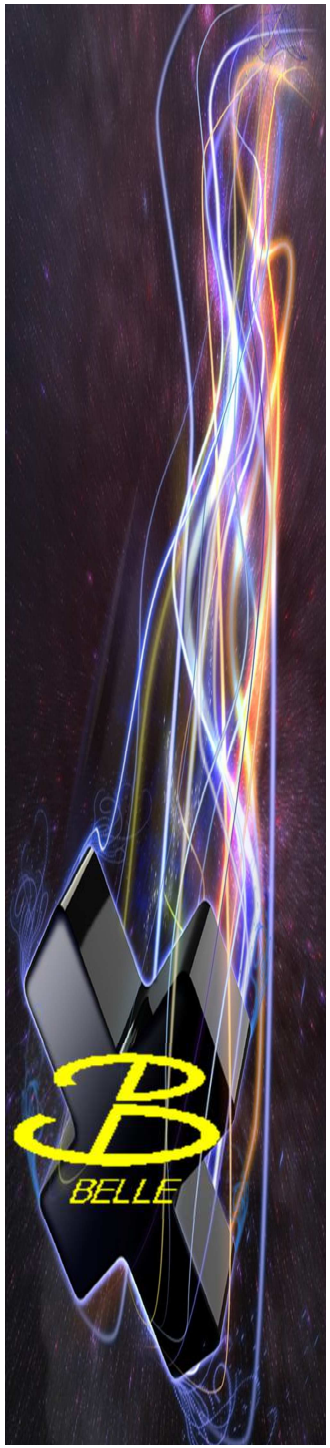
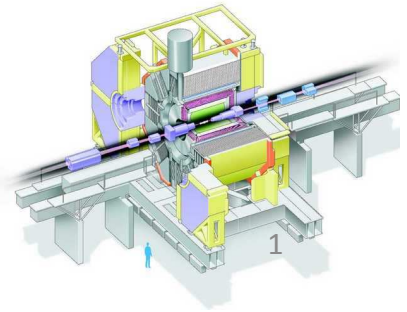
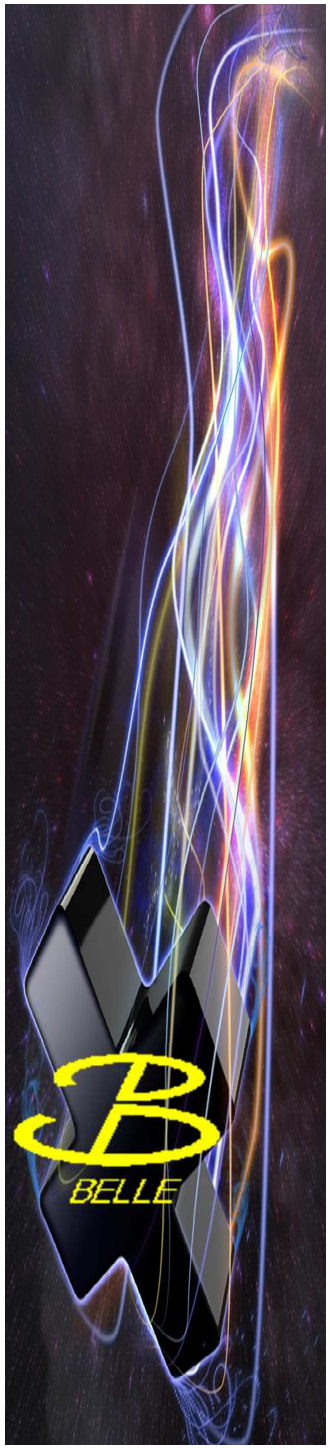


Studies of quarkonium and quarkonium-like exotic particles from Belle

Vishal Bhardwaj, NWU

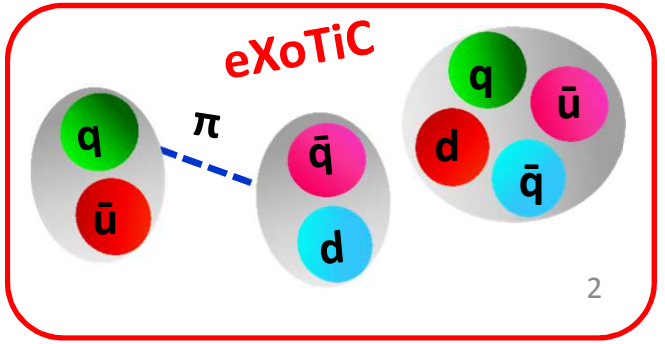
(for Belle collaboration)



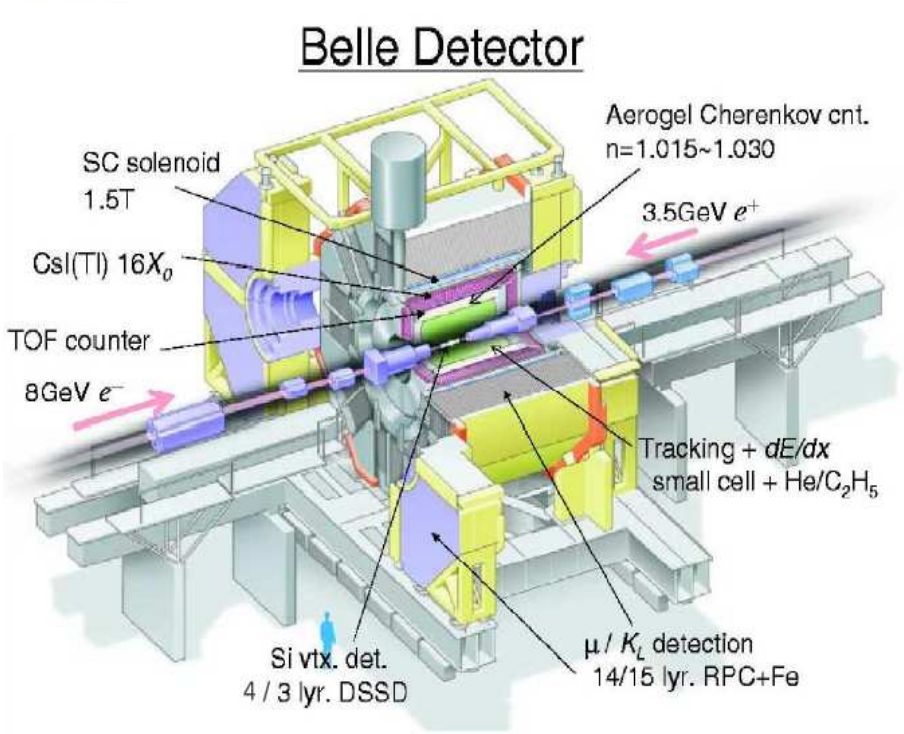


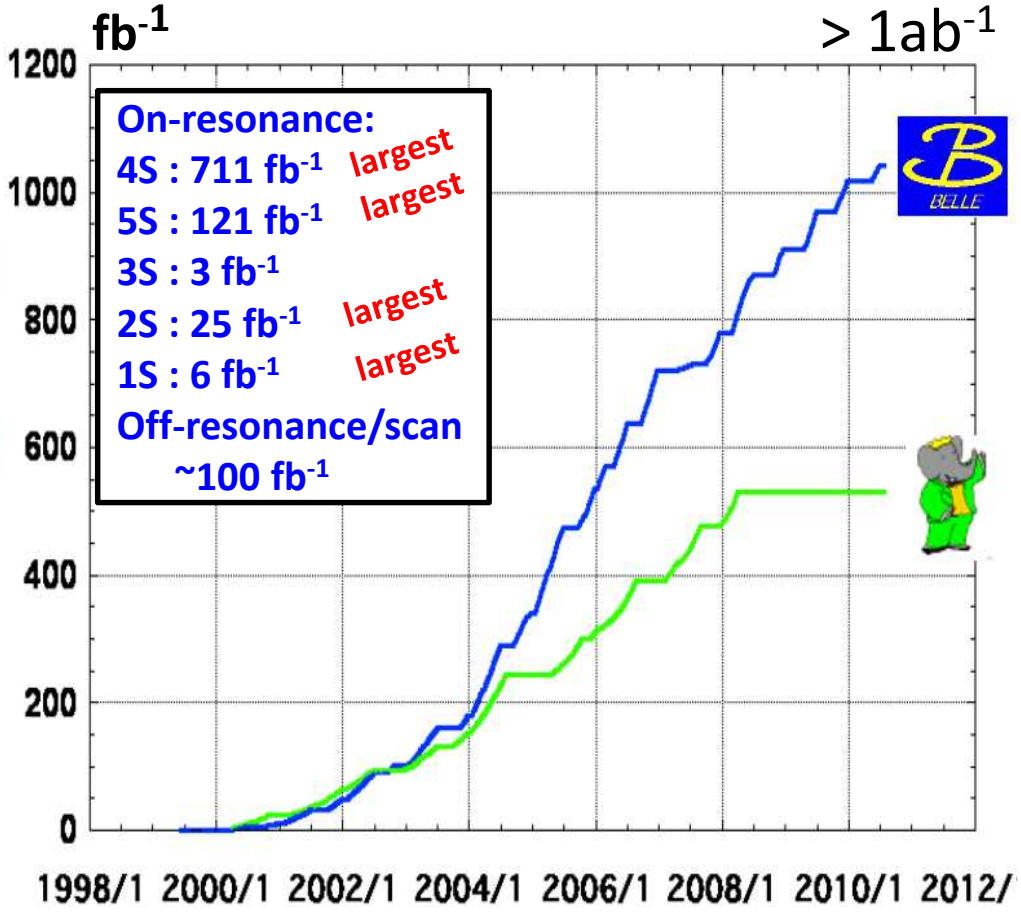
Outline

- Bottomonium (-like) family
  - $Z_b(10610)^+$ and $Z_b(10650)^+$ eXoTiC
  - Observation of neutral $Z_b(10610)^0$ eXoTiC
- Charmonium (-like) family
  - $Z(3895)^+$ eXoTiC
  - $Z(4430)^+$ eXoTiC
  - X(3823)
- Summary



qq̄ (-like) states at Belle





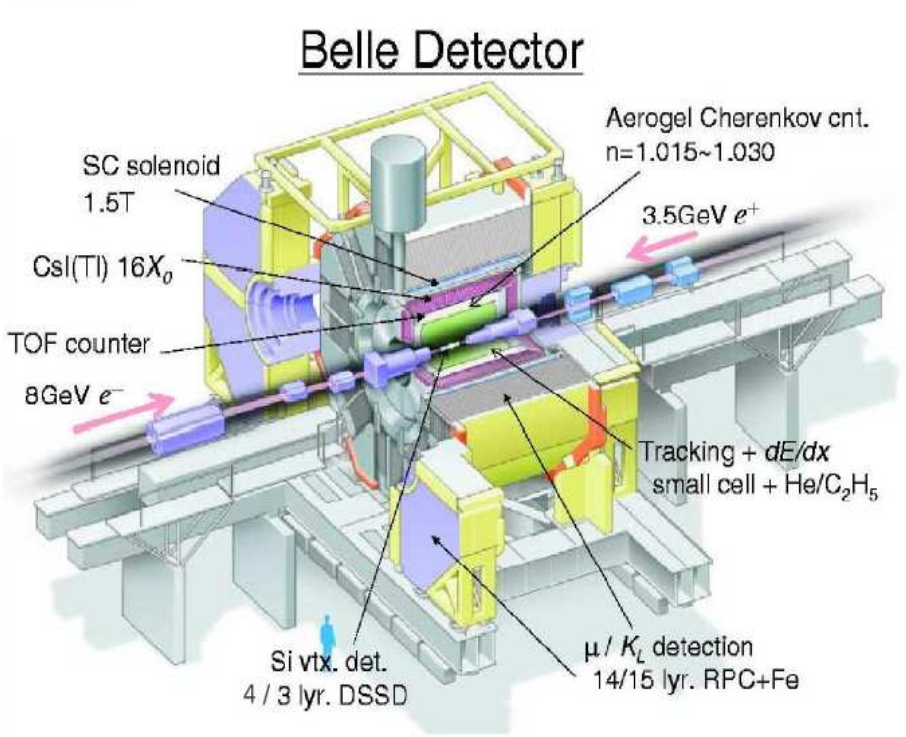
General purpose detector, built to test Standard Model mechanism for CP violation in B decays to charmonium ($B^0 \rightarrow J/\Psi, \Psi', \chi_{c1}\ K^0$).

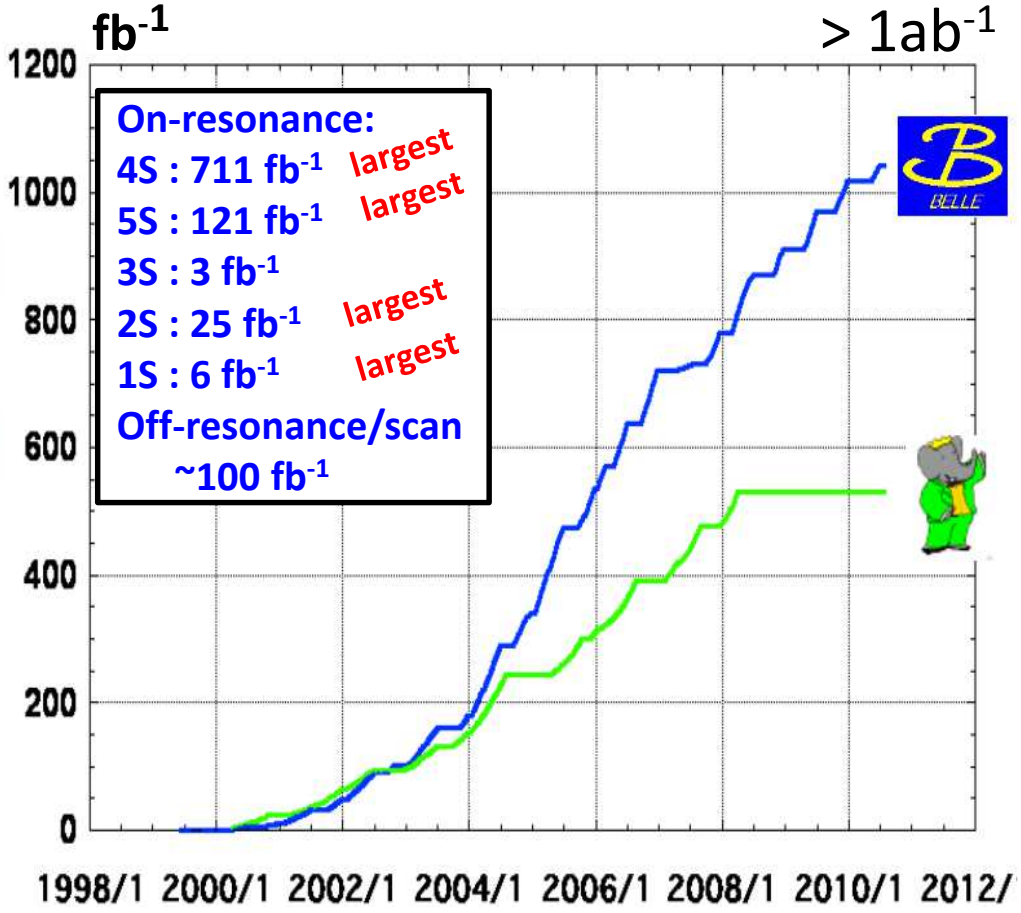
Belle,PRL 108, 171802 (2012)

Contribution to charmonium (-like) states:

$\eta_c(2S)$, X(3823), X(3872), $Z(3895)^+$, Y(3940), Z(3930), X(3940), X(3915), Y(4260), Y(4660), $Z(4430)^+$, $Z_1(4050)^+$, $Z_2(4250)^+$ …

$q\bar{q}$ (-like) states at Belle





General purpose detector, built to test Standard Model mechanism for CP violation in B decays to charmonium ($B^0 \rightarrow J/\Psi, \Psi', \chi_{c1}\ K^0$).

Belle,PRL 108, 171802 (2012)

Contribution to bottomonium (-like) states:

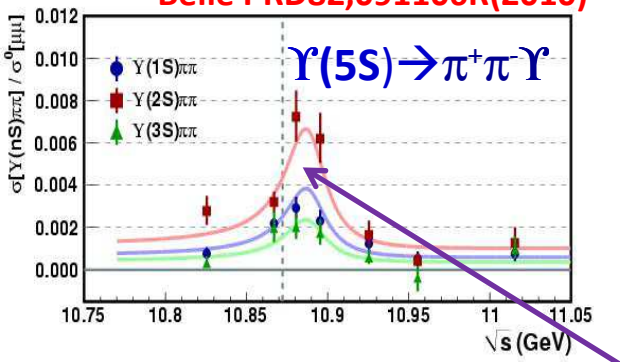
Y_b, $\eta_b(2S)$, $h_b(1P)$, $h_b(2P)$, $Z_b(10610)^+$, $Z_b(10610)^0$, $Z_b(10650)^+$, ...

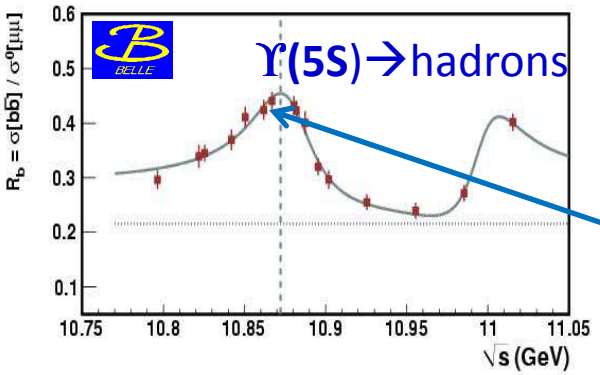
"Υ(5S)" more interesting than other Υ states

Anomalous large production of Υ(nS) $\pi^+\pi^-$ was observed at the Υ(5S) by Belle with 21 fb^{-1}.

Belle,PRL100,112001(2008)

Belle PRD82,091106R(2010)





	Γ(MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

x 10^{-2}

M = (10889.6±1.8±1.5) MeV

Γ = $54.7^{+8.5}_{-7.2}$±2.5 MeV

~2σ discrepancies in the peak mass and width

M = (10865±8) MeV

Γ = (110±13) MeV

Nature of Υ(5S) is puzzling

Exotic resonance Y_b near Υ(5S) analogue of Y(4260) resonance !

Belle found twin charged states $Z_b(10610)^+$ and $Z_b(10650)^+$ having masses just above B*B̄ and B*B̄* thresholds. Belle, PRL108, 122001 (2012)

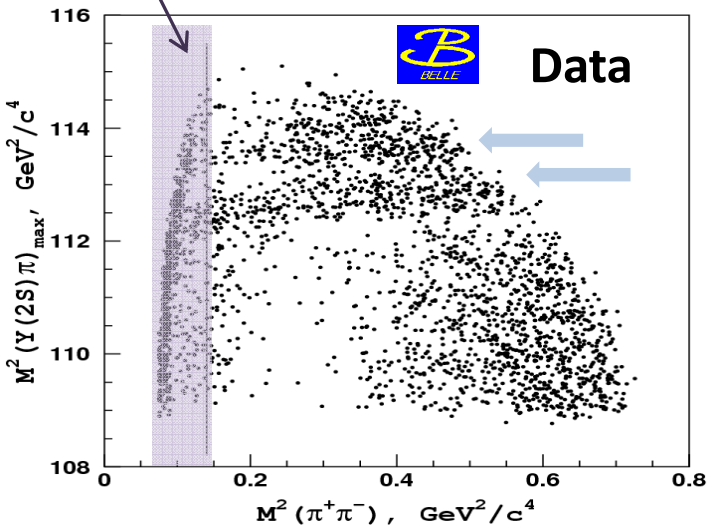
121 fb^{-1}

Measurement of J^P

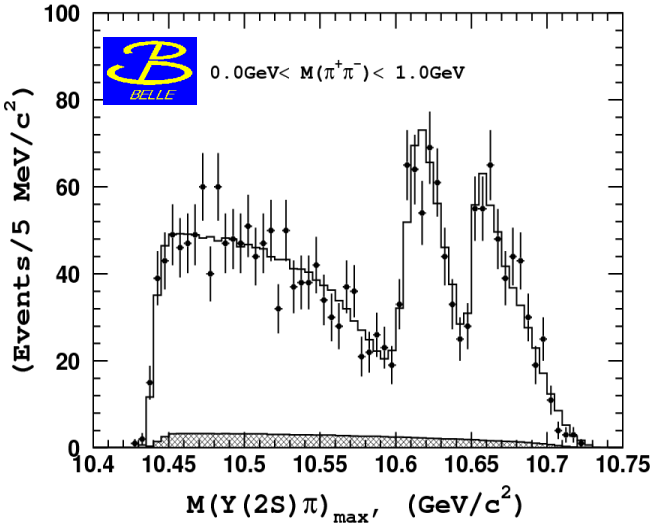
preliminary

Full amplitude analysis of $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^- \rightarrow \mu^+\mu^-\pi^+\pi^-$ (n=1,2,3)

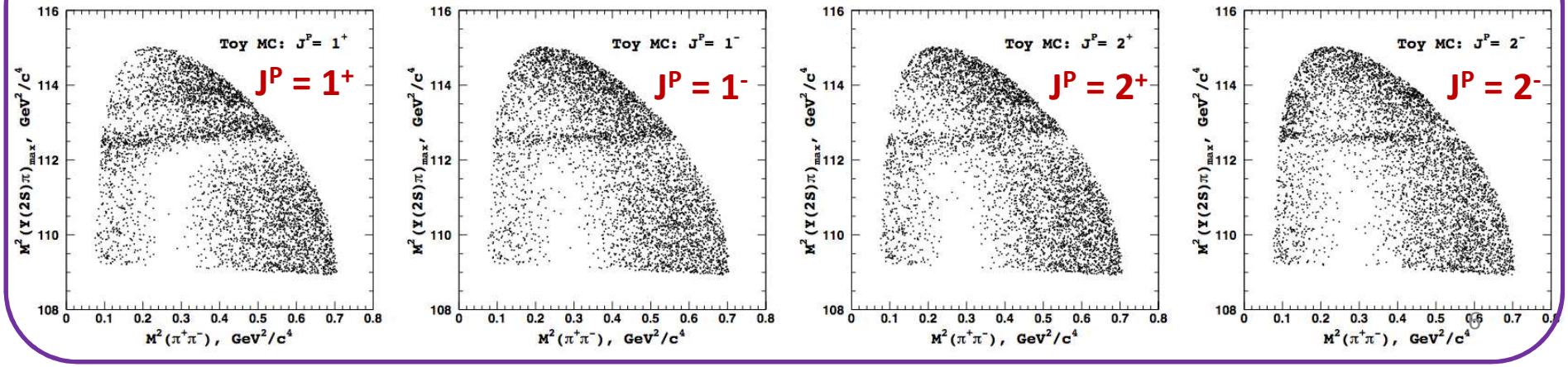
Excluded region with large background from photon conversions



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



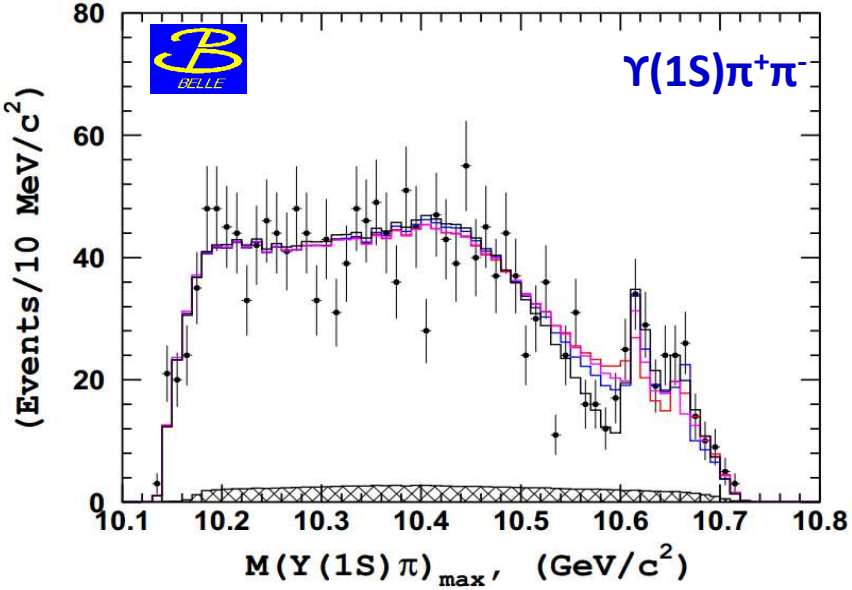
Toy MC with various J^P



121 fb^{-1}

J^P result

preliminary

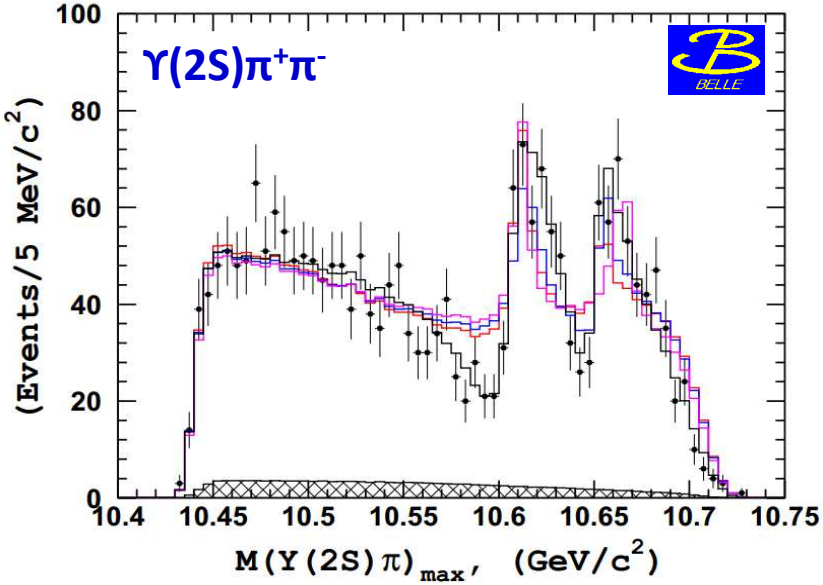


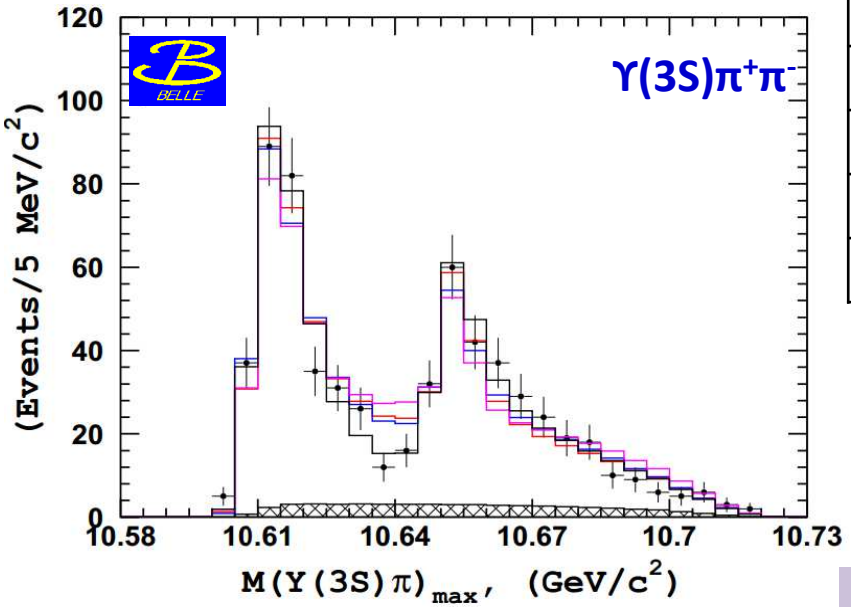
1^+

1^-

2^+

2^-





Projection in M(Υ(nS)π)$_{max}$

J^P Hypothesis\Decay Mode	Υ(1S)π⁺π⁻	Υ(2S)π⁺π⁻	Υ(3S)π⁺π⁻
1^+	0	0	0
1^-	64	264	73
2^+	41	207	87
2^-	59	304	125

Highest sensitivity provided by $e^+e^- \rightarrow \Upsilon(2S)\pi\pi$

Reject $J^P=1^-$ and $J^P=2^\pm$ combinations at confidence level exceeding 7σ.

Spin parity of $Z_b(10610)$ and $Z_b(10650)$ is 1^+

Nature of Z_b^+

$Z_b(10610)$

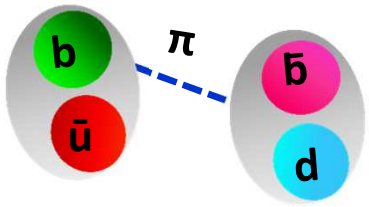
M=10607.2±2.0 MeV
Γ=18.4±2.4 MeV

PDG: $M_{\bar{B}} + M_{B^*} = 10604.8 \pm 0.4$ MeV

$Z_b(10650)$

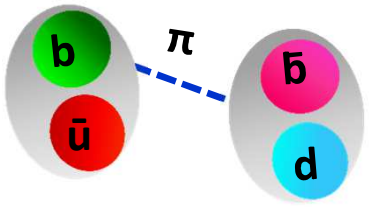
M=10652.2±1.5 MeV
Γ=11.5±2.2 MeV

PDG: $M_{\bar{B}^*} + M_{B^*} = 10650.4 \pm 0.8$MeV



Bondar *et al.* arXiv:1105.4473
Sun *et al.* PRD 84, 054002 (2011)
Zhang *et al.* PLB 704,312 (2011)
Ohkoda *et al.* PRD 86, 014004 (2012), …

Molecular picture



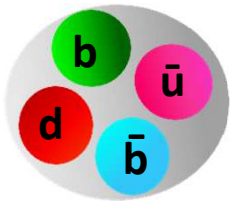
B^- B^{*0}

$M_{Z_b(106010)} - (M_B + M_{B^*}) = + 2.4 \pm 2.0$MeV

B^{*-} B^{*0}

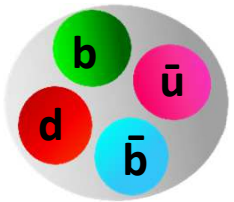
$M_{Z_b(106050)} - 2M_{B^*} = + 1.8 \pm 1.7$ MeV

Slightly unbound threshold resonances?



Karliner arXiv:0802.0649
Ali *et al.*PRD 85, 054011 (2012), …

Tetraquark picture



Coupled channel resonance : Dankiklin *et al.* PRD 85,034012 (2012)

Cusp: Bugg, Europhys. Lett.96,11002 (2011)

+ others …

I.S.P.E
PRD84,094003(2011)

If Z_b^+ is $B^*\bar{B}^{(*)}$ molecule, it should decay into $B^*\bar{B}^{(*)}$

Personal : Sorry, if I didn't cite your paper

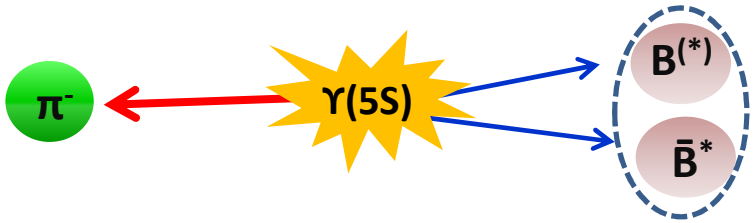
121 fb^{-1}

$\Upsilon(5S) \rightarrow B^{*}\bar{B}^{(*)}\pi$

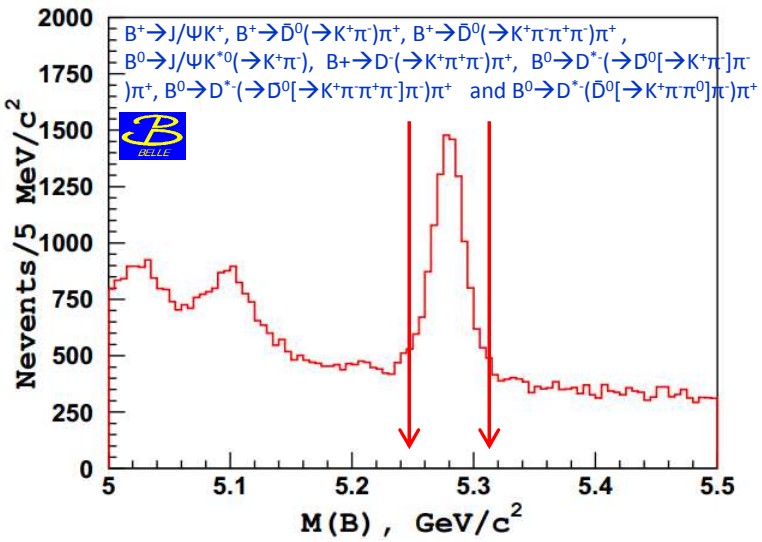
preliminary

Belle, arXiv:1209.6450

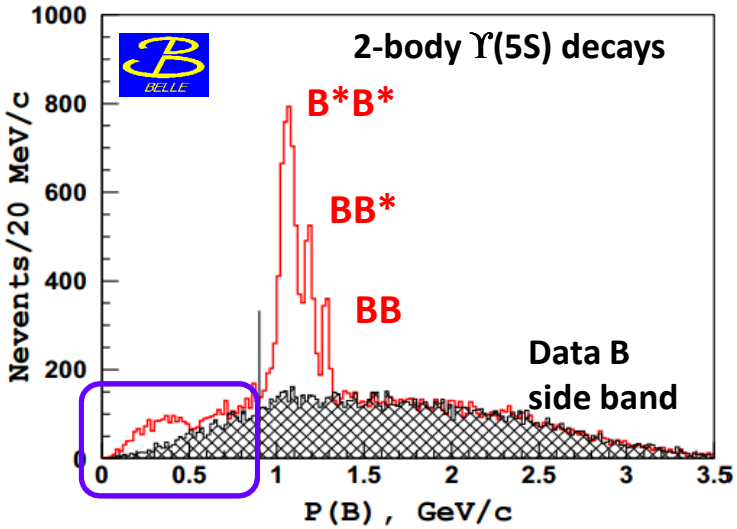
Masses of $Z_b(10610)^+$ and $Z_b(10650)^+$ close to $B\bar{B}^*$ and $B^*\bar{B}^*$ threshold



One B is fully reconstructed



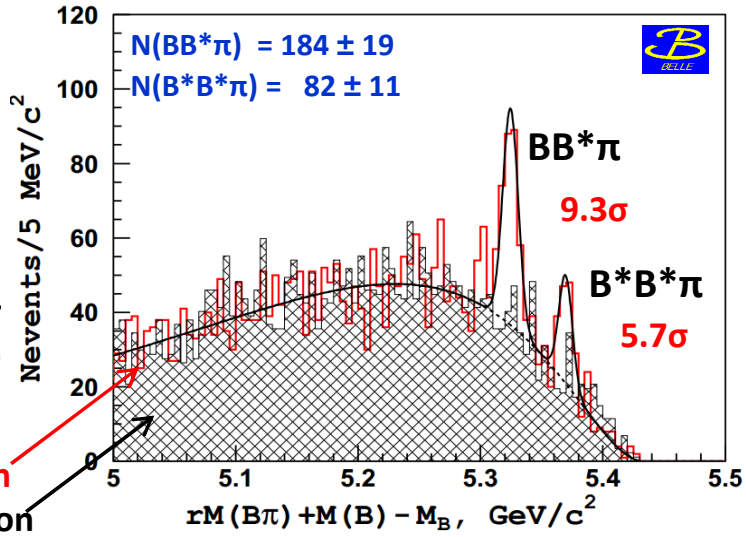
Select events by using cut in M(B) and p(B)



3 body $\Upsilon(5S) \rightarrow B(*)B(*)\pi$ decays and rad. return to $\Upsilon(4S)$: P(B) < 0.9 GeV/c

B is combined with π and recoil mass to (Bπ) combination is calculated

$$rM(B\pi) = \sqrt{E^2_{cms} - P^2_{B\pi}}$$



Right sign Bπ combination

Wrong sign Bπ combination

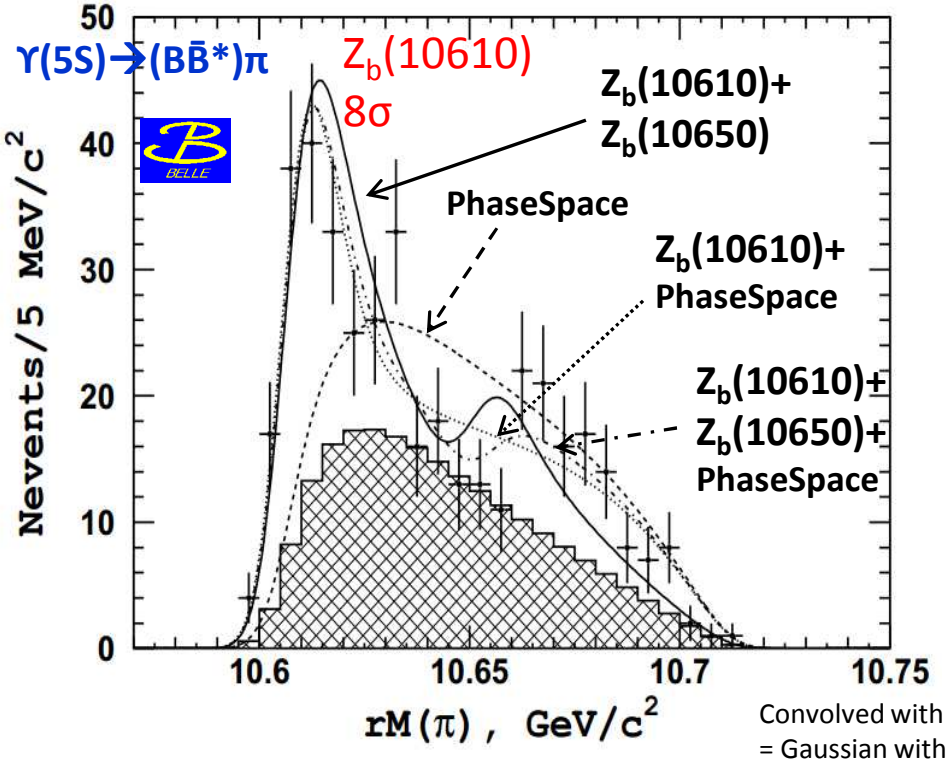
Look at recoil mass of (π) to see if there is Z_b peak.

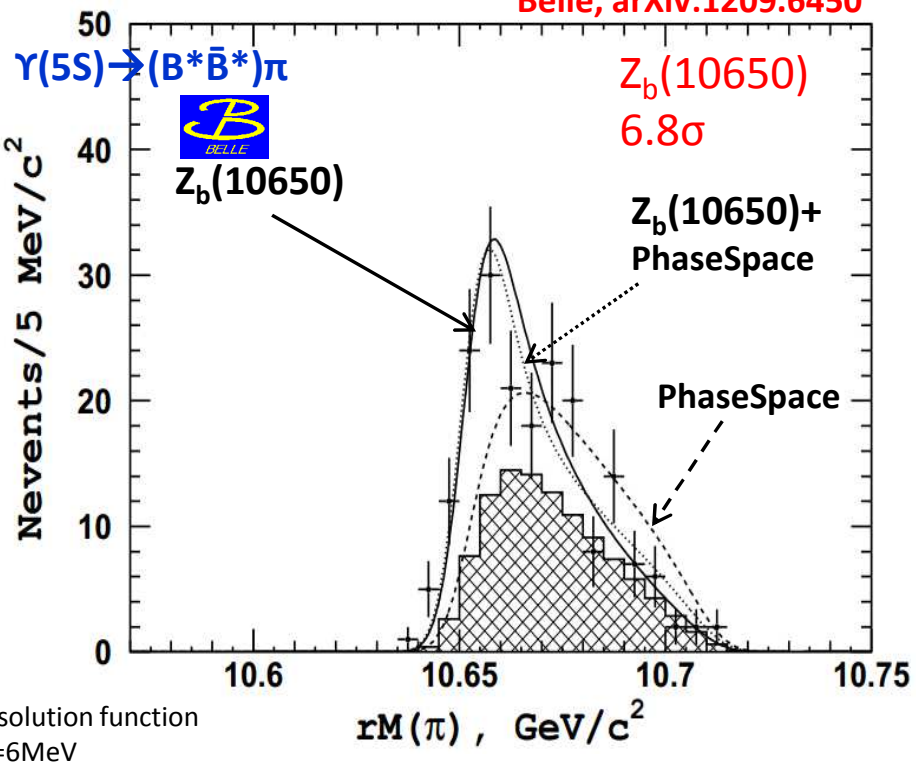
preliminary

Recoil mass of (π) in Υ(5S) → $B^*\bar{B}^{(*)}\pi$

121 fb^{-1}

Belle, arXiv:1209.6450





Convolved with resolution function
= Gaussian with σ=6MeV

Channel\Fraction(%)	$Z_b(10610)^+$	$Z_b(10650)^+$
$\Upsilon(1S)\pi^+$	0.32±0.09	0.24±0.07
$\Upsilon(2S)\pi^+$	4.38±1.21	2.40±0.63
$\Upsilon(3S)\pi^+$	2.15±0.56	1.64±0.40
$h_b(1P)\pi^+$	2.81±1.10	7.43±2.70
$h_b(2P)\pi^+$	4.34±2.07	14.8±6.22
$B\bar{B}^*$	86.0±3.6	-
$B^*\bar{B}^*$	-	73.4±7.0

- $Z_b(10610)^+$ in $B\bar{B}^*$ and $Z_b(10650)^+$ seen in $B\bar{B}^*/B^*\bar{B}^*$.
- $B^{(*)}B^*$ dominant mode of Z_b decays

Support molecular picture ?

Is there neutral partner ?

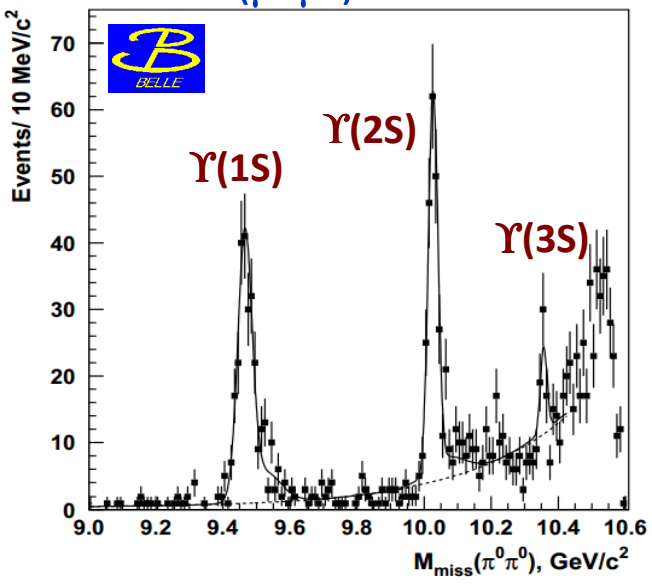
121 fb^{-1}

$\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^0\pi^0$

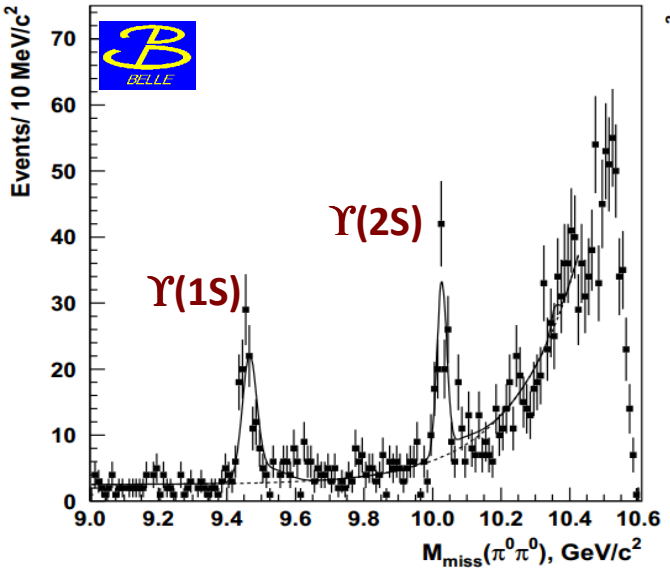
Belle, PRD88, 052016 (2013)

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

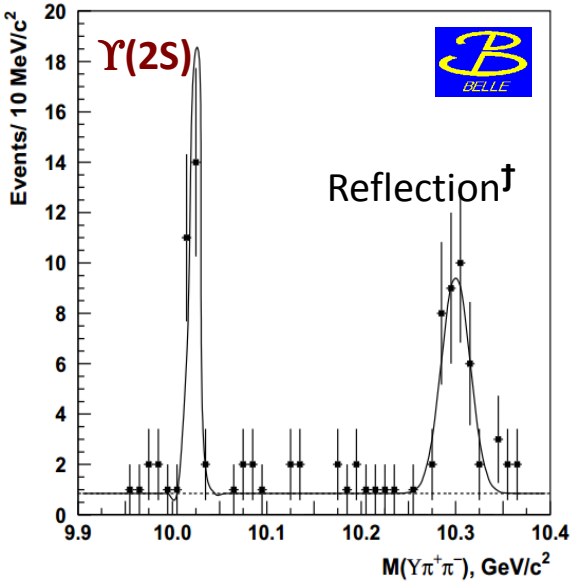
$(\mu^+\mu^-)\pi^0\pi^0$



$(e^+e^-)\pi^0\pi^0$



$(\Upsilon(1S)[\rightarrow l^+l^-]\,\pi^+\pi^-)\pi^0\pi^0$



$\sigma[e^+e^- \rightarrow \Upsilon(5S) \rightarrow \Upsilon(1S)\pi^0\pi^0] = (1.16 \pm 0.06 \pm 0.10)$ pb

$\sigma[e^+e^- \rightarrow \Upsilon(5S) \rightarrow \Upsilon(2S)\pi^0\pi^0] = (1.87 \pm 0.11 \pm 0.23)$ pb

$\sigma[e^+e^- \rightarrow \Upsilon(5S) \rightarrow \Upsilon(3S)\pi^0\pi^0] = (0.98 \pm 0.24 \pm 0.19)$ pb

Consistent with ½ of $\Upsilon(nS)\pi^+\pi^-$

† due to cross-feed from $\Upsilon(5S) \rightarrow \Upsilon(2S)[\rightarrow \Upsilon(1S)\pi^0\pi^0]\pi^+\pi^+$

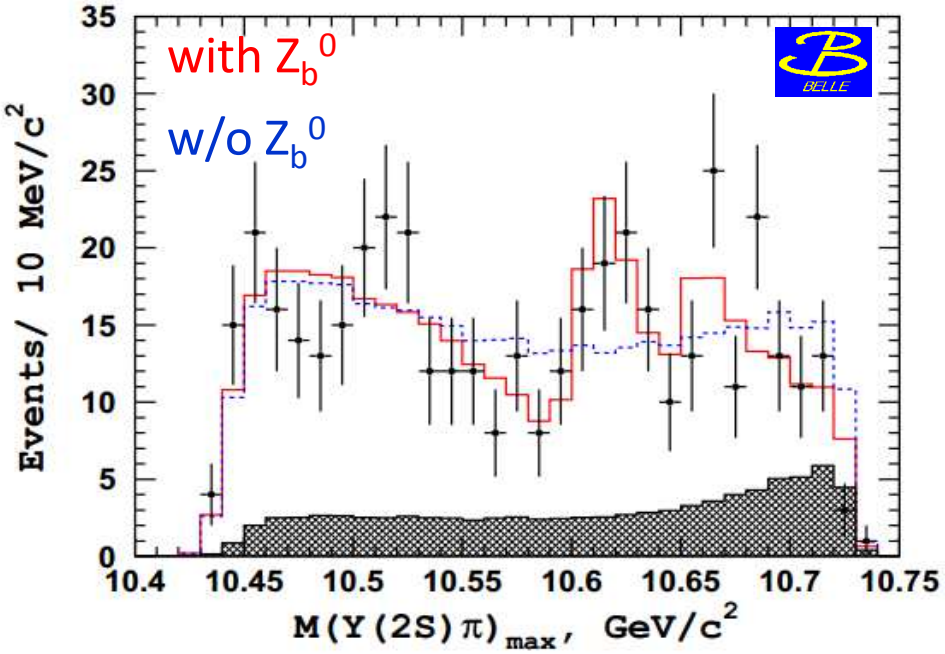
121 fb^{-1}

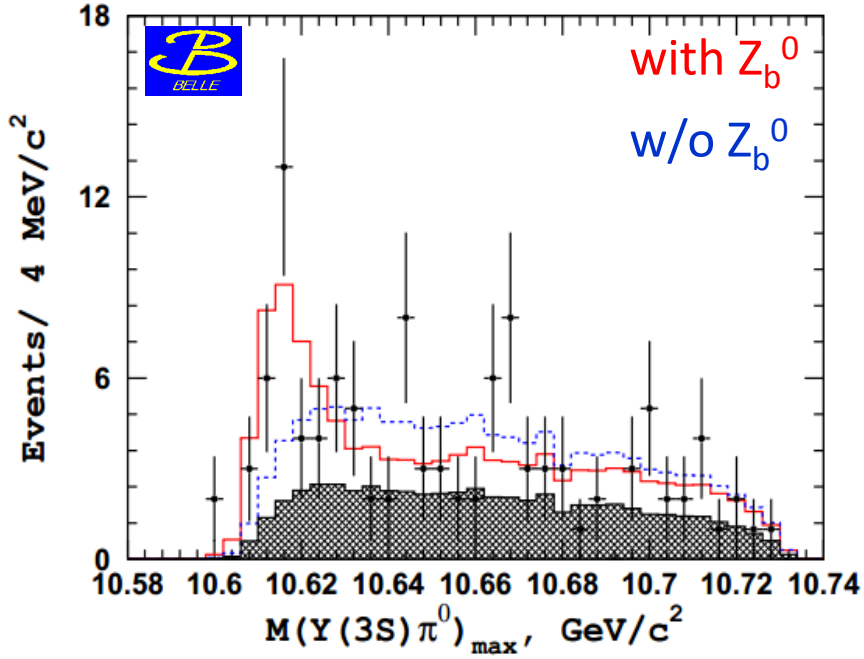
Neutral Z_b^0 in $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^0\pi^0$

Belle, PRD88, 052016 (2013)

Dalitz analysis

$M = A_{Z1} + A_{Z2} + A_{f0} + A_{f2} + a^{NR}$





$Z_b(10650)^0$ is included in the fit

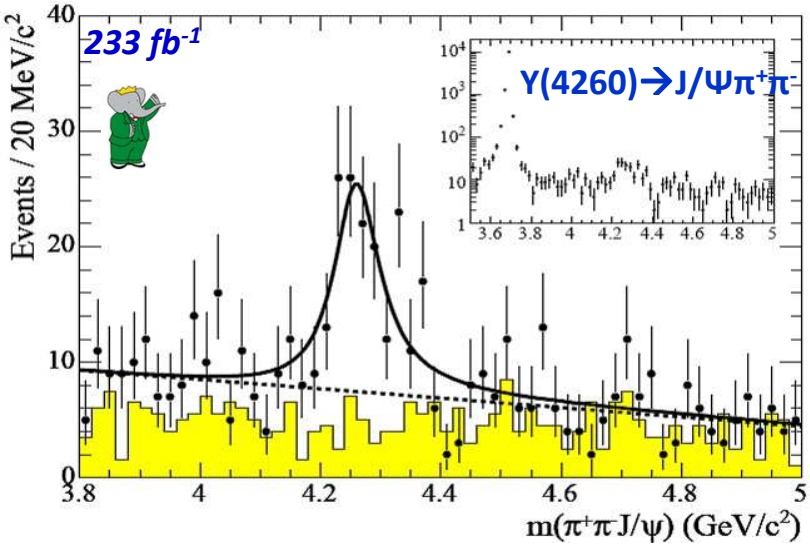
- Z_b^0 resonant structure observed in $\Upsilon(2S)\pi^0\pi^0$ and $\Upsilon(3S)\pi^0\pi^0$.
- Statistical significance of $Z_b(10610)^0$ is 6.5σ (including systematics).
- Our data consistent with existence $Z_b(10650)^0$, but available statistics insufficient for observation of it.
- $Z_b(10610)^0$ mass from fit : 10609±4±4 MeV/c^2

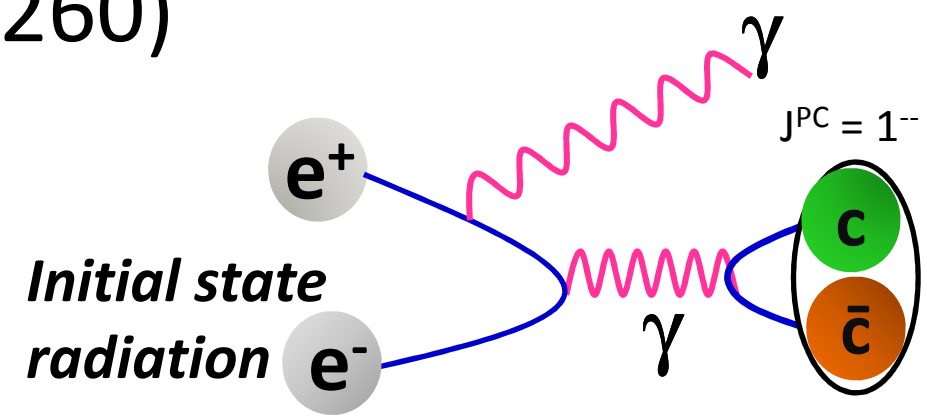
$M[Z_b(10610)^+] = 10607.2 \pm 2.0$ MeV/c^2

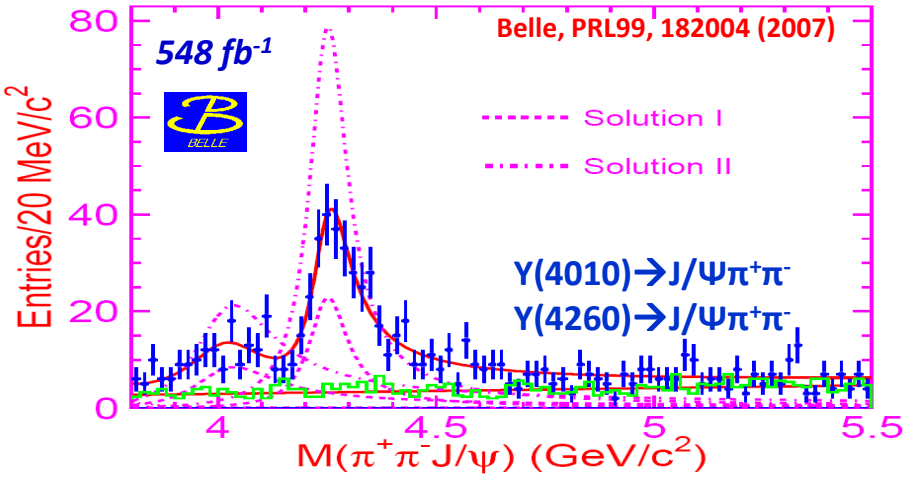
First observation of $Z_b(10610)^0$

Y(4260)

BaBar, PRL95, 142001 (2005)





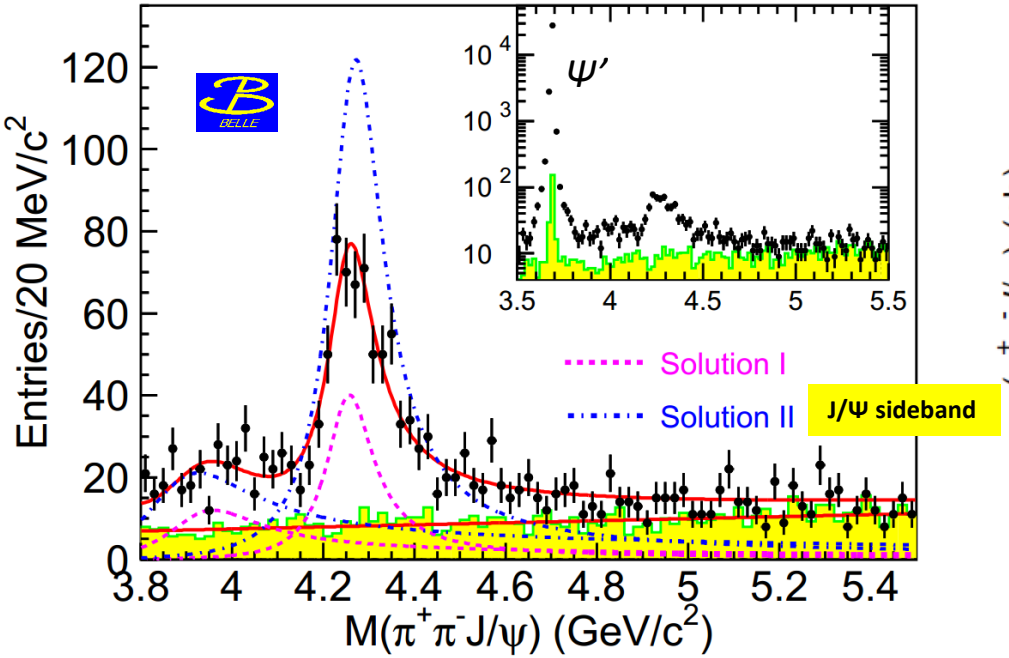


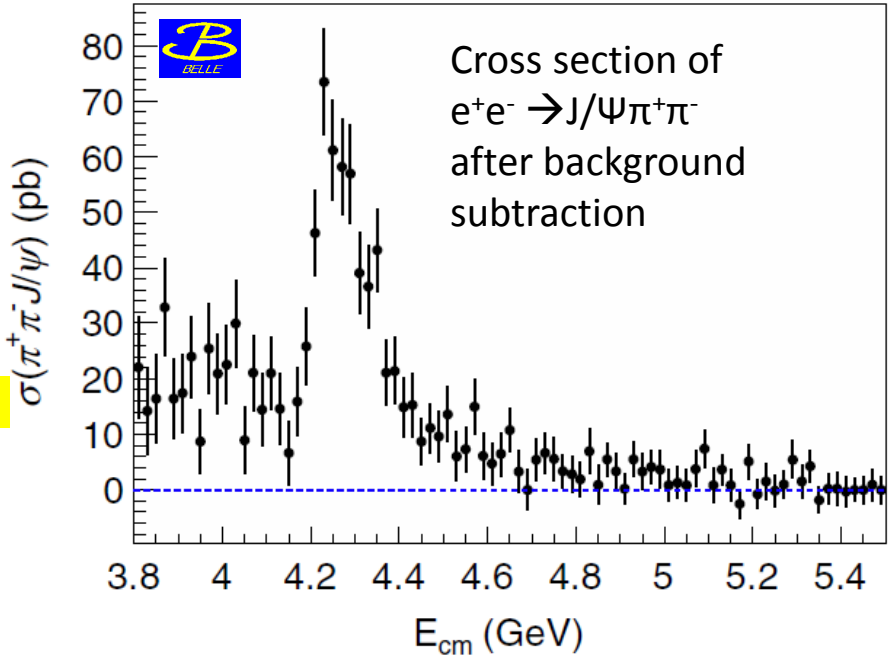
	Name	Process	M (MeV/c^2)	Γ (MeV)
BaBar(233 fb^{-1})	Y(4260)	J/Ψππ	$4259\pm8^{+2}_{-6}$	$88\pm23^{+6}_{-4}$
Belle (548 fb^{-1})	Y(4260)	J/Ψππ	$4247\pm12^{+17}_{-32}$	$108\pm19\pm10$
Belle (548fb^{-1})	Y(4010) ?	J/Ψππ	$4008\pm40^{+114}_{-28}$	$226\pm44\pm87$

Also confirmed by CLEO-c and CLEOIII !

967 fb^{-1}

Revisit Y @ Belle

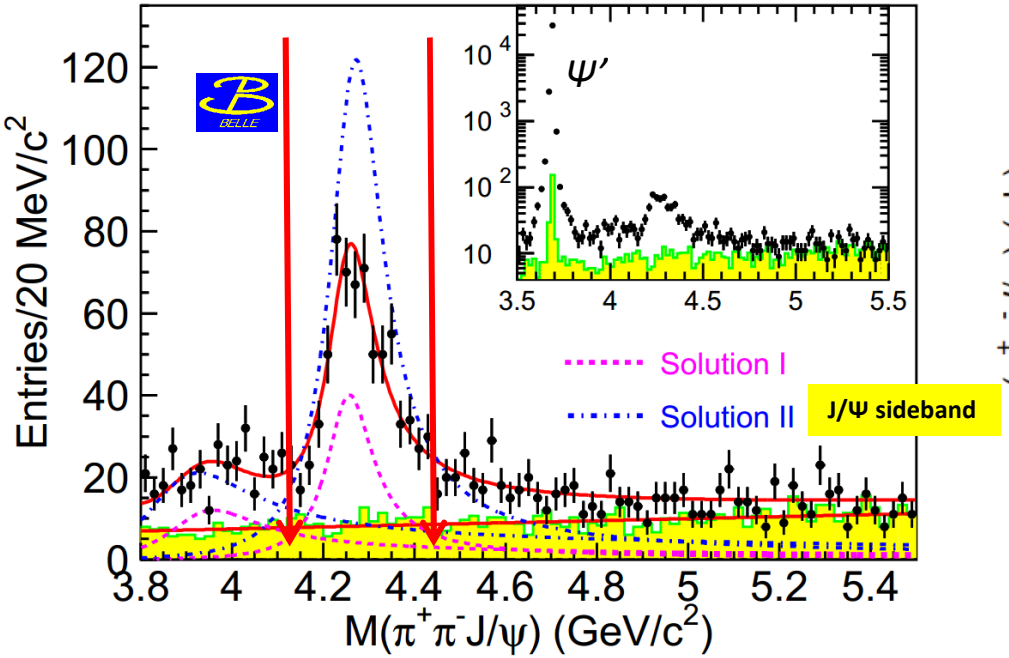


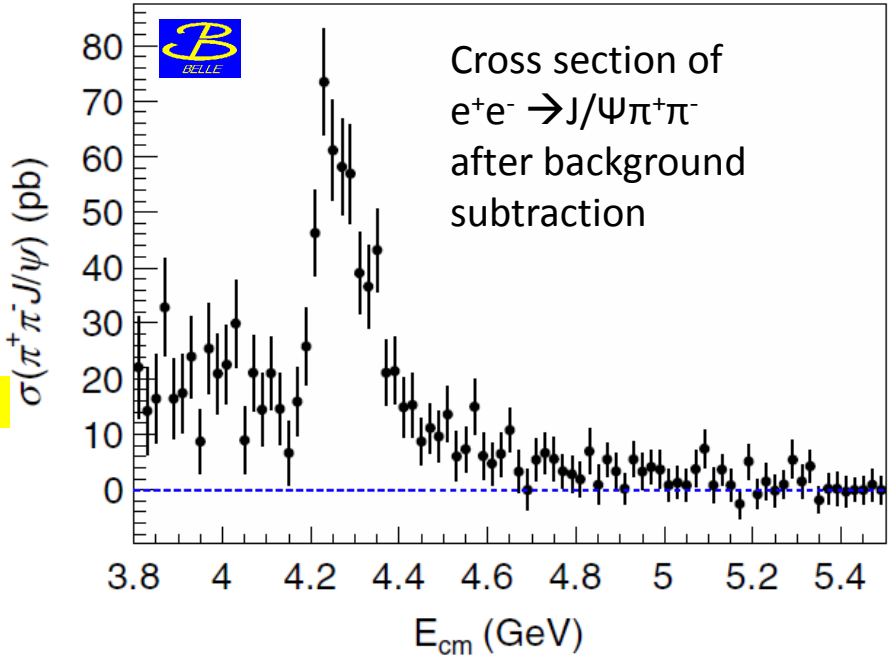


Parameters	Solution I	Solution II
$M(R_1)$	$3890.8 \pm 40.5 \pm 11.5$	
$\Gamma_{\rm tot}(R_1)$	$254.5 \pm 39.5 \pm 13.6$	
$\Gamma_{ee}\mathcal{B}(R_1 \to \pi^+\pi^- J/\psi)$	$(3.8 \pm 0.6 \pm 0.4)$	$(8.4 \pm 1.2 \pm 1.1)$
$M(R_2)$	$4258.6 \pm 8.3 \pm 12.1$	
$\Gamma_{\rm tot}(R_2)$	$134.1 \pm 16.4 \pm 5.5$	
$\Gamma_{ee}\mathcal{B}(R_2 \to \pi^+\pi^- J/\psi)$	$(6.4 \pm 0.8 \pm 0.6)$	$(20.5 \pm 1.4 \pm 2.0)$
ϕ	$59 \pm 17 \pm 11$	$-116 \pm 6 \pm 11$

967 fb^{-1}

Revisit Y @ Belle

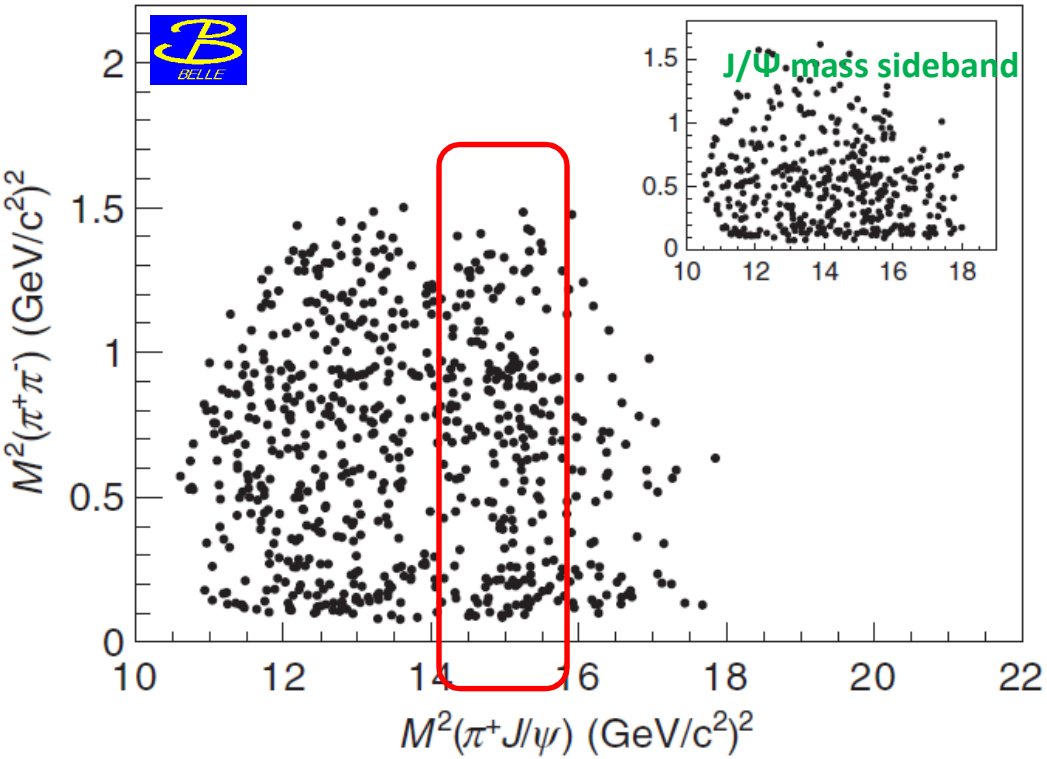




Parameters	Solution I	Solution II
$M(R_1)$	$3890.8 \pm 40.5 \pm 11.5$	
$\Gamma_{\rm tot}(R_1)$	$254.5 \pm 39.5 \pm 13.6$	
$\Gamma_{ee}\mathcal{B}(R_1 \to \pi^+\pi^- J/\psi)$	$(3.8 \pm 0.6 \pm 0.4)$	$(8.4 \pm 1.2 \pm 1.1)$
$M(R_2)$	$4258.6 \pm 8.3 \pm 12.1$	
$\Gamma_{\rm tot}(R_2)$	$134.1 \pm 16.4 \pm 5.5$	
$\Gamma_{ee}\mathcal{B}(R_2 \to \pi^+\pi^- J/\psi)$	$(6.4 \pm 0.8 \pm 0.6)$	$(20.5 \pm 1.4 \pm 2.0)$
ϕ	$59 \pm 17 \pm 11$	$-116 \pm 6 \pm 11$

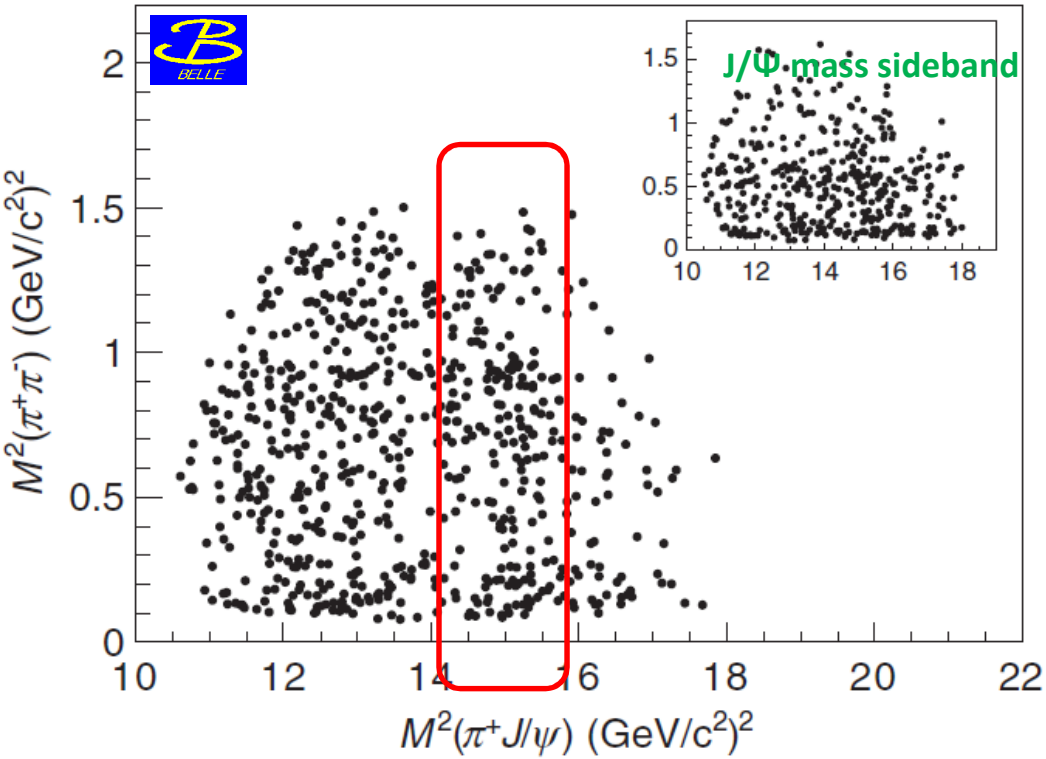
967 fb^{-1}

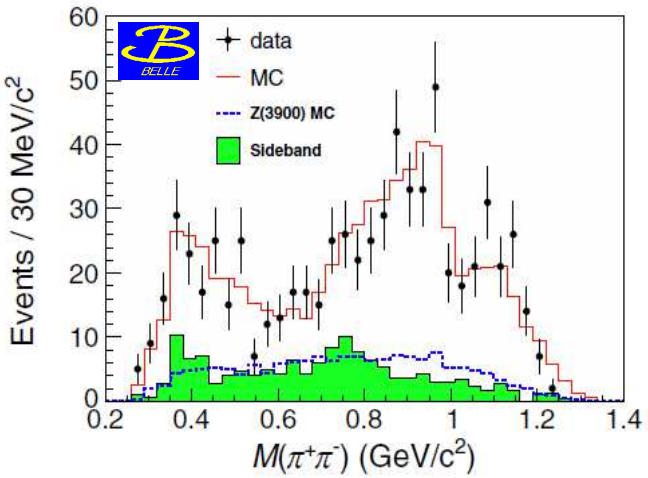
Intermediate state in Y(4260)→J/Ψππ

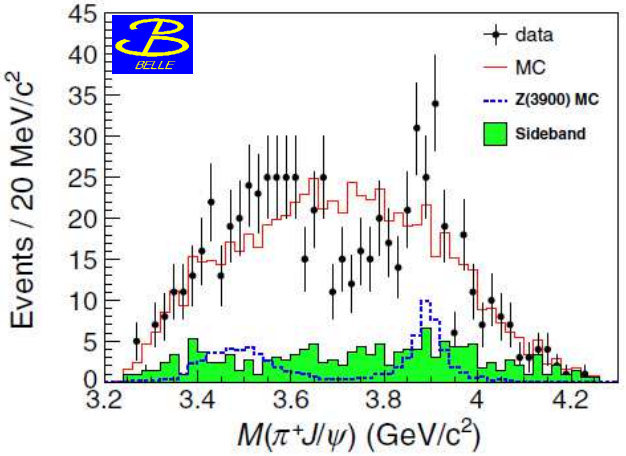


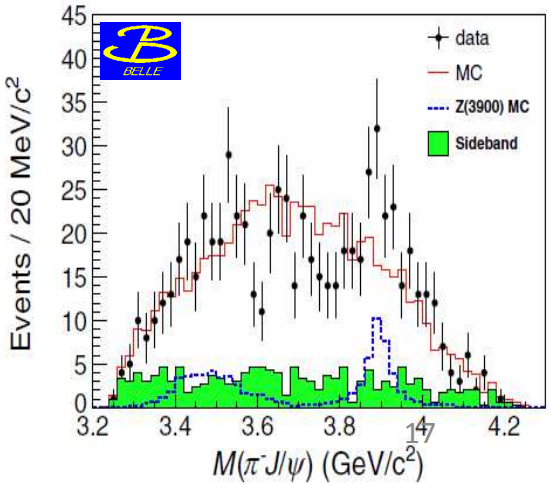
967 fb^{-1}

Intermediate state in Y(4260)→J/Ψππ



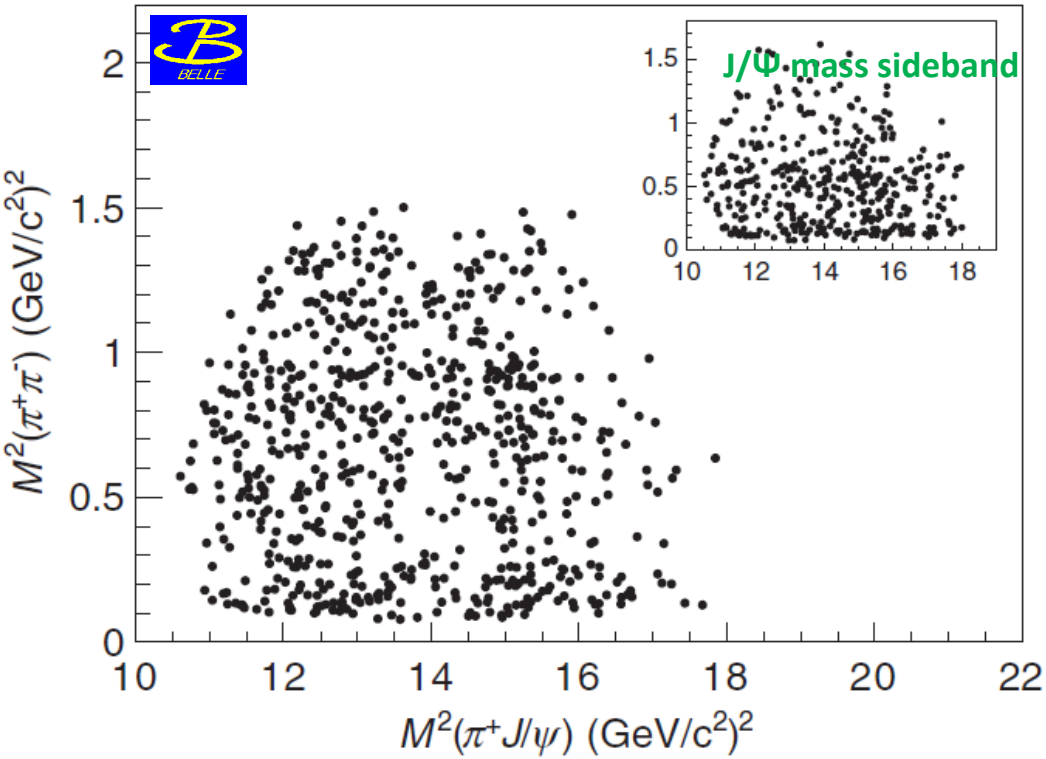


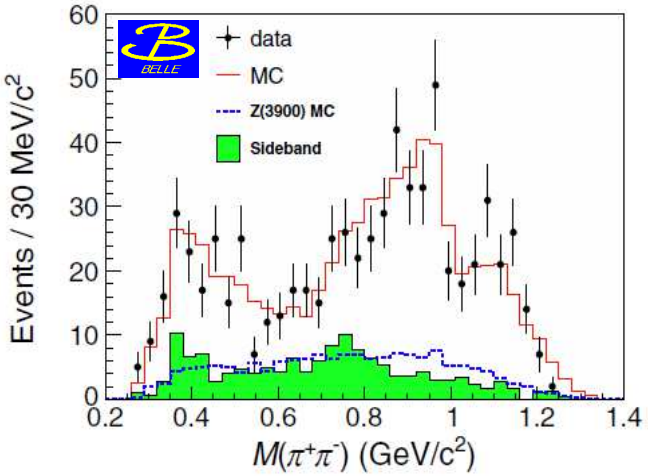


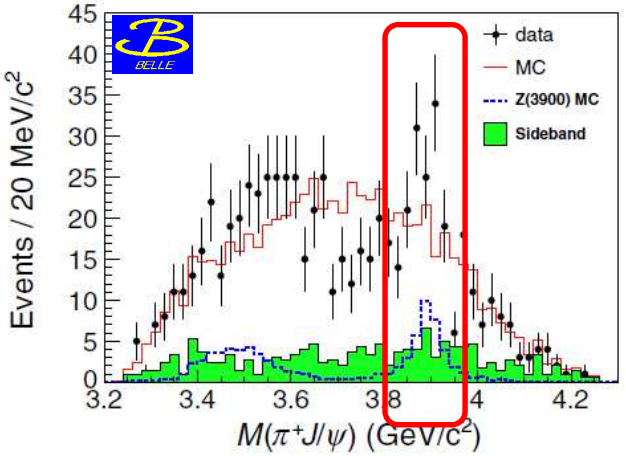


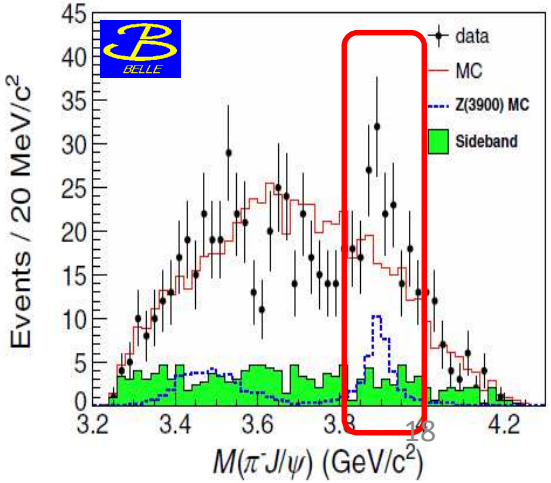
967 fb^{-1}

Intermediate state in Y(4260)→J/Ψππ



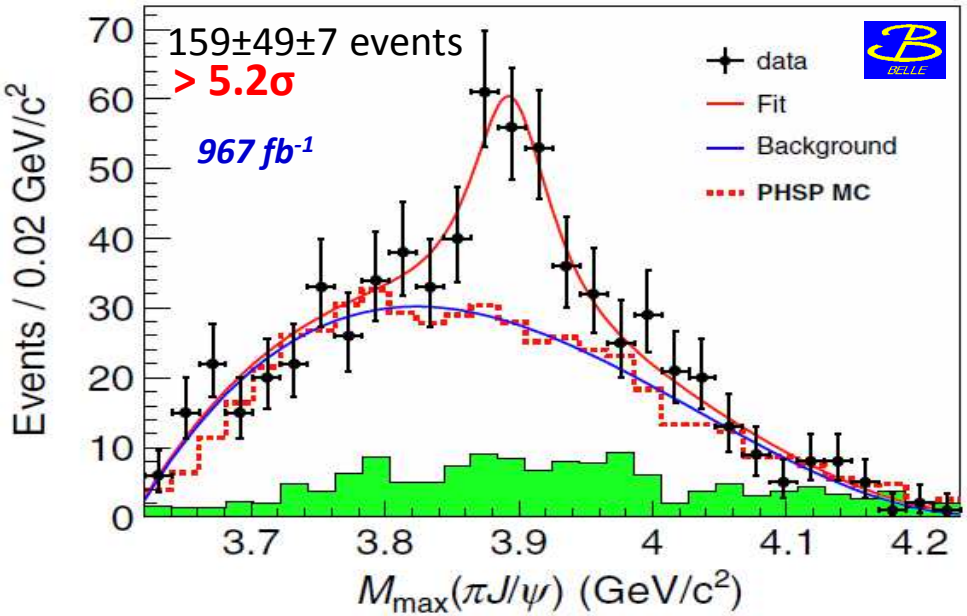






Observation of Z(3895)$^+$

Belle PRL110, 252002 (2013)



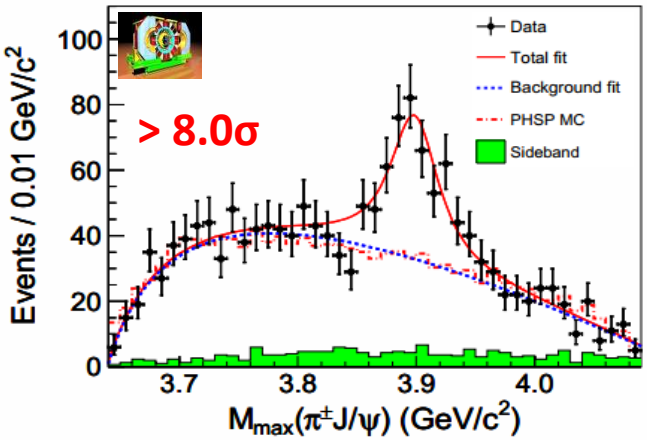
Measured properties

- Mass = (3894.5±6.6± 4.5) MeV/c^2
- Width = (63±24±26) MeV/c^2

$$\frac{BR[Y(4260) \to Z(3895)^{\pm}\pi^{\mp}]}{BR[Y(4260) \to J/\psi\pi^+\pi^-]} = (29.0 \pm 8.9)\%$$

Test hypothesis that interference between S and D waves in $\pi^+\pi^-$ system might produce structure similar to the enhancement.

➢ Partial waves alone cannot produce $J/\Psi\pi^{\pm}$ invariant mass peak near 3.9 GeV/c^2.



BESIII PRL110, 252001 (2013)

Measured by BES III

- Mass = (3899.0±3.6± 4.9) MeV/c^2
- Width = (46±10±20) MeV/c^2

$$\frac{BR[Y(4260) \to Z(3900)^{\pm}\pi^{\pm}]}{BR[Y(4260) \to J/\psi\pi^+\pi^-]} = (21.5 \pm 3.3)\%$$

T. Xiao, *et al.* arXiv:1304.3036

Using CLEO data, T. Xiao *et al.* has also confirmed Z$^+$ and claim for an evidence for neutral Z !

711 fb^{-1}

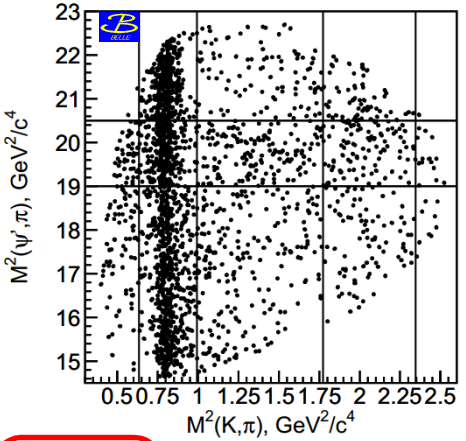
Quantum number of Z(4430)$^+$

Belle,PRD 88, 074026 (2013)

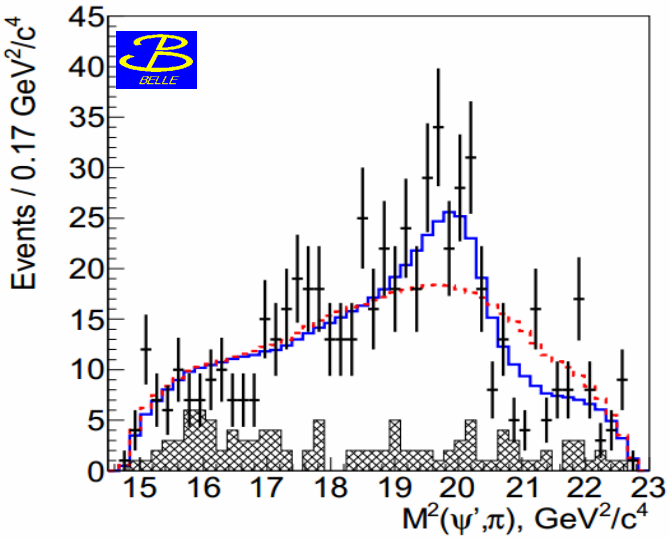
$B^0 \rightarrow (\Psi'\pi^+)K^-$ decay mode

Amplitude analysis in 4D space is performed

M(Kπ), M(Ψ'π),Ψ' helicity and angle between Ψ' and K*

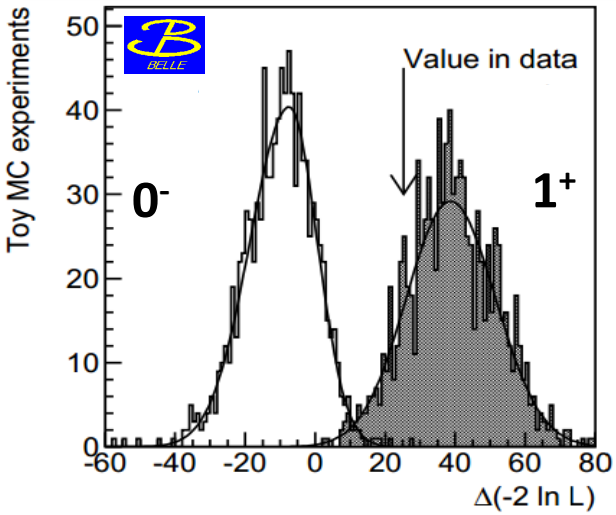


Projection of the fit results with K* veto



Mass and width consistent with previous Belle result

J^P	0^-	1^-	1^+	2^-	2^+
Mass,MeV/c^2	4479±16	4477±4	4485±20	4478±22	4384±19
Width,MeV	110±50	22±14	200±40	83±25	52±28
Significance	4.5σ	3.6σ	6.4σ	2.2σ	1.8σ



1^+ hypothesis is favored

Exclusion levels calculated from toy MC

- **0^- not excluded**
- **1^+ is favored over 0^- by 2.9σ**
- **1^-, 2^- and 2^+ are excluded at levels of 5.5σ,4.3σ and 5.4σ**

BR($B^0 \rightarrow \Psi' K^+\pi^-$) = (5.80±0.39)x 10^{-4}

BR($B^0 \rightarrow \Psi' K^*(892)$)=($5.55^{+0.22+0.41}_{-0.23-0.84}$)x 10^{-4}

BR($B^0 \rightarrow Z(4430)^- K^+$) x BR($Z(4430)^- \rightarrow \Psi'\pi^-$)= $6.0^{+1.7+2.5}_{-2.0-1.4}$)x 10^{-5}

711 fb^{-1}

$B^0 \rightarrow \chi_{c1}\gamma K^+\pi^-$

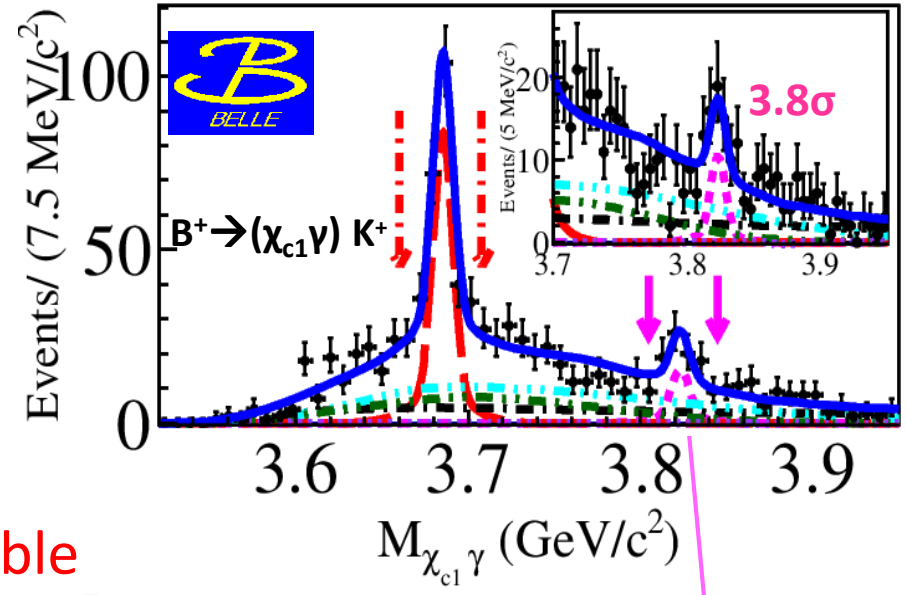
Belle, PRL 111, 032001 (2013)

Belle found a narrow peak $X(3823) \rightarrow \chi_{c1}\gamma$ in $B^+ \rightarrow (\chi_{c1}\gamma)\, K^+$

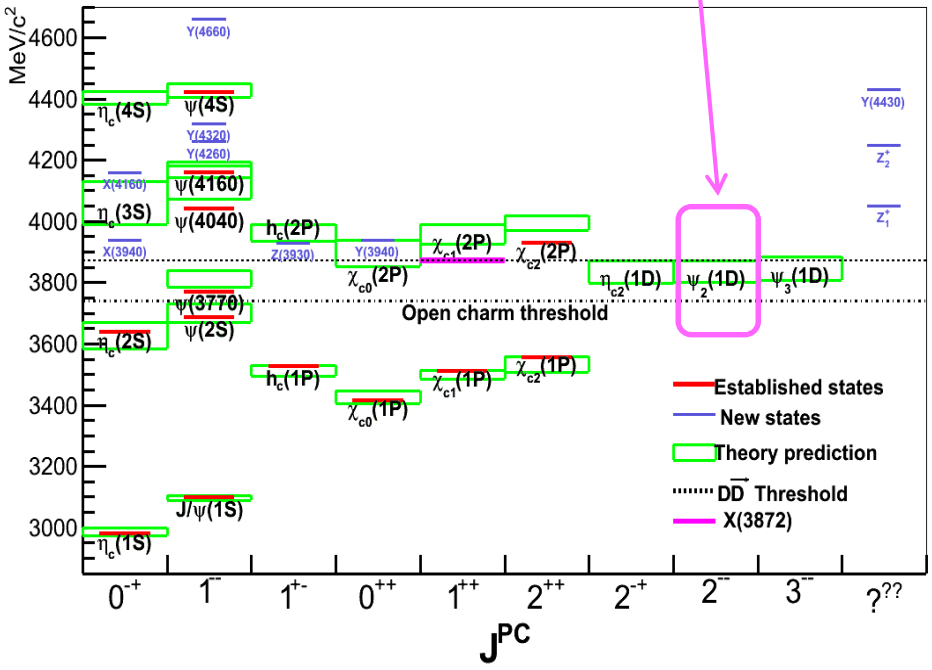
Its narrow width and properties suggest, it to be Ψ_{2D} (2^{--},1^3D_2 $c\bar{c}$) charmonium state.

If so, it is suppressed in $B^+ \rightarrow \Psi_{2D}K^+$

But one can expect it to have reasonable $BR(B^+ \rightarrow \Psi_{2D}K^+\pi^-)$



$B^0 \rightarrow \chi_{cJ}\gamma K^+\pi^-$ useful mode to search for X(3823) .

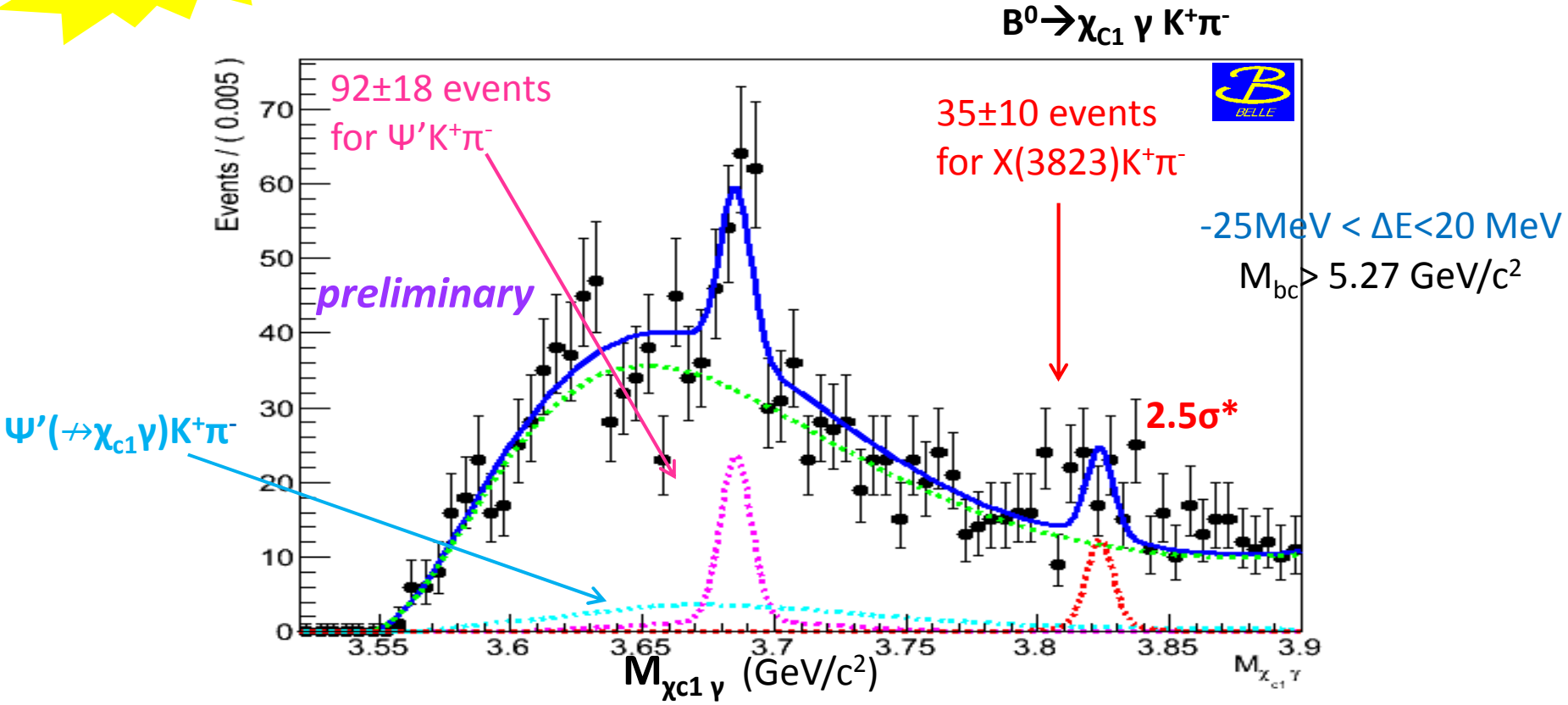


- **-25 MeV < ΔE<20 MeV**
- **E_γ scaled (ΔE=0) to improve the resolution of $M_{\chi c1,c2\gamma}$.**
- **Search for X(3823) and other new state in $M_{\chi c1,c2\gamma}$**

NEW

Fit to X(3823)

772 x 10^6 $N_{B\bar{B}}$



Resolution fixed from Belle previous study of $B^+ \rightarrow (\chi_{c1}\gamma)K^+$ study

$$\frac{BR^{\dagger}(B^0 \rightarrow X(3823)K^+\pi^-)}{BR(B^+ \rightarrow X(3823)K^+)} = 2.5 \pm 1.0(\text{stat. only})$$

- Large $BR(B \rightarrow X(3823)\, K^+\pi^-)$, suggest its J to be 2.

*with systematic inclusion

† **assumed efficiency for three body decay and one consider the central value**

Summary

Bottomonium (-like)

- J^P of Z_b favored to be 1^+
- $Z_b(10610)^+$ and $Z_b(10650)^+$ decay to $B^{(*)}\bar{B}^*$
- First observation of neutral $Z_b(10610)^0$ in $\Upsilon(2S,3S)\pi^0$

Charmonium (-like)

- $Y(4260)$ is found to decay into $Z(3895)^+ \pi^-$ and further $Z(3895)^+$ decay into $J/\Psi\pi^+$
- J^P of $Z(4430)^+$ preferred as 1^+
- Hint of large $BR(B \rightarrow X(3823)\, K^+\pi^-)$, suggest its J to be 2

Belle is quite active in finding new quarkonium (-like) states and also in solving their mystery.

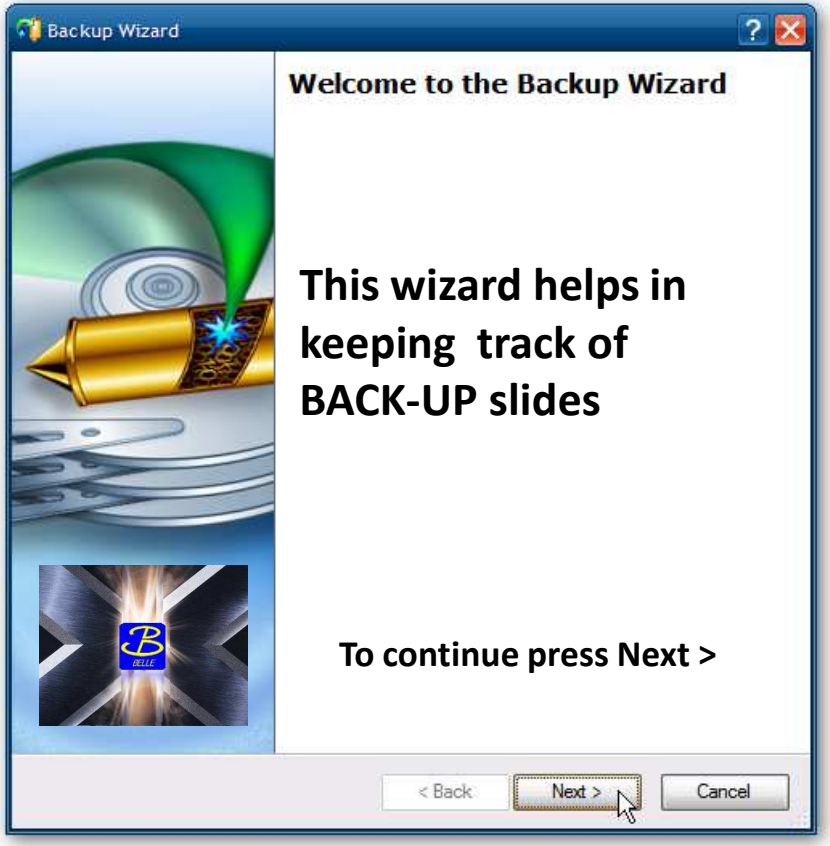
Other results, I didn't cover

- Observation of $h_b(1P,2P) \rightarrow \eta_b(1S)\gamma$ **Belle PRL 109 232002(2012)**
- First evidence for $\eta_b(2S)$ **Belle PRL 109, 232002 (2012)**
- Disconfirmation of $X_{bb}(9975)$ by Belle. **Belle, PRL 111, 112001 (2013)**
- Search for C-odd partner of X(3872) in $B \rightarrow (J/\Psi\eta)K$ **Belle,arXiv:1310.2704**
- Search for C-odd partner of $X(3872) \rightarrow \chi_{cJ}\gamma$ **Belle PRL 111, 032001 (2013)**
- Search for X(3872) and χ_{c1}' in $\chi_{c1}\pi\pi$ K. **E.Panzenboeck(Belle), Hadron 2013**
- Observation of $B \rightarrow X(3872)K\pi$. **A.Bala(Belle), Hadron2013**
- Observation of $\Psi(4040)$ and $\Psi(4160)$ decay into $\eta J/\Psi$ **Belle PRD 87, 051101(R) (2013)**
- Hadronic transistions $\Upsilon(2S) \rightarrow (\eta,\pi^0)\Upsilon(1S)$ **Belle,PRD 87, 011104(R) (2013)**
- Search for an H-dibaryon with mass near $2m_\Lambda$ in $\Upsilon(1S)$ and $\Upsilon(2S)$ decays **Belle,PRL 110, 222002 (2013)**

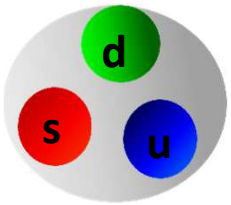
Visit archive of belle results

http://belle.kek.jp/bdocs/b_journal.html

Thank you


Backup Wizard
Welcome to the Backup Wizard
This wizard helps in keeping track of BACK-UP slides
To continue press Next >
< Back
Next >
Cancel

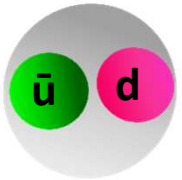
QCD : real particles are color singlet



Baryons are red-blue-green triplets

Λ=usd

Mesons are color-anticolor pairs

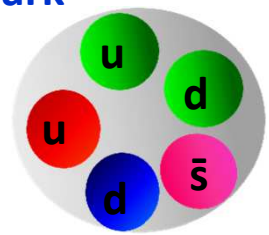


π=ūd

Other possible combinations of quarks and gluons :

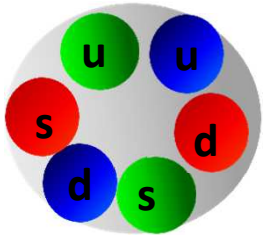
Pentaquark

S= +1 Baryon



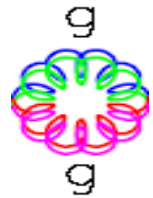
H di-Baryon

Tightly bound 6 quark state



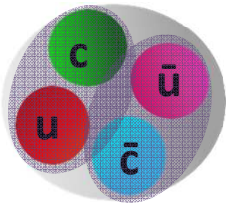
Glueball

Color-singlet multi-gluon bound state



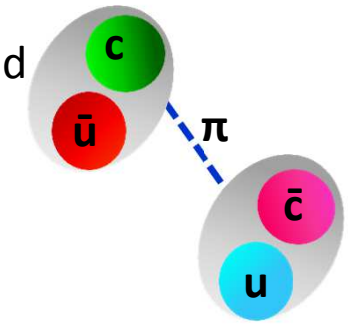
Tetraquark

Tightly bound diquark & anti-diquark

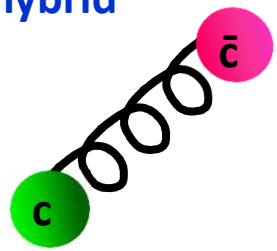


Molecule

loosely bound meson-antimeson "molecule"



qq̄ -gluon hybrid mesons



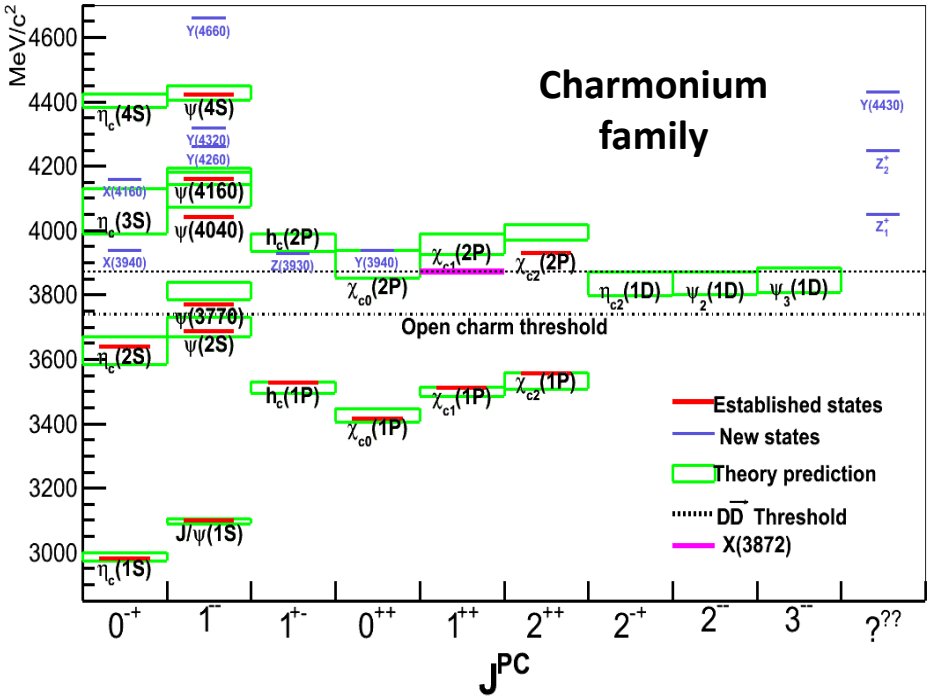
artistic illustration

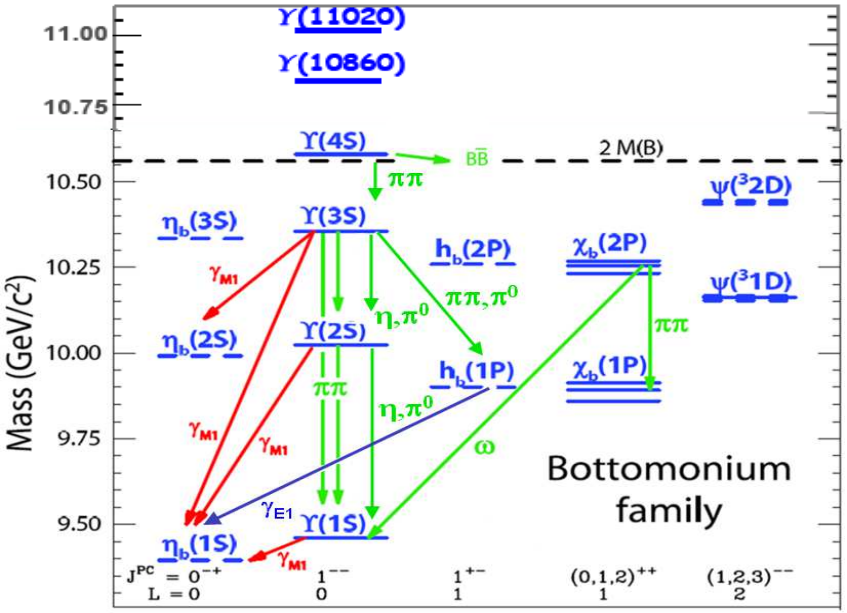
Adapted from S. Olsen's talk

Search for exotic states

Basic strategy follow:

- Search for meson decaying into $c\bar{c}$ or similar state and study its properties.
- Observed particle found state among the expected states and also show expected properties then standard particle.
- If properties can't be easily explained, most probably exotic state

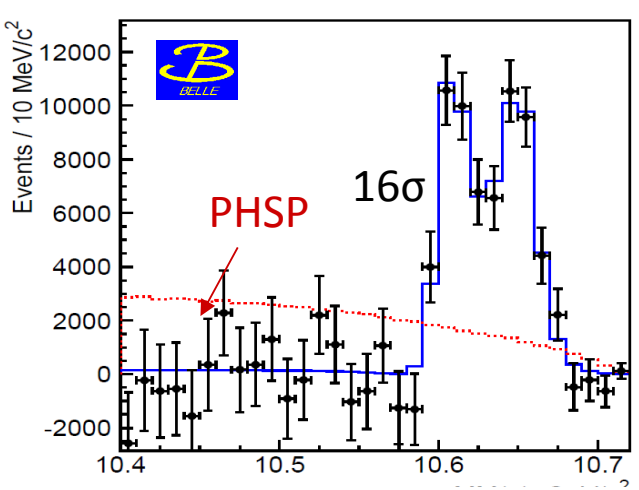


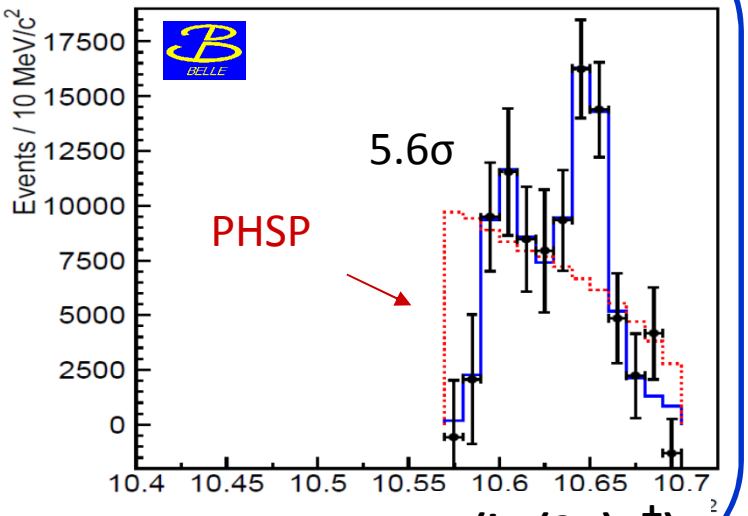


Resonant structure in $\Upsilon(5S) \to [(b\bar{b})\pi^+]\pi^-$

measure $\Upsilon(5S) \to h_b\pi\pi$ yield in bins of MM(π)

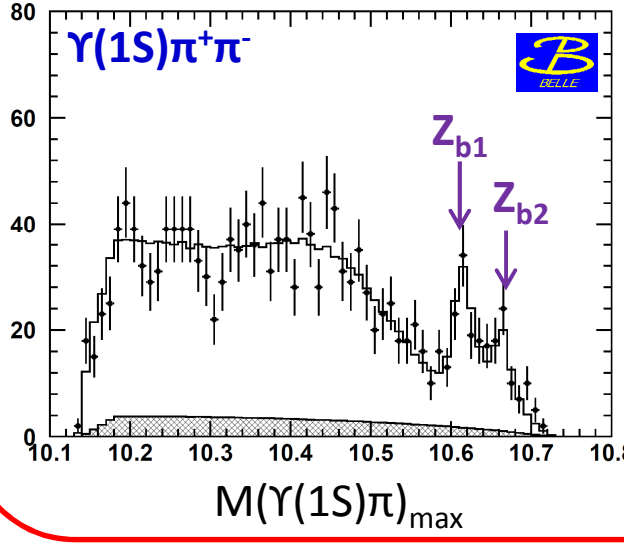
Belle, PRL108, 122001 (2012)

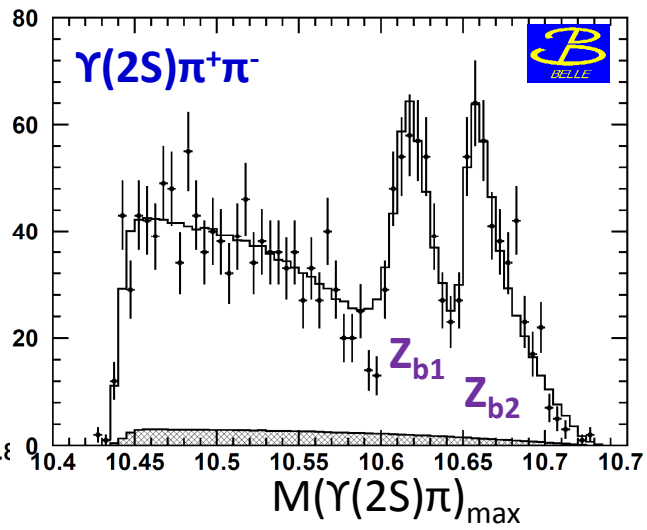


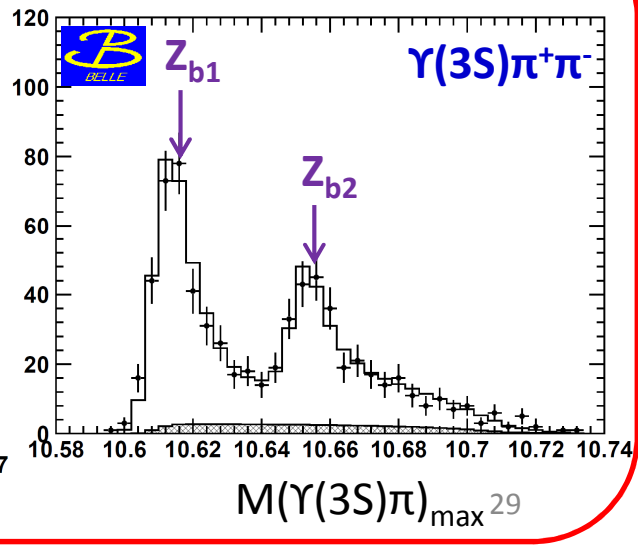


Two charged states observed $Z_b(10610)$ and $Z_b(10650)$!

Dalitz plot analysis of $\Upsilon(5S) \to \Upsilon(nS)\pi\pi$

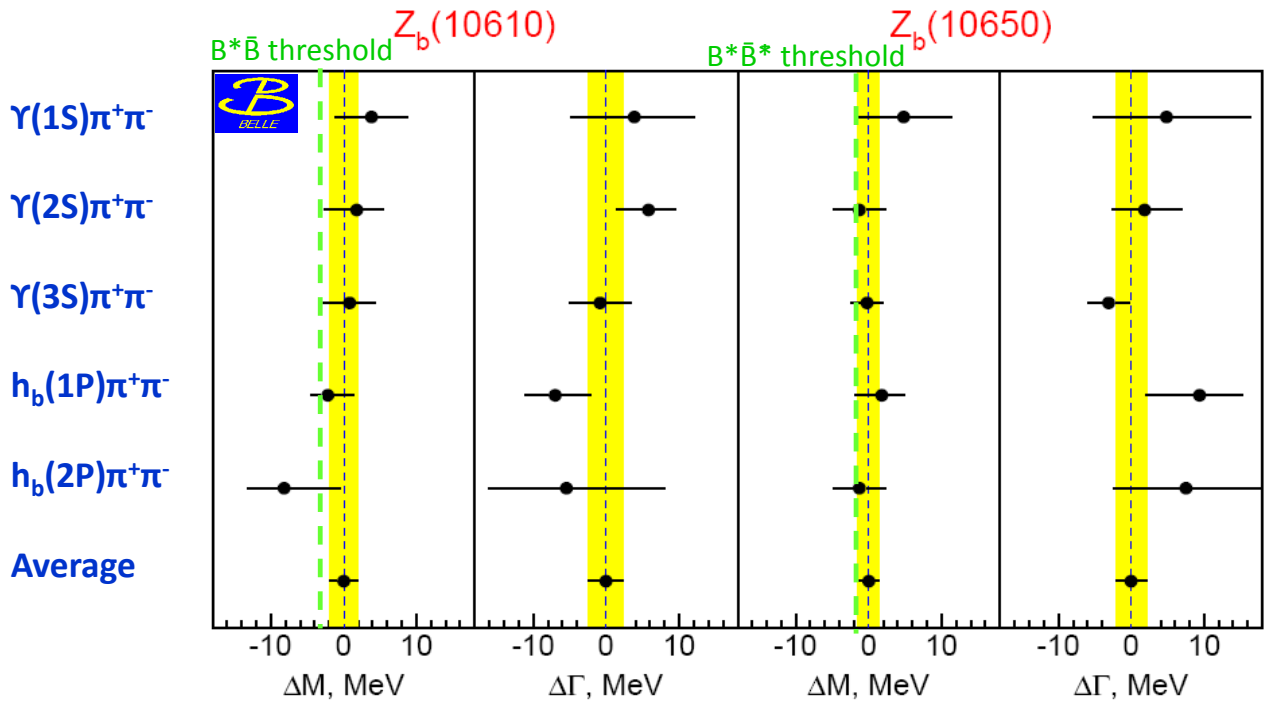






$Z_b(10610)$ & $Z_b(10650)$

Belle, PRL108, 122001 (2012)



$Z_b(10610)$

M=10607.2±2.0 MeV
Γ=18.4±2.4 MeV

PDG: $M_{\bar{B}} + M_{B^*} = 10604.8 \pm 0.4$ MeV

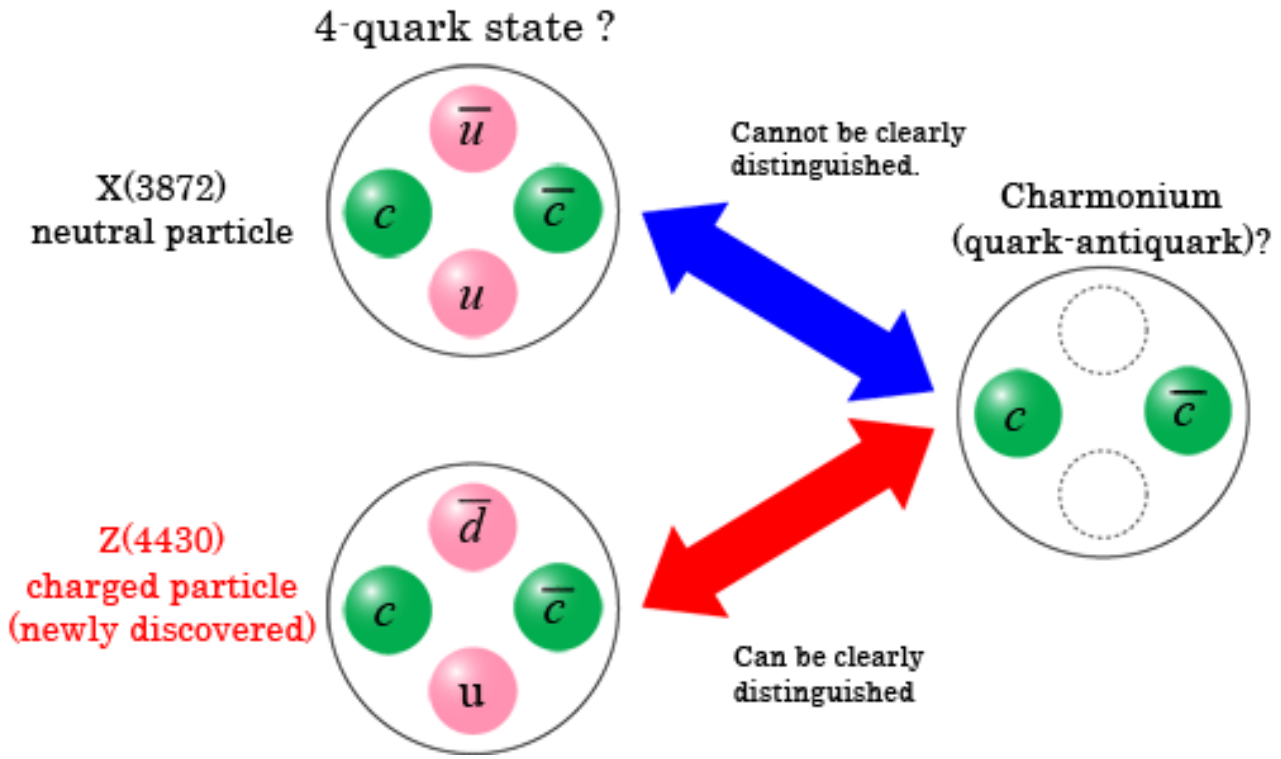
$Z_b(10650)$

M=10652.2±1.5 MeV
Γ=11.5±2.2 MeV

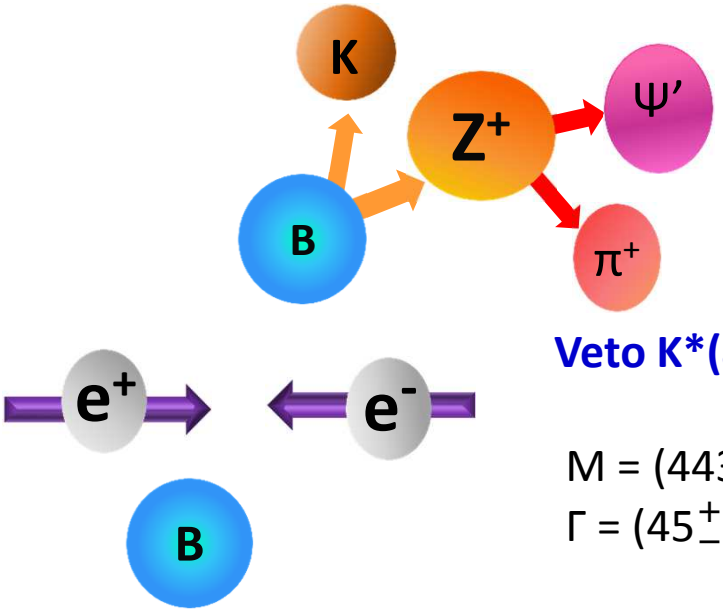
PDG: $M_{\bar{B}^*} + M_{B^*} = 10650.4 \pm 0.8$MeV

Parameters are consistent between the five states.
Masses just above B*B̄ and B*B̄* thresholds.

Charged $c\bar{c}$ -like states



$Z^+(4430)$

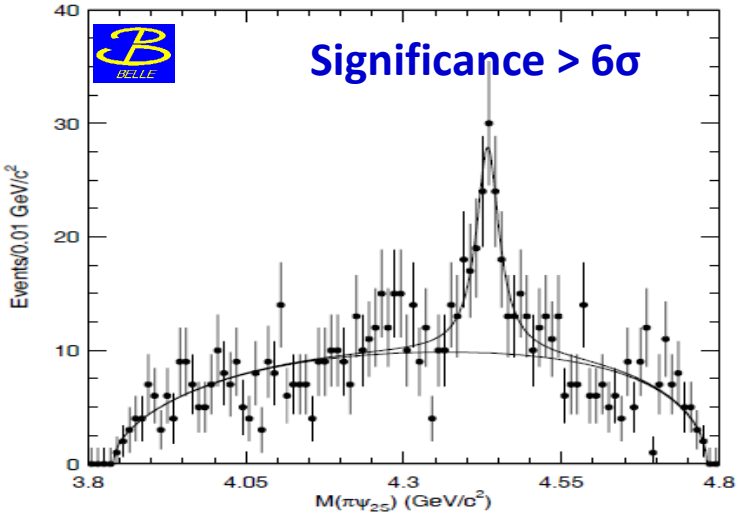


Veto K*(890) & K_2*(1430)

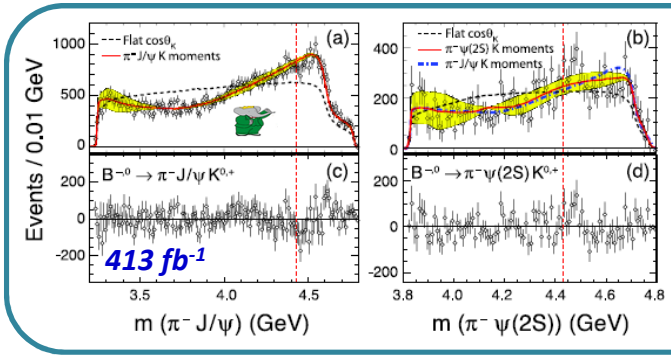
M = (4433±4±2) MeV

$\Gamma = (45^{+18+30}_{-13-13})$ MeV

Belle, PRL 100, 142001 (2007)



$BR(\bar{B}^0 \to K^- Z(4430)^+) \times BR(Z(4430)^+ \to \Psi'\pi^+) = (4.1\pm1.0\pm1.4)\times 10^{-5}$



BaBar didn't found conclusive evidence for the $Z(4430)^+$

$BR(\bar{B}^0 \to K^- Z(4430)^+) \times BR(Z(4430)^+ \to \Psi'\pi^+) < 3.1\times 10^{-5}$

BaBar data (due to less statistics) doesn't refute the Belle observation of $Z^+(4430)$

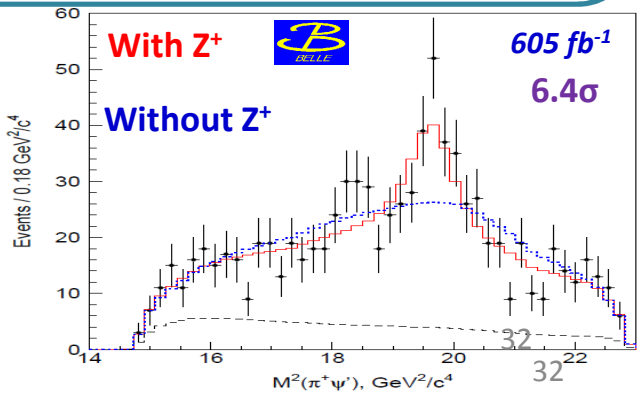
BaBar, PRD79, 112001 (2009)

Re-analysis by Belle using sophisticated Dalitz fit

Belle, PRD80, 031104 (2009)

$M = (4443^{+15+17}_{-12-13})$ MeV

$\Gamma = (109^{+86+57}_{-43-52})$ MeV



$BR(\bar{B}^0 \to K^- Z(4430)^+) \times BR(Z(4430)^+ \to \Psi'\pi^+) = (3.2^{+1.8+5.3}_{-0.9-1.6}) \times 10^{-5}$

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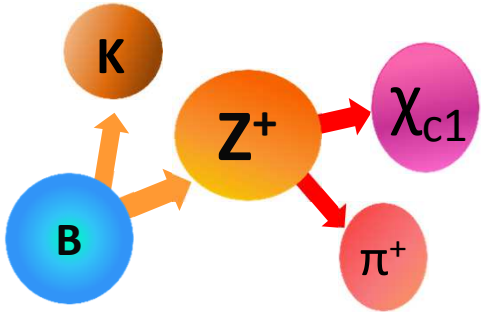
$Z_1^+(4050)$ & $Z_2^+(4250)$



Isobar model :

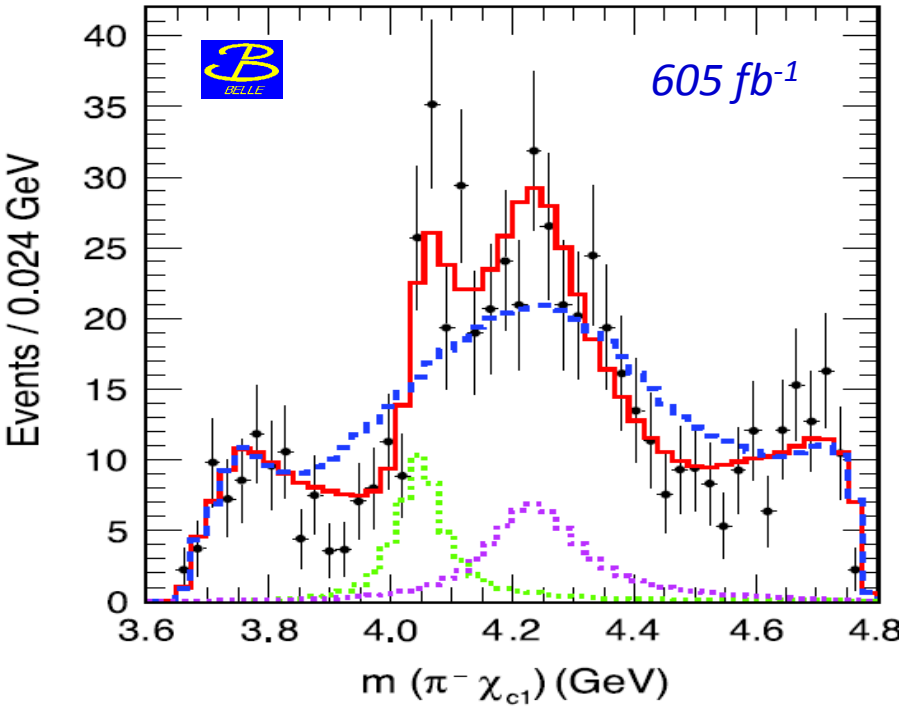
$\chi_{c1}\pi^-$ resonance+ known $K^-\pi^+$

Without two Z^+ resonance

With two Z^+ resonance

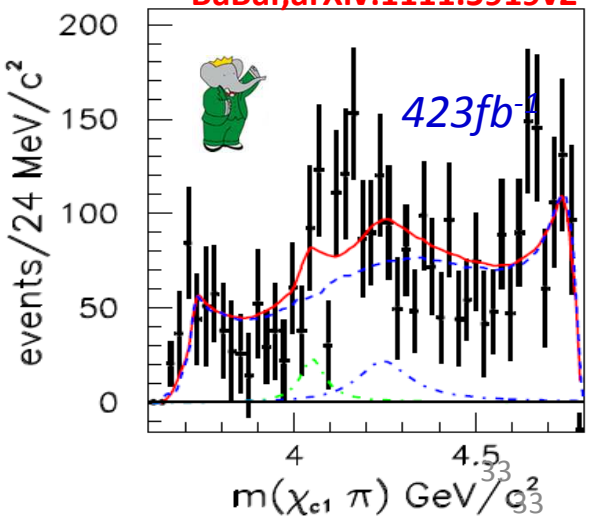
Two resonance preferred at > 5σ

Belle, PRD80, 031104 (2009)



	Z_1^+	Z_2^+
M (MeV)	$4051 \pm 14^{+20}_{-41}$	$4248^{+44\,+180}_{-29\,-35}$
Γ (MeV)	$82^{+21\,+47}_{-17\,-22}$	$177^{+54\,+316}_{-39\,-61}$
$B_{\bar{B}^0} \times B_{Z^+}$ $(\times 10^{-5})$	$(3.1^{+1.5\,+3.7}_{-0.9\,-1.7})$	$(4.0^{+2.3\,+19.7}_{-0.9\,-0.5})$

BaBar,arXiv:1111.5919v2



BaBar didn't find any strong evidence (in their search). However, they are limited by less statistics.

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Measurement of J^P

Full amplitude analysis of $e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^- \rightarrow \mu^+\mu^-\pi^+\pi^-$ (n=1,2,3)

Amplitude analysis performed in 6D space :

- $M(\Upsilon(nS)\pi)_{max}$
- $M(\pi^+\pi^-)$
- θ_1 : angle between prompt π and beam axis in c.m. frame
- $\theta^{hel}_{\mu\mu}$: angle between Υ(nS) momentum in Z_b rest frame and μ+ momentum in Υ(nS) rest frame.
- ϕ angle between plane formed by π system and Υ(nS) decay plane in Z_b rest frame
- Ψ angle between plane formed by prompt pion and beam axis and the Z_b decay plan calculated in Z_b rest frame.

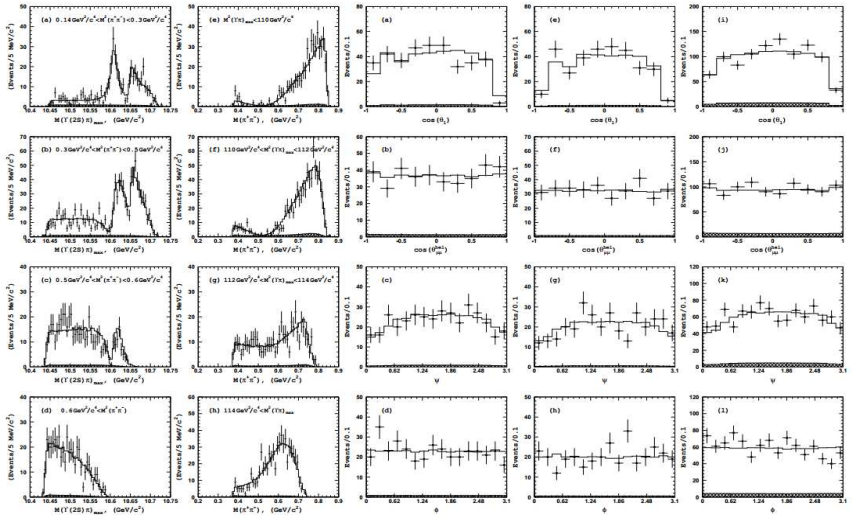
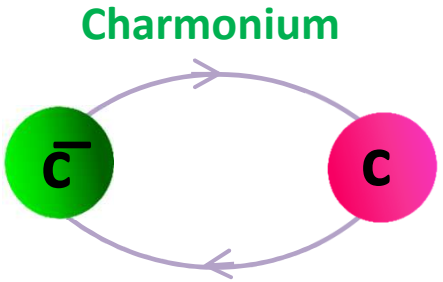


FIG. 8: A detailed comparison of fit results (open histogram) with experimental data (points with error bars) for $\Upsilon(2S)\pi^+\pi^-$ events in the signal region. Hatched histogram shows the background component.

$J^P = 0^+$ and 0^- combinations are forbidden because of the observed decay channels $Z_b \rightarrow \Upsilon(nS)\pi$ and $Z_b \rightarrow h_b(mP)\pi$

Charmonium

Bound state of c and $\bar{c}$
Spin : ½ and ½ = 0,1
Orbital angular momentum: L =0,1,2,…
Parity (P) = $(-1)^{L+1}$
Charge Conjugation (C) = $(-1)^{L+S}$
Total Spin : $\vec{J} = \vec{L} + \vec{S}$



$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

(Cornell potential)

Quark model quantum numbers

L=0, S=0 : J=0	$J^{PC}=0^{-+}$
L=0, S=1 : J=1	$J^{PC}=1^{--}$
L=1, S=0 : J=1	$J^{PC}=1^{+-}$
L=1, S=1 : J=0,1,2	$J^{PC} = 0^{++}\ 1^{++}\ 2^{++}$
L=2, S=0 : J=1	$J^{PC}= 2^{-+}$
L=2, S=1 : J=1,2,3	$J^{PC}=1^{--}\ 2^{--}\ 3^{--}$

and so on..

Spectrum based on this, with spin-orbital, spin-spin and tensor term.

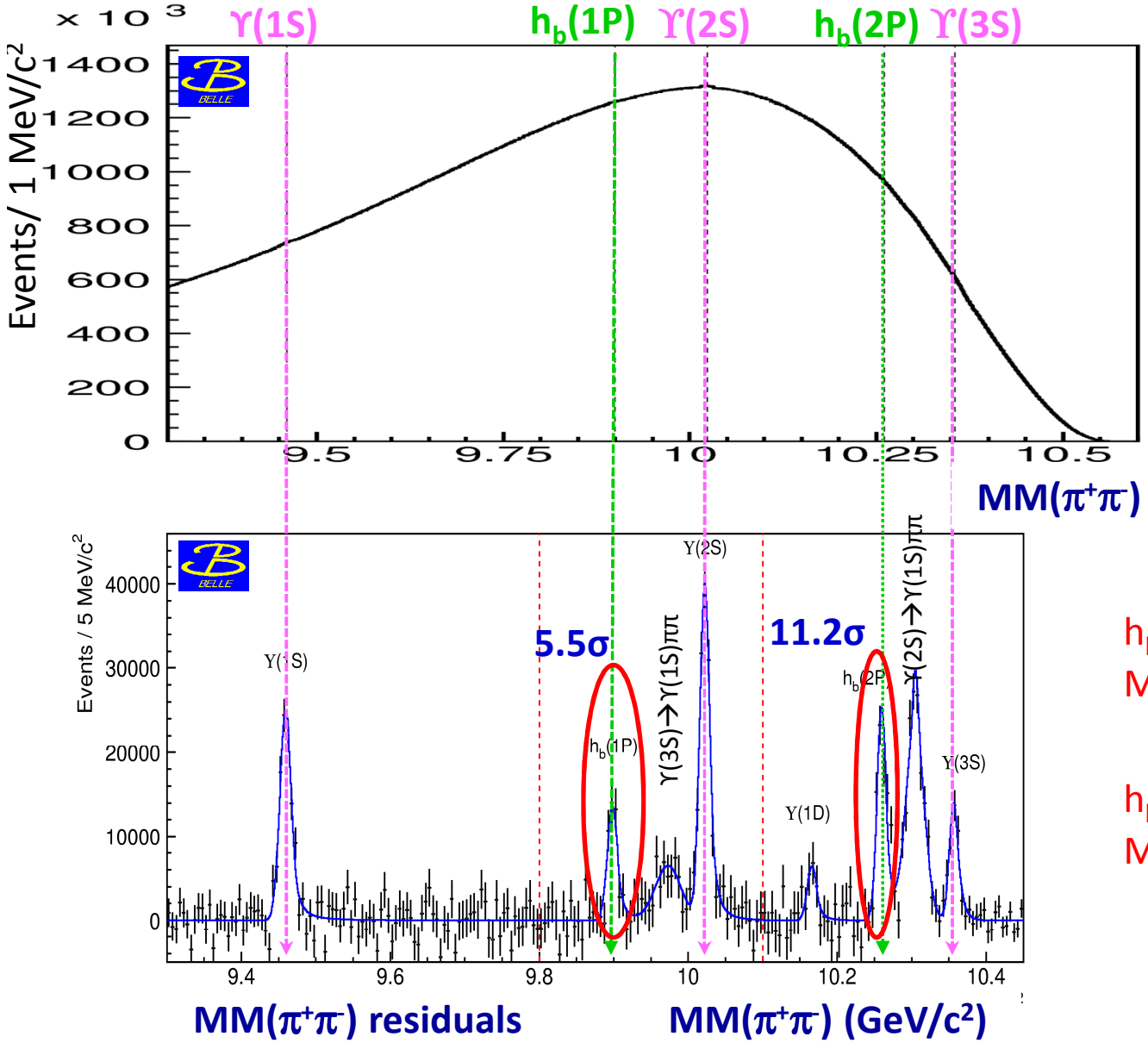
Exotic quantum number
0^{+-}, 0^{--}, 1^{-+}, 2^{+-} and so on..

States not easily accommodated, candidates for exotic nature.

$\pi^+\pi^-$ recoil mass in $\Upsilon(5S) \rightarrow X\ \pi^+\pi^-$

121 fb^{-1}

Belle, PRL 108 032001

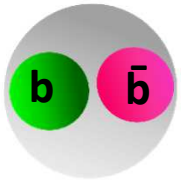


First observations
h_b(1,2P)
$J^{PC}=1^{+-}$

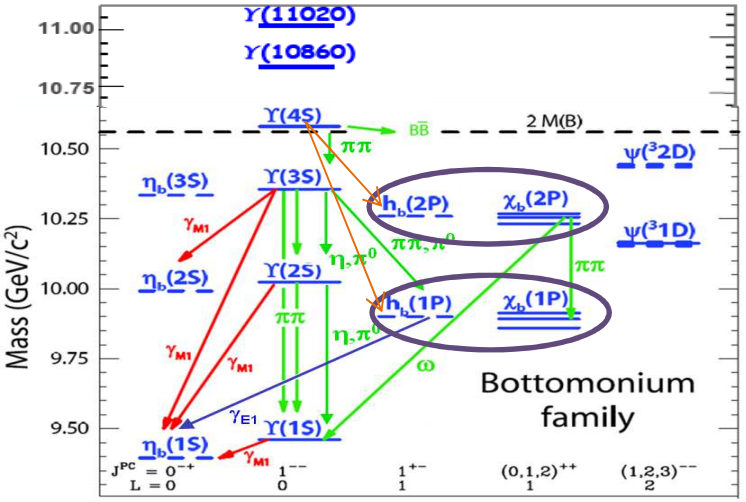
h_b(1P),
$M = (9898.25 \pm 1.06^{+1.03}_{-1.07})$ MeV

h_b(2P)
$M = (10259.25 \pm 0.64^{+1.04}_{-1.03})$ MeV

$h_b(1P)$ & $h_b(2P)$



S=0, L=1,
$J^{PC}=1^{+-}$



Expected mass ≈ $(M_{\chi b0} + 3\,M_{\chi b1} + 5\,M_{\chi b2}) / 9$

Hyperfine splitting :
ΔM_{HF} = M (singlet) – M(triplet)

$h_b(1P)$ (1.7 ± 1.5) MeV/c^2
$h_b(2P)$ $(0.5^{+1.6}_{-1.2})$ MeV/c^2

Deviation from CoG of χ_{bJ} mass consistent with zero as expected

Production ratio

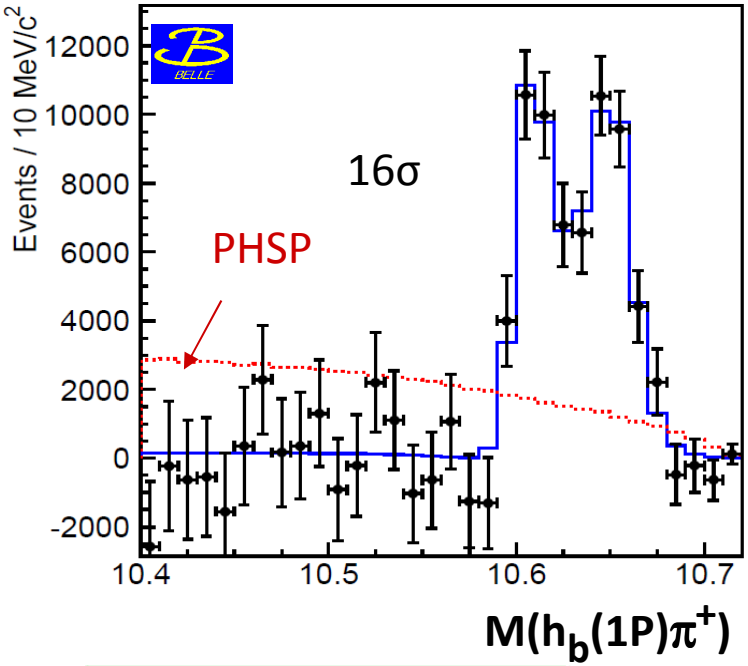
$$\frac{\Gamma(\Upsilon(5S) \to h_b(nP)\pi^+\pi^-)}{\Gamma(\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-)} = \begin{cases} 0.45 \pm 0.08^{+0.07}_{-0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08^{+0.22}_{-0.17} & \text{for } h_b(2P) \end{cases}$$

Decay to h_b should be suppressed due to spin flip !

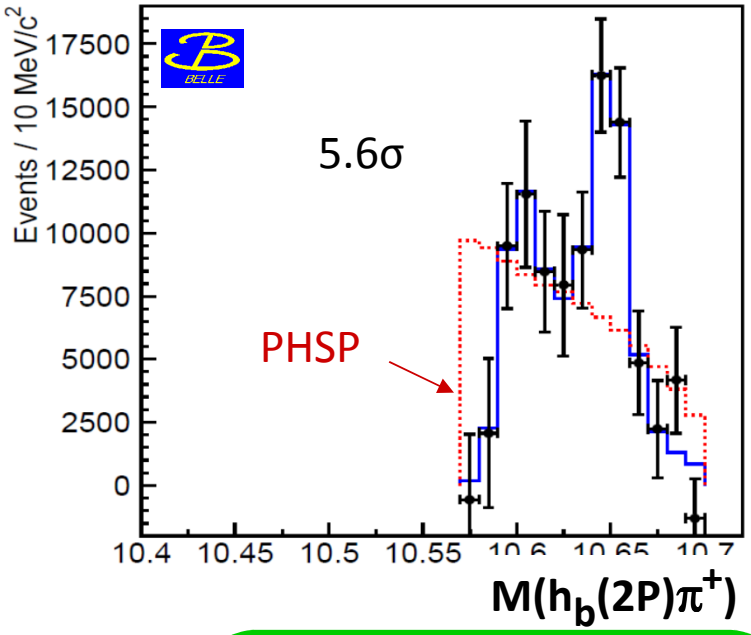
$\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$ decay mechanism seems to be exotic

Resonant structure of $\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$

measure $\Upsilon(5S) \to h_b\pi\pi$ yield in bins of MM(π)



Fit MM(π) in $M(h_b\pi)$ bins



$M_{Zb1} = (10605 \pm 2^{+3}_{-1})$ MeV

$\Gamma = (11.4^{+4.5+2.1}_{-3.9-1.2})$ MeV

$M_{Zb2} = (10654 \pm 3^{+1}_{-2})$ MeV

$\Gamma = (20.9^{+5.4+2.1}_{-4.7-5.7})$ MeV

~$\bar{B}$ B* threshold

~$\bar{B}$* B* threshold

$M_{Zb1} = (10599^{+6+5}_{-3-4})$ MeV

$\Gamma = (13^{+10+2.1}_{-8-1.2})$ MeV

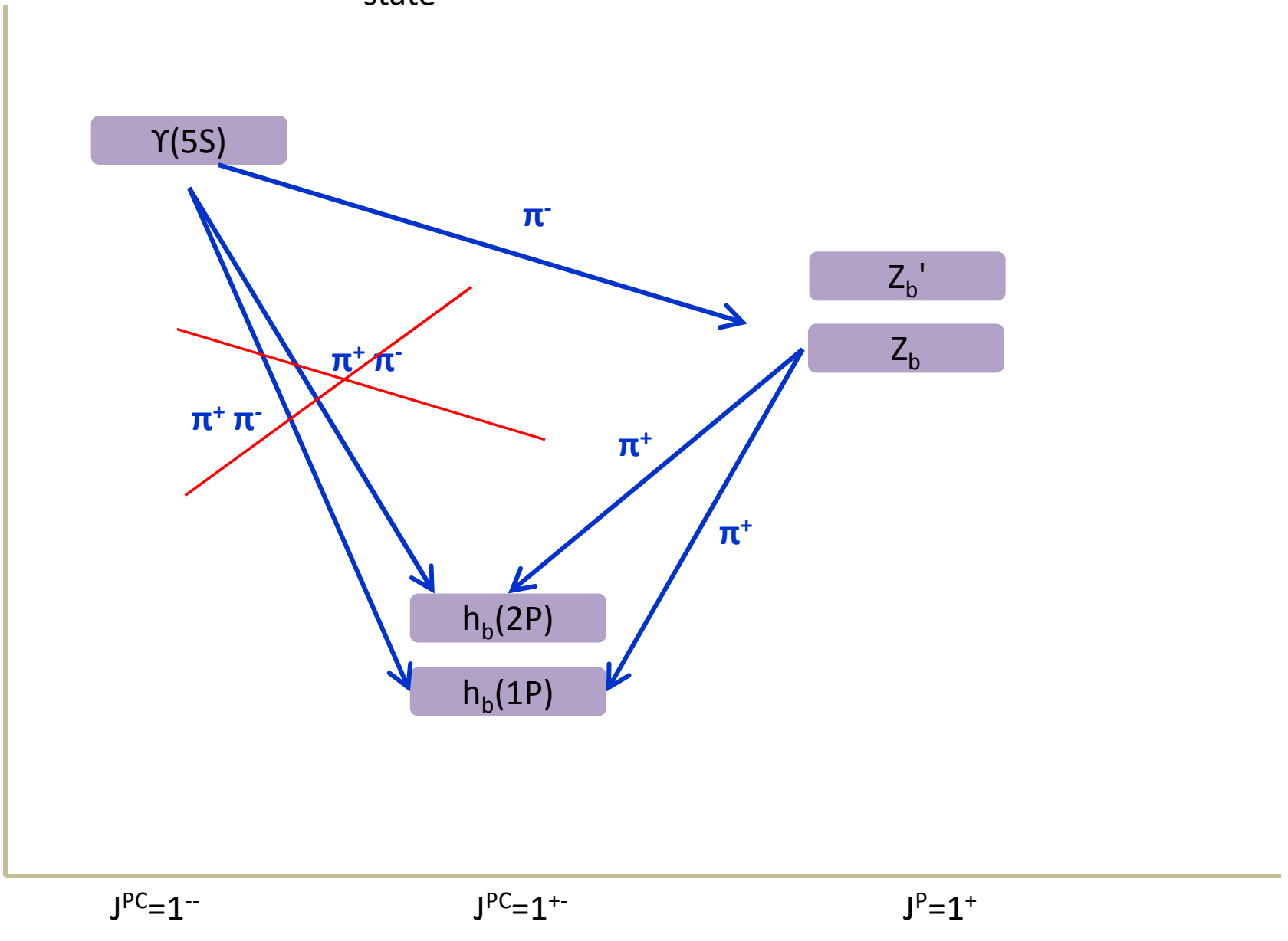
$M_{Zb2} = (10651^{+2+3}_{-3-2})$ MeV

$\Gamma = (19 \pm 7^{+11}_{-7})$ MeV

Resonance parameters are consistent for $h_b(1P)\pi\pi$ and $h_b(2P)\pi\pi$

Almost all $h_b(nP)$ are produced through $\Upsilon(5S) \to Z_b^+\pi^- \to h_b\pi^+\pi^-$

Instead, Υ(5S) decays via intermediate charged state

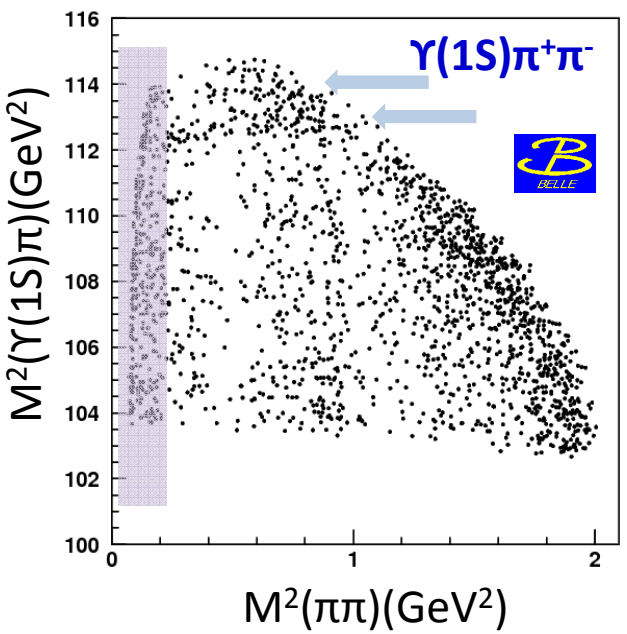


Z^+_b should also be visible in $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$

Resonant structure of $\Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-$

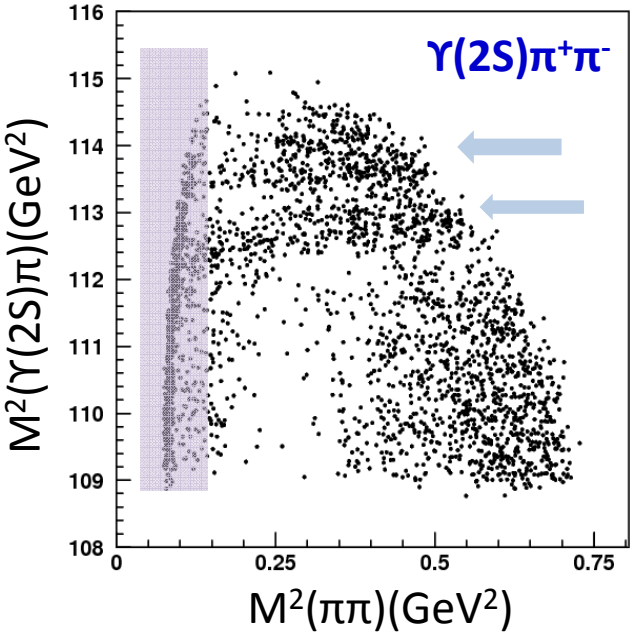
Dalitz distribution

9.43 GeV <MM($\pi^+\pi^-$) < 9.48 GeV



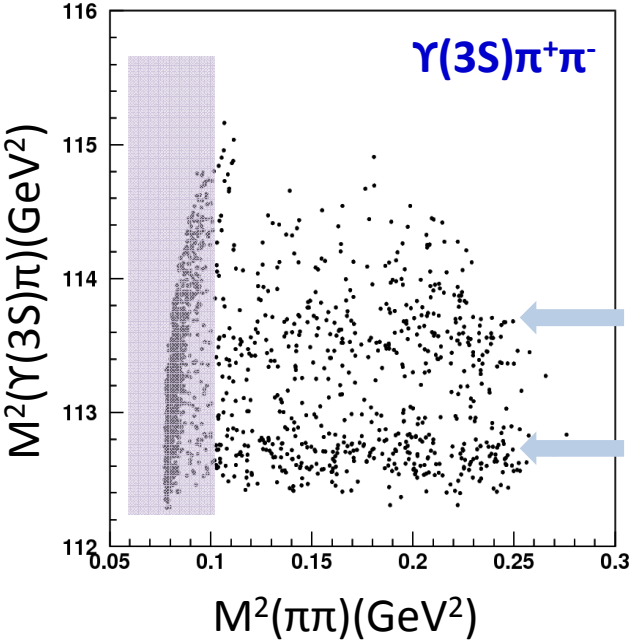
$M^2(\pi\pi)>0.20\ GeV^2/c^4$

10.05 GeV <MM($\pi^+\pi^-$) < 10.10 GeV



$M^2(\pi\pi)>0.14\ GeV^2/c^4$

10.33 GeV <MM($\pi^+\pi^-$) < 10.38 GeV



$M^2(\pi\pi)>0.10\ GeV^2/c^4$

Excluded region with large background from photon conversions

Signal amplitude parameterization:

$S(s1,s2) = A(Z_{b1}) + A(Z_{b2}) + A(f_0(980)) + A(f_2(1275)) + A_{NR}$

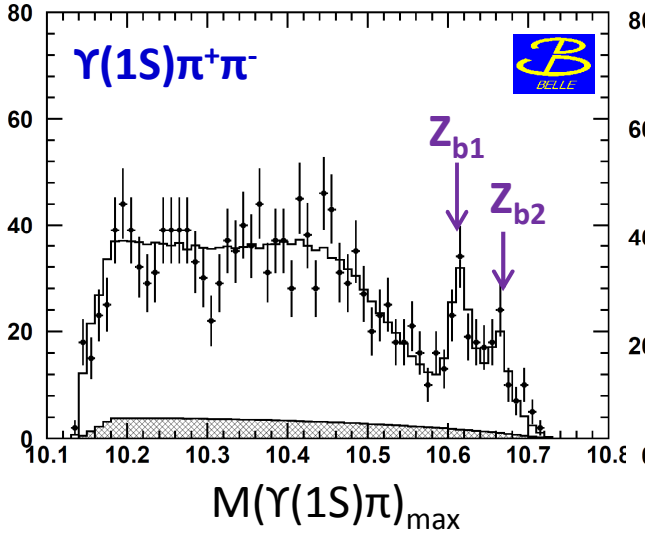
$A_{NR} = C_1 + C_2 \cdot m^2(\pi\pi)$

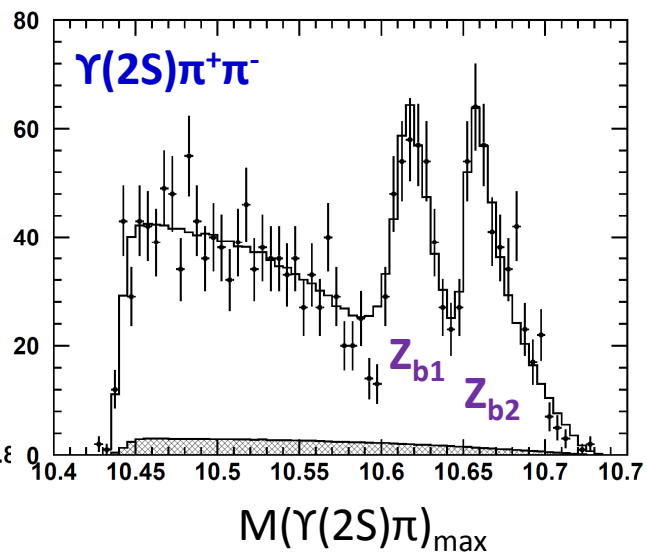
$A(Z_{b1}) + A(Z_{b2}) + A(f_2(1275))$ → Breit-Wigner

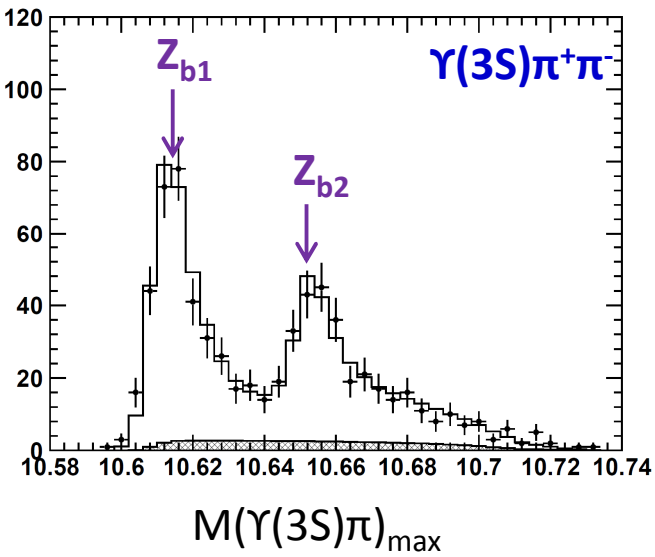
$A(f_0(980))$ → Flatte

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

Fit result







M_{Zb1} =(10611±4±3) MeV

$\Gamma = (22.3 \pm 7.7^{+3.0}_{-4.0})$ MeV

M_{Zb2} =(10657±6±3) MeV

$\Gamma = (16.3 \pm 9.8^{+6.0}_{-2.0})$ MeV

M_{Zb1} =(10609±2±3) MeV

$\Gamma = (24.2 \pm 3.1^{+2.0}_{-3.0})$ MeV

M_{Zb2} =(10651±2±3) MeV

$\Gamma = (13.3 \pm 3.3^{+4.0}_{-3.0})$ MeV

M_{Zb1} =(10608±2±3) MeV

$\Gamma = (17.6 \pm 3.0 \pm 3.0)$ MeV

M_{Zb2} =(10652±1±2) MeV

$\Gamma = (8.4 \pm 2.0 \pm 2.0)$ MeV

Consistent peaks in all three channels