Experimental review of exotic states discoveries in the last 20 years

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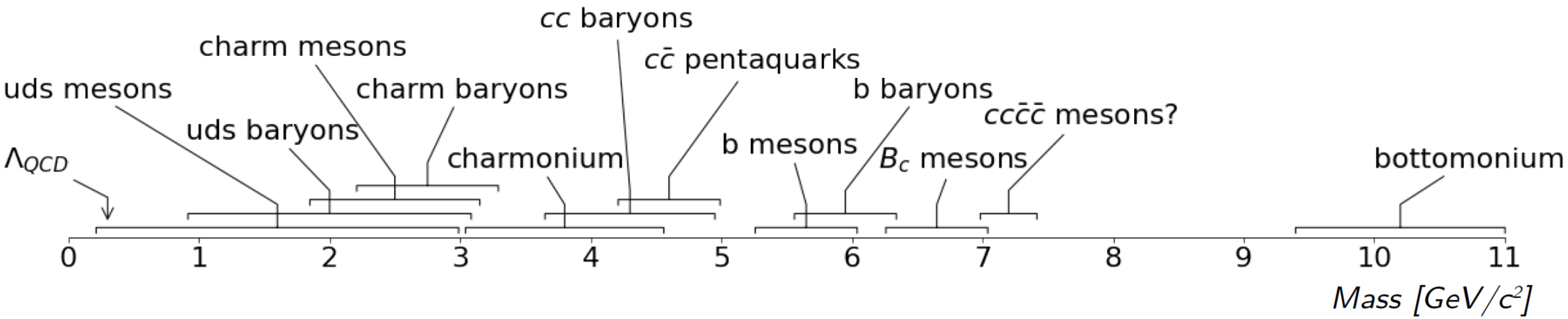
XVIth Quark Confinement and the Hadron Spectrum Conference
Cairns Convention Centre, Cairns, Queensland, Australia
19-24 August 2024 (inclusive)

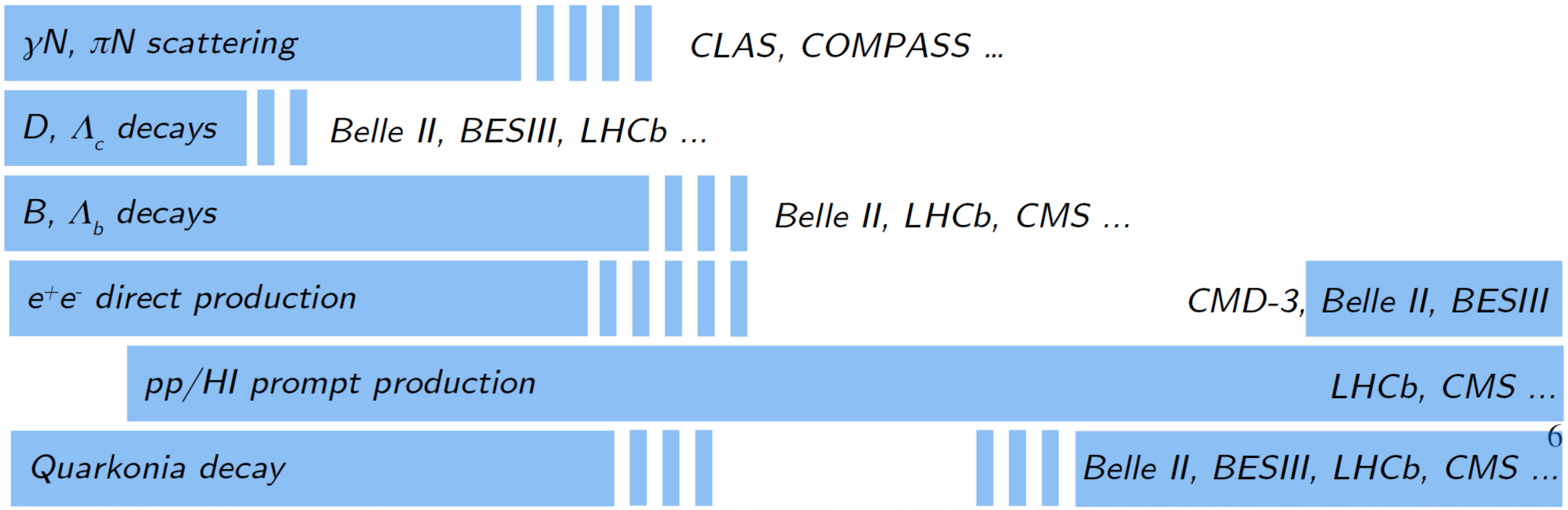
There are four interactions !

- It all started with the big bang! ➔ Gravity governed by General Relativity (it was good!)
- Let there be light: and there was light! ➔ Electromagnetic and weak interactions governed by Electroweak theory (it was good!)
- Let there be quarks and gluons! ➔ strong interaction governed by QCD (it was good at short distance only!)

- Yes, let’s study the strong interaction at long distance — non-perturbative part of QCD!

The study of hadron spectrum





γN, πN scattering — CLAS, COMPASS ...

D, Λ_c decays — Belle II, BESIII, LHCb ...

B, Λ_b decays — Belle II, LHCb, CMS ...

e^+e^- direct production — CMD-3, Belle II, BESIII

pp/HI prompt production — LHCb, CMS ...

Quarkonia decay — Belle II, BESIII, LHCb, CMS ...

6

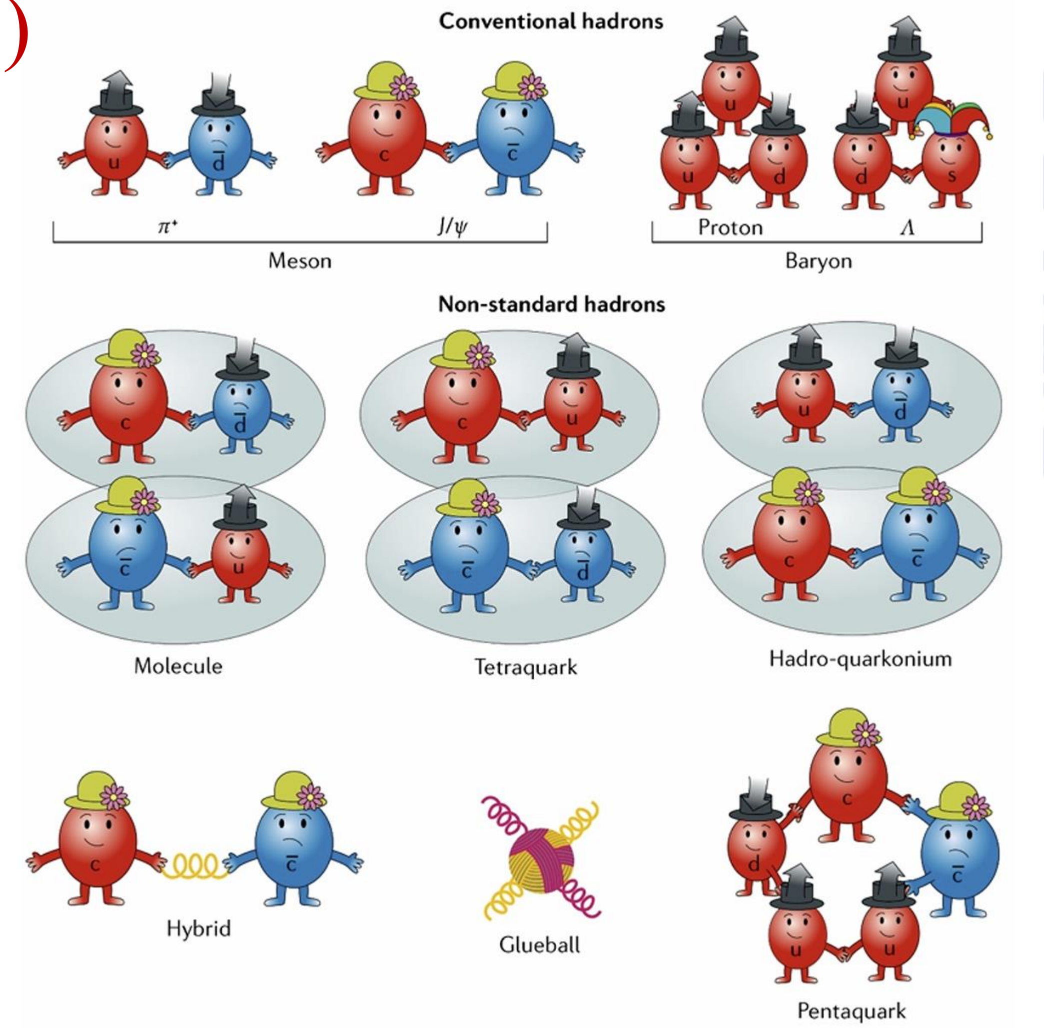
Exotic States

Due to the limited time, in this talk I just focus on some typical exotic states.

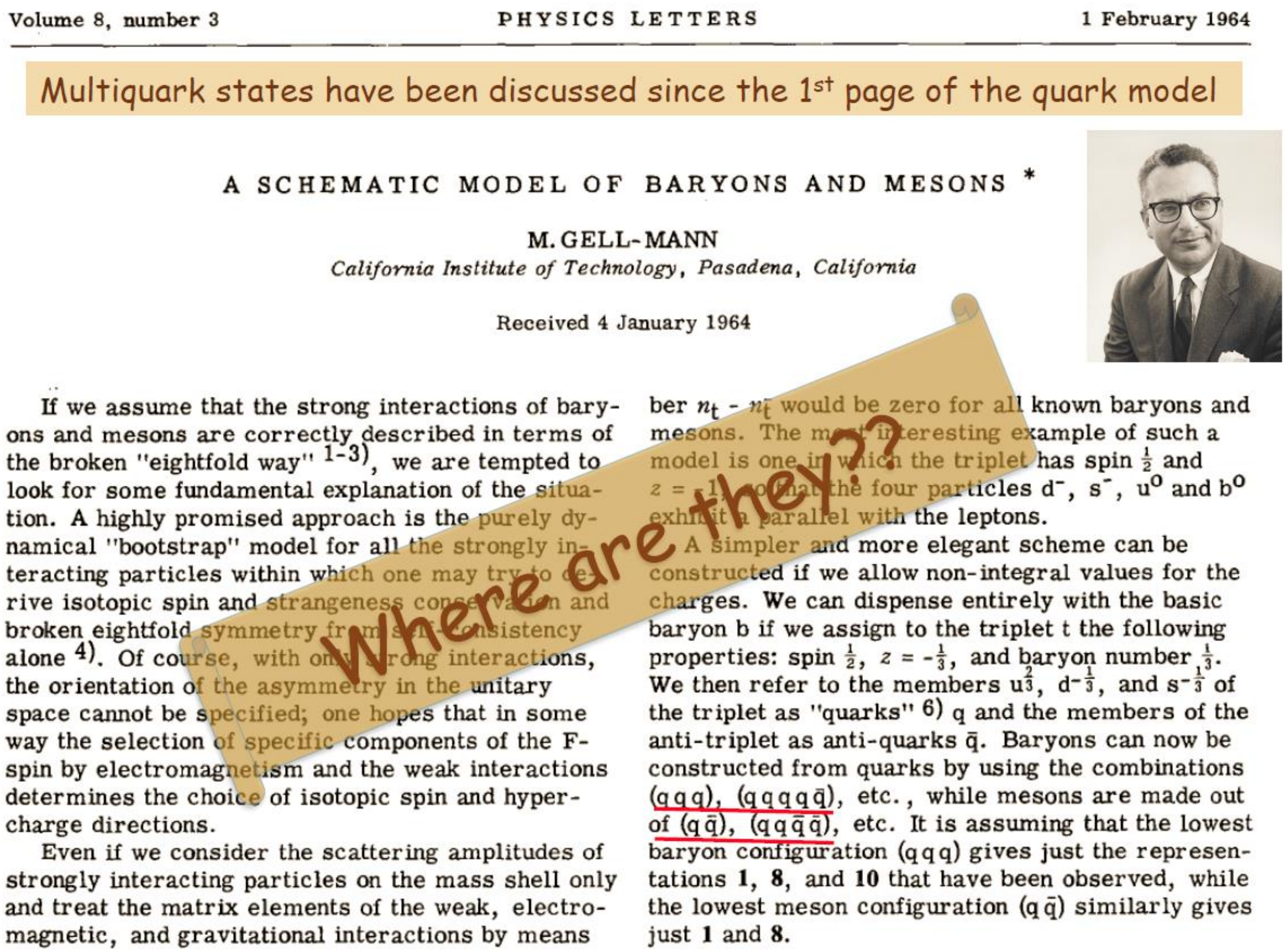
Hadrons: normal & multiquarks (exotic)

- Quark model: hadrons are composed from 2 (meson) quarks or 3 (baryon) quarks

- QCD does not forbid hadrons with $N_{quarks} \neq 2, 3$
  - Glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - Hybrid : $N_{quarks} = 2$ (or more) + excited gluon
  - Multiquark state : $N_{quarks} > 3$
  - Molecule : bound state of more than 2 hadrons
  - …



Nature Reviews Physics 1, 480 (2019)



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" 1-3), we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone 4). Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

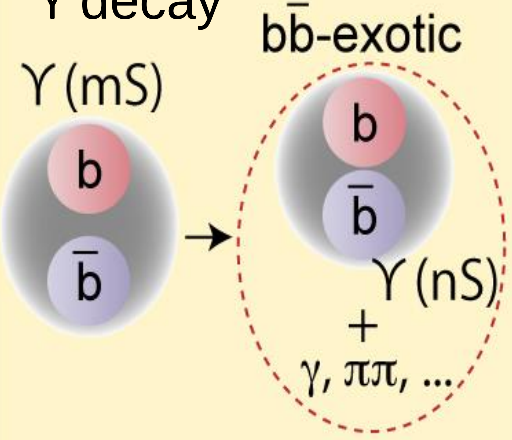
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

M. Gell-Mann, Phys. Lett. 8, 214 (1964)

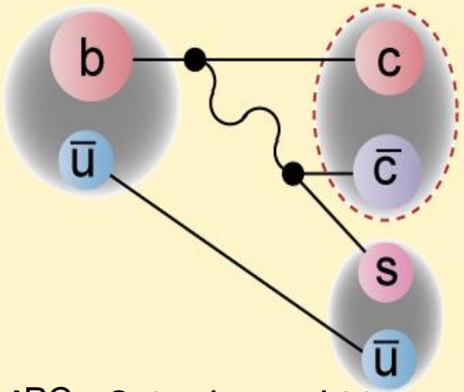
Gell-Mann in his quark model paper has mentioned "exotic states" since 1964. After that, many experiments focused on finding exotic hadrons.

Variety of recorded reactions

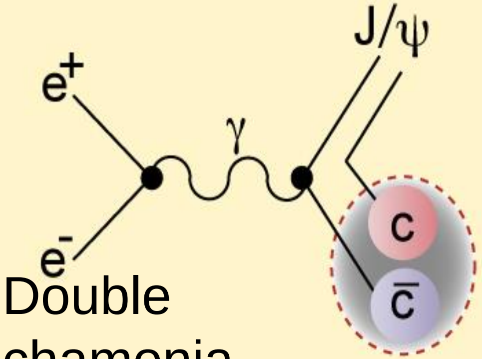
Υ decay



B decay



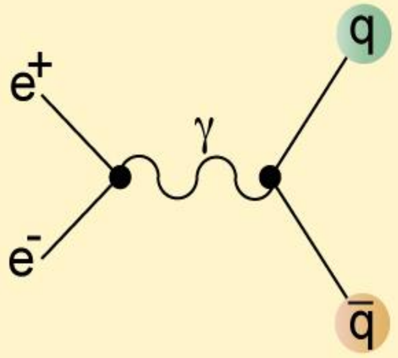
$J^{PC}=0^{-+}, 1^{--}, 1^{++}$ in factorization limit.



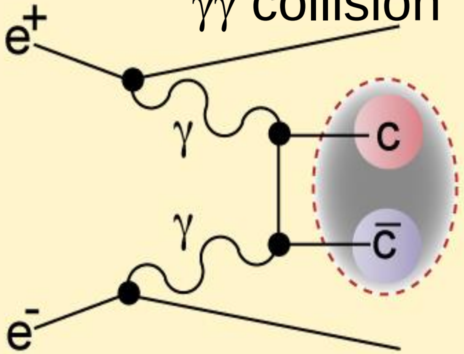
Double chamonia production

C=+1.

Continuum

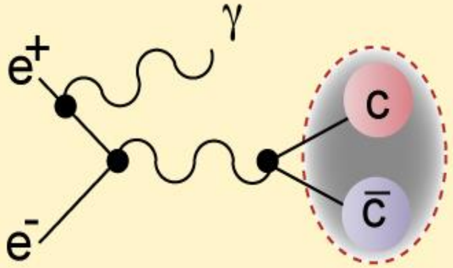


γγ collision



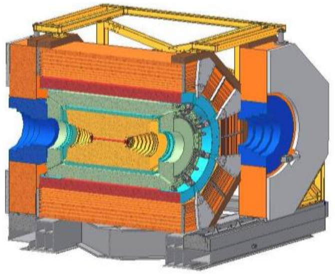
$J^{PC}=0^{-+}, 2^{++}$.

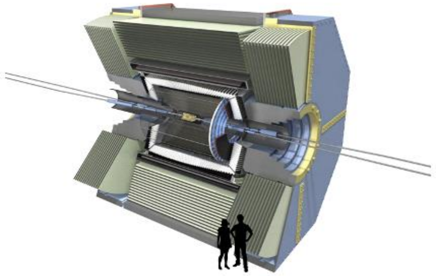
Initial state radiation

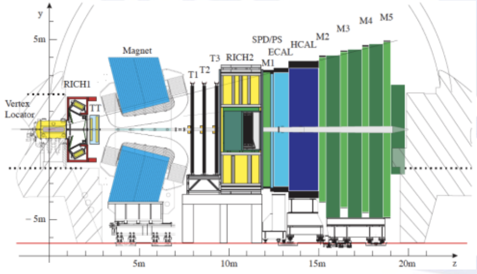


$J^{PC}=1^{--}$.

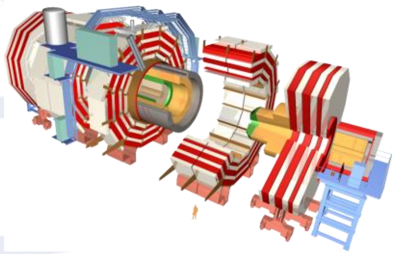
Main suppliers

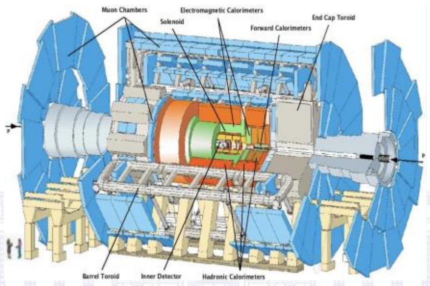

BESIII


Belle (II)



LHCb


CMS



ATLAS


BaBar

XYZ states

Success=X+Y+Z

Classification:

- $Q\bar{Q}q\bar{q}$

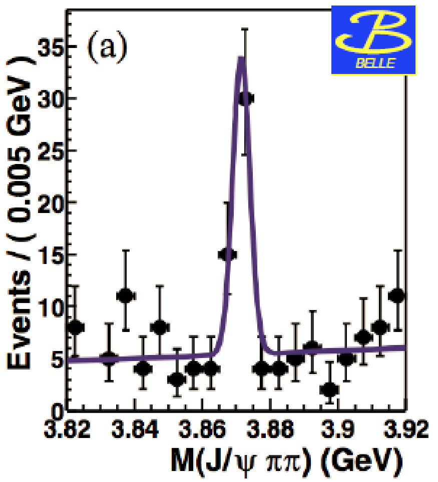
X: Neutral, $J^{PC} \neq 1^{--}$;
Y: Neutral, $J^{PC} = 1^{--}$;
Z: Charged

- $Q\bar{Q}qqq$: P_c^+

- Study of exotic hadrons can
  - provide new insights into internal structure and dynamics of hadrons
  - act as a unique probe to non-perturbative behavior of QCD

- Quarkonium: $q\bar{q}$, the simplest system of a hadron.
- Below $D\bar{D}/B\bar{B}$ thresholds – both charmonium and bottomonium are successful stories of QCD.
- But there are many exotic states observed in the past decades, and they are hard to fit in the two families.

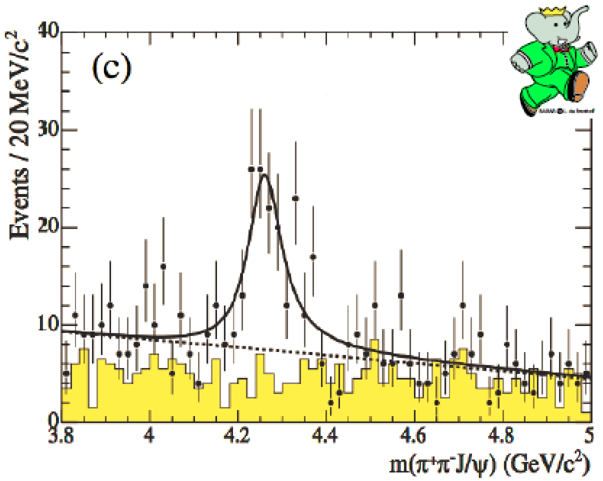
"X Y Z" – *the beginning*



$X(3872)$

PRL 91, 262001 (2003)

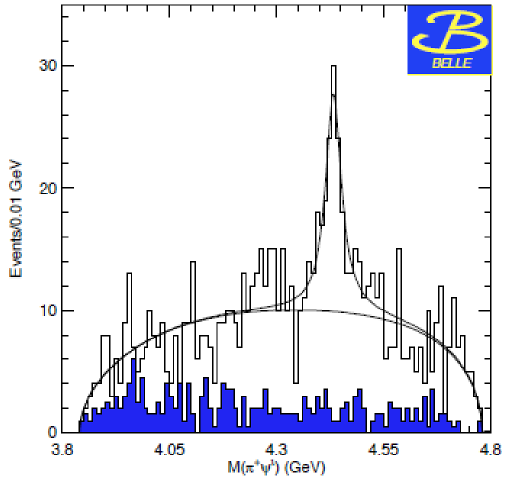
$B^{\pm} \rightarrow K^{\pm}[\pi^{+}\pi^{-}J/\psi]$



$Y(4260)$

PRL 95, 142001 (2005)

$e^{+}e^{-} \rightarrow \gamma[\pi^{+}\pi^{-}J/\psi]$



$Z_c(4430)^{\pm}$

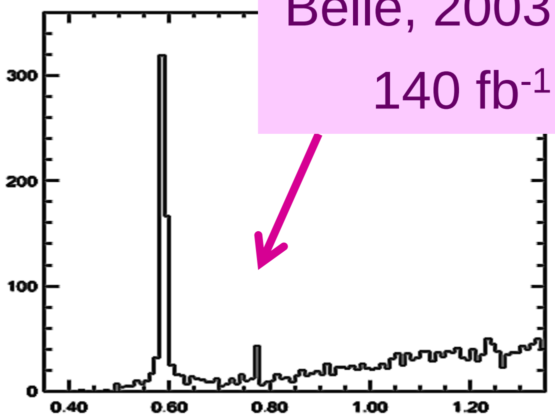
PRL 100, 142001 (2008)

$B \rightarrow K[\pi^{\pm}\psi']$

X States

What is the X(3872)?

- Mass: Very close to D^0D^{*0} threshold
- Width: Very narrow, 1.19±0.21 MeV [LHCb, PRD102, 092005; JHEP (2008) 123]
- $J^{PC}=1^{++}$
- Production
  - in $\bar{p}p/pp$ collision – rate similar to charmonia
  - In B decays – KX similar to $\bar{c}c$, K*X smaller than $\bar{c}c$
  - $Y(4260) \rightarrow \gamma + X(3872)$
- Decay BR: open charm ~ 50%, charmonium~O(%)
- Nature (very likely exotic)
  - Loosely $\bar{D}^0D^{*0}$ bound state (like deuteron)?
  - Mixture of excited $\chi_{c1}(2P)$ and $\bar{D}^0D^{*0}$ bound state?



Belle, 2003

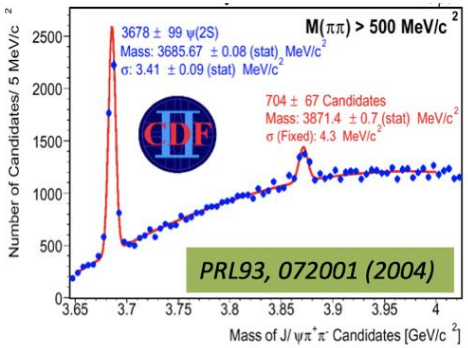
140 fb^{-1}

$M(\pi\pi J/\psi) - M(J/\psi)$ [GeV]

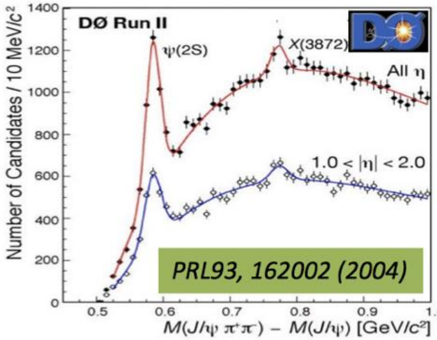
X(3872)→J/ψπ⁺π⁻

The most-cited article at Belle: >2500

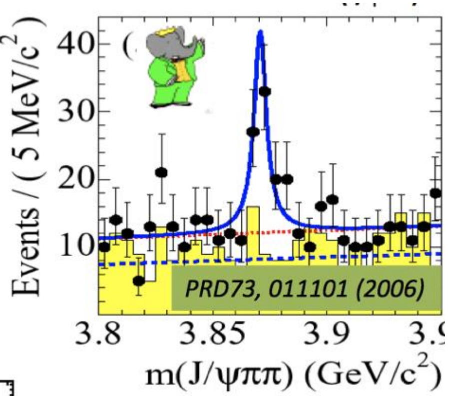
First observed by Belle in $B \to K\, J/\psi\pi^+\pi^-$ ***PRL91, 262001 (2003)***



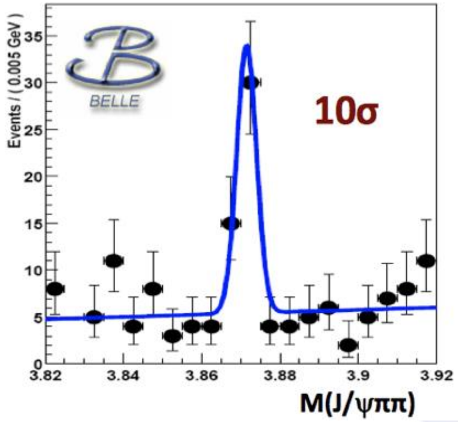
PRL93, 072001 (2004)

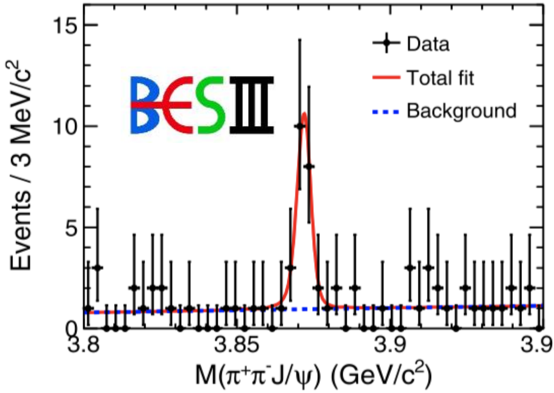


PRL93, 162002 (2004)

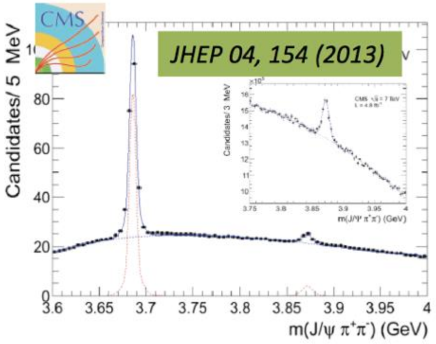


PRD73, 011101 (2006)

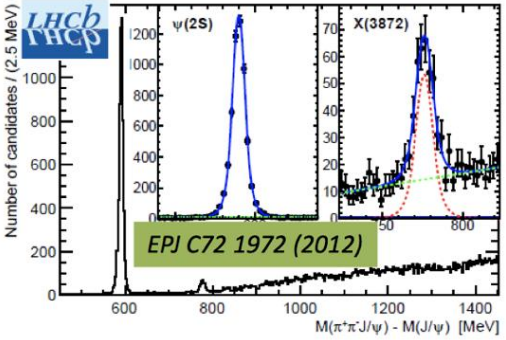




PRL112, 092001 (2014)



JHEP 04, 154 (2013)



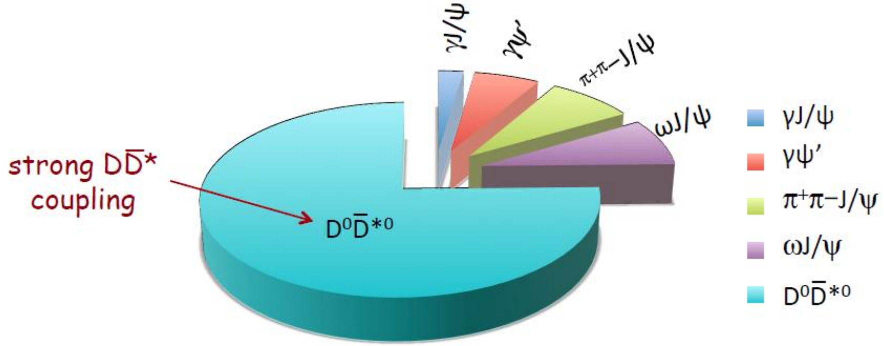
EPJ C72 1972 (2012)

X(3872)→J/ψγ: C-even

Angular analysis:

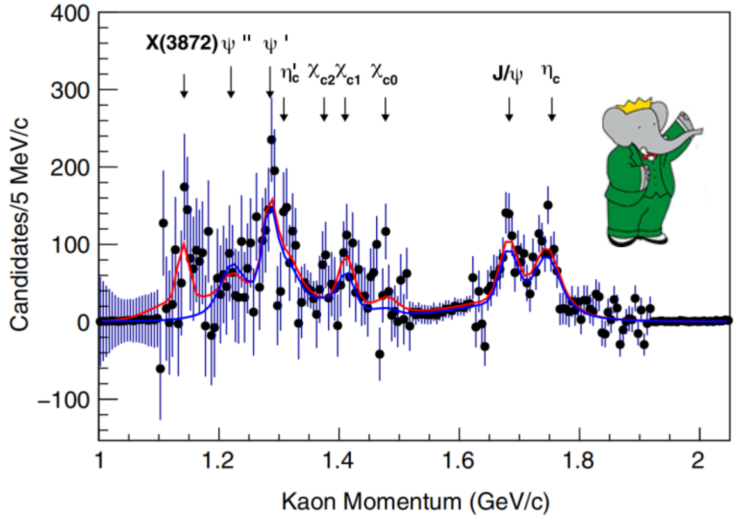
Belle 2006: **$J^{PC} = 1^{++}$ or ≥2**
CDF 2008: **$J^{PC} = 1^{++}$ or 2^{-+}**
Belle 2011: **$J^{PC} = 1^{++}$ or 2^{-+}**

LHCb 2013: **$J^{PC} = 1^{++}$**

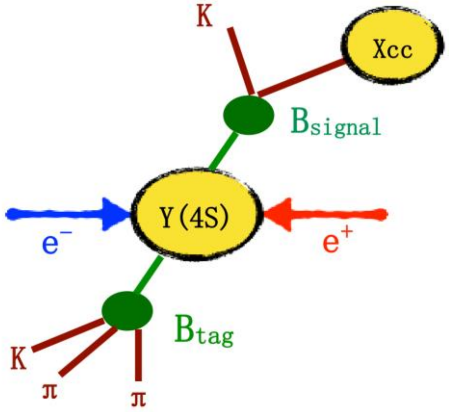


First determination of B(B$^{\pm}\rightarrow$X(3872)K$^{\pm}$)

- The determination of the B(B$^{\pm}\rightarrow$X(3872)K$^{\pm}$) leads to B(X(3872)$\rightarrow$J/$\psi\pi^{+}\pi^{-}$), bringing useful information regarding the complex nature of the X(3872).



BaBar, 424 fb^{-1}, PRL 124, 152001 (2020)



Branching fraction	Structure
$\mathcal{B}(X(3872)\rightarrow J/\psi\pi^{+}\pi^{-})$ $\sim 50\%$	Tetraquark State [PRD 71, 014028 (2005)]
$\mathcal{B}(X(3872)\rightarrow J/\psi\pi^{+}\pi^{-})$ $< 10\%$	Molecular state [PRD 72, 054022 (2005), PRD 69, 054008 (2004)]

- Increase signal efficiency by a factor of 3 by retaining all B tag candidates instead of the best one.
- There is 3σ evidence of the decay B$^{\pm}\rightarrow$X(3872)K$^{\pm}$, detected for the first time using this recoil technique.
- B(B$^{\pm}\rightarrow$X(3872)K$^{\pm}$) =(2.1±0.6±0.3) ×10^{-4}

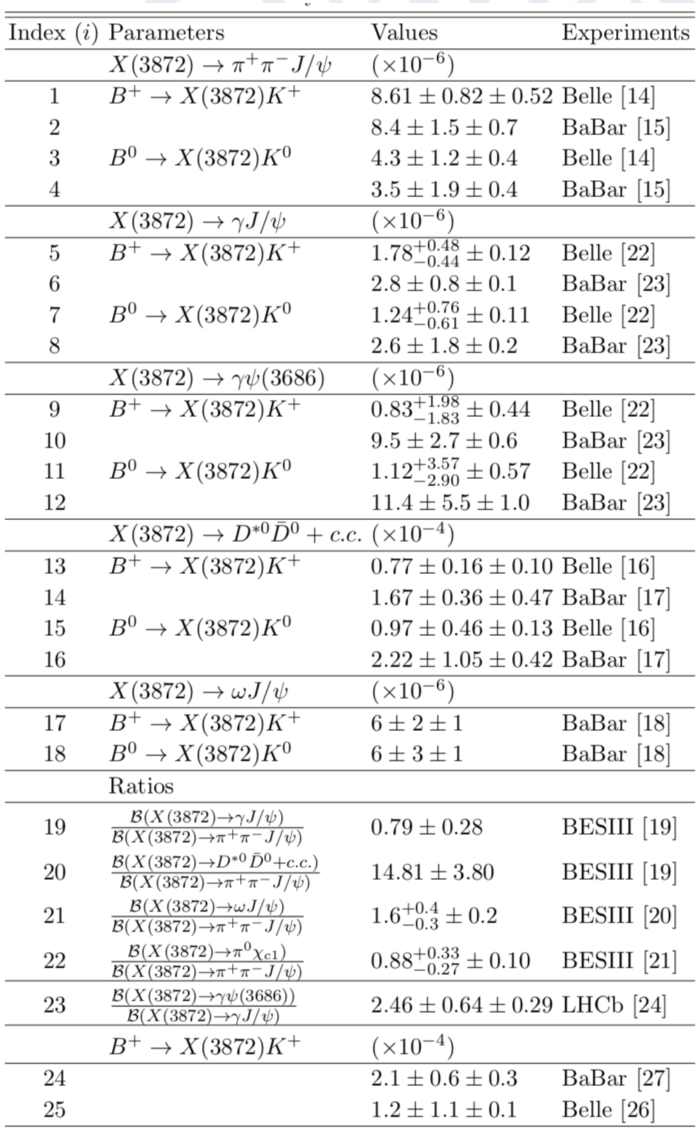
Absolute branching fractions of X(3872) decays

- Globally analyzing the measurements by BESIII, Belle, Babar, LHCb
- The absolute branching fractions of X(3872) are free parameters in the fitting

$$\chi^2(x) = \sum_{i=1}^{25} \frac{(x_i - x)^2}{\sigma_i^2},$$

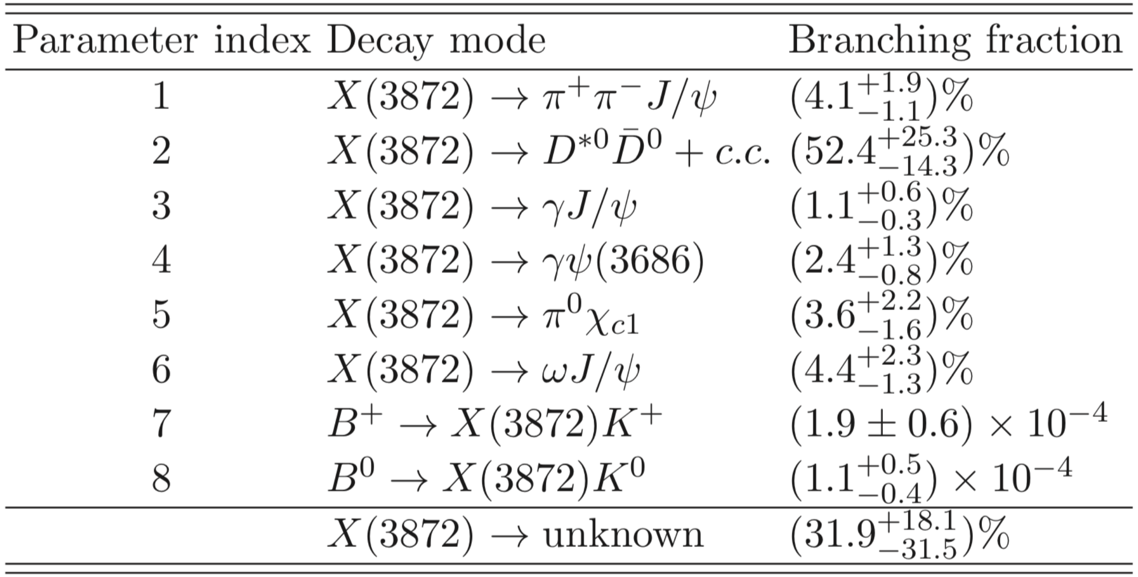
- Statistical uncertainties are dominant for most measurements.
- Possible correlation between the systematics of different measurements in an experiments is neglected.

C.H.Li, C.Z.Yuan, Phys.Rev. D100 (2019) 094003



Index (i)	Parameters	Values	Experiments
	$X(3872) \to \pi^+\pi^- J/\psi$	$(\times 10^{-6})$	
1	$B^+ \to X(3872)K^+$	$8.61 \pm 0.82 \pm 0.52$	Belle [14]
2		$8.4 \pm 1.5 \pm 0.7$	BaBar [15]
3	$B^0 \to X(3872)K^0$	$4.3 \pm 1.2 \pm 0.4$	Belle [14]
4		$3.5 \pm 1.9 \pm 0.4$	BaBar [15]
	$X(3872) \to \gamma J/\psi$	$(\times 10^{-6})$	
5	$B^+ \to X(3872)K^+$	$1.78^{+0.48}_{-0.44} \pm 0.12$	Belle [22]
6		$2.8 \pm 0.8 \pm 0.1$	BaBar [23]
7	$B^0 \to X(3872)K^0$	$1.24^{+0.76}_{-0.61} \pm 0.11$	Belle [22]
8		$2.6 \pm 1.8 \pm 0.2$	BaBar [23]
	$X(3872) \to \gamma\psi(3686)$	$(\times 10^{-6})$	
9	$B^+ \to X(3872)K^+$	$0.83^{+1.98}_{-1.83} \pm 0.44$	Belle [22]
10		$9.5 \pm 2.7 \pm 0.6$	BaBar [23]
11	$B^0 \to X(3872)K^0$	$1.12^{+3.57}_{-2.90} \pm 0.57$	Belle [22]
12		$11.4 \pm 5.5 \pm 1.0$	BaBar [23]
	$X(3872) \to D^{*0}\bar{D}^0 + c.c.$	$(\times 10^{-4})$	
13	$B^+ \to X(3872)K^+$	$0.77 \pm 0.16 \pm 0.10$	Belle [16]
14		$1.67 \pm 0.36 \pm 0.47$	BaBar [17]
15	$B^0 \to X(3872)K^0$	$0.97 \pm 0.46 \pm 0.13$	Belle [16]
16		$2.22 \pm 1.05 \pm 0.42$	BaBar [17]
	$X(3872) \to \omega J/\psi$	$(\times 10^{-6})$	
17	$B^+ \to X(3872)K^+$	$6 \pm 2 \pm 1$	BaBar [18]
18	$B^0 \to X(3872)K^0$	$6 \pm 3 \pm 1$	BaBar [18]
	Ratios		
19	$\frac{\mathcal{B}(X(3872)\to\gamma J/\psi)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	0.79 ± 0.28	BESIII [19]
20	$\frac{\mathcal{B}(X(3872)\to D^{*0}\bar{D}^0+c.c.)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	14.81 ± 3.80	BESIII [19]
21	$\frac{\mathcal{B}(X(3872)\to\omega J/\psi)}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$1.6^{+0.4}_{-0.3} \pm 0.2$	BESIII [20]
22	$\frac{\mathcal{B}(X(3872)\to\pi^0\chi_{c1})}{\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)}$	$0.88^{+0.33}_{-0.27} \pm 0.10$	BESIII [21]
23	$\frac{\mathcal{B}(X(3872)\to\gamma\psi(3686))}{\mathcal{B}(X(3872)\to\gamma J/\psi)}$	$2.46 \pm 0.64 \pm 0.29$	LHCb [24]
	$B^+ \to X(3872)K^+$	$(\times 10^{-4})$	
24		$2.1 \pm 0.6 \pm 0.3$	BaBar [27]
25		$1.2 \pm 1.1 \pm 0.1$	Belle [26]

Absolute branching fractions of X(3872) decays



Parameter index	Decay mode	Branching fraction
1	$X(3872) \to \pi^+\pi^- J/\psi$	$(4.1^{+1.9}_{-1.1})\%$
2	$X(3872) \to D^{*0}\bar{D}^0 + c.c.$	$(52.4^{+25.3}_{-14.3})\%$
3	$X(3872) \to \gamma J/\psi$	$(1.1^{+0.6}_{-0.3})\%$
4	$X(3872) \to \gamma\psi(3686)$	$(2.4^{+1.3}_{-0.8})\%$
5	$X(3872) \to \pi^0\chi_{c1}$	$(3.6^{+2.2}_{-1.6})\%$
6	$X(3872) \to \omega J/\psi$	$(4.4^{+2.3}_{-1.3})\%$
7	$B^+ \to X(3872)K^+$	$(1.9 \pm 0.6) \times 10^{-4}$
8	$B^0 \to X(3872)K^0$	$(1.1^{+0.5}_{-0.4}) \times 10^{-4}$
	$X(3872) \to \text{unknown}$	$(31.9^{+18.1}_{-31.5})\%$

- $X(3872) \to \pi^+\pi^- J/\psi \sim (4.1^{+1.9}_{-1.1})\%$
- $X(3872) \to D^0 D^{*0} \sim (52.4^{+25.3}_{-14.3})\%$
- Unknown decay $\sim (31.9^{+18.1}_{-31.5})\%$

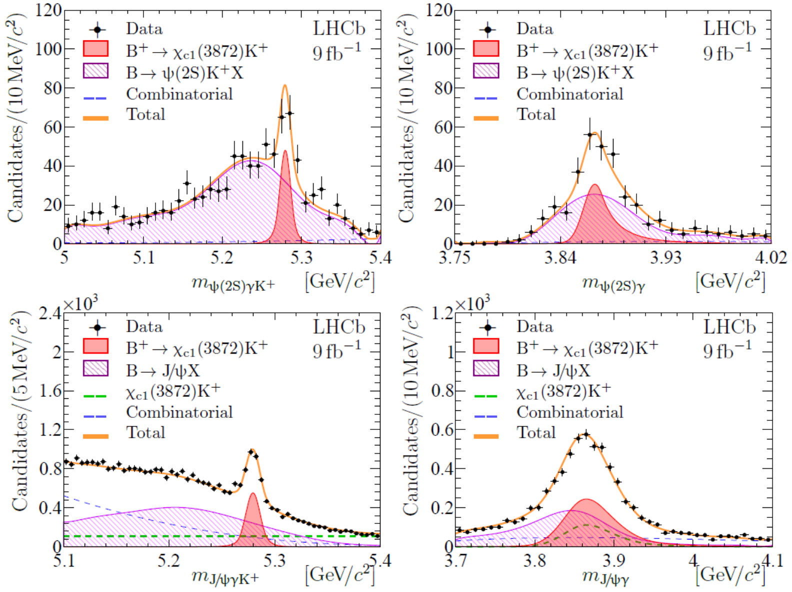
- Statistical uncertainties are dominant.
- At Belle II, we need improve the measurements related with X(3872) decays.

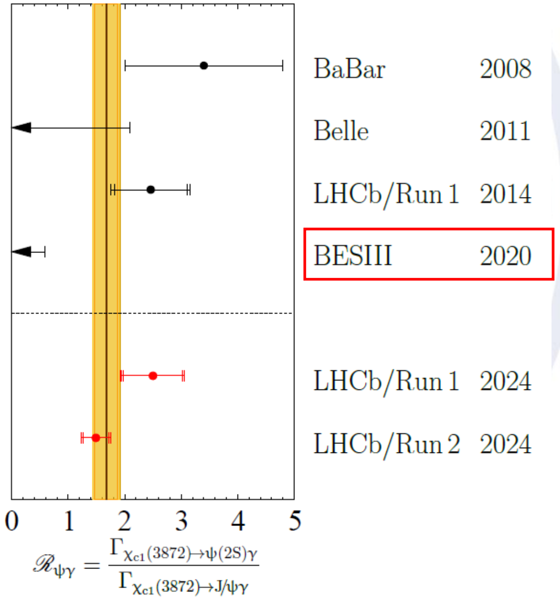
C.H.Li, C.Z.Yuan, Phys.Rev. D100 (2019) 094003

X(3872) radiative decays at LHCb

arXiv:2406.17006

- The ratio of the partial radiative decay widths into ψ(2S)γ and J/ψγ vary widely depending on the different hypothesis for X(3872)
- Large values of this ratio (>=1) are expected for a conventional charmonium $\chi_{c1}(2P)$ state; smaller values for pure DD* molecular hypothesis ($R_{\psi\gamma} \ll 1$)
- Mixture of a predominantly DD* molecular state and a compact component cover a wide range of $R_{\psi\gamma}$





The significance of the X(3872)→ ψ(2S)γ signal is 4.8σ and 6.0σ for the Run 1 and Run 2

$$\mathcal{R}^{\text{Run 1}}_{\psi\gamma} = 2.50 \pm 0.52^{+0.20}_{-0.23} \pm 0.06\,,$$
$$\mathcal{R}^{\text{Run 2}}_{\psi\gamma} = 1.49 \pm 0.23^{+0.13}_{-0.12} \pm 0.03\,,$$

$$\mathcal{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04\,.$$

A strong argument in favour of a compact component in the X(3872) structure

Hints before the discovery of X(3872)→J/ψπ⁺π⁻

Observation of a narrow charmonium-like state in exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays

Belle Collaboration • S.K. Choi (Gyeongsang Natl. U.) et al. (Sep, 2003)

Published in: *Phys.Rev.Lett.* 91 (2003) 262001 • e-Print: hep-ex/0309032 [hep-ex]

2016 W.K.H. Panofsky Prize in Experimental Particle Physics Recipient

Stephen L Olsen
Institute for Basic Science

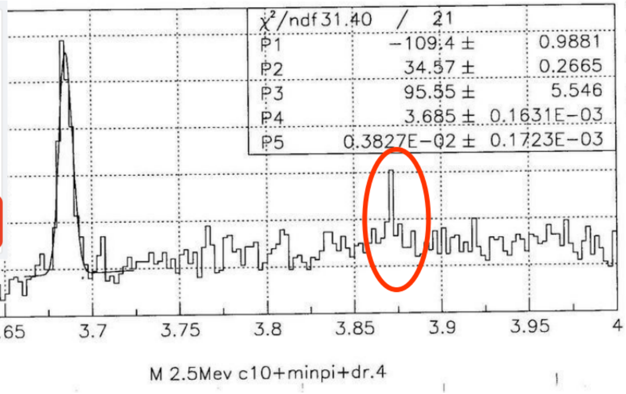
Citation:

"*For leadership in the BaBar and Belle Experiments, which established the violation of CP symmetry in B-meson decay, and furthered our understanding of quark mixing and quantum chromodynamics.*"

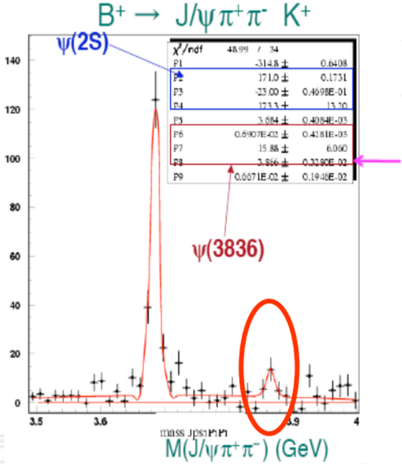
Background:

Stephen Lars Olsen received a B.S. from the City College of New York in 1963 and a Ph.D. in physics from the University of Wisconsin in 1970. He is currently an Emeritus Research Fellow at the Center for Underground Physics of the Institute for Basic Science in Korea. His research has concentrated mostly on studies of heavy quarks and their associated hadrons using CLEO at Cornell, AMY and Belle experiments at KEK in Japan, and the BES experiments at IHEP in Beijing. He currently participates in the KIMS dark matter and AMoRE neutrinoless double beta decay searches at the Yangyang Underground Laboratory in Korea. Olsen was an Alfred P. Sloan Fellow (1972-1977), a John Simon Guggenheim Fellow (1986-1987), a Japan Society for the Promotion of Science Fellow (1987-1988). He was awarded the University of Hawaii Regents Medal for Excellence inResearch in 2002 and was designated as a University of Wisconsin Distinguished Alumni in 2007. He was elected Fellow of the APS in 1984.

CDF internal, 1994



BaBar internal, 2003

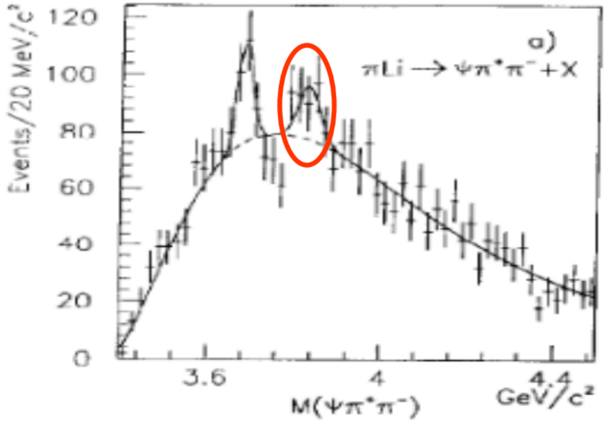


Mass=3866±6

AWG meeting June 2003
motivation: background to
J/ψ K$_L$; test factorization…

From BaBar B-Factory Symposium (C. Hearty)
http://www-conf.slac.stanford.edu/b-factory-symposium/talks.asp

E705, PRD 50, 4258 (1994)
E705 saw ψ(3836) (2⁻⁻)in 1994, 3.836±0.013 GeV
PRL 115 011803, PRL 111 032001



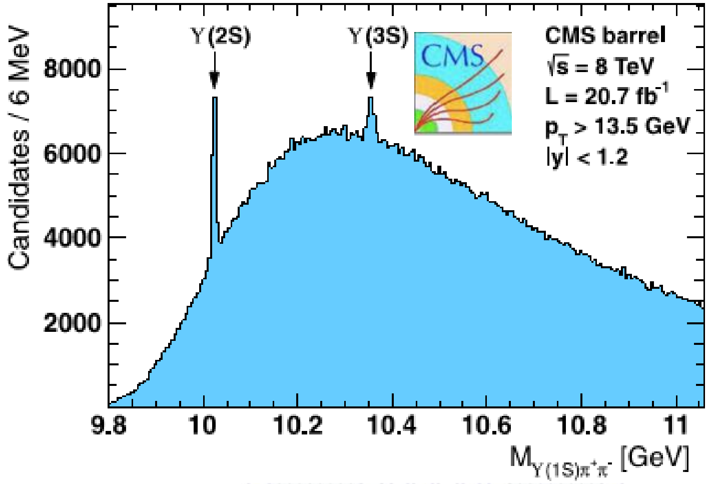
***CDF saw a hint in 1994**, unpublished*
***BaBar saw a hint in 2003**, unpublished*

Both CDF and Babar spotted hints of X(3872) before its discovery!

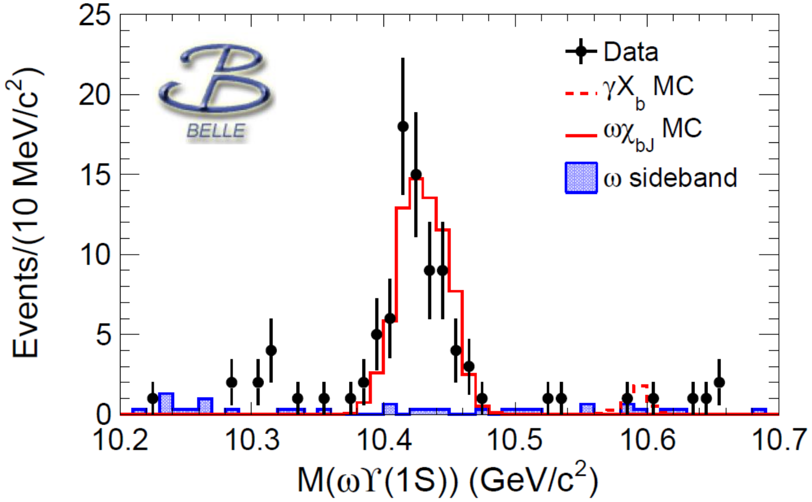
What can we learn from this story ?

Search for X_b in $e^+e^- \to \gamma\pi^+\pi^-\pi^0\Upsilon(1S)$ at 10.867 GeV

- **The X(3872) counterpart in the bottomonium sector X_b, NOT observed decay channel $\pi^+\pi^-\Upsilon(1S)$.**
- **As X_b is above $\omega\Upsilon(1S)$ threshold, this Isospin-conserving process should be a more promising decay mode.** [PRD88, 054007].



PLB 727, 57 (2013)

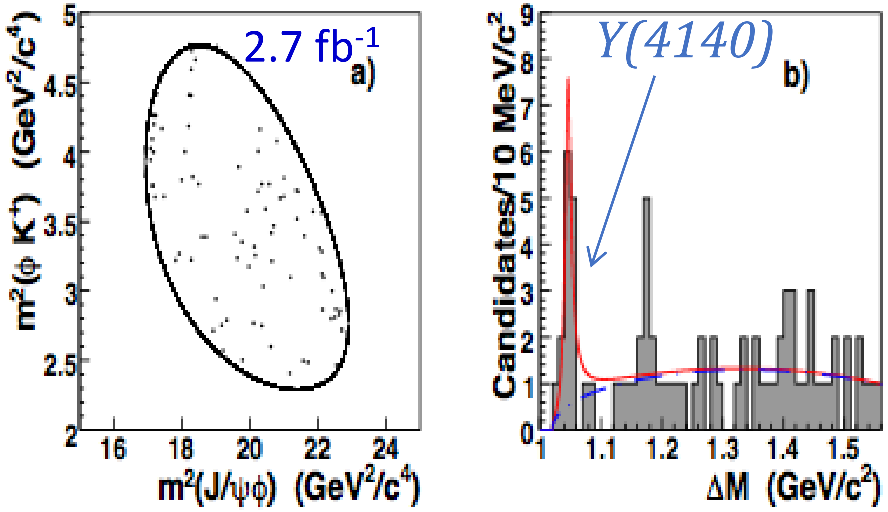


PRL 113, 142001 (2014)

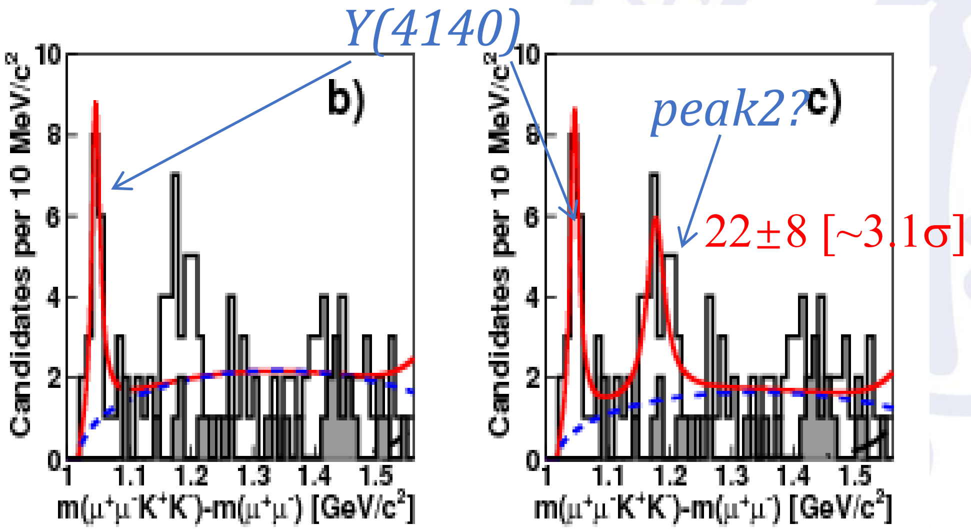
Assuming X_b is narrow, the upper limit on the product branching fraction was given.

The history/story of X(4140)/Y(4140)

CDF—PRL102:242002 (2009)



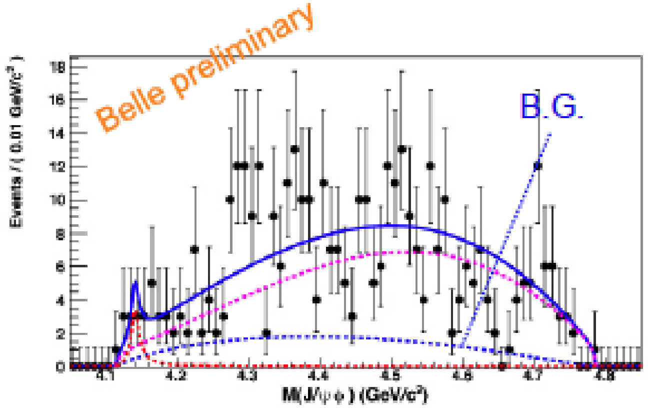
Mod.Phys.Lett. A32 (2017), 1750139



X(4140) (renamed), mass-4.14 GeV, width—15 MeV
This is the first unexpected particle discovered by Tevatron!
Possible second state: mass—4.27 GeV, width—30 MeV
Experienced a long road for confirmation!

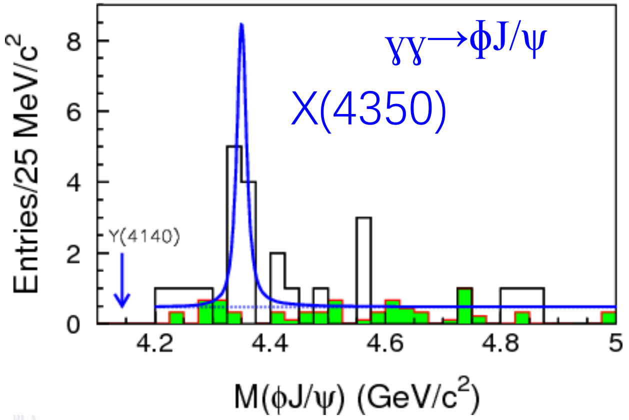
- Necessarily exotic since it is narrow and above the DsDs threshold
- $[cs\bar{c}\bar{s}]$ tetraquark ?
- Hint of a second structure: $X(4274)$

Belle: Confirm or refute? (2009, 2010)



Y(4140): 7.5 +4.9/-4.4events
Statistical significance: 1.9σ
Signal could not be identified.

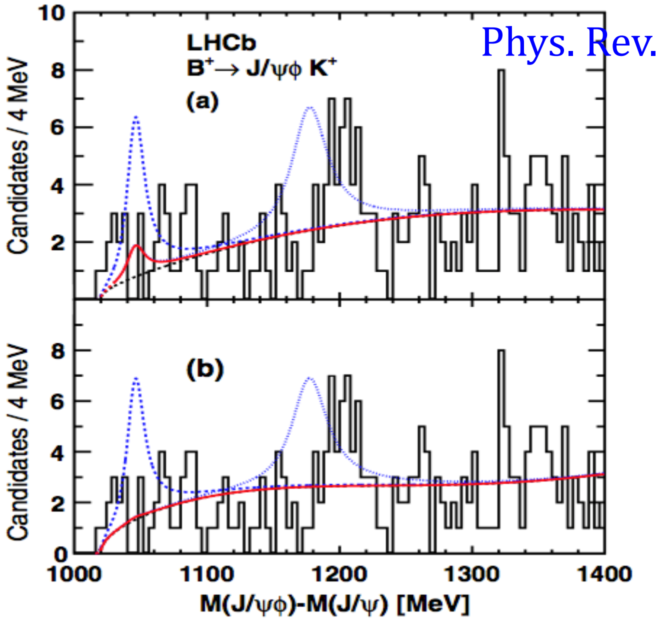
Belle, PRL 104 (2010) 112004



- B factories suffer from low p_t track inefficiency
- Belle cannot confirm or deny the existence of Y(4140)

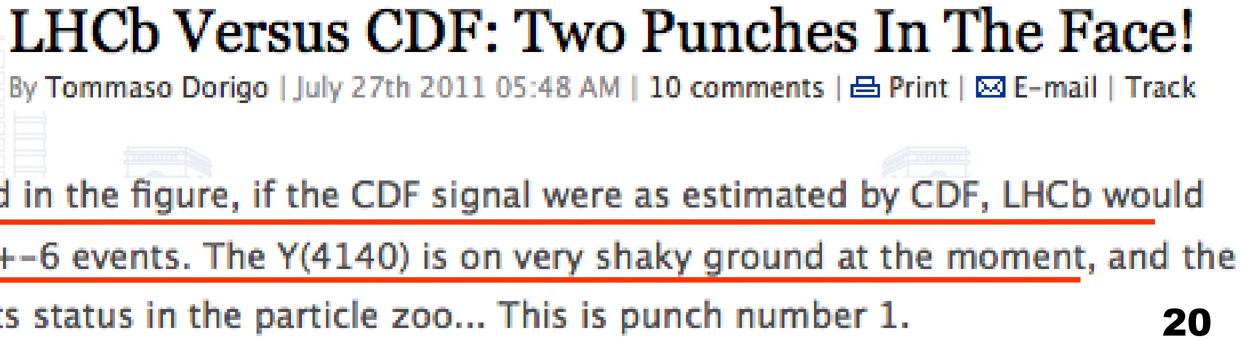
Belle spotted another possible new state in the same final state but from a different production: X(4350) needs to be confirmed at Belle II with larger data samples.

LHCb: contests CDF report (2011)



Phys. Rev. D85 (2012) 091103

LHCb confirms neither structure(s) with part of their data taken in 2011

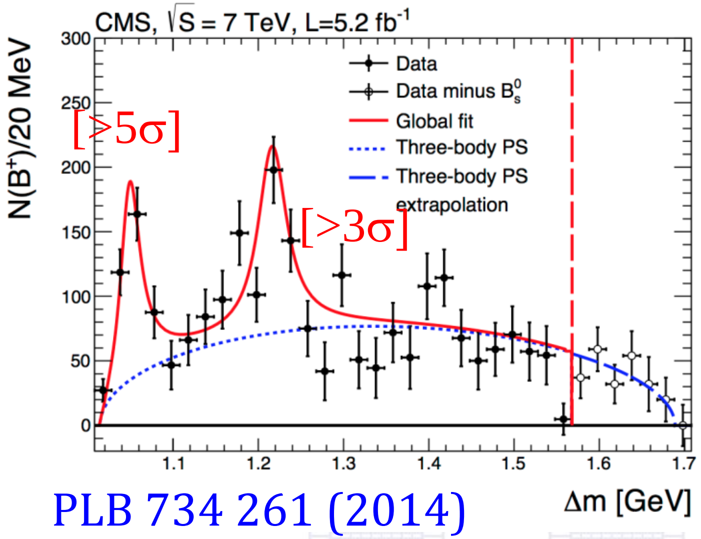


LHCb Versus CDF: Two Punches In The Face!

By Tommaso Dorigo | July 27th 2011 05:48 AM | 10 comments | Print | E-mail | Track

result. Note that, as reported in the figure, if the CDF signal were as estimated by CDF, LHCb would have been able to fit 39+-9+-6 events. The Y(4140) is on very shaky ground at the moment, and the new PDG will likely change its status in the particle zoo... This is punch number 1.

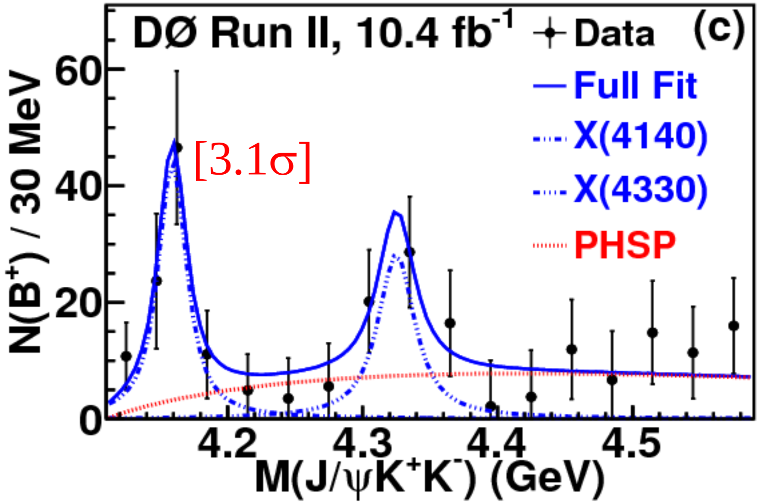
Result from CMS (2012)



PLB 734 261 (2014)

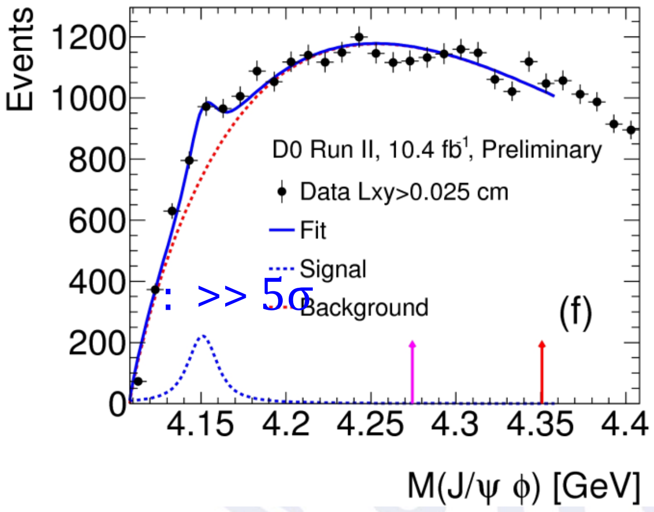
Y(4140) @ D0 (2013)

PRD 89, 012004 (2014)



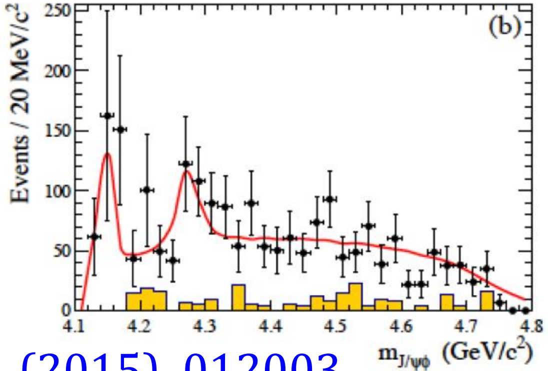
Y(4140) @ D0 (2015)

PRL 115(2015), 232001



Y(4140) @ BaBar (2015)

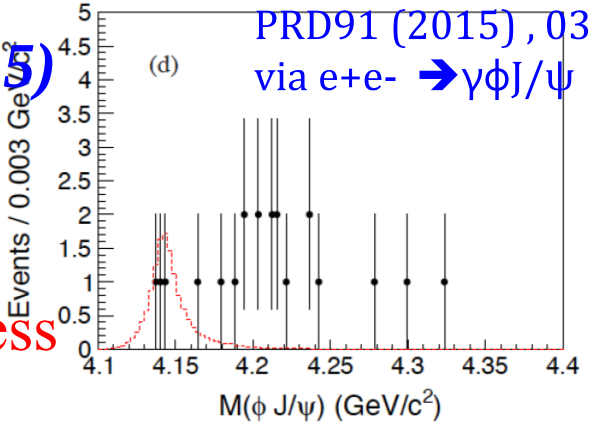
No significance for both structures though there are hints



PRD91 (2015), 012003

Y(4140) @ BES (2015)

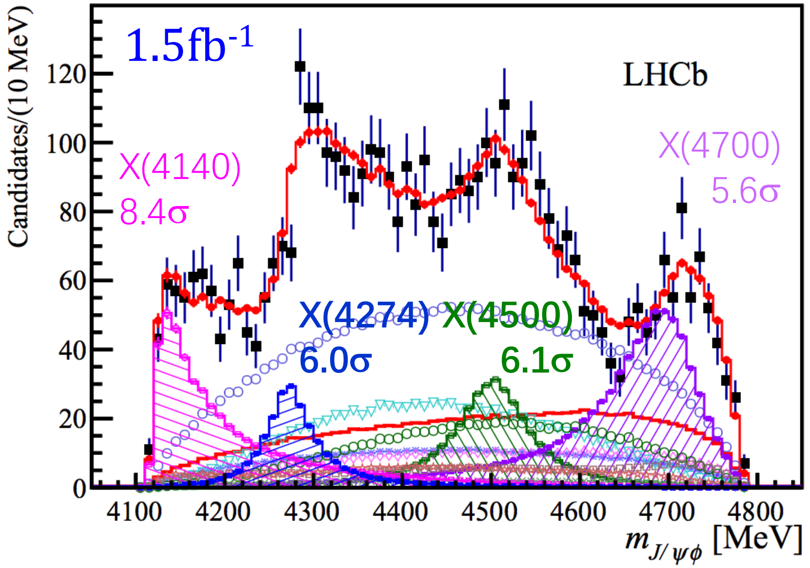
BES sets limits, cannot compare because it is from a different process



PRD91 (2015) , 032002
via e+e- ➔γϕJ/ψ

Results from LHCb (2016)

LHCb, PRL 118 (2017), 022003; PRD 95 (2017), 012002

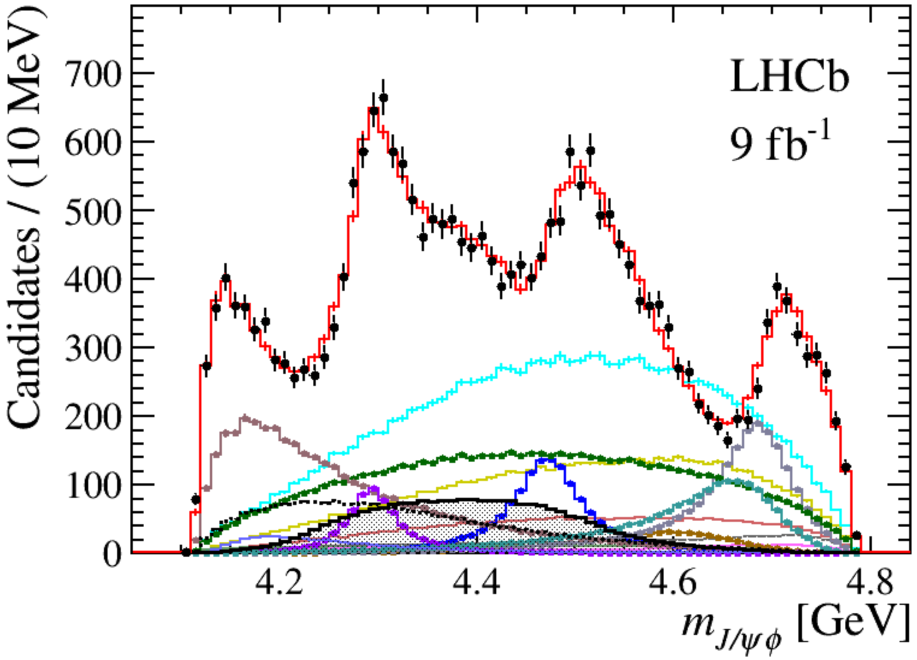


- No light quark (u,d) components
- Cannot exchange pion—J/**φ** or **ϕ** has no isospin
- Cannot exchange photon--pion—J/**φ** or **ϕ** has no charge
- A case of more general tetra-quark dynamics
- New important piece to the exotic meson family

- LHCb re-confirmed both X(4140) and X(4274), Observed $X(4500)$ and $X(4700)$
- LHCb found two additional resonances in the same mass spectrum
- This is 7 years after the first report from CDF
- Waing for Belle II larger data samples: signals should be more cleaner

Updated Results from LHCb (2021)

Phys.Rev.Lett. 127 (2021) 082001



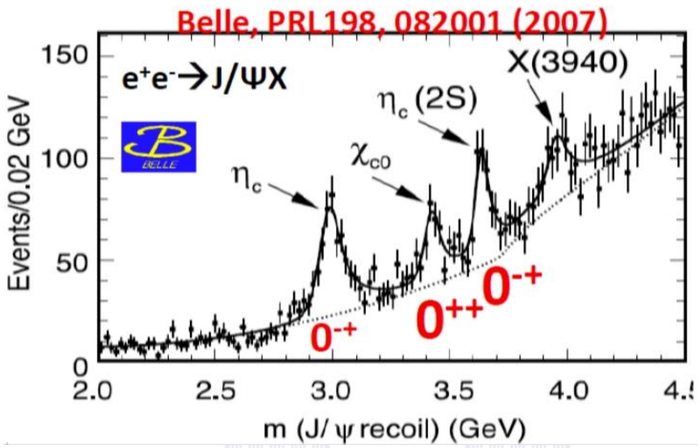
6D amplitude fit: Measured mass of $X(4140)$ is $4118 \pm 11^{+19}_{-36}$ MeV, **width $162 \pm 21^{+24}_{-49}$ MeV**, not very narrow; the mass is around the threshold of $J/\psi\phi$.

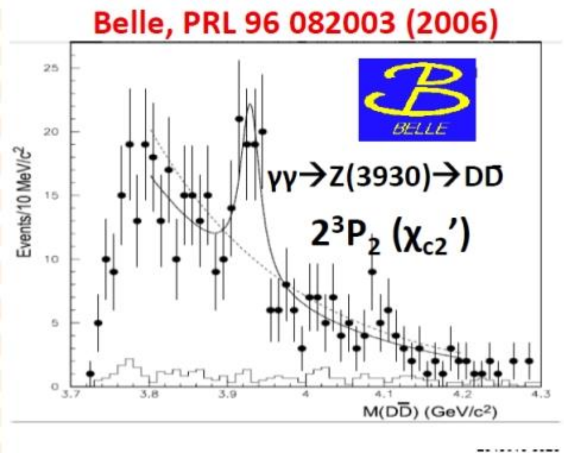
- New states: $Z_{cs}(4000)$, $X(4685)$ > 15σ; $Z_{cs}(4220)$, $X(4630)$ > 5σ
  $X(4150)$ < 5σ

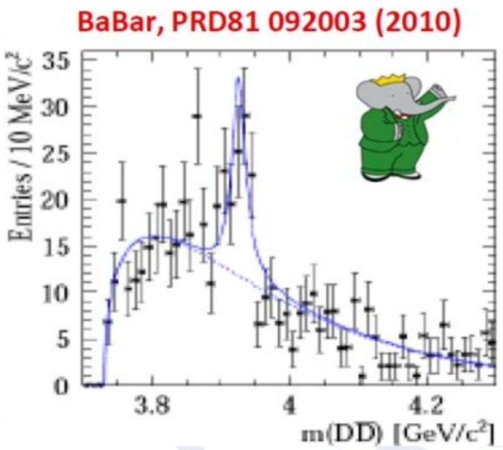
Stat.(Syst. included)

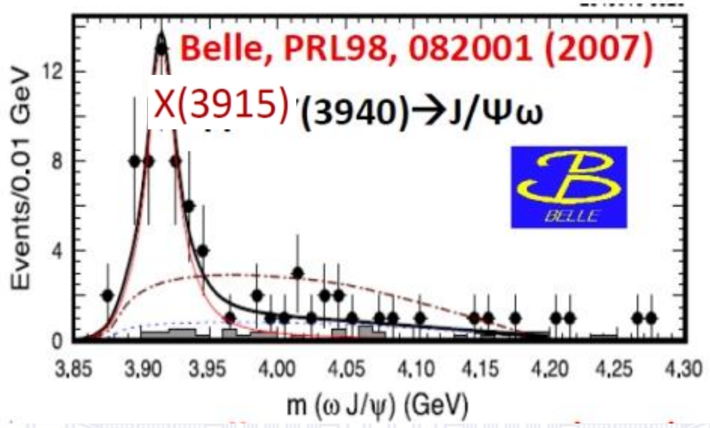
Contribution	Significance [$\times\sigma$]	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	$2.0 \pm 0.5^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	$2.6 \pm 0.5^{+2.9}_{-1.5}$
All $X(0^+)$				$20 \pm 5^{+14}_{-7}$
$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	$5.6 \pm 0.7^{+2.4}_{-0.6}$
$X(4700)$	17 (18)	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	$8.9 \pm 1.2^{+4.9}_{-1.4}$
$\mathrm{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8^{+19}_{-11}$
All $X(1^+)$				$26 \pm 3^{+8}_{-10}$
$X(4140)$	13 (16)	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	$17 \pm 3^{+19}_{-6}$
$X(4274)$	18 (18)	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5^{+0.8}_{-0.4}$
$X(4685)$	15 (15)	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	$7.2 \pm 1.0^{+4.0}_{-2.0}$
All $Z_{cs}(1^+)$				$25 \pm 5^{+11}_{-12}$
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

Other productions for charmonium-like states

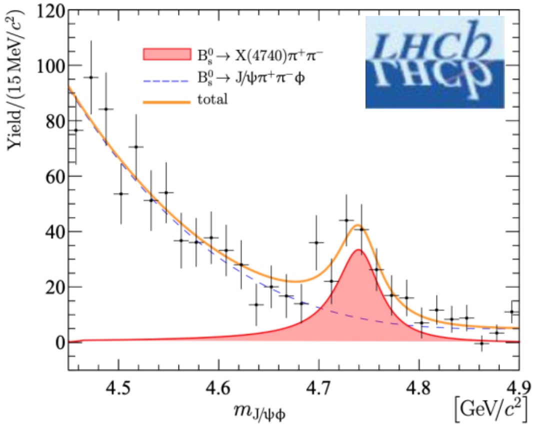

Belle, PRL198, 082001 (2007)


Belle, PRL 96 082003 (2006)


BaBar, PRD81 092003 (2010)



JHEP 02 (2021) 024

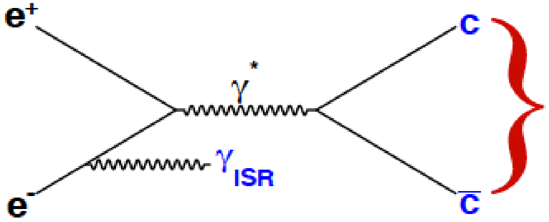


$$
\begin{aligned}
m_{X(4740)} &= 4741 \pm 6 \ \pm 6 \ \ \mathrm{MeV}/c^2\,, \\
\Gamma_{X(4740)} &= 53 \pm 15 \pm 11\,\mathrm{MeV}\,,
\end{aligned}
$$

$$B_s^0 \to J/\psi\pi^+\pi^-K^+K^-$$

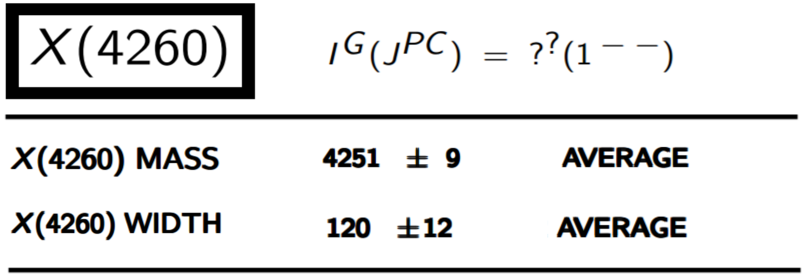
Υ States

$e^+e^-\rightarrow\pi^+\pi^-J/\psi$ cross section : Y(4260)



$J^{PC} = 1^{--}$

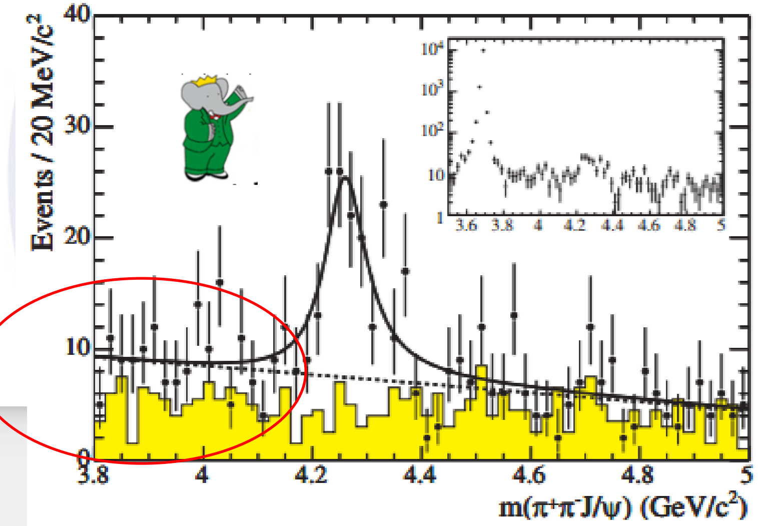
ψ', ψ'', Y…

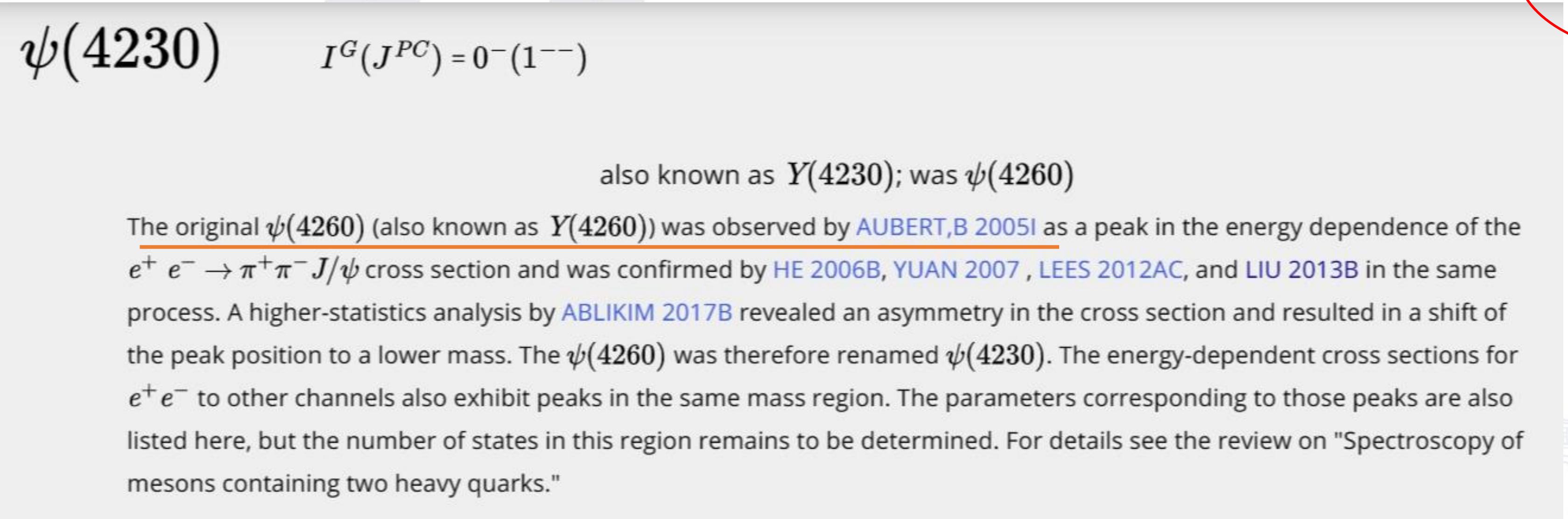


$X(4260)$ $I^G(J^{PC}) = ?^?(1^{--})$

$X(4260)$ MASS	4251 ± 9	AVERAGE
$X(4260)$ WIDTH	120 ±12	AVERAGE

BABAR PRL95,142001(2005)

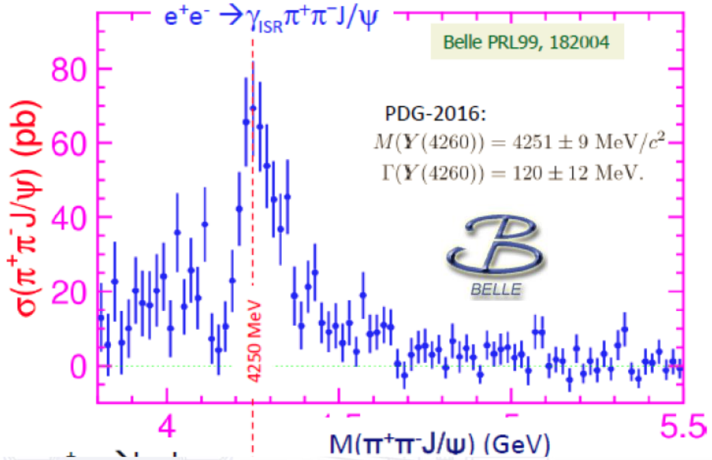




$\psi(4230)$ $I^G(J^{PC}) = 0^-(1^{--})$

also known as $Y(4230)$; was $\psi(4260)$

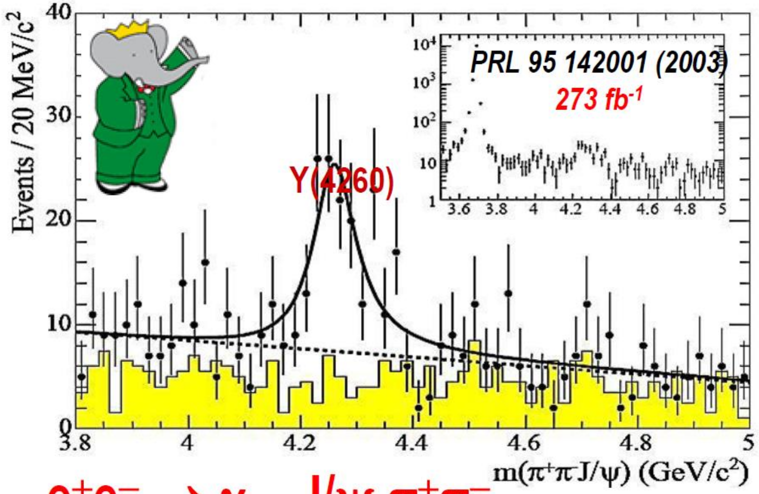
The original $\psi(4260)$ (also known as $Y(4260)$) was observed by AUBERT,B 2005I as a peak in the energy dependence of the $e^+e^-\rightarrow\pi^+\pi^-J/\psi$ cross section and was confirmed by HE 2006B, YUAN 2007 , LEES 2012AC, and LIU 2013B in the same process. A higher-statistics analysis by ABLIKIM 2017B revealed an asymmetry in the cross section and resulted in a shift of the peak position to a lower mass. The $\psi(4260)$ was therefore renamed $\psi(4230)$. The energy-dependent cross sections for e^+e^- to other channels also exhibit peaks in the same mass region. The parameters corresponding to those peaks are also listed here, but the number of states in this region remains to be determined. For details see the review on "Spectroscopy of mesons containing two heavy quarks."



Belle PRL99, 182004

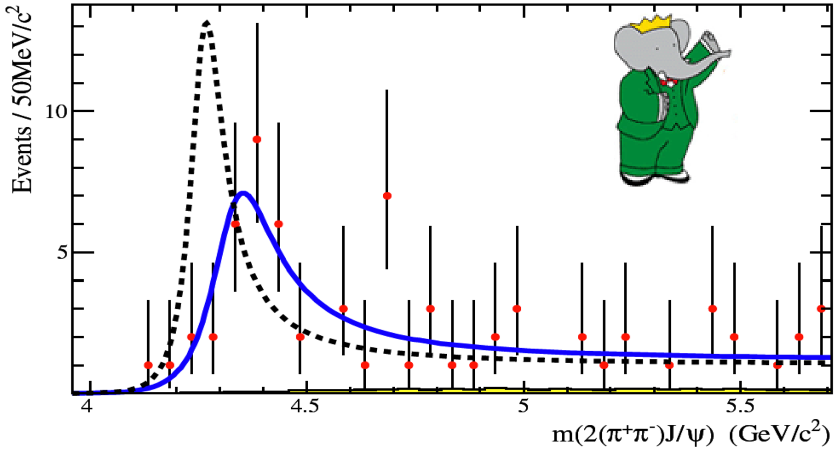
PDG-2016:
$M(Y(4260)) = 4251 \pm 9\ \mathrm{MeV}/c^2$
$\Gamma(Y(4260)) = 120 \pm 12\ \mathrm{MeV}.$

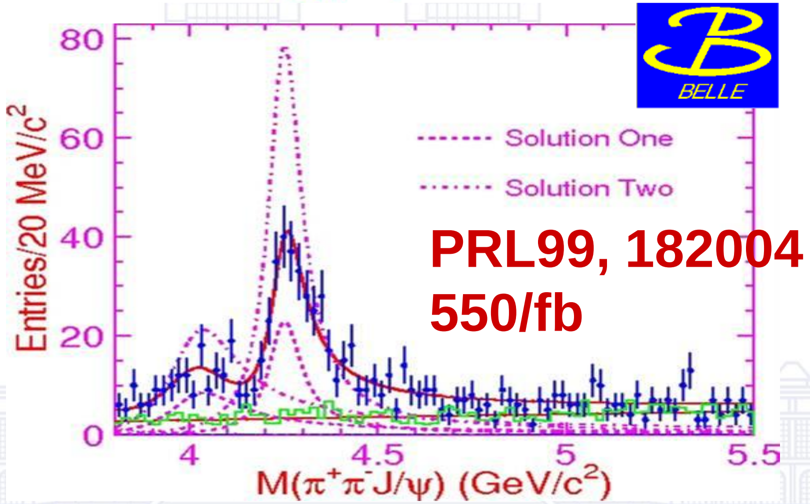
The Y states



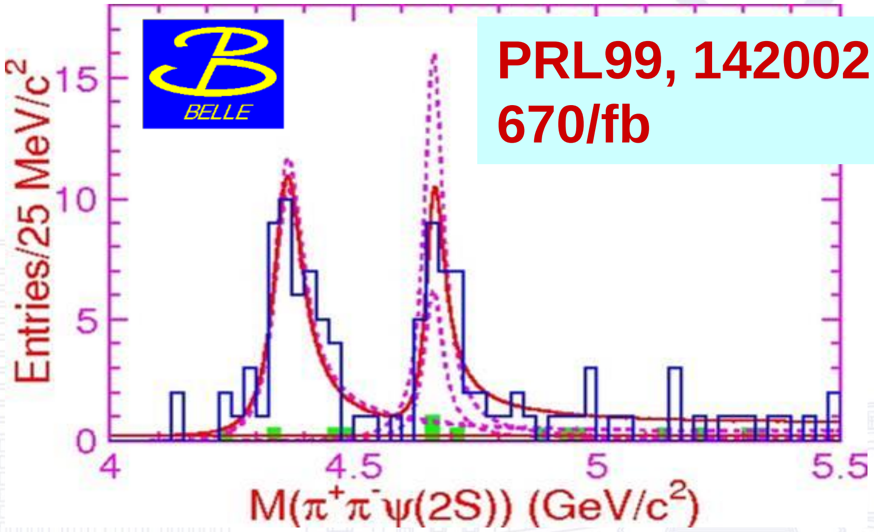
$e^+e^- \rightarrow \gamma_{ISR} J/\psi\ \pi^+\pi^-$

PRL98, 212001. 298/fb





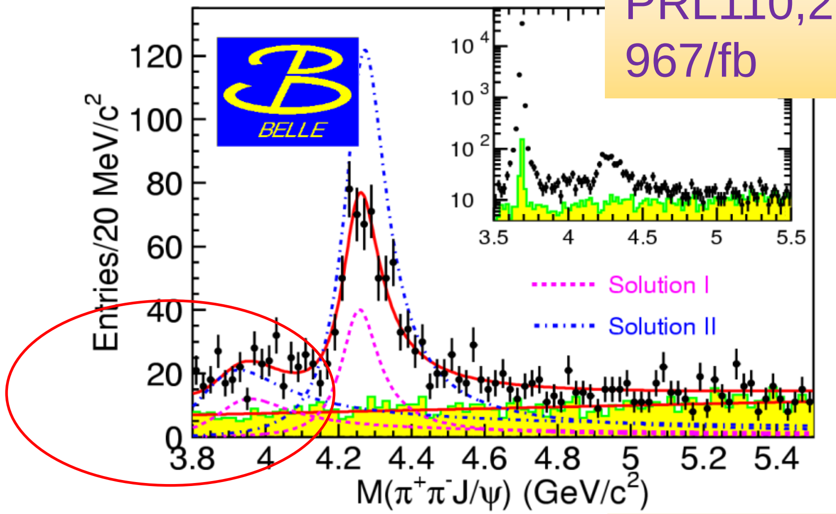
PRL99, 182004
550/fb



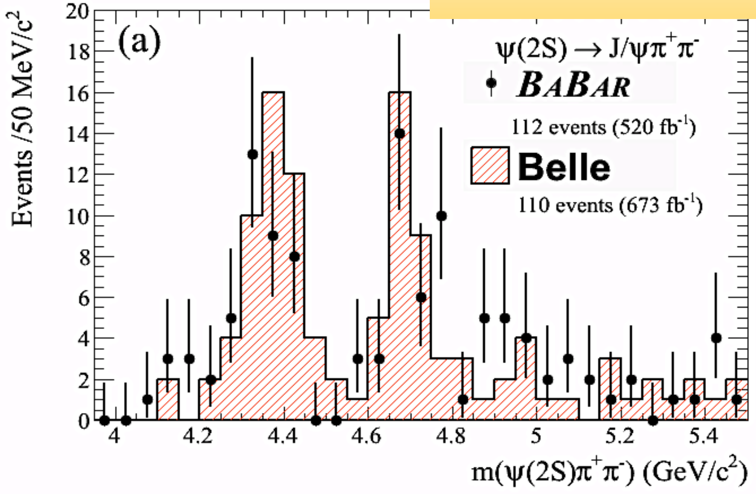
PRL99, 142002
670/fb

Y(4008) Y(4260)
Y(4360) Y(4660)

The Y states

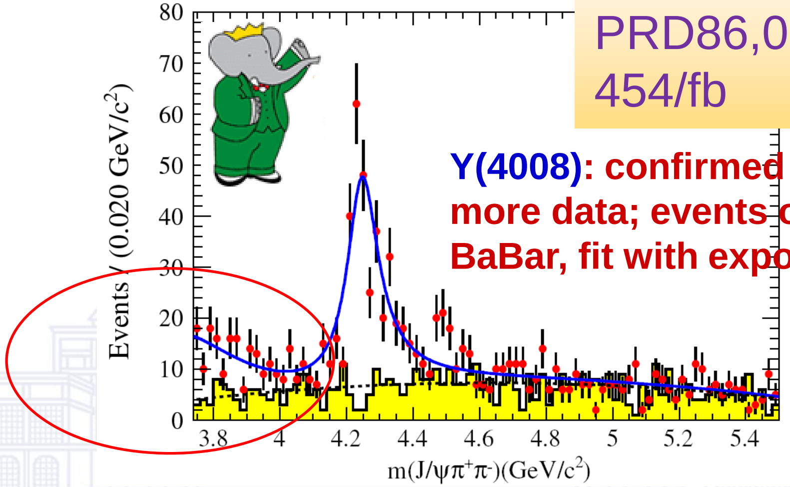


PRL110,252002
967/fb



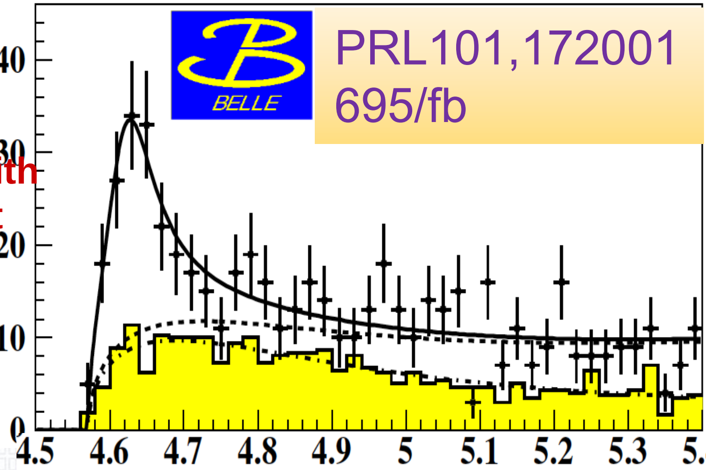
Belle: PRL99,142002, 670/fb
BaBar: PRD89, 111103, 520/fb

Y(4660): confirmed by BaBar



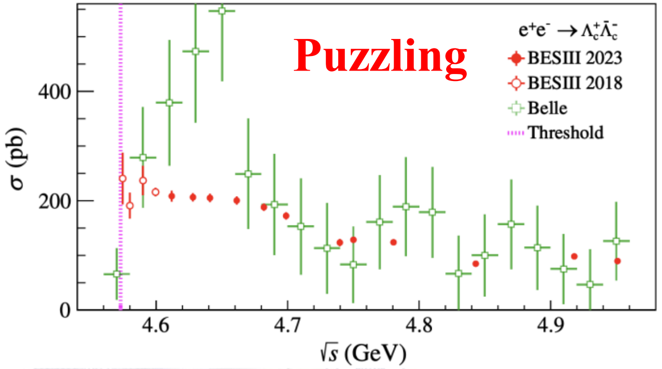
PRD86,051102
454/fb

Y(4008): confirmed by Belle with more data; events observed at BaBar, fit with exponential



PRL101,172001
695/fb

PRL 131, 191901 (2023)

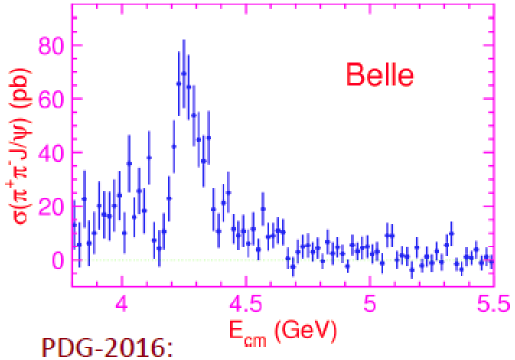


Puzzling

$M(\Lambda_c^+\Lambda_c^-)$

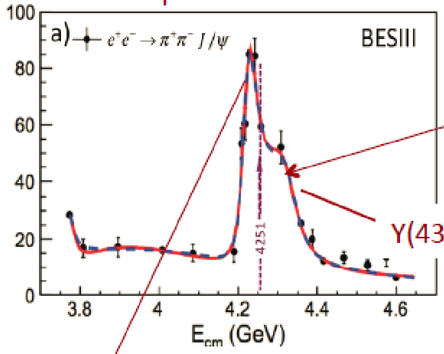
Y(4260): mass → lower & width → narrower

pre-2017



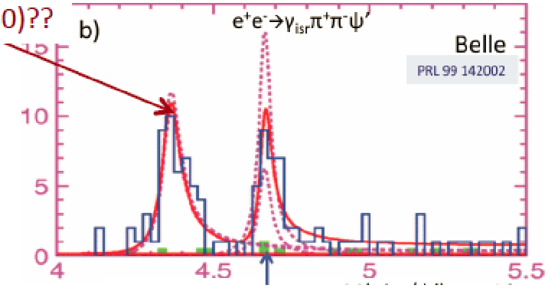
PRL118, 092001 (2017)

post-2017



what is the 2nd peak?

Y(4360)??



PDG-2016:

$$M(Y(4260)) = 4251 \pm 9\ \mathrm{MeV}/c^2 \xrightarrow{-31\ \mathrm{MeV}} M_1 = 4220 \pm 4\ \mathrm{MeV}/c^2$$

$$\Gamma(Y(4260)) = 120 \pm 12\ \mathrm{MeV}. \xrightarrow{\times 1/3} \Gamma_1 = 44 \pm 5\ \mathrm{MeV}$$

$$M_2 = 4320 \pm 13\ \mathrm{MeV}/c^2 \xrightarrow{\delta M \approx -1.8\sigma} M(Y(4360)) = 4346 \pm 6\ \mathrm{MeV}/c^2$$

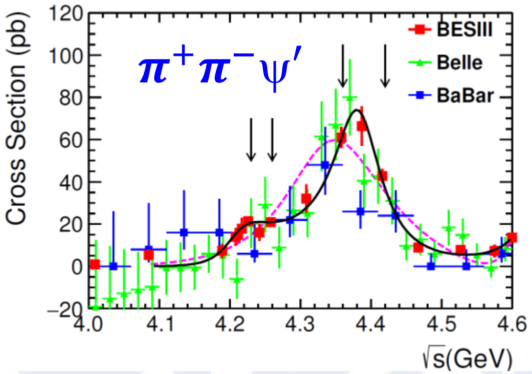
$$\Gamma_2 = 101^{+27}_{-22}\ \mathrm{MeV} \xrightarrow{\text{spot on}} \Gamma(Y(4360)) = 102 \pm 12\ \mathrm{MeV}.$$

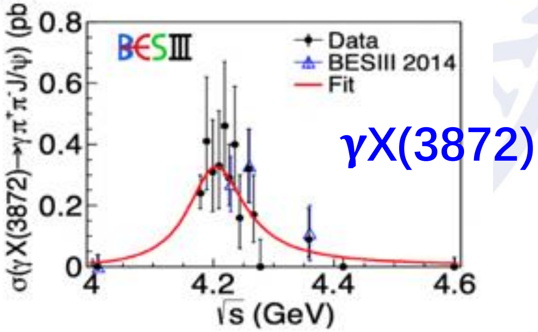
Y(4220) decay modes:

- $\pi^+\pi^-$J/ψ
  - πZ_c(3900)
  - f_0(980) J/ψ
- $\pi^+\pi^- h_c$
- $\omega\chi_{c0}$
- ηJ/ψ
- γX(3872)
- $\pi D\bar{D}^*$

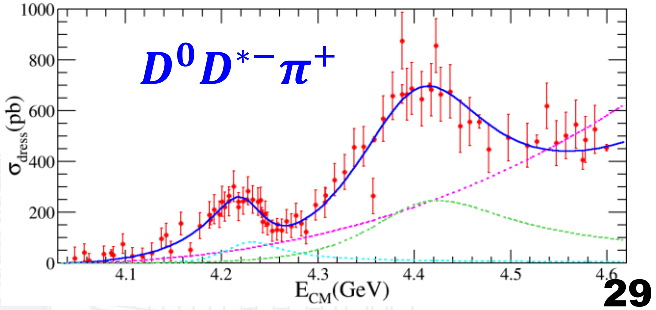
Y(4320) decay modes:

- $\pi^+\pi^-$J/ψ
- $\pi^+\pi^-\psi'$





PRL 122, 232002 (2019)



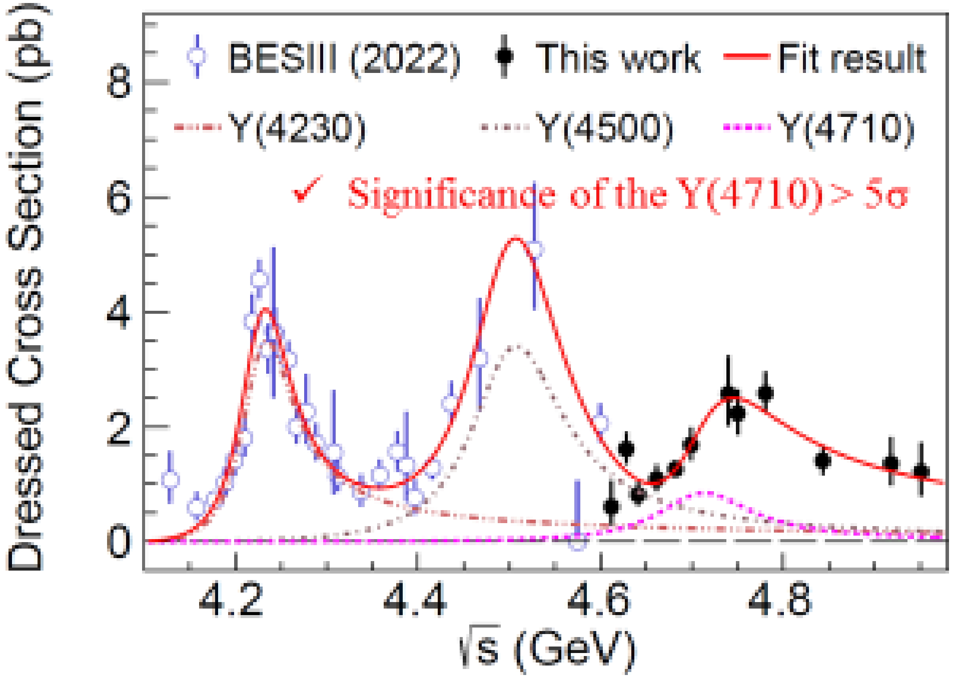
BESIII

An even higher mass vector state Y(4710) in KKJ/ψ

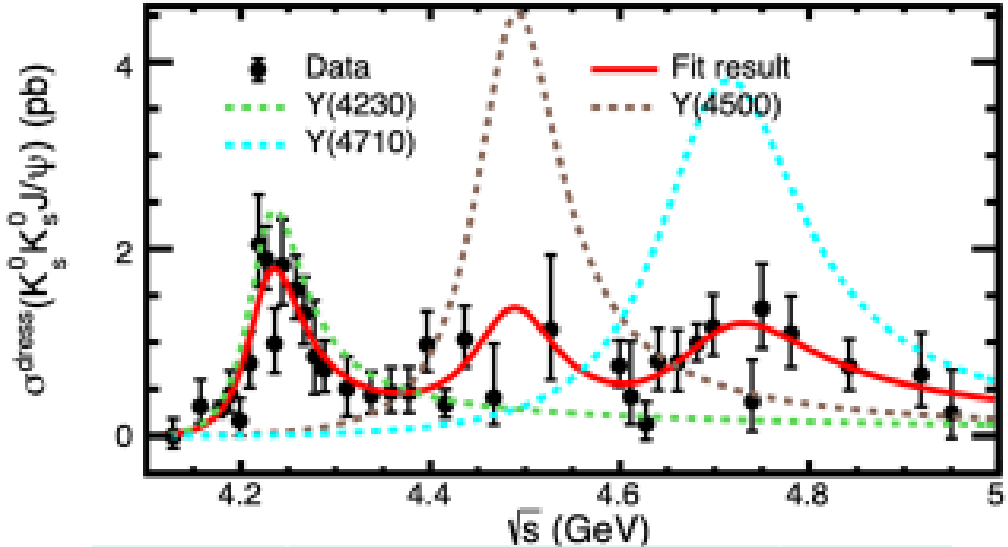
PRL131, 211902 (2023) $e^+e^- \to K^+K^-J/\psi$

5.85 fb^{-1}, Ecm=4.61-4.95 GeV

PRD107, 092005 (2023) $e^+e^- \to K_SK_SJ/\psi$



✓ Significance of the Y(4710) > 5σ

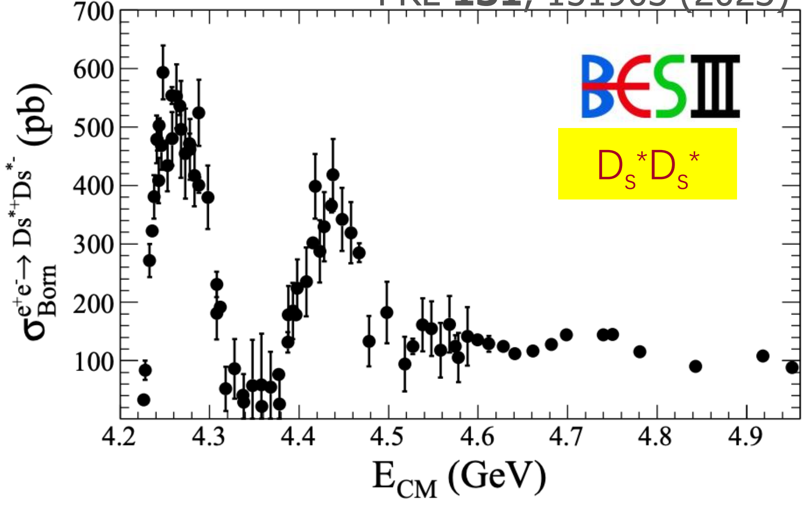


resonance	mass (MeV)	width (MeV)	note
Y(4230)	4226±2	70±4	Stat. only
Y(4500)	4499±8	124±20	Stat. only
Y(4710)	4708^{+17}_{-15}±21	126^{+27}_{-23}±30	>5σ

resonance	mass (MeV)	width (MeV)	note
Y(4230)	4227±7±22	72±16±33	
Y(4500)	Fixed	Fixed	1.4σ
Y(4710)	4704±52±70	183±114±96	4.0σ

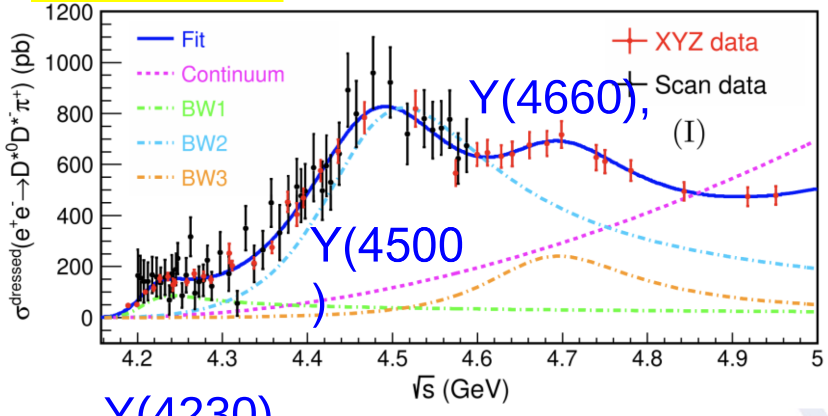
5S vector charmonium states?

PRL **131**, 151903 (2023)

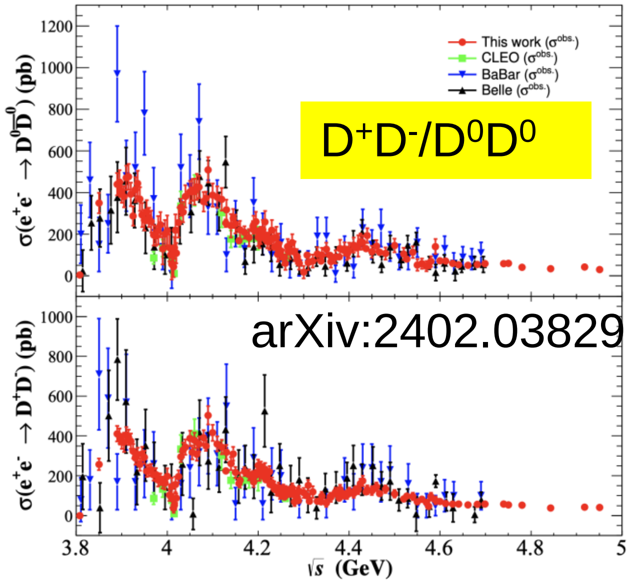


$D^{*0}D^{*+}\pi^-$

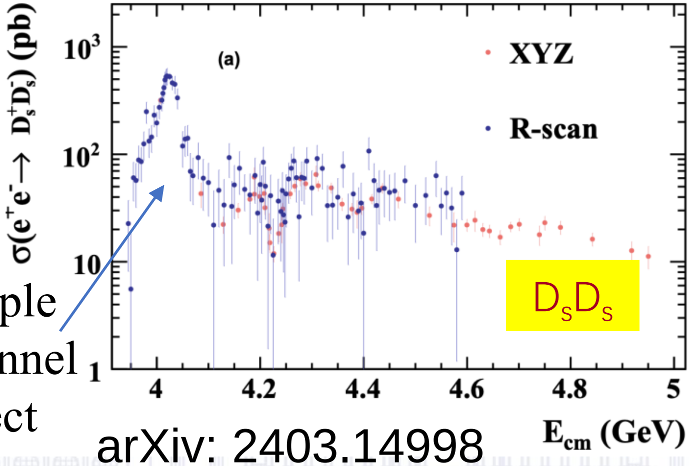
PRL 130, 121901 (2023)



Y(4230)

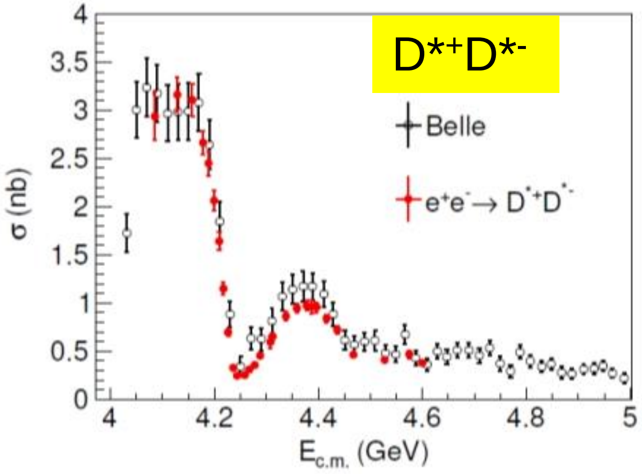


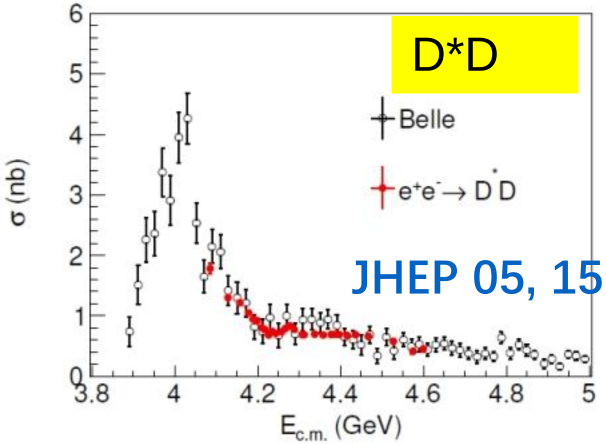
arXiv:2402.03829



couple
channel
effect

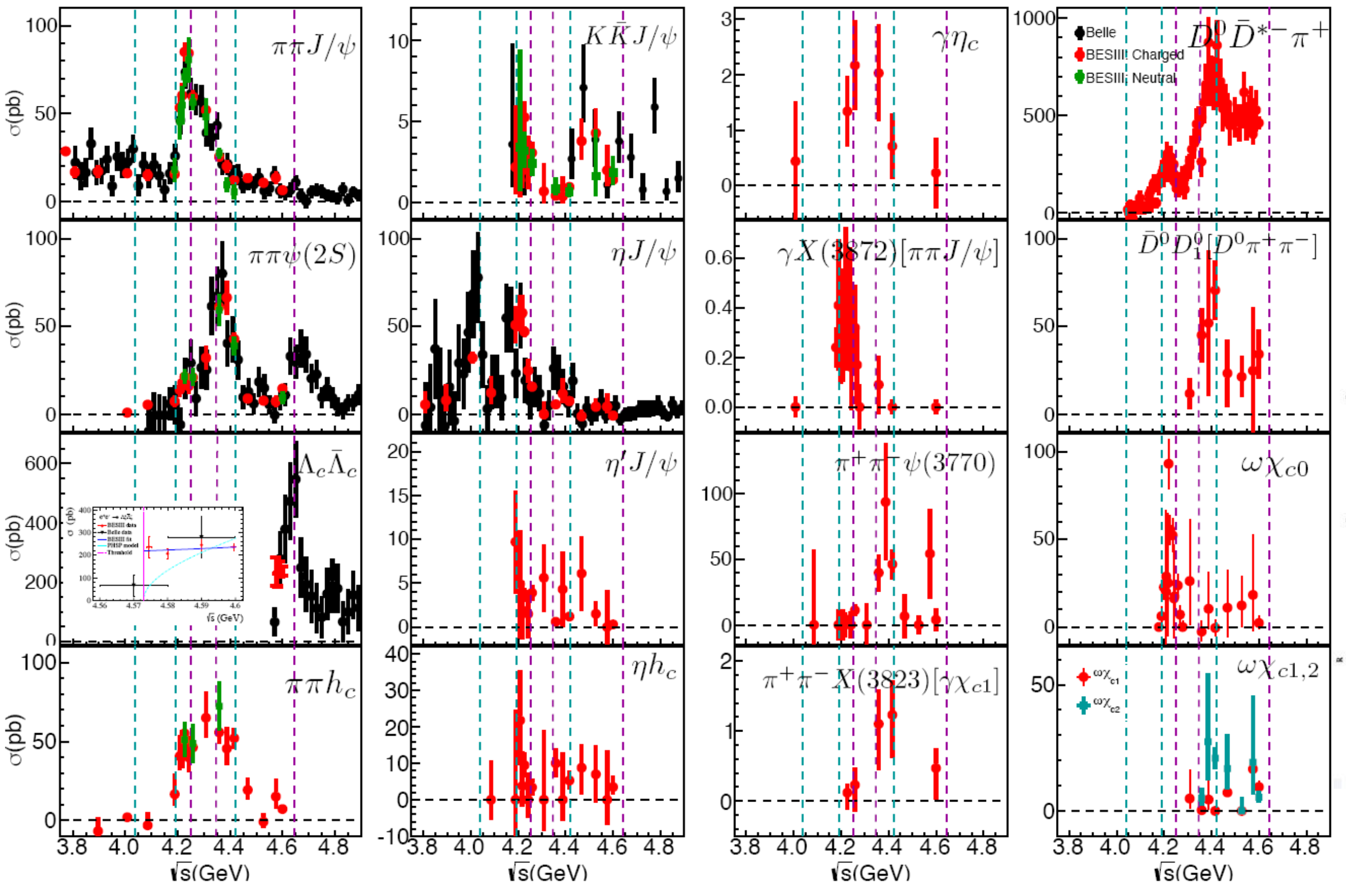
arXiv: 2403.14998

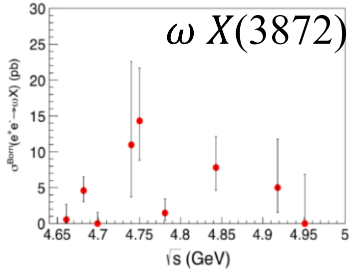


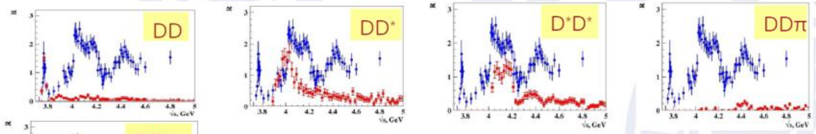


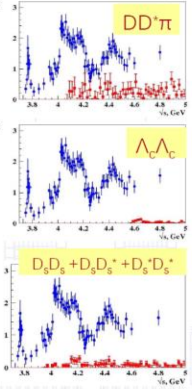
JHEP 05, 155, (2022)

After we have measured all the e^+e^- annihilation cross sections, what do we do to get the resonant parameters of the vector charmonium(-like) states?



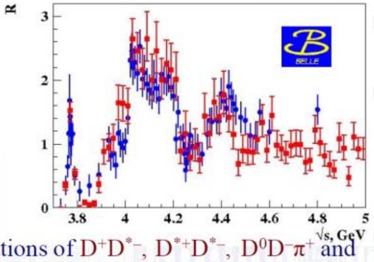






Exclusive cross sections contribution to the total cross section

Blue: R-measurement
Red: Cross section measurements

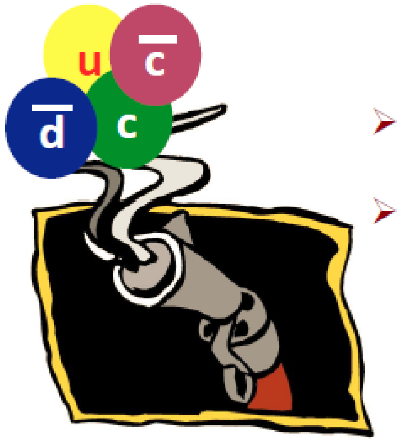


Contributions of D^+D^{*-}, $D^{*+}D^{*-}$, $D^0D^-\pi^+$ and $D^0D^{*-}\pi^+$ are scaled following isospin symmetry

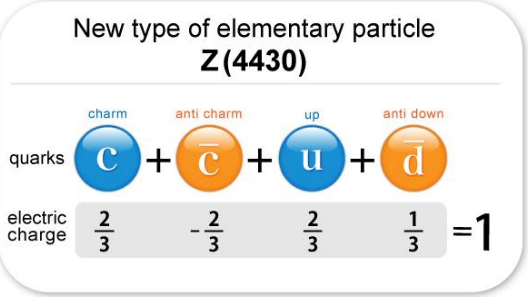
Z States

The Z(4430)$^+$→π$^+$ ψ’

“smoking gun” evidence for a 4-quark meson



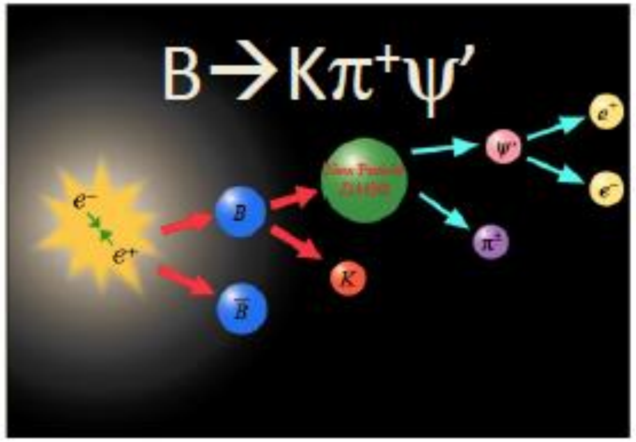
- decays to ψ’ ➔ must contain c$\bar{c}$ pair
- electrically charged ➔ must contain u$\bar{d}$ pair



New type of elementary particle

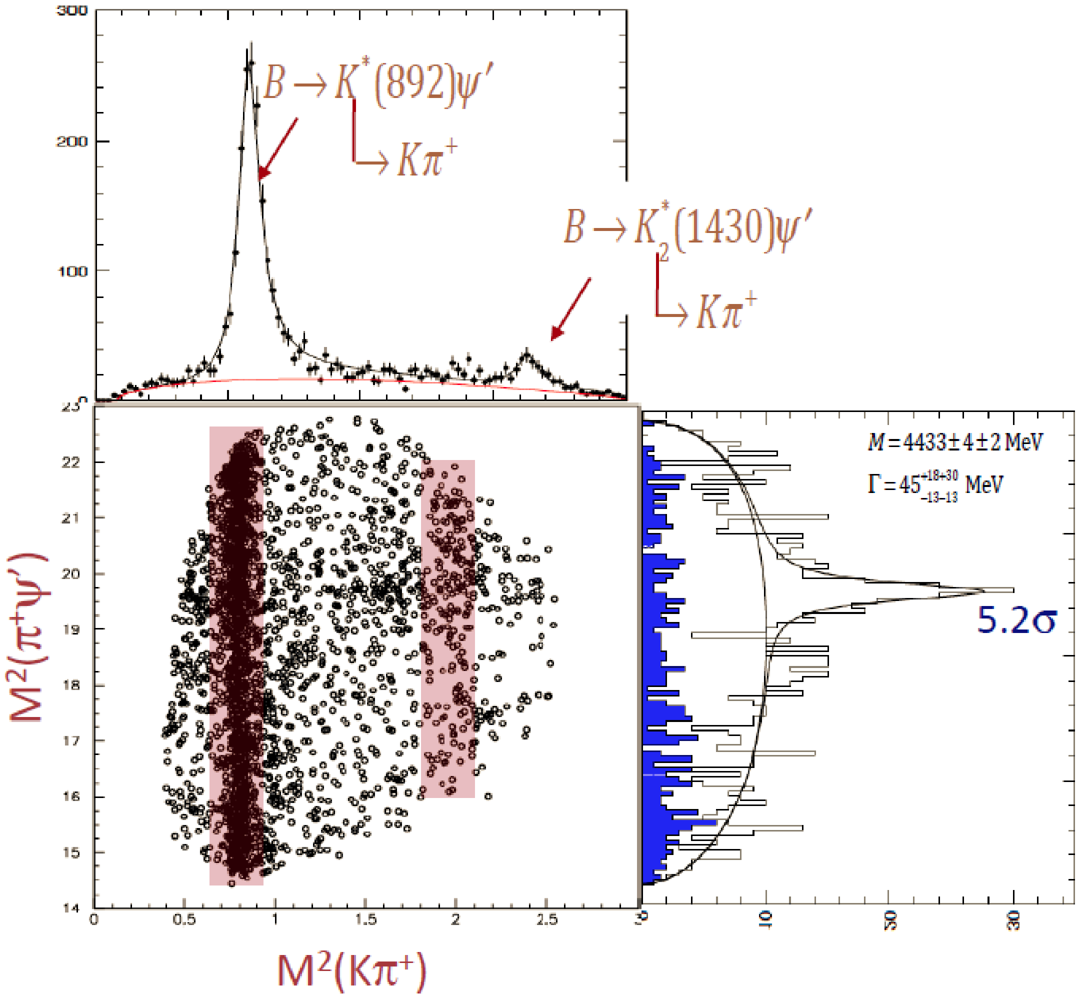
Z(4430)

	charm		anti charm		up		anti down	
quarks	c	+	c̄	+	u	+	d̄	
electric charge	$\frac{2}{3}$		$-\frac{2}{3}$		$\frac{2}{3}$		$\frac{1}{3}$	=1

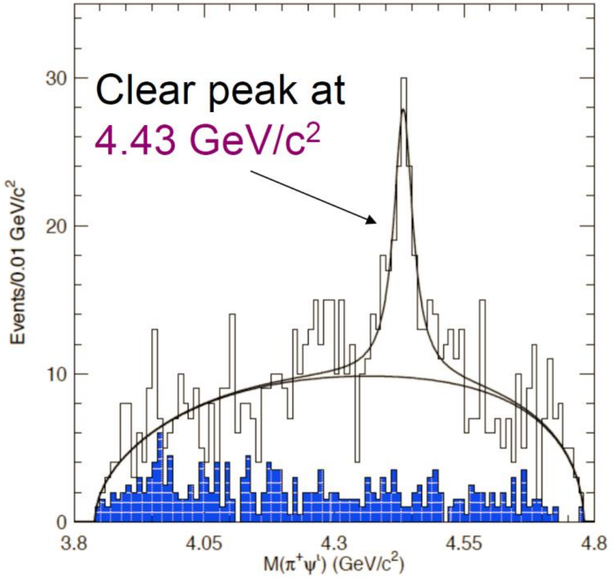


PRL 100, 142001 (2008)

S-K Choi et al Belle: PRL 100 142001



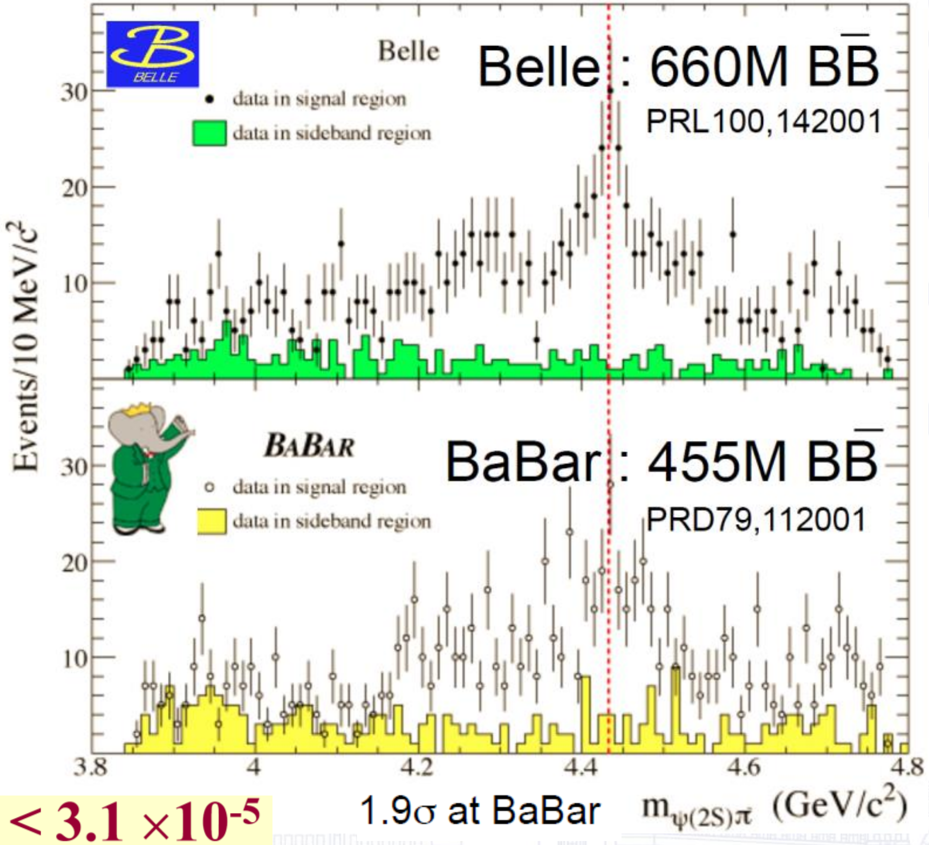
$Z_c(4430)^{\pm}$ exist or not ?



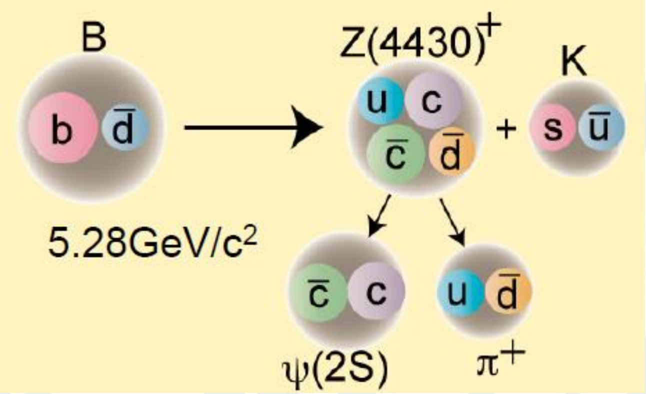
PRL 100, 142001 (2008)

$BF(B^0 \to Z^+K) \times BF(Z^+ \to \psi(2S)\pi^+) < 3.1 \times 10^{-5}$

Belle PRL: $(4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$



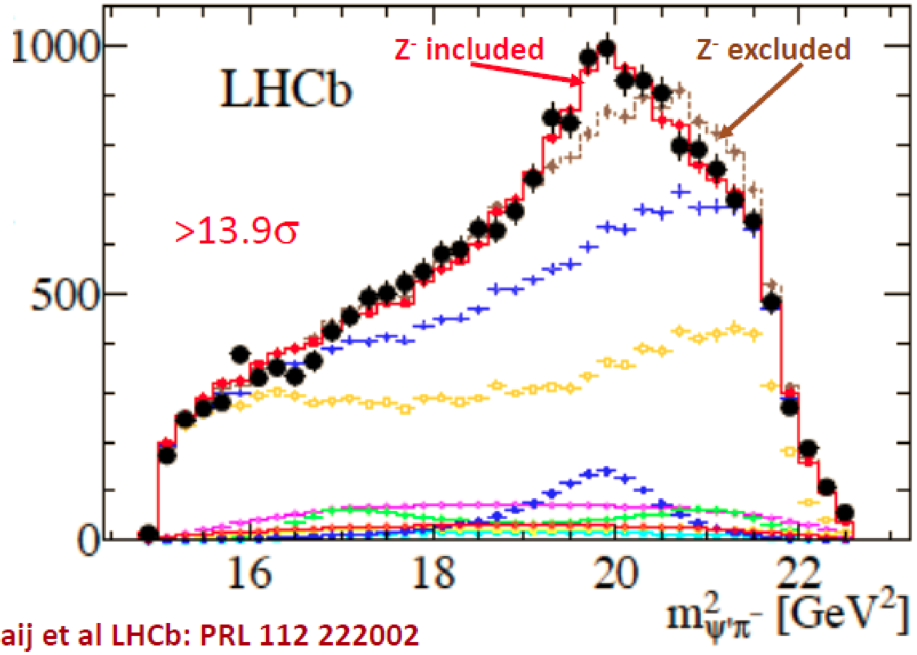
Phys. Rev. D 79 (2009) 112001



"For the fit … equivalent to the Belle analysis…we obtain mass & width values that are consistent with theirs,… but only ~1.9σ from zero; fixing mass and width increases this to only ~3.1σ."

LHCb 4-dim analysis of B→K$^+\pi^-\psi'$

B→K$^+\pi^-$ ψ' 4-dim amplitude analysis



R. Aaij et al LHCb: PRL 112 222002

$$J^P = 1^+$$

$$M = 4475 \pm 7^{+15}_{-25}\ \text{MeV}$$

$$\Gamma = 172 \pm 13^{+37}_{-34}\ \text{MeV}$$

Good agreement with Belle,
(with smaller errors)

$$Bf(B^0 \to Z(4430)^- K^+) \times Bf(Z(4430)^- \to \pi^-\psi') \approx (3.4^{-1.1}_{-2.3}) \times 10^{-5}$$

- *PRL* 112 (2014) 222002

Belle observed Two $Z^{\pm}\rightarrow\chi_{c1}\pi^{\pm}$

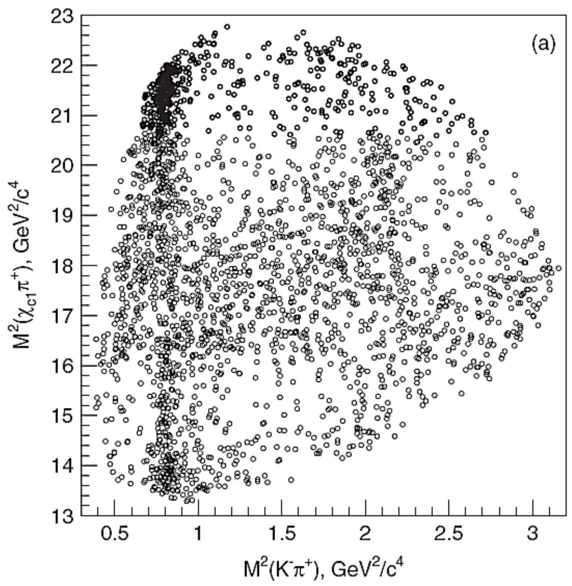
- Dalitz-plot analysis of $\underline{B}^0\rightarrow\chi_{c1}\pi^+K^-$ $\chi_{c1}\rightarrow J/\psi\gamma$ with 657M B$\underline{B}$
- Dalitz plot models: known K*→Kπ only

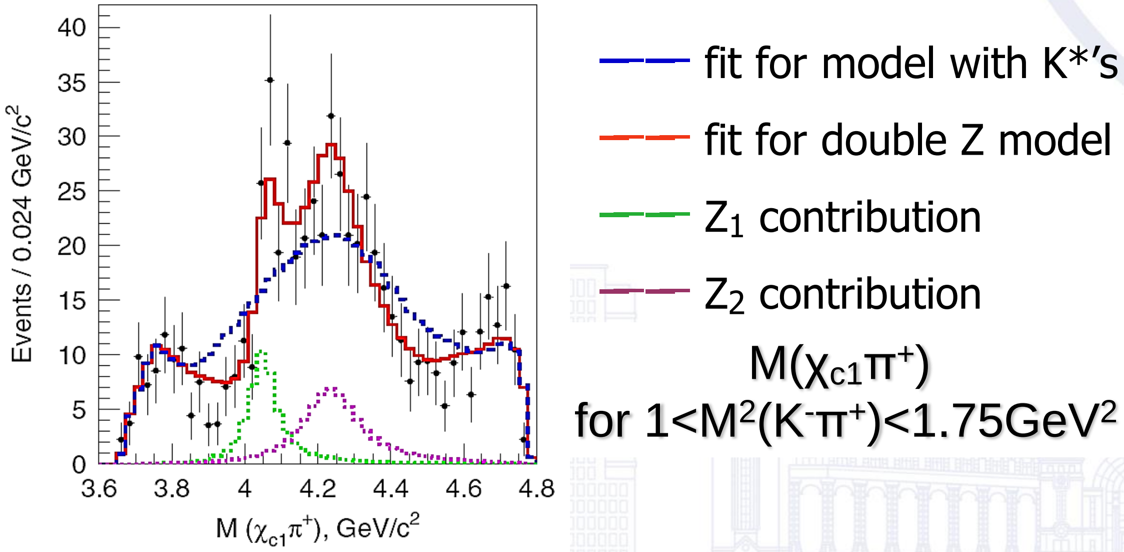
  K*’s + one Z $\rightarrow\chi_{c1}\pi^{\pm}$

  K*’s + two $Z^{\pm}$ states ⇨ favored by data

PRD 78, 072004 (2008)

Significance: 5.7σ





$M(\chi_{c1}\pi^+)$
for $1<M^2(K^-\pi^+)<1.75\text{GeV}^2$

$$M_{Z_1}=4051\pm14\,^{+20}_{-41}\ \text{MeV}$$

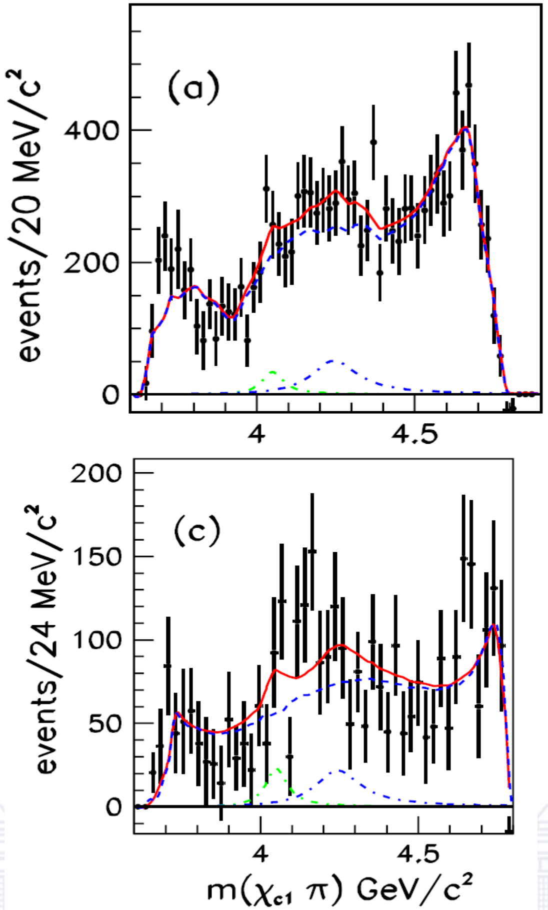
$$\Gamma_{Z_1}=82\,^{+21}_{-17}\,^{+47}_{-22}\ \text{MeV}$$

$$M_{Z_2}=4248\,^{+44}_{-29}\,^{+180}_{-35}\ \text{MeV}$$

$$\Gamma_{Z_2}=177\,^{+54}_{-39}\,^{+316}_{-61}\ \text{MeV}$$

BaBar doesn’t see significant $Z^{\pm}\to\chi_{c1}\pi^{\pm}$

PRD85, 052003 (2012)



for $1<M^2(K^-\pi^+)<1.75\mathrm{GeV}^2$

$$\mathcal{B}(\bar{B}^0\to Z_1(4050)^+K^-)\times\mathcal{B}(Z_1(4050)^+\to\chi_{c1}\pi^+)<1.8\times10^{-5},$$

Belle: $(3.0^{+1.5}_{-0.8}{}^{+3.7}_{-1.6})\mathrm{x}10^{-5}$

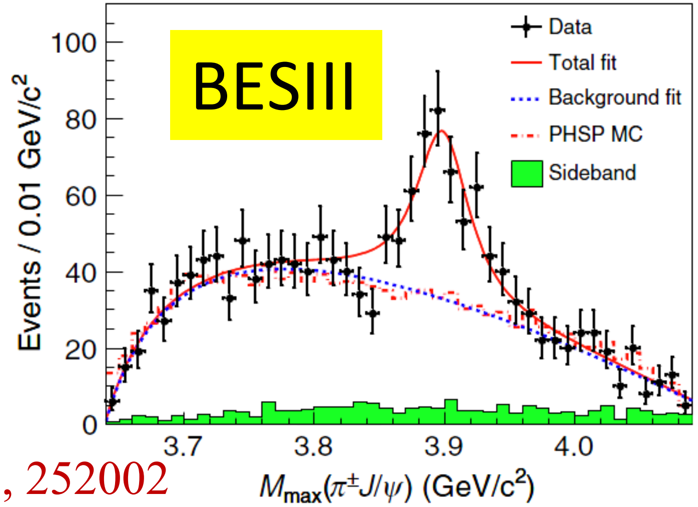
$$\mathcal{B}(\bar{B}^0\to Z_2(4250)^+K^-)\times\mathcal{B}(Z_2(4250)^+\to\chi_{c1}\pi^+)<4.0\times10^{-5},$$

Belle: $(4.0^{+2.3}_{-0.9}{}^{+19.7}_{-0.5})\mathrm{x}10^{-5}$

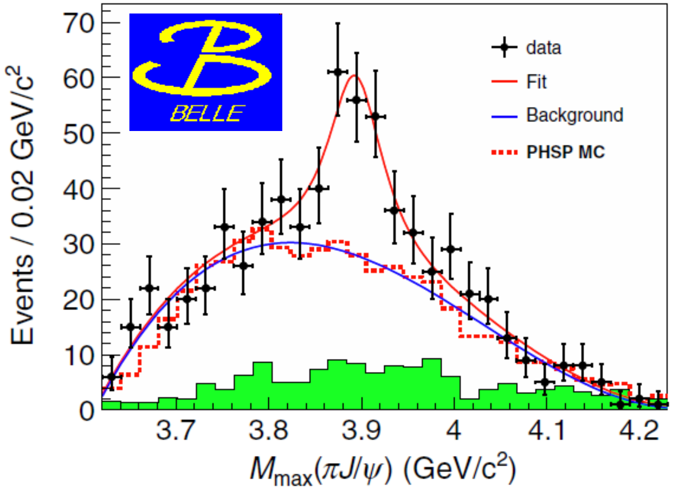
“We find that it is possible to obtain a good description of our data without the need for additional resonances in the $\chi_{c1}\pi$ system.”

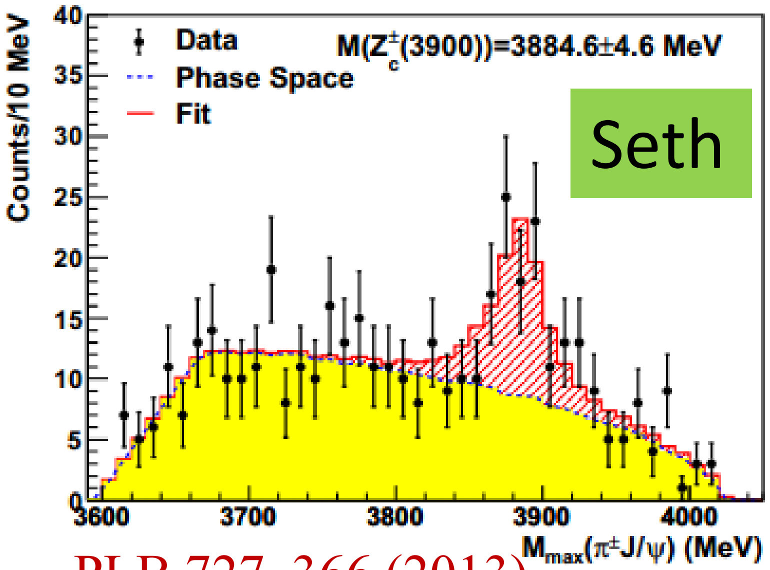
Zc(3900)$^{\pm}$ in BESIII + Belle + CLEO's data

PRL 110, 252001 (2013)

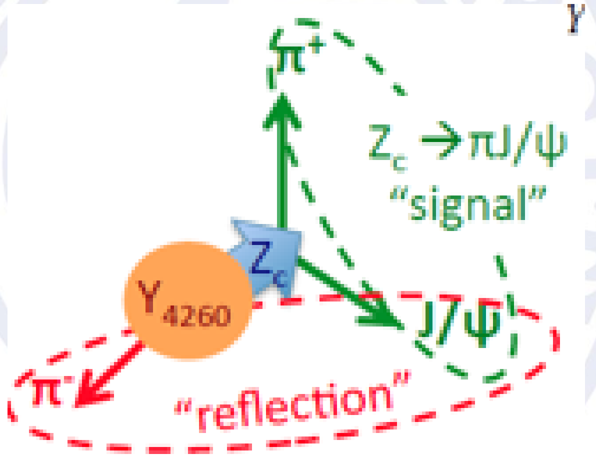


PRL 110, 252002 (2013)





PLB 727, 366 (2013)



BESIII: 2013.3.24
Belle: 3.30
CLEOc: 4.10
Z_c established!

$$M(Z_c(4430)) - M(Z_c(3900)) = 589 \pm 30\ \mathrm{MeV}$$
$$M(\psi') - M(J/\psi) = 589\ \mathrm{MeV}$$

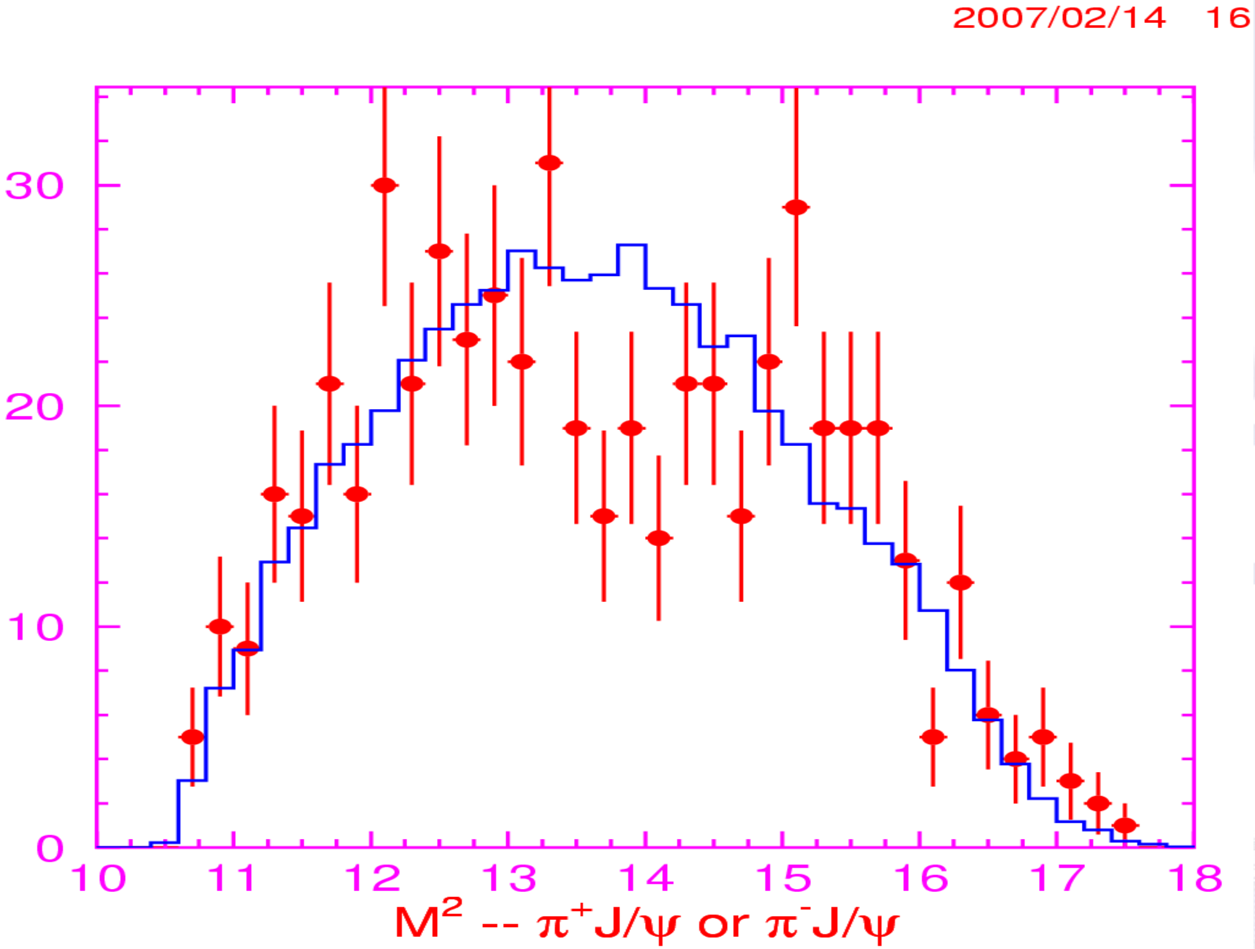
Question: Zc has been confirmed. How about Zs ? How to search for it ?

M(ππJ/ψ)∈[4.2, 4.4] GeV via ISR

548/fb at 10.58 GeV

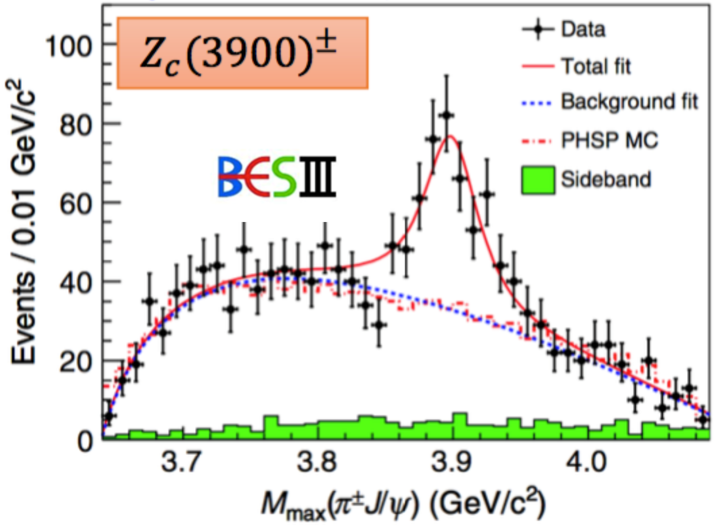
Peaks at 12 & 15 GeV^2?

Shown at QWG'2011



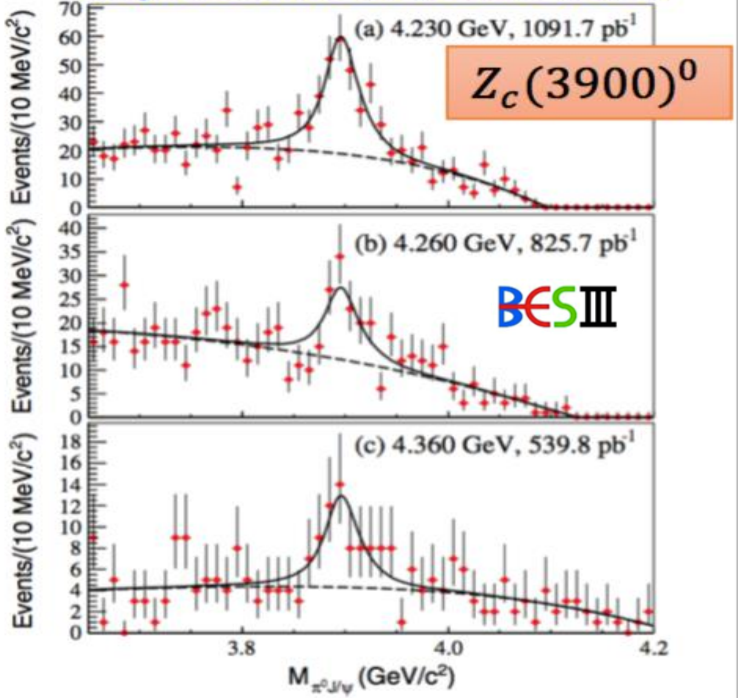
Z_c(3900) State (I=1)

Phys. Rev. Lett 110, 252001 (2013)



- ➢Charged charmonium-like structure (>10 σ)
- ➢Decay to J/ψ ($c\bar{c}$) and electric charge ($u\bar{d}$ or $d\bar{u}$)
- ➢$M = 3899.0 \pm 3.6 \pm 4.9$ MeV/c², $\Gamma = 46 \pm 10 \pm 20$ MeV
- ➢$\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = 62.9 \pm 1.9 \pm 3.7$ pb at 4.26 GeV
- ➢$\frac{\sigma(e^+e^- \to \pi^{\mp} Z_c(3900)^{\pm} \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} = 21.5 \pm 3.3 \pm 7.5$ %
- ➢The first Z_c state observed by more than one experiment (Belle and CLEO-c)!

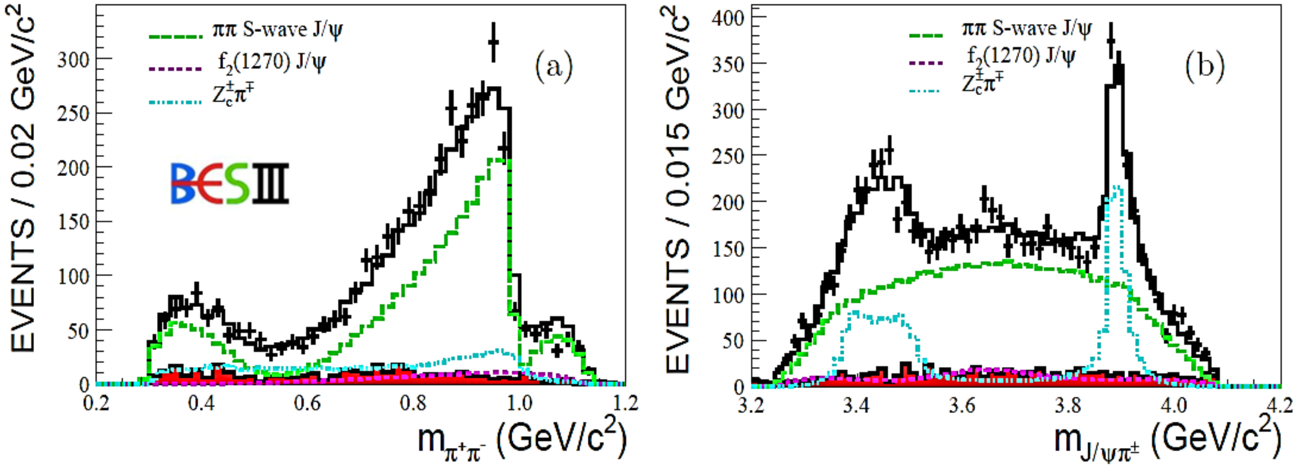
Phys. Rev. Lett 115, 112003 (2015)



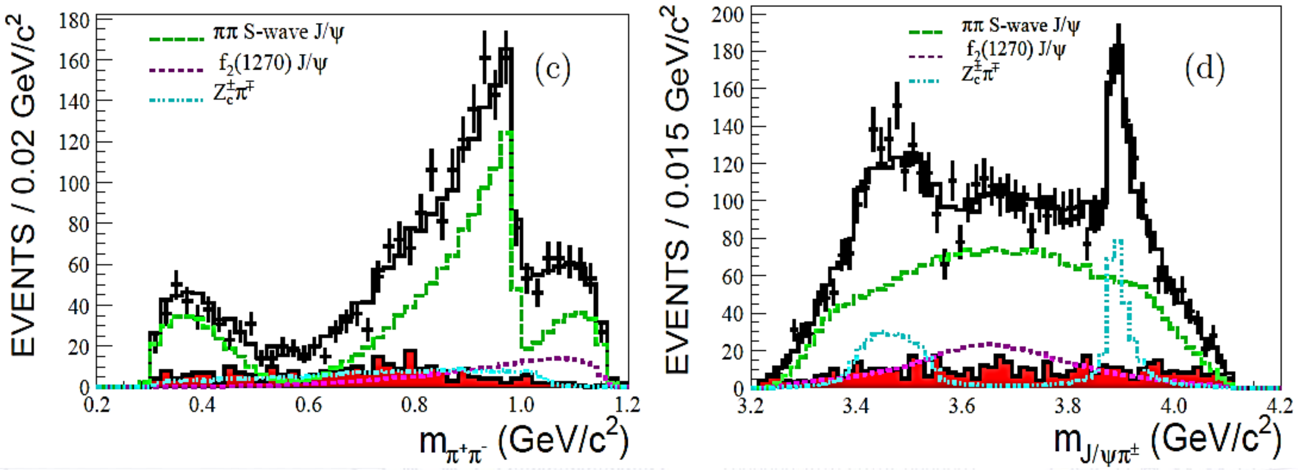
- ➢ Neutral charmonium-like structure (10.4 σ)
- ➢ Using 3 data samples (~2.5 fb^{-1})
- ➢Evidence with 3.7σ by using CLEO-c data
- ➢$M = 3894.8 \pm 2.3 \pm 3.2$ MeV/c², $\Gamma = 29.6 \pm 8.2 \pm 8.2$ MeV
- ➢An iso-spin triplet is established!

Spin and parity measurement of Zc(3900)

4.23 GeV
1092/pb



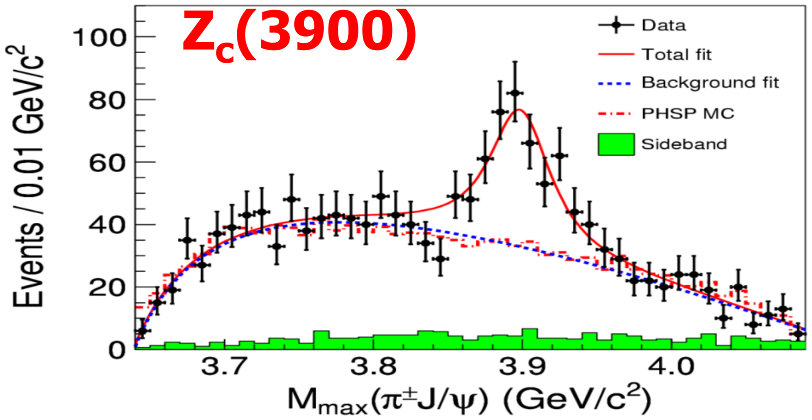
4.26 GeV
826/pb



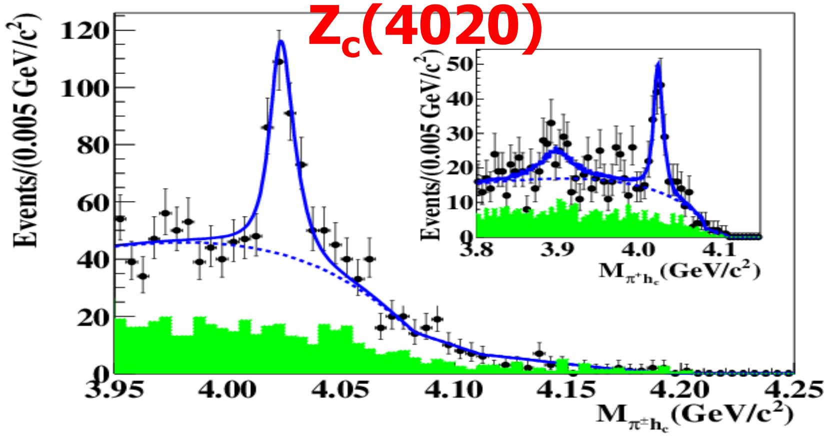
- ✓ simultaneous fit of two data sets
- ✓ Isobar model: $\sigma, f_0, f_0(1370), f_2(1270), Z_c^{\pm}$
- ✓ $Z_c^{\pm}$ as 1^+ state

Phys.Rev.Lett.119, 072001 (2017)

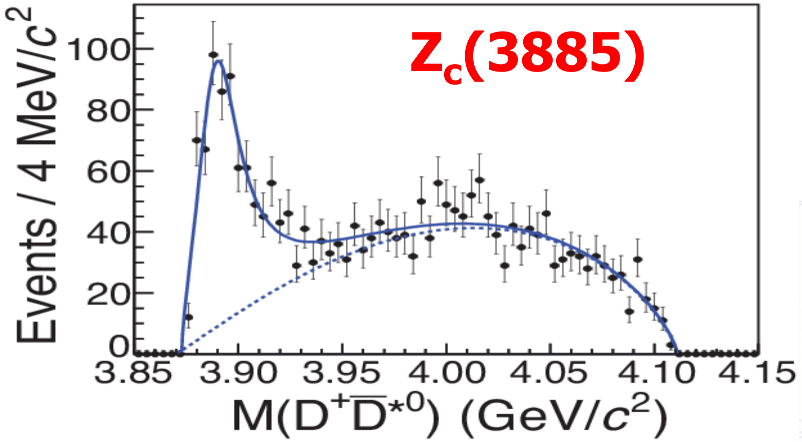
Open the Zc door !



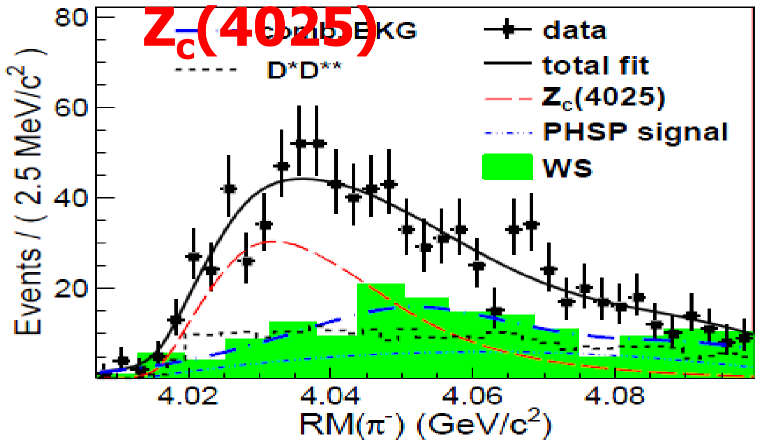
Phys. Rev. Lett. 110, 252001 (2013)



Phys. Rev. Lett. 111, 242001 (2013)



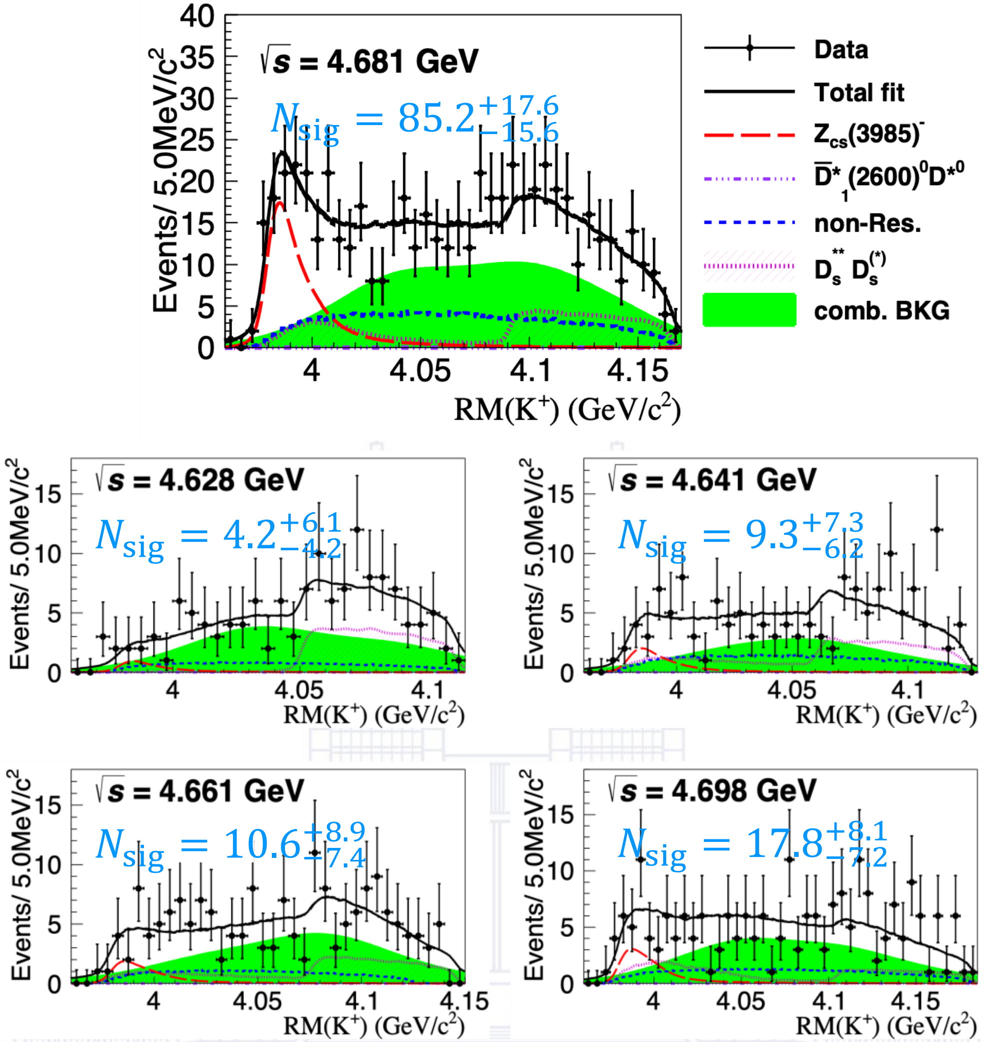
Phys. Rev. Lett. 112, 022001 (2014)



Phys. Rev. Lett. 112, 132001 (2014)

Observation of $Z_{cs}(3985)$—first Z_c with a strange quark

BESIII

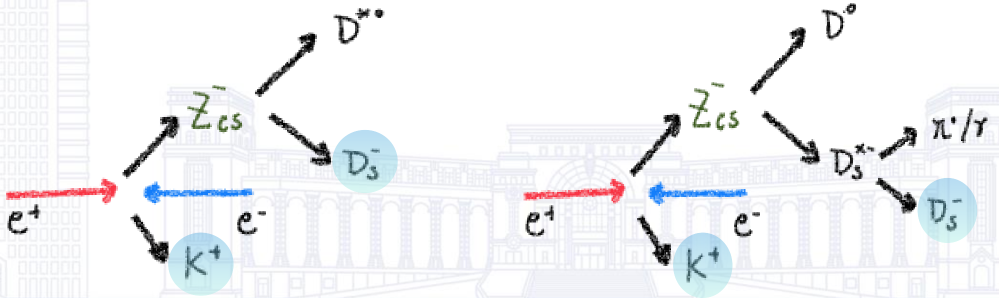


PRL 126, 102001 (2021)

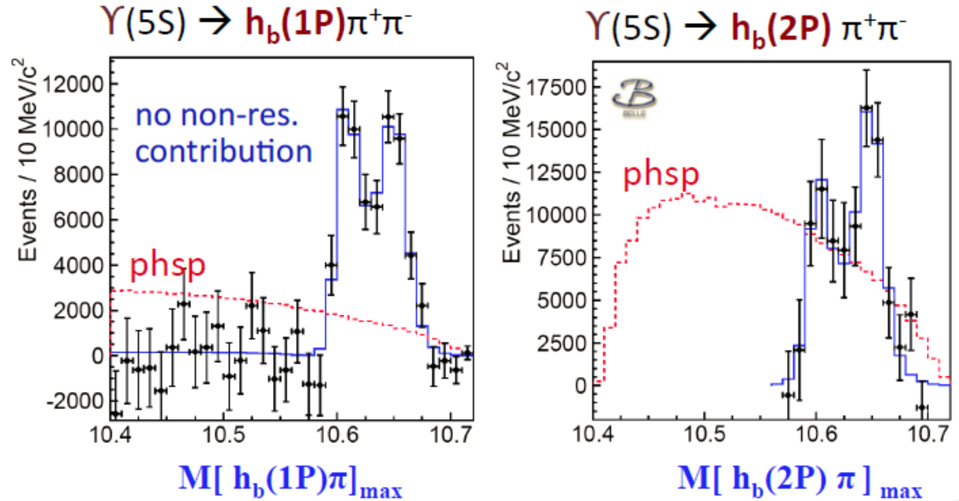
- $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$
  - 3.7fb^{-1} data at 4628, 4640, 4660, 4680, and 4700
- Assume J^P=1$^+$
- Simultaneous fit to five data samples
- Pole position:

$$m = 3982.5^{+1.8}_{-2.6} \pm 2.1\text{MeV}/c^2 \quad \Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0\text{MeV}$$

- Significance: 5.3σ
- At least four quarks $c\bar{c}s\bar{u}$



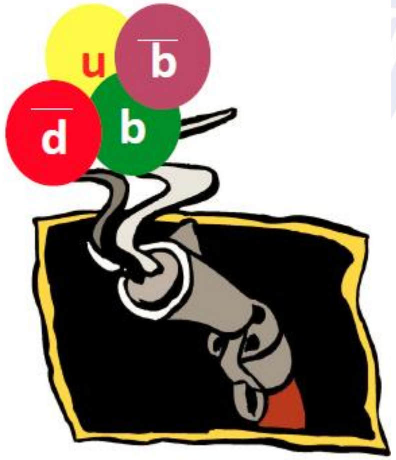
Resonant structure of $\Upsilon(5S)\rightarrow(b\bar{b})\pi^+\pi^-$



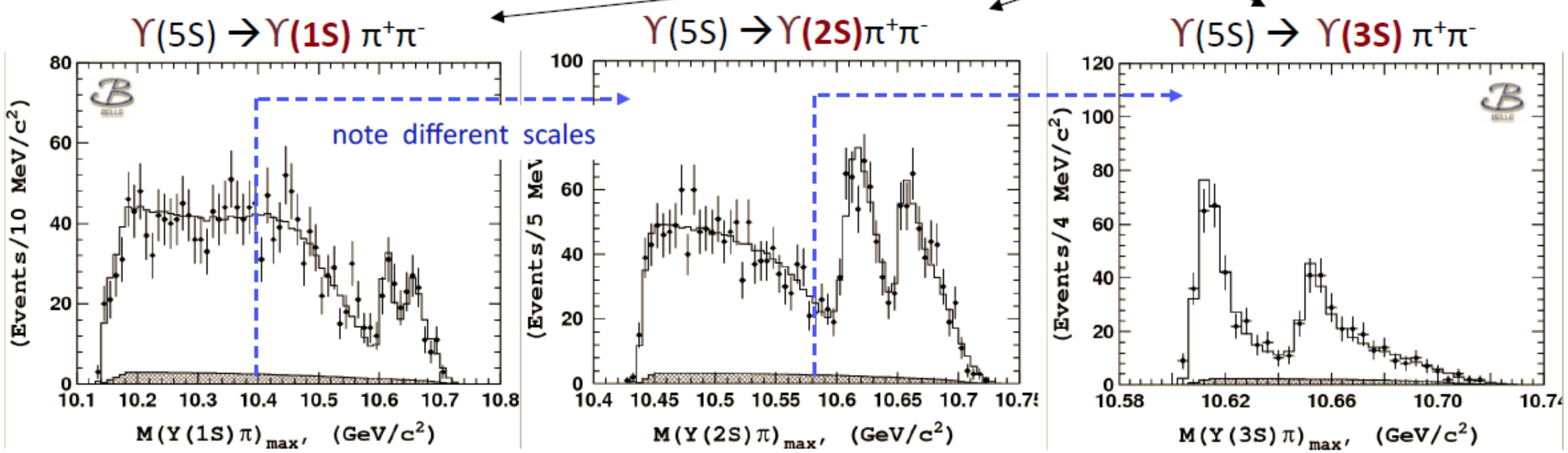
- ➢decays to $\Upsilon(nS)$ & $h_b(nP)$ ➔ must contain $b\bar{b}$ pair
- ➢electrically charged ➔ must contain $u\bar{d}$ pair

Belle: PRL108, 232001 (2012)

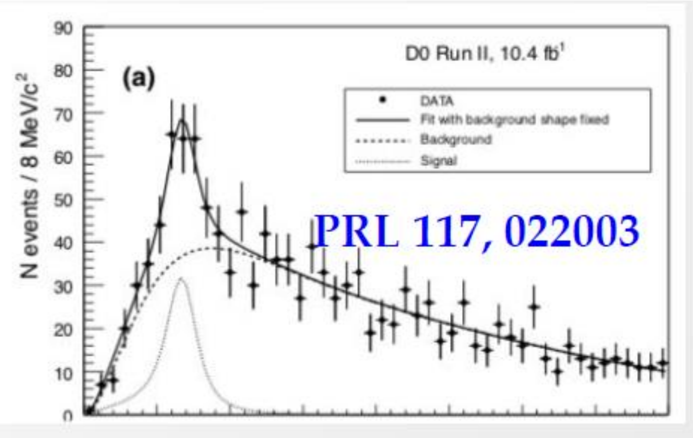
$Z_b(10610)$ and $Z_b(10650)$
should be multiquark states



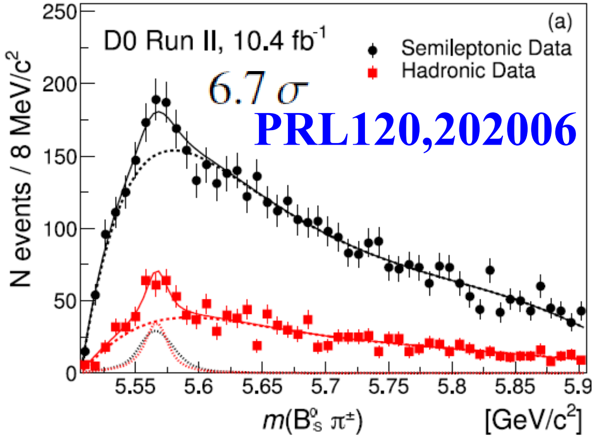
Dalitz plot analysis



X(5568) – puzzle ?



PRL 117, 022003



6.7 σ

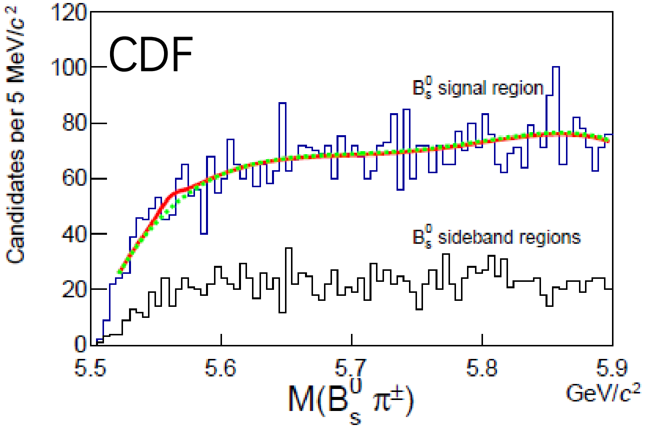
PRL120,202006

- Possible tetraquark candidate of four different quarks
- Seen by D0 with $\mathbf{4.8}\ \boldsymbol{\sigma}$ significance

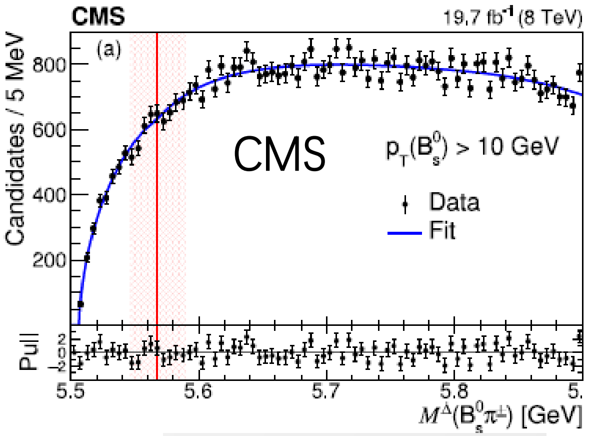
$$m = 5567.8 \pm 2.9\,(\text{stat})^{+0.9}_{-1.9}\,(\text{syst})\ \text{MeV}/c^2$$

$$\Gamma = 21.9 \pm 6.4\,(\text{stat})^{+5.0}_{-2.5}\,(\text{syst})\ \text{MeV}/c^2$$

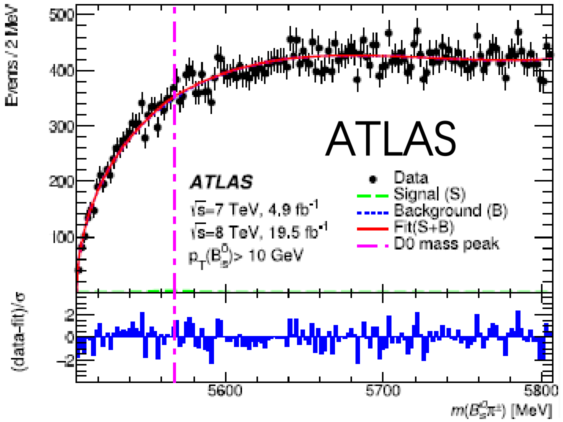
If confirmed, would be unique with 4 different flavors



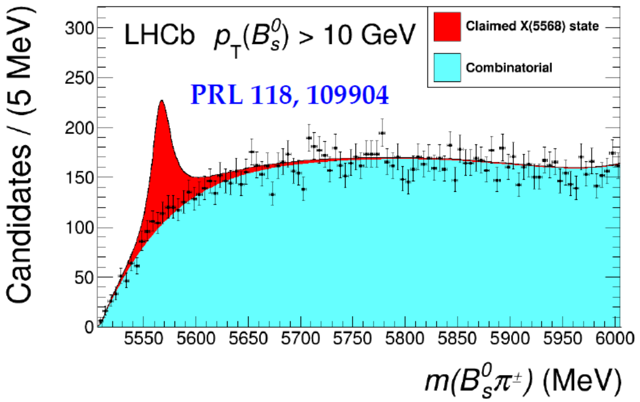
PRL 120, 202006



PRL 120, 202005



PRL 120, 202007



PRL 118, 109904

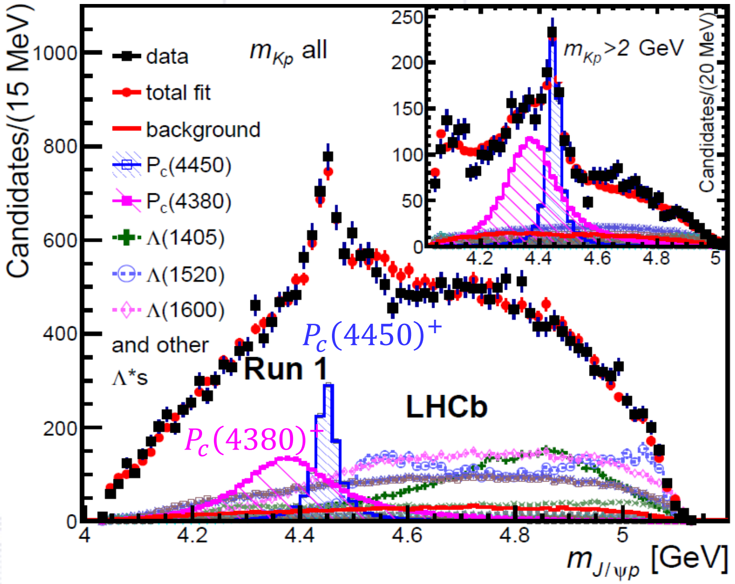
Pc States

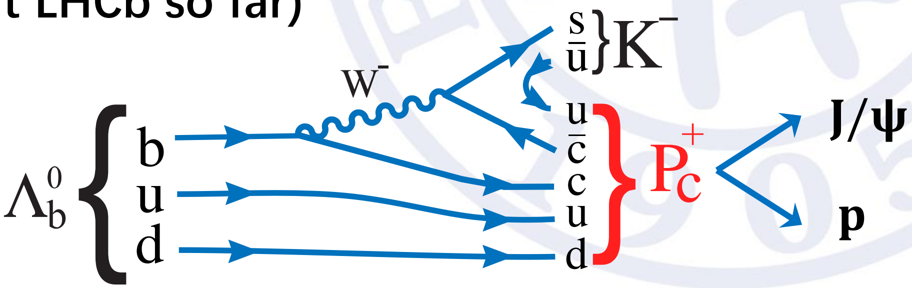
Open the pentaquark door: LHCb observation in 2015

- **Two $J/\psi p$ resonant structures** are revealed by a full 6D amplitude analysis
  - $P_c(4450)^+$ ← the prominent peak
  - $P_c(4380)^+$ ← required to obtain a good fit to the data
  - Consistent with **pentaquarks** with minimal quark content of $uudc\bar{c}$

26k Λ_b signals

PRL 115 (2015) 072001 (most cited paper at LHCb so far)





	$P_c(4380)^{\pm}$	$P_c(4450)^{\pm}$
Mass (MeV)	4380 ± 8 ± 29	4449.8 ± 1.7 ± 2.5
Width (MeV)	205 ± 18 ± 86	39 ± 5 ± 19
Fit Fraction (%)	8.4 ± 0.7 ± 4.2	4.1 ± 0.5 ± 1.1

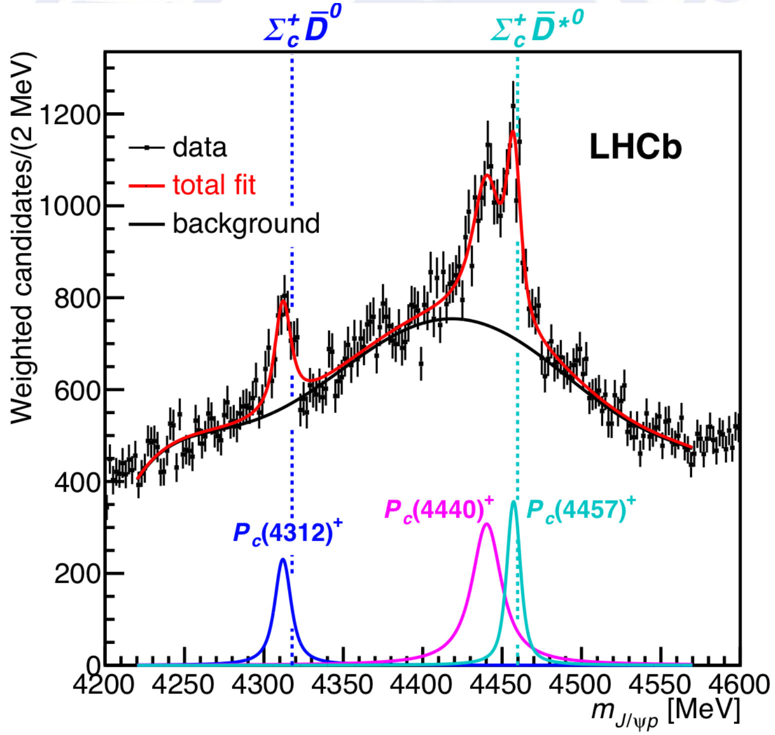
Fine structures from update in 2019

- Run1+Run2, x10 $\Lambda_b^0 \to J/\psi p K^-$ yield
  - Inclusion of Run 2 data (x 5)
  - Improved data selection (x 2)
- $P_c(4312)^+$ is observed
- $P_c(4450)^+$ peak structure is an overlap of two narrower states, $P_c(4440)^+$ and $P_c(4457)^+$
- Their near-threshold masses **favor** the predicted "molecular" pentaquarks with meson-baryon substructure, but **other hypotheses are not ruled out**

State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

246k Λ_b signals

PRL 122 (2019) 222001



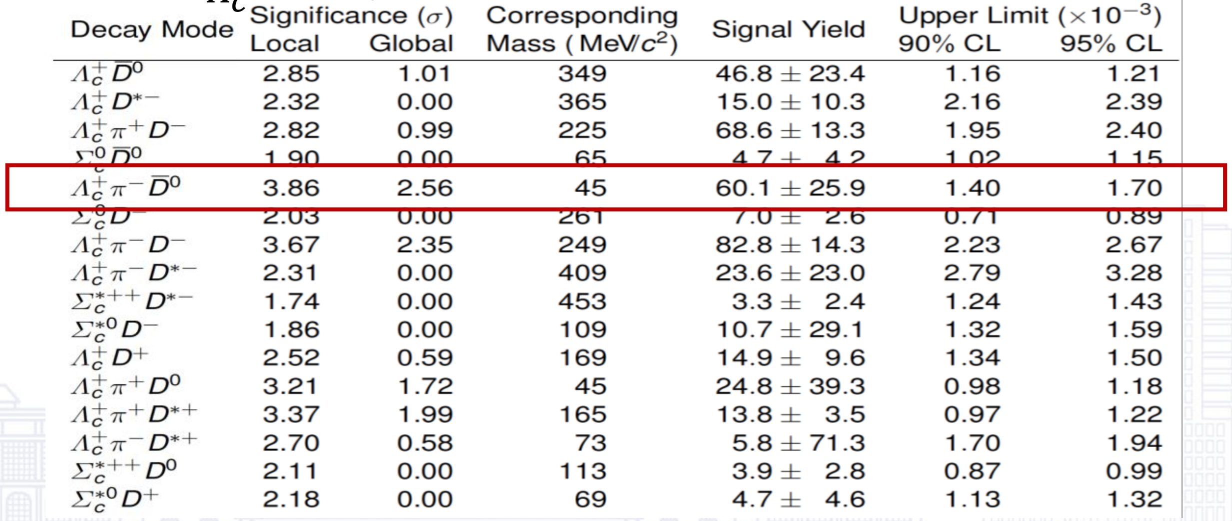
1D $m_{J/\psi p}$ is fitted, ongoing amplitude analysis is in advanced stage

Search for pentaquarks via open charm

[LHCb-PAPER-2023-018]

- Prompt production with 32 final states
  - $\Lambda_c^+\bar{D}$, $\Lambda_c^+\bar{D}^*$, $\Lambda_c^+\pi\bar{D}$, $\Sigma_c^{(*)}\bar{D}^{(*)}$ and Λ_c^+D, $\Lambda_c^+D^*$, $\Lambda_c^+\pi D$, $\Sigma_c^{(*)}D^{(*)}$
- Scan to search for pentaquarks with narrow width (0-15 MeV)
- No significant narrow peak is found for all the modes
- Upper limits are set on the production rates related to Λ_c^+

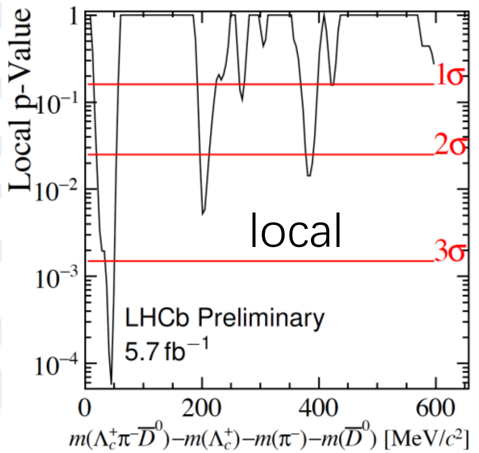
$$R = \frac{N_{P_c}}{N_{\Lambda_c^+}} \times \frac{\varepsilon_{\Lambda_c^+}}{\varepsilon_{P_c}} \rightarrow \frac{\sigma(P_c)\times\mathcal{B}\left(P_c\to\Lambda_c^+D(\pi)\right)\times\mathcal{B}(D)}{\sigma(\Lambda_c^+)}$$

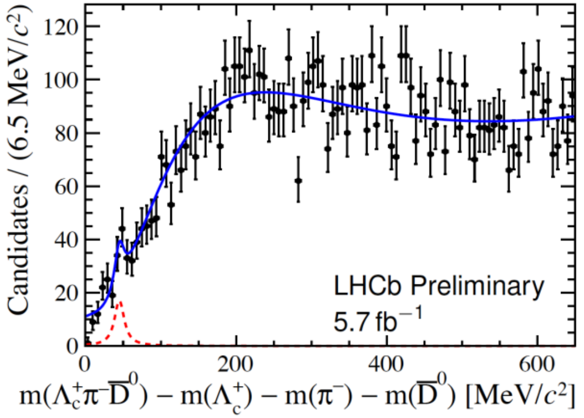


Decay Mode	Significance (σ) Local	Global	Corresponding Mass (MeV/c^2)	Signal Yield	Upper Limit ($\times10^{-3}$) 90% CL	95% CL
$\Lambda_c^+\bar{D}^0$	2.85	1.01	349	46.8 ± 23.4	1.16	1.21
$\Lambda_c^+D^{*-}$	2.32	0.00	365	15.0 ± 10.3	2.16	2.39
$\Lambda_c^+\pi^+D^-$	2.82	0.99	225	68.6 ± 13.3	1.95	2.40
$\Sigma_c^0\bar{D}^0$	1.90	0.00	65	$4.7\pm\ \ 4.2$	1.02	1.15
$\Lambda_c^+\pi^-\bar{D}^0$	3.86	2.56	45	60.1 ± 25.9	1.40	1.70
$\Sigma_c^0D^-$	2.03	0.00	261	$7.0\pm\ \ 2.6$	0.71	0.89
$\Lambda_c^+\pi^-D^-$	3.67	2.35	249	82.8 ± 14.3	2.23	2.67
$\Lambda_c^+\pi^-D^{*-}$	2.31	0.00	409	23.6 ± 23.0	2.79	3.28
$\Sigma_c^{*++}D^{*-}$	1.74	0.00	453	$3.3\pm\ \ 2.4$	1.24	1.43
$\Sigma_c^{*0}D^-$	1.86	0.00	109	10.7 ± 29.1	1.32	1.59
$\Lambda_c^+D^+$	2.52	0.59	169	$14.9\pm\ \ 9.6$	1.34	1.50
$\Lambda_c^+\pi^+D^0$	3.21	1.72	45	24.8 ± 39.3	0.98	1.18
$\Lambda_c^+\pi^+D^{*+}$	3.37	1.99	165	$13.8\pm\ \ 3.5$	0.97	1.22
$\Lambda_c^+\pi^-D^{*+}$	2.70	0.58	73	5.8 ± 71.3	1.70	1.94
$\Sigma_c^{*++}D^0$	2.11	0.00	113	$3.9\pm\ \ 2.8$	0.87	0.99
$\Sigma_c^{*0}D^+$	2.18	0.00	69	$4.7\pm\ \ 4.6$	1.13	1.32

Largest significance

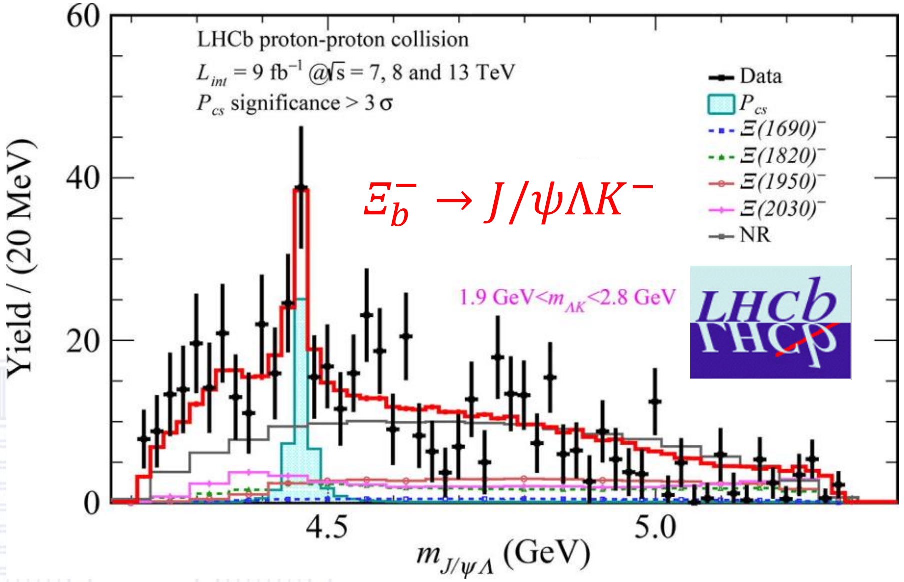
preliminary



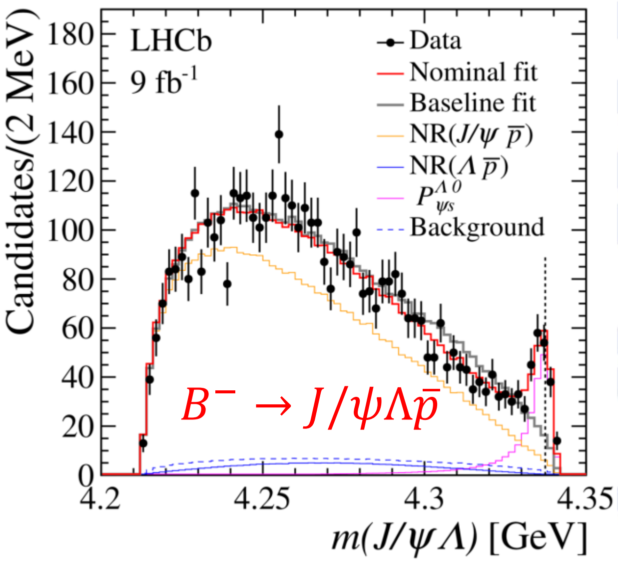


$c\bar{c}udd: M\sim4335.87$ MeV

Evidence of P_{cs}



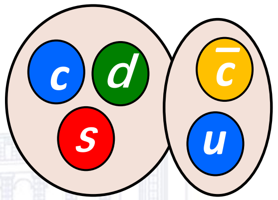
[Science Bulletin 66 (2021) 1278]



[PRL 131 (2023) 031901]

State	M_0 [MeV]	Γ [MeV]	FF (%)	Threshold
$P_{cs}(4459)^0$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$	$2.7^{+1.9+0.7}_{-0.6-1.3}$	$\Xi_c \bar{D}^*$
$P_{cs}(4338)^0$	$4338.2 \pm 0.7 \pm 0.4$	$7.0 \pm 1.2 \pm 1.3$	$12.5 \pm 0.7 \pm 1.9$	$\Xi_c \bar{D}$

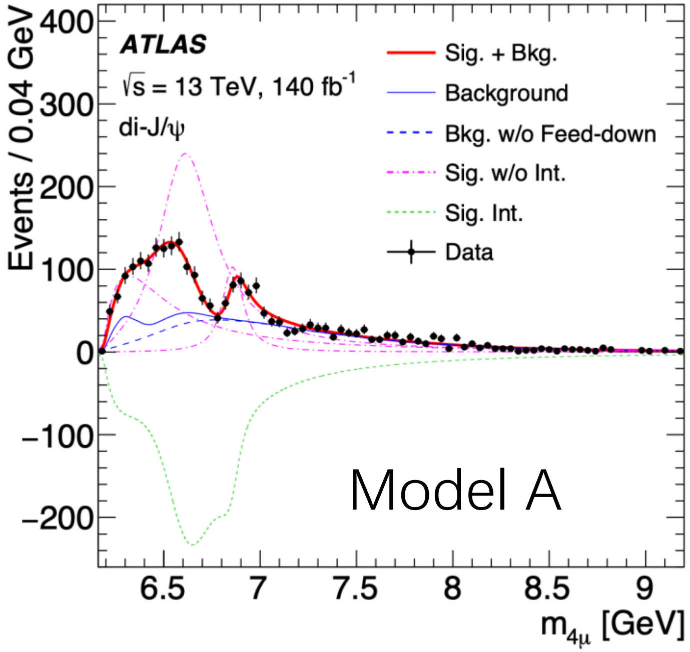
- more P_{cs}?
- Open-charm pentaquarks?

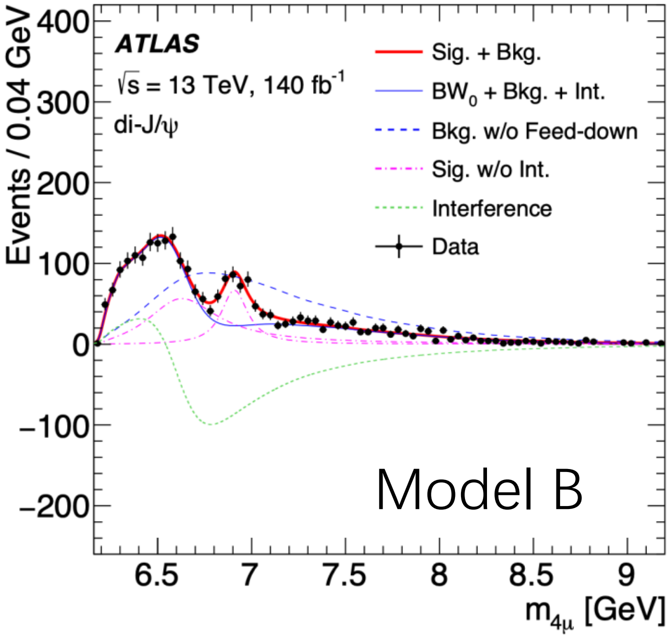


di-J/ψ　States

X(4c) states at ATLAS

Phys. Rev. Lett. 131 (2023) 151902





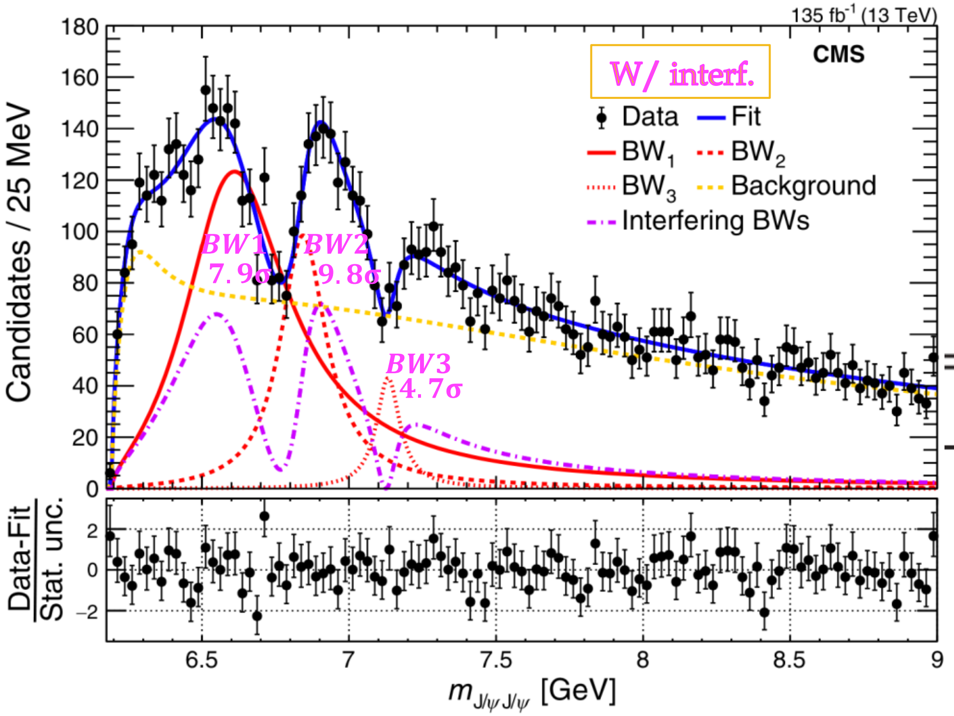
di-J/ψ	model A	model B
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$	—
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$	
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$	—

X(6900) > 5σ

- In the di-J/ψ channel, two signal models are tested:
  - **Model A**: three interfering signal peaks; **Model B**: two signal peaks
- The peak around **6.9 GeV** is consistent with the LHCb observed X(6900) (arXiv:2006.16957), with significance far above 5σ

X(4c) structures in di-Jpsi channel at CMS

Phys. Rev. Lett. 132 (2024) 111901



- **Interference model:**
  - Signal: interference between BW1, BW2, BW3
  - Background: BW0 + NRSPS + NRDPS

	BW_1	BW_2	BW_3
m (MeV)	6638^{+43+16}_{-38-31}	6847^{+44+48}_{-28-20}	7134^{+48+41}_{-25-15}
Γ (MeV)	$440^{+230+110}_{-200-240}$	191^{+66+25}_{-49-17}	97^{+40+29}_{-29-26}

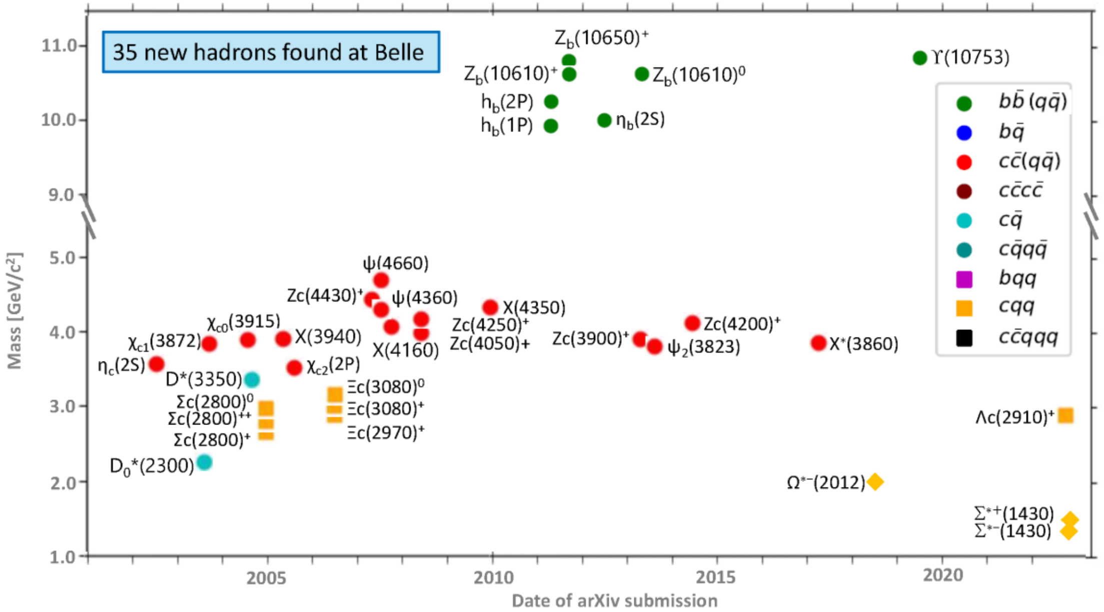
CMS found 3 significant $J/\psi J/\psi$ structures using Run II data

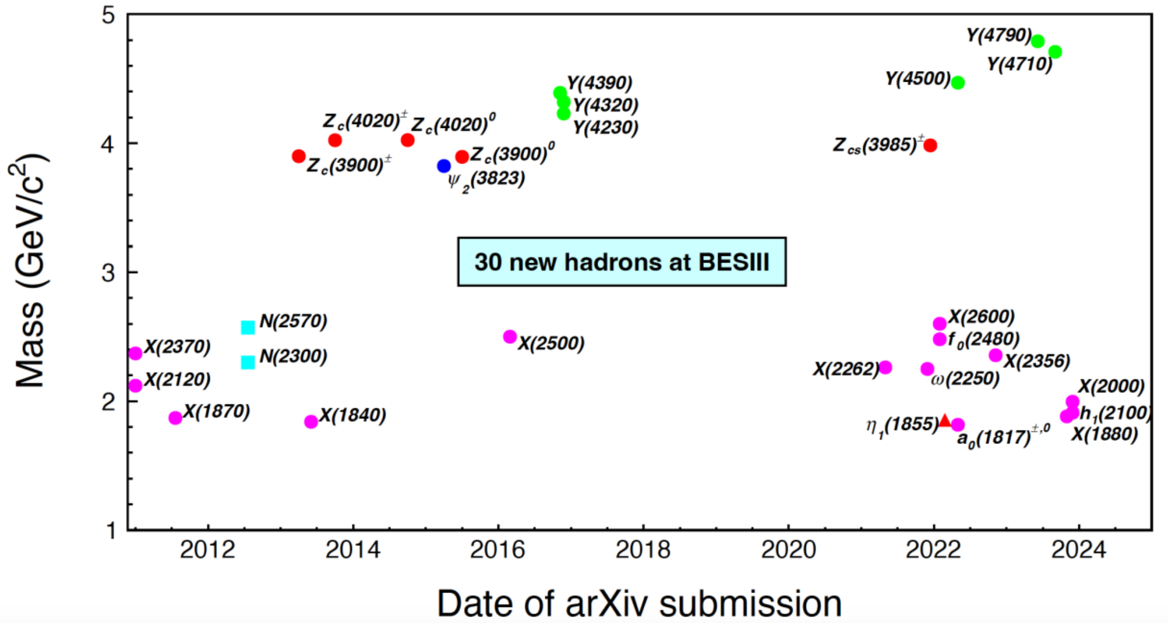
- BW2 consistent with X(6900) reported by LHCb [Sci. Bull. 65, 1983 (2020)]
- Two new structures named as X(6600) [>5σ], X(7300) [4.7σ]

A family of structures which are candidates for all-charm tetra-quarks

Update using RUN3 data and J^{PC} determination are on the way.

XYZ Summary



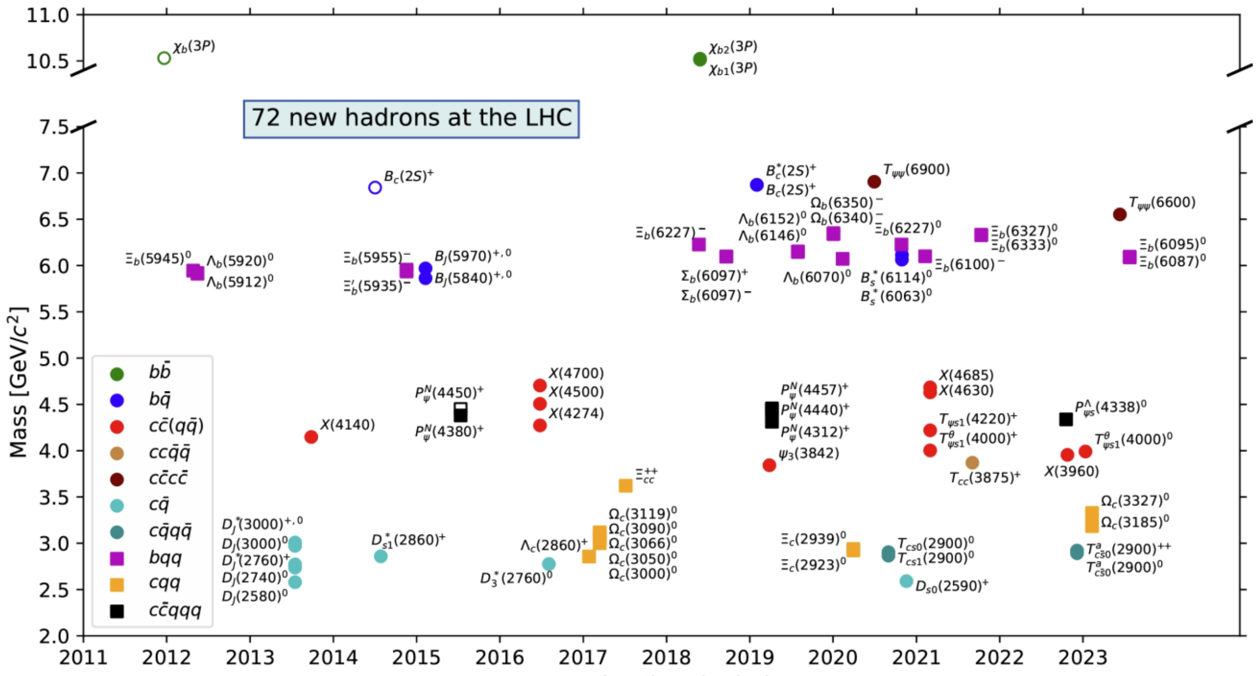


https://qwg.ph.nat.tum.de/exoticshub/

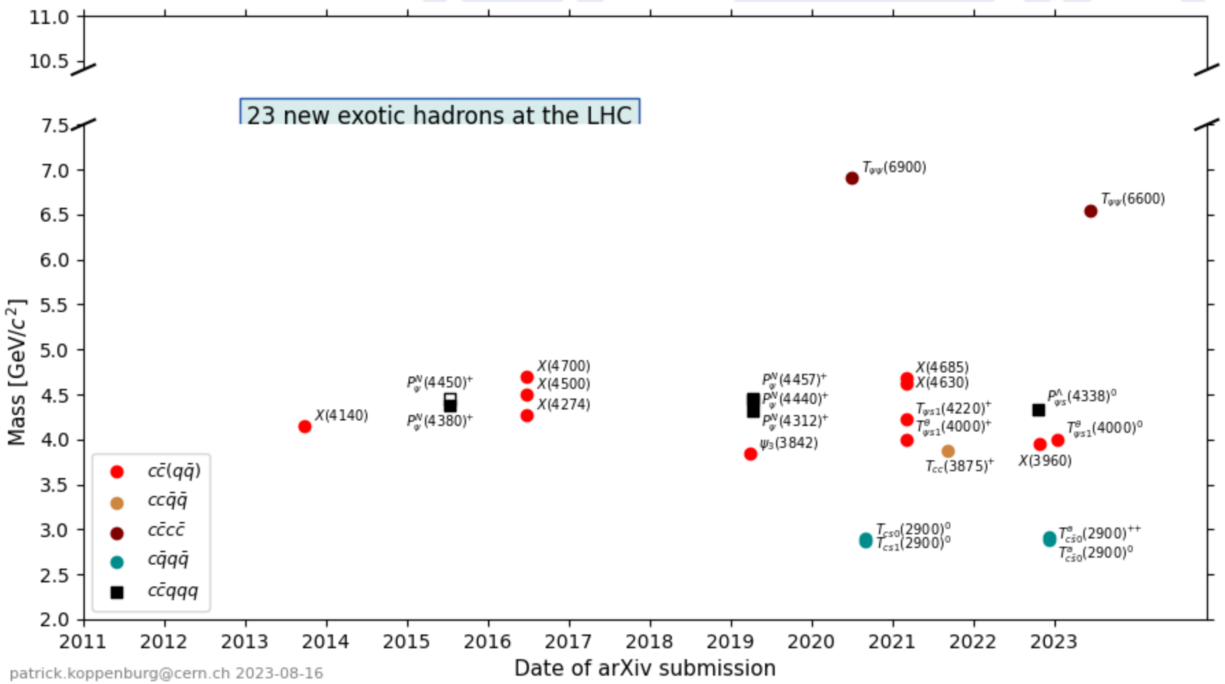
Belle: 35 new hadrons; 10 of these are "exotic" .

BESIII: 30 new hadrons; 12 of these are "exotic" .

72 new hadrons were found at LHC. **23 of these are "exotic"**



patrick.koppenburg@cern.ch 2023-08-16

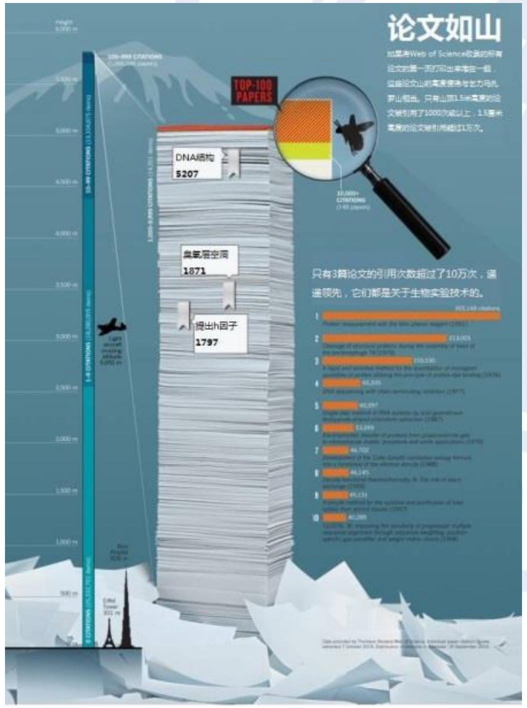


patrick.koppenburg@cern.ch 2023-08-16

Particle “Zoo” again !

Too many models !

- Theory 1: screened potential
- Theory 2: hybrids with excited gluons
- Theory 3: tetraquark states
- Theory 4: meson molecules
- Theory 5: cusps effect
- Theory 6: final state interaction
- Theory 7: coupled-channel effect
- Theory 8: mixing of normal quarkonium and exotics
- Theory 9: mixture of all these effects
- Theories …



We need clear features to identify exotic hadronic states !

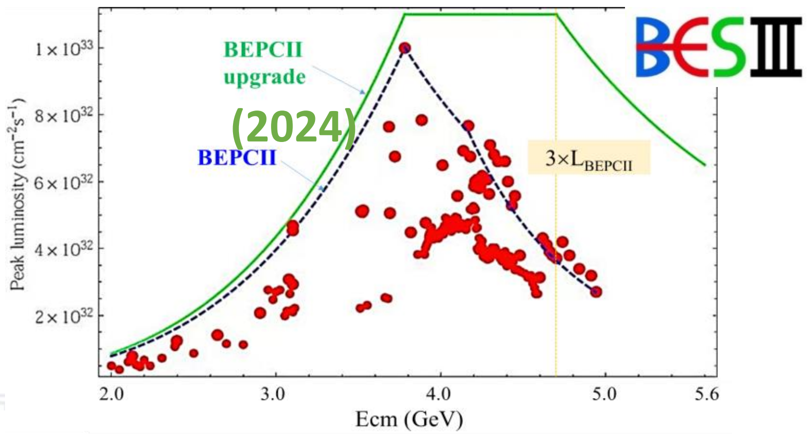
We found more questions to answer, works to do

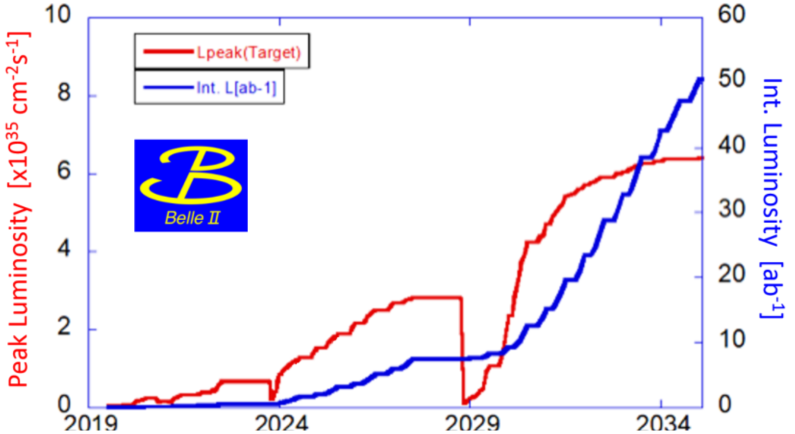
- In the Experiments sector
  - Search for flavor analog exotic states (Z_s, X_b, …)
  - Confirm marginal states (X(3940), Y(4008), Z_1(4050), X(4160), Z_2(4250), X(4350)….)
  - Search for missing charmonium/bottomonium states (η_{c2}, , h_c(2P) …)
  - Are there excited Z_c states and Z_{cs} states [D^*D_s or DD_s^*]?
  - Search for flavor analogs of the P_{cs} (P_s, …)
  - Search for quantum number partners of XYZ states
  - Precise measurements of relative strength to different final states
  - Check more di-charmonium systems or di-bottomonium systems
  - Correlation between charm production & charmonium transitions?
  - Make experimental results more accessible for subsequent interpretation (publish Dalitz plot in text format, supply also efficiency curve …)
  - Publish upper limits for negative searches
  - …….

We found more questions to answer, works to do

- In the Theory sector
  - Study exclusive e^+e^- cross sections using better coupled-channel formalism
  - Give differences in key physical quantities to distinguish between different interpretations (molecule, hybrid, tetraquark state, …)
  - Improve parameterizations of the data (when appropriate and beneficial, experimentalists and theorists directly work together)
  - theorists, when possible, publish complete functional forms
  - ……

More data, more surprises, more opportunities

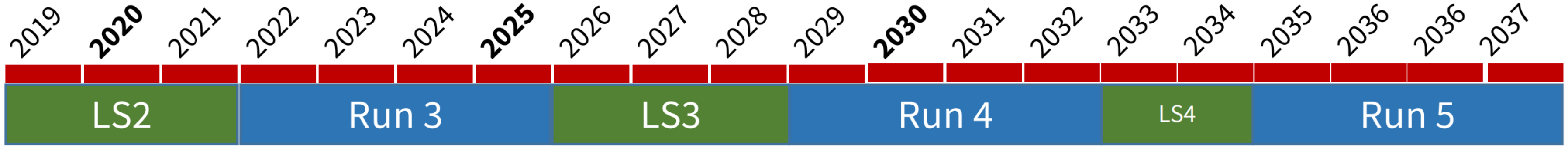




LHC: L = 2-3x10^{34} cm^{-2}.s^{-1}
~80 interactions per bunch crossing

HL-LHC, Phase II Upgrade : L = 7.5x10^{34} cm^{-2}.s^{-1}
~200 interactions per bunch crossing

LHC



Upgrade I : L = 2x10^{33} cm^{-2}.s^{-1}
~5 interactions per bunch crossing
~50 fb^{-1} (Run 3 and 4)

Upgrade II : L = 1.5x10^{34} cm^{-2}.s^{-1}
~50 interactions per bunch crossing
~300 fb^{-1} (Run 5….)

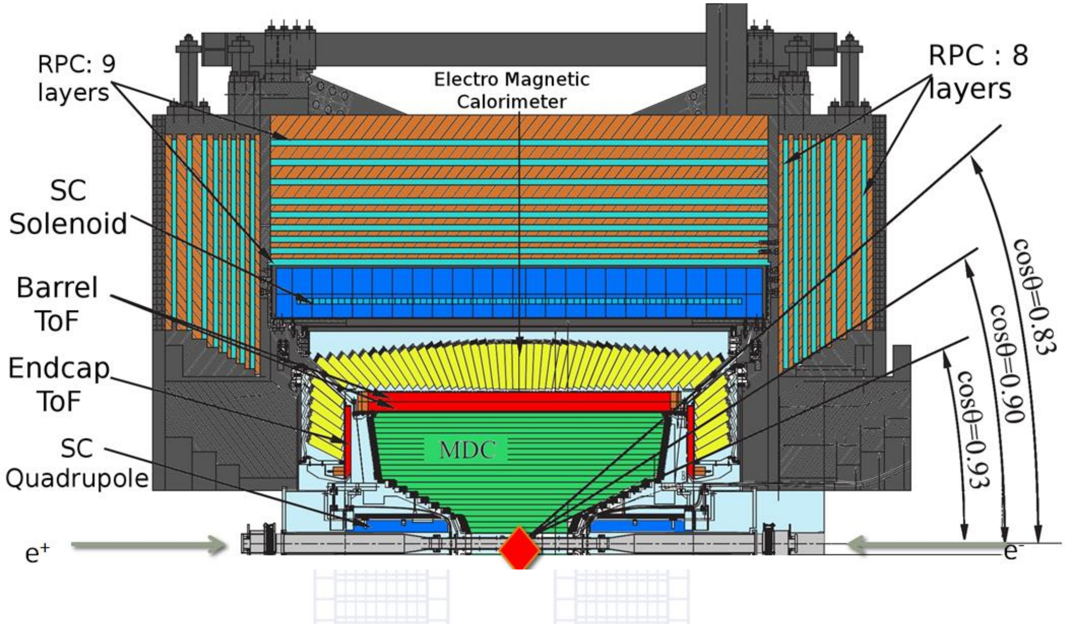
XYZ particles: review articles, books, & web pages

- H.-X. Chen et al., The hidden-charm pentaquark and tetraquark states, Phys. Rept. 639 (2016) 1
- A. Hosaka et al., Exotic hadrons with heavy flavors: X, Y, Z, and related states, PTEP 2016 (2016) 062C01
- J.-M. Richard, Exotic hadrons: review and perspectives, Few Body Syst. 57 (2016) 1185
- R. F. Lebed, R. E. Mitchell, E. Swanson, Heavy-quark QCD exotica, PPNP 93 (2017) 143
- A. Esposito, A. Pilloni, A. D. Polosa, Multiquark resonances, Phys. Rept. 668 (2017) 1
- A. Ali, J. S. Lange, S. Stone, Exotics: Heavy pentaquarks and tetraquarks, PPNP 97 (2017) 123
- F. K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou, Hadronic molecules, RMP 90 (2018) 015004
- S. L. Olsen, T. Skwarnicki, Nonstandard heavy mesons and baryons: Experimental evidence, RMP 90 (2018) 015003
- Y.-R. Liu et al., Pentaquark and tetraquark states, PPNP107 (2019) 237
- **N. Brambilla et al., The XYZ states: experimental and theoretical status and perspectives, Phys. Rept. 873 (2020) 1**
- Y. Yamaguchi et al., Heavy hadronic molecules with pion exchange and quark core couplings: a guide for practitioners, JPG 47 (2020) 053001
- F. K. Guo, X.-H. Liu, S. Sakai, Threshold cusps and triangle singularities in hadronic reactions, PPNP 112 (2020) 103757
- G. Yang, J. Ping, J. Segovia, Tetra- and penta-quark structures in the constituent quark model, Symmetry 12 (2020) 1869
- C. Z. Yuan, Charmonium and charmoniumlike states at the BESIII experiment, Natl. Sci. Rev. 8 (2021) nwab182
- H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, S.-L. Zhu, An updated review of the new hadron states, RPP 86 (2023) 026201
- L. Meng, B. Wang, G.-J. Wang, S.-L. Zhu, Chiral perturbation theory for heavy hadrons and chiral effective field theory for heavy hadronic molecules, Phys. Rept. 1019 (2023) 1
- A. Ali, L. Maiani, A. D. Polosa, Multiquark Hadrons, Cambridge University Press (2019)
- QWG: https://qwg.ph.nat.tum.de/exoticshub/

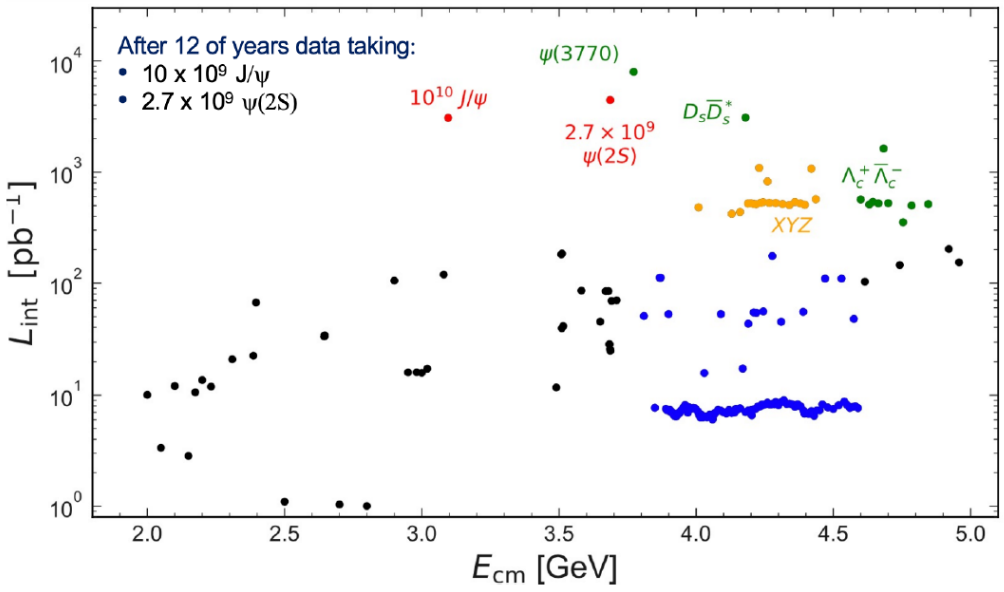
The future development is promising！

✧ Welcome to join the study of hadrons！

BESIII



$\sqrt{s} = 2\sim4.95$ GeV
Peak luminosity: $1.02 \times 10^{33} \text{cm}^{-1}\text{s}^{-1}$

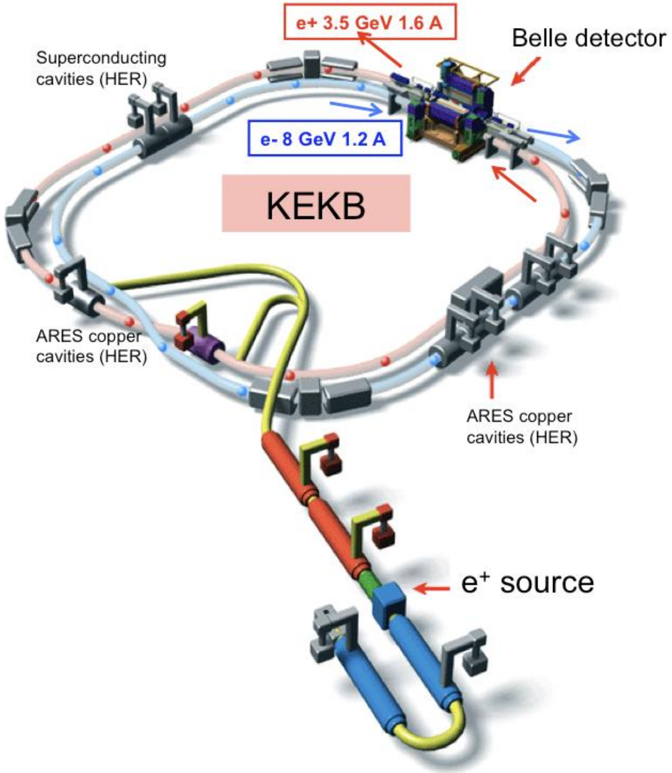


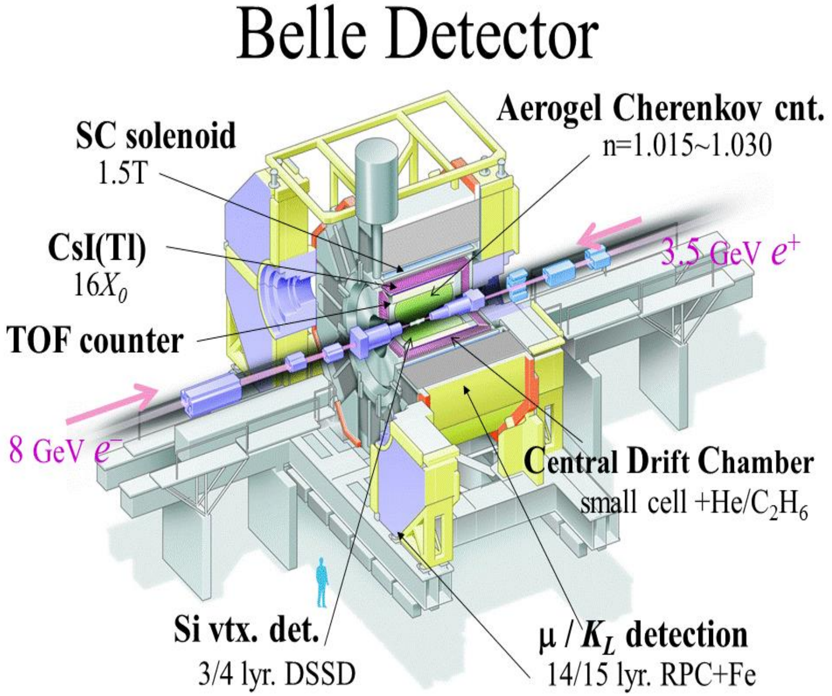
$10 \times 10^9\ J/\psi$ events
$2.7 \times 10^9\ \psi(3686)$ events
$16\ \text{fb}^{-1}\ \psi(3770)$ events
World largest J/ψ, $\psi(3686)$, and $\psi(3770)$ data samples on resonance

- BESIII has collected rich datasets in the XYZ region $\sqrt{s} > 3.8$ GeV with integrated luminosity of around 22 fb^{-1}.

KEKB and Belle

Peak luminosity: $2.11 \times 10^{34}\mathrm{cm}^{-1}\mathrm{s}^{-1}$
Integrated luminosity (~980 fb^{-1} in total):
$\Upsilon(5S)$: 121 fb^{-1}, $\Upsilon(4S)$: 711 fb^{-1}, $\Upsilon(3S)$: 3 fb^{-1},
$\Upsilon(2S)$: 25 fb^{-1}, $\Upsilon(1S)$: 6 fb^{-1}, continuum: 90 fb^{-1}

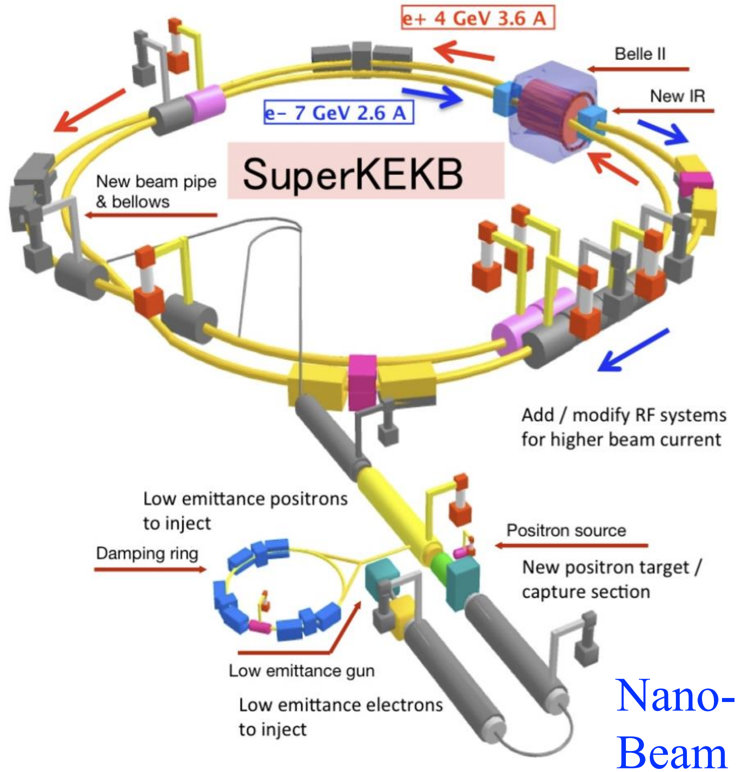




$\sqrt{s} \sim 10.6$ GeV

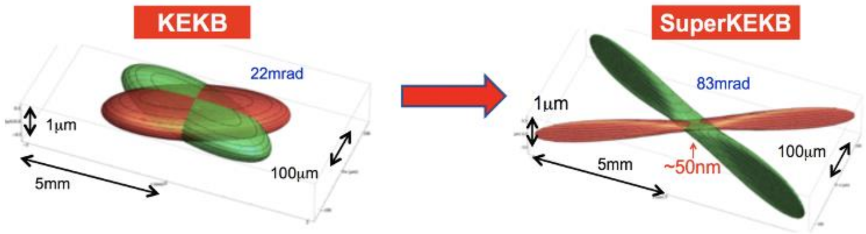
SuperKEKB and Belle II

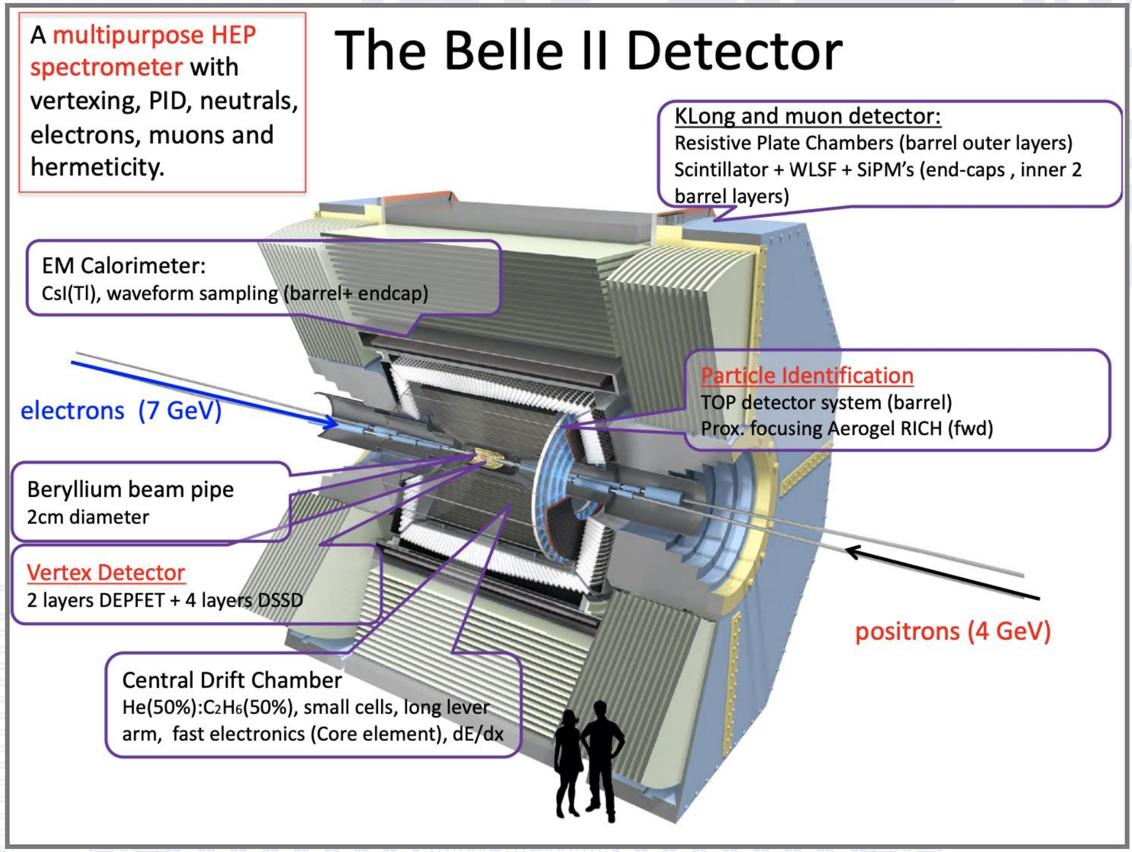
- Achieved peak luminosity: 4.7×10^{34} $cm^{-2}s^{-1}$
- Integrated luminosity: 435/fb



$\sqrt{s}\sim 10.58$ GeV

Nano-beam design:
Beam squeezing: ×20 smaller
Target luminosity: KEKB×40





A multipurpose HEP spectrometer with vertexing, PID, neutrals, electrons, muons and hermeticity.

The Belle II Detector

KLong and muon detector:
Resistive Plate Chambers (barrel outer layers)
Scintillator + WLSF + SiPM's (end-caps , inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling (barrel+ endcap)

Particle Identification
TOP detector system (barrel)
Prox. focusing Aerogel RICH (fwd)

electrons (7 GeV)

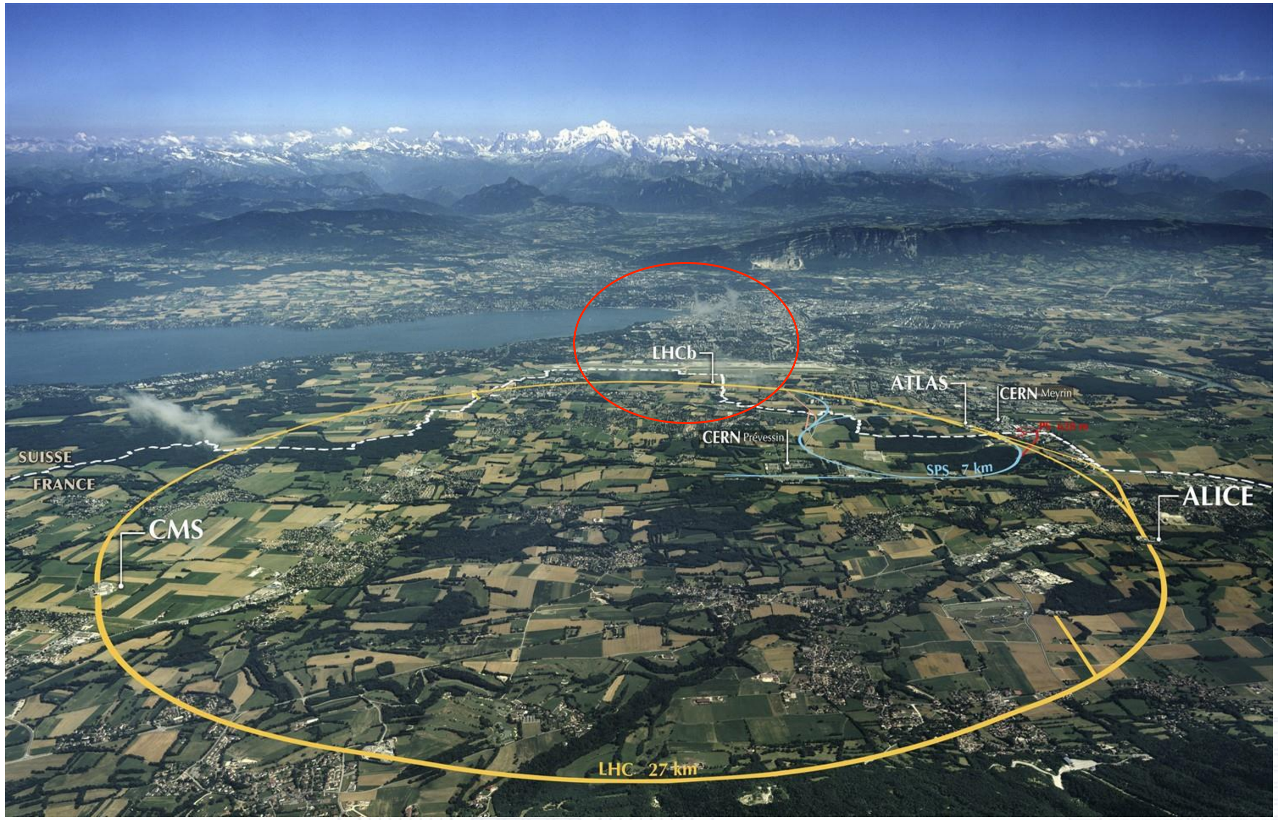
Beryllium beam pipe
2cm diameter

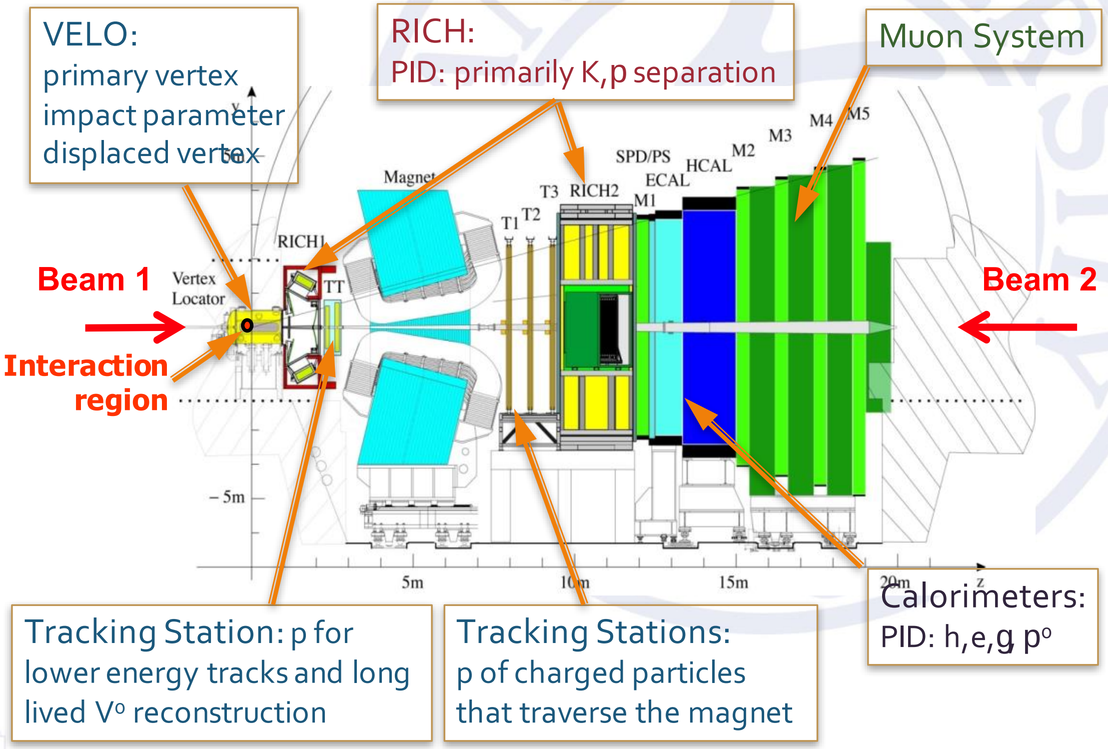
Vertex Detector
2 layers DEPFET + 4 layers DSSD

positrons (4 GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics (Core element), dE/dx

The LHC as a Beauty and Charm factory





VELO:
primary vertex
impact parameter
displaced vertex

RICH:
PID: primarily K,p separation

Muon System

Tracking Station: p for lower energy tracks and long lived V° reconstruction

Tracking Stations: p of charged particles that traverse the magnet

Calorimeters:
PID: h,e,g, p°

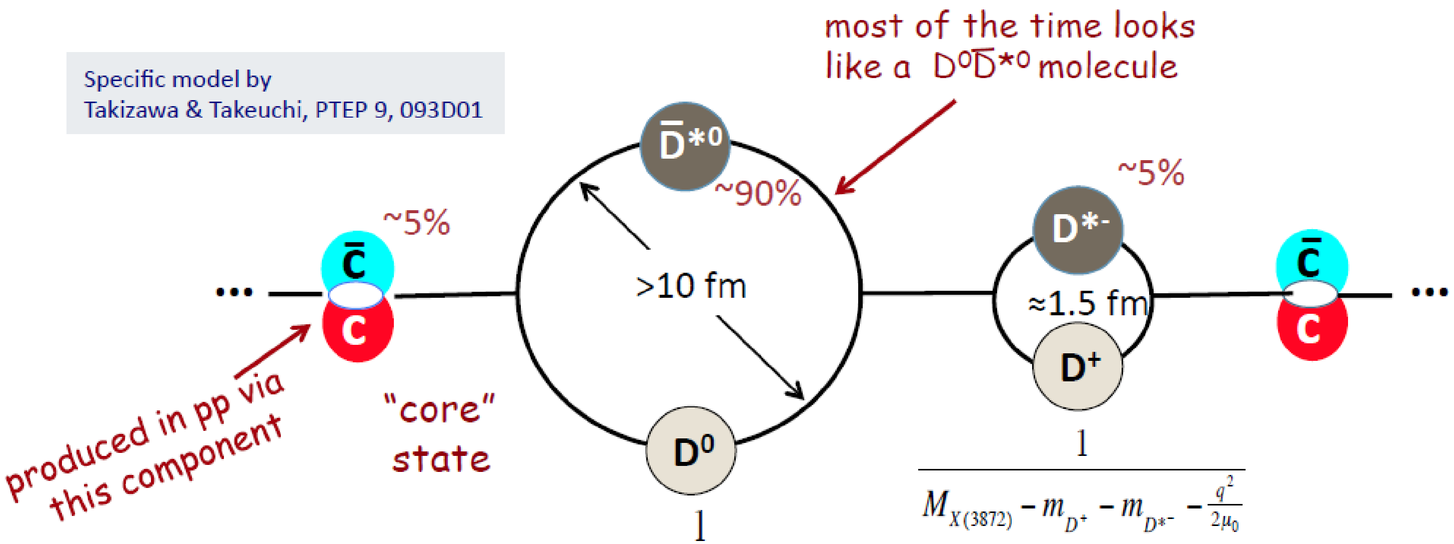
Proton-Proton Collisions at $\sqrt{s} = 13$ TeV
~ 20 000 $b\bar{b}$ pairs per second, x 20 of $c\bar{c}$ pairs

High B-baryon production fraction

$$\begin{array}{ccccccc} B^+ & : & B^0 & : & B_s^0 & : & \Lambda_b^0 \\ (u\bar{b}) & & (d\bar{b}) & & (s\bar{b}) & & (udb) \\ 4 & : & 4 & : & 1 & : & 2 \end{array}$$

Probably a mixture of DD̄* & a cc̄ “core”

Specific model by
Takizawa & Takeuchi, PTEP 9, 093D01



$$\frac{1}{M_{X(3872)} - m_{D^0} - m_{D^{*0}} - \frac{q^2}{2\mu_0}}$$

$$|BE| < 0.2\ \text{MeV}$$

$$d_{\text{rms}}^{D^0\bar{D}^{*0}} > 10\ \text{fm}$$

$$\frac{1}{M_{X(3872)} - m_{D^+} - m_{D^{*-}} - \frac{q^2}{2\mu_0}}$$

$$|BE| \simeq 8\ \text{MeV}$$

$$d_{\text{rms}}^{D^+D^{*-}} \simeq 1.5\ \text{fm}$$

$$d_{\text{rms}} \approx \frac{1}{\sqrt{2\mu_D|BE|}}:$$

reduced mass

$|m_D+m_{D*}-m_{X3872}|$

What is the Y(4260)?

The Y(4260) mass is lower and width narrower than previously thought

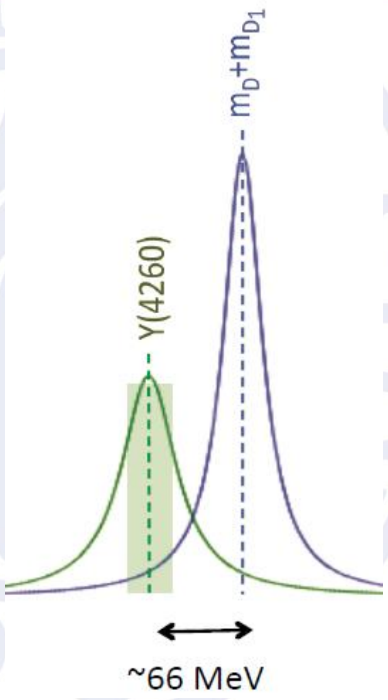
"Y(4260)" → Y(4220)?

2012 LQCD calc. (m_π≈400 MeV):

"Lowest 1^{--} $c\bar{c}$-gluon hybrid: M=4285 ± 14 MeV"

pre-2017: too high by ~35 MeV
post-2017: too high by ~65 MeV

Had. Spectr. Collab. JHEP07, 126



If it is a $D\bar{D}_1$(2420) molecule:

B.E. ≈ 66 MeV ←too large??

"affinity" to $D\bar{D}_1$(2420) should be high

If it is a $c\bar{c}$-gluon hybrid:

its mass is ~65 MeV below current (m_π≈400 MeV) LQCD predictions ← not so bad?

"affinity" to $D\bar{D}_0$(2400) should be high

If it is a QCD diquark–diantiquark tetraquark: Maiani et al. PRD89,114010

it should have Isospin- & $SU_F(3)$-multiplet partner states ← not seen

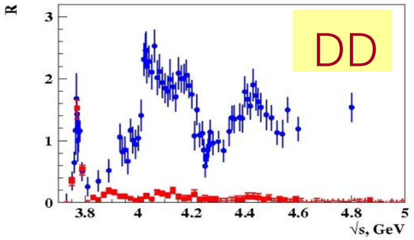
Dubynskiy & Voloshin, PLB 666, 344

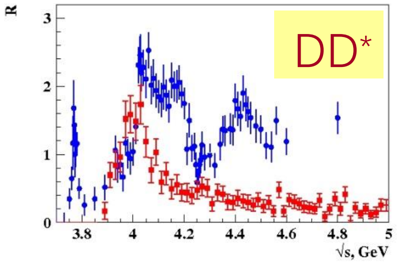
Li & Voloshin, Mod. Phys. Lett. A29, 1450060

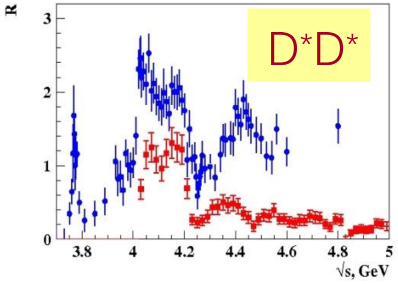
If it is hadrocharmonium:

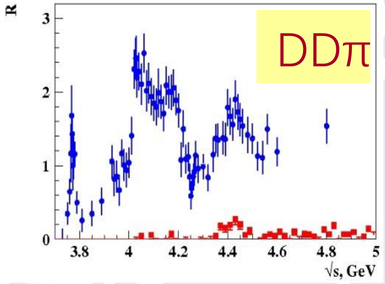
decays to non-J/ψ(h_c) charmonium states should be suppressed ←they aren't

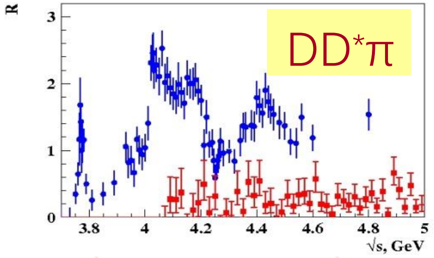
BESIII is well suited to further investigate this intriguing puzzle← a "Y(4260)" factory







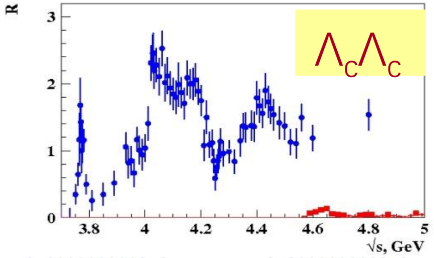


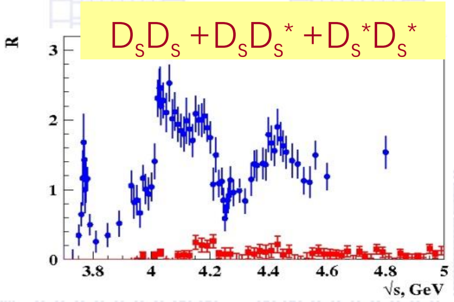


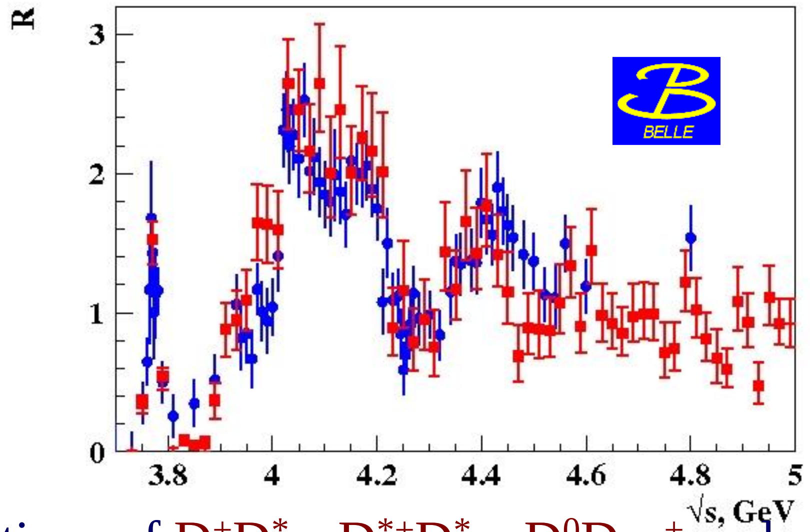
Exclusive cross sections contribution to the total cross section

Blue: R-measurement

Red: Cross section measurements

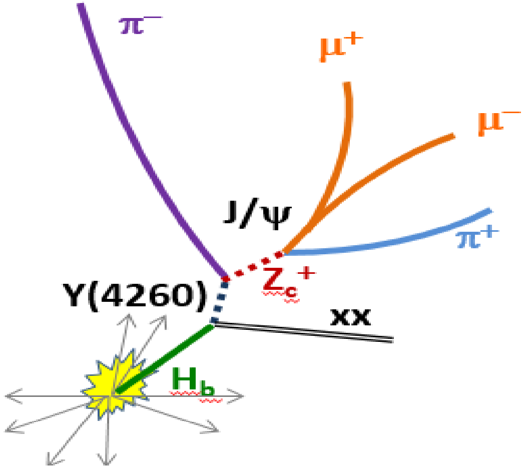






Contributions of D^+D^{*-}, $D^{*+}D^{*-}$, $D^0D^-\pi^+$ and $D^0D^{*-}\pi^+$ are scaled following isospin symmetry

Production of $Z_c^{\pm}(3900)$ in b-hadron Decays



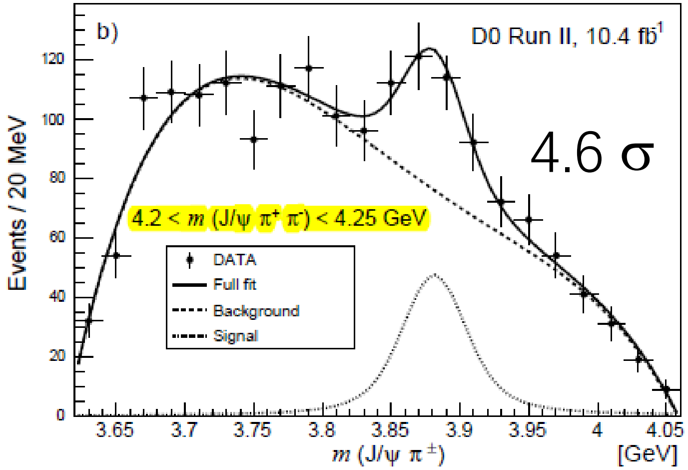
- Search for the $Z_c^{+}(3900)$ production in H_b decays via the following decays:

Phys. Rev. D98 (2018) 052010

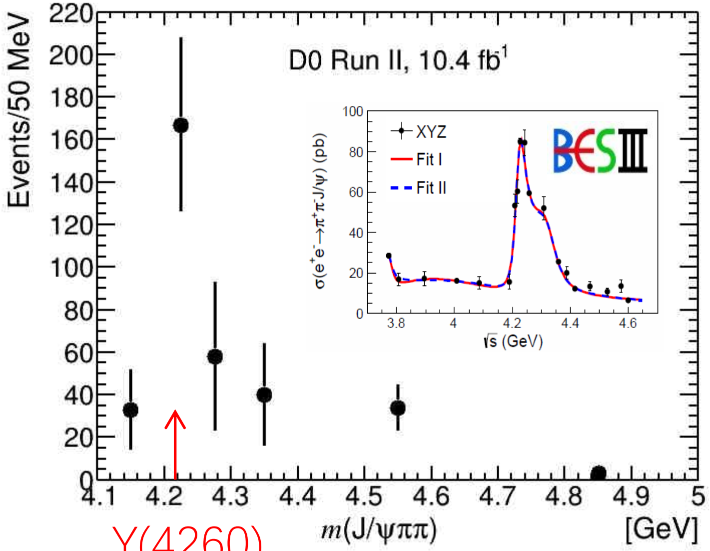
$$H_b \rightarrow Y(4260) + \text{anything}$$
$$Y(4260) \rightarrow Z_c^{\pm}(3900)\pi^{\mp}$$
$$Z_c^{\pm}(3900) \rightarrow J/\psi\pi^{\pm}$$

where H_b is any b-flavored hadron

1.96 TeV



4.6 σ



Y(4260)

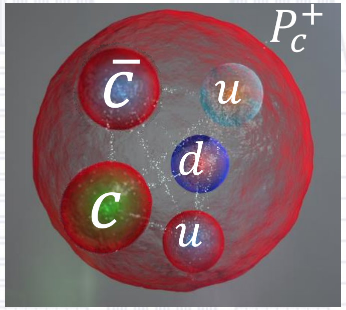
- $M = 3895.0 \pm 5.2\ (\text{stat})^{+4.0}_{-2.7}\ (\text{syst})$ MeV

Lots of open questions

- To interpret the nature of P_c, more studies are needed
  - Inner structures?
  - More states, SU(3) partners?
  - J^P, mode decay modes, production mechanism …?

$M_{P_c^+} = M_{J/\psi} + M_p + \sim 400\text{MeV}$

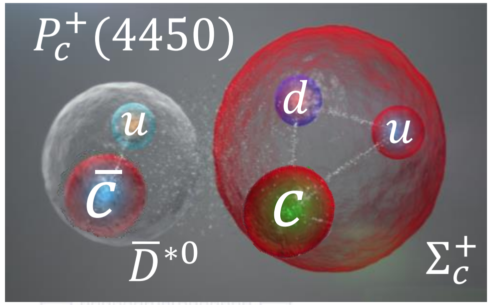
Tightly-bound pentaquark?



Maiani,Polosa, Riquer, PLB 749 (2015) 289
Lebed, PLB 749 (2015) 454
Anisovich,Matveev,Nyiri, Sarantsev PLB 749 (2015) 454
and others

$M_{P_c^+} = M_{\bar{D}^{*0}} + M_{\Sigma_c^+} - \sim\text{few MeV}$

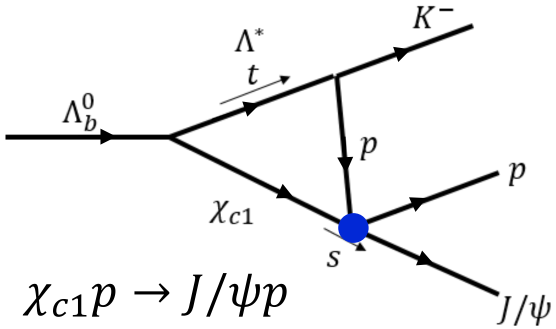
Loosely-bound pentaquark?



Wu,Molina,Oset,Zou, PRL105 (2010) 232001
Wang,Huang,Zhang,Zou, PRC84 (2011) 015203
Karliner,Rosner, PRL 115 (2015) 122001
and others

$P_c(4450)^+ = \chi_{c1}p$ threshold?

Kinematical effect: triangle diagram?



$\chi_{c1}p \to J/\psi p$

Guo,Meissner,Wang,Yang, PRD 92 (2015) 071502
Liu, Wang, Zhao, PLB 757 (2016) 231
Mikhasenko, arXiv:1507.06552
Szczepaniak, PLB 757 (2016) 61
and others

1st observation of $\Lambda_b^0 \to \eta_c p K^-$

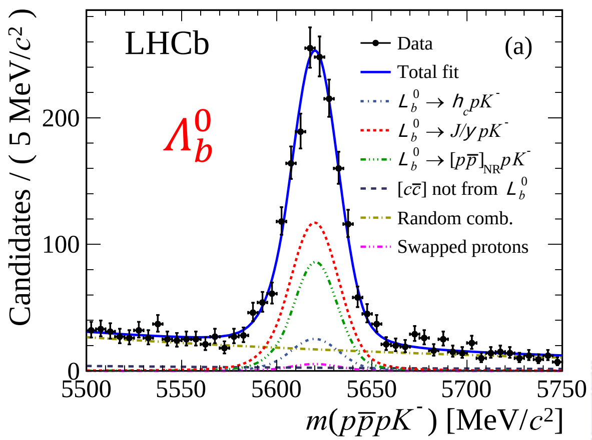
- $\eta_c p$ **final state is very sensitive to** $1/2^-$ P_c, **where** $\eta_c p$ **is in S-wave**
- If $P_c(4312)^+$ is $\Sigma_c \bar{D}$ molecule, predicted $\frac{\mathcal{B}(P_c(4312)^+ \to \eta_c p)}{\mathcal{B}(P_c(4312)^+ \to J/\psi p)} \sim 3$

  [PRD 100 (2019) 034020, 100 (2019) 074007, 102 (2020) 036012]
- LHCb run2 data (5.5 fb^{-1}) using $\eta_c \to p\bar{p}$
- Fit 2D mass spectrum to confirm the existence
- Obtain

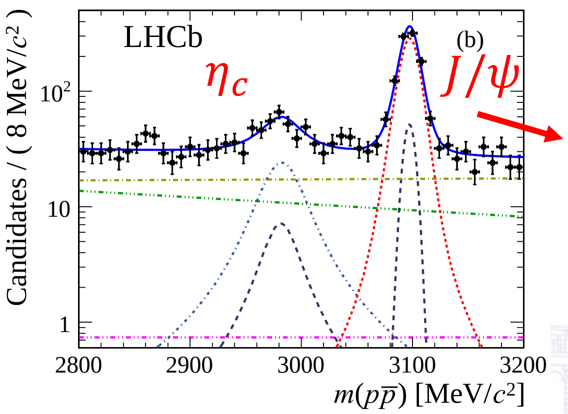
$$\frac{\mathcal{B}(\Lambda_b^0 \to \eta_c p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p K^-)} = 0.333 \pm 0.050\ (\text{stat.}) \pm 0.019\ (\text{syst.}) \pm 0.032\ (\mathcal{B})$$

[PRD 102 (2020) 112012]

$P_c(4312)^+$ production fraction in $\Lambda_b^0 \to \eta_c p K^-$ is ~ 3% (predicted)



~170 $\Lambda_b^0 \to \eta_c p K^-$ signals



$\Lambda_b^0 \to J/\psi p K^-$ used as reference mode for branching fraction measurement

Search for P_c^+ in $\eta_c p$ system

[PRD 102 (2020) 112012]

- Check background-subtracted $\eta_c p$ mass spectrum

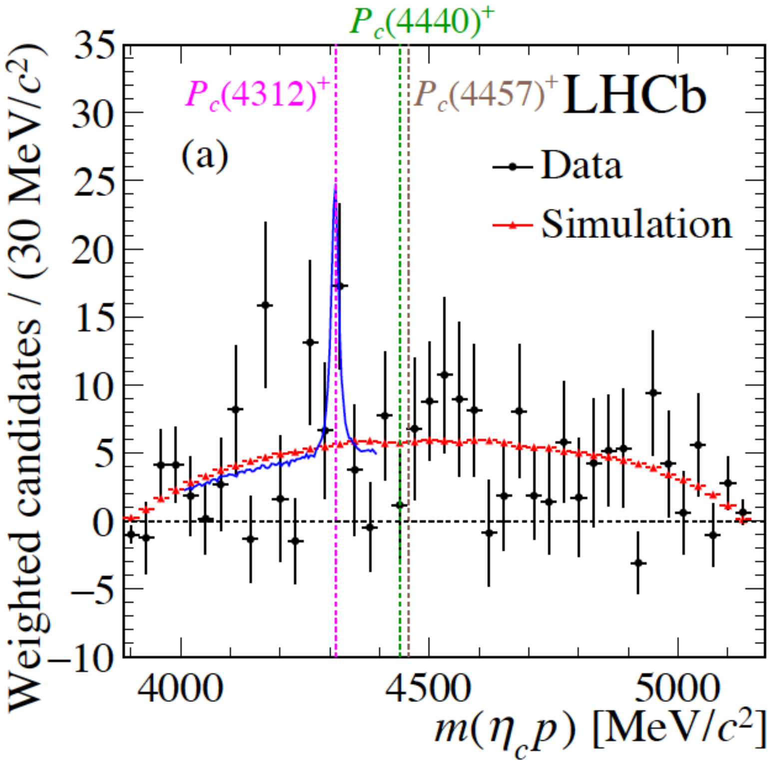
No significant $P_c(4312)^+$ contribution (~2σ)

P_c^+ production fraction obtained

$$R(P_c(4312)^+) < 24\% \text{ @ } 95\% \text{ C.L.}$$

much larger than the predicted value 3%
(no conclusion yet)

- **Need run3+4 data, amplitude fit can be performed**



Search for Ps states at Belle

PRD96, 051102(R) (2017); 915fb^{-1}

Belle: arXiv: 1707.00089, PRD (in press) 915 fb^{-1} data

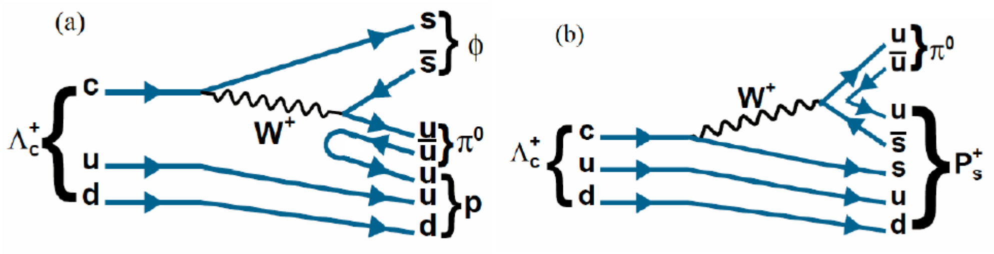
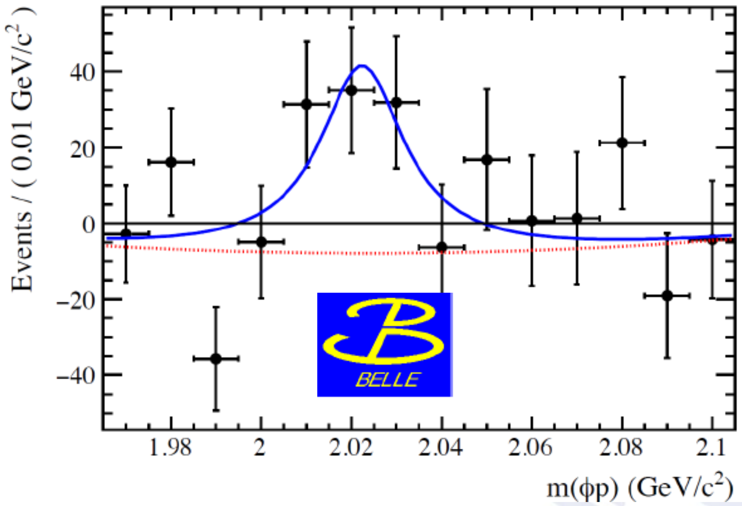


FIG. 1. Feynman diagram for the decay (a) $\Lambda_c^+ \to \phi p \pi^0$ and (b) $\Lambda_c^+ \to P_s^+ \pi^0$.



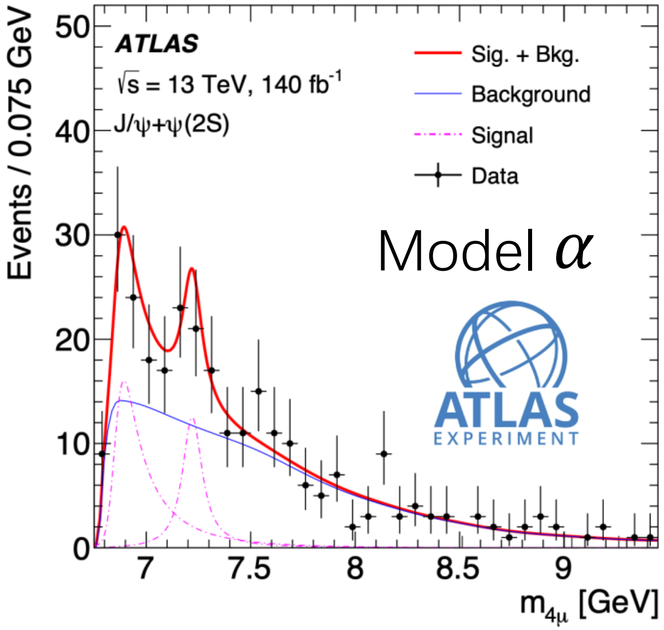
$\Sigma^+ \to p\pi^0$ vetoed

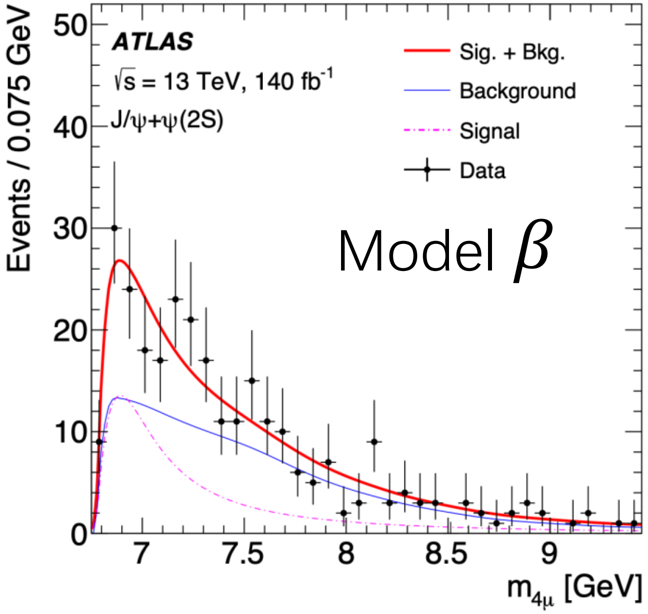
- **No significant Ps signal**
- **Best fit yields a peak at M=(2025±5) MeV/c^2 and Γ=(22±12) MeV**

Number of candidate $\Lambda_c \to P_s \pi^0 \to \phi p \pi^0$ events: 77.6±28.1

$B(\Lambda_c \to P_s \pi^0) \times B(P_s \to \phi p) < 8.3 \times 10^{-5}$ @90% C.L.

X(4c) states at ATLAS



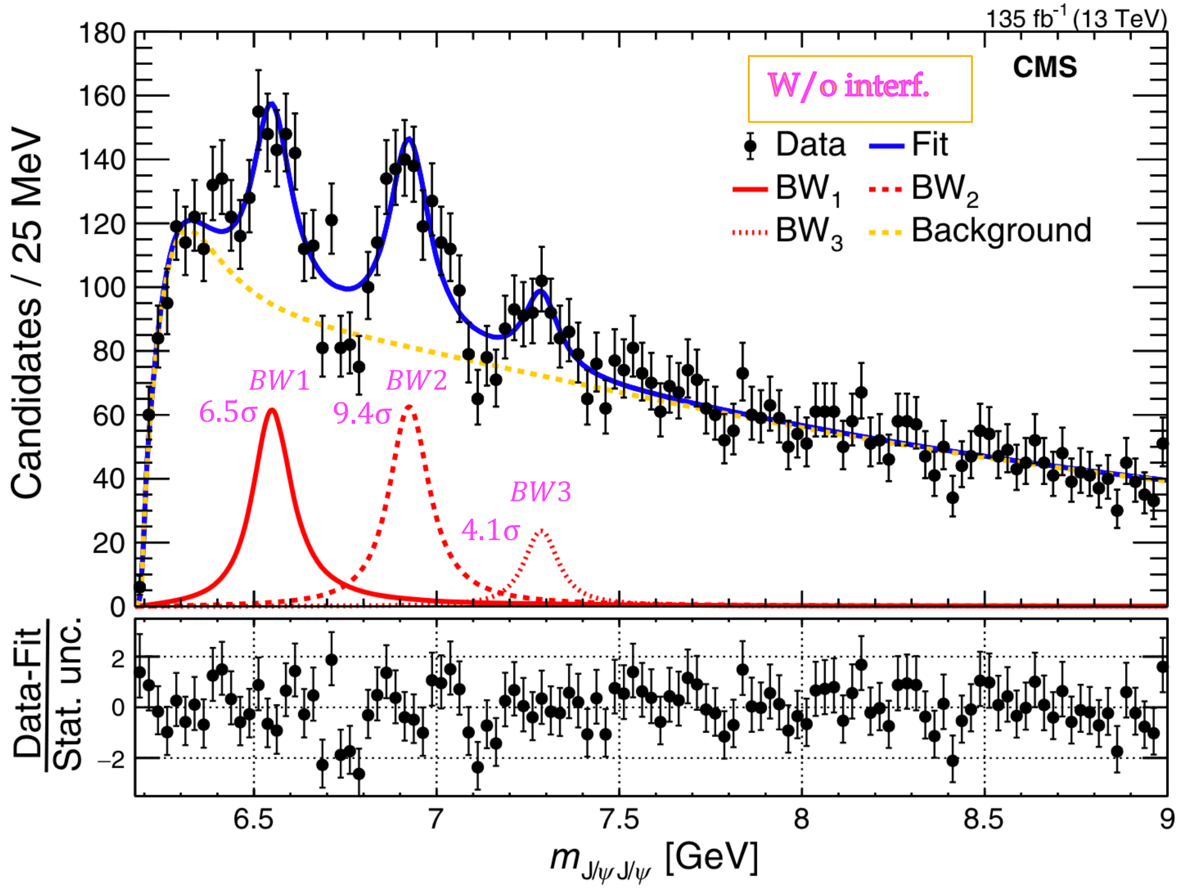


J/ψ+ψ(2S)	model α	model β
m_3	$7.22 \pm 0.03^{+0.01}_{-0.04}$	$6.96 \pm 0.05 \pm 0.03$
Γ_3	$0.09 \pm 0.06^{+0.06}_{-0.05}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 21\%^{+25\%}_{-15\%}$	$\pm 20\% \pm 12\%$

- The signal significance is 4.7σ (4.3σ) for model α (β). The significance of the **2nd peak** (7.2 GeV) reaches **3.0**σ, also hinted by LHCb and CMS (arXiv:2306.07164) in the di-J/ψ spectrum

- In the $J/\psi + \psi(2S)$ channel, also two signal models are tested:
  - **Model** α: the same peaks observed in the di-J/ψ channel also decaying into $J/\psi + \psi(2S)$ plus a standalone peak.
  - **Model** β: only one signal peak

X(4c) structures in di-Jpsi channel at CMS



- **No interference model:** Phys. Rev. Lett. 132 (2024) 111901
  - Signal: BW1, BW2, BW3
  - Background: BW0 + NRSPS + NRDPS

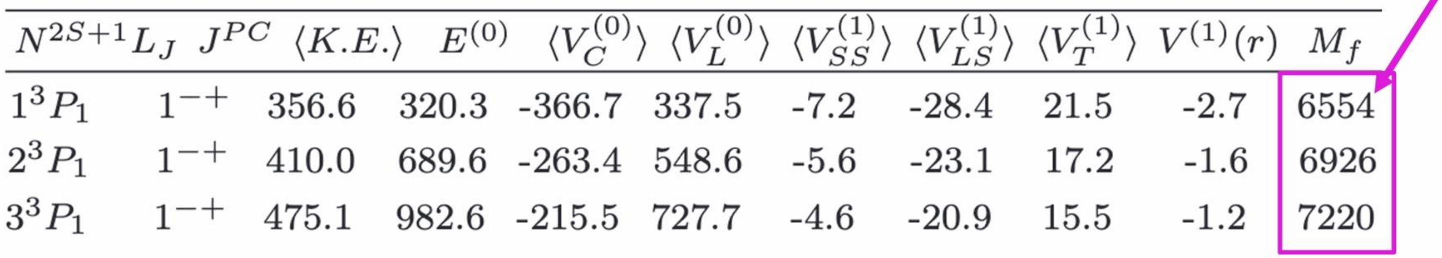
	BW$_1$	BW$_2$	BW$_3$
m (MeV)	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 4$	$7287^{+20}_{-18} \pm 5$
Γ (MeV)	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
N	470^{+120}_{-110}	492^{+78}_{-73}	156^{+64}_{-51}

- BW2 [X(6900)] (9.4σ) – confirmation
- Observation of BW1 (6.5σ)
- Evidence for BW3 (4.1σ)

Comparison with some theoretical calculations

arXiv:2108.04017 [hep-ph] *P-wave*

Ground state



$N^{2S+1}L_J$	J^{PC}	$\langle K.E.\rangle$	$E^{(0)}$	$\langle V_C^{(0)}\rangle$	$\langle V_L^{(0)}\rangle$	$\langle V_{SS}^{(1)}\rangle$	$\langle V_{LS}^{(1)}\rangle$	$\langle V_T^{(1)}\rangle$	$V^{(1)}(r)$	M_f
1^3P_1	1^{-+}	356.6	320.3	-366.7	337.5	-7.2	-28.4	21.5	-2.7	6554
2^3P_1	1^{-+}	410.0	689.6	-263.4	548.6	-5.6	-23.1	17.2	-1.6	6926
3^3P_1	1^{-+}	475.1	982.6	-215.5	727.7	-4.6	-20.9	15.5	-1.2	7220

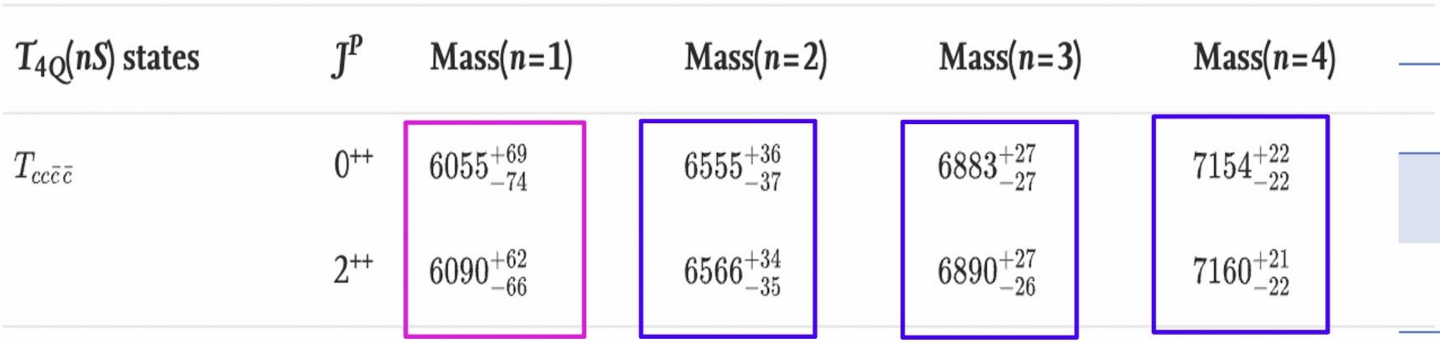
M[BW1] = 6552^{+10+12}_{-10-12} MeV

M[BW2] = 6927^{+9+4}_{-9-4} MeV

M[BW3] = 7287^{+20+5}_{-18-5} MeV

CMS: Interference fit results

Nucl. Phys. B 966 (2021) 115393 *S-wave*



$T_{4Q}(nS)$ states	J^P	Mass(n=1)	Mass(n=2)	Mass(n=3)	Mass(n=4)
$T_{cc\bar{c}\bar{c}}$	0^{++}	6055^{+69}_{-74}	6555^{+36}_{-37}	6883^{+27}_{-27}	7154^{+22}_{-22}
	2^{++}	6090^{+62}_{-66}	6566^{+34}_{-35}	6890^{+27}_{-26}	7160^{+21}_{-22}

M[BW1] = 6638^{+43+16}_{-38-31} MeV

M[BW2] = 6847^{+44+48}_{-28-20} MeV

M[BW3] = 7134^{+48+41}_{-25-15} MeV

CMS: Non-interference fit results

Ground states
Missing n=1

- Radial excited states?
- measure J^{PC} to clarify
- PRD 109, 054034 (2024) new theoretical result