Belle studies of exotic hadrons with heavy flavor

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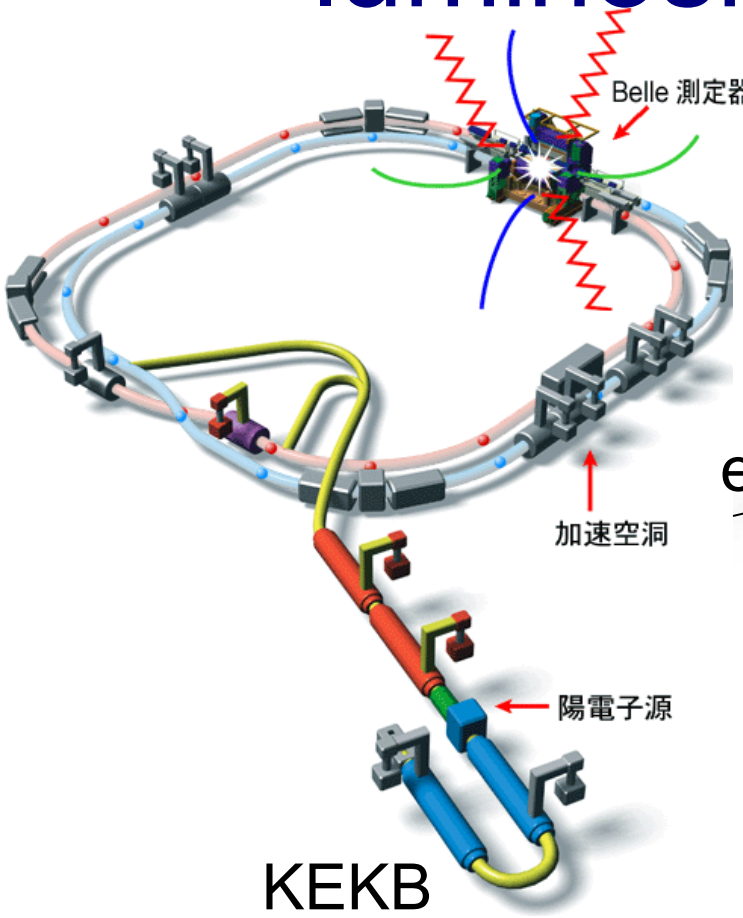
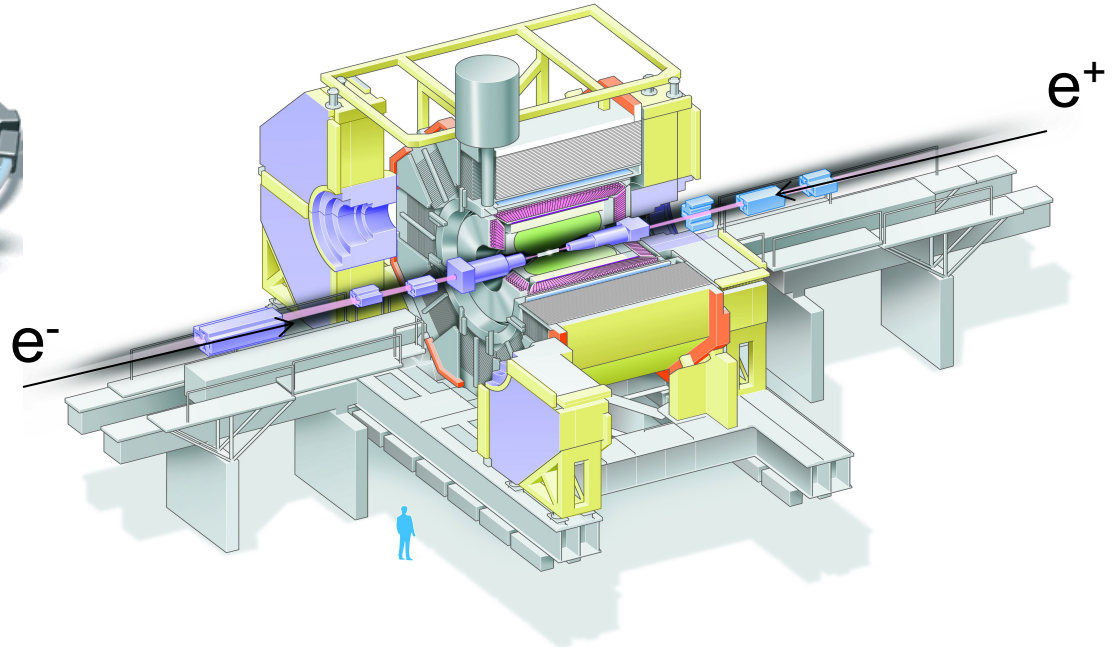
Outline

- KEKB e^+e^- collider and Belle detector
- Production mechanisms of hadrons.
- X(3872) and $Z_c(4430)^+$: exotics in B decays
- $Z_b(10610)^+$ and $Z_b(10650)^+$ at $\Upsilon(10860)$
- $Z_c(3900)^+$ at Y(4260) and similar states
- Extension to charm baryons
- Challenges at higher statistics
- Summary

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

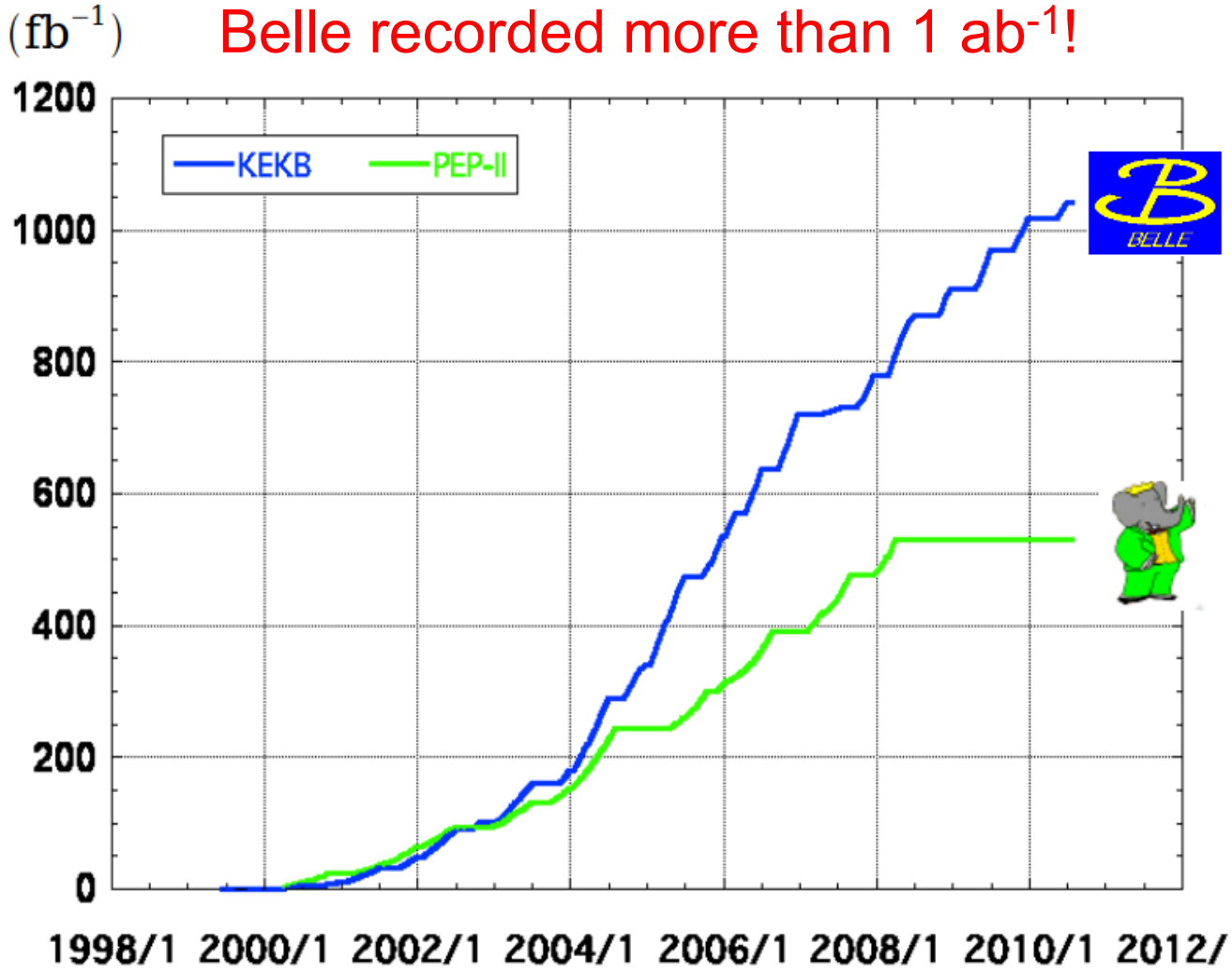


KEKB
8GeV × 3.5GeV@ϒ(4S)



Belle
High resolution 4π spectrometer with particle identification capability

Integrated luminosity of B factories



> 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}

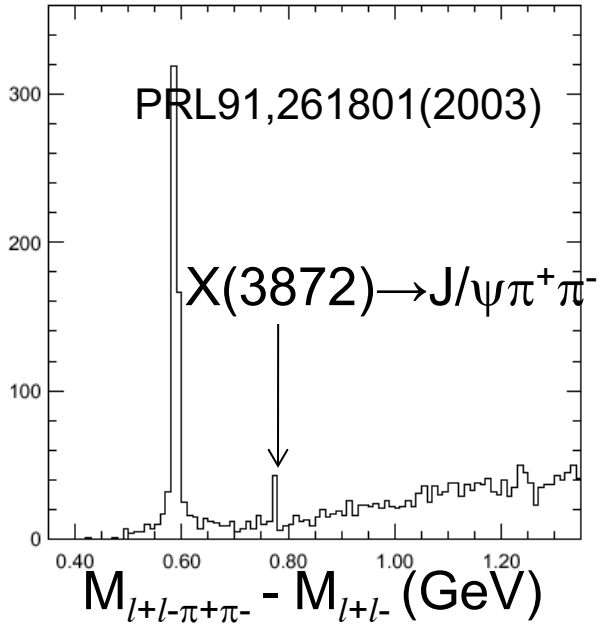
$\Upsilon(3S)$: 30 fb^{-1}

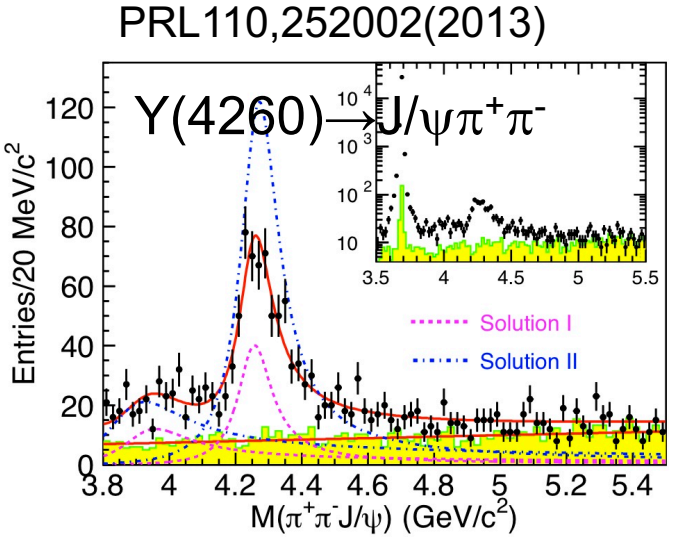
$\Upsilon(2S)$: 14 fb^{-1}

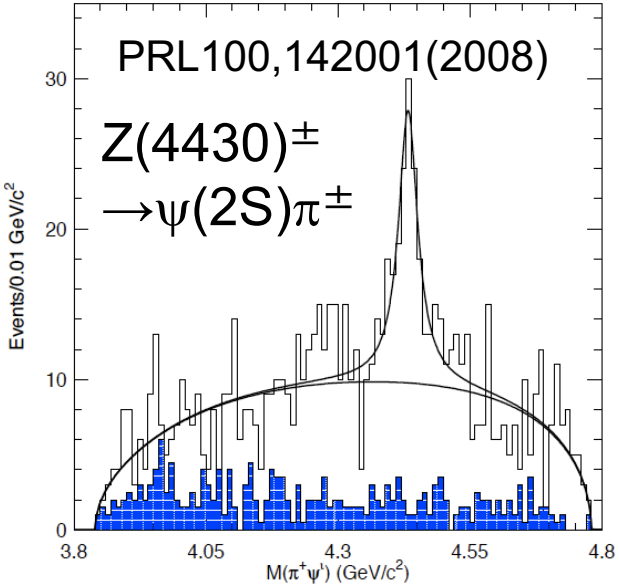
Off resonance:

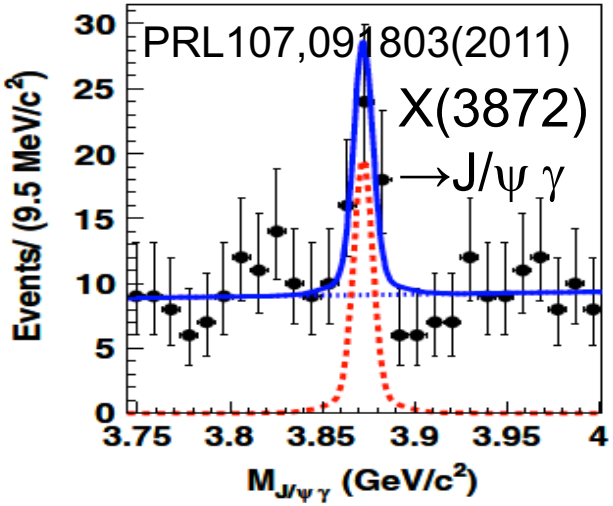
~ 54 fb^{-1}

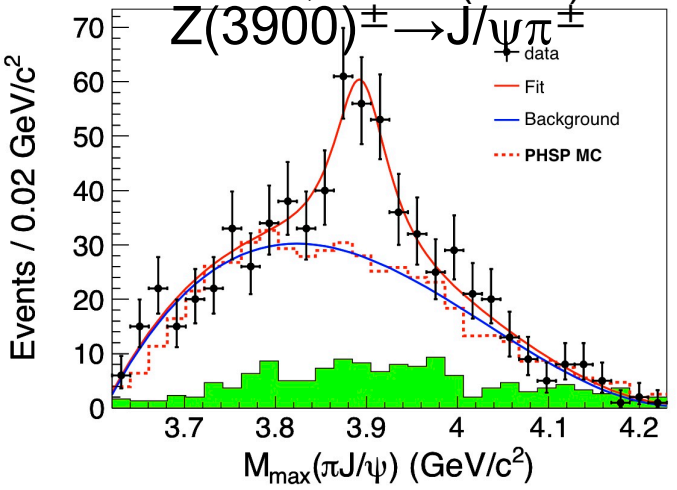
"XYZ" sensations at Belle

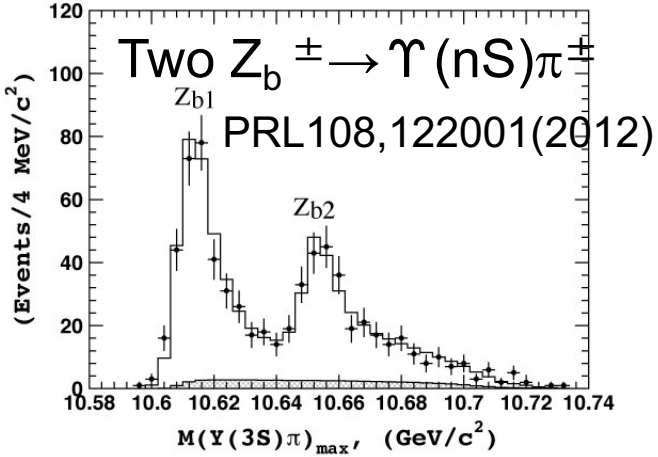












What made it possible?

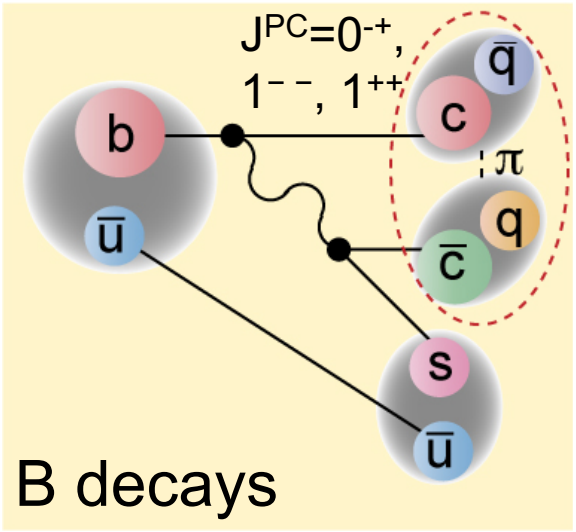
First of all, the world highest luminosity by KEKB.

High resolution 4π spectrometer, Belle.

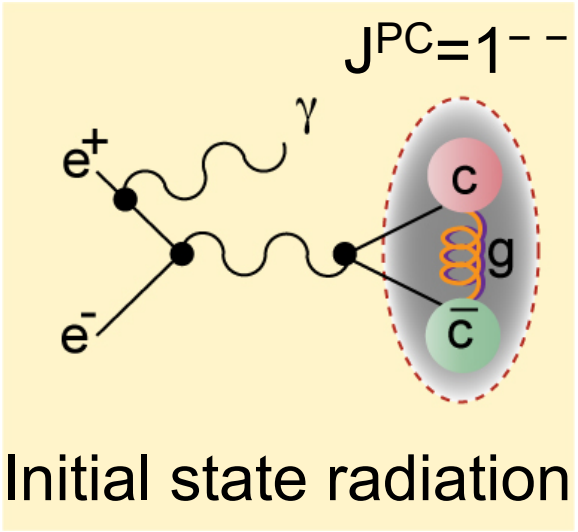
Those two brought us possibilities to access;

- 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.

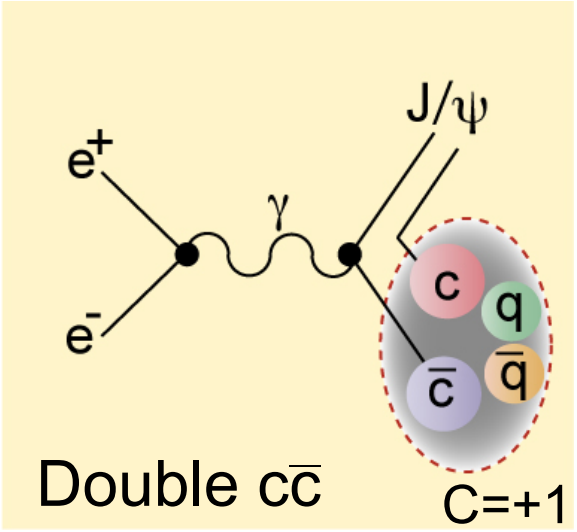
Variety of recorded reactions



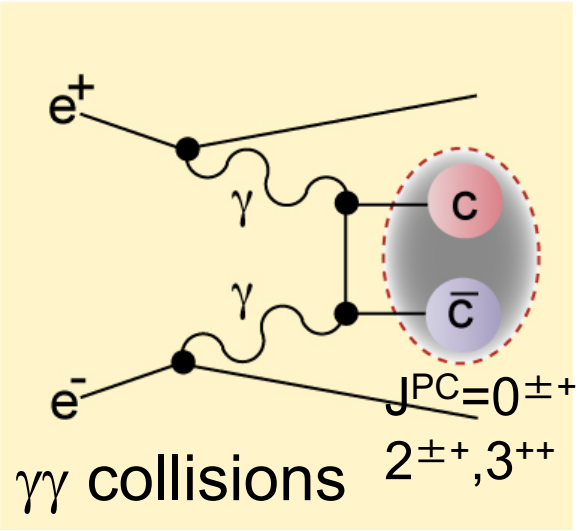
B decays



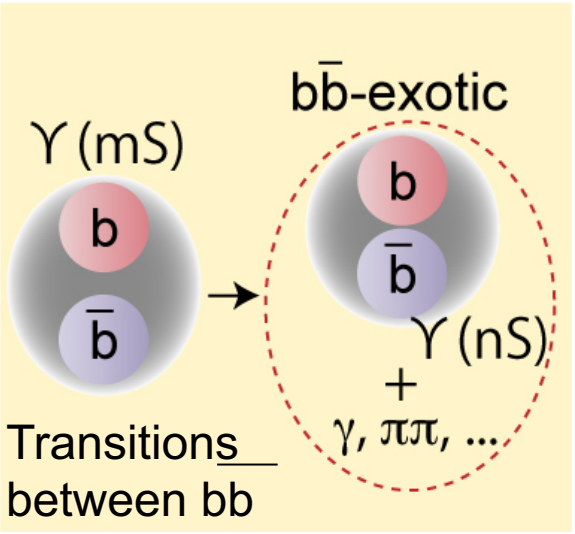
Initial state radiation



Double $c\bar{c}$ C=+1



$\gamma\gamma$ collisions



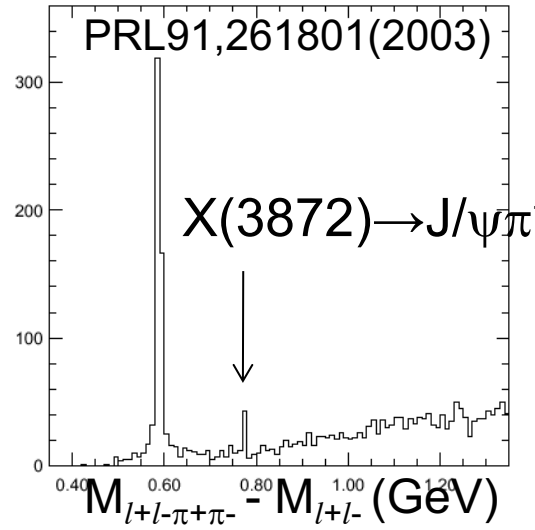
Transitions between bb states

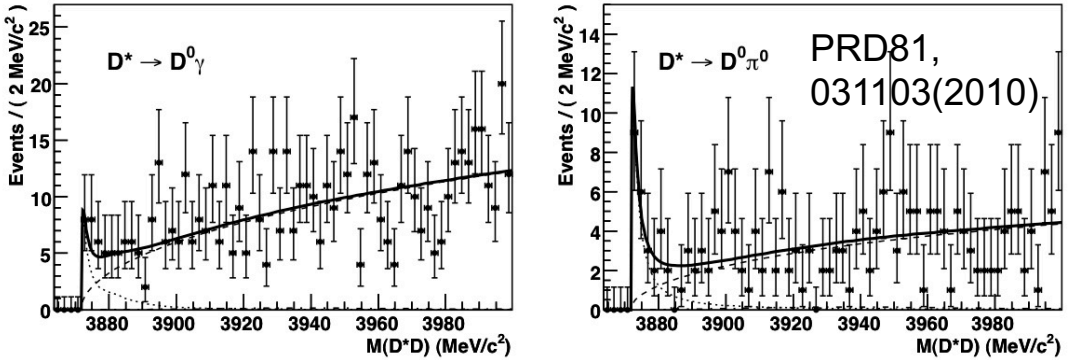
Allowed/favored quantum numbers are different depending on production processes.

Exotic candidate states found in B meson decays

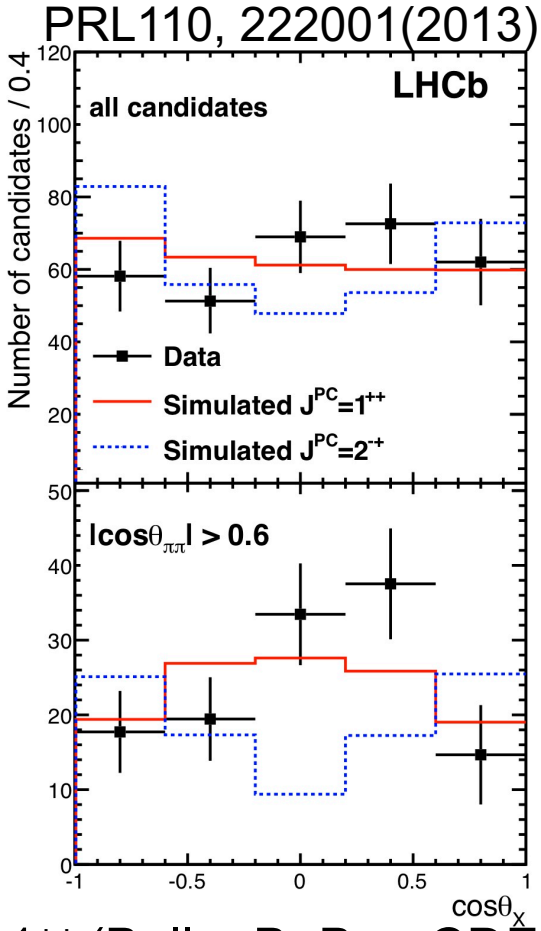
X(3872) and $Z_c(4430)^{\pm}$

X(3872); various decay modes





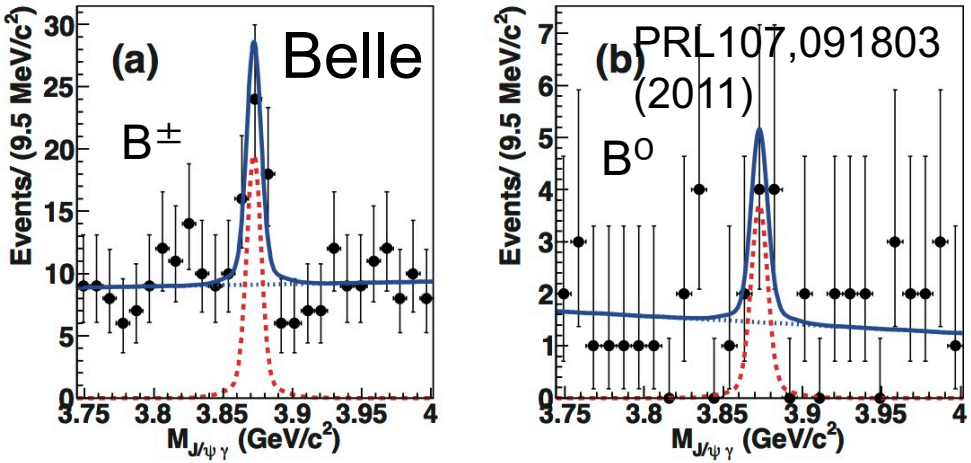
Br(X(3872)→$D^0\bar{D}^{*0}$) is about Br(X(3872)→J/ψ $\pi^+\pi^-$) × 10.

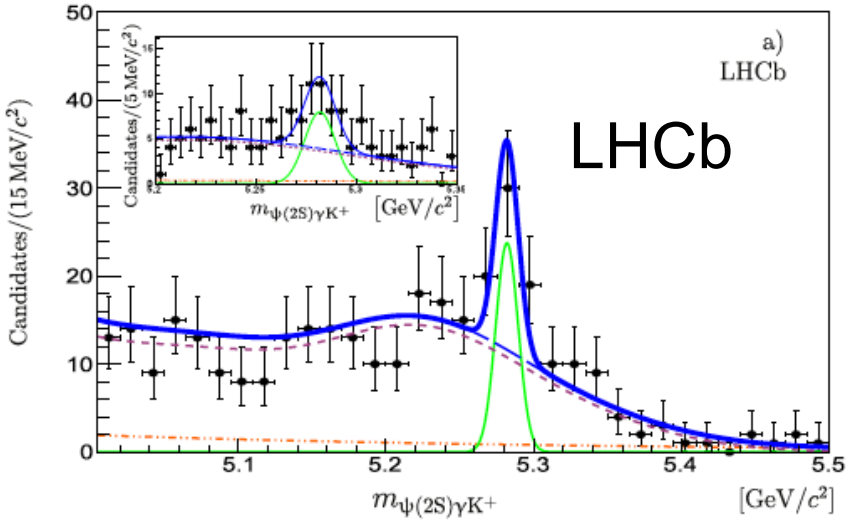


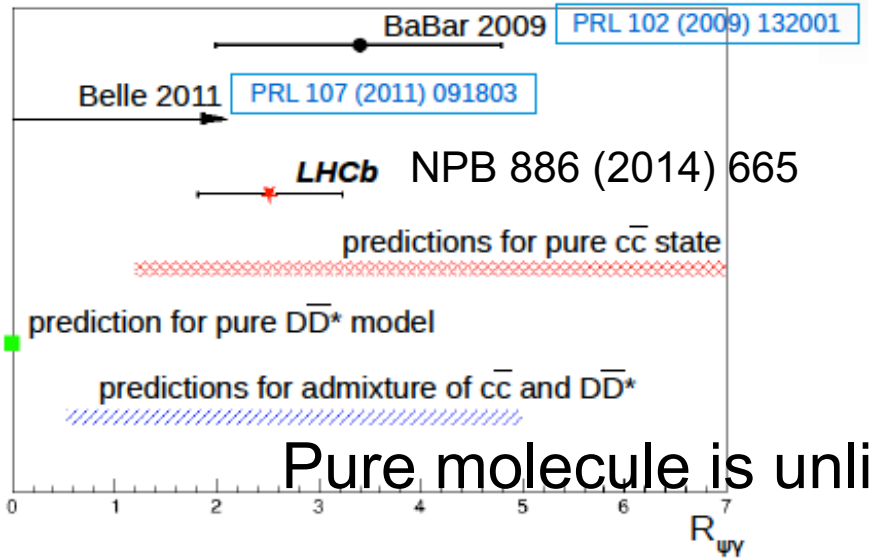
$J^{PC}=1^{++}$ (Belle, BaBar, CDF, LHCb) from J/ψ $\pi^+\pi^-$ angular distribution.

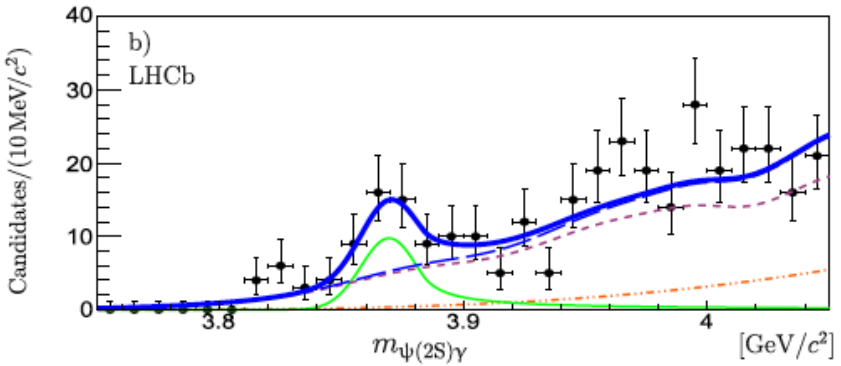
More decay modes

X(3872)→J/ψ γ; C=+1





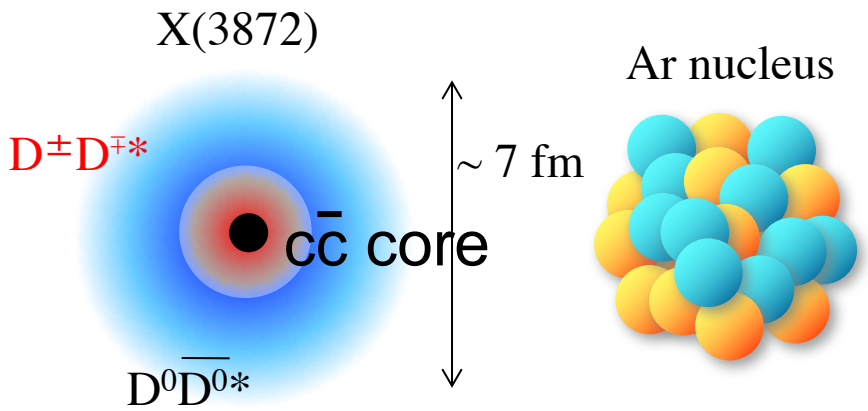




Pure molecule is unlikely ..

X(3872)→ψ(2S) γ found at LHCb.

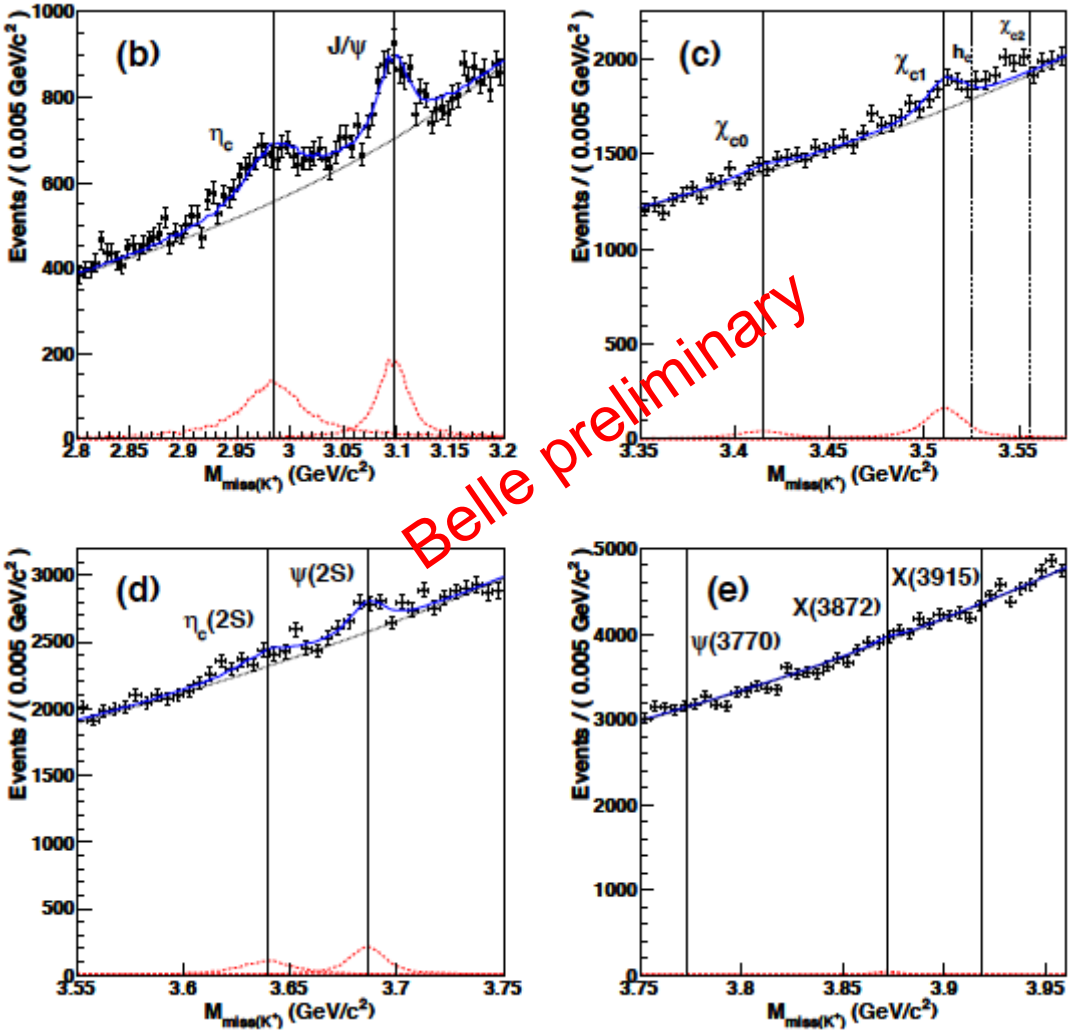
Admixture : most plausible interpretation for X(3872)



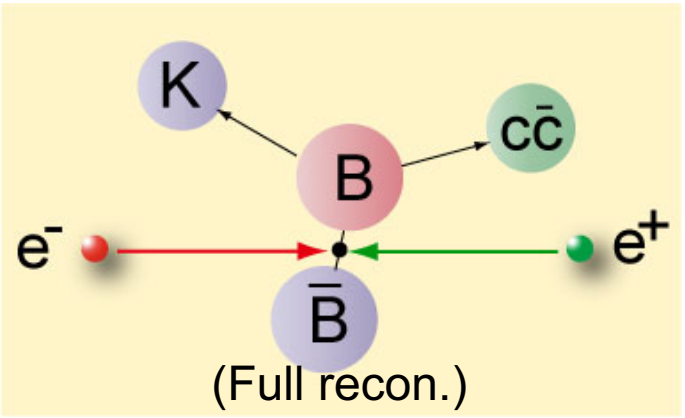
E. J. Eichiten et al., PRD73,014014(2006); A. M. Badalian et al., PRD85,031103(2012), S.Takeuchi, K.Shimizu and M.Takizawa, PTEP2014(2014)123D01

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

More info., absolute br.

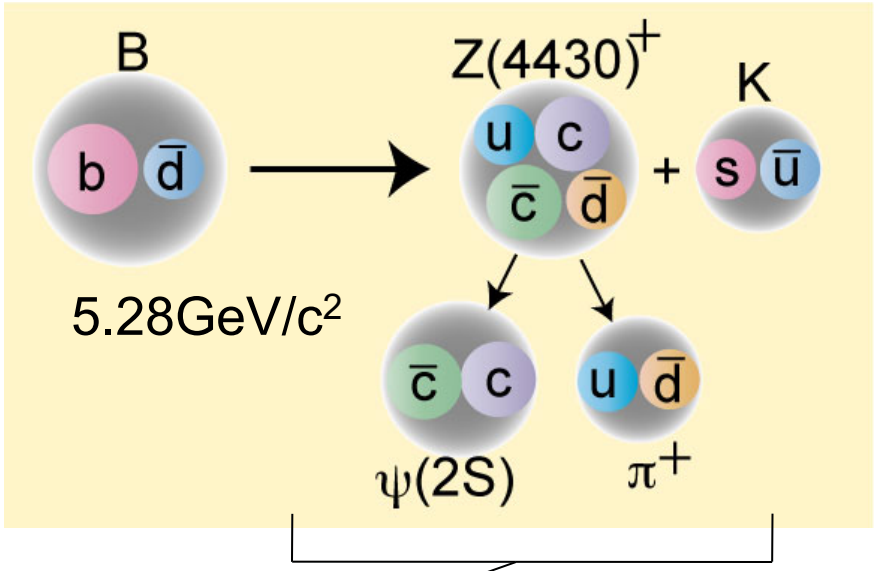


At $\Upsilon(4S)$, one B is fully reconstructed, then charmonium spectrum seen in the recoil mass w.r.t. a Kaon by two-body decays.

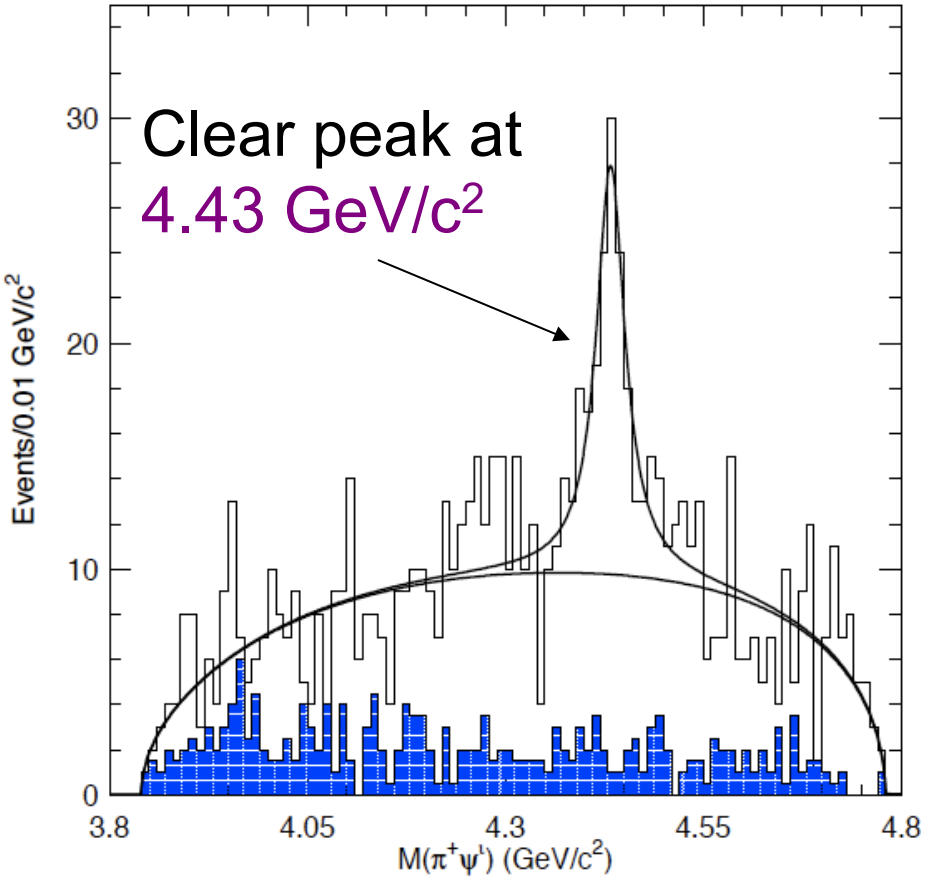


$Br(B^+ \to X(3872)K^+) < 2.7 \times 10^{-4}$ ($< 3.2 \times 10^{-4}$ in PDG2016) at 90% C.L.

$Z_c(4430)^{\pm}$ in $\psi(2S)\pi^{\pm}$ final state

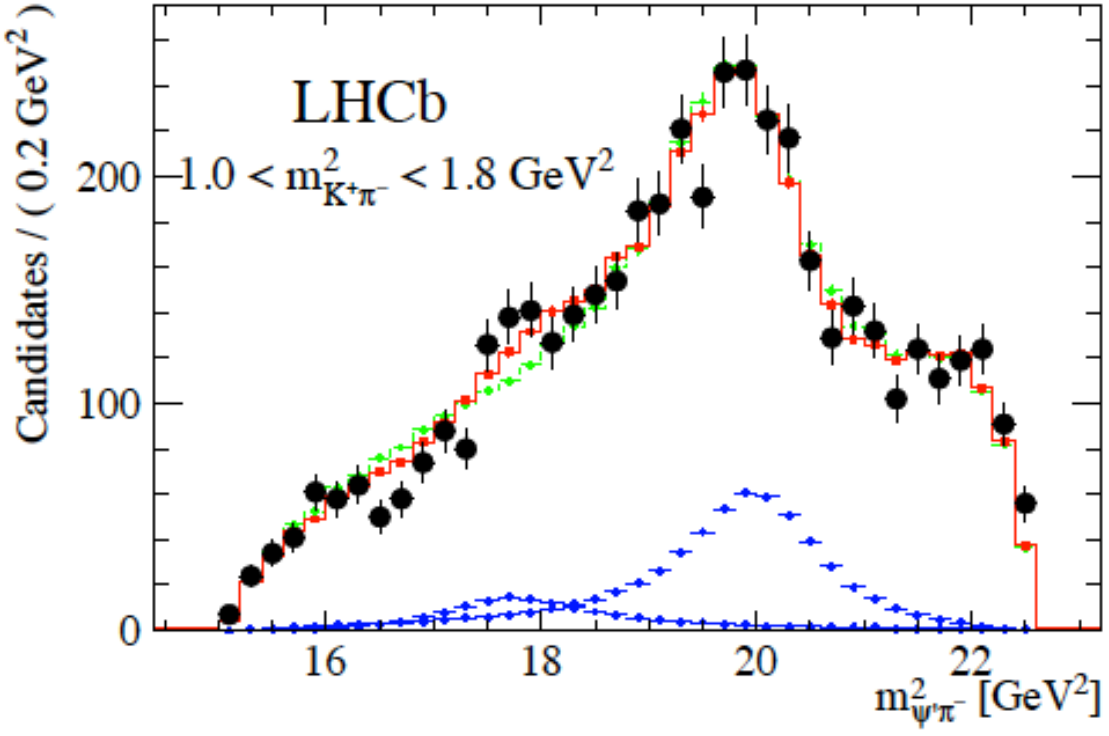


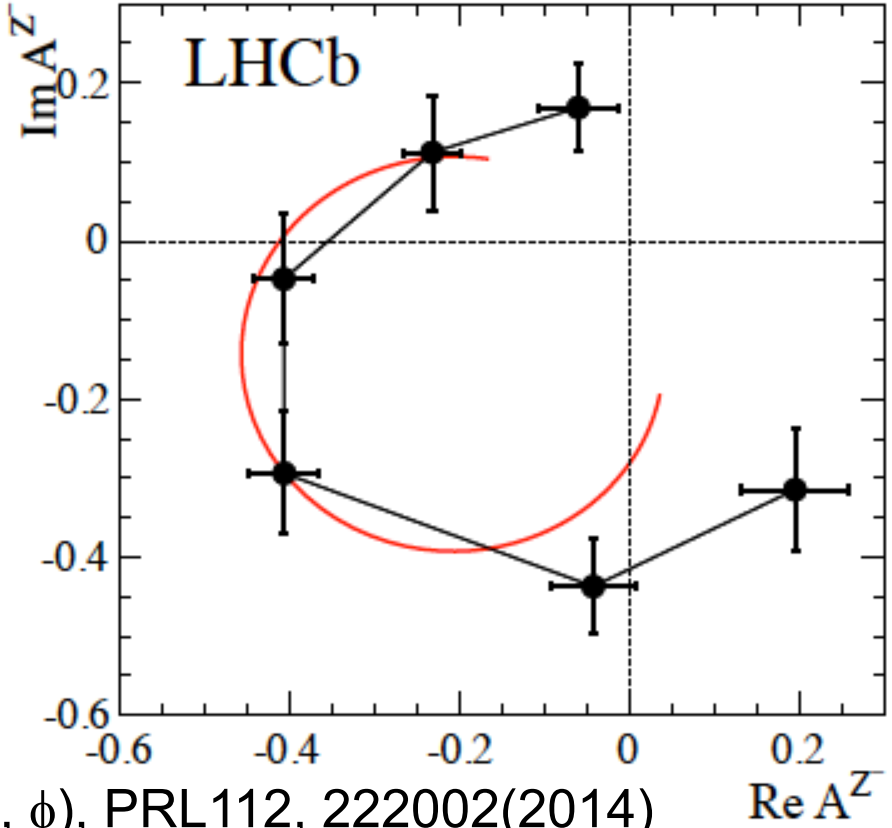
Reconstructing B → ψ(2S) $\pi^{\pm}$ K,
M(ψ(2S) $\pi^{\pm}$) is looked back.
Confirmed by LHCb
PRL112, 222002(2014)



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

Confirmation by LHCb





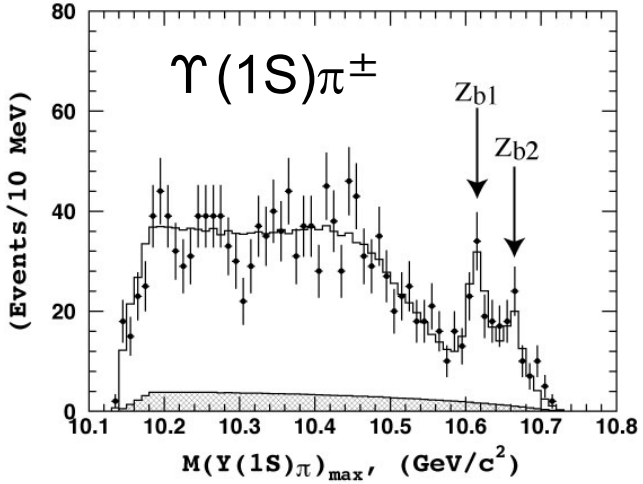
4D fit(M(ψ(2S)$\pi^{\pm}$), M(Kπ), cos$\theta_{\psi(2S)}$, ϕ), PRL112, 222002(2014)
Argand diagram gives a proof of resonance.
Such approach will be possible to study other states with Belle II statistics only.

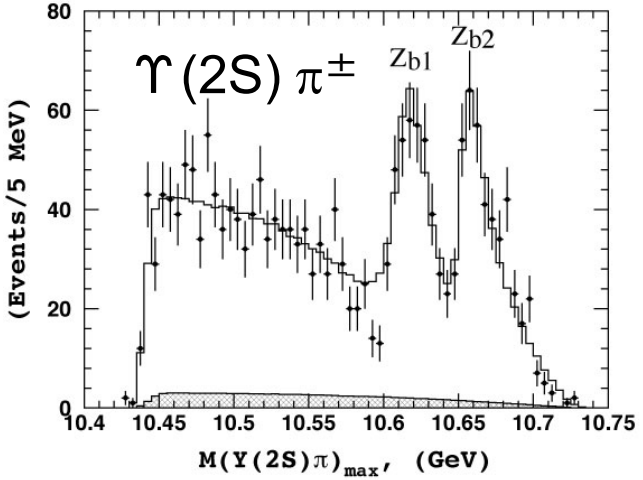
Charged states in $J^{PC}=1^{-}$ quarkonium-like decay above open bottom/charm meson pair thresholds.

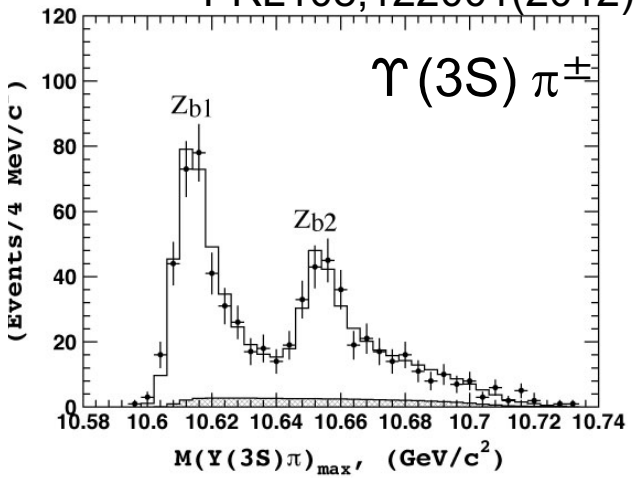
$Z_b(10610)^{\pm}$, $Z_b(10650)^{\pm}$ at $\Upsilon(10860)$ and $Z_c(3900)^{\pm}$ at Y(4260)

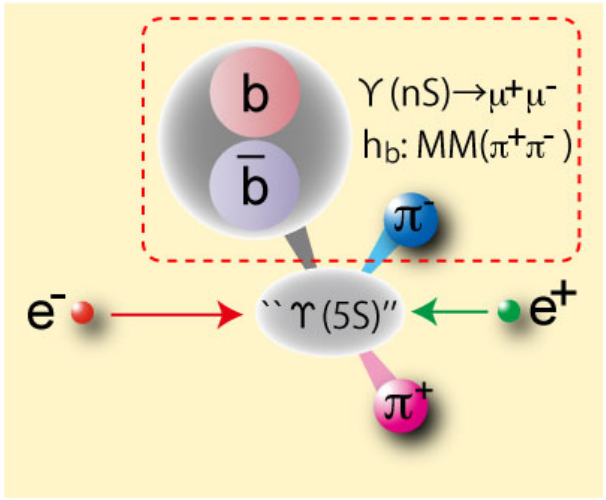
Two $Z_b^{\pm}$ states seen in all bottomonium $\pi^{\pm}$ systems at $\Upsilon(10860)$

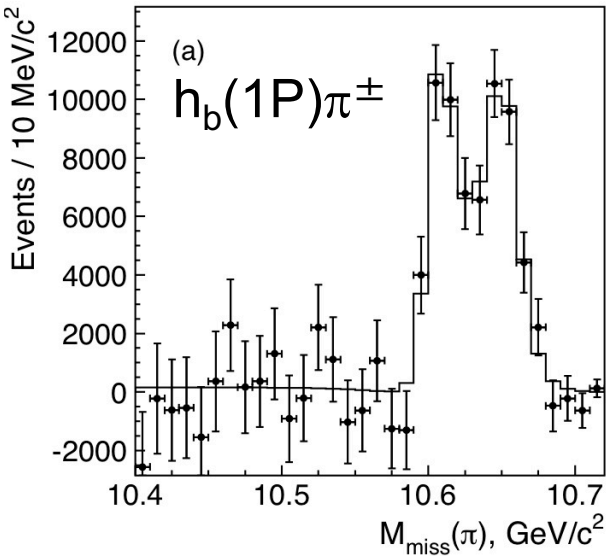
PRL108,122001(2012)

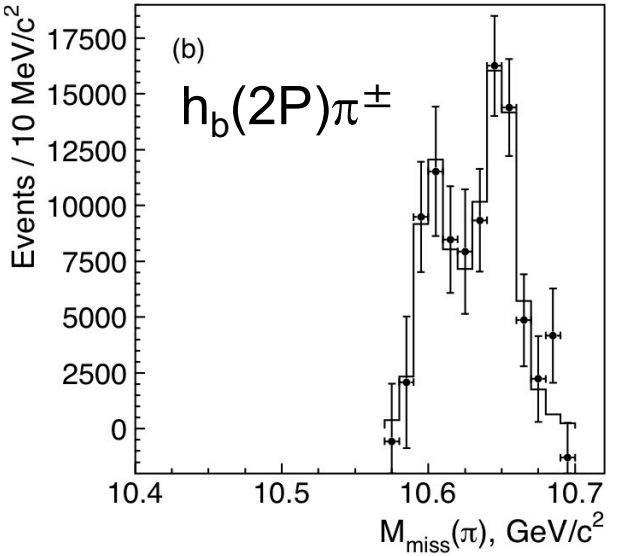








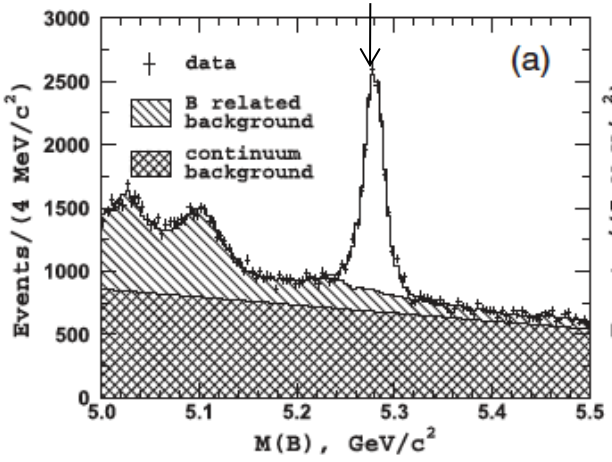




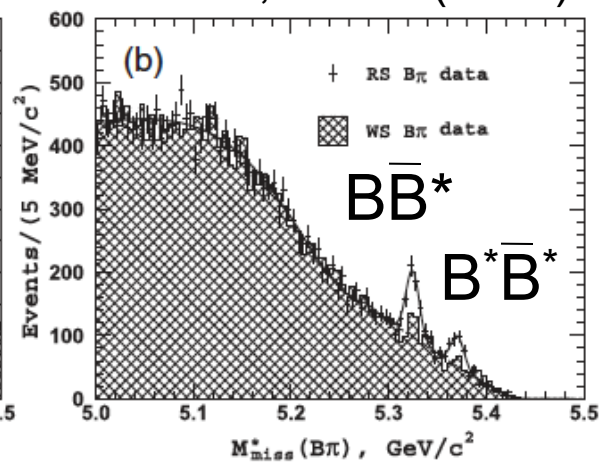
$Z_b(10610)^{\pm} \to B\bar{B}^*$, $Z_b(10650)^{\pm} \to B^*\bar{B}^*$

One B reconstructed

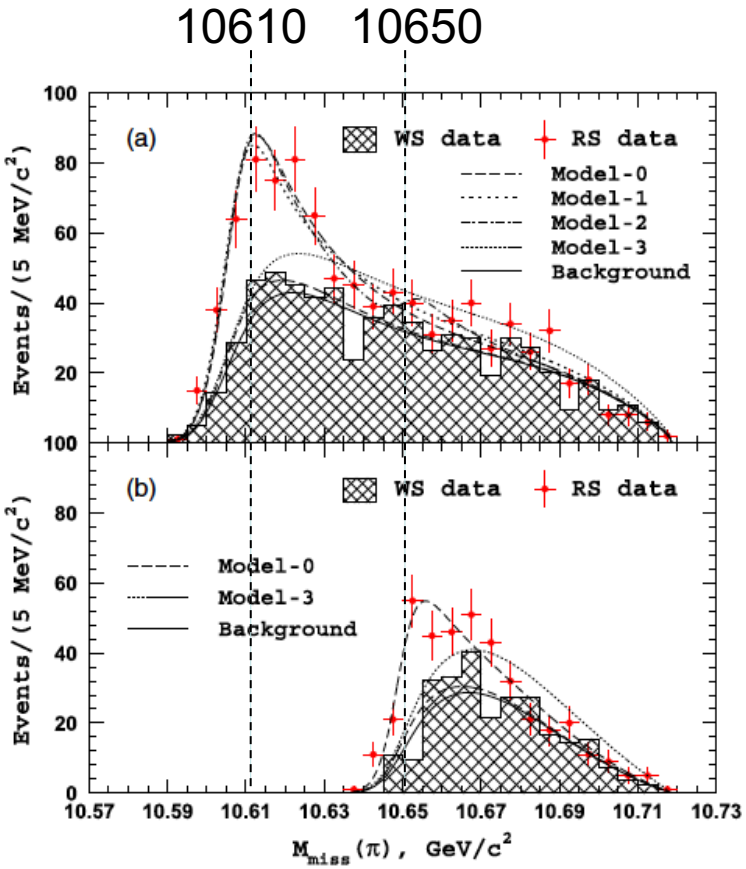
PRL116,212001(2016)



B cand. Mass (GeV)



MM(Bπ)



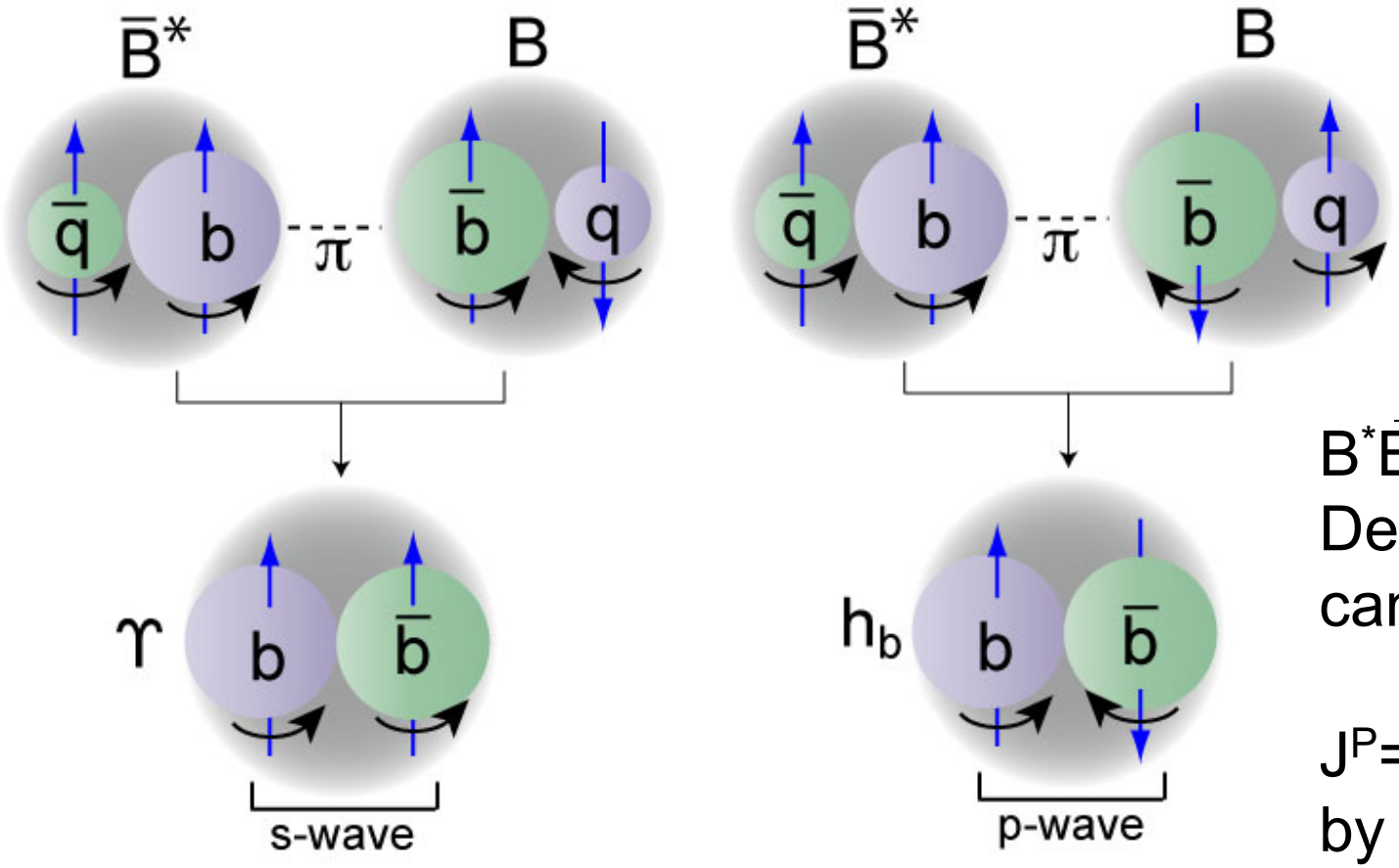
MM(π)=M($B^{(*)}B^*$)

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

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

Found to be dominant!

Molecular picture works



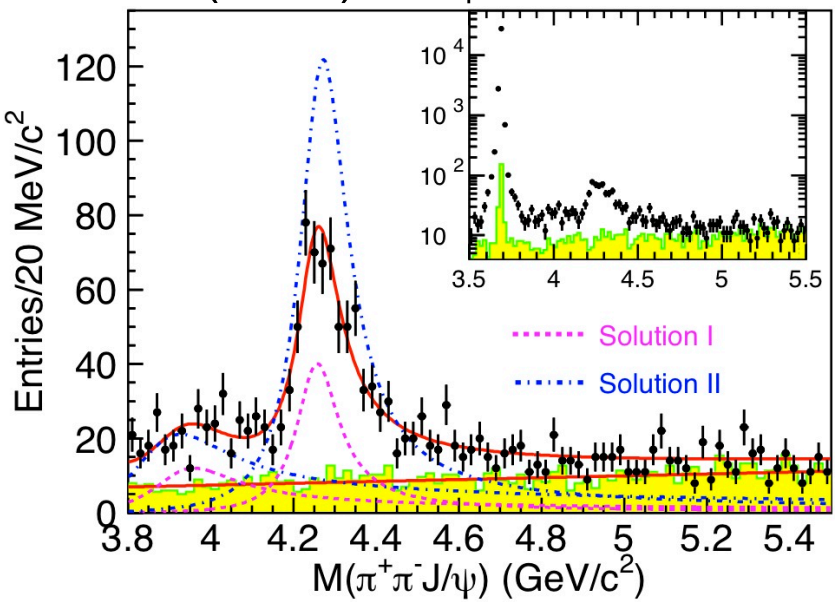
A.E.Bondar et al., PRD84,054010(2011)

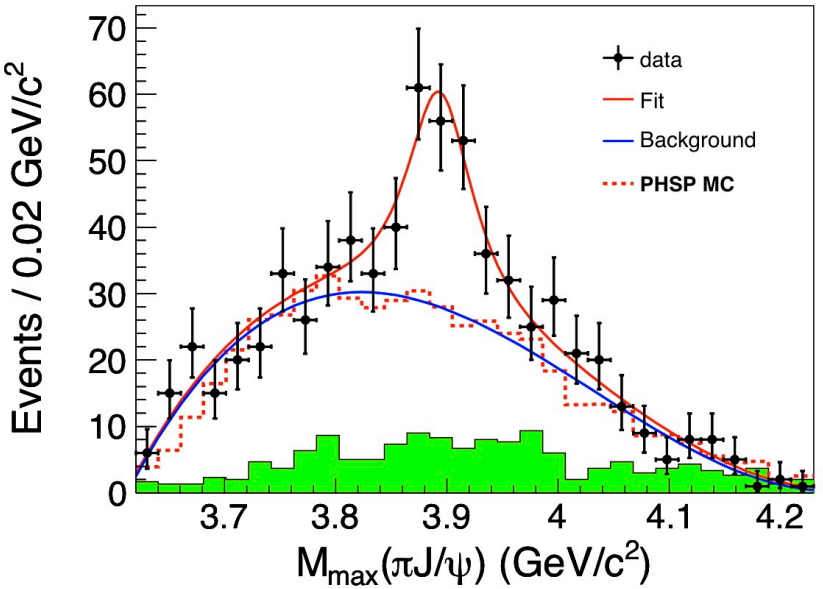
$B^*\bar{B}^{(*)}$ dominant Br. Decays to ϒ and h_b can co-exist.

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

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

$Y(4260)\to J/\psi\pi^+\pi^-$ PRL110,252002(2013) $Z(3900)^{\pm}\to J/\psi\pi^{\pm}$





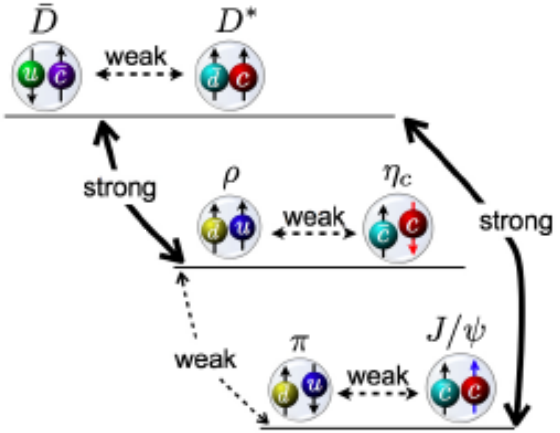
$J^{PC}=1^{--}$ state decaying to quarkonium $\pi^+\pi^-$ contains charged state as an intermediate!

PRD91,112007(2015)

Also $Z_c(4060)^{\pm}$ in $\psi(2S)\pi^{\pm}$ at $Y(4360)\to\psi(2S)\pi^+\pi^-$.

Lessons from these discoveries

- The decays of $J^{PC}=1^-$ states above open charm/bottom threshold contain charged state(s).
  - $Y(4260) \rightarrow Z_c(3900)^+\pi^-$
  - $\Upsilon(10860) \rightarrow Z_b(10610)^+\pi^-$ and $Z_b(10650)^+\pi^-$
- Near the meson-meson threshold, molecular state plays an important role.

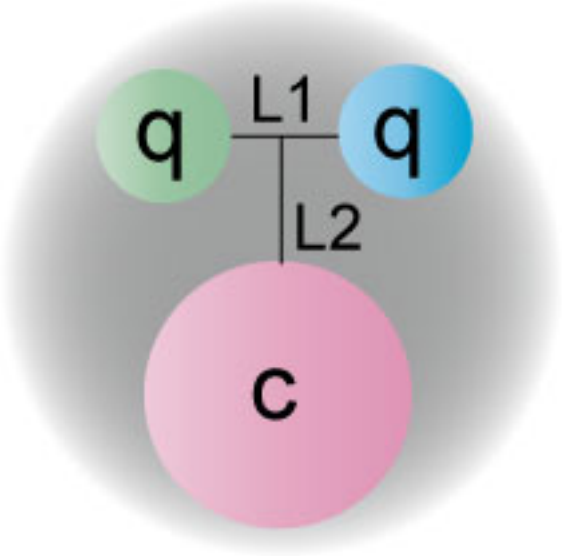


- HAL QCD simulation shows $Z_c(3900)^{\pm}$ is likely to be a "threshold cusp". PRL117,242001(2016)

It should be a natural extension ..

Charmed baryon(-like) states

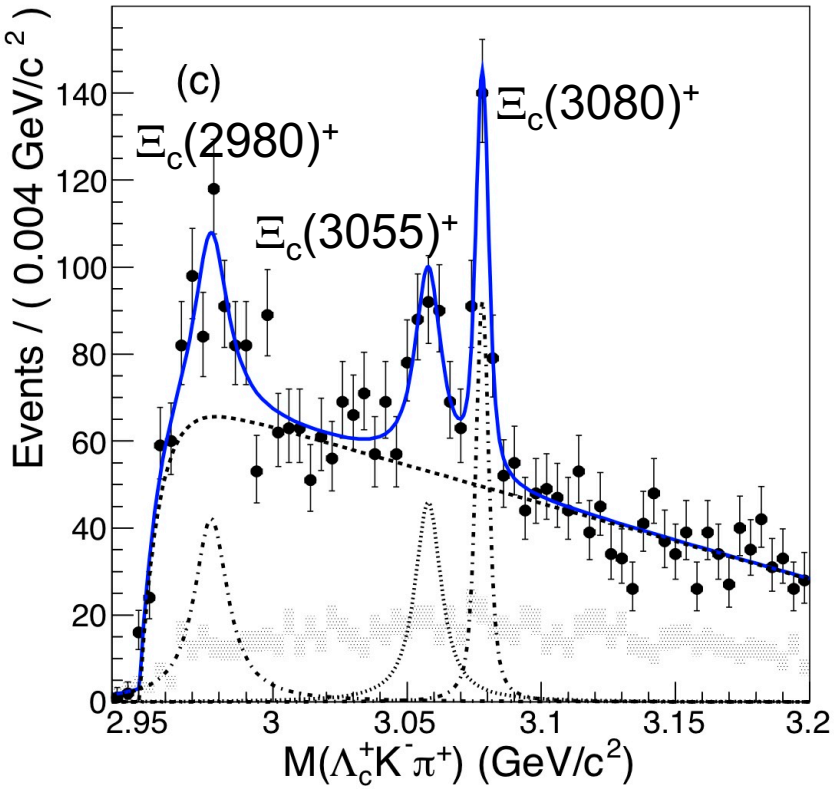
As for charm baryons



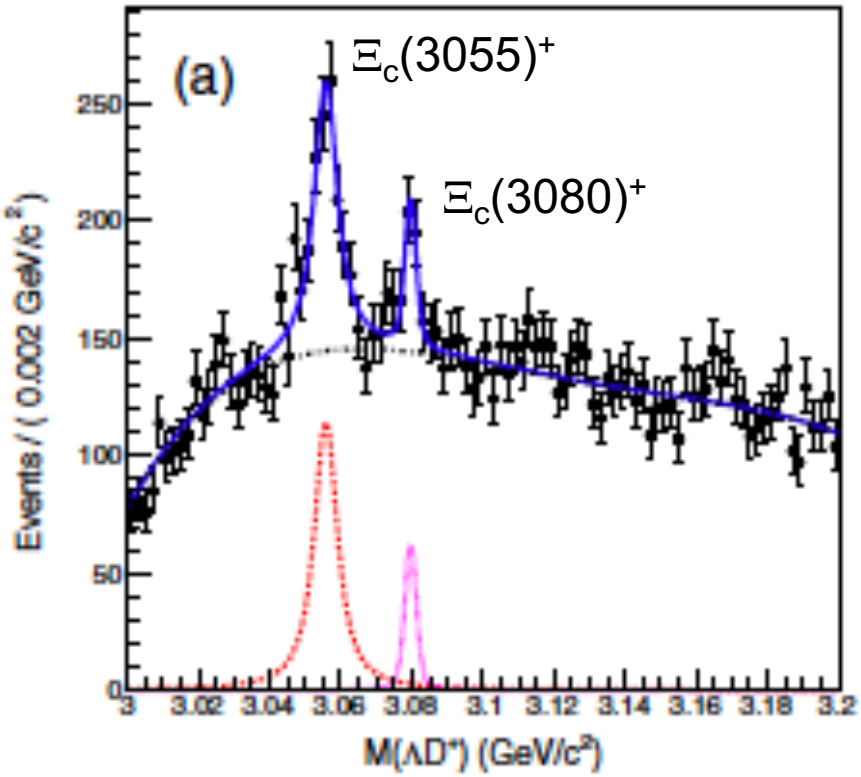
- Need to clarify “what are ordinary”.
- One of the constituent quarks is heavy, the remaining light quarks may behave “di-quark”; a good degree of freedom?.
- L_1 : ρ mode, L_2 : λ mode.
- Still limited knowledge about excited states $\rightarrow$ need to visit.
- Also think about possible hunting for an exotic.

Observation of excited states

PRD89,052003(2014)



PRD94,032002(2016)

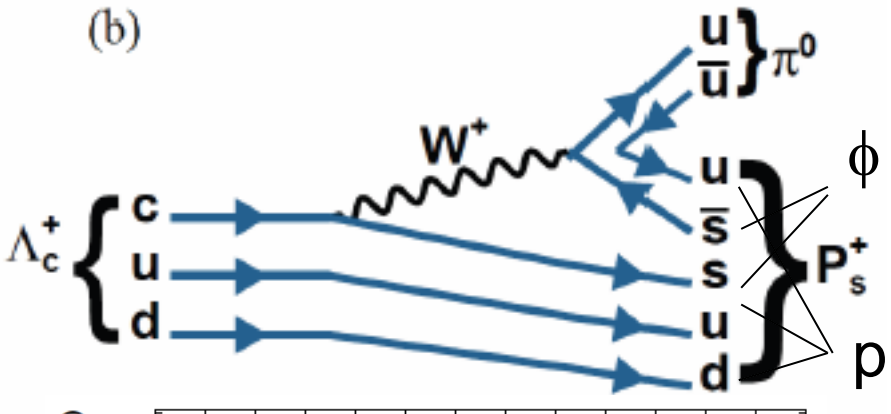


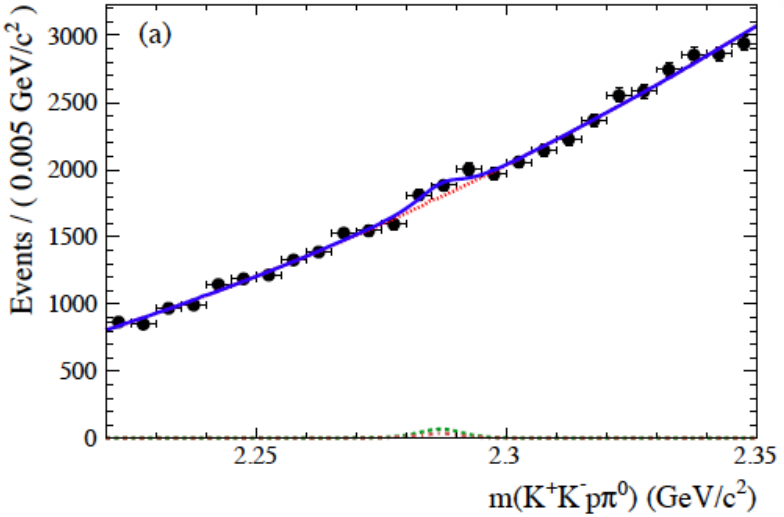
Both “charm baryon + light hadron” and “charm meson + baryon” modes being visited, very important input for theories.

Determination of J^P needs more data.

Pentaquark search in Λ_c decay

arXiv:1707.00089 to appear on PRD

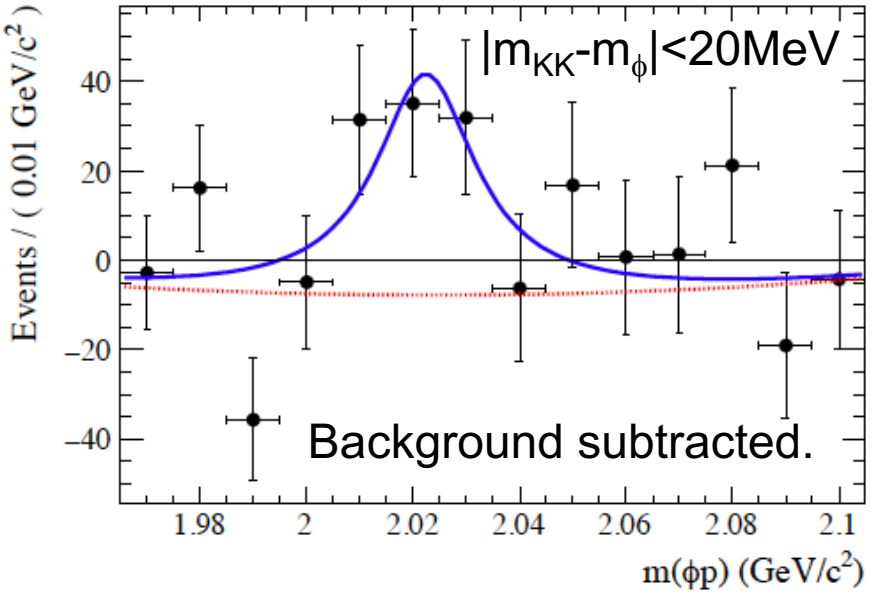




$$\mathcal{B}(\Lambda_c^+ \to \phi p \pi^0) < 15.3 \times 10^{-5}$$
$$\mathcal{B}(\Lambda_c^+ \to K^+K^- p\pi^0)_{\rm NR} < 6.3 \times 10^{-5}$$

@90% C.L.

Analogous to discovery of P_c states in Λ_b decay by LHCb.
PRL117,082003(2016)

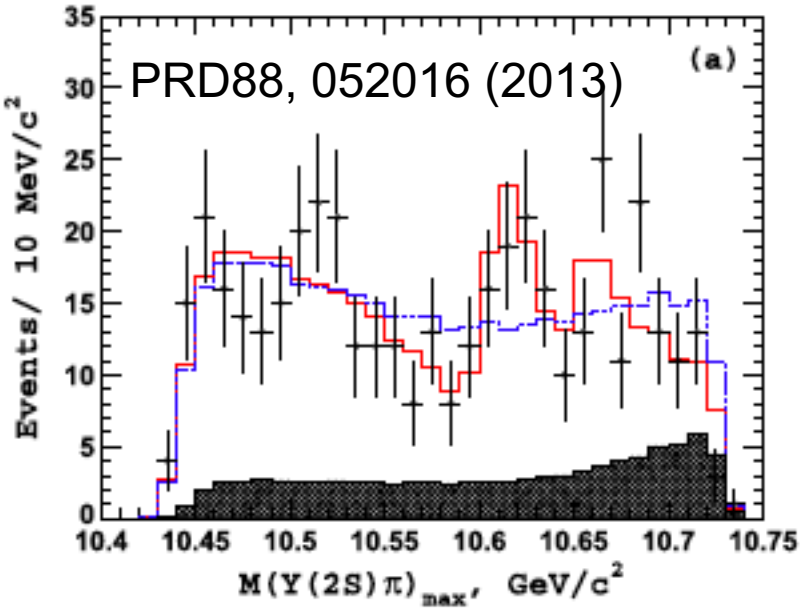


$$\mathcal{B}(\Lambda_c^+ \to P_s^+ \pi^0) \times \mathcal{B}(P_s^+ \to \phi p) < 8.3 \times 10^{-5}$$

@90% C.L.

Challenges with higher statistics

- Search for partner states



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

For example, in Z_b case,

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

↓

Higher statistics needed.

- Determination of quantum numbers

Summary

- Molecular picture plays important role near the threshold.
  - X(3872) : $D^0 D^{*0}$ and mixing with $\chi_{c1}(2P)$.
  - $Z_b(10610)^{\pm}$: $B \overline{B^*}$, $Z_b(10650)^{\pm}$: $B^* \overline{B^*}$
  - $Zc(3900)^{\pm}$: Cusp due to $D\overline{D^*} \rightleftarrows J/\psi\ \pi$ (and $\eta_c\ \pi$) transition according to the HAL QCD calculation.
- Activities to be extended to charm baryon(-like) system.
  - Started to identify excited states in different decay modes.
  - Pentaquark search in Λ_c decay performed.
- Need more data; mission at SuperKEKB/Belle II
  - For partner searches because of anticipated decay modes.
  - For determination of quantum numbers.
  - Argand diagram approach only possible with Belle II statistics.