X states (X(3872), …)

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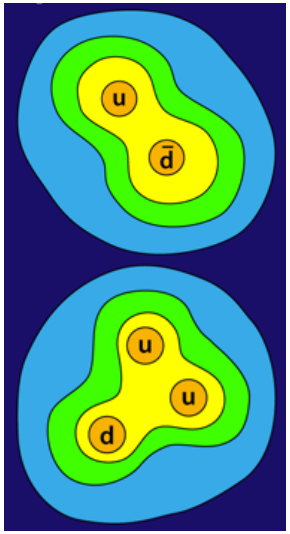
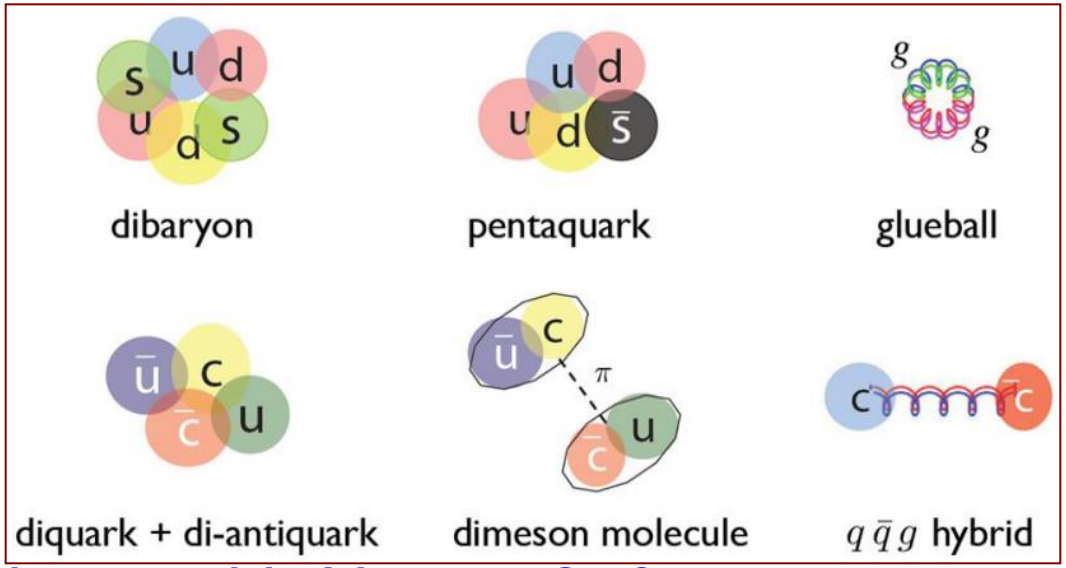
Hadrons: normal & exotic

- Quark model: hadrons are composed from 2 (meson) quarks or 3 (baryon) quarks



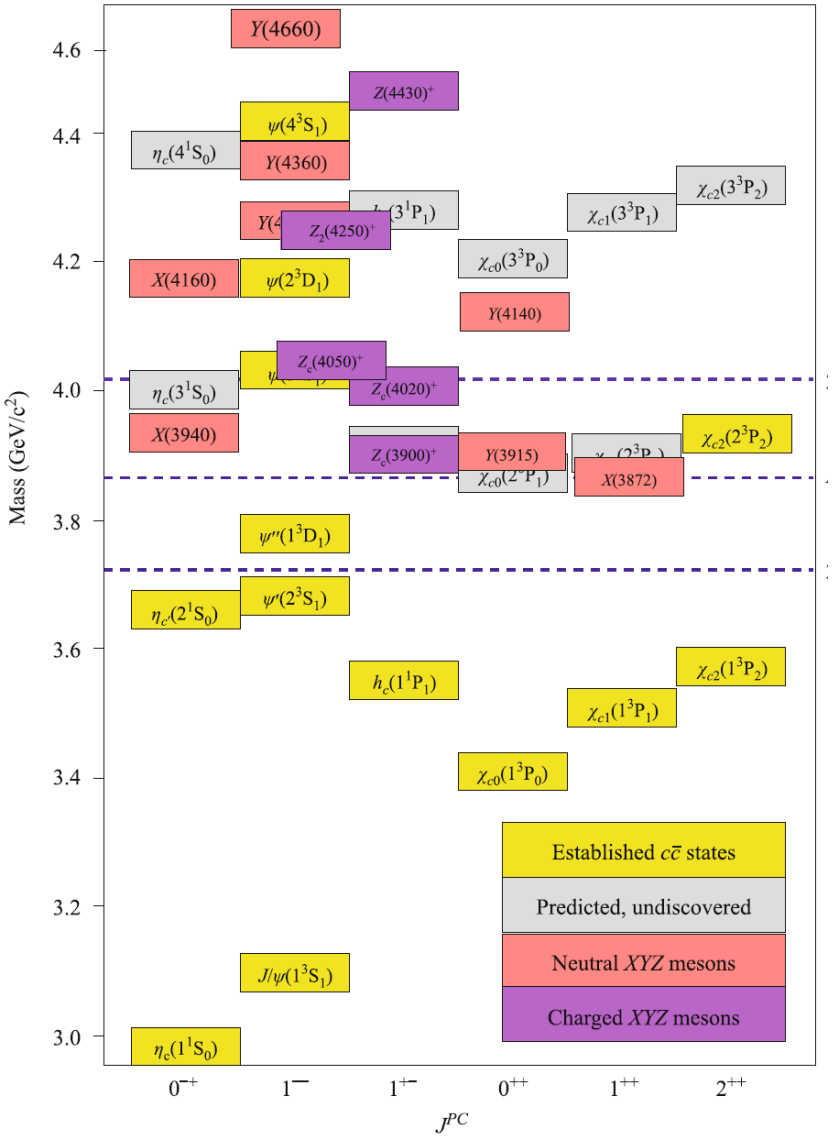
Normal vs. Exotic

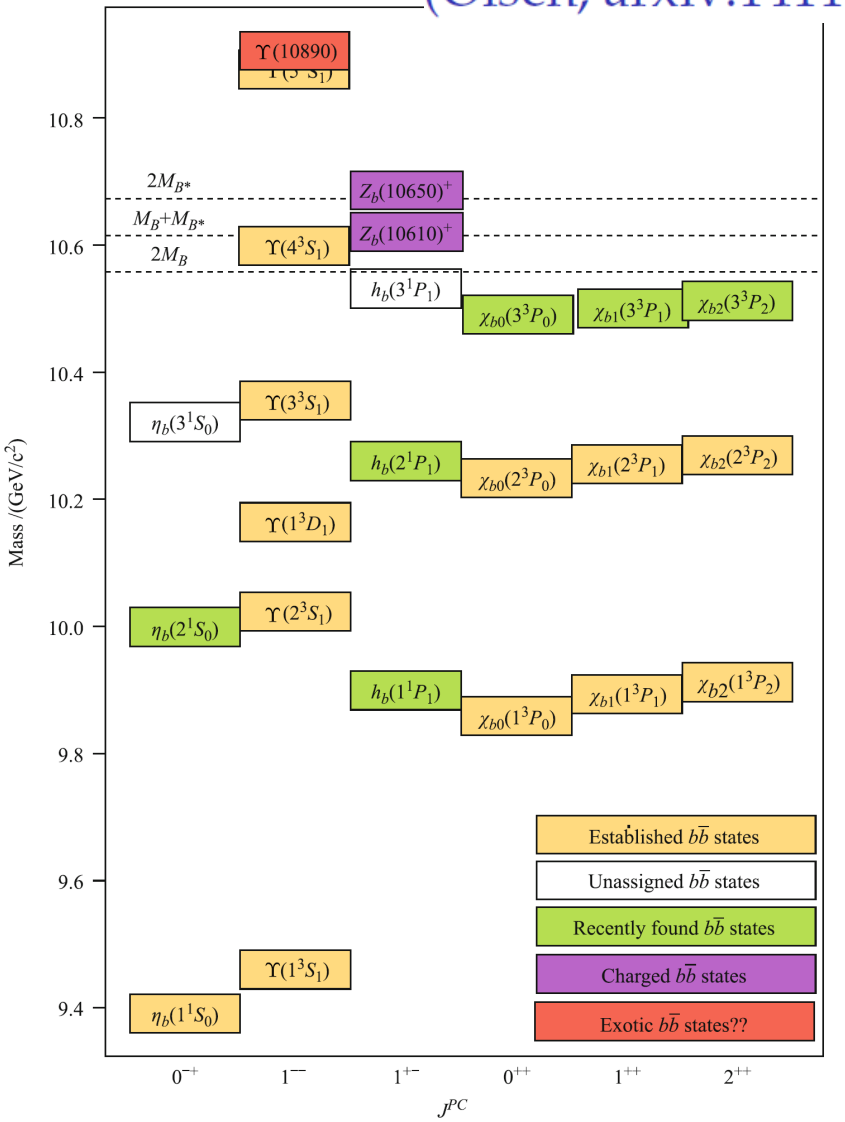


- QCD does not forbid hadrons with $N_{quarks} \neq 2, 3$
  - Glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - Hybrid : $N_{quarks} = 2$ (or more) + excited gluon
  - Multiquark state : $N_{quarks} > 3$
  - Molecule : bound state of more than 2 hadrons
  - …

Quarkonium(like) systems

(Olsen, arxiv:1411.7738)

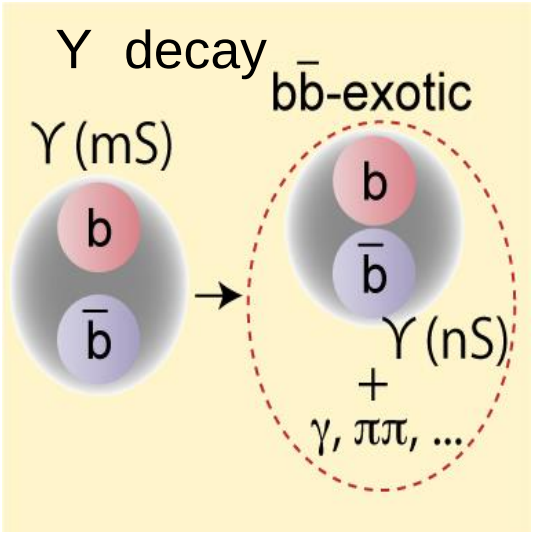


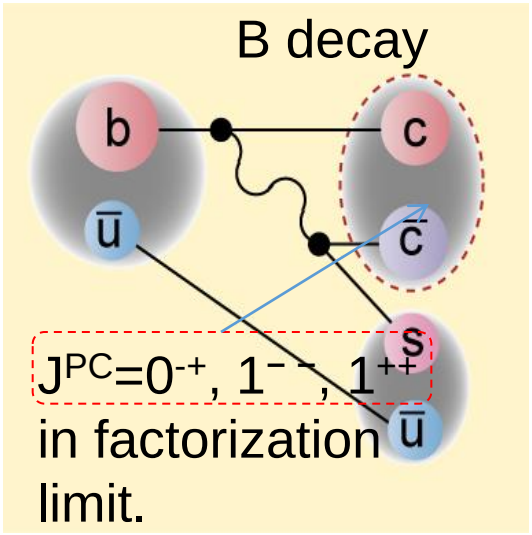


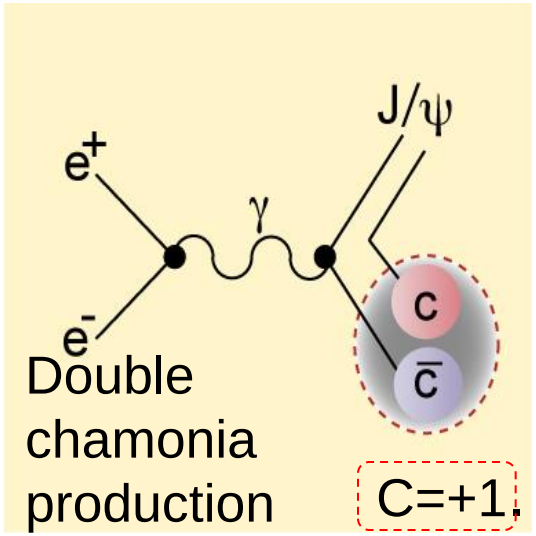
Charmonium(like) states

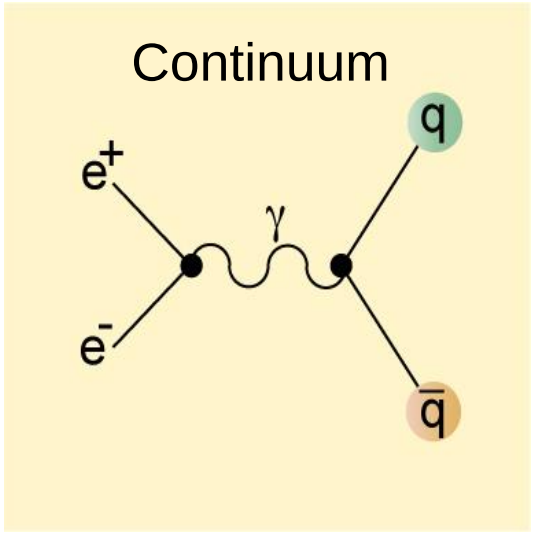
Bottomonium(like) states

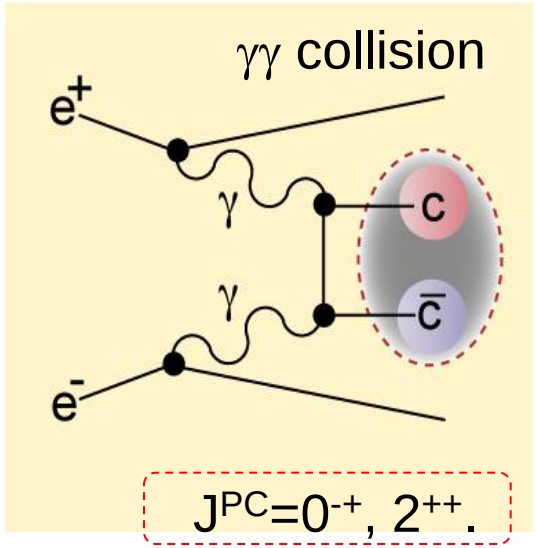
Variety of recorded reactions

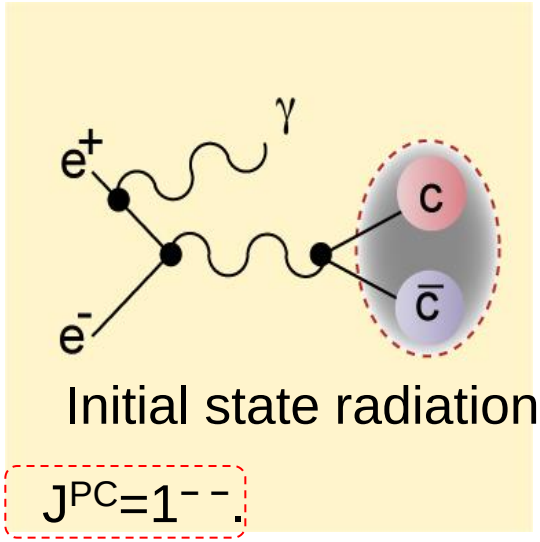






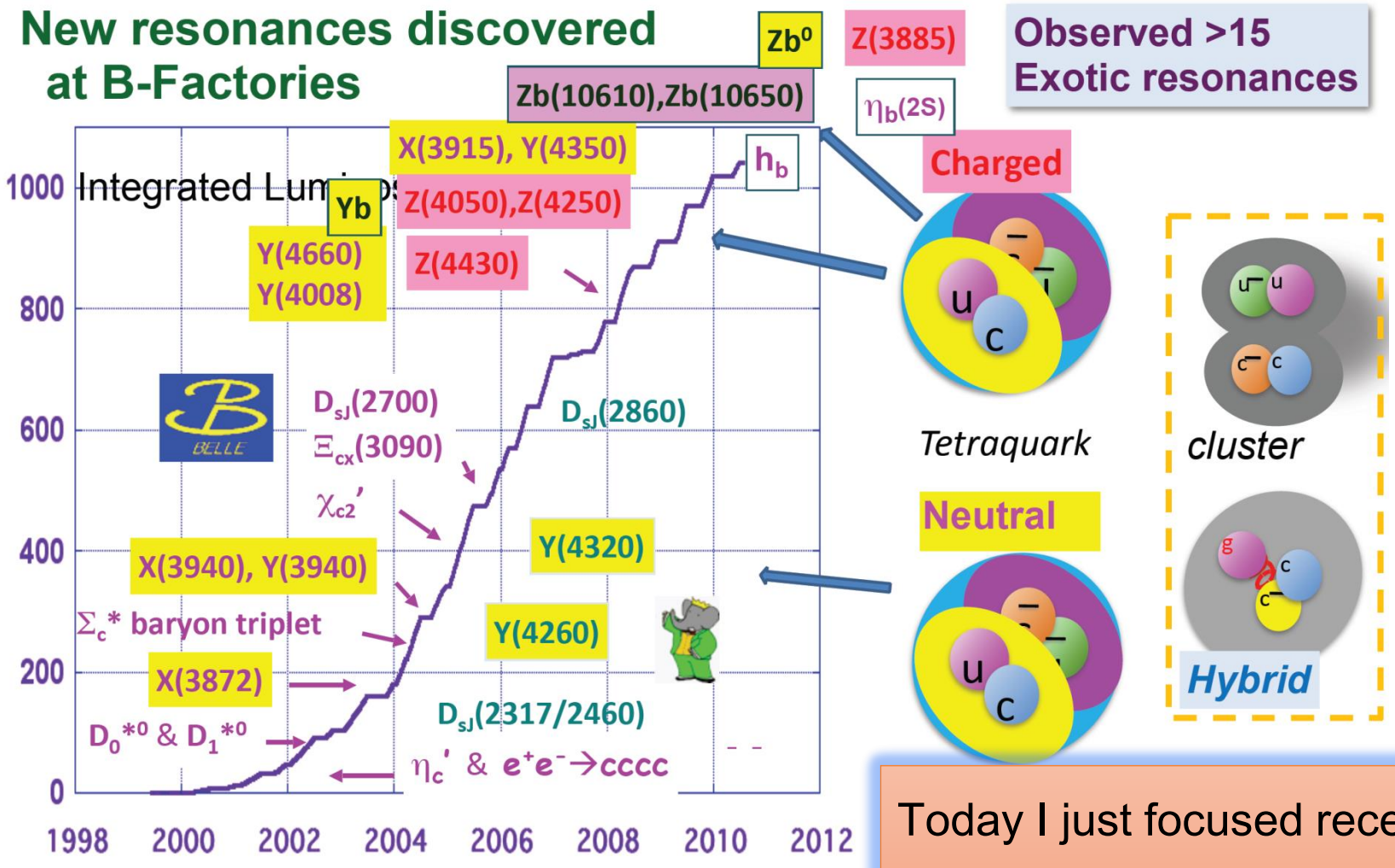






Thanks B-factories !

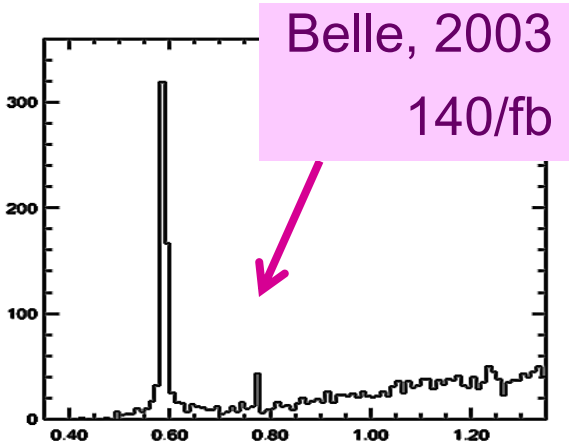
- Discovery of X(3872) and other many XYZ states etc.
- Unexpected bonus of the B-factories



Today I just focused recent results on X states from Belle

What is the X(3872)?

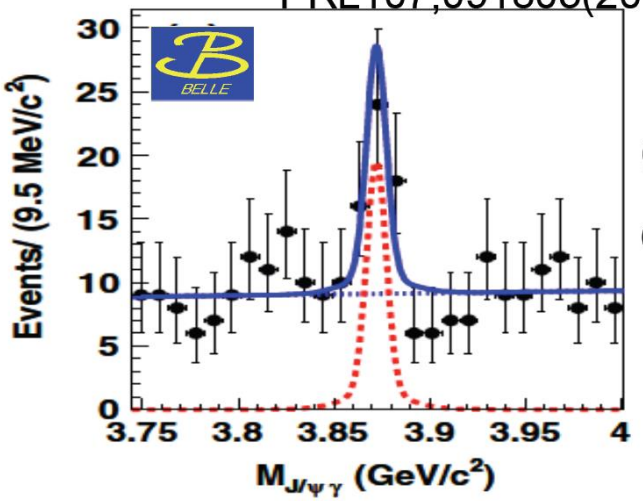
- Mass: Very close to $D^0\bar{D}^{*0}$ threshold
- Width: Very narrow, < 1.2 MeV
- $J^{PC}=1^{++}$
- Production
  - in $p\bar{p}$/pp collison – rate similar to charmonia
  - In B decays – KX similar to $c\bar{c}$, K*X smaller than $c\bar{c}$
  - Support Y(4260)→γ+X(3872)
- Decay BR: open charm ~ 50%, charmonium~O(%)
- Nature (very likely exotic)
  - Loosely $D^0\bar{D}^{*0}$ bound state (like deuteron?)?
  - Mixture of excited χ_{c1} and $D^0\bar{D}^{*0}$ bound state?
  - Many other possibilities (if it is not χ'_{c1}, where is χ'_{c1}?)



Radiative decays of X(3872)

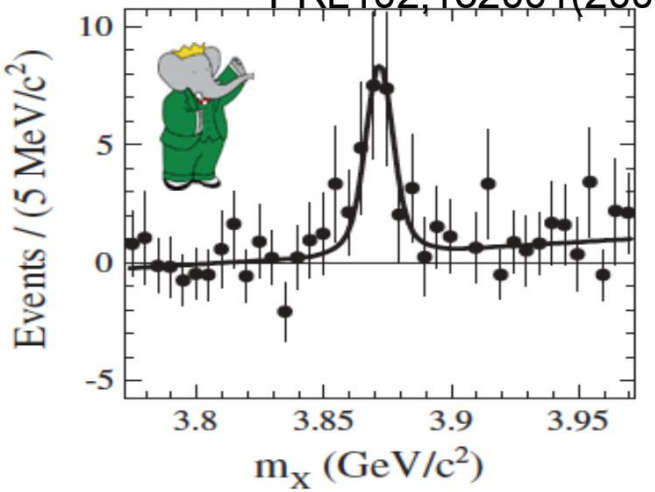
X(3872)→J/ψ γ : established

PRL107,091803(2011)

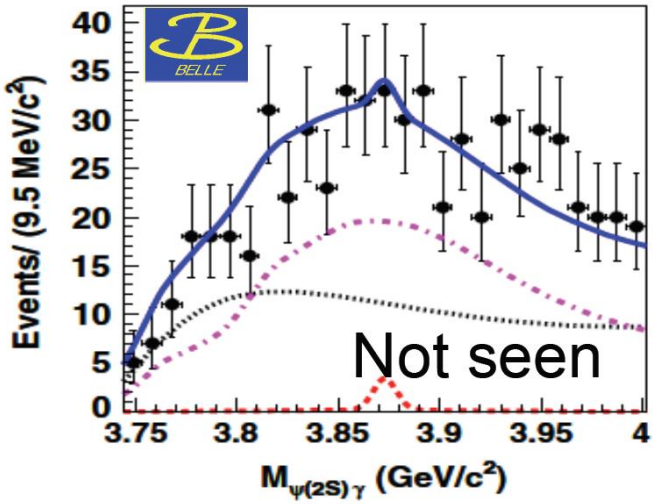


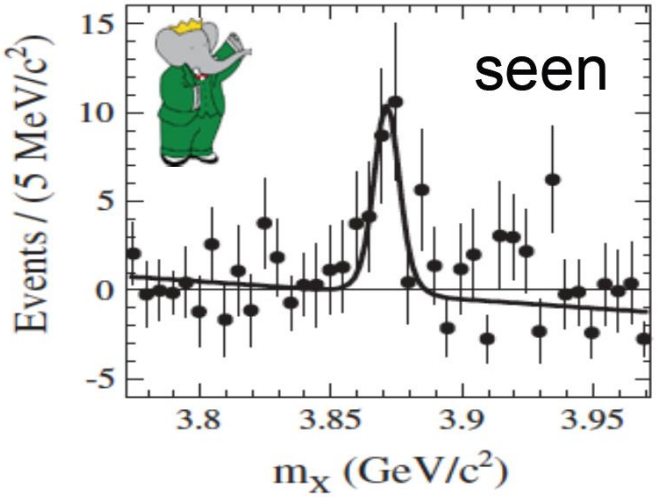
C=+1 established

PRL102,132001(2009)



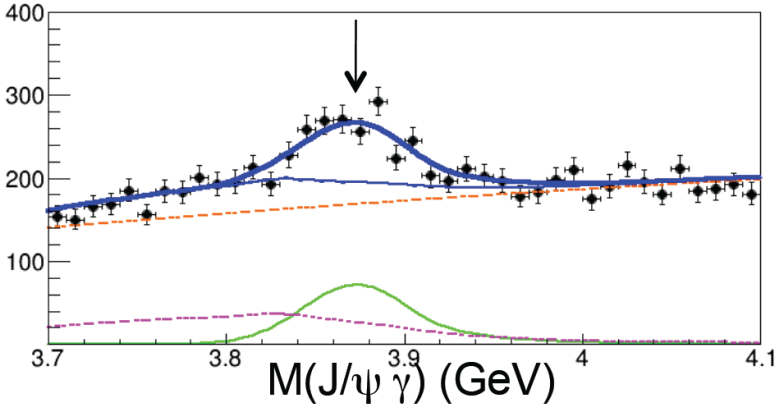
X(3872)→ψ(2S) γ : ??

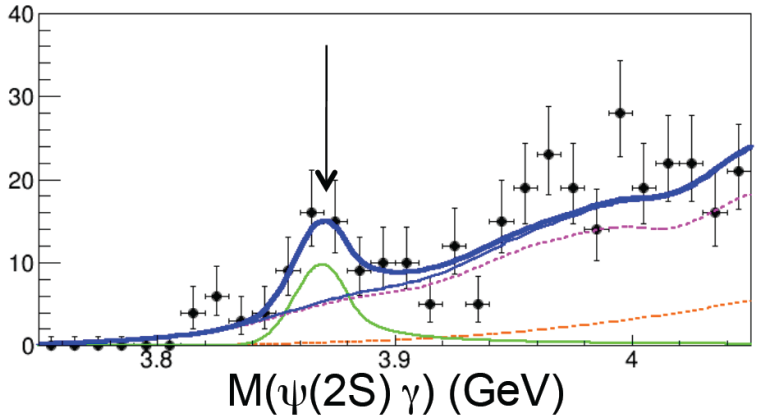


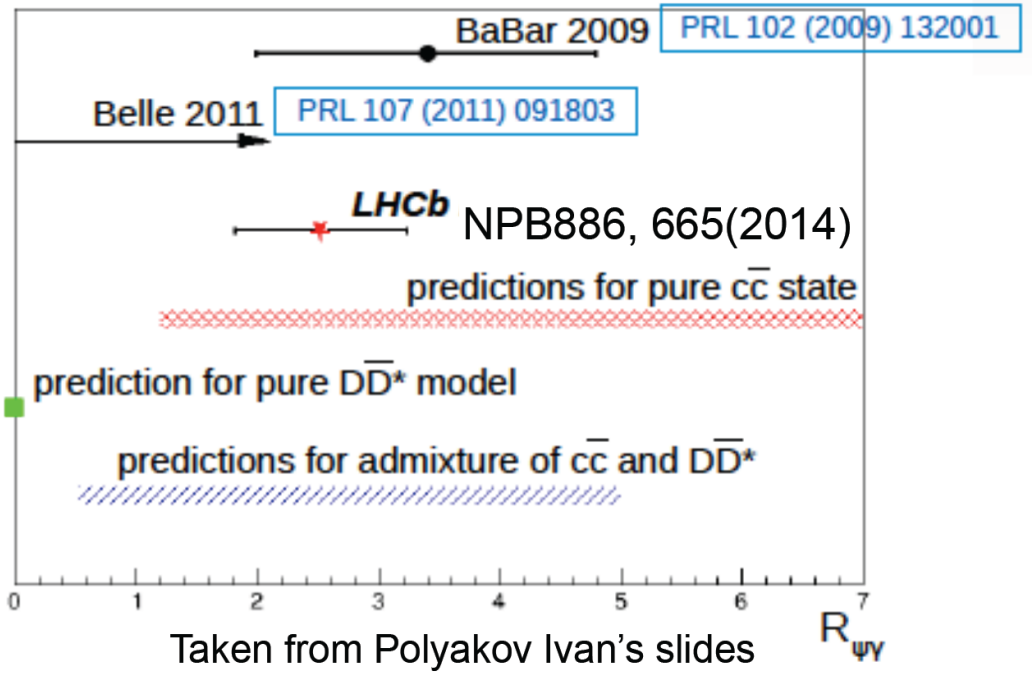


LHCb visited this question

$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$







Taken from Polyakov Ivan's slides in Moriond QCD

LHCb results confirm the γΨ(2S) mode; and do not favor pure DD* model

PRD91, 051101 (R) (2015)

Study of B→X(3872) Kπ

- Attempt to understand the *production* of X(3872) in B→X(3872) Kπ, in comparison to normal charmonium state.

- First study was done by Belle using 605 fb^{-1} arXiv:0809.1224, BELLE-CONF-0849
  - ✓ Saw signal of $B^0 \to X(3872)\, K^+\pi^-$.
  - ✓ $\mathcal{B}(B^0 \to X(3872)K^+\pi^-)\mathcal{B}(X(3872) \to J/\Psi\pi\pi) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$
  - ✓ $\mathcal{B}(B \to X(3872)K^{*0})\mathcal{B}(X(3872) \to J/\Psi\pi\pi) < 3.4 \times 10^{-6}$ (90% CL)
  - ✓ Non-resonant contribution dominates, unlike other $c\bar{c}$ states.

- With full data sample (711fb^{-1}) and reprocessed data, one expects more sensitivity to the study.
  - ➢ Improved analysis technique.

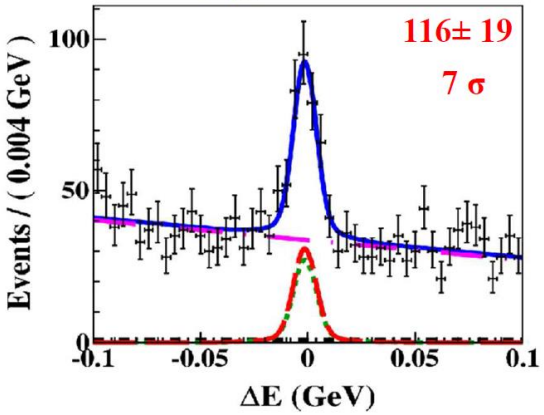
- Further, $B^+ \to X(3872)K_S^0\pi^+$ is also studied in an attempt to increase the statistics.
- Exploit B→ψ' Kπ as calibration model to train and calibrate B→X(3872) Kπ decay mode.

Observation of $X(3872)$ in $B \to X(3872)K\pi$ decays

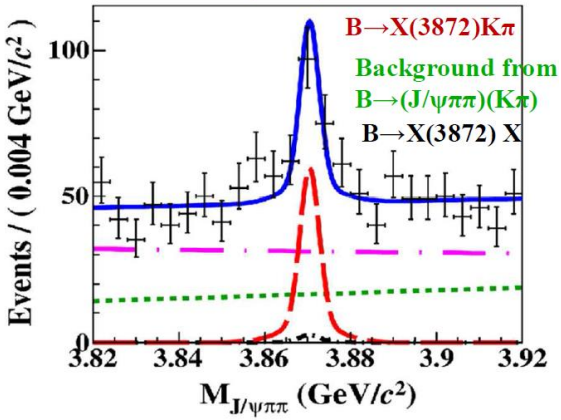
PRD91,051101(R) (2015)

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

Projection of
$3.863 < M_{J/\psi\pi\pi} < 3.878$ in GeV/c^2



Projection of
$|\Delta E| < 0.02$ GeV



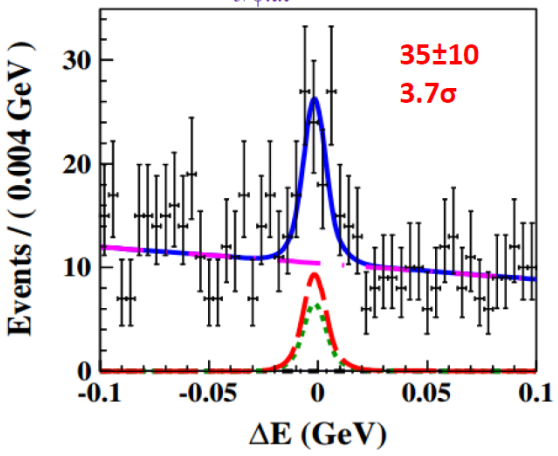
2-D fit to ΔE & $M_{J/\psi\pi\pi}$

$$\mathcal{B}(B \to X(3872)K\pi) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$$

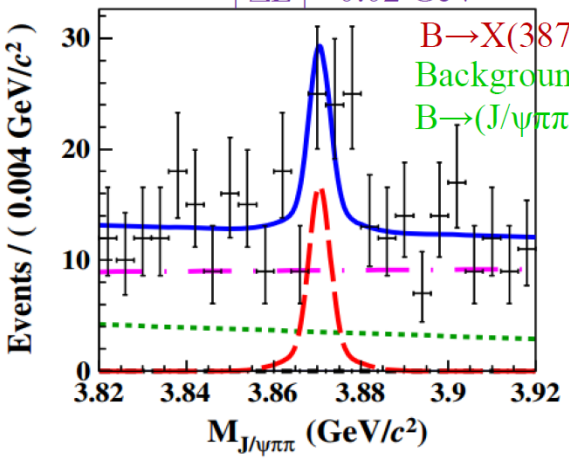
$$(7.91 \pm 1.29 \pm 0.43)\times 10^{-6}$$

$B^+ \to X(3872)K_S{}^0\pi^+$

Projection of
$3.863 < M_{J/\psi\pi\pi} < 3.878$ in GeV/c^2



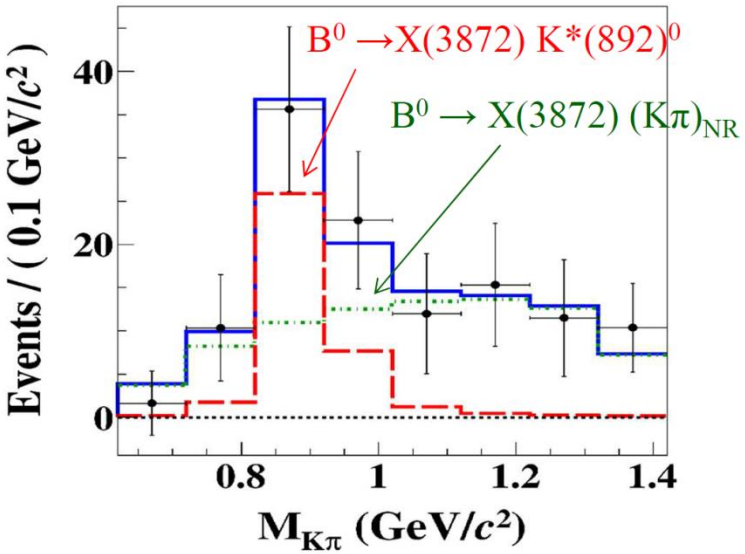
Projection of
$|\Delta E| < 0.02$ GeV



$$(10.61 \pm 3.04\ (\text{stat}) \pm 0.85(\text{syst}))\times 10^{-6}$$

$K^+\pi^-$ mass spectrum study

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



$B^0 \to X(3872) K^*(892)^0$ signal is fitted with Histogram from signal MC

$B^0 \to X(3872) (K\pi)_{NR}$ is also fitted with Histogram from signal MC.

We do not consider the interference between the them.

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

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

Upper bound on M(Kπ) due to the kinematics is 1.41GeV/c^2. In light of this, we excluded $K_2^*(1430)$ in this fit.

In contrast to ψ' results, here non resonant component in M(Kπ) system seems to be more as compared to resonant one.

X-like states decaying to η_c modes

- Motivation:
  - $X(3872)$: observed by Belle in $B \to K(J/\psi\pi^+\pi^-)$; $J^{PC} = 1^{++}$ determined by LHCb from angular analysis.
  - If $X(3872)$ is a $D^0\bar{D}^{*0}$ molecule, there may be other "X-like" particles.

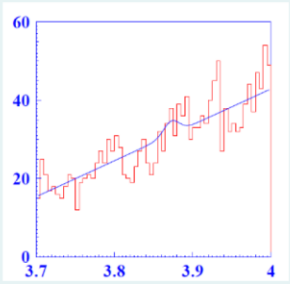
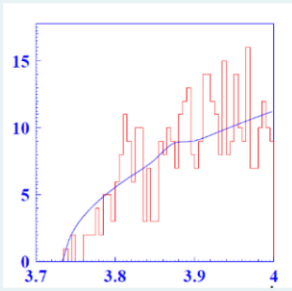
- Assumption:

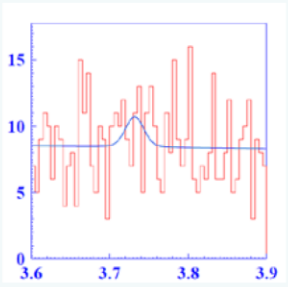
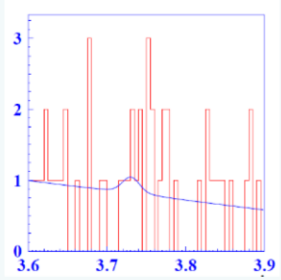
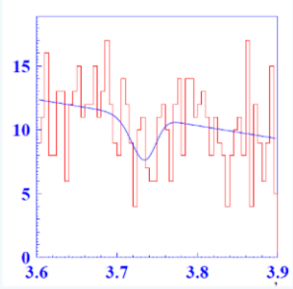
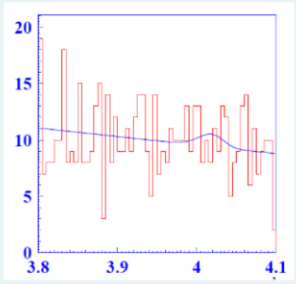
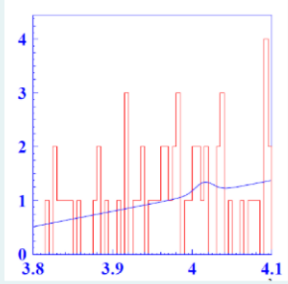
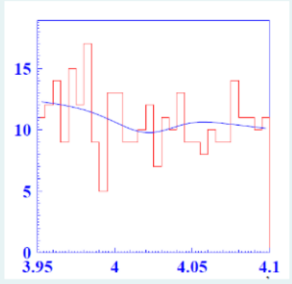
Candidate	Combination	Quantum number J^{PC}	Decay modes
$X_1(3872)$	$D^0\bar{D}^{*0} - \bar{D}^0 D^{*0}$	1^{+-}	$\eta_c\omega$, $\eta_c\rho$
$X(3730)$	$D^0\bar{D}^0 + \bar{D}^0 D^0$	0^{++}	$\eta_c\eta$, $\eta_c\pi^0$
$X(4014)$	$D^{*0}\bar{D}^{*0} + \bar{D}^{*0} D^{*0}$	0^{++}	$\eta_c\eta$, $\eta_c\pi^0$

- Analysis features:
  - $B^\pm \to K^\pm X$ with $\eta_c \to K_s K\pi$, $K_s \to \pi^+\pi^-$
  - Combined fit of $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$
  - Test mode: $B^\pm \to K^\pm\psi(2S)(\to J/\psi\pi^+\pi^-)$, consistent with PDG.
  - The same final states without intermediate X are studied.

X-like states decaying to η_c modes

arXiv:1501.06351

	$X \to \eta_c \pi^+\pi^-$	$X \to \eta_c \omega$
$X_1(3872)$		

	$X \to \eta_c \eta$		$X \to \eta_c \pi^0$
	$\eta \to \gamma\gamma$	$\eta \to \pi^+\pi^-\pi^0$	
X(3730)			
X(4014)			

X: M(X) GeV/c^2 - Y: N events

X-like states decaying to η_c modes

No signal was observed in any of the studied decay channels. The upper limits of their productions are determined at 90% C.L..

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.

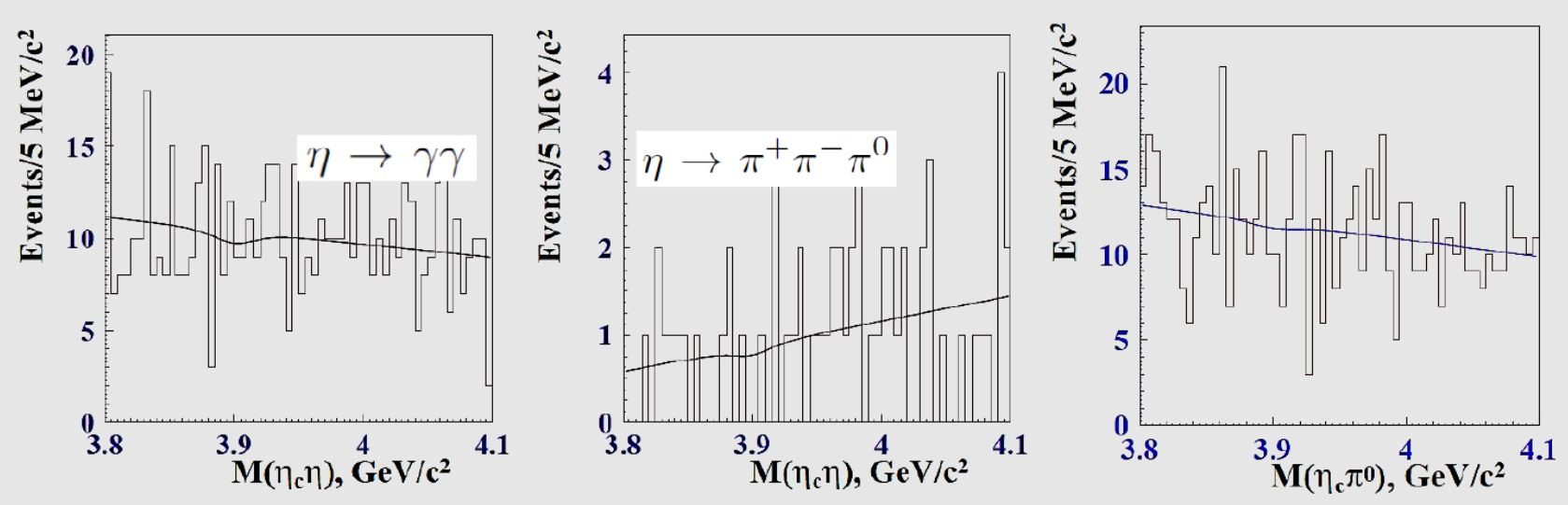
Mode	Yield	UL
$\eta_c \pi^+ \pi^-$	155 ± 72	3.9
$\eta_c \omega$	-41 ± 27	5.3
$\eta_c \eta(\gamma\gamma)$	-14.1 ± 26.1	2.2
$\eta_c \eta(3\pi)$	-1.8 ± 3.4	
$\eta_c \pi^0$	-1.9 ± 12.1	6.2

arXiv:1501.06351

$Z(3900)^0$ / $Z(4020)^0$ / $X(3915)$ decaying to η_c modes

- $Z_c^{\pm}(3900)$ was observed in $\pi^{\pm} J/\psi$ final states and $Z_c^{\pm}(4020)$ was observed in $\pi^{\pm} h_c$ final states. Could they have neutral partners?
- $X(3915)$ was observed in $\gamma\gamma$ collisions.

arXiv:1501.06351



Upper limits of branching fractions at 90% C.L.

Resonance	Decay mode	$\mathcal{B}(B \to K + R)$
$Z^0(3900)$	$\eta_c\pi^+\pi^-$	4.7×10^{-5}
$Z^0(4020)$		1.6×10^{-5}
$X(3915)$	$\eta_c\eta$	3.3×10^{-5}
	$\eta_c\pi^0$	1.8×10^{-5}

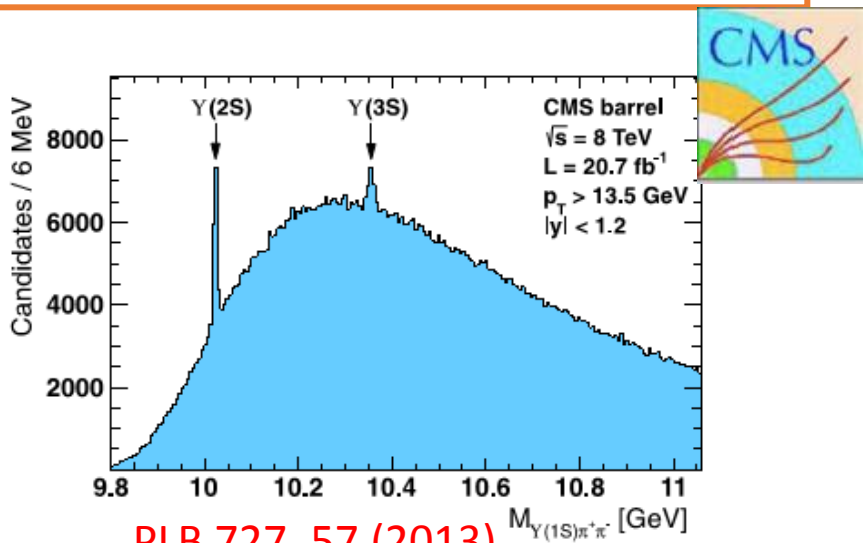
$\Upsilon(5S) \rightarrow \pi^+\pi^-\pi^0\gamma l^+l^-$

•Hadronic transitions between heavy quarkonia have been successfully described using the QCD multipole expansion (QCDME) model.

•Search for the process $\Upsilon(5S) \rightarrow \pi^+\pi^-\pi^0 \chi_{bJ}(nP)$ would be very helpful for understanding QCD dynamics.

• A detailed analysis of the three-body e+e- →π+π- Υ(mS) and e+e- → π+π- hb(nP) processes revealed Zb(10610)+- and Zb(10650)+-. The follow-up similar investigation of π+π-π0 hadronic decay modes between the Υ(5S) and X_{bJ} may offer additional insight into strong interactions in heavy quarkonium systems.

- CMS collaboration searched for X(3872) counterpart in the bottomnium sector, called here X_b, in the decay channel $\pi^+\pi^-\Upsilon(1S)$. No signal was observed.

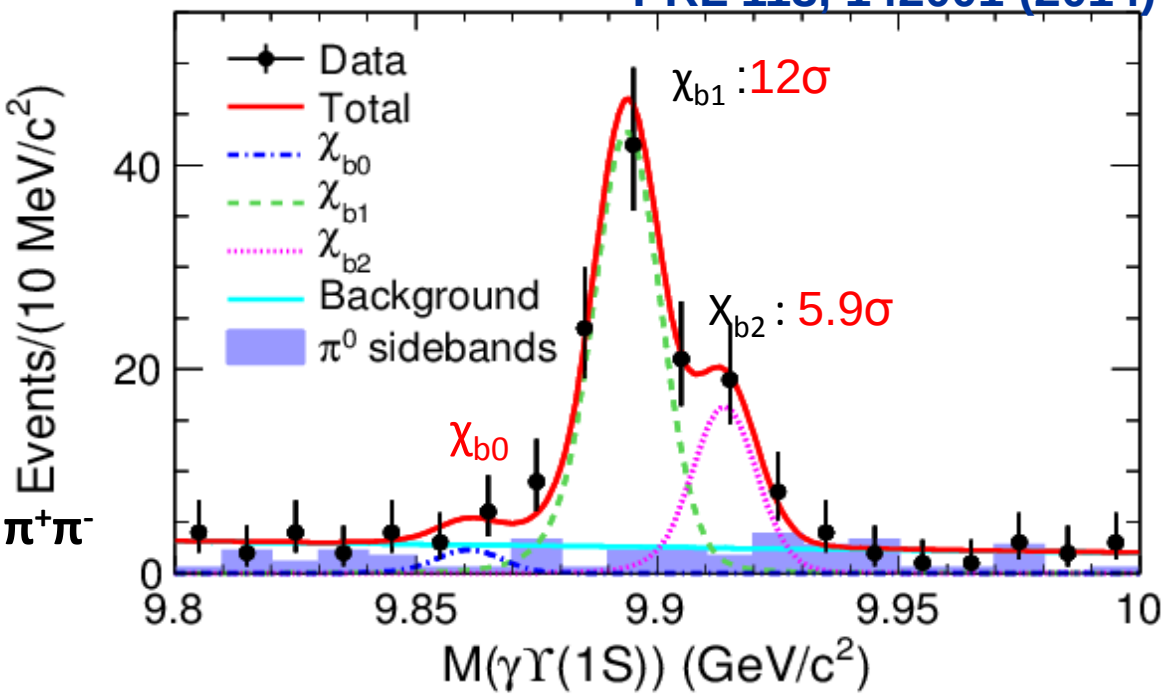


PLB 727, 57 (2013) .

$e^+e^- \to \pi^+\pi^-\pi^0 \chi_{bJ}$

PRL 113, 142001 (2014)

118 fb^{-1} Υ(5S) data sample
$\chi_{bJ} \to \gamma\Upsilon$(1S)



- **The same order as $e^+e^- \to \pi^+\pi^-\Upsilon$(nS).** [PRL 100, 112001].
- **Hadronic loop effect?** [arXiv:1406.6763]

Assuming all events decay from Υ(5S).

Born cross section:

$\sigma(e^+e^- \to \pi^0\pi^+\pi^- \chi_{b0}) < 3.1$ (pb) at 90% C.L.

$\sigma(e^+e^- \to \pi^0\pi^+\pi^-\chi_{b1}) = 0.90 \pm 0.11 \pm 0.13$ (pb)

$\sigma(e^+e^- \to \pi^0\pi^+\pi^- \chi_{b2}) = 0.57 \pm 0.13 \pm 0.08$ (pb)

Product BF :

BF(Υ(5S) $\to \pi^0\pi^+\pi^- \chi_{b0}$) $< 6.3 \times 10^{-3}$ at 90% C.L.

BF(Υ(5S) $\to \pi^0\pi^+\pi^-\chi_{b1}$) $= (1.85 \pm 0.23 \pm 0.23) \times 10^{-3}$

BF(Υ(5S) $\to \pi^0\pi^+\pi^- \chi_{b2}$) $= (1.17 \pm 0.27 \pm 0.14) \times 10^{-3}$

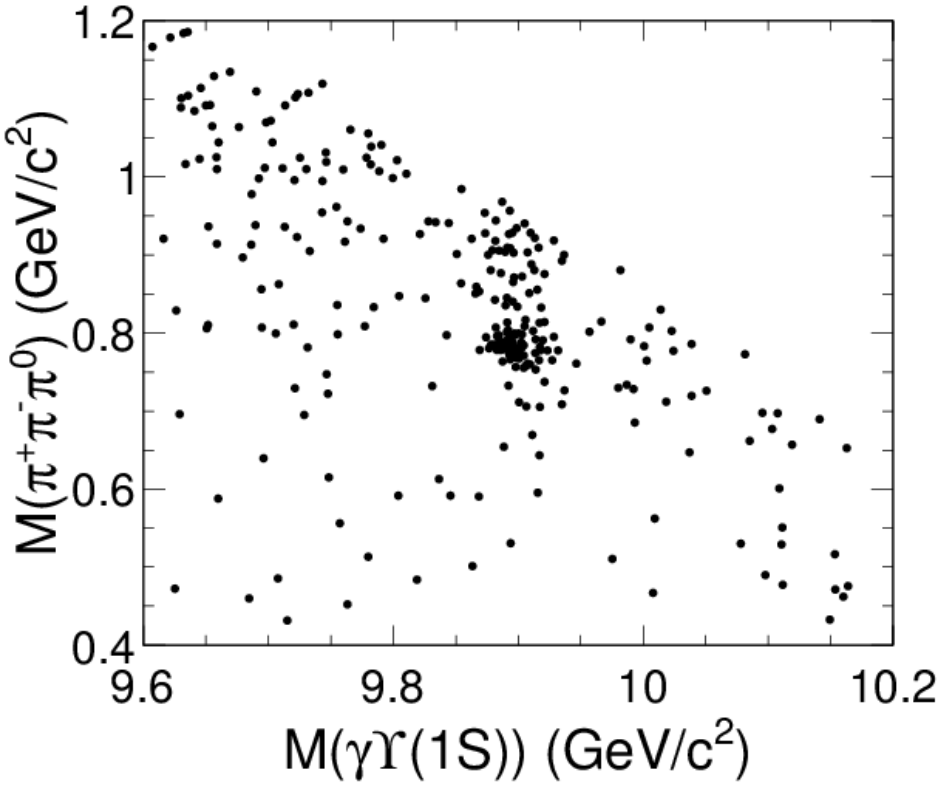
$e^+e^- \to \pi^+\pi^-\pi^0 \chi_{bJ}$

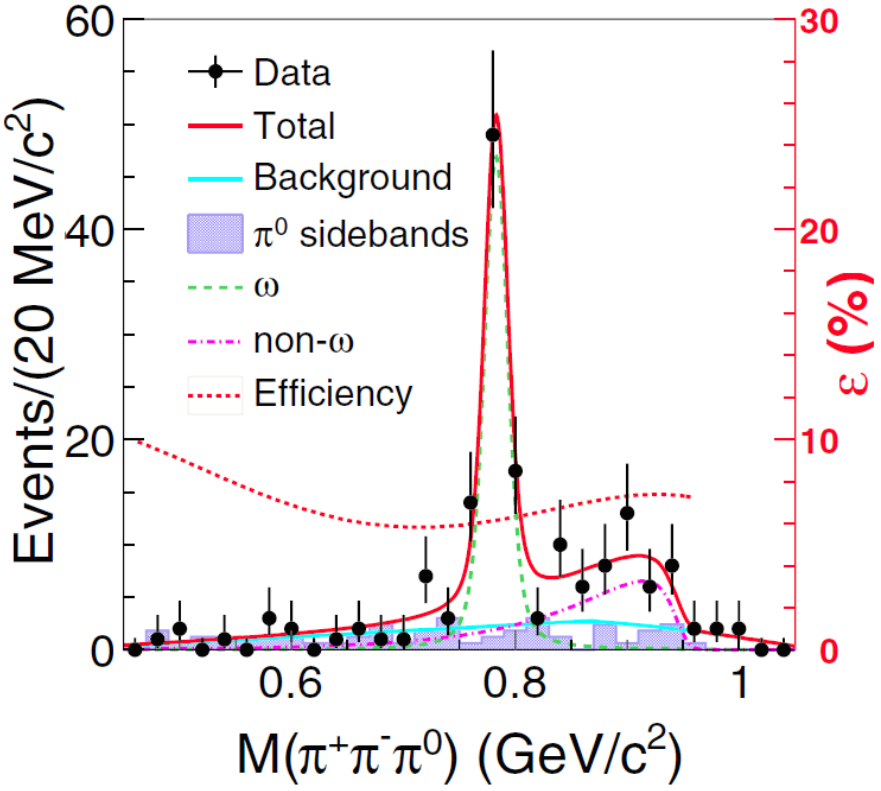
PRL 113, 142001 (2014)

$\pi^+\pi^-\pi^0$ invariant mass distribution:

- **ω signal**
- **An enhancement in higher $M(\pi^+\pi^-\pi^0)$**

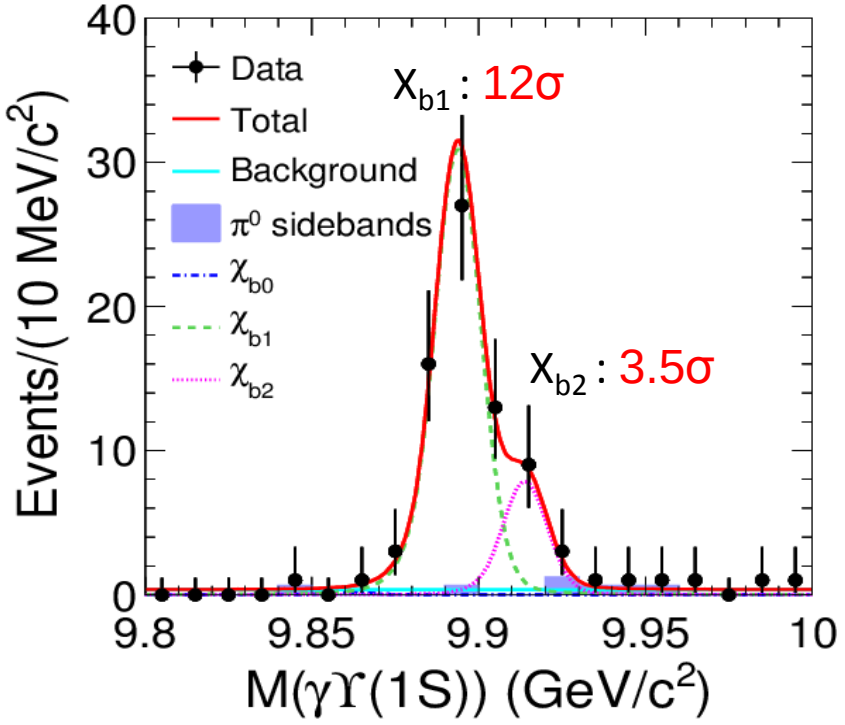
2D fit to scatter plot of $M(\pi^+\pi^-\pi^0)$ vs $M(\gamma\Upsilon(1S))$.

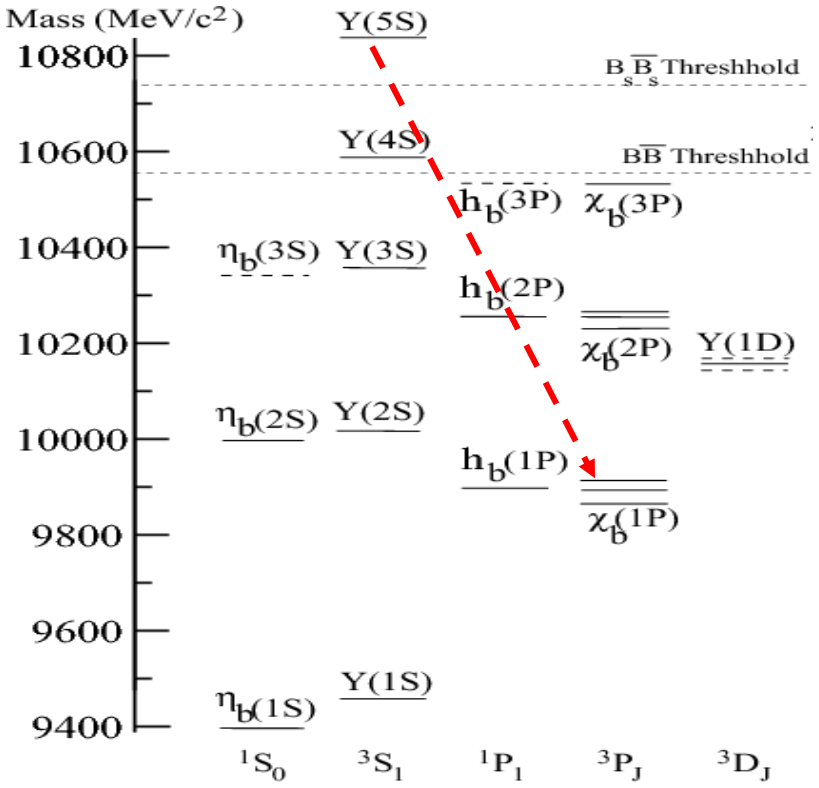




$e^+e^- \to \omega\chi_{bJ}$

ω signal region.





PRL 113, 142001 (2014)

Born cross section:

$\sigma(e^+e^- \to \omega\chi_{b0}) < 1.9$ (pb) at 90% C.L.

$\sigma(e^+e^- \to \omega\chi_{b1}) = 0.76 \pm 0.11 \pm 0.11$ (pb)

$\sigma(e^+e^- \to \omega\chi_{b2}) = 0.29 \pm 0.11 \pm 0.08$ (pb)

The $\frac{Br(\Upsilon(5S) \to \omega\chi_{b2})}{Br(\Upsilon(5S) \to \omega\chi_{b1})}$ higher than **expectation from quark symmetry**. [PLB 346, 129 (1995)].

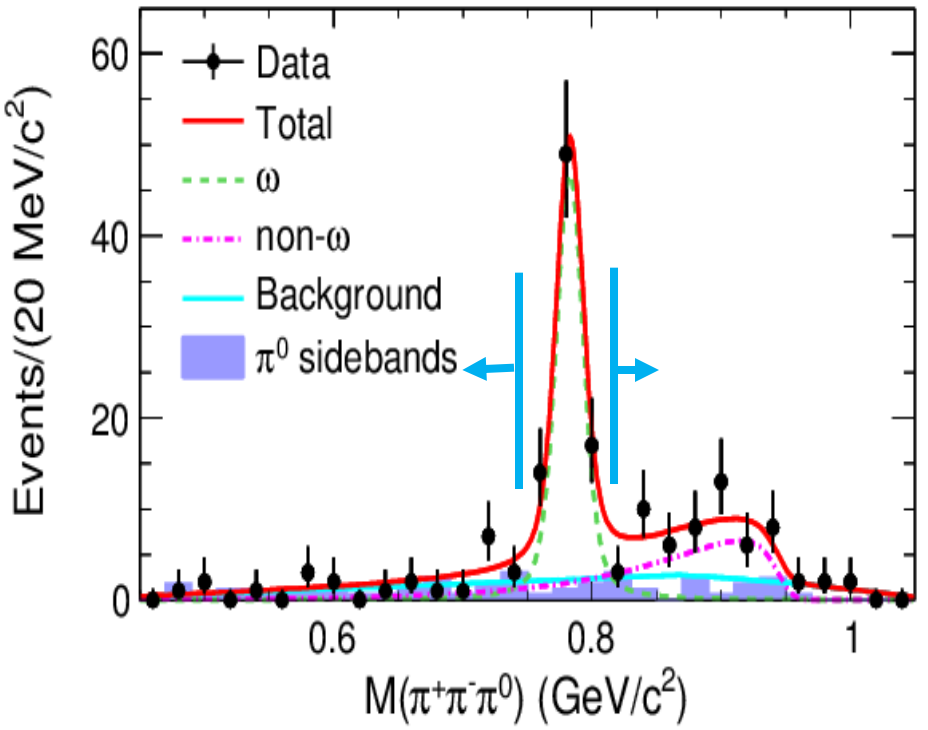
→ **a molecular component in** ϒ(5S) [arXiv: 1406.0082]

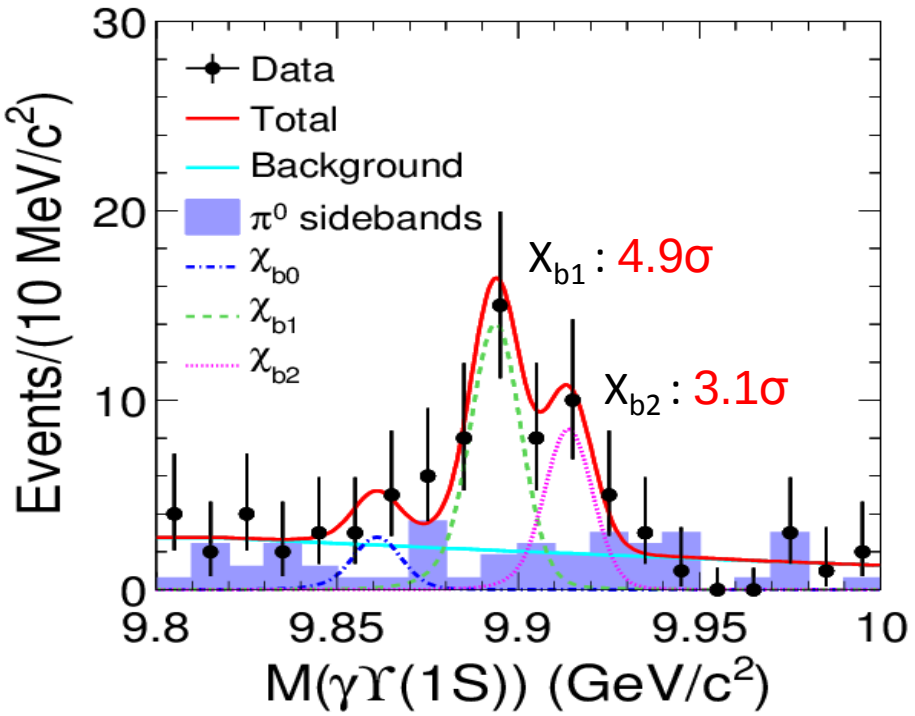
→ **S- and D- wave mixing** [arXiv:1406.6543]

$e^+e^- \to (\pi^+\pi^-\pi^0)_{non\text{-}\omega}\chi_{bJ}$

PRL 113, 142001 (2014)

- The χ_{bJ} candidates out of ω signal region.
- Possible cascade decay from $\Upsilon(5S) \to \pi Z_b \to \pi\rho\chi_{bJ}$ [arXiv:1406.0082]
- **The interpretation is currently limited.**





Born cross section:

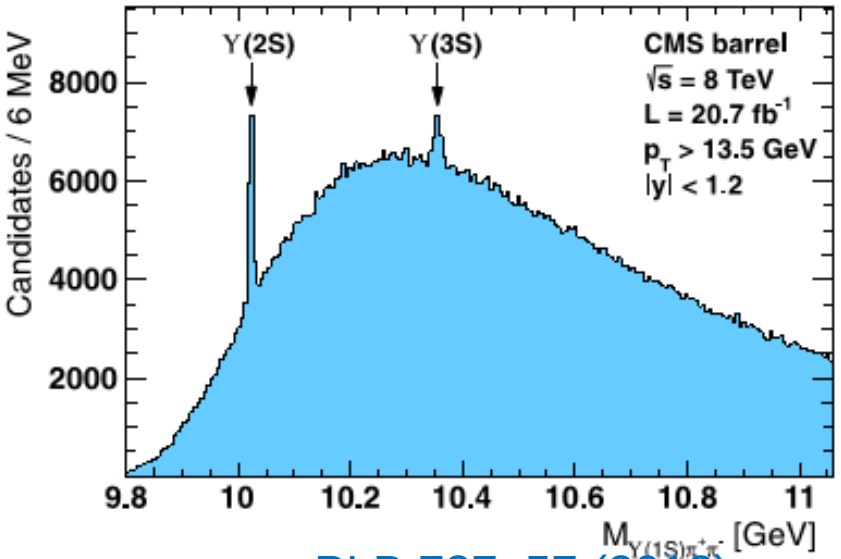
$\sigma(e^+e^- \to (\pi^+\pi^-\pi^0)_{non\text{-}\omega}\chi_{b0}) < 2.3$ (pb) at 90% C.L.

$\sigma(e^+e^- \to (\pi^+\pi^-\pi^0)_{non\text{-}\omega}\chi_{b1}) = 0.25 \pm 0.07 \pm 0.06$ (pb)

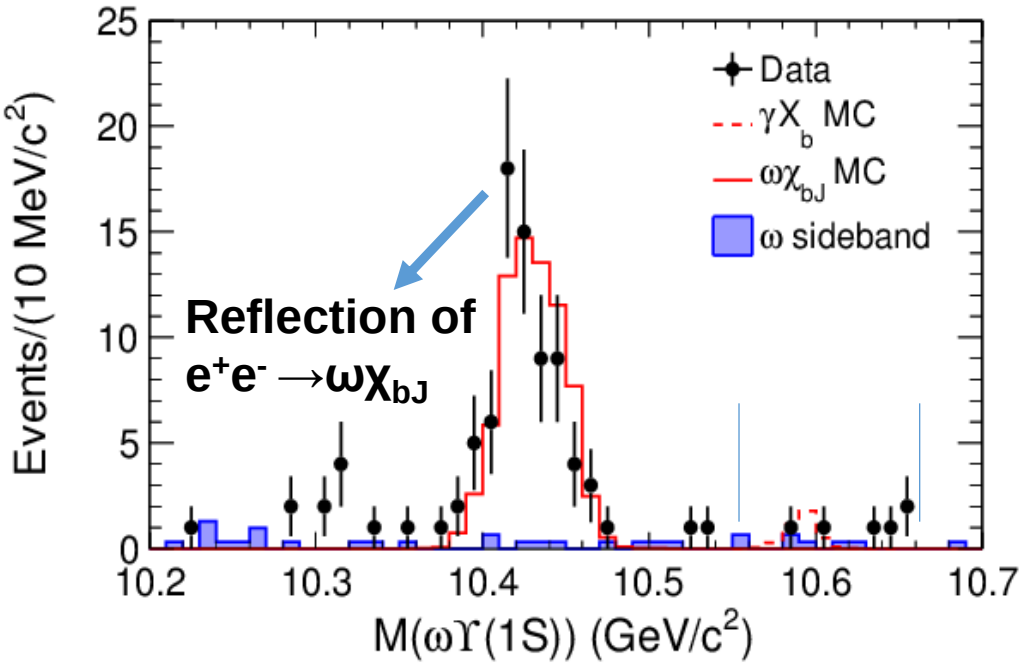
$\sigma(e^+e^- \to (\pi^+\pi^-\pi^0)_{non\text{-}\omega}\chi_{b2}) = 0.30 \pm 0.11 \pm 0.14$ (pb)

$e^+e^- \to \gamma X_b \to \gamma\omega\Upsilon(1S)$

- **The X(3872) counterpart in the bottomonium sector X_b, NOT observed decay channel $\pi^+\pi^-\Upsilon(1S)$.**
- **As X_b is above $\omega\chi_{bJ}$ threshold, this Isospin-conserving process should be a more promising decay mode.** [PRD88, 054007].



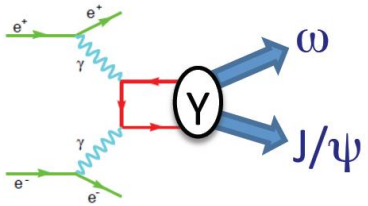
PLB 727, 57 (2013) .



Assuming X_b is narrow, the upper limit on the product branching fraction :

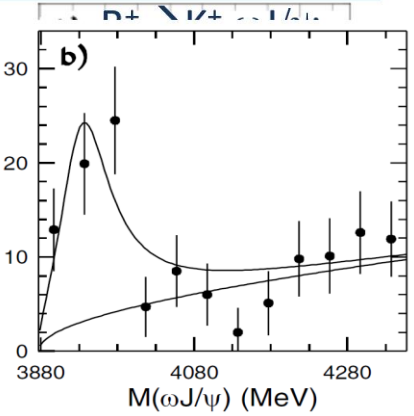
Br(Υ(5S) → γX_b) Br(X_b → **ωΥ(1S)**) varies from **2.6** × **10^{-5}** to **3.8** × **10^{-5}** between 10.55 and 10.65 GeV/c^2.

X(3915)→ωJ/ψ

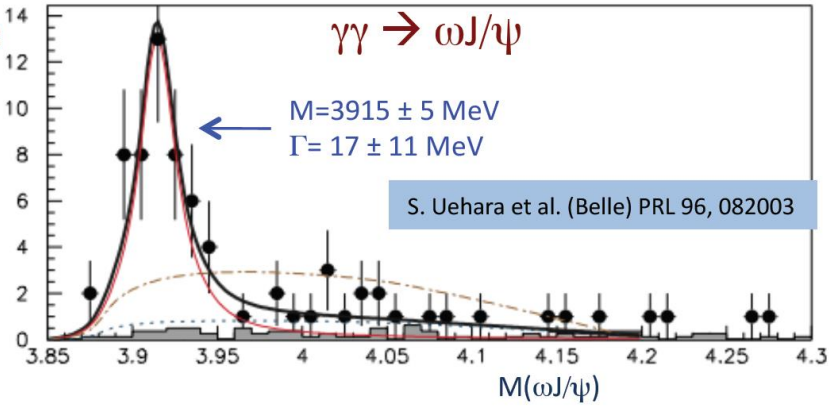


S.-K. Choi et al. (Belle) PRL 94, 182002

Belle
2005



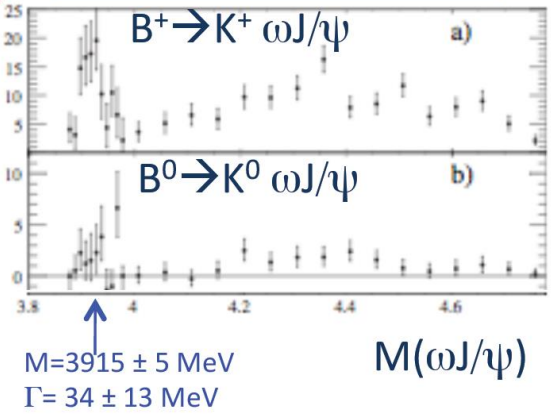
Belle
2010

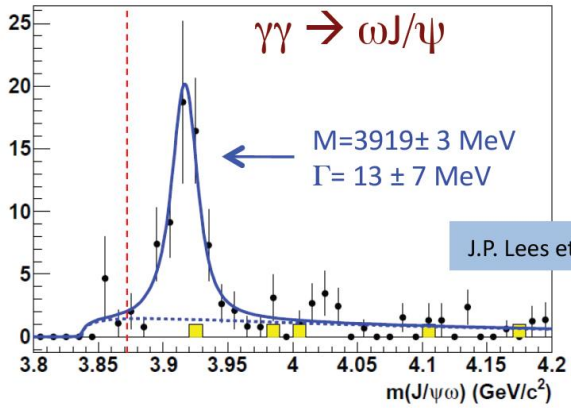


S. Uehara et al. (Belle) PRL 96, 082003

B. Aubert et al. (BaBar) PRL101, 182001

BaBar
2008





BaBar
2012

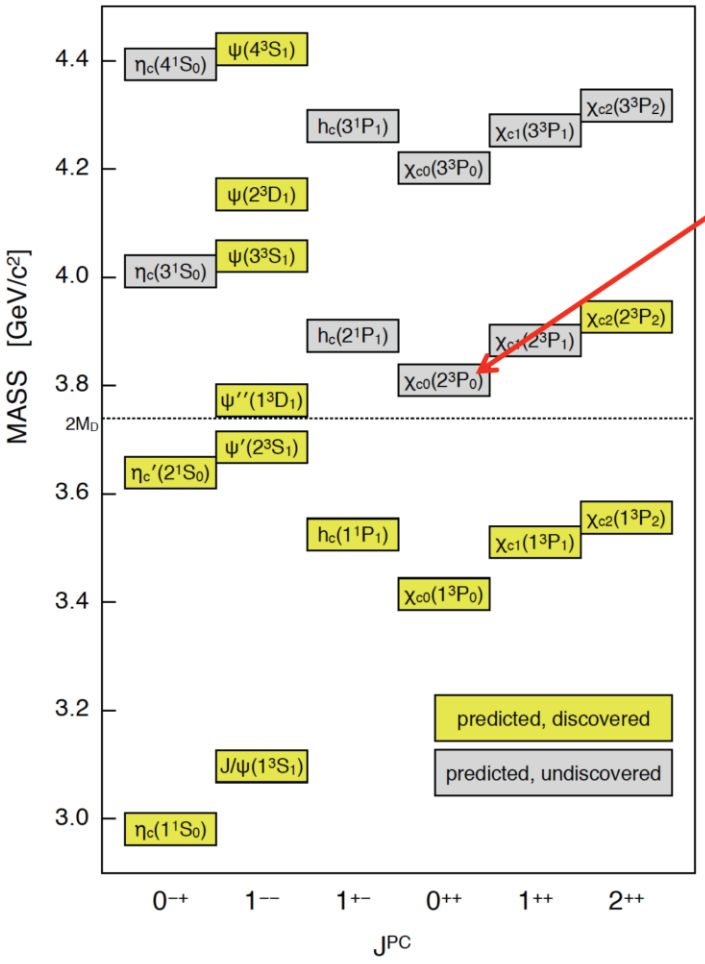
J.P. Lees et al. (BaBar) PRD 86, 072002

PDG : $Bf(B \to X(3915))Bf(X(3915) \to \omega J/\psi) = (3.0^{+0.9}_{-0.7}) \times 10^{-5}$

PDG : $\Gamma(X(3915) \to \gamma\gamma)Bf(X(3915) \to \omega J/\psi) = (54 \pm 9)\text{eV}$

BaBar measurements favor $J^{PC}=0^{++}$

PDG: X(3915) = χ_{c0}' ?



$\chi_{c0}(2P)$ was $X(3915)$

$I^G(J^{PC}) = 0^+(0^{++})$

$\chi_{c0}(2P)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3918.4± 1.9 OUR AVERAGE					
3919.4± 2.2± 1.6	59 ± 10	LEES	12AD	BABR	$e^+e^- \to e^+e^-\omega J/\psi$
$3919.1^{+3.8}_{-3.4}$± 2.0		DEL-AMO-SA..	10B	BABR	$B \to \omega J/\psi K$
3915 ± 3 ± 2	49 ± 15	UEHARA	10	BELL	10.6 $e^+e^- \to e^+e^-\omega J/\psi$
3943 ±11 ±13	58 ± 11	[1] CHOI	05	BELL	$B \to \omega J/\psi K$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$3914.6^{+3.8}_{-3.4}$± 2.0		[1] AUBERT	08W	BABR	Superseded by DEL-AMO-SANCHEZ 10B

[1] $\omega J/\psi$ threshold enhancement fitted as an S-wave Breit-Wigner resonance.

$\chi_{c0}(2P)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
20± 5 OUR AVERAGE Error includes scale factor of 1.1.					
13± 6± 3	59 ± 10	LEES	12AD	BABR	$e^+e^- \to e^+e^-\omega J/\psi$
31^{+10}_{-8}± 5		DEL-AMO-SA..	10B	BABR	$B \to \omega J/\psi K$
17±10± 3	49 ± 15	UEHARA	10	BELL	10.6 $e^+e^- \to e^+e^-\omega J/\psi$
87±22±26	58 ± 11	[2] CHOI	05	BELL	$B \to \omega J/\psi K$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
34^{+12}_{-8}± 5		[2] AUBERT	08W	BABR	Superseded by DEL-AMO-SANCHEZ 10B

[2] $\omega J/\psi$ threshold enhancement fitted as an S-wave Breit-Wigner resonance.

$\chi_{c0}(2P)$ DECAY MODES

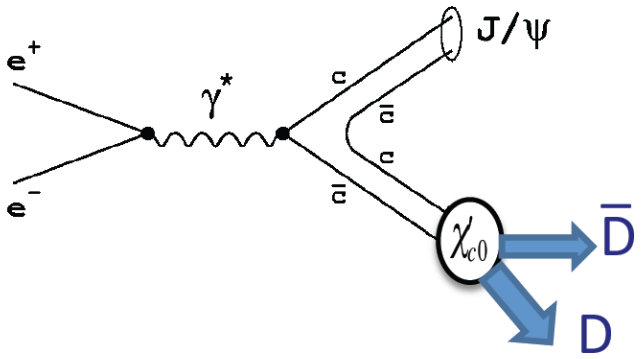
	Mode	Fraction (Γ_i/Γ)
Γ_1	$\omega J/\psi$	seen
Γ_2	$\overline{D}^{*0} D^0$	
Γ_3	$\pi^+\pi^-\eta_c(1S)$	not seen
Γ_4	$\gamma\gamma$	seen

Disagreement ? For example: S.Olsen, PRD91,057501(2015)

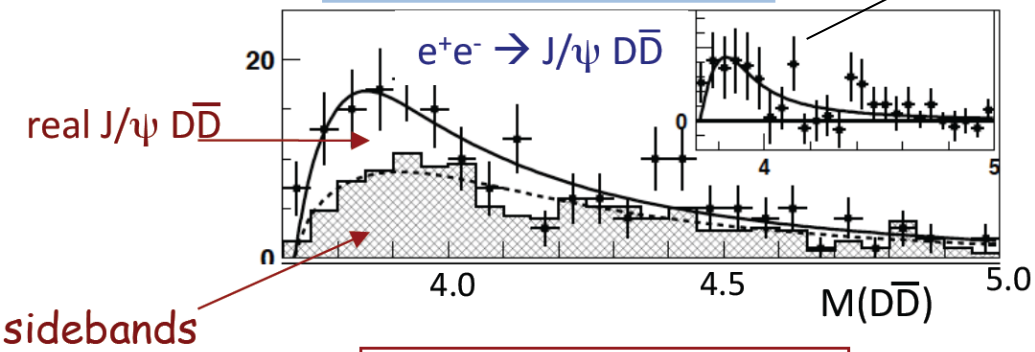
Another χ_{c0}' candidate?

$e^+e^- \rightarrow J/\psi\chi'_{c0}$

↳ $D\bar{D}$??



P. Pakhlov et al. (Belle): PRL 100, 202001



2nd peak ?

Year: 2008
693fb^{-1}
Significance: 3.8σ
Fit: not stable

$M(\chi_{c0}') = 3878 \pm 4\ 8$ MeV
$\Gamma(\chi_{c0}') = 347\ ^{+316}_{-143}$ MeV

Belle is using full of data sample to update this analysis

Summary

- We report the first observation of the X(3872) in $B^0 \to X(3872)K^+\pi^-$. In the $K^+\pi^-$ system, $K^*(892)^0$ is not dominant, which is marked contrast to the ψ' case.
- No evident peaks in X(3872)K and X(3872) π
- We report a search for B decays to final states with the η_c meson. We also search for X(3872)-like molecular-state, neutral partners of the $Z(3900)^{\pm}$ and $Z(4020)^{\pm}$, and X(3915).
- We observe clear $\pi^+\pi^-\pi^0\chi_{b1,b2}$ signals, while no significant $\pi^+\pi^-\pi^0\chi_{b0}$ is found from Y(5S) decays for the first time. In $M(\pi^+\pi^-\pi^0)$, besides ω, significant non-ω signals are also observed.
- No $X_b \to \omega Y(1S)$ signal is seen in Y(5S) decays between 10.55 and 10.65 GeV.
- X(3915) was confirmed by Babar, which may not be χ'_{c0}. Belle is updating $e^+e^- \to J/\psi$ DD to confirm X(3878).

Thanks