X(3872) results at Belle and other experiments

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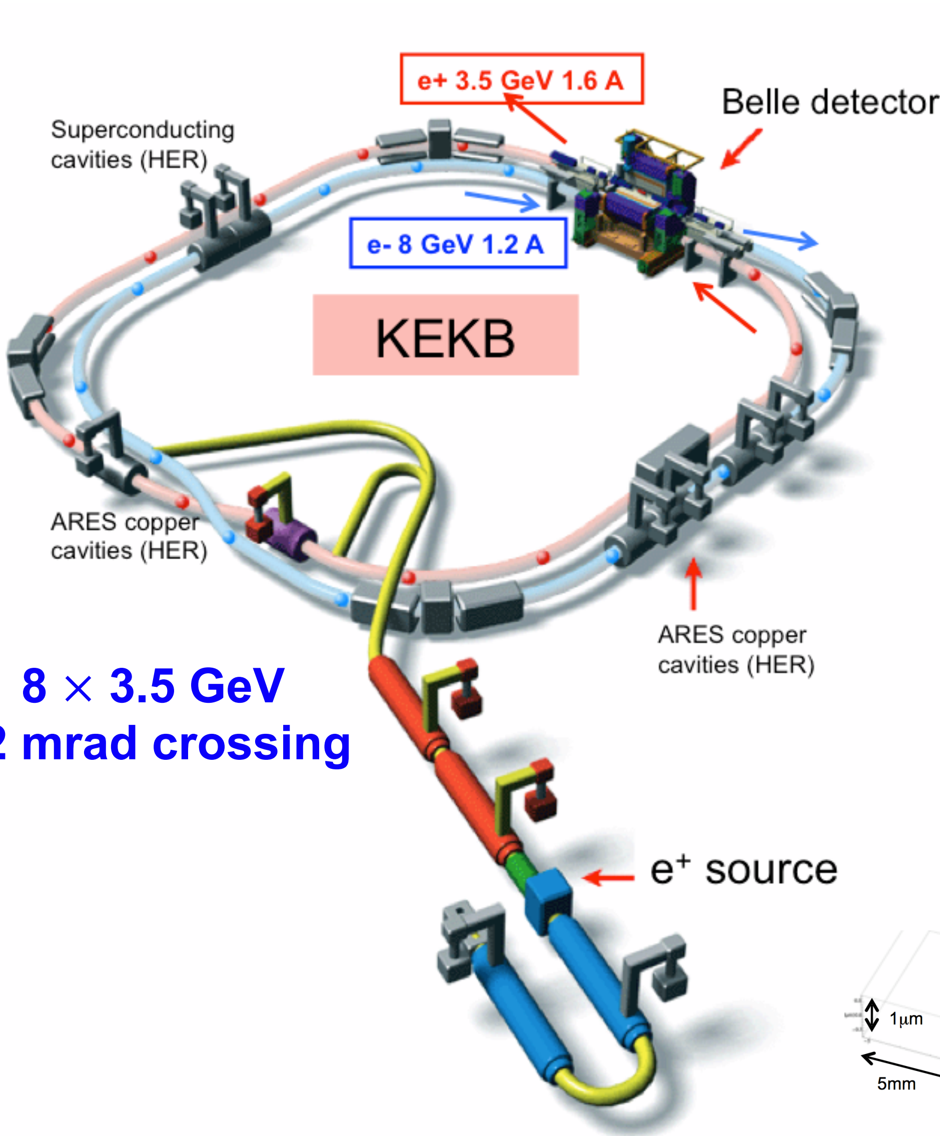
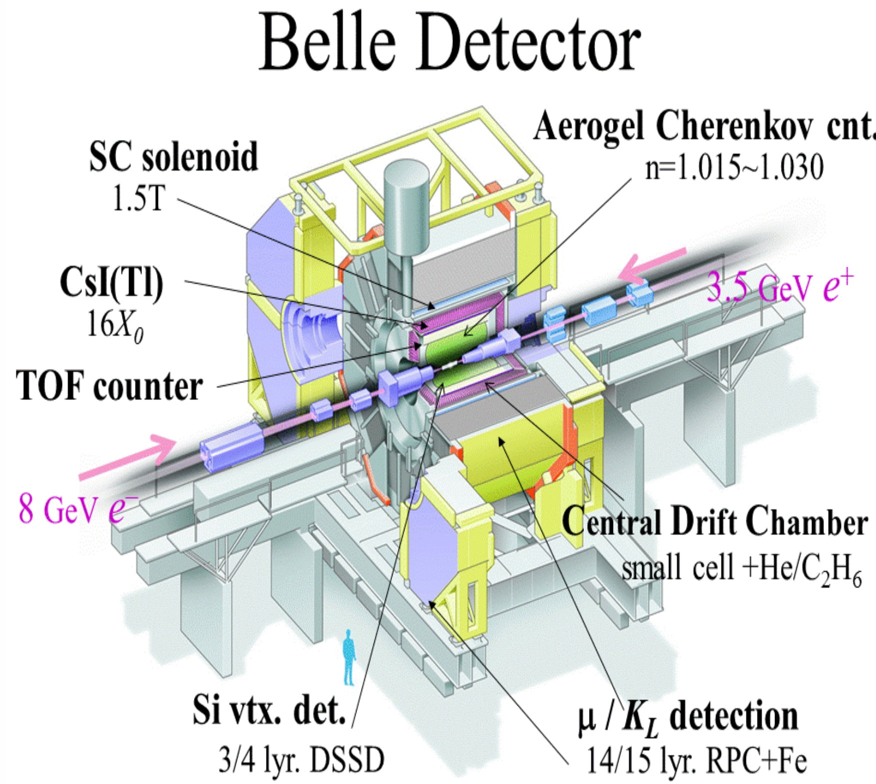
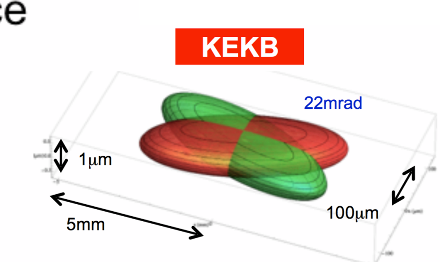
Belle experiment



8 × 3.5 GeV
22 mrad crossing

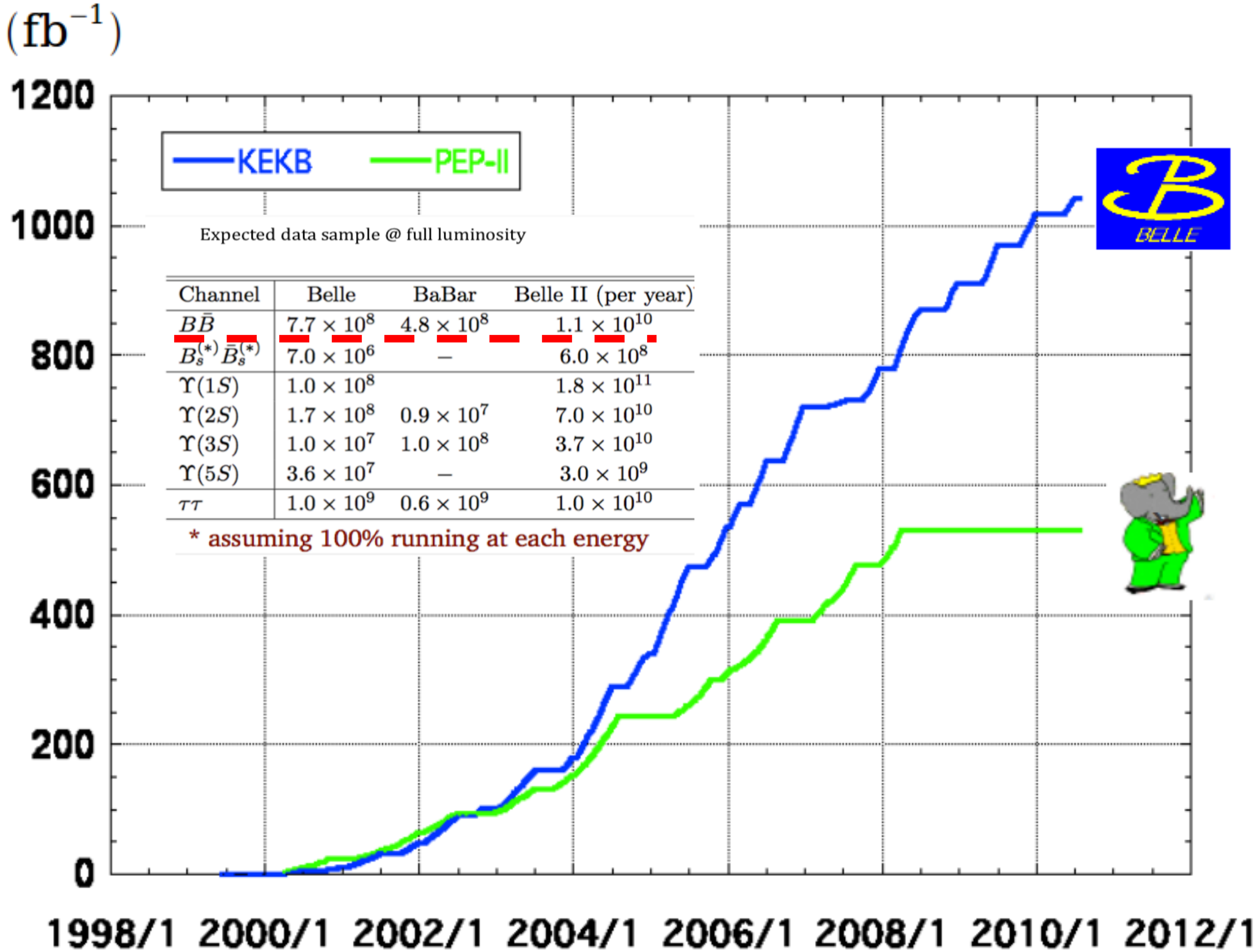




World record:

$L=2.1\times10^{34}/cm^2/sec$

Integrated luminosity of B factories



Expected data sample @ full luminosity

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

* assuming 100% running at each energy

> 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}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

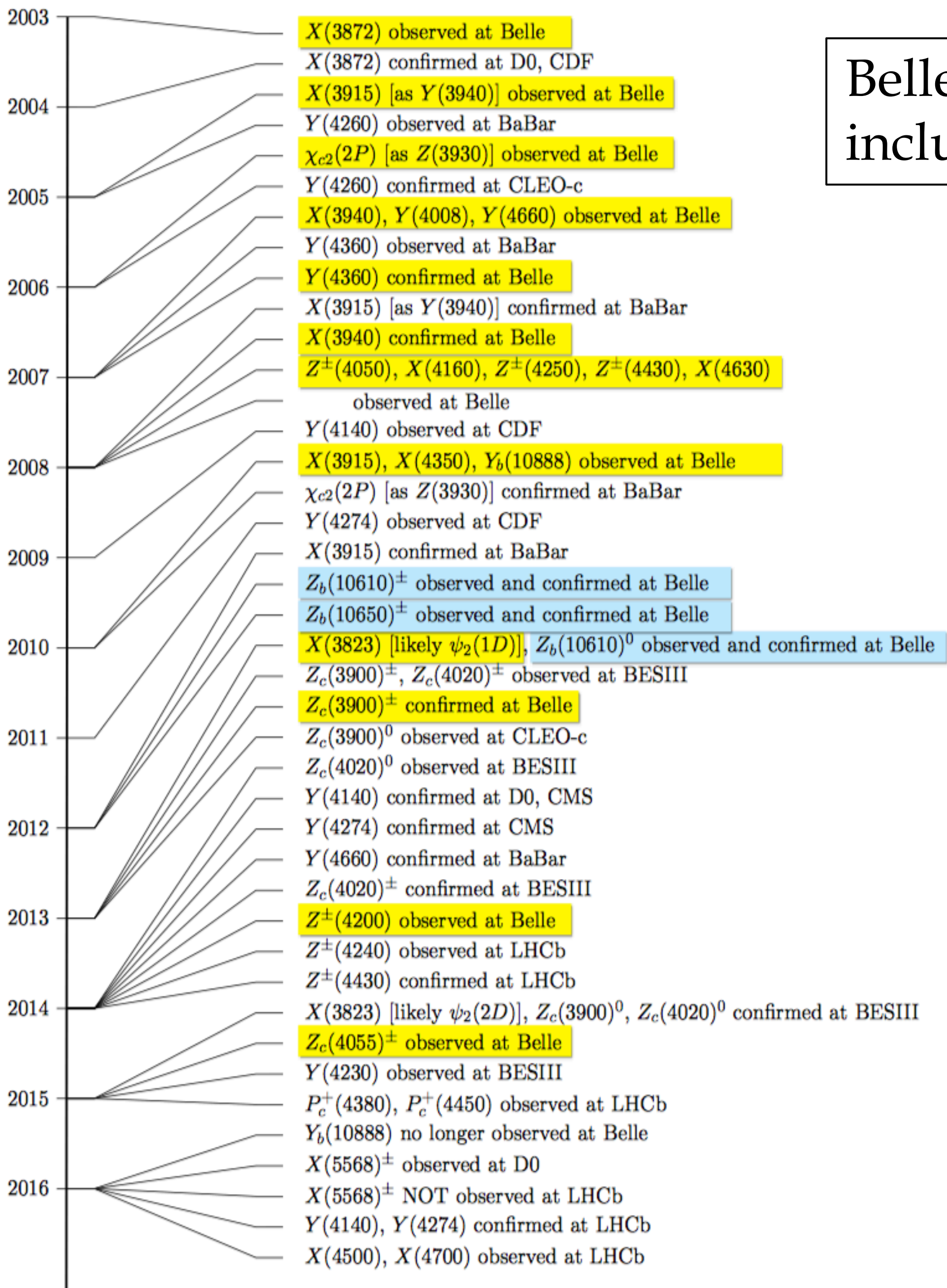
$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

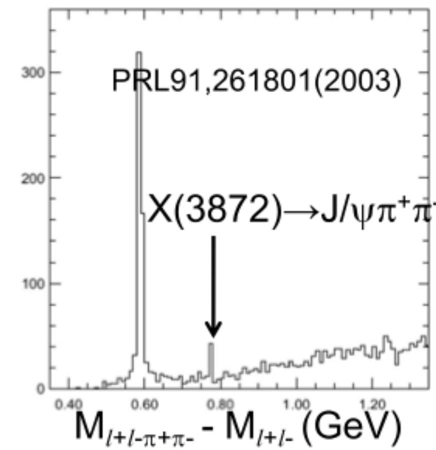
Off resonance:

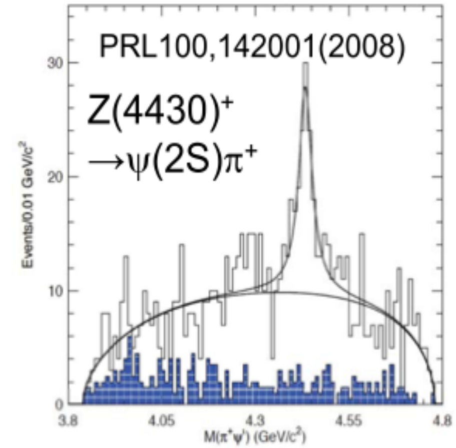
~ 54 fb^{-1}

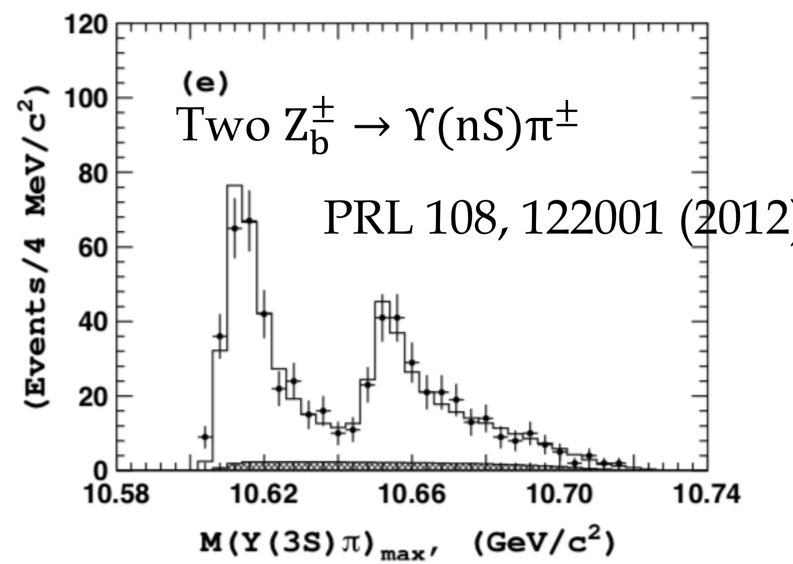
Belle accounts for ~1/2 of the discoveries, including the first X, Z_c and Z_b states !!



adapted from Lebed, Mitchell, Swanson, *PPNP* 93, 143 (2017)

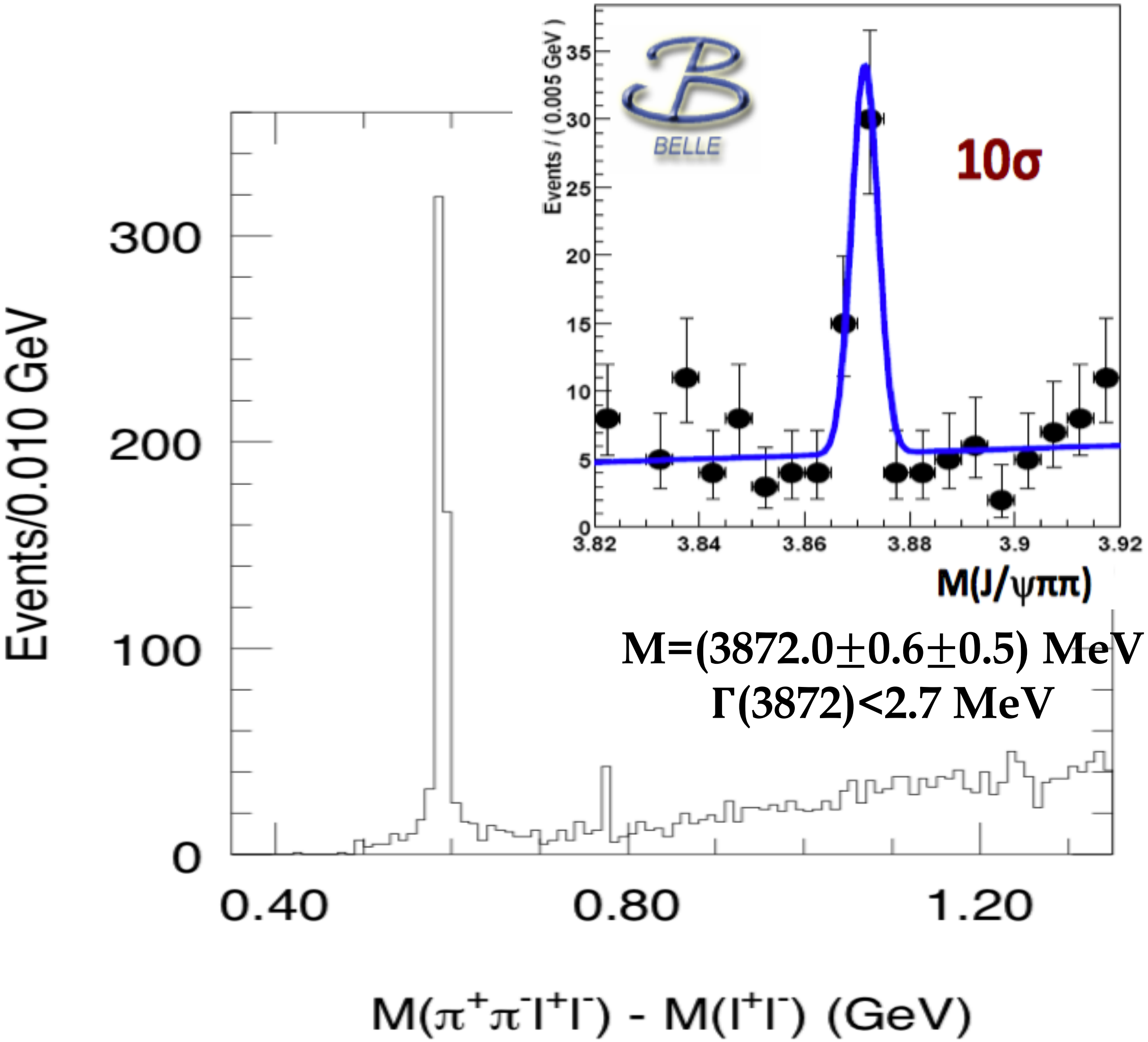






The first XYZ state: X(3872)

Belle's most cited paper: 1700+ [PRL91, 262001 (2003)]



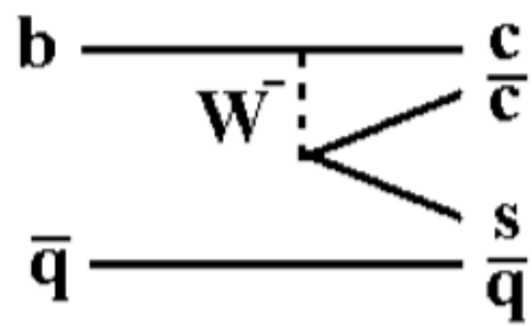
M=(3872.0±0.6±0.5) MeV

Γ(3872)<2.7 MeV

A gift from *B*-factory

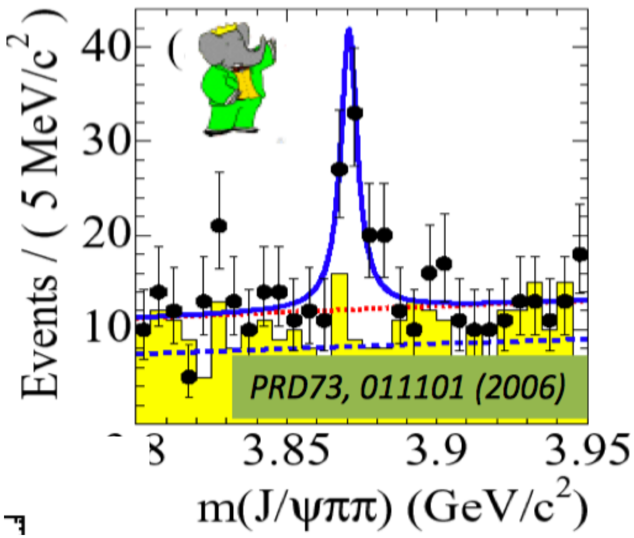
$B \to KX_{c\bar{c}}$

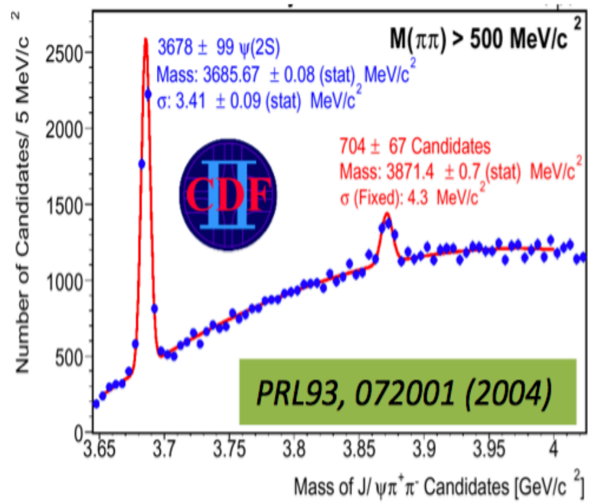
- CKM favored process, large branching fractions $10^{-4} - 10^{-3}$
- Many quantum numbers are allowed.

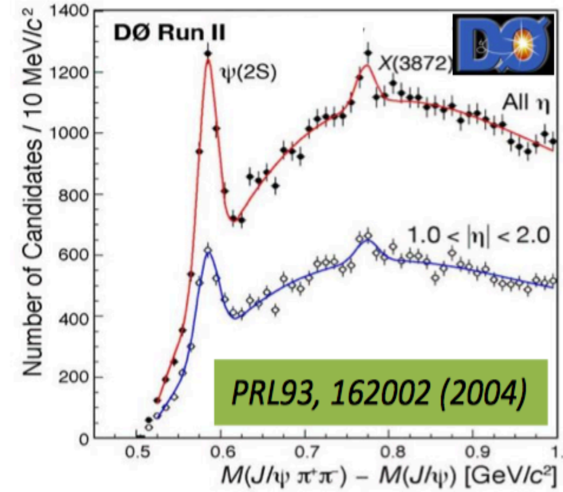


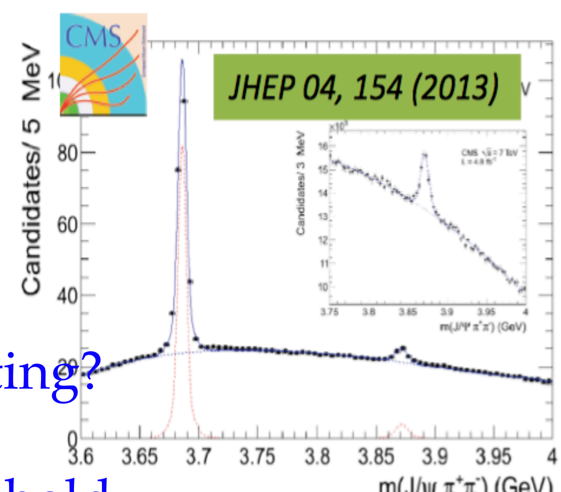
X(3872)

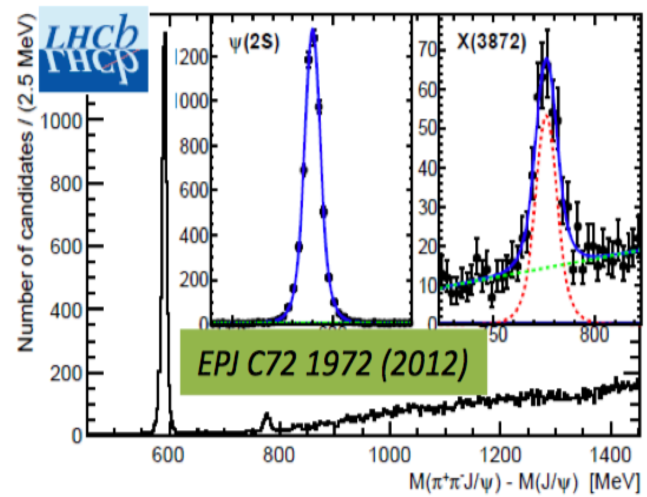
$X(3872) \to \pi^+\pi^- J/\psi$











Why X(3872) is so interesting?

- Very narrow
- Very close to DD* threshold
- No place in charmonium potential model
- $\pi\pi$ from ρ decays thus isospin-violating process

Outline

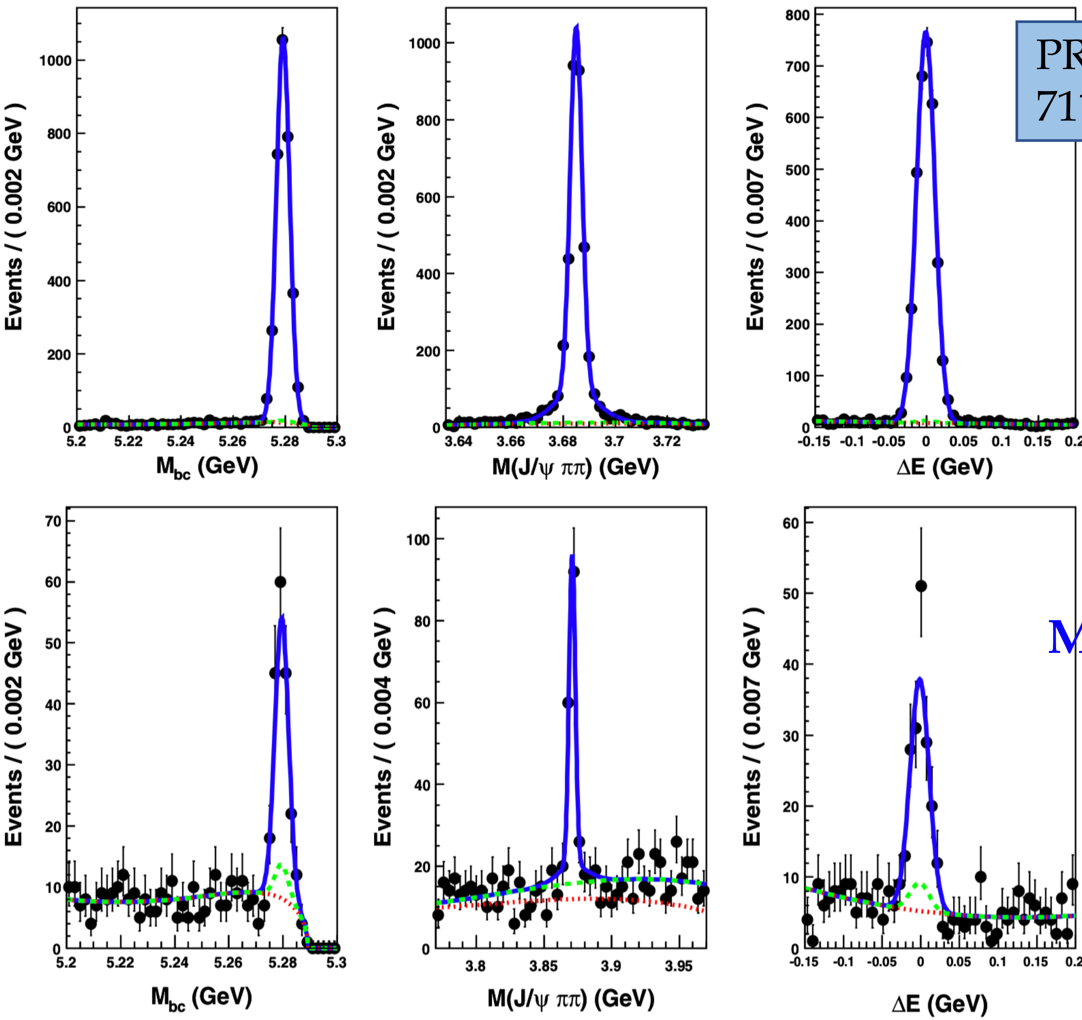
To understand it, we need to know

- **Mass, width, and J^{PC}**
- **Production mechanism of *X(3872)***
- **Decay patterns of *X(3872)***
- **Absolute branching fraction of X(3872)**
- **An exotic bottomonium counterpart: X_b**

Mass, width, and J^{PC}

M(X(3872))

Thanks to the ψ(2S) calibration!



PRD 84, 052004 (2010)
711/fb

A correction $\delta M = (0.92 \pm 0.06)$ MeV is the MC-determined X(3872) mass measurement bias scaled by the ratio of the measured and MC-determined ψ(2S) mass biases.

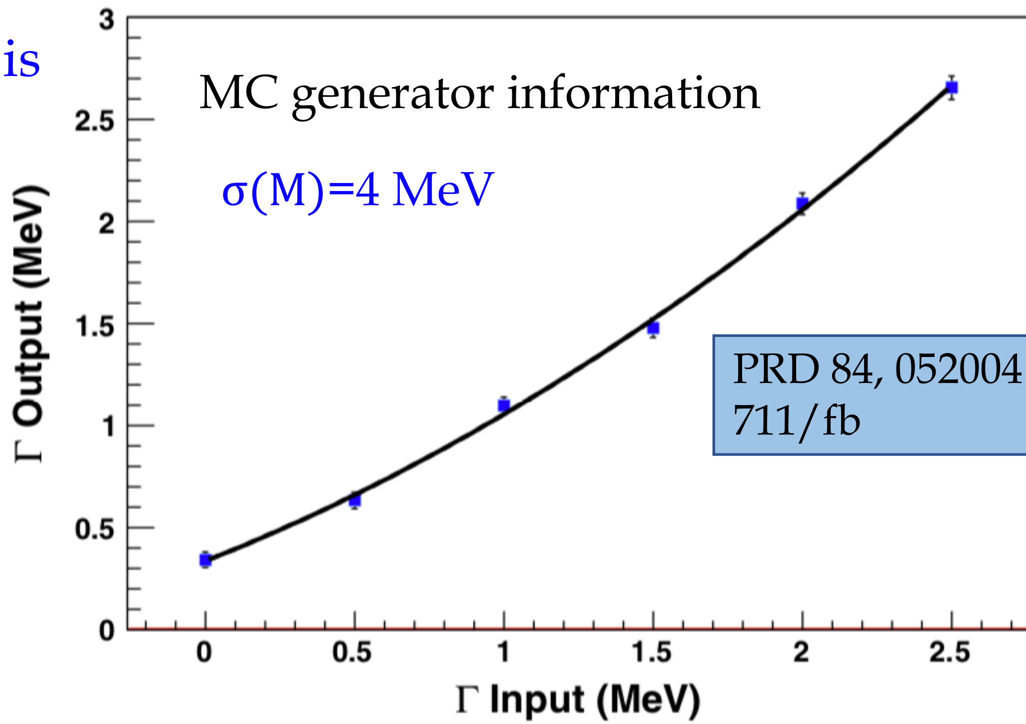
M(X(3872))=(3871.85±0.27±0.19) MeV

M(X(3872))−M($D^0\overline{D}^0$) = 142 MeV
M(X(3872))−M($D^0\overline{D}^{*0}$) = 0.17 MeV

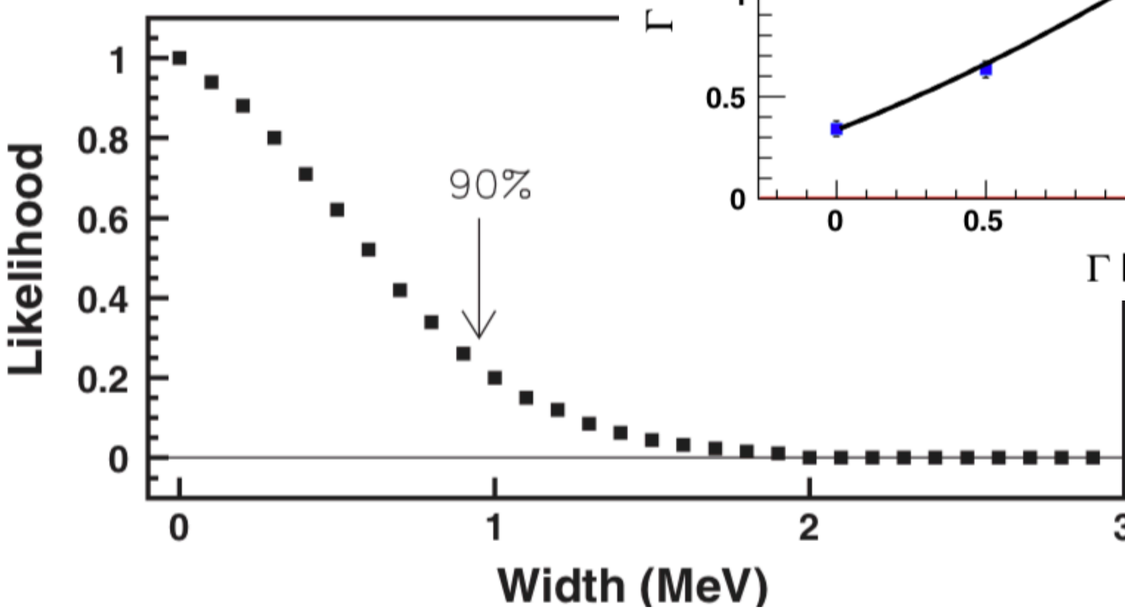
very close to $D^0\overline{D}^{*0}$ threshold!

Γ(3872)

The measured peak height is sensitive to X(3872).



PRD 84, 052004 (2010)
711/fb

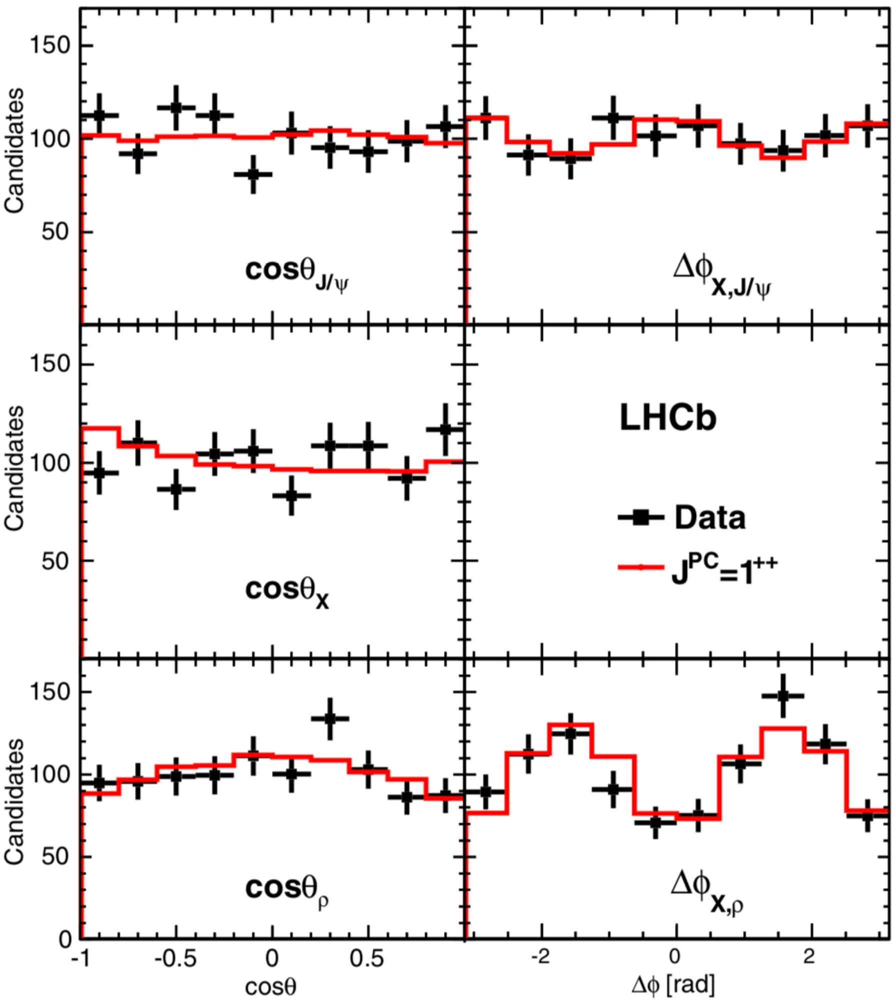


After the correction by utilizing ψ(2S) case, we obtain

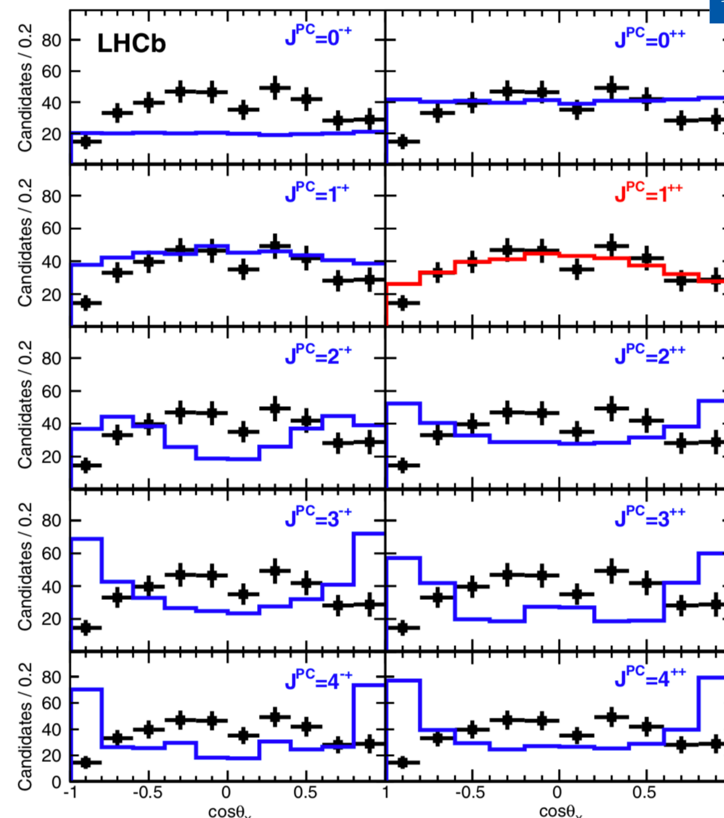
Γ(3872)<1.2 MeV 90% C.L.

J^{PC}

A five-dimensional angular correlation analysis in $B^+ \to K^+X(3872)$, $X(3872) \to \rho^0 J/\psi$, $\rho^0 \to \pi^+\pi^-$, $J/\psi \to \mu^+\mu^-$ with 1011±38 events.



$|\cos\theta_\rho| > 0.6$



1^{++} quantum numbers are consistent with those predicted by the molecular or tetraquark models and with the $\chi_{c1}(2P)$ charmonium state, possibly mixed with a molecule.

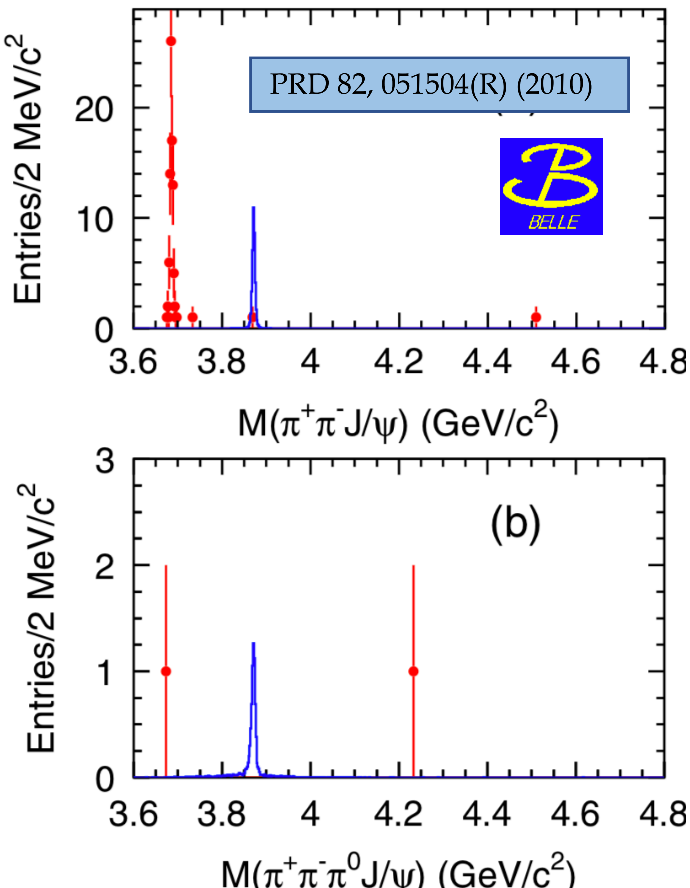
Production mechanism of *X(3872)*

- Bottomonium radiative and inclusive decays
- Λ_b^0 decays
- Exclusive photoproduction reactions

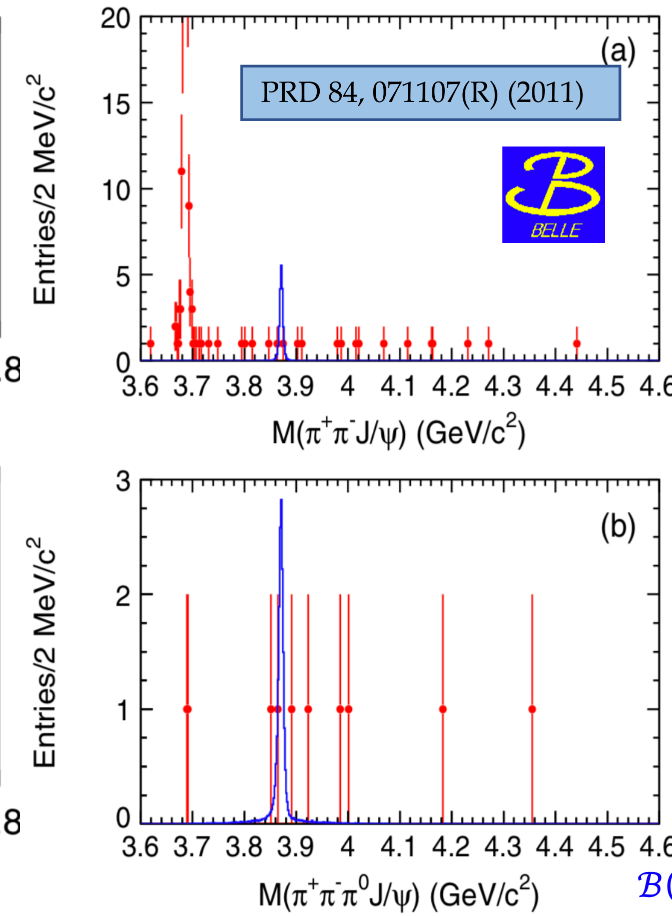
Bottomonium radiative and inclusive decays

Belle has the largest Υ(1S) and Υ(2S) data samples in the world.

Υ(1S) radiative decay

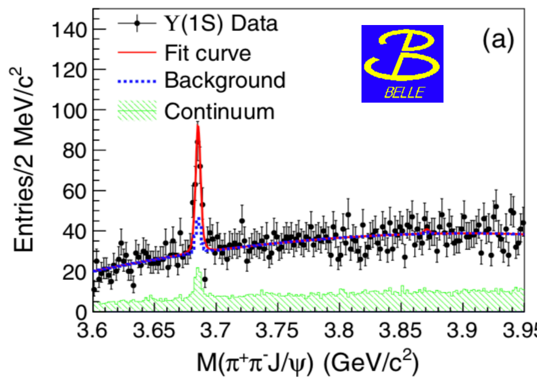


Υ(2S) radiative decay



Υ(1S)@Belle	Υ(2S)@Belle
5.74 fb^{-1}	24.91 fb^{-1}
102 million	158 million

Υ(1S) inclusive decay



PRD 93, 112013 (2016)

90% C.L.

$\mathcal{B}(\Upsilon(1S) \to X(3872) + \text{anything})$
$\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 9.5\times10^{-6}$

90% C.L.

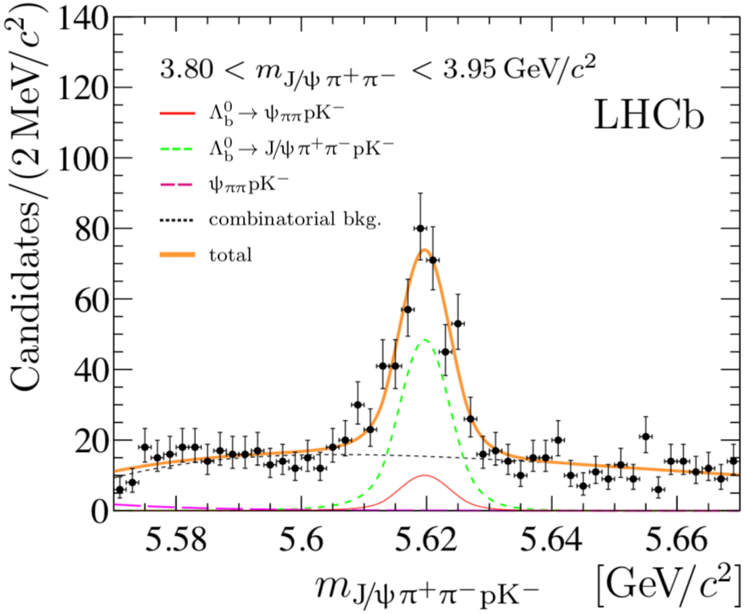
$$\mathcal{B}\big(\Upsilon(1S)/\Upsilon(2S) \to \gamma X(3872)\big)\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 1.6/0.8\times10^{-6}$$

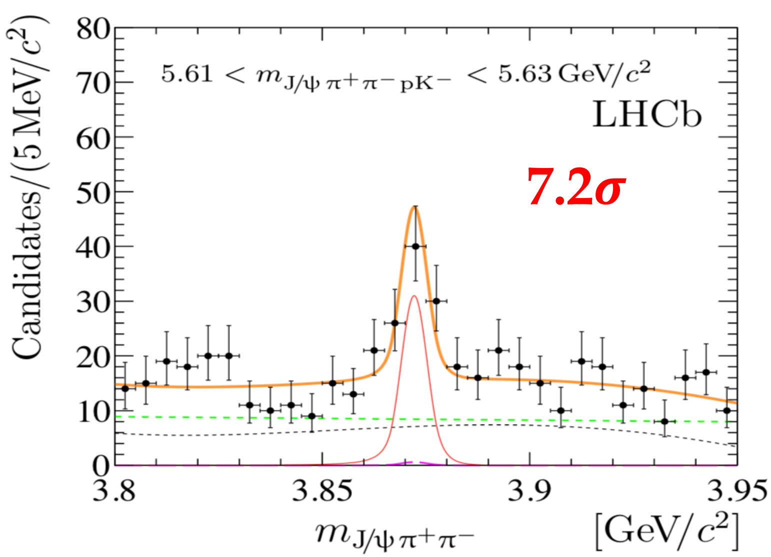
$$\mathcal{B}\big(\Upsilon(1S)/\Upsilon(2S) \to \gamma X(3872)\big)\mathcal{B}(X(3872) \to \pi^+\pi^-\pi^0 J/\psi) < 2.8/2.4\times10^{-6}$$

X(3872) in Λ_b^0 decays

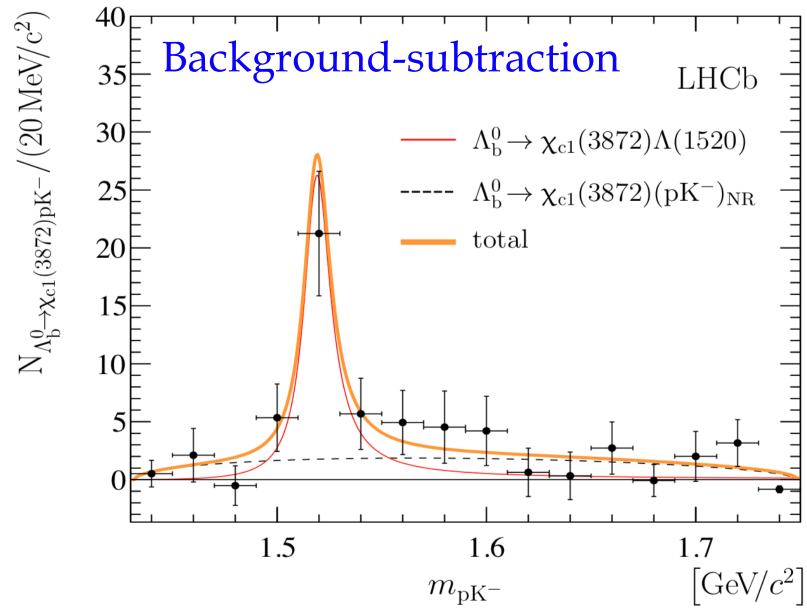
A 2D unbinned fit to $M(J/\psi\pi^+\pi^- pK^-)$ and $M(J/\psi\pi^+\pi^-)$.

JHEP 09, 028 (2019)





pp collision: 1.0, 2.0 and 1.9 fb^{-1} of integrated luminosity at the C.M. energies of 7, 8, and 13 TeV

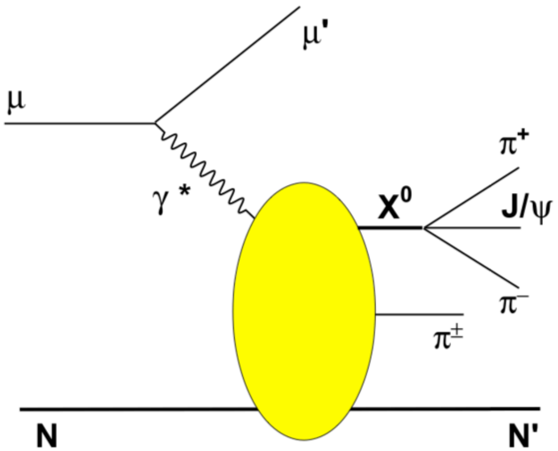


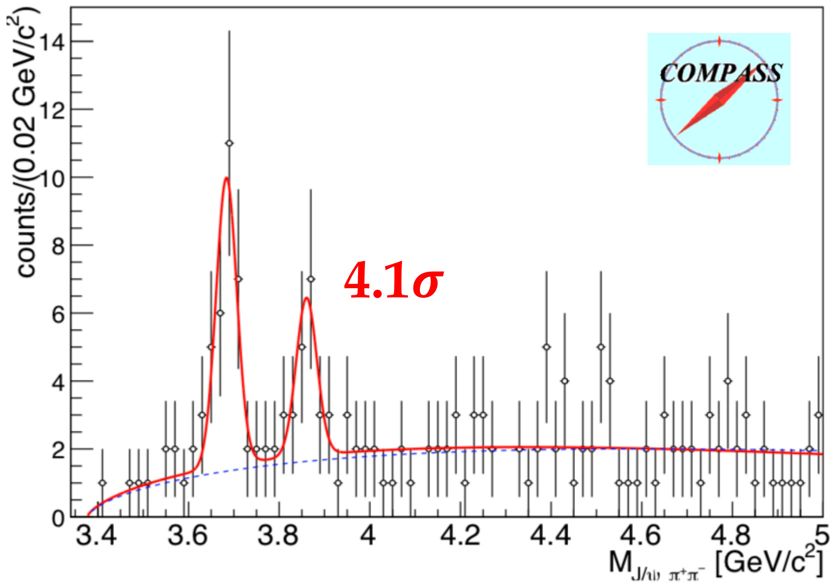
$$\frac{\mathcal{B}(\Lambda_b^0 \to X(3872)pK^-)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)pK^-)} \times \frac{\mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to J/\psi\,\pi^+\pi^-)}$$
$$= (5.4 \pm 1.1(\mathrm{stat}) \pm 0.2(\mathrm{syst}))\times 10^{-2}$$

Exclusive photoproduction reactions

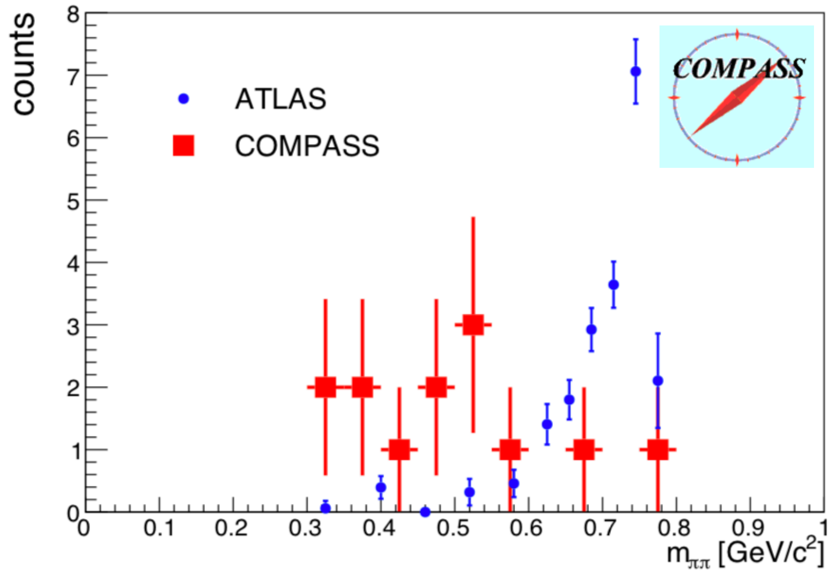
PLB 783, 334 (2018)

$\mu^+ N \rightarrow \mu^+ J/\psi \pi^+ \pi^- \pi^\pm N'$





$M(\widetilde{X}(3872))$	(3860.0±10.4) MeV/c²
$\Gamma(\widetilde{X}(3872))$	<51 MeV (90% C.L.)
$\sigma_{\gamma N \rightarrow \widetilde{X}(3872)\pi N'} \times \mathcal{B}_{\widetilde{X}(3872) \rightarrow J/\psi\pi\pi}$	71±28(stat)±39(syst) pb



The observed state is the C = -1 partner of X(3872) as predicted by a tetraquark model[PRD 71, 014028 (2005), PRD 89, 114010 (2014)].

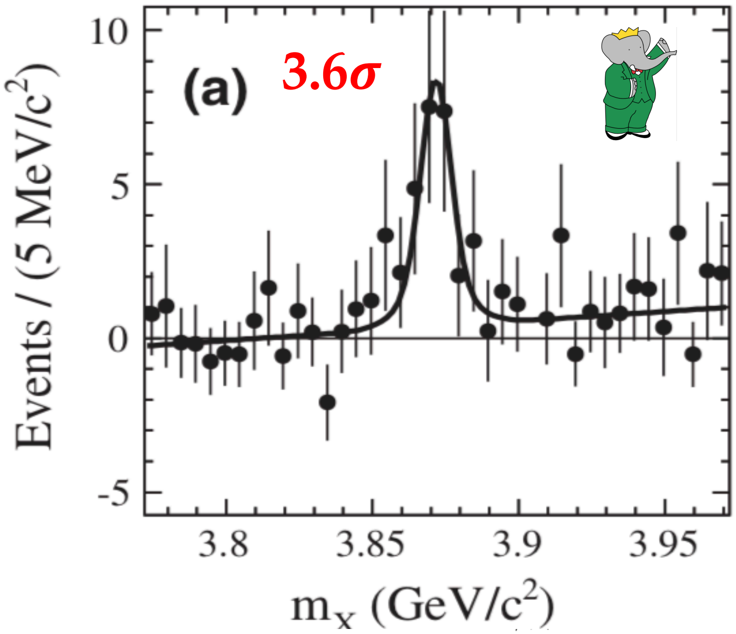
Decay patterns of *X(3872)*

- $X(3872) \rightarrow \gamma J/\psi$
- $X(3872) \rightarrow \gamma\psi(2S)$
- $X(3872) \rightarrow \pi^0\chi_{c1}$
- $X(3872) \rightarrow \omega J/\psi$
- $X(3872) \rightarrow D^0\overline{D}^{*0}$
- $X(3872) \rightarrow p\bar{p}$ and $X(3872) \rightarrow \phi\phi$

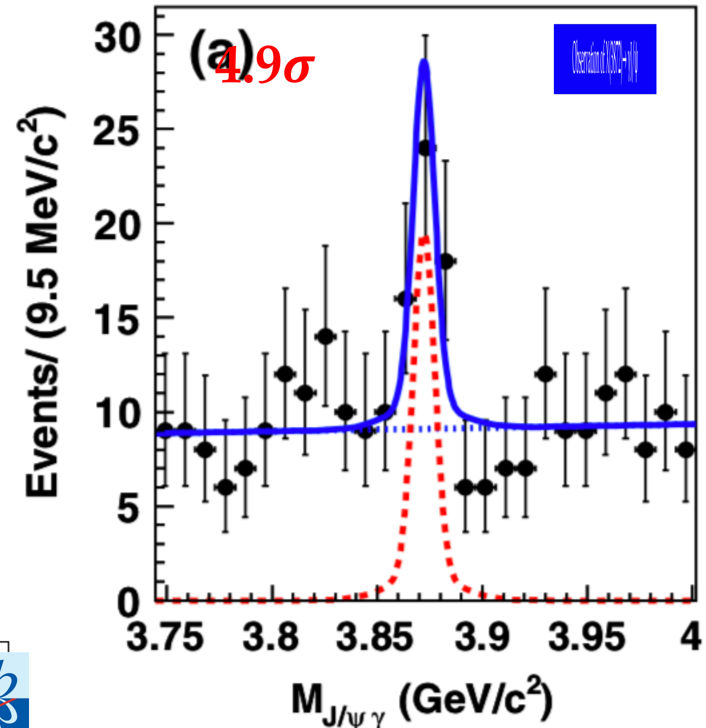
Observation of X(3872)→ γJ/ψ

$B^+ \to X(3872)(\to J/\psi\gamma)K^+$

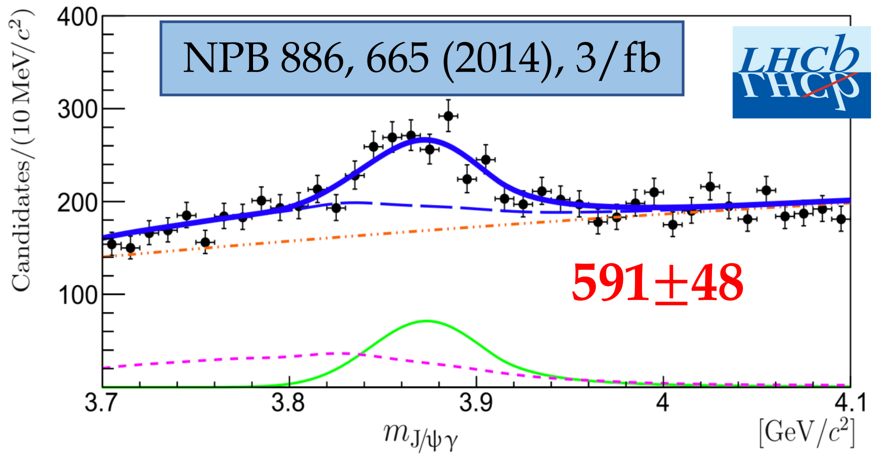
PRL 102, 132001 (2009), 424/fb



PRL 107, 091803 (2011), 711/fb



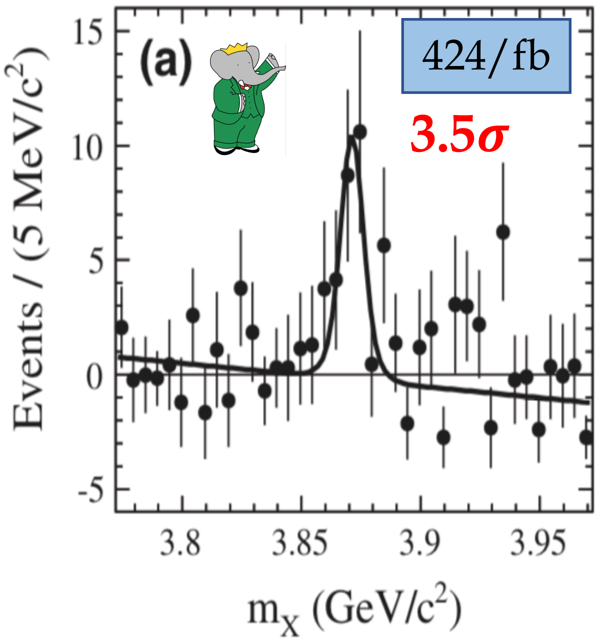
NPB 886, 665 (2014), 3/fb

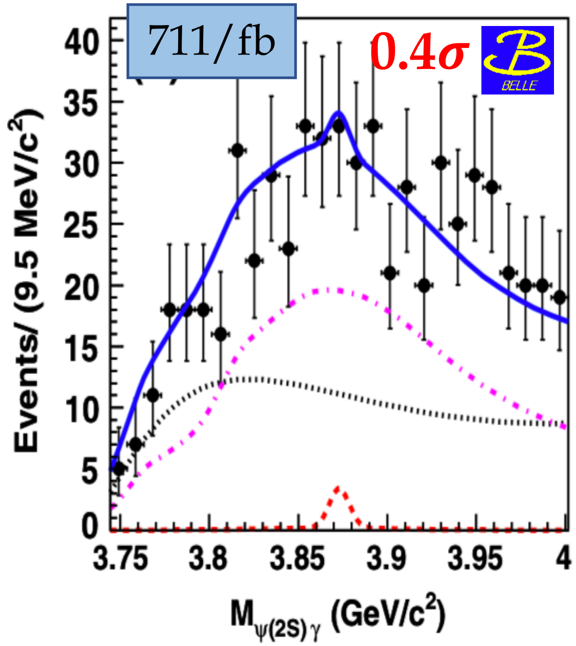


The decay X(3872)→ γJ/ψ has been well established.

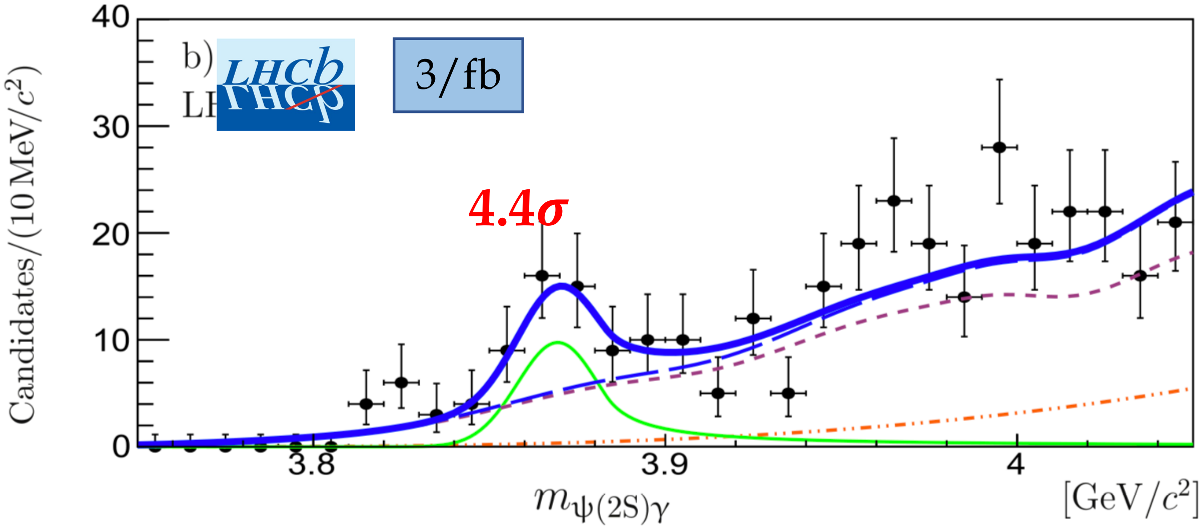
Debate on X(3872)→ γψ(2S)

$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$





$\mathcal{B}(X(3872) \to \gamma\psi(2S))/\mathcal{B}(X(3872) \to \gamma\psi(2S))$	
BABAR	3.4±1.4
Belle	<2.1
LHCb	2.46±0.46±0.29



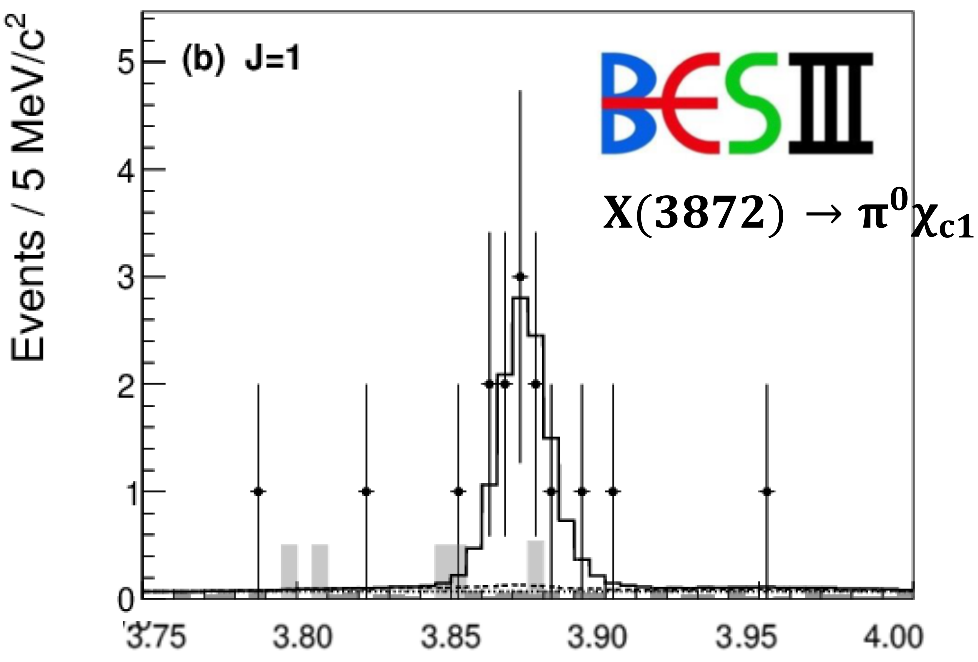
- A pure $D^0\overline{D}^{*0}$ molecule proposals can accommodate decays to γJ/ψ, and the branching fraction for γψ(2S) is expected to be very small.
- A relatively large branching fraction for X(3872)→ γψ(2S) is expected if the X(3872) is a pure charmonium or a mixture of a molecule and a charmonium.

$X(3872) \to \pi^0\chi_{c1}$

- If the X(3872) is a conventional $c\bar{c}$ state, pionic transitions to the χ_{cJ} should be very small ($R^X_{\chi_{c1}/\psi} = \mathcal{B}(X \to \pi^0\chi_{c1})/\mathcal{B}(X \to \pi^+\pi^-\chi_{c1}) \approx 4\%$) [PRD77, 014013 (2018)].
- If the X(3872) is a tetraquark or molecular state, the ratios of the pionic transitions are excepted to be sizeable [PRD77, 014013 (2018)], PRD92, 034019 (2015)].

$e^+e^- \to \gamma X(3872)$

PRL 122, 202001 (2019), 9/fb



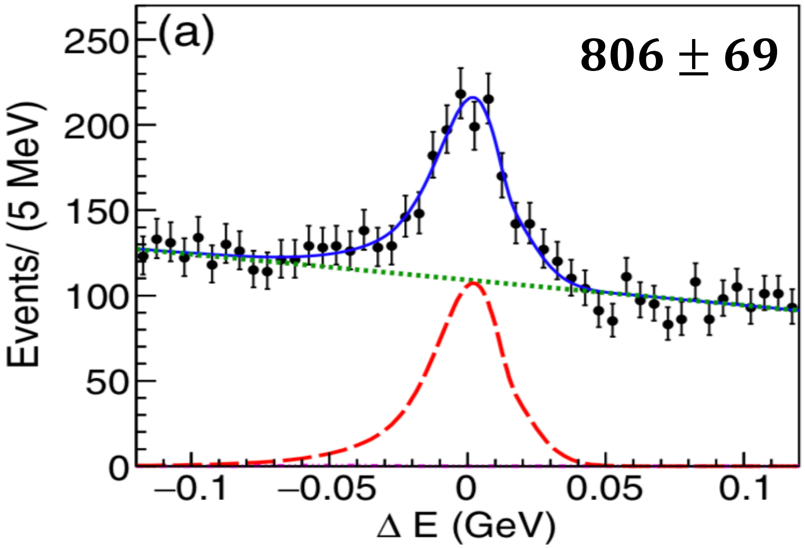
$$\frac{\mathcal{B}(X \to \pi^0\chi_{c1})}{\mathcal{B}(X \to \pi^+\pi^- J/\psi)} < 0.88^{+0.33}_{-0.27} \pm 0.10$$

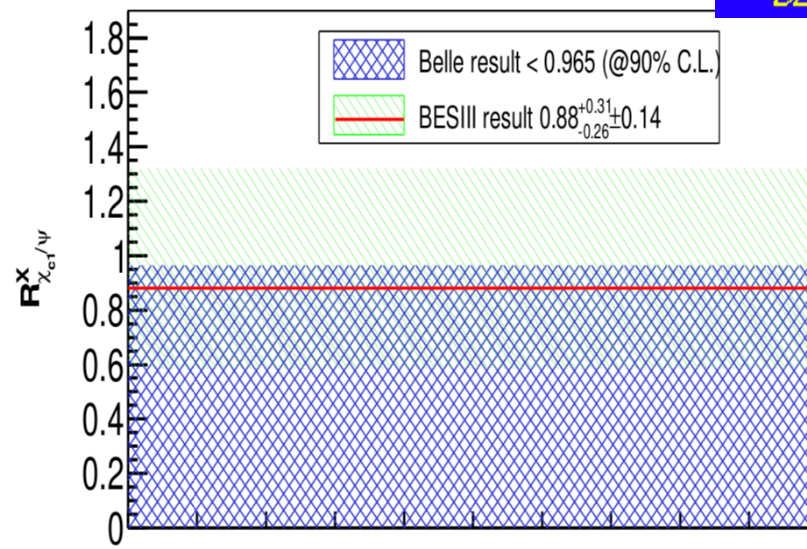
- Clear signal of X(3872) in Y(4620) region, $N_{X(3872)} = 16.9^{+5.2}_{-4.9}$
- First observation of X(3872)→ $\pi^0\chi_{c1}$ with significance > 5σ
- BESIII results disfavors a pure $c\bar{c}$ interpretation for X(3872)

$X(3872) \to \pi^0\chi_{c1}$

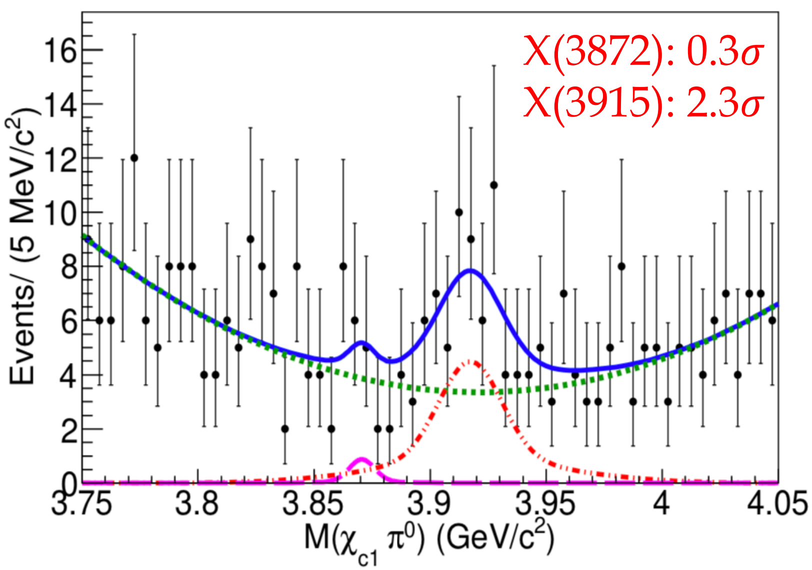
$B^+ \to X(3872)(\to \pi^0\chi_{c1})K^+$

PRD 99, 111101(R) (2019), 711/fb





The $R^X_{\chi_{c1}/\psi}$ from Belle does not contradict the BESIII result. But more data collected at Belle II are expected to study this process precisely.



Upper limits at 90% C.L.:

$\mathcal{B}(B^+ \to X(3872)K^+)\times\mathcal{B}(X(3872) \to \pi^0\chi_{c1}) < 8.1\times10^{-6}$

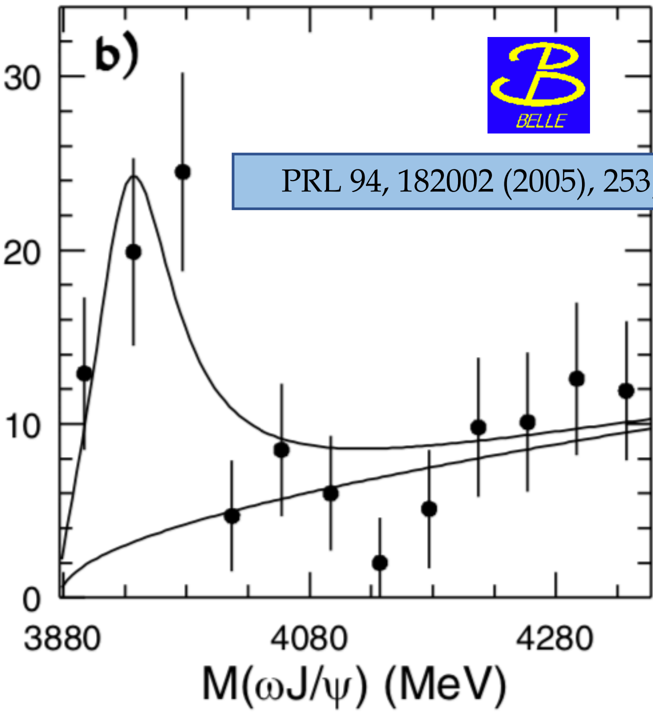
$\mathcal{B}(B^+ \to X(3915)K^+)\times\mathcal{B}(X(3915) \to \pi^0\chi_{c1}) < 3.8\times10^{-5}$

X(3872) → ωJ/ψ

Unlike $X(3872) \to J/\psi\pi^+\pi^-$, $X(3872) \to \omega J/\psi$ decay process conserves isospin symmetry.

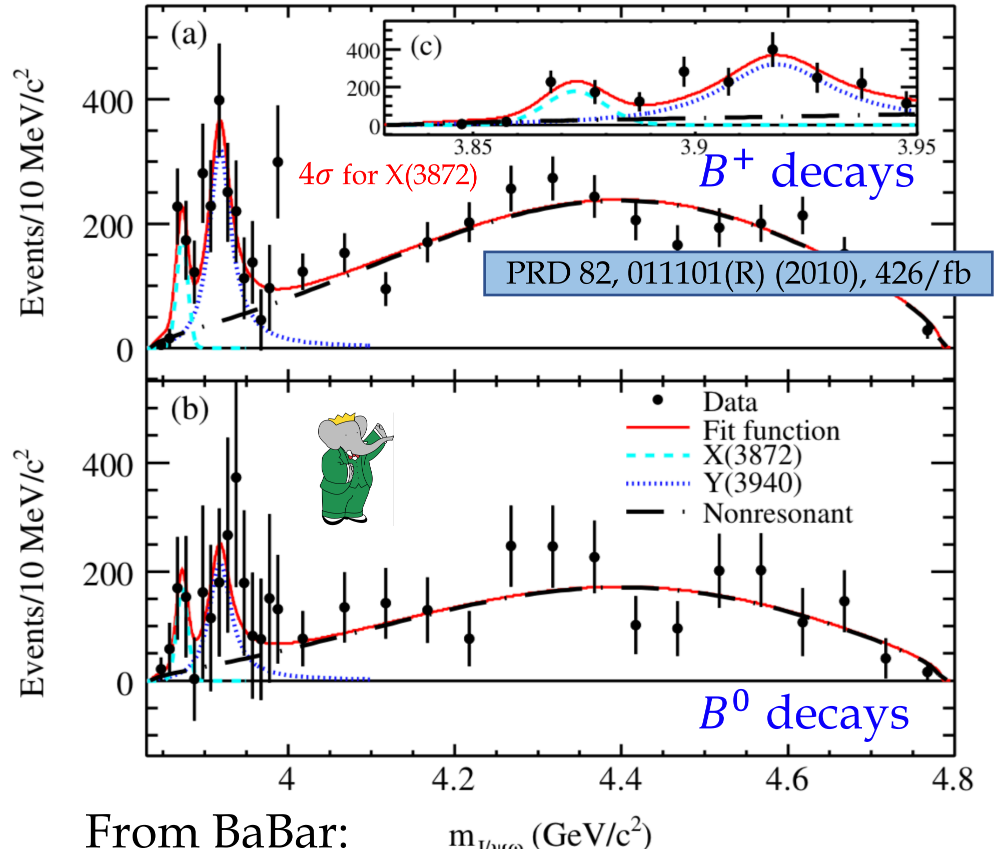
$B \to X(3872)(\to \omega J/\psi)K$

$0.760\ \text{GeV} < M(\pi^+\pi^-\pi^0) < 0.805\ \text{GeV}$



PRL 94, 182002 (2005), 253/fb

$0.5\ \text{GeV} < M(\pi^+\pi^-\pi^0) < 0.9\ \text{GeV}$: η and ω



BaBar: 2 resonance: X(3872) + X(3930)

Belle: only X(3930)

Finally, $X(3872) \to \omega J/\psi$ was established by BESIII with $>5\sigma$ significance.

From BaBar:

$$M(3872) = 3873.0^{+1.8}_{-1.6}(\text{stat}) \pm 1.3(\text{syst})$$

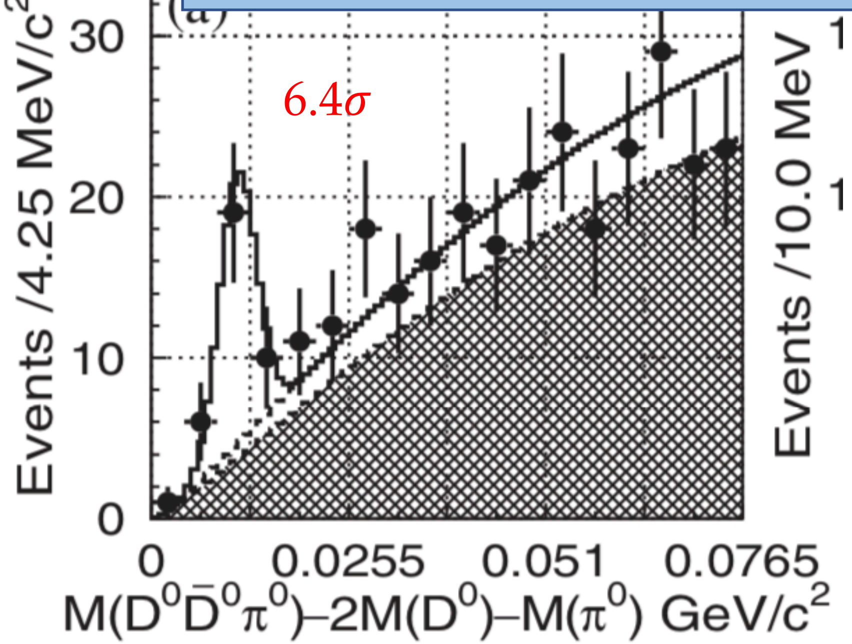
$$\frac{\mathcal{B}(X \to \omega J/\psi)}{\mathcal{B}(X \to J/\psi\pi^+\pi^-)} = 0.8 \pm 0.3$$

$X(3872) \to D^0\bar{D}^0\pi^0$ and $X(3872) \to D^0\bar{D}^{*0}$

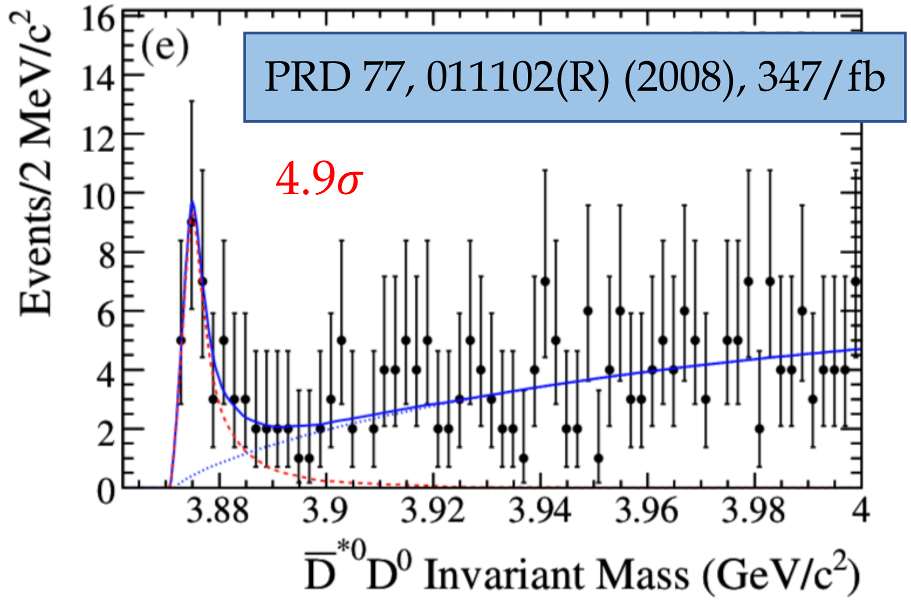
$B \to X(3872)(\to D^0\bar{D}^0\pi^0)K$

$B \to X(3872)(\to D^0\bar{D}^{*0})K$

PRL 97, 162002 (2006), 414/fb



PRD 77, 011102(R) (2008), 347/fb

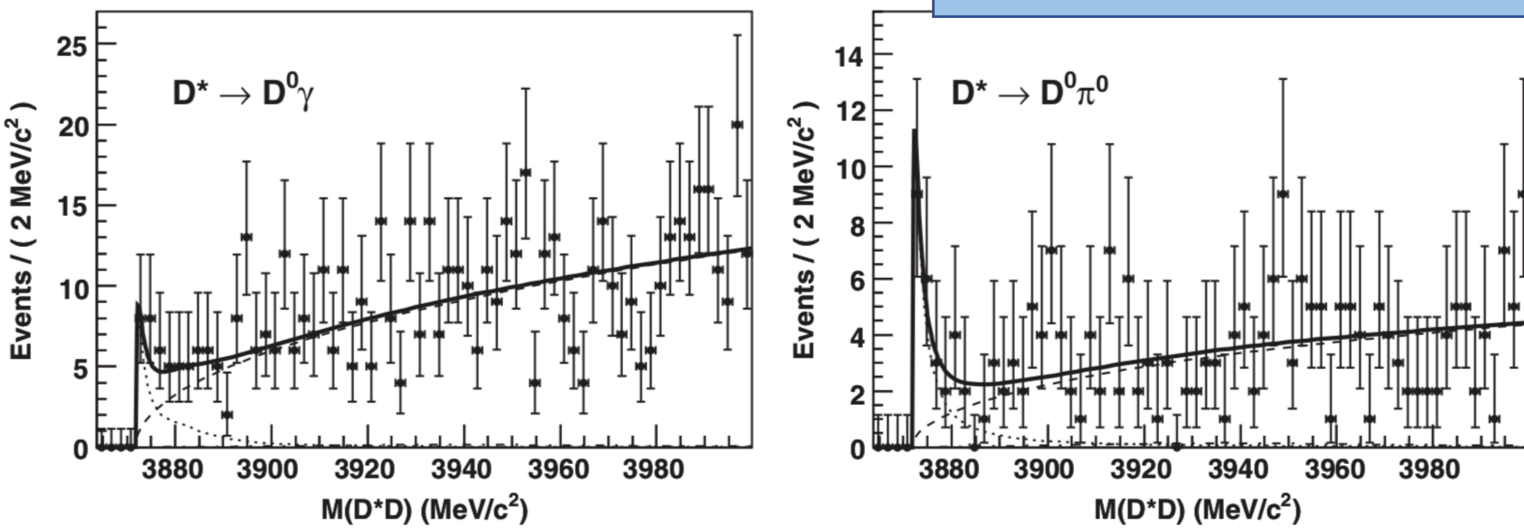


Experiment	Belle	BaBar
X(3872) Mass (MeV/c^2)	$3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8$	$3875.1^{+0.7}_{-0.5} \pm 0.5$
PDG	3871.69±0.17	

>3σ higher than the world-average value of the X(3872) mass

$X(3872) \to D^0\bar{D}^{*0}$

PRD 81, 031103(R) (2010), 605/fb



$$\frac{\mathcal{B}(X \to D^0\bar{D}^{*0})}{\mathcal{B}(X \to J/\psi\pi^+\pi^-)} \approx 10$$

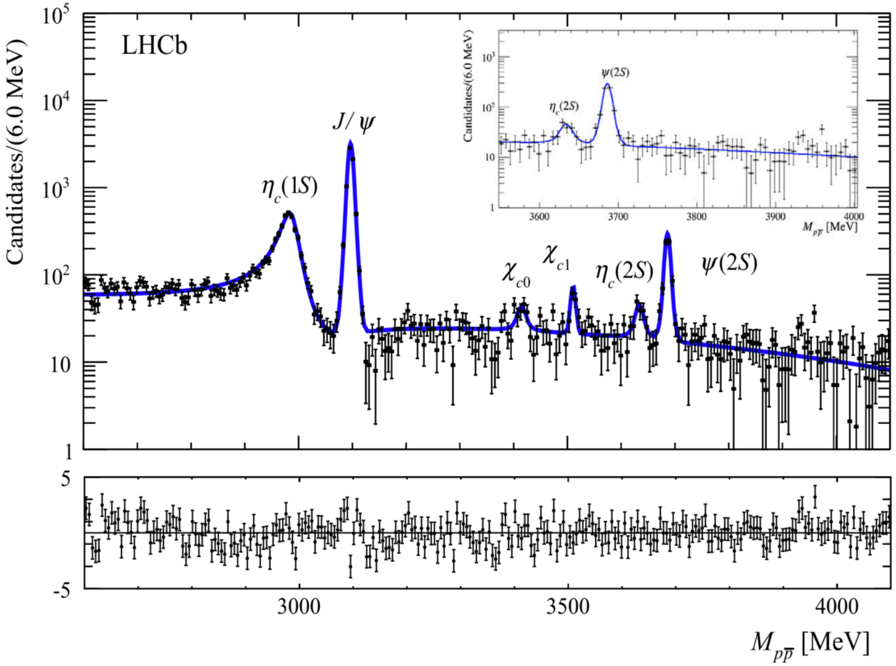
Sample	M_X (MeV/c^2)	Γ (MeV/c^2)	Yield	$\epsilon \times \mathcal{B}$	$\mathcal{B}$ (10^{-4})	σ
$D^{*0} \to D^0\gamma$ (XK^+ and XK^0)	3873.4 ± 1.0	$4.2^{+3.7}_{-1.8}$	$26.2^{+9.0}_{-7.6}$	4.56×10^{-4}	$0.87 \pm 0.28 \pm 0.10$	4.4σ
$D^{*0} \to D^0\pi^0$ (XK^+ and XK^0)	3872.8 ± 0.7	$3.1^{+4.1}_{-1.5}$	$22.0^{+10.7}_{-6.4}$	4.93×10^{-4}	$0.68 \pm 0.26 \pm 0.09$	6.8σ
All (free $D^0\gamma/D^0\pi^0$ ratio)	$3872.9^{+0.6}_{-0.4}$	$3.9^{+2.7}_{-1.4}$	$50.6^{+14.2}_{-11.0}$	9.49×10^{-4}	$0.81 \pm 0.20 \pm 0.10$	7.9σ
All (fixed $D^0\gamma/D^0\pi^0$ ratio)	$3872.9^{+0.6}_{-0.4}$	$3.9^{+2.8}_{-1.4}$	$50.1^{+14.8}_{-11.1}$	9.49×10^{-4}	$0.80 \pm 0.20 \pm 0.10$	7.9σ
$B^+ \to XK^+$	3872.9 (fixed)	3.9 (fixed)	$41.3^{+9.1}_{-8.1}$	8.17×10^{-4}	$0.77 \pm 0.16 \pm 0.10$	7.6σ
$B^0 \to XK^0$	3872.9 (fixed)	3.9 (fixed)	$8.4^{+4.5}_{-3.6}$	1.32×10^{-4}	$0.97 \pm 0.46 \pm 0.13$	2.8σ

Mass	Width	Mass - $D^0\bar{D}^{*0}$ threshold
$(3872.9^{+0.6+0.4}_{-0.4-0.5})$ MeV/c²	$(3.9^{+2.8+0.2}_{-1.4-1.1})$ MeV/c²	$(1.1^{+0.6+0.1}_{-0.4-0.3})$ MeV/c²

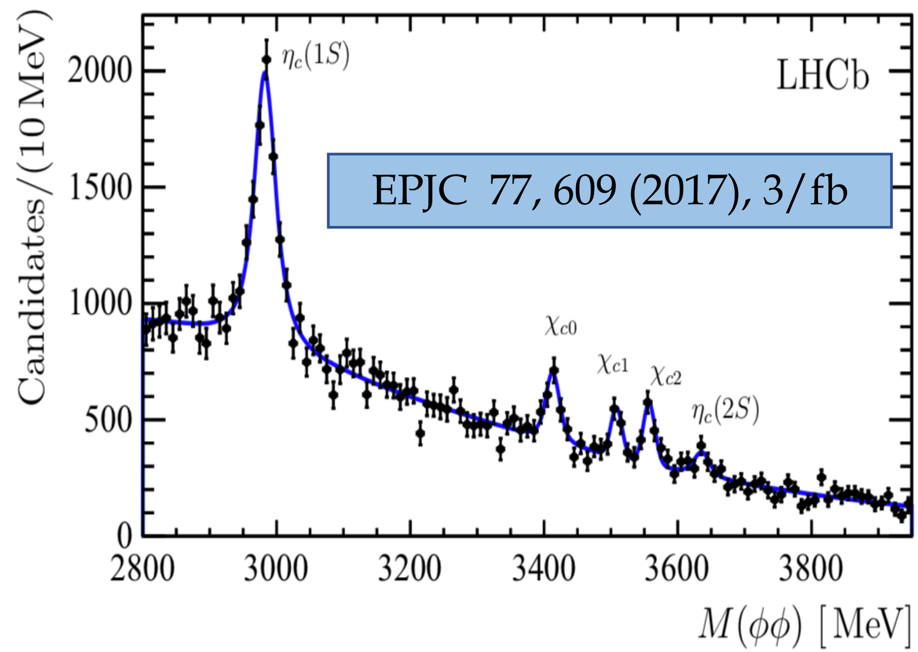
$X(3872) \to p\bar{p}$ and $X(3872) \to \phi\phi$

PLB 769, 305 (2017), 3/fb

$B^+ \to X(3872)(\to p\bar{p})K^+$



b − hadron (B^+, B^0, B_s^0, B_c^+ and b-baryon) inclusive decays



EPJC 77, 609 (2017), 3/fb

90%(95%) upper limits:

$$\frac{\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(B^+ \to p\bar{p})} < 0.20(0.25) \times 10^{-2}$$

$$\mathcal{B}(b \to X(3872)X) \times \mathcal{B}(X(3872) \to \phi\phi) < 3.9(4.5) \times 10^{-7}$$

$$\frac{\mathcal{B}(b \to X(3872)X) \times \mathcal{B}(X(3872) \to \phi\phi)}{\mathcal{B}(b \to \chi_{c1}X) \times \mathcal{B}(\chi_{c1} \to \phi\phi)} < 0.34(0.39)$$

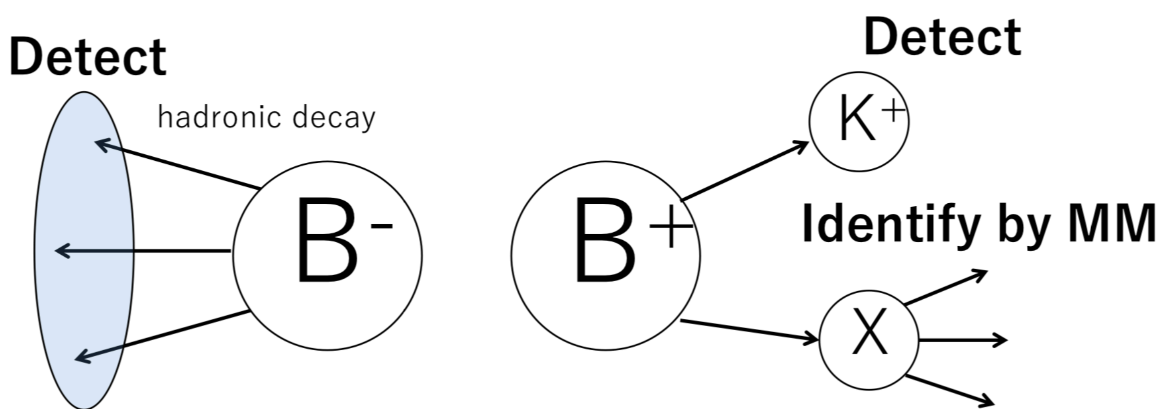
Absolute branching fraction of X(3872)

Motivation:

- The determination of the absolute branching fraction $\mathcal{B}(X(3872 \rightarrow J/\psi\pi^+\pi^-)$ brings useful information regarding the complex nature of the X(3872) particle.
- The original tetraquark model [Phys. Rev. D 71, 014028 (2005)] predicted this branching fraction to be around 50%.
- Various molecular models [PRD 72, 054022 (2005), PRD 69, 054008 (2004)] predict this branching fraction to be $\lesssim$ 10%.

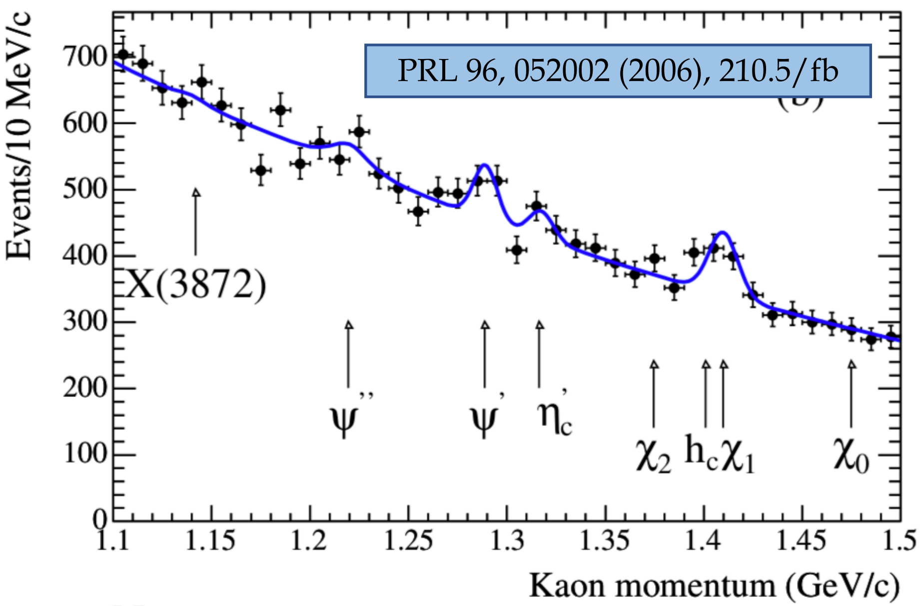
Analysis method:

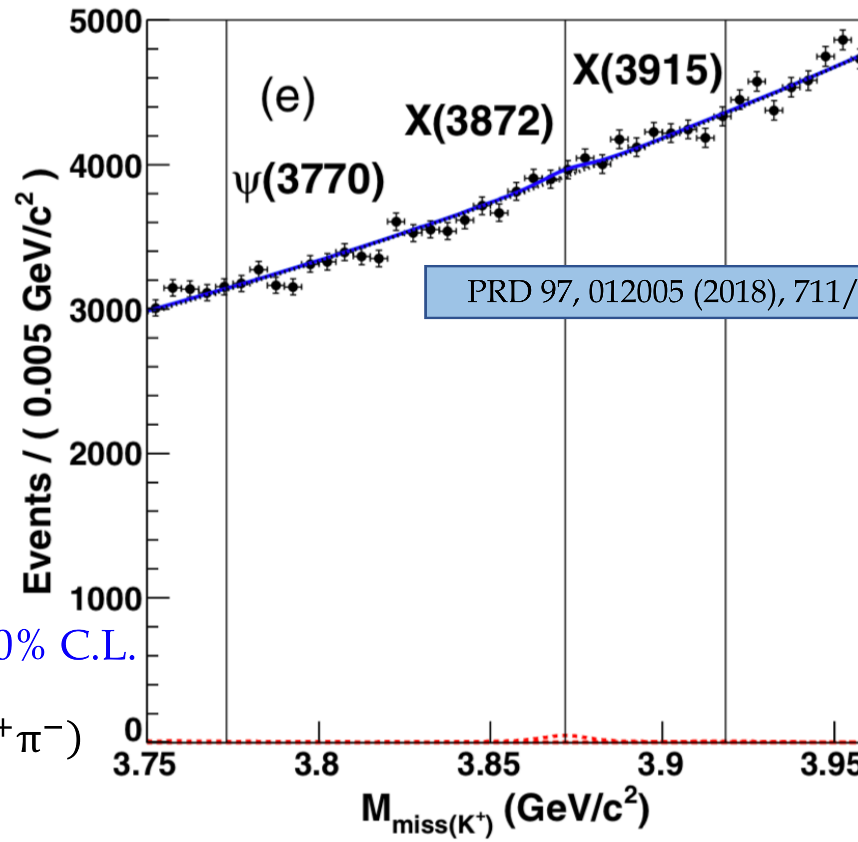
- Fully reconstruct one of the two charged B mesons (**B_{tag}**)
- Identify the signal by calculating K momentum in the **B_{sig} system or** missing mass recoiling against



- B-tag: BaBar: $D^{(*)}H$; Belle: $D^{(*)}/D_s^{\pm}/J/\psi + H$
- BaBar: NN1 + NN2 to suppress continuum events and reject secondary kaons from D meson decays
- Belle: NN to suppress continuum events

$$m_X = \sqrt{m_B^2 + m_K^2 - 2E_K m_B} \qquad M_{\mathrm{miss(h)}} = \sqrt{(p^*_{\mathrm{e^+e^-}} - p^*_{\mathrm{tag}} - p^*_{\mathrm{h}})^2}/c$$





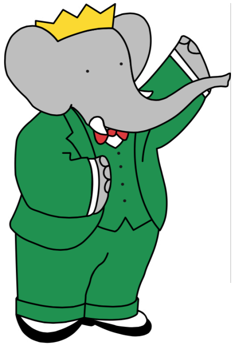
$$\mathcal{B} = \frac{N_{\mathrm{sig}}}{2N_{B^\pm}\epsilon}$$

$\mathcal{B}(B^- \to X(3872)K^-) < 3.2\times10^{-4}$ at 90% C.L.

Assuming $\mathcal{B}(B^- \to X(3872)K^-)\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (8.6\pm0.8)\times10^{-6}$

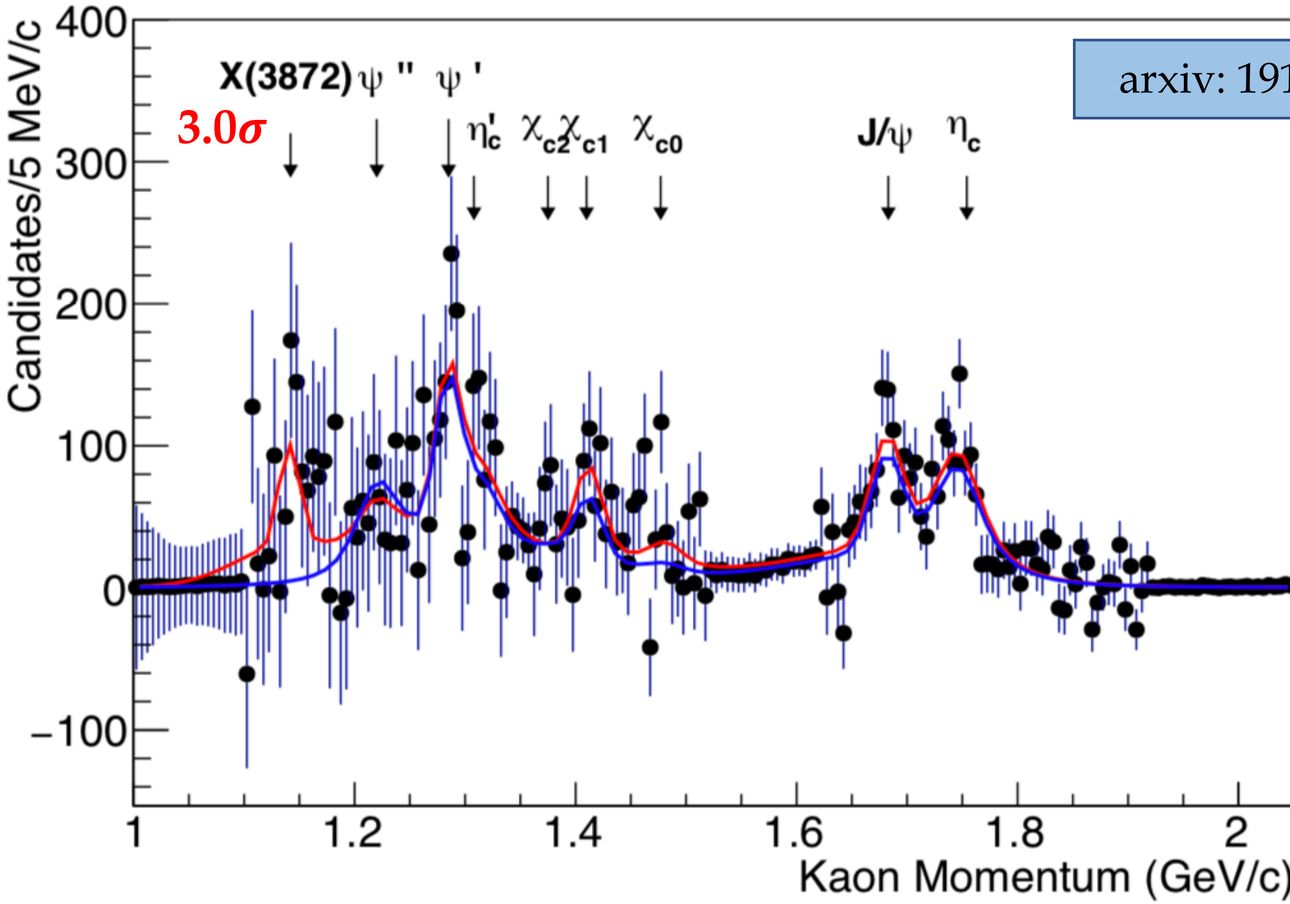
BaBar	$\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) > 2.7\%$
Belle	$\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) > 3.2\%$

$\mathcal{B}(B^- \to X(3872)K^-) < 2.7\times10^{-4}$ at 90% C.L.



If more than one B candidate is found in a given event, all candidates are retained.

- increase the efficiency
- decouple the signal and tag sides in B^+B^- events



arxiv: 1911.11740, 424/fb

$$\mathcal{B}(B^- \to X(3872)K^-) = (0.96 \pm 0.12(\text{stat}) \pm 0.06(\text{syst}) \pm 0.03(\text{ref}))\times 10^{-4}$$

$$\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (4.1 \pm 1.3)\%$$

This measurement therefore suggests that the X(3872) has a significant molecular component.

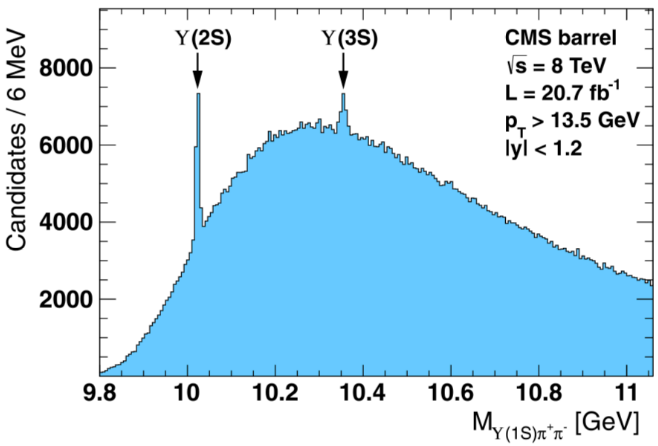
Search for X_b state

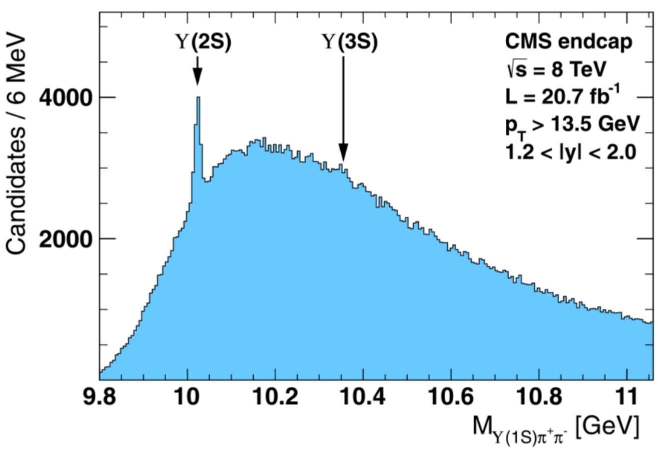
- $X_b \to \pi^+\pi^-\Upsilon(1S)$
- $X_b \to \omega\Upsilon(1S)$

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

- X_b: A similar state with $J^{PC} = 1^{++}$ in the bottomonium system
- The existence of the X_b is predicted in both the tetraquark model [PLB 684, 28 (2010)] and those involving a molecular interpretation [PRD 88, 054007 (2013), JHEP 07, 153 (2013)].

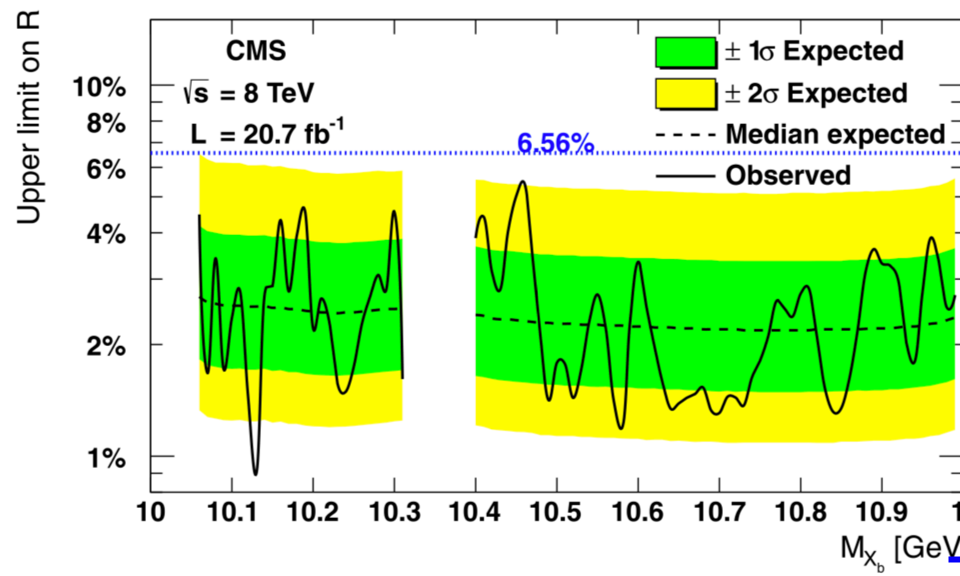
PLB 727, 57 (2013), 20.7/fb





$$R = \frac{\sigma(pp \rightarrow X_b \rightarrow \Upsilon(1S)\pi^+\pi^-)}{\sigma(pp \rightarrow \Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-)}$$

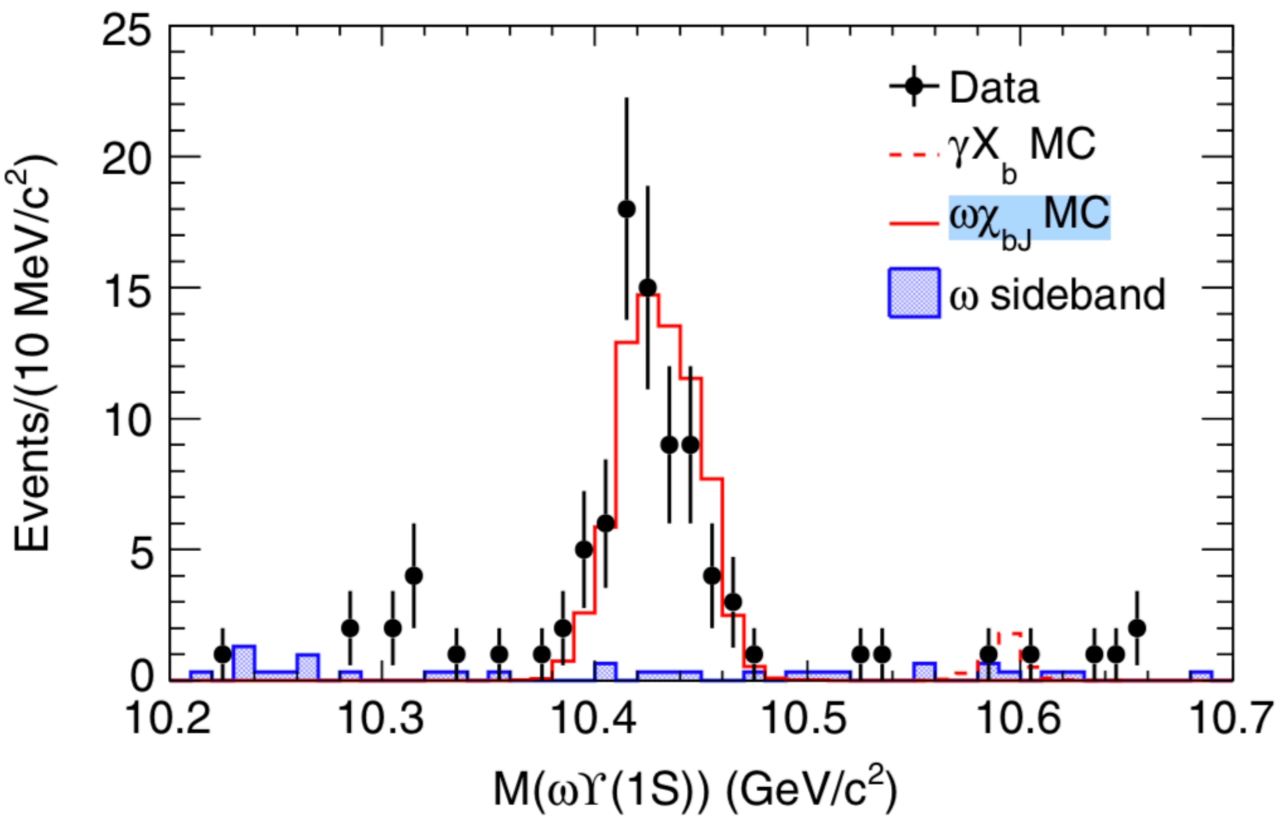
In the range 0.9-5.4% at 95% C.L., depending on the assumed X_b mass.



$X_b \to \omega\Upsilon(1S)$

Unlike the X(3872), whose decays exhibit large isospin violation, the X_b decay preferably into $\pi^+\pi^-\pi^0\Upsilon(1S)$ rather than $\pi^+\pi^-\Upsilon(1S)$ if it exists [PRD 88, 054007 (2013) , JHEP 07, 153 (2013), EPJC 74, 3063 (2014)].

$e^+e^- \to \gamma\pi^+\pi^-\pi^0\Upsilon(1S)$ at $\sqrt{s}$=10.867 GeV



The red solid histogram: Normalized contribution of $e^+e^- \to \omega\chi_{bJ}$ (J=0,1,2)

The red dashed histogram: The yield fixed at upper limit at 90% C.L.

$\mathcal{B}(\Upsilon(10860) \to \gamma X_b)\times\mathcal{B}(X_b \to \omega\Upsilon(1S))$ vary smoothly from 2.6×10^{-5} to 3.8×10^{-5} between 10.55 and 10.65 GeV/c².

Summary

Now, we know

- M(X(3872)) is very close to DD* threshold; Γ(3872) is very narrow(<1.2 @90% C.L.); $J^{PC} = 1^{++}$
- X(3872) has been observed in B decays, $p\bar{p}$ collisions, Λ_b^0 decays, etc.
- X(3872) decays to γJ/ψ, $\pi^0\chi_{c1}$, ωJ/ψ, and $D^0\bar{D}^{*0}$.
- BR: open charm ~50%, charmonium ~O(%) [$\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (4.1 \pm 1.3)\%$]
- $\boldsymbol{X_b}$ has not been observed yet.

Nature:

- Loosely DD* bound state?
- Mixture of DD* and a $c\bar{c}$ "core"?
- Tight Tetraquark?
- Many other possibilities …

Acknowledgement:
Some materials are from Ref.[C.P.Shen, C. Z. Yuan etc, arXiv:1907.07583] and a talk from C. Z. Yuan in the last Belle II China Group Winter School in Hefei. Thanks much!

Thank you for your attention!

谢谢大家！