Heavy hadron spectroscopy at Belle

Kenkichi Miyabayashi

(Nara Women's University)

Hadrons and Hadron Interactions in QCD 2015

2015 Mar. 2nd

Outline

- Advantage with heavy flavors in hadron spectroscopy
- KEKB e^+e^- collider and Belle detector
- Variety of recorded reactions
- Quarkonium(-like) states
  - X, Y and Z states in charmonium and bottomonium sectors
- Charm baryons
- Summary

Advantage of heavy flavors

- Light flavors (u,d,s) may mix;

example:

$$f' = \psi_8 \cos\theta - \psi_1 \sin\theta \quad \rightarrow \eta$$

$$f = \psi_8 \sin\theta + \psi_1 \cos\theta \quad \rightarrow \eta'$$

$$\psi_8 = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$$

$$\psi_1 = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$$

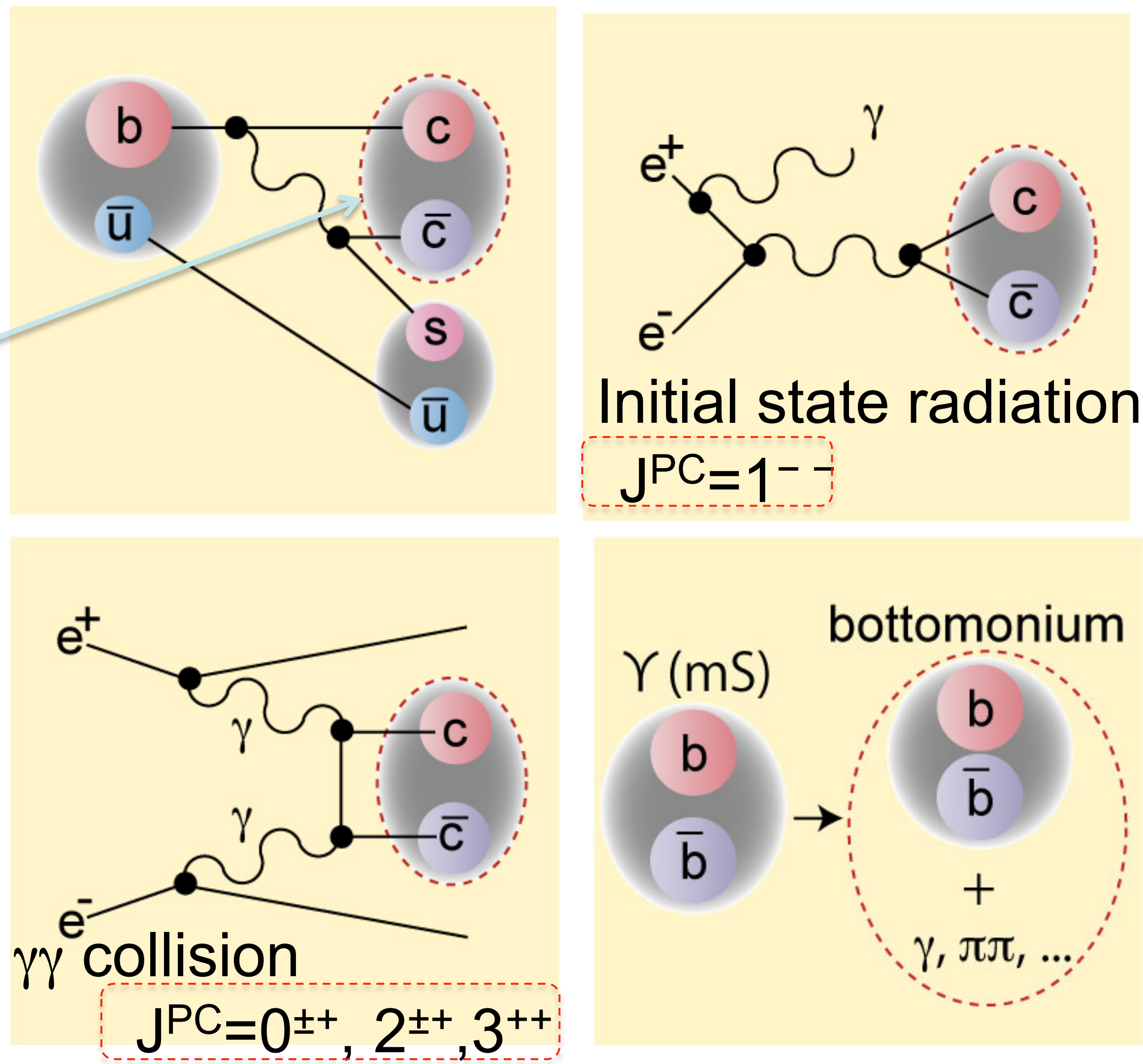
- Heavy, well-separated masses: relation between observed states and constituent quarks would be straight-forward.
- J/ψ, $\psi(2S) \rightarrow e^+e^-$ or $\mu^+\mu^-$, Υ(1S or 2S or 3S)$\rightarrow\mu^+\mu^-$: clean signature.

Variety of recorded reactions

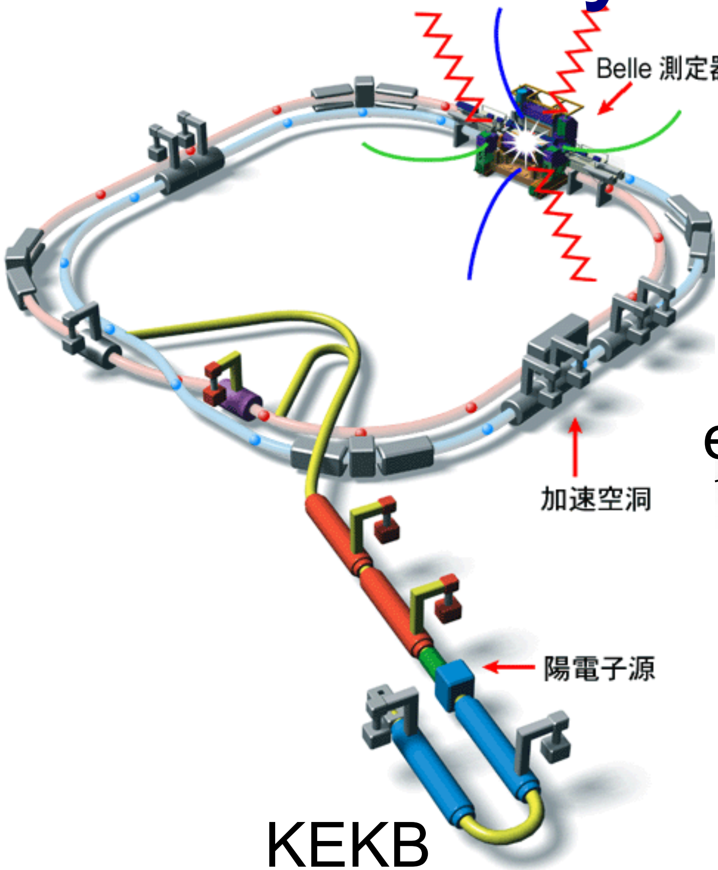
There are various processes to produce charmonium(-like) particles.

- In two-body B-decays, $J^{PC}=0^{-+}, 1^{--}, 1^{++}$ in factorization limit.

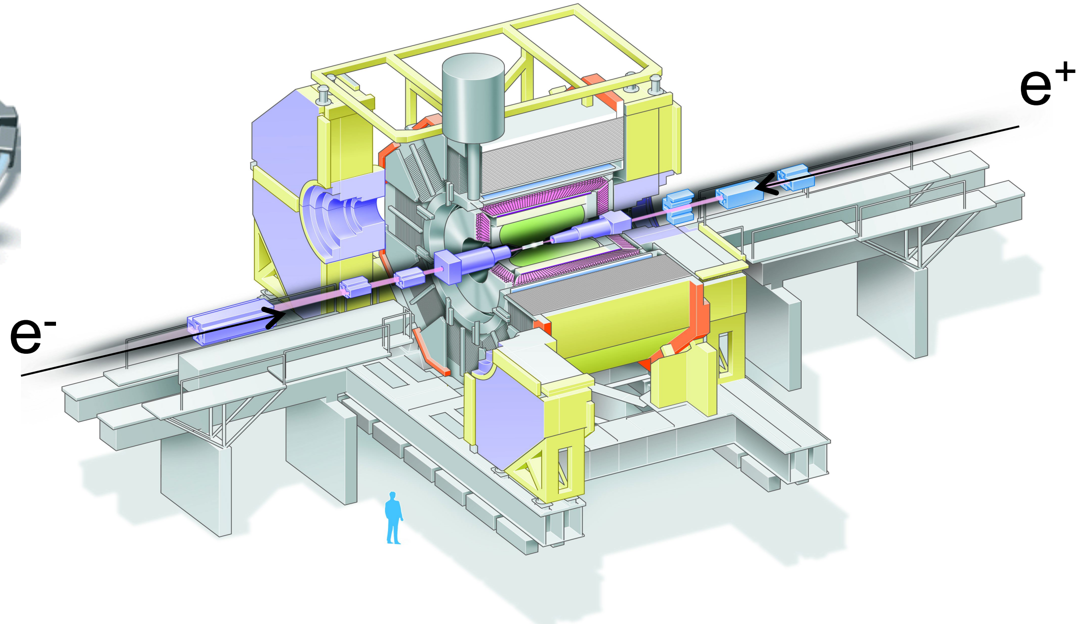
Allowed/favored quantum numbers are different depending on production processes.



KEKB/Belle : world highest luminosity as e^+e^- at ϒ region



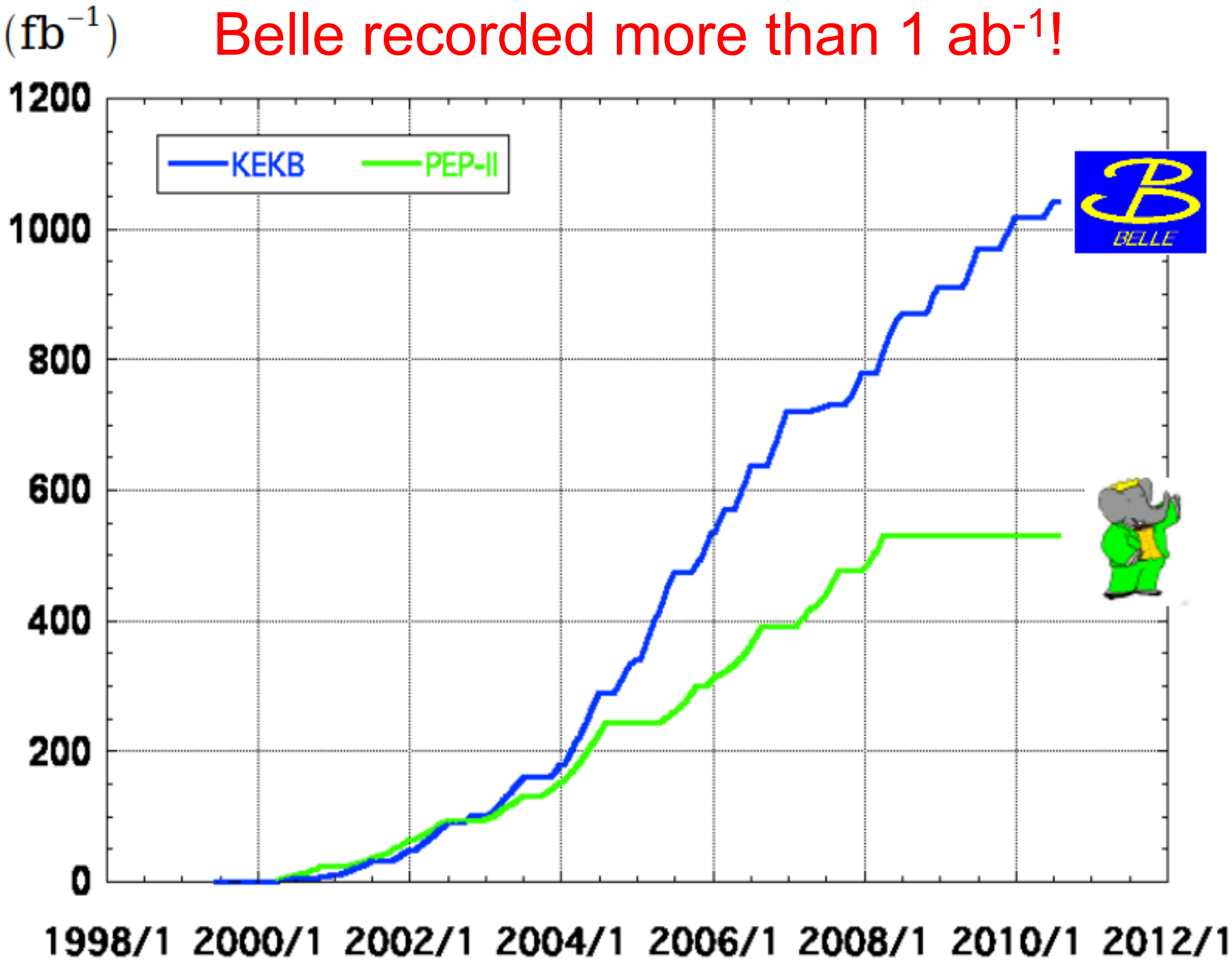
KEKB
8GeV×3.5GeV@ϒ(4S)



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:

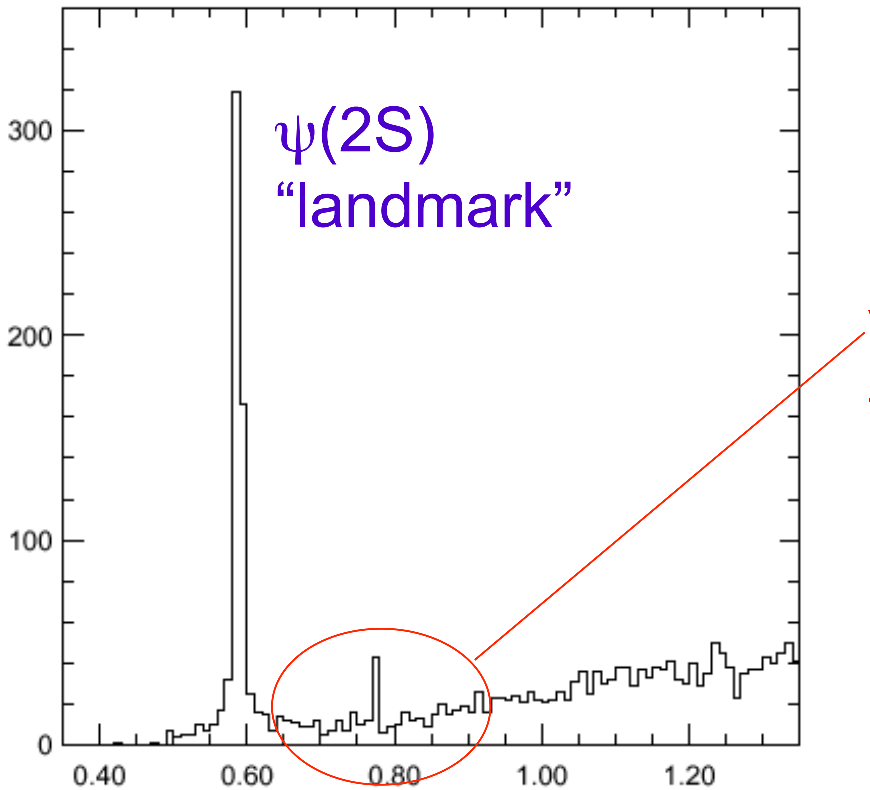
~ 54 fb^{-1}

Detector performance: great benefit

- Originally designed/constructed/operated for time-dependent CP violation measurement in B system.
- 4π general purpose spectrometer with
  - High momentum resolution, σ_p/p = 0.3%@1GeV/c.
  - Ability to detect γ down to 30 MeV.
  - Good γ energy resolution, σ_M =5MeV for $\pi^0\rightarrow\gamma\gamma$.
  - Lepton identification capability, ε>0.9, fake<0.01.
  - K/π/p separation capability, ε~0.9, fake<0.1.
  - Excellent B decay vertex reconstruction, $\sigma_{\Delta z}$ =80μm.

All these features led us to a lot of discoveries

First sensation was already 12 years ago; X(3872)



$M_{\pi\pi ll} - M_{ll}$ (GeV)

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

Look this system invariant mass.

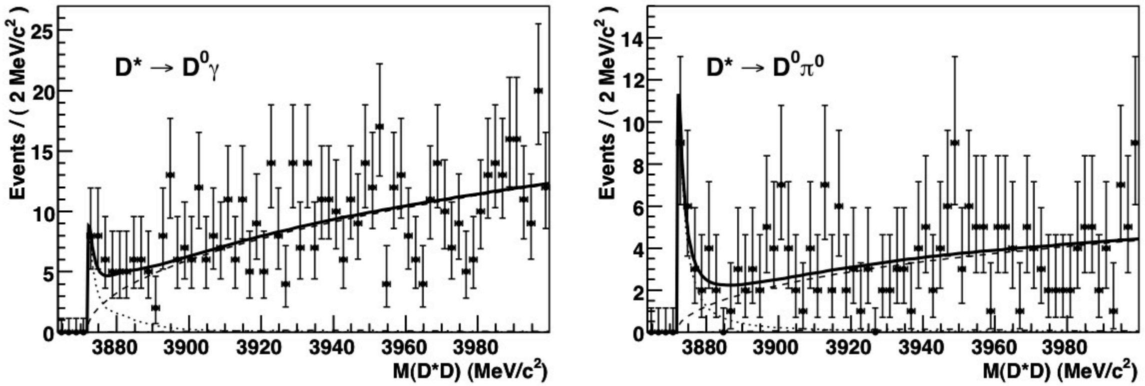
Very narrow peak is there, above $D\bar{D}$ threshold!

Many things have been done, still actively discussed object.

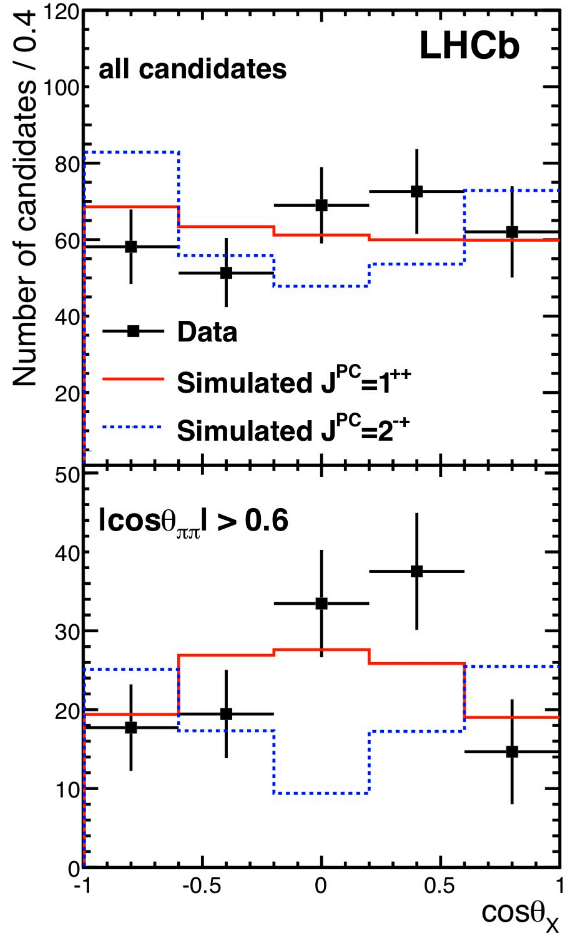
Belle, 152M $B\bar{B}$, PRL91,261801(2003)

More information about X(3872)

PRD81, 031103(2010)



PRL110, 222001(2013)

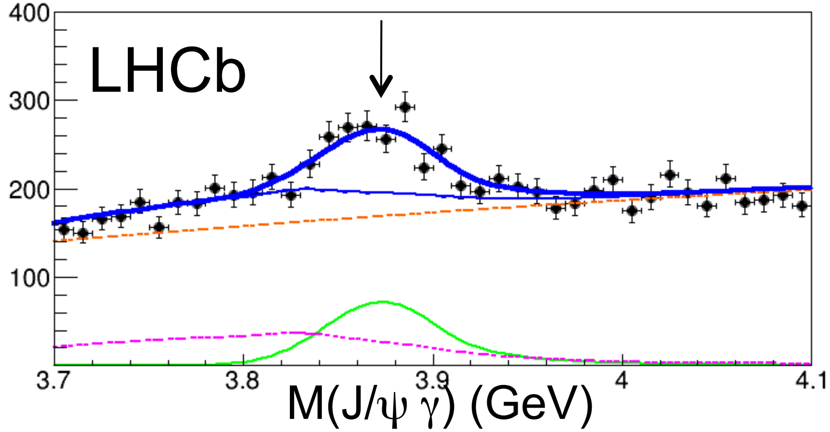


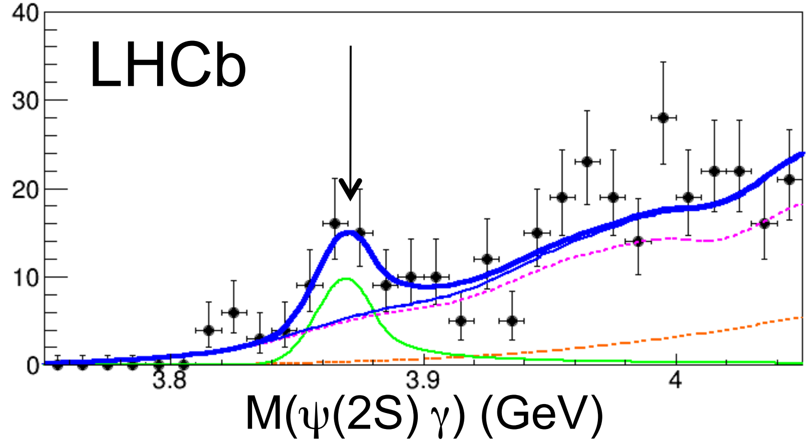
$X(3872) \rightarrow D^0\overline{D}^{*0}$ seen.
$Br(X(3872) \rightarrow D^0\overline{D}^{*0})$ is about $Br(X(3872) \rightarrow J/\psi\ \pi^+\pi^-) \times 10$.

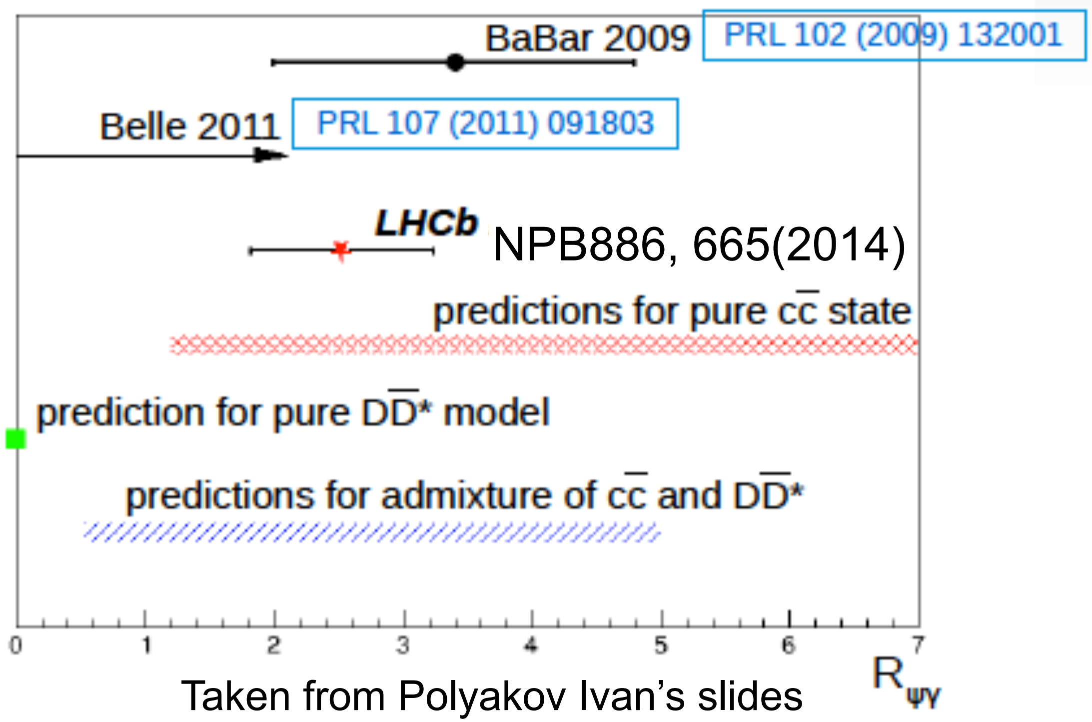
Determined to be $J^{PC}=1^{++}$ (Belle, BaBar, CDF, LHCb) by $J/\psi\ \pi^+\pi^-$ angular distribution.

LHCb visited radiative decay

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

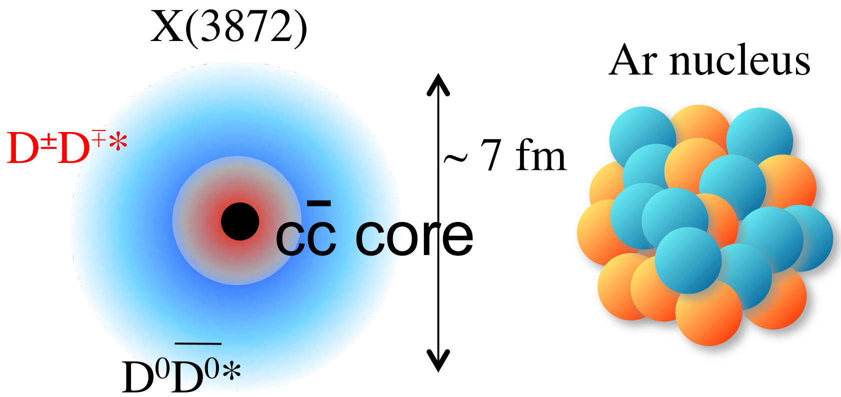






Taken from Polyakov Ivan's slides in Moriond QCD

Admixture : most plausible interpretation for X(3872)



S.Takeuchi, K.Shimizu and M.Takizawa, arXiv:1408.0973

No signature for
- charged partner in $J/\psi\ \pi^+\pi^0$.
- C=-1 partner in $J/\psi\ \eta$ and $\chi_{c1}\ \gamma$.

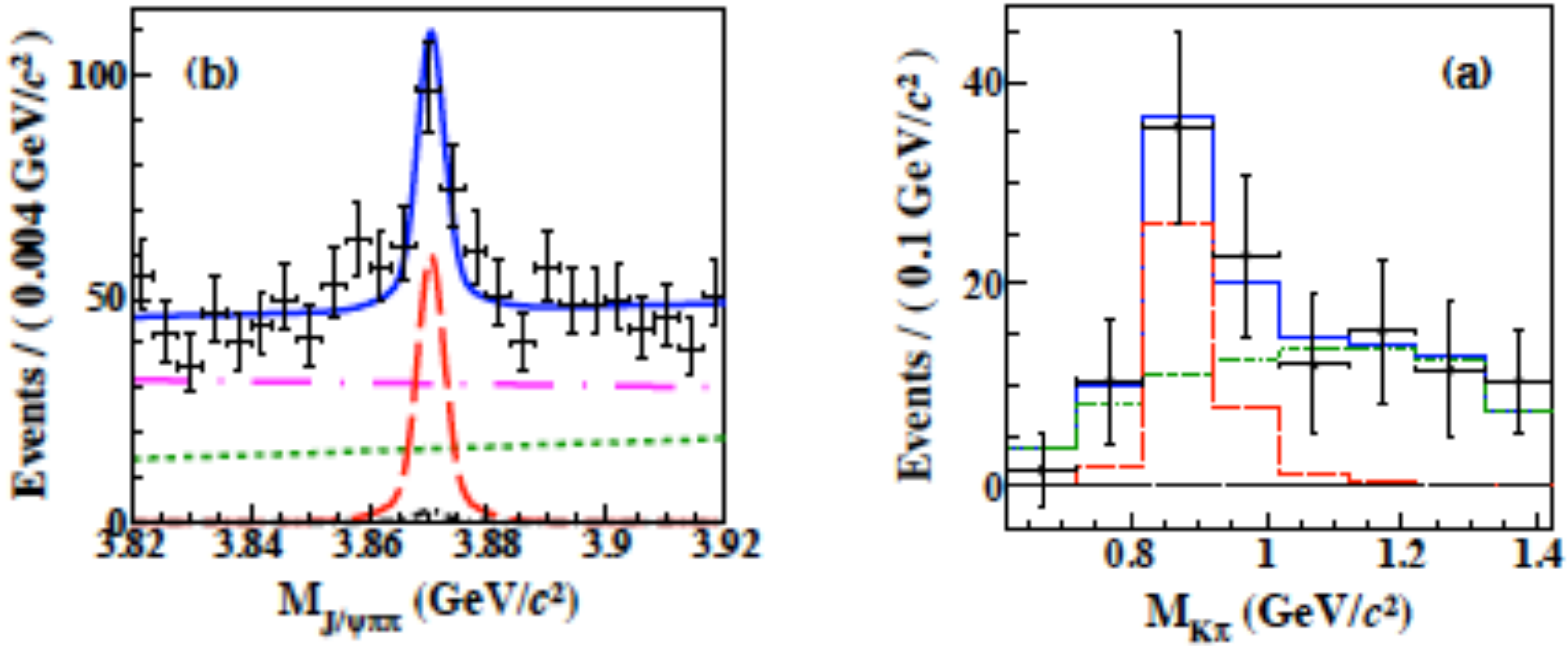
→ most likely, isospin=0.
→ disfavor tetraquark hypothesis.

$D\overline{D}^*$ molecule is mixing with the same J^{PC} $c\bar{c}$, $\chi_{c1}(2P)$ (yet unseen).
→can explain $Br(X \to D^0\overline{D}^{*0})/Br(X \to J/\psi\ \pi^+\pi^-)$ is about 10.
(pure molecule case, to be about 1000).
→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.

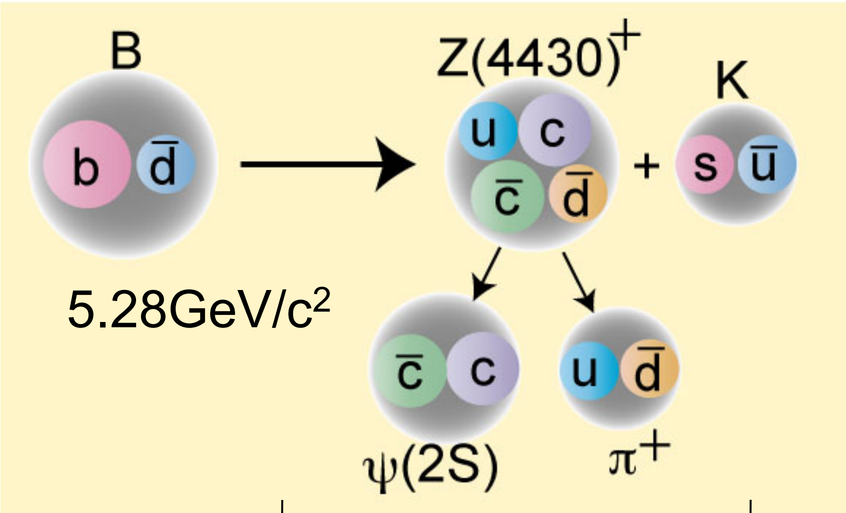
Additional recent knowledge

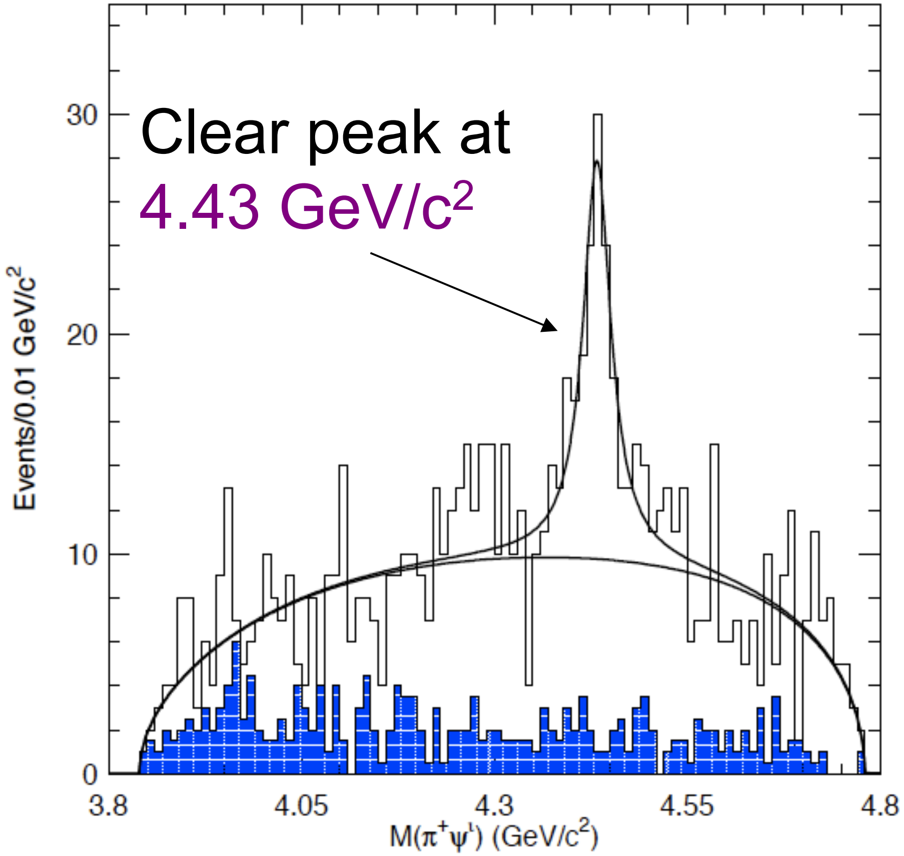
PRD 90, 112009 (2014)



$B^0 \to X(3872)\, K^-\pi^+$ has been observed in $X(3872) \to J/\psi\ \pi^+\pi^-$.
Fraction of $B^0 \to X(3872)\, K^{*0}$ is small, different feature from ordinary $J^{PC}=1^{++}$ charmonium = χ_{c1}.

Z(4430)$^+$ in $\psi(2S)\pi^\pm$ final state



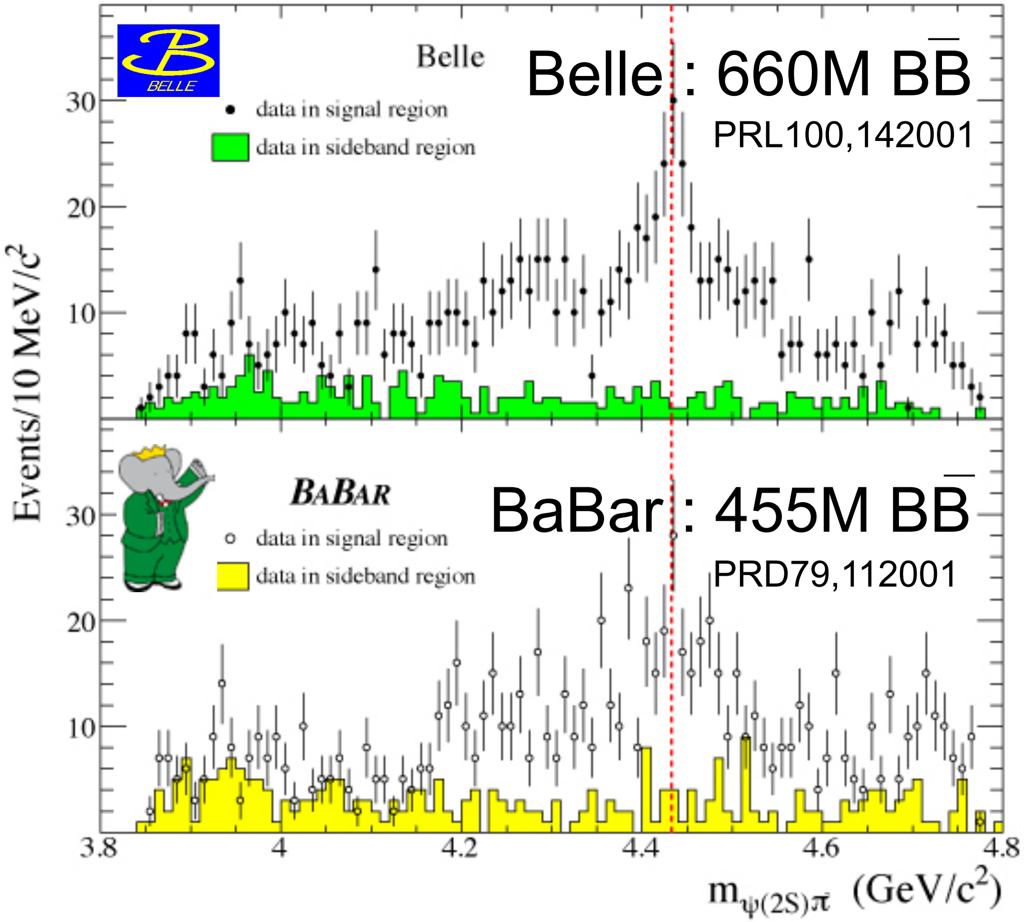


Reconstructing B $\rightarrow \psi(2S)\ \pi^\pm$ K,
M($\psi(2S)\ \pi^\pm$) is looked back.

It is charged and contains $c\bar{c}$, at least 4 constituents are necessary.

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

Situation at current B-factories

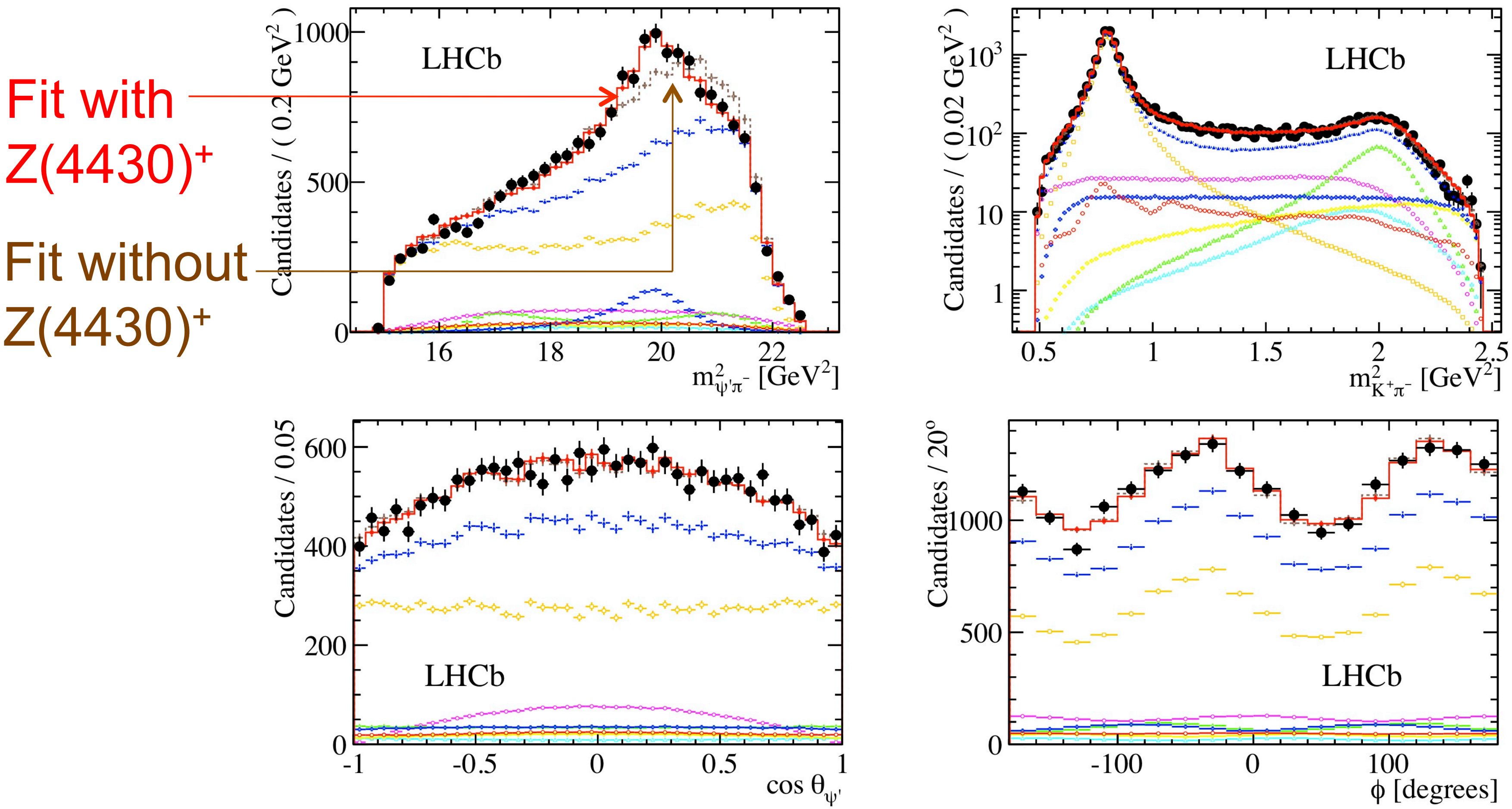


Significant signal at Belle
v.s.
Only hint with 1.9σ at BaBar

Belle's Dalitz plot analysis confirmed a resonance at 4430 MeV;PRD80 031104, (2009).

Statistically, both are not contradicting with each other, but clear answer is to be given by higher statistics data.

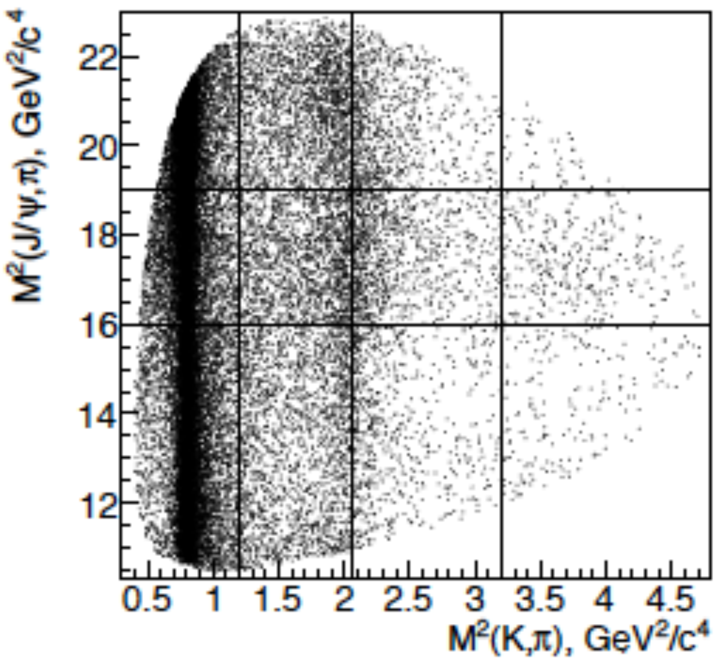
LHCb confirmed Z(4430)$^+$

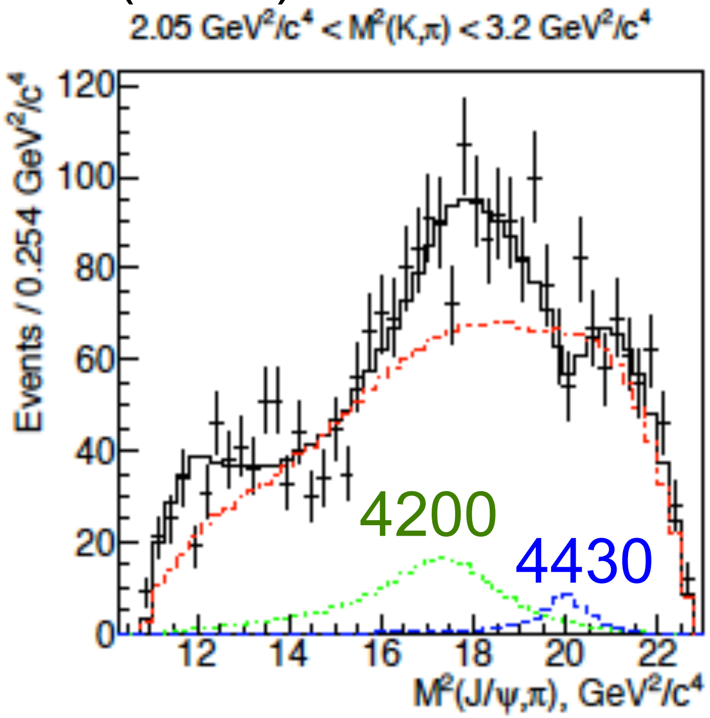


4D fit(M(ψ(2S)$\pi^{\pm}$), M(Kπ), cos$\theta_{\psi(2S)}$, ϕ), PRL112, 222002(2014)
Z(4430)$^+$ interpretation is not as established as X(3872).

$J/\psi\ \pi^+$ system in $\bar{B}^0 \rightarrow J/\psi \pi^+ K^-$

PRD90, 112009 (2014)



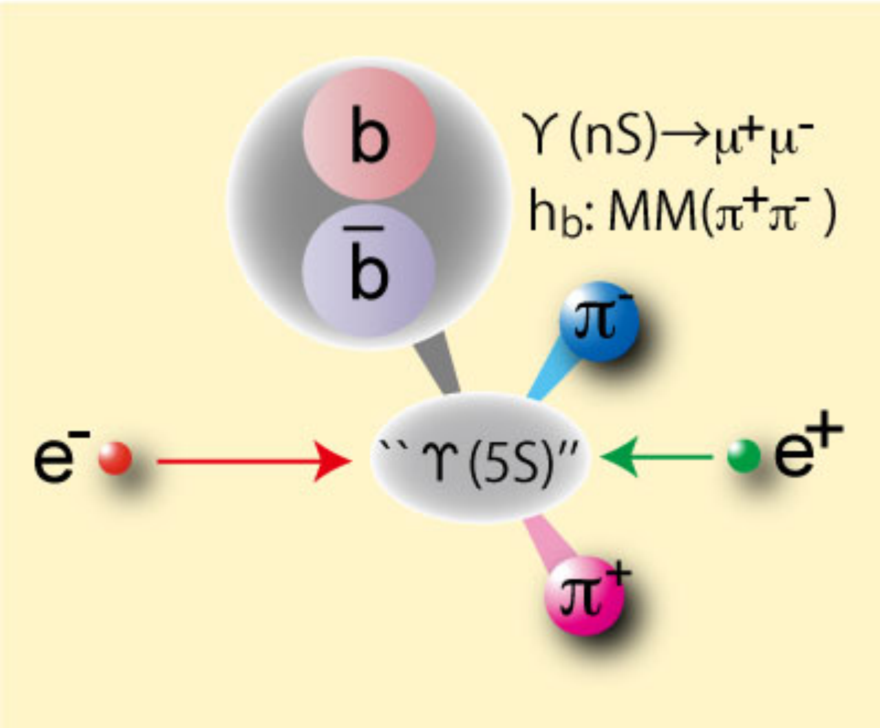


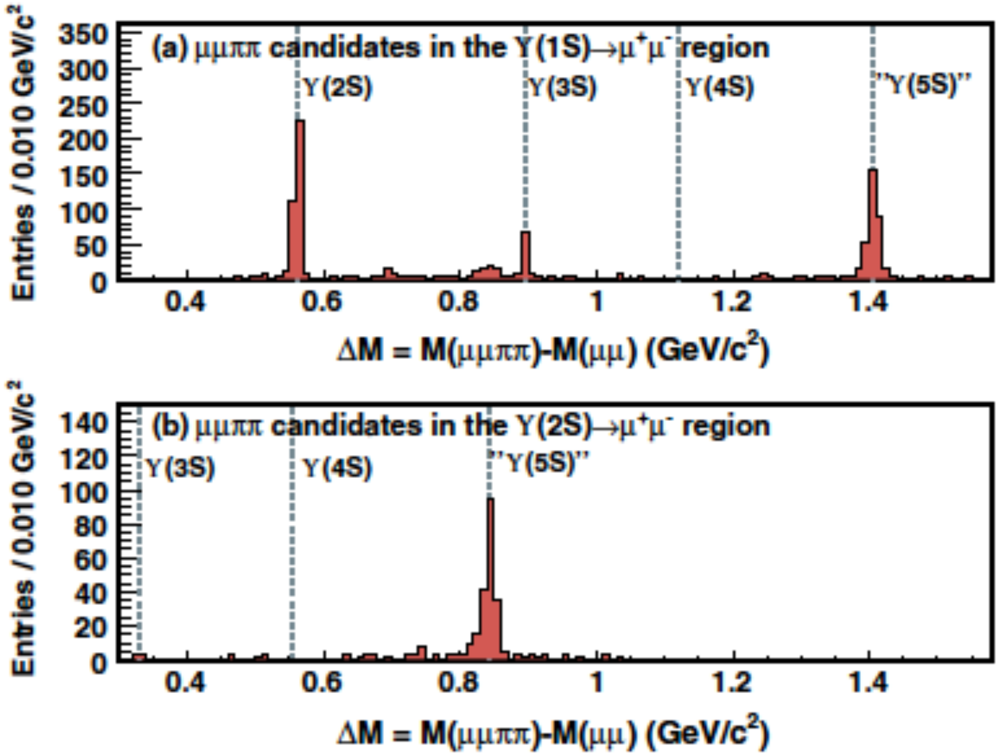
One more charged state observed, $J^P=1^+$

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

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

Surprise in bottomonium sector



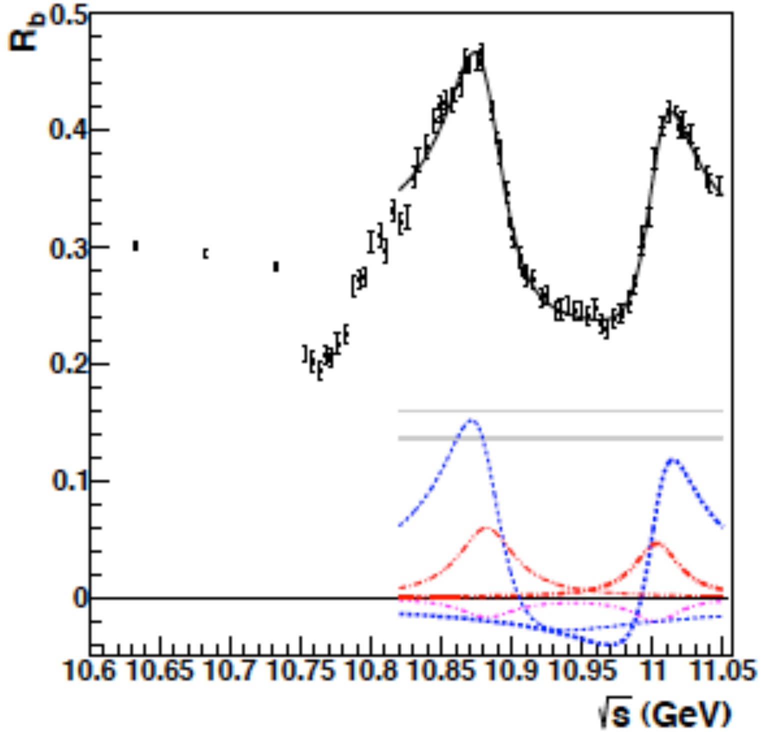


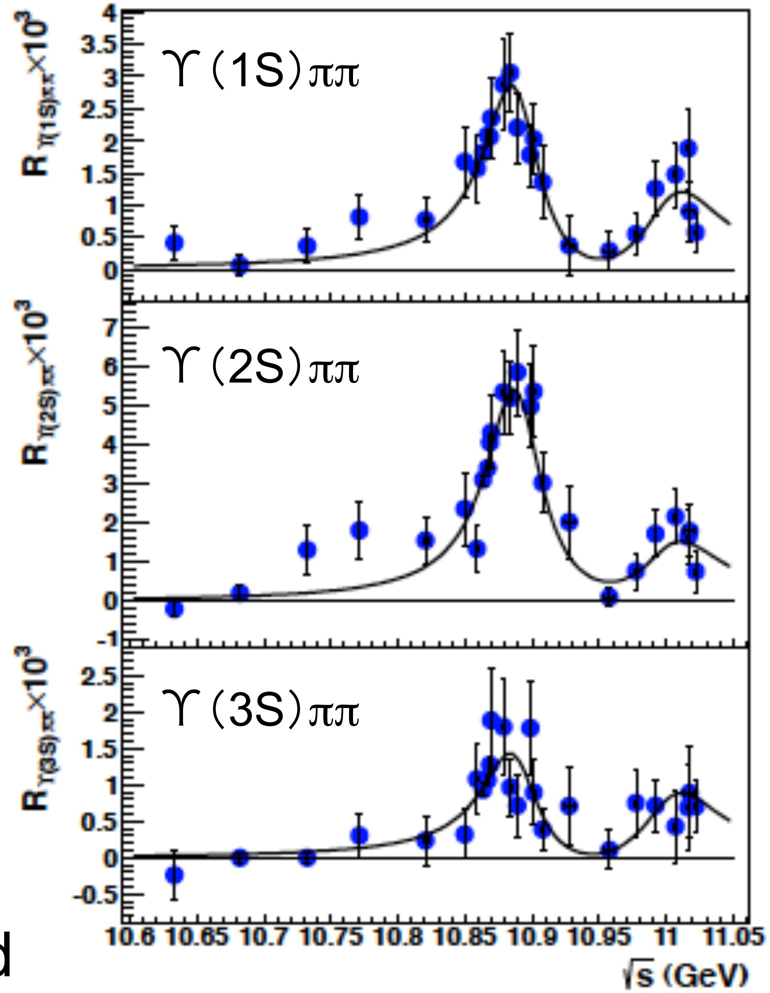
At Υ(5S)(@10880MeV), Υ(ns) $\pi^+\pi^-$ (n=1,2,3) production rate is 2 order of magnitude larger than Υ(4s) state.

PRL100,112001(2008)

Energy scan performed

arXiv:1501.01137

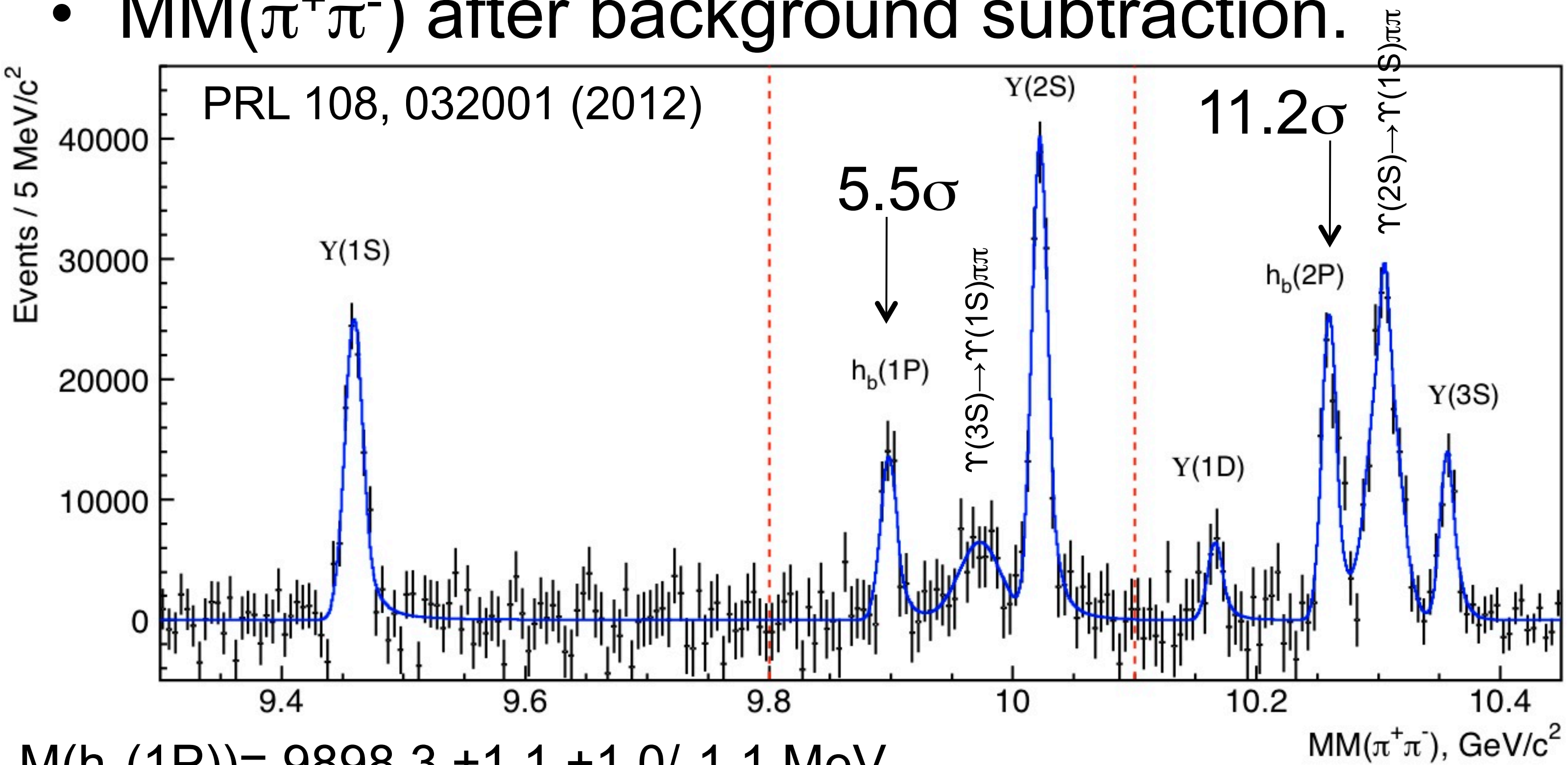




ϒ(nS) $\pi^+\pi^-$ also show peak around 10880 MeV.
Different feature from around ϒ(4S) (10580 MeV).

Observation of $h_b(1P, 2P)$ in E_{cms}=10880 MeV data

- $MM(\pi^+\pi^-)$ after background subtraction.



$M(h_b(1P))$= 9898.3 ±1.1 +1.0/-1.1 MeV

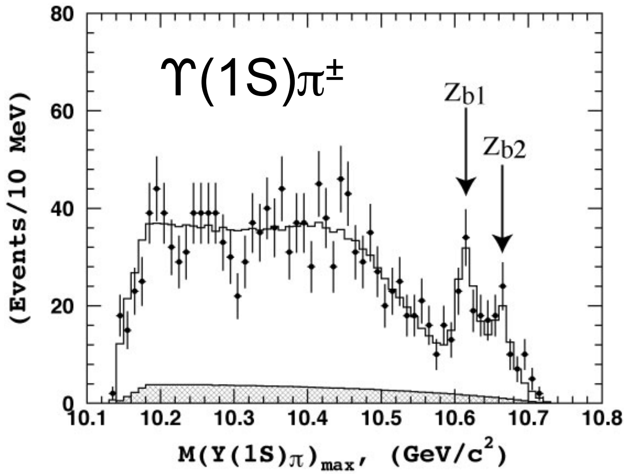
$M(h_b(2P))$=10259.8 ±0.6 +1.4/-1.0 MeV

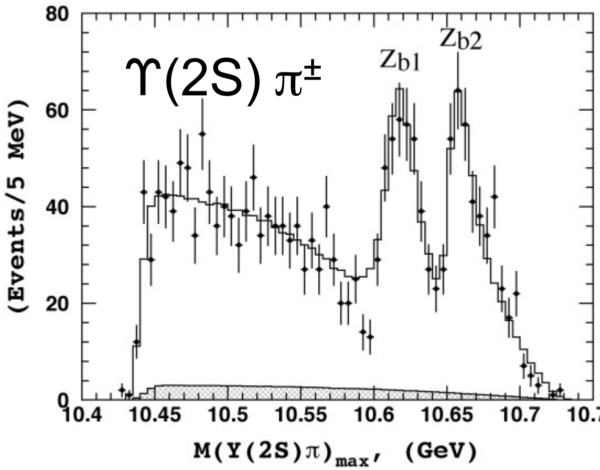
$R(h_b(nP)\pi^+\pi^-)/R(\Upsilon(2S)\ \pi^+\pi^-)$=0.46±0.08 +0.07/-0.12, higher than expected.

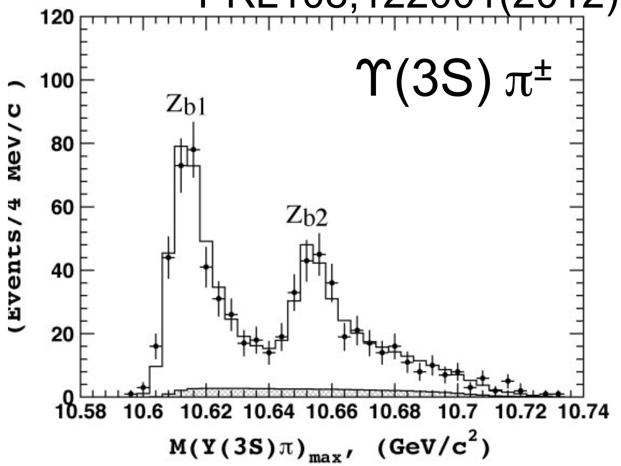
(For example, no $h_b(nP)$ signal in $\Upsilon(4S)$ data.)

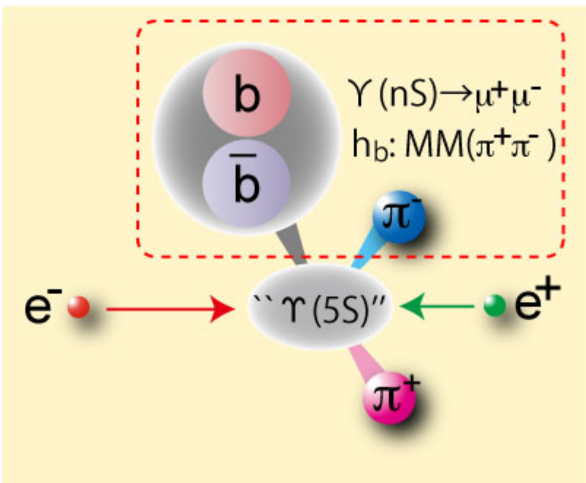
Two charged states, $Z_b(10610)^+$ and $Z_b(10650)^+$

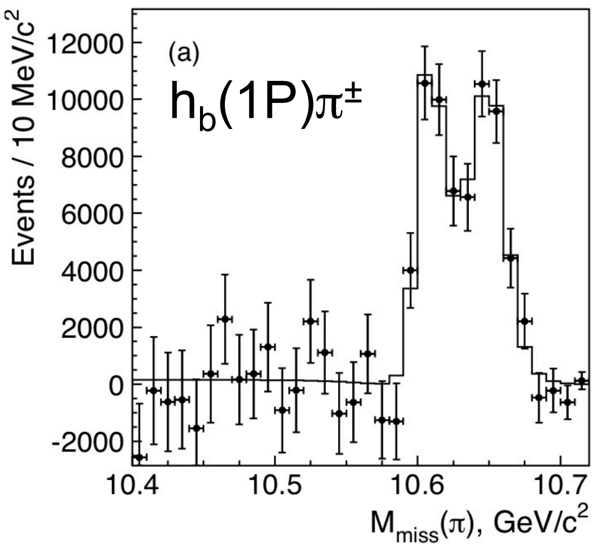
PRL108,122001(2012)

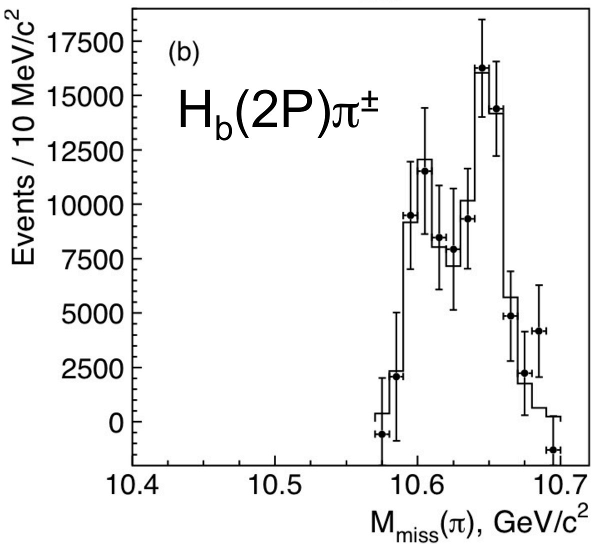




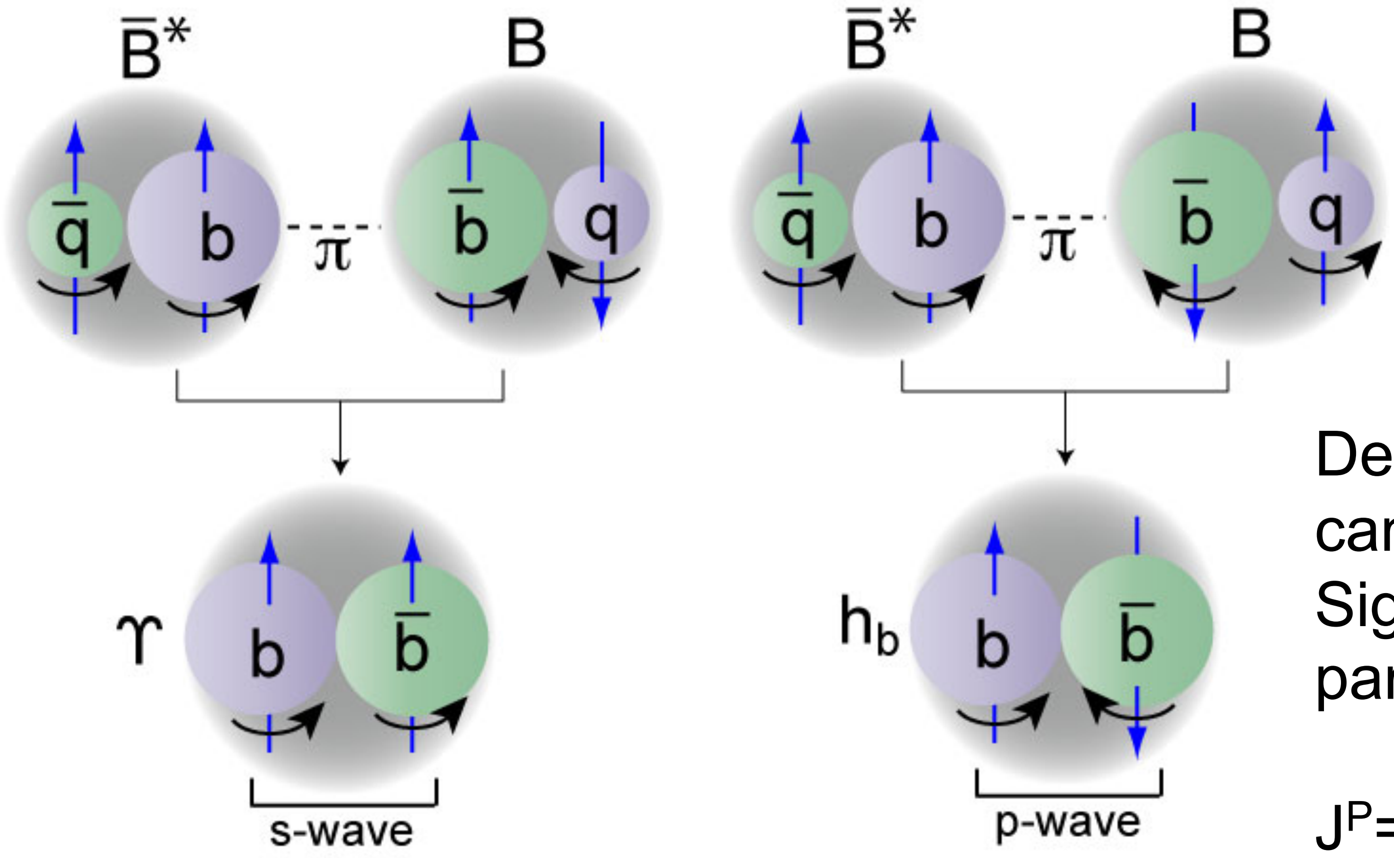








Molecule picture works



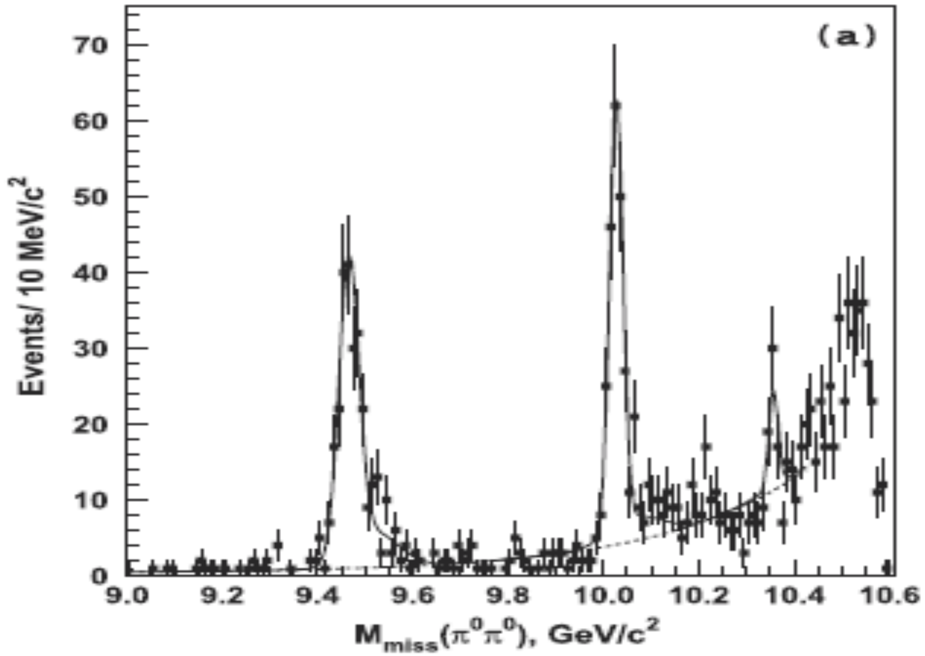
A.E.Bondar et al., PRD84,054010(2011)

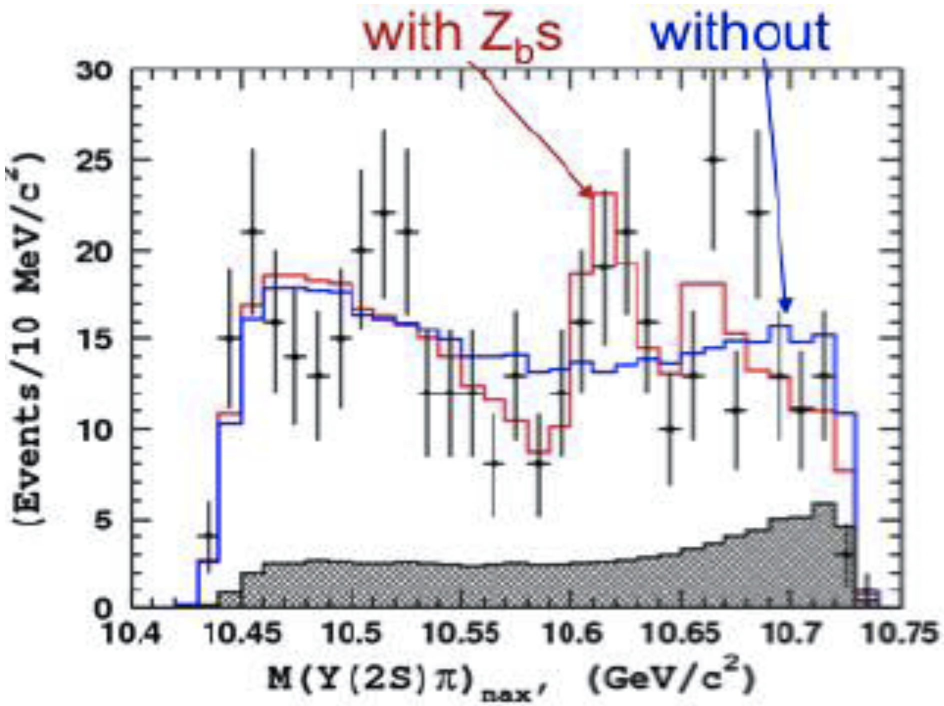
Decays to ϒ and h_b can co-exist.
Signature in $\bar{B}^*B^{(*)}$ partial recon. seen.

$J^P=1^+$ is supported by Dalitz analysis.
arXiv:1403.0992.

Neutral Partner of Z_b^0

PRD88, 052016 (2013)



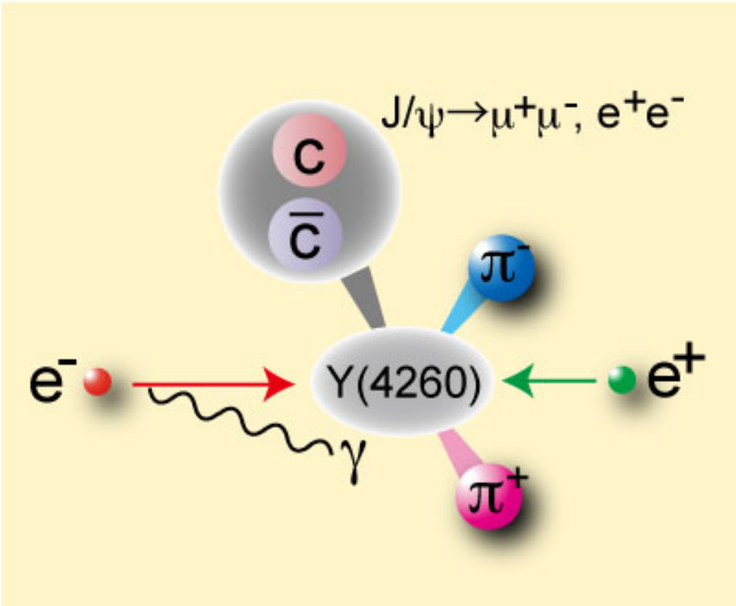


First observation of
$\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^0\pi^0$
Rates: about half of $\Upsilon(nS)\pi^+\pi^-$

Neutral partner in $\Upsilon(nS)\pi^0\pi^0$
6.5σ stat. significance
Mass 10609±4±4 MeV

$I^G=1^+$, first example to observe isospin partner among "XYZ".

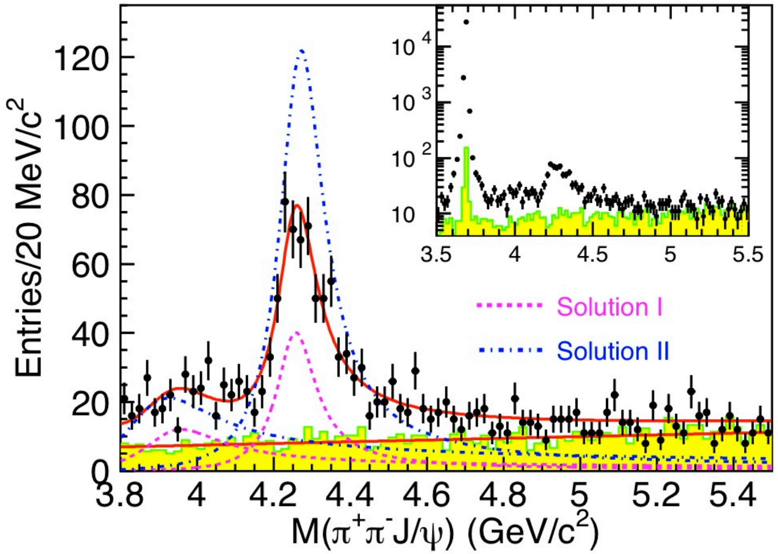
Back to charmonium(-like) by ISR



Initial State Radiation

BES III also confirmed the peak at 3885 MeV in $(D\bar{D}^*)^+$.

PRL110,252002(2013)
PRL112,022001(2014)

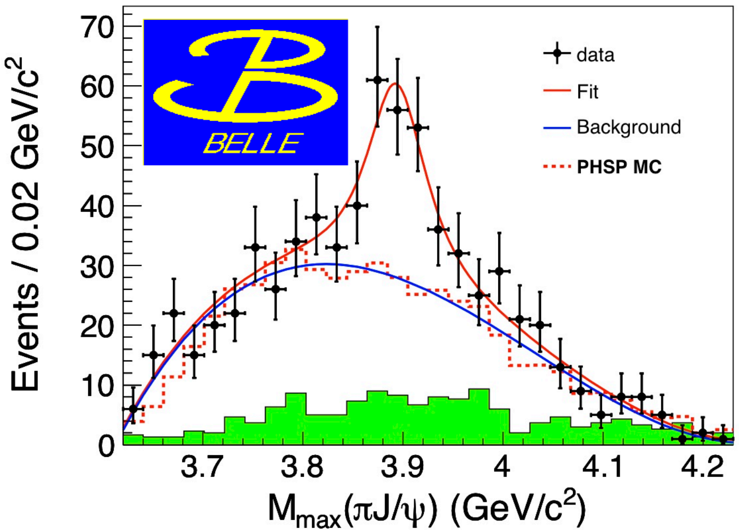


$Y(4260) \rightarrow J/\psi\pi^+\pi^-$

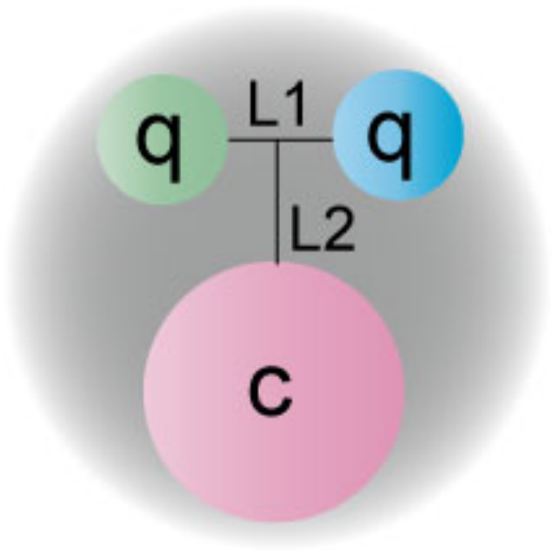
↓

$Z(3895)^+$ in $J/\psi\pi^+$

PRL110,252002 (2013)



Charm baryon to check "di-quark"



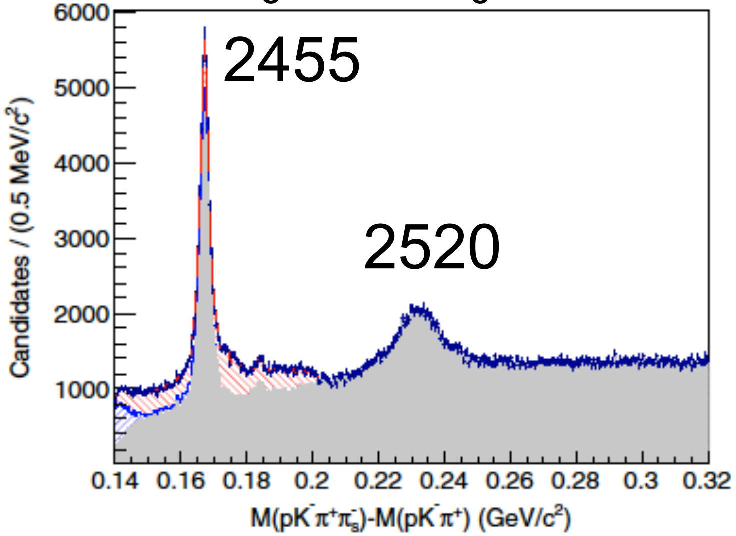
- Thought to be a good place to check if "di-quark" is behaving as a good degree of freedom to form hadrons.
- One of the constituent quark is heavy, correlation between the remained light quarks would become clear.

Reconstructed states with Λ_c

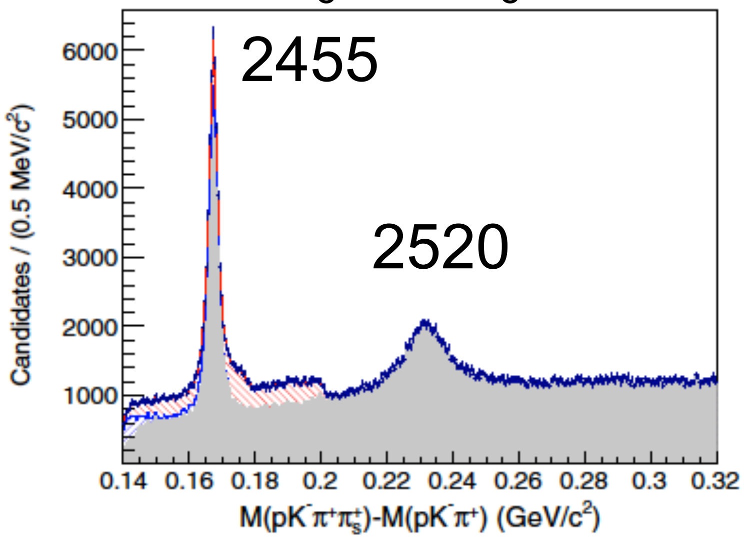
Reconstruct $\Lambda_c \to pK^- \pi^+$ and add one pion.

PRD89,091102(2014)

$\Sigma_c^{++} \to \Lambda_c^+ \pi^+$



$\Sigma_c^{0} \to \Lambda_c^+ \pi^-$

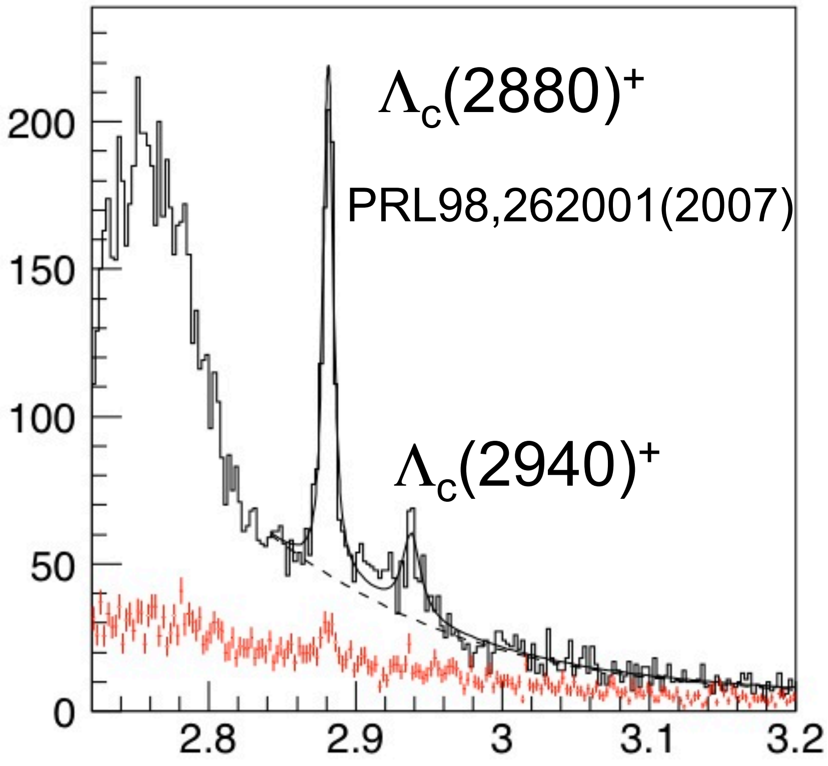


$$M(\Sigma_c(2455)^0) - M(\Lambda_c^+) = 167.29 \pm 0.01 \pm 0.02 \text{ MeV}/c^2,$$
$$M(\Sigma_c(2455)^{++}) - M(\Lambda_c^+) = 167.51 \pm 0.01 \pm 0.02 \text{ MeV}/c^2,$$
$$M(\Sigma_c(2520)^0) - M(\Lambda_c^+) = 231.98 \pm 0.11 \pm 0.04 \text{ MeV}/c^2,$$
$$M(\Sigma_c(2520)^{++}) - M(\Lambda_c^+) = 231.99 \pm 0.10 \pm 0.02 \text{ MeV}/c^2,$$

$$\Gamma(\Sigma_c(2455)^0) = 1.76 \pm 0.04^{+0.09}_{-0.21} \text{ MeV}/c^2,$$
$$\Gamma(\Sigma_c(2455)^{++}) = 1.84 \pm 0.04^{+0.07}_{-0.20} \text{ MeV}/c^2,$$
$$\Gamma(\Sigma_c(2520)^0) = 15.41 \pm 0.41^{+0.20}_{-0.32} \text{ MeV}/c^2,$$
$$\Gamma(\Sigma_c(2520)^{++}) = 14.77 \pm 0.25^{+0.18}_{-0.30} \text{ MeV}/c^2,$$

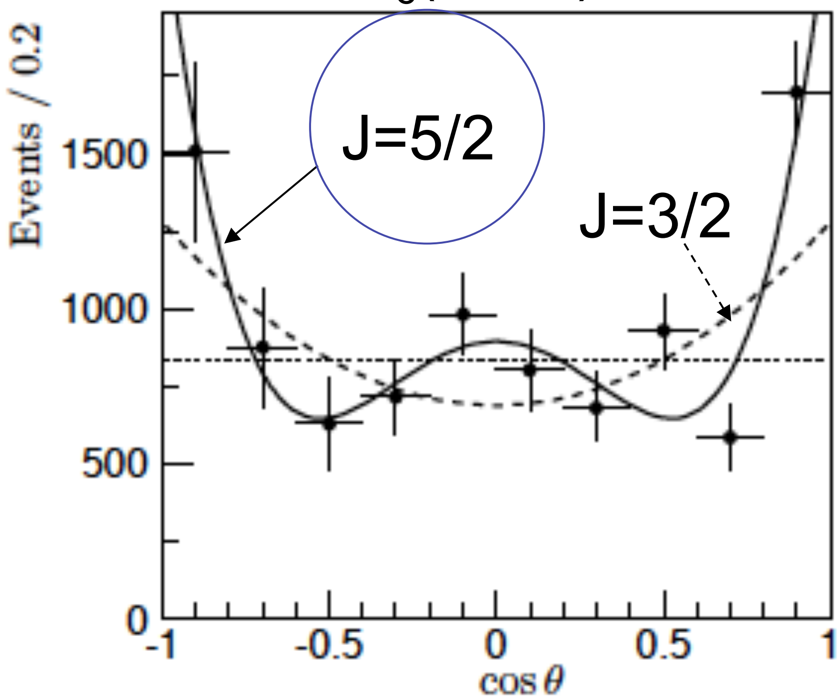
Reconstructed states with Λ_c(cont.)

Select $\Sigma_c(2455)\ \pi$ to see $\Lambda_c^+\pi^+\pi^-$



$M(\Lambda_c^+\pi^+\pi^-)$ [GeV]

$\Lambda_c(2880)^+$

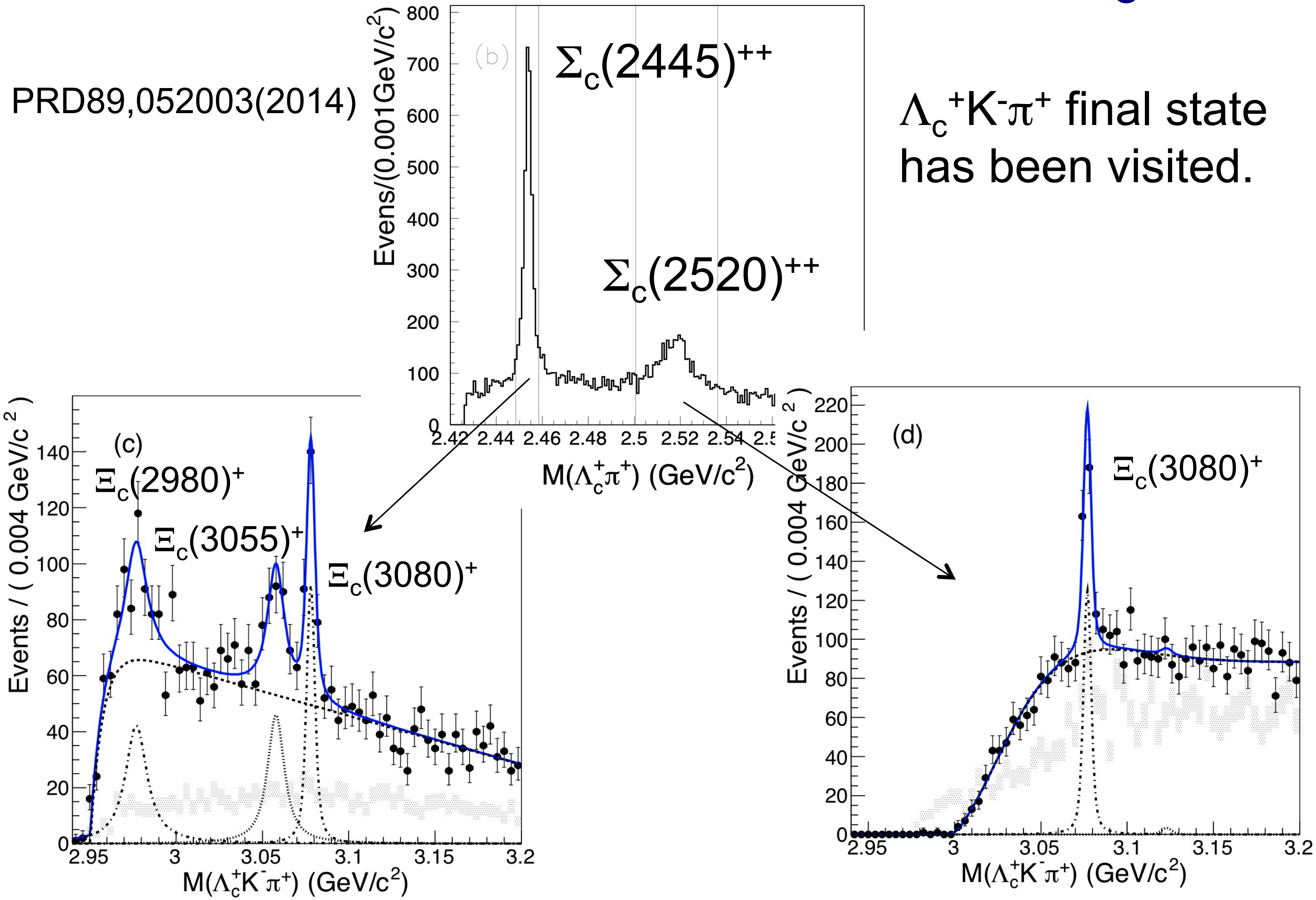


pion angular distribution

Reconstructed states with Λ_c(cont.^{2})

PRD89,052003(2014)

$\Lambda_c^+K^-\pi^+$ final state has been visited.

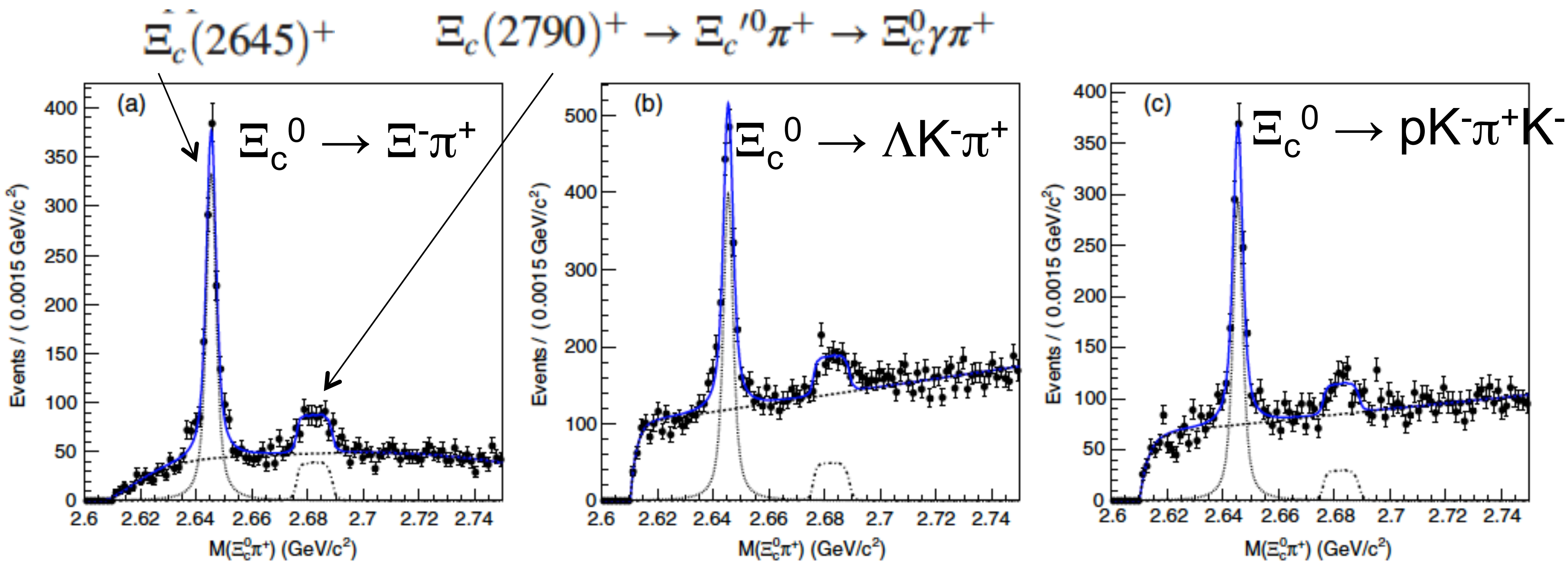


Reconstructed states with Ξ_c^0(cont.)

Ξ_c^0 is reconstructed in $\Xi^- \pi^+$, $pK^-\pi^+K^-$ and $\Lambda K^-\pi^+$

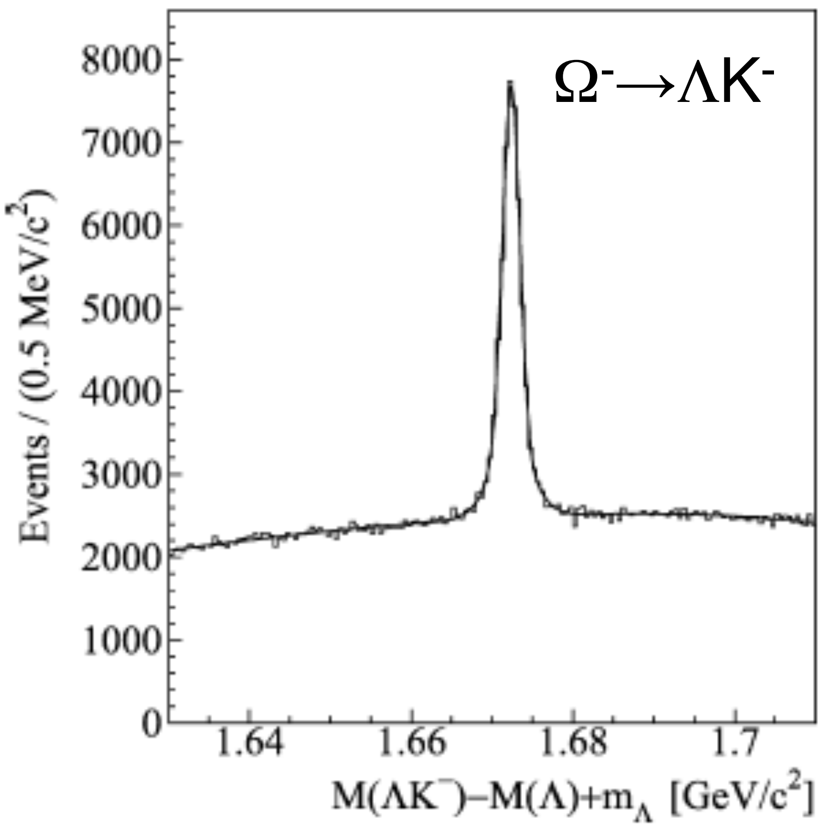
$\Xi_c^0 \pi^+$ has been visited.

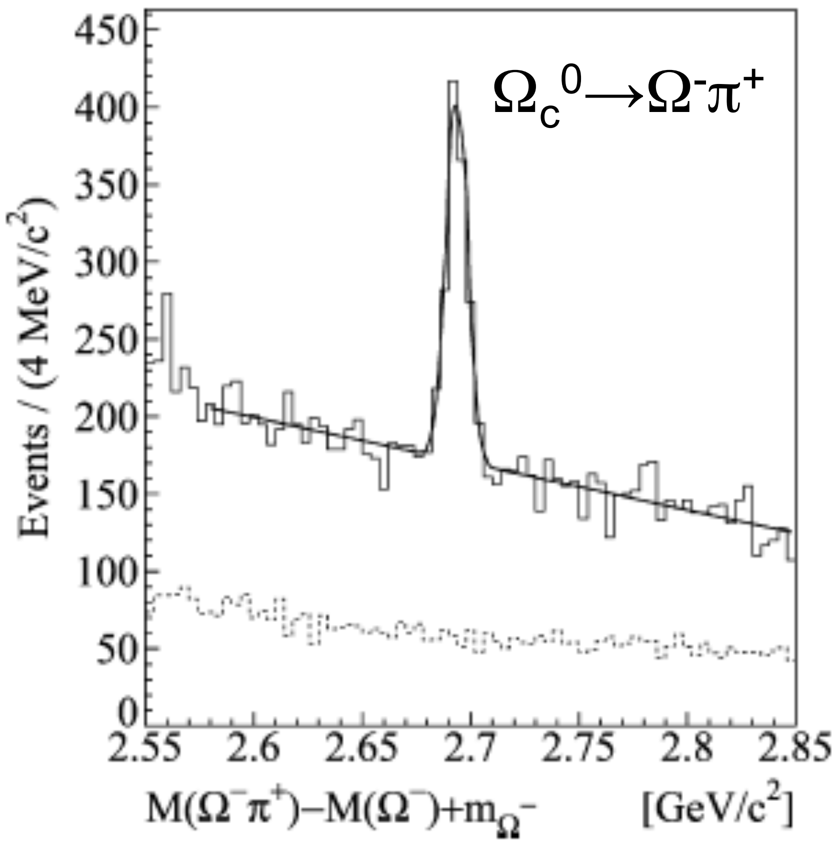
PRD89,052003(2014)



Reconstructed states with Ω_c^0

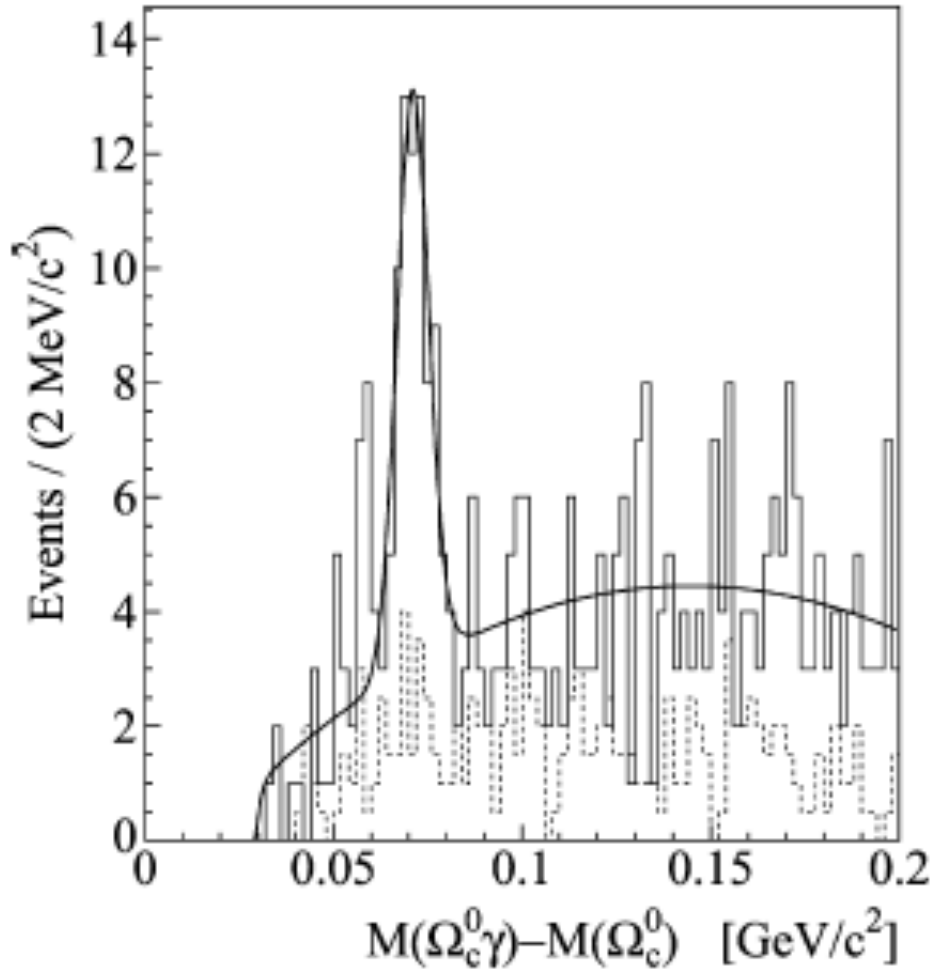
PLB672,1(2009)





$\Omega_c^0(2770) \rightarrow \Omega_c^0\ \gamma$

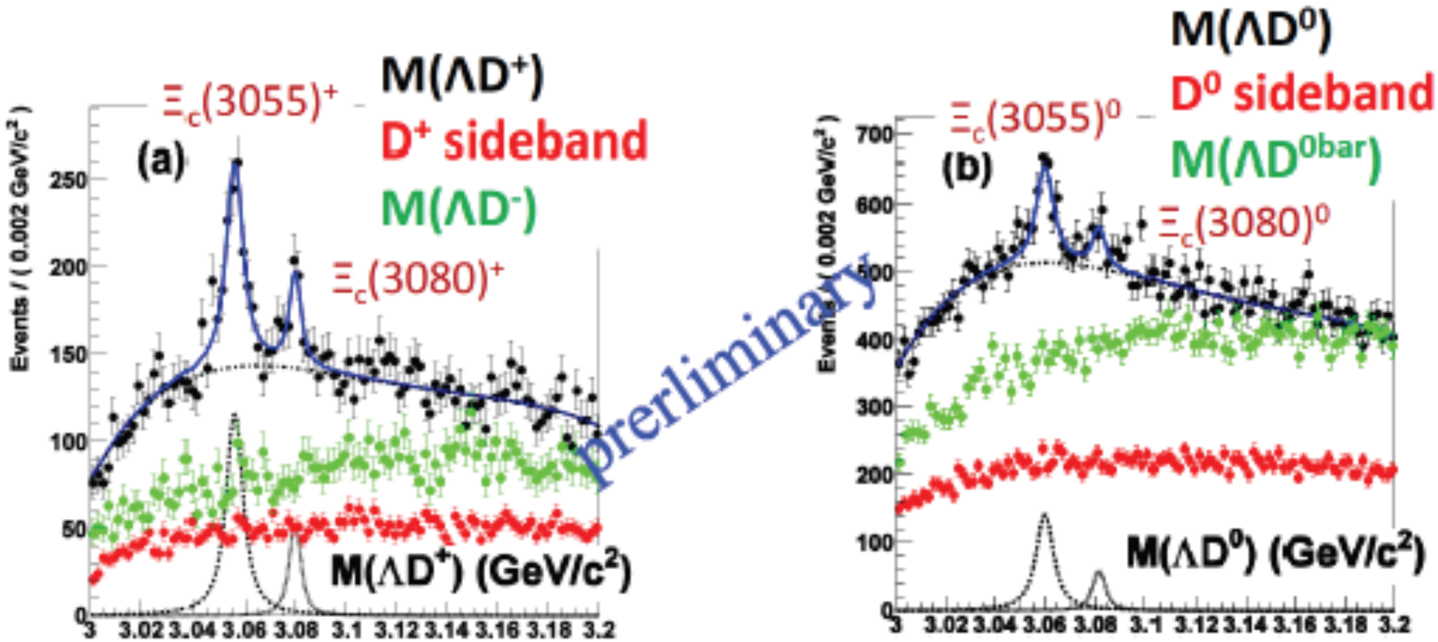
PLB672,1(2009)



States seen in ΛD mode

- $\Xi_c(3055)^+$ (11.7σ), $\Xi_c(3080)^+$(4.7σ) in ΛD^+
  - Further confirmation of $\Xi_c(3055)^+$
- $\Xi_c(3055)^0$ (7.6σ) , $\Xi_c(3080)^0$ (2.6σ) in ΛD^0
  - First observation of $\Xi_c(3055)^0$

Belle preliminary



Note for charmed baryons

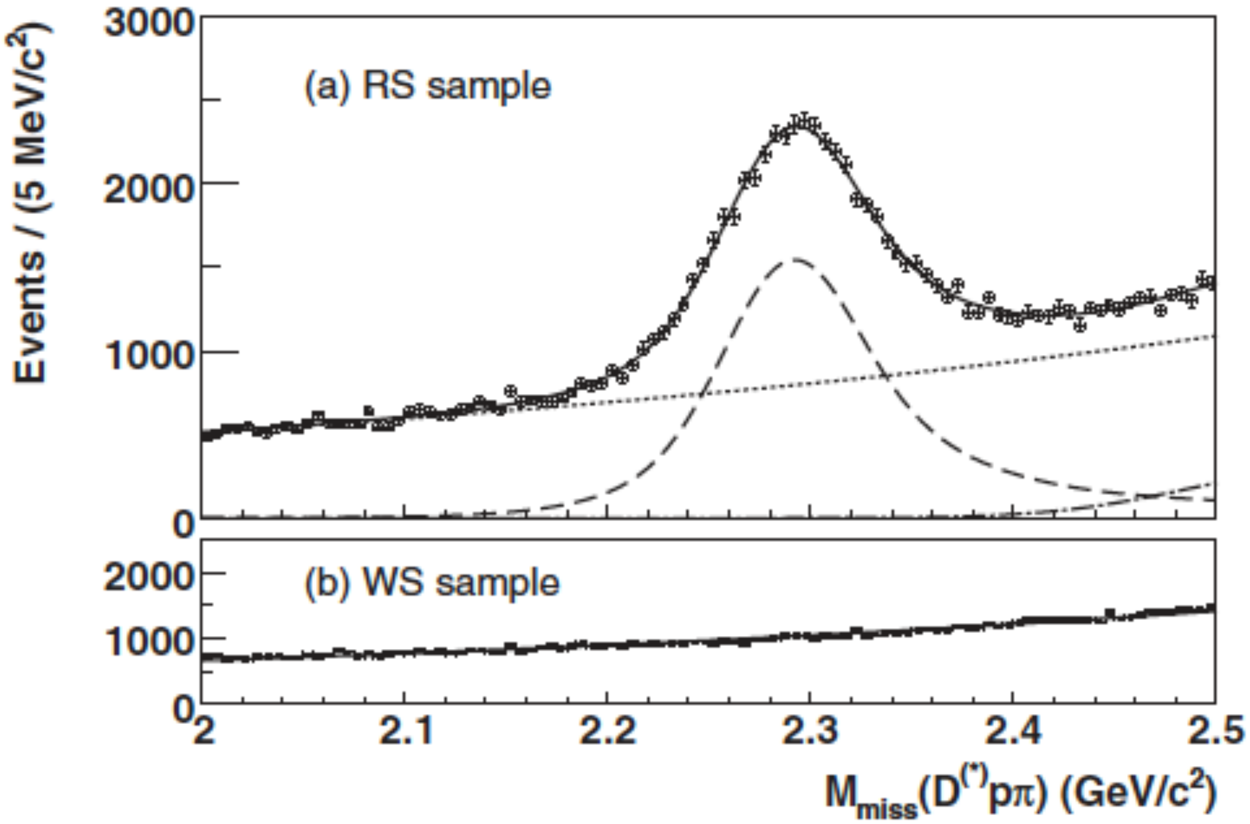
- For many states, mass and width were poorly known, B-factory results have been updating them.
- In $\Lambda_c^+\pi^+K^-$ case, only $\Xi_c(3080)^+$ appears in $\Sigma_c(2445)^{++}$ K^- and $\Sigma_c(2520)^{++}$ K^-, while $\Xi_c(2980)^+$ and $\Xi_c(3055)^+$ appear only in $\Sigma_c(2445)^{++}$ K^-. Can resolving intermediate states help to see if di-quark is a good picture?
- For most of cases, branching fractions are also poorly known. To get information from the production rate, decay from higher states (feed-down) would become a problem
- Even PDG Br($\Lambda_c \rightarrow pK\pi$), several underlying assumptions. New model-independent approach published from Belle.

Tag $D^{(*)-}\,\bar{p}\,\pi^+$ to get M_{miss}

$$e^+e^- \to c\bar{c} \to \underline{D^{(*)-}\bar{p}\pi^+}\Lambda_c^+$$

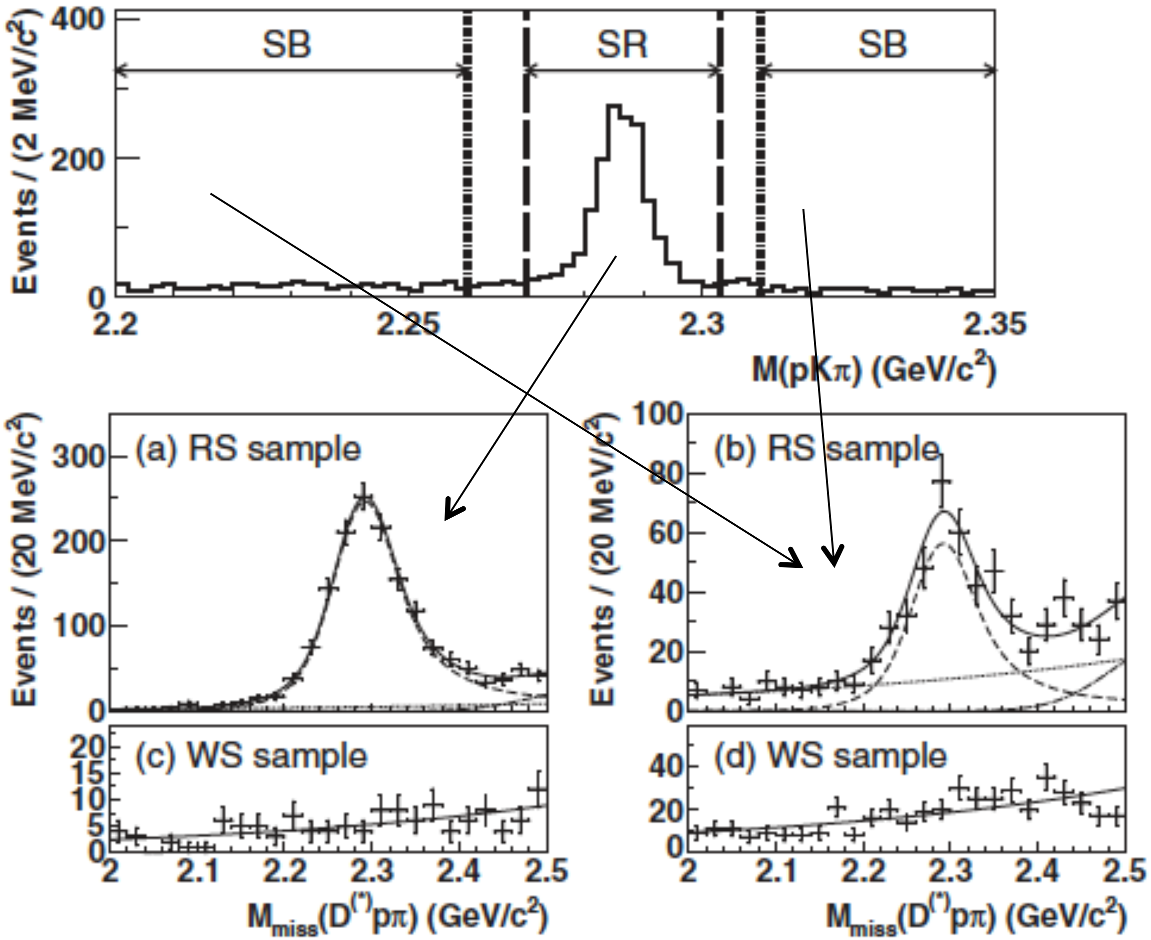
PRL113,042002(2014)

Detect only these



Then explicitly reconstruct $pK^-\pi^+$

PRL113,042002(2014)



PDG was 5.0±1.3%

$$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.84 \pm 0.24^{+0.21}_{-0.27})\%$$

Summary

- Because of superb detector performance with excellent accelerator luminosity, we got many exciting surprises, so far mainly quarkonium(-like).
- Some of those reached very plausible interpretation.
  - X(3872) as admixture of molecule and charmonium(χ_{c1}(2P))
  - $Z_b(10610)^+$ and $Z_b(10650)^+$ as $B^*\overline{B}^{(*)}$ molecule.
  - For the state close to the threshold, molecular state turned out to be playing important role.
- Extension to charmed baryons to test “di-quark” picture.
- Still unsettled interpretation for many states (ex. $Z(4430)^+$, etc).
- Searches for new decay modes, partner states, attempt for J^P determination with higher statistics data to cheer up relevant theorists to come up with convincing interpretation is a Belle II mission in hadron spectroscopy.