Experimental studies on fragmentation and exotic hadrons

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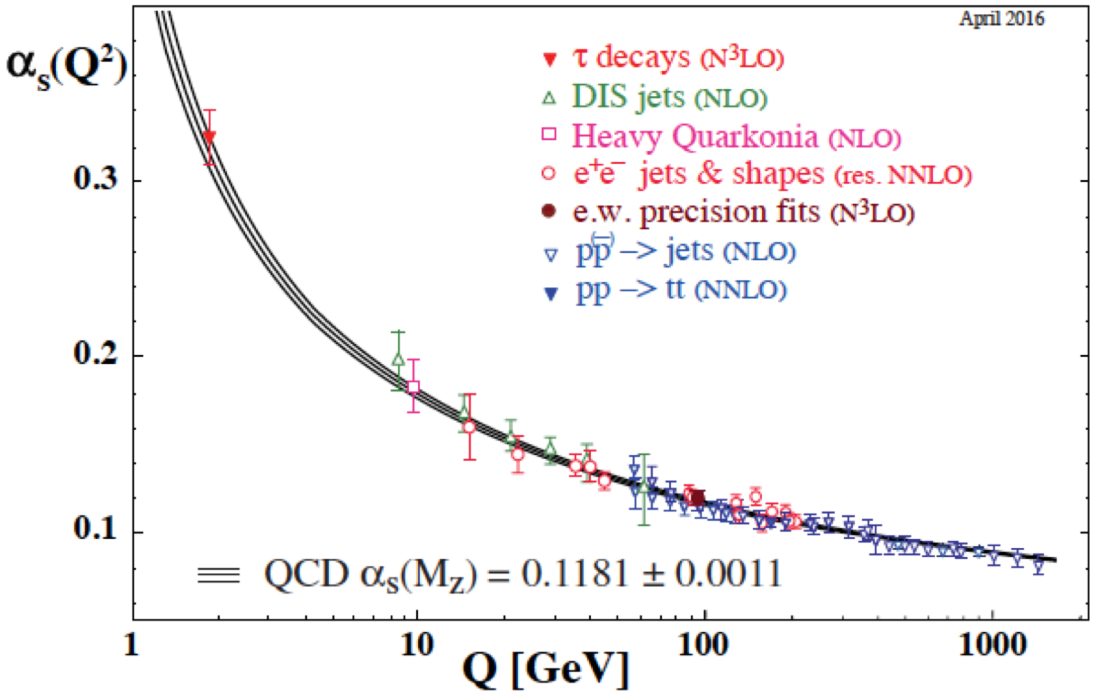
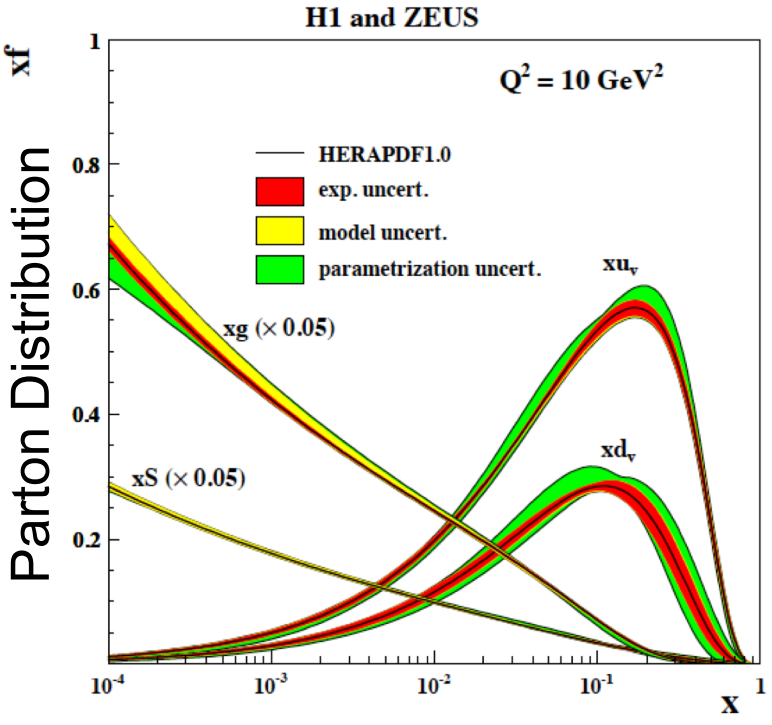
DIS2018 conference

2018 Apr. 16th

For QCD, LEP, HERA, .. gave





Running of α_S and Parton Distribution established, i.e. we have good knowledge about the region of perturbative treatment.

Challenges in non-perturbative region

Two items in this category:

- Fragmentation
  - Quarks and gluons turn into hadrons in jets

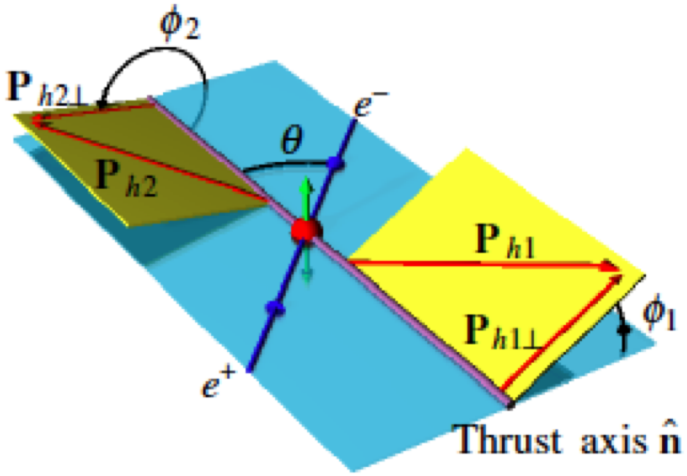
- Exotic hadrons
  - Interpretation directly related to identify “what is the proper unit to construct” = effective degree of freedom

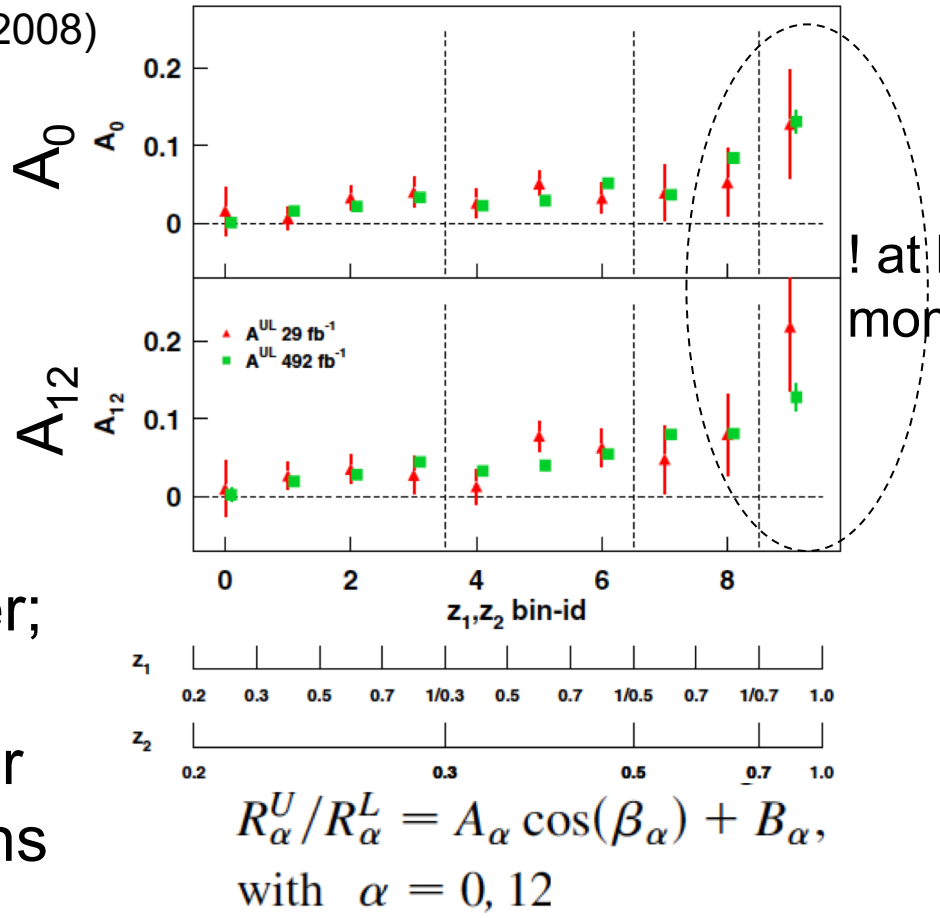
May it be a probe to initial quark state and produced hadron structure?

FRAGMENTATION

Fragmentation function as a probe of initially produced quarks

Belle, PRL96,232002(2006), PRD78,032001(2008)





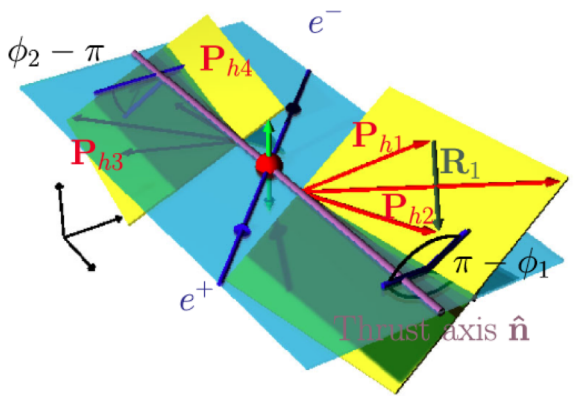
! at high momentum

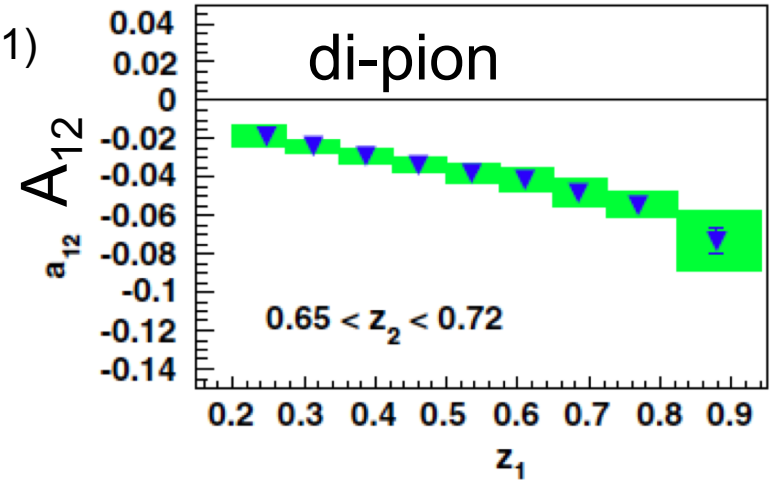
Azimuthal angle defined either;
ϕ_0 between the planes of
$\boldsymbol{P}_{h1}$ – beam and $\boldsymbol{P}_{h2}$ – beam or
$\phi_1 + \phi_2$ for single charged pions

Found to be sensitive to initial quarks' transverse polarization

Measurements of di-hadrons

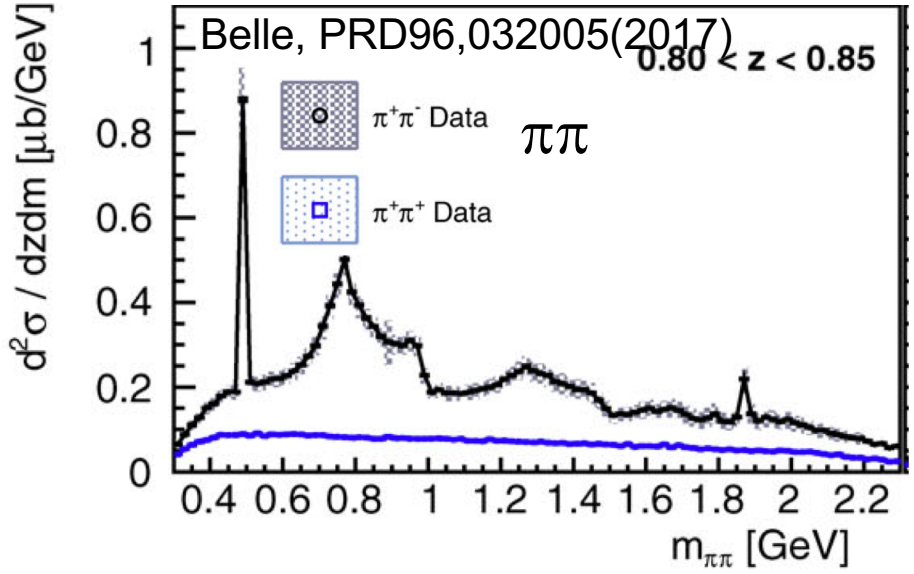
Belle, PRL107,072004(2011)

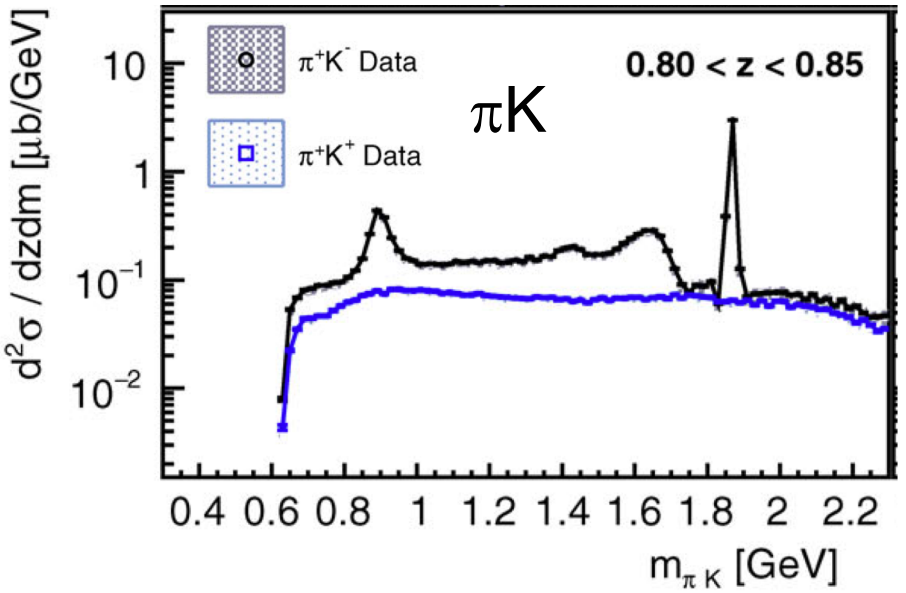




Again $\cos(2(\phi_1+\phi_2))$ modulation seen in high momentum region

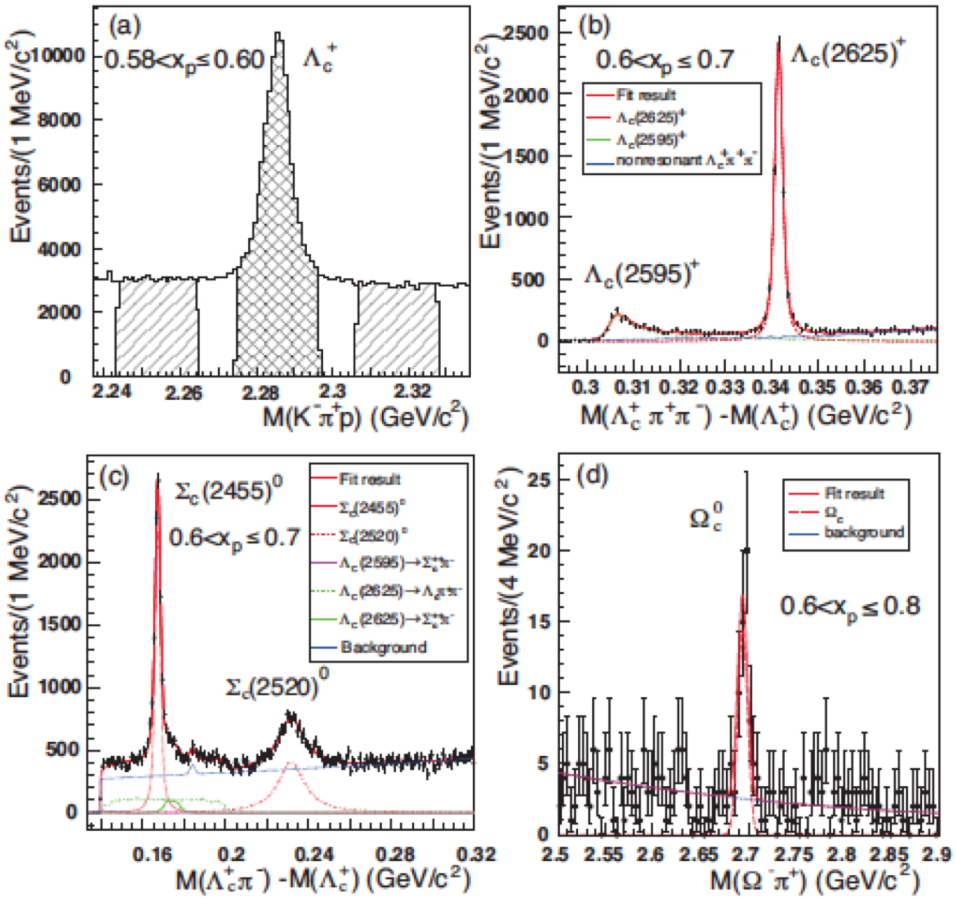
See also PRL111,062002(2013)



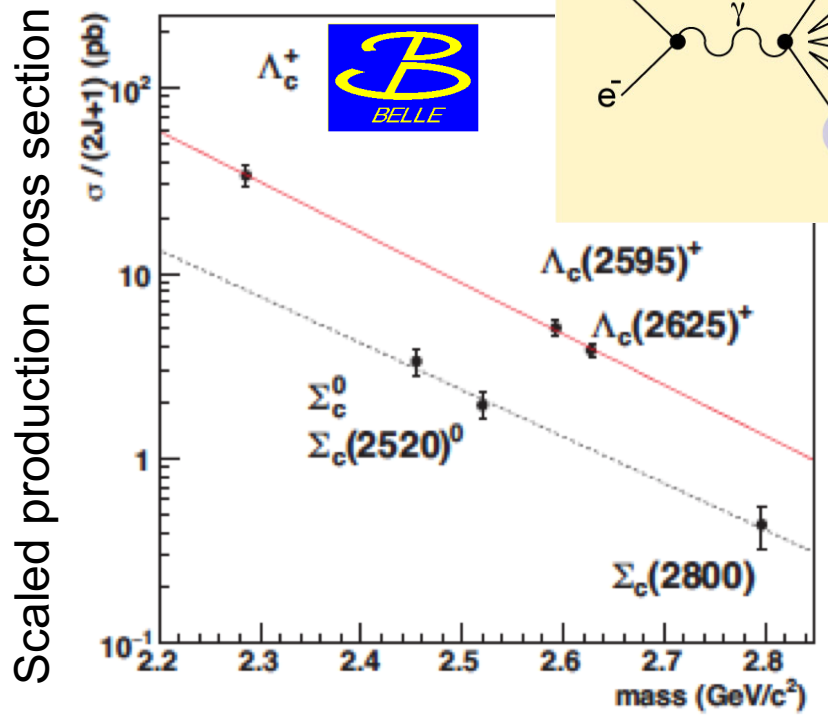


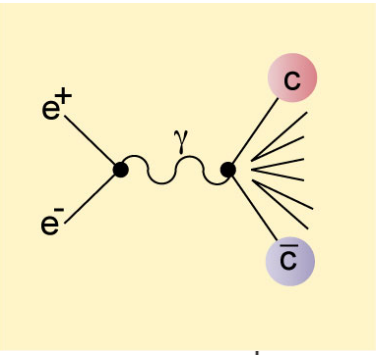
Listen R. Seidl's talk on Wed. in WG6 session for more details.

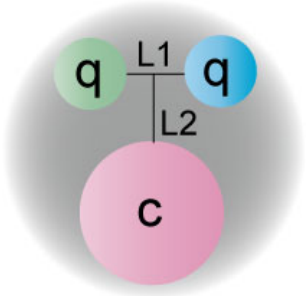
Production of charm baryons



Belle, PRD97,072005(2018)







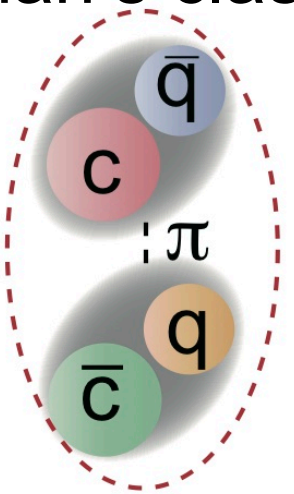
When di-quark is isosinglet (Λ_c), higher production than isotriplet (Σ_c).

What is the proper effective degree of freedom for the description of hadrons?

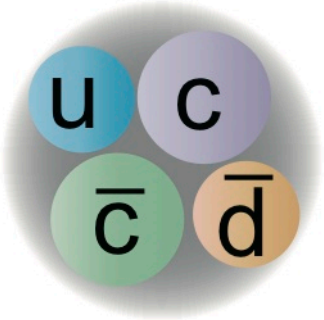
EXOTIC HADRONS

Exotic hadrons
number of constituents > 3

- No explicit forbidding rule to form unusual structure (not conventional $q\bar{q}$ or qqq) hadrons. Discussed in Gellman's classic paper(Phys. Lett. ,8, p.216, 29164).



molecule

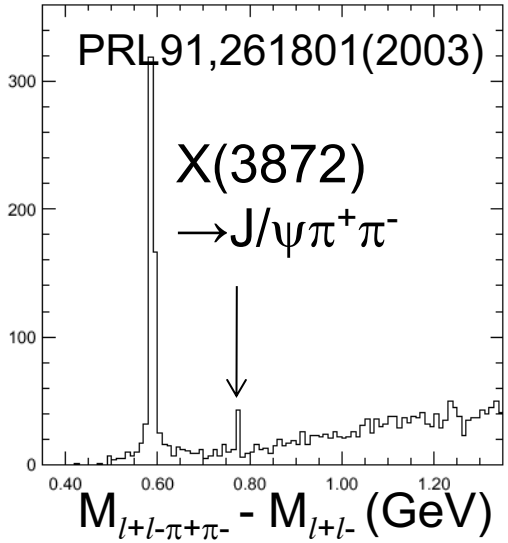


tetraquark

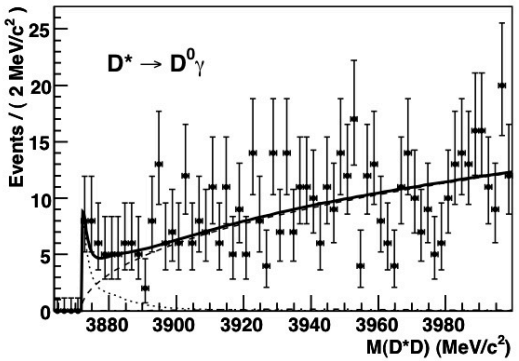
+glueball,
pentaquark, …

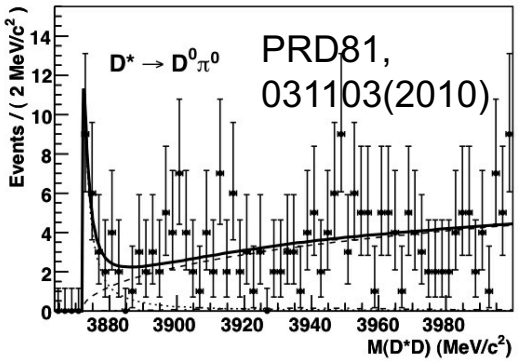
- But lack of experimental evidence for long time.
- A key to open unrevealed aspect of QCD.

X(3872) containing $c\bar{c}$, unusually narrow above DD threshold

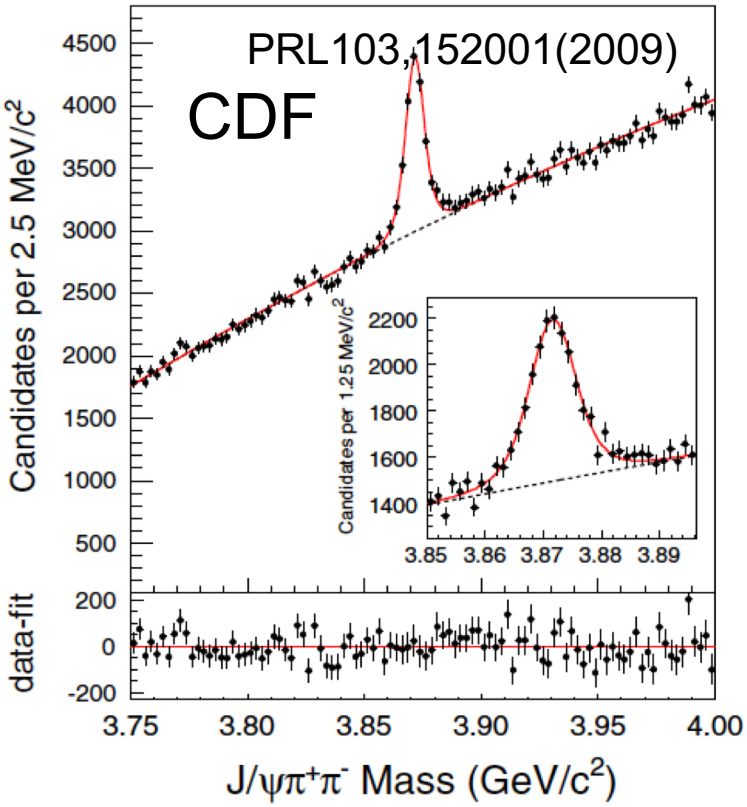


$J^{PC}=1^{++}$ (Belle, BaBar, CDF, LHCb) from $J/\psi\ \pi^+\pi^-$ angular distribution.
PRL110, 222001(2013) and cited papers





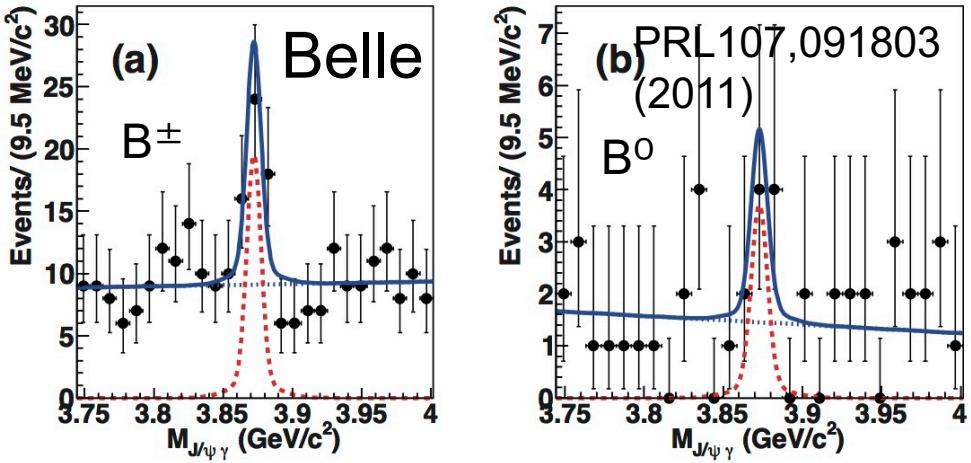
$Br(X(3872)\to D^0\bar{D}^{*0})$ is about $Br(X(3872)\to J/\psi\ \pi^+\pi^-)\times 10$.

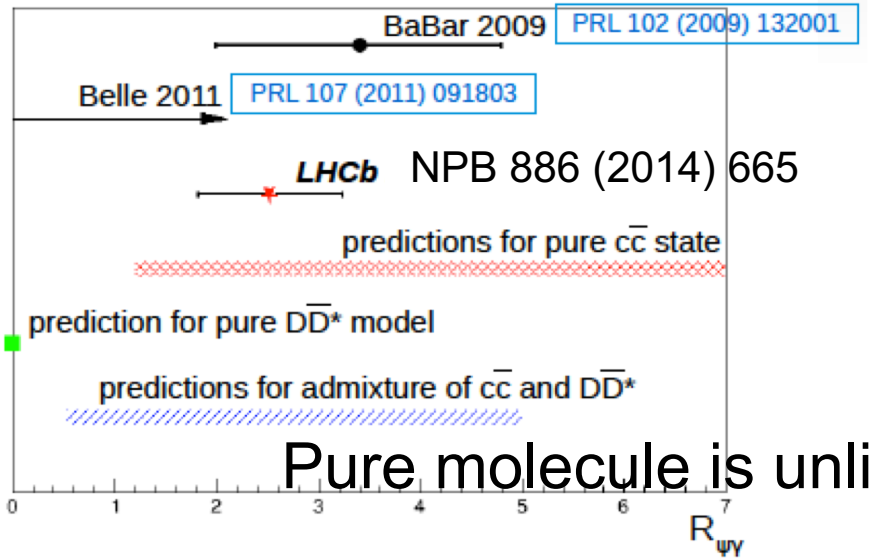


Production in high energy $p\bar{p}$ collision observed.

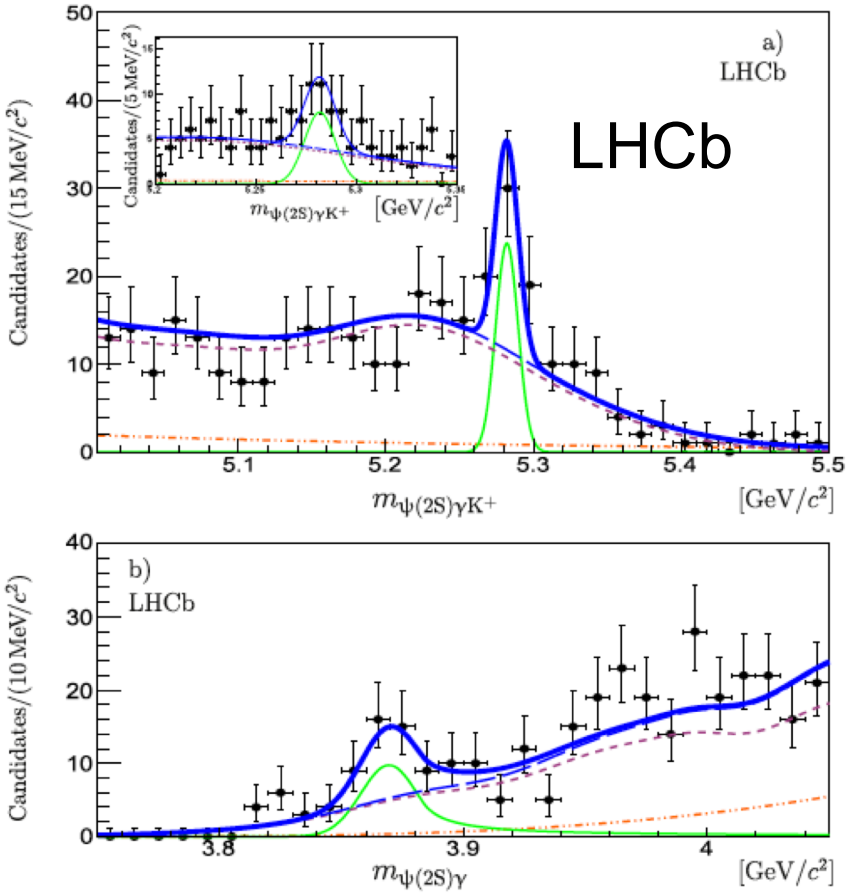
X(3872) radiative decay

X(3872)→J/ψ γ; C=+1



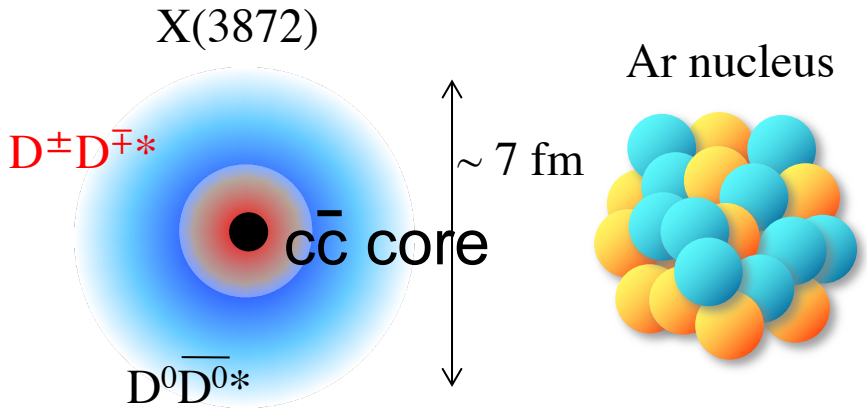


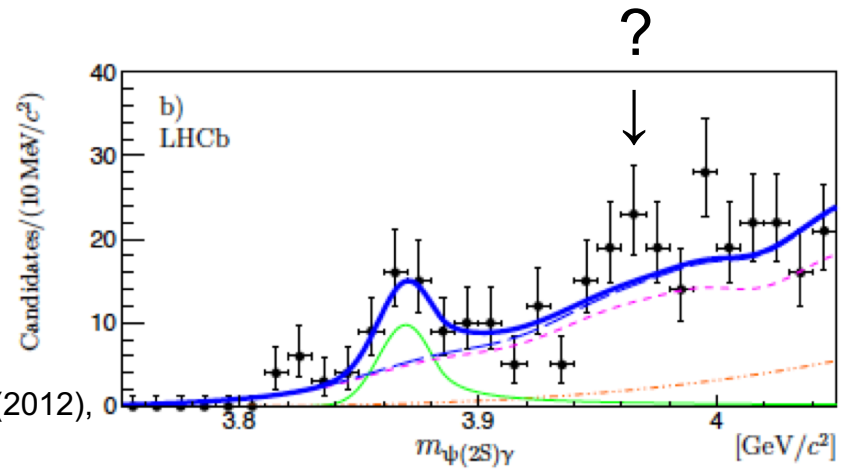
Pure molecule is unlikely ..



X(3872)→ψ(2S) γ found at LHCb.

Admixture : most plausible interpretation for X(3872)



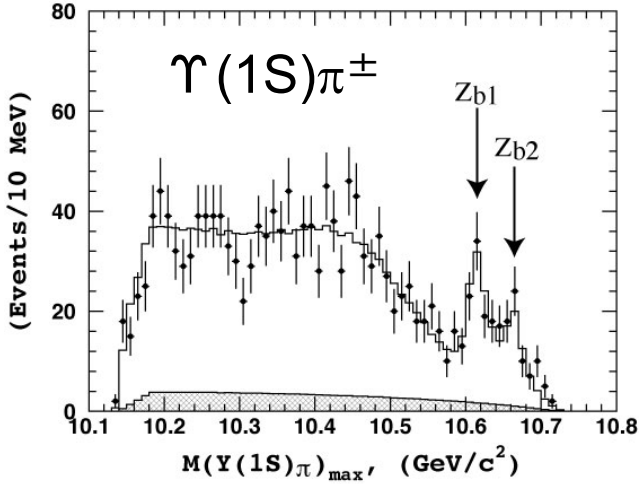


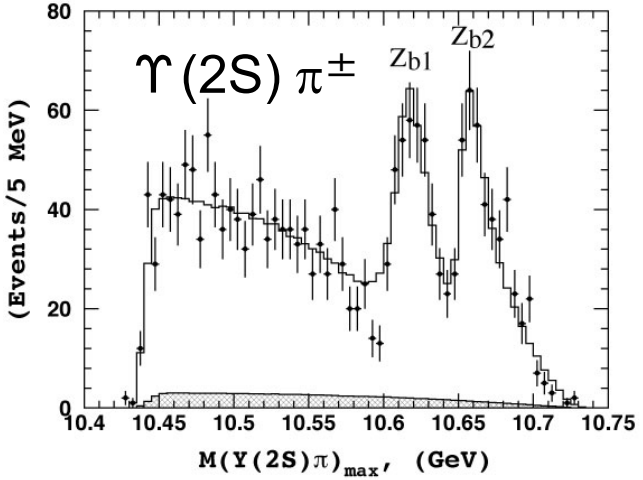
E. J. Eichiten et al., PRD73,014014(2006); A. M. Badalian et al., PRD85,031103(2012), S.Takeuchi, K.Shimizu and M.Takizawa, PTEP2014(2014)123D01

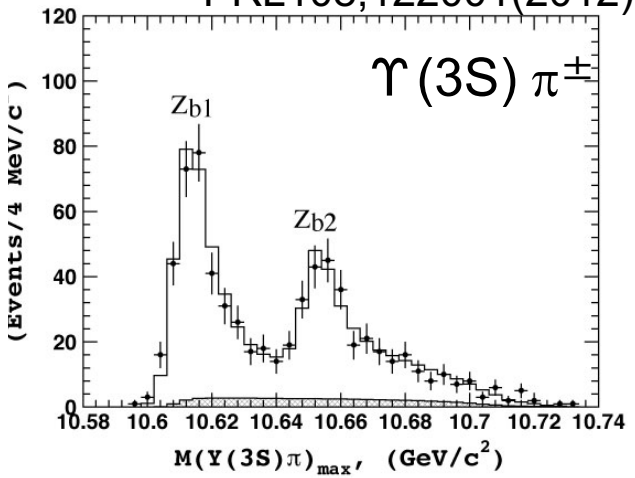
$D\bar{D}^*$ component is coupled with the same J^{PC} $c\bar{c}$, $\chi_{c1}(2P)$ (unseen).
→can explain $Br(X\to D^0\bar{D}^{*0})/Br(X\to J/\psi\,\pi^+\pi^-)$ is about 10.
→pure molecule is too fragile to be produced at Tevatron/LHC.
→another $\chi_{c1}(2P)$ dominant state would become broad.
Reaching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

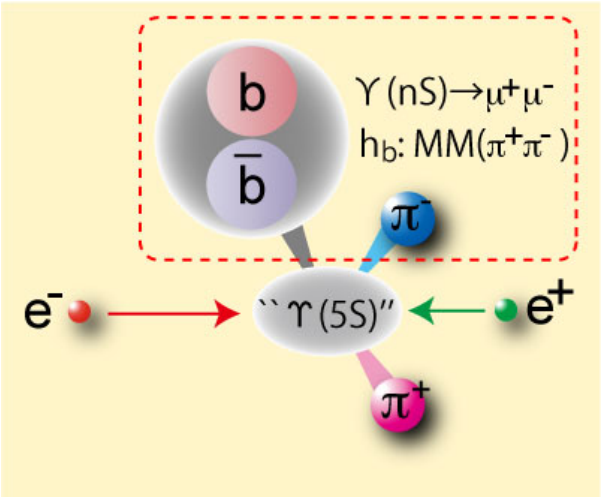
Two $Z_b^{\pm}$ states seen in all bottomonium $\pi^{\pm}$ systems at $\Upsilon(10860)$

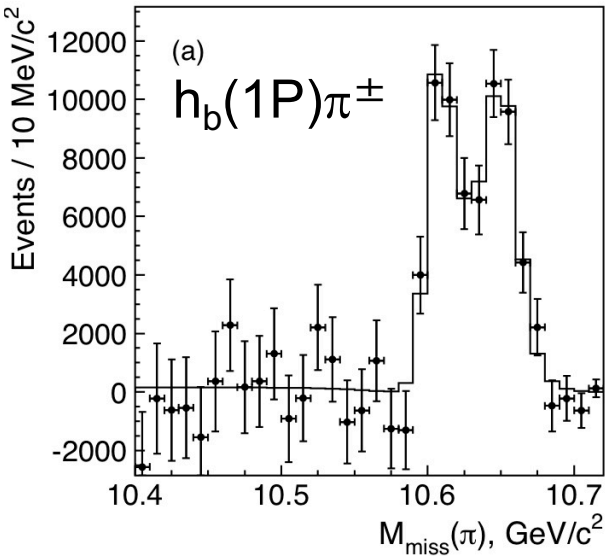
PRL108,122001(2012)

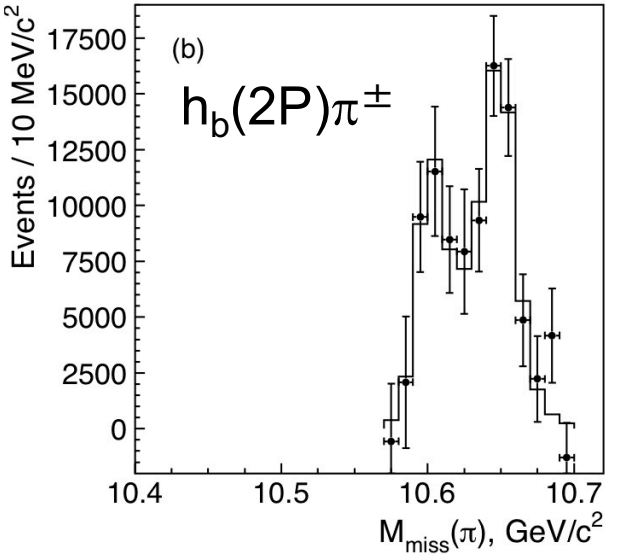








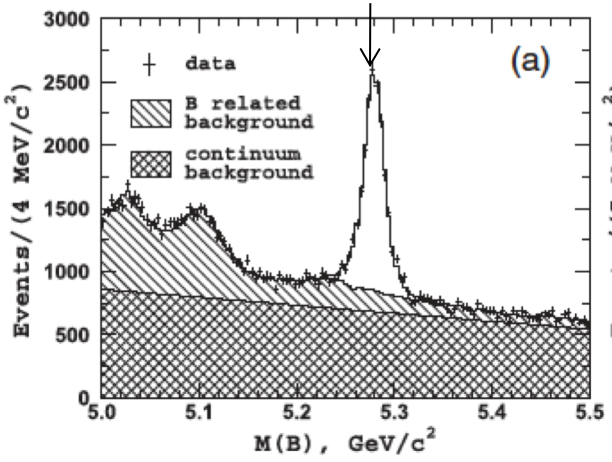




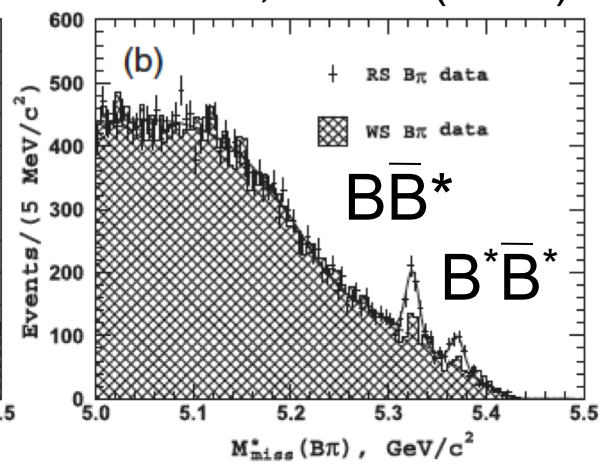
$Z_b(10610)^{\pm} \to B\bar{B}^*$, $Z_b(10650)^{\pm} \to B^*\bar{B}^*$

One B reconstructed

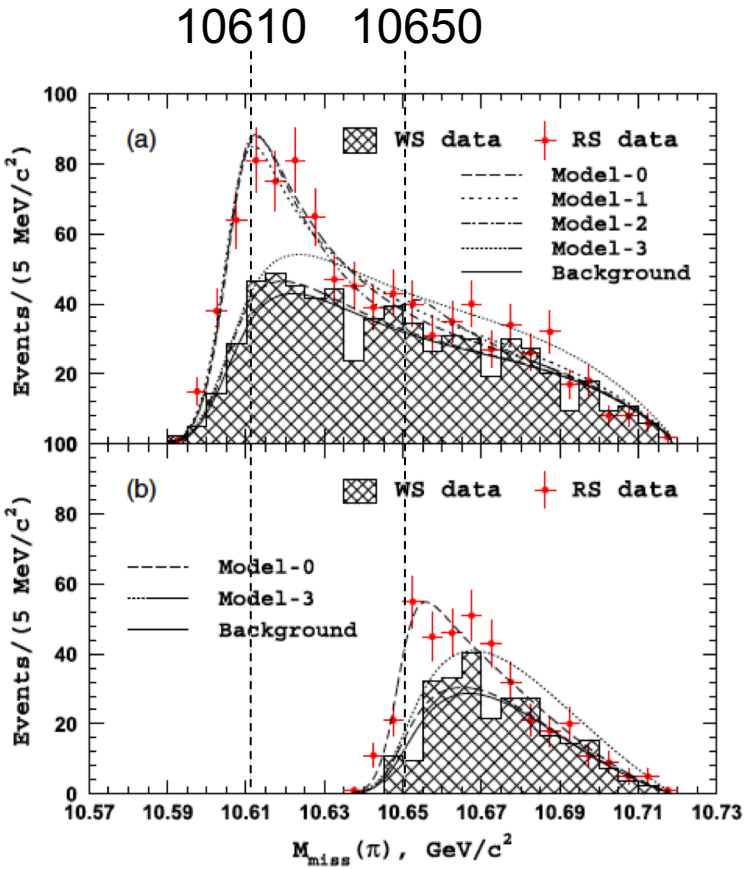
PRL116,212001(2016)



B cand. Mass (GeV)



MM(Bπ)



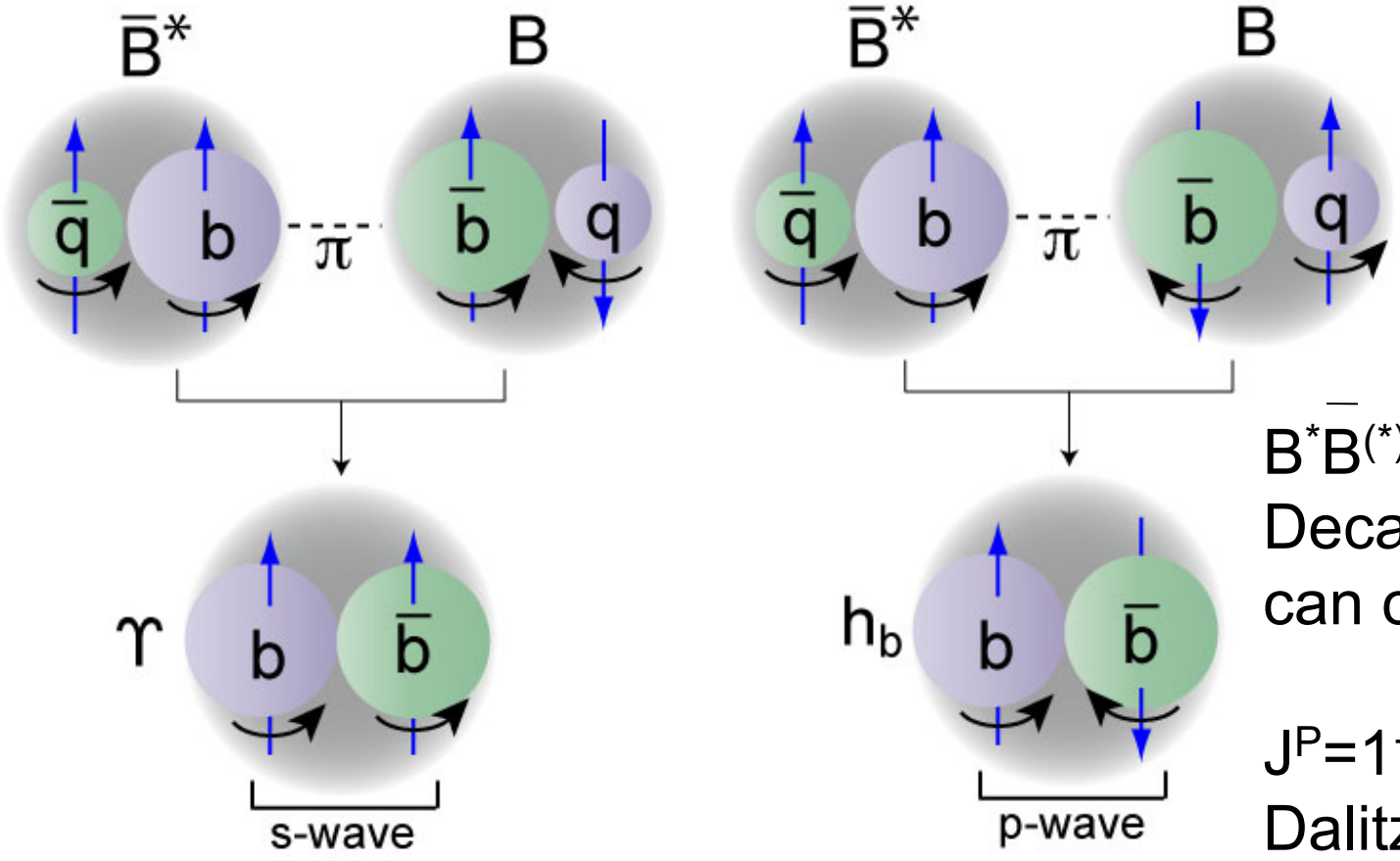
MM(π)=M($B^{(*)}B^*$)

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

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

Found to be dominant!

Molecular picture works

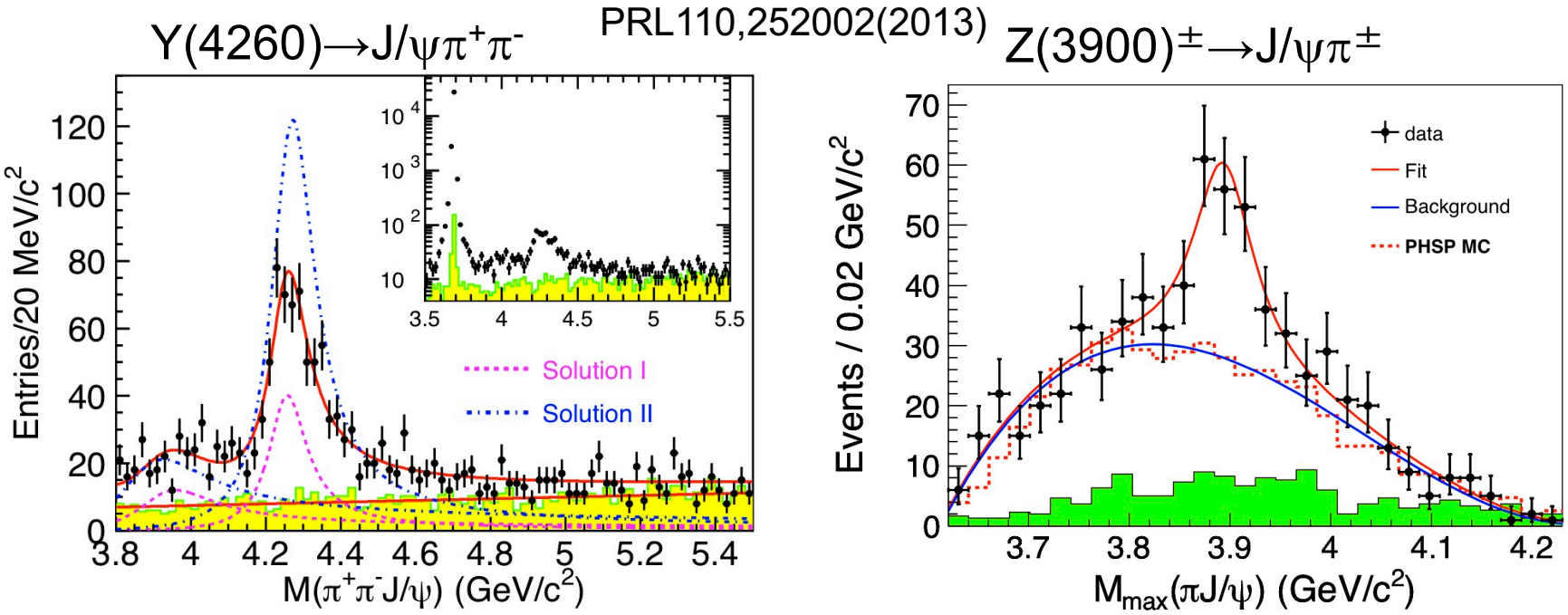


A.E.Bondar et al., PRD84,054010(2011)

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

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

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



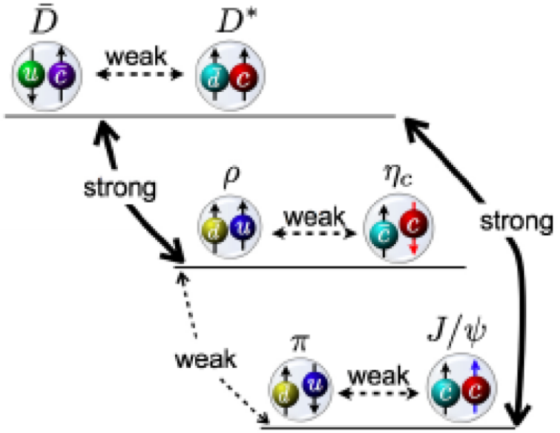
$J^{PC}=1^{--}$ state decaying to quarkonium $\pi^+\pi^-$ contains a charged state as an intermediate!

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

PRD91,112007(2015)

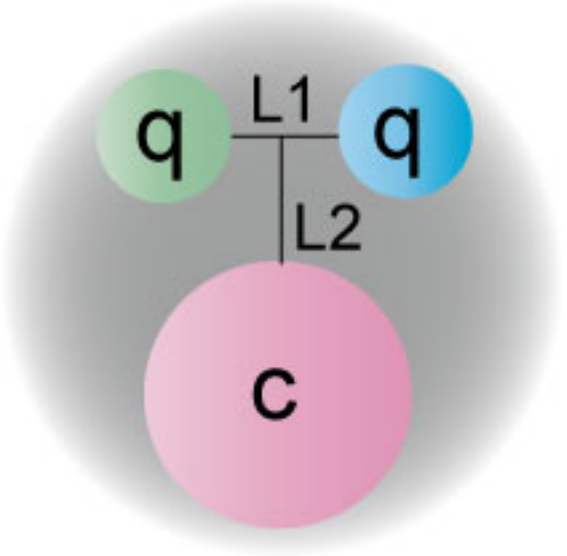
Lessons from these discoveries

- 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)

As for heavy flavored baryons



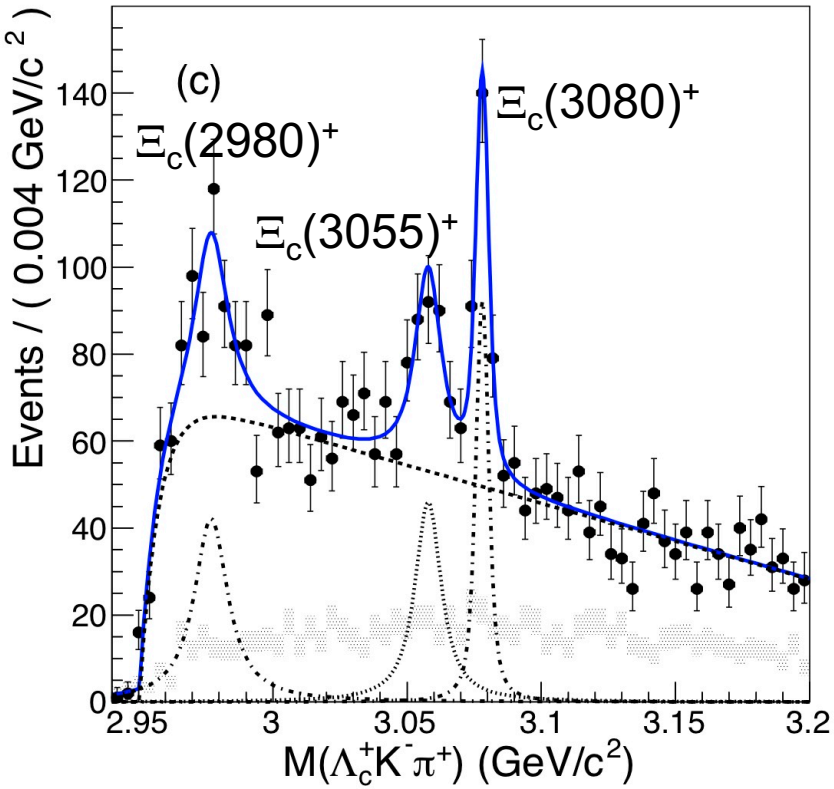
- Need to clarify “what are ordinary”.
- One of the constituent quarks is heavy, the remaining light quarks may behave as “di-quark”; a good degree of freedom?.

  L_1 : ρ mode, L_2 : λ mode.

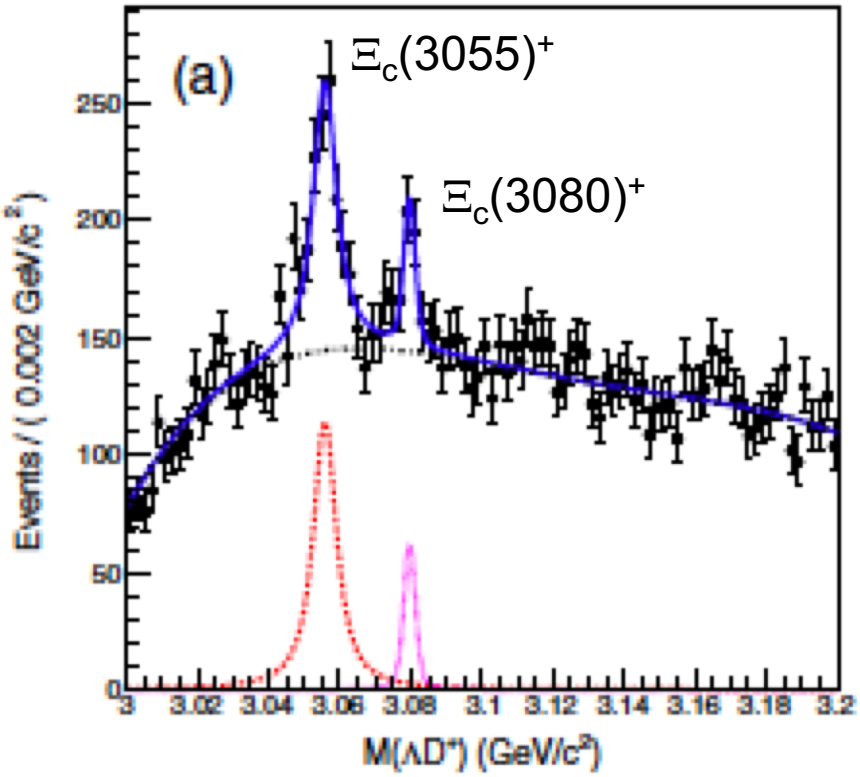
  Still limited knowledge about excited states $\rightarrow$ more investigation necessary.
- Also think about possible hunting for an exotic.

Observation of excited states

Belle, PRD89,052003(2014)



Belle, 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.

Discoveries in pp collisions

Doubly charmed baryon, Ξ_{cc}^{++} seen at LHCb.

PRL119, 112001 (2017)

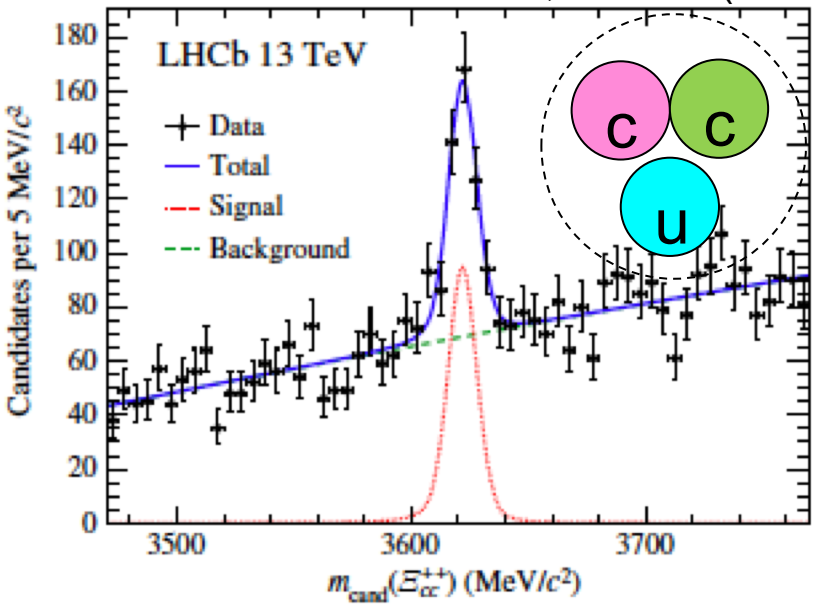
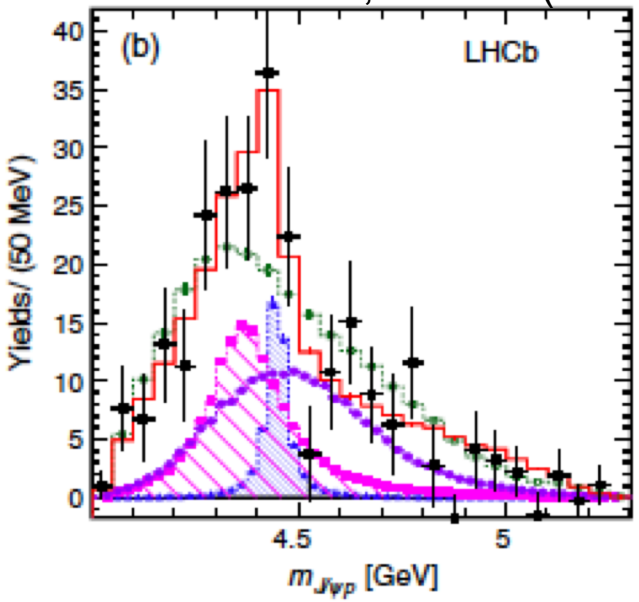


FIG. 3. Invariant mass distribution of $\Lambda_c^+ K^- \pi^+ \pi^+$ candidates with fit projections overlaid.

Pentaquark candidates in J/ψ p final state in $\Lambda_b \to J/\psi\ p\ \pi^-$.

PRL117, 082003 (2016)



To utilize large b and c production with larger boost in pp collisions, vertex information are exploited to clean up backgrounds.

Summary

Thanks to high-statistics experiments in 21st century,

- Fragmentation measurements got sensitive to
  - Initial-quark spin state
  - Correlation to the structure of produced hadrons
- Molecular picture plays important role near the threshold.
  - X(3872) : $D^0 \overline{D^{*0}}$ 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 $DD^* \rightleftarrows J/\psi\,\pi$ and $\eta_c\,\pi$ (HAL QCD)
- Activities to be extended to baryon(-like) system.
  - Many excited states confirmed.
  - Ξ_{cc} and Pentaquark and. in Λ_b decay discovered.

There are a lot of opportunities to increase our knowledge on non-perturbative QCD.