A Discovery of the tetraquark by the Belle Experiment

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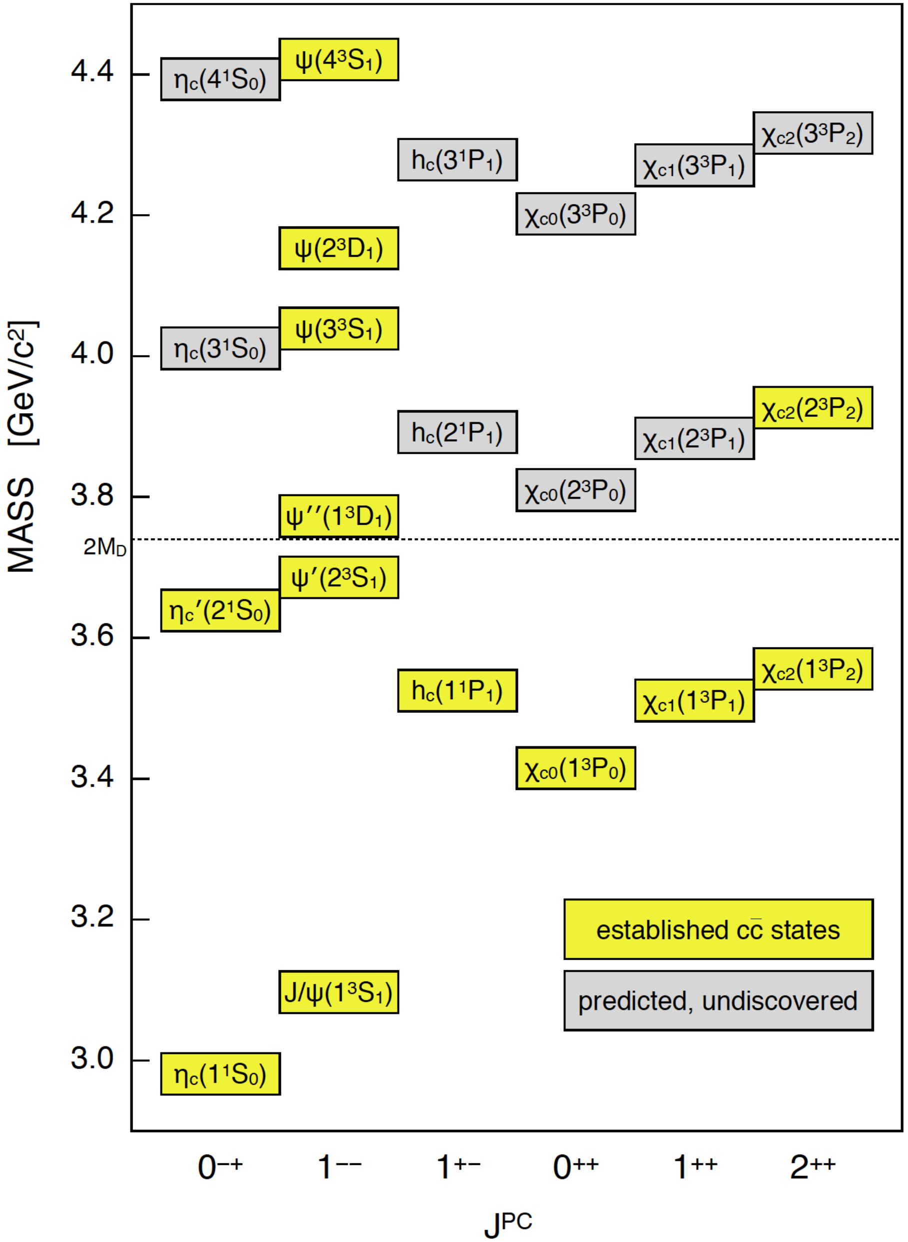
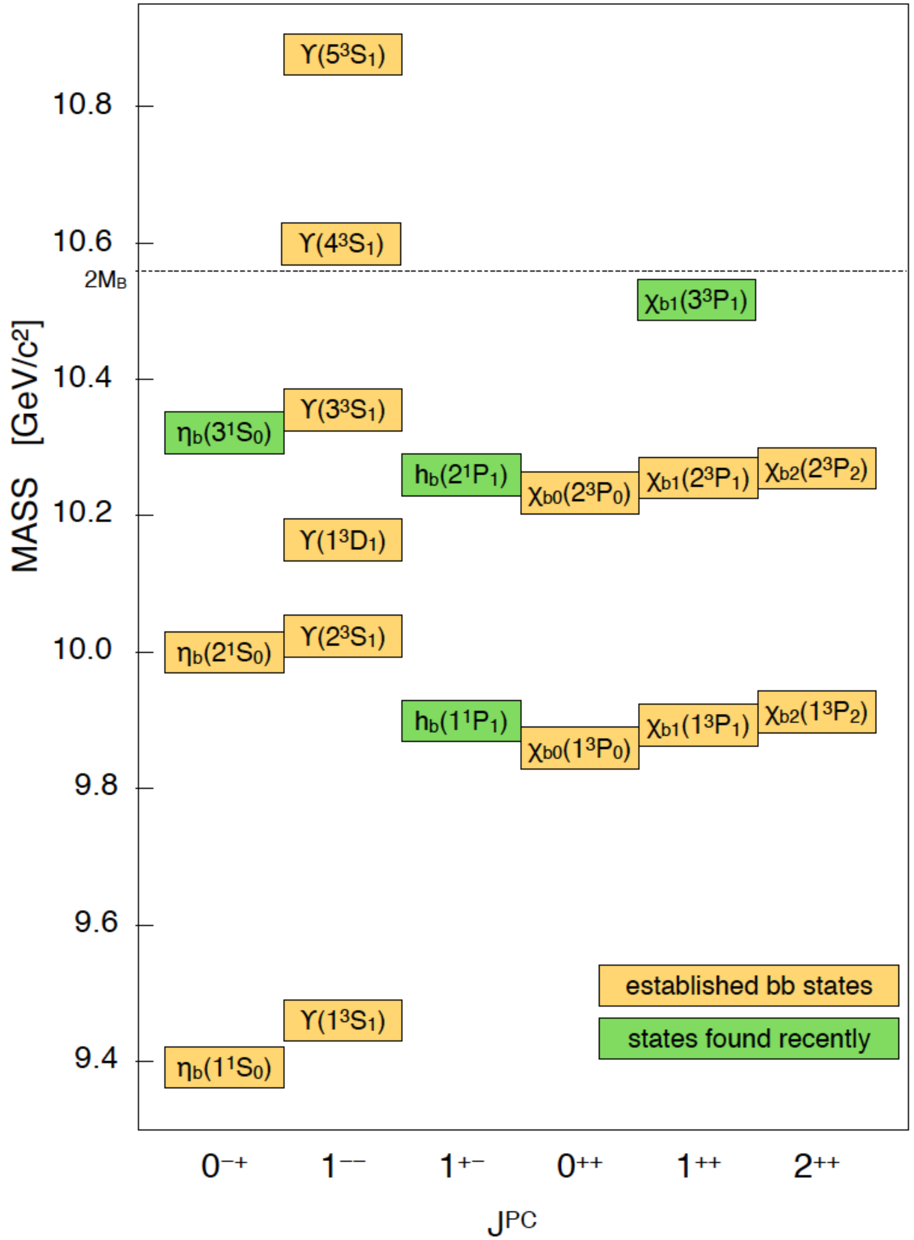
Outline

- X(3872)
- Charged Charmonium-like states : Z(4430), Z(4200), …
- Charged Bottomonium-like states : Z_b's
- More charged charmonium-like states : Z_c (3895), … , more BESIII Z_c's

Charmonium & Bottomonium spectrum

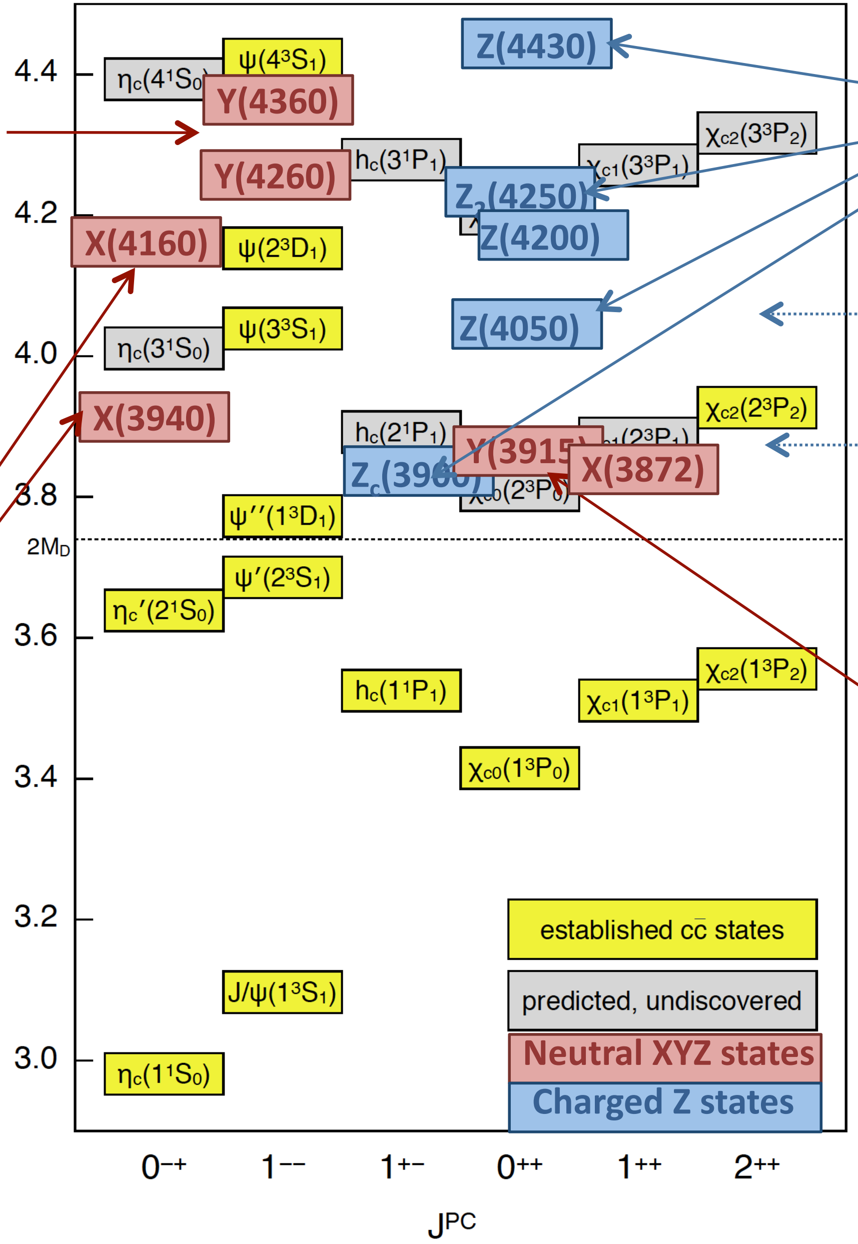




$c\bar{c}$ assignments for the XYZ mesons?

S Olsen, Front. Phys. 10, 101401 (2015)

no unassigned levels for the 1^{--} Y(4260) & Y(4360)



the (5) charged Zs must have a minimal quark content of $c\bar{c}u\bar{d}$

Close to D*D* threshold

Close to D*D threshold

the X(3940) & X(4160) as the $\eta_c(3S)$ & $\eta_c(4S)$ would imply huge hyperfine splittings for n=3&4

the Y(3915) mass and $\Gamma(Y\rightarrow\omega J/\psi)$ are too high for the $\chi_{c0}(2P)$

The list of XYZ states keeps growing

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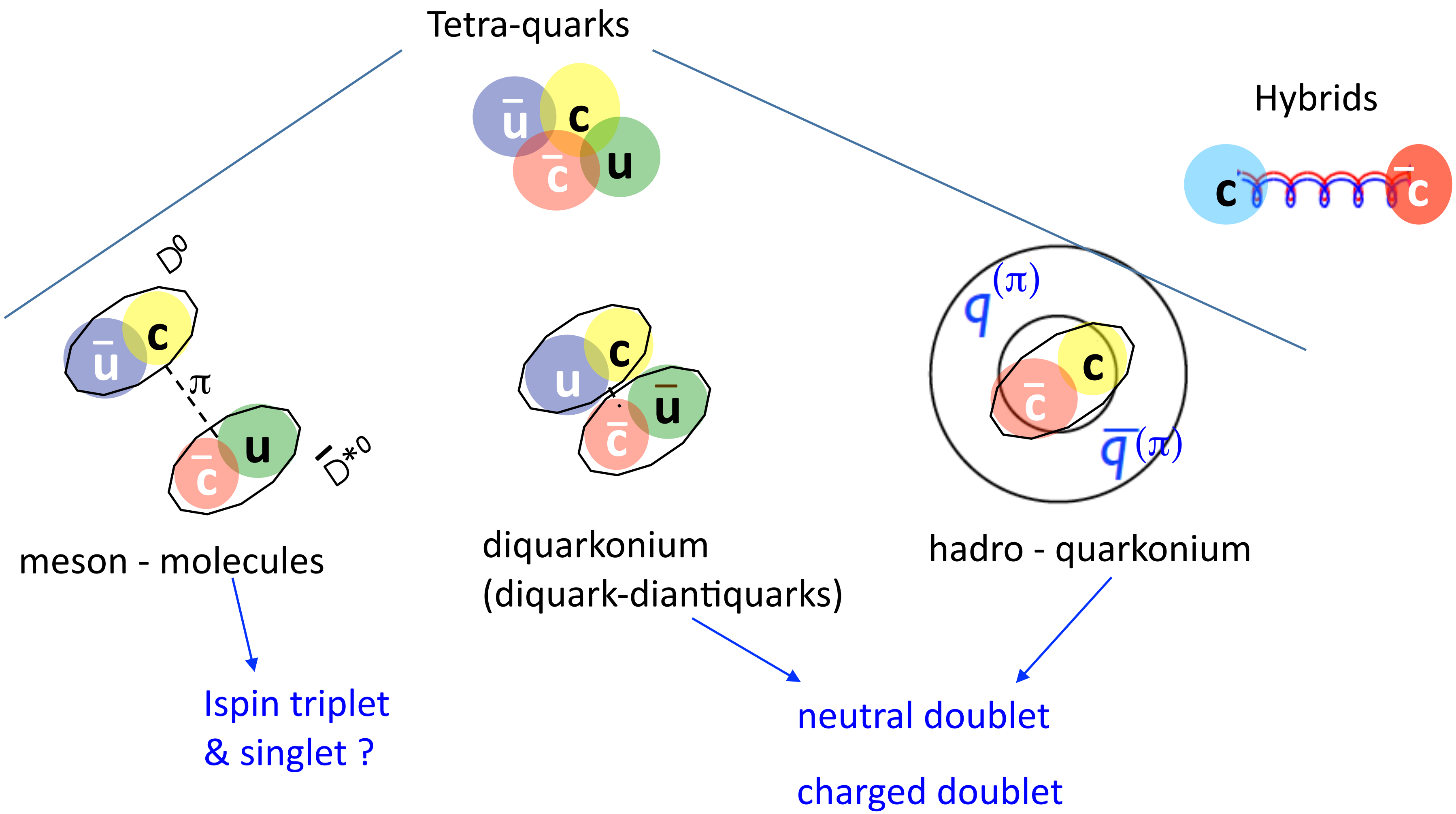
State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.68 ± 0.17	<1.2	1^{++}	$B \to K + (J/\psi\,\pi^+\pi^-)$	Belle [82, 89] , BaBar [85], LHCb [90]
				$p\bar{p} \to (J/\psi\,\pi^+\pi^-) + ...$	CDF [83, 91, 92, 125], D0 [84]
				$B \to K + (J/\psi\,\pi^+\pi^-\pi^0)$	Belle [94] , BaBar [59]
				$B \to K + (D^0\bar{D}^0\pi^0)$	Belle [95] , BaBar [96]
				$B \to K + (J/\psi\,\gamma)$	BaBar [126], Belle [127] , LHCb [128]
				$B \to K + (\psi'\,\gamma)$	BaBar [126], Belle [127] , LHCb [128]
				$pp \to (J/\psi\,\pi^+\pi^-) + ...$	LHCb [86], CMS [87]
$X(3915)$	3917.4 ± 2.7	$28^{+10}_{-\ 9}$	0^{++}	$B \to K + (J/\psi\,\omega)$	Belle [58] , BaBar [59]
				$e^+e^- \to e^+e^- + (J/\psi\,\omega)$	Belle [60] , BaBar [61]
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^- + (D\bar{D})$	Belle [64] , BaBar [65]
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27]
				$e^+e^- \to J/\psi + (...)$	Belle [26]
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma + (D\bar{D})$	BaBar [129], Belle [130]
$Y(4008)$	$4008^{+121}_{-\ 49}$	226 ± 97	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	Belle [32]
$Y(4140)$	4144 ± 3	17 ± 9	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [74, 75], CMS [77]
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27]
$Y(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	BaBar [30, 131], CLEO [132] , Belle [32]
				$e^+e^- \to (J/\psi\,\pi^+\pi^-)$	CLEO [133]
				$e^+e^- \to (J/\psi\,\pi^0\pi^0)$	CLEO [133]
$Y(4274)$	4292 ± 6	34 ± 16	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [75], CMS [77]
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(J/\psi\,\phi)$	Belle [81]
$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	BaBar [31], Belle [33]
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [134]
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	Belle [33]
$Z_c^+(3900)$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII [39], Belle [40]
				$Y(4260) \to \pi^- + (D\bar{D}^*)^+$	BESIII [56]
$Z_c^+(4020)$	4024 ± 2	10 ± 3	$1(?)^{+(?)-}$	$Y(4260) \to \pi^- + (h_c\,\pi^+)$	BESIII [41]
				$Y(4260) \to \pi^- + (D^*\bar{D}^*)^+$	BESIII [42]
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [43], BaBar [53]
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$B \to K + (J/\psi\,\pi^+)$	Belle [51]
$Z_2^+(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle [43], BaBar [53]
$Z^+(4430)$	4477 ± 20	181 ± 31	1^{+-}	$B \to K + (\psi'\,\pi^+)$	Belle [44, 46, 47], LHCb [48]
				$B \to K + (J\psi\,\pi^+)$	Belle [51]
$Y_b(10890)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$	Belle [117]
$Z_b^+(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	"$\Upsilon(5S)$" $\to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$	Belle [119, 122]
				"$\Upsilon(5S)$" $\to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$	Belle [119]
				"$\Upsilon(5S)$" $\to \pi^- + (B\bar{B}^*)^+$, $n=1,2$	Belle [123]
$Z_b^0(10610)$	10609 ± 6		1^{+-}	"$\Upsilon(5S)$" $\to \pi^0 + (\Upsilon(nS)\,\pi^0)$, $n=1,2,3$	Belle [121]
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	"$\Upsilon(5S)$" $\to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$	Belle [119]
				"$\Upsilon(5S)$" $\to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$	Belle [119]
				"$\Upsilon(5S)$" $\to \pi^- + (B^*\bar{B}^*)^+$, $n=1,2$	Belle [123]

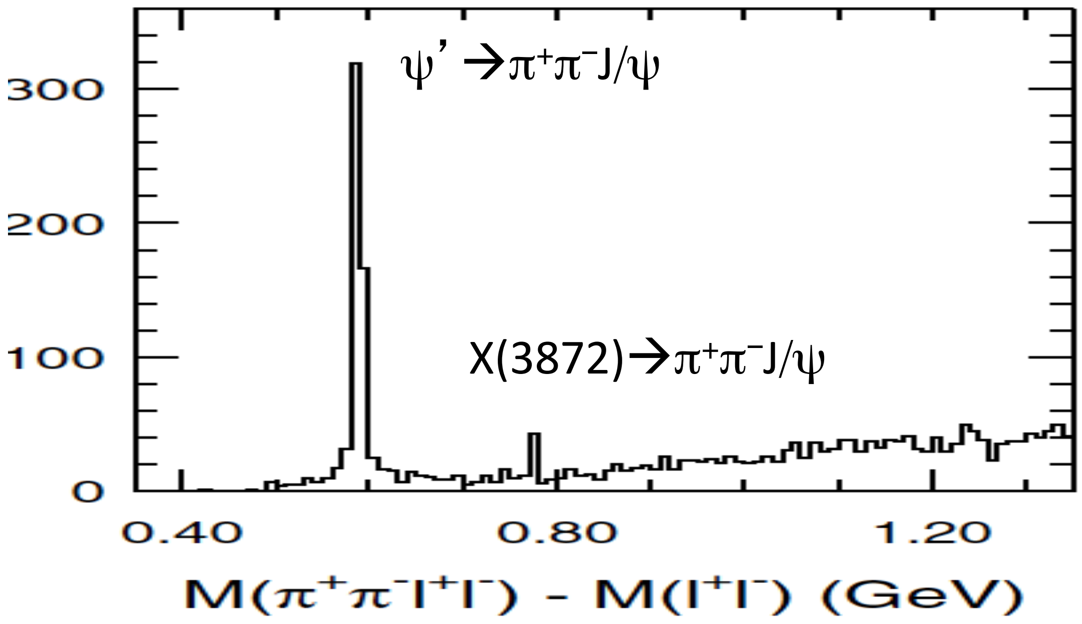
Models for XYZ Mesons



X(3872)YZ should have partner states:
Three missing states in any pictures

The X(3872)

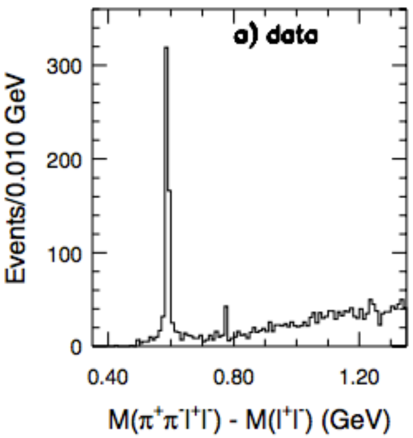
$B \rightarrow K\pi^+\pi^- J/\psi$

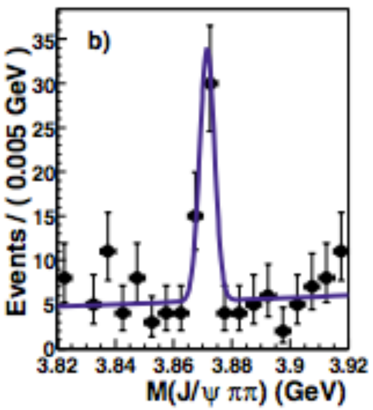


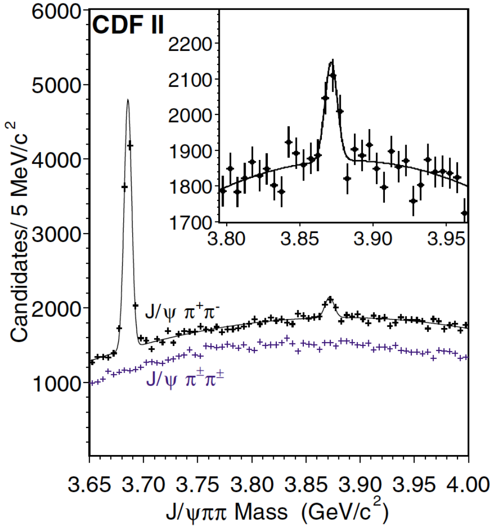
X(3872) after 11 years (& >1000 cites, by 2014 Nov)

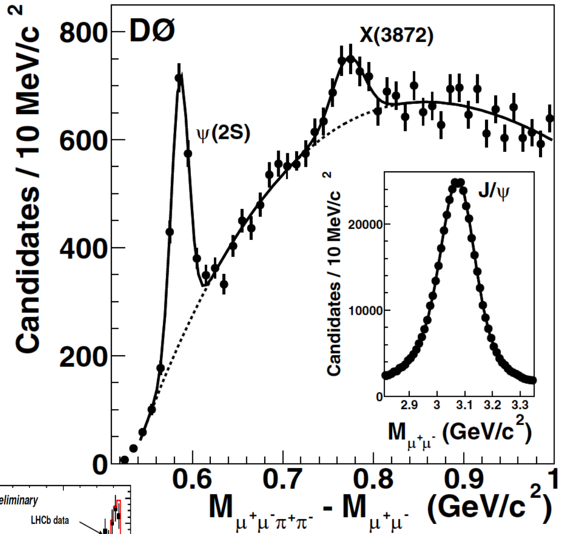
What do we know about the X(3872)?

Belle

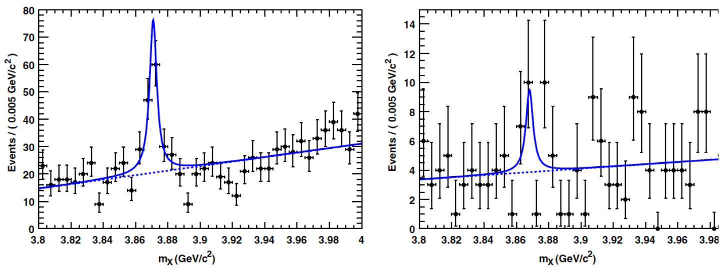


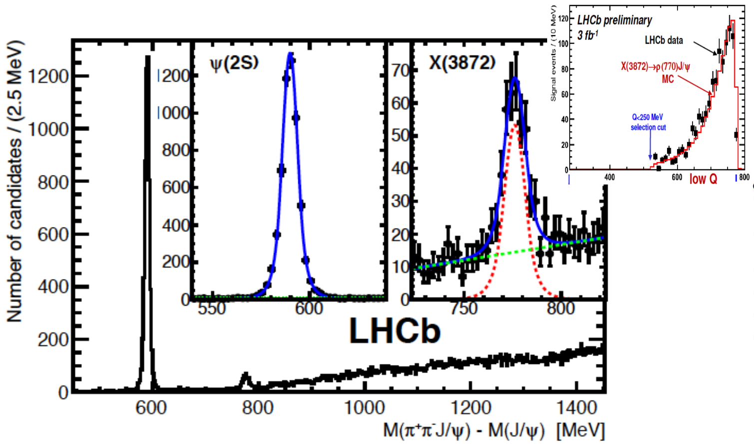


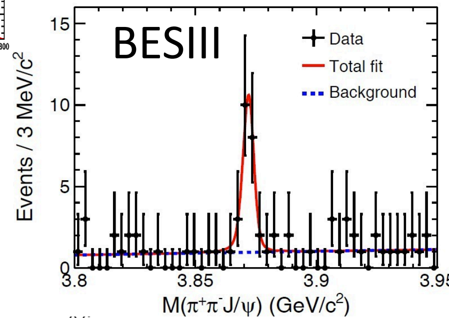


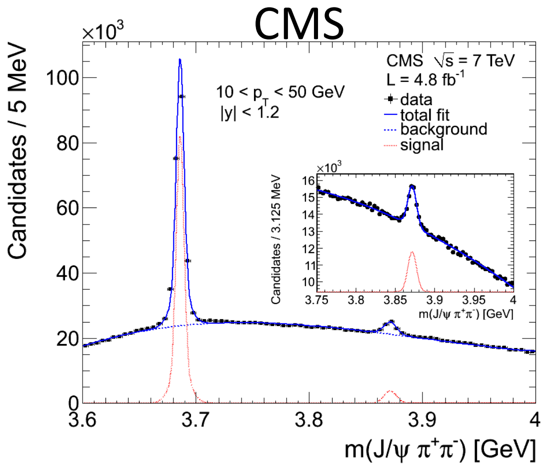


BaBar





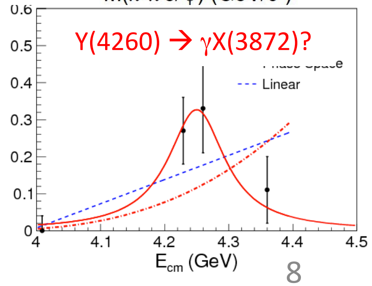




$M_{X(3872)} = 3871.69 \pm 0.17$ MeV

$m_{D0} + m_{D*0} = 3871.80 \pm 0.17$ MeV

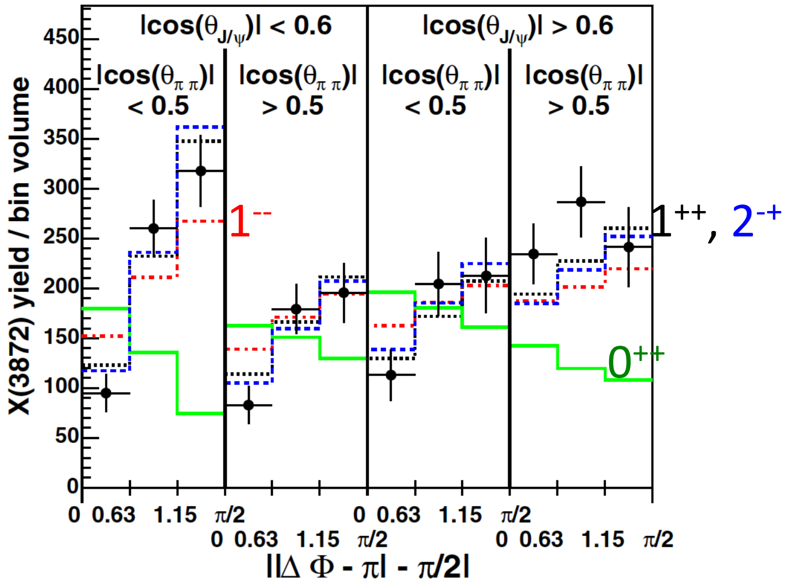
➔ “B.E.” = 100 ± 210 keV



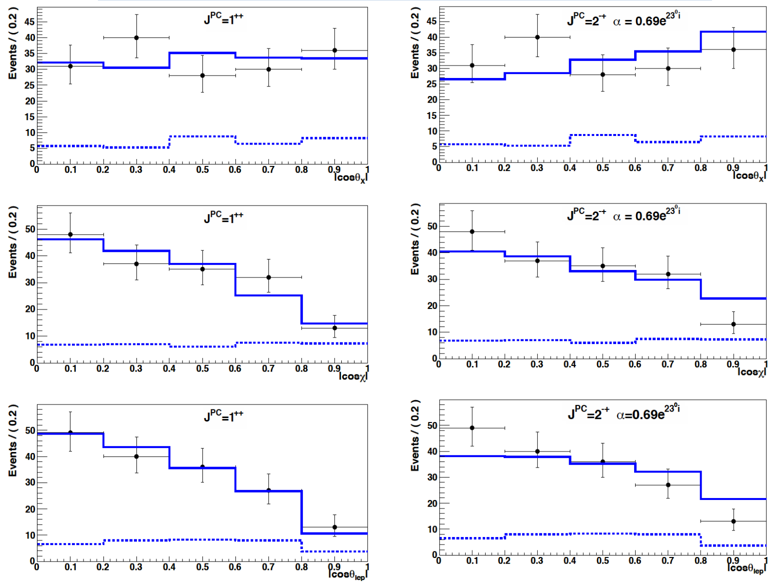
$\Gamma_{X(3872)} < 1.2$ MeV (90% CL)

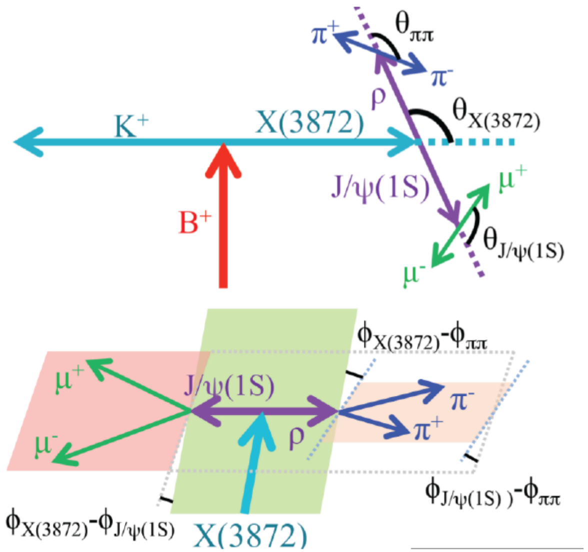
$J^{PC}=1^{++}$

CDF PRL 98, 132002: **J^{PC} = 1^{++} or 2^{-+}**

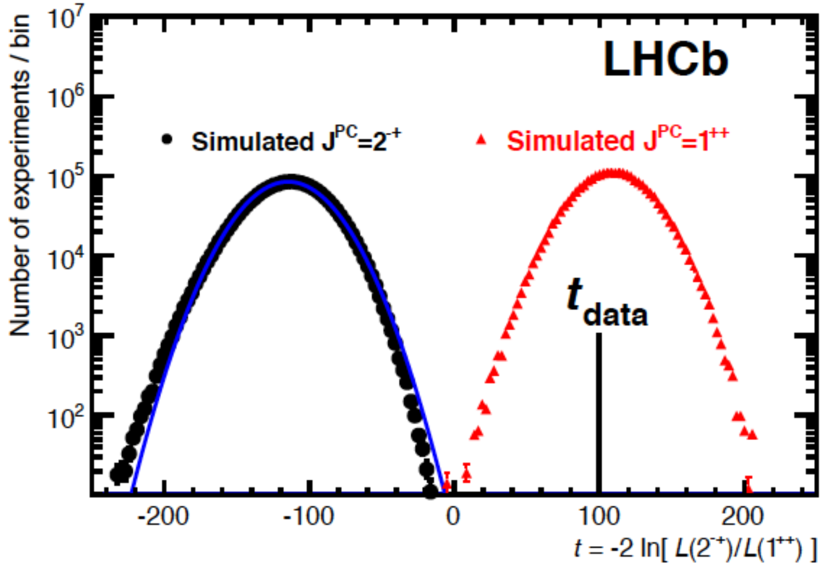


Belle PRD 84, 052004(R): **J^{PC} = 1^{++} or 2^{-+}**



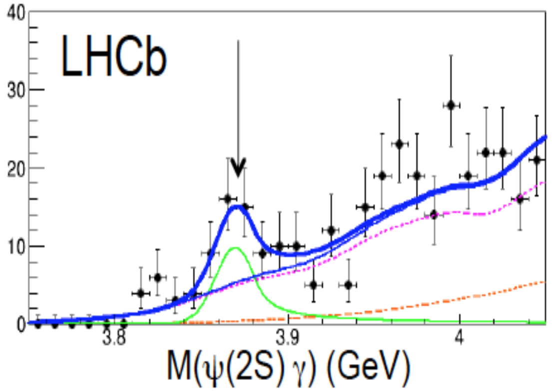


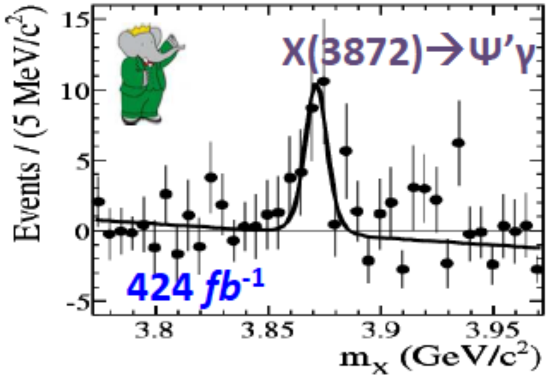
LHCb PRL 110, 222001: **J^{PC} = 1^{++}**

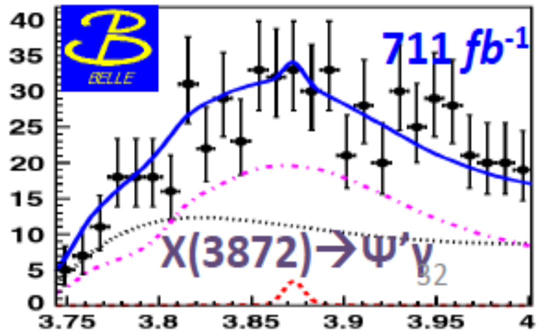


Radiative decays of X(3872)

$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)}$$: a probe of the nature of X(3872)

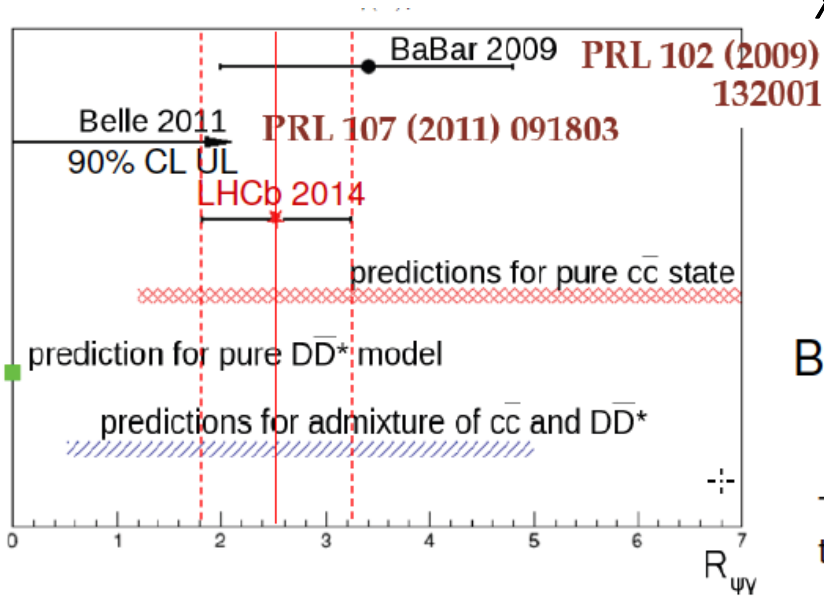






X(3872) → γ ψ′, γ J/ψ   C=+1

γ ψ′	γ J/ψ	
3.6σ	3.5σ	BaBar
0.4σ	4.9σ	Belle
4.4σ,	12.0σ	LHCb



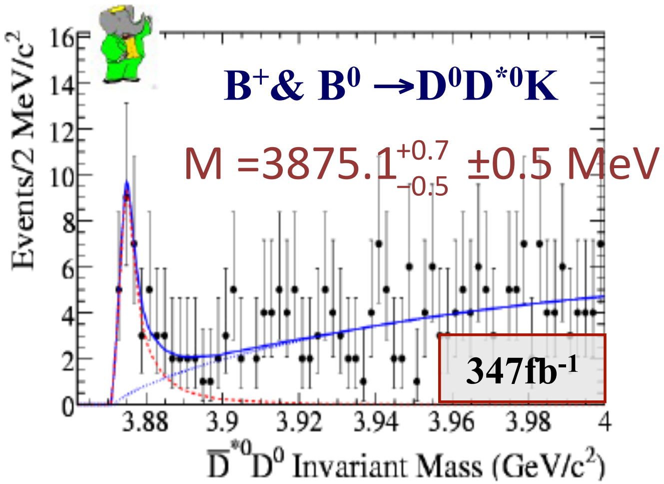
BR(X(3872)→ψ(2S)γ)/BR(X(3872)→J/ψγ)
= 2.48±0.64±0.29

The LHCb results are consistent with, but more precise than, the BaBar and Belle results

From T. Skwarnicki (Moriond QCD 2015)

Strong decay X(3872)→D$\overline{\text{D}}$*

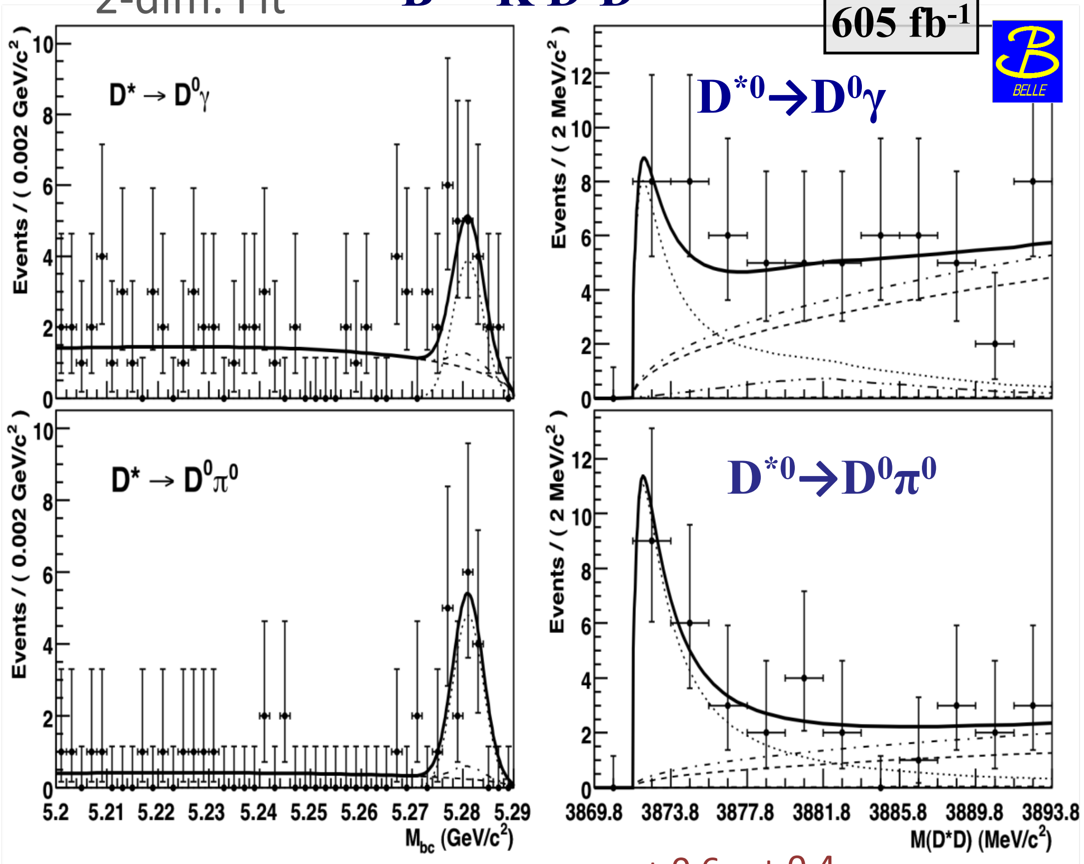
PRD81, 031103(2010)



M =3875.1$^{+0.7}_{-0.5}$ ±0.5 MeV

2-dim. Fit

B →K D0D*0



BaBar PRD77, 011102(2008)

Belle PRL97, 162002(2006)

Both groups saw a high mass value
& a Bf(DD*) ≈ 10x Bf($\pi^+\pi^-$J/ψ)

$M = 3872.9^{+0.6}_{-0.4}\ ^{+0.4}_{-0.5}$ MeV

Agrees with Mass from ππJ/ψ mode

$\Gamma(BW) = 3.9^{+2.8}_{-1.4}\ ^{+0.2}_{-1.1}$ MeV

B(B→K X_{3872})xB(X_{3872}→$D^{*0}D^0$) = (0.80±0.20± 0.10)x10^{-4}

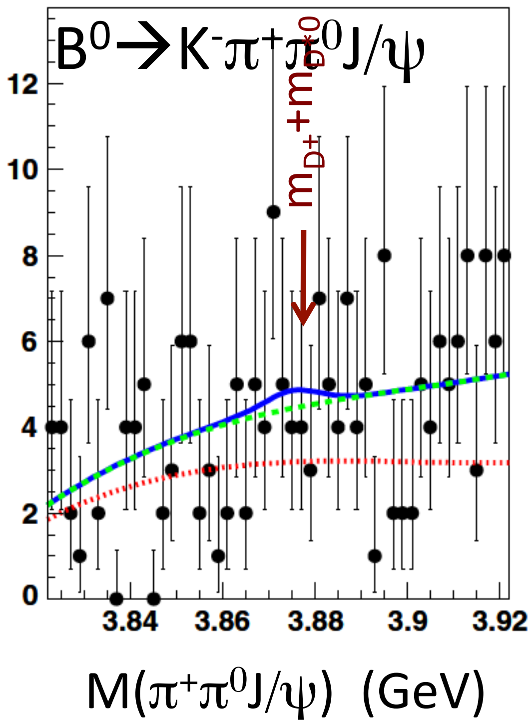
Isospin of the X(3872)

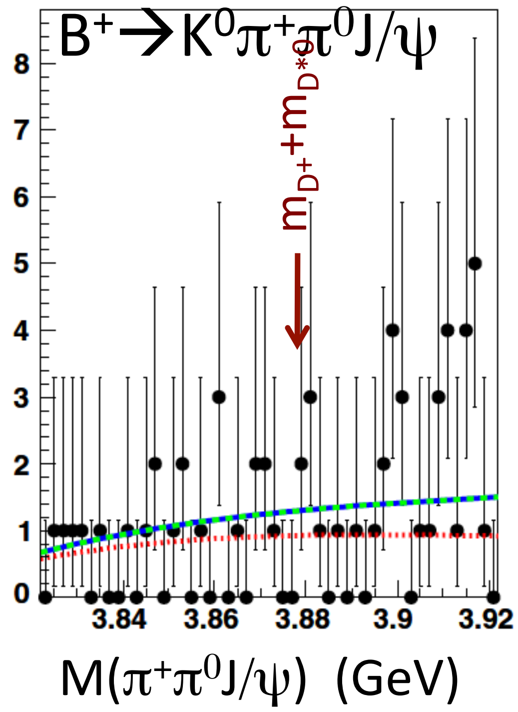
No X(3872) charged partner states in $B \rightarrow K\pi^+\pi^0 J/\psi$

(If $M(X^+) > m_{D^+}+m_{D^{*0}} \approx 3877$ MeV, $\Gamma(X^+)$ may be wide)

Belle PRD 84, 052004(R)

& BaBar PRD 71, 031501





Isospin mixing in the X(3872)

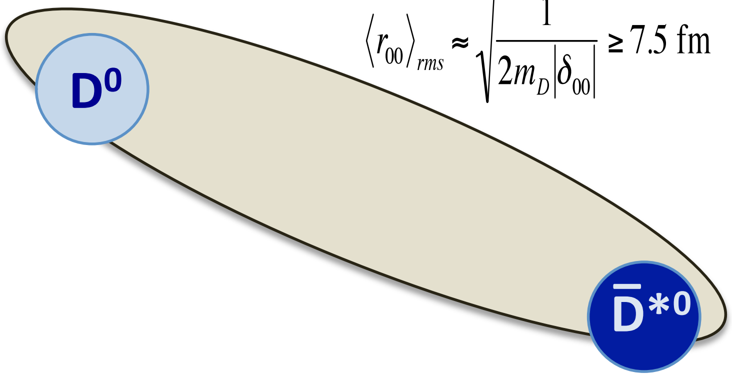
X(3872) → ρ J/ψ
→ω J/ψ } Isospin violating decay modes (each other) with similar BFs

X(3872)→$D^0\bar{D}^{*0}$ ~ 10 x BF(X→ J/ψππ)

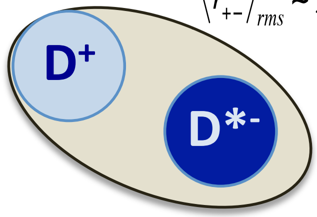
Eric Braaten: "S-wave $D\bar{D}^*$ molecular components must exist"

$$|\delta_{00}| = |M_{X(3872)} - (m_{D^0} + m_{D^{*0}})| \leq 0.2 \text{ MeV}$$

$$\delta_{+-} = M_{X(3872)} - (m_{D^+} + m_{D^{*-}}) \approx -8 \text{ MeV}$$



$$\langle r_{00} \rangle_{rms} \approx \sqrt{\frac{1}{2m_D|\delta_{00}|}} \geq 7.5 \text{ fm}$$



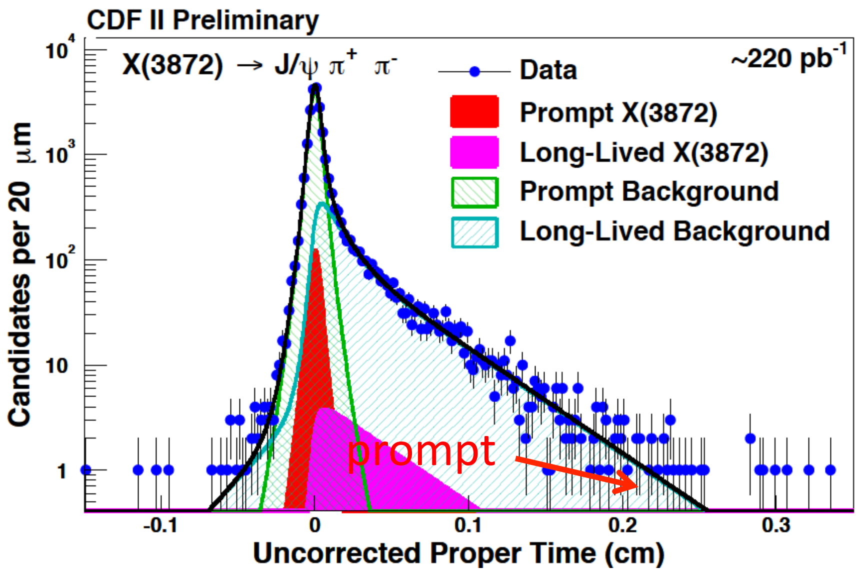
$$\langle r_{+-} \rangle_{rms} \approx \sqrt{\frac{1}{2m_D|\delta_{+-}|}} \approx 1.2 \text{ fm}$$

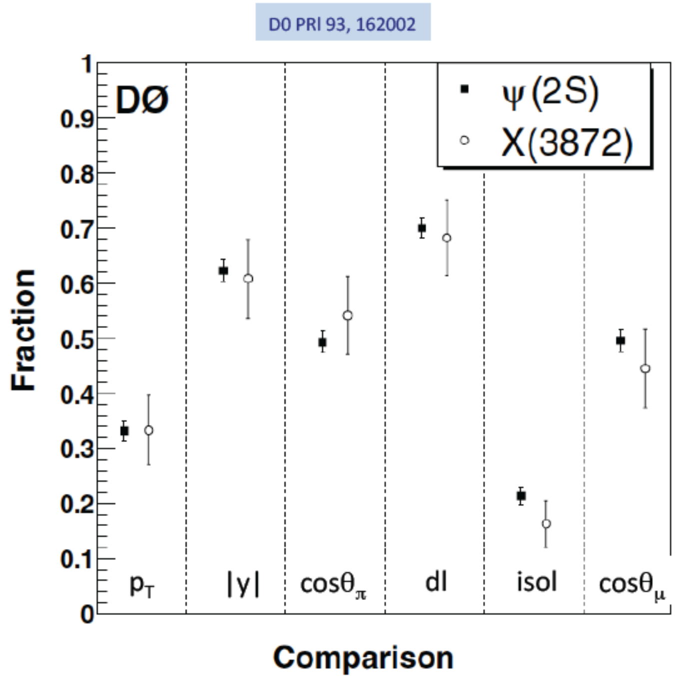
$$|D^0\bar{D}^{*0}\rangle = \tfrac{1}{\sqrt{2}}\left[|0,0\rangle + |1.0\rangle\right]$$

$$|D^+\bar{D}^{*-}\rangle = \tfrac{1}{\sqrt{2}}\left[|0,0\rangle - |1.0\rangle\right]$$

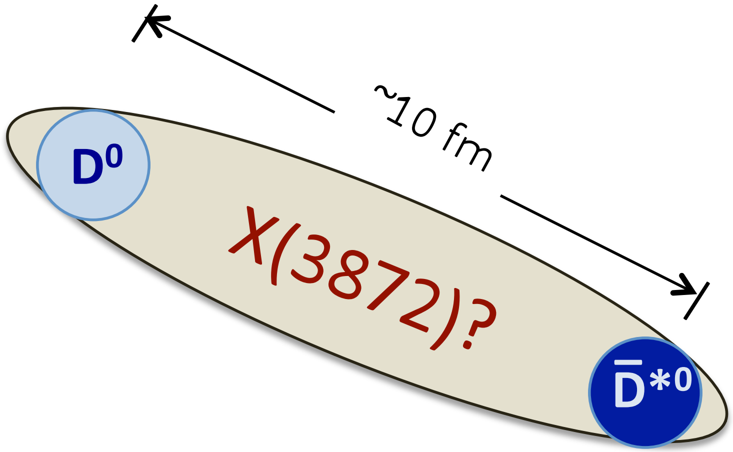
X(3872) is mostly |$D^0\bar{D}^{*0}$> ➔ mixture of |I=0 >& |I=1>

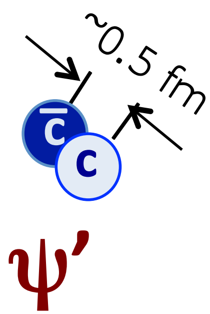
CDF: ~85% of $\bar{p}p \rightarrow X(3872)$ is prompt
D0: prompt $pp \rightarrow X(3872)X \approx pp \rightarrow \psi' X$





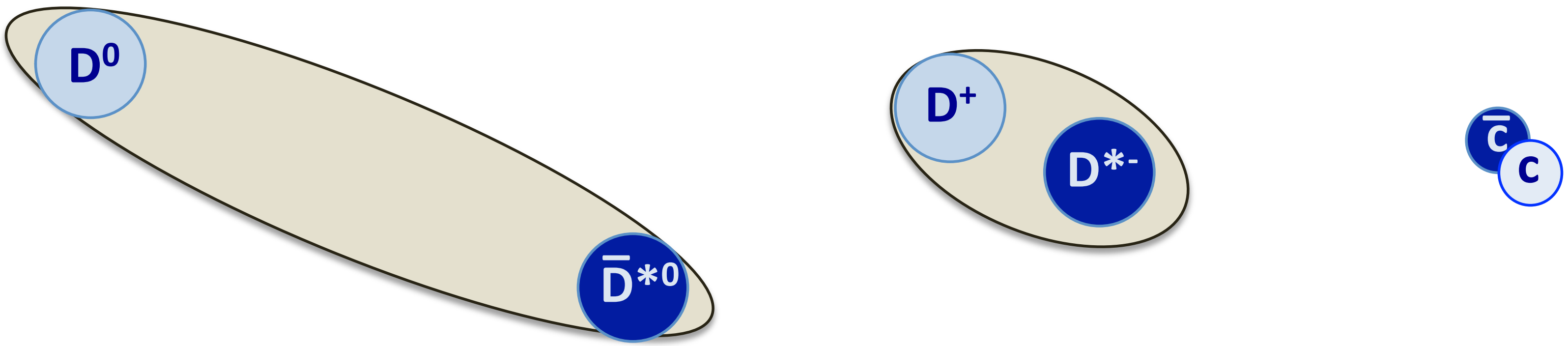
X(3872) & ψ' have similar production characteristics (i.e. p_T- & |y|-dependence, isolation, etc.)





"hybrid" model for the X(3872)

e.g., Takizawa & Takeuchi PTEP 9, 093D01



$$\left|X(3872)\right\rangle = 0.944\left|D^0\overline{D}^{*0}\right\rangle + 0.228\left|D^+D^{*-}\right\rangle - 0.237\left|c\overline{c}\right\rangle$$

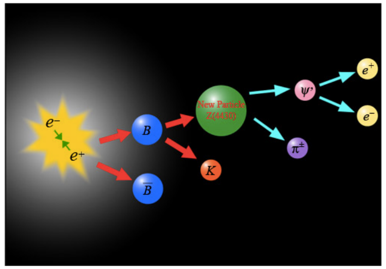
$$\left|X(3872)\right\rangle = 0.83\left|\left(D\overline{D}^*\right)_{I=0}\right\rangle + 0.51\left|\left(D\overline{D}^*\right)_{I=1}\right\rangle - 0.24\left|c\overline{c}\right\rangle$$

X→ωJ/ψ decays | X→ρJ/ψ decays | production

Charged Charmonium-like states :

Z(4430), Z(4050), Z(4250) , Z(4200) (new)

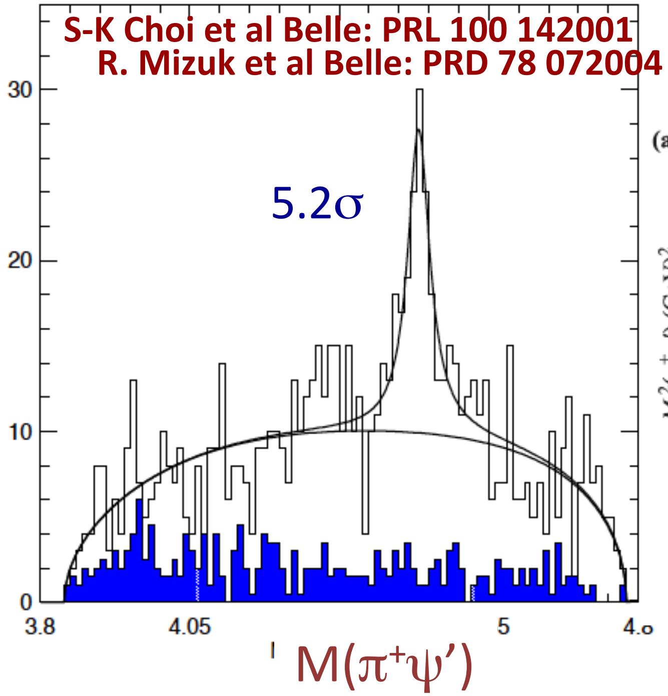
and Z(3885)..

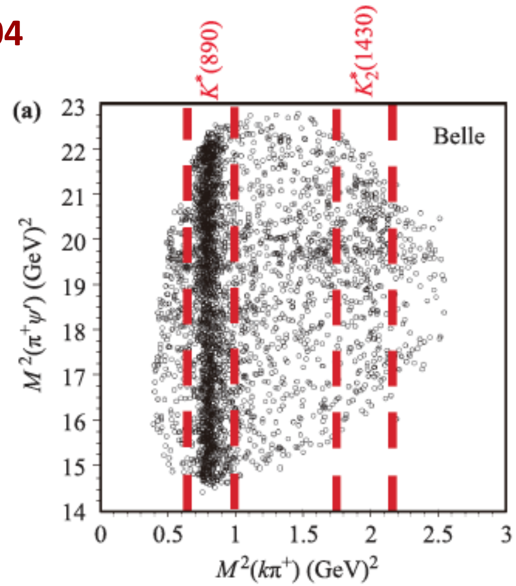


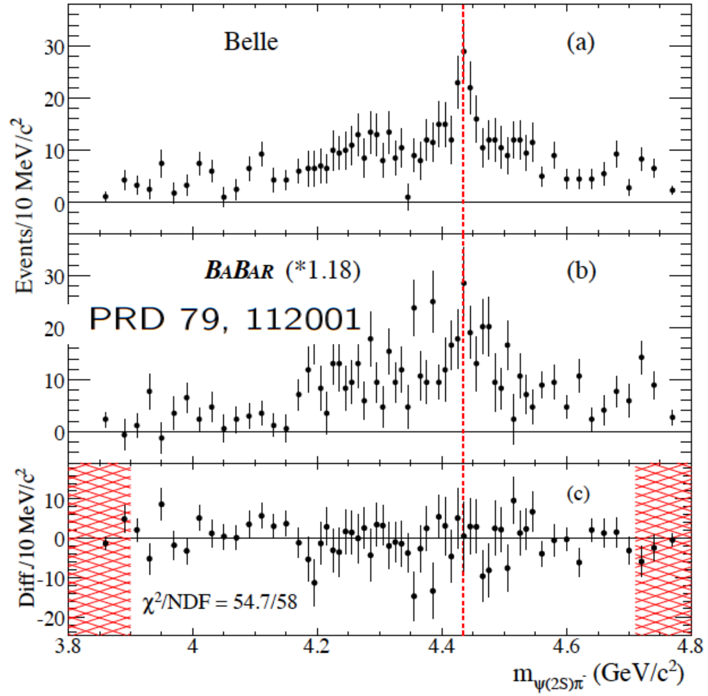
The Z(4430)$^+$

Found by Belle in 2007

Belle : 660M BB







Charged state cannot be $c\bar{c}$

Not seen by BaBar

But both Data seems consistent

Belle published two more results

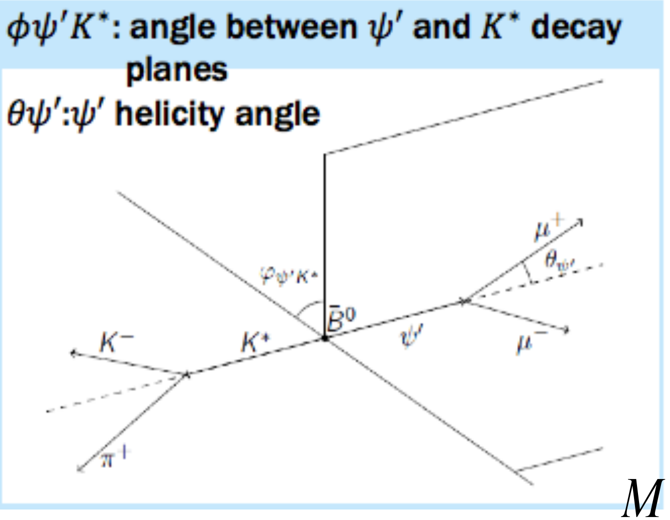
Latest one uses

4D amplitude analysis ➔

Quantum numbers of the Z(4430)$^+$

$Z(4430)^+ \to \pi^+\psi'$ in $B \to K^-\pi^+\psi'$

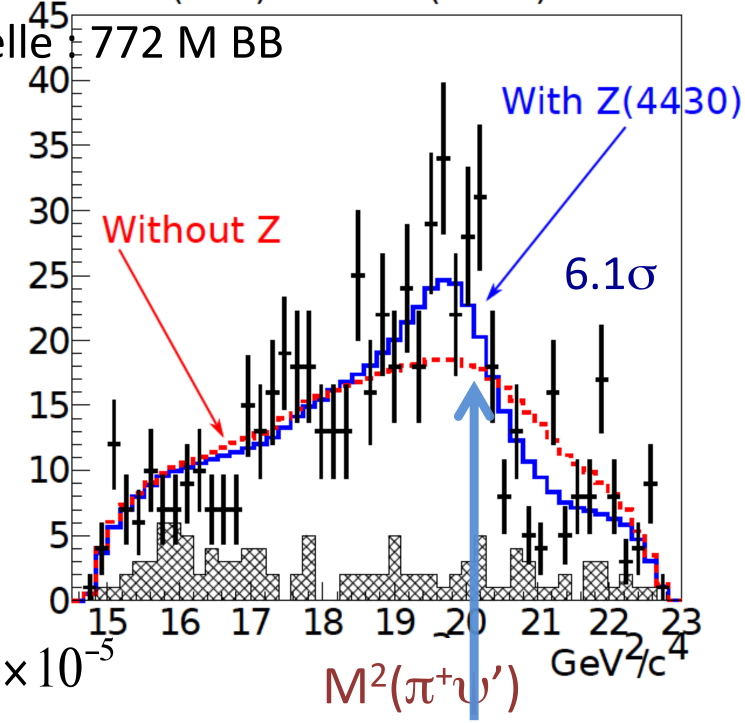
K Chilikin et al Belle: PRD 88 07402 (2013)



$(M^2(K\pi),\ M^2(\psi'\pi),\ \phi\psi$

$$M = 4485^{+22+28}_{-22-11}\ \text{MeV}$$

$$\Gamma = 200^{+41+26}_{-46-35}\ \text{MeV}$$



$$Bf(B^0 \to Z(4430)^- K^+) \times Bf(Z(4430)^- \to \pi^-\psi') = (6.0^{+1.7+2.5}_{-2.0-1.4}) \times 10^{-5}$$

Results from 4D fit
(4-dimensional amplitude analysis of $B^0 \to \psi(2S)K^+\pi^-$)

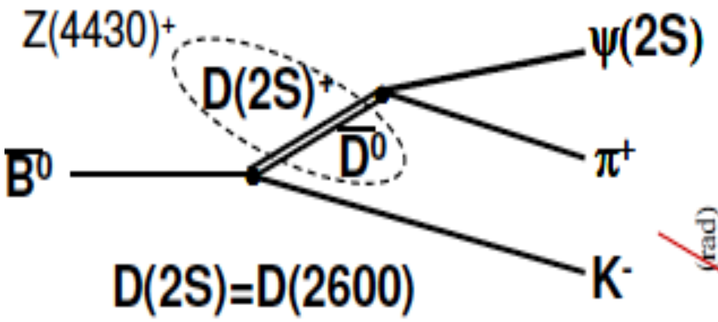
J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4479 ± 16	4477 ± 4	4485 ± 20	4478 ± 22	4384 ± 19
Width, MeV	110 ± 50	22 ± 14	200 ± 40	83 ± 25	52 ± 28
Significance	4.5σ	3.6σ	6.4σ	2.2σ	1.8σ

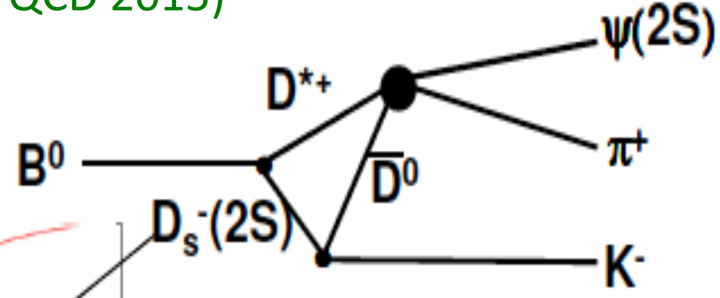
1^+ is favored over 0^- by 3.4 σ

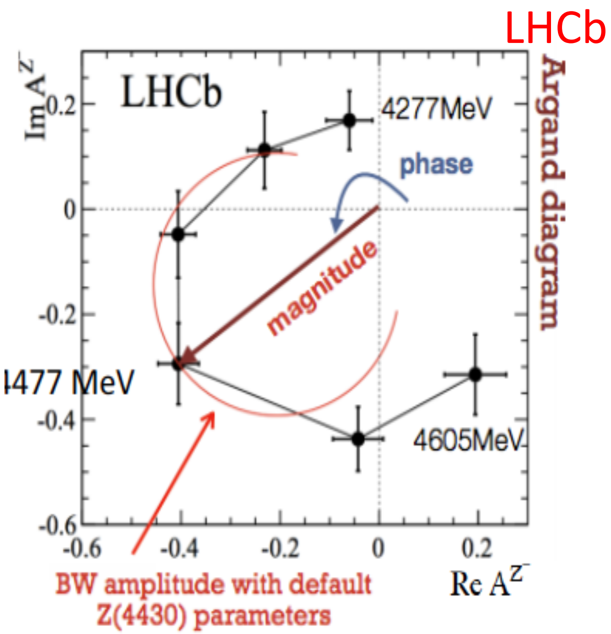
18

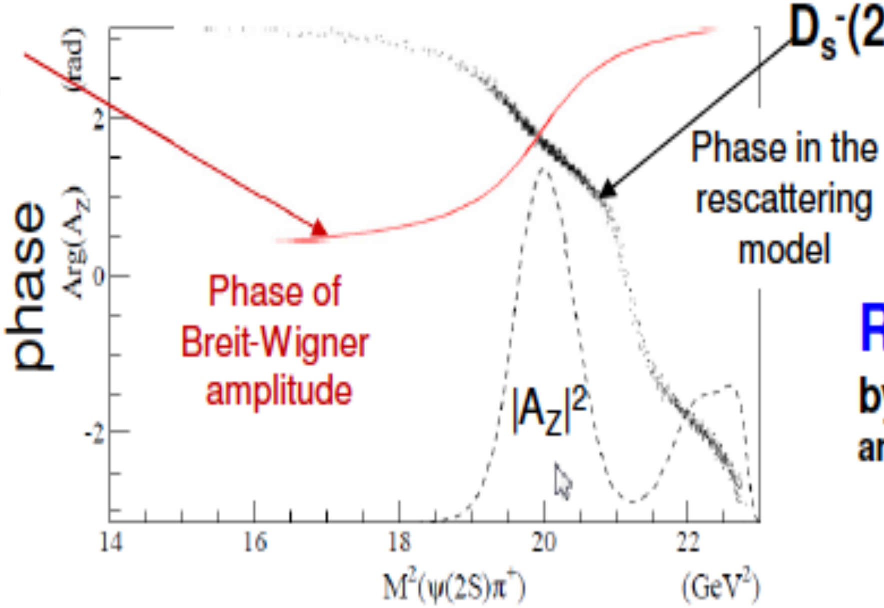
Is Z(4430)$^+$ a resonance or rescattering effect ?

Taken from T. Skwarnicki (Moriond QCD 2015)









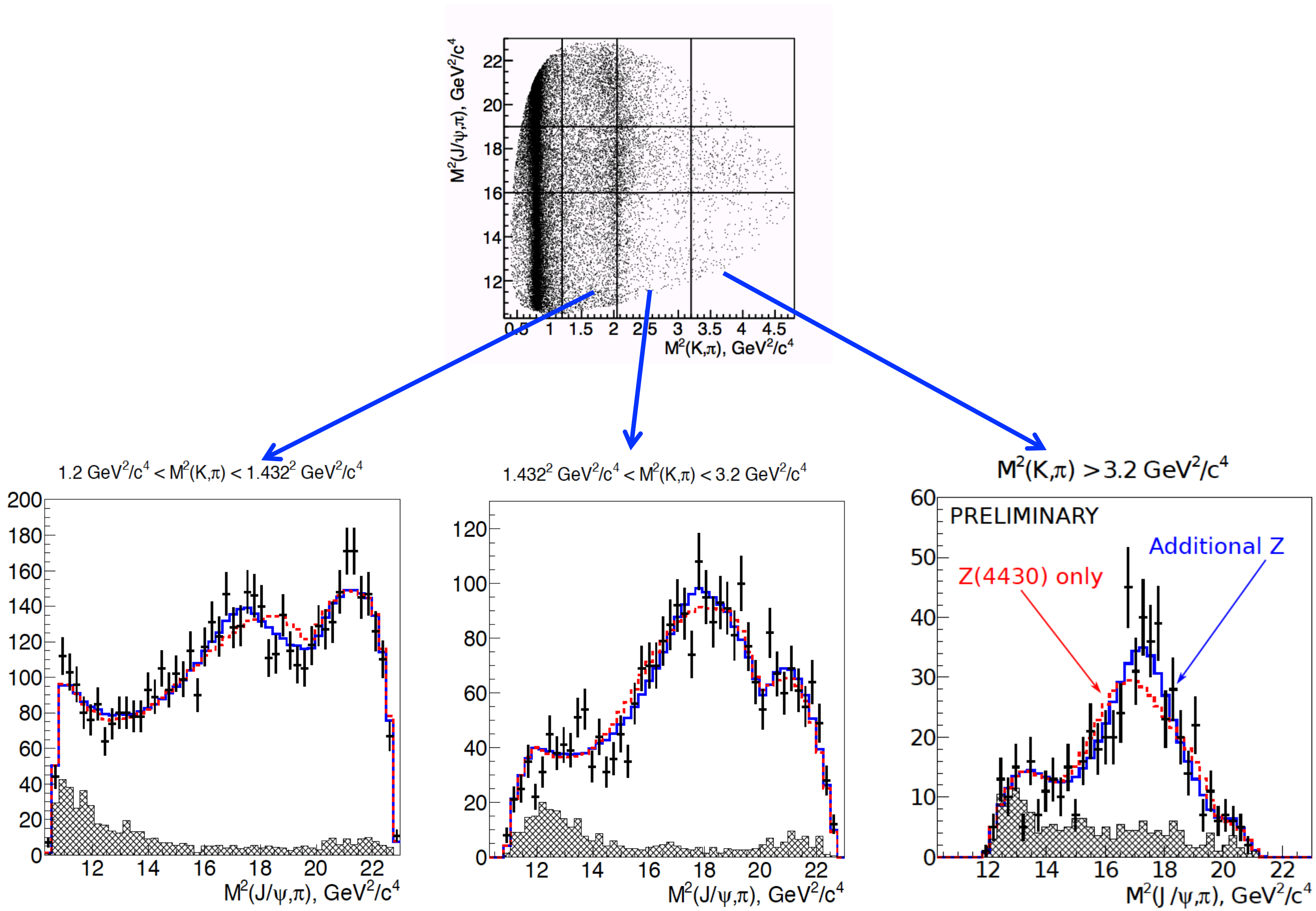
Rescattering model

by P. Pakhlov, T. Uglov

arXiv:1408.5295

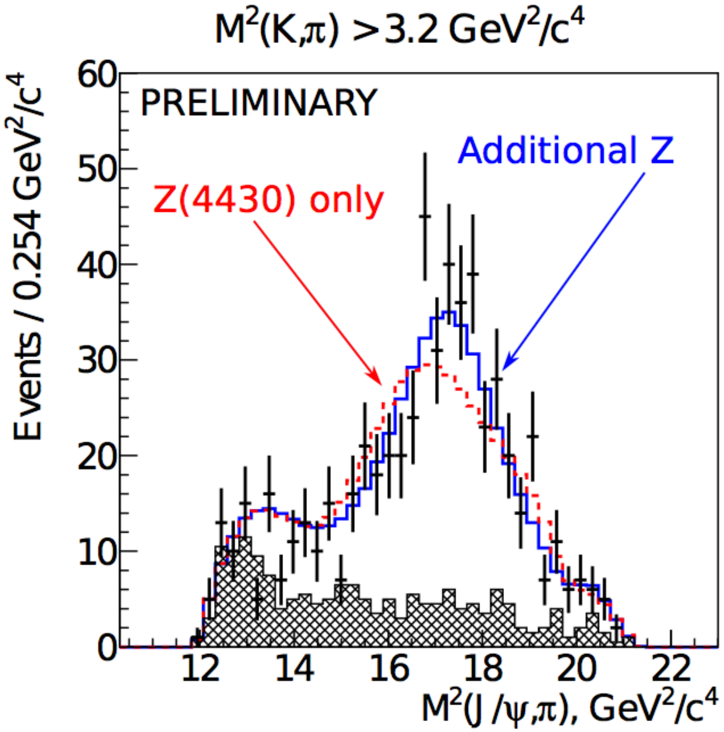
The phase from rescattering runs in the opposite way to the Breit-Wigner amplitude i.e. in disagreement with the Argand diagram obtained by LHCb.

The Z(4200)$^+$
New from Belle: 4-dim analysis of $B \rightarrow K^+\pi^- J/\psi$



K Chilikin et al Belle: PRD 90 112009 (arXiv: 1408.6457) (2014)

New state $Z(4200)^+ \rightarrow \pi^- J/\psi$



6.2 σ

$$M = 4196^{+31+17}_{-29-13}\ \mathrm{MeV}/c^2$$

$$\Gamma = 370^{+70+70}_{-70-132}\ \mathrm{MeV}$$

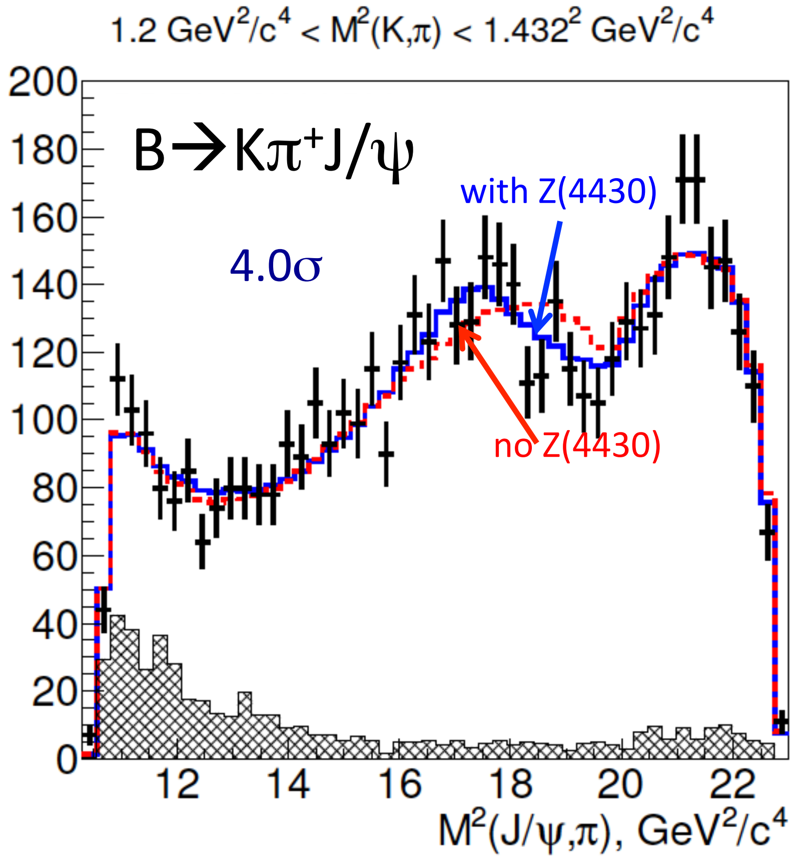
$$\mathcal{B}(\bar{B}^0 \to Z_c(4200)^+ K^-) \times \mathcal{B}(Z_c(4200)^+ \to J/\psi\pi^+) = (2.2^{+0.7+1.1}_{-0.5-0.6}) \times 10^{-5}$$

Amplitude analysis of $B \to J/\psi K\pi$

J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4318 ± 48	4315 ± 40	4196^{+31}_{-29}	4209 ± 14	4203 ± 24
Width, MeV	720 ± 254	220 ± 80	370 ± 70	64 ± 18	121 ± 53
Significance	3.9σ	2.3σ	8.2σ	3.9σ	1.9σ

1^+ is favored over 0^- by 6.1σ and 2^- by $4.4\ \sigma$

$Z(4430)^+ \rightarrow \pi^- J/\psi$



$$\frac{\mathcal{B}(Z_c(4430)^+ \to \psi(2S)\pi^+)}{\mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+)} \sim 10$$

$\mathcal{B}(\bar{B}^0 \to J/\psi K^- \pi^+) = (1.15 \pm 0.01 \pm 0.05) \times 10^{-3}$

$\mathcal{B}(\bar{B}^0 \to J/\psi K^*(892)) = (1.19 \pm 0.01 \pm 0.08) \times 10^{-3}$

This may support the Z(4430) as an hadro-charmonium other than conventional tetraquark state

S. Dubynskiy and M.B. Voloshin, Phys. Lett. B 666, 344 (2008)

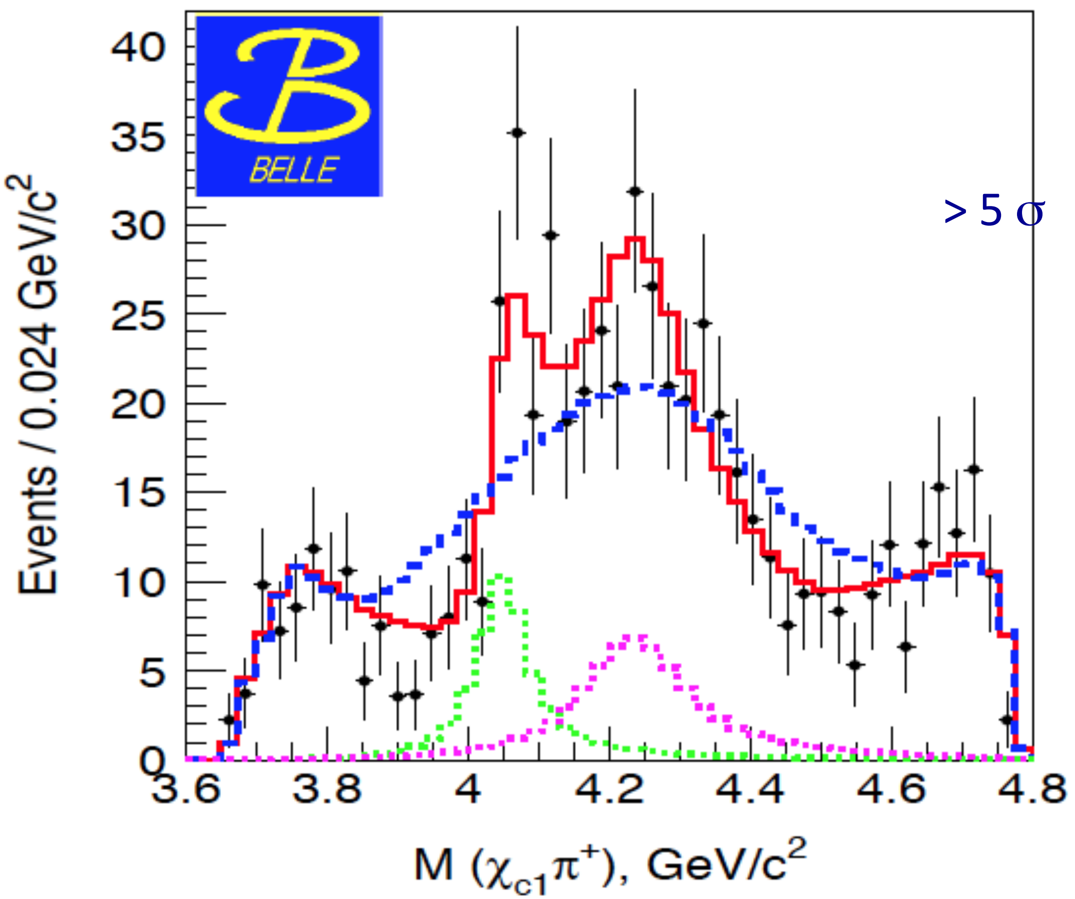
$$\mathcal{B}(\bar{B}^0 \to Z_c(4430)^+ K^-) \times \mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+) = (5.4^{+4.0+1.1}_{-1.0-0.9}) \times 10^{-6}$$

$M(Z_c(4430))-M(Z_c(3900)) = 589 \pm 30$ MeV
$M(\psi') - M(J/\psi) = 589$ MeV

Is Z(4430) a radial excitation of the ground state of $Z_c(3900)$?

$Z(4050)^+$ and $Z(4250)^+ \rightarrow \pi^+\chi_{c1}$
in $B^0 \rightarrow K^-\pi^+\chi_{c1}$

PRD 78, 072004 (2008)

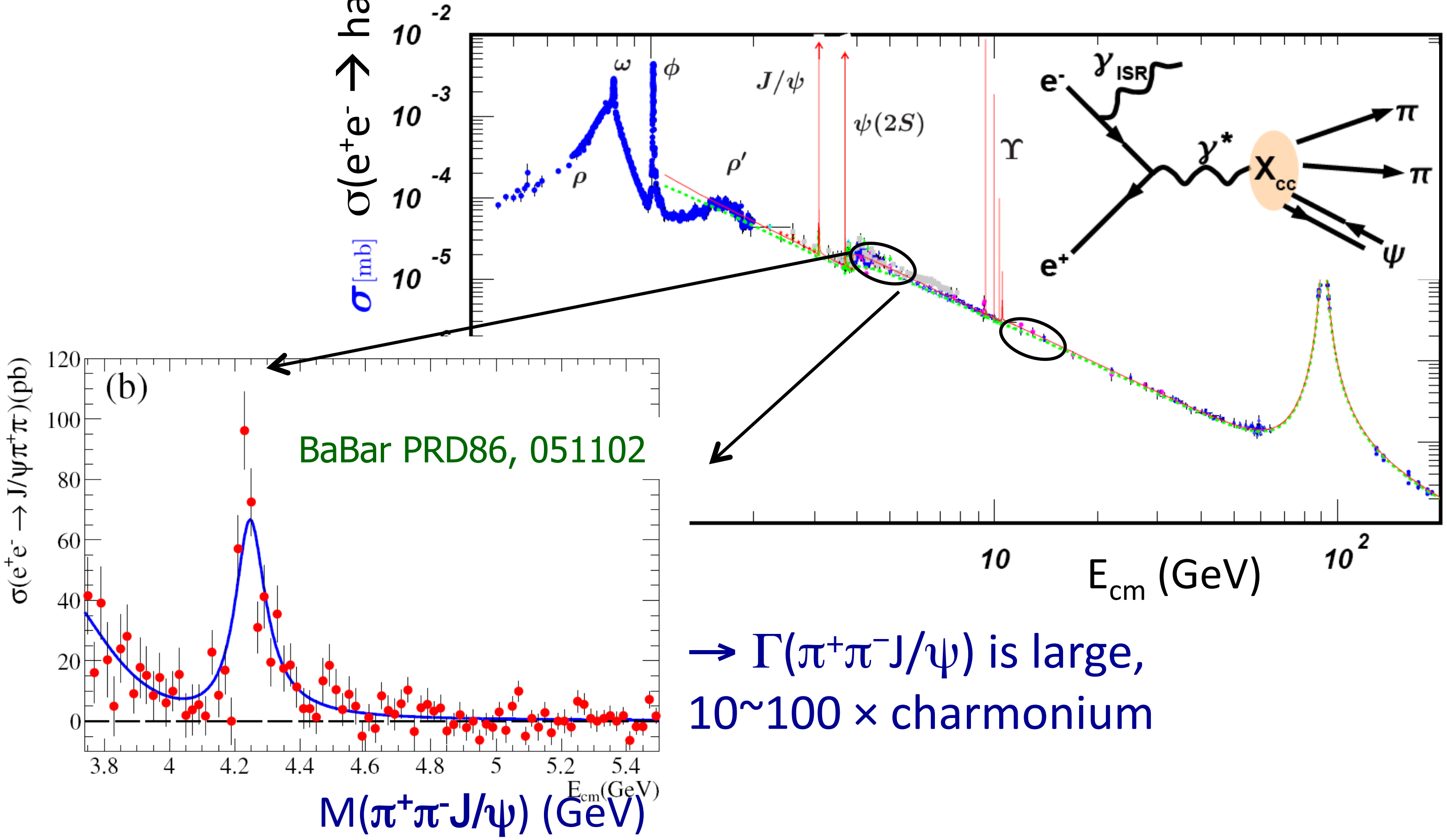


Charged Bottomonium-like Z_b states
and
neutral partner state:

$Z_b(10610)^+$, $Z_b(10650)^+$ and $Z_b(10610)^0$

The Y(4260)

found by BaBar in $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$



Confirmed by Cleo, Belle and BES

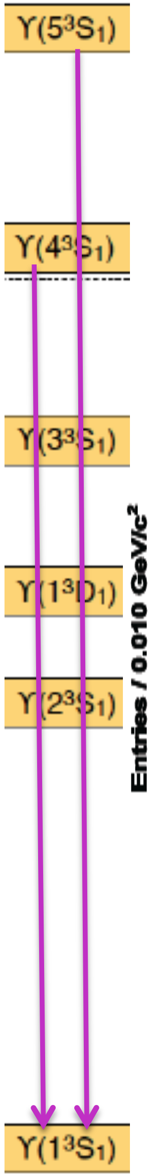
→ $\Gamma(\pi^+\pi^- J/\psi)$ is large, 10~100 × charmonium

Is there a b-quark version of Y(4260)?

“bottomonium” $b\bar{b}$ mesons

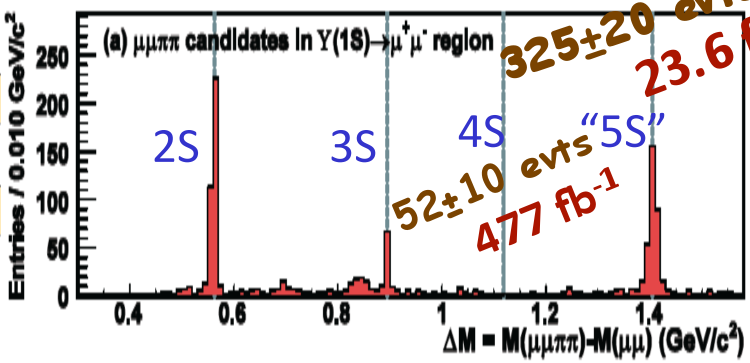
New Measurement of R_b , $R_{\Upsilon(nS)\pi\pi}$

arXiv:1501.01137



Is there any anomaly in $\Upsilon(4S,5S) \rightarrow \pi^+\pi^- \Upsilon(1S)$?

Lum ~1/20th
σ ~1/5th
Signal ~×6



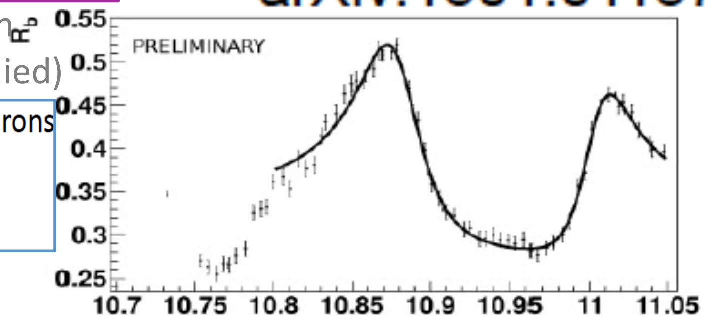
parent	$\Gamma(\Upsilon_{4,5S} \rightarrow \pi\pi\Upsilon_{1S})$
Υ(4S)	1.75 ± 0.35 keV
“Υ(5S)”	590 ± 110 keV

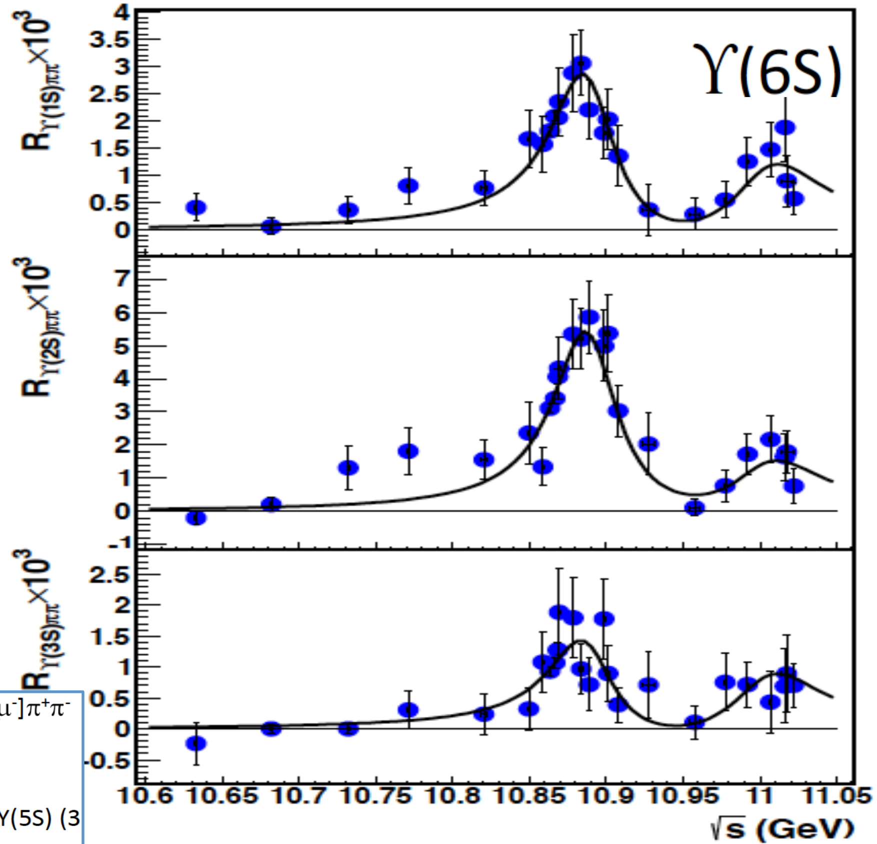
→ Energy scan

$R_X = \sigma_{e^+e^- \to X} / \sigma_{e^+e^- \to \mu^+\mu^-}$

(Continuum subtraction and ISR correction applied)

Data Sample: $e^+e^- \rightarrow bb \rightarrow$ hadrons
- 61 ~50 pb^{-1} scan points
- 16 ~1 fb^{-1} scan points



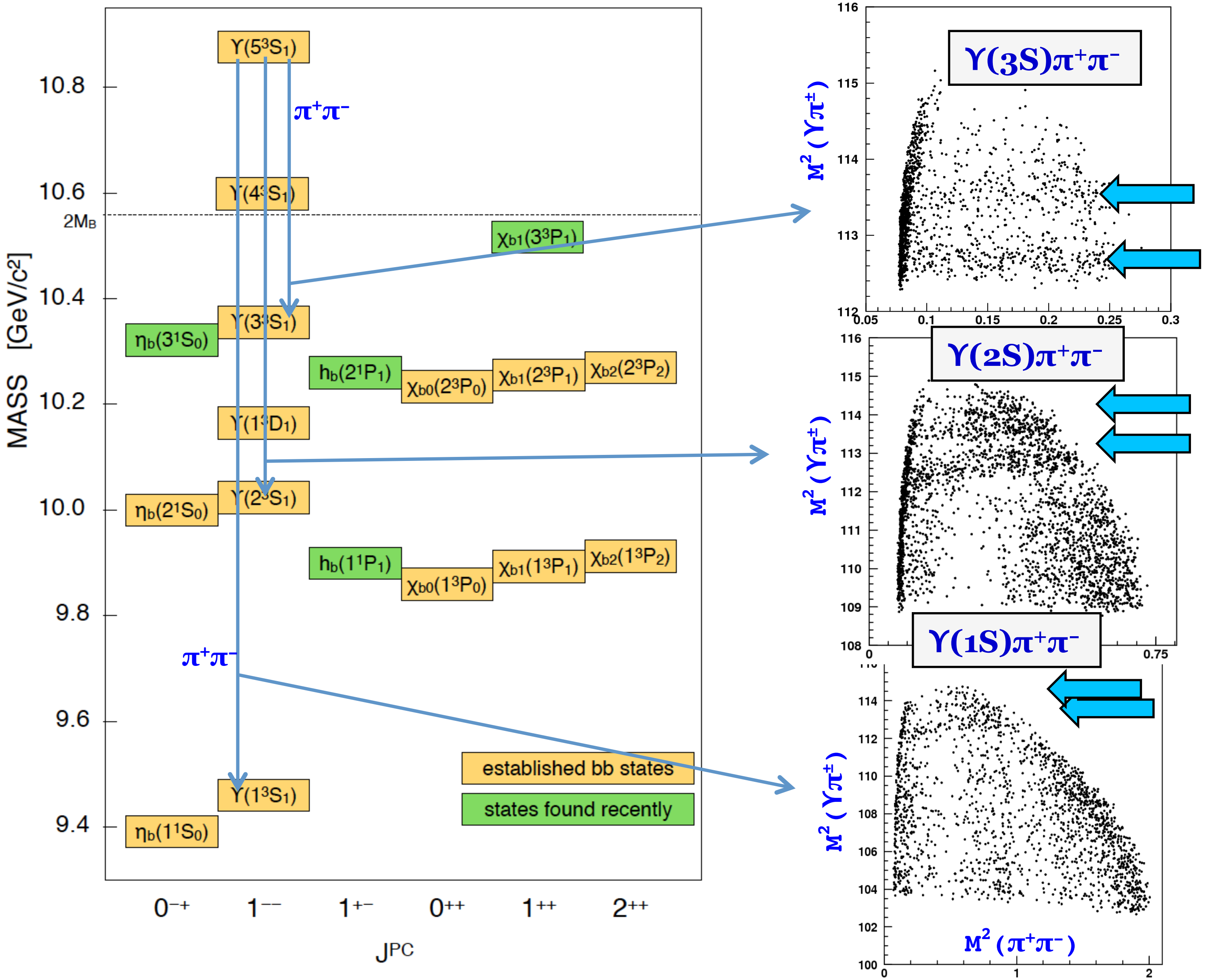


Data sample: $e^+e^- \rightarrow \Upsilon(nS)[\mu^+\mu^-]\pi^+\pi^-$
- 10.6-11.02 GeV
- 22 ~1 fb^{-1} scan points
- 121 fb^{-1} on-resonance at Υ(5S) (3 points)

Belle PRL 108, 122001 (2012)

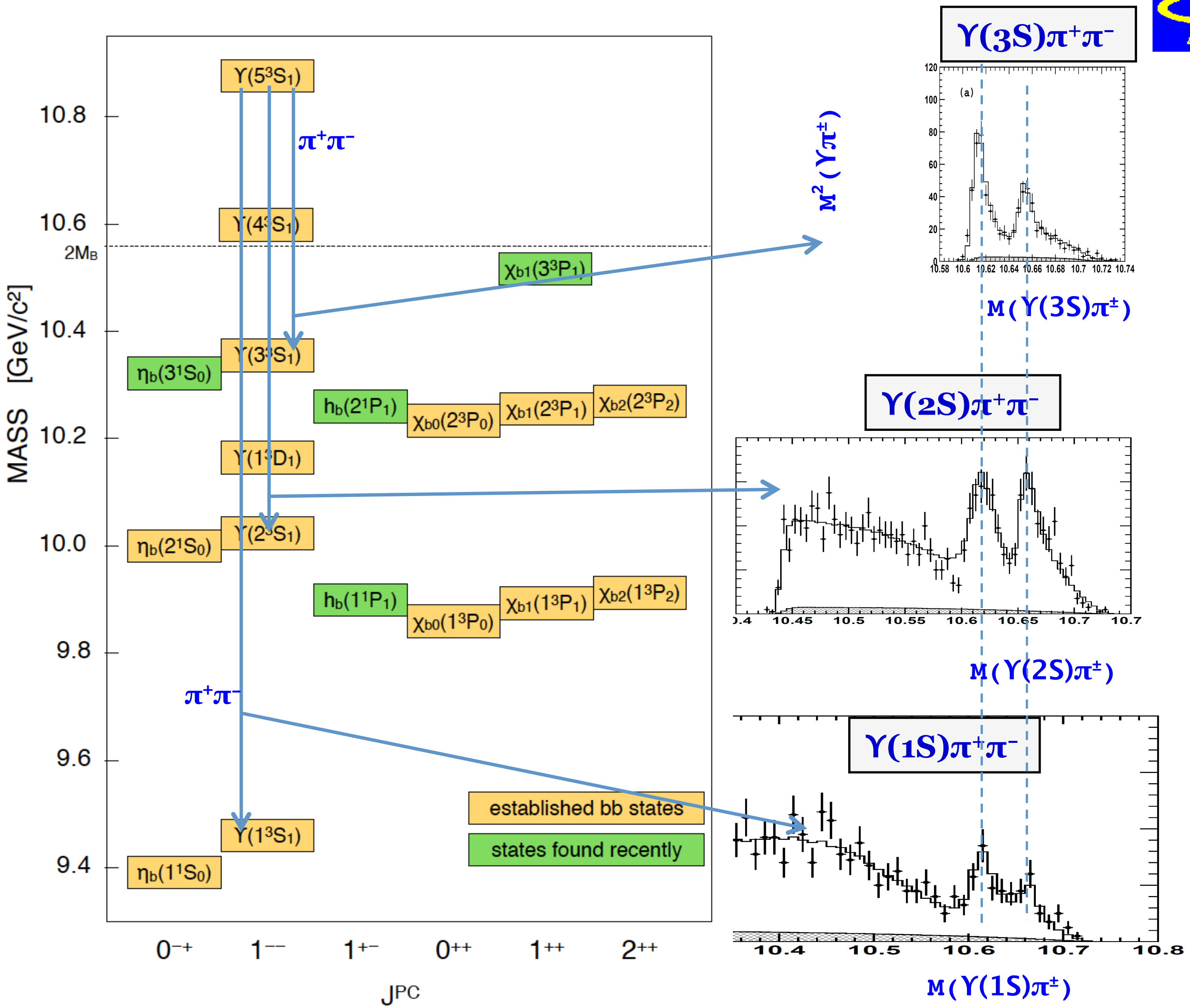
"Υ(5S)" → $\pi^+\pi^-\Upsilon$(1,2,3S) ?

121.4 fb^{-1}



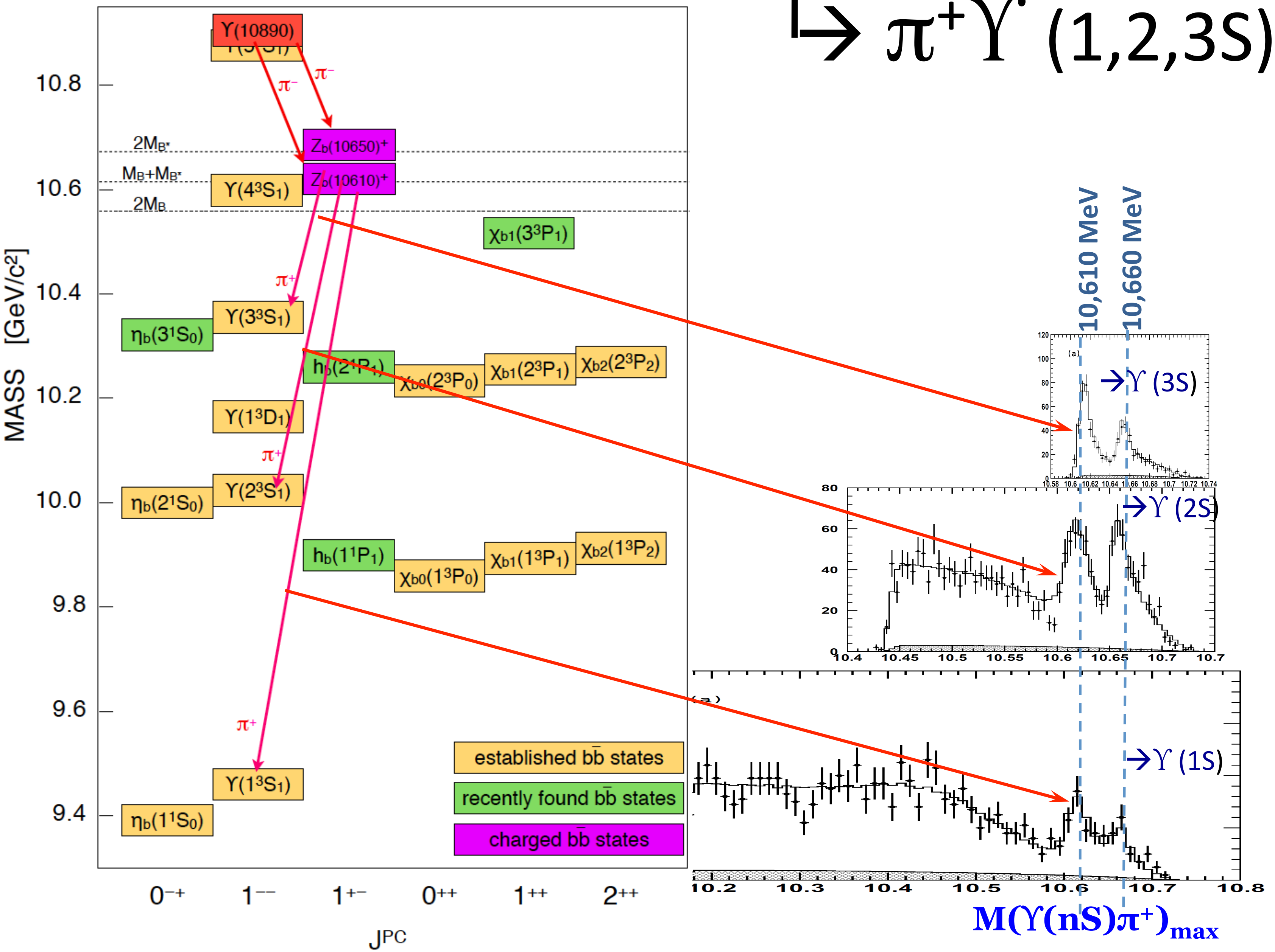
"Υ(5S)" → $\pi^+\pi^-$ Υ (1S) ?

Belle PRL 108, 122001 (2012)
121.4 fb^{-1}



"$\Upsilon(5S)$" → $\pi^- Z^+_{b1,2}$ ↳ $\pi^+\Upsilon$ (1,2,3S)

Belle PRL 108, 122001 (2012)
121.4 fb^{-1}

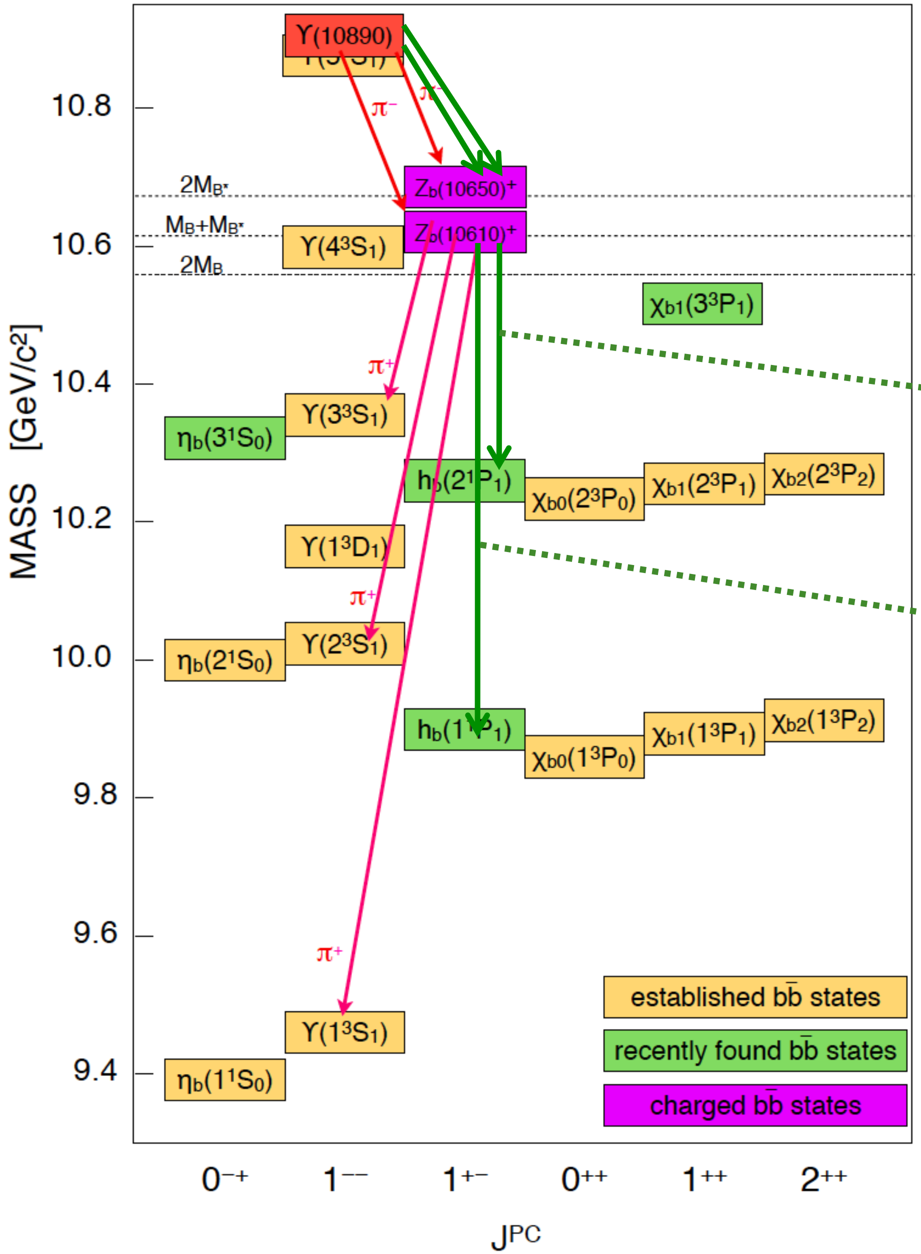


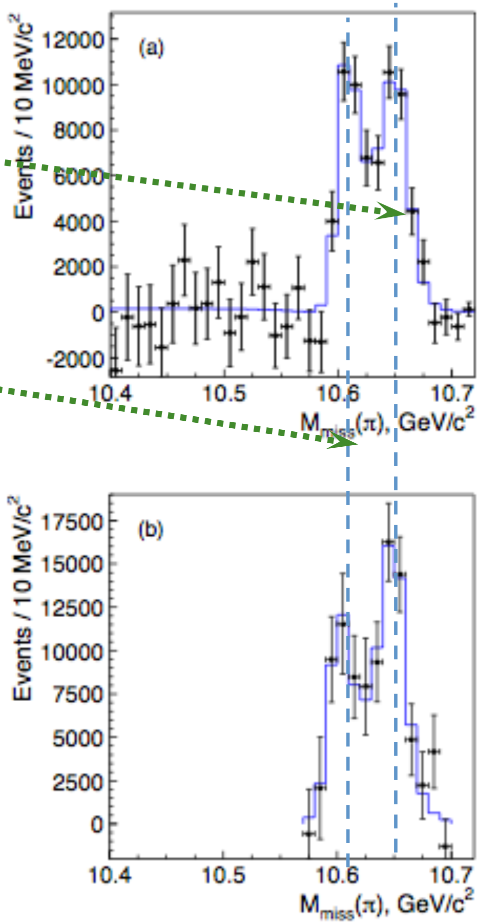
"Υ(5S)" → $\pi^- Z_{b1,2}^+$

↳ $\pi^+ h_b(1P, 2P)$

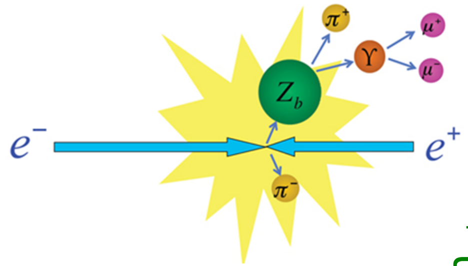
Belle PRL 108, 122001 (2012)
121.4 fb^{-1}

Bottomonium spectrum

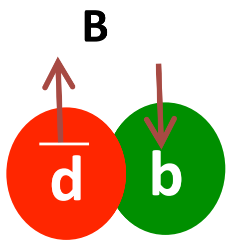


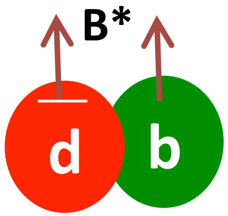


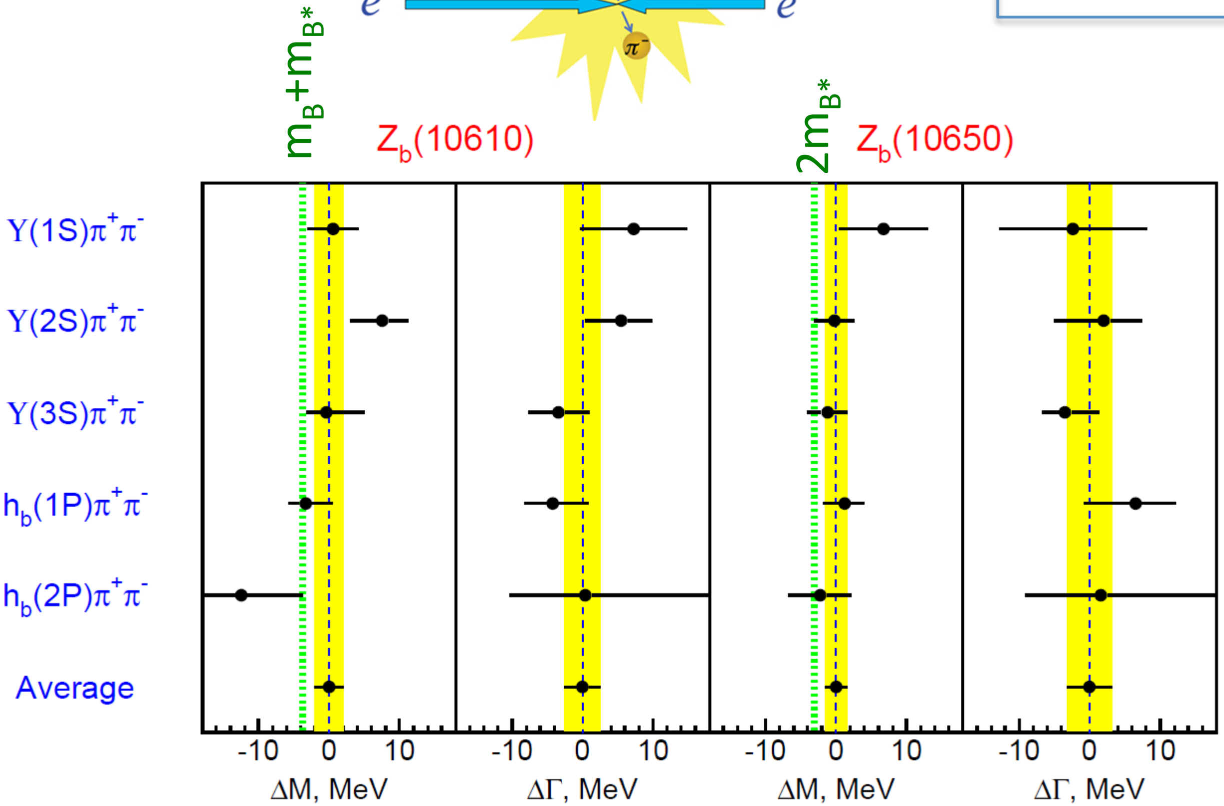
Summary of parameter measurements



Belle PRL 108, 122001



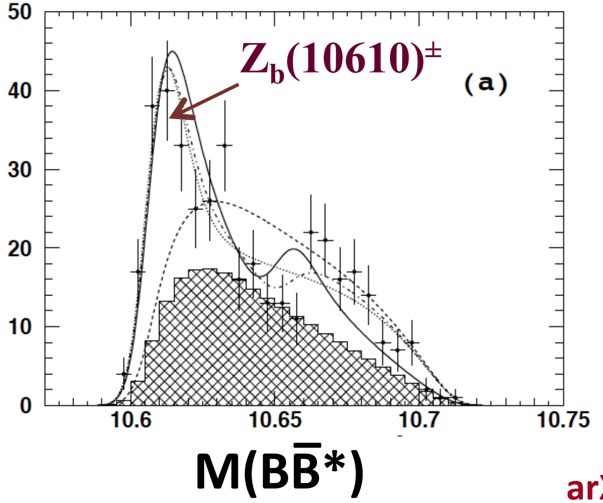




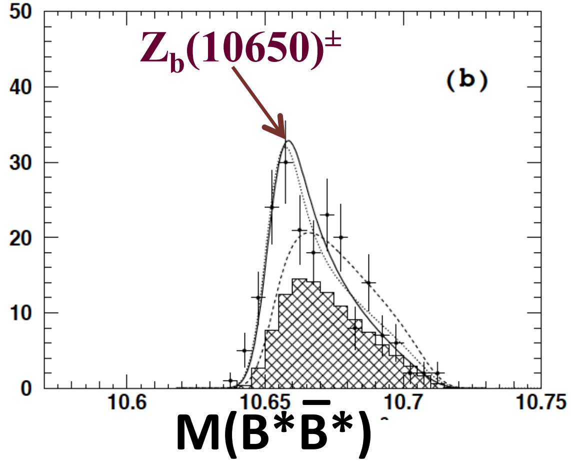
$Z_b(10610)$	$Z_b(10650)$
M=10607.2±2.0 MeV	M=10652.2±1.5 MeV
Γ=18.4±2.4 MeV	Γ=11.5±2.2 MeV

$Z_b(10610) \rightarrow B\bar{B}^*$ & $Z_b(10650) \rightarrow B^*\bar{B}^*$

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



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



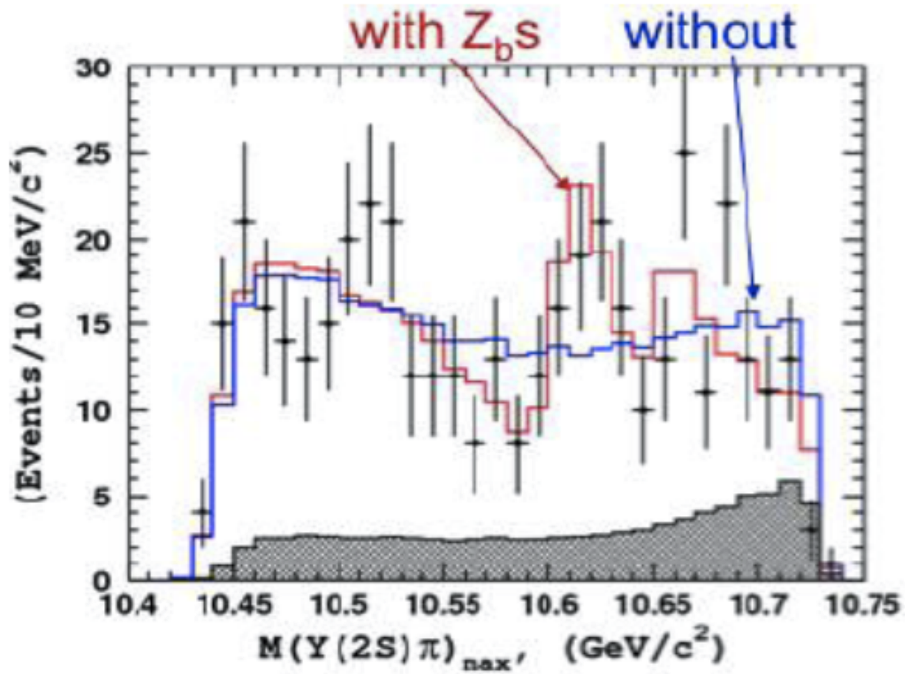
arXiv : 1209.6450

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
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	$-$
$B^{*+}\bar{B}^{*0}$	$-$	73.4 ± 7.0

$$\frac{Bf(Z_b(10610) \rightarrow B\bar{B}^*)}{Bf(Z_b(10610) \rightarrow \pi^+(b\bar{b}))} = 6.2 \pm 0.7$$

$$\frac{Bf(Z_b(10650) \rightarrow B^*\bar{B}^*)}{Bf(Z_b(10650) \rightarrow \pi^+(b\bar{b}))} = 2.8 \pm 0.4$$

Z_b^0 search in $\Upsilon(5S) \rightarrow \pi^0\pi^0\,\Upsilon(1,2S)$



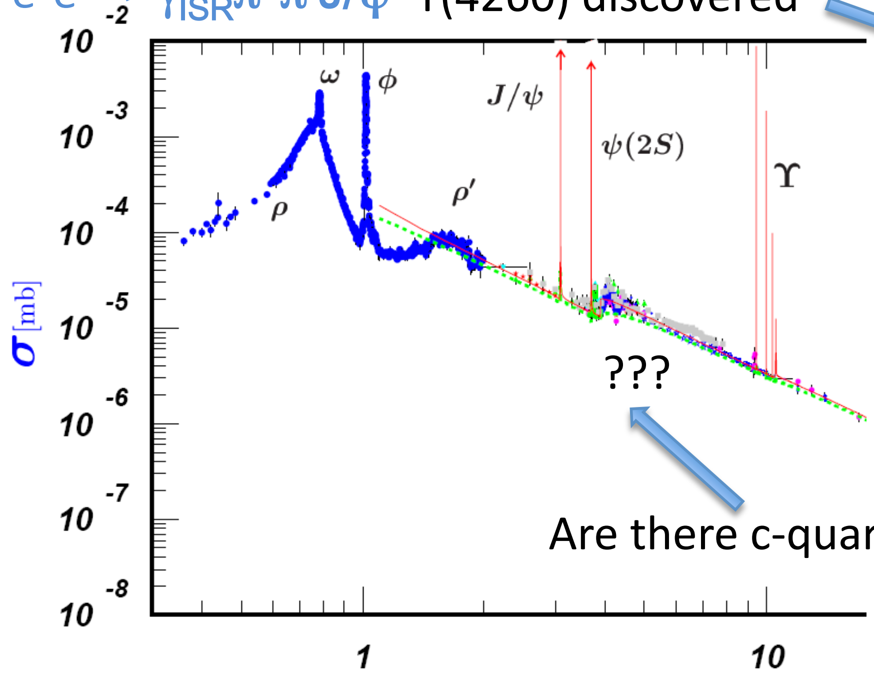
6.5σ stat. significance
Mass 10609±4±4 MeV

Belle PRD 88 052016 (2013)

More Z_c states

Discovery chain from Y(4260) to $Z_{b(c)}$'s

by BaBar in $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$ Y(4260) discovered



???

Is there a b-quark equivalent?

Yes, & it decays to Z_b states

$\Upsilon(5S) \rightarrow \pi^+ Z_b^-$
$\rightarrow \pi^+\pi^- \Upsilon(1S)$

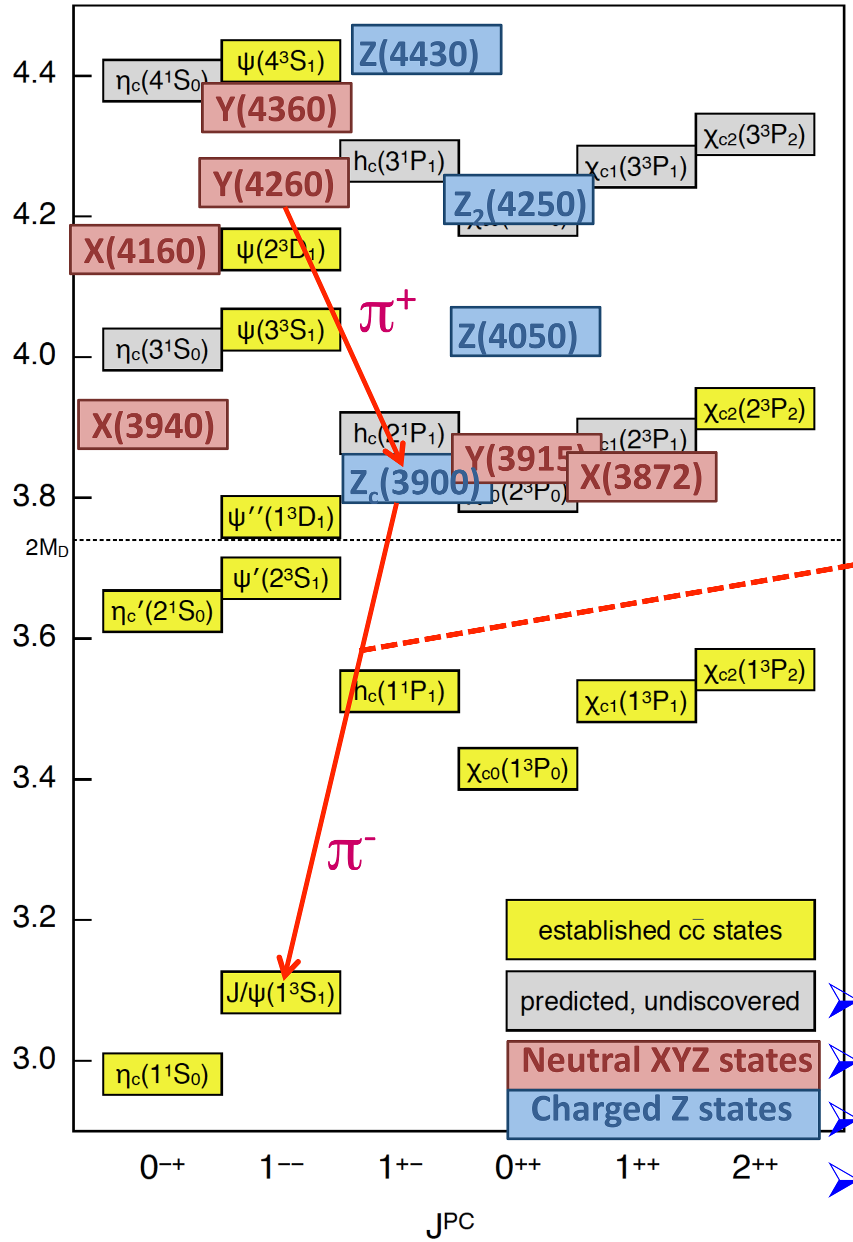
Are there c-quark versions of Z_b's?

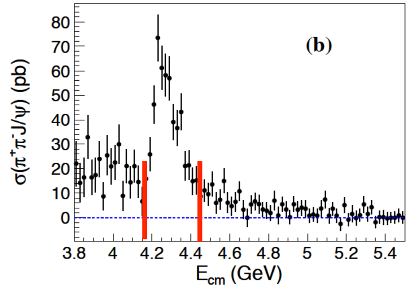
→ Yes, many Z_c's !!

$Z_c(3895)$ by Belle

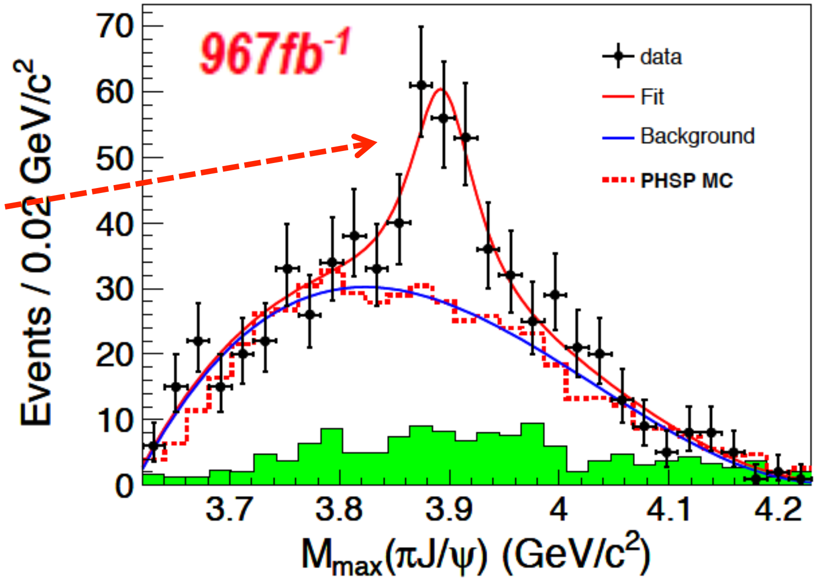
PRL 110, 252002 (2013)
arXiv:1304.0121

$e^+e^- \rightarrow (\gamma) Y(4260) \rightarrow \pi^- Z_c(3895)^+ \rightarrow \pi^+\pi^- J/\psi$





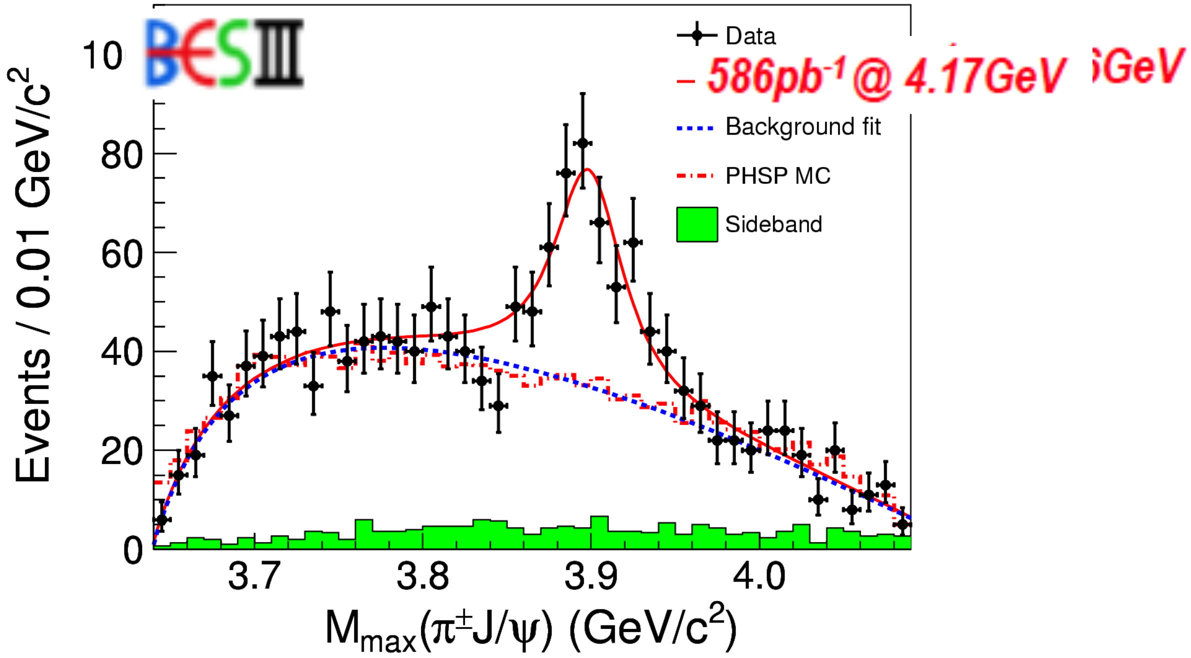
BESIII data clearly establish $J^P=1^+$ From DD*



- Mass = $(3894.5 \pm 6.6 \pm 4.5)$ MeV
- Width = $(63 \pm 24 \pm 26)$ MeV
- Fraction = $(29.0 \pm 8.9)\%$ (stat. error only)
- Significance = $5.2\ \sigma$

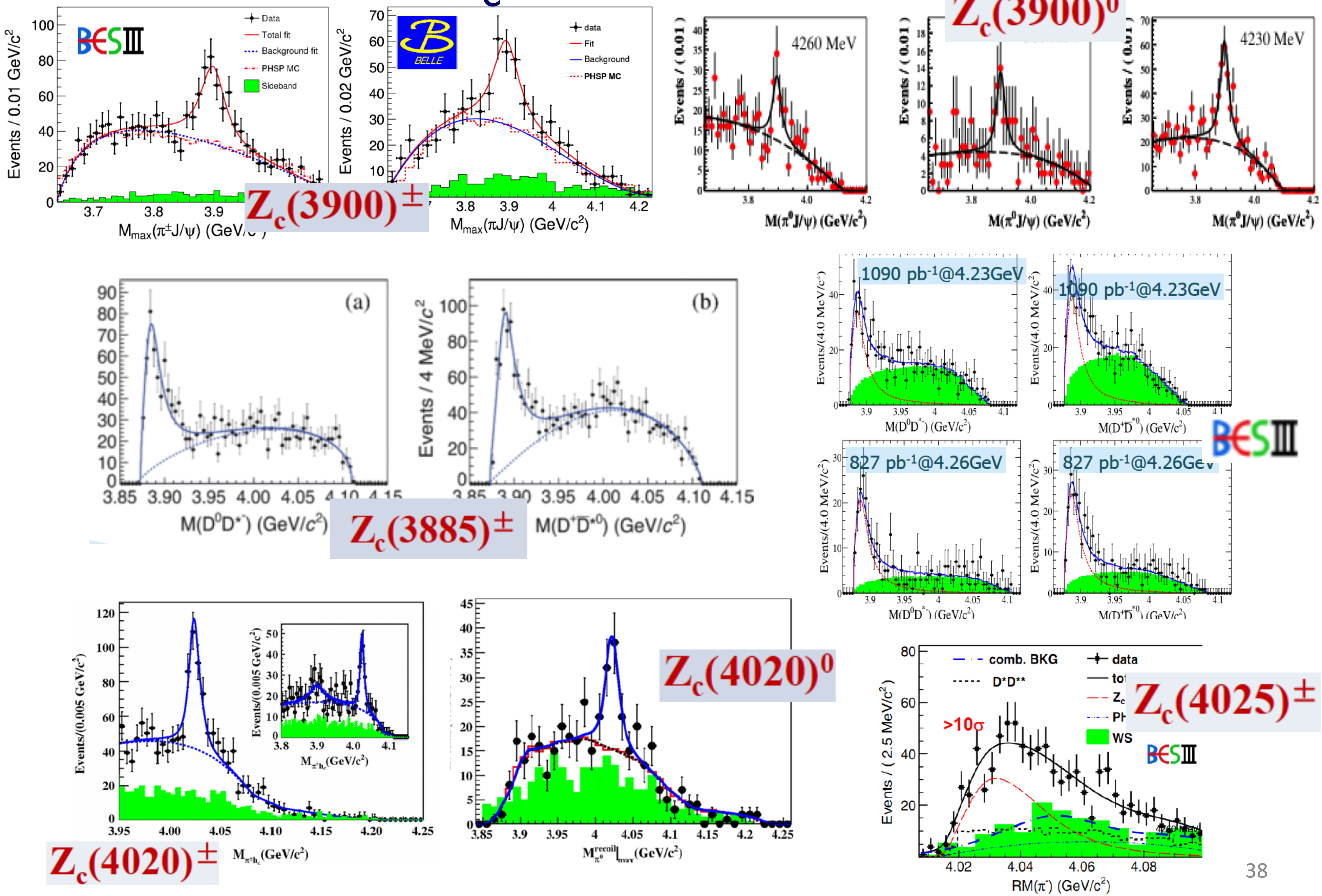
$Y(4260) \to \pi^{\mp} Z_c(3900)^{\pm} \to \pi^{\mp} \pi^{\pm} J/\psi$

BESIII: PRL 110, 252001
arXiv:1303.5949



- Mass = (3899.0±3.6±4.9) MeV
- Width = (46±10±20) MeV
- Fraction = (21.5±3.3±7.5)%
- Significance > 8 σ

Z_c states from BESIII



Summary of Z_c states

discovered in the BESIII experiment

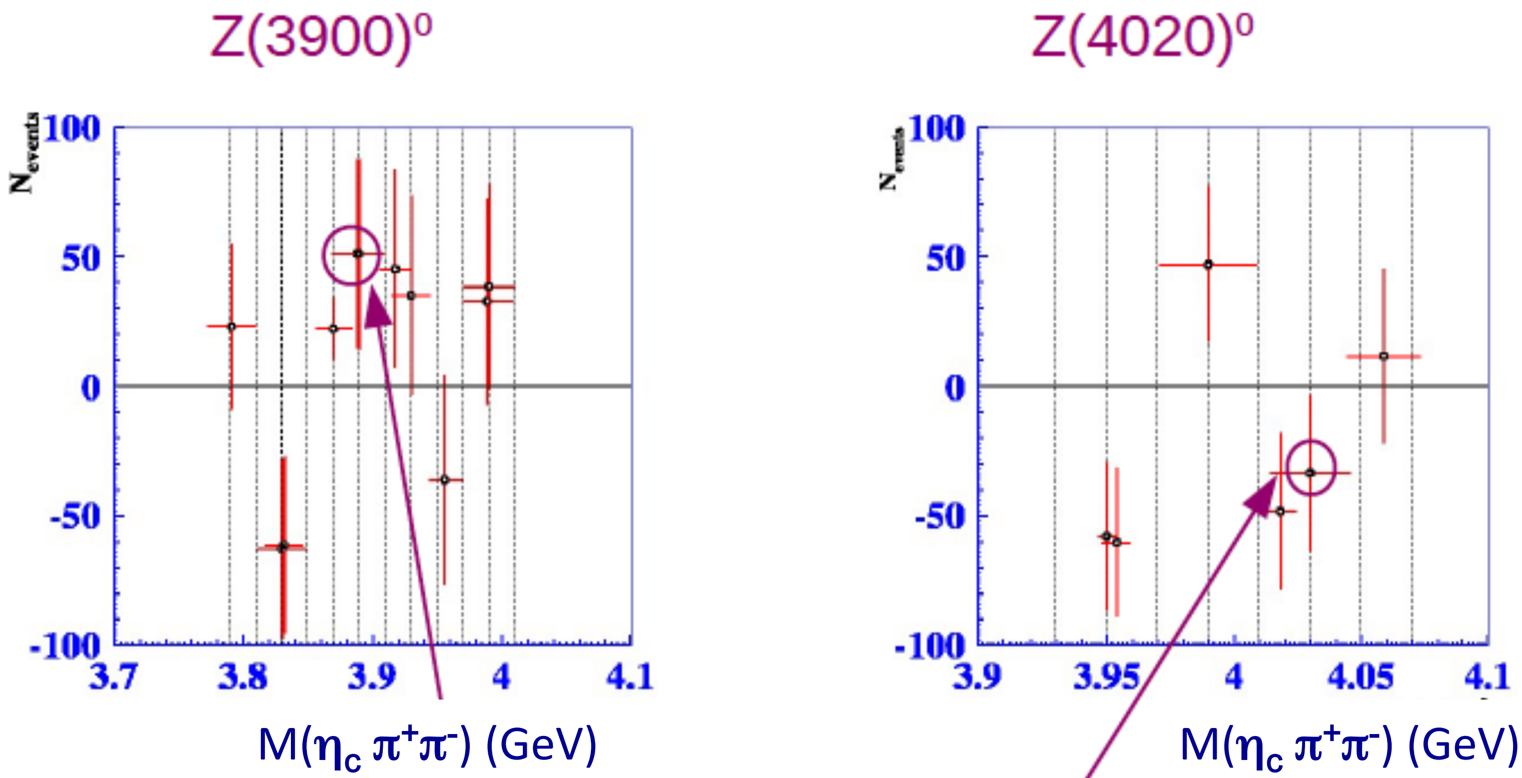
State	Mass(MeV)	Width(MeV)	Decay mode	Process
$Z_c(3900)^{\pm}$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	$\pi^{\pm} J/\psi$	$e^+e^- \to \pi^+\pi^- J/\psi$
$Z_c(3900)^0$	$3894.8 \pm 2.3 \pm 2.7$	$29.6 \pm 8.2 \pm 8.2$	$\pi^0 J/\psi$	$e^+e^- \to \pi^0\pi^0 J/\psi$
$Z_c(3885)^{\pm}$	$3883.9 \pm 1.5 \pm 4.2$ [single D tag] $3884.3 \pm 1.2 \pm 1.5$ [double D tag]	$24.8 \pm 3.3 \pm 11.0$ [single D tag] $23.8 \pm 2.1 \pm 2.6$ [double D tag]	$D^0 D^{*-}$ $D^- D^{*0}$	$e^+e^- \to \pi^+ D^0 D^{*-}$ $e^+e^- \to \pi^+ D^- D^{*0}$
$Z_c(4020)^{\pm}$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	$\pi^{\pm} h_c$	$e^+e^- \to \pi^+\pi^- h_c$
$Z_c(4020)^0$	$4023.9 \pm 2.2 \pm 3.8$	fixed	$\pi^0 h_c$	$e^+e^- \to \pi^0\pi^0 h_c$
$Z_c(4025)^{\pm}$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$D^{*0} D^{*-}$	$e^+e^- \to \pi^+ (D^* \bar{D}^*)^-$

From Xu Xinping, C. Yuan (QWG2014)

$Z(3900)^0$ & $Z(4020)^0$ search at Belle

From Anna Vinokurova at CHARM2015
arXiv : 1501:06351 JHEP..

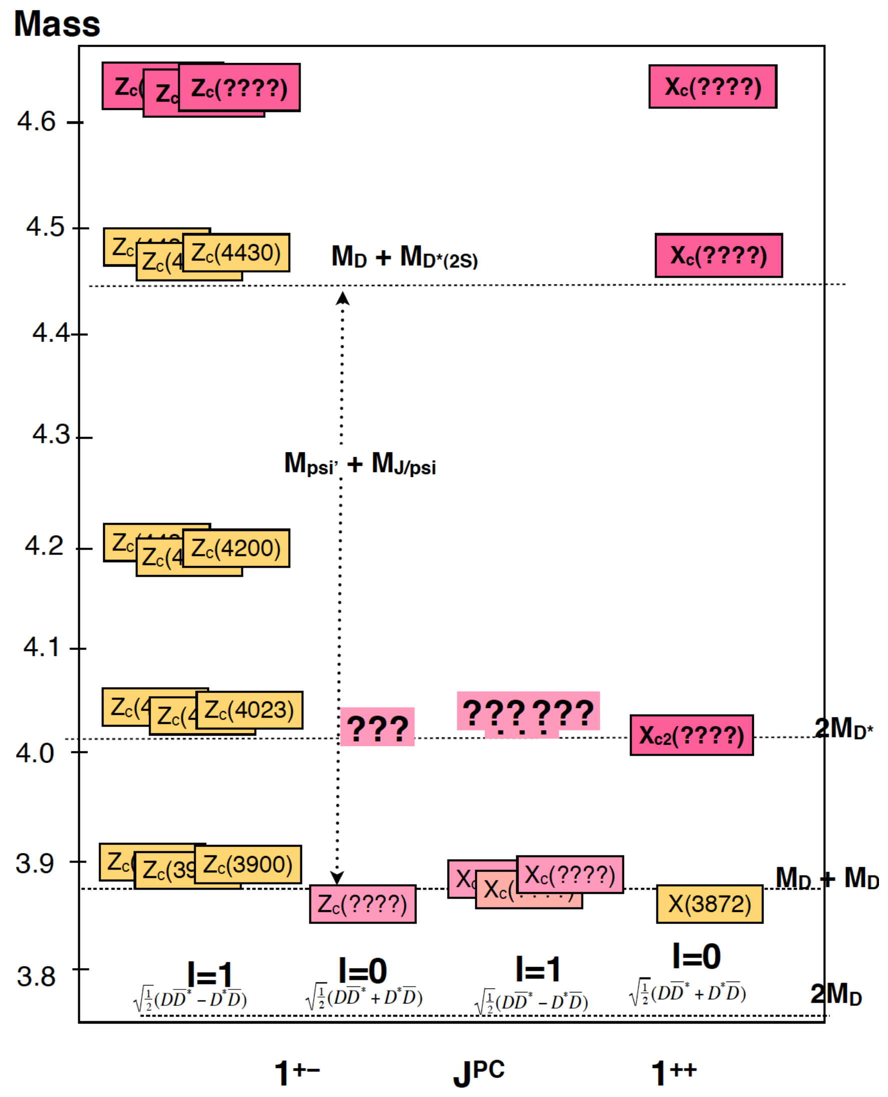
Mass scan:



Masses closest to the corresponding charged partners

X(3872) and other 1^+ XYZ states

Molecules Level Diagram ? (By S. Olsen Front. Phys. 10, 101401 (2015)



The $J^P=1^+$ bottomonium states? (See above ref.)

Summary

◆ Belle discovered many XYZ states .

◆ List of XYZ mesons keeps growing, however, their nature is still in a mystery. Remains opportunities for LHCb and BelleII.

◆10 years after the X(3872)'s discovery, this is the most highly cited B-factory paper and

- ◆ BE = $(m_{\overline{D^{*0}}} + m_{D^0}) - M_{X(3872)}$ gets smaller, and now the BE= 0.1 +- 0.2MeV
- ◆ Models for the X(3872)YZ suggest the existence of additional states

◆ Z(4430)+ from Belle is confirmed and J^P is conclusively 1^+.

- ◆ Argand plot (LHCb) shows resonance behavior
- ◆ Charge and quantum numbers rule out conventional charmonium interpretation
- ◆ But still non-resonant interpretation (rescattering) possible.

◆ NEW charged state $Z(4200)^+$ is observed in $B \to J/\psi\, \pi^+ K^-$ decay. The quantum number is 1^+. Evidence of the $Z(4430)^+ \to \pi^+ J/\psi$ is found.

◆ $Z_b(10610)^+$, $Z_b(10650)^+$ and $Z_b(10610)^0$ are the first candidate of ispin triplet in Belle.

◆ Many Z_c states are recently discovered from BESIII (Belle) : including two sets of Isospin triplet states $Z_c(3900)$ and $Z_c(4020)$.

Back-up slides

VOLUME 91, NUMBER 26 PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2003

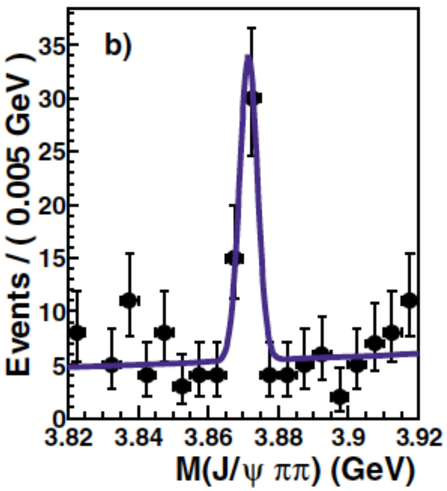
Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays

S.-K. Choi,[5] S. L. Olsen,[6] K. Abe, (Belle Collaboration) n,[14] H. Aihara,[43] K. Akai,[7] M. Akatsu,[20]
...

(Received 8 September 2003; published 23 December 2003)

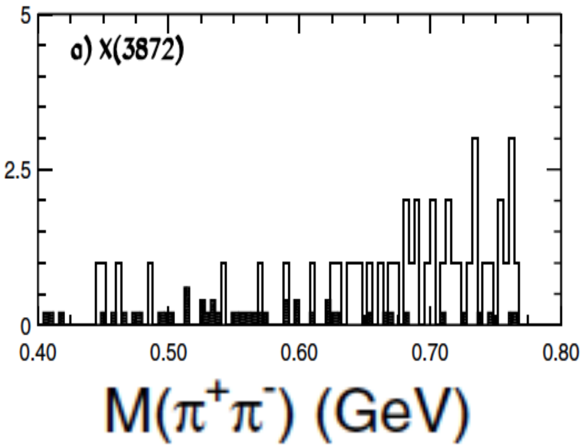
We report the observation of a narrow charmoniumlike state produced in the exclusive decay process $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$. This state, which decays into $\pi^{+}\pi^{-}J/\psi$, has a mass of $3872.0 \pm 0.6(\text{stat}) \pm 0.5(\text{syst})$ MeV, a value that is very near the $M_{D^0} + M_{D^{*0}}$ mass threshold. The results are based on an analysis of 152M B-$\bar{B}$ events collected at the $\Upsilon(4S)$ resonance in the Belle detector at the KEKB collider. The signal has a statistical significance that is in excess of 10σ.

M = 3872.0±0.6±0.5 MeV



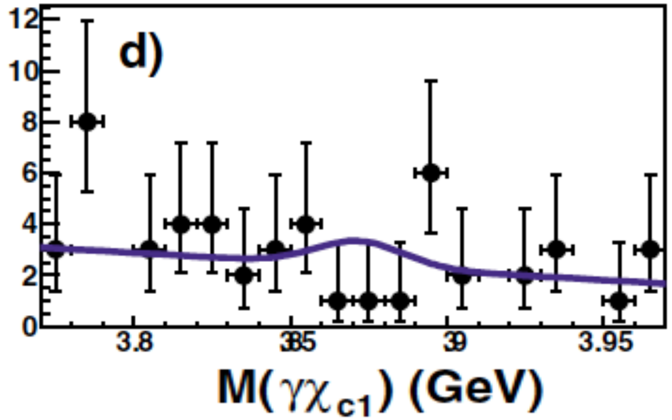
$M_{X(3872)} \approx m_{D0}+m_{D^*0}$

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



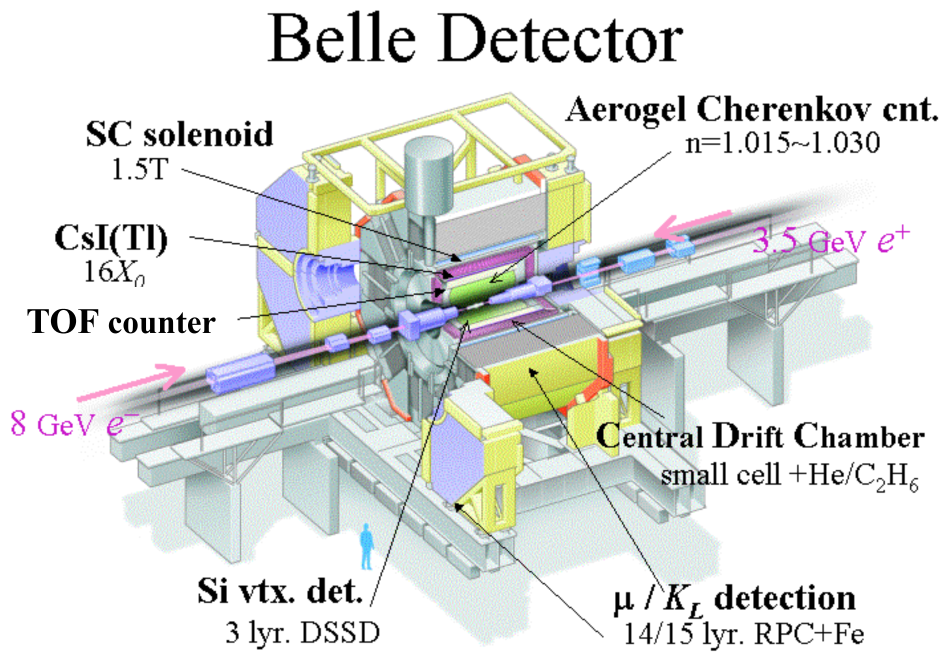
C=+

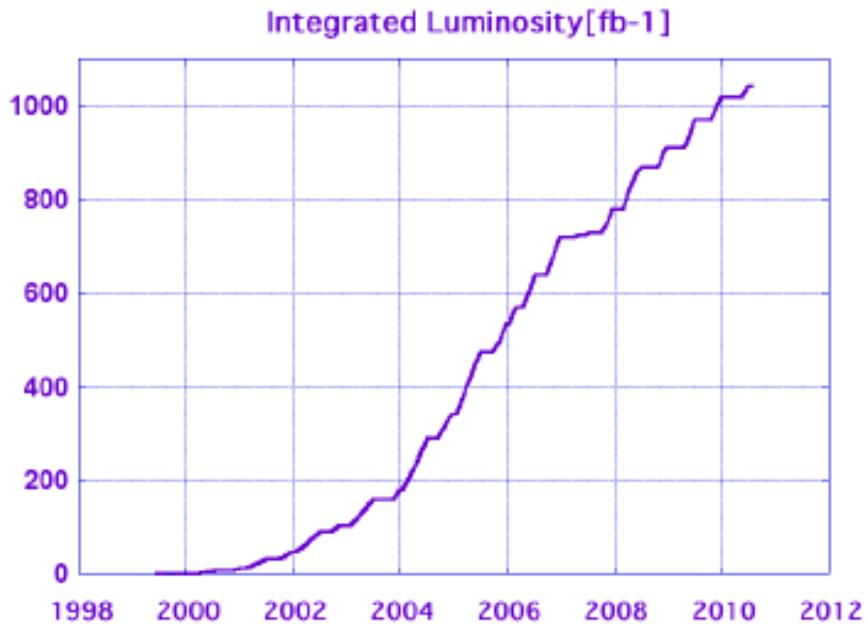
$X(3872) \not\to \gamma\chi_{c1}$



$X(3872) \neq 1^3D_2\ (\psi_2)$

The Belle experiment





Peak luminosity recorded at KEKB:
L=2.1 x 10^{34}/cm^2/sec with crab cavities

> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

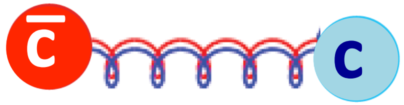
$\Upsilon(2S)$: 25 fb^{-1}

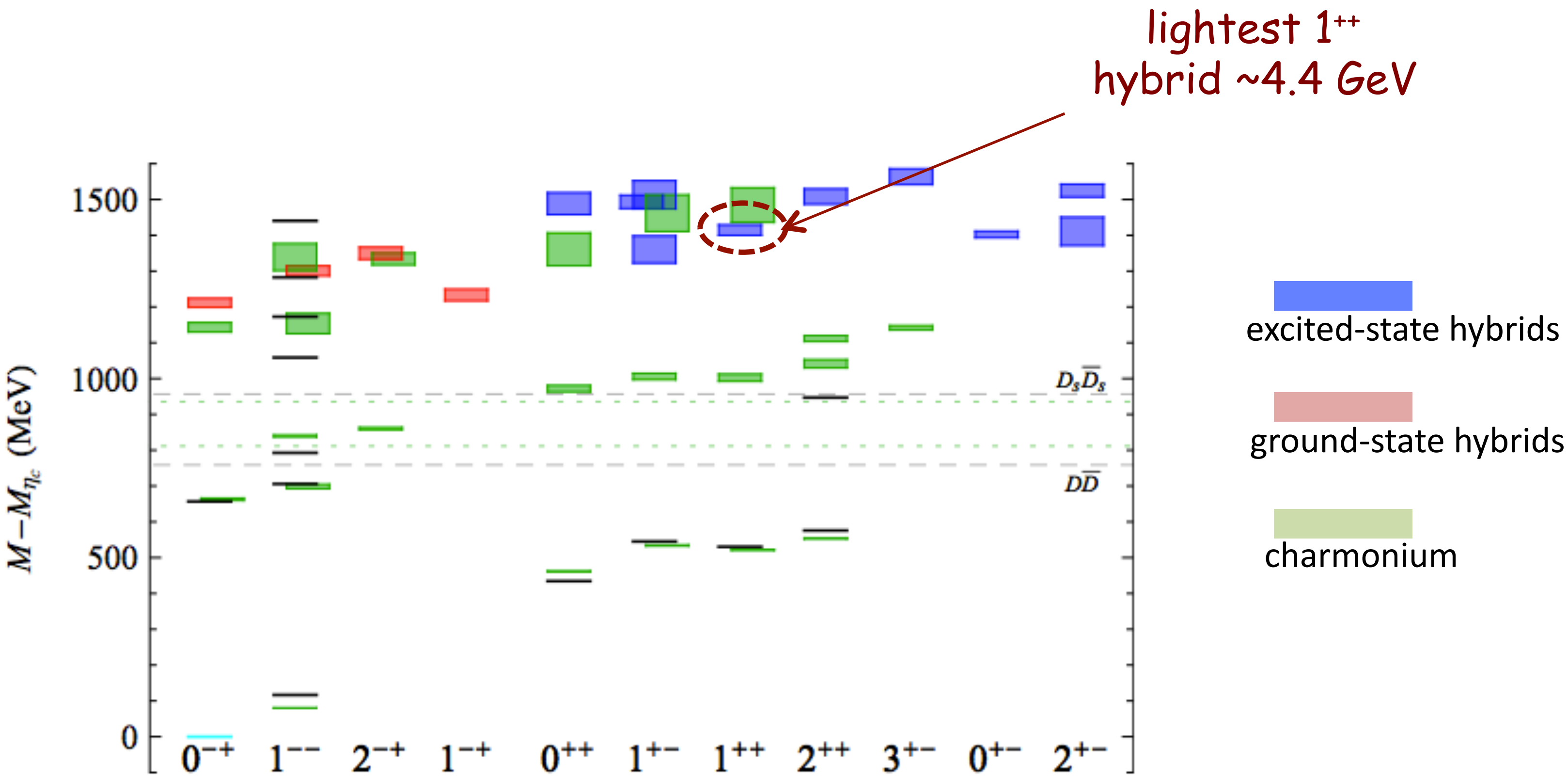
$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

QCD hybrid?

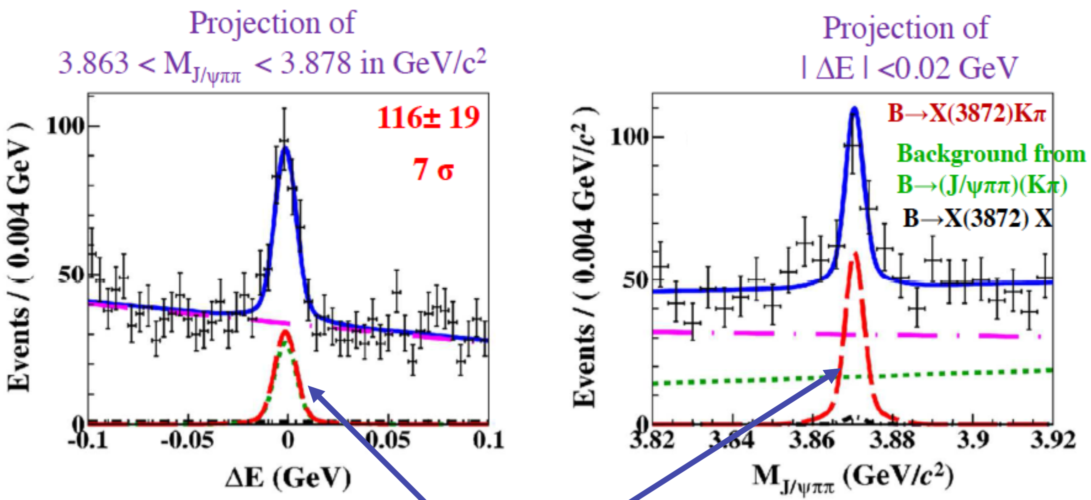




L Liu *et al.*, JHEP **1207**, 126 (2012)
(Hadron Spectrum Collaboration)

$B^0 \rightarrow X(3872)K^+\pi^-$

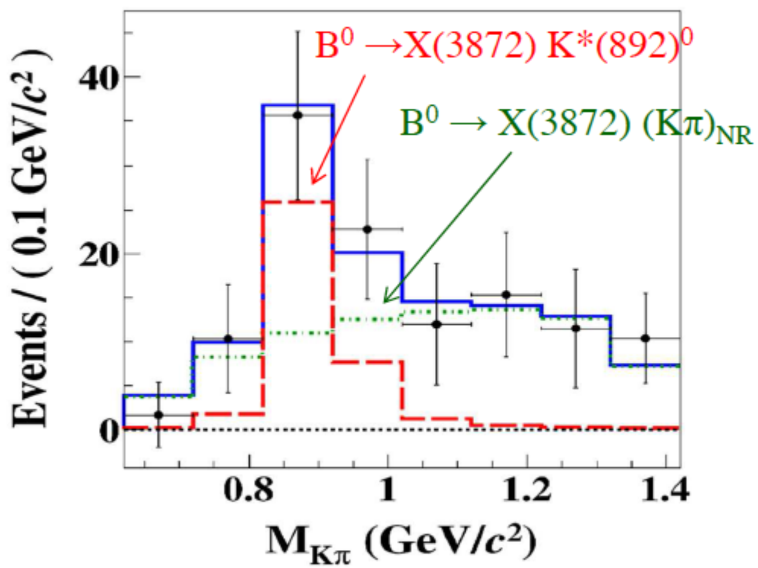
PRD91, 051101 (R) (2015)



[both K*and (K+π–)$_{NR}$]

$B(B^0 \rightarrow X(K^+\pi^-)_{K*+NR})\ B(X \rightarrow J/\psi\pi^+\pi^-)$
$= (7.9 \pm 1.3 \pm 0.4) \times 10^{-6}$

$(B(B^+ \rightarrow X(K^0\pi^-)_{K*+NR})\ B(X \rightarrow J/\psi\pi^+\pi^-)$
$= (10.6 \pm 3.0 \pm 0.9) \times 10^{-6})$



$$\frac{B(B^0 \rightarrow X(3872)K^*(892)^0) \times B(K^*(892)^0 \rightarrow K^+\pi^-)}{B(B^0 \rightarrow X(3872)K^+\pi^-)}$$

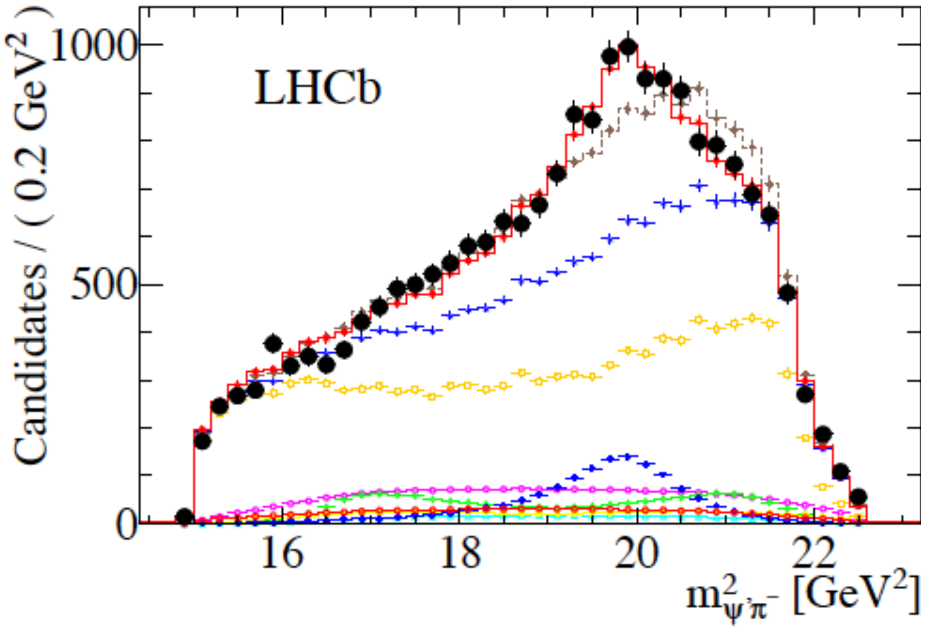
$= 0.34 \pm 0.09(\text{stat.}) \pm 0.02(\text{syst.})$

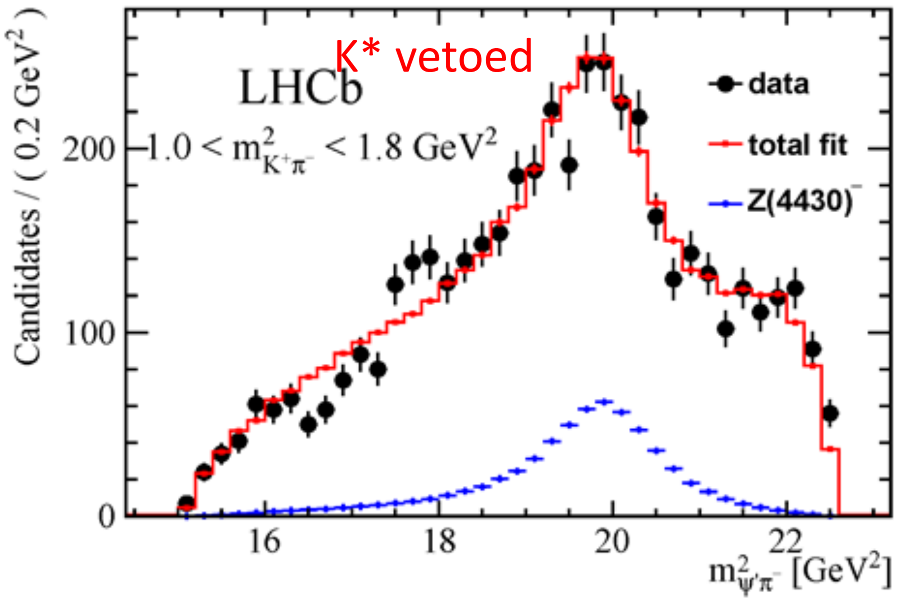
$$\frac{B(B^0 \rightarrow \psi' K^*(892)^0) \times B(K^*(892)^0 \rightarrow K^+\pi^-)}{B(B^0 \rightarrow \psi' K^+\pi^-)}$$

$= 0.68 \pm 0.01(\text{stat.})$

Results by Adding Z^+ (LHCb)

PRL 112, 222002 (2014)





$$M(Z) = 4475 \pm 7^{+15}_{-25} \text{ MeV}$$

$$\Gamma(Z) = 172 \pm 13^{+37}_{-34} \text{ MeV}$$

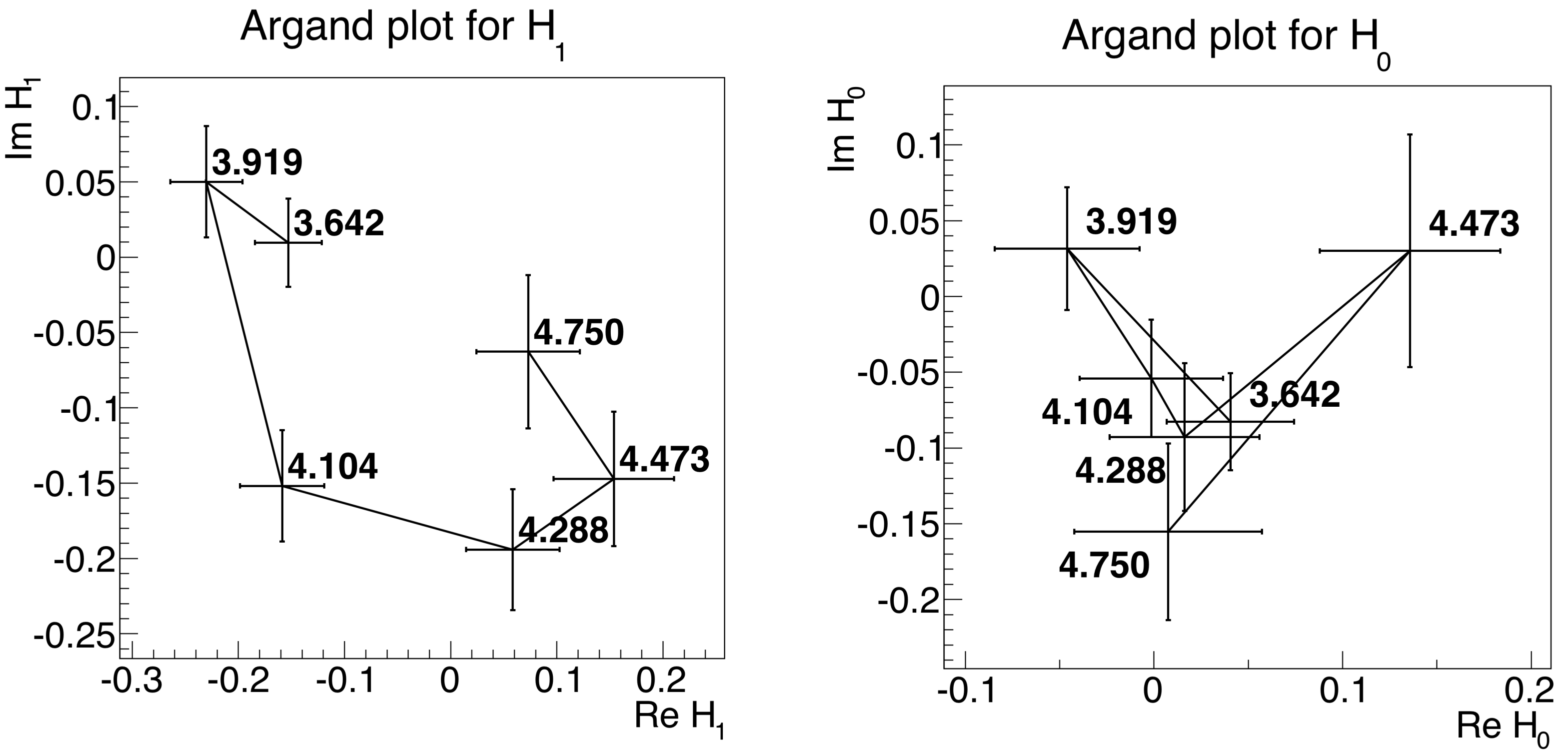
Significance $> 13.9\,\sigma$

f_Z	$5.9 \pm 0.9^{+1.5}_{-3.3}$ %
f_Z^I	$16.7 \pm 1.6^{+2.6}_{-5.2}$ %

$$Bf(B^0 \to Z(4430)^- K^+) \times Bf(Z(4430)^- \to \pi^- \psi') = (0.059 \pm 0.009^{+0.015}_{-0.033}) \times Bf(B^0 \to K^+ \pi^- \psi')$$

$$\Rightarrow Bf(B^0 \to Z(4430)^- K^+) \times Bf(Z(4430)^- \to \pi^- \psi') \approx (3.4^{-1.1}_{-2.3}) \times 10^{-5}$$

Argand plot for $Z_c(4200)^+$



Clearly shows Resonance-like change of the amplitude

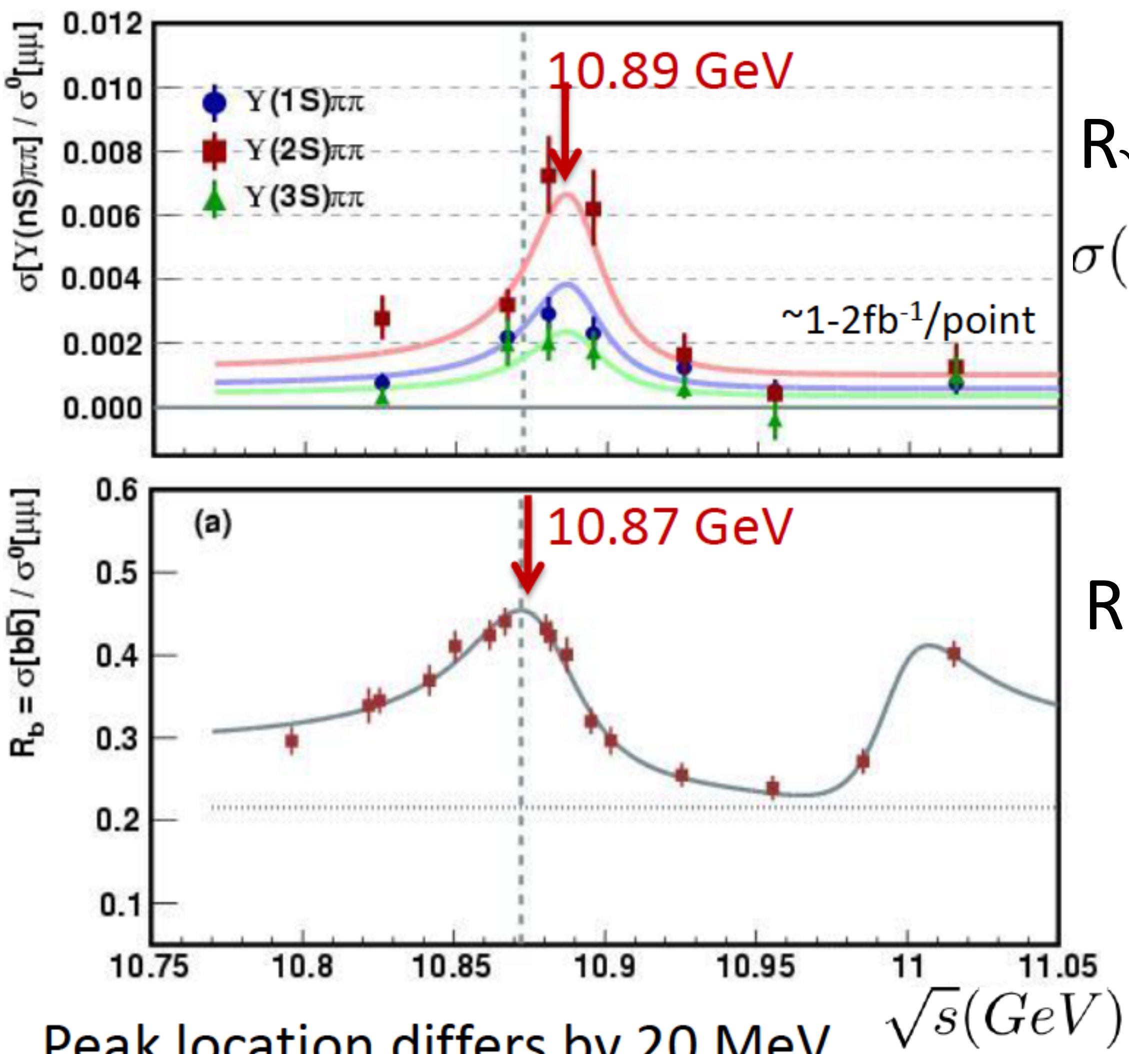
Much larger errors and impossible to Draw any conclusion yet.

Unlike LHCb, Belle have two plots for two helicity amplitudes including higher waves. For S-wave, $H_1 = H_0$

Belle PRD 82, 091106R (2010)

Energy scan to search for anomalous structure

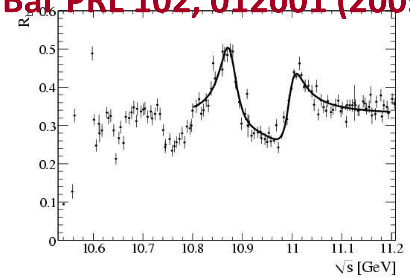
Total 29.8 fb^{-1}



$R_{\Upsilon(nS)\pi\pi}$ =
$$\sigma(\Upsilon(nS)\pi^+\pi^-)/\sigma^0(\mu\mu)$$

$R_b = \sigma(b\bar{b})/\sigma^0(\mu\mu)$

BaBar PRL 102, 012001 (2009)



10.865 ± 0.008 GeV

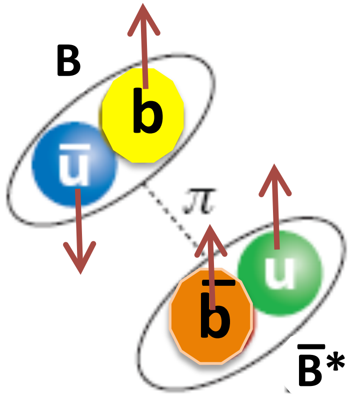
Peak location differs by 20 MeV

$\Delta M = M_{5S}(\Upsilon\pi\pi) - M_{5S}(bb) = 9 \pm 4$ MeV

Recall Y(4260) with anomalous $\Gamma(J/\psi\,\pi^+\pi^-)$ $\Rightarrow$ Is there a Υ_b equivalent close to $\Upsilon(5S)$

B-$\bar{B}$* & B*-$\bar{B}$* molecules??

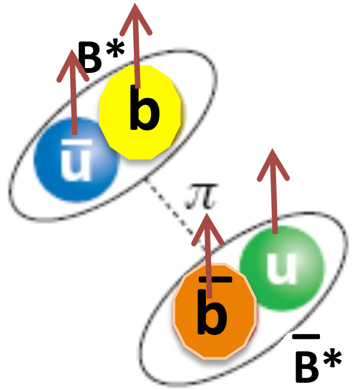
$Z_b(10610)^{\pm}$



B-$\bar{B}$* "molecule"

$M_{Z_b(10610)} - (M_B + M_{B^*}) = +\,2.7 \pm 2.1$ MeV

$Z_b(10650)^{\pm}$



B*-$\bar{B}$* "molecule"

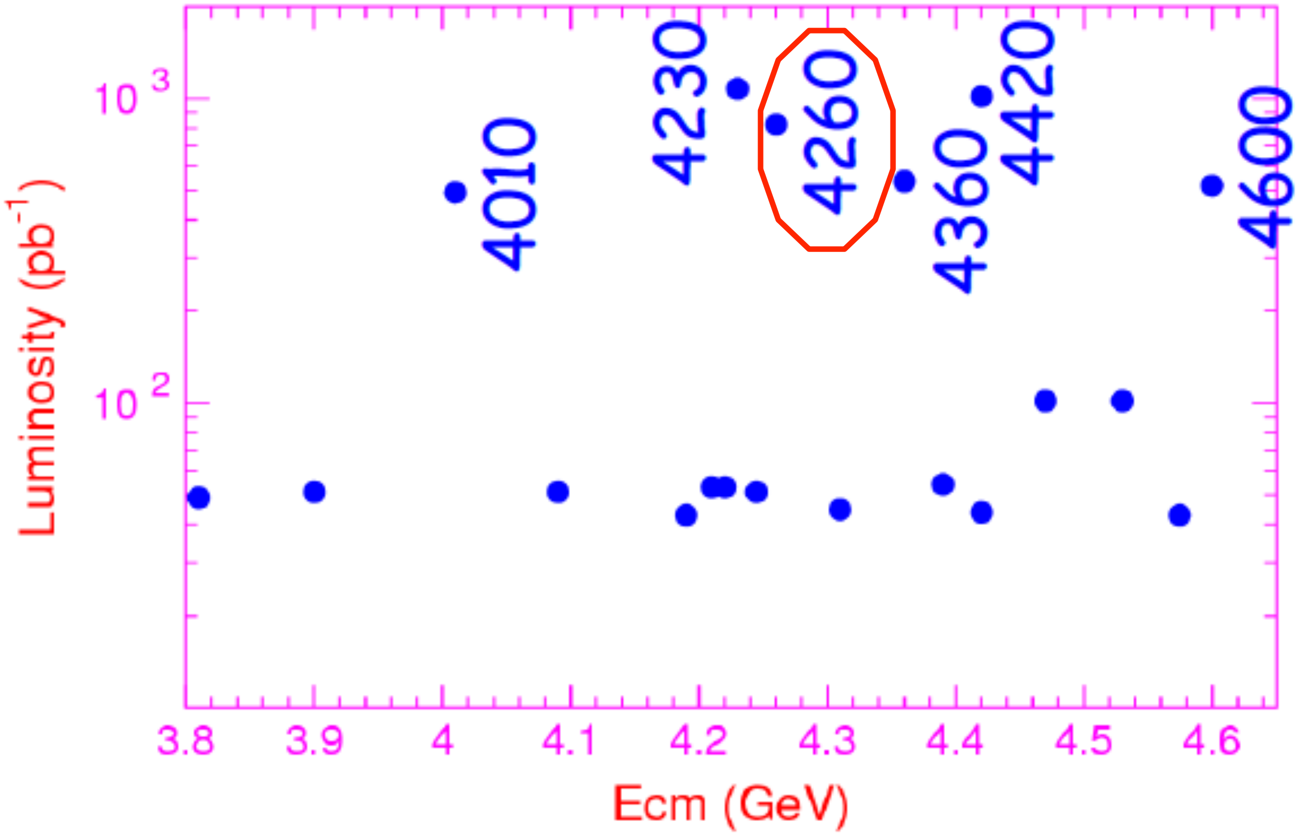
$M_{Z_b(10650)} - 2M_{B^*} = +\,2.0 \pm 1.8$ MeV

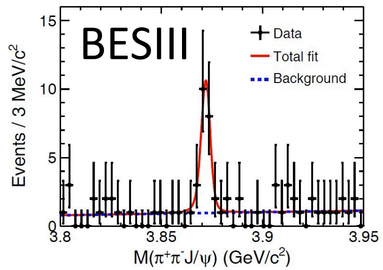
Slightly unbound threshold resonances??

Belle: M=10607.2±2.0 MeV, Γ=18.4±2.4 MeV | M=10652.2±1.5 MeV, Γ=11.5±2.2 MeV

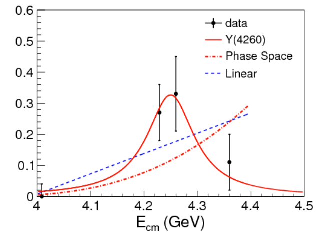
PDG: $M_B + M_{B^*} = 10604.5 \pm 0.6$ MeV | $M_{B^*} + M_{B^*} = 10650.2 \pm 1.0$ MeV

BESIII collected 5 /fb above 4GeV for XYZ study





Y(4260) → γX(3872)



~ 0.6 B $\psi(3686)$ events ~ 24×CLEO-c

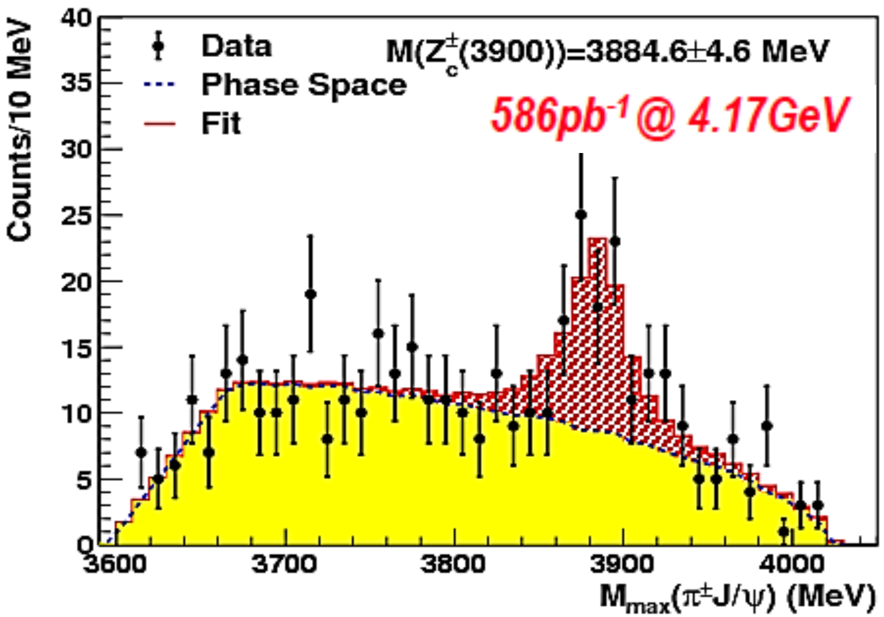
~ 1.3 B J/ψ events ~ 21×BESII

~ $2.9fb^{-1}$ $\psi(3770)$ ~ 11×CLEO-c

~ others including scan and continuum data, etc.

CLEOc data

at 4.17 GeV:(PLB 727, 366)



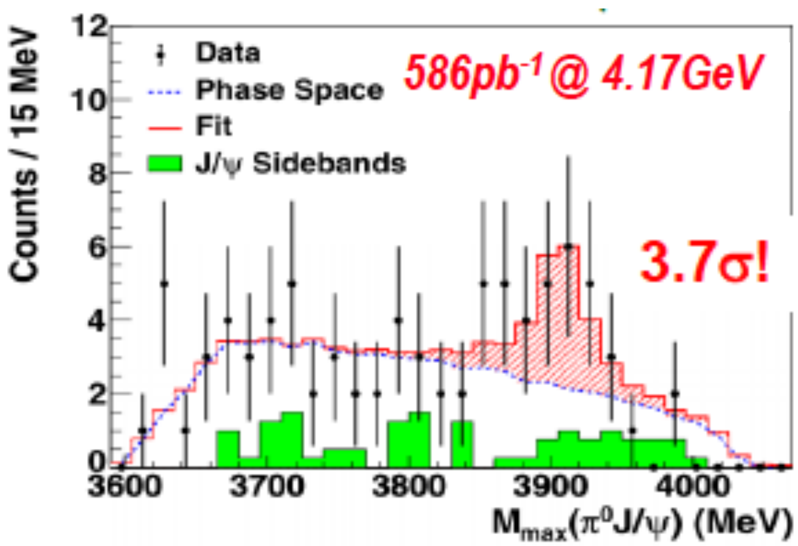
- M = 3885±5±1 MeV
- Γ = 34±12±4 MeV
- 81 ± 20 events
- 6.1σ

Is there a $Z_c(3900)^0$?
(a neutral isospin partner state)

$$e^+e^- \to \pi^0 Z_c(3900)^0 \to \pi^0\pi^0 J/\psi$$

First hint from

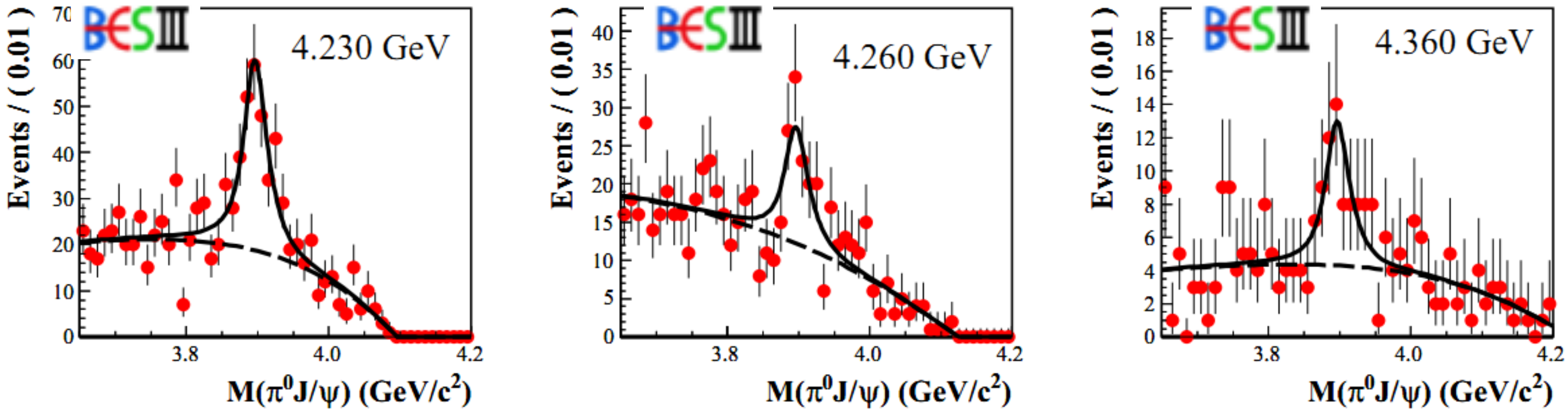
CLEOc data at 4.17 GeV (PLB 727, 366)



Search for $Z_c(3900)^0$

$$e^+e^- \to \pi^0 Z_c(3900)^0 \to \pi^0\pi^0 J/\psi$$

New BES III analysis (**preliminary !!**)



M= 3894.8 ± 2.3 MeV, Γ = 29.6 ± 8.2 MeV

Significance = 10.4 σ

This establishes the Isospin triplet of $Z_c(3900)$