Advances in (experimental) hadron physics

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Outline

- Introduction
- Light hadron spectroscopy
- Heavy hadron spectroscopy
  - ✓ Heavy meson
  - ✓ Heavy baryon
- Summary

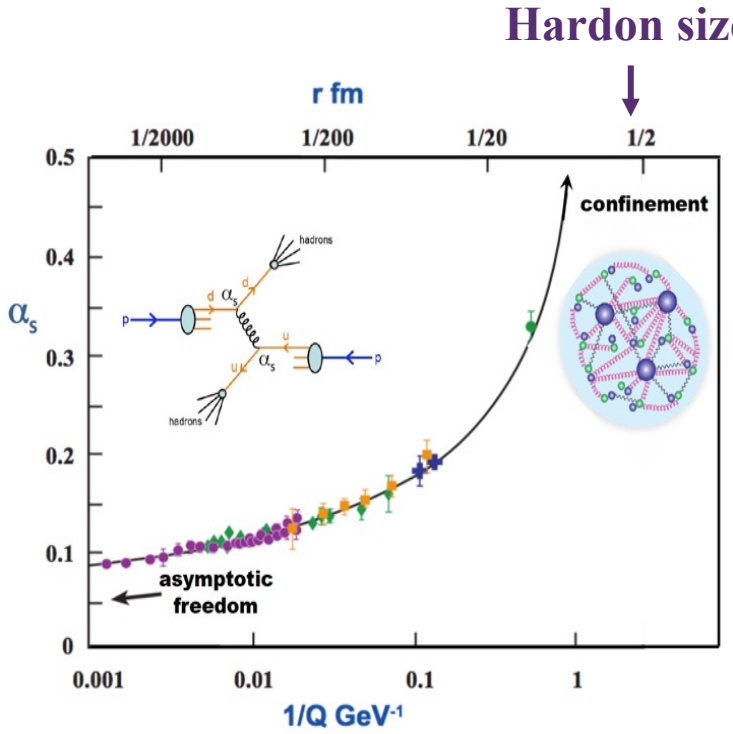
See more results in below contributions by

- Lorenzo Capriotti
- Xin Chen
- Francesca De Mori
- Yuping Guo
- Beijiang Liu
- Roman Mizuk
- Alexis Pompili
- Raul Rabadan
- Zan Ren
- Miroslav Saur
- …

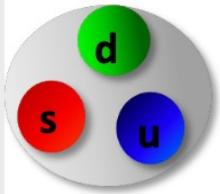
I apologize for not covering all the experiments results.

Introduction

- Quarks and gluons not isolated in nature.
  - Formation of colorless bound states: "**Hadrons**"
  - **1-fm scale** size of hadrons?
- Hadron spectroscopy provides opportunities to study QCD in the non-perturbative region
  - Extensive and precise spectroscopy combined with a thorough theoretical analysis, will add substantially to our knowledge of QCD
- Complex exotic hadrons can reveal new or hidden aspects of the dynamics of strong interactions
  - Predicted in quark model
  - Recent results show strong evidence for their existence



Different types of hadrons to be explored



Baryons are red-blue-green triplets

Λ=usd

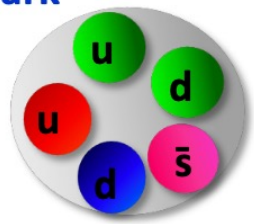
Mesons are color-anticolor pairs

π=ūd

Other possible combinations of quarks and gluons : ***exotic states!!!***

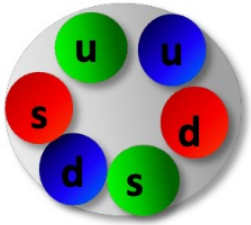
Pentaquark

S= +1
Baryon



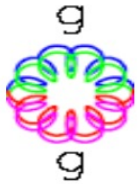
H di-Baryon

Tightly bound
6 quark state



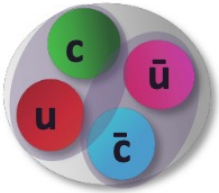
Glueball

Color-singlet multi-gluon bound state



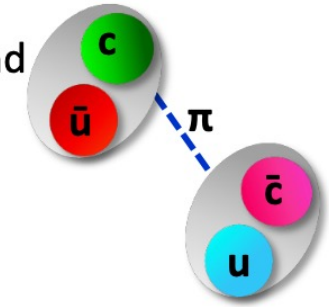
Tetraquark

Tightly bound diquark & anti-diquark

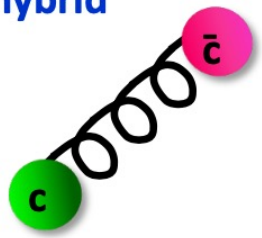


Molecule

loosely bound meson-antimeson "molecule"

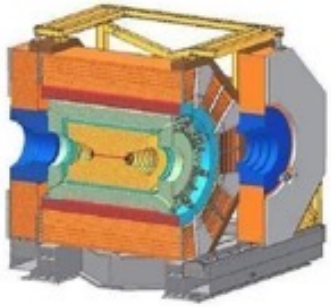


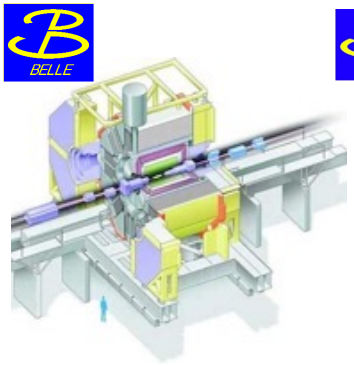
qq̄ -gluon hybrid mesons

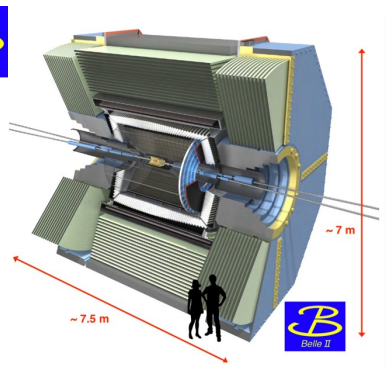


Main contributors worldwide

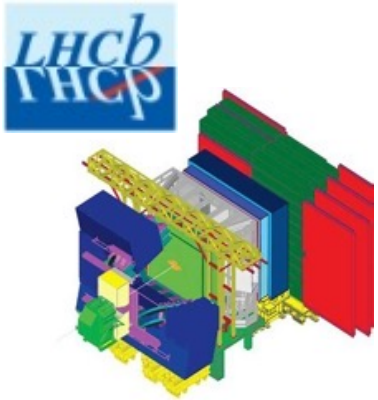
- e^+e^- collider

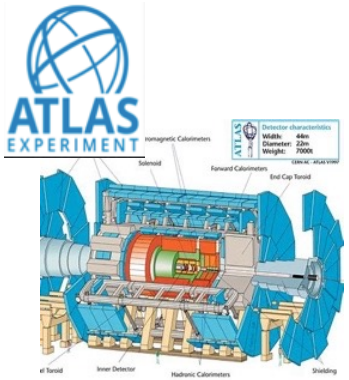


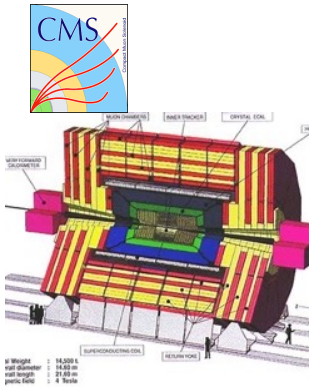




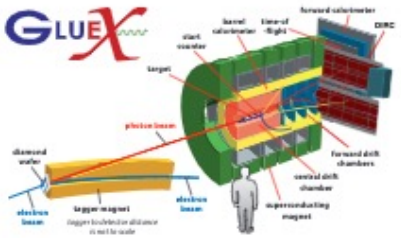
- Hadron collider



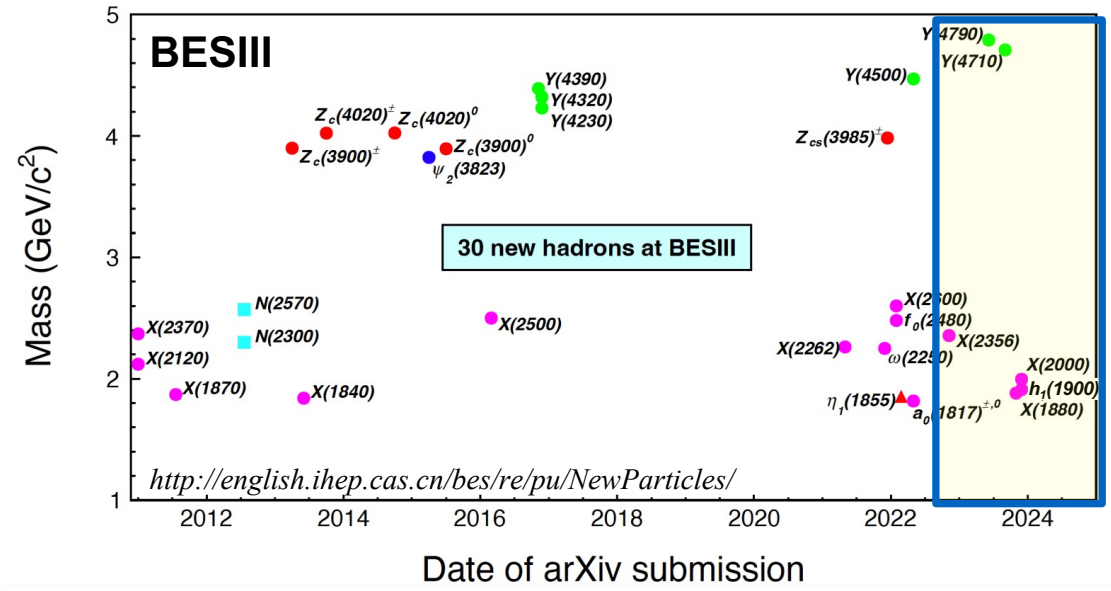


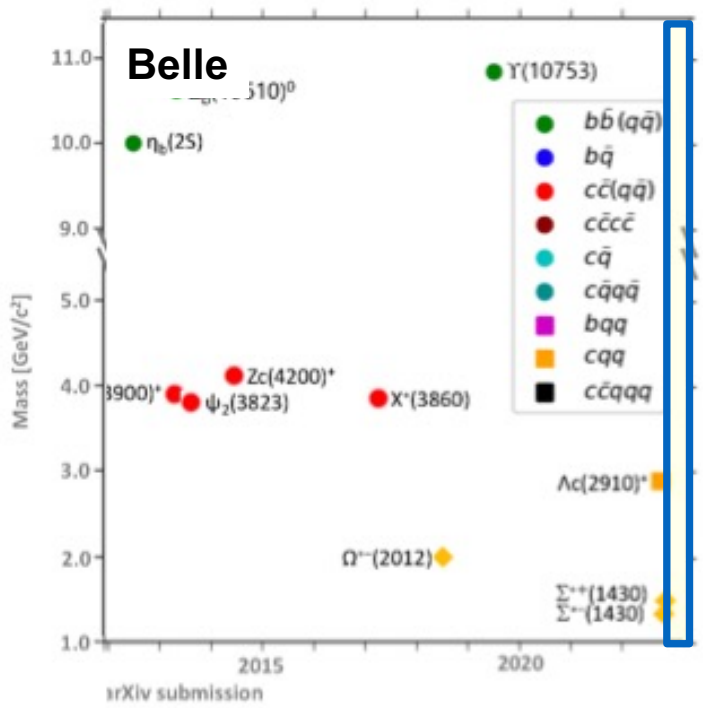


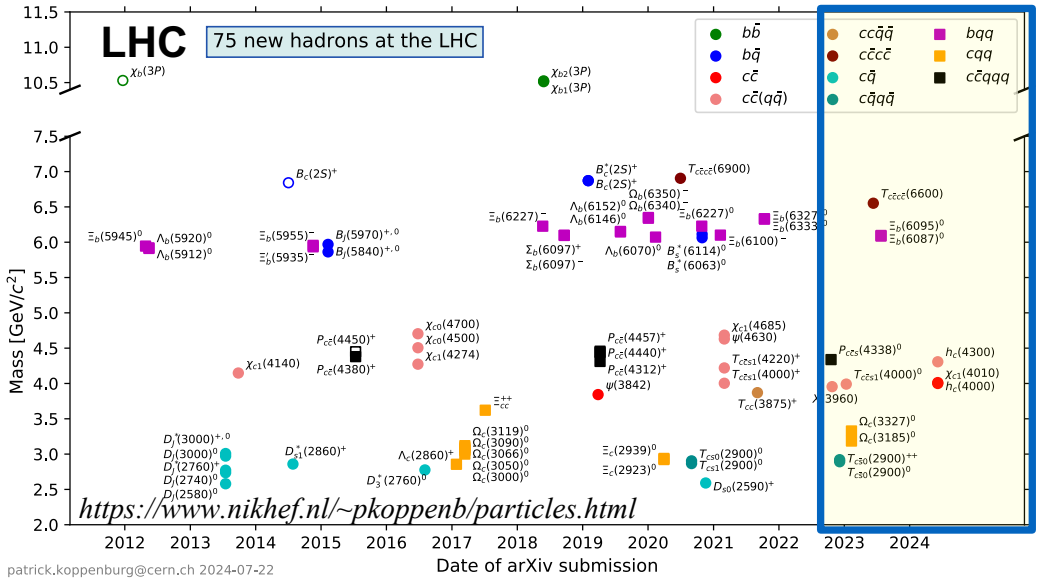
- Fixed-target experiments



Discoveries of many new hadrons



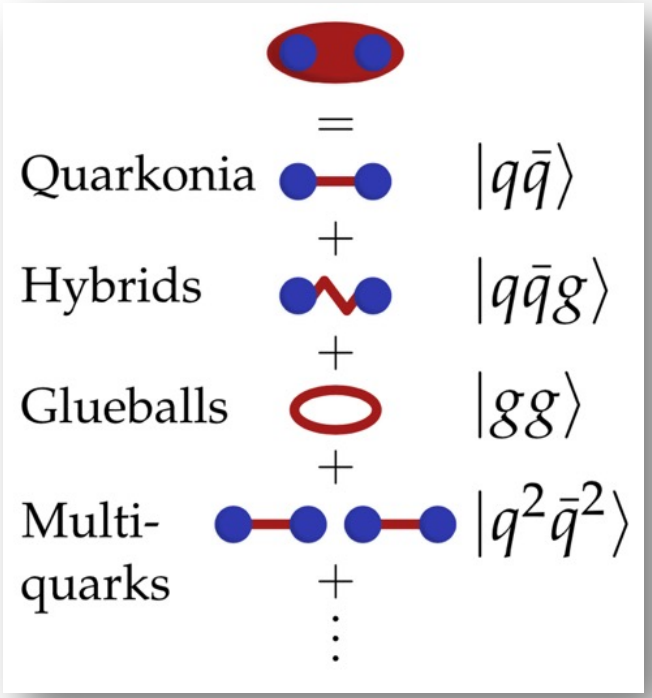




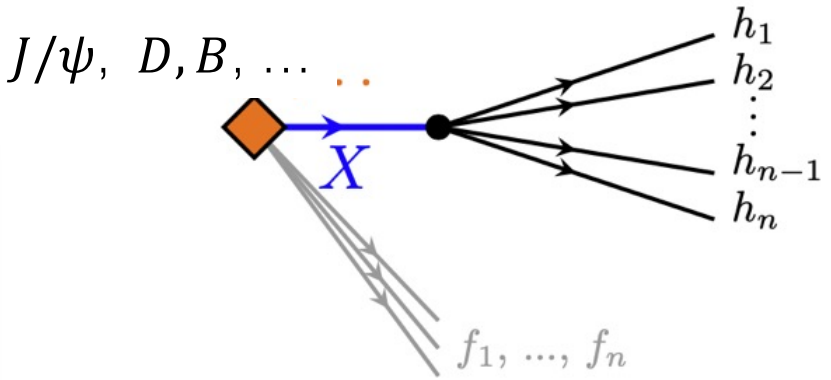
more than 20 new hadrons since the ICHEP2022

Light hadrons

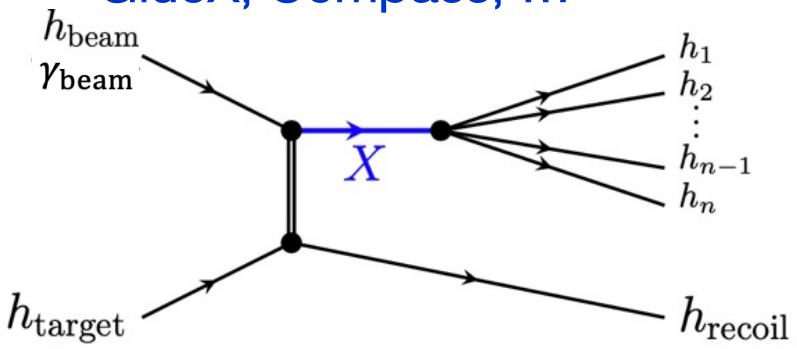
Light hadron spectroscopy



BESIII, LHCb, Belle (II) …



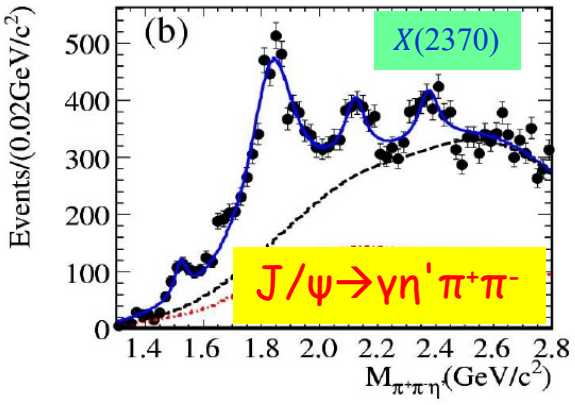
GlueX, Compass, …



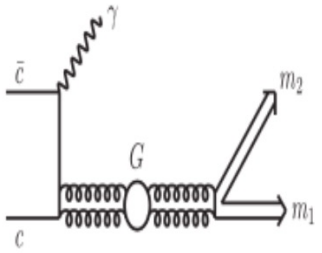
A glueball-like state X(2370)

PRL 132.181901 (2024)

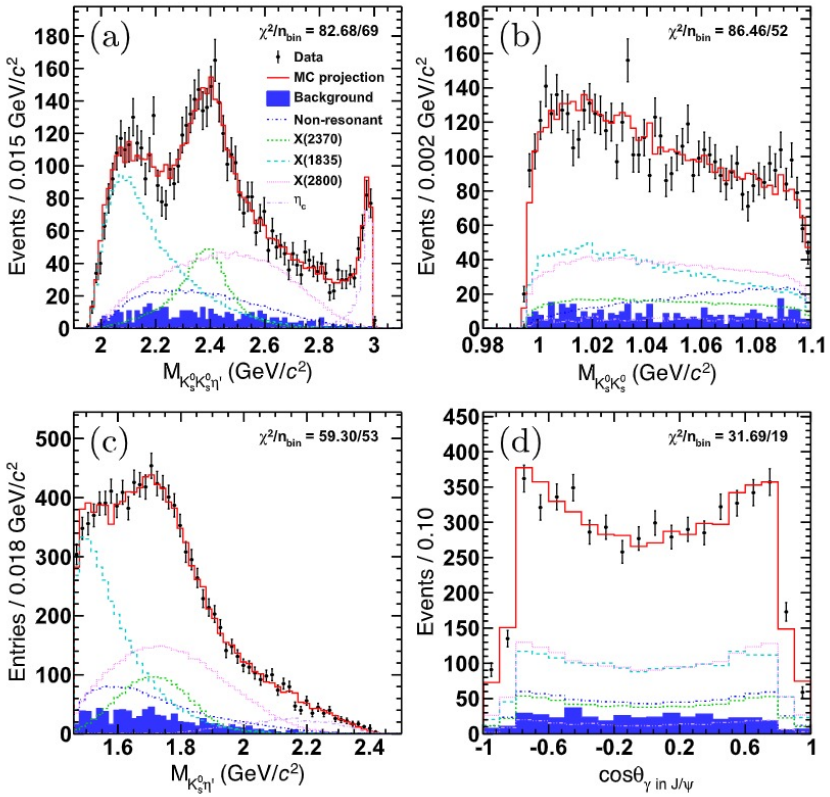
$X(2370)$ firstly seen in $J/\psi \to \gamma\pi^+\pi^-\eta'$



J/ψ radiative decays are gluon-rich processes

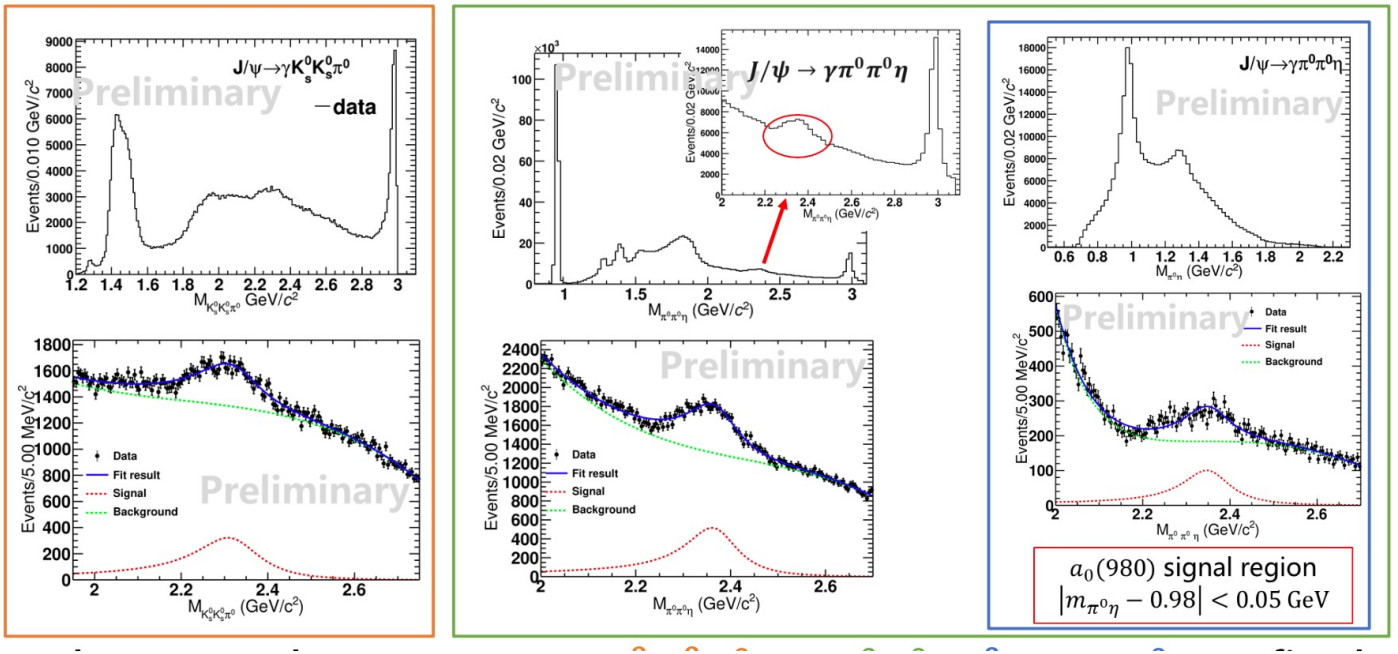


- Partial wave analysis $J/\psi \to \gamma K_S K_S \eta'$ in 10B J/ψ decays
- X(2370) $\to K_S K_S \eta'$ significance larger than 14 σ
- mass $2395 \pm 11^{+26}_{-94}$ MeV/c^2
- width $188^{+18}_{-17}{}^{+124}_{-33}$ MeV
- spin-parity is determined to be 0^{-+}
- candidate for lightest pseudoscalar glueball predicted by LQCD



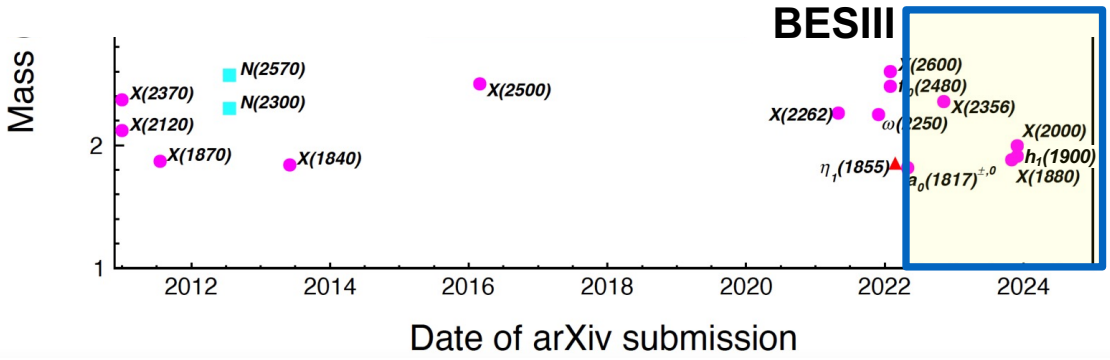
Observation of new decay modes of X(2370)

- More J/ψ radiative decays to X(2370) are investigated



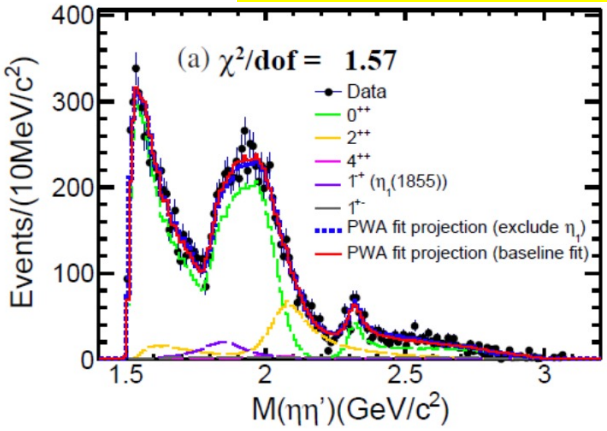
- **X(2370) observed in the gluon-rich J/ψ radiative decays**
  - **J^{PC} determined to be 0^{-+}**
  - **Mass and production rate consistent with LQCD**
  - **Decay modes X(2370) → $\eta'\pi\pi, \eta'KK, K_S^0K_S^0\eta, K_S^0K_S^0\pi^0, \eta\pi^0\pi^0$, $a_0^0(980)\pi^0$ observed, in analog to η_c**

Consistent with 0^{-+} glueball



Observation of $\eta_1(1855)(1^{-+})$ with exotic quantum number

PRL129, 192002 (2022)
PRD106, 072012 (2022)

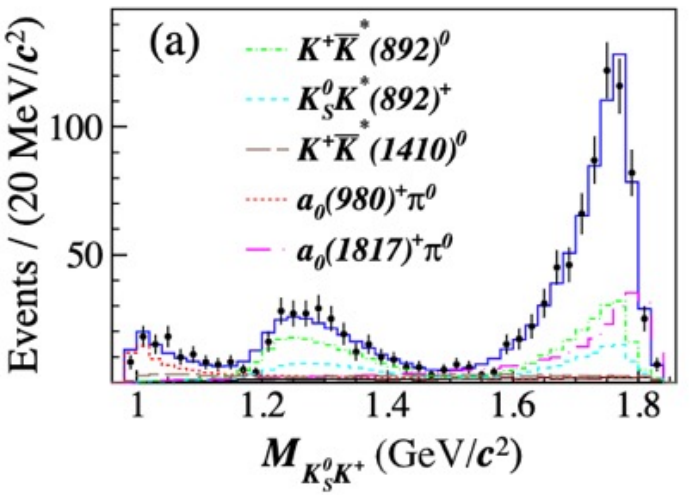


PWA of $J/\psi \to \gamma\eta\eta'$ in 10B J/ψ events

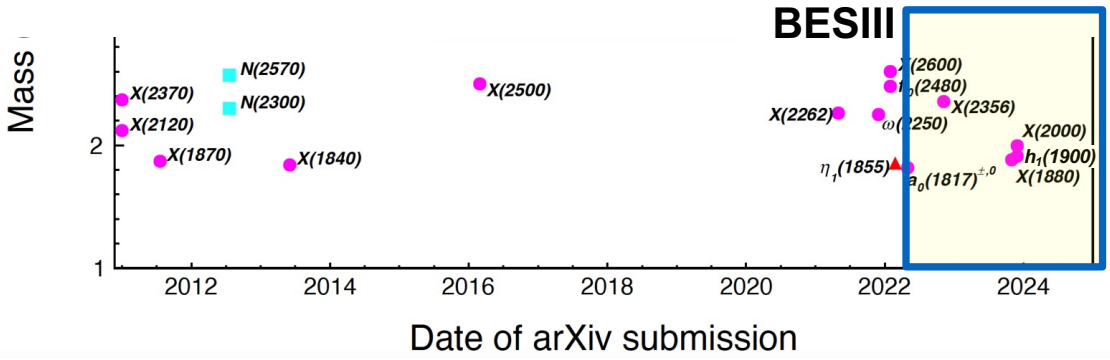
Must be exotic state!
Hybrid? Molecule? Tetraquark?

Observation of $a_0(1817)^+$ in $D_s^+ \to K_S K^+ \pi^0$

PRL129, 182001 (2022)

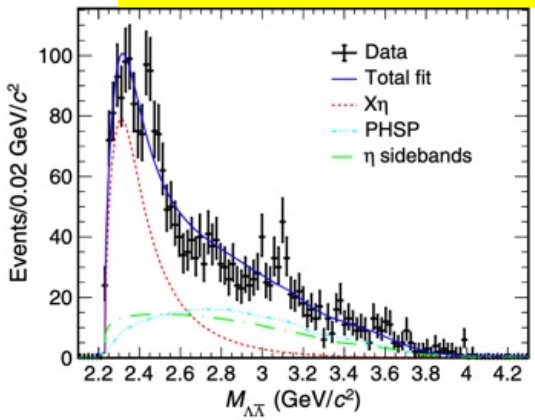


A new a_0 isospin triplet!



Observation of $X(2356) \to \Lambda\bar{\Lambda}$ in $e^+e^- \to \eta\Lambda\bar{\Lambda}$

PRD 107, 112001 (2023)

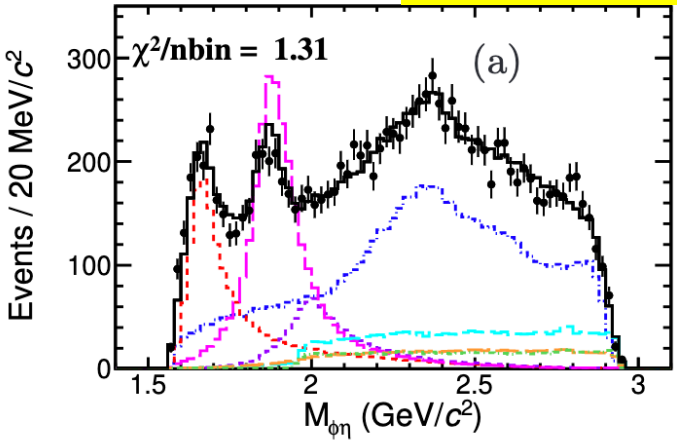


- Clear enhancement is seen near the $\Lambda\bar{\Lambda}$ mass threshold combining 31 datasets
- Simultaneous 1D fit to the $\Lambda\bar{\Lambda}$ mass spectra assuming a 1^{--} state:
  mass: $2536 \pm 7 \pm 15$ MeV/c^2
  width: $304 \pm 28 \pm 54$ MeV

hexaquark? baryonium?

New strangeonium in $J/\psi \to \phi\eta\pi^0$

arXiv:2311.0704



PWA fit to the isospin violating process $J/\psi \to \phi\eta\pi^0$ in 10B J/ψ events

Observations:

- $h_1(1900)(\mathbf{1^{+-}})$:
  $h_1(2P)$ strangeonium state?
- X(2000) $(\mathbf{1^{--}})$:
  $\phi(3S)$ or $\phi(3D)$ strangeonium state?

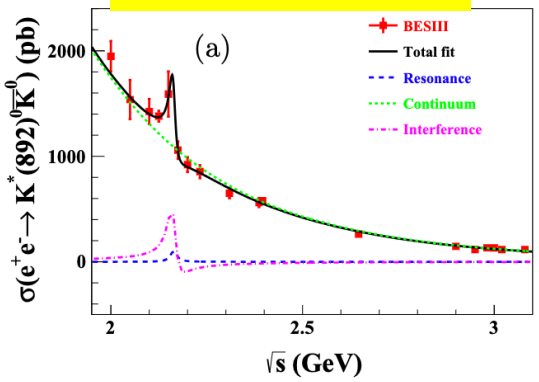
Rediscovery of Y(2175)/ϕ(2170)

- A strangeonium(-like) state: *Y*-particle with strange quark

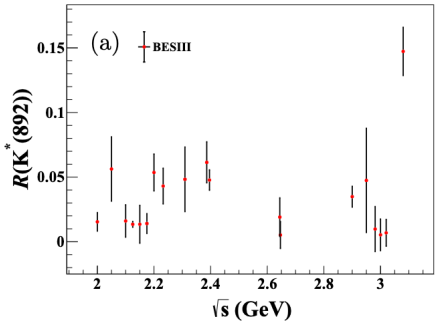
➢ **Theorists explain ϕ(2170) as**
- ✓ $s\bar{s}g$ hybrid
- ✓ 2^3D_1 or 3^3S_1 $s\bar{s}$
- ✓ tetraquark
- ✓ Molecular state $\Lambda\bar{\Lambda}$
- ✓ $\phi f_0(980)$ resonance with FSI
- ✓ Three body system ϕKK

$e^+e^- \to K^*(892)^0\bar{K}^0$

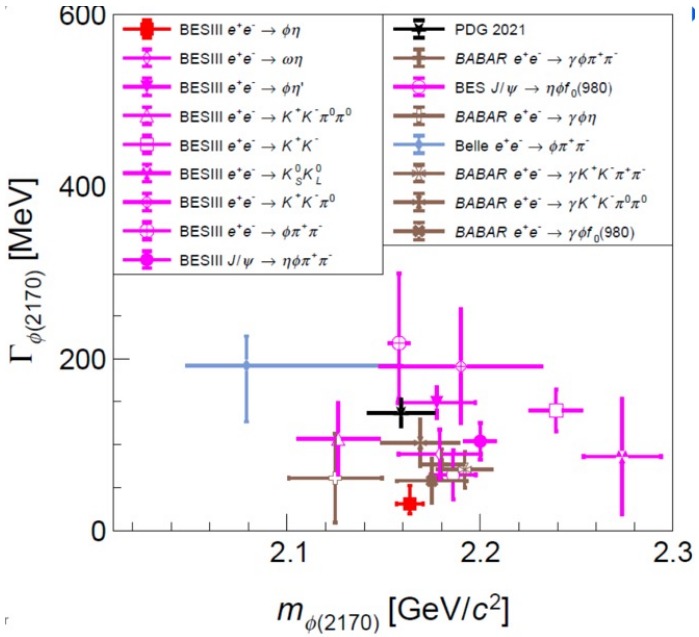
JHEP 01, 180(2024)



$$R(K^*(892)) = \frac{\sigma(e^+e^- \to K^*(892)^+K^-)}{\sigma(e^+e^- \to K^*(892)^0\bar{K}^0)}$$

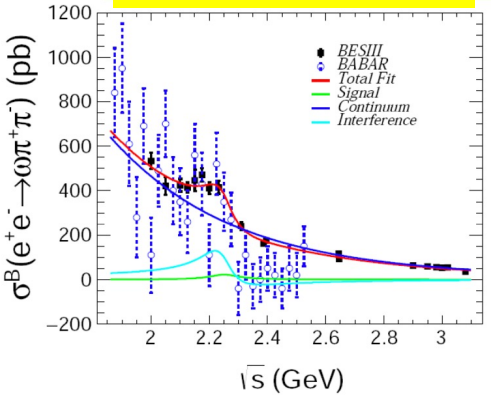


R<0.2: much less than 1?



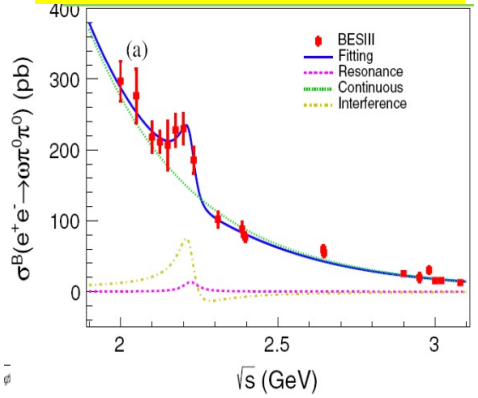
$e^+e^- \to \omega\pi^+\pi^-$

JHEP 01, 111 (2023)

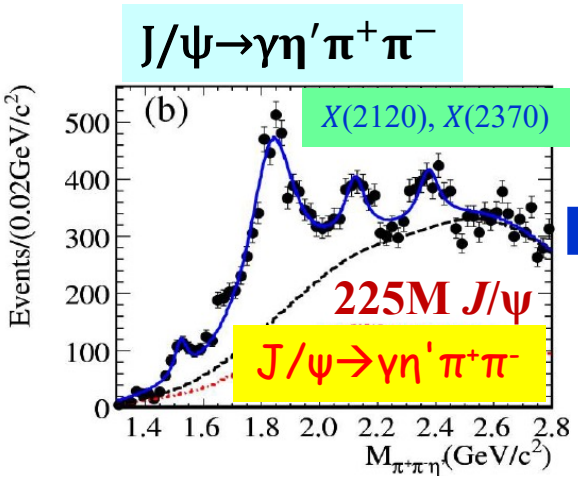


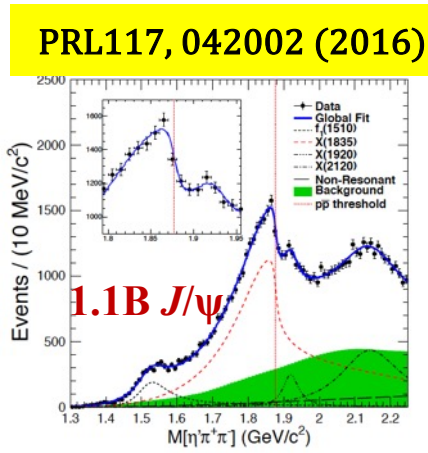
$e^+e^- \to \omega\pi^0\pi^0$

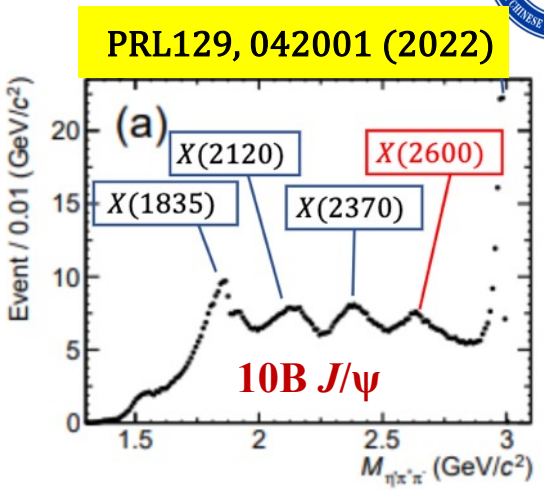
PRD105, 032005 (2022)

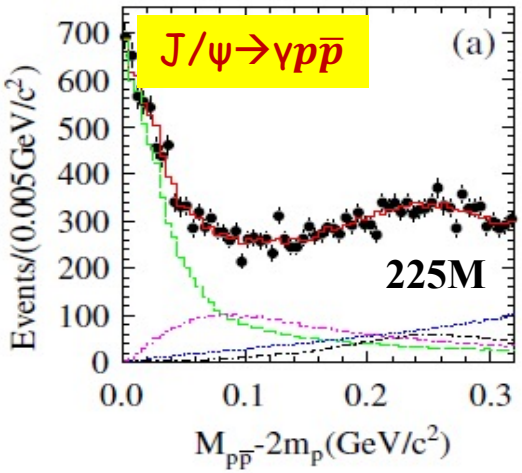


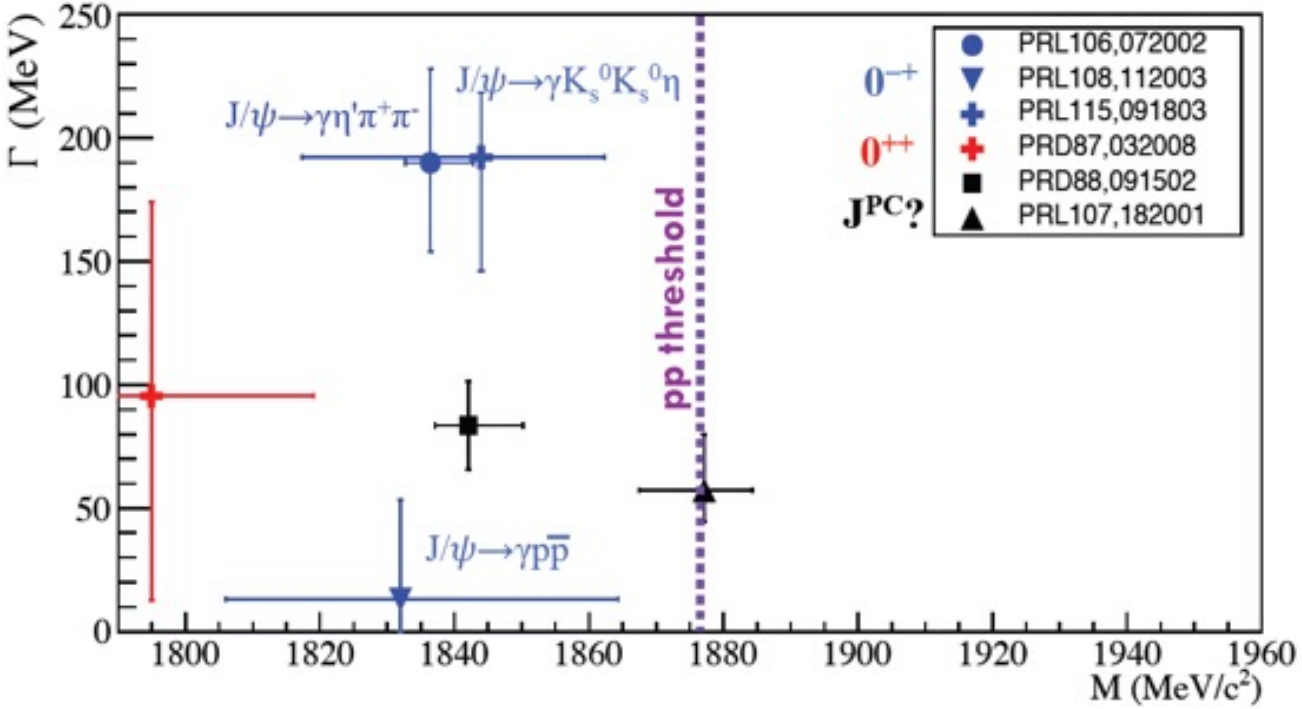
X($p\bar{p}$)/X(18??) from J/ψ radiative decays











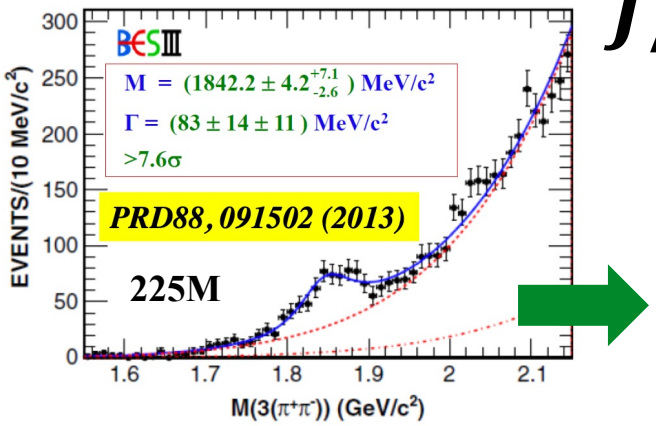
Are they the same state? It is crucial to understand their connections.

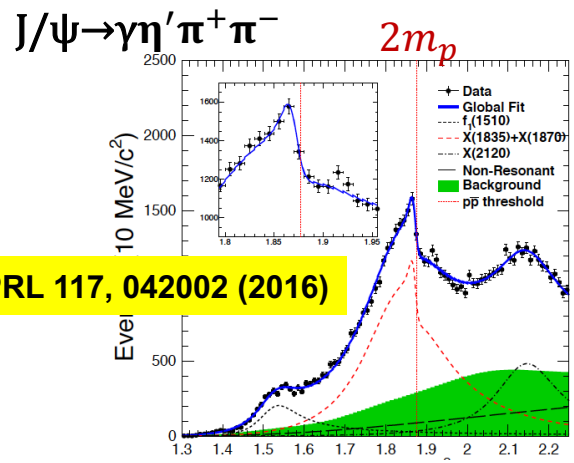
Anomolous lineshape of X(1840) in $J/\psi \to \gamma 3(\pi^+\pi^-)$

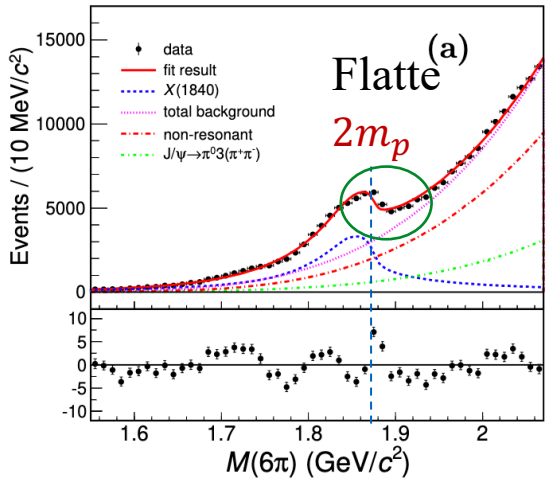
PRL132, 151901 (2024)

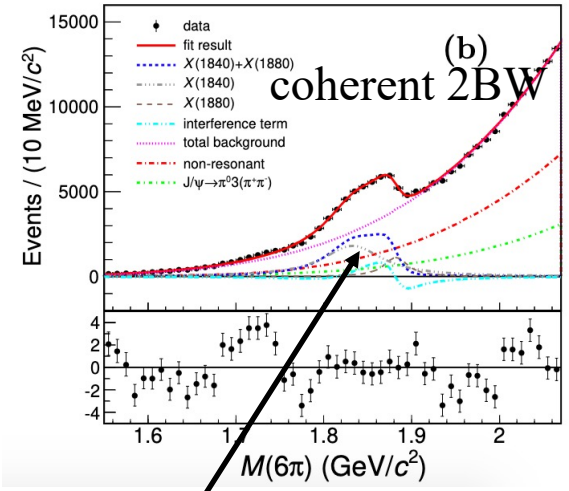
10B J/ψ events are analyzed:

50x more than the previous BESIII work







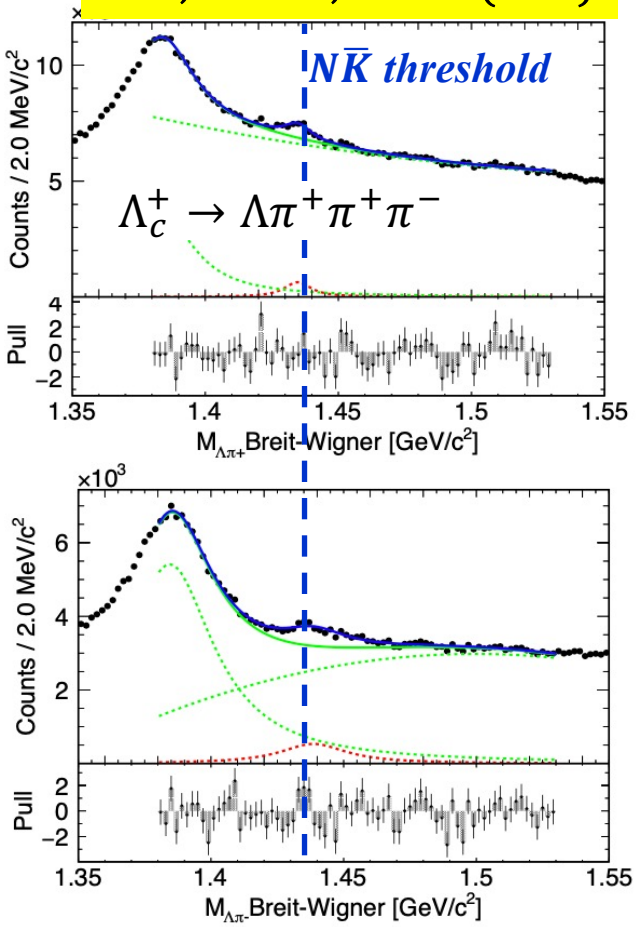


$X(1835)$	
Mass (MeV/c^2)	$1825.3 \pm 2.4^{+17.3}_{-2.4}$
Width (MeV/c^2)	$245.2 \pm 13.1^{+4.6}_{-9.6}$
$X(1870)$	
Mass (MeV/c^2)	$1870.2 \pm 2.2^{+2.3}_{-0.7}$
Width (MeV/c^2)	$13.0 \pm 6.1^{+2.1}_{-3.8}$

Parameters	Solution I	Solution II
$M_{X(1840)}$ (MeV/c^2)	$1832.5 \pm 3.1 \pm 2.5$	
$\Gamma_{X(1840)}$(MeV)	$80.7 \pm 5.2 \pm 7.7$	
$\mathcal{B}_{X(1840)}(\times 10^{-5})$	$1.19 \pm 0.30 \pm 0.15$	$2.07 \pm 0.50 \pm 0.36$
$M_{X(1880)}$ (MeV/c^2)	$1882.1 \pm 1.7 \pm 0.7$	
$\Gamma_{X(1880)}$(MeV)	$30.7 \pm 5.5 \pm 2.4$	
$\mathcal{B}_{X(1880)}(\times 10^{-5})$	$0.29 \pm 0.20 \pm 0.09$	$1.19 \pm 0.31 \pm 0.18$

Hyperons from charmed baryon decays

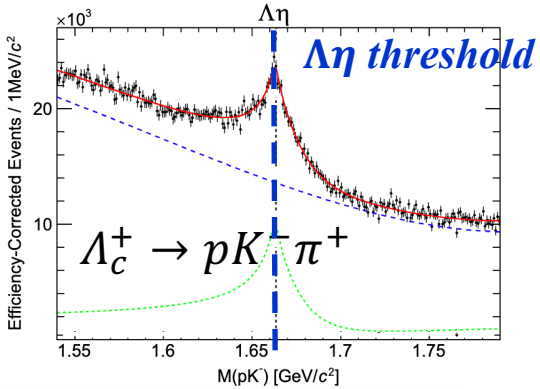
Belle, PRL 130, 151903 (2023)



Enhancement around 1.43 GeV

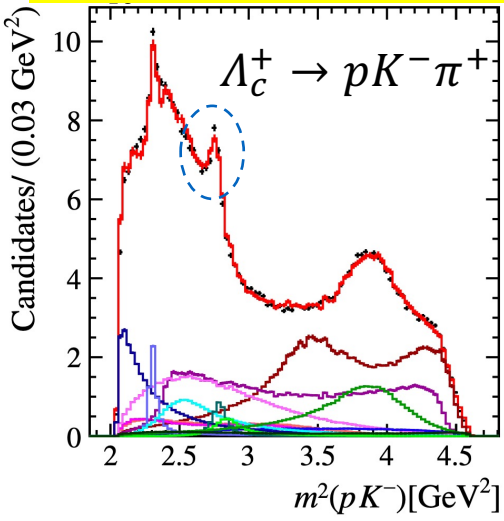
$\Sigma(1430)$ or $N\bar{K}$ threshold cusp?

BELLE, PRD108, L031104 (2023)

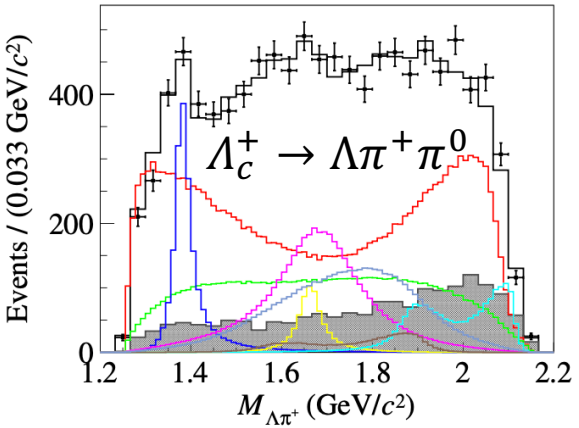


$\Lambda\eta$ threshold cusp enhanced due to $\Lambda(1670)$

LHCb, PRD108, 012023 (2023)

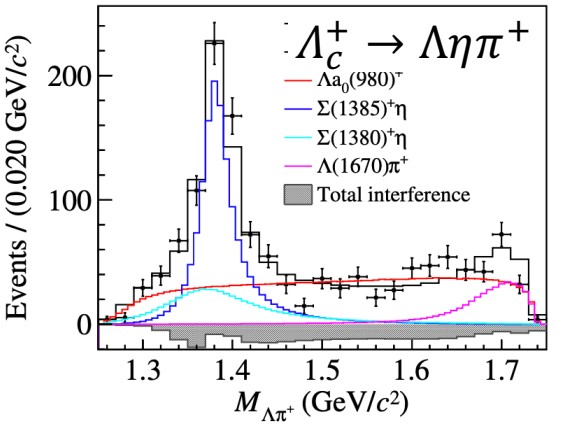


BESIII, JHEP12(2022)033



Many Σ^* contributions

BESIII, arXiv:2407.12270

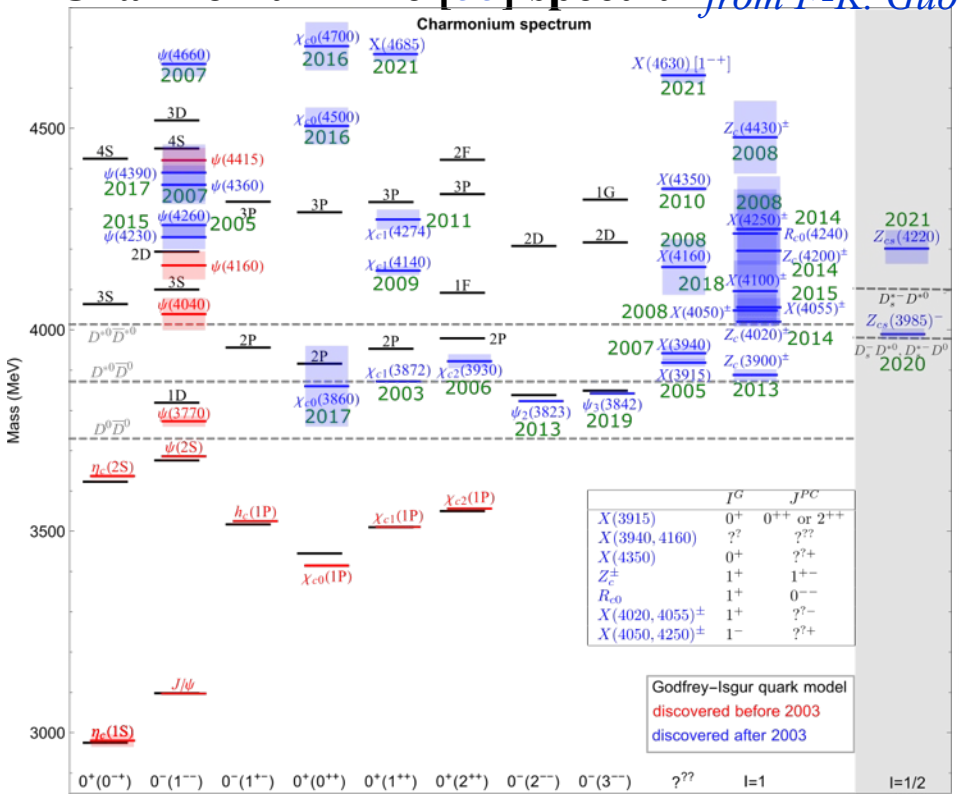


Evidence for $\Sigma(1380)^+$

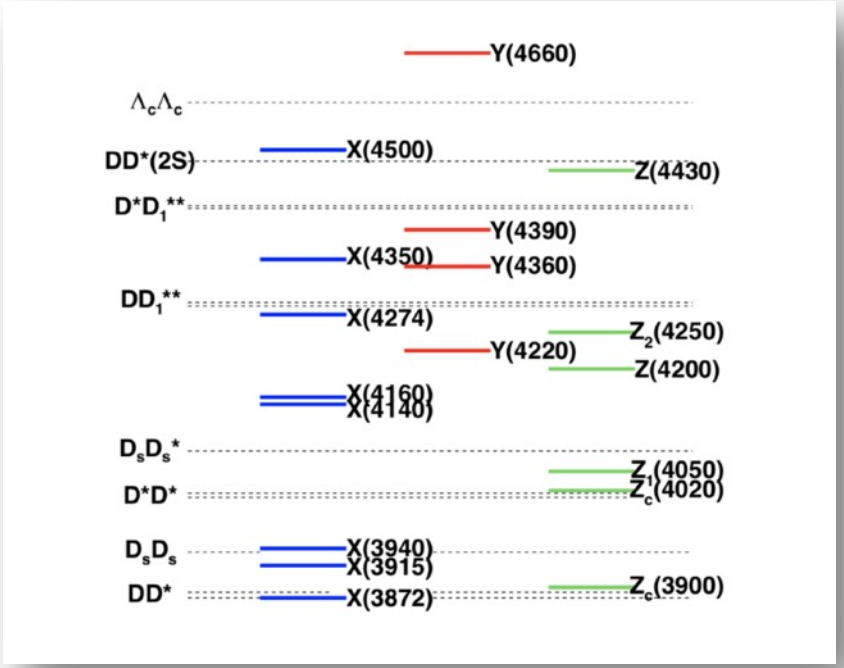
Heavy mesons

Overpopulated charmonium spectrum

Charmonium-like [$c\bar{c}$] spectrum *from F-K. Guo*



arXiv:1511.01589, arXiv:1812.10947



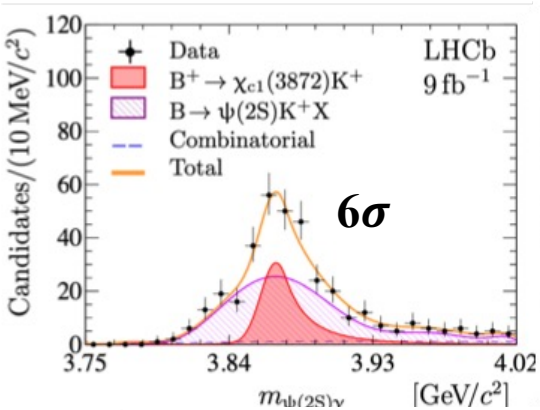
Overpopulated observed new charmonium-like states, i.e. "XYZ":

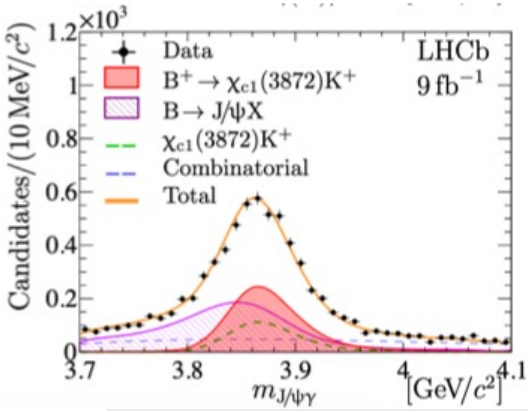
- Most of them are close to the mass thresholds of charmed meson pairs
- Some are not accommodated as conventional meson
  ==> candidate of exotic hadron states
- More efforts are needed to pin down their nature

Observation of $\chi_{c1}(3872) \to \gamma\psi(2S)$

arXiv:2406.17006

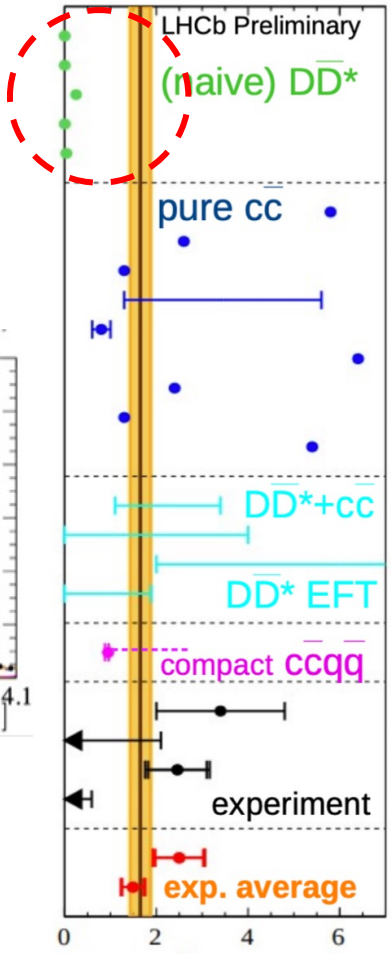
- $\chi_{c1}(3872)$ nature is still uncertain, although many studies are performed since 2003
- What is it? $\chi_{c1}(2P)$? **loosely $D^0\bar{D}^{0*}$ bound state? or their mixture?**
- Radiative decays provide crucial discrimination on its nature





$$\mathcal{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}}$$

$$= 1.67 \pm 0.21 \pm 0.12 \pm 0.04$$



E. S. Swanson
Y. Dong *et al.*
D. P. Rathaud and A. K. Rai
R. F. Lebed and S. R. Martinez
B. Grinstein, L. Maiani and A. D. Polosa

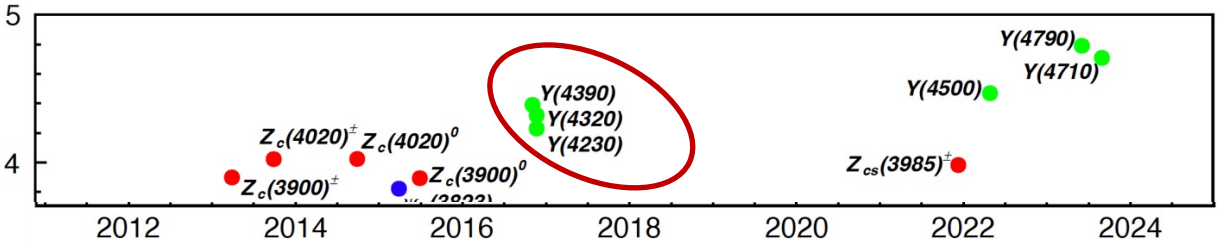
T. Barnes and S. Godfrey
T. Barnes, S. Godfrey and S. Swanson
B.-Q. Li and K. T. Chao
Y. Dong *et al.*
A. M. Badalian *et al.*
J. Ferretti, G. Galata and E. Santopinto
A. M. Badalian, Yu. A. Simonov and B. L. G. Bakker
W. J. Deng *et al.*
F. Giacosa, M. Piotrowska and S. Goito

S. Takeuchi, M. Takizawa and K. Shimizu
E. Cincioglu *et al.*
D. A.-S. Molnar, R. F. Luiz and R. Higa
F.-K. Guo *et al.*

B. Grinstein, L. Maiani and A. D. Polosa

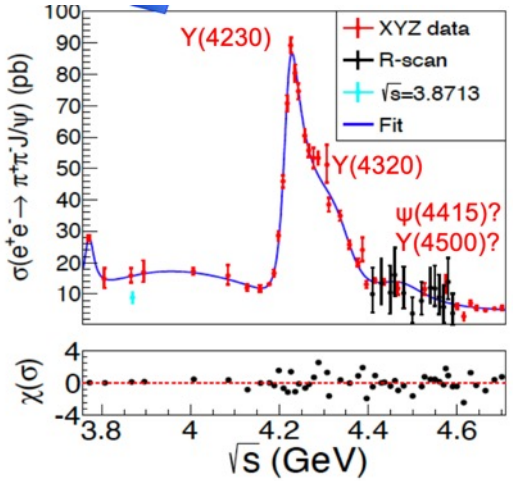
BaBar	2008
Belle	2011
LHCb/Run 1	2014
BESIII	2020
LHCb/Run 1	2024
LHCb/Run 2	2024

Strong indication of a sizeable charmonium or tetraquark compact component of the $\chi_{c1}(3872)$!



PRD106, 072001 (2022)

Date of arXiv submission



Y(4260) ➔ Y(4230) & Y(4320)

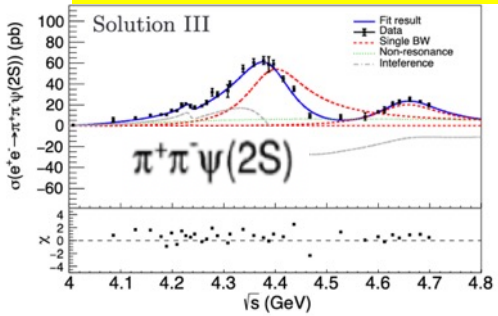
$M_{Y(4230)} = 4221.4 \pm 1.5 \pm 2.0$ MeV/c^2

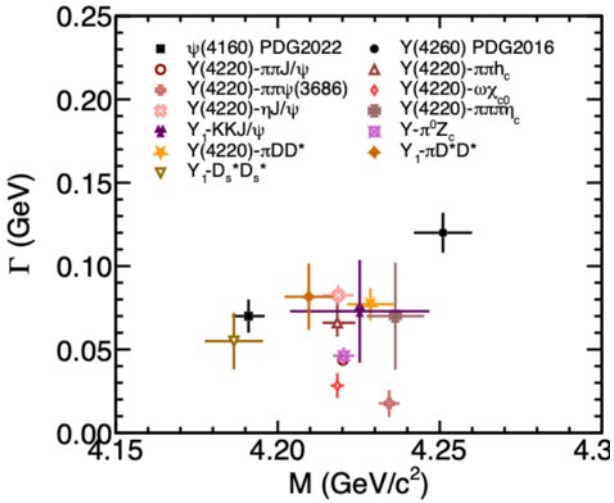
$\Gamma_{Y(4230)} = 41.8 \pm 2.9 \pm 2.7$MeV

$M_{Y(4320)} = 4298 \pm 12 \pm 26$ MeV/c^2

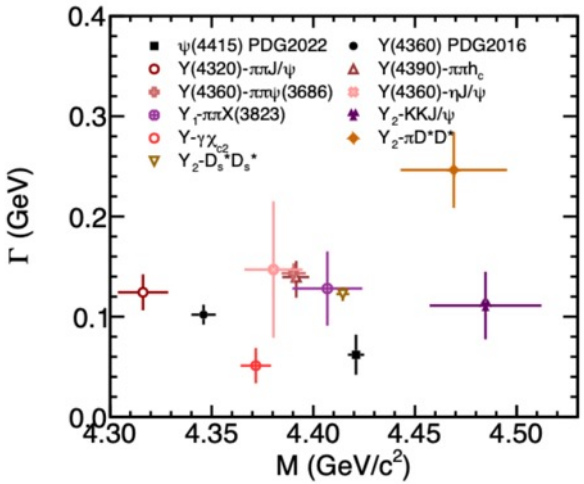
$\Gamma_{Y(4320)} = 127 \pm 17 \pm 10$ MeV

PRD 104, 052012 (2021)

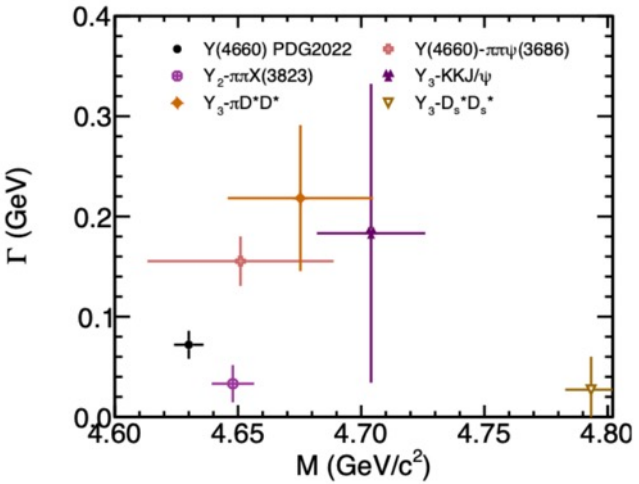




Y(42XX)



Y(43XX), $\psi(4415)$, Y(4500)

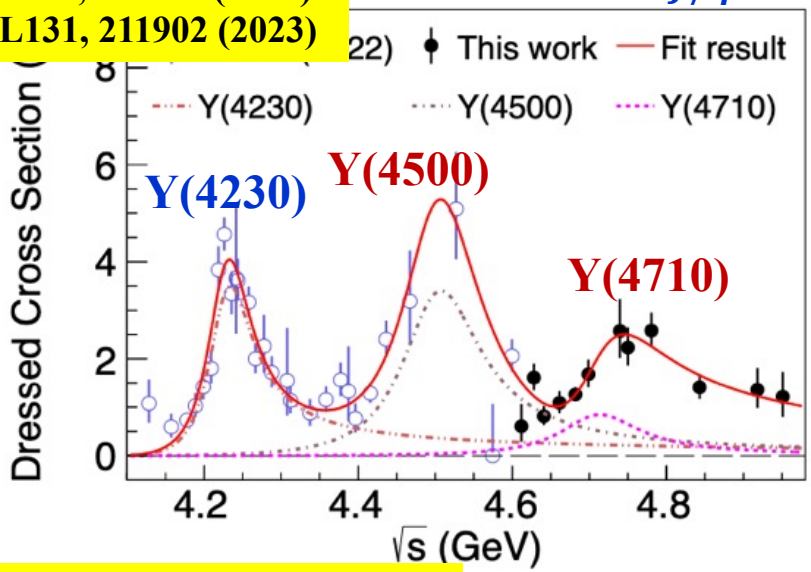


Y(46XX), Y(47XX)

Observations of three heavy Y(4500), Y(4710) and Y(4790) states

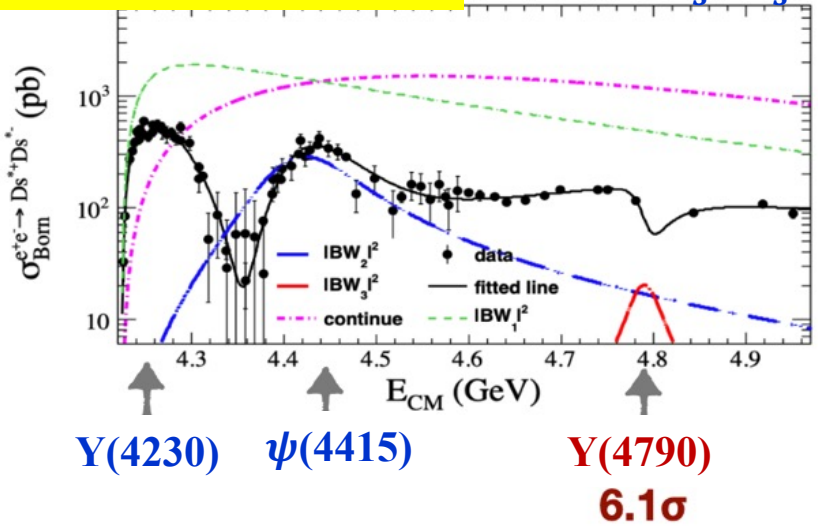
CPC 46, 111002 (2022)
PRL131, 211902 (2023)

$e^+e^- \to K^+K^-J/\psi$



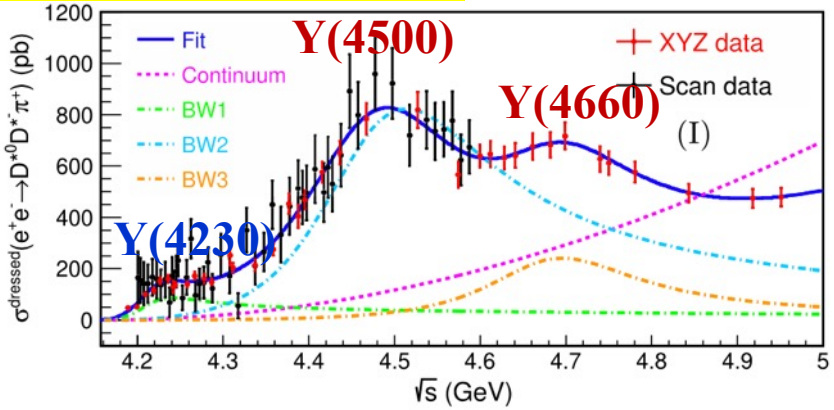
PRL131, 151903 (2023)

$e^+e^- \to D_s^{*+}D_s^{*-}$



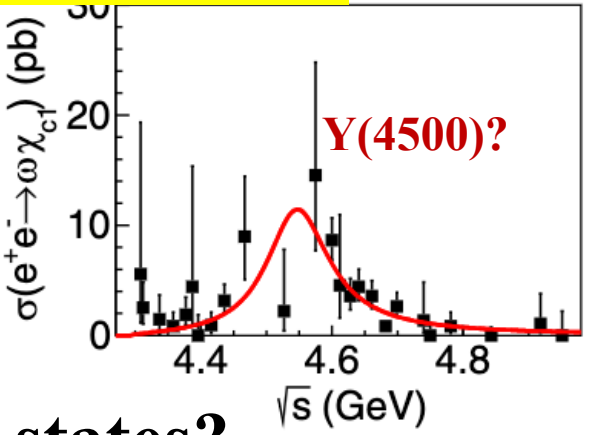
PRL130, 121901 (2023)

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



PRL 132, 161901 (2024)

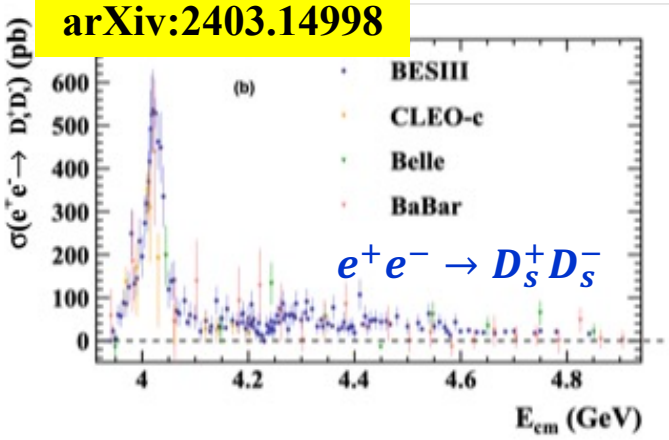
$e^+e^- \to \omega\chi_{c1}$



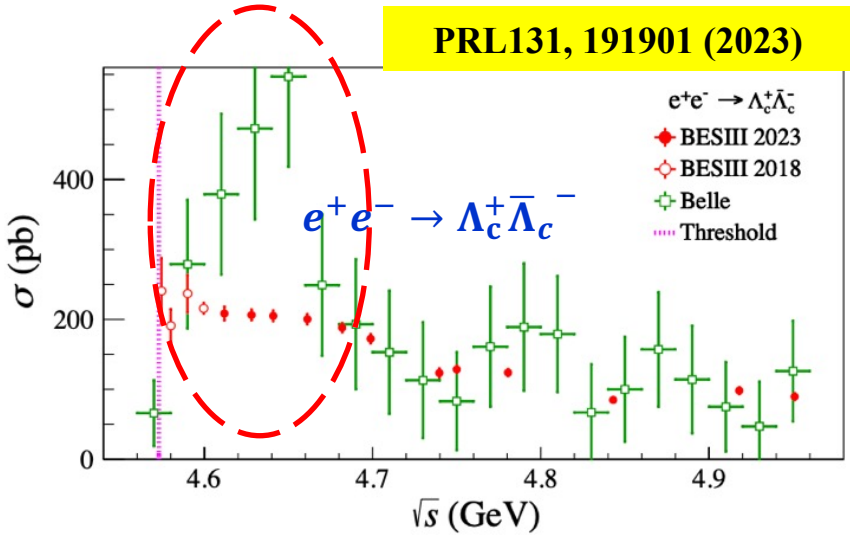
Are they $[c\bar{c}s\bar{s}]$ states?

Cross sections of charmed hadron pairs

arXiv:2403.14998

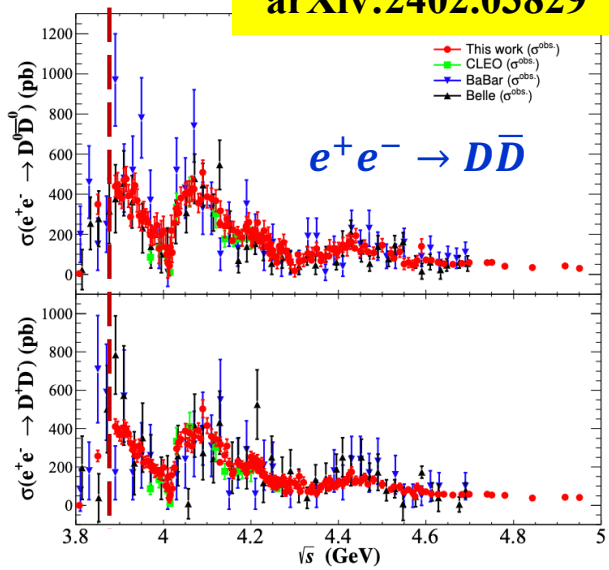


PRL131, 191901 (2023)



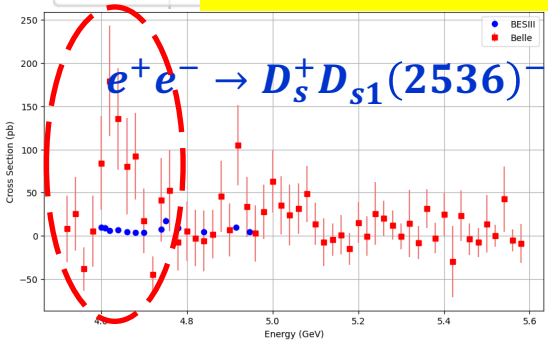
$D^*\bar{D}$

arXiv:2402.03829



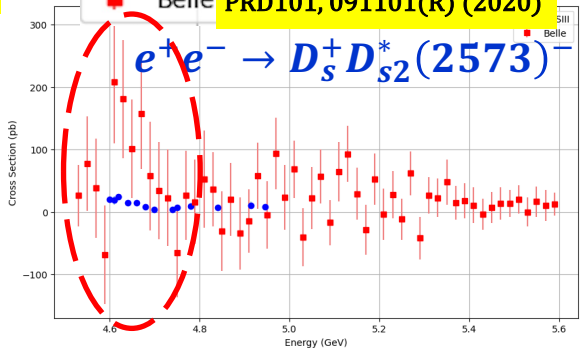
BESIII arXiv: 2407.07651

Belle PRD 100, 111103(R) (2019)



BESII arXiv: 2407.07651

Belle PRD101, 091101(R) (2020)



Rich ψ/Y resonances in the final states of the charmed hadron pairs.

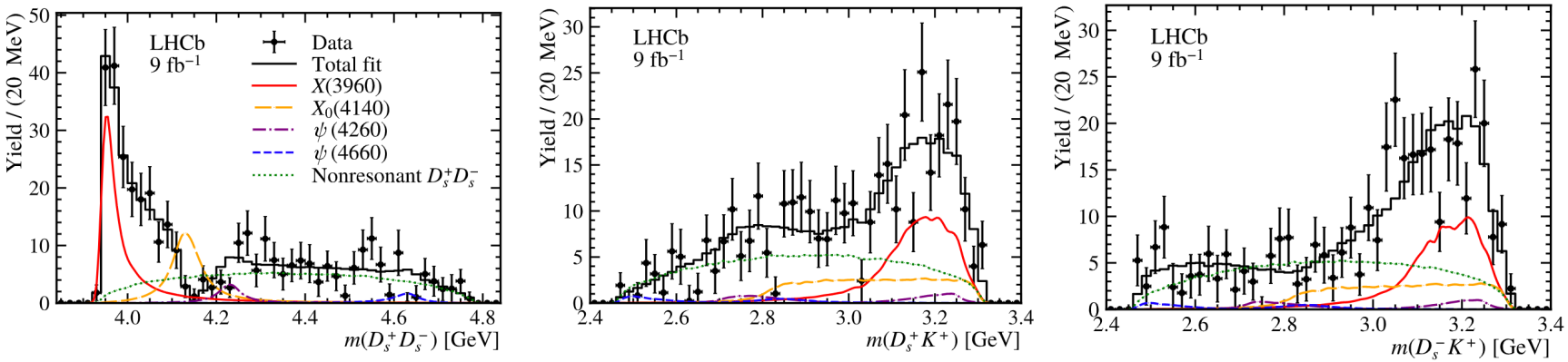
- **Mind**: Tension of cross sections near threshold between direct (BESIII) and ISR(Belle) methods
- BESIII negates the $Y(4630)$ reported by Belle

New $X(3960)[c\bar{c}s\bar{s}]$ state in $D_s^+ D_s^-$

PRD 108, 034012 (2023)
PRL131, 071901 (2023)

Amplitude analysis of $B^+ \to D_s^+ D_s^- K^+$ based on LHCb RUN1+2 data

- Near threshold structure $X(3960)$: $\mathbf{12\sigma}$, $J^{PC} = 0^{++}$
- $X_0(4140)$ accounts for the dip around 4.14 GeV



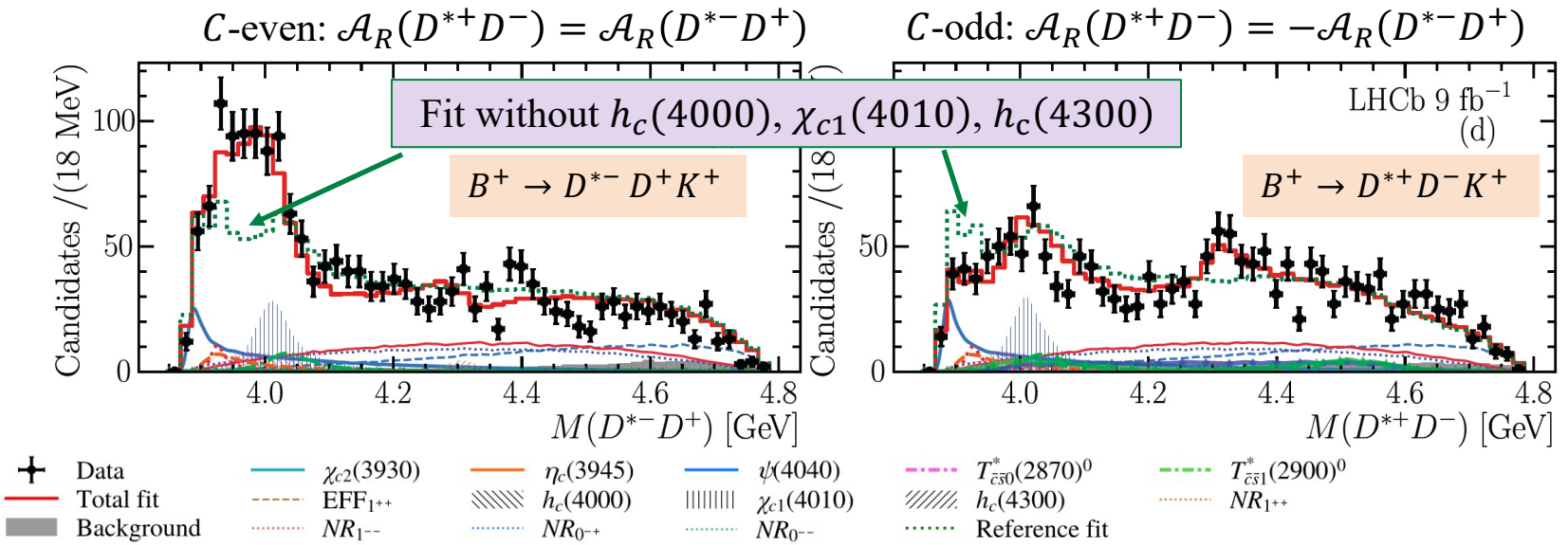
Components	J^{PC}	Mass (MeV)	Width (MeV)	Fit fraction (%)	Significance (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 10$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 5.0$	12.6 (14.6)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 6$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 3.9$	3.8 (4.1)
$\psi(4260)$	1^{--}	4230 (fixed)	55 (fixed)	$3.6 \pm 0.4 \pm 3.2$	3.2 (3.6)
$\psi(4660)$	1^{--}	4633 (fixed)	64 (fixed)	$2.2 \pm 0.2 \pm 0.8$	3.0 (3.2)
NR	S-wave	–	–	$46.1 \pm 13.2 \pm 11.3$	3.1 (3.4)

dip at 4.14 GeV via interference

Three new charmonium(-like) states in $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

arXiv:2406.03156

- **Simultaneous fit to $B^+ \to D^{*+} D^- K^+$ and $D^{*-} D^+ K^+$ to relate the C-parities of the charmonium(-like) states $R \to D^{*+} D^-$ and $R \to D^{*-} D^+$:**



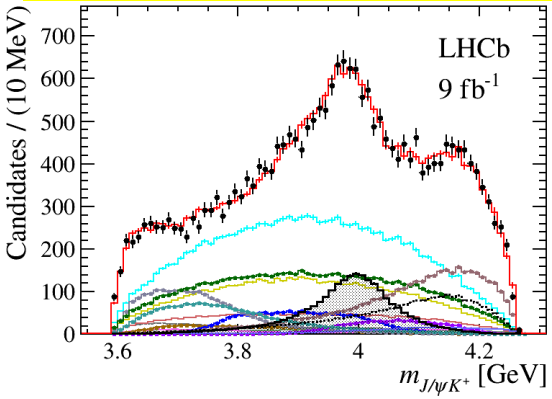
This work		Known states [6]		$c\bar{c}$ prediction [34]	
$\eta_c(3945)$	$J^{PC} = 0^{-+}$	$X(3940)$ [9,10]	$J^{PC} = ?^{??}$	$\eta_c(3S)$	$J^{PC} = 0^{-+}$
$m_0 = 3945\,^{+28}_{-17}\,^{+37}_{-28}$	$\Gamma_0 = 130\,^{+92}_{-49}\,^{+101}_{-70}$	$m_0 = 3942 \pm 9$	$\Gamma_0 = 37\,^{+27}_{-17}$	$m_0 = 4064$	$\Gamma_0 = 80$
~~$h_c(4000)$~~	$J^{PC} = 1^{+-}$	$T_{c\bar{c}}(4020)^0$ [35]	$J^{PC} = ?^{?-}$	$h_c(2P)$	$J^{PC} = 1^{+-}$
$m_0 = 4000\,^{+17}_{-14}\,^{+29}_{-22}$	$\Gamma_0 = 184\,^{+71}_{-45}\,^{+97}_{-61}$	$m_0 = 4025.5\,^{+2.0}_{-4.7} \pm 3.1$	$\Gamma_0 = 23.0 \pm 6.0 \pm 1.0$	$m_0 = 3956$	$\Gamma_0 = 87$
~~$\chi_{c1}(4010)$~~	$J^{PC} = 1^{++}$			$\chi_{c1}(2P)$	$J^{PC} = 1^{++}$
$m_0 = 4012.5\,^{+3.6}_{-3.9}\,^{+4.1}_{-3.7}$	$\Gamma_0 = 62.7\,^{+7.0}_{-6.4}\,^{+6.4}_{-6.6}$			$m_0 = 3953$	$\Gamma_0 = 165$
~~$h_c(4300)$~~	$J^{PC} = 1^{+-}$			$h_c(3P)$	$J^{PC} = 1^{+-}$
$m_0 = 4307.3\,^{+6.4}_{-6.6}\,^{+3.3}_{-4.1}$	$\Gamma_0 = 58\,^{+28}_{-16}\,^{+28}_{-25}$			$m_0 = 4318$	$\Gamma_0 = 75$
		$\chi_c(4274)$ [36]	$J^{PC} = 1^{++}$	$\chi_{c1}(3P)$	$J^{PC} = 1^{++}$
		$m_0 = 4294 \pm 4\,^{+6}_{-3}$	$\Gamma_0 = 53 \pm 5 \pm 5$	$m_0 = 4317$	$\Gamma_0 = 39$

- different $D^{*\pm} D^{\mp}$ mass distributions due to interference of two C-parities
- At least three charmonium(-like) states are observed for the first time, which are candidates for $h_c(2P)$, $\chi_{c1}(2P)$ and $h_c(3P)$

Zcs $[c\bar{c}u\bar{s}]$ states

- Charged Zcs states are observed at BESIII and LHCb: $Z_{cs}(3985)$, $Z_{cs}(4000)$, $Z_{cs}(4220)$
- It is natural to search for the neutral isospin partners

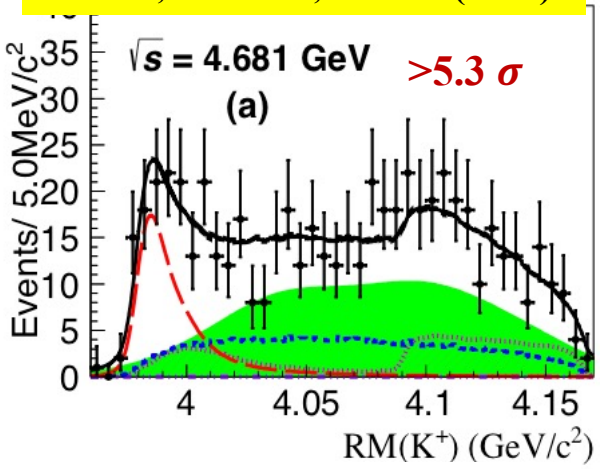
LHCb, PRL127, 082001 (2021)



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)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

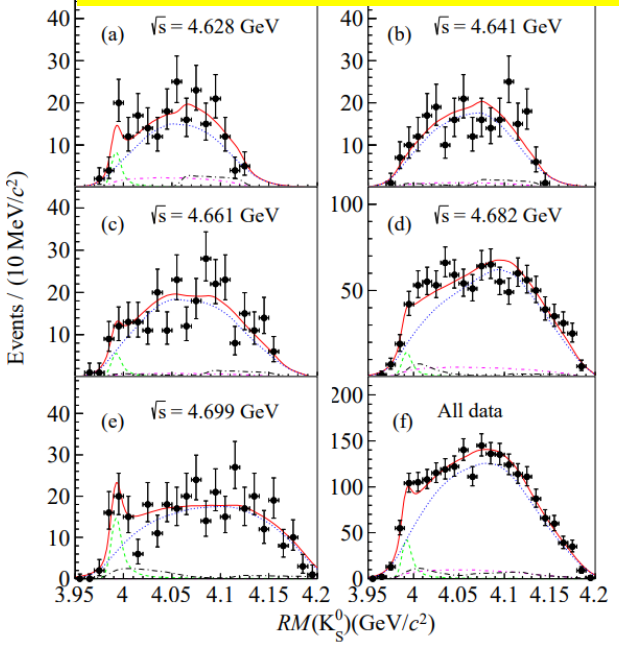
	Mass (MeV/c^2)	Width (MeV)
$Z_{cs}(3985)^0$	$3992.2 \pm 1.7 \pm 1.6$	$7.7^{+4.1}_{-3.8} \pm 4.3$
$Z_{cs}(3985)^+$	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$

BESIII, PRL 126, 102001 (2021)



$e^+e^- \to K_S^0(D_s^- D^{*+} + D_s^{*-} D^+)$

BESIII, PRL 129 , 112003 (2022)

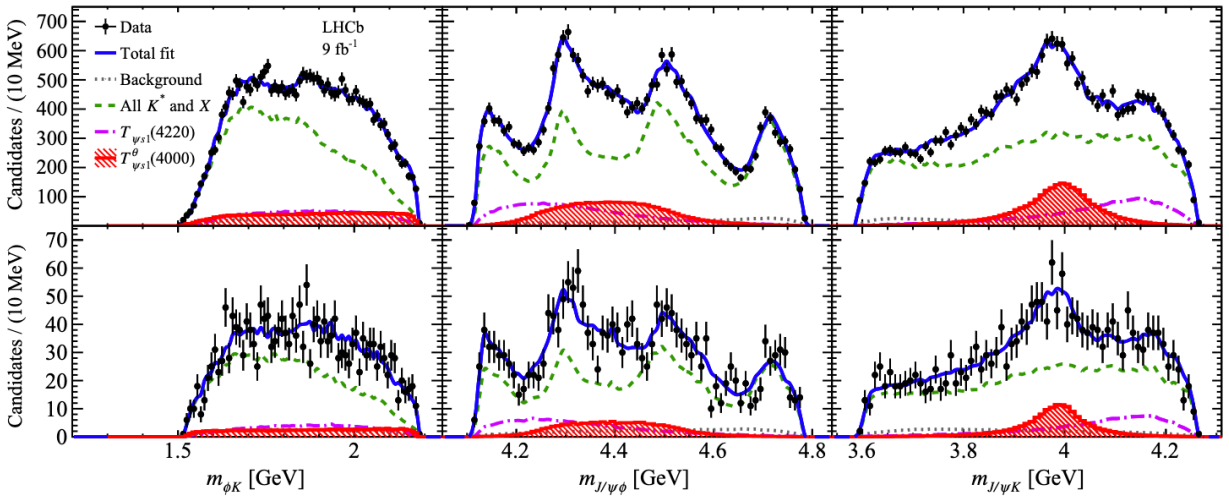


$Z_{cs}^0/T_{c\bar{c}\bar{s}1}(4000)^0$ in $B^0 \to J/\psi\phi K_S^0$

PRL131, 131901(2023)

$B^+ \to J/\psi\phi K^+$

$B^0 \to J/\psi\phi K_S$



- **Simultaneous fits to $B^0 \to J/\psi\phi K_S$ and $B^+ \to J/\psi\phi K^+$,** assuming isospin symmetry for all the intermediate states, except for the charged and neutral $T_{c\bar{c}\bar{s}1}(4000)$ states.
- Consistent with being isospin partners: $\Delta m = -12^{+11+6}_{-10-4}$ MeV/c^2
- Significance is. 4.0σ without isospin symmetry for $T_{c\bar{c}\bar{s}1}(4000)^0$, while 5.4$\sigma$ with isospin symmetry constrains

	J^P	Mass (MeV/c^2)	Width (MeV)	Fit fraction
$T_{c\bar{c}\bar{s}1}(4000)^0 \to J/\psi K_S^0$	1^+	3991^{+12+9}_{-10-17}	105^{+29+17}_{-25-23}	$7.9 \pm 2.5^{+3.0}_{-2.8}$
$Z_{cs}^+ /T_{c\bar{c}\bar{s}1}(4000)^+ \to J/\psi K^+$	1^+	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$

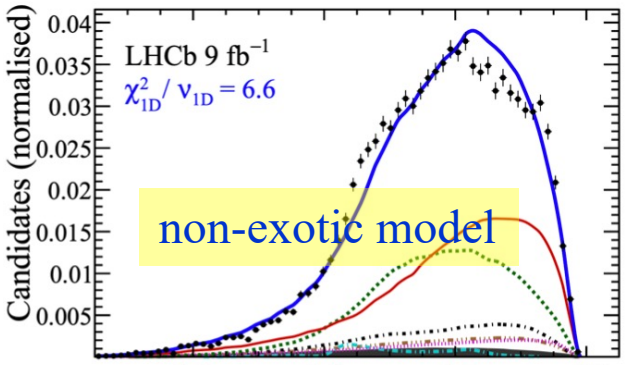
New Z_{cs}^0 $[c\bar{c}d\bar{s}]$ exotics in $B^+ \to \psi(2S)K^+\pi^+\pi^-$

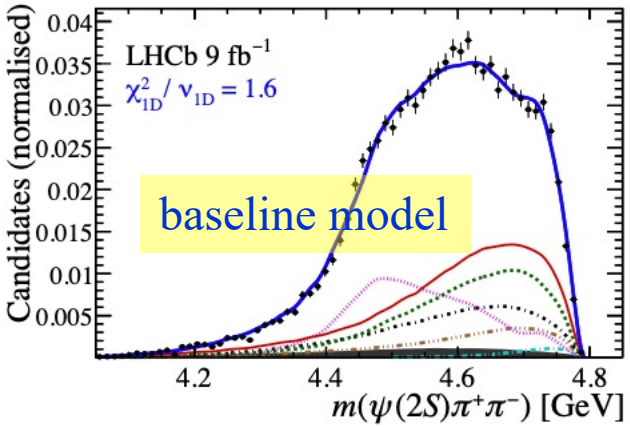
arXiv:2407.12475

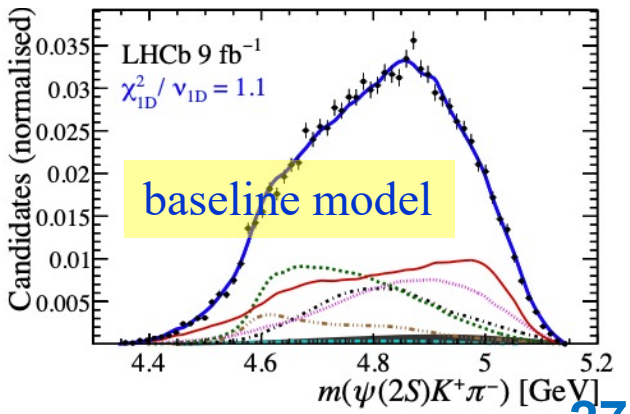
7D amplitude analysis of ~30k signals of $B^+ \to \psi(2S)K^+\pi^+\pi^-$

- The data cannot be described by conventional strange and charmonium resonances only
- An amplitude model with 53 components is developed comprising 6 known $K^* \to K^+\pi^+\pi^-$ states, 5 known neutral charmonium(-like) hadrons, 4 known charged exotic hadrons and **3 new exotic states $T_{c\bar{c}s1} \to \psi(2S)K^+\pi^-$**

Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	Sign. [σ]
$\chi_{c0}(4475)$	0^+	4475± 7 ±12	231±19±32	> 20 (19)
$\chi_{c1}(4650)$	1^+	4653±14±27	227±26±22	15 (13)
$\chi_{c0}(4710)$	0^+	4710± 4 ±5	64± 9 ±10	14 (10)
$\eta_{c1}(4800)$	1^-	4785±37±119	457±93±157	17 (12)
$T^*_{c\bar{c}1}(4055)^+$	1^-	4054 (fixed)	45 (fixed)	8 (7)
$T_{c\bar{c}1}(4200)^+$	1^+	4257±11±17	308±20±32	> 20 (> 20)
$T_{c\bar{c}1}(4430)^+$	1^+	4468±21±80	251±42±82	15 (8)
$T_{c\bar{c}\bar{s}1}(4600)^0$	1^+	4578±10±18	133±28±69	15 (12)
$T_{c\bar{c}\bar{s}1}(4900)^0$	1^+	4925±22±47	255±55±127	12 (8)
$T^*_{c\bar{c}\bar{s}1}(5200)^0$	1^-	5225±86±181	226±76±374	10 (8)
$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)	> 20 (14)





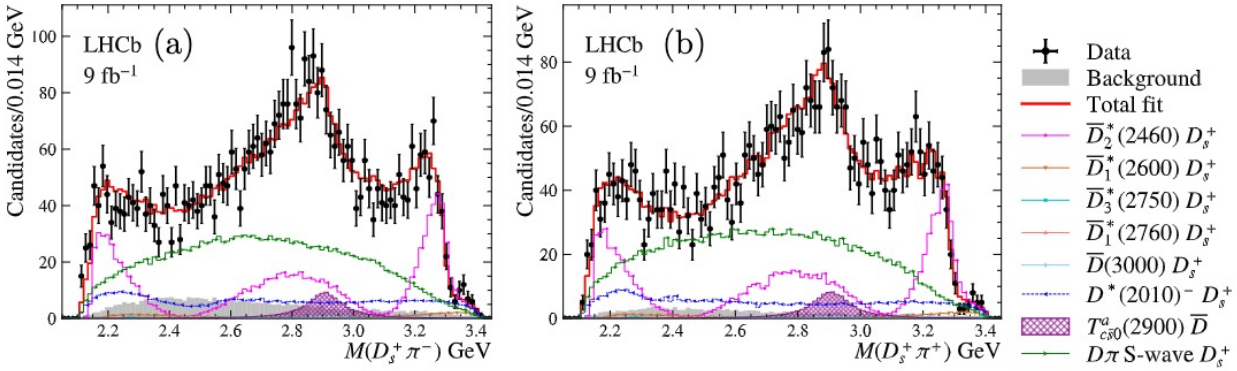


Observation of a doubly charged tetraquark $T^*_{c\bar{s}0}(2900)^{++}$ $[c\bar{s}u\bar{d}]$ and its neutral partner $T^*_{c\bar{s}0}(2900)^0$ $[c\bar{s}\bar{u}d]$

PRL131, 041902(2023)
PRD108, 012017(2023)

- First simultaneous amplitude analysis of $B^+ \to D^- D_s^+ \pi^+$ & $B^0 \to \bar{D}^0 D_s^+ \pi^-$ with RUN 1+2 9 fb^{-1} data

- $D_s\pi$ mass spectra well described by adding $J^P = 0^+$ (> **7.5 σ**)
  $T^a_{c\bar{s}0}(2900)$ > **9 σ**



	Mass (GeV)	Width (GeV)	J^P
$T^*_{c\bar{s}0}(2900)^0$ & $T^*_{c\bar{s}0}(2900)^{++}$	$2.908 \pm 0.011 \pm 0.020$	$0.136 \pm 0.023 \pm 0.020$	0^+
$X_0(2900)/T^*_{cs0}(2870)$	$2.866 \pm 0.007 \pm 0.002$	$0.057 \pm 0.012 \pm 0.004$	0^+
$X_1(2900)/T^*_{cs1}(2900)$	$2.904 \pm 0.005 \pm 0.001$	$0.110 \pm 0.011 \pm 0.004$	1^-

- $T^*_{c\bar{s}0}(2900)$ v.s. $X_0(2900)$
  - ✓ Similar mass, but width and flavor contents are different.

- no isospin relation: $[c\bar{s}u\bar{d}]$ v.s. $[cs\bar{u}\bar{d}]$
- U-spin relation: $[c\bar{s}\bar{u}d]$ v.s. $[c\bar{d}\bar{u}s]$
- $T^*_{c\bar{s}0}(2900)$ mass and width larger than $X_0(2900)$

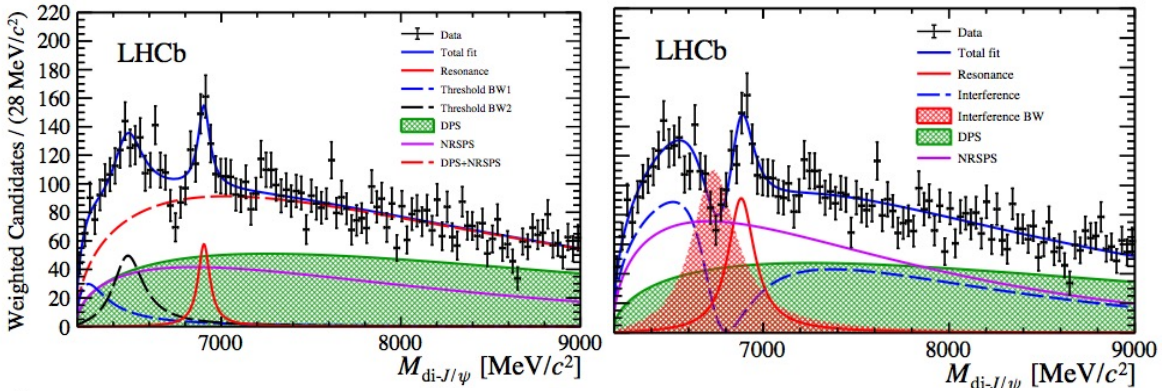
Study on fully heavy tetraquark state

- Existence of $T_{Q_1Q_2\bar{Q}_3\bar{Q}_4}$ states ($Q_i = c$ or b) is expected by many QCD models
- $T_{bb\bar{b}\bar{b}}$ was searched for at LHCb and CMS, but not observed

[LHCb, JHEP 10, 086 (2018); CMS, PLB808, 135578(2020)]

- $T_{cc\bar{c}\bar{c}}$ states predicted to have $M \in [5.8, 7.4]$ GeV/c, away from known quarkonia and quarkonium-like exotic states
- LHCb observation of the first fully charmed tetraquark state X(6900) [$cc\bar{c}\bar{c}$] in J/ψ+J/ψ final states

[LHCb, Sci. Bull. 23, 1983 (2020)]



- ✓ Model I: Based on no-interference fit (worse fitting quality)

$$M[\text{X(6900)}] = 6905 \pm 11(\text{stat}) \pm 7(\text{syst})\ \text{MeV}/c^2$$
$$\Gamma[\text{X(6900)}] = 80 \pm 19(\text{stat}) \pm 33(\text{syst})\ \text{MeV}/c^2$$

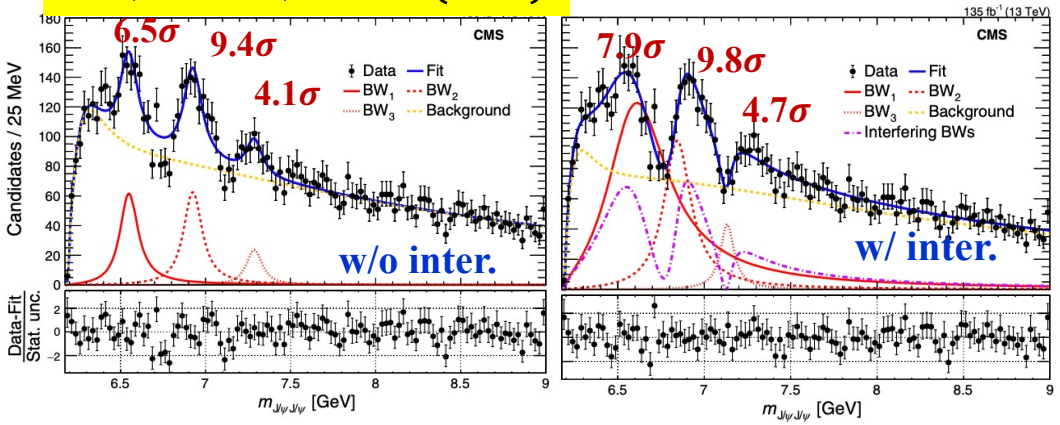
- ✓ Model II: Based on the simple model with interference (better fitting quality)

$$M[\text{X(6900)}] = 6886 \pm 11(\text{stat}) \pm 11(\text{syst})\ \text{MeV}/c^2$$
$$\Gamma[\text{X(6900)}] = 168 \pm 33(\text{stat}) \pm 69(\text{syst})\ \text{MeV}/c^2$$

consistent with predicted $T_{cc\bar{c}\bar{c}}$ states

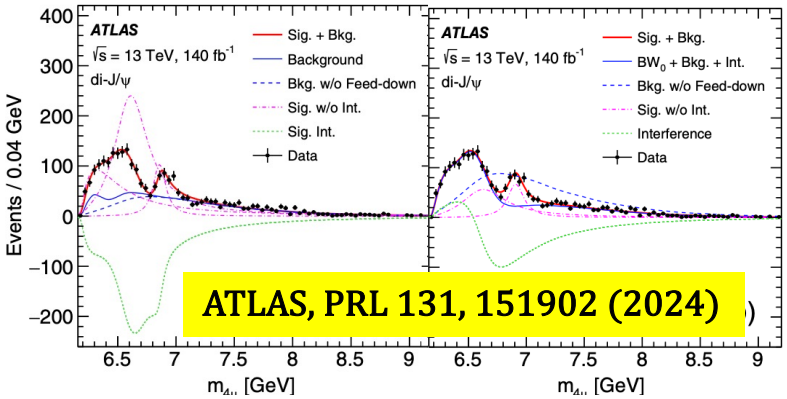
Observations of fully charmed tetraquark state X(6600) [$cc\bar{c}\bar{c}$]

CMS, PRL 132, 111901 (2024)



w/o inter.	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)	$124^{+32}_{-26} \pm 33$	$122^{+24}_{-21} \pm 18$	$95^{+59}_{-40} \pm 19$
w/ inter.	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}

- ATLAS and CMS both confirm the X(6900) state in $J/\psi+J/\psi$ final states
- CMS observe a new structure X(6600) and find an evidence of the X(7100)
- LHCb, ATLAS and CMS all see a broad enhancement at the low mass region

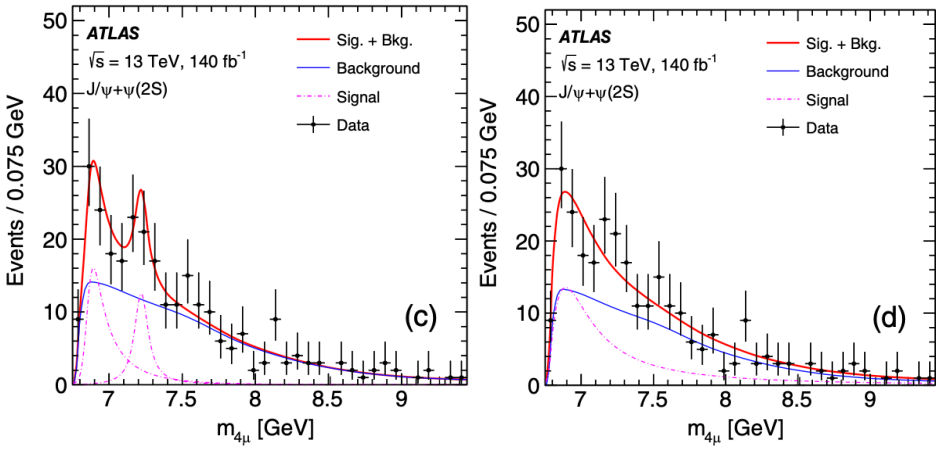


ATLAS, PRL 131, 151902 (2024)

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	$0.11 \pm 0.05^{+0.02}_{-0.01}$	$0.15 \pm 0.03 \pm 0.01$

Searches for $T_{cc\bar{c}\bar{c}}$ in other double charmonia

- ATLAS finds evidence of enhancement around 6.9 GeV in $J/\psi+\psi(2S)$ final states

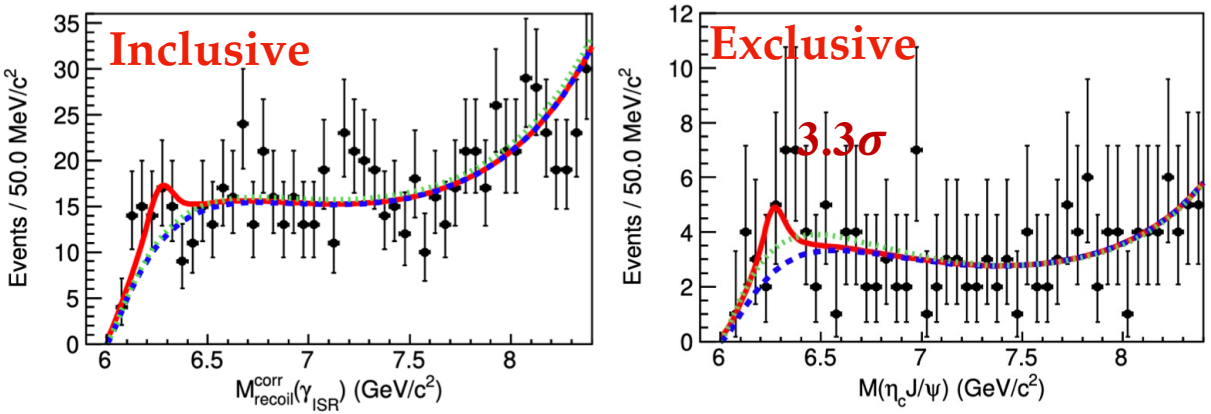


ATLAS, PRL 131, 151902 (2024)

$J/\psi+\psi(2S)$	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	$0.09 \pm 0.06^{+0.06}_{-0.05}$	$0.51 \pm 0.17^{+0.11}_{-0.10}$

- Belle finds evidence of threshold enhancement in η_c+J/ψ final states

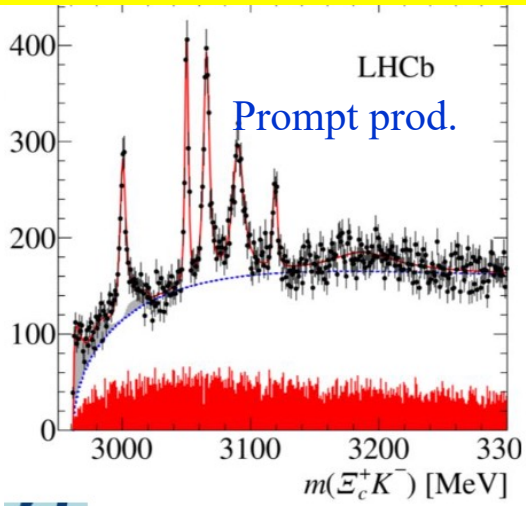
Belle, JHEP 08 2023, 121 (2023)



Heavy baryons

New excited Ω_c^0 states

LHCb, PRL118, 182001 (2017)

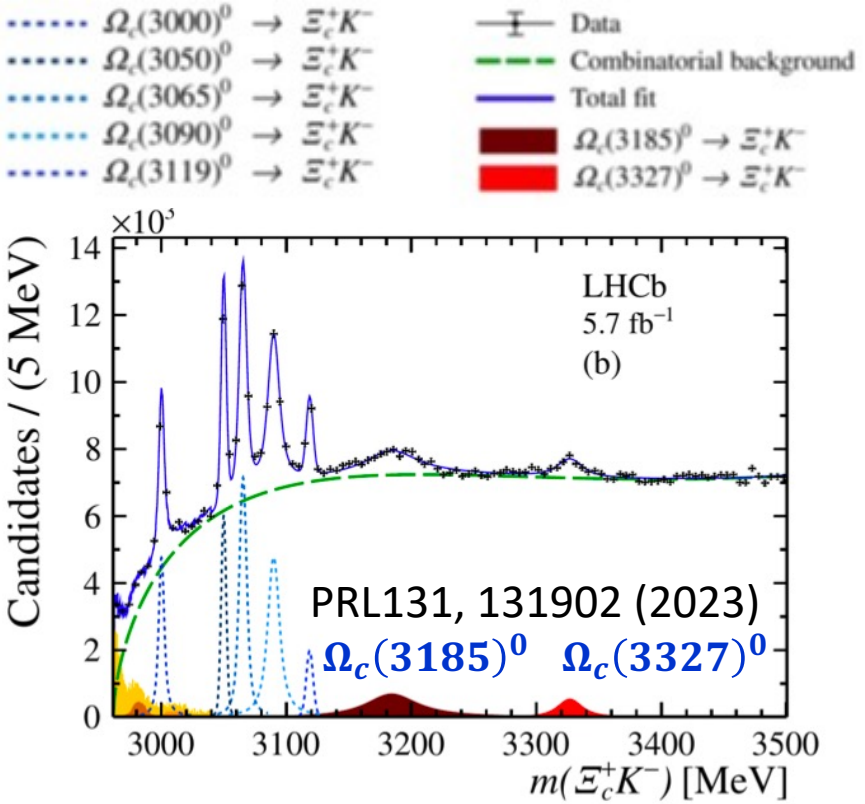


- Five Ω_c^{*0} states have been observed at LHCb
- Hint of another broad structures at 3.2 GeV and 3.3 GeV

New study of prompt $\Xi_c^+K^-$ based on a full LHCb dataset

Besides the previous 5 states, two new states **$\Omega_c(3185)^0$ and $\Omega_c(3327)^0$** are observed.

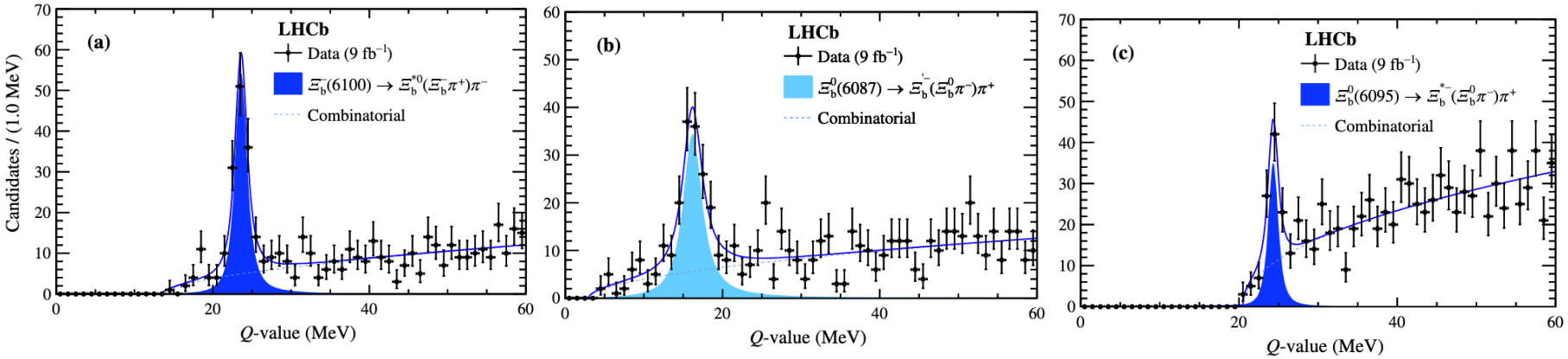
Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	3000.44 ± 0.07	3.83 ± 0.23
$\Omega_c(3050)^0$	3050.18 ± 0.04	0.67 ± 0.17
$\Omega_c(3065)^0$	3065.63 ± 0.06	3.79 ± 0.20
$\Omega_c(3090)^0$	3090.16 ± 0.11	8.48 ± 0.44
$\Omega_c(3119)^0$	3118.98 ± 0.12	0.60 ± 0.63
★ $\Omega_c(3185)^0$	3185.1 ± 1.7	50 ± 7
★ $\Omega_c(3327)^0$	3327.1 ± 1.2	20 ± 5



Observation of new excited Ξ_b states

PRL131, 171901(2023)

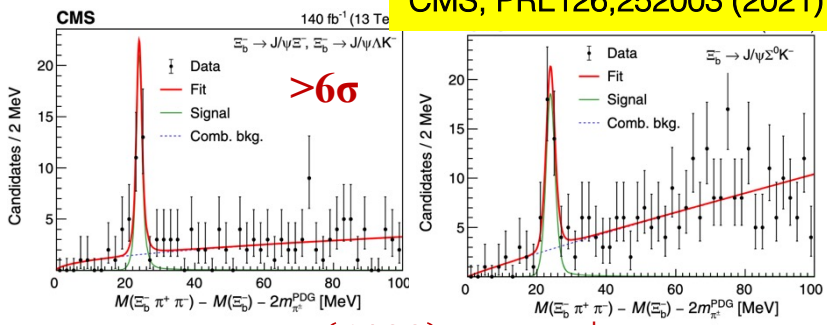
Ξ_b is reconstructed via $\Xi_b \to \Xi_c \pi$ and $\Xi_c 3\pi$



- Observes two new Ξ_b states $\Xi_b(6087)^0$ and $\Xi_b(6095)^0$ in $\Xi_b^0 \pi^+ \pi^-$
- Confirms the $\Xi_b(6100)^-$ observed by CMS

State	Observable	Value (MeV)
$\Xi_b(6100)^-$	Q_0	$23.6 \pm 0.11 \pm 0.02$
	Γ	$0.94 \pm 0.30 \pm 0.08$
	m_0	$6099.74 \pm 0.11 \pm 0.02 \pm 0.6(\Xi_b^-)$
$\Xi_b(6087)^0$	Q_0	$16.20 \pm 0.20 \pm 0.06$
	Γ	$2.43 \pm 0.51 \pm 0.10$
	m_0	$6087.24 \pm 0.20 \pm 0.06 \pm 0.5(\Xi_b^0)$
$\Xi_b(6095)^0$	Q_0	$24.32 \pm 0.15 \pm 0.03$
	Γ	$0.50 \pm 0.33 \pm 0.11$
	m_0	$6095.36 \pm 0.15 \pm 0.03 \pm 0.5(\Xi_b^0)$

CMS, PRL126,252003 (2021)



$\Xi_b(6100)^- \to \Xi_b^- \pi^+ \pi^-$

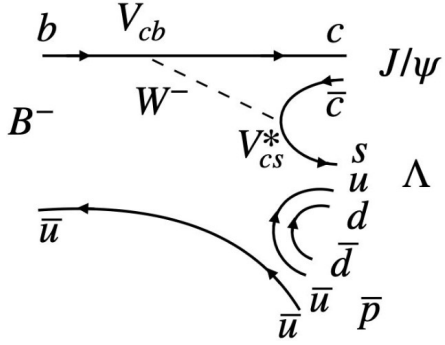
$M = 6100.3 \pm 0.2 \pm 0.1 \pm 0.6$ MeV

$\Gamma < 1.9$ MeV at 95% CL

Observation of the hidden-charm strange pentaquark [$c\bar{c}uds$]

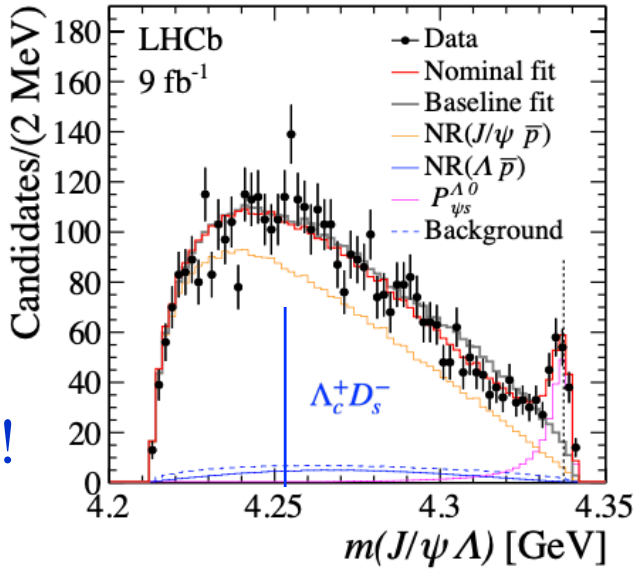
PRL131, 031901(2023)

- narrow structure in $J/\psi\Lambda$ in $B^- \to J/\psi\Lambda\bar{p}$, with 9 fb^{-1} LHCb data
- $\boldsymbol{P_{c\bar{c}s}(4338)^0 \to J/\psi\Lambda}$ observed with significance larger than 10σ
- $J^P = \frac{1}{2}^-$ preferred and close to $\Xi_c^+ D^-$ threshold
  - 0.8 MeV above $\Xi_c^+ D^-$;
  - 2.9 MeV above $\Xi_c^0 \bar{D}^0$



$$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4\,\text{MeV}$$

$$\Gamma_{P_{cs}} = 7.0 \pm 1.2 \pm 1.3\,\text{MeV}$$



First heavy pentaquark with strangeness!

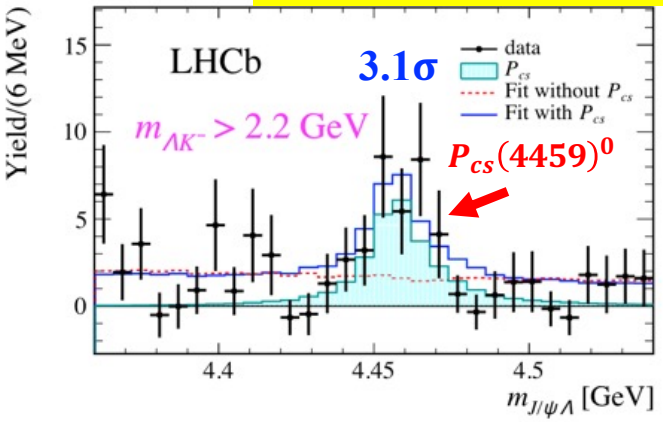
Evidence for $\Upsilon(1S, 2S) \to P_{c\bar{c}s}(4459)^0 X$

- **LHCb found evidence for [$c\bar{c}uds$] pentaquark candidate with strangeness:**

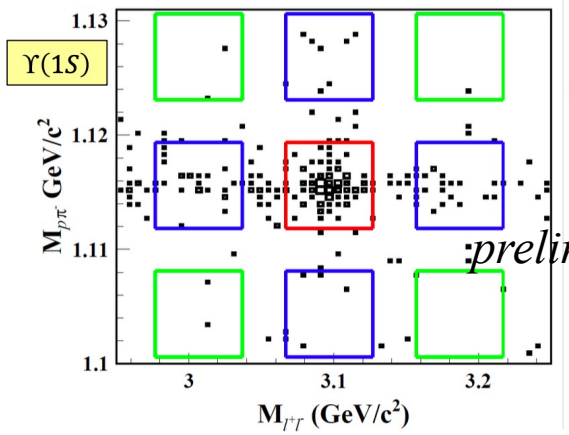
$P_{c\bar{c}s}(4459)^0$ in $\Xi_b^- \to J/\psi \Lambda K^-$ decays, near threshold of $\Xi_c^0 \overline{D}^{*0}$:

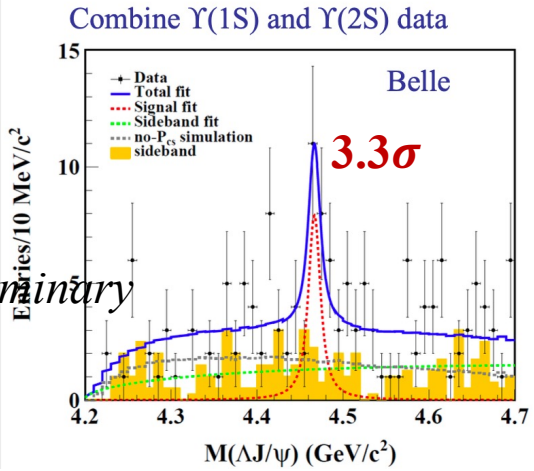
$$m(P_{c\bar{c}s}(4459)^0) = 4458.8 \pm 2.9^{+4.7}_{-1.1}\ \text{MeV}$$
$$\Gamma(P_{c\bar{c}s}(4459)^0) = 17.3 \pm 6.5^{+8.0}_{-5.7}\ \text{MeV}$$

Sci.Bull. 66, 1278(2021)



- **Belle reports evidence for $P_{c\bar{c}s}(4459)^0 \to J/\psi\Lambda$ in inclusive $\Upsilon(1S, 2S)$ decays**





Local significance is 4.0σ

mass: $4469.6 \pm 4.1 \pm 4.1$ MeV
width: $17.3 \pm 9.2 \pm 6.3$ MeV

consistent with LHCb results

Add Gaussian constraint on mass and width
➔ significance is 3.3σ including systematics.

Summary

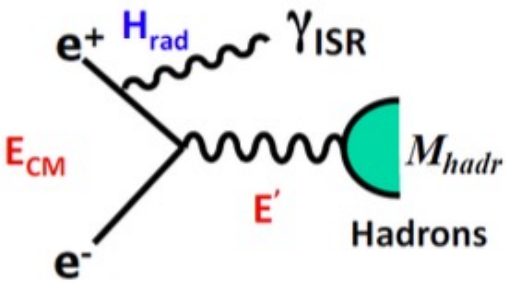
- Two years of exciting period of finding new hadrons (mainly) from BESIII and LHCb, among which most of them are candidates of exotic hadrons
- **Light hadrons:** high statistics data is crucial to identify exotic feature of different known states and find new particles
  - a glueball-like state X(2370)
  - emerging strangenium(-like) states
  - distorted lineshape at thresholds of $p\bar{p}$, $N\bar{K}$ and $\Lambda\eta$
- **Heavy hadrons:**
  - better understanding of the X(3872) via its radiative decays
  - 8 new neutral charmonium(-like) states: **[$c\bar{c}$] or [$c\bar{c}q\bar{q}$]**
  - 7 new tetraquark states: **[$c\bar{c}u\bar{s}$]; [$c\bar{s}u\bar{d}$]; [$c\bar{s}\bar{u}d$]**
  - 1 new pentaquark state with strangeness: **[$c\bar{c}uds$]**
  - 2 new Ω_c states and 2 new Ξ_b states
- More results based on higher statistics data can be expected regarding to the upcoming 3x$\mathcal{L}$ upgraded BEPCII-U, ongoing LHC RUN3 and Belle II.

Thank you!

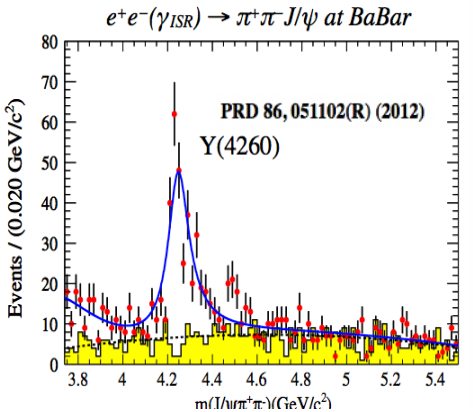
谢谢!

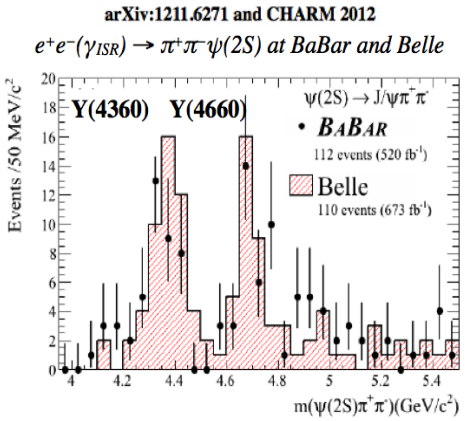
Backup

The Y states



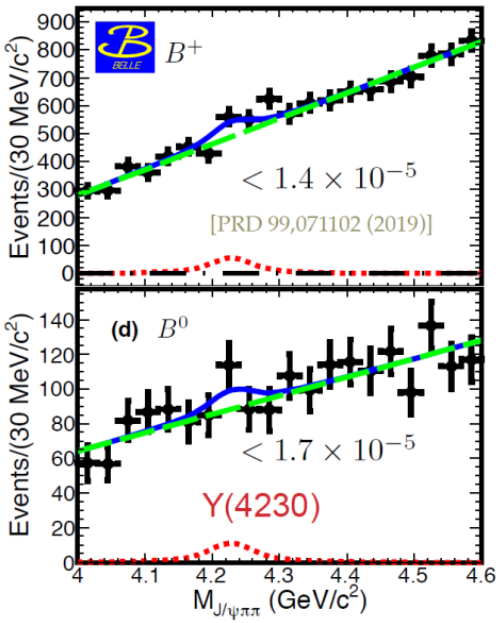
Y states: charmonium-like states with $J^{PC}=1^{--}$; Observed in direct e+e- annihilation or initial state radiation (ISR).



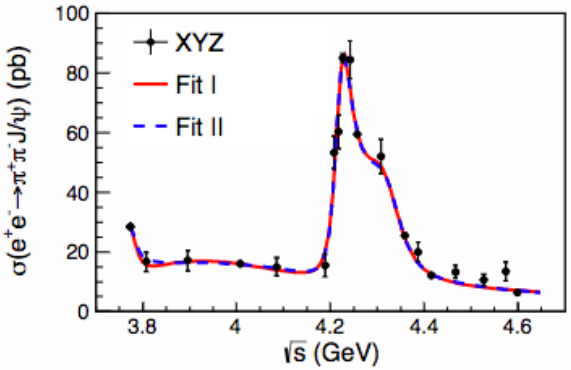


- **While not seen yet in B decays**

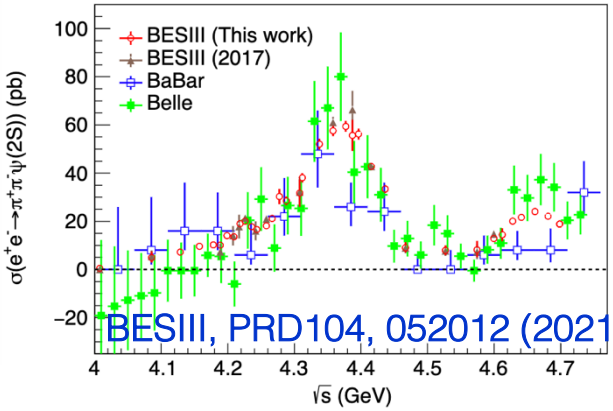
$B^{\pm,0} \to K^{\pm,0}\pi^+\pi^- J/\psi$



- **Improved knowledges from BESIII**



BESIII, PRL118, 092001 (2017)

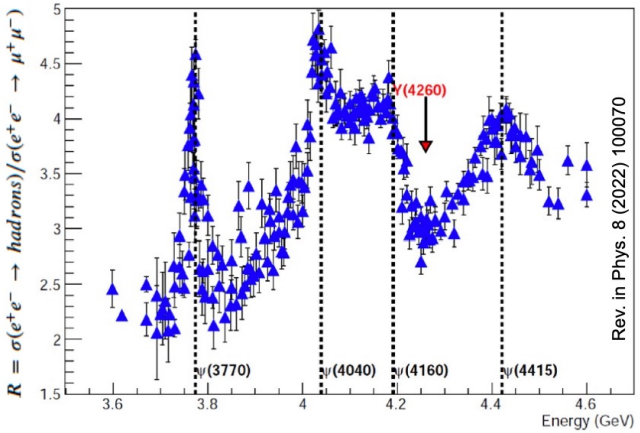


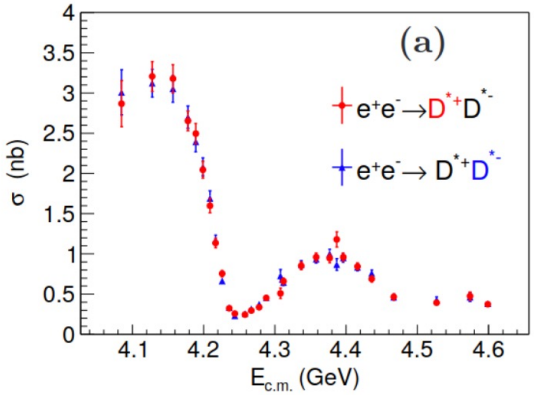
BESIII, PRD104, 052012 (2021)

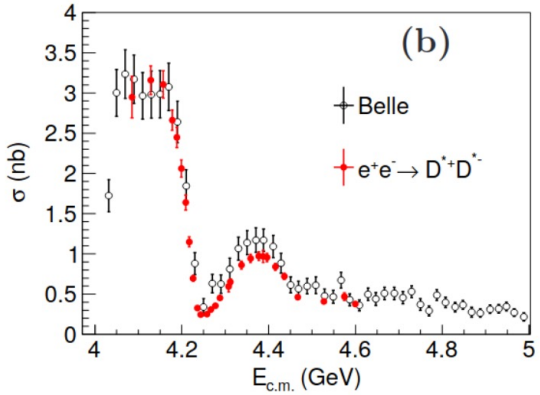
Open charm cross sections

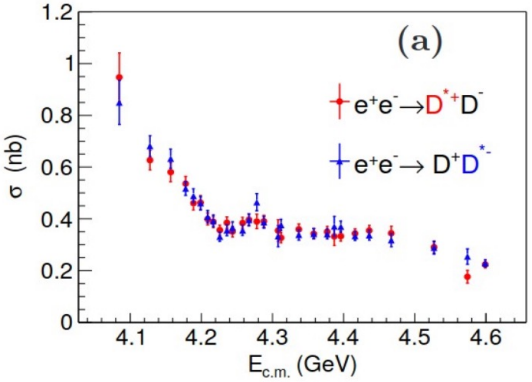
- essential to fully understand the XYZ states
- Important input for coupled-channel analysis

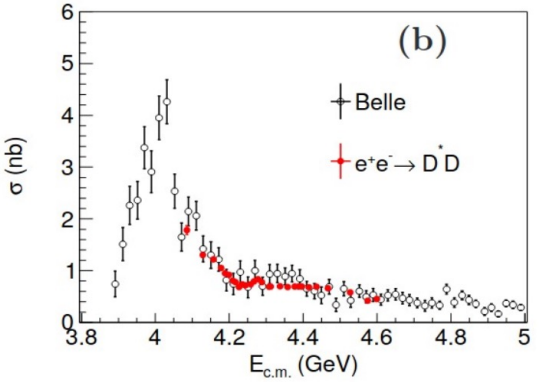
JHEP2022, 55 (2022)







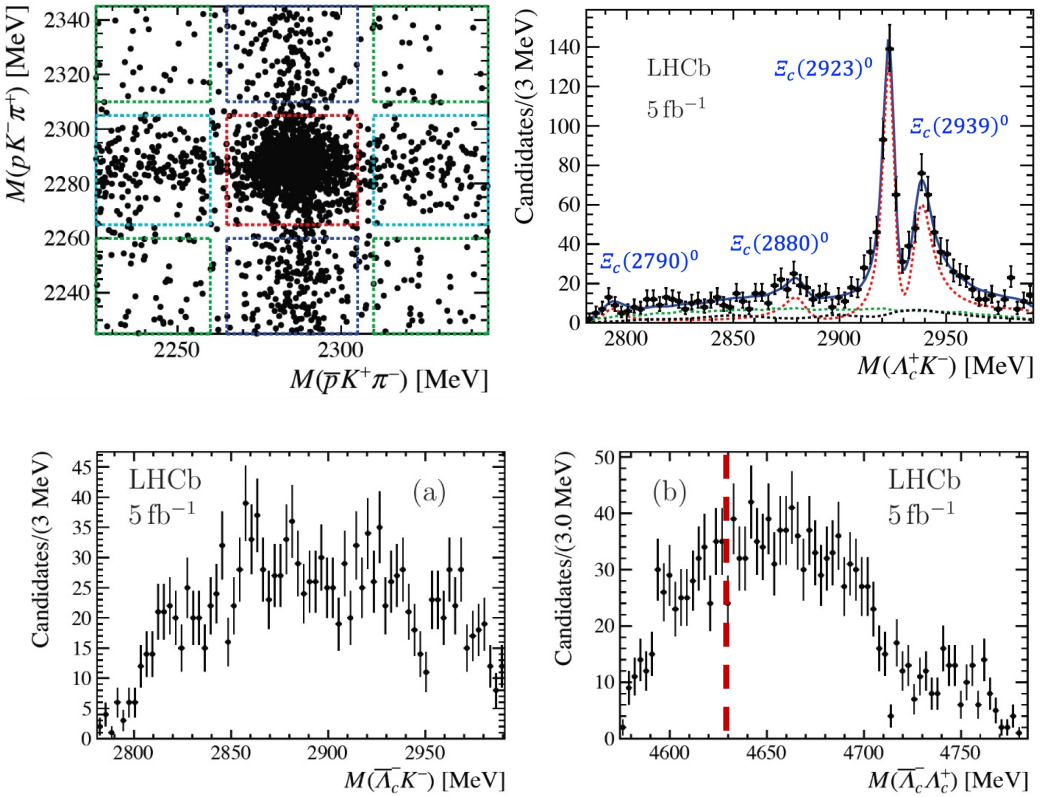




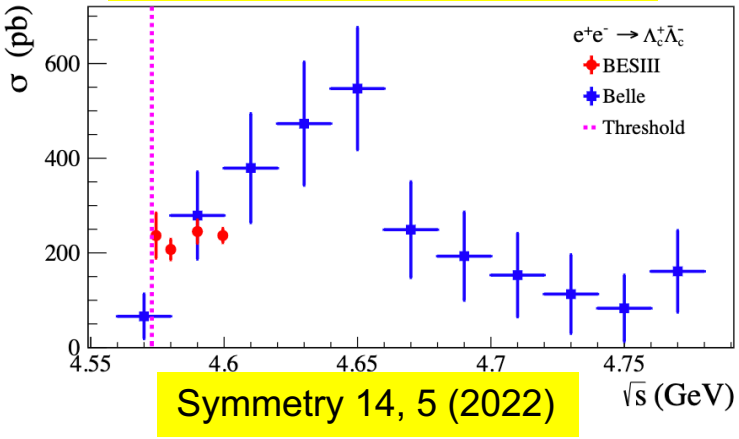
- Good agreement with existing measurements, with best precisions
- Structure at 4.39 GeV in D^*D^*?

Search for exotics in $B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$

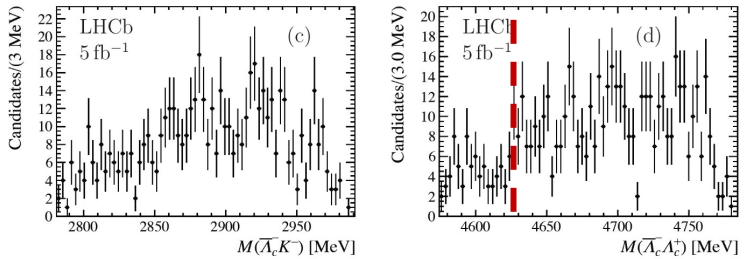
- $\Lambda_c^+ \bar{\Lambda}_c^-$ and $\Lambda_c^- K^-$ systems are good places to search for exotics **PRD 108, 012020 (2023)**
- Near threshold enhancment of $Y(4630) \to \Lambda_c^+ \bar{\Lambda}_c^-$ is observed at Belle. However, the Breit-Wigner line shape is not supported by BESIII



Belle: PRL101, 172001 (2008)
BESIII: PRL120,132001(2018)



Symmetry 14, 5 (2022)



vetoing 2.90 GeV $< M(\Lambda_c^+ K^-) <$ 2.97 GeV

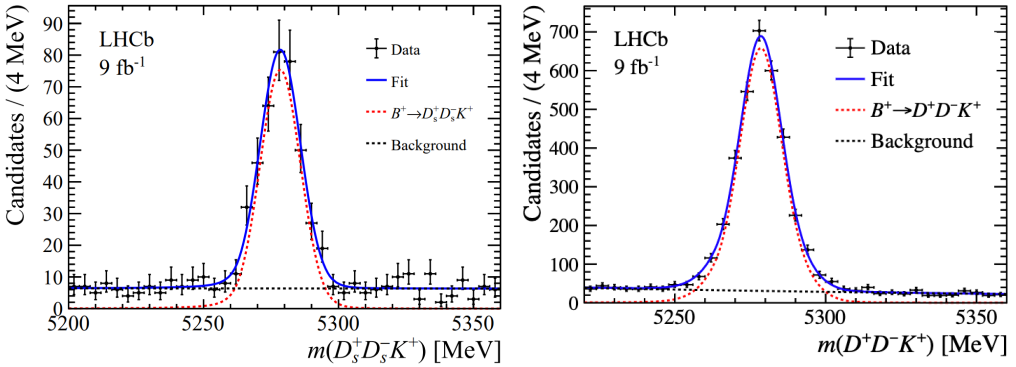
No obvious structures are seen in $\Lambda_c^+ \bar{\Lambda}_c^-$ and $\Lambda_c^- K^-$ systems

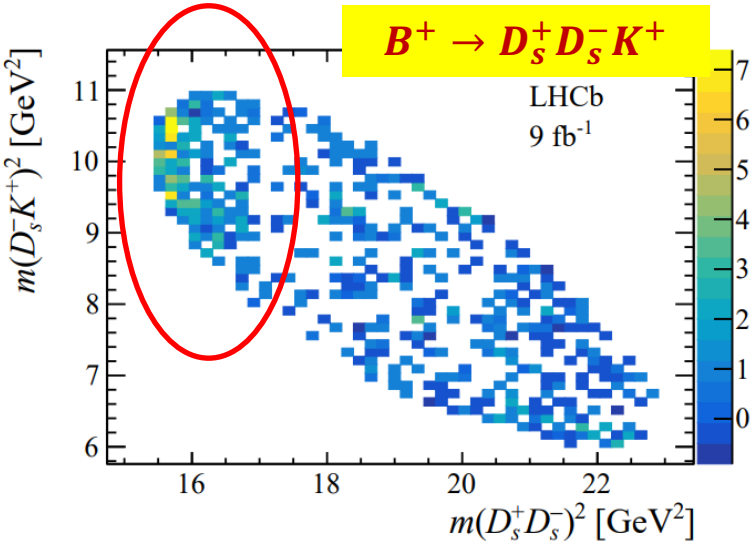
Study on $B^+ \to D_s^+ D_s^- K^+$

PRD 108, 034012 (2023)
PRL131, 071901 (2023)

- Relative measurement of branching fractions :

$$\frac{\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)}{\mathcal{B}(B^+ \to D^+ D^- K^+)} = 0.525 \pm 0.033 \pm 0.027 \pm 0.034$$

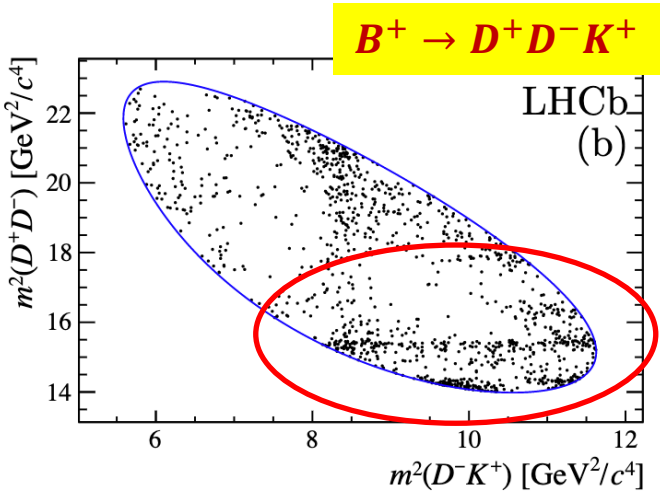




- $D_s^+ D_s^-$ near-threshold enhancement is seen
- Similar to the $\chi_{c0,2}(3930)$ observed in $B^+ \to D^+ D^- K^+$?

PRL125, 242001 (2020)

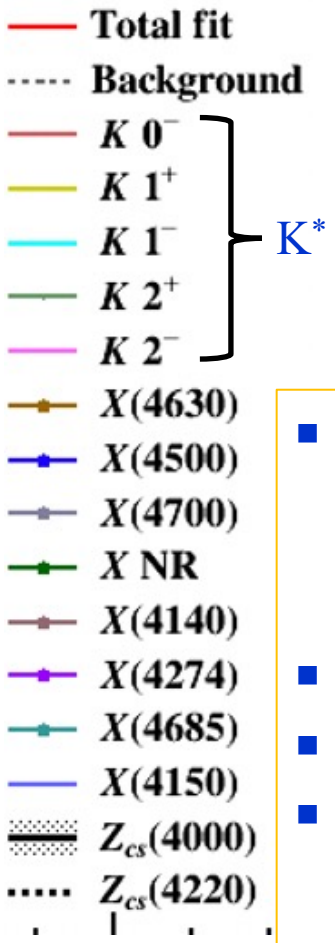
Resonance	Mass (GeV/c^2)	Width (MeV)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$

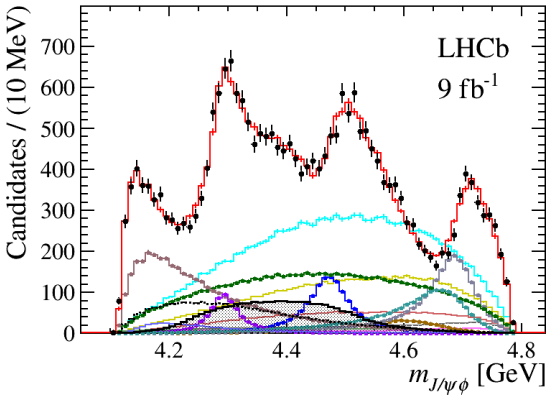


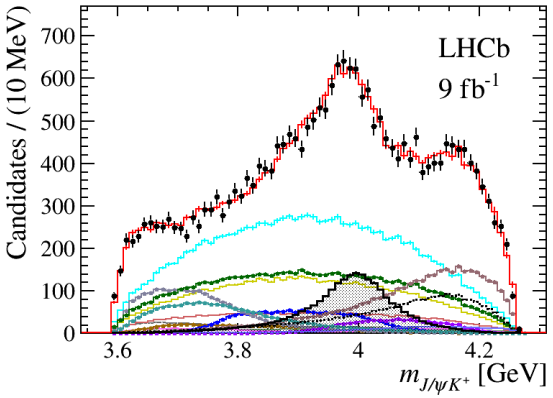
Amplitude analysis of $B^+ \to J/\psi\phi K^+$

- With Run 1 $B^+ \to J/\psi\phi K^+$ data, LHCb performed 1st amplitude fit and observed the $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$ ➔ $[c\bar{c}s\bar{s}]$ tetraquark?
- **LHCb RUN 1+2**: 24K signals, about 6× larger than RUN 1

PRL127, 082001 (2021)





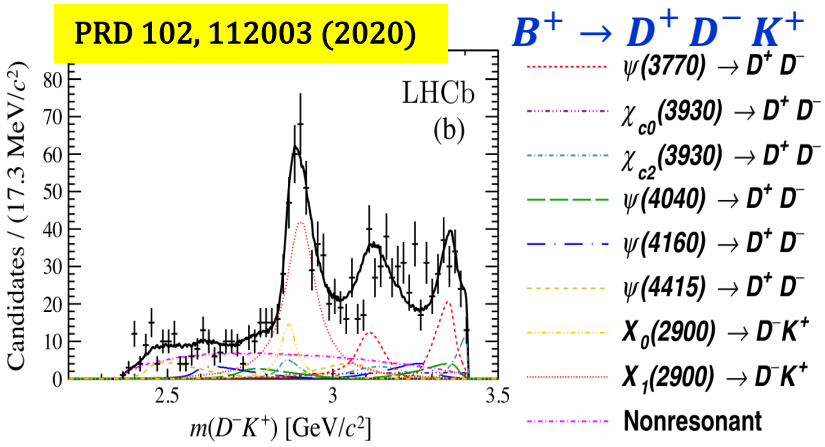


- New states:
  $Z_{cs}(4000)$, $X(4685)$ > 15σ
  $Z_{cs}(4220)$, $X(4630)$ > 5σ
  $X(4150)$ < 5σ
- $Z_{cs}(4000)$ & $X(4685)$: 1^+
- $Z_{cs}(4220)$ can be 1^+ or 1^-
- Confirmed states:
  $X(4140)$, $X(4274)$,
  $X(4500)$, $X(4700)$

Contribution	Significance [×σ]	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$	Syst. included(Stat.)			
$X(4150)$	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)	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	$8.9 \pm 1.2^{+4.9}_{-1.4}$
$NR_{J/\psi\phi}$	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)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

Open flavor tetraquark

- D0 claimed evidence for the X(5568) in decaying to $B_s\pi^+$, interpreted as tetraquark state [$bsud$], but not seen in other experiments
- **Observation of the open flavor tetraquark states $X_0(2900)$ and $X_1(2900)[cs\bar{u}\bar{d}]$ in $B^+ \to D^+D^-K^+$**
- **The $D_{s0}^*(2317)^+$ ($D_s^+\pi^0$) state was observed in 2003.**
- It is argued to contain some **tetraquark component** in several theoretical descriptions, whose $I = 1$ partners can exist in the $D_s^+\pi^\pm$ **final states.**
- *Cheng & Hou:* It would be astonishing if a doubly charged resonance is found. [PLB 566, 193 (2003)]



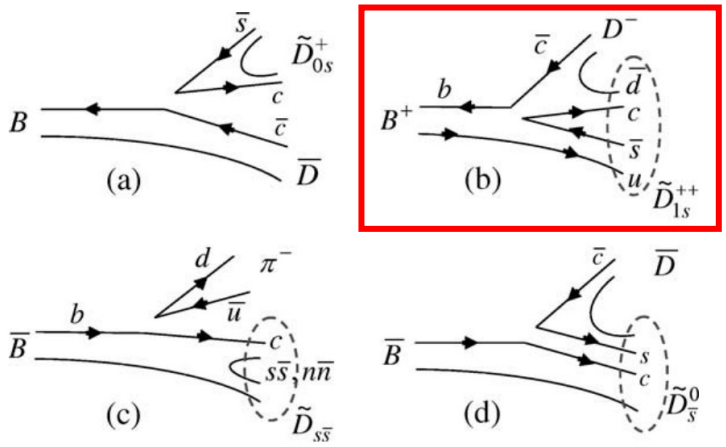
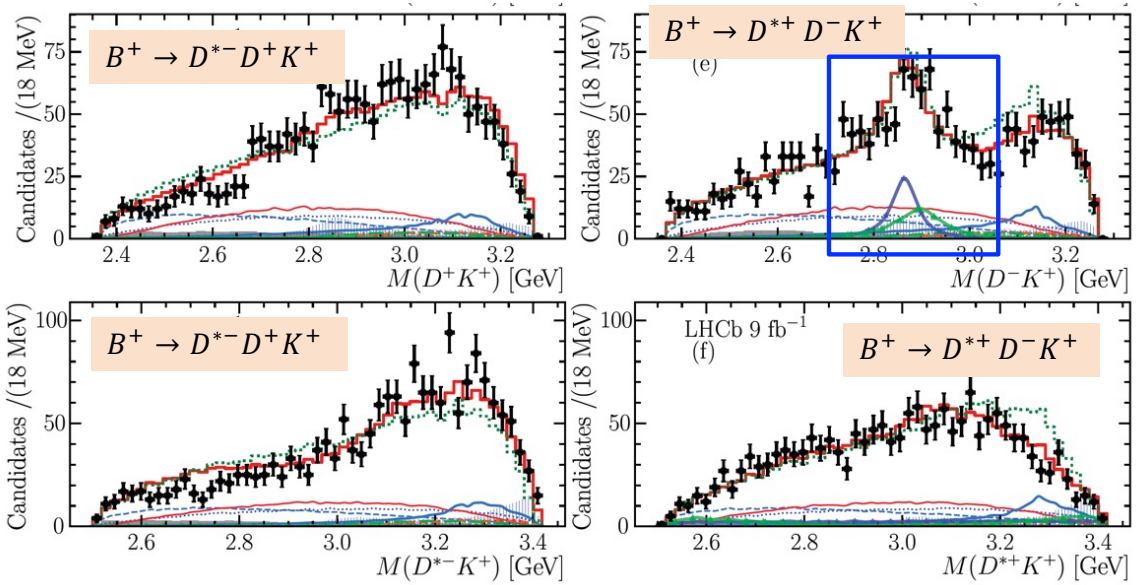


Fig. 2. Diagrams for (a) $B \to \bar{D}\tilde{D}_{0s}^+$, (b) $B^+ \to D^-\tilde{D}_{1s}^{++}$ ($B \to \bar{D}\tilde{D}_{Is}$), (c) $\bar{B} \to \pi^-\tilde{D}_{s\bar{s}}$, $\pi^-\tilde{D}$, (d) $B \to D\tilde{D}_{\bar{s}}^0$.

Confirmation of open charm tetraquarks T^*_{cs} [$cs\bar{u}\bar{d}$]

arXiv:2406.03156



- $T^*_{\bar{c}\bar{s}0}(2870)^0$ and $T^*_{\bar{c}\bar{s}1}(2900)^0$ are confirmed in a different decay channel $B^+ \to D^{*+}T^*_{\bar{c}\bar{s}}$
- No obvious structure in $D^{*\pm}K^+$ and D^+K^+ mass spectra

Property	This work	Previous work
$T^*_{\bar{c}\bar{s}0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{\bar{c}\bar{s}0}(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{\bar{c}\bar{s}1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{\bar{c}\bar{s}1}(2900)^0$ width [MeV]	$92 \pm 16 \pm 16$	110 ± 12
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})$	$(4.5\,^{+0.6}_{-0.8}\,^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-5}$
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})$	$(3.8\,^{+0.7}_{-1.0}\,^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$	$(6.7 \pm 2.3) \times 10^{-5}$
$\frac{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})}{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05

New charmonium-like states in $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

2020 $D^- K^+$

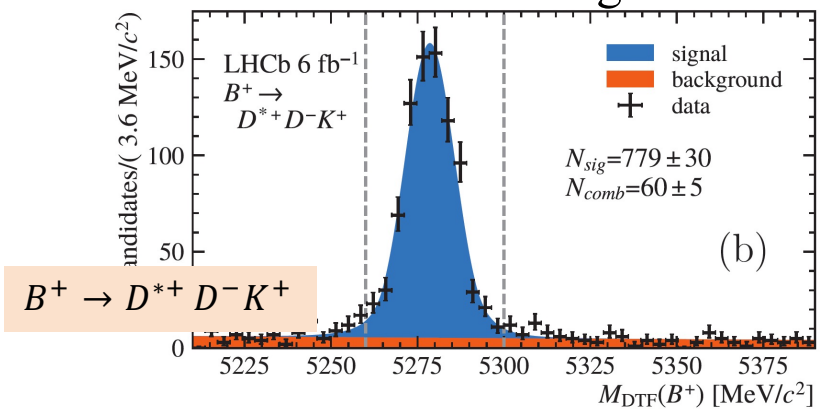
2023 $D_s^+ \pi^\pm$

2024 $B^+ \to D^{*-} D_s^+ \pi^+$ No obvious exotics

2024 $B^+ \to D^{*\pm} D^{\mp} K^+$ arXiv:2406.03156

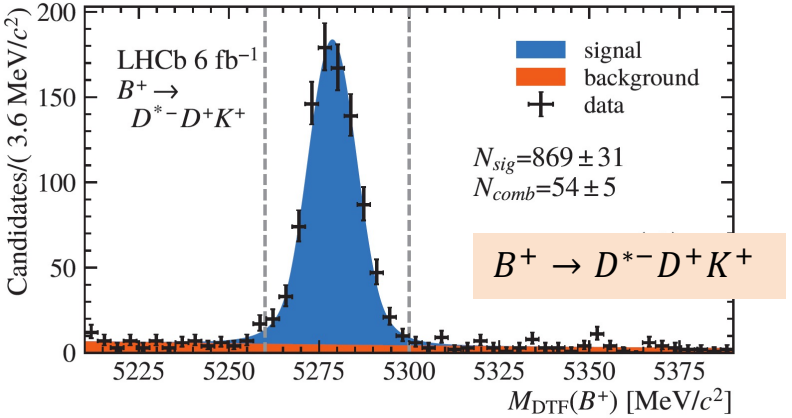
$B^+ \to D^{*\pm} D^{\mp} K^+$ topology similar to $B^+ \to D^- D^+ K^+$ decays

About 1700 signals



$B^+ \to D^{*+} D^- K^+$

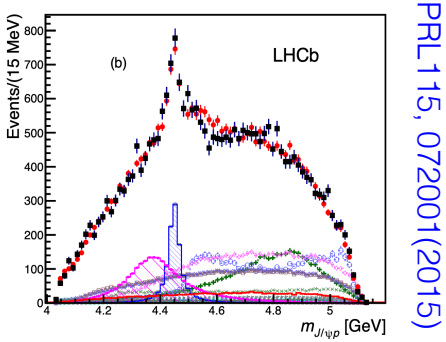
About 1700 signals



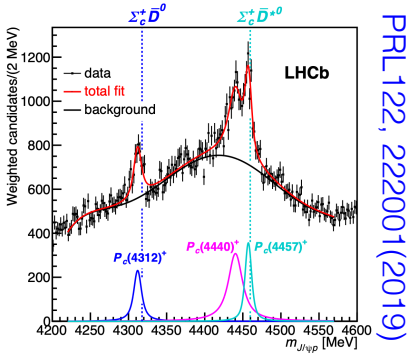
$B^+ \to D^{*-} D^+ K^+$

Pentaquark states at LHCb

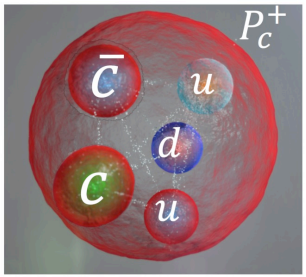
- **Observation of $[c\bar{c}uud]$ pentaquarks:** $P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ in $\Lambda_b^0 \to J/\psi p K^-$ decays; near thresholds of $\Sigma_c^+ \overline{D}^0$, $\Sigma_c^+ \overline{D}^{*0}$, J^P not determined



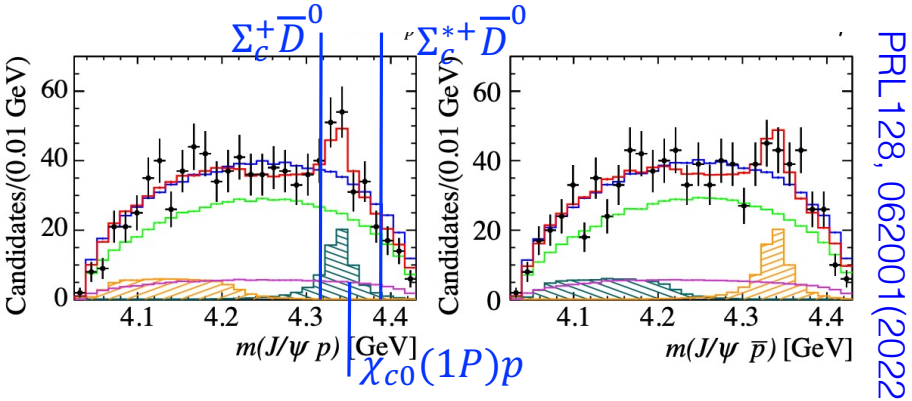
PRL115, 072001(2015)



PRL122, 222001(2019)

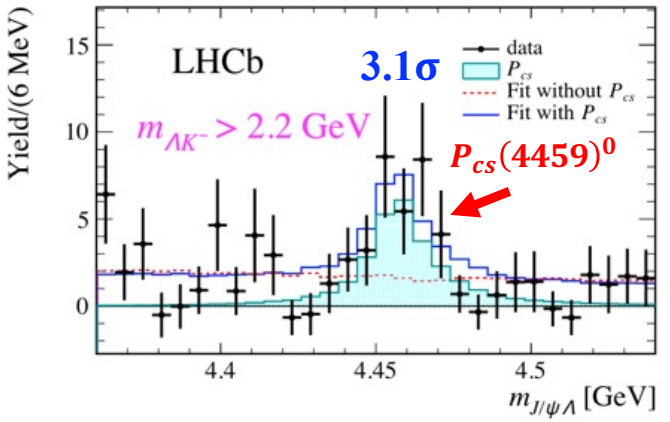


- **Evidence of $[c\bar{c}uud]$ pentaquark:** $P_{c\bar{c}}(4337)^+$ in $B_s^0 \to J/\psi p\bar{p}$ decays



PRL128, 062001(2022)

- **Evidence for $[c\bar{c}uds]$ pentaquark candidate with strangeness:** $P_{c\bar{c}s}(4459)^0$ in $\Xi_b^- \to J/\psi \Lambda K^-$ decays, near threshold of $\Xi_c^0 \overline{D}^{*0}$

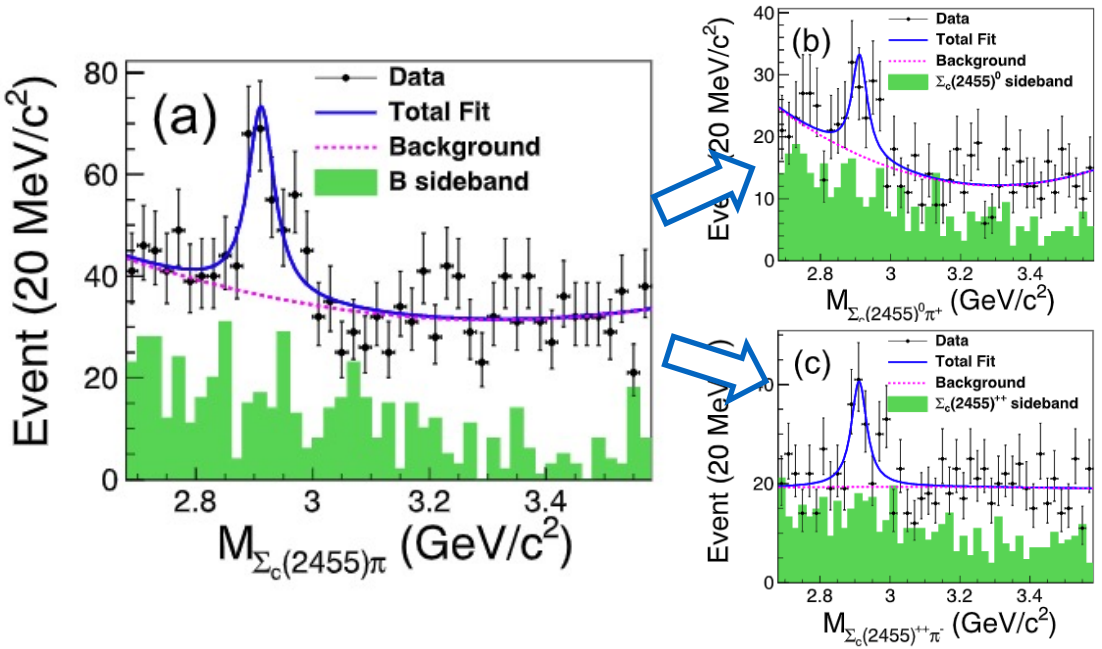


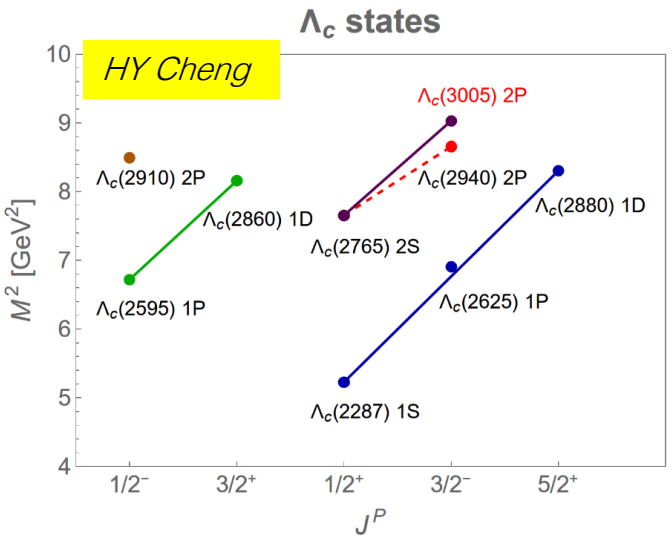
Sci.Bull.66, 1278(2021)

Evidence of new excited charmed baryon Λ_c^*

- Study on $\bar{B}^0 \to \Sigma_c\ (2455)^{0,++}\pi^{\pm}\bar{p}$ with Belle data
- Combined fit to $\Sigma_c\ (2455)^{0,++}\pi^{\pm}$ mass spectra

arXiv: 2206.08822





State	Mass (MeV/c^2)	Width (MeV)
$\Lambda_c(2880)^+$	2881.63 ± 0.24	$5.6^{+0.8}_{-0.6}$
$\Lambda_c(2940)^+$	$2939.6^{+1.3}_{-1.5}$	20^{+6}_{-5}
$\Lambda_c(2910)^+$ (this analysis)	$2913.8 \pm 5.6 \pm 3.8$	$51.8 \pm 20.0 \pm 18.8$

a good candidate for $\Lambda_c\left(\frac{1}{2}^-, 2P\right)$ [arXiv:2207.03022]

significance with 4.2 σ after considering possible $\Lambda_c(2880)$ and $\Lambda_c(2940)$ contributions