Recent experimental progress on hadron spectroscopy

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Outline

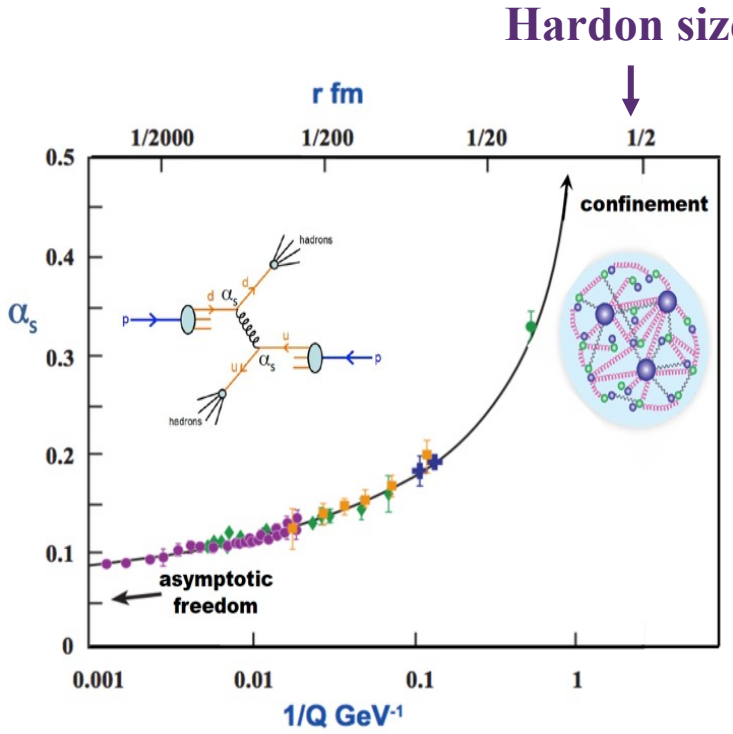
- Introduction
- Light hadron spectroscopy
- Heavy hadron spectroscopy

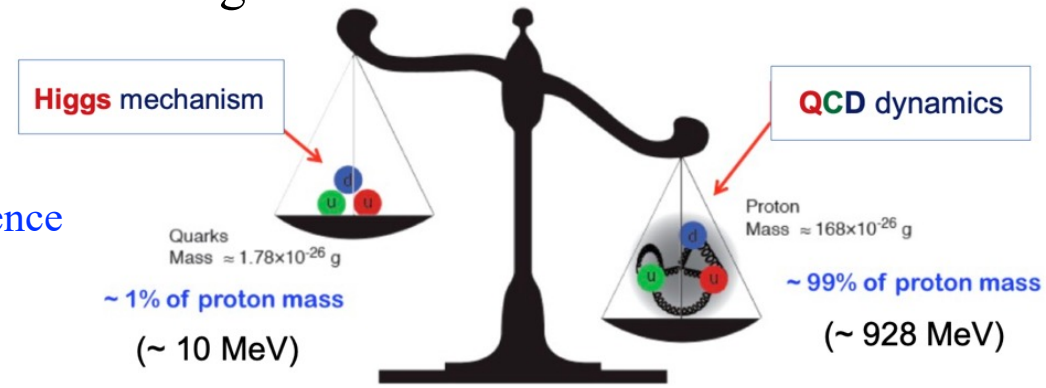
  conventional and exotic
  - ✓ Heavy meson
  - ✓ Heavy baryon
- Summary

I apologize for not covering all the experiments results.

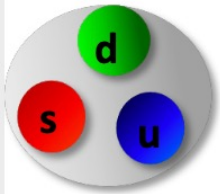
Introduction

- 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

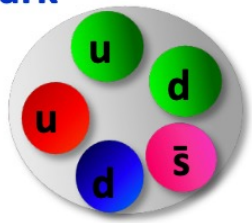
Mesons are color-anticolor pairs

π=ūd

Other possible combinations of quarks and gluons :

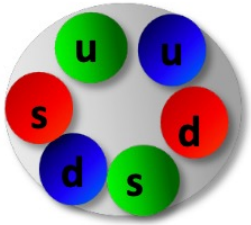
Pentaquark

S= +1 Baryon



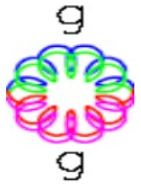
H di-Baryon

Tightly bound 6 quark state



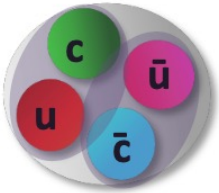
Glueball

Color-singlet multi-gluon bound state



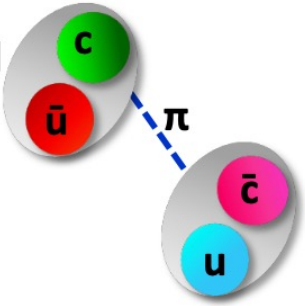
Tetraquark

Tightly bound diquark & anti-diquark

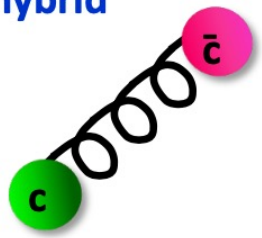


Molecule

loosely bound meson-antimeson "molecule"



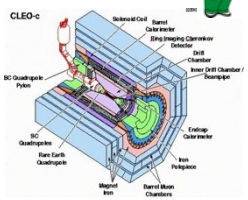
qq̄ -gluon hybrid mesons

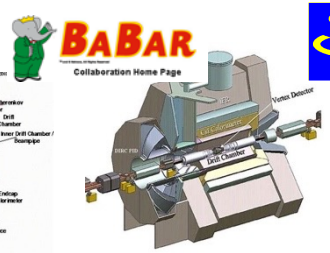


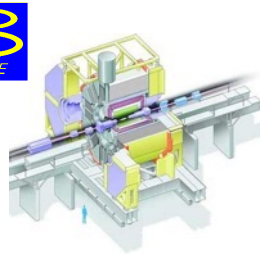
Main contributors worldwide

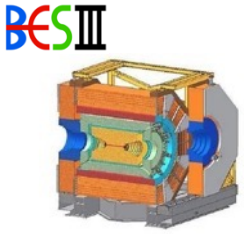
- e^+e^- collider

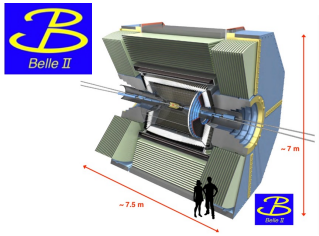
CLEO-c



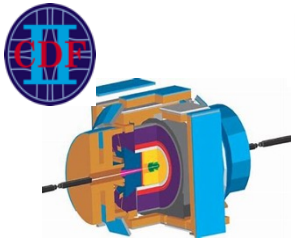


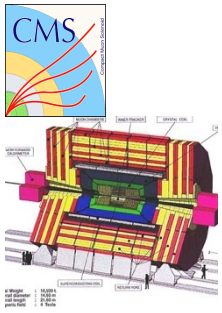




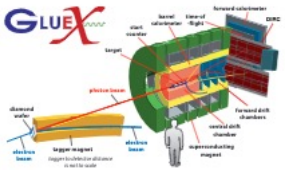


- Hadron collider

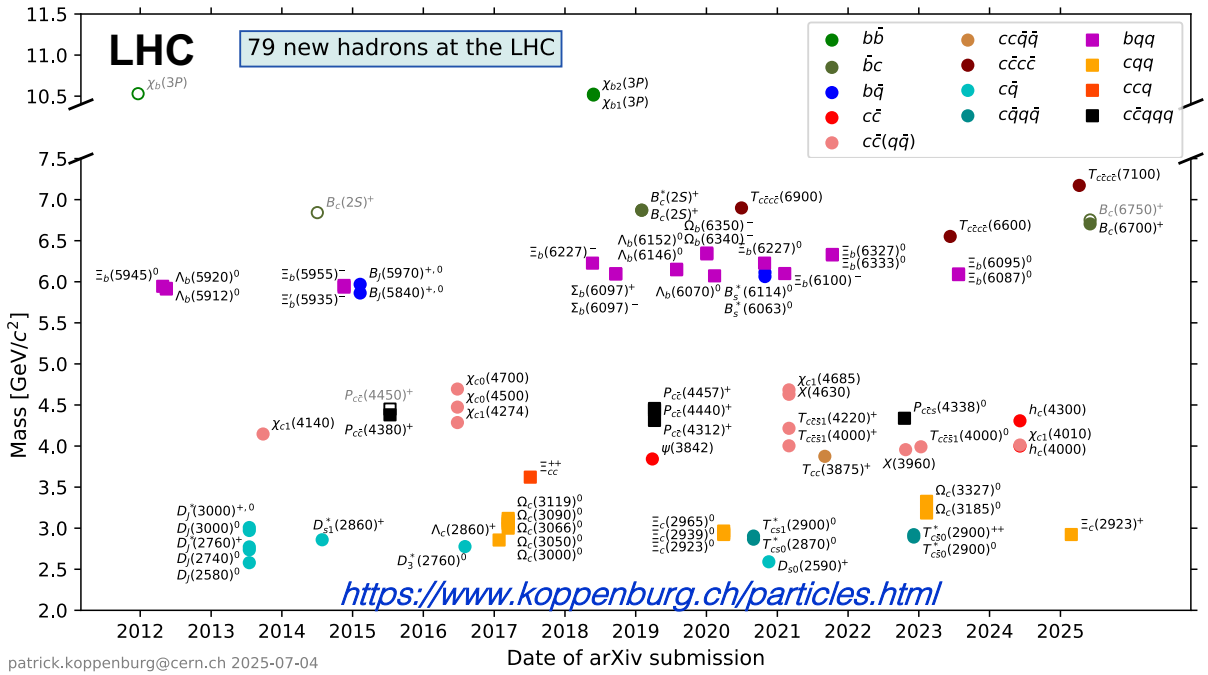


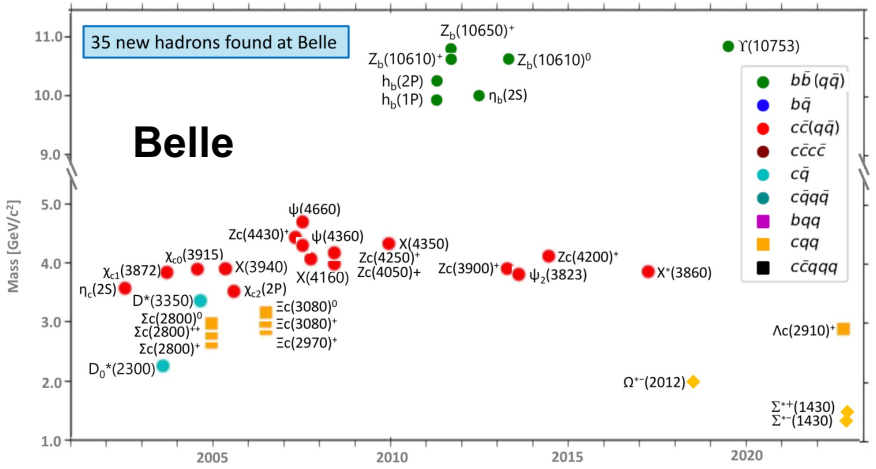


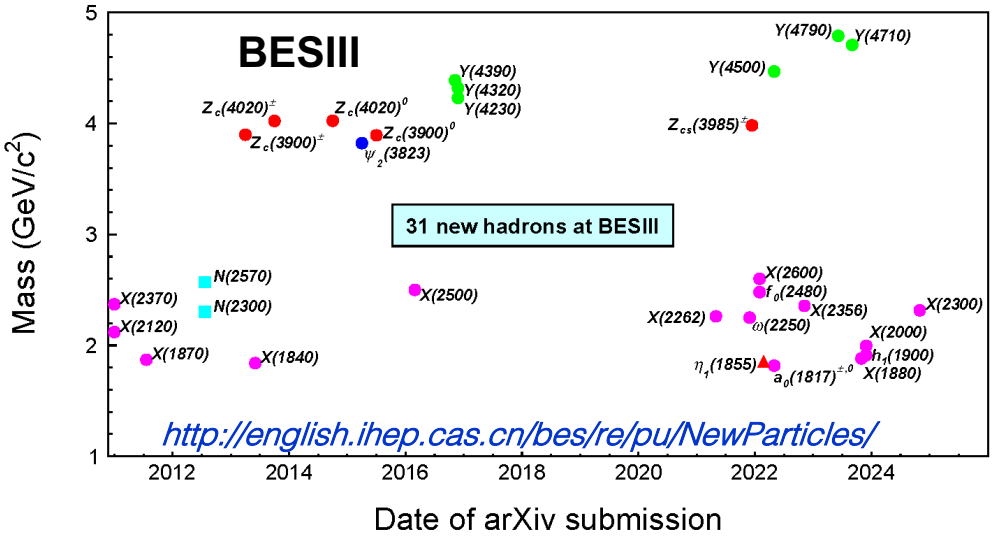
- Fixed-target experiments



Discoveries of many new hadrons

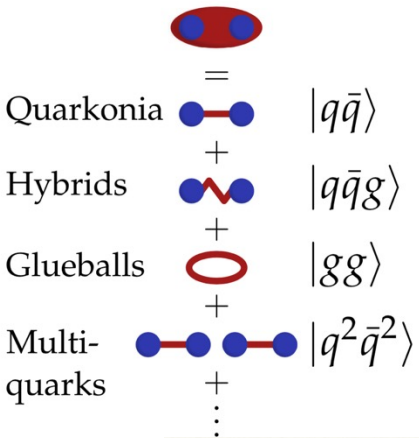




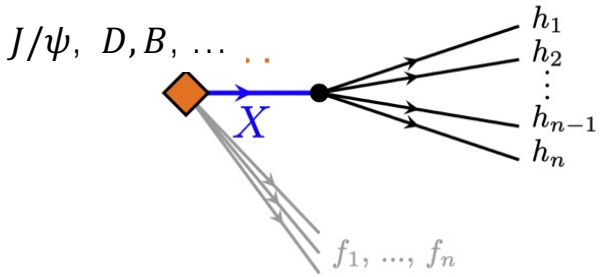


Light hadorns

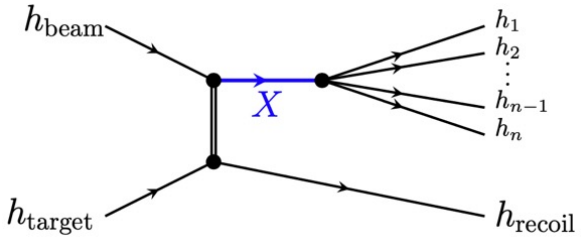
Light hadron spectroscopy

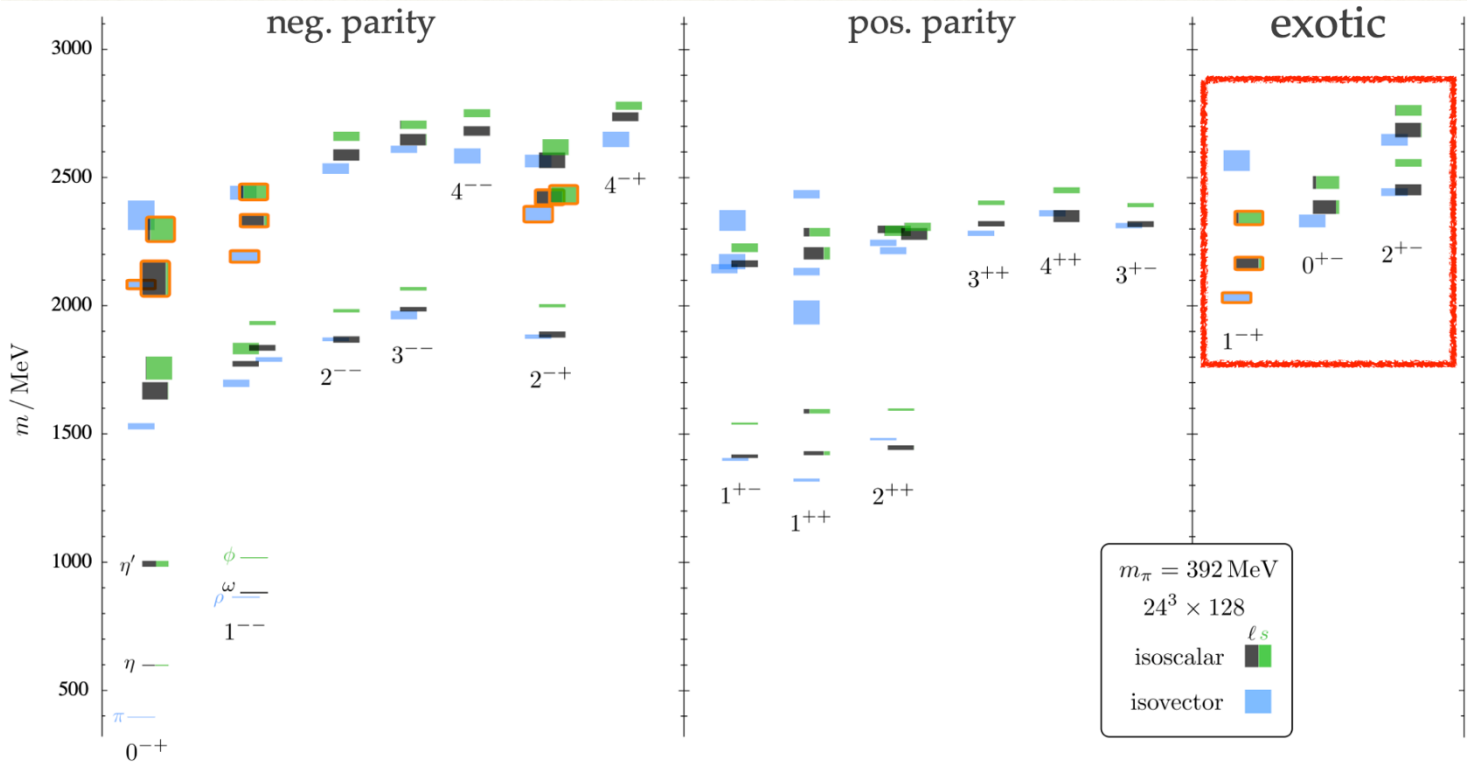


BESIII, LHCb, Belle (II) …

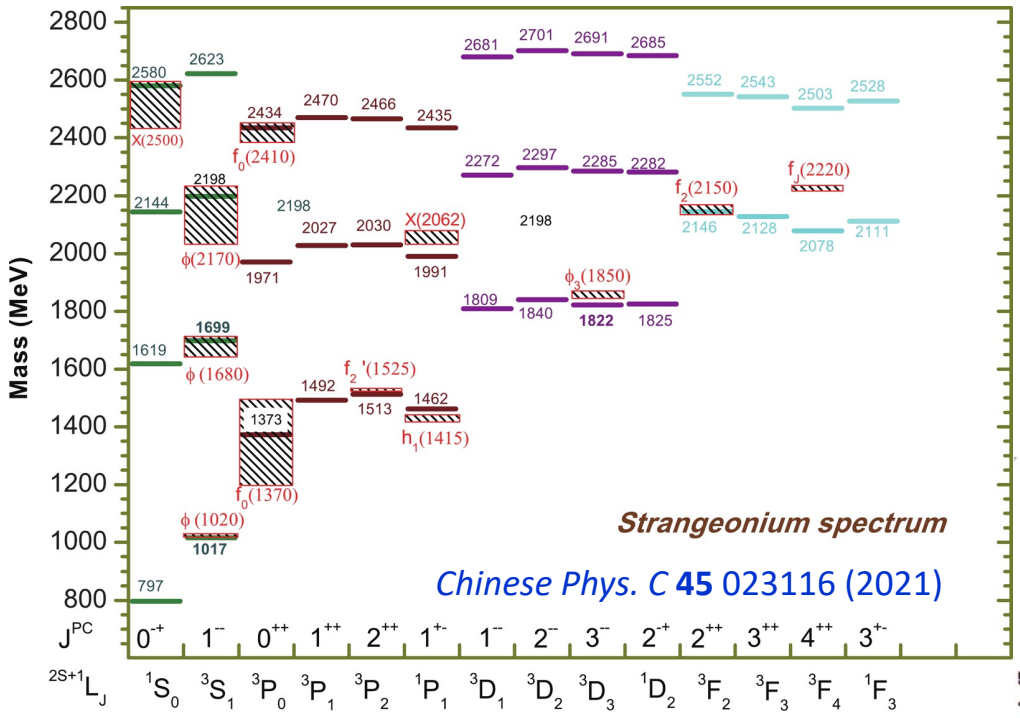


GlueX, Compasss, …

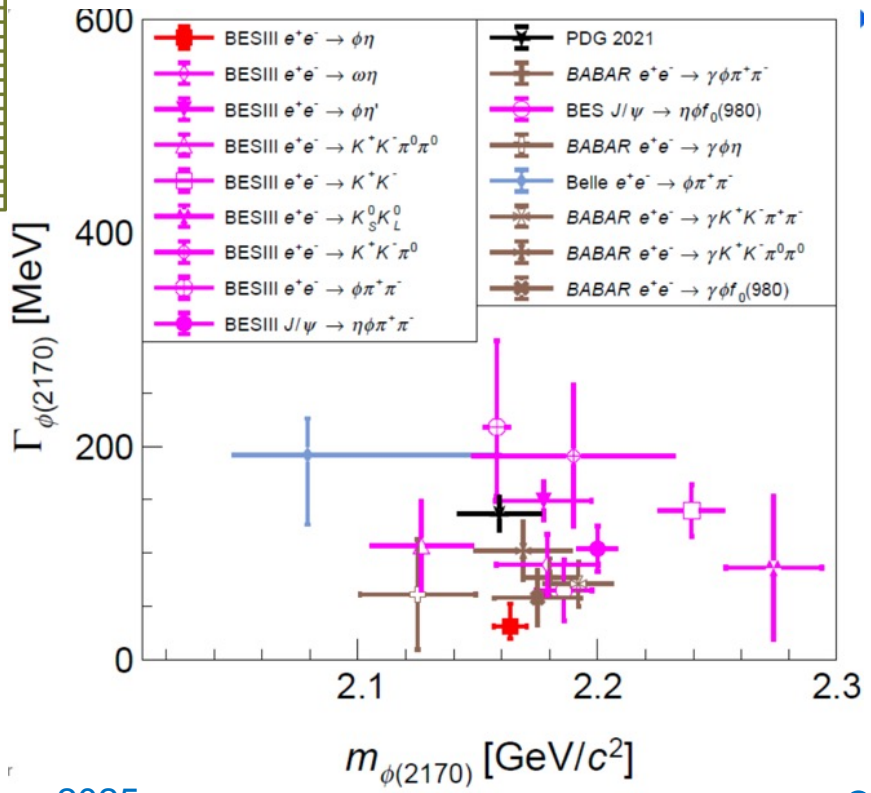




Strangeonium [$s\bar{s}$] spectroscopy



- **Y(2175)/ϕ(2170): a strangeonium(-like) state**

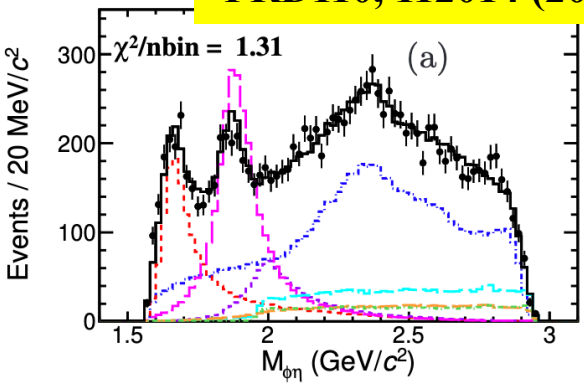


- **Theorists explain ϕ(2170) as**
  - ✓ **$s\bar{s}g$ hybrid**
  - ✓ **2^3D_1 or 3^3S_1 $s\bar{s}$**
  - ✓ **tetraquark**
  - ✓ **Molecular state $\Lambda\bar{\Lambda}$**
  - ✓ **$\phi f_0(980)$ resonance with FSI**
  - ✓ **Three body system ϕKK**

New axial-Vector strangeonia

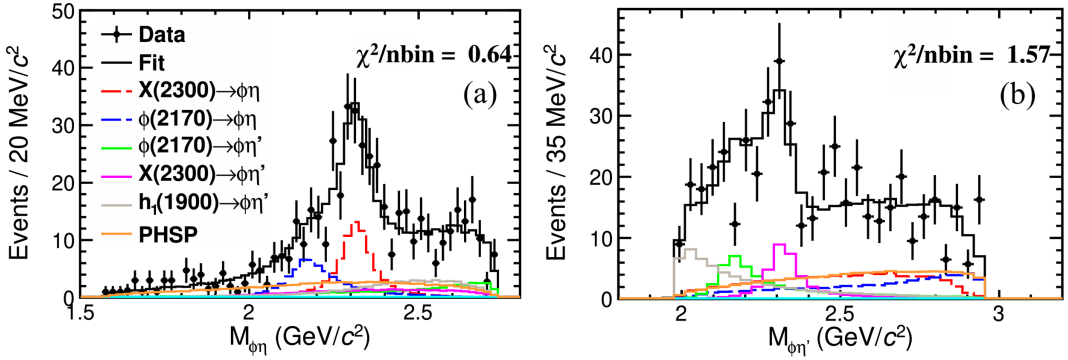
Based on 10B J/ψ events,
a PWA fit to $J/\psi \to \phi\eta\pi^0$

PRD110, 112014 (2024)



Based on 2.7B $\psi(3686)$ events,
a PWA fit to $\psi(3686) \to \phi\eta\eta'$

PRL134, 191901 (2025)



Process	M (MeV/c^2)	Γ (MeV)
$\phi(1680)\pi^0$	$1668 \pm 7 \pm 25$	$147 \pm 14 \pm 35$
$J^{PC} = 1^{--}$ $X(2000)\pi^0$	$1996 \pm 11 \pm 30$	$148 \pm 16 \pm 66$
$J^{PC} = 1^{+-}$ $h_1(1900)\pi^0$	$1911 \pm 6 \pm 14$	$149 \pm 12 \pm 23$
$\phi a_0(980)_{\rm EM}$	–	–
$\phi a_0(980)_{\rm mix}$	–	–

observations!

$h_1(2300)$ $\mathbf{J^{PC} = 1^{+-}}$ *observations!*

$M = 2316 \pm 9 \pm 30 \text{MeV/c}^2$
$\Gamma = 89 \pm 15 \pm 26$ MeV

- $h_1(1900)$: candidate for $h_1(2P)$ strangeonium state
- X(2000): candidate for $\phi(3S)$ or for $\phi(3D)$ strangeonium state
- $h_1(2300)$: mass lower than the predicted mass of $h_1(3P)$. Full strange $[s\bar{s}s\bar{s}]$ tetraquark candidate?

Spin-exotic light mesons

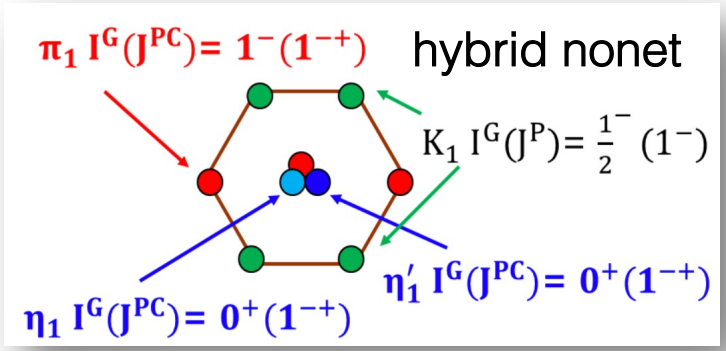
Over three decades, 4 candidates are reported so far.

Three 1^{-+} isovectors

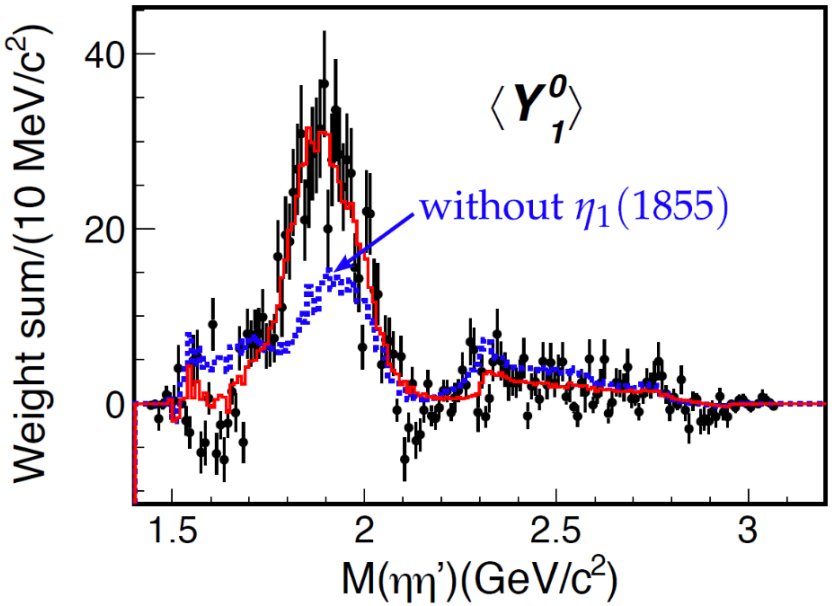
- $\pi_1(1400)$: seen in $\eta\pi$
- $\pi_1(1600)$: seen in $\rho\pi$, $\eta'\pi$, $b_1\pi$, $f_1\pi$
- $\pi_1(2015)$: seen in $b_1\pi$ and $f_1\pi$

One 1^{-+} isoscalar

- $\eta_1(1855)$: observed in $J/\psi \to \gamma\eta\eta'$



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



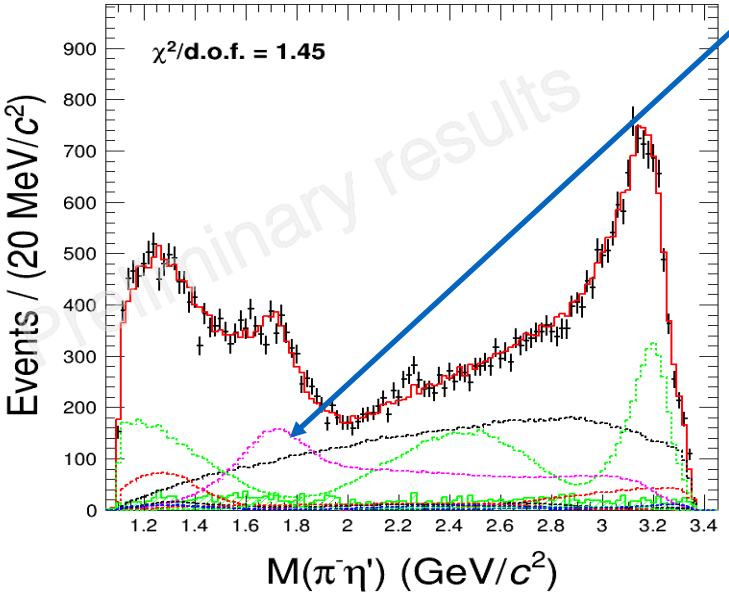
	Decay mode	Reaction	Experiment
$\pi_1(1400)$	$\eta\pi$	$\pi^-p \to \pi^-\eta p$ $\pi^-p \to \pi^0\eta n$ $\pi^-p \to \pi^-\eta p$ $\pi^-p \to \pi^0\eta n$ $\bar{p}n \to \pi^-\pi^0\eta$ $\bar{p}p \to \pi^0\pi^0\eta$	GAMS KEK E852 E852 CBAR CBAR
	$\rho\pi$	$\bar{p}p \to 2\pi^+2\pi^-$	Obelix
$\pi_1(1600)$	$\eta'\pi$	$\pi^-Be \to \eta'\pi^-\pi^0Be$ $\pi^-p \to \pi^-\eta' p$	VES E852
	$b_1\pi$	$\pi^-Be \to \omega\pi^-\pi^0Be$ $\bar{p}p \to \omega\pi^+\pi^-\pi^0$ $\pi^-p \to \omega\pi^-\pi^0 p$	VES CBAR E852
	$\rho\pi$	$\pi^-Pb \to \pi^+\pi^-\pi^-X$ $\pi^-p \to \pi^+\pi^-\pi^- p$	COMPASS E852
	$f_1\pi$	$\pi^-p \to p\eta\pi^+\pi^-\pi^-$ $\pi^-A \to \eta\pi^+\pi^-\pi^-A$	E852 VES
$\pi_1(2015)$	$f_1\pi$	$\pi^-p \to \omega\pi^-\pi^0 p$	E852
	$b_1\pi$	$\pi^-p \to p\eta\pi^+\pi^-\pi^-$	

Some studies indicated that $\pi_1(1400)$ and $\pi_1(1600)$ can be one pole [EPJC 81, 1056 (2021)][PRL122, 042002 (2019)]

Observation of $\pi_1(1600)$ in $\chi_{c1} \to \eta'\pi^+\pi^-$

- $\chi_{c1} \to \pi^+\pi^-\eta'$ process provides an opportunity to search for $J^{PC} = 1^{-+}$ exotics in the $\eta'\pi$ systems.
- CLEO-c found evidence for an exotic P-wave $\eta'\pi$ amplitude around 1.6 GeV with ~4σ in this process.

- With 2.7B $\psi(3686)$ events, BESIII performs amplitude analysis of $\chi_{c1} \to \pi^+\pi^-\eta'$ via $\psi(3686) \to \gamma\chi_{c1}$



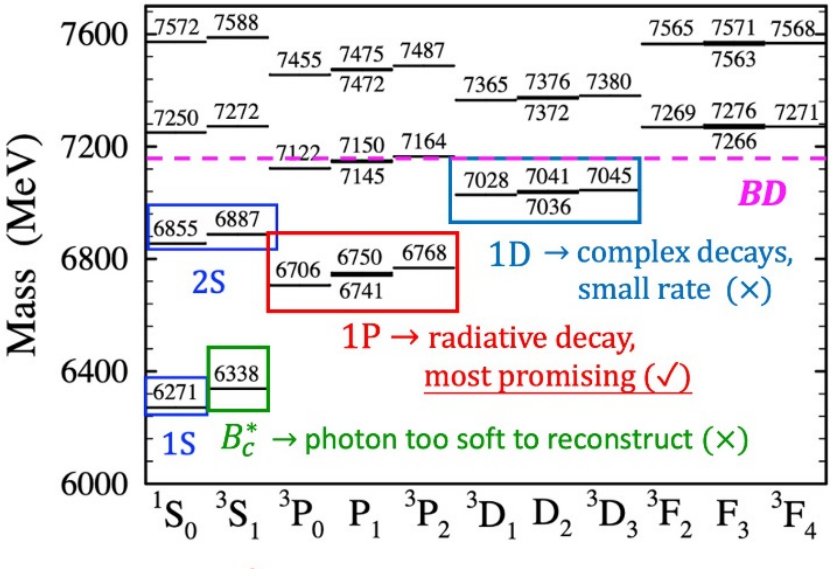
state	J^{PC}	Decay mode	Significance
$\pi_1(1600)$	1^{-+}	$\pi^\pm\eta'$	$>> 10\sigma$
$(\pi\pi)_{S-wave}$	0^{++}	$\pi^\pm\eta'$	$>> 10\sigma$
$a_0(980)$	0^{++}	$\pi^\pm\eta'$	$> 10\sigma$
$f_2(1270)$	2^{++}	$\pi^+\pi^-$	$>> 10\sigma$
$a_2(1320)$	2^{++}	$\pi^\pm\eta'$	$> 5\sigma$
$f_2(1950)$	2^{++}	$\pi^+\pi^-$	$> 10\sigma$
$f_0(2200)$	0^{++}	$\pi^+\pi^-$	$> 10\sigma$
$a_0(1710)$	0^{++}	$\pi^\pm\eta'$	$> 10\sigma$
$f_2(PHSP)$	2^{++}	$\pi^+\pi^-$	$> 5\sigma$

Spin-parity of the $\pi_1(1600)$ favors $J^{PC} = 1^{-+}$ is favored over 0^{++}, 2^{++} and 4^{++} assignments with significances larger than 10σ

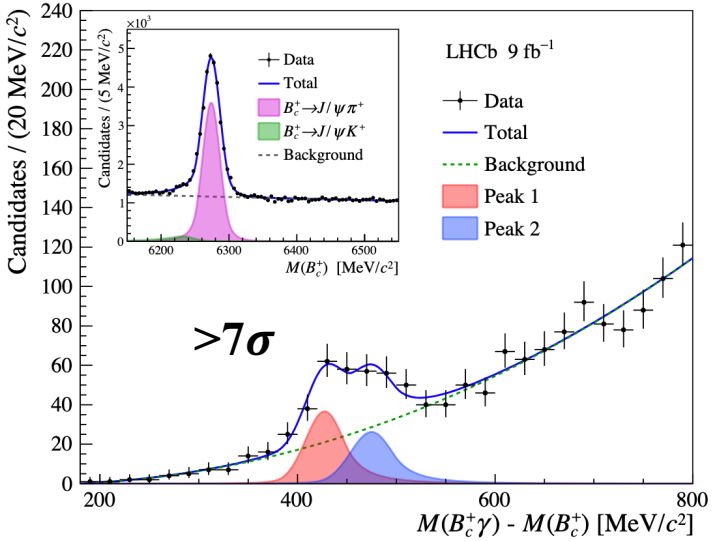
Heavy mesons

Observation of the P-wave $B_c^+(1P)$

- In 1998, the B_c meson was discovered at the Tevatron
- Despite its ground state, only the 2S states have been observed at the LHC in 2014 and 2019
- LHCb studies $B_c^+(1P) \to \gamma B_c^+$

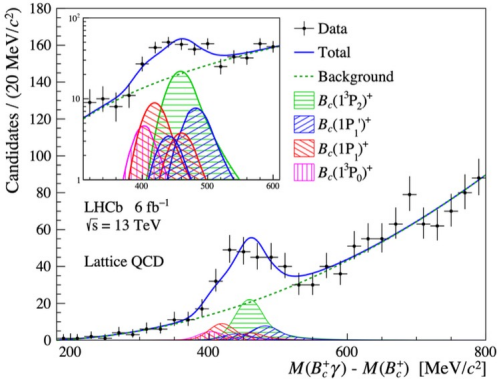


arXiv:2507.02142; arXiv:2507.02149



$$M_1 = 6704.8 \pm 5.5 \pm 2.8 \pm 0.3 \ \text{MeV}/c^2,$$
$$M_2 = 6752.4 \pm 9.5 \pm 3.1 \pm 0.3 \ \text{MeV}/c^2,$$

Theory-constrained six-peak fit



The observed structure is expected to be contributed from multiple $B_c^+(1P) \to B_c^{*+}\gamma$ decays, which requires larger statistics and better resolution to be distinguished.

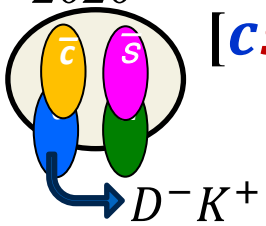
Open-charm tetraquark states

$B^+ \to D^+ D^- K^+$

$B^+ \to D^- D_s^+ \pi^+$
$B^0 \to \bar{D}^0 D_s^+ \pi^-$

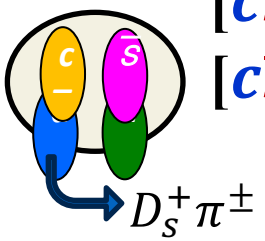
$B^+ \to D^{*\pm} D^{\mp} K^+$

2020 $[cs\bar{u}\bar{d}]$



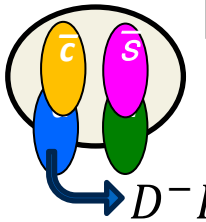
PRL125, 242001 (2020)
PRD102, 112003 (2020)

2023 $[c\bar{s}\bar{u}d]$ $[c\bar{s}u\bar{d}]$

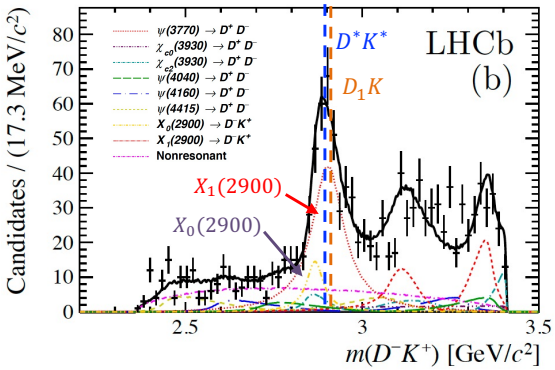


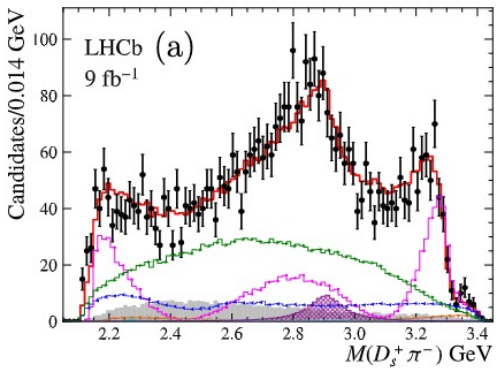
PRL131, 041902(2023)
PRD108, 012017(2023)

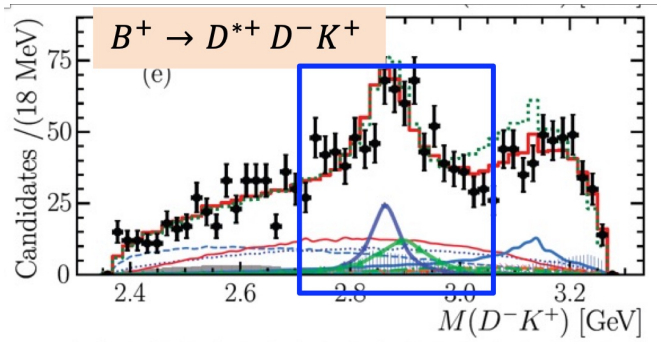
2024 $[cs\bar{u}\bar{d}]$



PRL133, 131902 (2024)





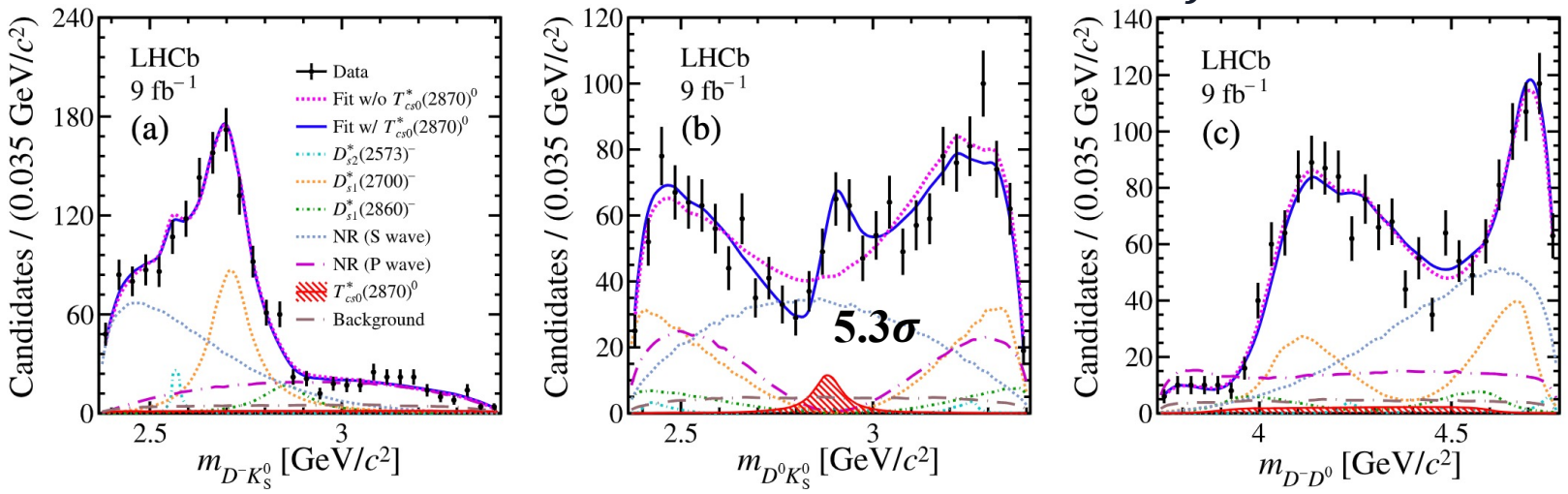


	Mass (GeV)	Width (GeV)	J^P
$T^*_{c\bar{s}0}(2900)^0$ & $T^*_{c\bar{s}0}(2900)^{++}$	$2.908 \pm 0.011 \pm 0.020$	$0.136 \pm 0.023 \pm 0.020$	0^+
$X_0(2900)/T^*_{cs0}(2870)^0$	$2.866 \pm 0.007 \pm 0.002$	$0.057 \pm 0.012 \pm 0.004$	0^+
$X_1(2900)/T^*_{cs1}(2900)^0$	$2.904 \pm 0.005 \pm 0.001$	$0.110 \pm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

$T^*_{cs0}(2870)^0$ [$cs\bar{u}\bar{d}$] in $B^- \to D^- D^0 K^0_S$

PRL134, 101901 (2025)

Amplitude analysis of various components of D^{**-}_{sJ} and T^*_{cs0} states



- **Observation** of a resonant $J^P = 0^+$ structure, named $T^*_{cs0}(2870)^0$, in the $D^0K^0_s$ system with 5.3σ significance, **no observation** of $T^*_{cs1}(2900)^0$
- Relative decay width provide precise tests of the **isospin symmetry**

$$R_{\rm I}(T^{*0}_{cs}) = \frac{\mathcal{B}(B^- \to D^- D^0 \overline{K}^0)\mathrm{FF}(T^{*0}_{cs} \to D^0 K^0_{\rm S})}{\mathcal{B}(B^- \to D^- D^+ K^-)\mathrm{FF}(T^{*0}_{cs} \to D^+ K^-)}$$

$$M(T^{*0}_{cs0}) = 2883 \pm 11 \pm 8 \ \mathrm{MeV}/c^2,$$
$$\Gamma(T^{*0}_{cs0}) = 87^{+22}_{-47} \pm 17 \ \mathrm{MeV},$$

- $R_{\rm I}(T^*_{cs0}(2870)^0) = 3.3 \pm 1.1_{\rm stat.} \pm 1.1_{\rm syst.} \pm 1.1_{\rm ext.}$ and $R_{\rm I}(T^*_{cs1}(2900)^0) = 0.15 \pm 0.15_{\rm stat.} \pm 0.05_{\rm syst.} \pm 0.05_{\rm ext.}$

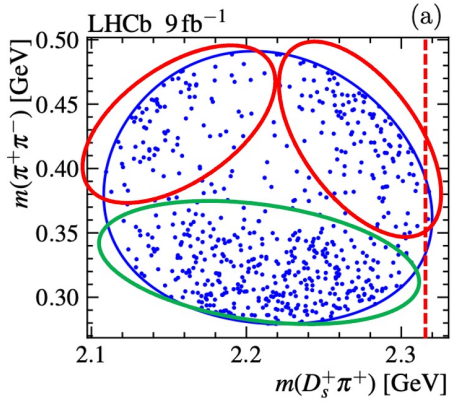
isospin violation indicated for $T^*_{cs0}(2900)^0$

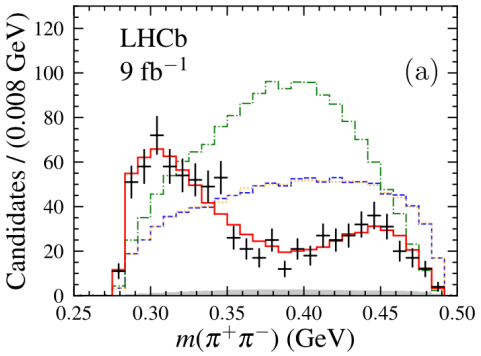
$T_{c\bar{s}}^{0/++}$ in $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$

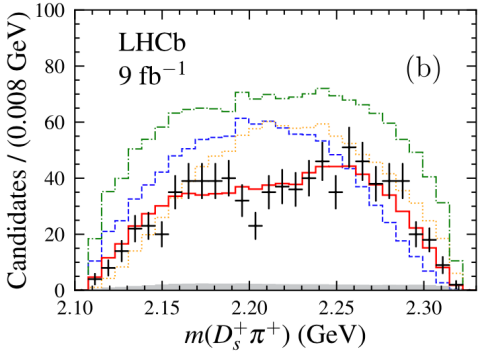
Joint amplitude analysis of the three channels

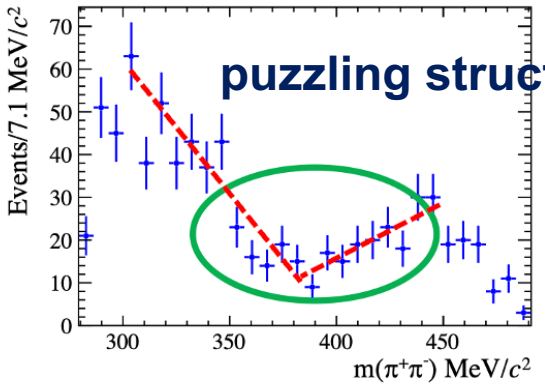
Sci. Bull. 70, 1432 (2025)

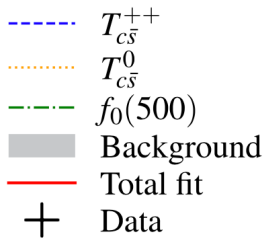
$B^+ \to \bar{D}^0 D_{s1}(2460)^+$, $B^0 \to D^{(*)-} D_{s1}(2460)^+$ ($D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$)

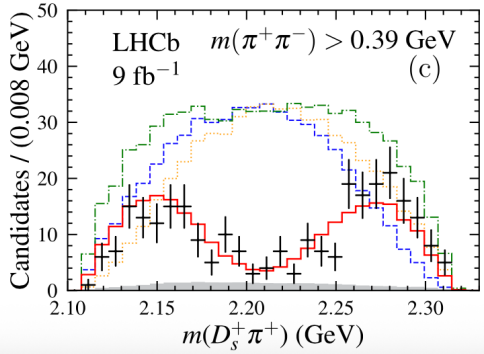










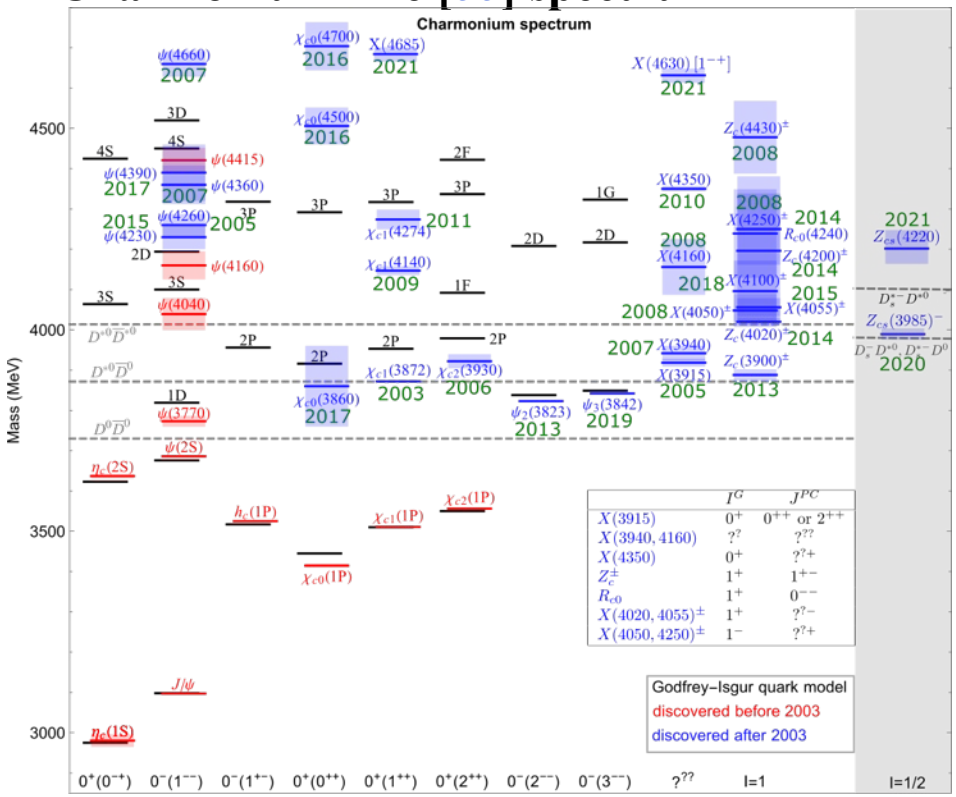


Resonance	Mass (MeV)	Width (MeV)	Fractions (%)
$f_0(500)$	$474 \pm 30 \pm 18$	$224 \pm 23 \pm 16$	$248^{+40}_{-54} \pm 39$
$T_{c\bar{s}}^{++}/T_{c\bar{s}}^{0}$	$2327 \pm 13 \pm 13$	$96 \pm 16 \pm 23$	$156^{+27}_{-38} \pm 25$

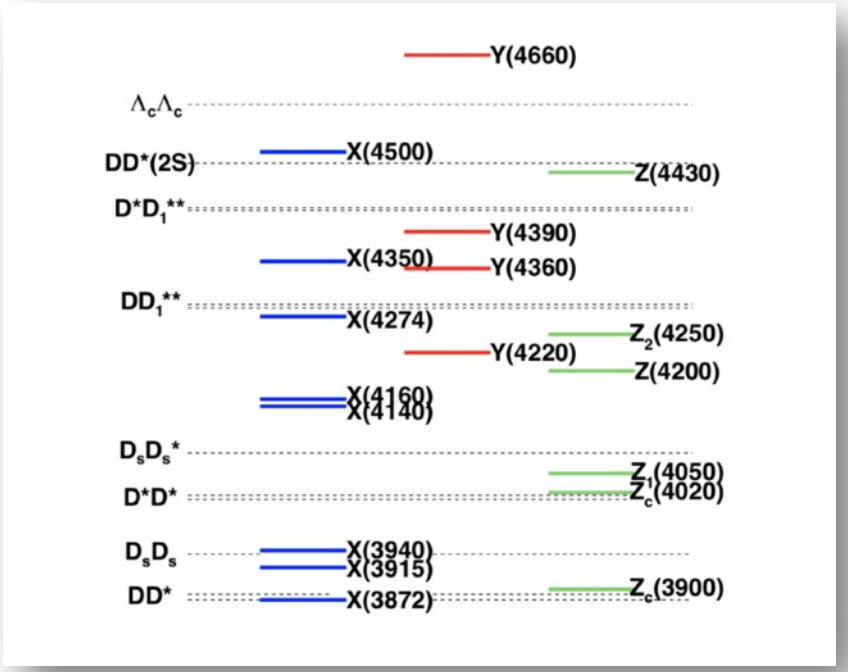
$T_{c\bar{s}}^{0/++}$ is observed with significance larger than 10σ

Overpopulated charmonium spectrum

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

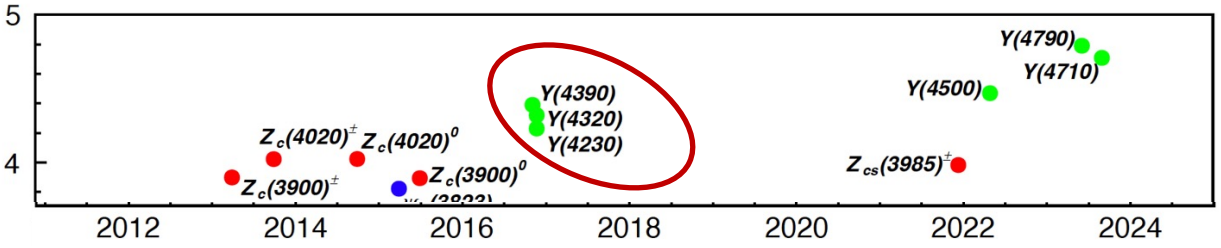


arXiv:1511.01589, arXiv:1812.10947



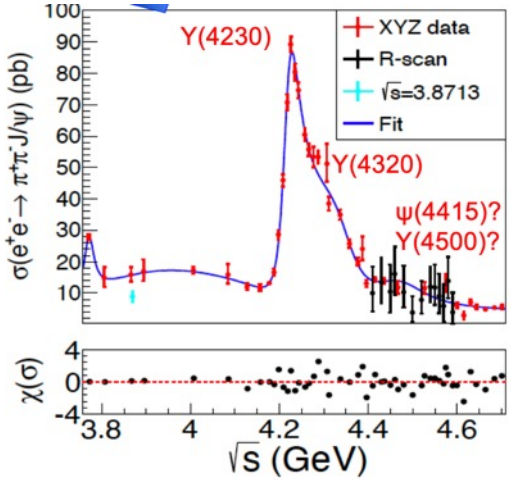
Overpopulated observed new charmonium-like states, i.e. "XYZ":

- 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



PRD106, 072001 (2022)

Date of arXiv submission



Y(4260) ➔ Y(4230) & Y(4320)

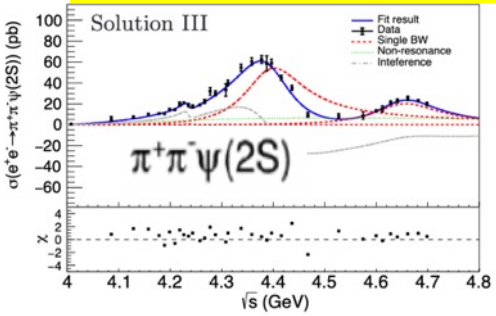
$M_{Y(4230)} = 4221.4 \pm 1.5 \pm 2.0$ MeV/c^2

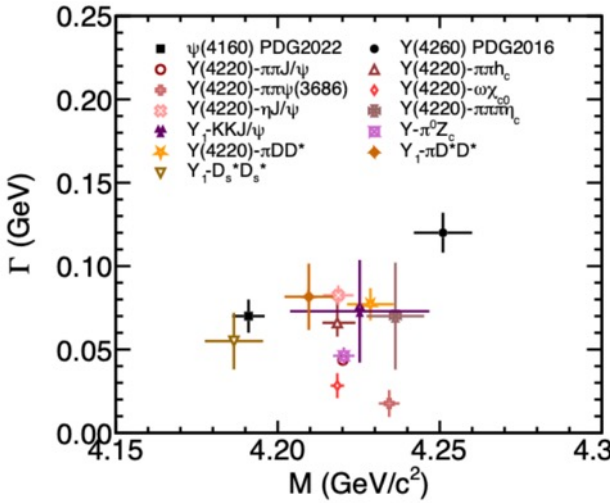
$\Gamma_{Y(4230)} = 41.8 \pm 2.9 \pm 2.7$MeV

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

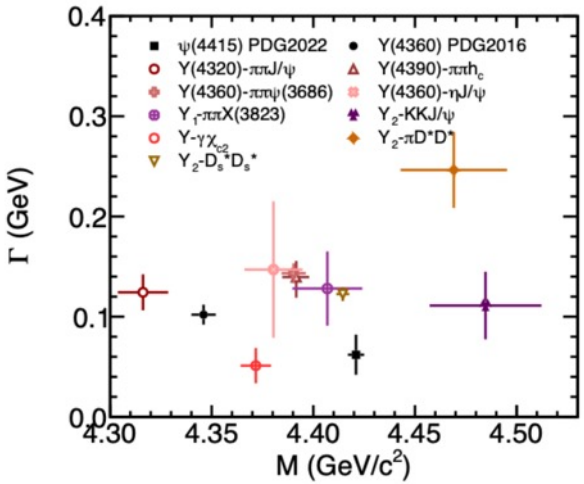
$\Gamma_{Y(4320)} = 127 \pm 17 \pm 10$ MeV

PRD 104, 052012 (2021)

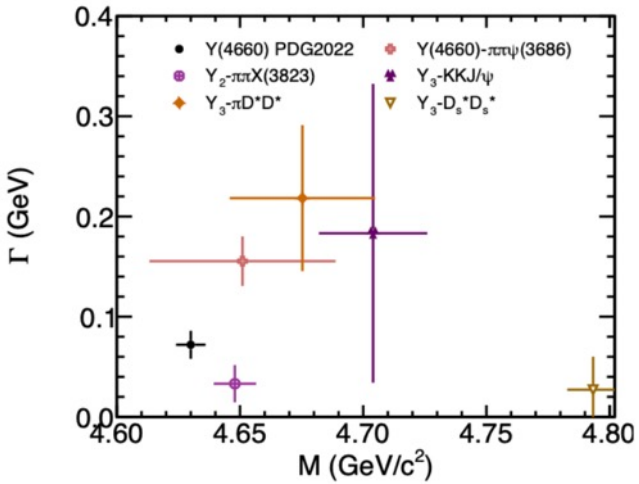




Y(42XX)



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

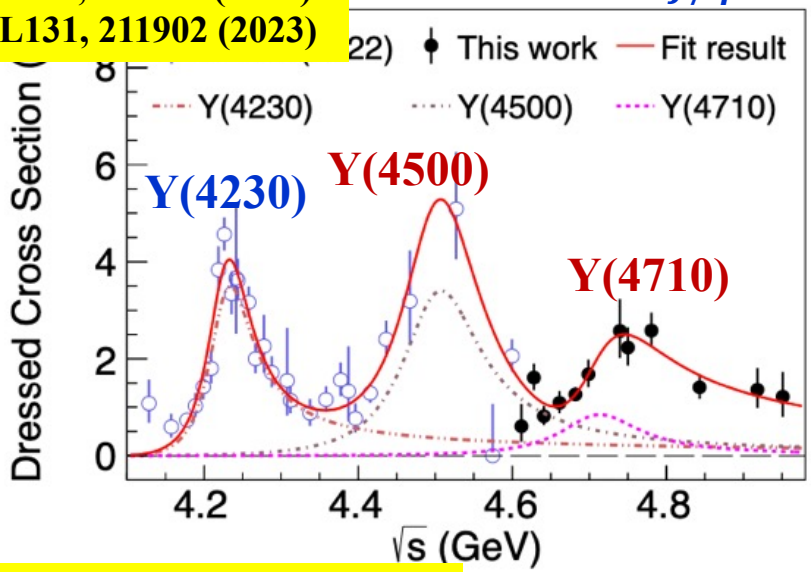


Y(46XX), Y(47XX)

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

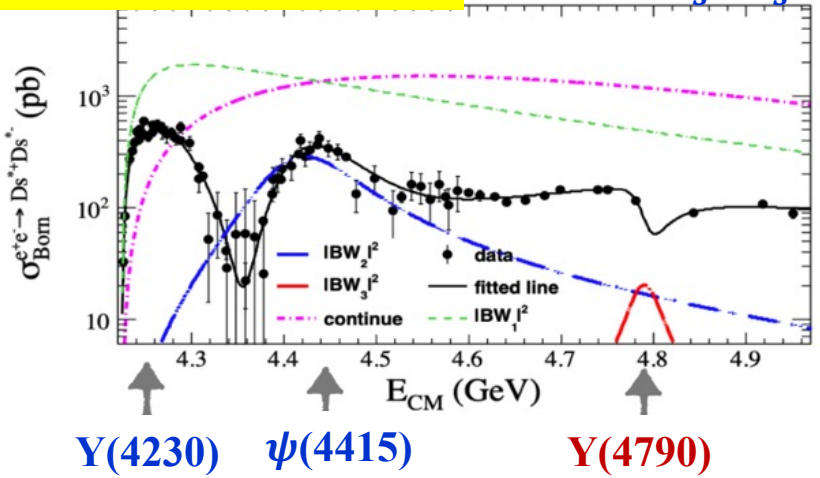
CPC 46, 111002 (2022)
PRL131, 211902 (2023)

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



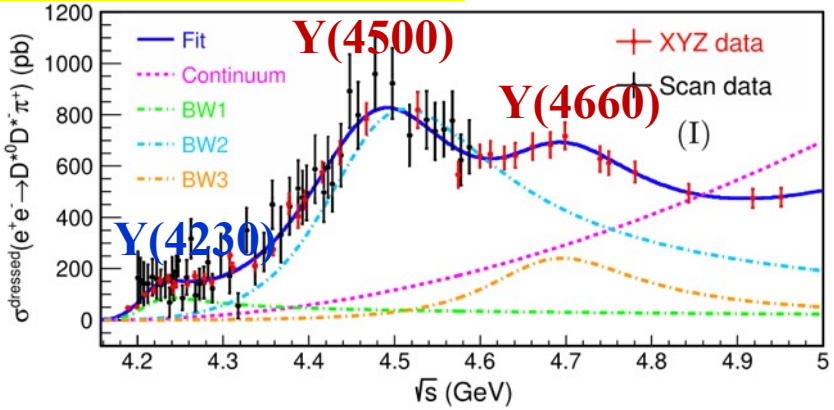
PRL131, 151903 (2023)

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



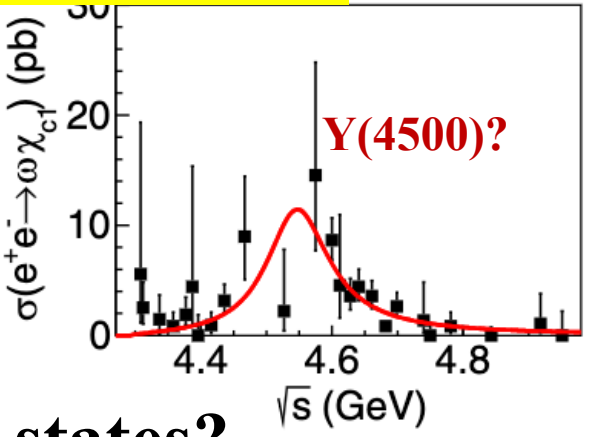
PRL130, 121901 (2023)

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



PRL 132, 161901 (2024)

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

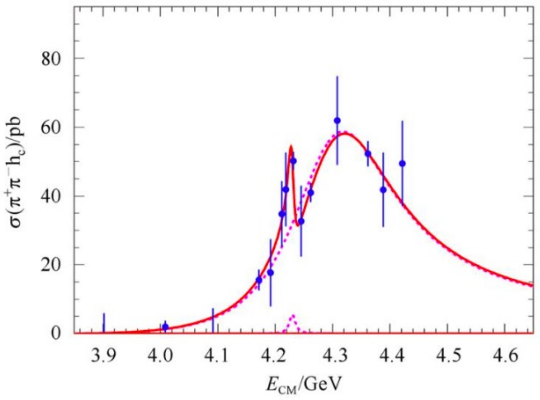


Are they $[c\bar{c}s\bar{s}]$ states?

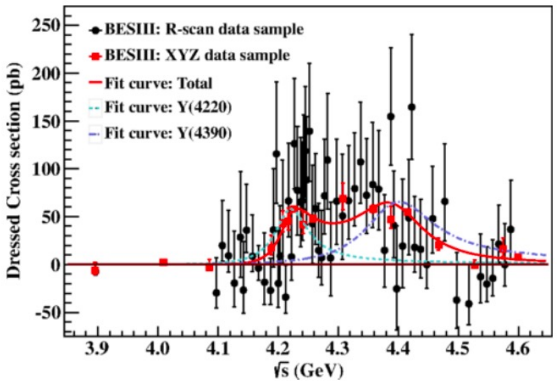
Improved measurement of $\sigma(e^+e^- \to \pi^+\pi^- h_c)$

PRL135, 071901 (2025)

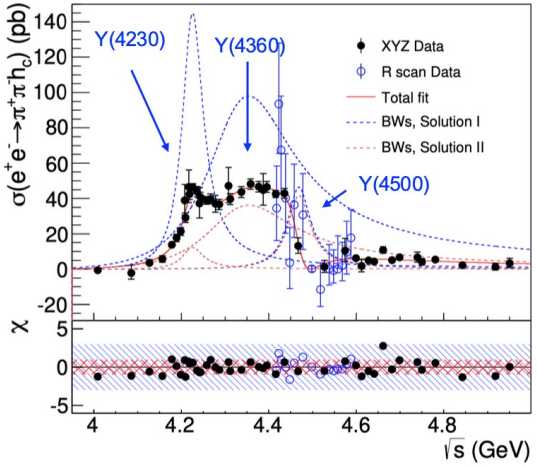
- Initially observed by CLEO-c at √s=4.17 GeV [PRL107, 041803 (2011)]
- Cross sections of $e^+e^- \to \pi^+\pi^- h_c$ obtained by BESIII at 3.9-4.6 GeV, found two structures [PRL118, 092002 (2017)]
- New data collected by BESIII between 4.18-4.95 GeV (27 data samples)



PRL107, 041803 (2011) – CLEO-c
PRL111, 242001 (2013) – BESIII
CPC 38, 043001 (2014)



PRL118, 092002 (2017) - BESIII



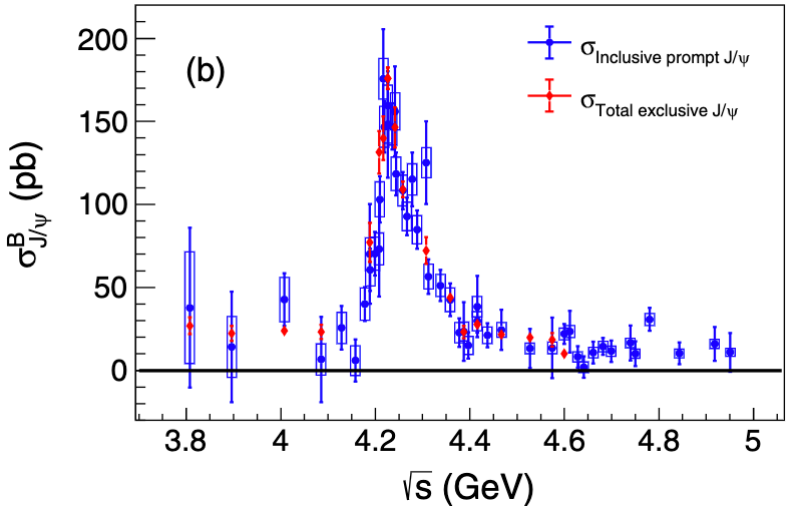
PRL135, 071901 (2025)

Parameter	Y(4230) R_1	Y(4360) R_2	>5σ Y(4500) R_3
M (MeV/c^2)	$4223.6^{+3.6+2.6}_{-3.7-2.9}$	$4327.4^{+20.1+10.7}_{-18.8-9.3}$	$4467.4^{+7.2+3.2}_{-5.4-2.7}$
Γ (MeV)	$58.5^{+10.8+6.7}_{-11.4-6.5}$	$244.1^{+34.0+24.2}_{-27.1-18.3}$	$62.8^{+19.2+9.9}_{-14.4-7.0}$

a bit larger width
$\Gamma_{Y(4360)}$= 120±21 MeV

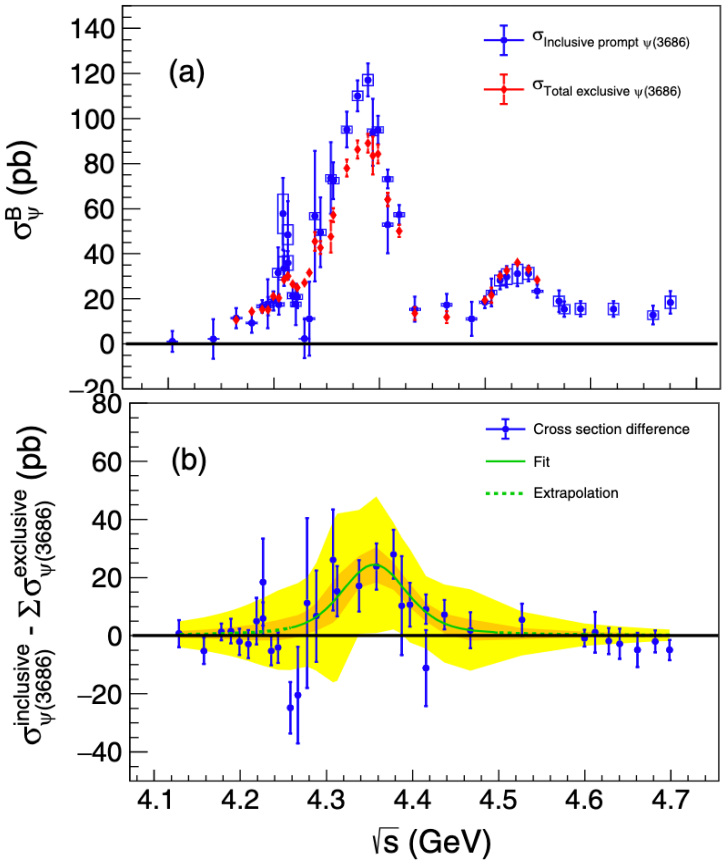
Inclusive and exclusive J/ψ and $\psi(3686)$ production

PRD111, 052007 (2025)



no evidence of hidden decays involving the J/ψ meson

$c\bar{c}$ Meson	Decays into J/ψ	Decays into $\psi(3686)$
$\chi_{c1}(3872)$	$\pi^+\pi^- J/\psi, \omega J/\psi, \gamma J/\psi$	$\gamma\psi(3686)$
$Z_c(3900)$	$\pi J/\psi$	...
$\chi_{c0}(3915)$	$\omega J/\psi$	...
$\psi(4040)$	$\eta J/\psi$	...
$X(4160)$	$\phi J/\psi$	...
$\psi(4230)$	$\pi\pi J/\psi, KK J/\psi, \eta J/\psi$	$\pi^+\pi^-\psi(3686)$
$X(4350)$	$\phi J/\psi$	...
$\psi(4360)$	$\pi^+\pi^- J/\psi, \eta J/\psi$	$\pi^+\pi^-\psi(3686)$
$Y(4500)$	$K^+K^- J/\psi$	...
$\psi(4660)$	...	$\pi^+\pi^-\psi(3686)$
$Y(4710)$	$K^0K^0 J/\psi$	...

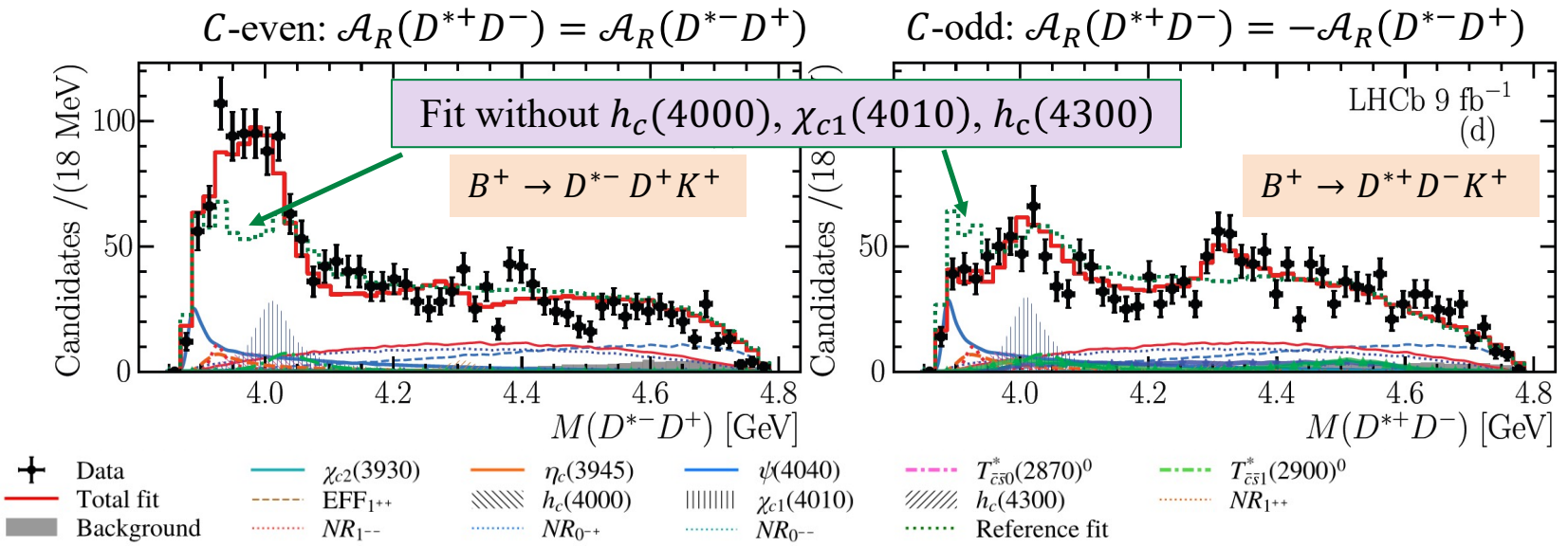


- Missing exclusive processes around the Y(4360) region
- Excess ~ 23% of the $Y(4360)_{\text{prompt}}$ inclusive cross section

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

PRL133, 131902 (2024)

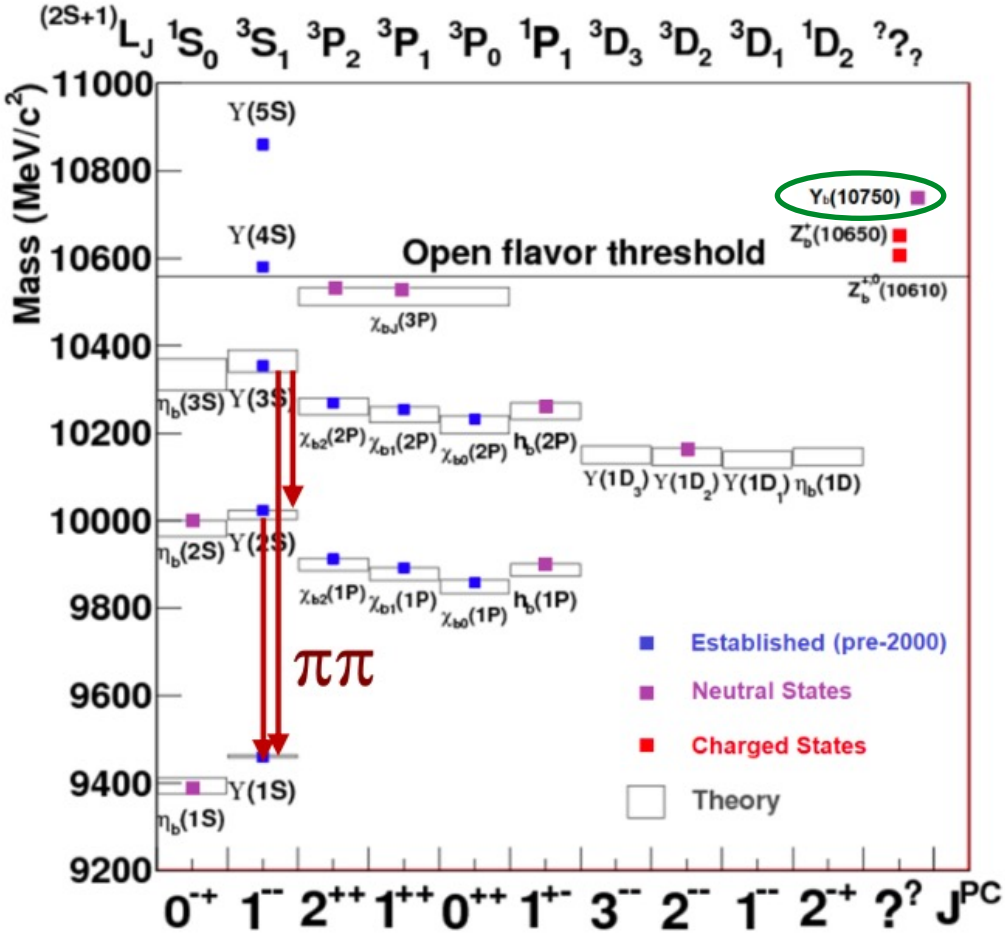
- **Simultaneous fit to $B^+ \to D^{*+} D^- K^+$ and $D^{*-} D^+ K^+$ to relate the C-parities of the charmonium(-like) states $R \to D^{*+} D^-$ and $R \to D^{*-} D^+$:**



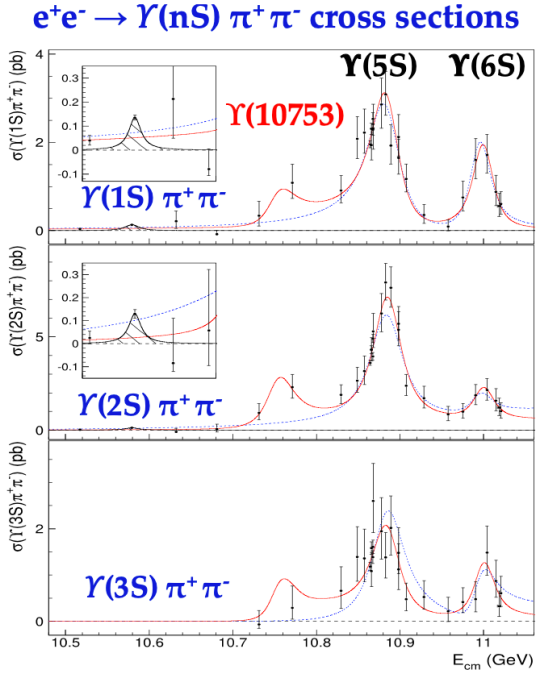
This work		Known states [6]		$c\bar{c}$ prediction [34]	
$\eta_c(3945)$	$J^{PC} = 0^{-+}$	$X(3940)$ [9,10]	$J^{PC} = ?^{??}$	$\eta_c(3S)$	$J^{PC} = 0^{-+}$
$m_0 = 3945\,^{+28}_{-17}\,^{+37}_{-28}$	$\Gamma_0 = 130\,^{+92}_{-49}\,^{+101}_{-70}$	$m_0 = 3942 \pm 9$	$\Gamma_0 = 37\,^{+27}_{-17}$	$m_0 = 4064$	$\Gamma_0 = 80$
~~$h_c(4000)$~~	$J^{PC} = 1^{+-}$	$T_{c\bar{c}}(4020)^0$ [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 $h_c(3P)$

Bottomium(-like) [$b\bar{b}$] states



Belle, JHEP10, 220 (2019)

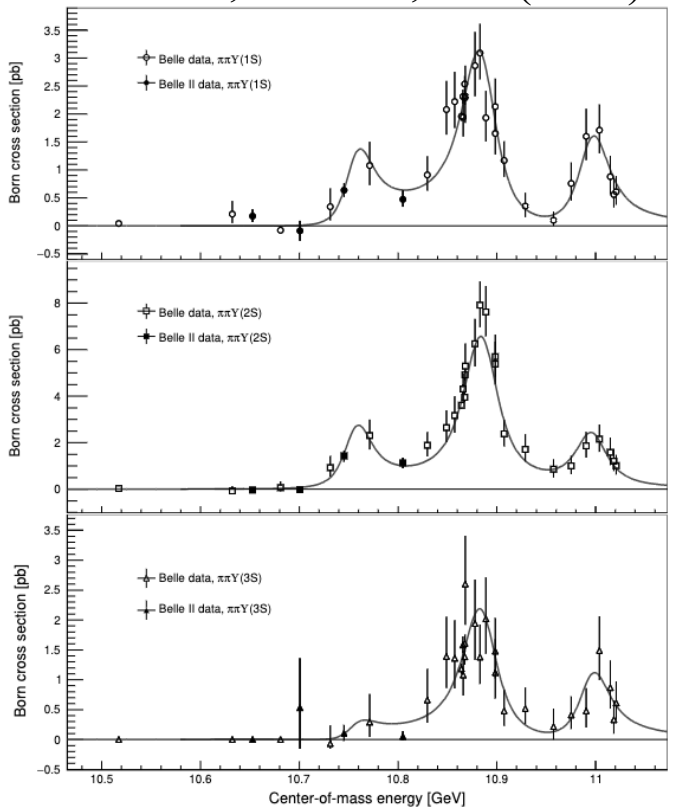


$\Upsilon(10753)$ property has Very high partial widths of hadronic transitions

- D-wave state with S-D mixing enhanced due to hadron loops
- exotic state: hybrid, tetraquark

Further investigation on the $\Upsilon(10753)$

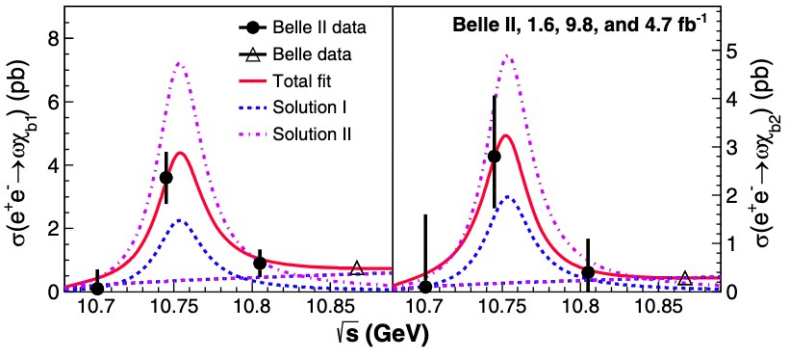
Belle II, JHEP07, 116 (2024)



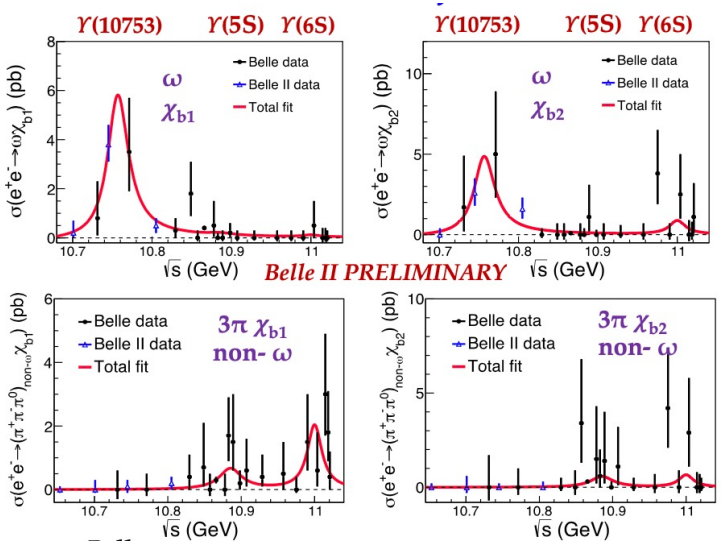
Excellent confirmation

- **M = (10756.6 ± 2.7 ± 0.9) MeV/c²**
- **Γ = (29.0 ± 8.8 ± 1.2) MeV**

Belle II, PRL130, 091902 (2023)



observation of $\Upsilon(10753) \to \omega\chi_{b1,2}$

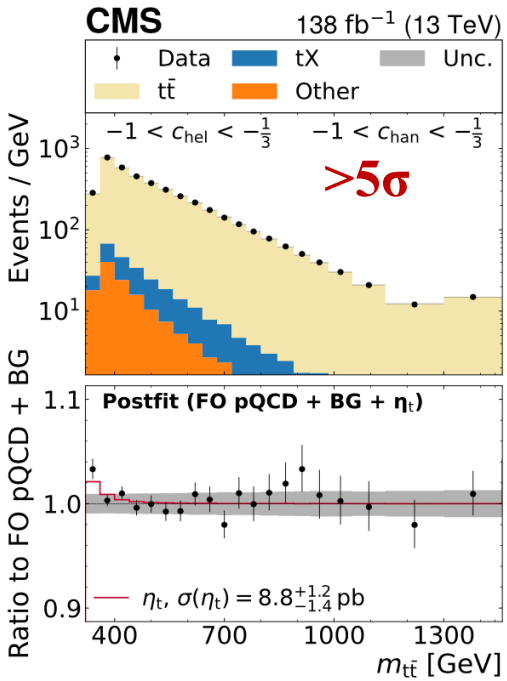


Different resonances display different preferences for ω vs. 3π (non-ω) decays!

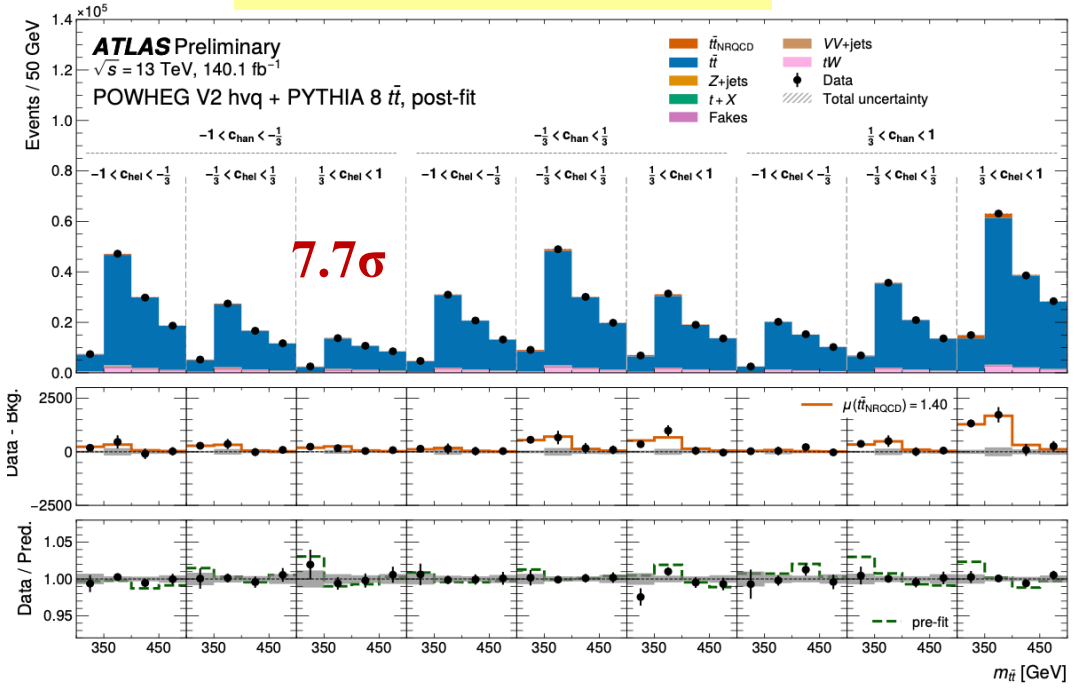
Toponium [$t\bar{t}$] state?

- $t\bar{t}$ pairs do not form stable bound states given the short lifetime of the top quark
- Non-Relativistic QCD predicts the formation at threshold ($m_{t\bar{t}}$~345 GeV) of **quasi-bound-state** (**Toponium**): spin-singlet-color-singlet ${}^1S_0^{[1]}$ η_t
- Experimentally extremely challenging: small effect (1% of total xs) and very large experimental resolution

CMS, arXiv:2503.22382;
arXiv:2507.05119



ATLAS-CONF-2025-008



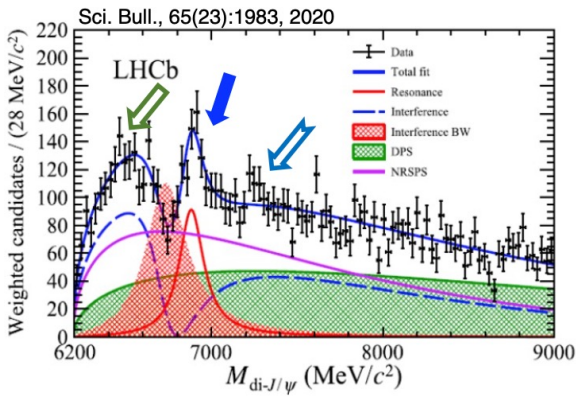
Data are consistent with a color-singlet ${}^1S_0^{[1]}$ $t\bar{t}$ quasi-bound state η_t

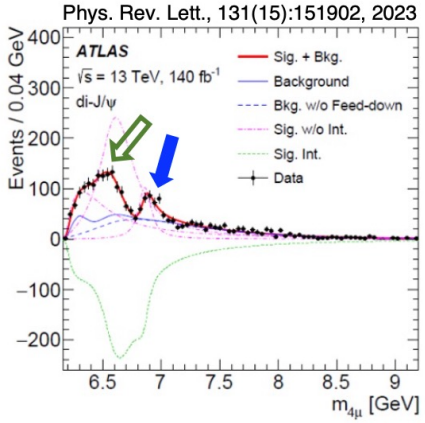
Study on fully heavy tetraquark state

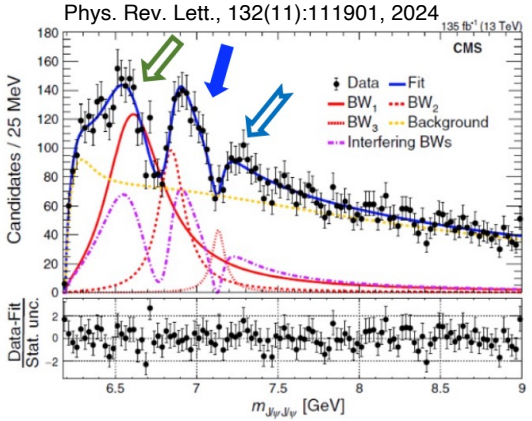
- Existence of $T_{Q_1Q_2\bar{Q}_3\bar{Q}_4}$ states ($Q_i = c$ or b) is expected by many QCD models
- $T_{bb\bar{b}\bar{b}}$ was searched for at LHCb and CMS, but not observed

[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)]



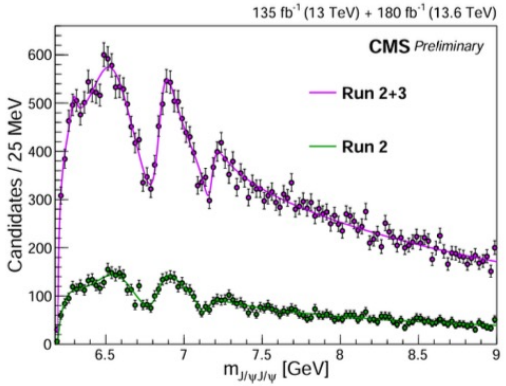


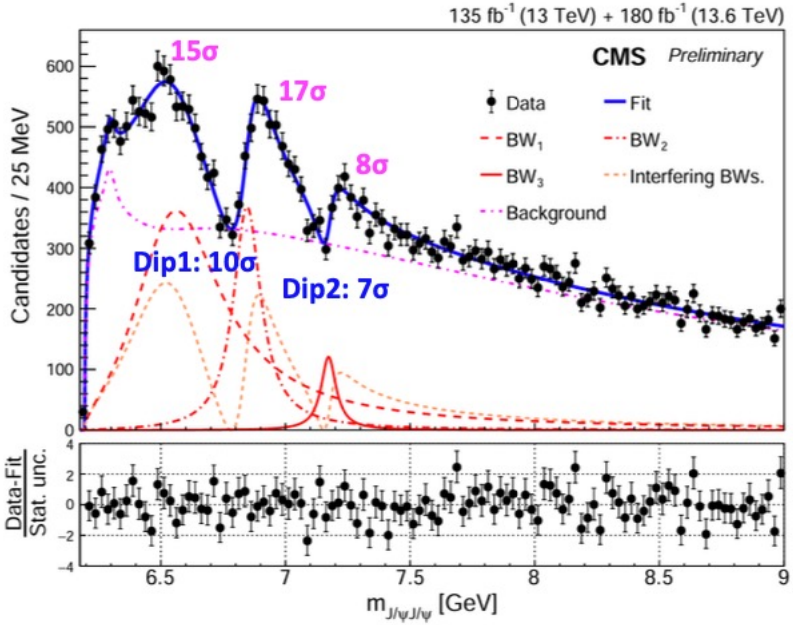


- ATLAS and CMS both confirmed the X(6900) state in J/ψ+J/ψ final states
- CMS observed a new structure X(6600) and find an evidence of the X(7100)
- LHCb, ATLAS and CMS all see a broad enhancement at the low mass region

Fully charmed tetraquark [$cc\bar{c}\bar{c}$] with run 2+3 data

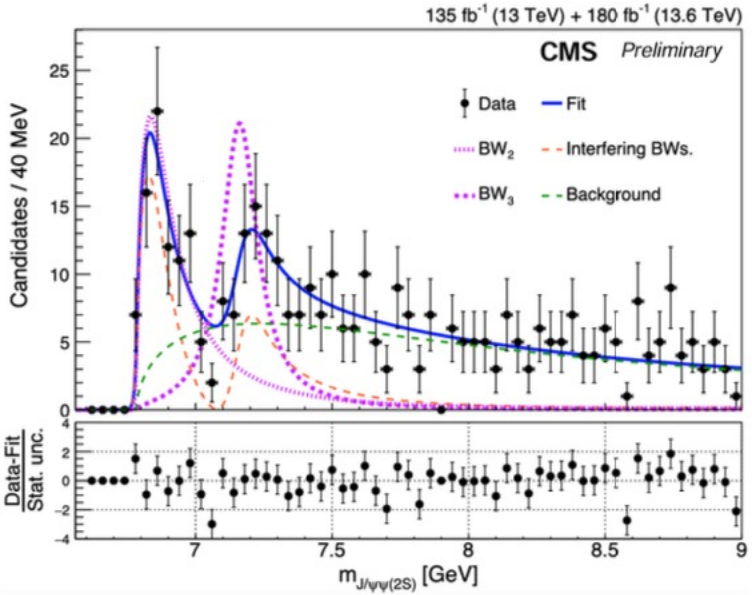
BPH-24-003





- **All states and dips are above 5σ**
- **Interferences are necessary**

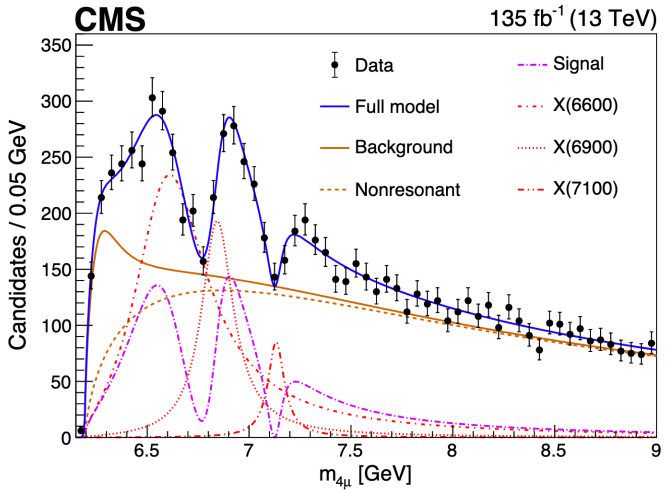
Parameter	Run 2 [12] [Interf.]		Run 2 + 3 [Interf.]		
$m(\mathrm{BW}_1)$	6638	$^{+43+16}_{-38-31}$	6593	$^{+15}_{-14}$	± 25
$\Gamma(\mathrm{BW}_1)$	440	$^{+230+110}_{-200-240}$	446	$^{+66}_{-54}$	± 87
$m(\mathrm{BW}_2)$	6847	$^{+44+48}_{-28-20}$	6847	$^{+10}_{-10}$	± 15
$\Gamma(\mathrm{BW}_2)$	191	$^{+66+25}_{-49-17}$	135	$^{+16}_{-14}$	± 14
$m(\mathrm{BW}_3)$	7134	$^{+48+41}_{-25-15}$	7173	$^{+9}_{-10}$	± 13
$\Gamma(\mathrm{BW}_3)$	97	$^{+40+29}_{-29-26}$	73	$^{+18}_{-15}$	± 10

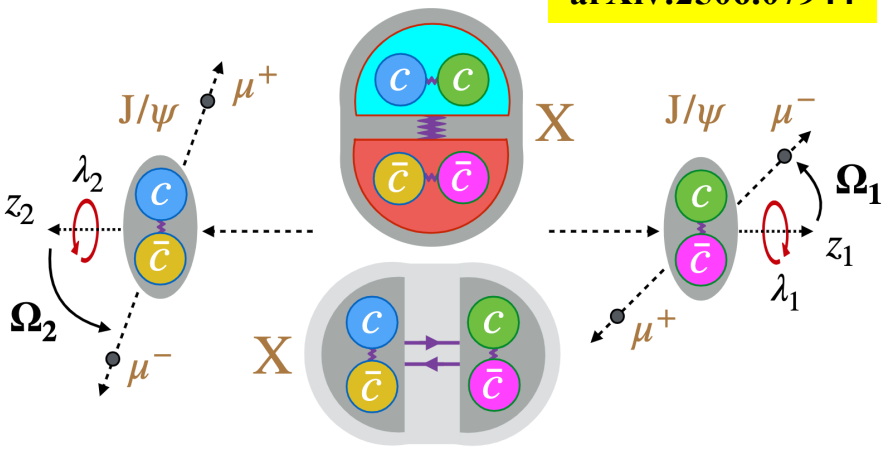


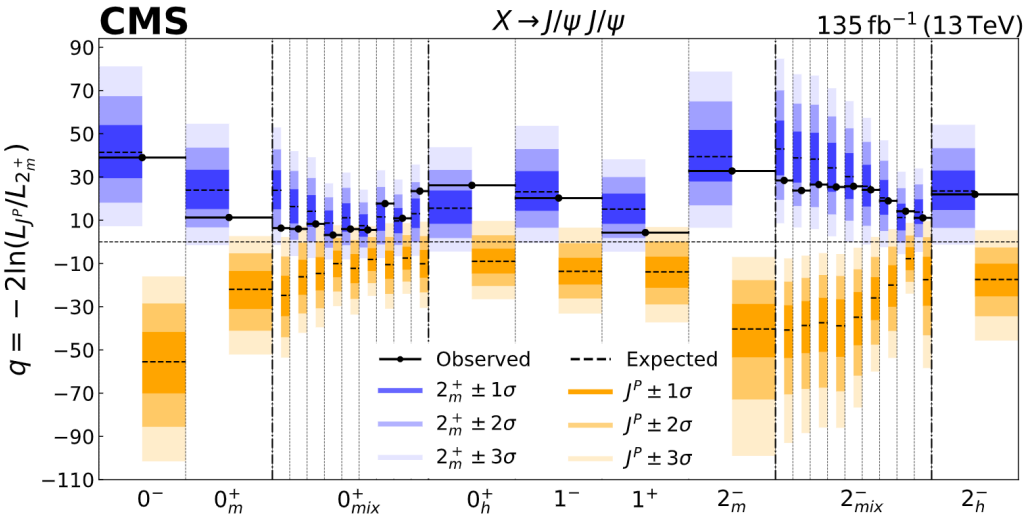
- Significance of **X(6900) = 7.9σ**
- Significance of **X(7100) = 4.0σ**

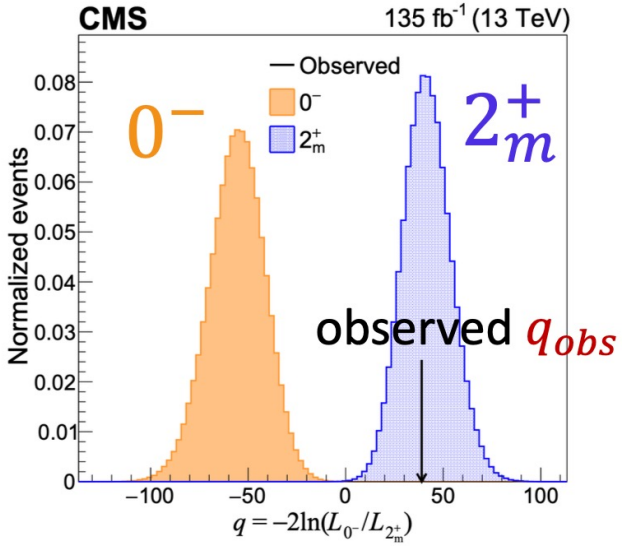
Spin analysis of X[$cc\bar{c}\bar{c}$] states

arXiv:2506.07944





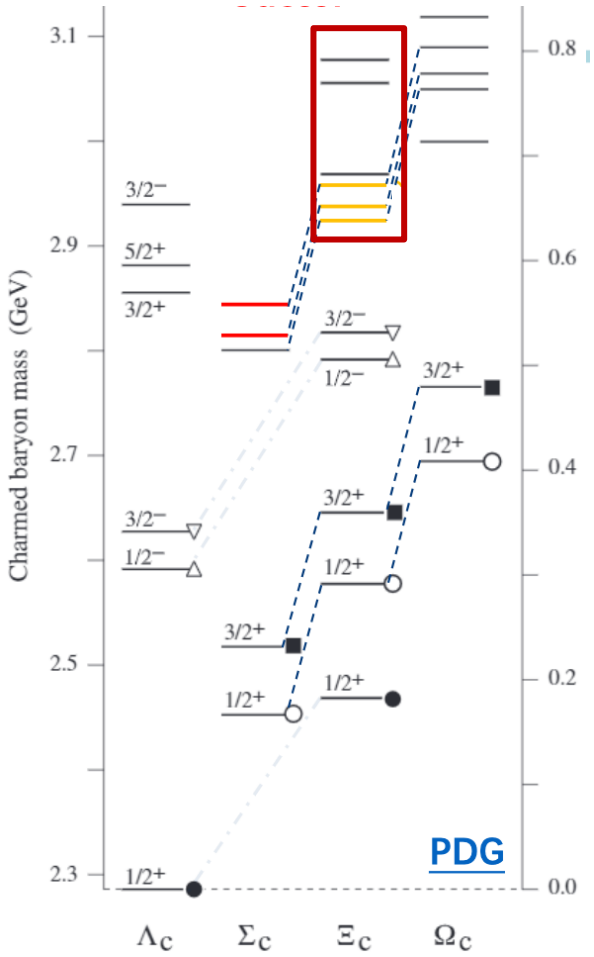




$J^{PC} = 2^{++}$ interpretation is preferred for the fully charmed tetraquark states $X(6600)$, $X(6900)$, and $X(7100)$.

Heavy baryons

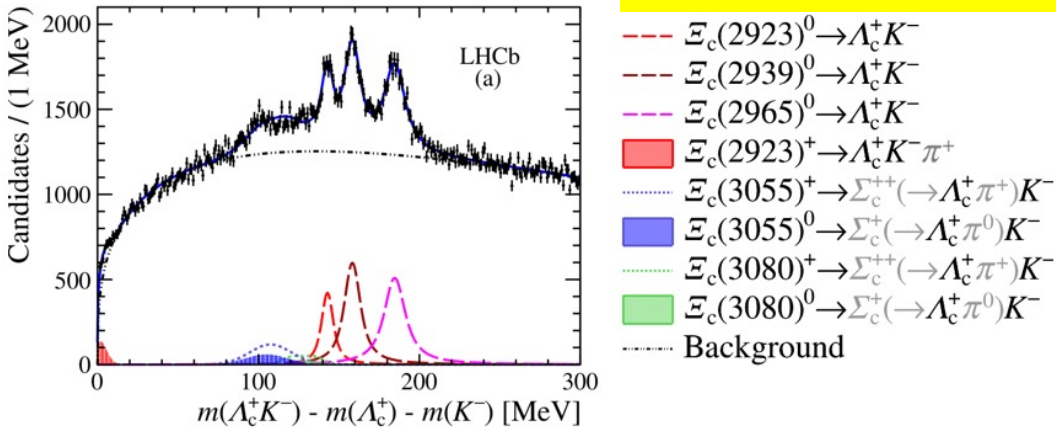
Observation of new Ξc baryons



Expecting a rich spectrum of charmed baryon states; yet many states not observed yet

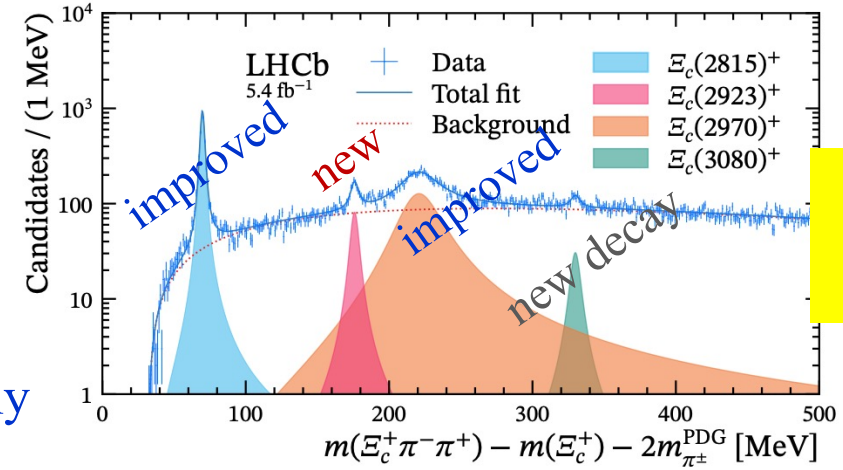
- Three excited Ξ_c^0 are observed in decaying into $\Lambda_c^+ K^-$

PRL124, 222001 (2020)



- Four excited Ξ_c^+ are observed in decaying into $\Xi_c^+ \pi^+ \pi^-$

arXiv:2502.18987



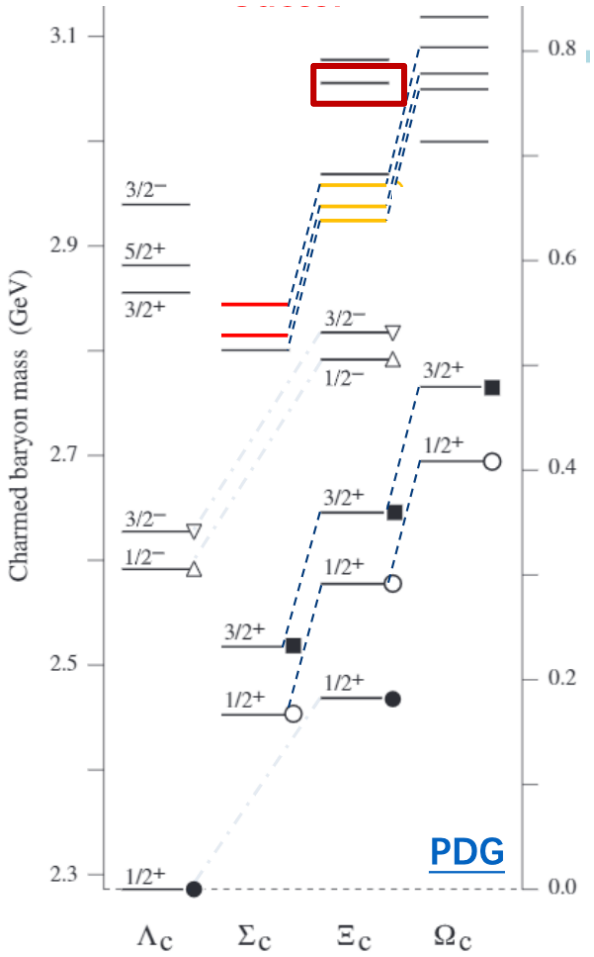
wider width of $\Xi_c(2970)^+$ than $\Xi_c(2965)^0$

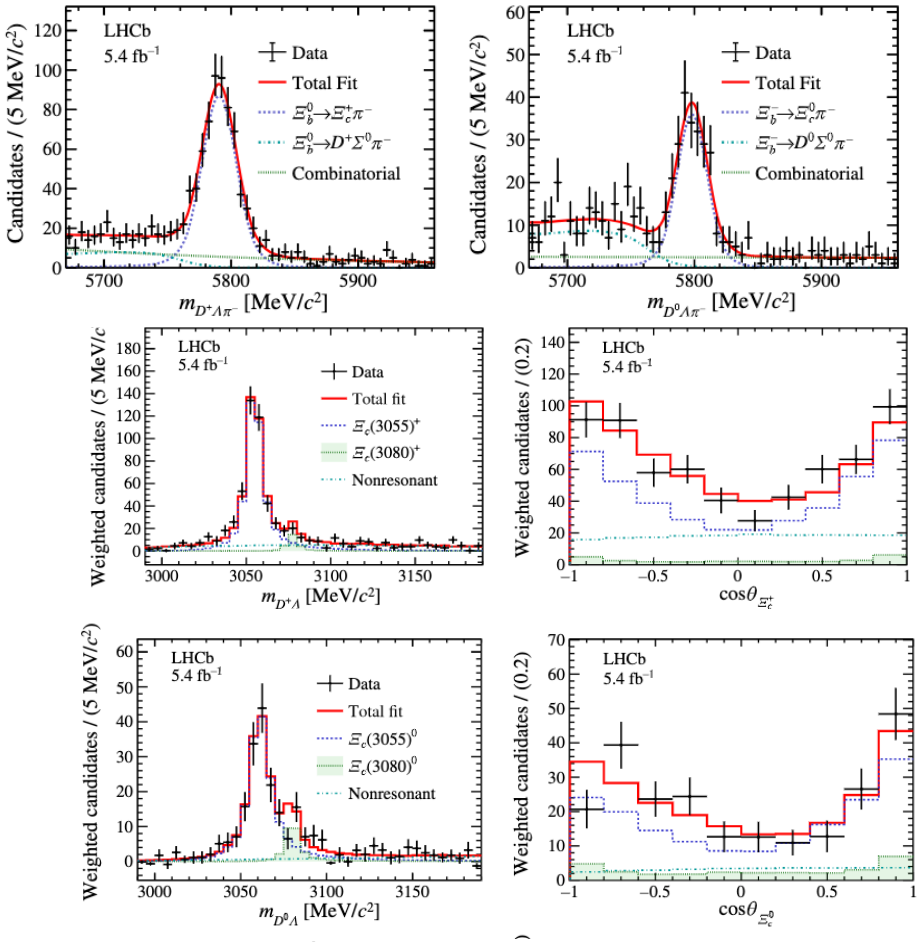
Spin-parity of the $\Xi_c(3055)$

Amplitude analysis of the cascade weak decay of

$\Xi_b^{0(-)} \to \Xi_c(3055)^{+(0)}(\to D^{+(0)}\Lambda)\pi^-$

PRL134.081901 (2025)





Expecting a rich spectrum of charmed baryon states; yet many states not observed yet

$J^P = \frac{3}{2}^+$ hypothesis favored over others:

$6.5(3.5)\sigma$ for charged (neutral) $\Xi_c(3055)$

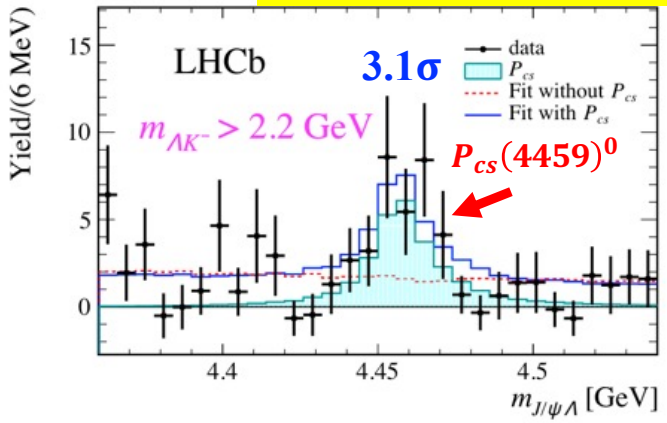
Observation of the hidden-charm strange pentaquark [$c\bar{c}uds$]

- 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 $\Xi_c^0\overline{D}^{*0}$:

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

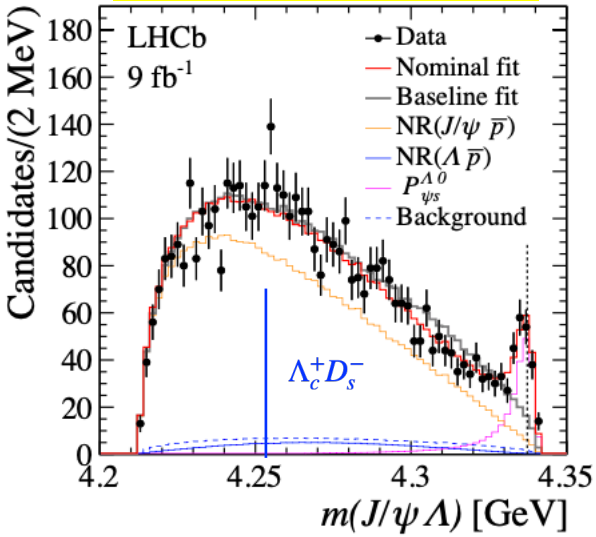
Sci.Bull.66, 1278(2021)



- $P_{c\bar{c}s}(4338)^0 \to J/\psi\Lambda$ observed in $B^- \to J/\psi\Lambda\bar{p}$ (>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 $\Xi_c^0 \bar{D}^0$

$$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4\ \text{MeV}$$
$$\Gamma_{P_{cs}} = 7.0 \pm 1.2 \pm 1.3\ \text{MeV}$$

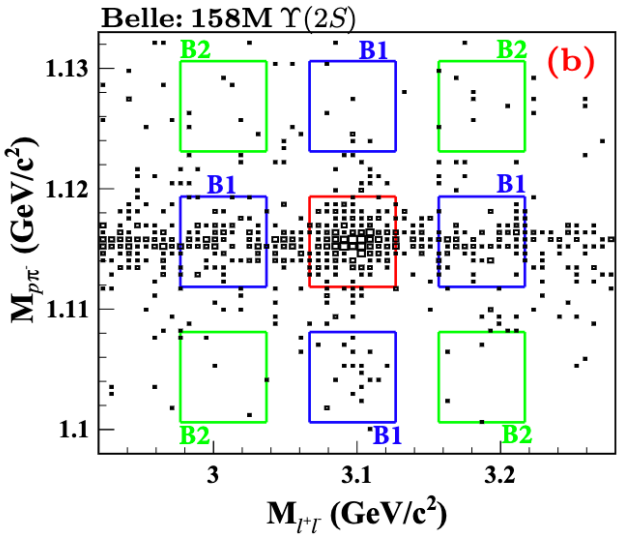
PRL131, 031901(2023)

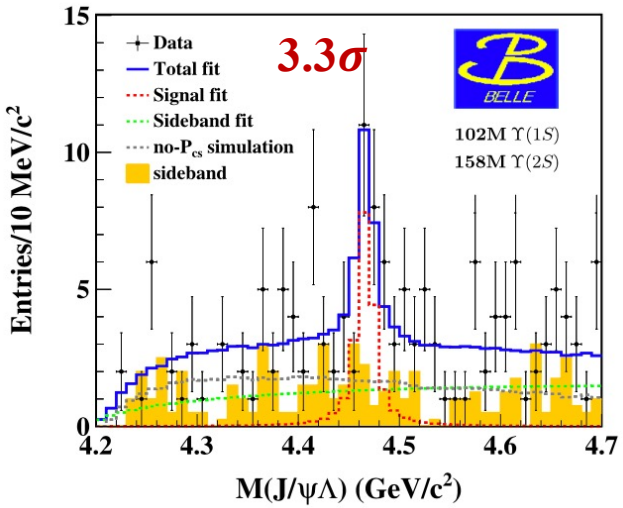


Evidence for $\Upsilon(1S, 2S) \to P_{c\bar{c}s}(4459)^0 X$

arXiv:2502.09951

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





mass: $4471.7 \pm 4.8 \pm 0.6$ MeV
width: $21.9 \pm 13.1 \pm 2.7$ MeV

significance is 3.3σ including systematics.

consistent with LHCb results

Mode	$\mathcal{B}(\times 10^{-6})$
$\Upsilon(1S) \to P_{c\bar{c}s}(4459)^0/\bar{P}_{c\bar{c}s}(4459)^0 + anything$	$3.5 \pm 2.0 \pm 0.2$
$\Upsilon(2S) \to P_{c\bar{c}s}(4459)^0/\bar{P}_{c\bar{c}s}(4459)^0 + anything$	$2.9 \pm 1.7 \pm 0.4$
$\Upsilon(1S) \to P_{c\bar{c}s}(4338)^0/\bar{P}_{c\bar{c}s}(4338)^0 + anything$	< 1.8
$\Upsilon(2S) \to P_{c\bar{c}s}(4338)^0/\bar{P}_{c\bar{c}s}(4338)^0 + anything$	< 1.6

No evidence for $P_{c\bar{c}s}(4338)^0$

Summary

- An exciting period of finding new hadrons, 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
  - strangenium(-like) states: axial-vector states $h_1(1900)$ and $h_1(2300)$
  - 1^{-+} spin-exotic state $\pi_1(1600)$ observed in charmonium decays
- **Heavy hadrons:**
  - observation of the P-wave $B_c^+(1P)$ states and the charged $\Xi_c\ (2923)^+$
  - $T_{c\bar{s}}^{0/++}$ observed $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$
  - better understanding of quarkonium(-like) states: $h_c(4000)$, $\chi_{c1}(4010)$ and $h_c(4300)$; Y(4500), Y(4710) and Y(4790); $\Upsilon(10753)$; $[Q\bar{Q}]$ or $[Q\bar{Q}\ q\bar{q}]$? Observation of toponium η_t?
  - advances in fully charmed tetraquark: $X(6600)$, $X(6900)$ and $X(7100)$ $\boldsymbol{[c\bar{c}c\bar{c}]}$
- 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.

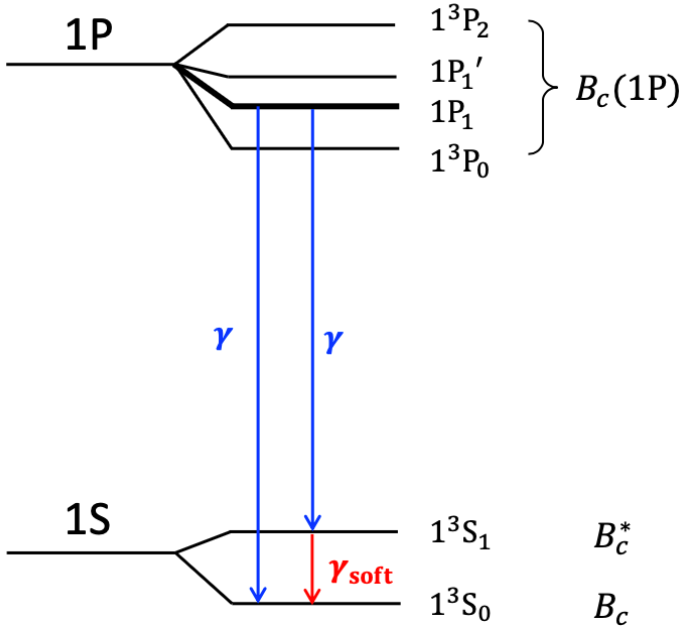
Thank you!

谢谢!

Backup

◉ Recall that the $1P_1', 1P_1$ are mixtures of $1^1P_1, 1^3P_1$ states

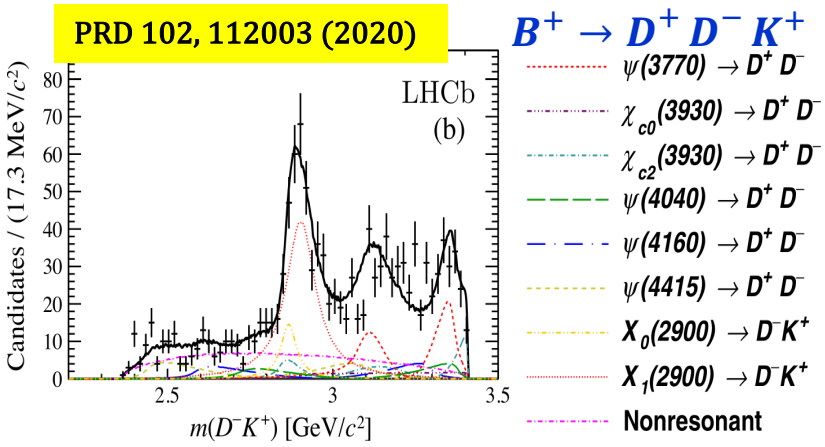
States	1^3P_0	$1P_1$	$1P_1'$	1^3P_2
Decays	$B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^+\gamma$ $B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^+\gamma$ $B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^{*+}(\to B_c^+\gamma)\gamma$
#peaks	1	2	2	1



◎ *The value* $\delta M = M(B_c^*) - M(B_c)$ *is unknown since* B_c^* *has not been observed yet*

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)]



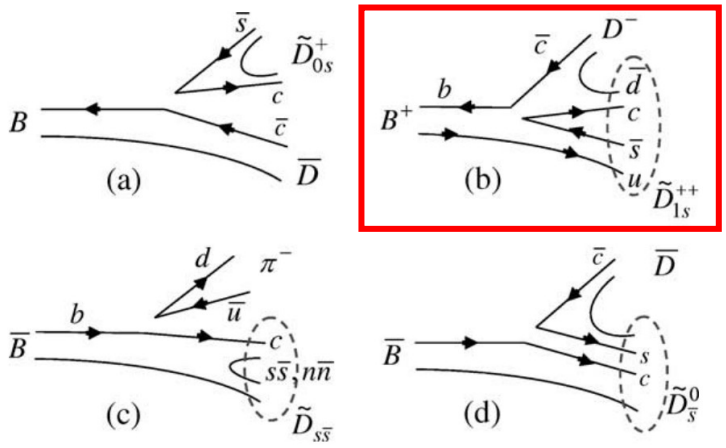


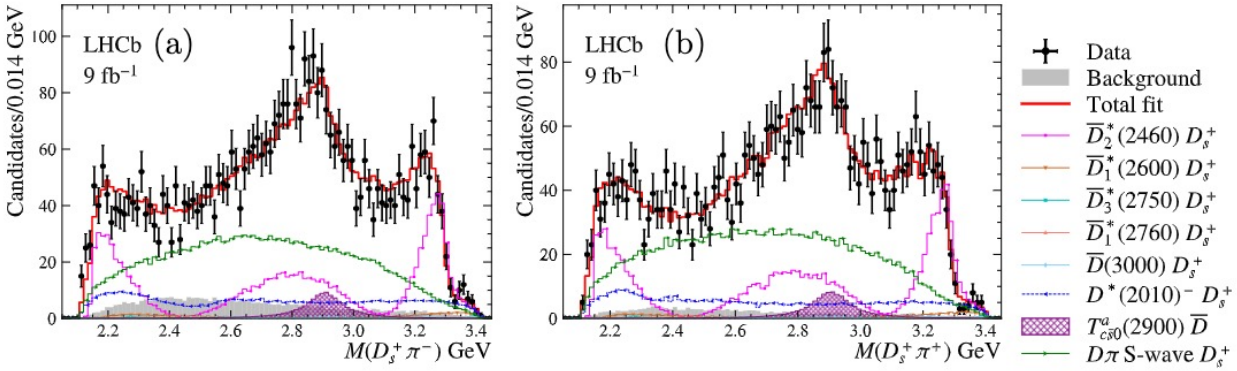
Fig. 2. Diagrams for (a) $B \to \bar{D}\tilde{D}_{0s}^+$, (b) $B^+ \to D^-\tilde{D}_{1s}^{++}$ ($B \to \bar{D}\tilde{D}_{Is}$), (c) $\bar{B} \to \pi^-\tilde{D}_{s\bar{s}}$, $\pi^-\tilde{D}$, (d) $B \to D\tilde{D}_{\bar{s}}^0$.

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**



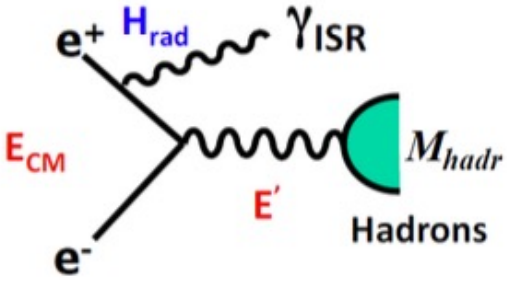
	Mass (GeV)	Width (GeV)	J^P
$T^*_{c\bar{s}0}(2900)^0$ & $T^*_{c\bar{s}0}(2900)^{++}$	$2.908 \pm 0.011 \pm 0.020$	$0.136 \pm 0.023 \pm 0.020$	0^+
$X_0(2900)/T^*_{cs0}(2870)$	$2.866 \pm 0.007 \pm 0.002$	$0.057 \pm 0.012 \pm 0.004$	0^+
$X_1(2900)/T^*_{cs1}(2900)$	$2.904 \pm 0.005 \pm 0.001$	$0.110 \pm 0.011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

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

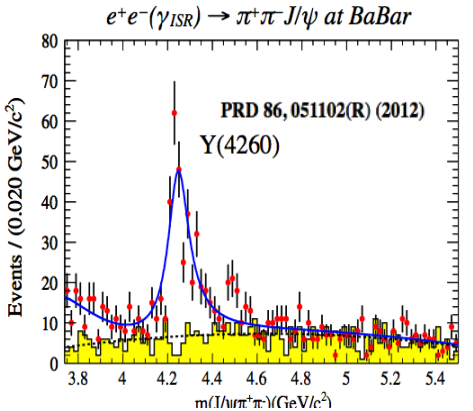
See parallel talk by Raul Rabadan

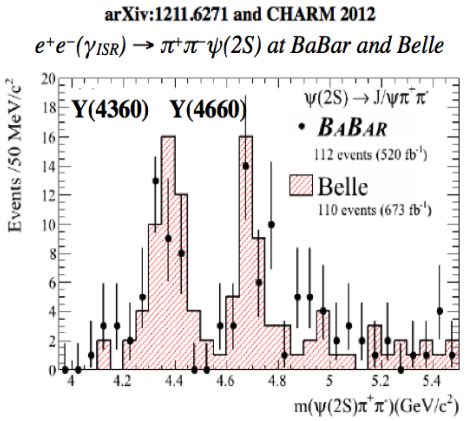
- **no isospin relation:** $[c\bar{s}u\bar{d}]$ **v.s.** $[cs\bar{u}\bar{d}]$
- **U-spin relation:** $[c\bar{s}\bar{u}d]$ **v.s.** $[c\bar{d}\bar{u}s]$
- $T^a_{c\bar{s}0}(2900)$ mass and width larger than $T_{cs0}(2900)$

The Y states



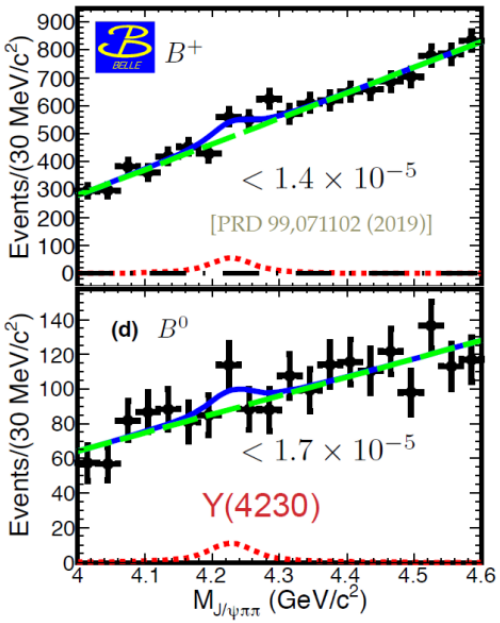
Y states: charmonium-like states with $J^{PC}=1^{--}$; Observed in direct e+e- annihilation or initial state radiation (ISR).



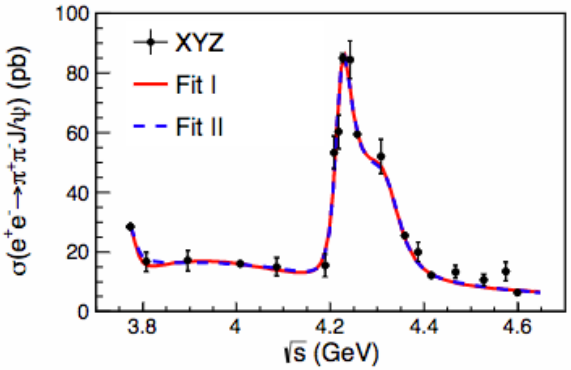


- **While not seen yet in B decays**

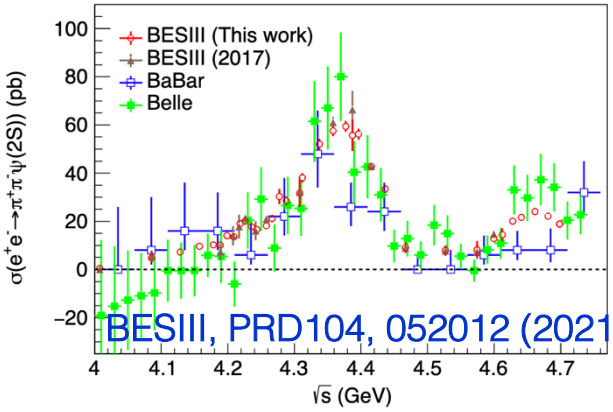
$B^{\pm,0} \to K^{\pm,0}\pi^+\pi^- J/\psi$



- **Improved knowledges from BESIII**



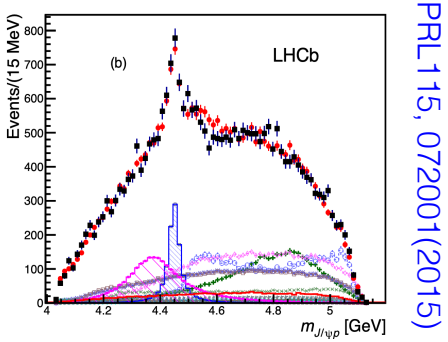
BESIII, PRL118, 092001 (2017)



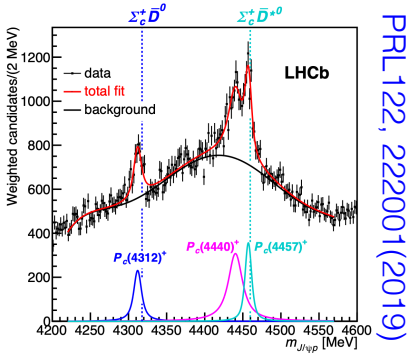
BESIII, PRD104, 052012 (2021)

Pentaquark states at LHCb

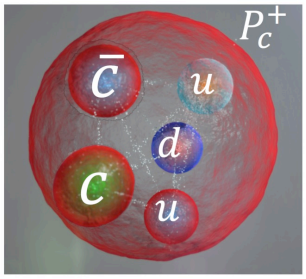
- **Observation of $[c\bar{c}uud]$ pentaquarks:** $P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ in $\Lambda_b^0 \to J/\psi p K^-$ decays; near thresholds of $\Sigma_c^+ \overline{D}^0$, $\Sigma_c^+ \overline{D}^{*0}$, J^P not determined



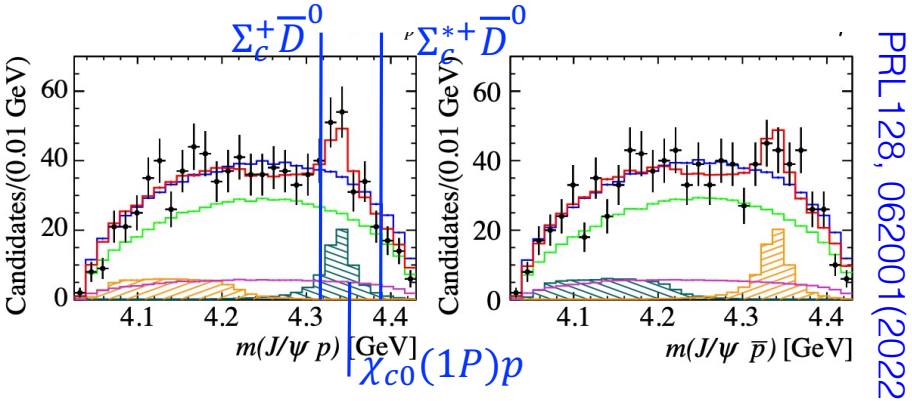
PRL115, 072001(2015)



PRL122, 222001(2019)

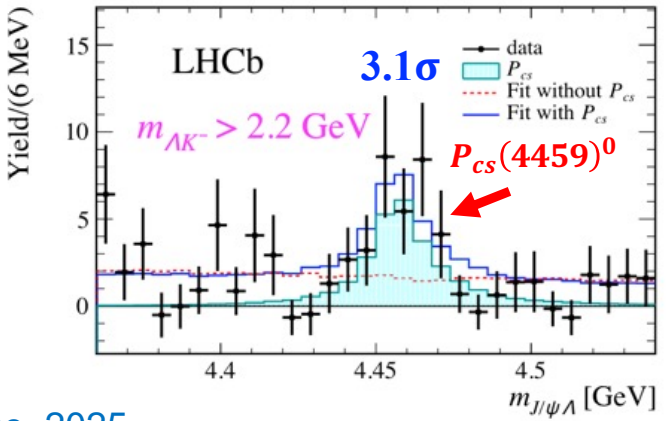


- **Evidence of $[c\bar{c}uud]$ pentaquark:** $P_{c\bar{c}}(4337)^+$ in $B_s^0 \to J/\psi p\bar{p}$ decays



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)