Belle Status and Prospects

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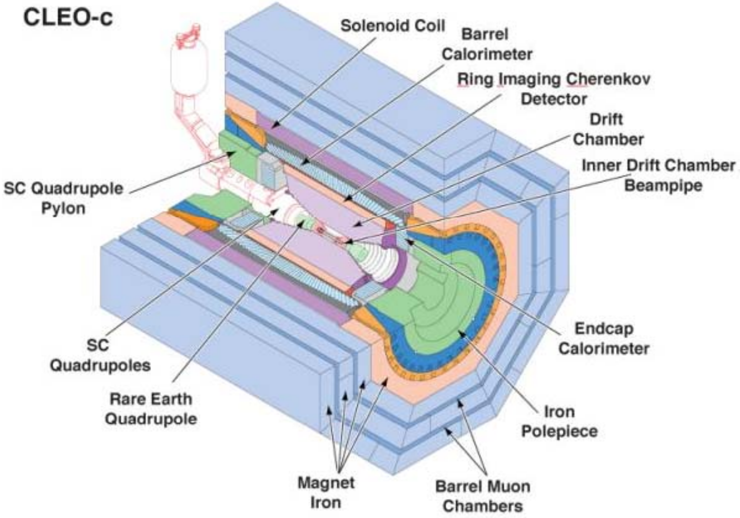
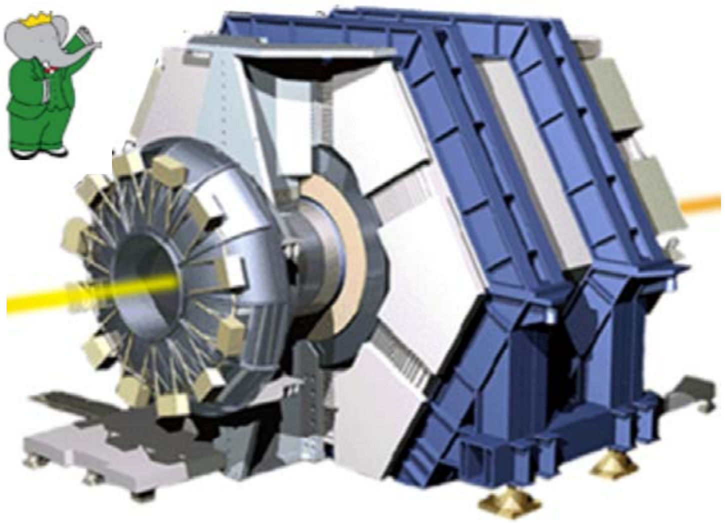
(on behalf of the BELLE collaboration)

- Introduction
- XYZ States @ Belle
- Prospects with Belle II

Main Suppliers of Exotics





E_{cms} = 2.0…4.6 GeV

E_{cms} = 9.46…11.02 GeV

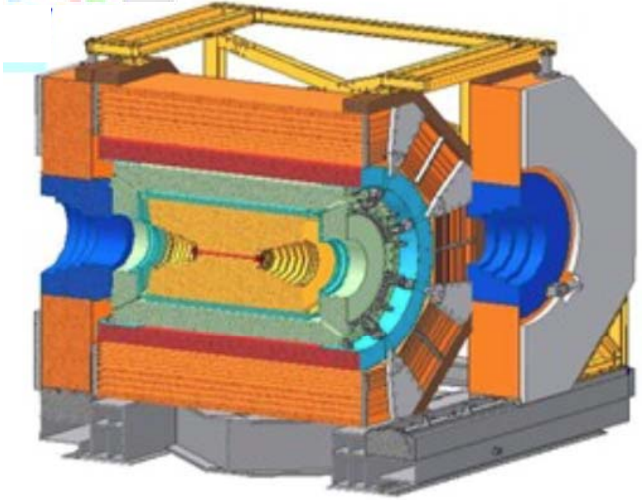
CDF

DØ

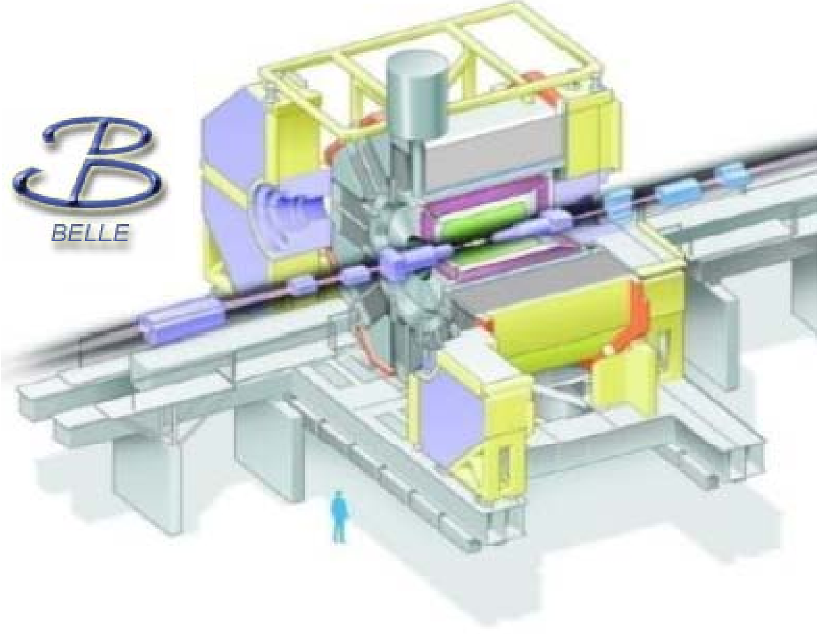
LHCb

CMS

BESIII



BELLE

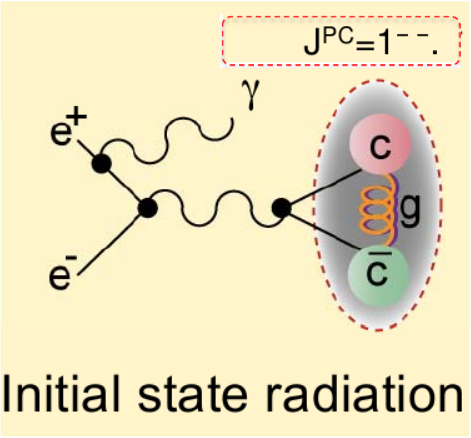


Introduction

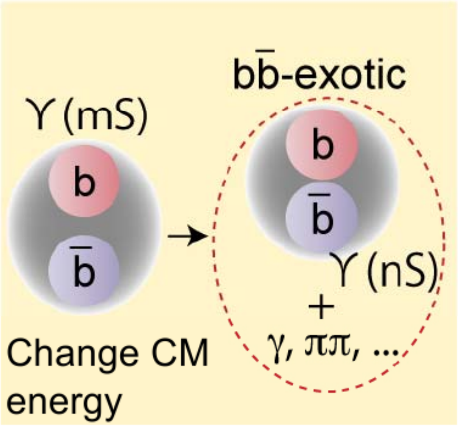
- Recently, PDG switched to a notation scheme common for all new states: X(NNNN), where NNNN is a resonance mass in MeV.

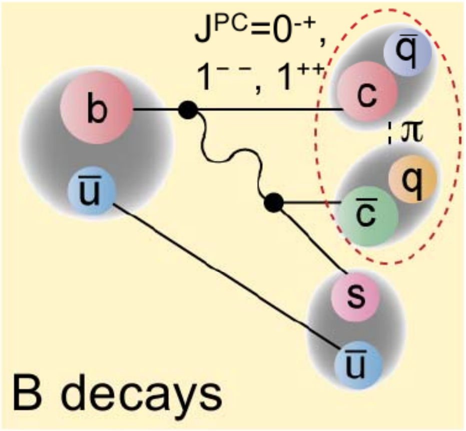
- In this talk I'll stick to an original scheme as it (to some extent) reflects production mechanism for a particular resonance.

Y states ($J^{PC}=1^{--}$)

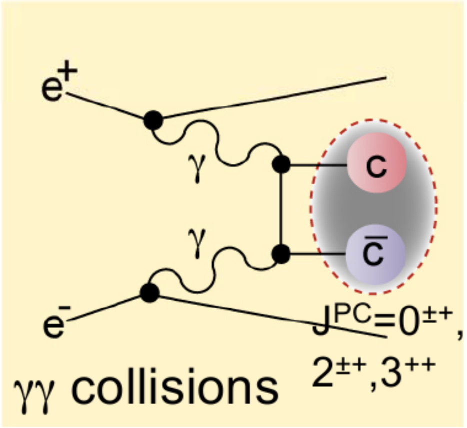


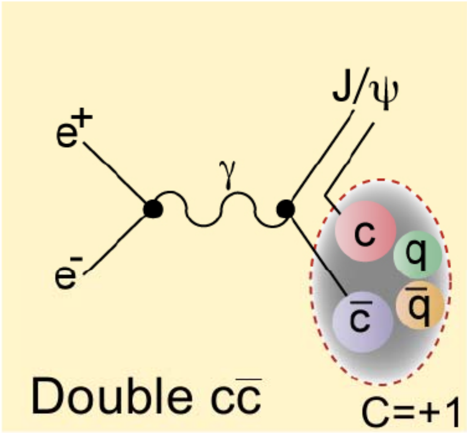
Z states (charged)





X states (all the rest)





X States

X(3872), X(3915) …

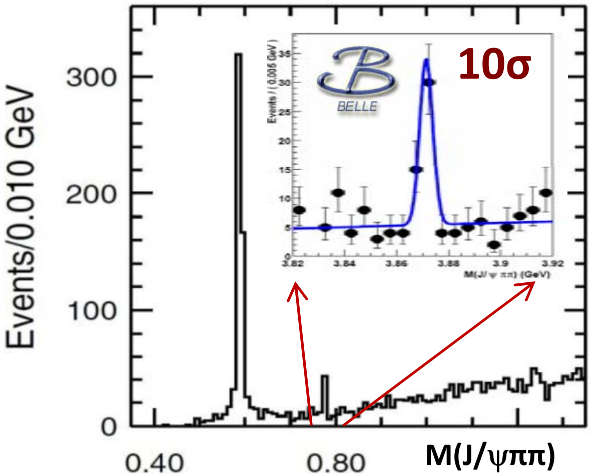
Observed in B decays and (suggestively) in decays of Y type states

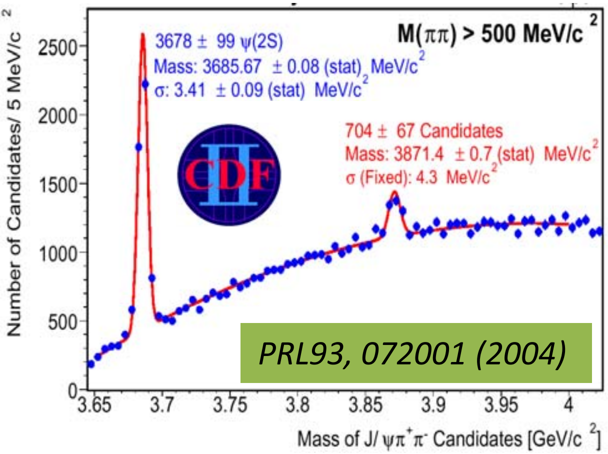
$X(3872) \rightarrow J/\psi \pi^+ \pi^-$

Belle’s most cited paper: ~1300

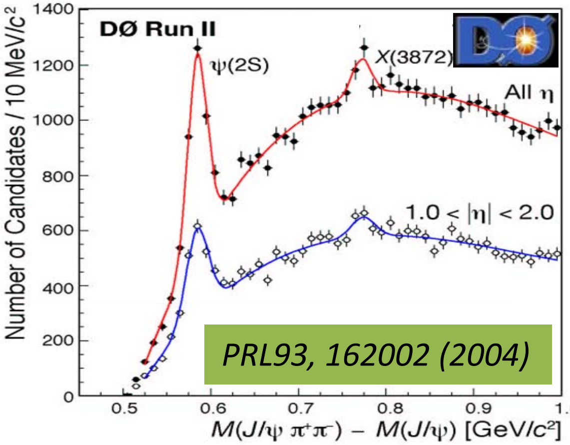
first observed by Belle in $B \rightarrow K\, J/\psi \pi^+ \pi^-$ ***PRL91, 262001 (2003)***

- **M_X close to $D^0 D^{*0}$ threshold M = 3871.68 ± 0.17 MeV (not clear below or above: $\Delta m = -0.16 \pm 0.32$ MeV)**
- **surprisingly narrow: $\Gamma_{tot} < 1.2$ MeV at 90% CL**

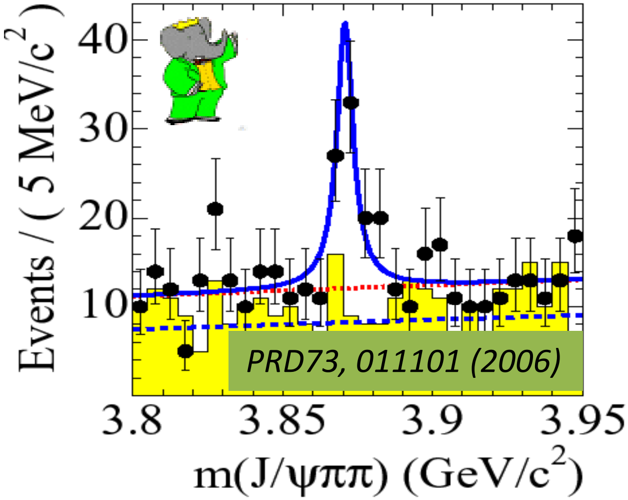




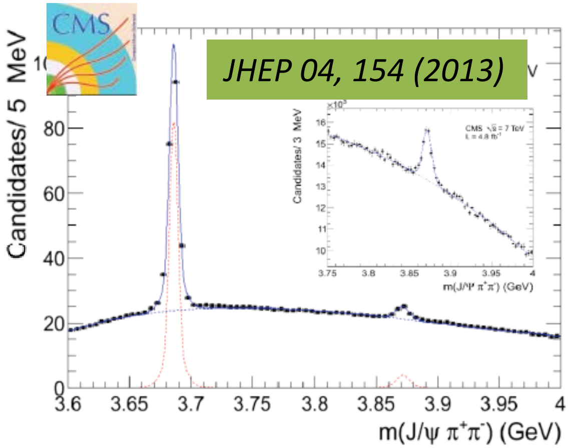
PRL93, 072001 (2004)



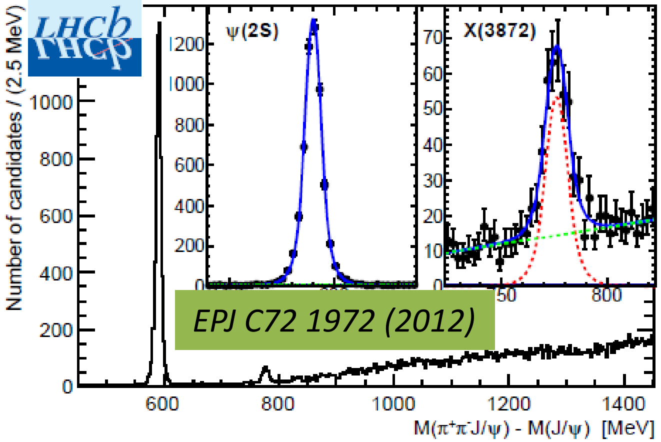
PRL93, 162002 (2004)



PRD73, 011101 (2006)



JHEP 04, 154 (2013)



EPJ C72 1972 (2012)

$X(3872) \rightarrow J/\psi\gamma$: C-even

Angular analysis:

Belle 2006: **$J^{PC} = 1^{++}$ or ≥2**

CDF 2008: **$J^{PC} = 1^{++}$ or 2^{-+}**

Belle 2011: **$J^{PC} = 1^{++}$ or 2^{-+}**

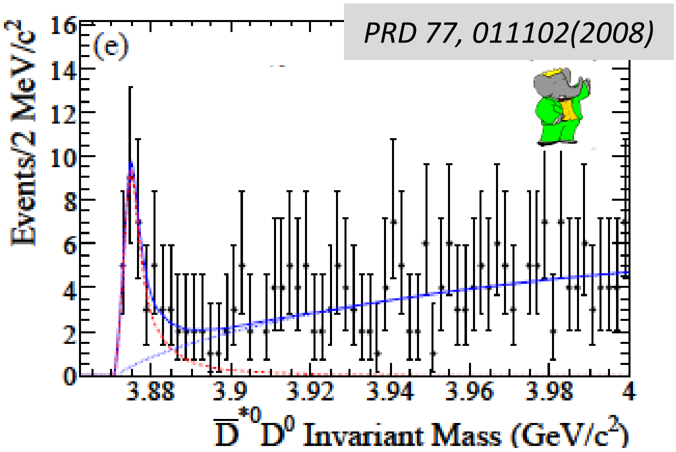
LHCb 2013: **$J^{PC} = 1^{++}$**

X(3872): Other Decay Modes

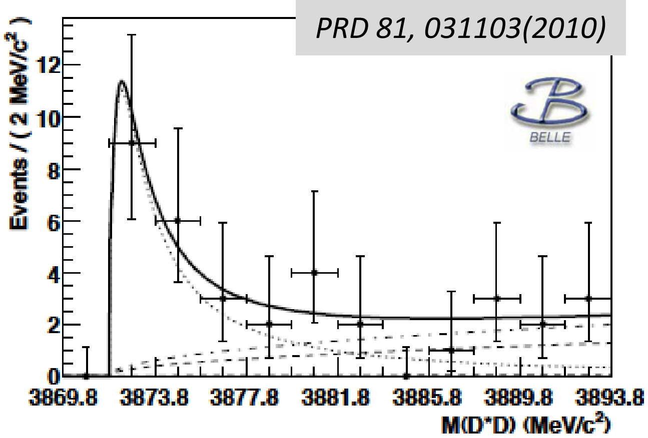
- X(3872)→J/ψρ & X(3872)→J/ψω is seen: isospin violation
  B(X(3872) → J/ψω)/B(X(3872) → J/ψππ)=0.8±0.3

- Radiative decays: Belle&Babar good agreement for X →J/ψγ;
  not consistent for X →ψ(2S)γ.
  LHCb confirms BaBar's not vanishing X →ψ(2S)γ.

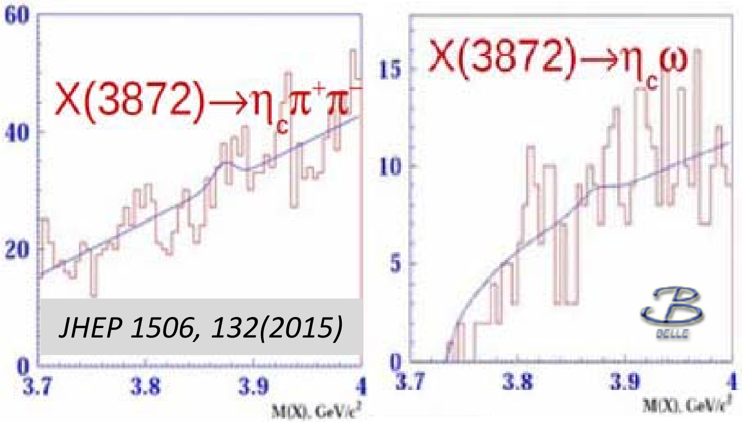
- X(3872) → $D\bar{D}^*$ - dominant mode:
  $B(X(3872) \rightarrow D^0\bar{D}^{*0})/B(X(3872) \rightarrow J/\psi\pi\pi)=8.92\pm2.42$



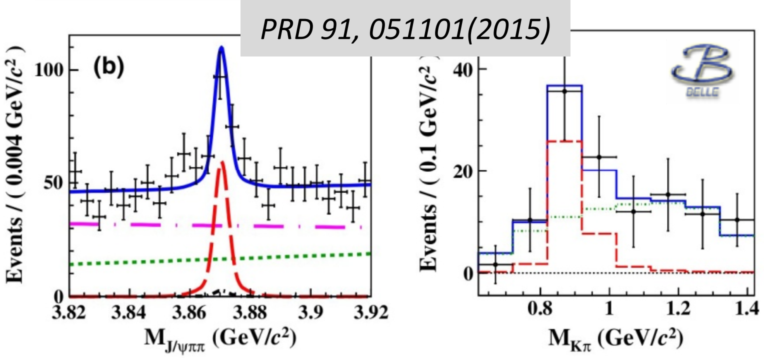
PRD 77, 011102(2008)



PRD 81, 031103(2010)



JHEP 1506, 132(2015)



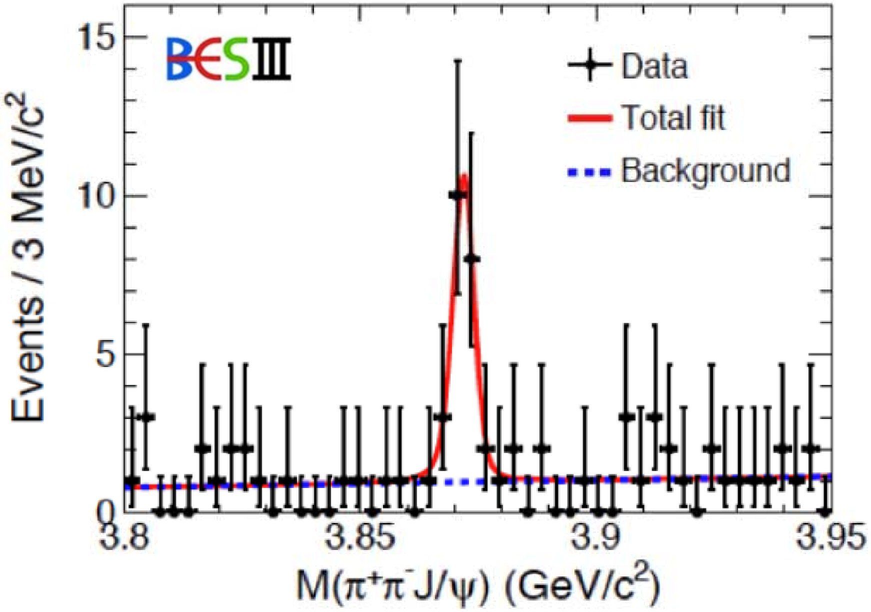
PRD 91, 051101(2015)

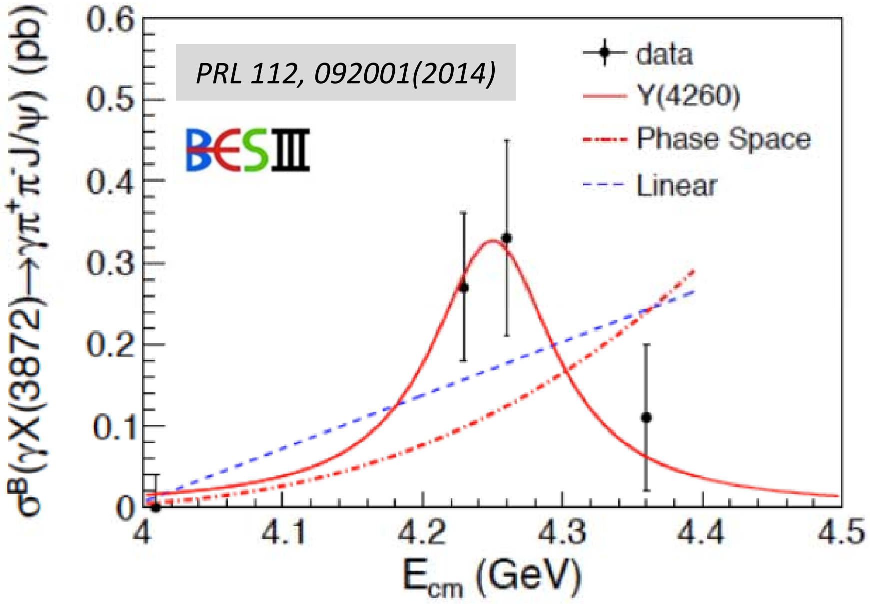
- **X(3872) → η_c ππ/ω no signal found**

- **B→X(3872)Kπ non-resonant Kπ dominates!**

X(3872): Other Production Mechanisms

BESIII measures the X(3872) yield as a function of E_{cms}:

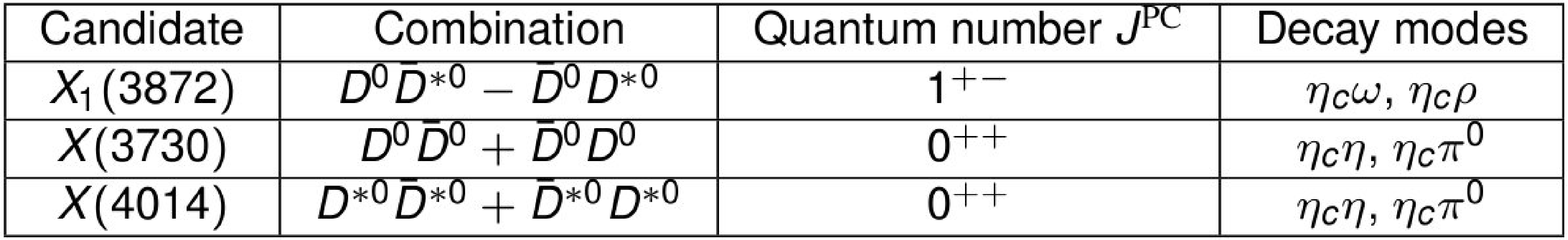



PRL 112, 092001(2014)

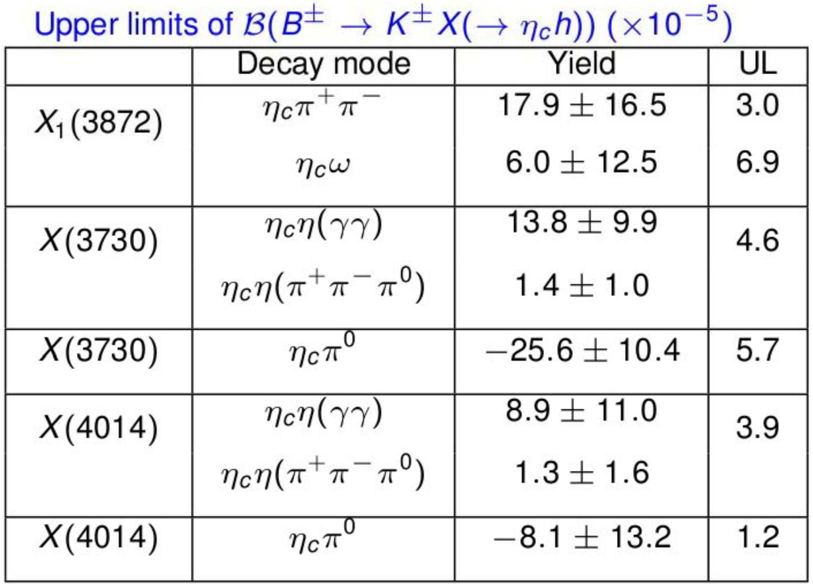
- The first observation of $e^+e^-\to\gamma X(3872)\to\gamma\pi^+\pi^-J/\psi$
- $M = 3871.9\pm0.7\pm0.2$ MeV/c^2, $\Gamma<2.4$ MeV, consistent with Belle's result
- Suggestive of $Y(4260)\to\gamma X(3872)$
- If $B(X(3872)\to\pi^+\pi^-J/\psi) = 5\%$, $\mathcal{R} = \dfrac{Br(e^+e^-\to\gamma X(3872))}{Br(e^+e^-\to\pi^+\pi^-J/\psi)} = 0.1$

X(3872) & Alike

Are there other X-like particles near D(*)D(*) thresholds?

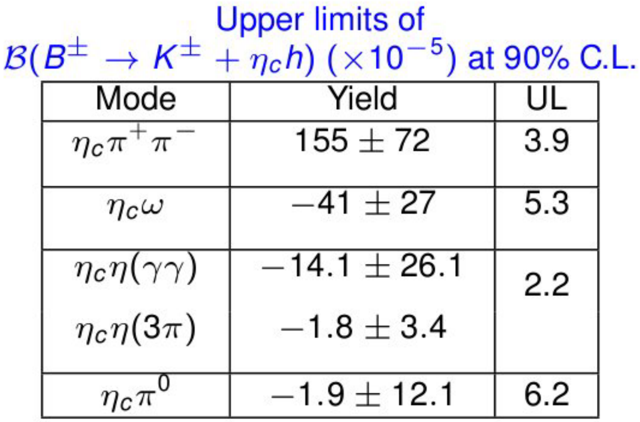


Candidate	Combination	Quantum number J^{PC}	Decay modes
$X_1(3872)$	$D^0\bar{D}^{*0} - \bar{D}^0 D^{*0}$	1^{+-}	$\eta_c\omega$, $\eta_c\rho$
$X(3730)$	$D^0\bar{D}^0 + \bar{D}^0 D^0$	0^{++}	$\eta_c\eta$, $\eta_c\pi^0$
$X(4014)$	$D^{*0}\bar{D}^{*0} + \bar{D}^{*0} D^{*0}$	0^{++}	$\eta_c\eta$, $\eta_c\pi^0$



Upper limits of $\mathcal{B}(B^\pm \to K^\pm X(\to \eta_c h))$ $(\times 10^{-5})$

	Decay mode	Yield	UL
$X_1(3872)$	$\eta_c\pi^+\pi^-$	17.9 ± 16.5	3.0
	$\eta_c\omega$	6.0 ± 12.5	6.9
$X(3730)$	$\eta_c\eta(\gamma\gamma)$	13.8 ± 9.9	4.6
	$\eta_c\eta(\pi^+\pi^-\pi^0)$	1.4 ± 1.0	
$X(3730)$	$\eta_c\pi^0$	-25.6 ± 10.4	5.7
$X(4014)$	$\eta_c\eta(\gamma\gamma)$	8.9 ± 11.0	3.9
	$\eta_c\eta(\pi^+\pi^-\pi^0)$	1.3 ± 1.6	
$X(4014)$	$\eta_c\pi^0$	-8.1 ± 13.2	1.2



Upper limits of
$\mathcal{B}(B^\pm \to K^\pm + \eta_c h)$ $(\times 10^{-5})$ at 90% C.L.

Mode	Yield	UL
$\eta_c\pi^+\pi^-$	155 ± 72	3.9
$\eta_c\omega$	-41 ± 27	5.3
$\eta_c\eta(\gamma\gamma)$	-14.1 ± 26.1	2.2
$\eta_c\eta(3\pi)$	-1.8 ± 3.4	
$\eta_c\pi^0$	-1.9 ± 12.1	6.2

JHEP 1506, 132 (2015)

BELLE

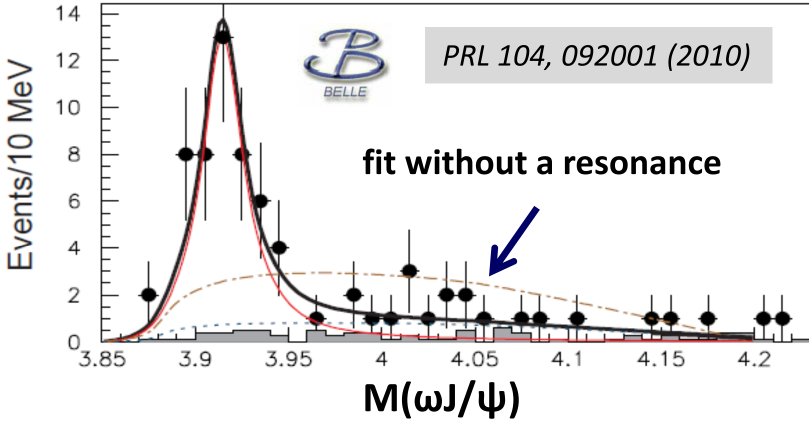
No signal is observed in any of the studied decay channels. The upper limits on their production are set at 90% C.L.

X(3915) [aka Y(3940)]

Observed in B decays and in γγ

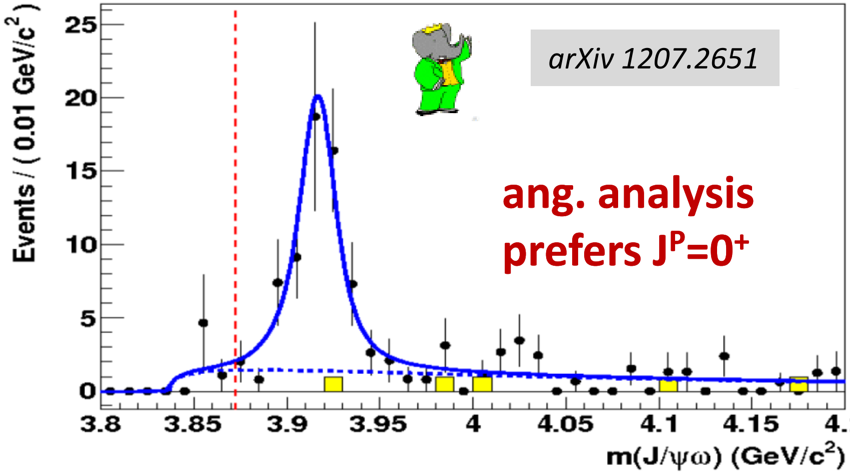
	Mass, MeV	Width, MeV
B → YK(Belle) B → YK(BaBar)	3943 ± 11 ± 13 3914.6 ± 2 ± 1.9	87 ± 22 ± 26 34^{+12}_{-8} ±6
γγ → Y(Belle) γγ → Y(BaBar)	3915 ± 3 ± 2 3919.6 ± 2.2 ± 1.6	17 ± 10 ± 3 13 ± 6 ± 3

	$\Gamma_{\gamma\gamma}$ Br (J=0)	$\Gamma_{\gamma\gamma}$ Br (J=2)
Belle BaBar	61 ± 17 ± 8 52 ± 10 ± 3	18 ± 5 ± 2 10.5 ± 1.9 ± 0.6



PRL 104, 092001 (2010)

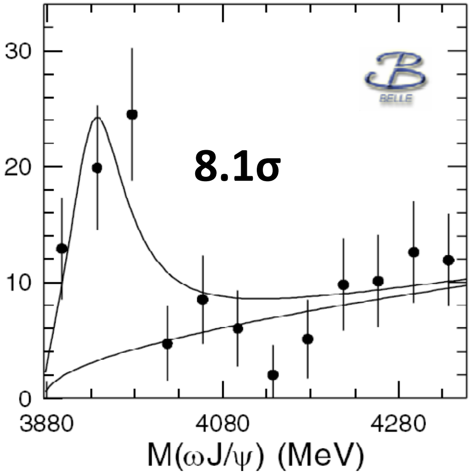
fit without a resonance



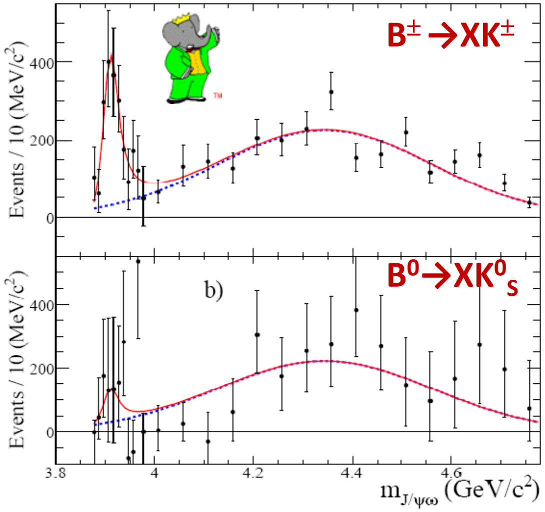
arXiv 1207.2651

ang. analysis prefers $J^P=0^+$

PRL 94, 182002 (2005)



PRL 101, 082001 (2008)



$B^\pm \rightarrow XK^\pm$

$B^0 \rightarrow XK^0_S$

Not observed in DD(*) final state

Partilce Data Group
Y(3940) = X(3915)= χ_{c0}(2P)

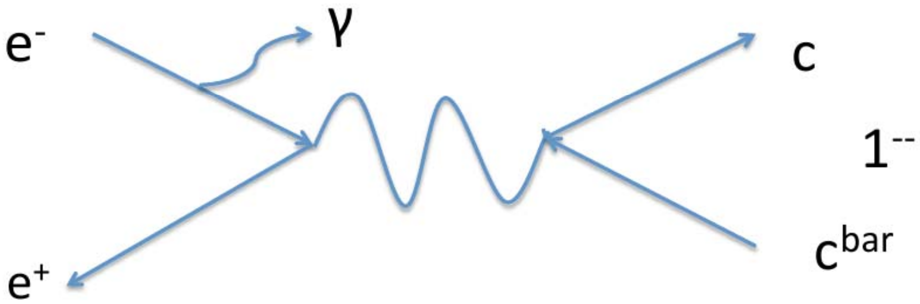
Theory

- ○ χ_{c0}(2P) production in two body B decays is suppressed
- ○ χ_{c0}(2P) → DD should be dominant

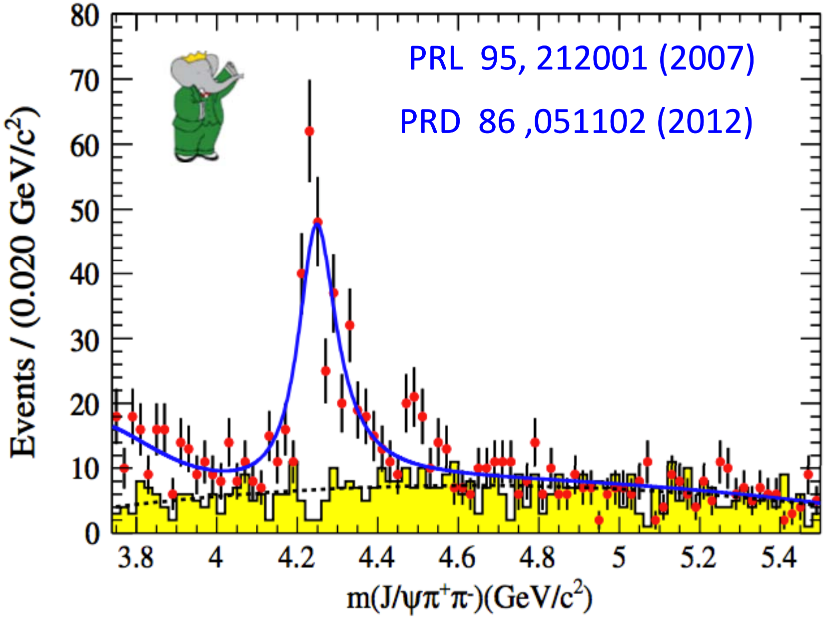
Y States

Y(4260), Y(4360), Y(4660)…

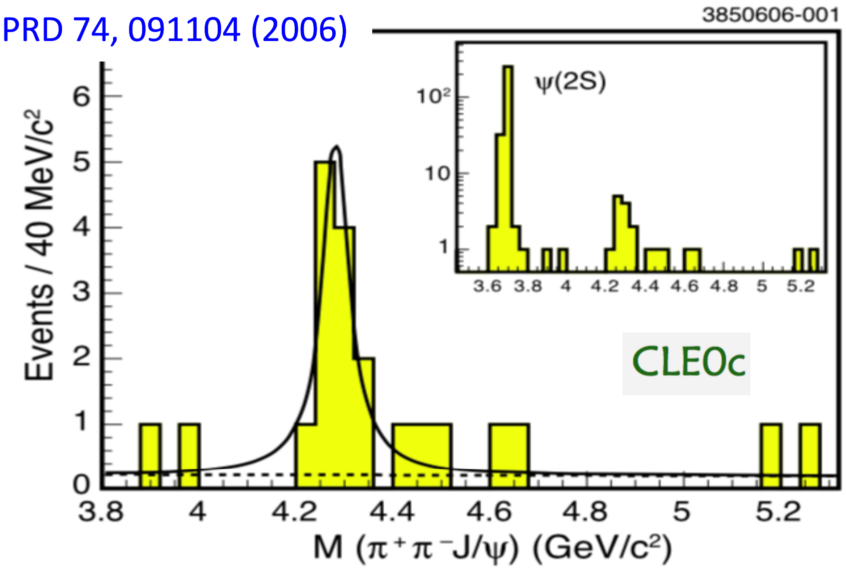
Observed in the e^+e^- annihilation (with ISR)

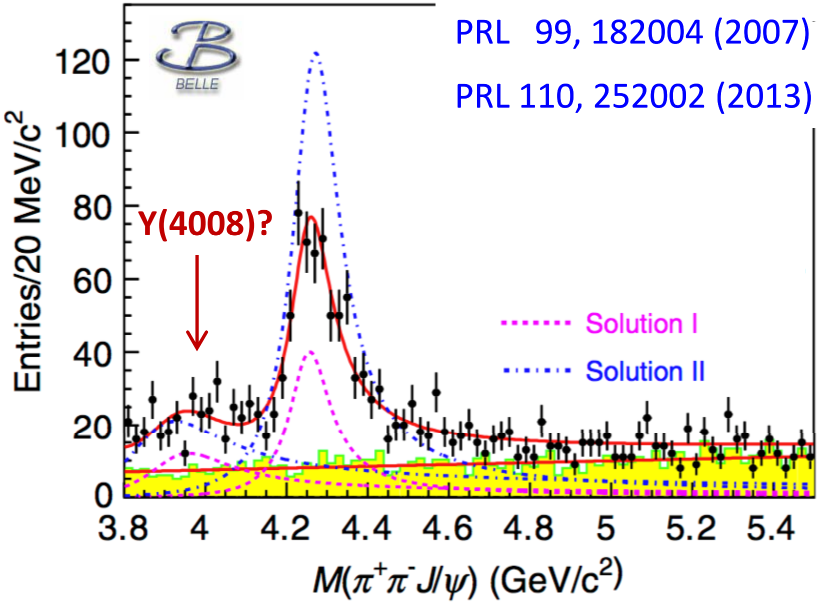


Studies with ISR: Y(4260)

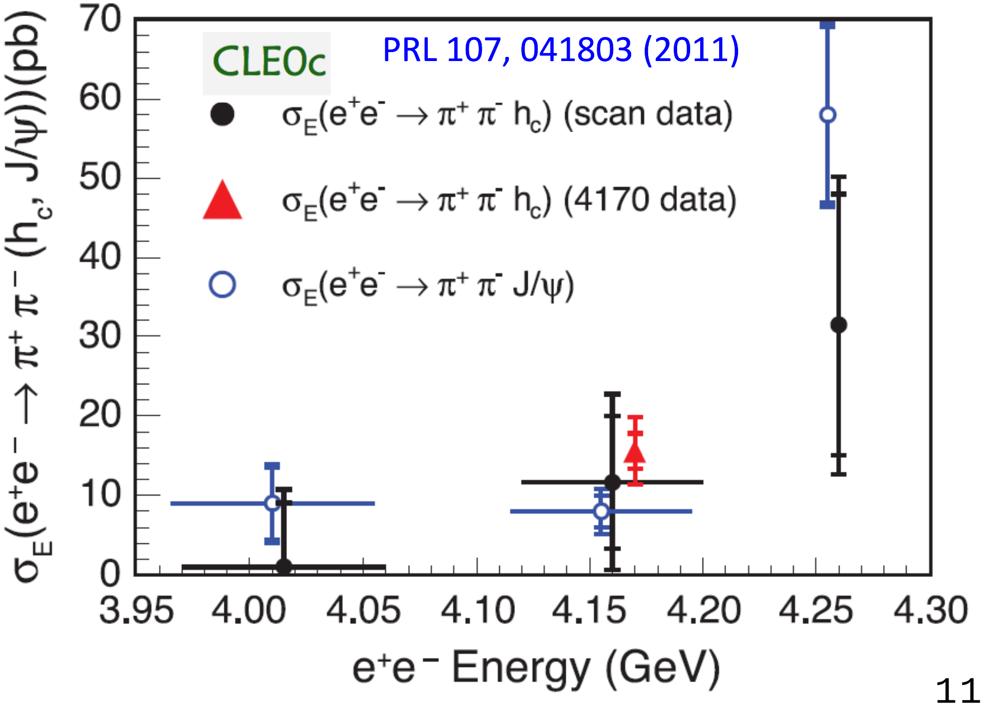

PRL 95, 212001 (2007)

PRD 86 ,051102 (2012)

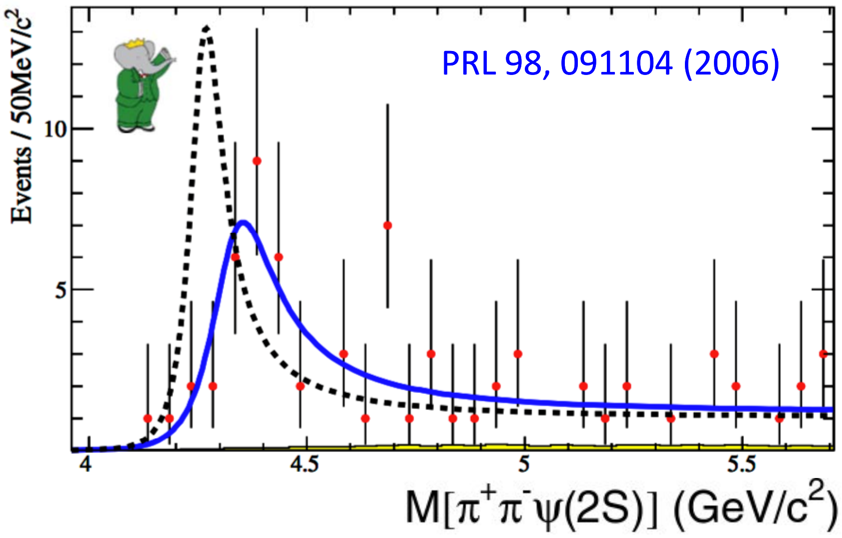

PRD 74, 091104 (2006)


PRL 99, 182004 (2007)

PRL 110, 252002 (2013)


PRL 107, 041803 (2011)

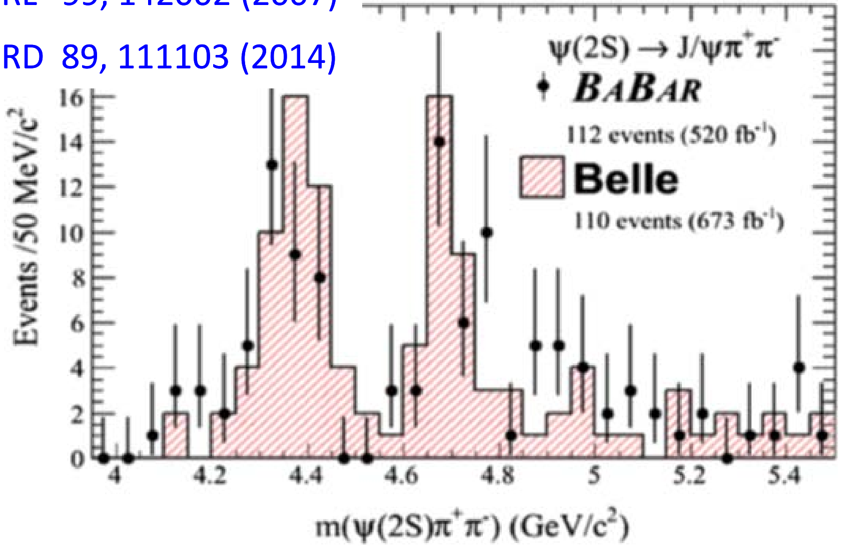
Studies with ISR: Y(4360) & Y(4660)



PRL 98, 091104 (2006)

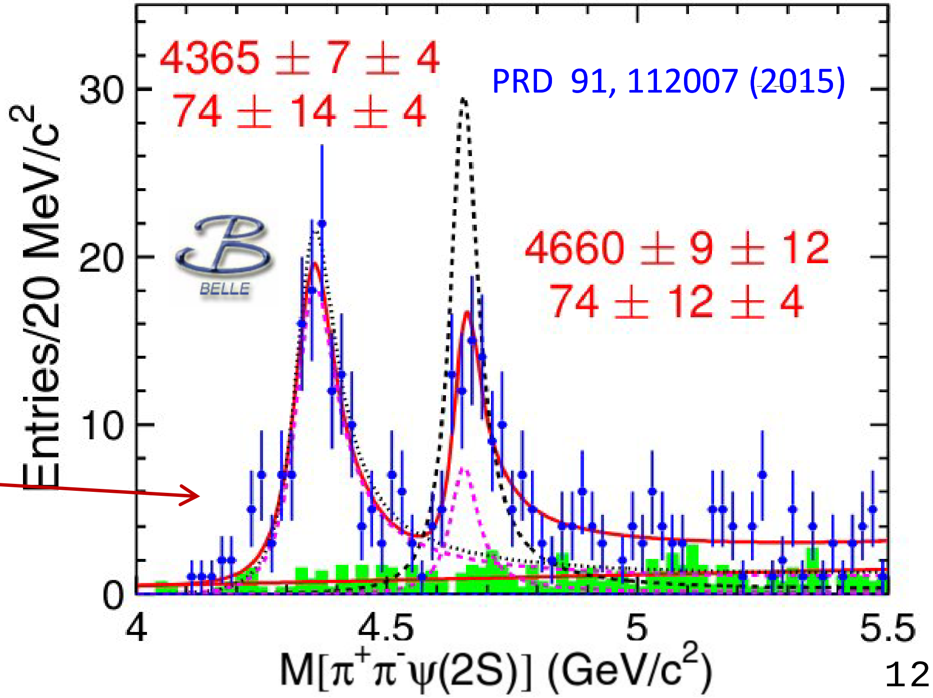
PRL 99, 142002 (2007)

PRD 89, 111103 (2014)



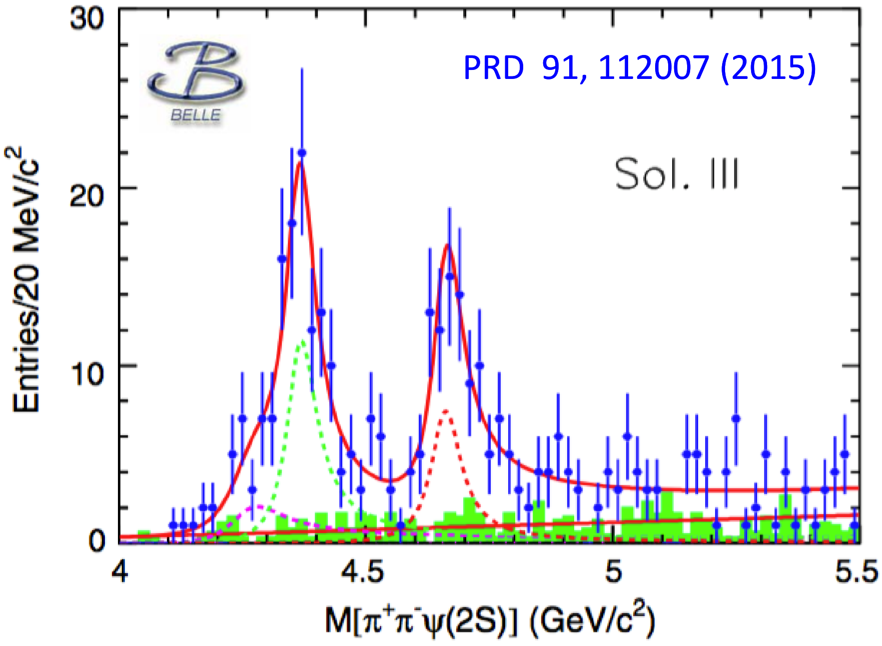
Belle update of the 2007 analysis with extra Lumi & much improved efficiency.

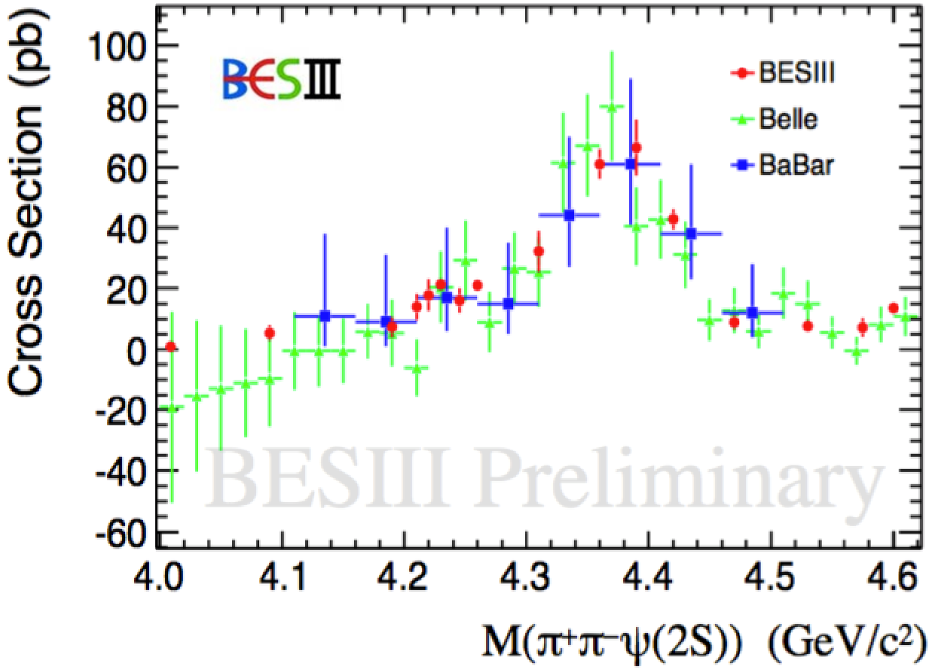
Some excess of signal events is observed at lower mass side. Y(4260) ?



PRD 91, 112007 (2015)

Studies with ISR: Y(4360) & Y(4660)





- In $\pi^+\pi^-\psi(2S)$, there are clear indications of the Y(4360) and Y(4660).
- Significance of the Y(4260) is $< 3\sigma$.

- BESIII confirms the lineshape for the Y(4360).
- More data will be taken soon to thoroughly study the region between 4.2 and 4.3 GeV.
- An analysis of the $\pi^\pm\psi(2S)$ substructure will be released soon.

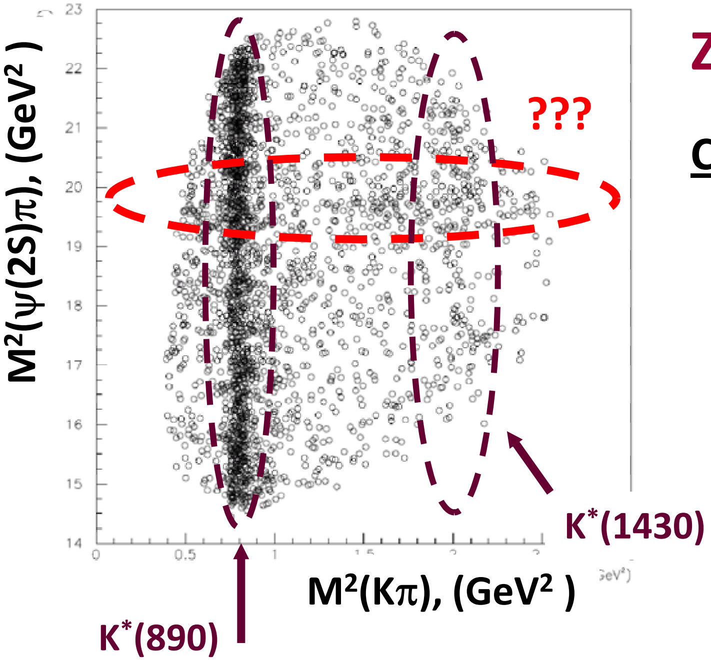
None of the Y(4260), Y(4360) or Y(4660) is observed in the $D^{(*)}D^{(*)}$ final state

Z States

Zc(3900), Zc(4020), Zc(4430), Zb(10610), Zb(10650), …

Observed in B decays and in decays of Y states

$Z_c(4430)$



$Z(4430)^+$ the first charged charmonium-like state

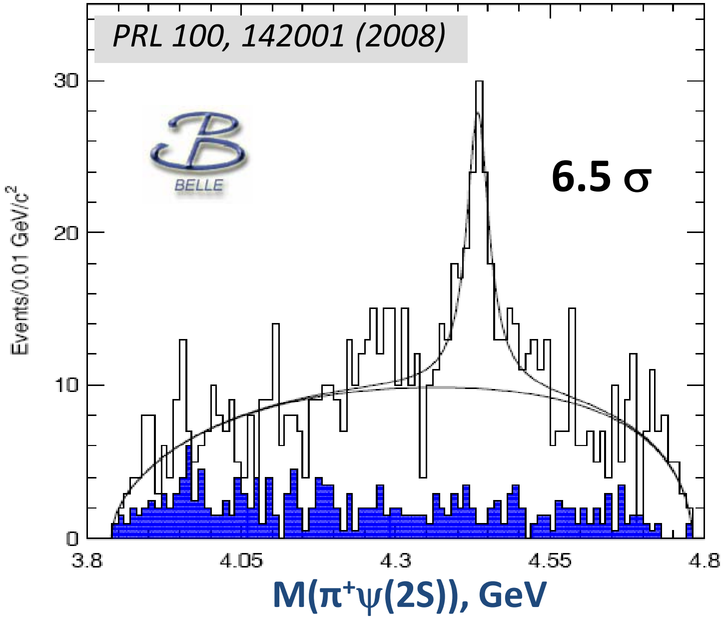
Charged – cannot be conventional charmonium or hybrid

$B \to KZ$, $Z(4430)^+ \to \pi^+\psi(2S)$
$K = K^-, K^0_s$; $\psi(2S) \to \ell^+\ell^-, \pi^+\pi^- J/\psi$

Fit: S-wave BW + phase space like function

after the K* veto

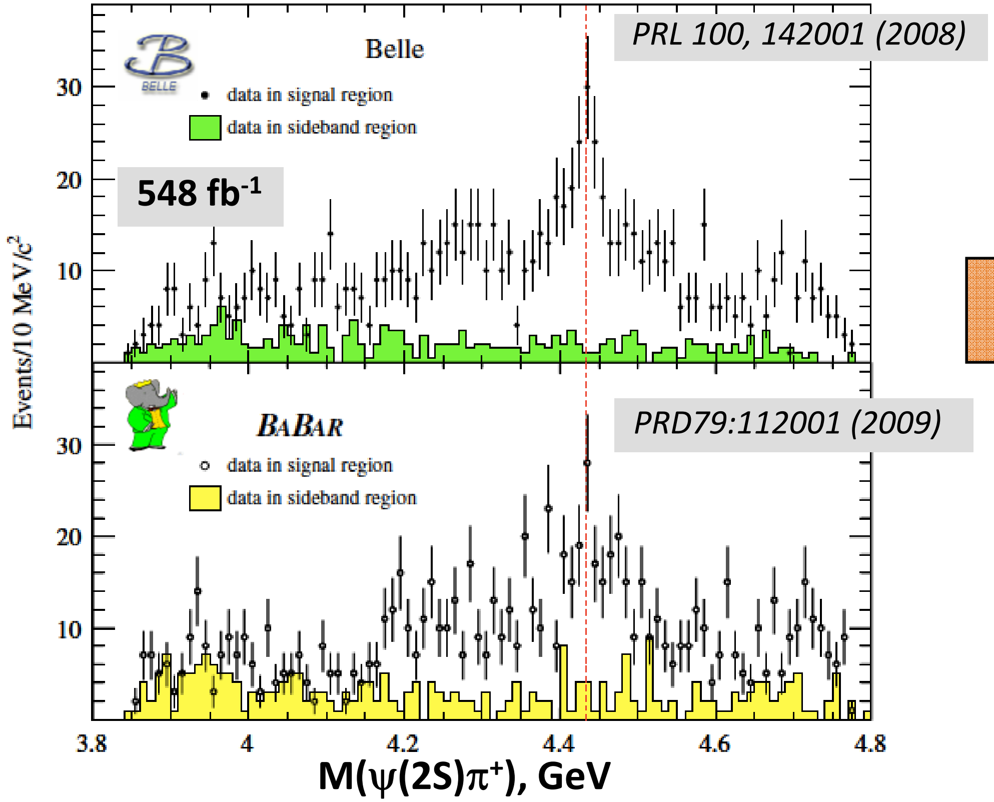
$M = (4433 \pm 4 \pm 2)$ MeV
$\Gamma = (45^{+18}_{-13}{}^{+30}_{-13})$ MeV

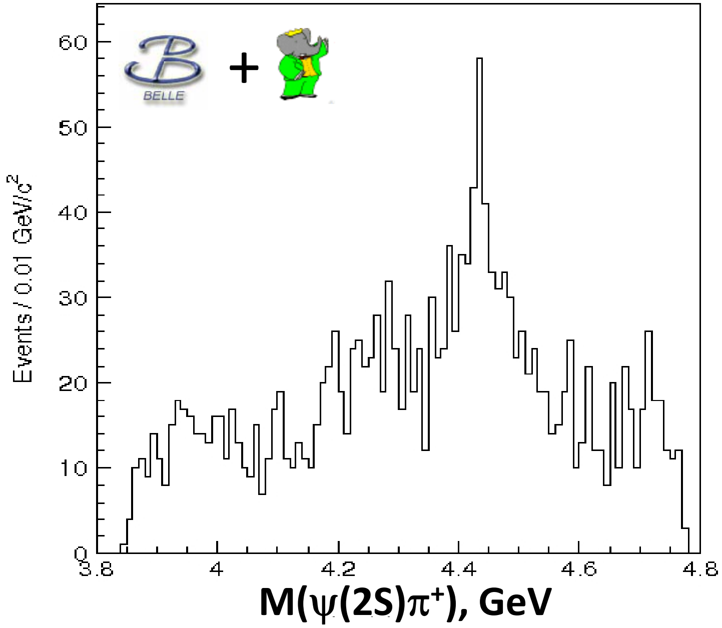

PRL 100, 142001 (2008)

$Br(B \to KZ) \times Br(Z \to \psi(2S)\pi) = (4.1 \pm 1.0 \pm 1.3) \times 10^{-5}$

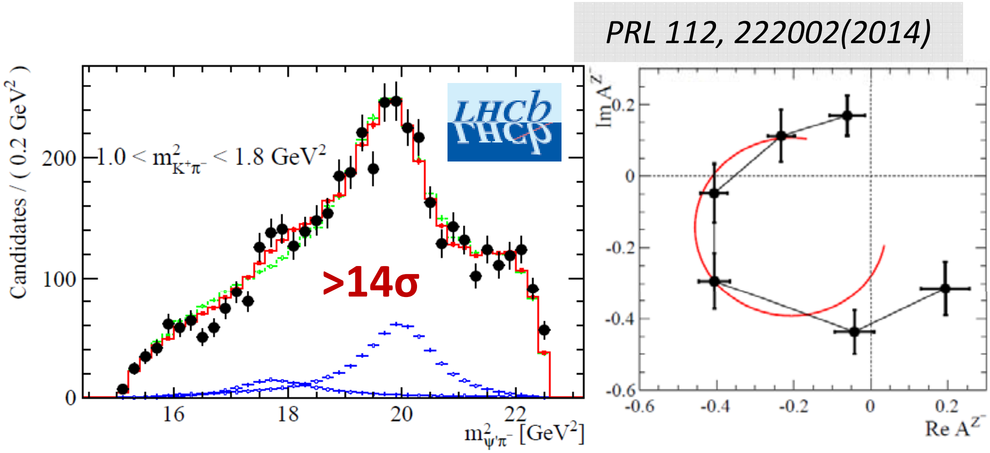
- ❑ **Could the Z(4430) be due to a reflection from the Kπ channel?**
  - ❑ **S- P- & D-waves cannot make a peak (+ nothing else)**

$Z_c(4430)$





4D-fit by Belle: confirms Zc(4430) & $J^P=1^+$

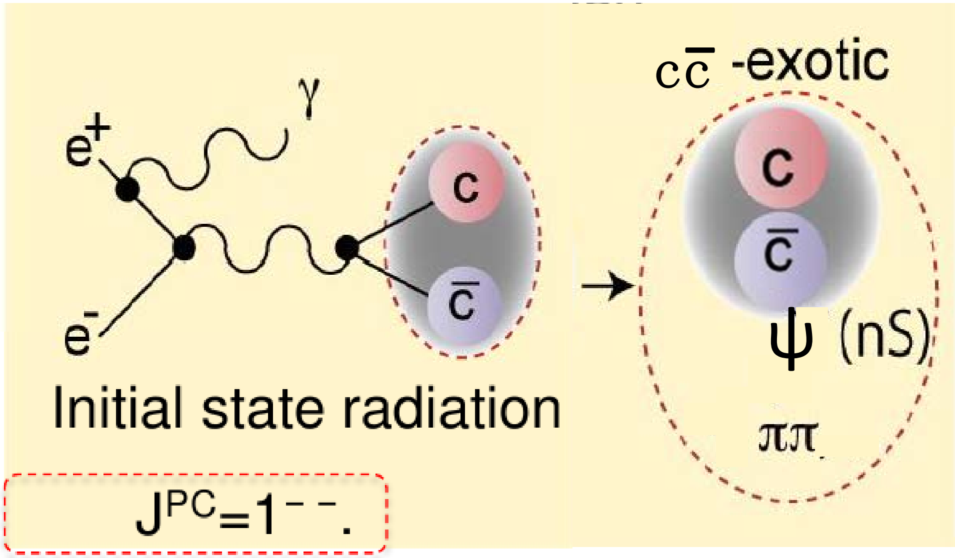


Belle and BaBar data look very similar; conclusions are different:

- **Belle**: observation of new resonance
- **BaBar**: after taking into account many Kπ waves, the peak is not significant

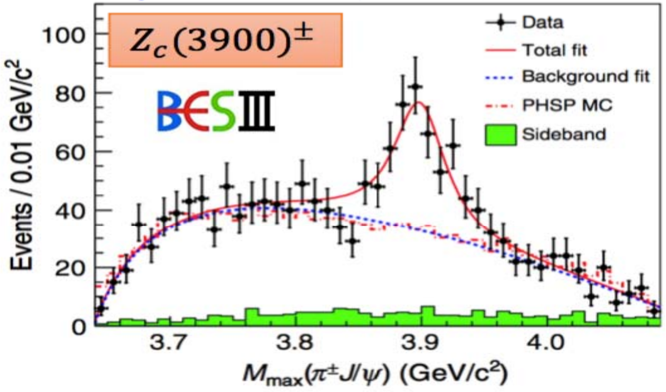
$Z_c(3900)$ State

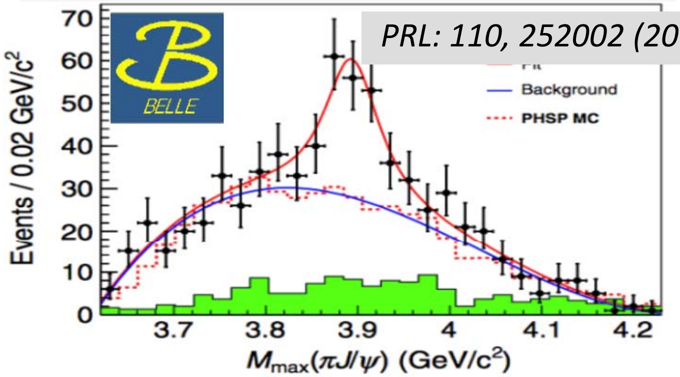
Observed in $e^+e^- \to (\gamma)Y(4260) \to J/\psi\pi^+\pi^-$



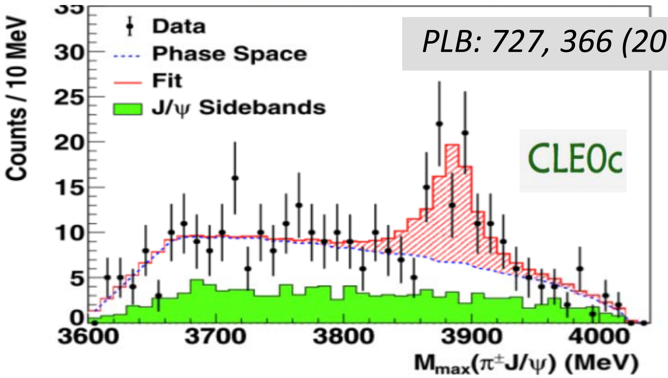
- Charged charmonium-like structure (>10 σ)
- Decay to J/ψ (cc̄) and electric charge (ud̄ or dū)
- $M = 3899.0 \pm 3.6 \pm 4.9$ MeV/c², $\Gamma = 46 \pm 10 \pm 20$ MeV
- $\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = 62.9 \pm 1.9 \pm 3.7$ pb at 4.26 GeV
- $\dfrac{\sigma(e^+e^- \to \pi^\mp Z_c(3900)^\pm \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} = 21.5 \pm 3.3 \pm 7.5\ \%$
- The first Z_c state observed by more than one experiment (Belle and CLEO-c)!

Phys. Rev. Lett 110, 252001 (2013)





PRL: 110, 252002 (2013)

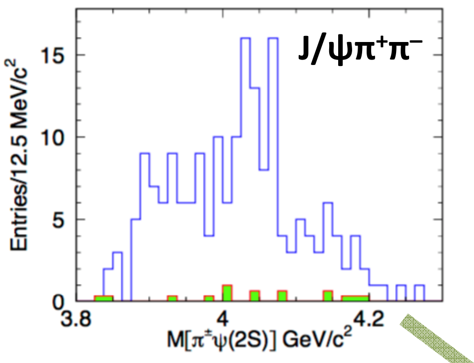


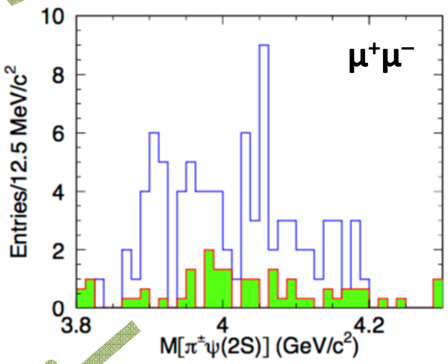
PLB: 727, 366 (2013)

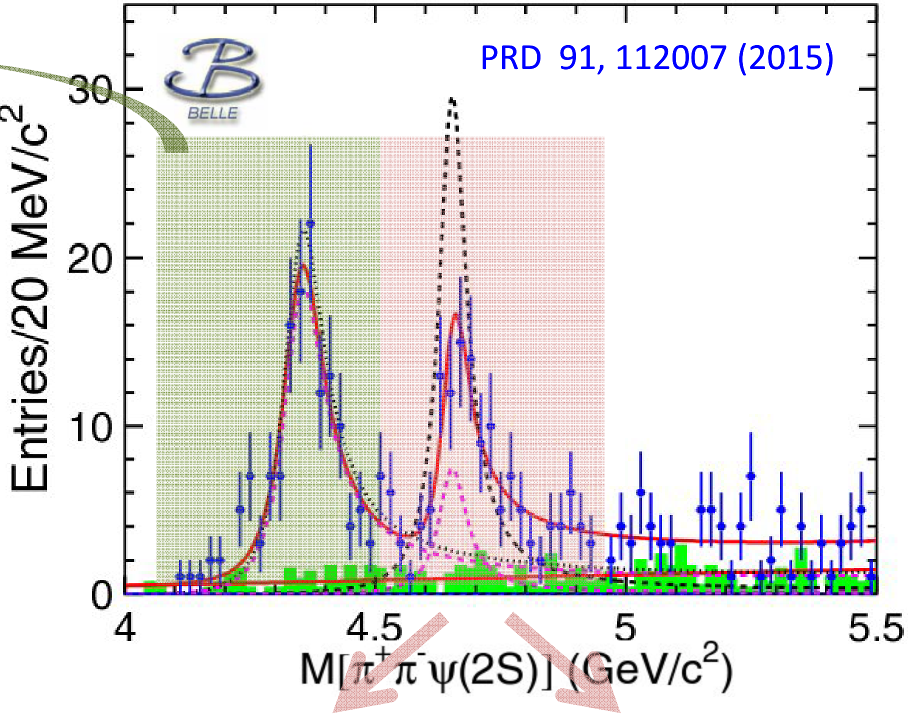
$Z_c(4050)$

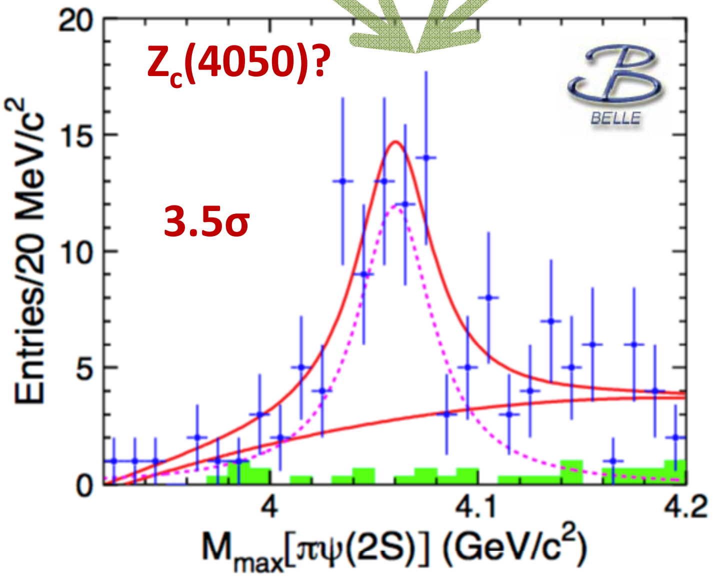
Observed by Belle in ISR

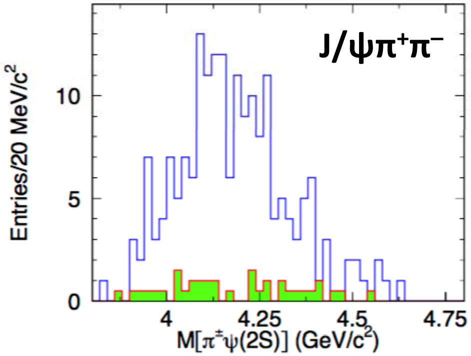
$e^+e^- \to \gamma Y(4360) \to \psi(2S)\pi^+\pi^-$

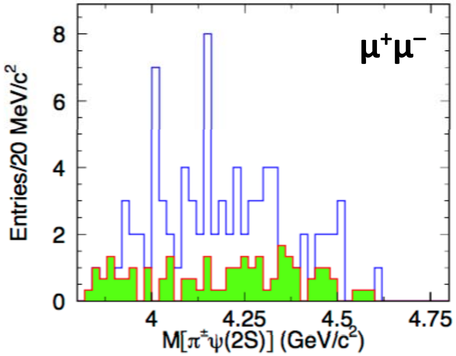












No clear signal found in the Y(4660) region

$M = 4054 \pm 3 \pm 1$ MeV/c²
$\Gamma = 45 \pm 11 \pm 6$ MeV

Another Z_c state? Need confirmation

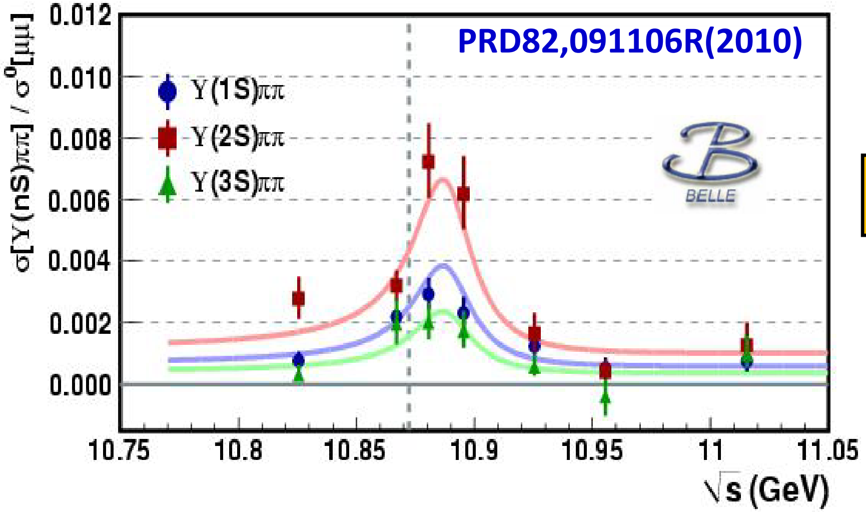
Exotics in Bottomonium Sector

- **No X_b states found so far**
- **Mass splitting between Υ(4S) and Υ(5S) states is in strong disagreement with potential model expectation**
- **Anomalously (~factor 100) large coupling to $\Upsilon\pi^+\pi^-$**
- **No $h_b\pi^+\pi^-$ suppression**

(2) An exotic resonance Y_b near Υ(5S) - analogue of the Y(4260) resonance with anomalous $\Gamma(J/\psi\ \pi^+\pi^-)$

(3) Tetraquarks

Anomalous $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$ Rates

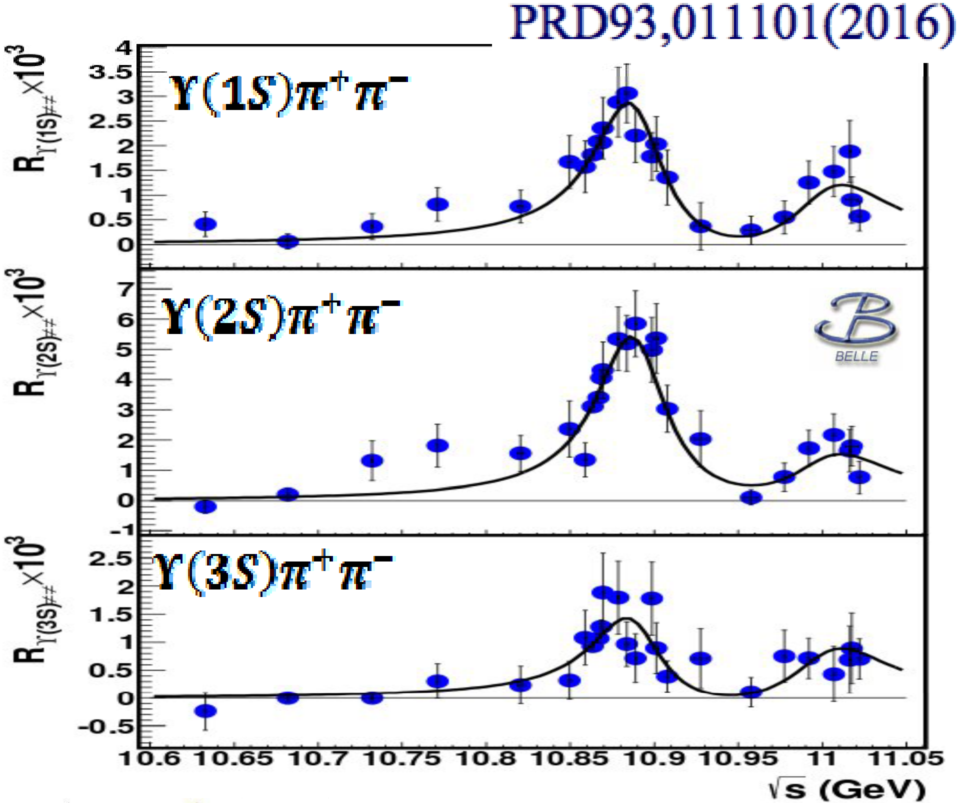


$\Upsilon(10860)$:	**$\Upsilon(11020)$:**
$10891.1 \pm 3.2^{+0.6}_{-1.7}$	$10987.5^{+6.4}_{-2.5}{}^{+9.0}_{-2.1}$
$53.7^{+7.1}_{-5.6}{}^{+1.3}_{-5.4}$	$61^{+9}_{-19}{}^{+2}_{-20}$

$$\phi_{6S} - \phi_{5S}(\delta)\ (\text{rad})\ -1.0 \pm 0.4^{+1.4}_{-0.1}$$

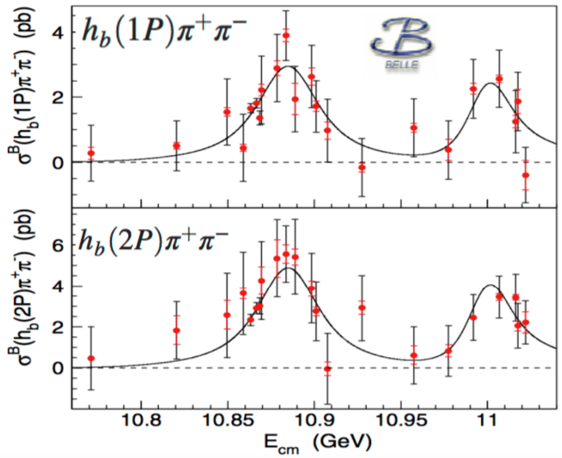
$10884.7^{+3.6}_{-3.4}{}^{+8.9}_{-1.0}$	$10999.0^{+7.3}_{-7.8}{}^{+16.9}_{-1.0}$
$40.6^{+12.7}_{-8.0}{}^{+1.1}_{-19.1}$	$27^{+27}_{-11}{}^{+5}_{-12}$

$$\phi = (0.1^{+0.4}_{-0.8} \pm 0.3)\pi$$



New

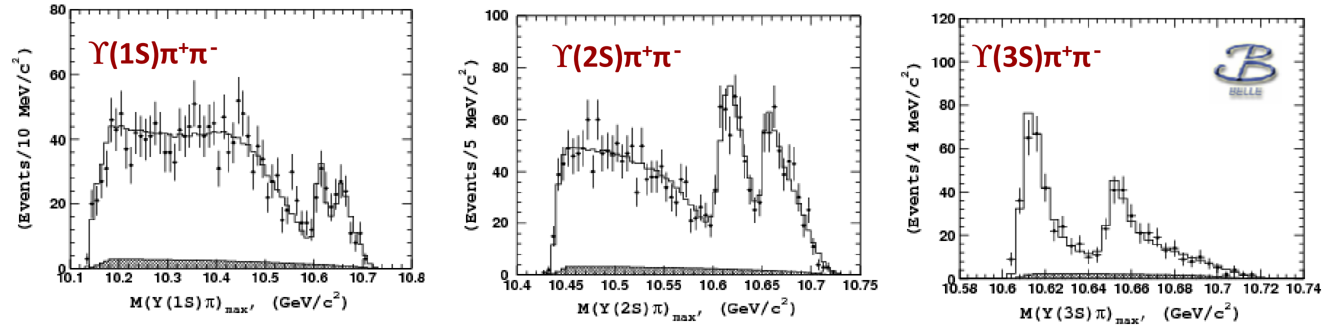
PRL117,142001(2016)

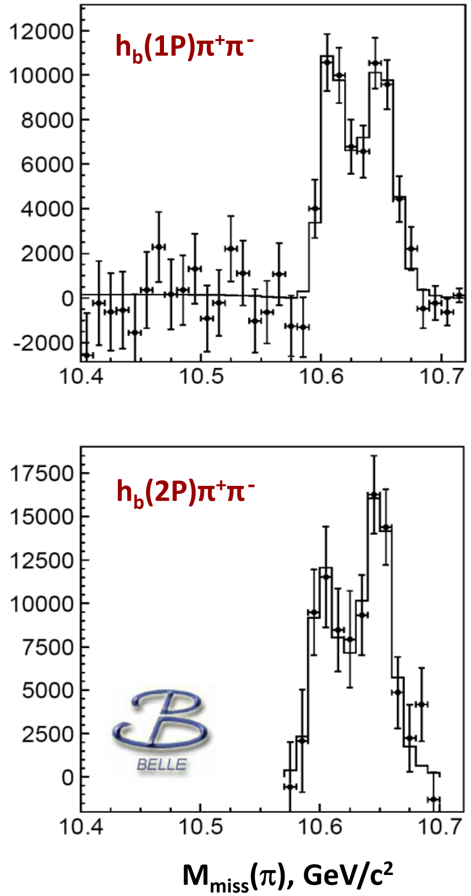


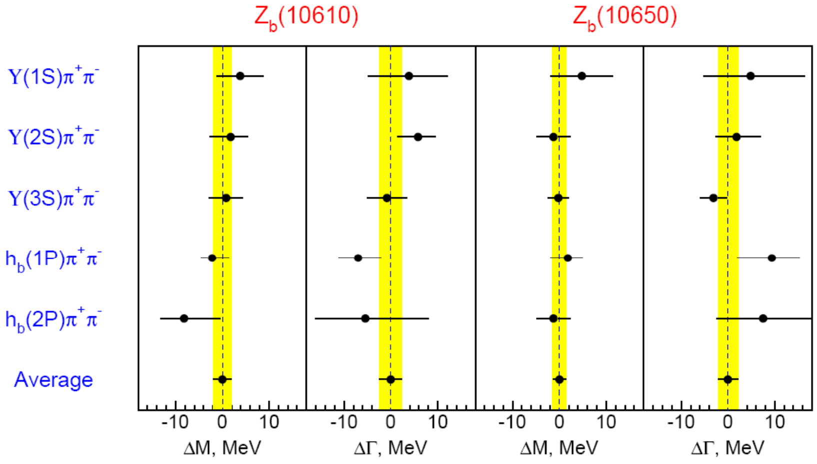
Summary on Z_b → Hidden Beauty

Υ(5S) Belle Data: 121.4 fb^{-1}

PRL 108, 122001(2012)







Average for $Z_b^{\pm}$:

$\langle M_1 \rangle = 10607.2 \pm 2.0$ MeV

$\langle \Gamma_1 \rangle = 18.4 \pm 2.4$ MeV

$\langle M_2 \rangle = 10652.2 \pm 1.5$ MeV

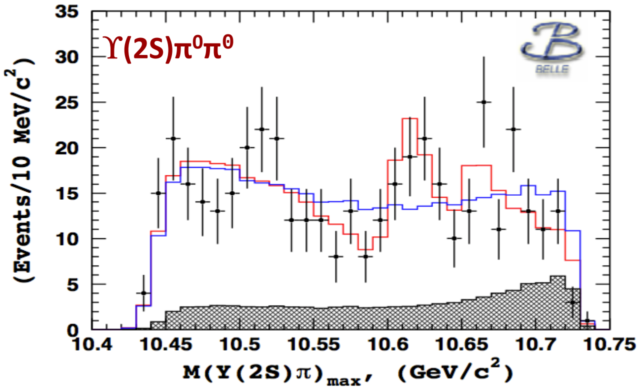
$\langle \Gamma_2 \rangle = 11.5 \pm 2.2$ MeV

Z_b^0 Results:

$\langle M_1 \rangle = 10609 \pm 7 \pm 6$ MeV

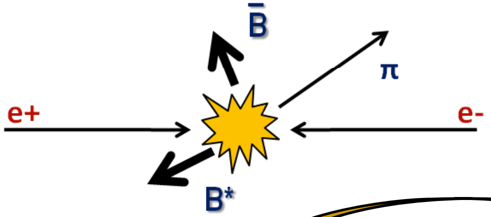
Consistent with $Z_b^{\pm}$

PRD88,052016 (2013)



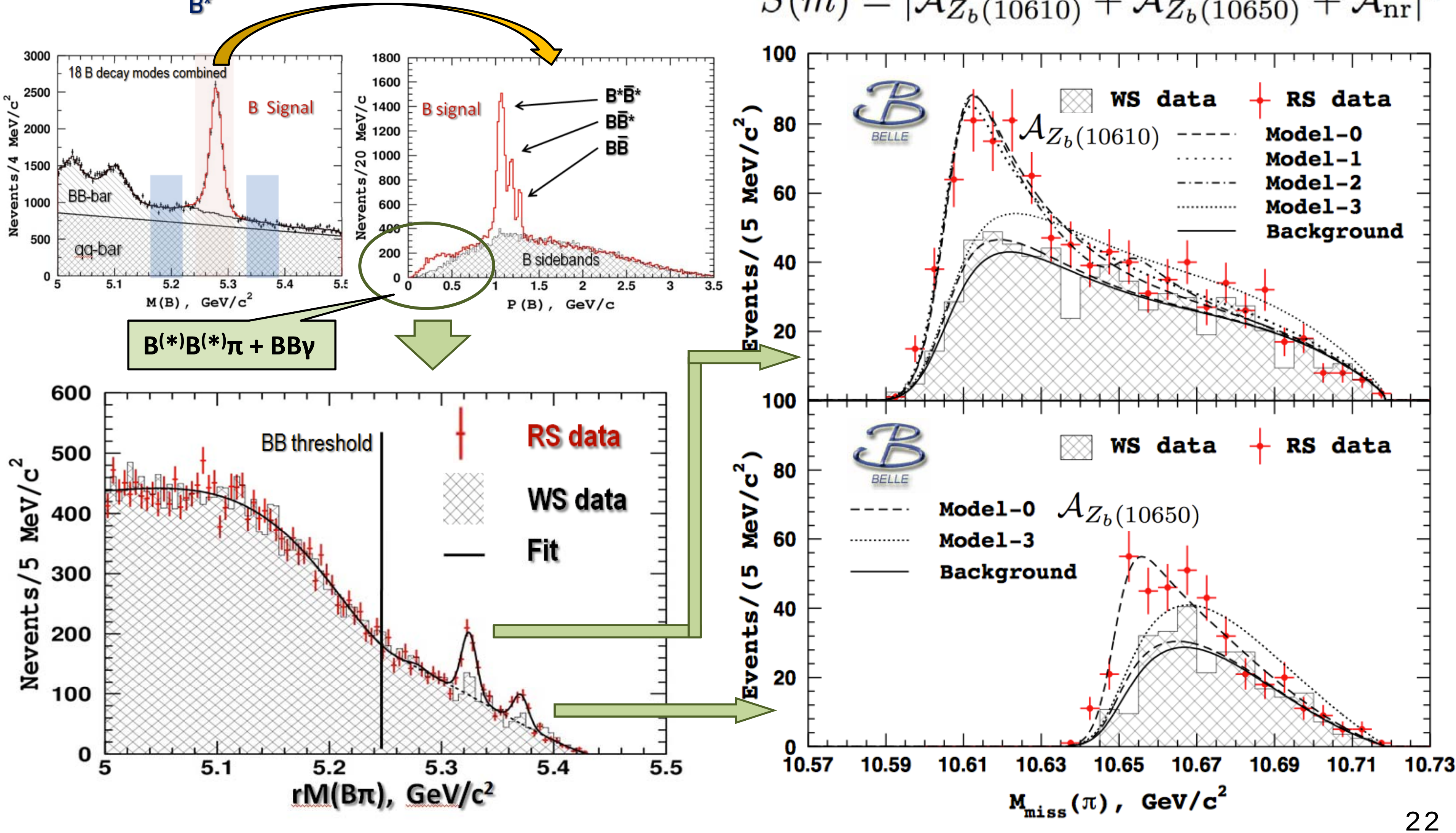
Angular analysis strongly favors $J^P=1^+$ assignement

$Z_b^{\pm} \rightarrow$ Open Beauty



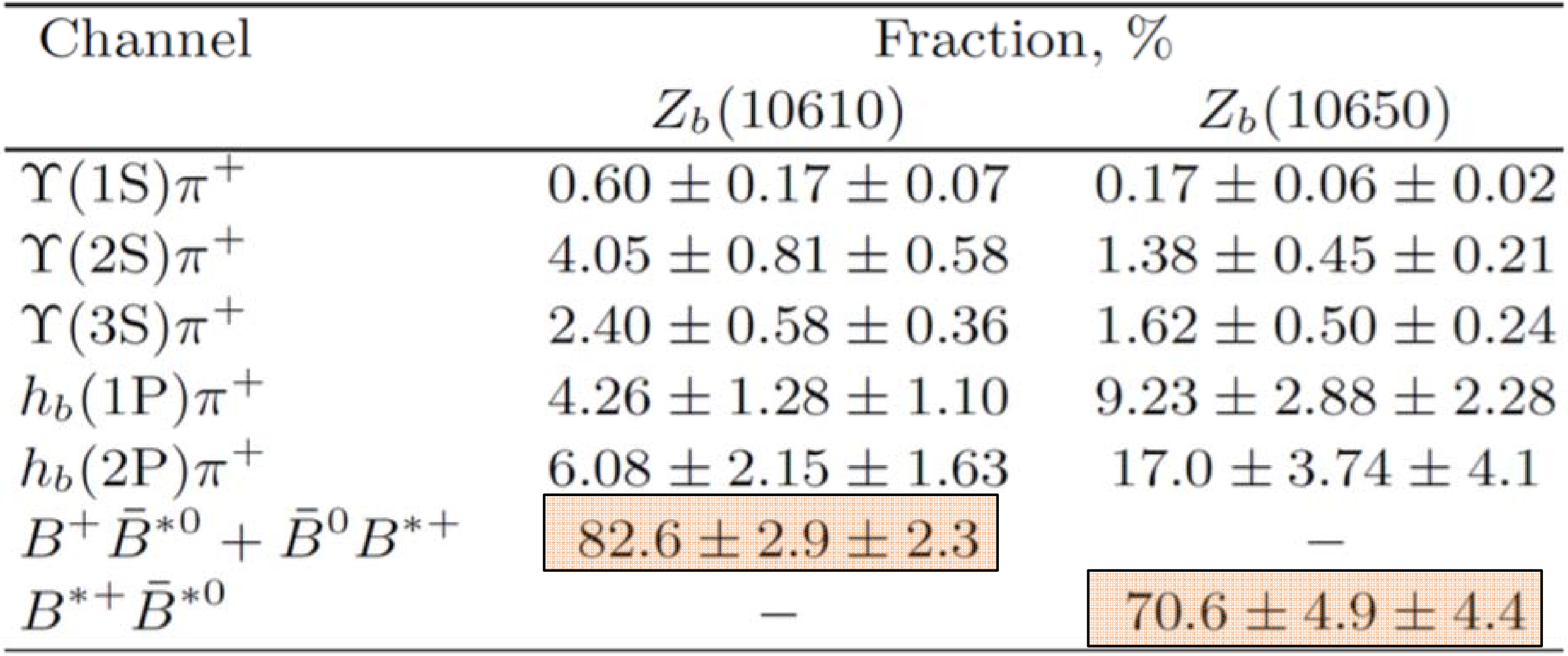
PRL116,212001(2016)

$$S(m) = |\mathcal{A}_{Z_b(10610)} + \mathcal{A}_{Z_b(10650)} + \mathcal{A}_{\rm nr}|^2$$



Summary on Z_b Decays by Belle

Assuming that Z_b decays are saturated by the $\Upsilon(nS)\pi$, $h_b(mP)\pi$ and $B^{(*)}B^*$ channels, one can calculate a table of relative branching fractions:



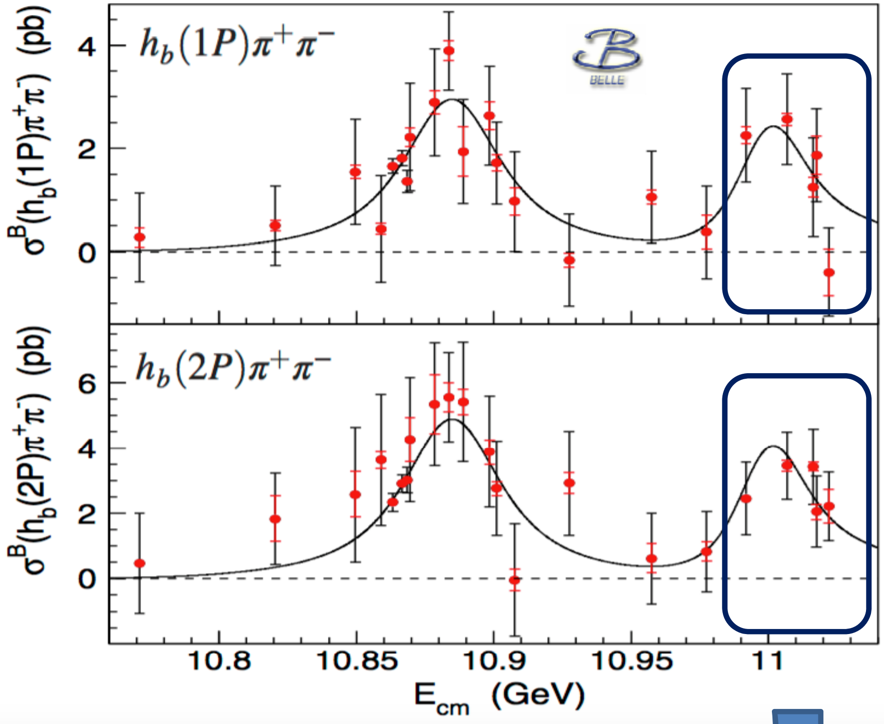
Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.60 \pm 0.17 \pm 0.07$	$0.17 \pm 0.06 \pm 0.02$
$\Upsilon(2S)\pi^+$	$4.05 \pm 0.81 \pm 0.58$	$1.38 \pm 0.45 \pm 0.21$
$\Upsilon(3S)\pi^+$	$2.40 \pm 0.58 \pm 0.36$	$1.62 \pm 0.50 \pm 0.24$
$h_b(1P)\pi^+$	$4.26 \pm 1.28 \pm 1.10$	$9.23 \pm 2.88 \pm 2.28$
$h_b(2P)\pi^+$	$6.08 \pm 2.15 \pm 1.63$	$17.0 \pm 3.74 \pm 4.1$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$82.6 \pm 2.9 \pm 2.3$	$-$
$B^{*+}\bar{B}^{*0}$	$-$	$70.6 \pm 4.9 \pm 4.4$

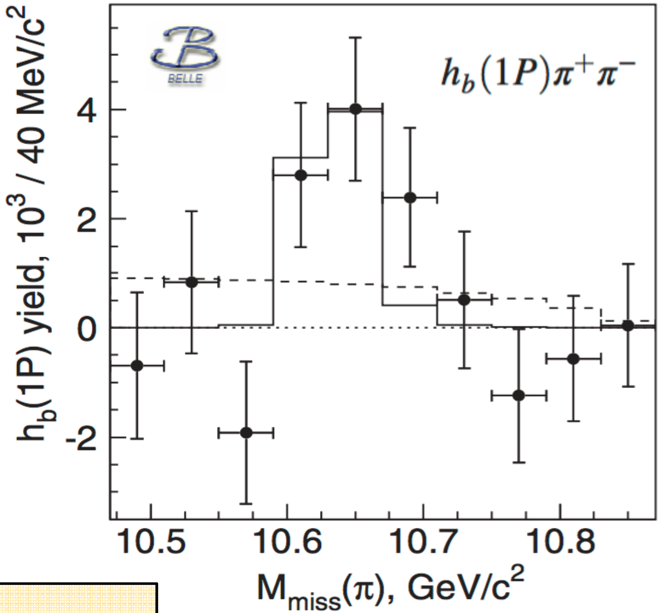
$$\frac{Br(Z_b(10610)^+ \to B\overline{B^*})}{Br(Z_b(10610)^+ \to b\overline{b})} = 5.93 {+0.99/{-0.59}} {+1.01/{-0.73}}$$

$$\frac{Br(Z_b(10650)^+ \to B^*\overline{B^*})}{Br(Z_b(10650)^+ \to b\overline{b})} = 2.80 {+0.69/{-0.40}} {+0.54/{-0.36}}$$

$B^{(*)}B^*$ channels dominate the Z_b decays

$Z_b^\pm$ Production at $\Upsilon(6S)$

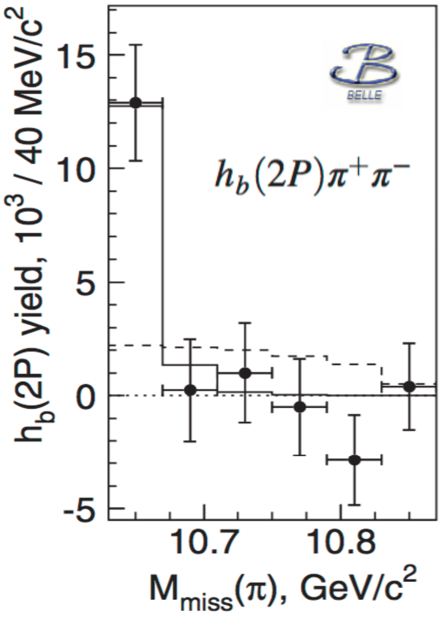




$\Upsilon(6S)$ Data: 5 fb^{-1}

PRL117,142001(2016)

New



The two Z_b states can not be separated with current statistics

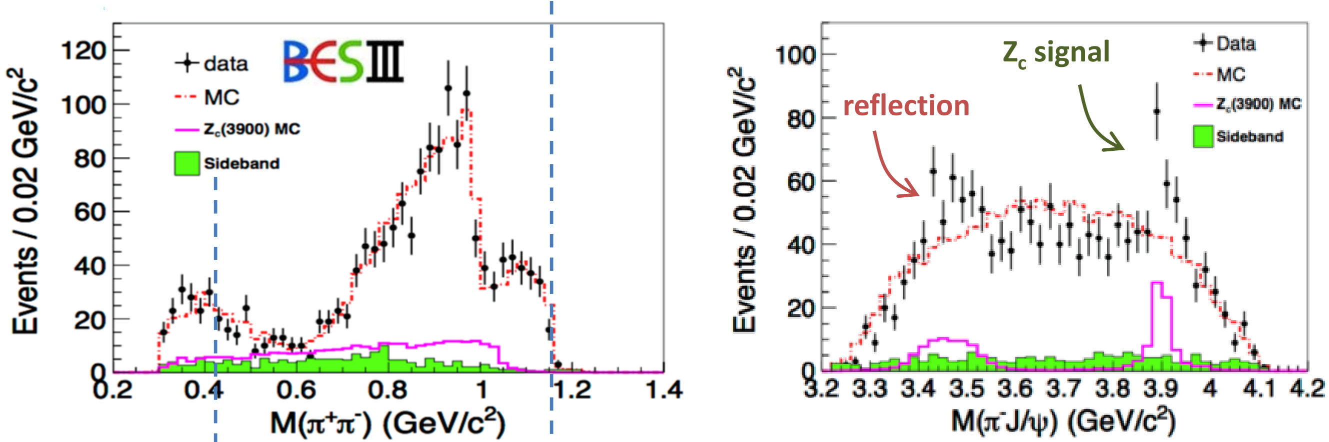
$\Upsilon(6S) \rightarrow h_b(mP)\pi^+\pi^-$ transition is dominated (saturated) by the intermediate $Z_b^\pm$ production

Charm vs. Beauty: I

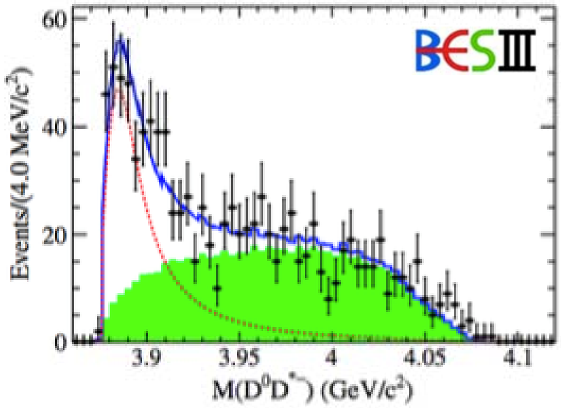
What is in common?

- $\Upsilon(10860)/Y(4260)$ demonstrates anomalously large coupling to $\Upsilon\pi^+\pi^-/\psi\pi^+\pi^-$ and $h_b\pi^+\pi^-/h_c\pi^+\pi^-$ final states.

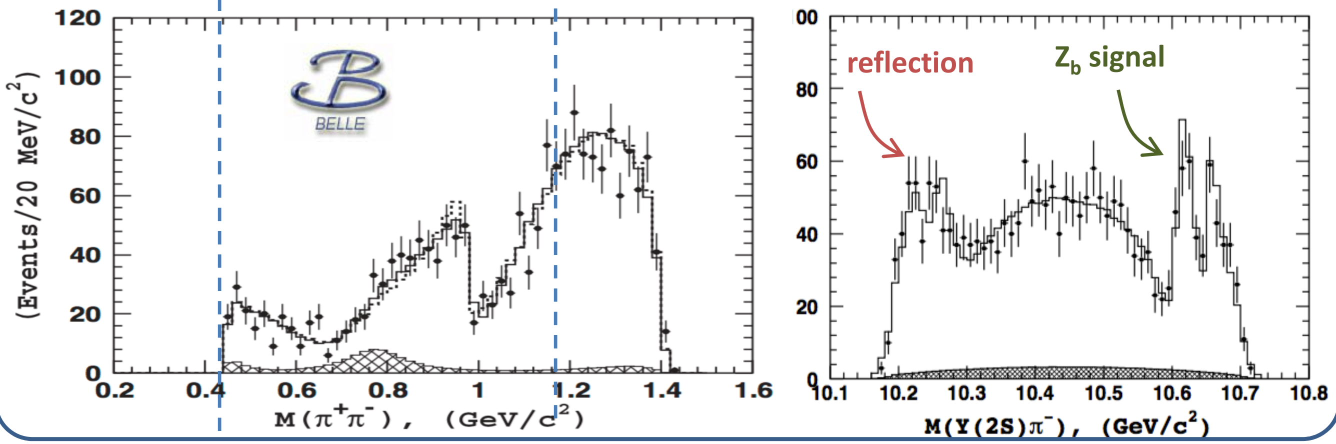
$Z_c(3900)$ is produced in $Y(4260)\rightarrow Z_c\pi\rightarrow \psi\pi^+\pi^-$



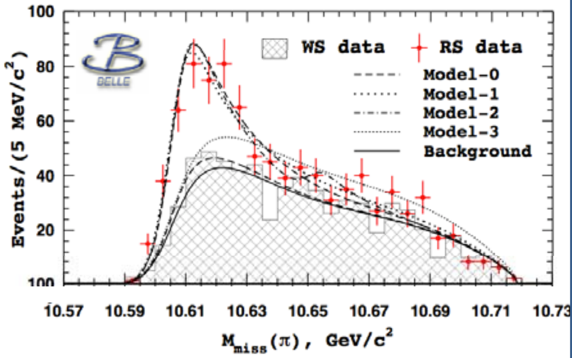
$\rightarrow Z_c\pi\rightarrow DD^*$



$Z_b(10610)$ is produced in $\Upsilon(10860)\rightarrow Z_b\pi\rightarrow \Upsilon(nS)\pi^+\pi^-$



$\rightarrow Z_b\pi\rightarrow BB^*$



Charm vs. Beauty: II

What is different?

- Both $Z_b(10610)$ and $Z_b(10650)$ isotriplets are observed in the $\Upsilon(nS)\pi$, $(n=1,2,3)$ and $h_b\pi$ final states.

- $\Upsilon(10860) \rightarrow h_b\pi^+\pi^-$ is saturated by the intermediate two-body $Z_b\pi$ production.

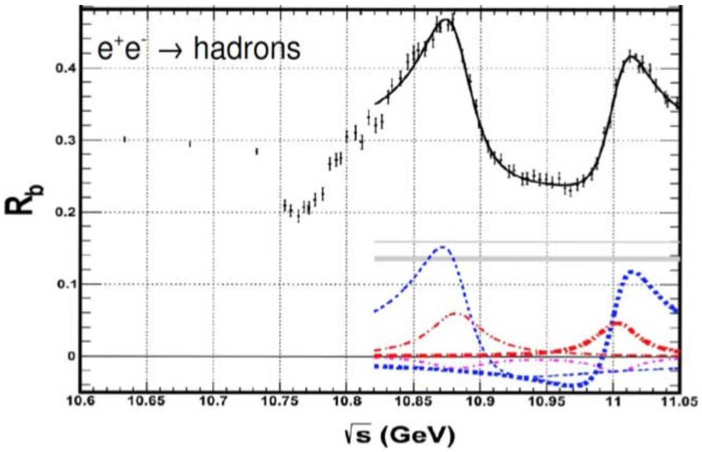
- Only $Z_c(3900)$ is observed in the $J/\psi\pi$ while both $Z_c(3900)$ and $Z_c(4020)$ are observed in the $h_c\pi$ final state. None of them is observed in the $\psi(2S)\pi$ final state (instead, another $Z_c(4430)$ is found).

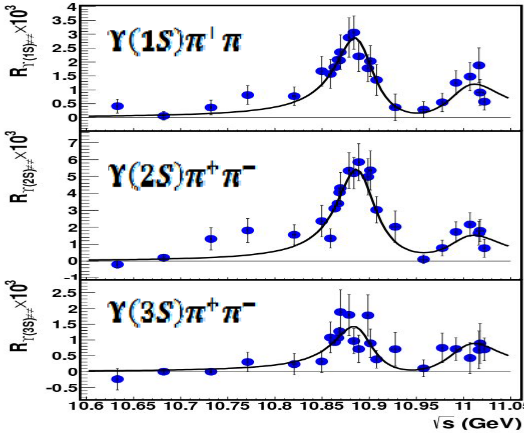
- Large non $Z_c\pi$ component is observed in the $Y(4260) \rightarrow h_c\pi^+\pi^-$ amplitude.

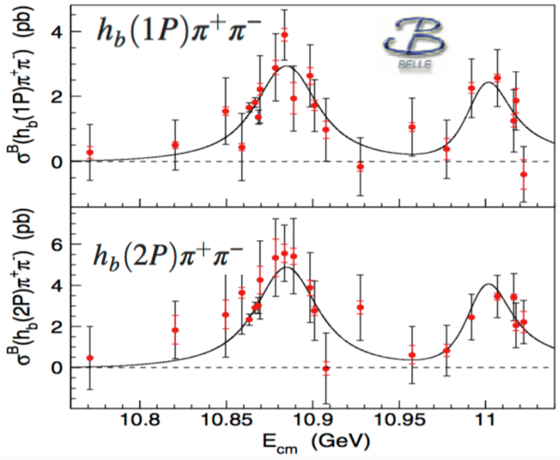
Belle II Prospects

Other Bottomonium-like States @ Belle II

- The energy dependence of the inclusive bb cross section in the $\Upsilon(4S) – \Upsilon(6S)$ exhibits very different behavior compared to exclusive channels measured so far

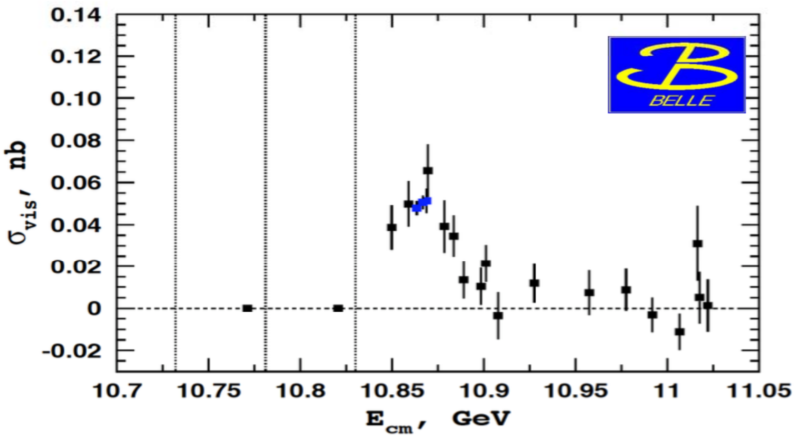






- One needs to measure energy dependence for other exclusive cross sections such as $B^{(*)}B^{(*)}$, $B^{(*)}B^{(*)}\pi$, $B_s^{(*)}B_s^{(*)}$ to see how the inclusive cross section is being filled

- Belle released preliminary results on the $e^+e^- \rightarrow B_s^{(*)}B_s^{(*)}$, still no significant signal outside the resonance regions…



Other Bottomonium-like States @ Belle II

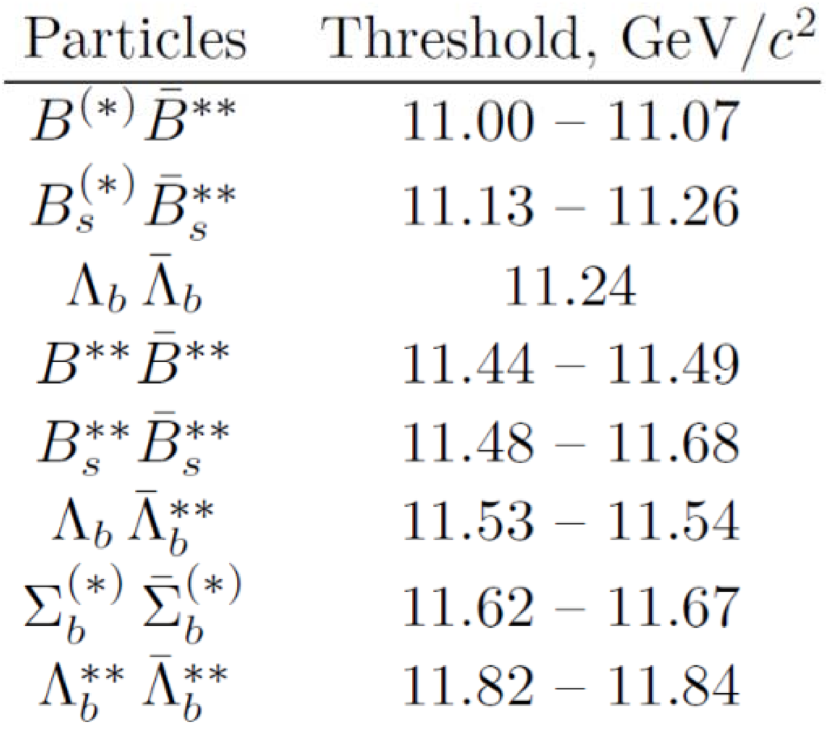
- Up to 40 1/fb of data might be collected by Belle II during Phase-2 (early 2018) at various c.m. energies including energy range of Υ(6S) and above

- Up to 300 1/fb of data might be collected by Belle II during Phase-3 (late 2018 – …) at various c.m. energies including energy range of Υ(6S) and above

- With 10 (50) 1/ab of data at (4S) Belle II will be able to perform precision measurements (with an equivalent luminosity of ~.5 (1.5) 1/fb per a 10MeV bin) of Y states in charm sector via ISR

Other Bottomonium-like States @ Belle II

Molecular states are naturally located near corresponding thresholds:



Particles	Threshold, GeV/c^2
$B^{(*)}\bar{B}^{**}$	11.00 – 11.07
$B_s^{(*)}\bar{B}_s^{**}$	11.13 – 11.26
$\Lambda_b\,\bar{\Lambda}_b$	11.24
$B^{**}\bar{B}^{**}$	11.44 – 11.49
$B_s^{**}\bar{B}_s^{**}$	11.48 – 11.68
$\Lambda_b\,\bar{\Lambda}_b^{**}$	11.53 – 11.54
$\Sigma_b^{(*)}\,\bar{\Sigma}_b^{(*)}$	11.62 – 11.67
$\Lambda_b^{**}\,\bar{\Lambda}_b^{**}$	11.82 – 11.84

arxiv:1610.01102

- Belle-II maximal energy of **11.24 GeV** covers $B_s^{(*)}B_s^{**}$ threshold region.
- Increase to **11.35 GeV** will give information about $\Lambda_b\Lambda_b$ threshold region.
- Increase to **11.5 GeV** is crucial to search for partners of Z_b states.

Summary

- A whole new field of exotic physics discovered in last decade; new information is still coming from both completed (Belle & BaBar) and currently ongoing (BESIII) e+e- experiments

- Much more data required for a better understanding (BelleII, BESIII)

- Belle extends searches for exotics to $\Upsilon(6S)$ energy. Start of the Belle II is approaching.

- Common features between charmonium and bottomonium sectors is gradually emerging. No direct identity though.

- No clear understanding of the nature of new states yet. Substantial progress in theory achieved recently; more efforts are required from both experimental and theoretical sides.

- Input from Belle II is crucial to push exotic studies into bottomonium sector. Energy scan up to 11.24 GeV is readily accessible by the SuperKEKB; higher energies are under discussion.

Bottomonium-like States @ Belle II

$$|Z_b'\rangle = \frac{1}{\sqrt{2}} 0^-_{bb} \otimes 1^-_{Qq} - \frac{1}{\sqrt{2}} 1^-_{bb} \otimes 0^-_{Qq}$$

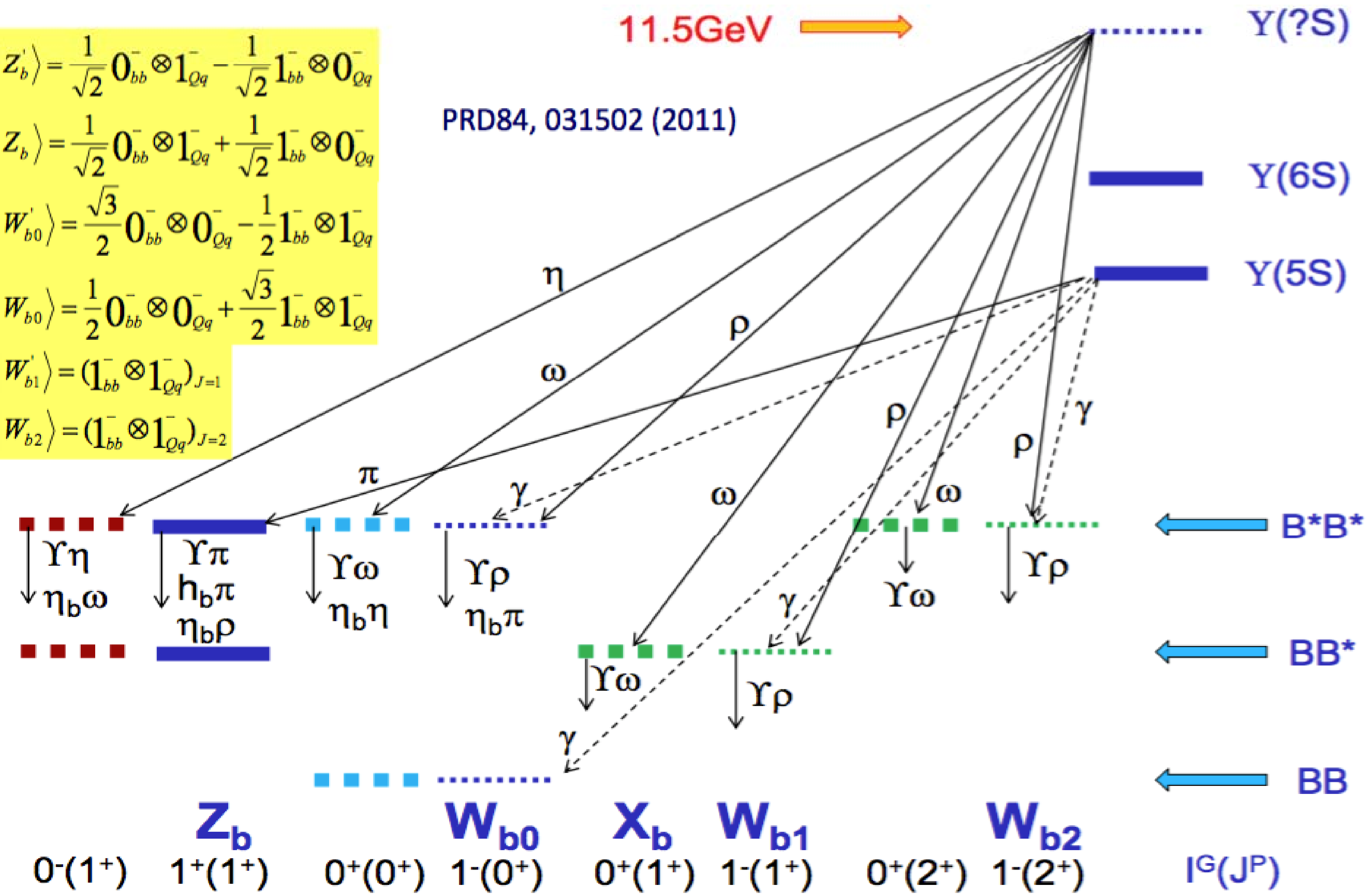
$$|Z_b\rangle = \frac{1}{\sqrt{2}} 0^-_{bb} \otimes 1^-_{Qq} + \frac{1}{\sqrt{2}} 1^-_{bb} \otimes 0^-_{Qq}$$

$$|W_{b0}'\rangle = \frac{\sqrt{3}}{2} 0^-_{bb} \otimes 0^-_{Qq} - \frac{1}{2} 1^-_{bb} \otimes 1^-_{Qq}$$

$$|W_{b0}\rangle = \frac{1}{2} 0^-_{bb} \otimes 0^-_{Qq} + \frac{\sqrt{3}}{2} 1^-_{bb} \otimes 1^-_{Qq}$$

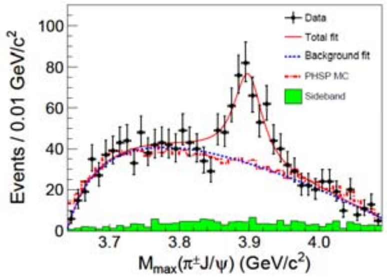
$$|W_{b1}'\rangle = (1^-_{bb} \otimes 1^-_{Qq})_{J=1}$$

$$|W_{b2}\rangle = (1^-_{bb} \otimes 1^-_{Qq})_{J=2}$$

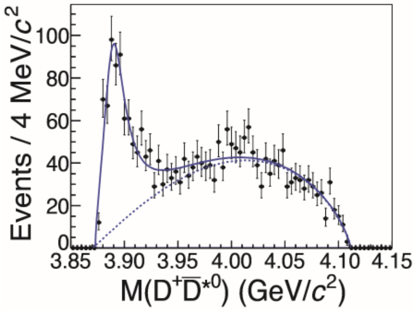

PRD84, 031502 (2011)

Input from the Belle II is critical!

Summary on Z_c States by BESIII

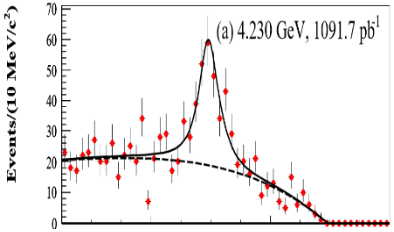


$e^+e^- \to \pi^+\pi^- J/\psi$

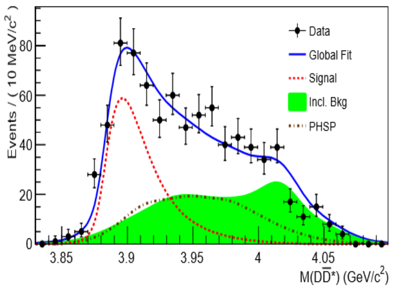


$e^+e^- \to \pi^+ (D\bar{D}^*)^-$

$Z_c(3900)^{\pm}$?

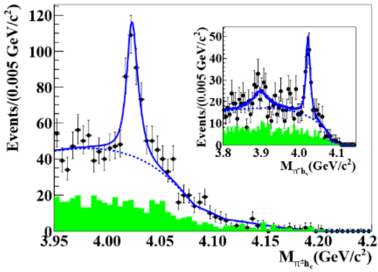


$e^+e^- \to \pi^0\pi^0 J/\psi$

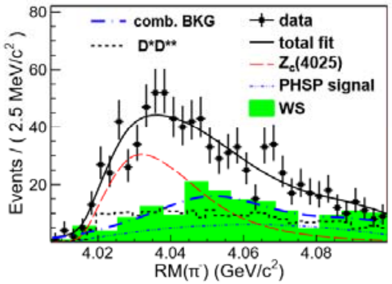


$e^+e^- \to \pi^0 (D\bar{D}^*)^0$

$Z_c(3900)^0$?

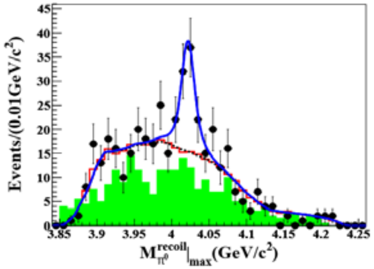


$e^+e^- \to \pi^+\pi^- h_c$

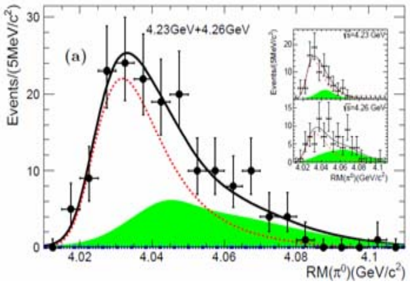


$e^+e^- \to \pi^+ (D^*\bar{D}^*)^-$

$Z_c(4020)^{\pm}$?



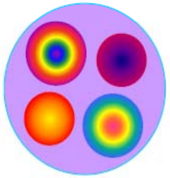
$e^+e^- \to \pi^0\pi^0 h_c$



$e^+e^- \to \pi^0 (D^*\bar{D}^*)^0$

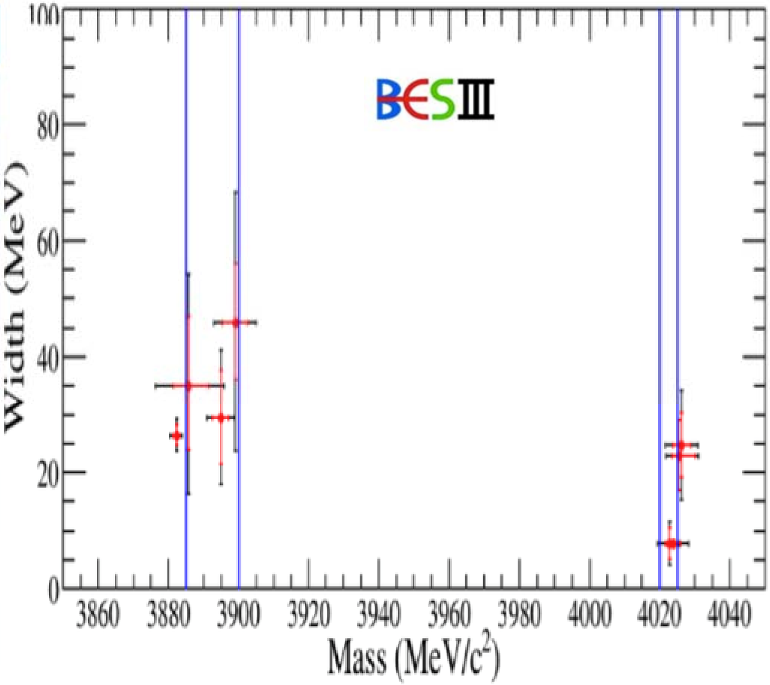
$Z_c(4020)^0$?

- If these structures are real QCD states, charged Z_c decays into $\pi^{+/-}$ J/ψ ($\pi^{+/-}h_c$) → at least four valence quarks to satisfy charge=±1 and strong couplings to ccbar components.



Summary on Z_c States by BESIII

State	Mass (MeV/c²)	Width (MeV)	Process
$Z_c(3900)^{\pm}$	3899.0±3.6±4.9	46±10±20	$e^+e^- \to \pi^+\pi^- J/\psi$
$Z_c(3900)^0$	3894.8±2.3±3.2	29.6±8.2±8.2	$e^+e^- \to \pi^0\pi^0 J/\psi$
$Z_c(3885)^{\pm}$ (ST)	3883.9±1.5±4.2	24.8±3.3±11.0	$e^+e^- \to \pi^{\mp}(D\bar{D}^*)^{\pm}$
$Z_c(3885)^{\pm}$ (DT)	3881.7±1.6±1.6	26.6±2.0±2.1	
Weighted average	3882.2±1.1±1.5	26.5±1.7±2.1	
$Z_c(3885)^0$ (DT)	$3885.7^{+4.3}_{-5.7}\pm8.4$	$35^{+11}_{-12}\pm15$	$e^+e^- \to \pi^0(D\bar{D}^*)^0$
$Z_c(4020)^{\pm}$	4022.9±0.8±2.7	7.9±2.7±2.6	$e^+e^- \to \pi^+\pi^- h_c$
$Z_c(4020)^0$	4023.9±2.2±3.8	7.9 (fixed)	$e^+e^- \to \pi^0\pi^0 h_c$
$Z_c(4025)^{\pm}$	4026.3±2.6±3.7	24.8±5.6±7.7	$e^+e^- \to \pi^{\mp}(D^*\bar{D}^*)^{\pm}$
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7}\pm3.1$	23.0±6.0±1.0	$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$



- $Z_c(3885)^{\pm}$ mass is about 2.6σ lower and the width 1.5σ lower than $Z_c(3900)^{\pm}$ value. If $Z_c(3885) = Z_c(3900)$, $\frac{\Gamma(Z_c(3885)^{\pm} \to (D\bar{D}^*)^{\pm})}{\Gamma(Z_c(3900)^{\pm} \to \pi^{\pm} J/\psi)} = 6.2 \pm 1.1 \pm 2.7$, coupling to $D\bar{D}^*$ is larger than to πJ/ψ;
- $Z_c(4020)^{\pm}$ and $Z_c(4025)^{\pm}$ mass and width are consistent within 1.5σ. If $Z_c(4020) = Z_c(4025)$, $\frac{\Gamma(Z_c(4025)^{\pm} \to (D^*\bar{D}^*)^{\pm})}{\Gamma(Z_c(4020)^{\pm} \to \pi^{\pm} h_c)} = 12 \pm 5$, coupling to $D^*\bar{D}^*$ is larger than to πh_c.

$Z_b^\pm$ Spin & Parity

Belle: Full (6D) amplitude analysis of the
$\Upsilon(5S) \to Z_b^\pm\pi^- \to \Upsilon(nS)\pi^+\pi^-$

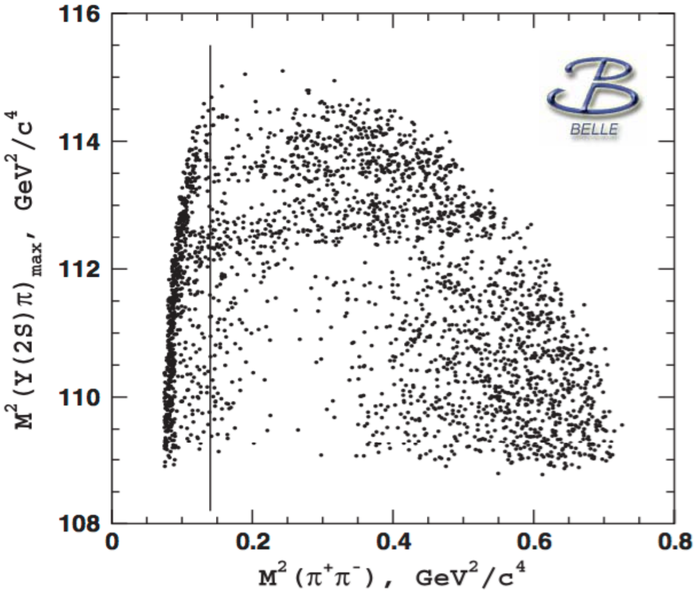
PRD91,072003 (2015)

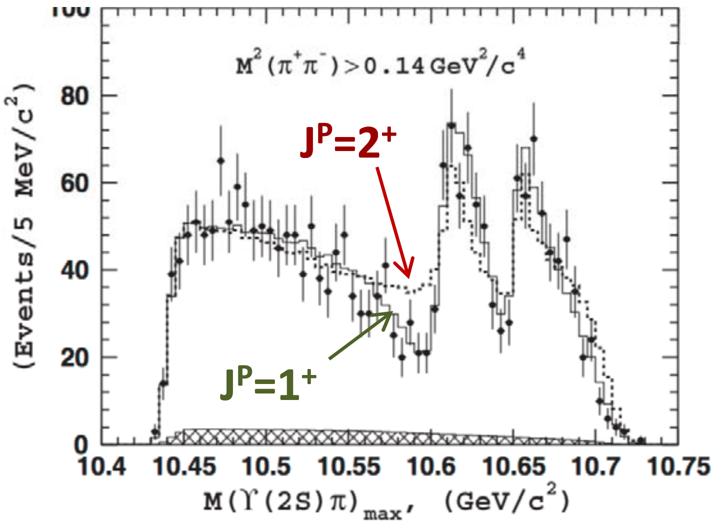
The $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ amplitude is parameterized as

$$\mathcal{M}_{\Upsilon\pi\pi} = \mathcal{A}_{Z_1\pi} + \mathcal{A}_{Z_2\pi} + \mathcal{A}_{\Upsilon\sigma} + \mathcal{A}_{\Upsilon f_0} + \mathcal{A}_{\Upsilon f_2} + \mathcal{A}_{\rm NR}$$

TABLE III. Results of the fit to $\Upsilon(2S)\pi^+\pi^-$ [$\Upsilon(3S)\pi^+\pi^-$] events with different J^P values assigned to the $Z_b(10610)$ and $Z_b(10650)$ states. Shown in the table is the difference in $\mathcal{L}$ values for fits to an alternative model and the nominal one.

	$Z_b(10650)$			
$Z_b(10610)$	1^+	1^-	2^+	2^-
1^+	0(0)	60(33)	42(33)	77(63)
1^-	226(47)	264(73)	224(68)	277(106)
2^+	205(33)	235(104)	207(87)	223(128)
2^-	289(99)	319(111)	321(110)	304(125)





Angular analysis strongly favors $J^P=1^+$ assignement

Spin Structure of Z_b

Molecules are not eigenstates of the total $b\bar{b}$ spin

PRD84,054010(2011)

Decomposition ⇒

$$|Z'_b\rangle = (0^-_{b\bar{b}} \otimes 1^-_{q\bar{q}} - 1^-_{b\bar{b}} \otimes 0^-_{q\bar{q}})/\sqrt{2}$$

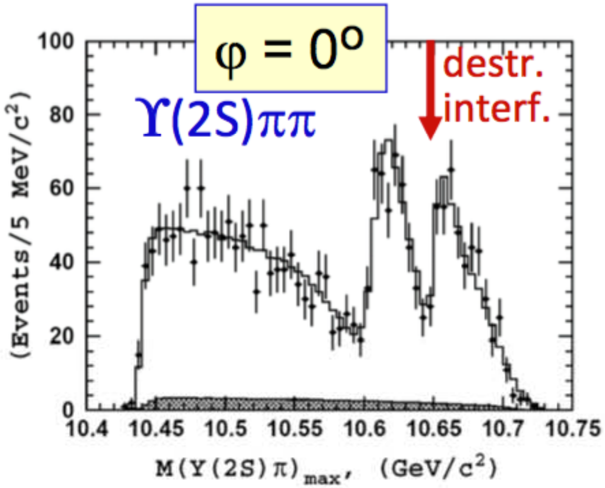
$$|Z_b\rangle = (0^-_{b\bar{b}} \otimes 1^-_{q\bar{q}} + 1^-_{b\bar{b}} \otimes 0^-_{q\bar{q}})/\sqrt{2}$$

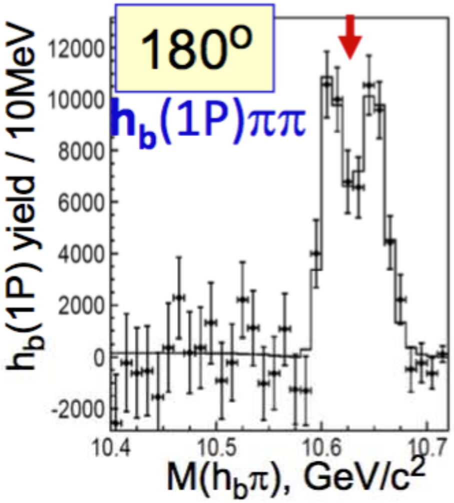
$h_b(mP)\pi$

$\Upsilon(nS)\pi$

relative phase

$$\boxed{BW(s, M_1, \Gamma_1) + ae^{i\phi} BW(s, M_2, \Gamma_2)}$$





Assumption of molecular structure allows to explain all properties of Z_b states.