Study of Quarkonium and Quarkonium-like States at Belle

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(on behalf of the Belle Collaboration)

DIS2018

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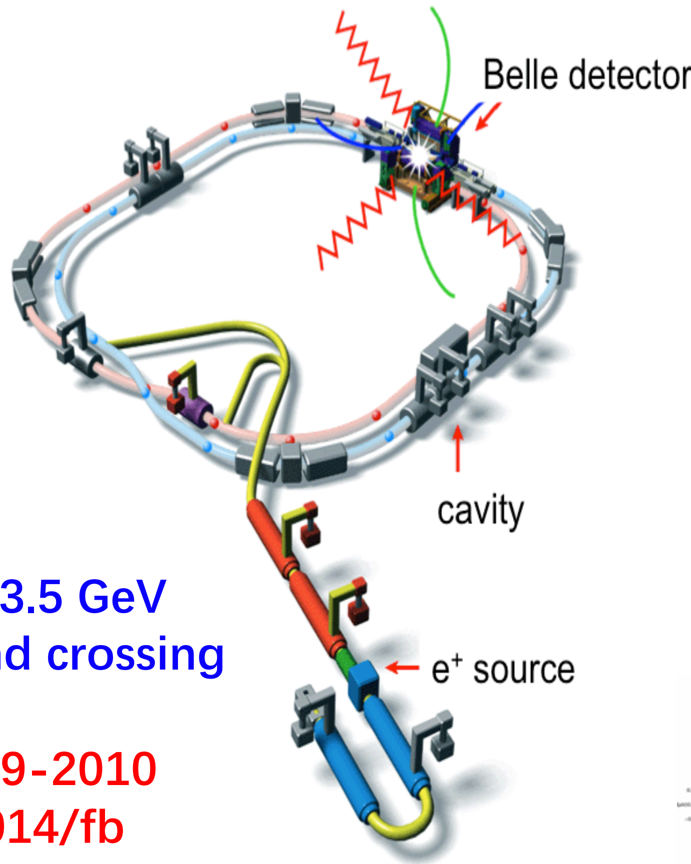
KEKB and Belle Detector

KEK, Tsukuba, Japan

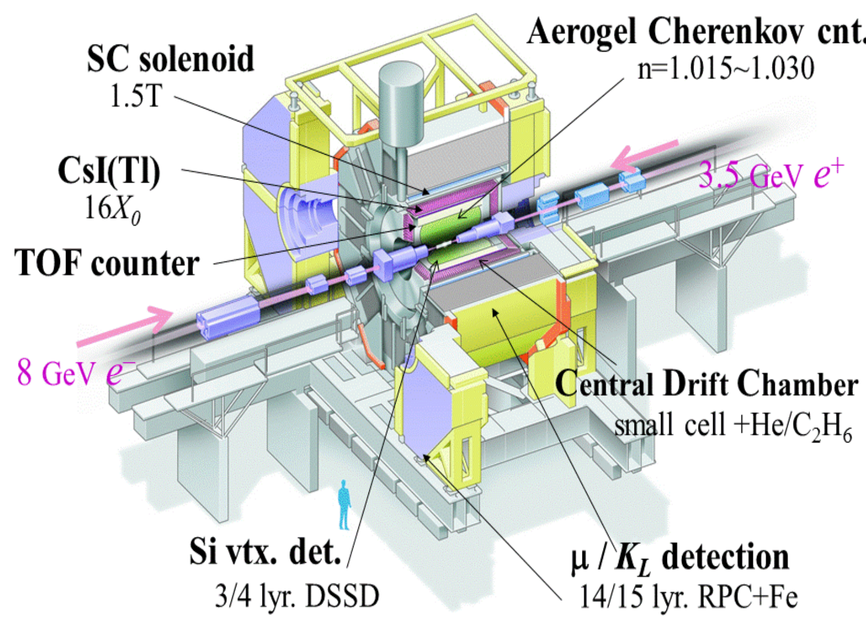


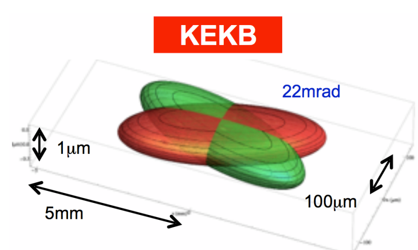
8 × 3.5 GeV
22 mrad crossing

1999-2010
1014/fb

The KEKB Collider

Belle Detector



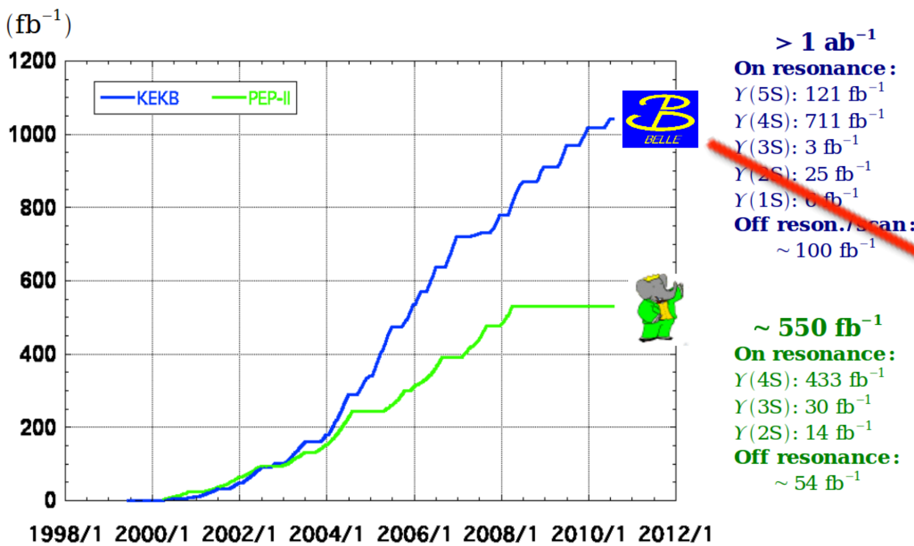


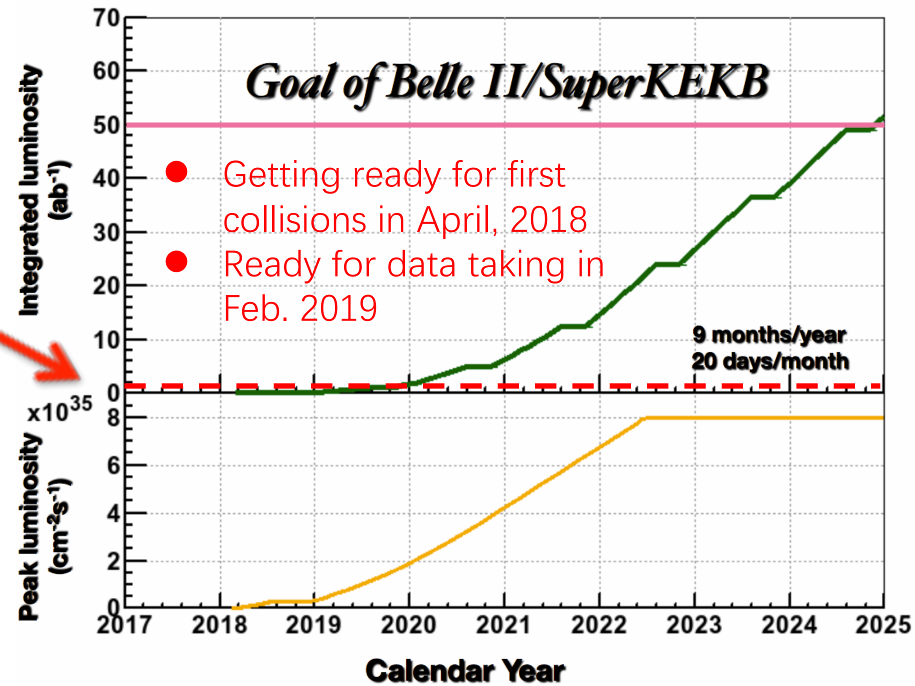
World record:

L=2.1×10^{34}/cm^2/sec

Data set at B-factories

Integrated luminosity of B factories





Expected data sample @ full luminosity

Channel	Belle	BaBar	Belle II (per year)
$B\bar{B}$	7.7×10^8	4.8×10^8	1.1×10^{10}
$B_s^{(*)}\bar{B}_s^{(*)}$	7.0×10^6	–	6.0×10^8
$\Upsilon(1S)$	1.0×10^8		1.8×10^{11}
$\Upsilon(2S)$	1.7×10^8	0.9×10^7	7.0×10^{10}
$\Upsilon(3S)$	1.0×10^7	1.0×10^8	3.7×10^{10}
$\Upsilon(5S)$	3.6×10^7	–	3.0×10^9
$\tau\tau$	1.0×10^9	0.6×10^9	1.0×10^{10}

* assuming 100% running at each energy

- Bottomonia below $B\bar{B}$ threshold
- Bottomonium-like states above $B\bar{B}$ threshold
- Initial State Radiation
- Two Photon Collisions
- Double Charmonium Production

Content:

Study of Quarkonium at Belle

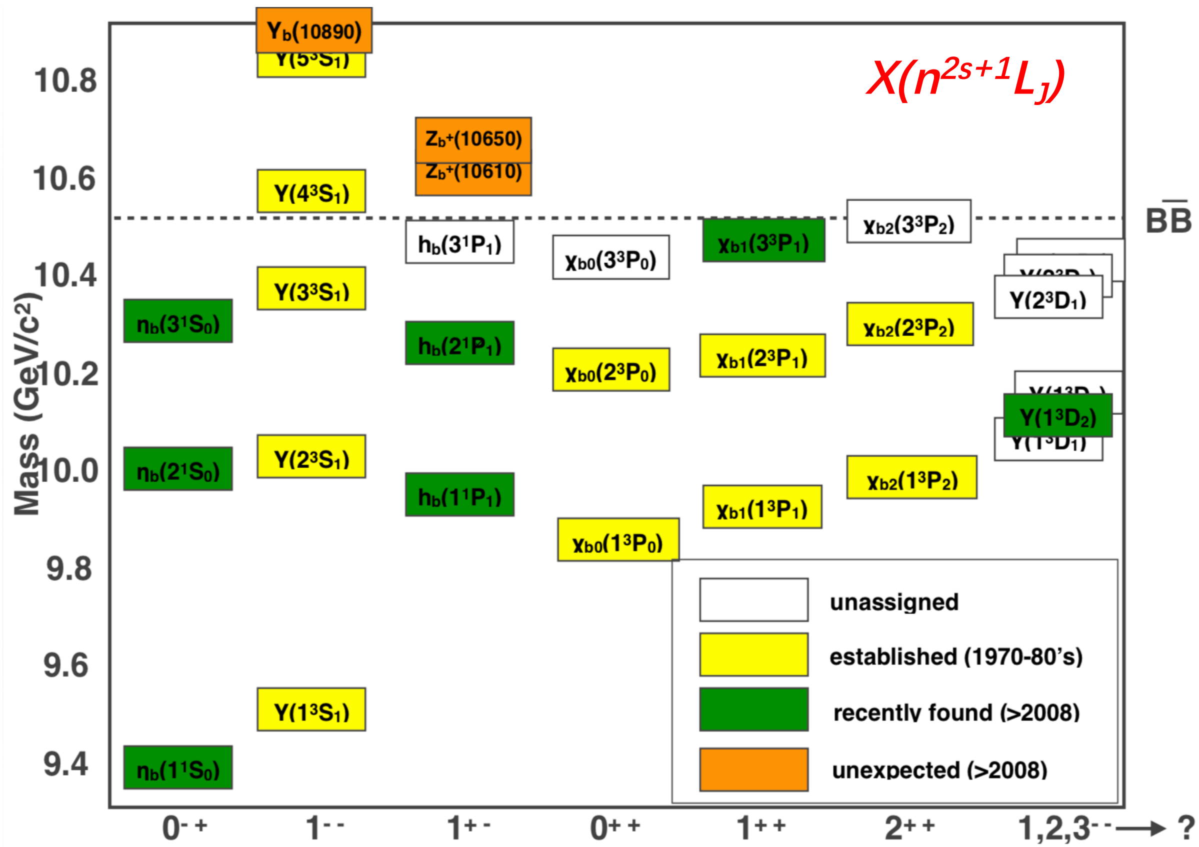
- Hadronic transitions in bottomonium
- A alternative $\chi_{cJ}(nP)$ candidates in the $D\bar{D}$ system
- Bottomonium inclusive decays

Study of Quarkonium-like states at Belle

- Measurements of $B^+ \to X_{c\bar{c}}K^+$
- Search for Y(4660) and its spin partner in $B^+ \to K^+\Lambda_c^+\bar{\Lambda}_c^-$
- Double Z_c states production

Bottomonium spectroscopy and Hadronic transitions

- Bottomonium spectroscopy was gradually developed in the past few decades.
- Important information on bottomonium is given by the study of transitions between its states.



Expectations:

- suppression of spin-flipping transitions

  (i.e. mS→ η nS wrt mS → $\pi^+\pi^-$nS, and mS → $\pi^+\pi^-$ nP wrt mS → $\pi^+\pi^-$ nS)

- Further suppression of isospin-violating transitions

  (i.e. mS → π^0 nS wrt others)

Experiment:

PRD 78, 112002 (2008)

$$\frac{\mathcal{B}(\Upsilon(4S)\to\eta\Upsilon(1S))}{\mathcal{B}(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S))}=2.41\pm0.40_{stat}\pm0.12_{syst}$$

$$\frac{\mathcal{B}(\Upsilon(3S)\to\pi^0 h_b(1P))}{\mathcal{B}(\Upsilon(3S)\to\eta\Upsilon(1S))}>8.6$$

PRD 84, 091101 (2011)

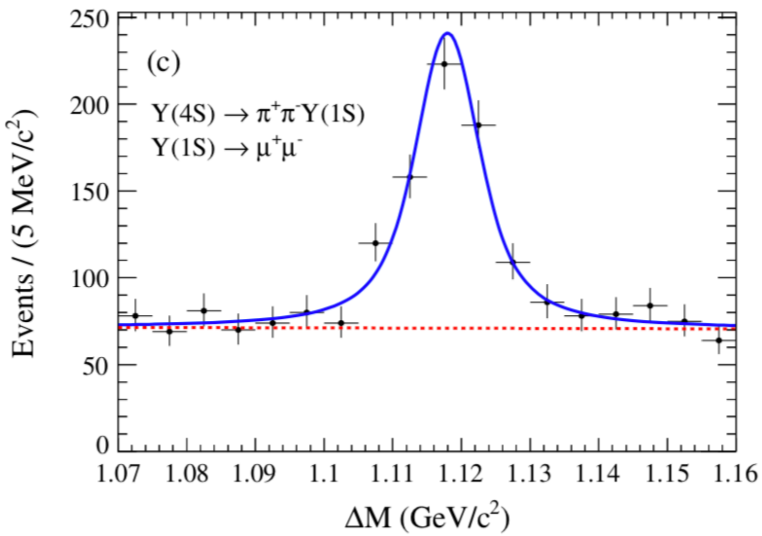
S. Jia, DIS 2018

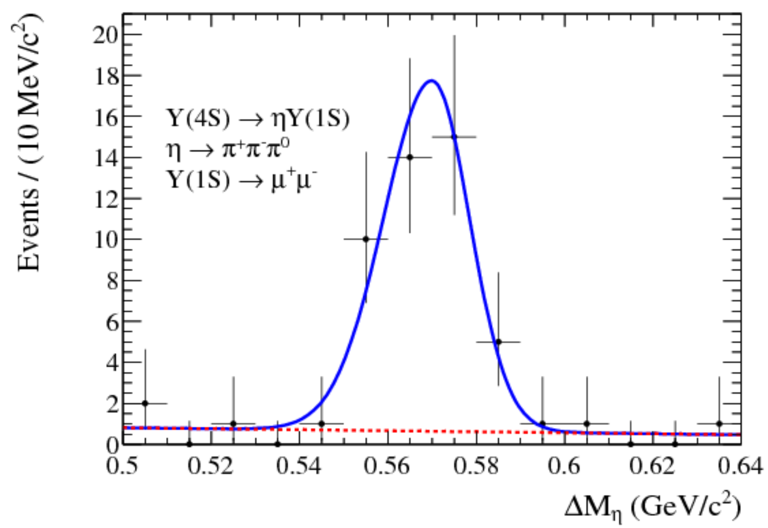
Diffuse failure of the theoretical calculations

η and dipion transitions in $\Upsilon(4S)$ decays

PRD 96, 052005 (2017)

- $\eta \to \pi^+\pi^-\pi^0, \pi^0 \to \gamma\gamma, \Upsilon(1S) \to \mu^+\mu^-$
- *Fit to* $\Delta M = M(\pi\pi\mu\mu) - M(\mu\mu)$ *and* $\Delta M_\eta = M(\pi\pi\gamma\gamma\mu\mu) - M(\mu\mu) - M(\pi\pi\gamma\gamma)$



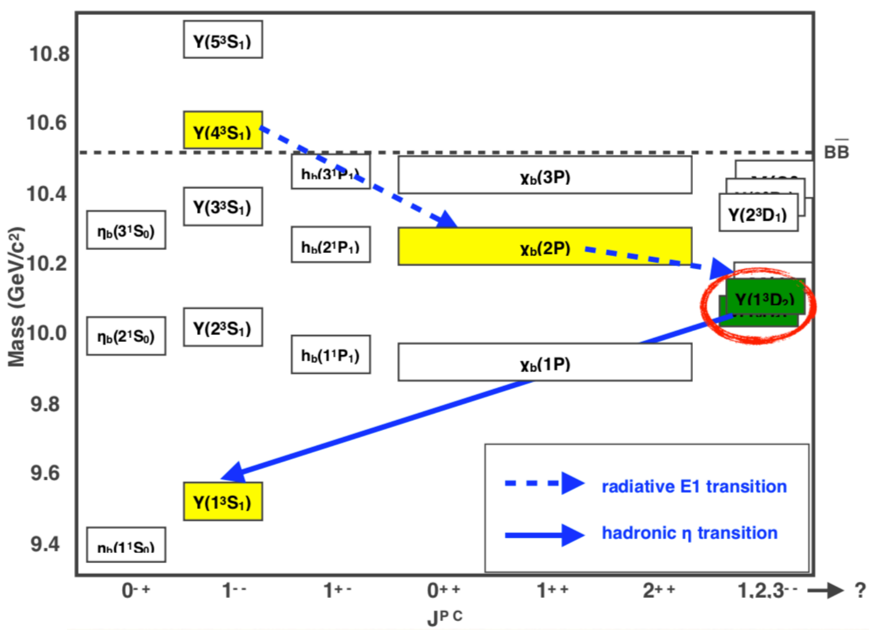


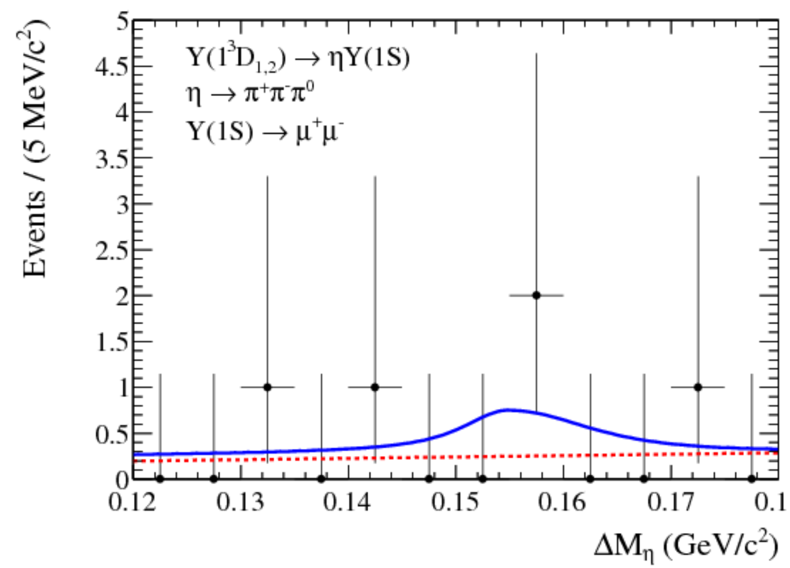
Results	*PRD 78, 112002 (2008)* BABAR	Belle
$\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S))$	$1.90 \pm 0.26 \pm 0.09$	$1.70 \pm 0.23 \pm 0.08$
$\mathcal{R} = \frac{\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S))}{\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))}$	$2.41 \pm 0.40 \pm 0.12$	$2.07 \pm 0.30 \pm 0.11$

- Confirmation of the enhancement with respect to dipion transition

$\Upsilon(1^3D_{1,2}) \to \eta\Upsilon(1S)$

- With the same analysis method and similar event selections.
- Predicted to be enhanced with respect to the transition $\Upsilon(1D)\to\pi\pi\Upsilon(1S)$ by the axial anomaly in QCD ***PLB 562, 68 (2003)***





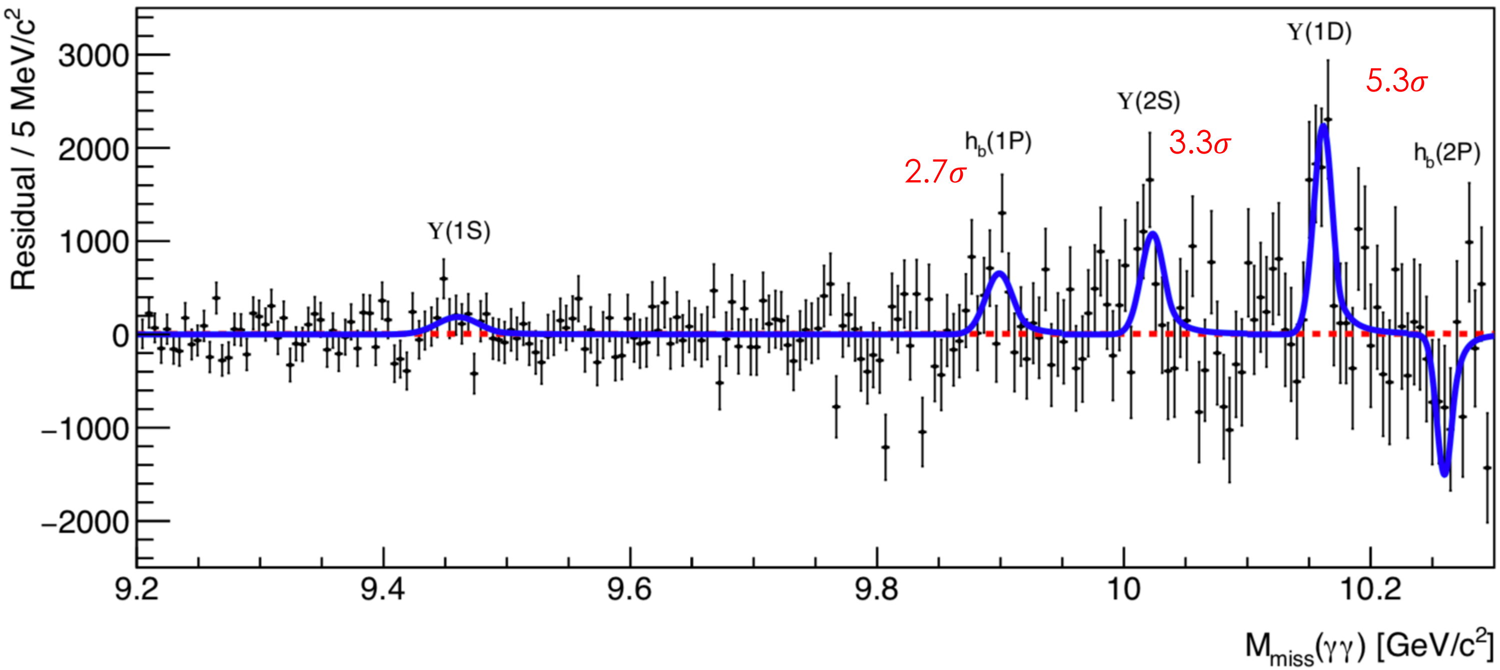
- Υ(1D) possibly produced via double-radiative transitions from Υ(4S) through χ_{bJ}(2P) states

$\mathcal{B}^{UL}\left(\Upsilon(4S) \to \gamma\gamma\Upsilon(1^3D_{1,2})\right) \times$
$\mathcal{B}^{UL}\left(\Upsilon(1^3D_{1,2}) \longrightarrow \gamma\Upsilon(1S)\right) < 2.3\times10^{-5}$
at 90% C. L.

η transitions from $\Upsilon(5S)$

arXiv:1803.03225, submitted to EPJC

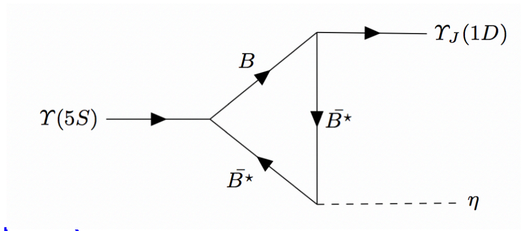
- After combinatorial background subtraction, the missing mass spectrum



- In particular, $\mathcal{B}(\Upsilon(5S)) \rightarrow \eta\Upsilon(1D))$ in compatible with the prediction (via hadronic loop mechanism) *PRD 94, 094039 (2016)*
- Observation of $\Upsilon(5S) \rightarrow \eta\Upsilon_J(1D)$

  $\sigma_v(\Upsilon(5S) \rightarrow \eta\Upsilon_J(1D) = (1.14 \pm 0.22 \pm 0.15)$ [pb]

  $\sigma_B(\Upsilon(5S) \rightarrow \eta\Upsilon_J(1D) = (1.64 \pm 0.31 \pm 0.21)$ [pb]



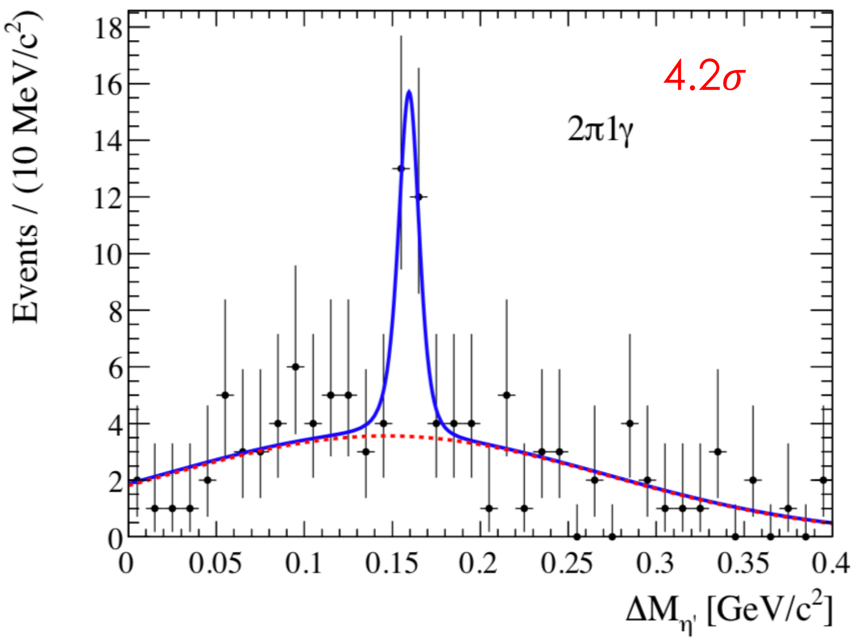
- Not resolving the Υ(1D) triplet (resolution~mass splitting)

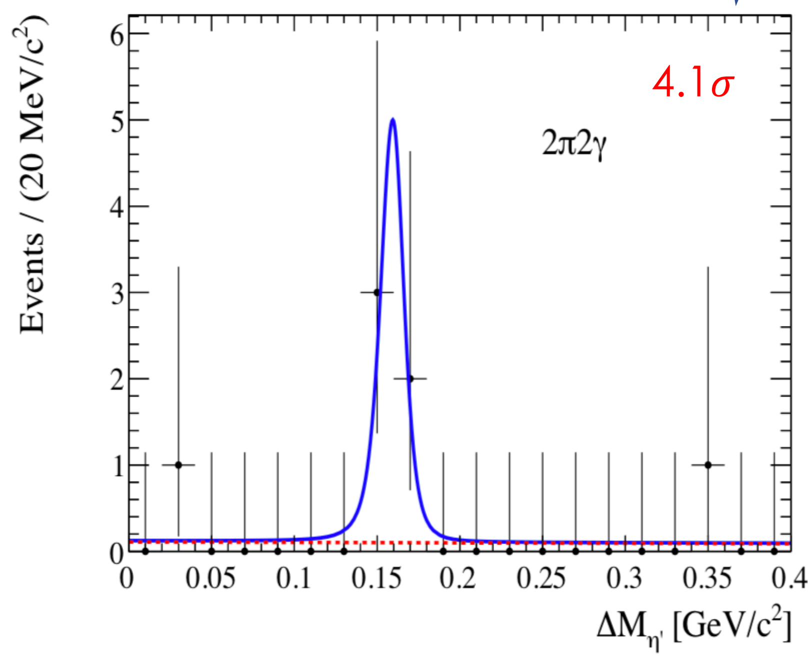
First observation of $\Upsilon(4S) \to \eta'\Upsilon(1S)$

arXiv:1803.10303, submitted to PRL

- $\eta' \to \rho^0\gamma$ (2π1γ), $\eta' \to \pi\pi\eta$ (2π2γ), $\Upsilon(1S) \to \mu^+\mu^-$ ***500th Belle paper***
- Fit to $\Delta M_{\eta'} = M(\Upsilon(4S)) - M(\Upsilon(1S)) - M(\eta')$, where $M(\Upsilon(4S)) = M(\mu\mu\pi\pi\gamma)[M(\mu\mu\pi\pi\gamma\gamma)]$, $M(\eta') = M(\pi\pi\gamma)[M(\pi\pi\gamma\gamma)]$ in the 2π1γ[2π2γ].

New!





- The statistical significance of combined measurement is 5.8σ

BR	result
$\mathcal{B}(\Upsilon(4S) \to \eta'\Upsilon(1S))/\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S))$	0.20 ± 0.06
$\mathcal{B}(\Upsilon(4S) \to \eta'\Upsilon(1S))/\mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$	0.42 ± 0.11

Agree with the case of four-quark admixture in transitions

MPLA 26, 773 (2011)

The history of $\chi_{c0}(2P)$ $[\chi_{c2}(2P)]$

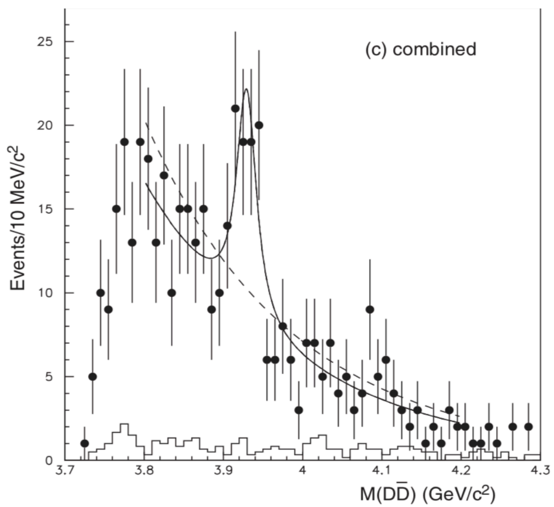
The $\chi_{c0}(2P)[\chi_{c2}(2P)]$ is expected to decay strongly to $D\bar{D}$ in an S-wave.
A large width of $\mathcal{T} \geq 100$MeV

PRL 94, 182002 (2005)

- The charmoniumlike state X(3915) was observed in $B \to J/\psi\omega K$ decays
- - ***But*** this process (X(3915) $\to J/\psi\omega$) belongs to Okubo-Zweig-Iizuka (OZI) suppression process
- - $\mathcal{T}$ of X(3915) (~20MeV) seems too small
- - X(3915) is no longer identified as the $\chi_{c0}(2P)$ candidate in PDG 2016

- Possible $\chi_{c2}(2P)$ candidates was observed in $\gamma\gamma \to D\bar{D}$. This charmonium state with M = (3838 $\pm$ 12MeV), $\mathcal{T}$ = (211 $\pm$ 19)MeV

PRL 96, 082003 (2006)



In Ref.[*PRD 86, 091501(2012)*], the authors show that there is an indication of the $\chi_{c0}(2P)$ with a mass around 3840 MeV and width of about 200 MeV.

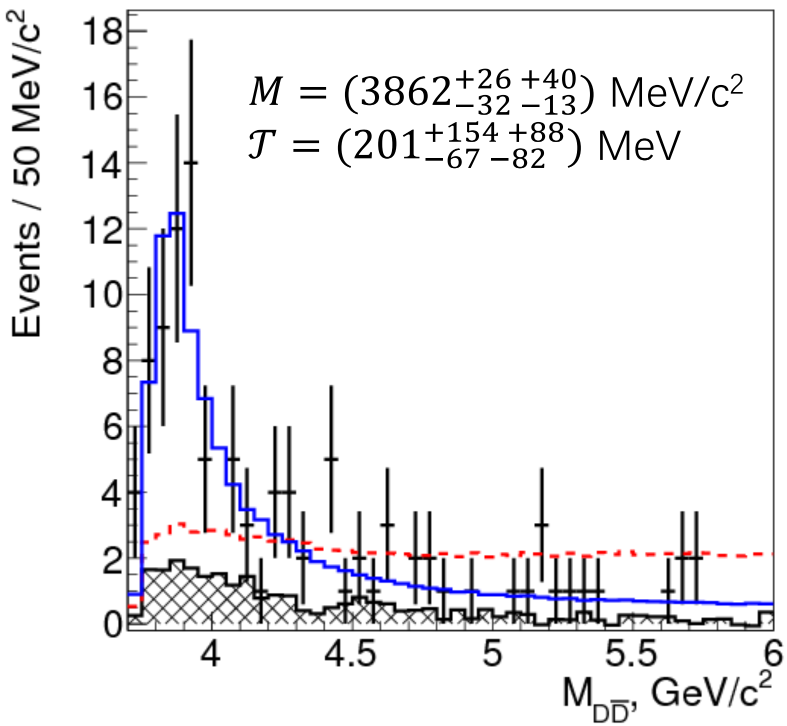
An updated analysis of $e^+e^- \to J/\psi D\bar{D}$

PRD 95, 112003 (2017)

Compared to previous analysis of $e^+e^- \to J/\psi D\bar{D}$ [*PRL 100, 202001 (2008)*]:

1. the integrated luminosity is **1.4 times** greater than before
2. apply **multivariate method** improve the discrimination of signal and background
3. **amplitude analysis** study the J^{PC} quantum numbers of the $D\bar{D}$ system

A alternative $\chi_{c0}(2P)$ candidate



- Points with error bars represent data
- The blue solid line is the fit results with new resonance ($J^{PC}=0^{++}$)
- The red dashed line is the fit with nonresonant amplitude
- The hatched histogram are the background

A two-dimensional ($M_{J/\psi}$, M_D) sideband as background

Energy, GeV	$\sigma^{(Born)}_{e^+e^-\to J/\psi X^*(3860)(\to D\bar{D})}$, (fb)
10.58	$21.7^{+3.9}_{-4.3}{}^{+2.9}_{-2.1}$
10.87	$17.9^{+7.2}_{-7.3}{}^{+2.4}_{-1.8}$

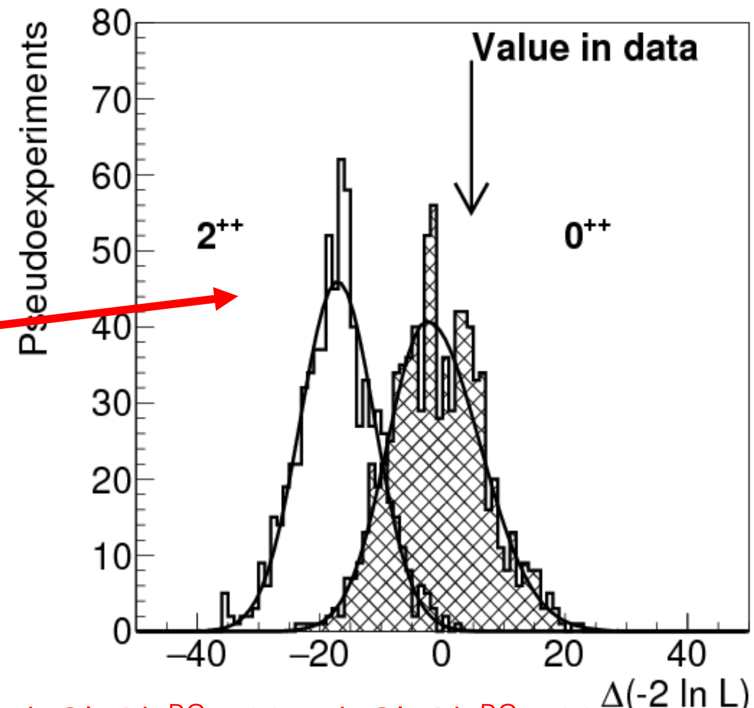
Comparison of J^{PC} hypotheses

- The X(3860) quantum-number hypotheses $J^{PC}=0^{++}$ and 2^{++} are compared using MC simulation.

PRD 95, 112003 (2017)

Default mode: a new resonance X(3860) in the $D\bar{D}$ system with $J^{PC}=0^{++}$ or 2^{++} + nonresonant amplitude

Model	2^{++} exclusion	0^{++} C.L.
Default (constant nonresonant)	3.8σ	77%
NRQCD nonresonant	3.4σ	73%
$M_{D\bar{D}}^{-4}$ nonresonant	3.6σ	70%
Background mass calculation	3.8σ	75%
Optimization ($a = 4$)	3.3σ	69%
Optimization ($a = 6$)	3.4σ	64%
Free r	2.5σ	74%



$(-2\ln L)_{J^{PC}=2^{++}} - (-2\ln L)_{J^{PC}=0^{++}}$

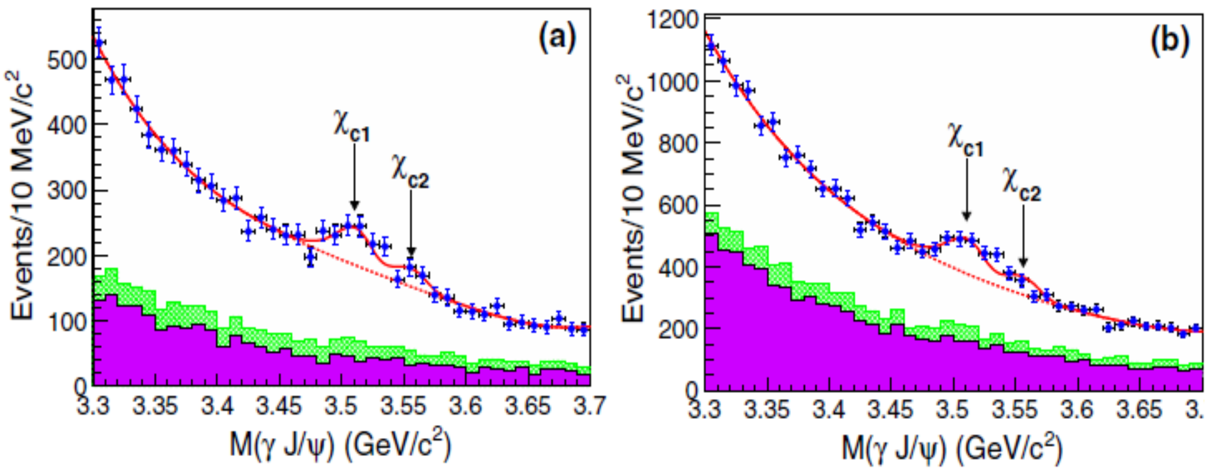
χ_{c1}(1P) in $\Upsilon(1S,2S)$ inclusive decays

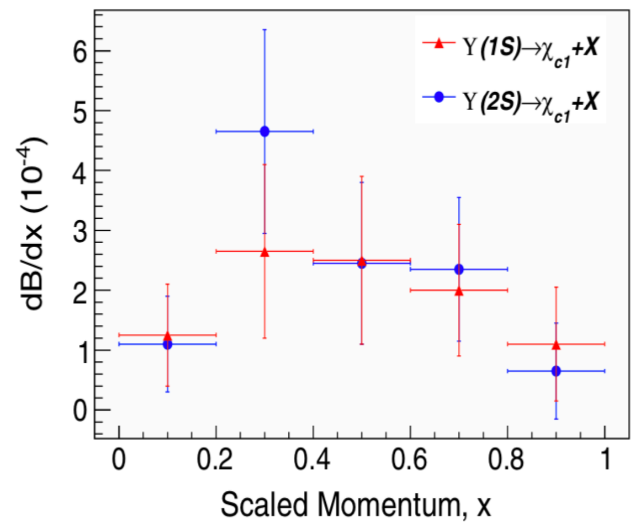
PRD 95, 012001 (2017)

- Original aim: search for 0^{--} glueballs in Υ(1S,2S)→$\chi_{c1}+G_{0^{--}}$
- Partition the data samples according to the scaled momentum to correct the efficiency

$$x = \frac{p^*_{\chi_{c1}}}{\frac{1}{2\sqrt{s}}\times(s - m^2_{\chi_{c1}})}$$

The differential BR





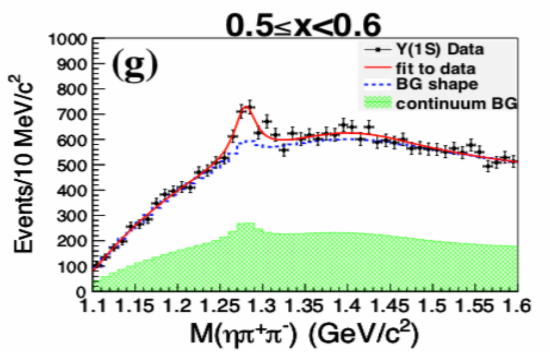
Mode	$BR(\times10^{-4})$	Comments
$\Upsilon(1S)\longrightarrow\chi_{c1}+anything$	$1.90\pm0.43\pm0.14$	*with an improved precision*
$\Upsilon(2S)\longrightarrow\chi_{c1}+anything$	$2.24\pm0.44\pm0.20$	*for the first time*

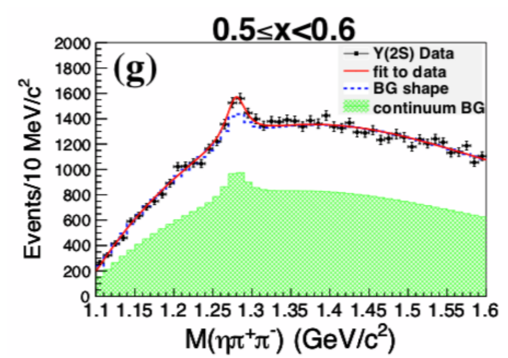
$\Upsilon(1S,2S) \to f_1(1285)$+X and $\chi_{bJ} \to J/\psi$+X

- Original aim: search for light tetraquarks in $\Upsilon(1S,2S) \to f_1(1285)+X_{tetra}$ and $\chi_{bJ} \to J/\psi+X_{tetra}$

PRD 96, 112002 (2017)

- Clear $f_1(1285)$ signal in $\Upsilon(1S,2S)$ inclusive decays
- Partition the data samples according to the scaled momentum

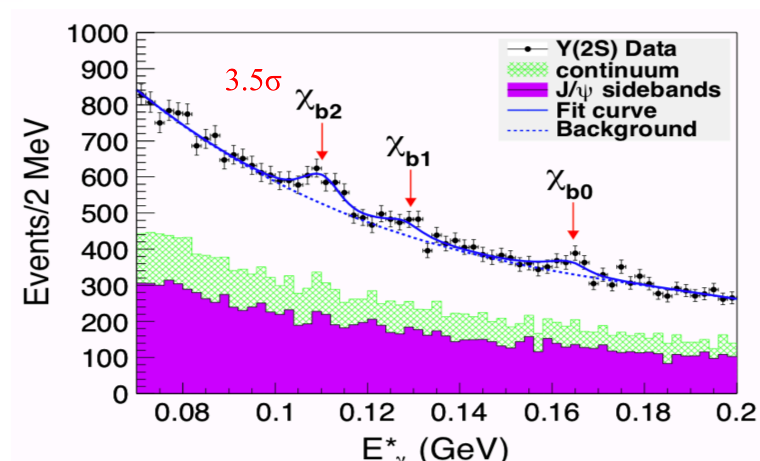




Mode	$BR(\times 10^{-4})$
$\Upsilon(1S) \longrightarrow f_1(1285) + \text{anything}$	$46 \pm 28 \pm 13$
$\Upsilon(2S) \longrightarrow f_1(1285) + \text{anything}$	$22 \pm 15 \pm 6.3$

- J/ψ production in χ_{bJ} (J = 0, 1, 2) decays

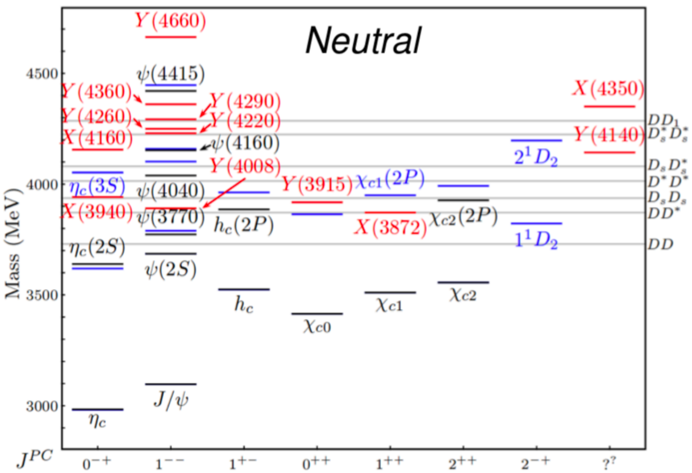
Mode	$BR(\times 10^{-3})$
$\chi_{b2} \longrightarrow J/\psi + \text{anything}$	$1.5 \pm 0.34 \pm 0.22$
$\chi_{b1} \longrightarrow J/\psi + \text{anything}$	1.1 at 90% C.L.
$\chi_{b0} \longrightarrow J/\psi + \text{anything}$	2.3 at 90% C.L.

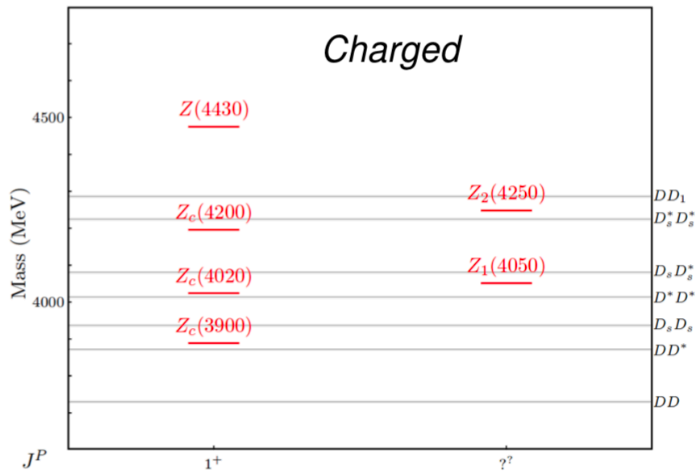


S. Jia, DIS 2018

Discovery of Charmonium-like and Bottomonium-like states

In the last 10 years we saw an explosion of new states populating the quarkonium spectrum….



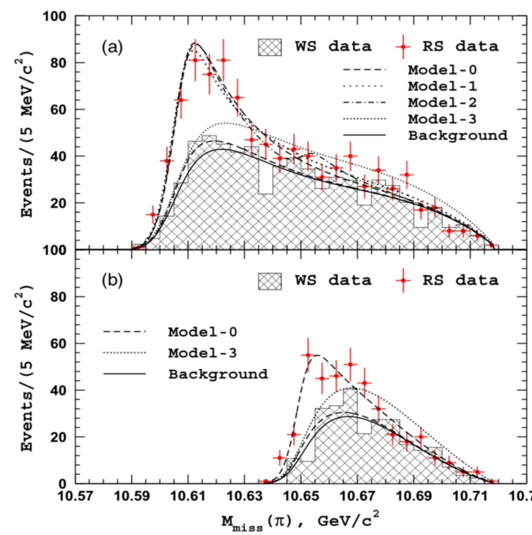


Many explanations

- Molecules
- Tetraquarks
- CUSP effect
- Rescattering
- Hybrids
- Hadroquarkonia

Bottomonium-like: Z_b states

State	Mode	Reference
$Z_b^{\pm}(10610)$	$\Upsilon(5S) \to h_b(mP)\,\pi^+\pi^-$	
$Z_b^{\pm}(10650)$	$\Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-$ $e^+e^- \to \pi\, B^{(*)}\bar{B}^*$	PRL 108, 122001 (2012) PRL 116, 212001 (2016)
$Z_b^{0}(10610)$	$\Upsilon(5S) \to \Upsilon(nS)\,\pi^0\pi^0$	PRD 88, 052016 (2013)



Measurements of $B^+ \to X_{c\bar{c}} K^+$

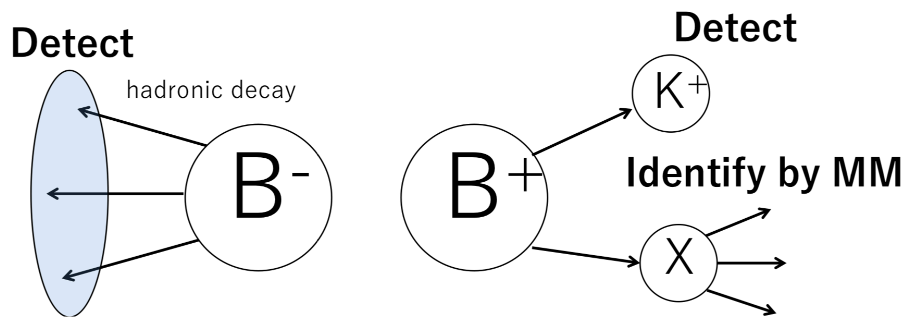
PRD 97, 012005 (2018)

- To determine absolute branching fraction $\mathcal{B}(B^+ \to X(3872)K^+)$
- Simultaneously measure the $\mathcal{B}(B^+ \to X_{c\bar{c}} K^+)$, where $X_{c\bar{c}}$ is η_c, J/ψ, χ_{c0}, χ_{c1}, η_c(2S), ψ(2S), $\psi(3770)$

Analysis method:

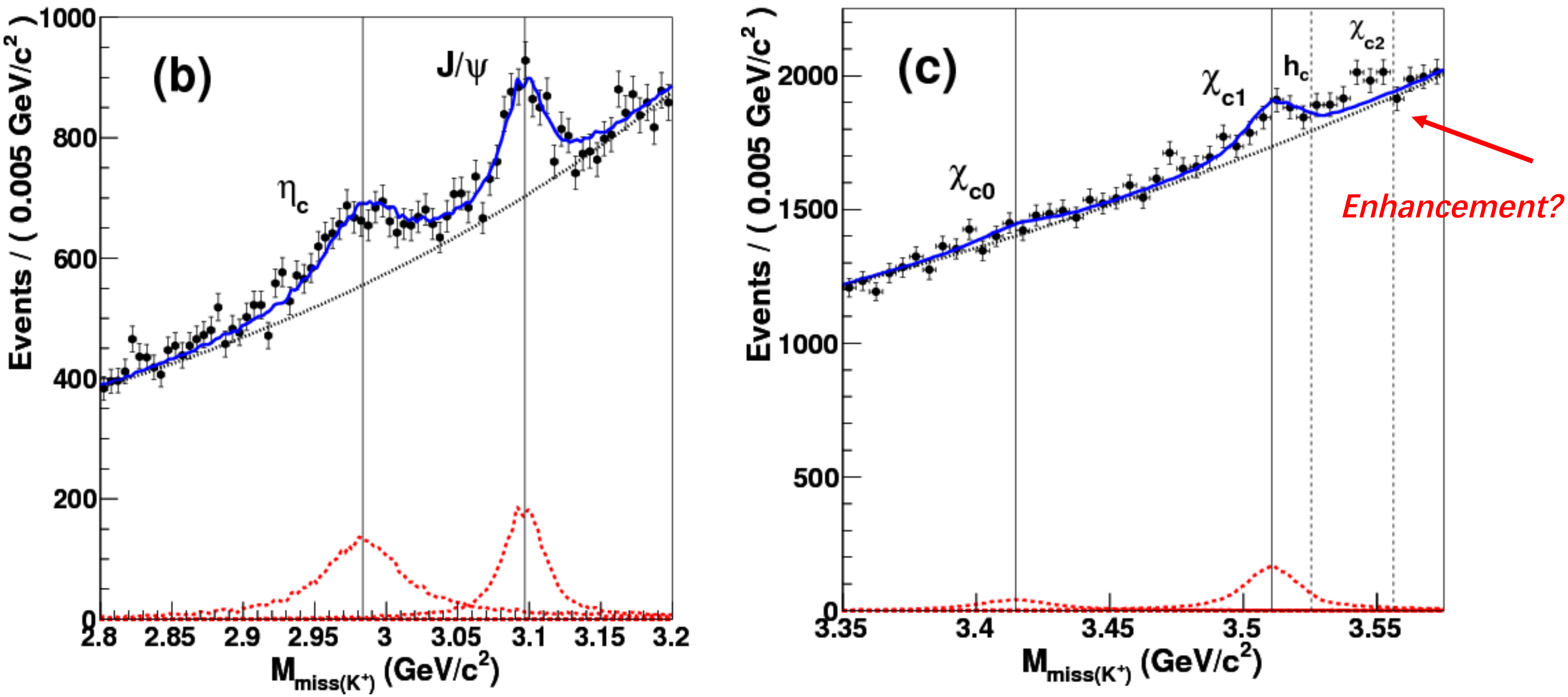
- Fully reconstruct one of the two charged B mesons (B_{tag})
- NeuroBayes neural-network used to suppress continuum events
- Identify the signal as a peak at the nominal $X_{c\bar{c}}$ mass in

$$M_{miss}(K^+) = \sqrt{(p^*_{e^+e^-} - p^*_{tag} - p^*_h)^2/c}$$



Measurements of $B^+ \to X_{c\bar{c}}K^+$

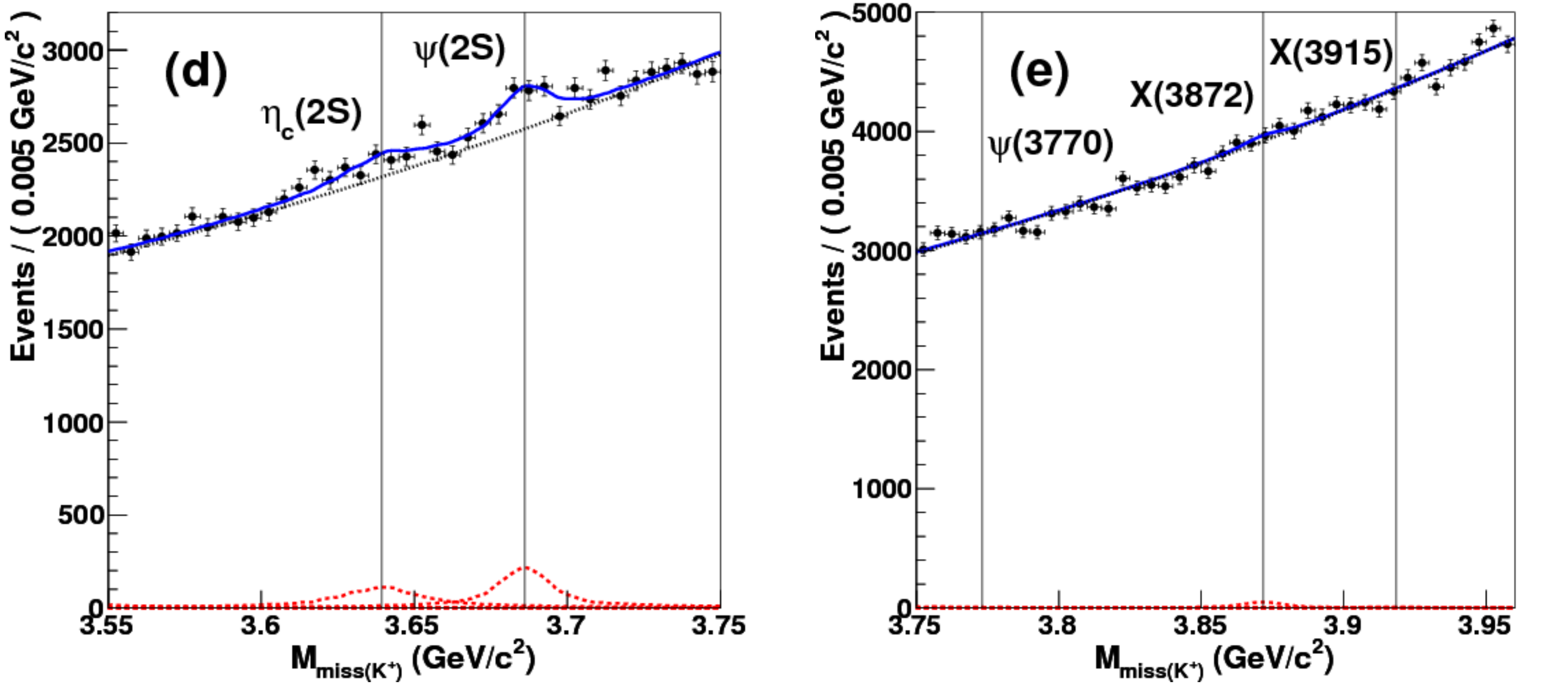
PRD 97, 012005 (2018)



Mode	Significance (σ)	$\mathcal{B}$ (10^{-4})	PDG results for $\mathcal{B}$ (10^{-4})	Comments
η_c	14.2	12.3±0.8±0.7	9.6±1.1	more precise
J/ψ	13.7	9.1±0.7±0.5	10.26±0.031	-
χ_{c0}	2.2	2.1±0.9±0.1 (<3.4)	$1.50^{+0.15}_{-0.14}$	
χ_{c1}	6.8	6.0±0.9±0.5	4.79±0.23	

Measurements of $B^+ \to X_{c\bar{c}} K^+$

PRD 97, 012005 (2018)



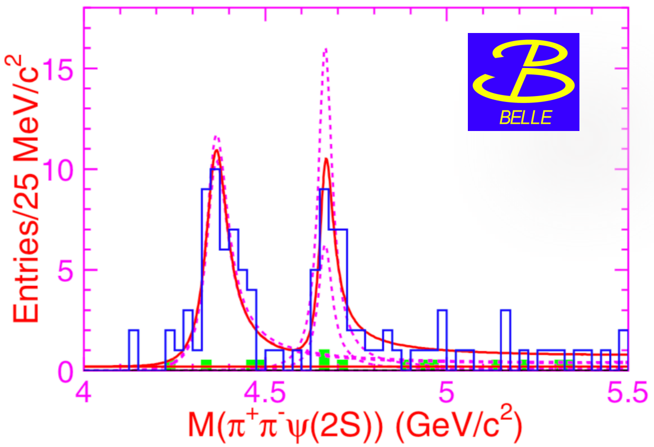
Mode	Significance (σ)	$\mathcal{B}$ (10^{-4})	PDG results for $\mathcal{B}$ (10^{-4})	Comments
η_c(2S)	4.1	4.9±1.1±0.3	3.4±1.8	First significant measurement
ψ(2S)	6.6	6.6±1.0±0.4	6.26±0.24	-
ψ(3770)	-	-0.2±1.4±0.0 (<2.4)	4.9±1.3	
X(3872)	1.1	1.2±1.1±0.1 (<2.7)	(<3.2)	From BABAR: ~0.4σ
X(3915)	0.3	0.4±1.6±0.0 (<2.9)	-	Measurement for the first time

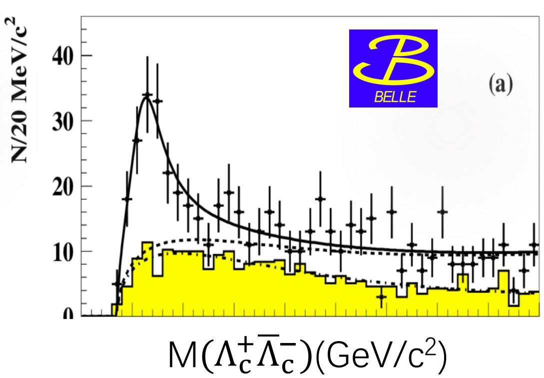
Search for Y(4660) and its spin partner in $B^+ \to K^+ \Lambda_c^+ \bar{\Lambda}_c^-$

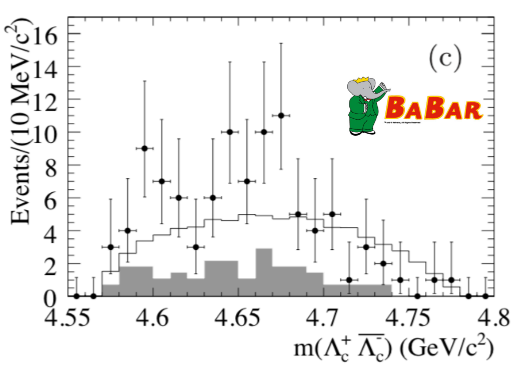
EPJC 78, 252 (2018)

- Belle reported a structure, called X(4630), in the $\Lambda_c^+\bar{\Lambda}_c^-$ invariant mass distribution in $e^+e^- \to \gamma_{ISR}\Lambda_c^+\bar{\Lambda}_c^-$ **PRL 101, 172001 (2008)**
- Y(4660) is observed in the invariant-mass distribution of $\pi^+\pi^-\psi(2S)$ by Belle. **PRL 99, 142002 (2007)**
- BarBar once studied $B^+ \to K^+\Lambda_c^+\bar{\Lambda}_c^-$ and found two small peaks in $M_{\Lambda_c^+\bar{\Lambda}_c^-}$ spectrum. Larger data is needed to verify them. **PRD 101, 172001 (2008)**
- Some theory explained that Y(4660) has a large partial decay width to $\Lambda_c^+\bar{\Lambda}_c^-$ and its isospin partner Y_η is also predicted.

PRD 82, 094008 (2010), PRL 102, 242004 (2009)





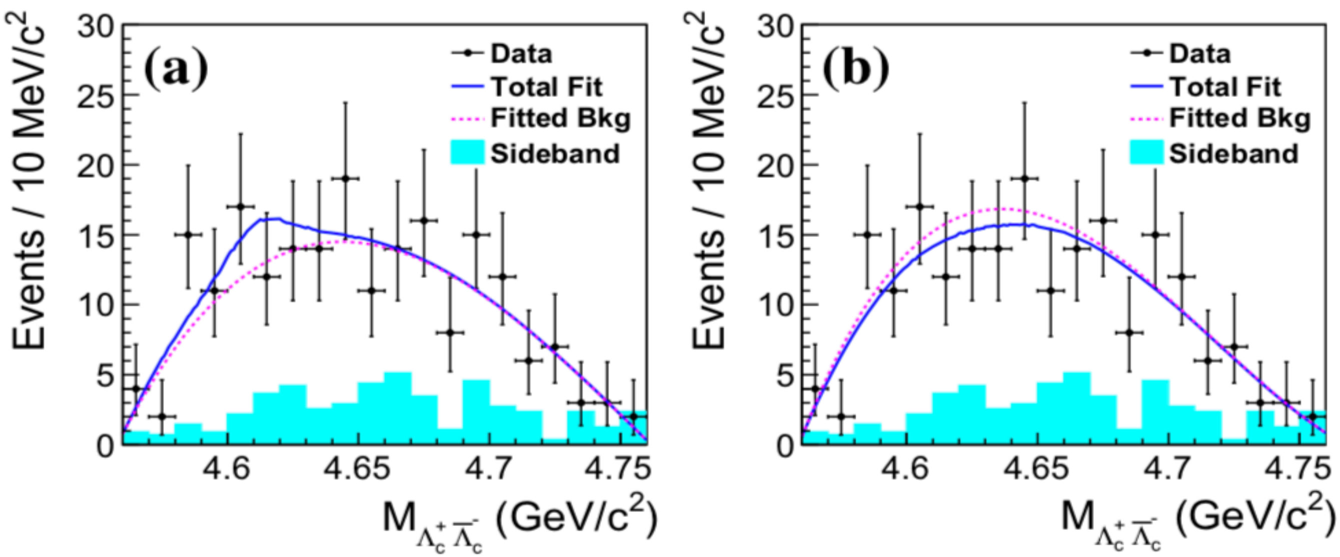


Search for Y(4660) and its spin partner in $B^+ \to K^+\Lambda_c^+\bar{\Lambda}_c^-$

EPJC 78, 252 (2018)

- $\Lambda_c^+ \to pK^-\pi^+, pK_S^0, \Lambda\pi^+, pK_S^0\pi^+\pi^-, \Lambda\pi^+\pi^+\pi^-$
- At least a $\Lambda_c^+(\bar{\Lambda}_c^-)$ candidate that decays to $pK^-\pi^+(\bar{p}K^+\pi^-)$ in combination of $\Lambda_c^+\bar{\Lambda}_c^-$
- One B signal candidate with minimun χ^2_{vertex} in an event

Fit with Y_η signal included — Fit with $Y(4660)$ signal included



Mode	Upper limits of product BR at 90% C.L.
$B^+ \to K^+Y(4660) \to K^+\Lambda_c^+\bar{\Lambda}_c^-$	1.2×10^{-4}
$B^+ \to K^+Y_\eta \to K^+\Lambda_c^+\bar{\Lambda}_c^-$	2.0×10^{-4}

Search for $\Upsilon(1S,2S) \to Z_c^+ Z_c^{(\prime)-}$ and $e^+e^- \to Z_c^+ Z_c^{(\prime)-}$ at $\sqrt{s}$ = 10.52, 10.58, and 10.867 GeV

- The interpretations for Z_c states are ambiguous, including tetraquarks, molecules, hybrids, or hadrocharmonia, etc.

For $e^+e^- \to Z_c^+ Z_c^-$	
$F_{Z_c^+ Z_c^-} \sim \frac{1}{s^3}$	tetraquark structure
$F_{Z_c^+ Z_c^-} \sim \frac{1}{s}$	two tightly bound diquarks

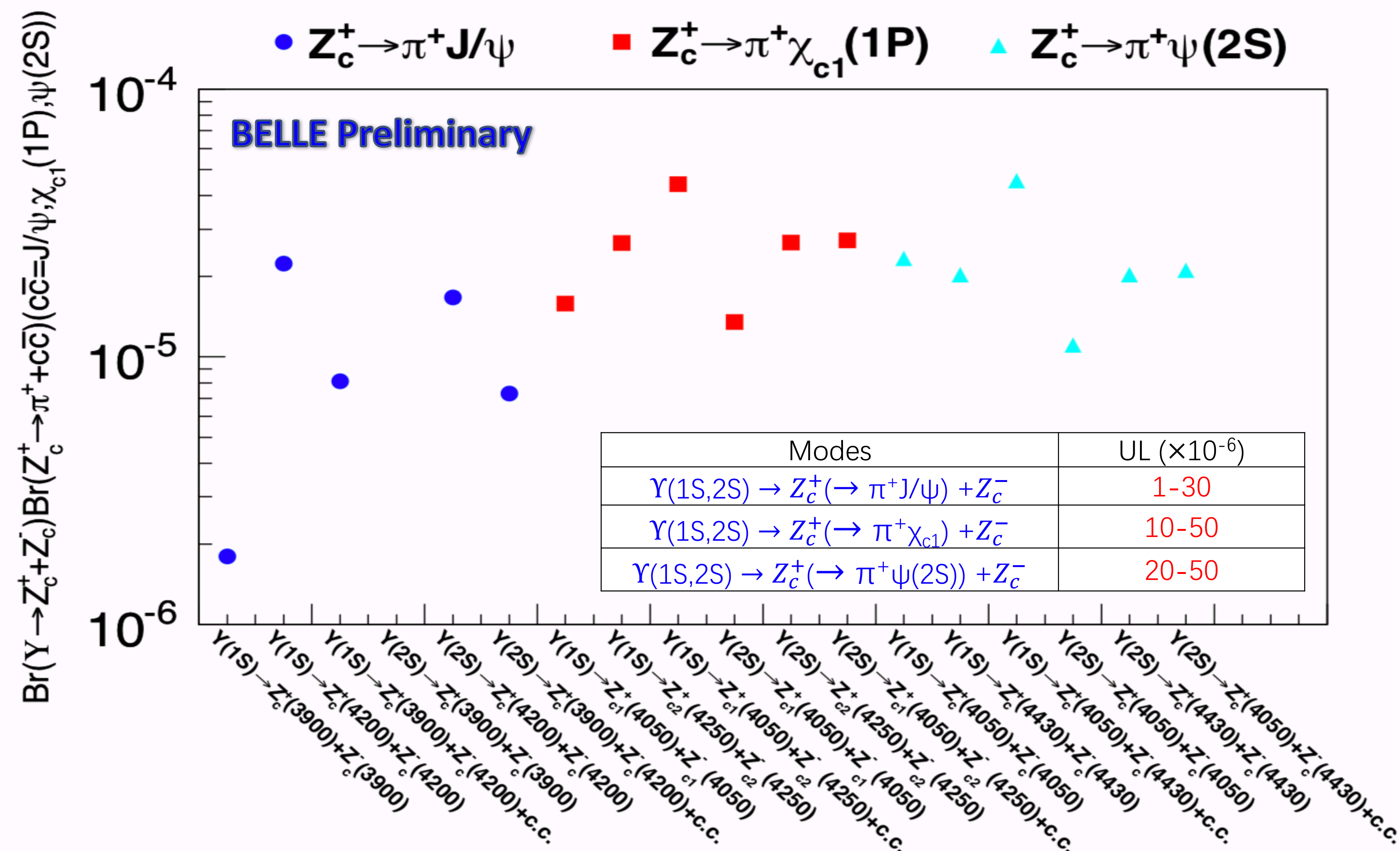
PLB 764, 174 (2017)
PRD 91, 114025(2015)

- In this analysis, this below modes are included

States	Studied channels
$Z_c(3900)/Z_c(4200) \to \pi^+ J/\psi$	$\Upsilon(1S,2S)$ /$e^+e^- \to Z_c(3900)+Z_c(3900)$, $Z_c(4200)/Z_c(4200)$, $Z_c(3900)/Z_c(4200)$
$Z_{c1}(4050)/Z_{c2}(4250) \to \pi^+\chi_{c1}$	$\Upsilon(1S,2S)$ /$e^+e^- \to Z_{c1}(4050) + Z_{c2}(4250)$, $Z_{c1}(4250) + Z_{c2}(4250)$, $Z_{c1}(4050) + Z_{c2}(4250)$
$Z_c(4050)/Z_c(4430) \to \pi^+\psi(2S)$	$\Upsilon(1S,2S)$ /$e^+e^- \to Z_c(4050) + Z_c(4430)$, $Z_c(4050) + Z_c(4430)$, $Z_c(4050) + Z_c(4430)$

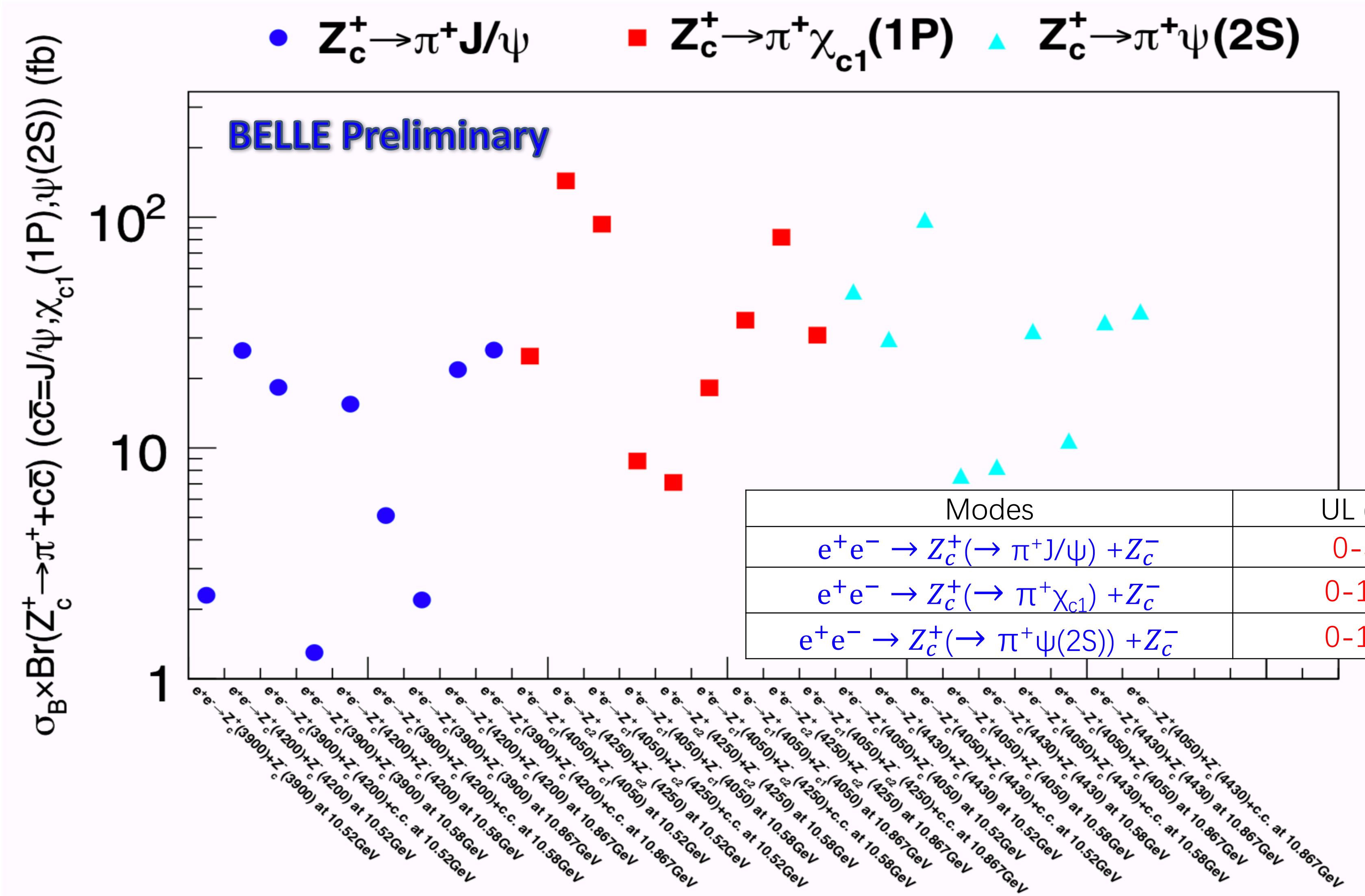
- For the Z_c pair in one event, one Z_c decays into π^+J/ψ, $\pi^+\chi_{c1}$, $\pi^+\psi(2S)$, the other is the inclusive decays.
- No clear signals are observed and 90% C.L. upper limits are obtained.

$\Upsilon(1S,2S) \rightarrow Z_c^+ Z_c^{(\prime)-}$



Modes	UL ($\times 10^{-6}$)
$\Upsilon(1S,2S) \rightarrow Z_c^+(\rightarrow \pi^+ J/\psi) + Z_c^-$	1-30
$\Upsilon(1S,2S) \rightarrow Z_c^+(\rightarrow \pi^+ \chi_{c1}) + Z_c^-$	10-50
$\Upsilon(1S,2S) \rightarrow Z_c^+(\rightarrow \pi^+ \psi(2S)) + Z_c^-$	20-50

$e^+e^- \to Z_c^+ Z_c^{(\prime)-}$ at $\sqrt{s}$ = 10.52, 10.58, and 10.867 GeV



Modes	UL (fb)
$e^+e^- \to Z_c^+(\to \pi^+ J/\psi) + Z_c^-$	0-30
$e^+e^- \to Z_c^+(\to \pi^+ \chi_{c1}) + Z_c^-$	0-150
$e^+e^- \to Z_c^+(\to \pi^+ \psi(2S)) + Z_c^-$	0-100

Summary

- Belle data taking is over, but still actively publishing results. Many interesting results are from the studies of Quarkonium and Quarkonium-like States.
  - ✓ Confirmation of the enhancement of $\Upsilon(4S) \to \eta\Upsilon(1S)$ with respect to $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$
  - ✓ First observation of $\Upsilon(4S) \to \eta'\Upsilon(1S)$ and $\Upsilon(5S) \to \eta\Upsilon_J(1D)$
  - ✓ Update the measurement for $\mathcal{B}(B^+ \to X(3872)K^+)$
  - ✓ Search for Y(4660) and Y_η in $B^+ \to K^+\Lambda_c^+\bar{\Lambda}_c^-$
  - ✓ Measurement of double Z_c production in e^+e^- reactions

- More promising results are expected at Belle II, where 50 times more statistics than Belle.
  - ✓ Investigate bottomonium spectroscopy, understand exotic states, and more…

BELLE → ***More opportunities*** → Belle II

Backup

Investigations on the Υ(1D) triplet

arXiv:1803.03225, submitted to EPJC

$$\mathcal{F}_{1D} = \frac{N_{1D}}{1+f_1+f_2} \cdot [\mathcal{C}_2(m_2) + f_1\mathcal{C}_1(m_1) + f_3\mathcal{C}_3(m_3)], \quad (2)$$

with

$$f_1 = \frac{\mathcal{B}[\Upsilon(5S) \to \eta\Upsilon(1D_1)]}{\mathcal{B}[\Upsilon(5S) \to \eta\Upsilon(1D)_2]} (= 0.68)_{theory} \quad (3)$$

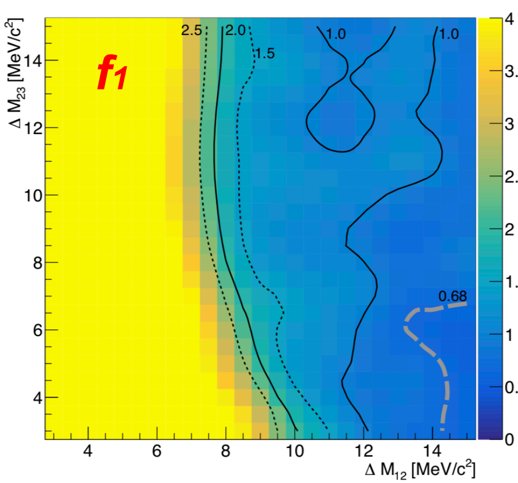
$$f_3 = \frac{\Upsilon(5S) \to \eta\Upsilon(1D_3)}{\mathcal{B}[\Upsilon(5S) \to \eta\Upsilon(1D_2)]} (= 0.13)_{theory} \quad (4)$$

Signal in $M^2_{miss}(\gamma\gamma)$: 3 Crystal Ball functions, with free miss relative fractions f_1,f_3 that are precisely predicted in Ref.[***PRD94, 094039(2016)***]

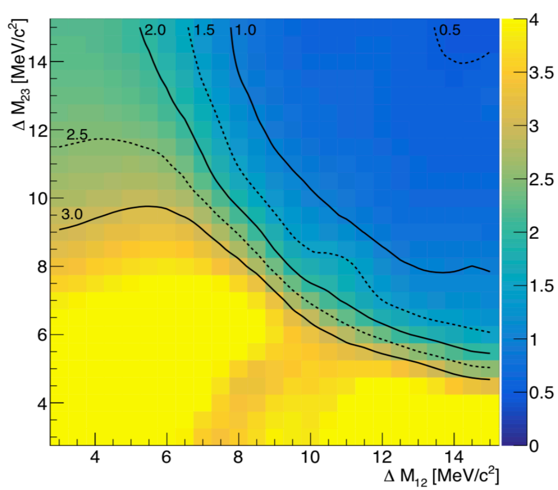
m_2 fixed to world average, ΔM_{ij} fixed to different values between 3 and 15 MeV/c^2 (reasonable according to calculations and observations)

$\Delta M_{12} = m_2 - m_1$, $\Delta M_{23} = m_3 - m_2$

90% CL ULs on f_1, f_3 as a function of ΔM_{12} and ΔM_{23}

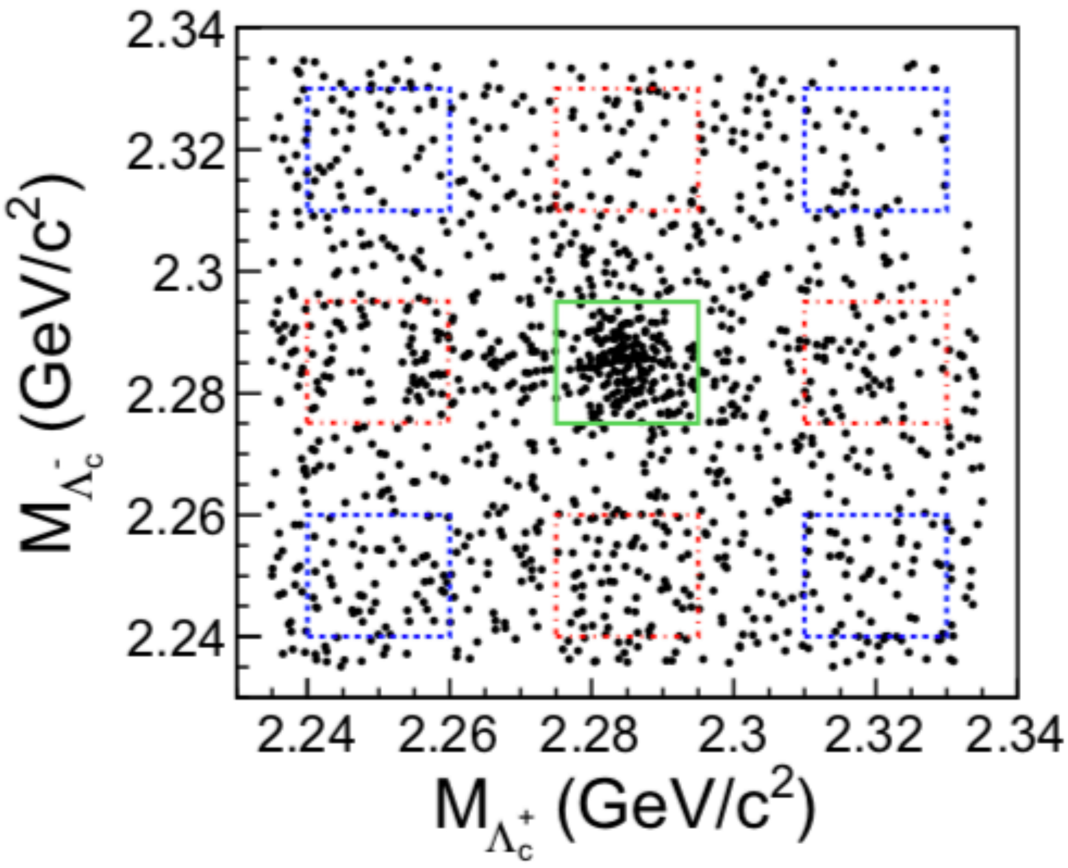


f3



Sideband determination

EPJC 78, 252 (2018)

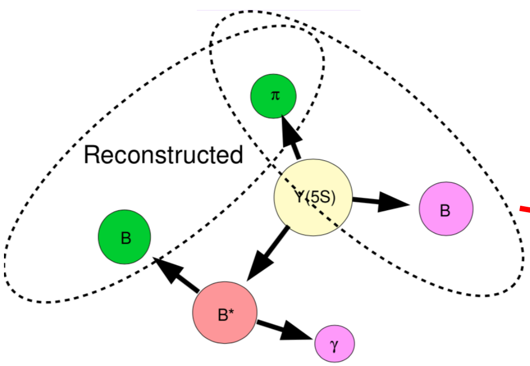


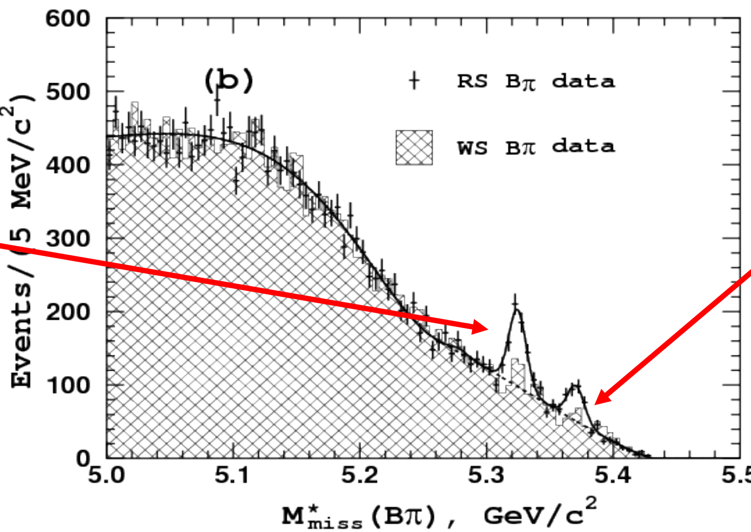
½ red sidebands - ¼ blue sidebands

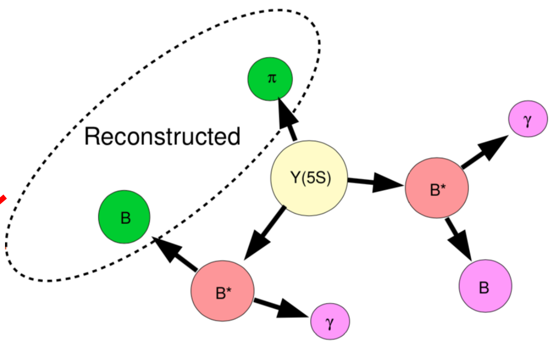
Analysis method for Z_b in $B^{(*)}\bar{B}^*$ systems

PRL 116, 212001 (2016)

- We expect the Z_b states to decay to final states with $B^{(*)}$ mesons at substantial rates.
- Three-body $e^+e^- \to B^+\bar{B}^0\pi^-, B^+\bar{B}^{*0}\pi^-$, and $B^{*+}\bar{B}^{*0}\pi^-$ processes near $\Upsilon(10860)$ peak.
- B mesons are reconstructed in the following decay channel: $B^+ \to J/\psi K^{(*)+}$, $B^+ \to \bar{D}^{(*)0}\pi^+$, $B^0 \to J/\psi K^{(*)0}$, $B^0 \to D^{(*)-}\pi^+$







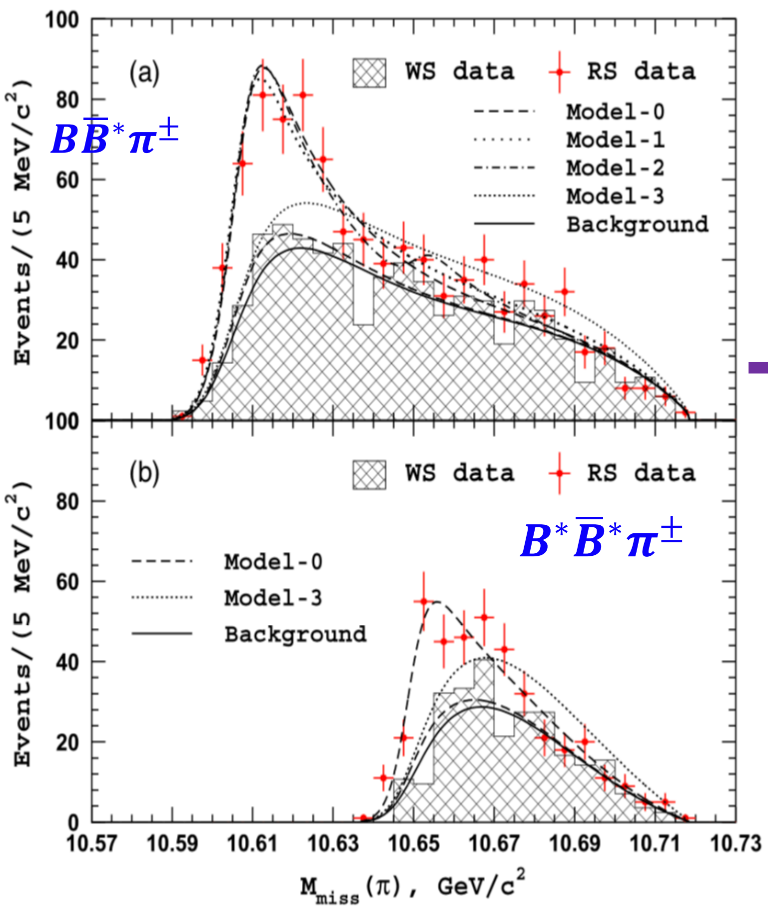
RS(right-sign): B^+ or $\bar{B}^0$combined with π^-
WS(wrong-sign): combinations with π^+

The statistical significance of the observed $BB^*\pi$ and $B^*B^*\pi$ is 9.3σ and 8.1σ.

$Z_b(10610)$ and $Z_b(10650)$ in $B\bar{B}^*$ and $B^*\bar{B}^*$ systems

PRL 116, 212001 (2016)

Model-0 only $Z_b(10610)[Z_b(10650)]$ amplitude ***Model-1*** add a nonresonant component
Model-2 add combination of two Z_b amplitudes ***Model-3*** a pure nonresonant amplitude



Significance in Mode-0	
$Z_b(10610)$	8.0 σ
$Z_b(10650)$	6.8 σ

Z_b parameters with *mode-0*

Sample	State	Mass(MeV/c²)	Width(MeV/c)
$B\bar{B}^*\pi^\pm$	$Z_b(10610)$	10605 ± 6	25 ± 7
$B^*\bar{B}^*\pi^\pm$	$Z_b(10650)$	10648 ± 13	23 ± 8

$$\frac{\mathcal{B}[Z_b^+(10610) \to \bar{B}^0 B^{*+} + B^+\bar{B}^{*0}]}{\mathcal{B}[Z_b^+(10610) \to bottomonium]} = 5.93^{+0.99\,+1.01}_{-0.69\,-0.73}$$

$$\frac{\mathcal{B}[Z_b^+(10650) \to B^{*+}\bar{B}^{*0}]}{\mathcal{B}[Z_b^+(10650) \to bottomonium]} = 2.80^{+0.69\,+0.54}_{-0.40\,-0.36}$$

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.54^{+0.16+0.11}_{-0.13-0.08}$	$0.17^{+0.07+0.03}_{-0.06-0.02}$
$\Upsilon(2S)\pi^+$	$3.62^{+0.76+0.79}_{-0.59-0.53}$	$1.39^{+0.48+0.34}_{-0.38-0.23}$
$\Upsilon(3S)\pi^+$	$2.15^{+0.55+0.60}_{-0.42-0.43}$	$1.63^{+0.53+0.39}_{-0.42-0.28}$
$h_b(1P)\pi^+$	$3.45^{+0.87+0.86}_{-0.71-0.63}$	$8.41^{+2.43+1.49}_{-2.12-1.06}$
$h_b(2P)\pi^+$	$4.67^{+1.24+1.18}_{-1.00-0.89}$	$14.7^{+3.2+2.8}_{-2.8-2.3}$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$85.6^{+1.5+1.5}_{-2.0-2.1}$	...
$B^{*+}\bar{B}^{*0}$	...	$73.7^{+3.4+2.7}_{-4.4-3.5}$

S. Jia, DIS 2018