- Besides a clear ω signal, significant non-ω signals of $\pi^+\pi^-\pi^0$ χ_{bJ} were also observed.
- Belle observed new hadronic transitions via η meson:
  $\Upsilon(4S) \rightarrow \eta\, h_b(1P)$ – First observation
  $\Upsilon(5S) \rightarrow \eta\Upsilon(1D)$ – First observation

  $\Upsilon(5S) \rightarrow \eta\, h_b(1P)$ – No evidence
- No X_b signals decaying into $\omega\Upsilon(1S)$ were found in $\Upsilon(10860)$ radiative decay.
- Belle reported an observation of the $B^{\pm} \rightarrow J/\psi\, \eta\, K^{\pm}$ and $B^0 \rightarrow J/\psi\, \eta\, K^0_S$ decays using 772 x 10^6 $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance.
- No significant excess of charmonium(-like) state X in the $J/\psi\, \eta$ mass spectrum was found.