Heavy exotic hadrons at KEKB

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KEK hadron physics workshop

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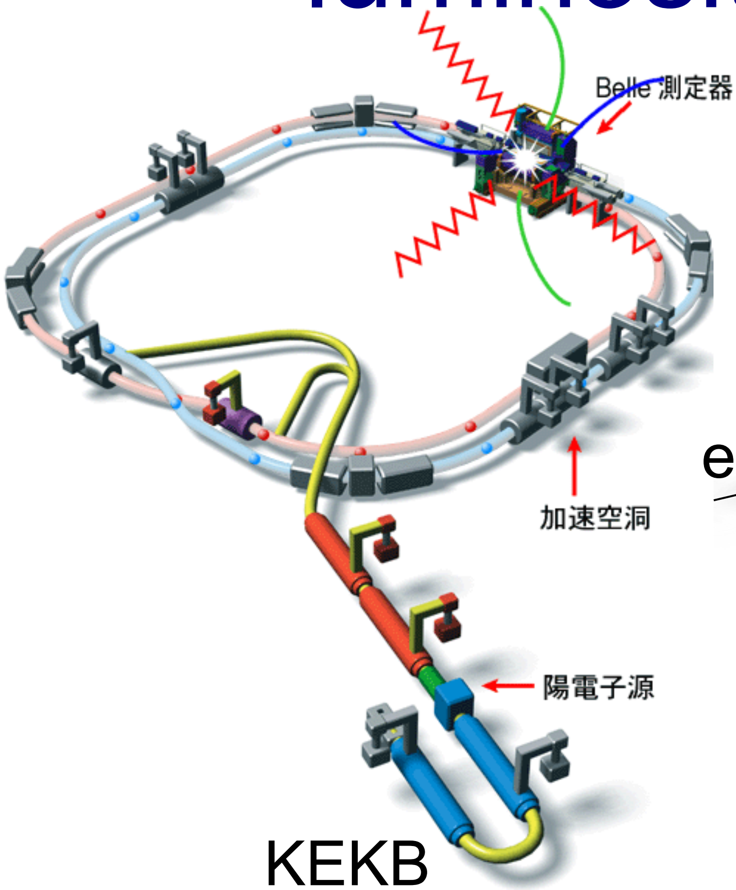
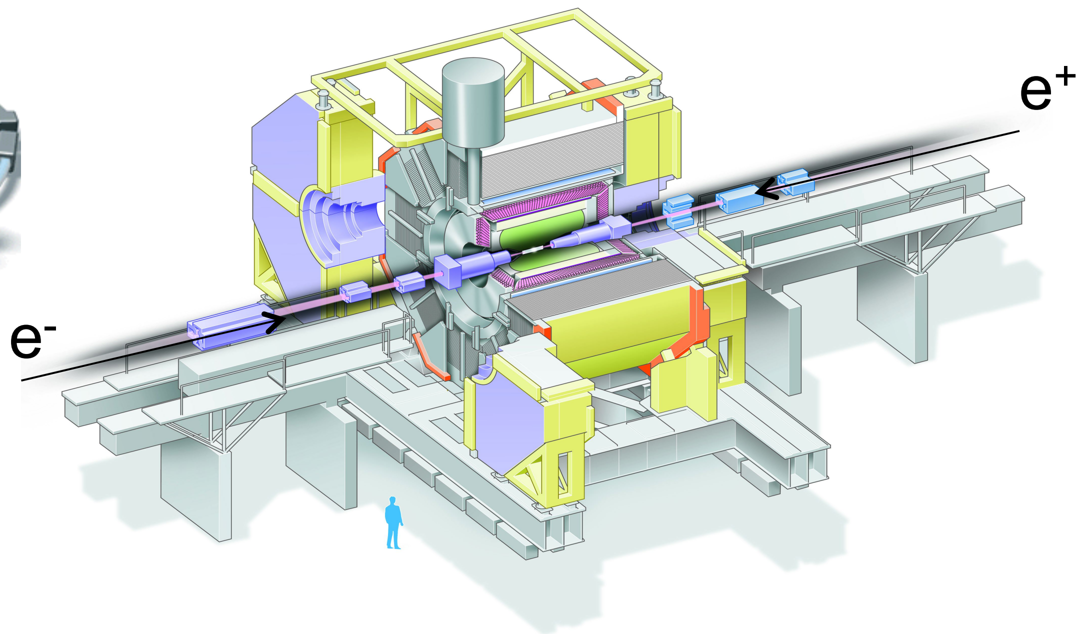
Outline

- KEKB/Belle
- Production mechanisms of hadrons.
- X(3872); how we get its interpretation.
- Z_b^+s at Υ(10860) and Υ(11020)
- $Z_c(3900)^+$ at Y(4260) and similar states
- $Z_c(4430)^+$ and similar states found in B decays
- Challenges at SuperKEKB/Belle II
- Summary

KEKB/Belle : world highest luminosity e^+e^- collider



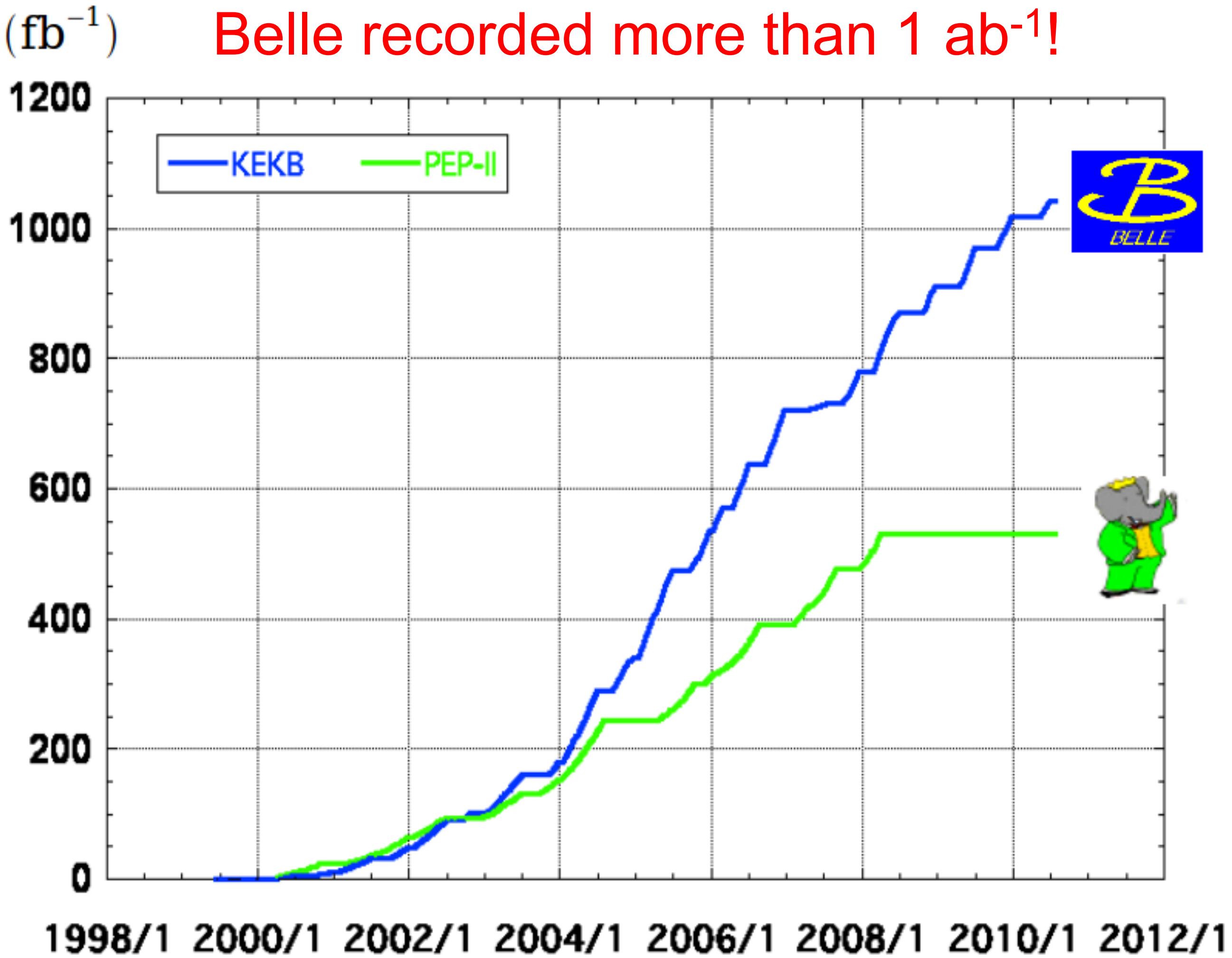
KEKB
8GeV×3.5GeV@ϒ(4S)



Belle
High resolution 4π spectrometer with particle identification capability

Integrated luminosity of B factories

Belle recorded more than 1 ab^{-1}!



> 1 ab^{-1}

On resonance:

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

$\Upsilon(4S)$: 711 fb^{-1} 772M $B\overline{B}$

$\Upsilon(3S)$: 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}

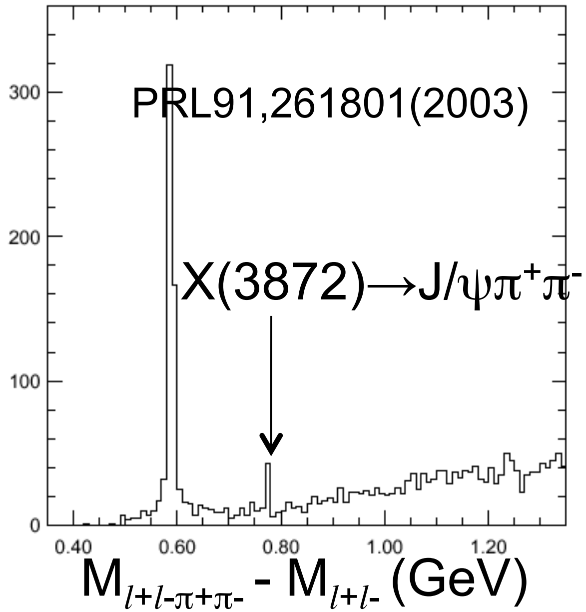
$\Upsilon(3S)$: 30 fb^{-1}

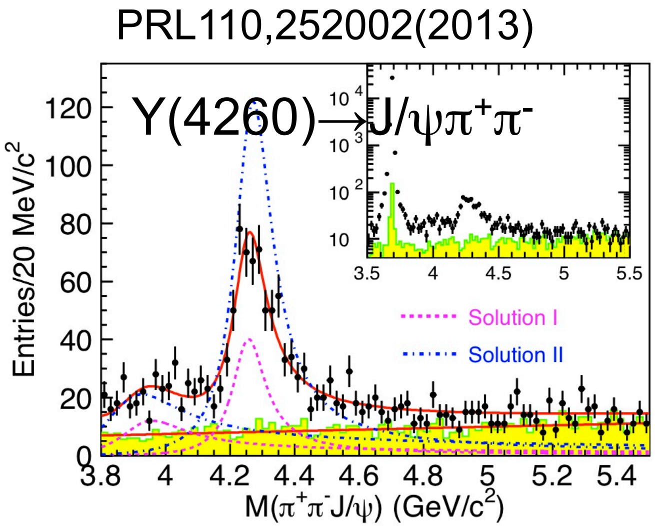
$\Upsilon(2S)$: 14 fb^{-1}

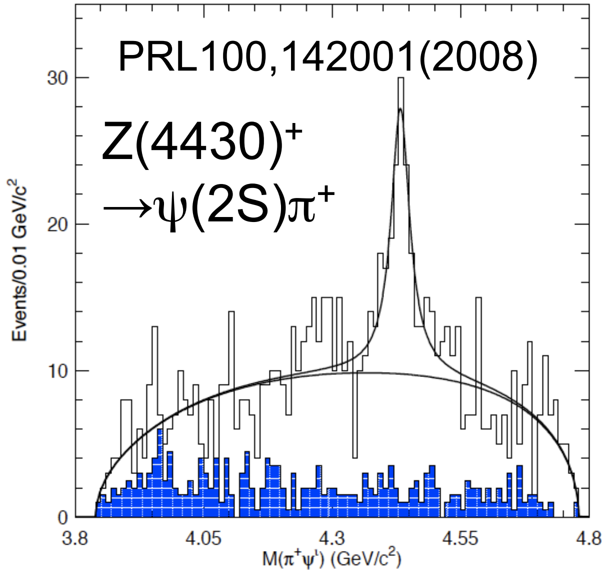
Off resonance:

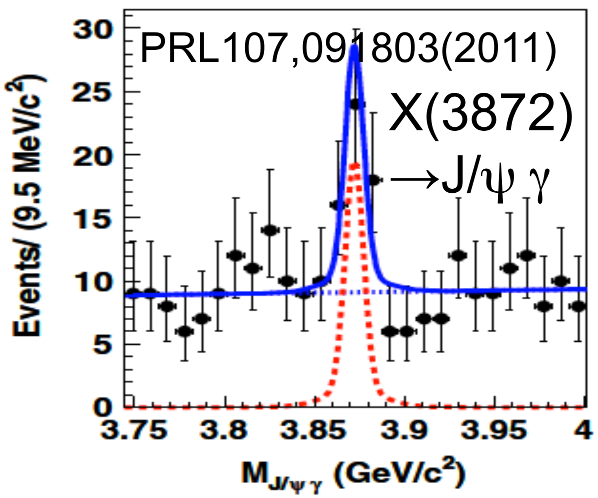
~ 54 fb^{-1}

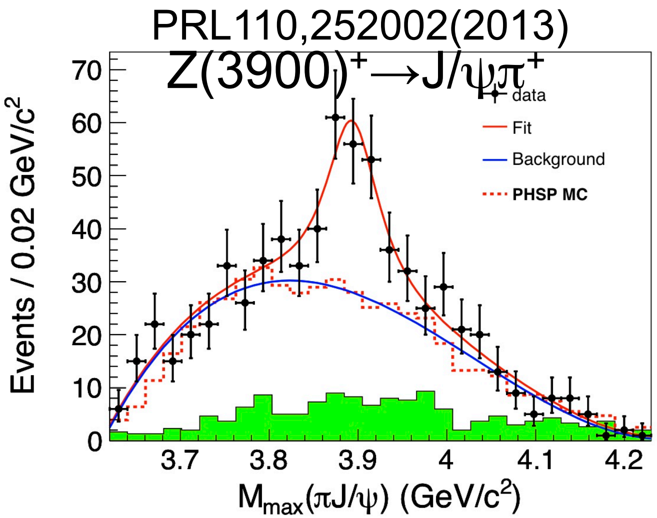
“XYZ” sensations at Belle

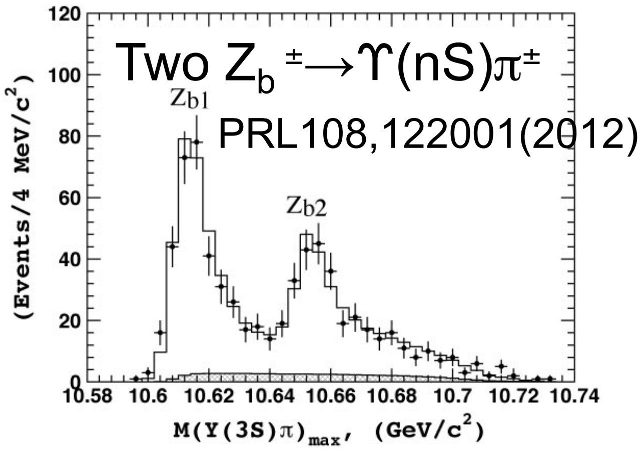












What made it possible?

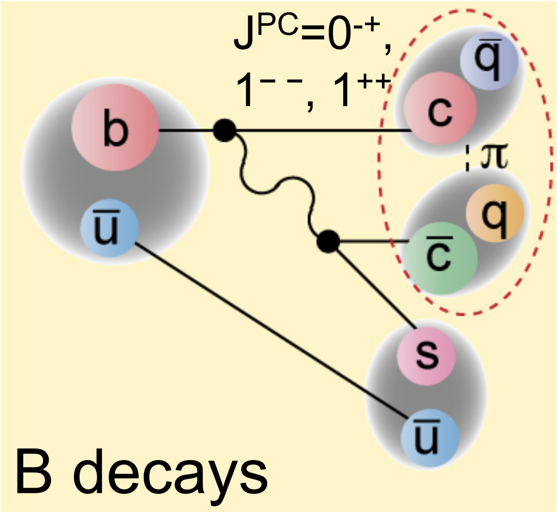
First of all, the world highest luminosity by KEKB.

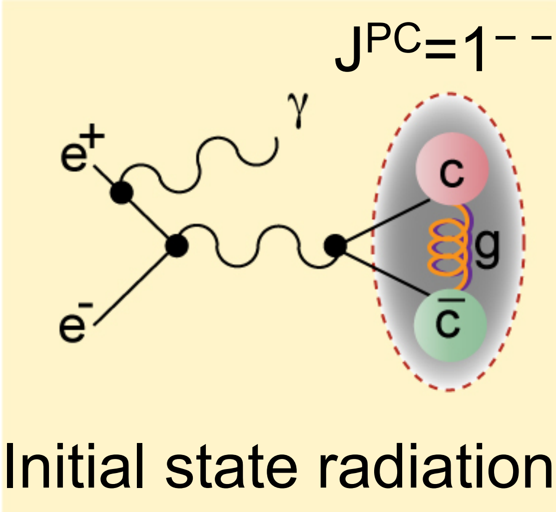
High resolution 4π spectrometer = Belle.

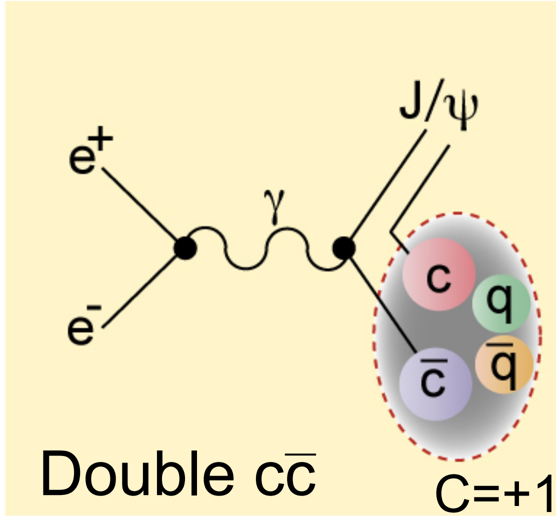
Those two brought us possibilities to access;

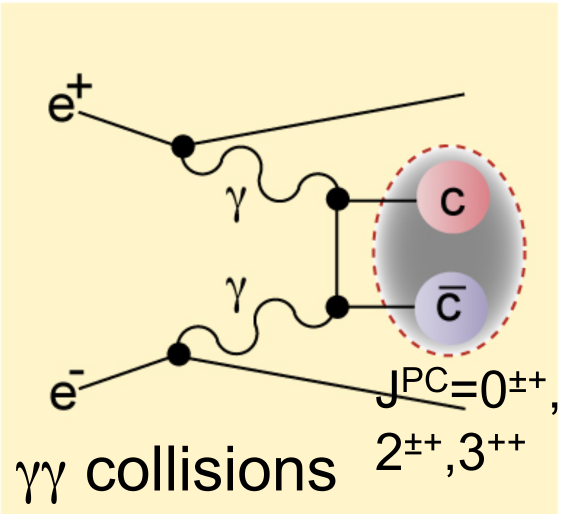
- Various production mechanisms
  - Each physics process has preferable states.
  - Interplay among several approaches is effective.
- Various decay modes
  - Each hypothesis; other decay modes, partner states.
  - Partner states have specific decay modes.

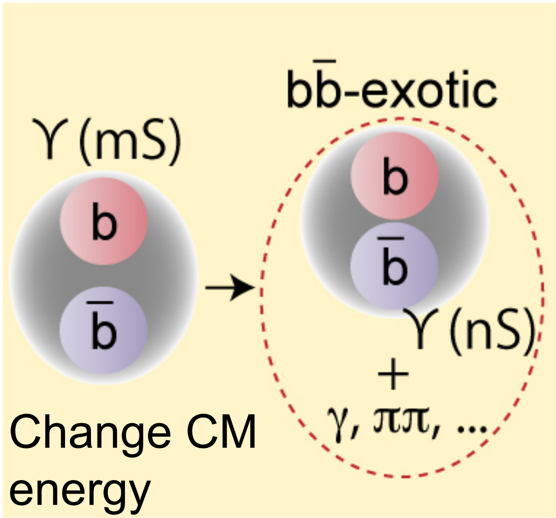
Variety of recorded reactions









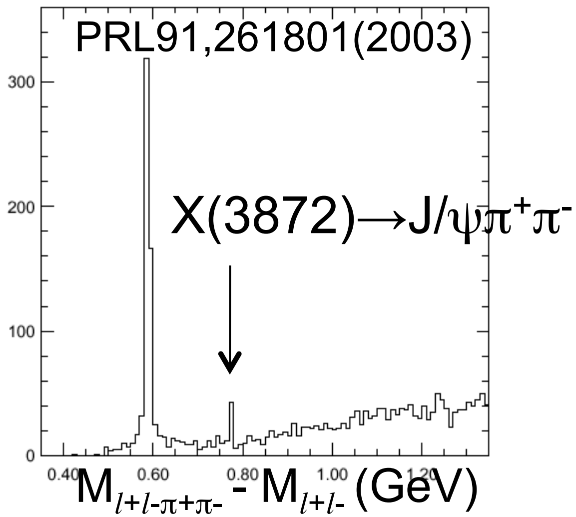


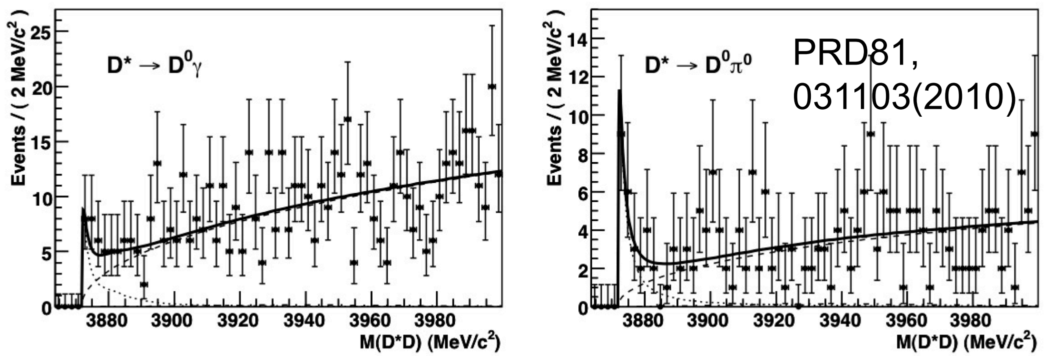
Allowed/favored quantum numbers are different depending on production processes.

Everything started from this …

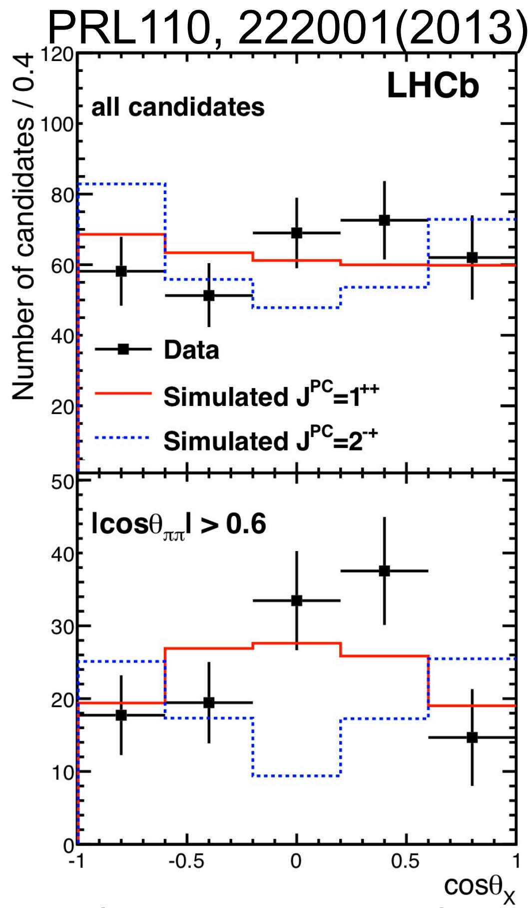
X(3872)

X(3872); various decay modes





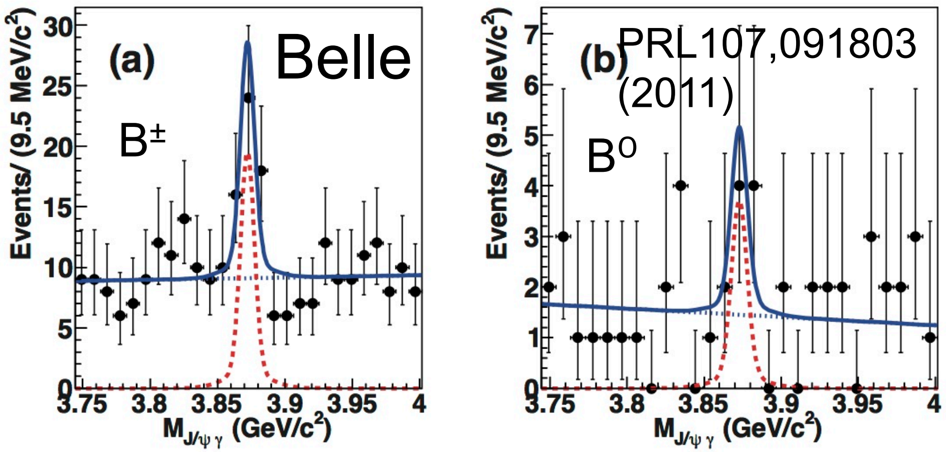
Br(X(3872)→$D^0\overline{D}^{*0}$) is about
Br(X(3872)→J/ψ $\pi^+\pi^-$)×10.

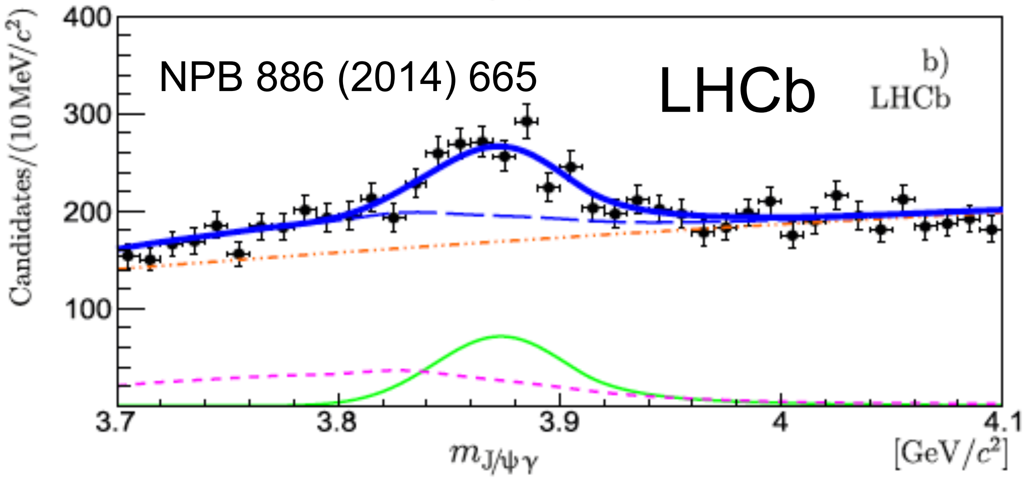


$J^{PC}=1^{++}$ (Belle, BaBar, CDF, LHCb) from J/ψ $\pi^+\pi^-$ angular distribution.

More decay modes

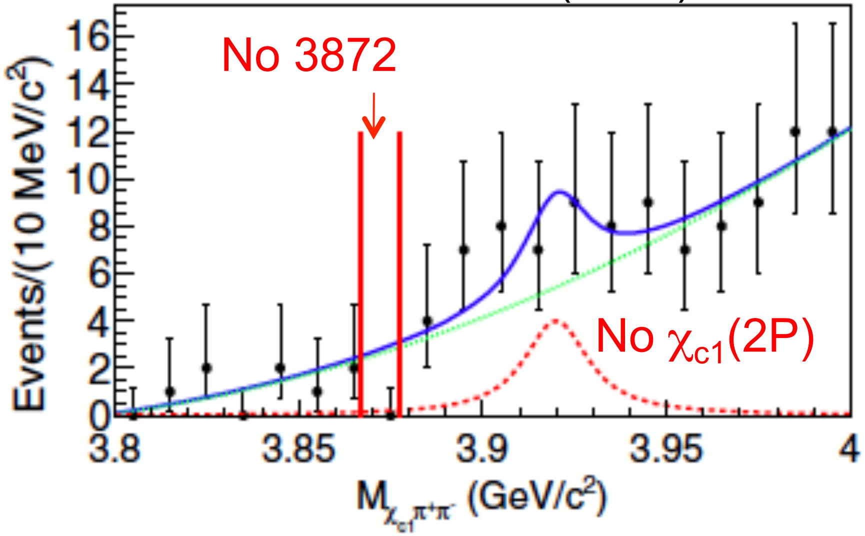
$X(3872) \to J/\psi\ \gamma$; C=+1



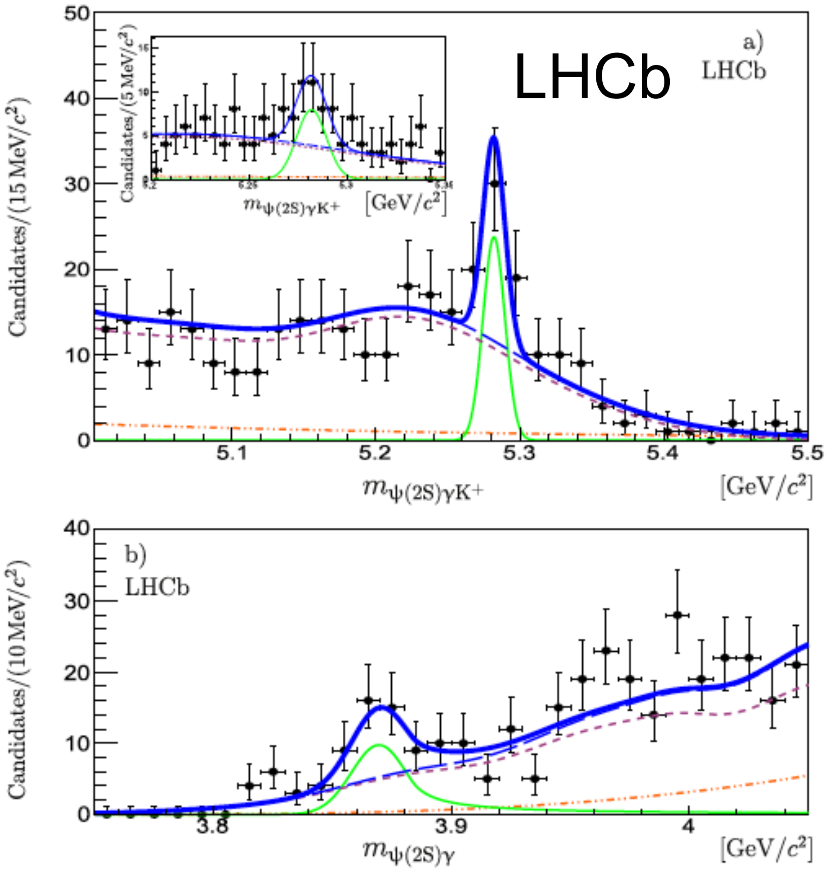


In $\chi_{c1}\pi^+\pi^-$, neither X(3872) nor χ_{c1} (2P) seen, though no explicit quantum number conflict.

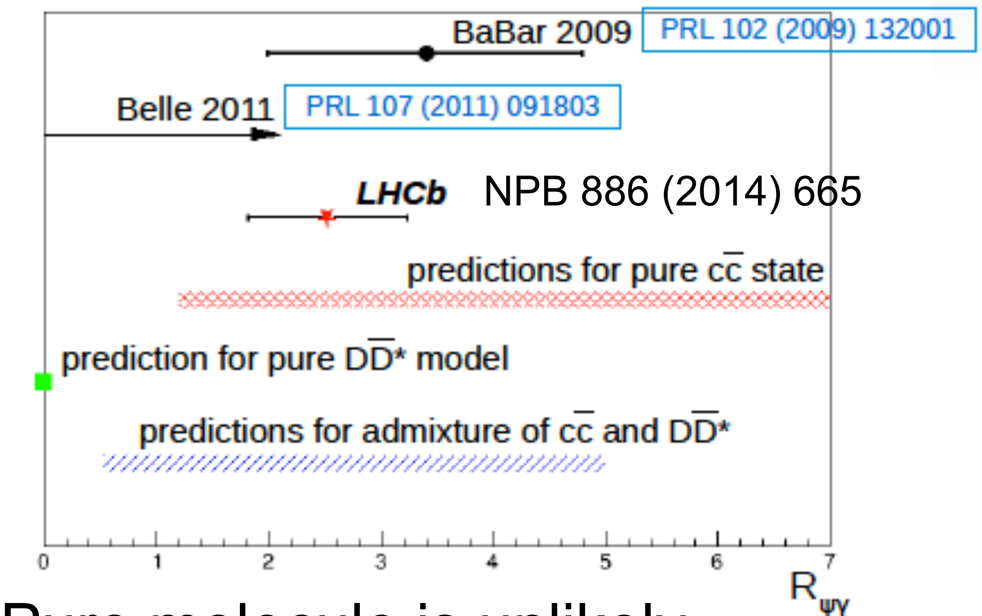
PRD93,052016(2016)



Information from a friendly competitor

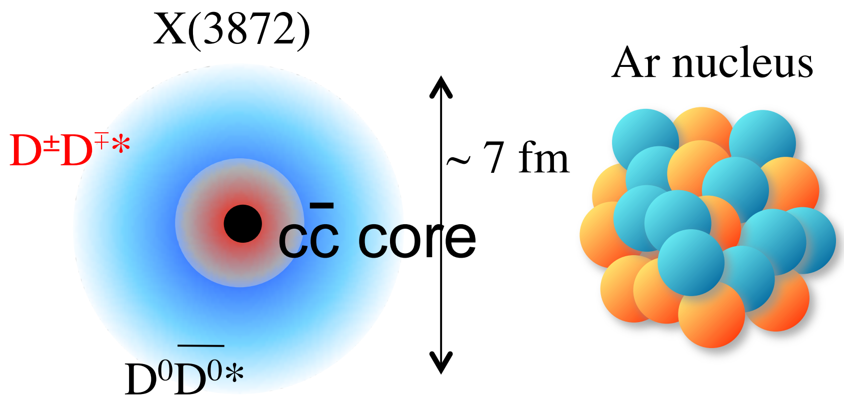


$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$



Pure molecule is unlikely ..

Admixture : most plausible interpretation for X(3872)



S.Takeuchi, K.Shimizu and M.Takizawa, PTEP2014(2014)123D01

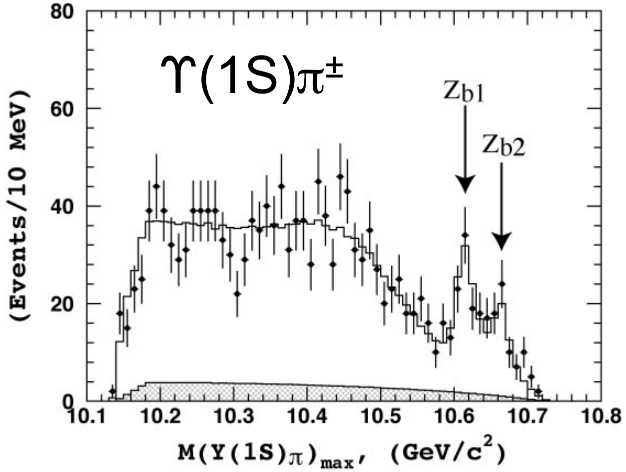
$D\overline{D}^*$ component is coupled with the same J^{PC} $c\bar{c}$, $\chi_{c1}(2P)$ (unseen).
→can explain $Br(X\rightarrow D^0\overline{D}^{*0})/Br(X\rightarrow J/\psi\ \pi^+\pi^-)$ is about 10.
→pure molecule is too fragile to be produced in Tevatron/LHC.
→another $\chi_{c1}(2P)$ dominant state would become broad.
Reaching such an interpretation is remarkable progress.

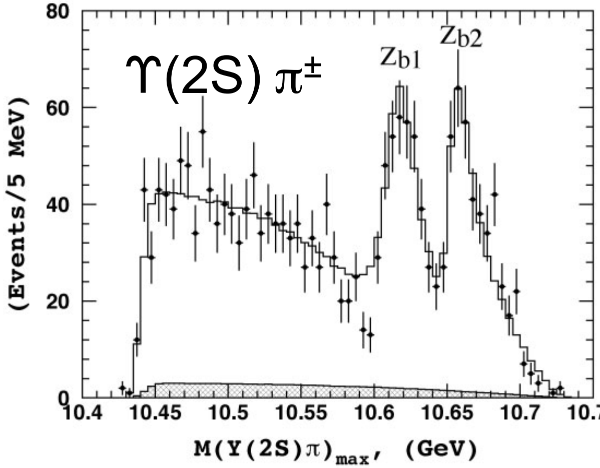
Charged states in bottomonium sector.

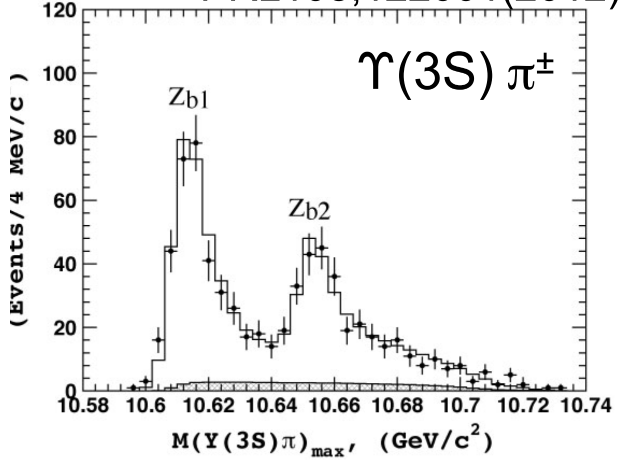
$Z_b(10610)^+$ and $Z_b(10650)^+$

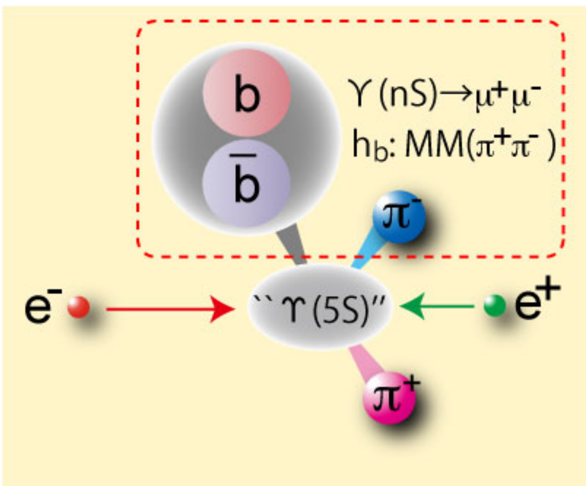
Seen in all bottomonium $\pi^{\pm}$ system at $\Upsilon(10860)$

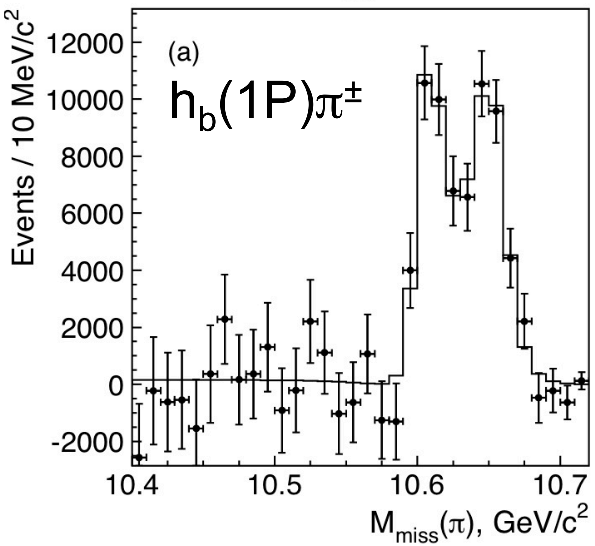
PRL108,122001(2012)

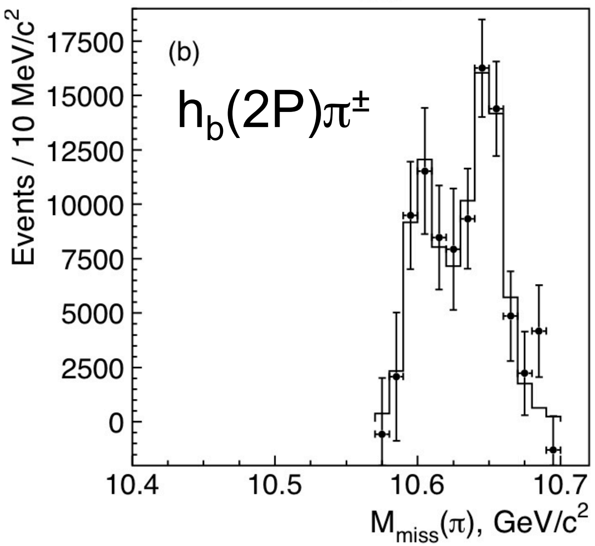








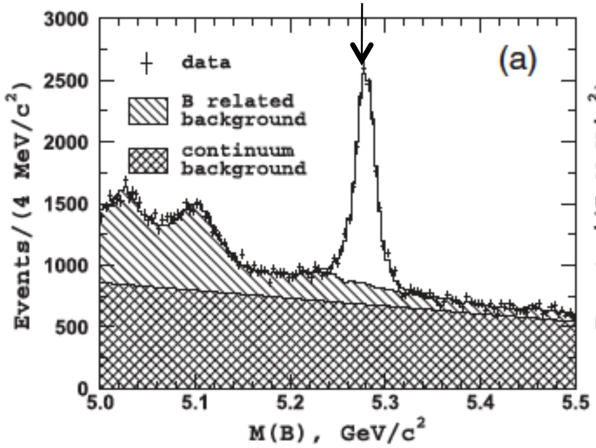


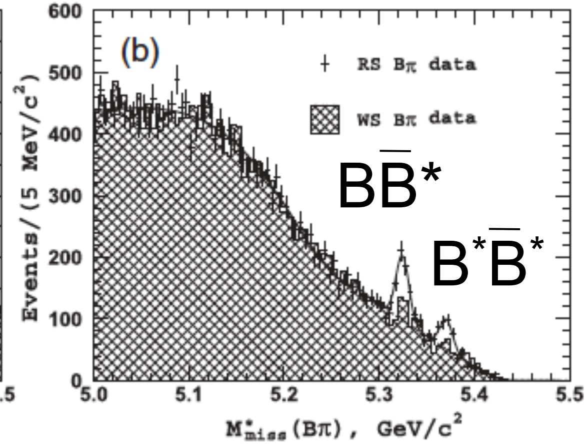


$Z_b(10610)^+ \to B\bar{B}^*$, $Z_b(10650)^+ \to B^*\bar{B}^*$

One B reconstructed

PRL116,212001(2016)





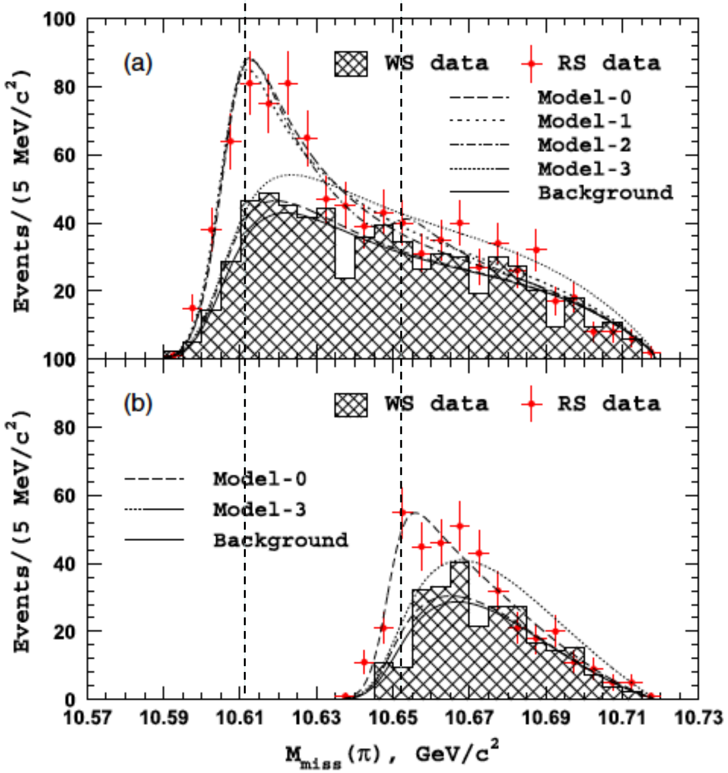
$B\bar{B}^*$

$B^*\bar{B}^*$

B cand. Mass (GeV)

MM(Bπ)

10610 10650



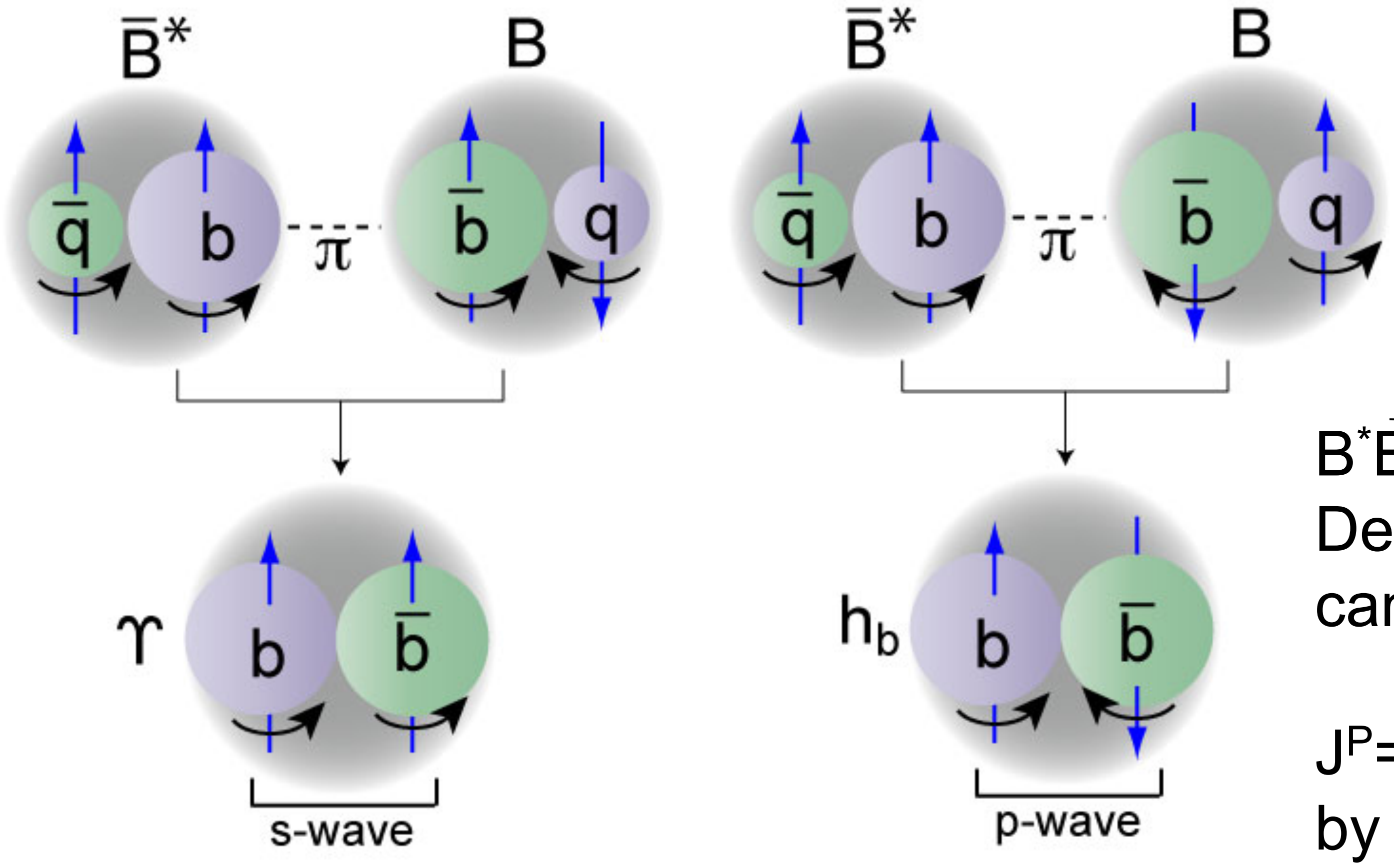
$MM(\pi)=M(B^{(*)}B^*)$

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

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

Found to be dominant!

Molecular picture works

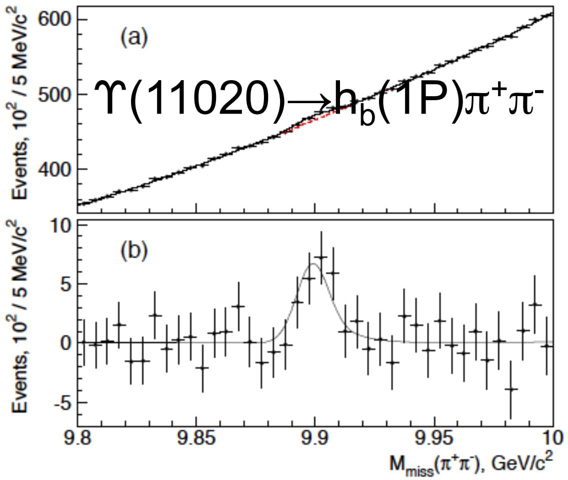


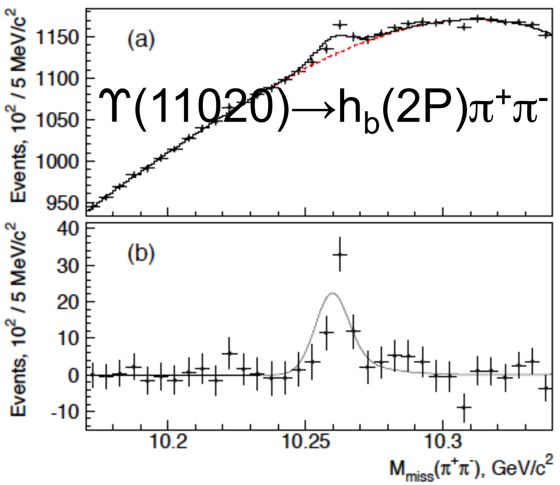
A.E.Bondar et al., PRD84,054010(2011)

$B^*\bar{B}^{(*)}$ dominant Br.
Decays to ϒ and h_b can co-exist.

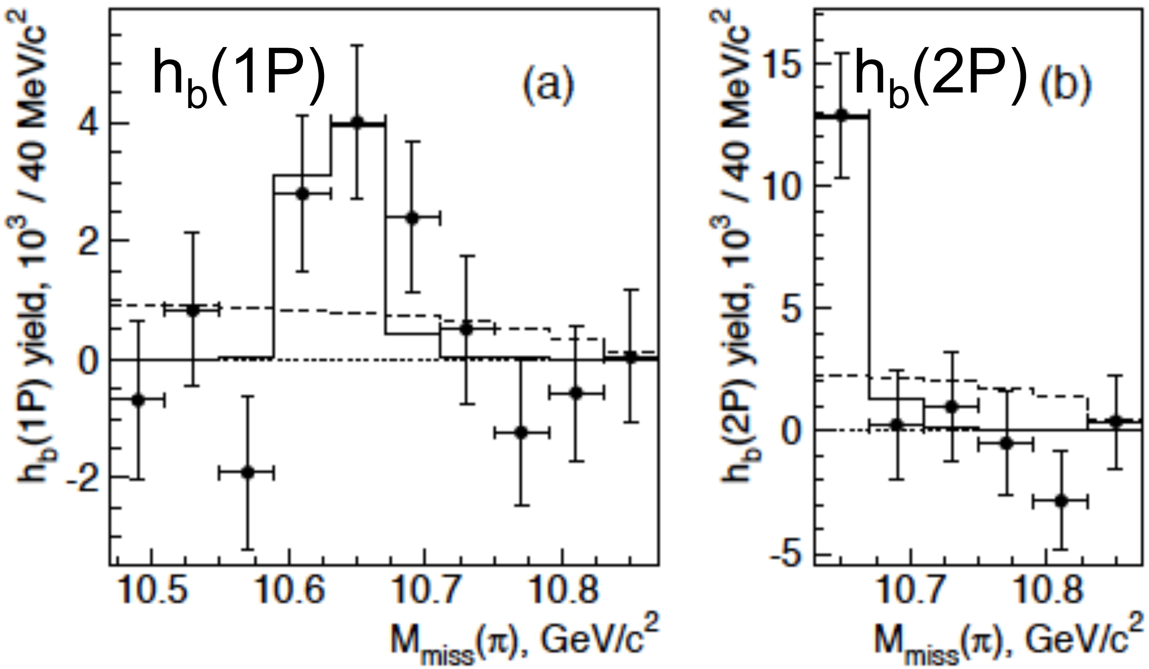
$J^P=1^+$ is supported by Dalitz analysis.
PRD91,072003(2015).

$Z_b(10610)^+$, $Z_b(10650)^+$ $\rightarrow h_b(1P,2P)\,\pi^+$ at $\Upsilon(11020)$





PRL117,142001(2016)



Phase space hypothesis is excluded at 3.6σ and 4.5σ for $h_b(1P)$ and $h_b(2P)$, respectively.

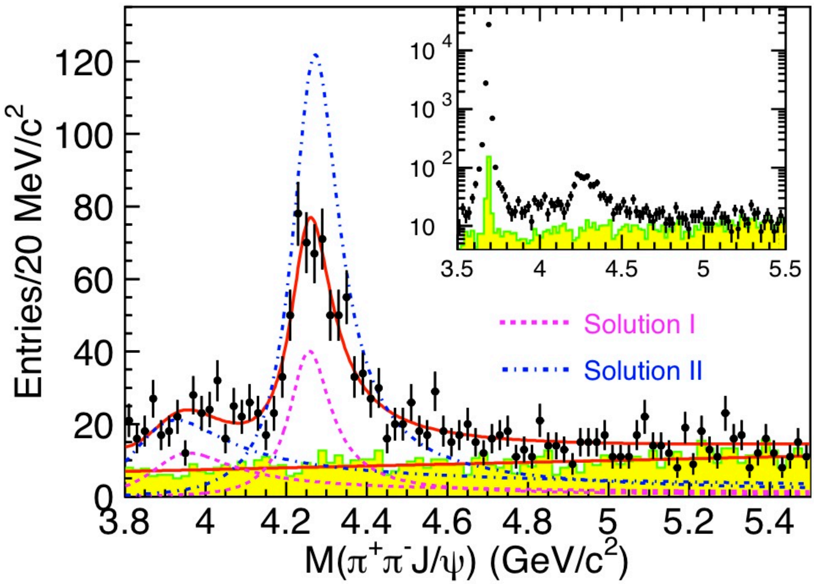
Analogous with Z_bs at $\Upsilon(10860)$

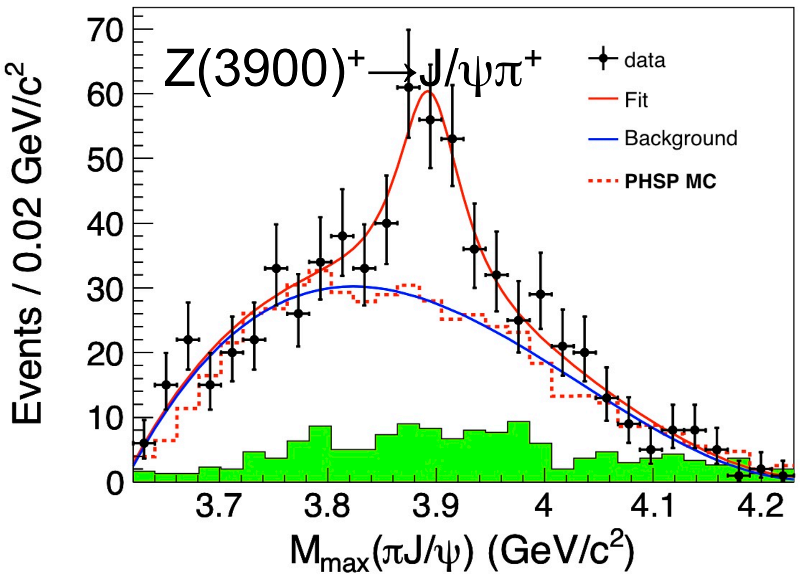
$Z_C(3900)^+$ AT Y(4260) AND SIMILAR STATES

$Z_c(3900)^+$ at $Y(4260) \rightarrow J/\psi\pi^+\pi^-$

Y(4260)→J/ψπ+π-

PRL110,252002(2013)



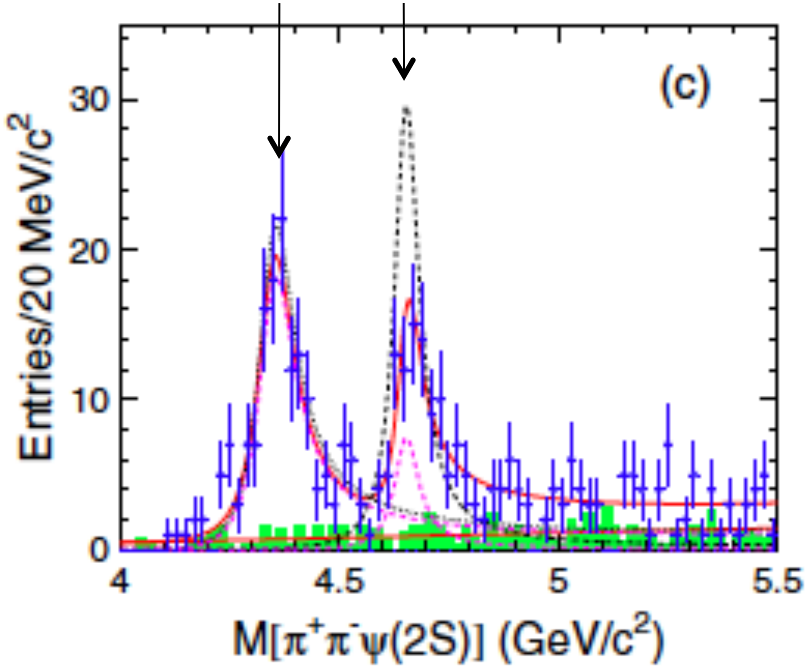


$J^{PC}=1^{-}$ state decaying to quarkonium $\pi^+\pi^-$ contains charged state as an intermediate!

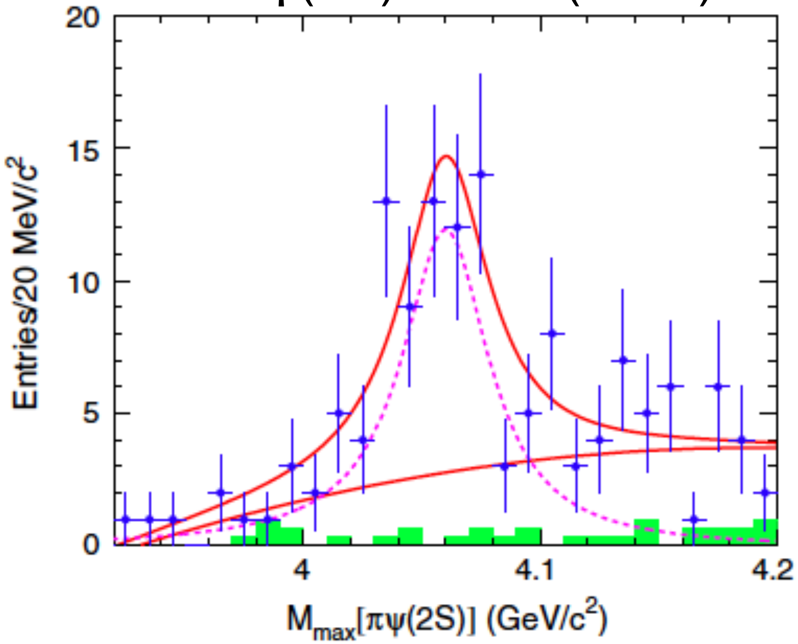
$Z_c(4060)^+$ at $Y(4360)\to\psi(2S)\pi^+\pi^-$

PRL110,252002(2013)

Y(4360), Y(4660)→ψ(2S) $\pi^+\pi^-$



Excess at 4060 MeV
for ψ(2S) π^+ In Y(4360)



Again charged state as an intermediate!

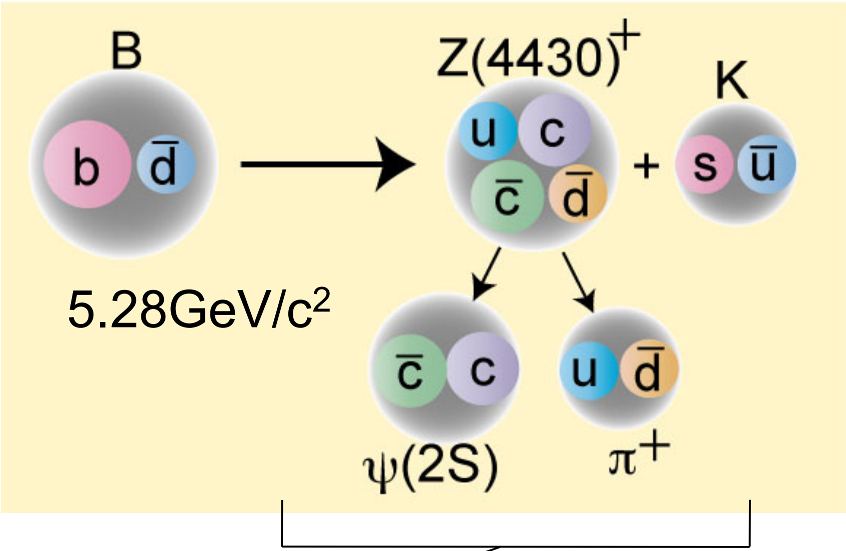
Note

- BES III reported charged charmonium-like states;
  - $Z_c(3885)^{\pm}$ in $(DD^*)^{\pm}$, $Z_c(4025)^{\pm}$ in $(D^*D^*)^{\pm}$ and $Z_c(4020)^{\pm}$ in $h_c\,\pi^{\pm}$
  - Molecular picture look still working, however ..
- In bottomonium-like case, $Z_b(10610)^{\pm}$ and $Z_b(10650)^{\pm}$ look explain all the observed features, while there seems to be more in charmonium-like case depending on the decay final state.
- Does such difference give a hint to reveal the proper degree of freedom to form heavy hadrons?

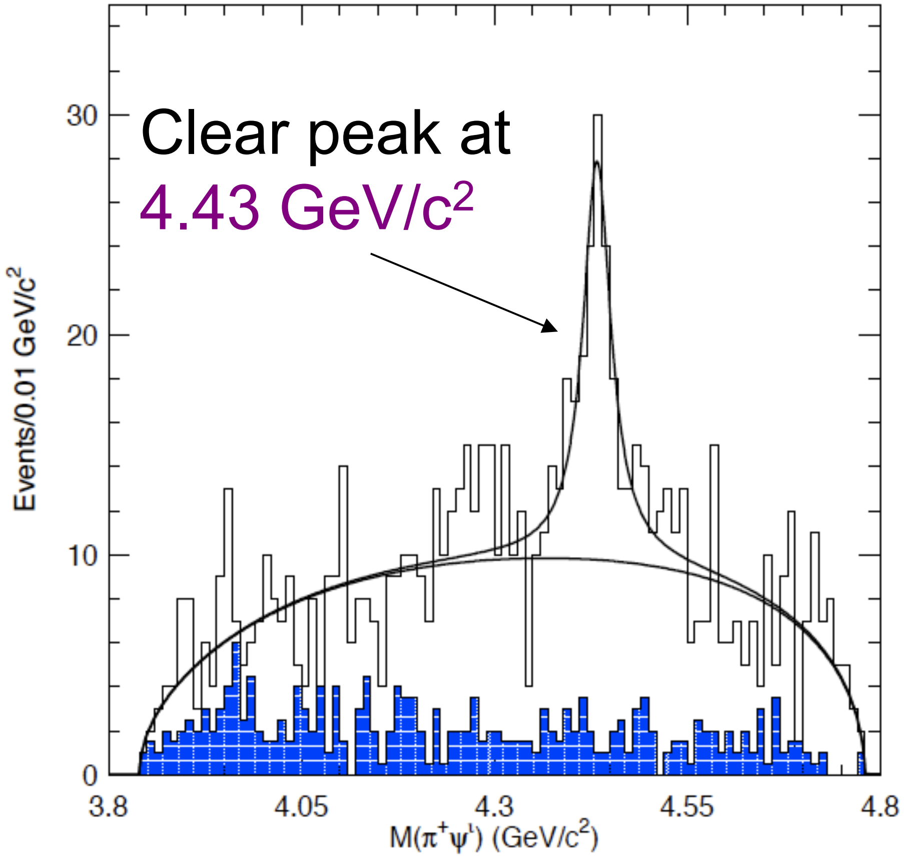
Charged charmonium-like states produced in B decays

$Z_c(4430)^+$ and SIMILAR STATES

Z(4430)$^{\pm}$ in ψ(2S)$\pi^{\pm}$ final state

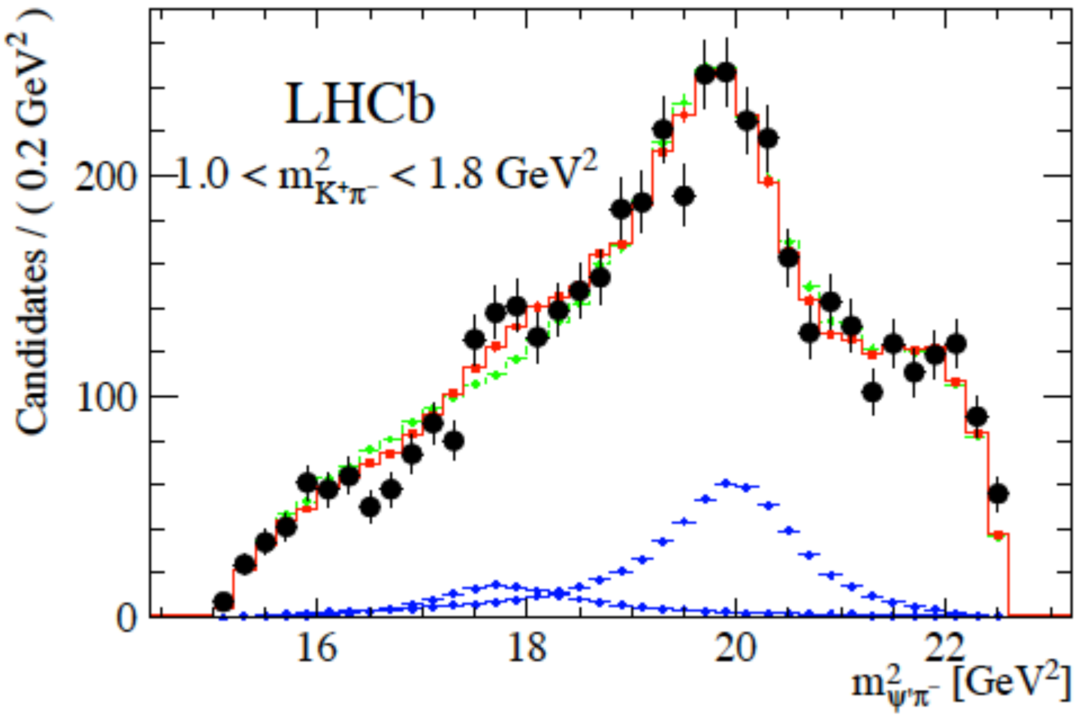


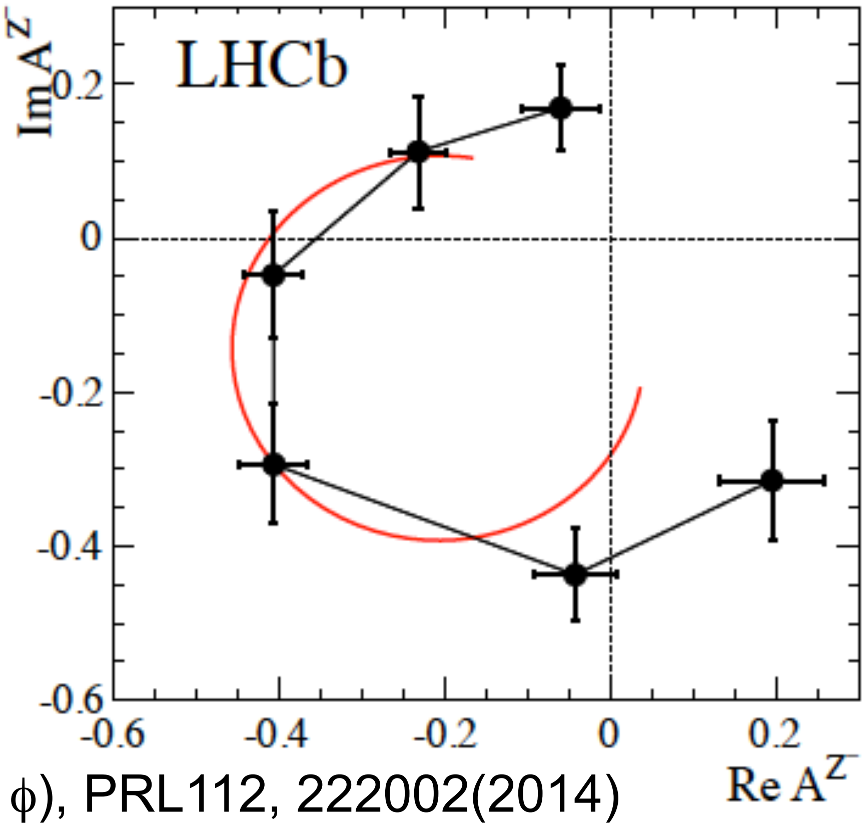
Reconstructing B → ψ(2S) $\pi^{\pm}$ K,
M(ψ(2S) $\pi^{\pm}$) is looked back.
Confirmed by LHCb
PRL112, 222002(2014)



PRL100,142001(2008)
PRD 80, 031104(2009)
PRD 88, 074026(2013)

Confirmation by LHCb





4D fit($M(\psi(2S)\pi^{\pm})$, $M(K\pi)$, $\cos\theta_{\psi(2S)}$, ϕ), PRL112, 222002(2014)

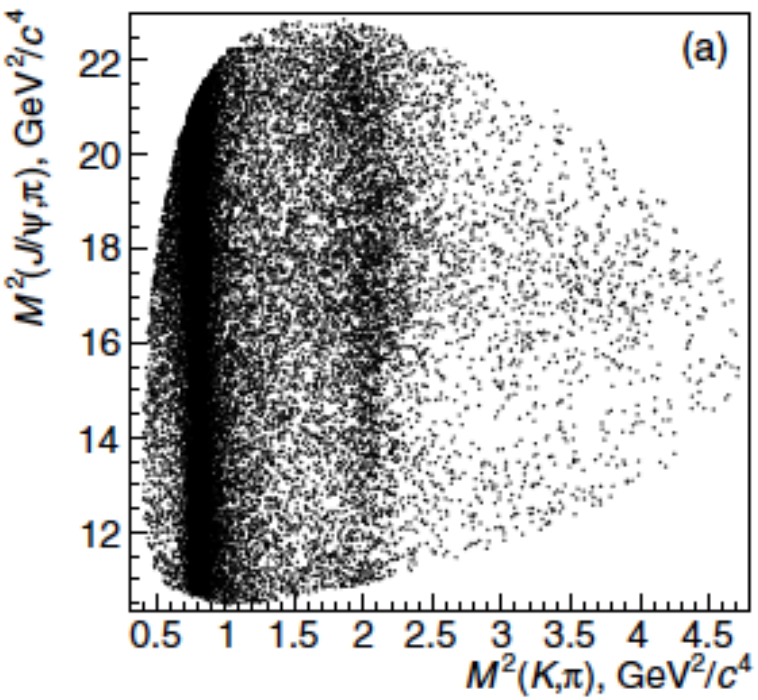
Argand diagram gives a proof of resonance.

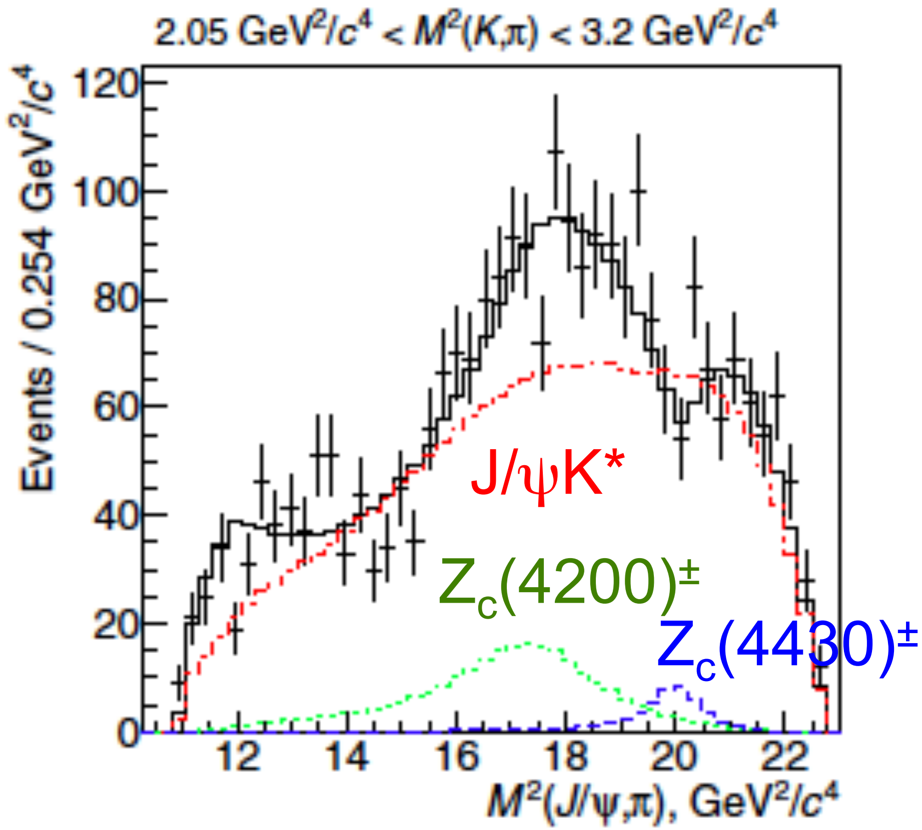
Such approach will be possible to study other states with Belle II statistics only.

How about J/ψ $\pi^{\pm}$ system?

PRD90,112009(2014)

In $B \to J/\psi \pi^{\pm} K$ decays

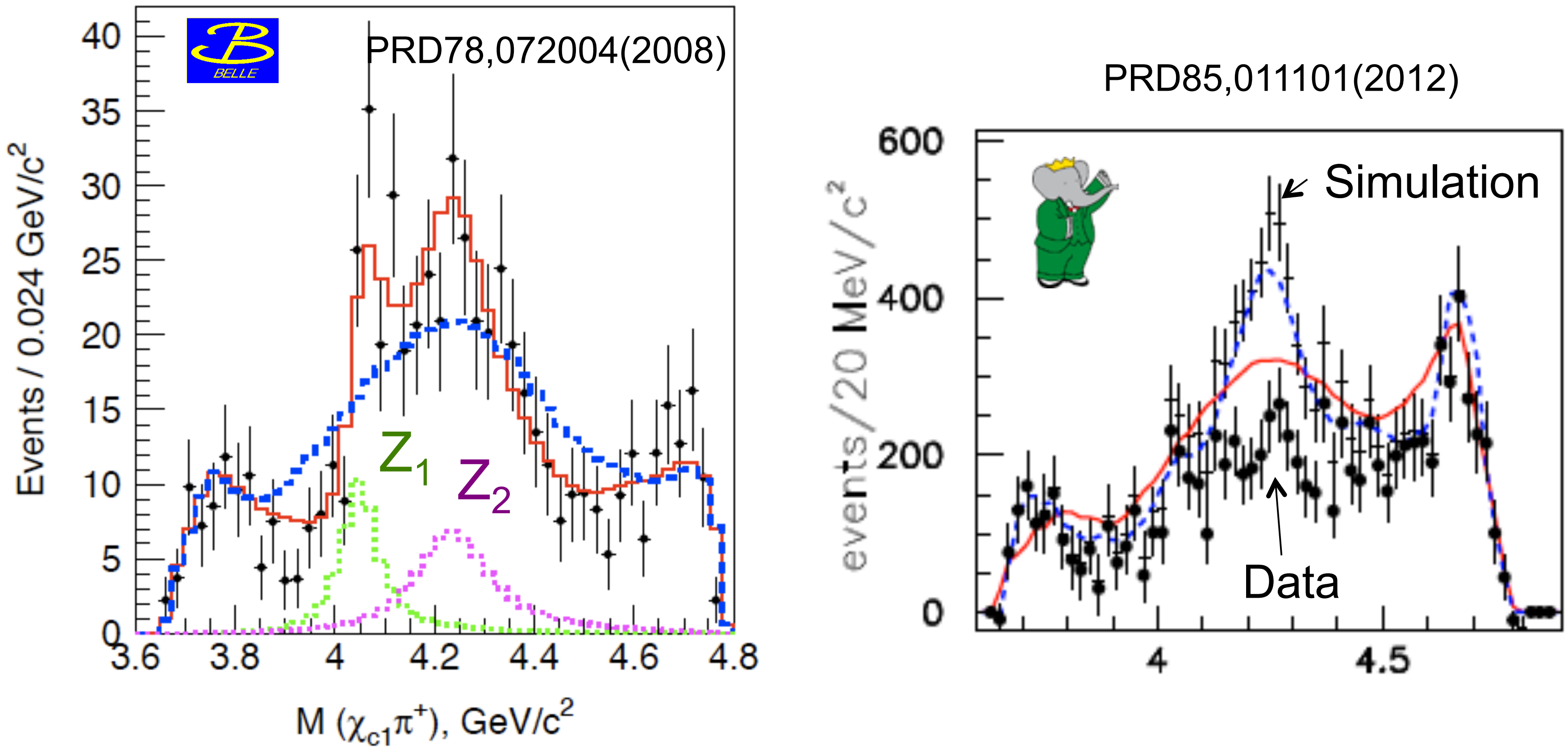




$Z_c(4430)^{\pm} \to J/\psi \pi^{\pm}$ seen, $Z_c(4200)^{\pm}$ observed.

M= 4196^{+31+17}_{-29-13} MeV$/c^2$ Γ= $370^{+70+70}_{-70-132}$ MeV

Limitation with available statistics



Z(4050)$^{\pm}$ and Z(4250)$^{\pm}$ in $\chi_{c1}\ \pi^{\pm}$ in $B\rightarrow\chi_{c1}\ \pi^{\pm}\ K$;
Seen v.s. Unseen, only higher statistics $e^{+}e^{-}$ data can give a clear answer.

Still many things we should attempt …

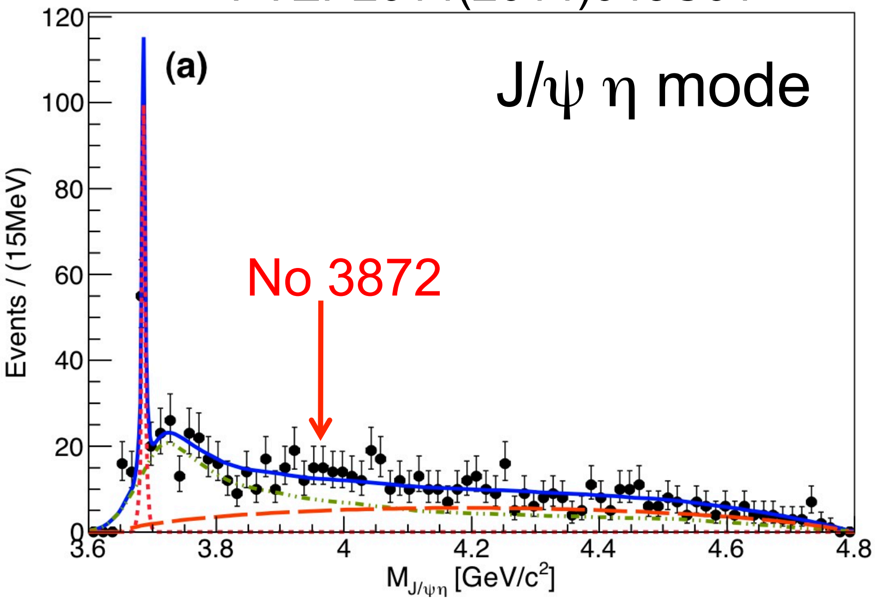
CHALLENGES AT HIGHER STATISTICS

Partner states; a key to go further

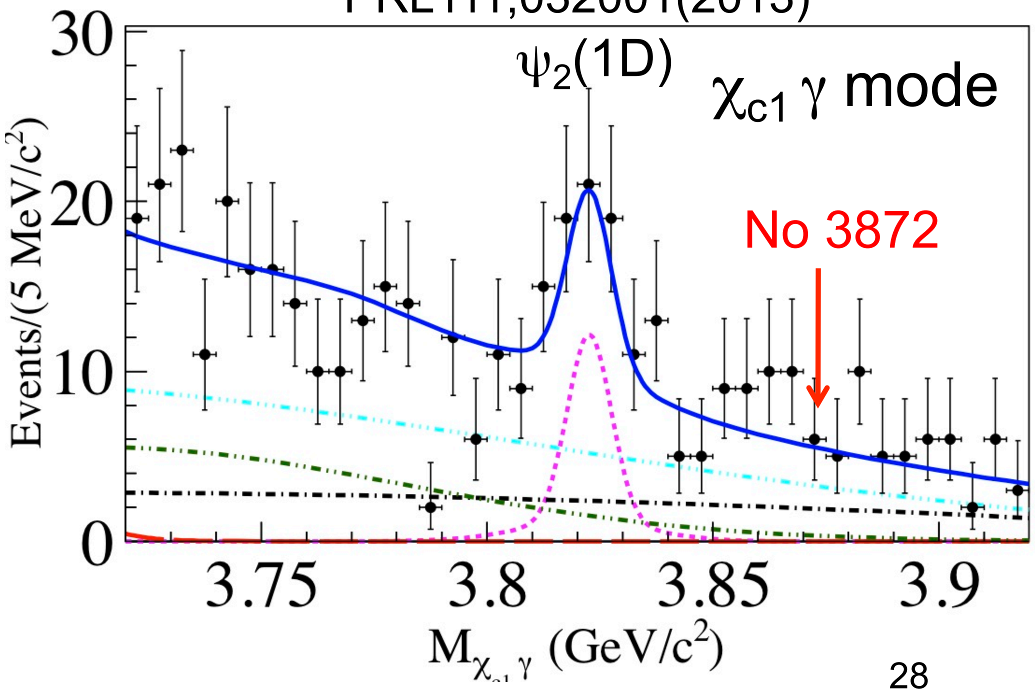
For X(3872), no signature for

- Charged partner in $J/\psi\ \pi^+\pi^0$. → most likely, isospin=0.
- C=-1 partner in $J/\psi\ \eta$ and $\chi_{c1}\ \gamma$. → disfavor tetraquark hypothesis.

PTEP2014(2014)043C01



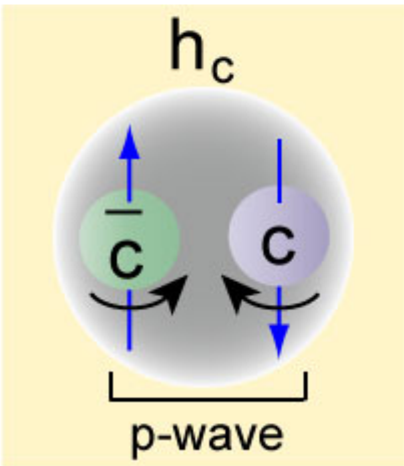
PRL111,032001(2013)



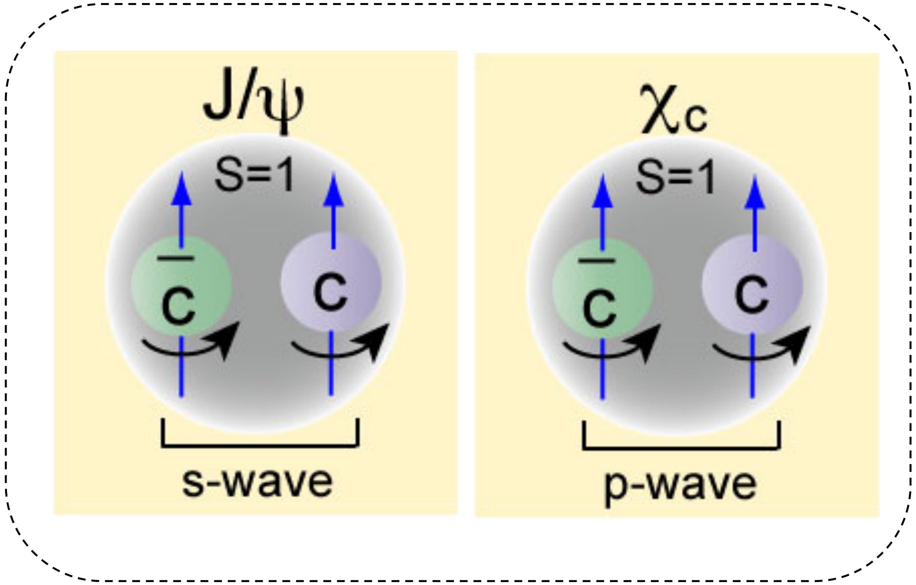
What does it mean?

If X(3872) is admixture of molecule and χ_{c1}(2P), its C-odd partner, $J^{PC}=1^{+-}$ state, is

mixing with



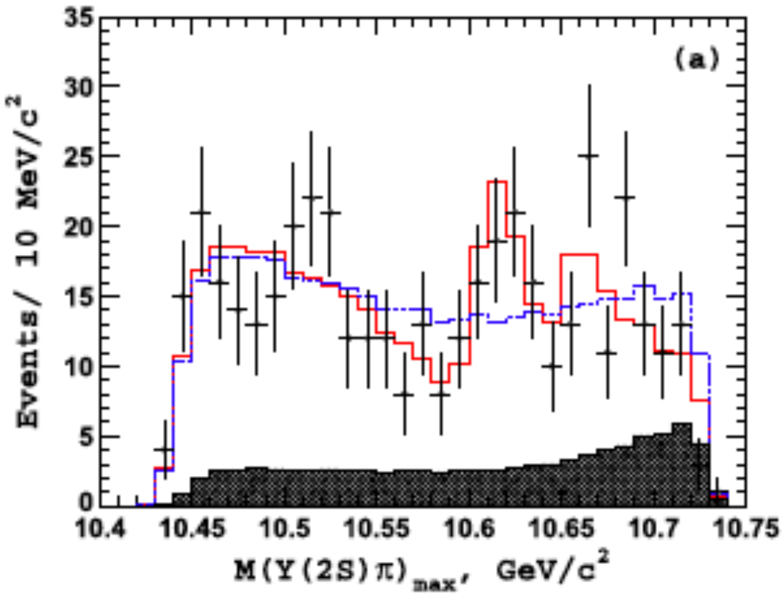
then not familiar with



Hadronic decays or radiative decay to η_c $\rightarrow$ low br. and S/N.
$J^{PC}=1^{+-}$ is factorization disfavored, three-body $B \rightarrow h_c K \pi$ should be at first looked for. Higher statistics desirable.

Partner states of Z_b case

PRD88, 052016 (2013)



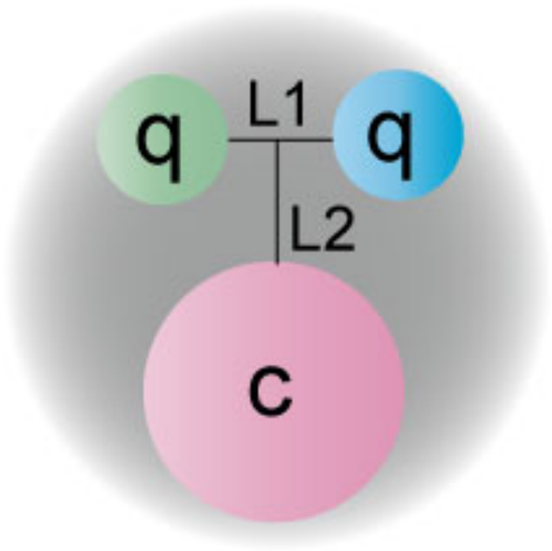
$Z_b(10610)^0 \rightarrow \Upsilon\,(2S)\pi^0\pi^0$ seen
6.5σ stat. significance
$I^G=1^+$, first isospin partner among "XYZ".

- Partners may decay into χ_{bJ} (PRD86,014004(2012)).
  - $Z_b \rightarrow \chi_{bJ}\,\pi$, $Z_{b0} \rightarrow \chi_{bJ}\,\gamma$
- $Br(\chi_{bJ}\rightarrow\Upsilon(1,2,3S)\gamma)$ and γ efficiency are multiplied, signal yield may be lower one order of magnitude.

↓

Higher statistics needed.

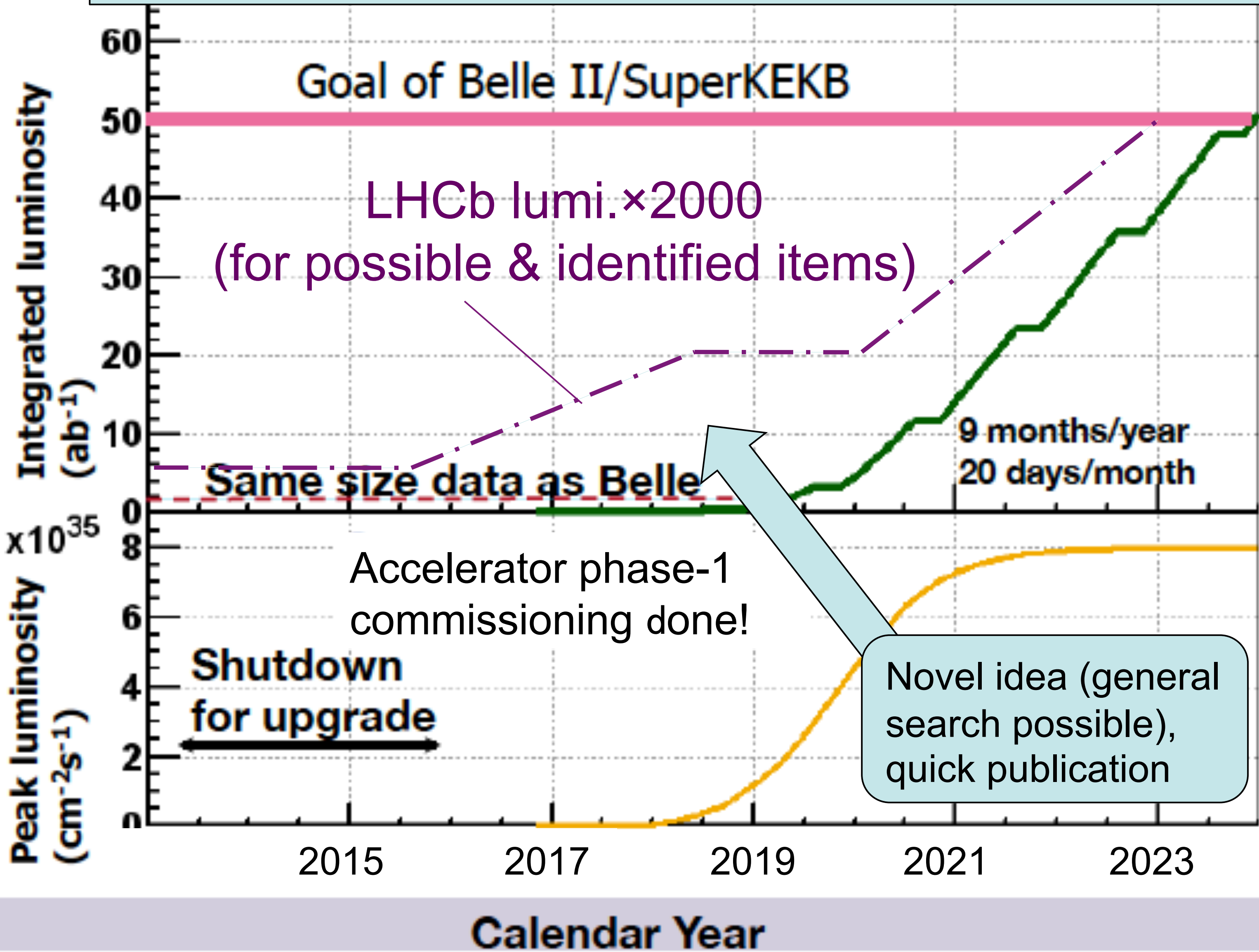
Charm baryon to check “di-quark”



- Thought to be a good place to check if “di-quarks” is behaving as a good degree of freedom to form hadrons.
- One of the constituent quark is heavy, correlation between the remaining light quarks would become clear.
- L_1 : ρ mode, L_2 : λ mode.

Determination of quantum numbers for excited states, attempt to look for molecule, pentaquark should be made.

Competition with LHCb



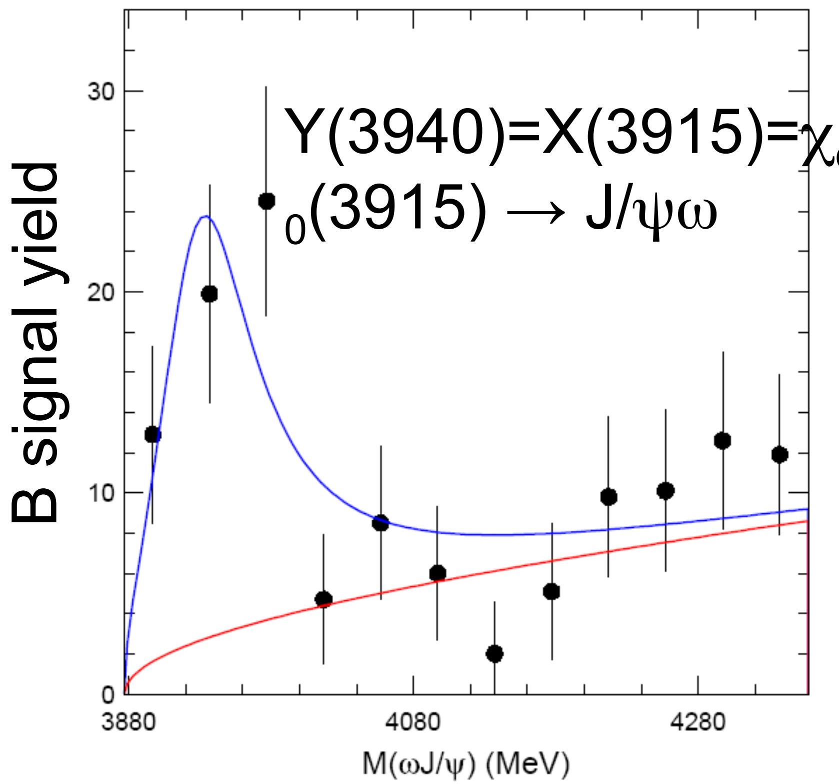
Summary

- Molecular picture turned out to play important role near the threshold.
  - X(3872) : $D^0 \overline{D^{*0}}$ and mixing with $\chi_{c1}(2P)$.
  - $Z_b(10610)^+$: $B \overline{B^*}$, $Z_b(10650)^+$: $B^* \overline{B^*}$
- $J^{PC}=1^{--}$ state decay contain a charged state as an intermediate in both charmonium-like and bottomonium-like cases.
- Searches for other partners states need more data.
  - Because of anticipated decay modes.
- Argand diagram approach only possible with Belle II statistics.

Backup

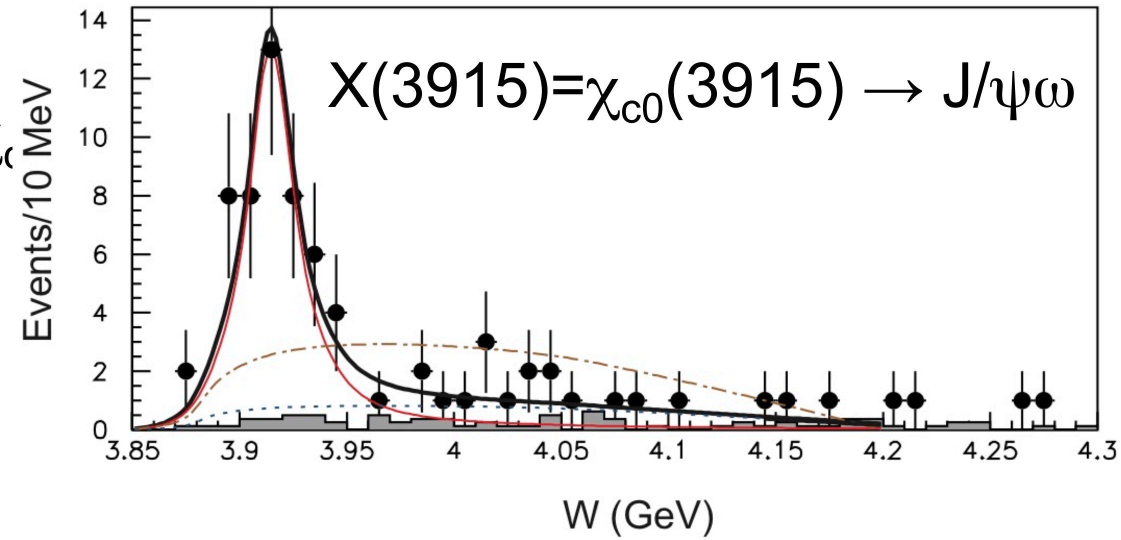
Variety of reactions; X(3915)=χ_{c0}(3915)

In $B^{\pm} \rightarrow J/\psi\omega K^{\pm}$ decay



M=3943±11(stat)±13(syst) MeV
Γ=87±22(stat)±36(syst) MeV
PRL94,182002(2005)

In $\gamma\gamma \rightarrow J/\psi\omega$ process



N_{sig}=49±14(stat)±4 events.
M=3915±3(stat)±2(syst) MeV,
Γ=17±10(stat)±3(syst) MeV
J^{PC} not yet determined.
(still need confirmation for PDG interpretation)