# Recent experimental progress on hadron spectroscopy

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# Outline

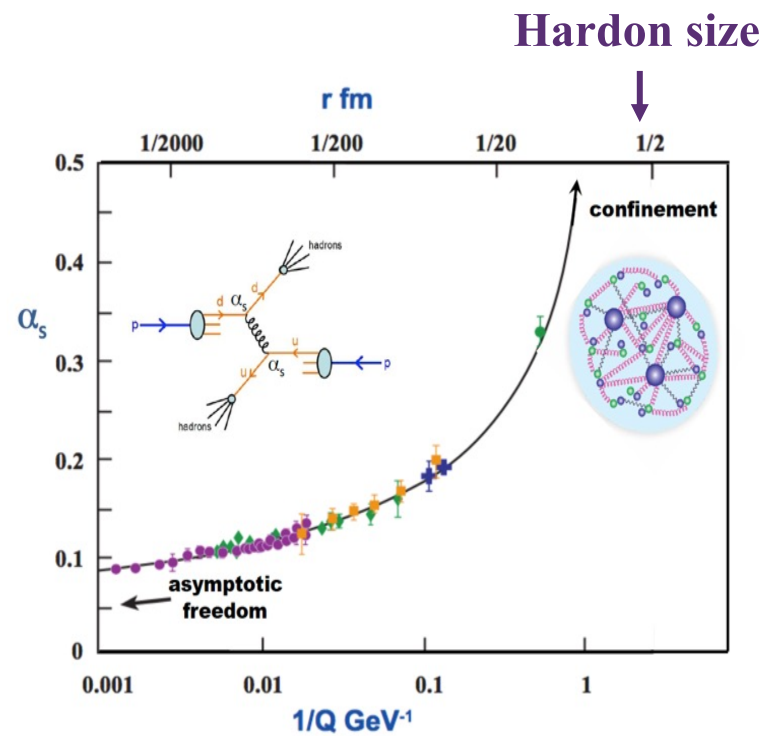
- Introduction
- Light hadron spectroscopy
- Heavy hadron spectroscopy
  conventional and exotic
  - ✓ Heavy meson
  - ✓ Heavy baryon
- Summary

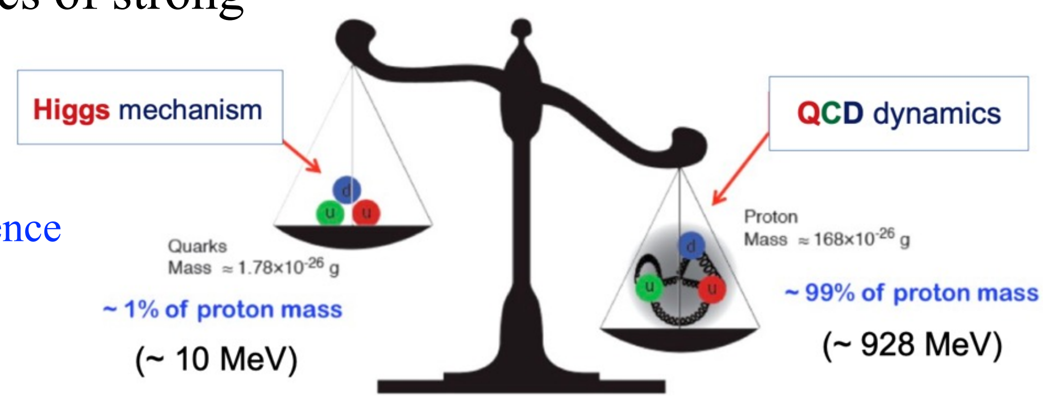
请见其他谱学相关报告：
- 金山：X(2370)
- 李龙科: Belle (II)
- 张敬庆: [$cc\bar{c}\bar{c}$] at CMS

*I apologize for not covering all the experiments results.*

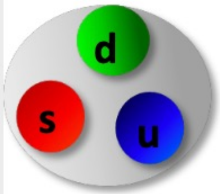
# Introduction

- 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

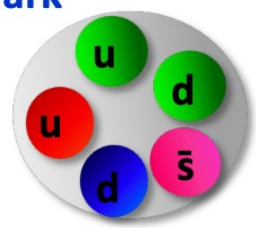
Mesons are color-anticolor pairs


π=ūd

Other possible combinations of quarks and gluons ：

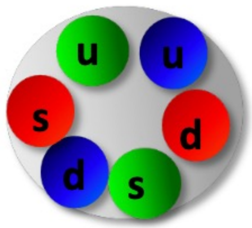
**Pentaquark**

S= +1 Baryon



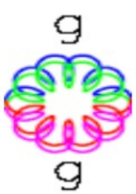

**H di-Baryon**

Tightly bound 6 quark state



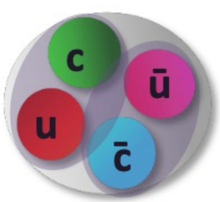

**Glueball**

Color-singlet multi-gluon bound state



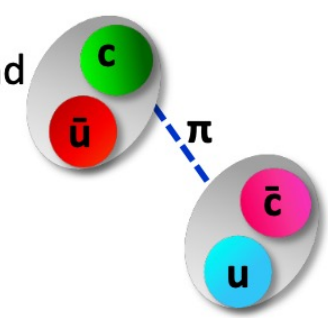

**Tetraquark**

Tightly bound diquark & anti-diquark

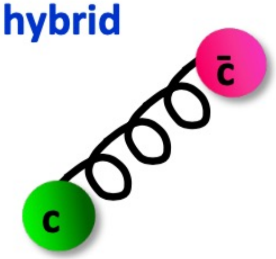



**Molecule**

loosely bound meson-antimeson "molecule"



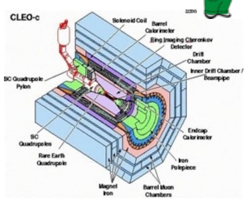

**qq̄ -gluon hybrid mesons**

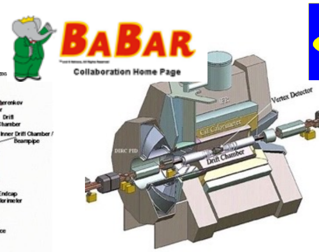


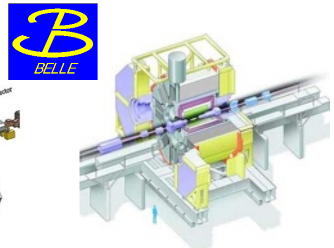
# Main contributors worldwide

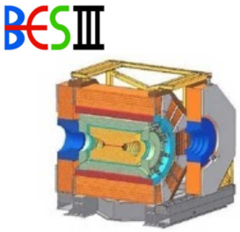
- $e^+e^-$ collider

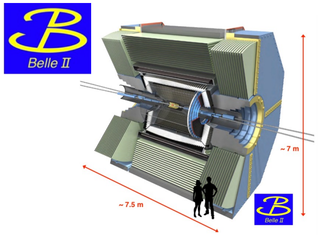
CLEO-c



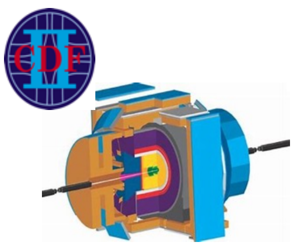



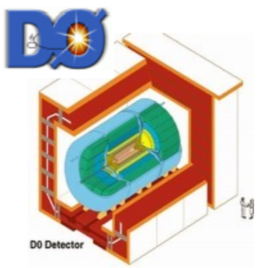



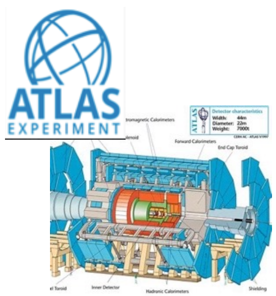



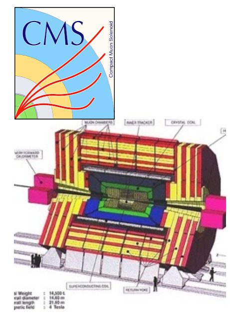




- Hadron collider



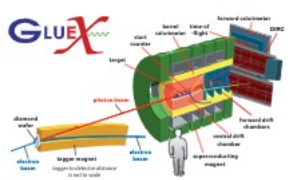



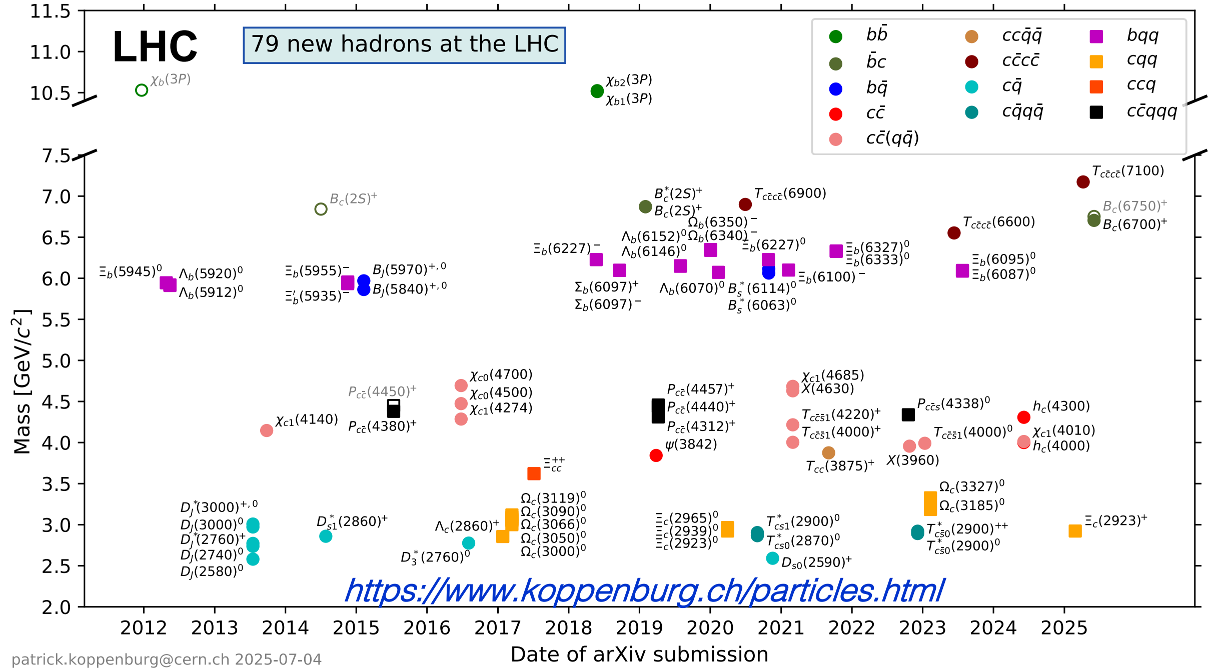


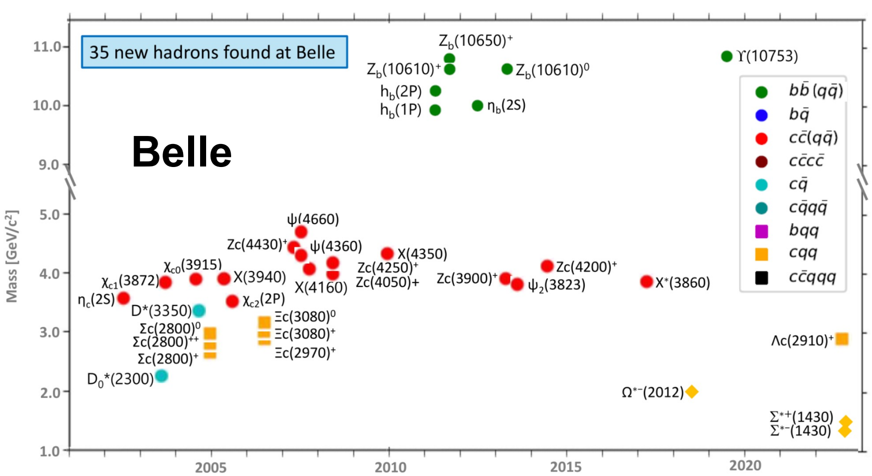
- Fixed-target experiments

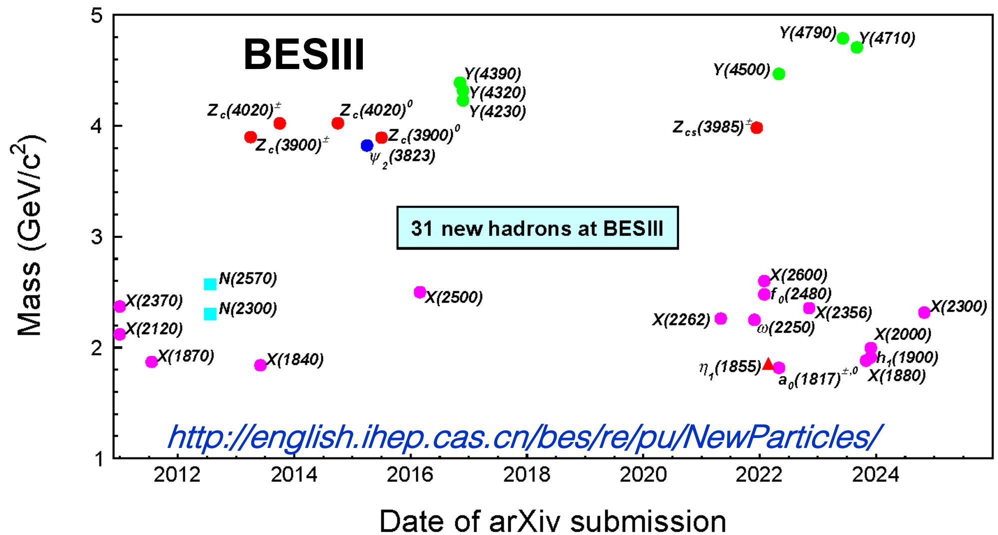
COMPASS



# Discoveries of many new hadrons

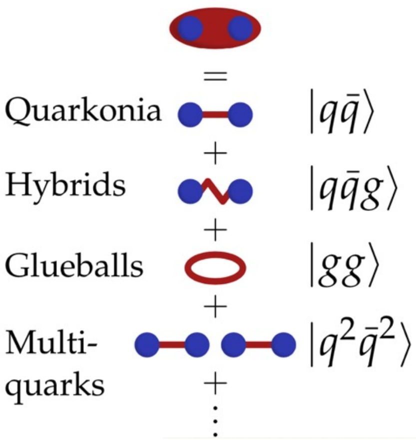


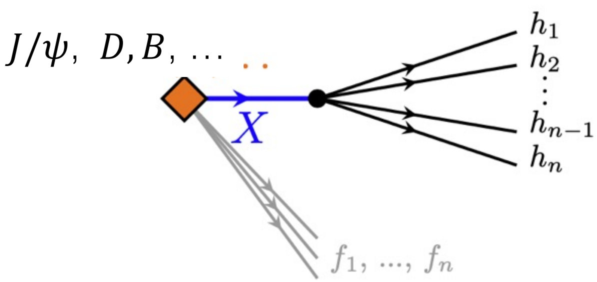



# Light hadrons

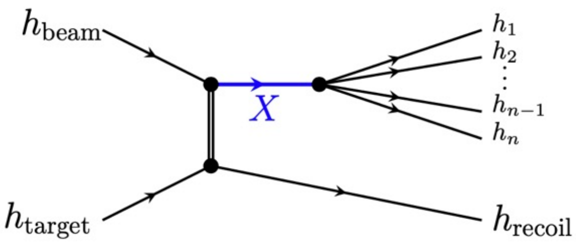
# Light hadron spectroscopy

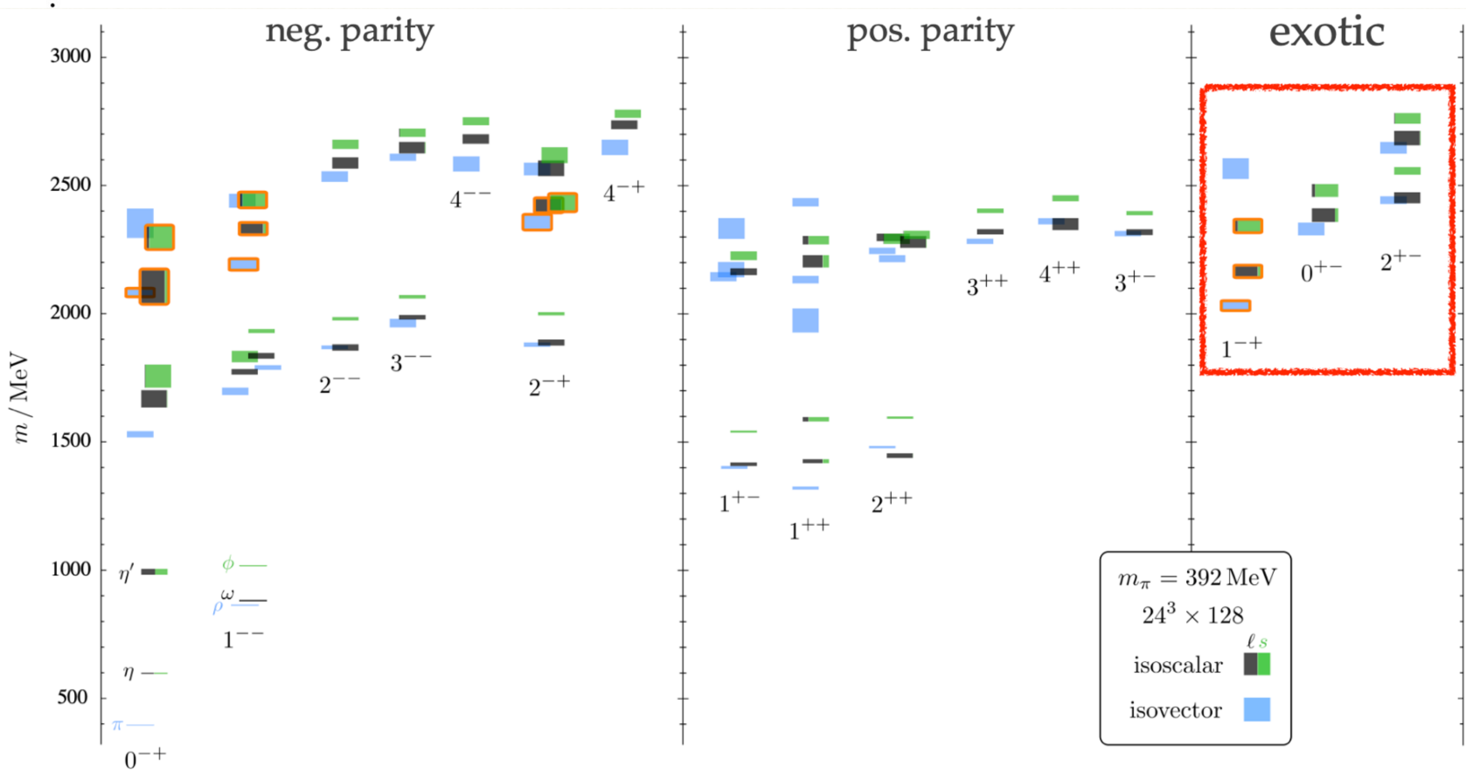



BESIII, LHCb, Belle (II) …

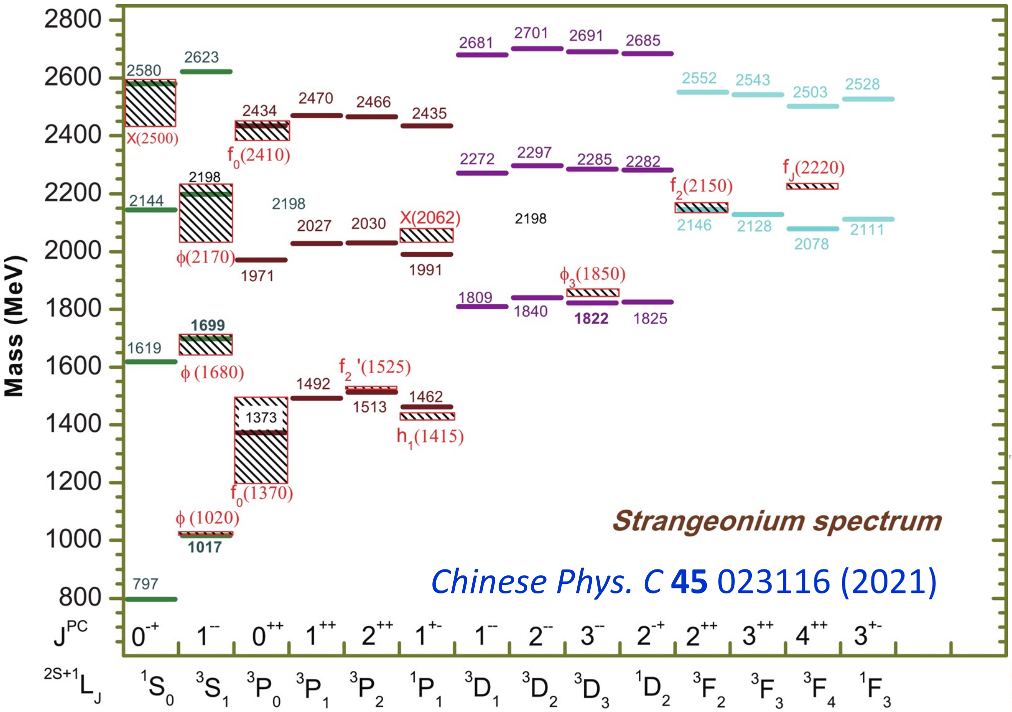



GlueX, Compass, …



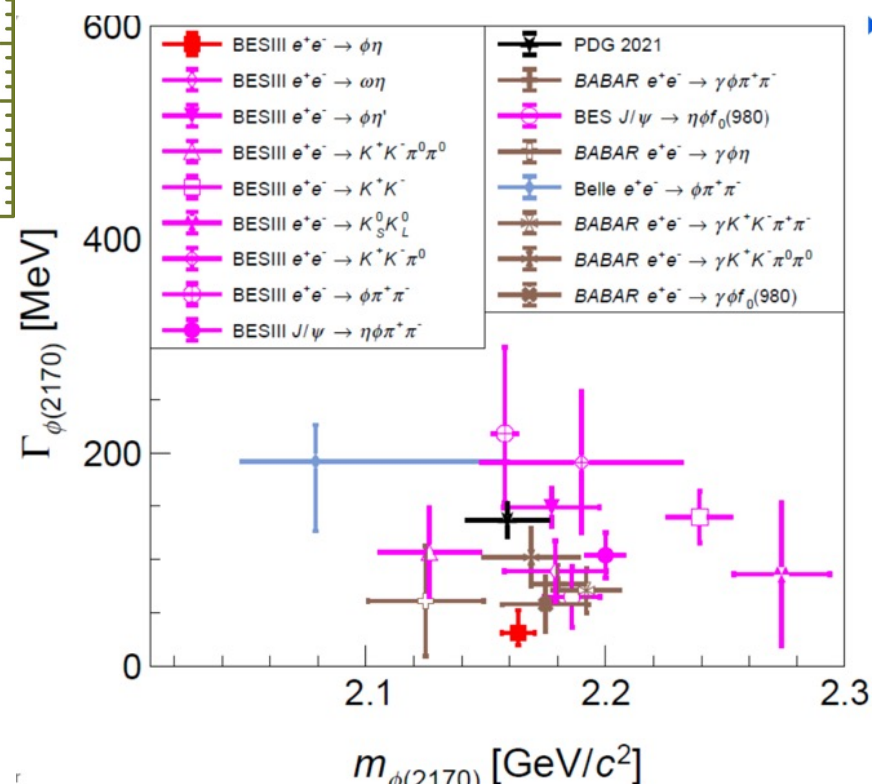



# Strangeonium [$s\bar{s}$] spectroscopy




- **Y(2175)/$\phi$(2170):**
  **a strangeonium(-like) state**

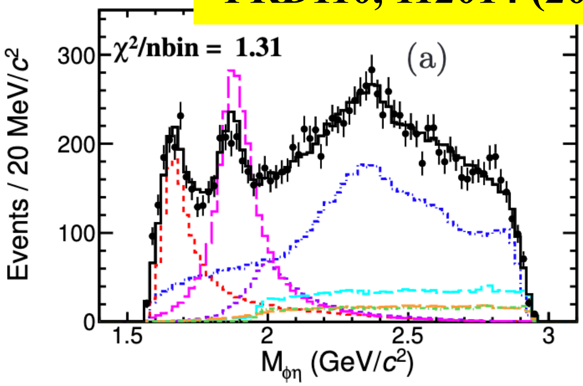
➢ **Theorists explain ϕ(2170) as**
- ✓ **$s\bar{s}g$ hybrid**
- ✓ **$2^3D_1$ or $3^3S_1$ $s\bar{s}$**
- ✓ **tetraquark**
- ✓ **Molecular state $\Lambda\bar{\Lambda}$**
- ✓ **$\phi f_0(980)$ resonance with FSI**
- ✓ **Three body system ϕKK**



# New axial-Vector strangeonia

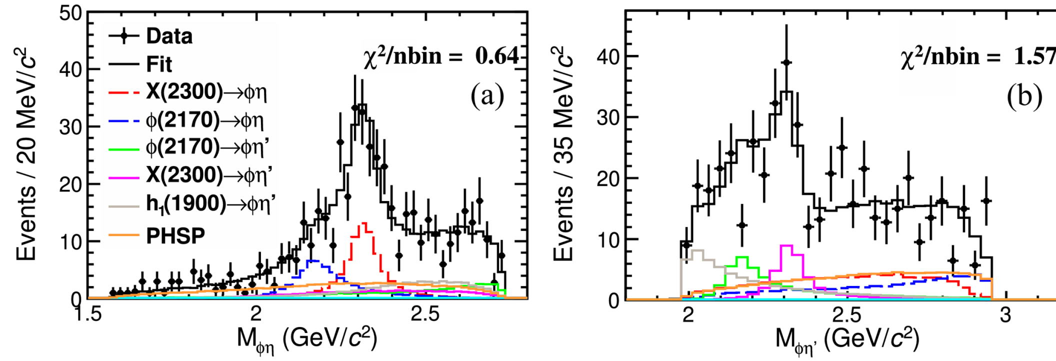
Based on 10B $J/\psi$ events, a PWA fit to $J/\psi \to \phi\eta\pi^0$

**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!*

$h_1(2300)$ $J^{PC} = 1^{+-}$ *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

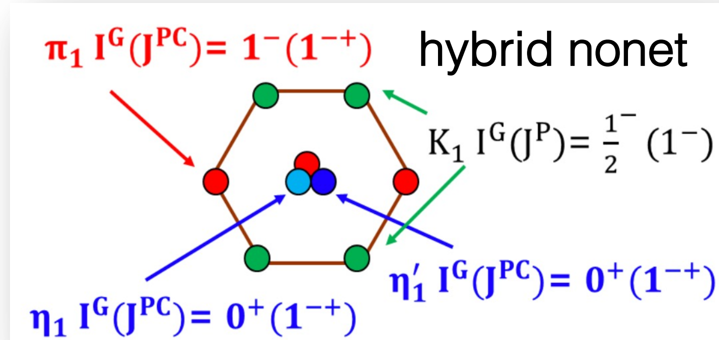
**Over three decades, 4 candidates are reported so far.**

Three $1^{-+}$ isovectors

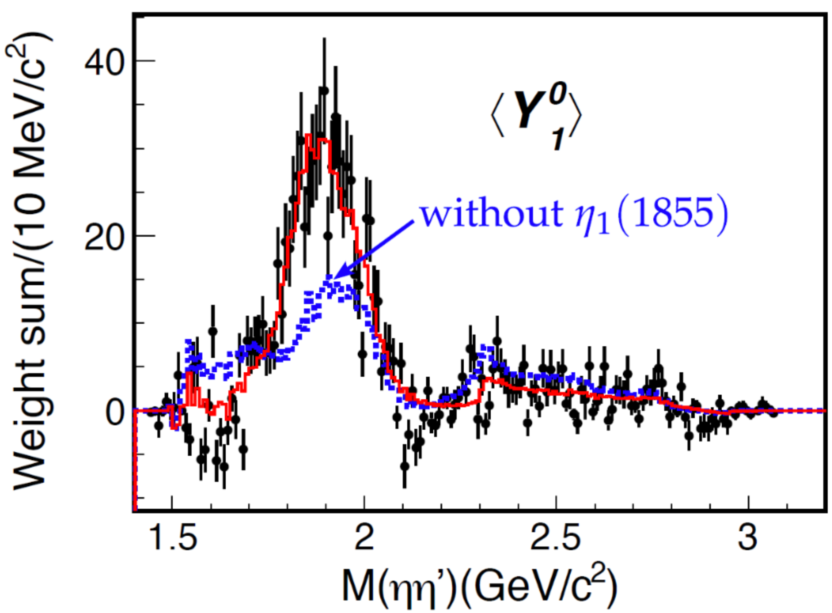
- $\pi_1(1400)$: seen in $\eta\pi$
- $\pi_1(1600)$: seen in $\rho\pi$, $\eta'\pi$, $b_1\pi$, $f_1\pi$
- $\pi_1(2015)$: seen in $b_1\pi$ and $f_1\pi$

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

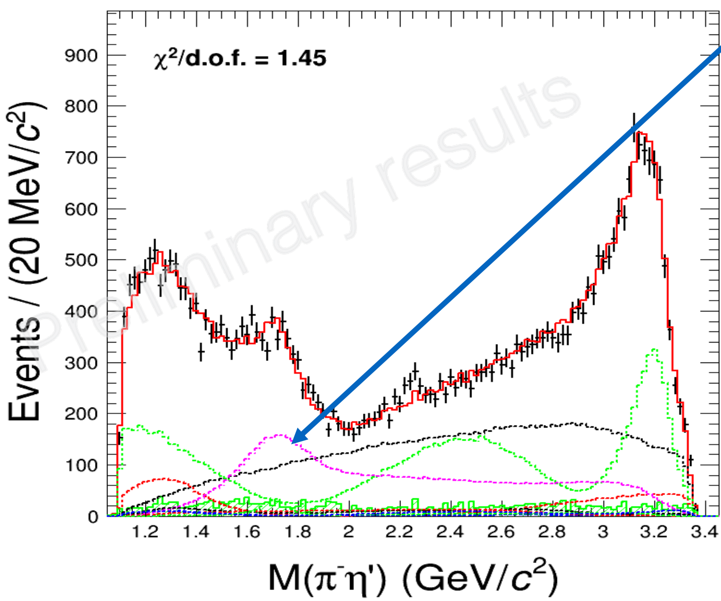
Some studies indicated that $\pi_1(1400)$ and $\pi_1(1600)$ can be one pole [EPJC 81, 1056 (2021) ][PRL122, 042002 (2019)]

# 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 ~4$\sigma$ 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 |
|---|---|---|---|
| $\pi_1(1600)$ | $1^{-+}$ | $\pi^\pm\eta'$ | $>> 10\sigma$ |
| $(\pi\pi)_{S-wave}$ | $0^{++}$ | $\pi^\pm\eta'$ | $>> 10\sigma$ |
| $a_0(980)$ | $0^{++}$ | $\pi^\pm\eta'$ | $> 10\sigma$ |
| $f_2(1270)$ | $2^{++}$ | $\pi^+\pi^-$ | $>> 10\sigma$ |
| $a_2(1320)$ | $2^{++}$ | $\pi^\pm\eta'$ | $> 5\sigma$ |
| $f_2(1950)$ | $2^{++}$ | $\pi^+\pi^-$ | $> 10\sigma$ |
| $f_0(2200)$ | $0^{++}$ | $\pi^+\pi^-$ | $> 10\sigma$ |
| $a_0(1710)$ | $0^{++}$ | $\pi^\pm\eta'$ | $> 10\sigma$ |
| $f_2(PHSP)$ | $2^{++}$ | $\pi^+\pi^-$ | $> 5\sigma$ |

Preliminary results

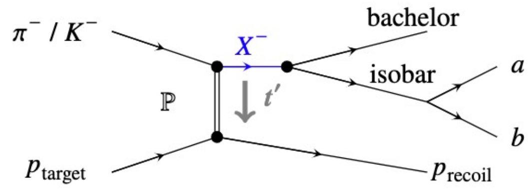



Spin-parity of the $\pi_1(1600)$ favors $J^{PC} = 1^{-+}$ is favored over $0^{++}$, $2^{++}$ and $4^{++}$ assignments with significances larger than $10\sigma$

# Diffractive scattering of $\pi$ with nucleon

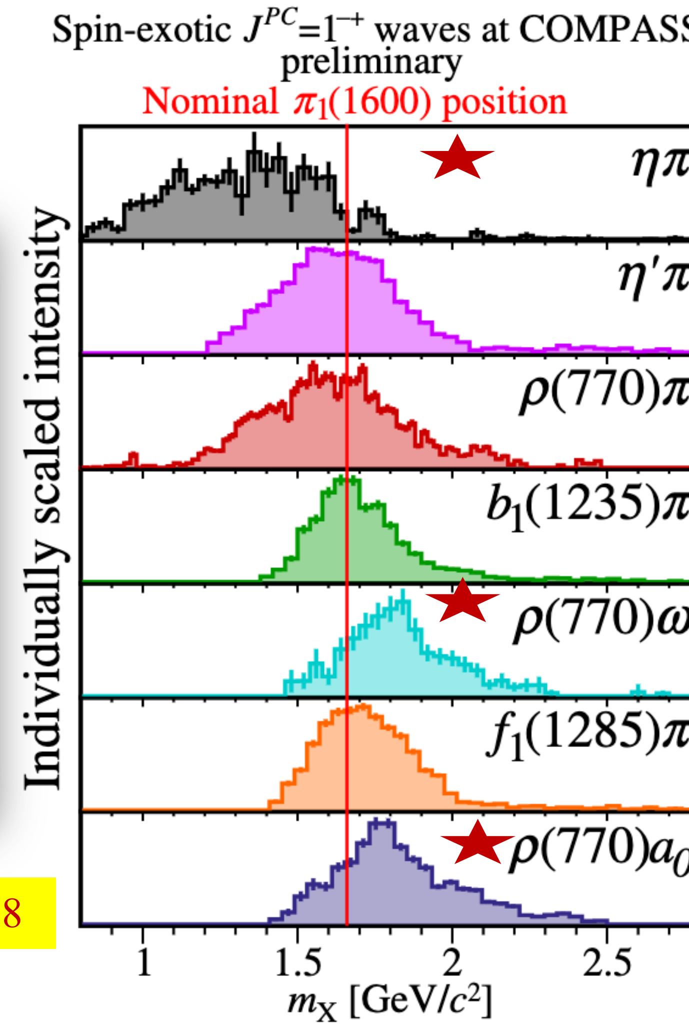
$$beam + p \to \boxed{X^-} + p \to \boxed{final\ state} + p$$

information on $X^-$ obtained from
partial wave analysis of the final state hadrons




- 2-body
  - $K_s^0K^-$, $\eta\pi$, $\eta'\pi$, $f_1(1285)\pi$
  - $K_s^0\pi^-$, $\Lambda\bar{p}$
- 3-body
  - $\pi^-\pi^+\pi^-$, $\pi^-\pi^0\pi^0$
  - $K^-\pi^+\pi^-$
- effective 3-body
  - $\omega\pi^-\pi^0$
- 4-body
  - $\eta\pi^+2\pi^-$
- 5-body
  - $\pi^-2\pi^+2\pi^-$

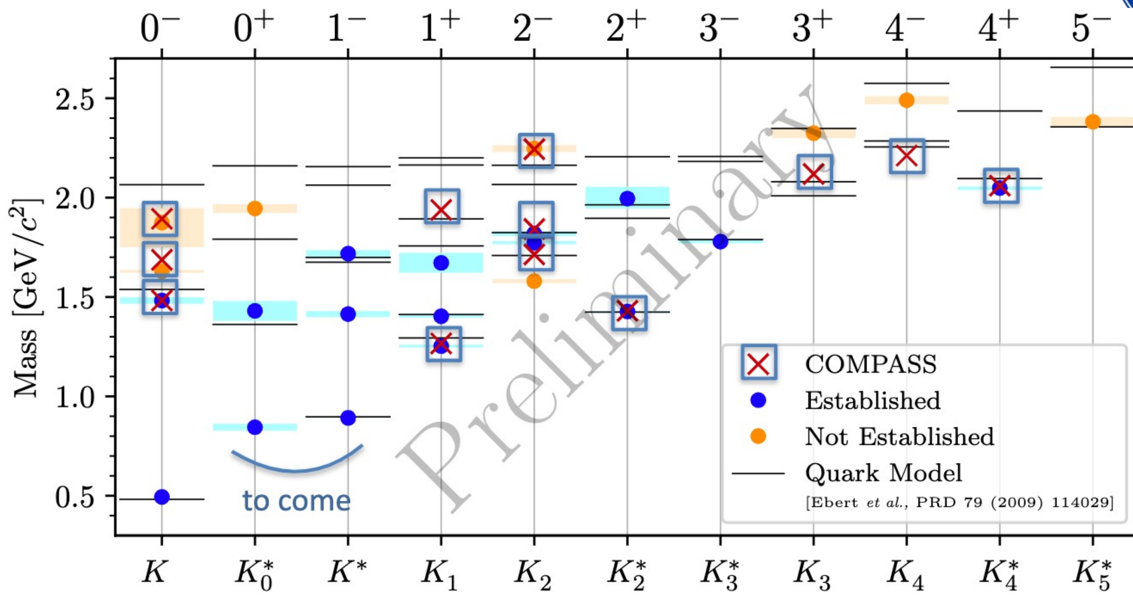
| Resonance | $m_0$ [MeV/$c^2$] | $\Gamma_0$ [MeV/$c^2$] |
|---|---|---|
| $\pi(1800)$ | $1768 \pm 6^{+21}_{-16}$ | $320 \pm 9^{+14}_{-16}$ |
| $a_1(1640)$ | $1660 \pm 20^{+30}_{-50}$ | $370 \pm 30^{+20}_{-50}$ |
| $a_1(1930)$ | $1970 \pm 20^{+30}_{-40}$ | $230 \pm 30^{+140}_{-40}$ |
| $\pi_1(1600)$ | $1723 \pm 6^{+37}_{-14}$ | $336 \pm 10^{+96}_{-33}$ |
| $\pi_2(1670)$ | $1698 \pm 6^{+18}_{-7}$ | $296 \pm 11^{+30}_{-15}$ |
| $\pi_2(1880)$ | $1876 \pm 4^{+4}_{-4}$ | $166 \pm 8^{+8}_{-18}$ |
| $\pi_2''$ | $2142 \pm 12^{+15}_{-21}$ | $304 \pm 21^{+14}_{-34}$ |
| $a_3$ | $2080 \pm 10^{+40}_{-40}$ | $560 \pm 20^{+100}_{-100}$ |
| $a_4(1970)$ | $1973 \pm 3^{+15}_{-8}$ | $311 \pm 8^{+10}_{-46}$ |
| $\pi_4(2250)$ | $2198 \pm 12^{+25}_{-27}$ | $550 \pm 30^{+90}_{-40}$ |
| $a_6(2450)$ | $2558 \pm 31^{+12}_{-73}$ | $600 \pm 90^{+60}_{-170}$ |




arXiv:2508.18908

# Diffractive scattering of $K$ with nucleon

$$K^- + p \rightarrow K^- \pi^- \pi^+ + p$$




arXiv:2504.09470

| Resonance | $m_0$ [MeV/$c^2$] | $\Gamma_0$ [MeV/$c^2$] |
|---|---|---|
| $K(1690)$ | $1687 \pm 10 ^{+2}_{-67}$ | $140 \pm 20 ^{+50}_{-50}$ |
| $K(1830)$ | $1893 \pm 17 ^{+13}_{-39}$ | $160 \pm 40 ^{+60}_{-80}$ |
| $K_1(1270)$ | $1266 \pm 2 ^{+5}_{-9}$ | $88 \pm 4 ^{+19}_{-19}$ |
| $K_1'$ | $1940 \pm 10 ^{+90}_{-60}$ | $430 \pm 20 ^{+160}_{-190}$ |
| $K_2(1770)$ | $1714 \pm 4 ^{+10}_{-13}$ | $152 \pm 8 ^{+78}_{-12}$ |
| $K_2(1820)$ | $1842 \pm 5 ^{+44}_{-19}$ | $273 \pm 10 ^{+128}_{-22}$ |
| $K_2(2250)$ | $2244 \pm 10 ^{+18}_{-54}$ | $260 \pm 20 ^{+50}_{-70}$ |
| $K_2^*(1430)$ | $1430.9 \pm 1.4 ^{+3.1}_{-1.5}$ | $111 \pm 3 ^{+4}_{-16}$ |
| $K_3$ | $2119 \pm 13 ^{+45}_{-12}$ | $270 \pm 30 ^{+40}_{-30}$ |
| $K_4$ | $2210 \pm 40 ^{+80}_{-30}$ | $250 \pm 70 ^{+50}_{-70}$ |
| $K_4^*(2045)$ | $2060 \pm 5 ^{+11}_{-3}$ | $189 \pm 10 ^{+13}_{-21}$ |

***K*(1690):**

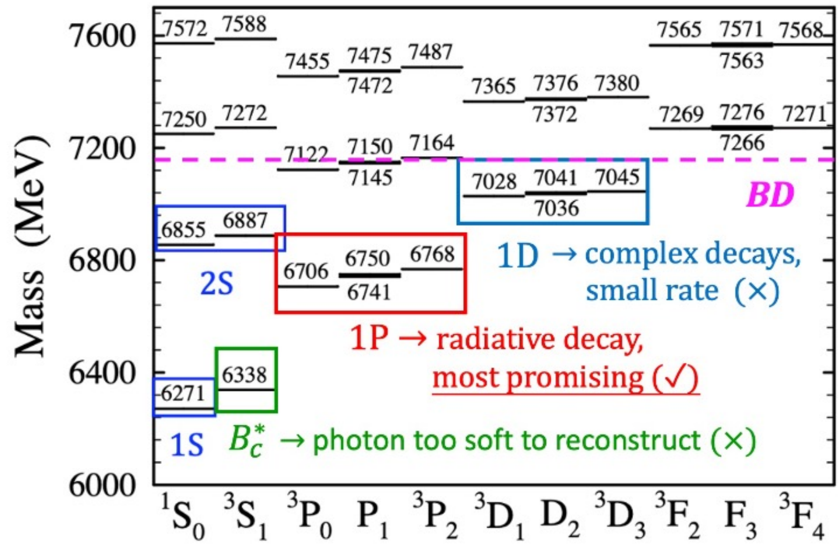
- a supernumerary pseudoscalar resonance signal with a mass of about 1.7 GeV
- lying in mass between the two predicted quark-model states
- the first candidate for a crypto-exotic strange meson with $J^P = 0^-$

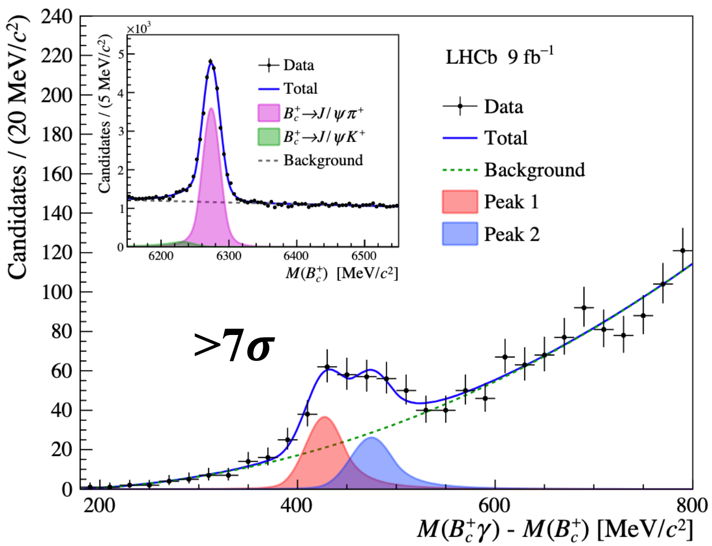
# Heavy mesons

# 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 $B_c^+(1P) \to \gamma B_c^+$

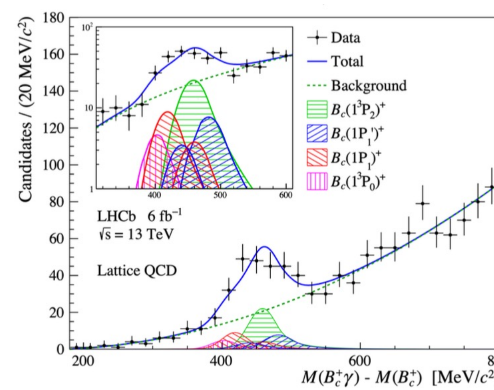
**arXiv:2507.02142; arXiv:2507.02149**




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

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.

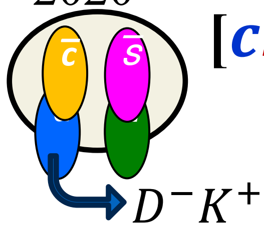
# Open-charm tetraquark states

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

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

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

2020

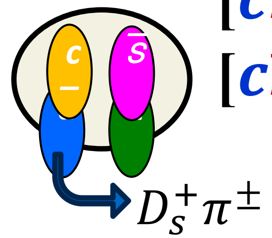



$[cs\bar{u}\bar{d}]$

$\to D^- K^+$

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

2023

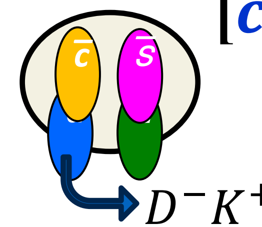



$[c\bar{s}u\bar{d}]$
$[c\bar{s}\bar{u}d]$

$\to D_s^+ \pi^\pm$

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

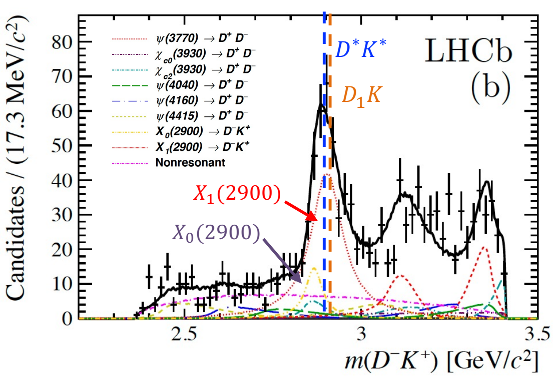
2024

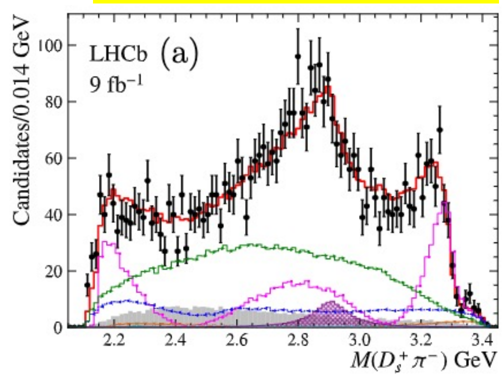


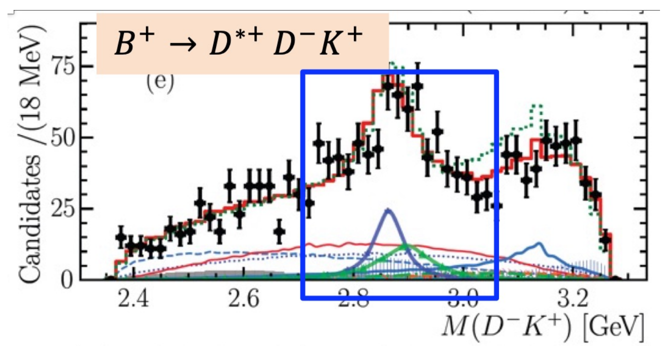

$[cs\bar{u}\bar{d}]$

$\to D^- K^+$

PRL133, 131902 (2024)



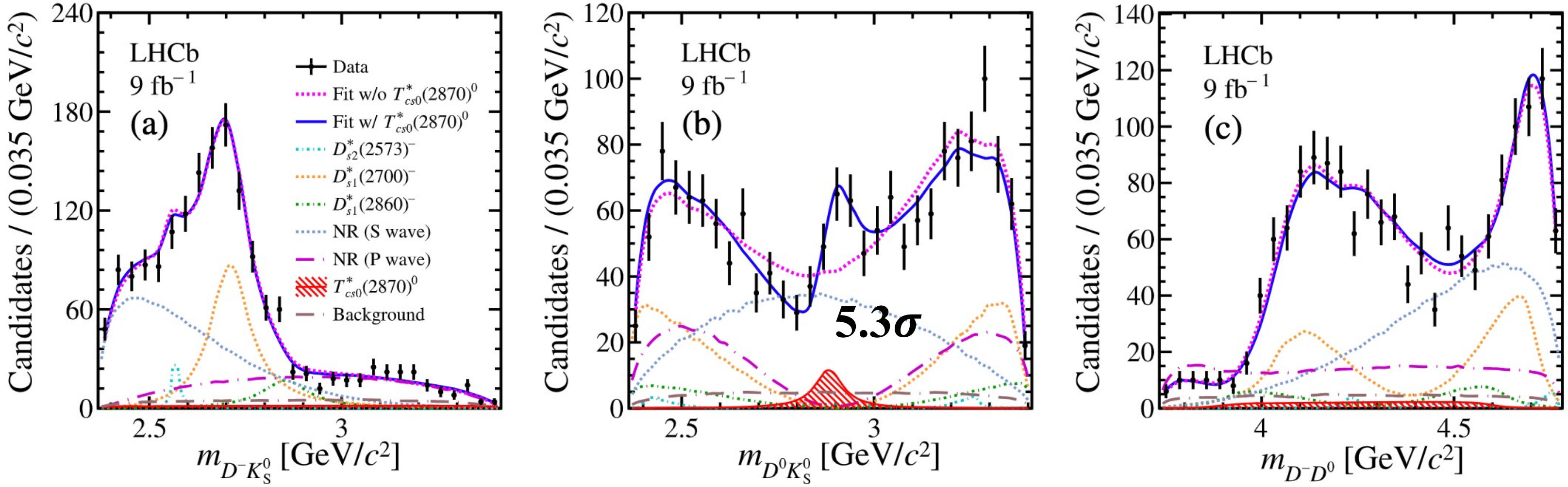




| | Mass (GeV) | Width (GeV) | $J^P$ |
|---|---|---|---|
| $T^*_{c\bar{s}0}(2900)^0$ & $T^*_{c\bar{s}0}(2900)^{++}$ | $2.908 \pm 0.011 \pm 0.020$ | $0.136 \pm 0.023 \pm 0.020$ | $0^+$ |
| $X_0(2900)/T^*_{cs0}(2870)^0$ | $2.866 \pm 0.007 \pm 0.002$ | $0.057 \pm 0.012 \pm 0.004$ | $0^+$ |
| $X_1(2900)/T^*_{cs1}(2900)^0$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

# $T^*_{cs0}(2870)^0$ [$cs\bar{u}\bar{d}$] 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 $D^0 K^0_s$ system with 5.3$\sigma$ significance, **no observation** of $T^*_{cs1}(2900)^0$
- Relative decay width provide precise tests of the **isospin symmetry**

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

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

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

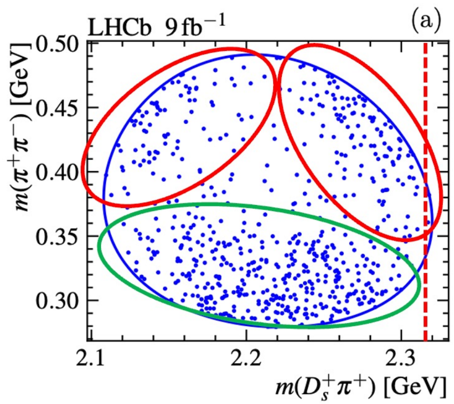
isospin violation indicated for $T^*_{cs0}(2900)^0$

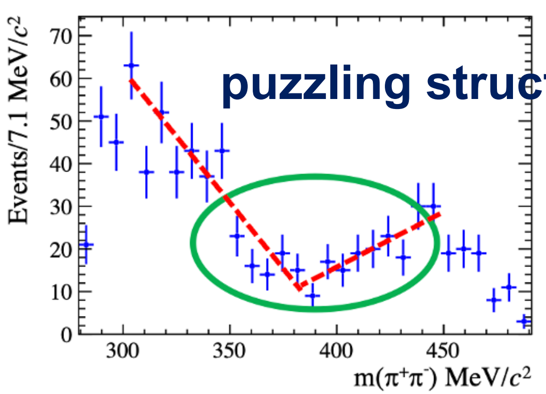
# $T_{c\bar{s}}^{0/++}$ in $D_{s1}(2460)^+ \to D_s^+\pi^+\pi^-$

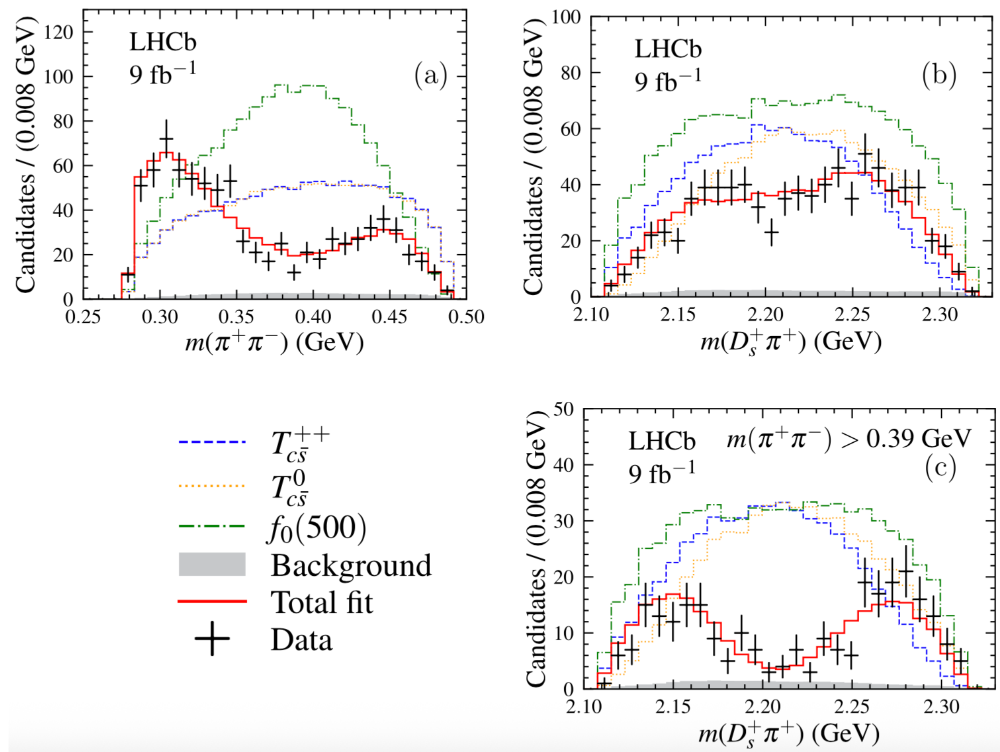
Sci. Bull. 70, 1432 (2025)

## Joint amplitude analysis of the three channels

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



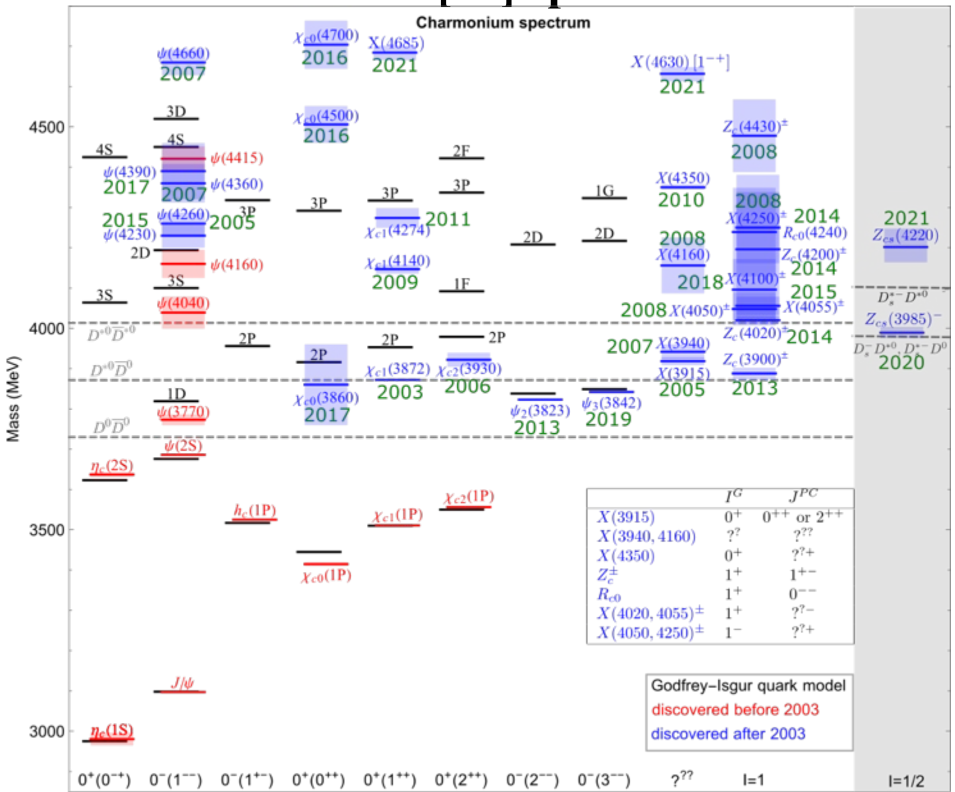

| Resonance | Mass (MeV) | Width (MeV) | Fractions (%) |
|---|---|---|---|
| $f_0(500)$ | $474 \pm 30 \pm 18$ | $224 \pm 23 \pm 16$ | $248^{+40}_{-54} \pm 39$ |
| $T_{c\bar{s}}^{++}/T_{c\bar{s}}^{0}$ | $2327 \pm 13 \pm 13$ | $96 \pm 16 \pm 23$ | $156^{+27}_{-38} \pm 25$ |

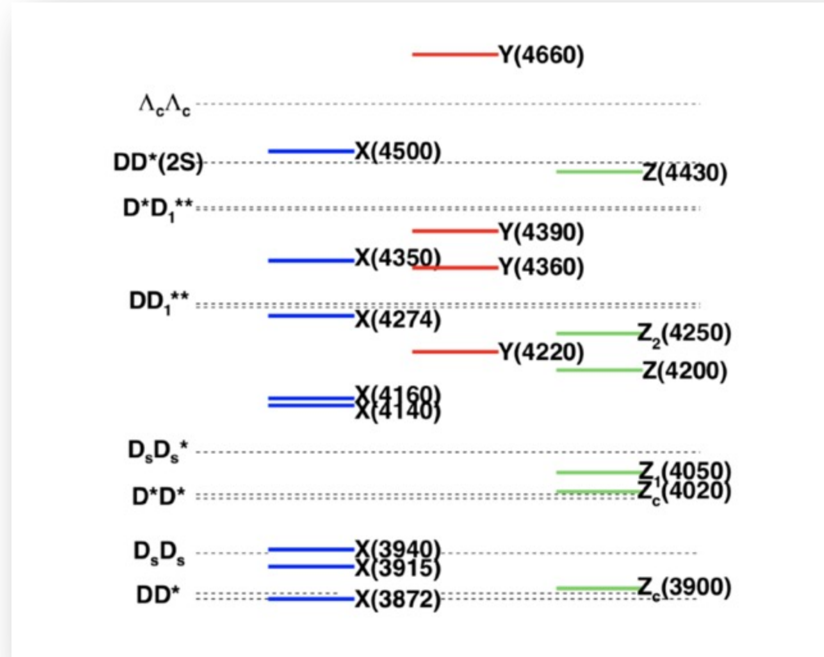
**$T_{c\bar{s}}^{0/++}$ is observed with significance larger than $10\sigma$**

# Overpopulated charmonium spectrum

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

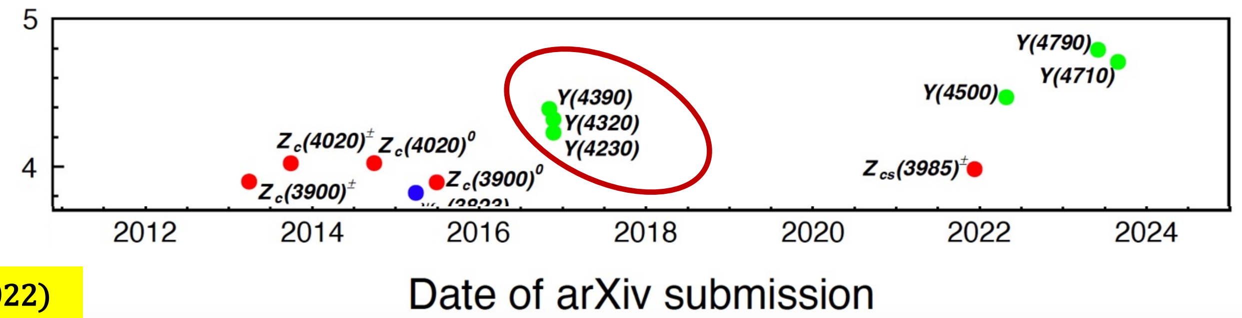
arXiv:1511.01589, arXiv:1812.10947



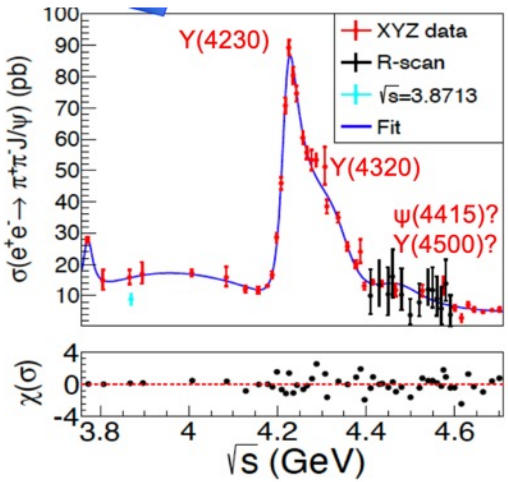




**Overpopulated observed new charmonium-like states, i.e. "XYZ":**

- 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)

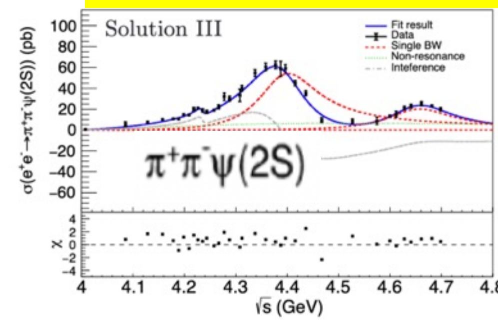


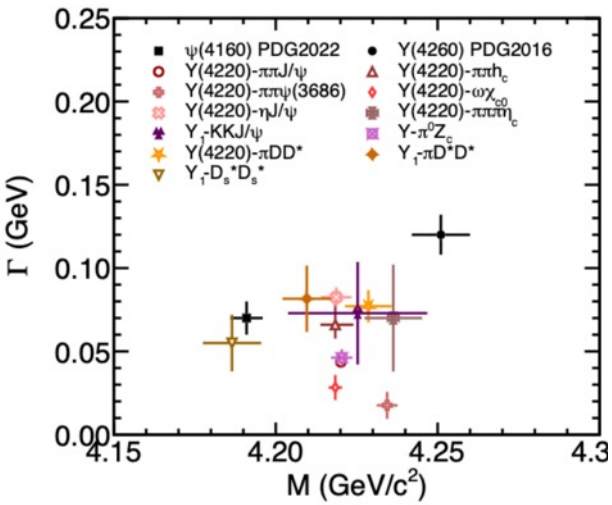

# Y(4260) ➔ Y(4230) & Y(4320)

$$M_{Y(4230)} = 4221.4 \pm 1.5 \pm 2.0\ \mathrm{MeV}/c^2$$
$$\Gamma_{Y(4230)} = 41.8 \pm 2.9 \pm 2.7\ \mathrm{MeV}$$

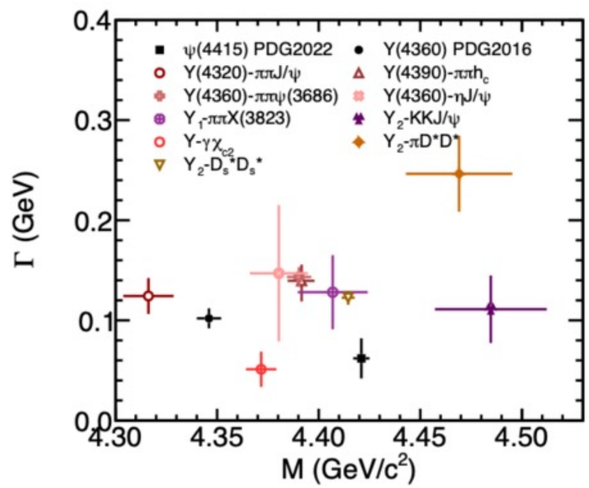
$$M_{Y(4320)} = 4298 \pm 12 \pm 26\ \mathrm{MeV}/c^2$$
$$\Gamma_{Y(4320)} = 127 \pm 17 \pm 10\ \mathrm{MeV}$$

PRD 104, 052012 (2021)

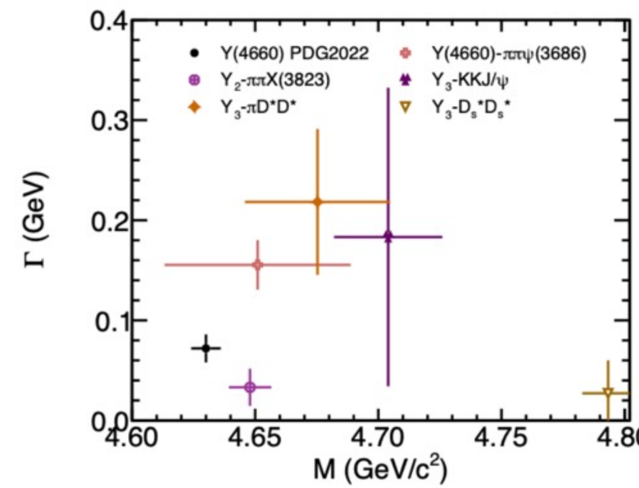



**Y(42XX)**




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

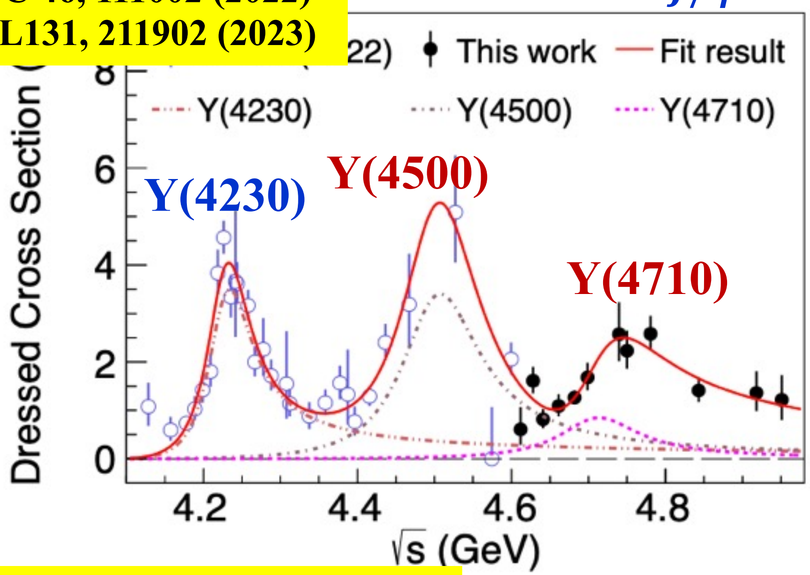



**Y(46XX), Y(47XX)**

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

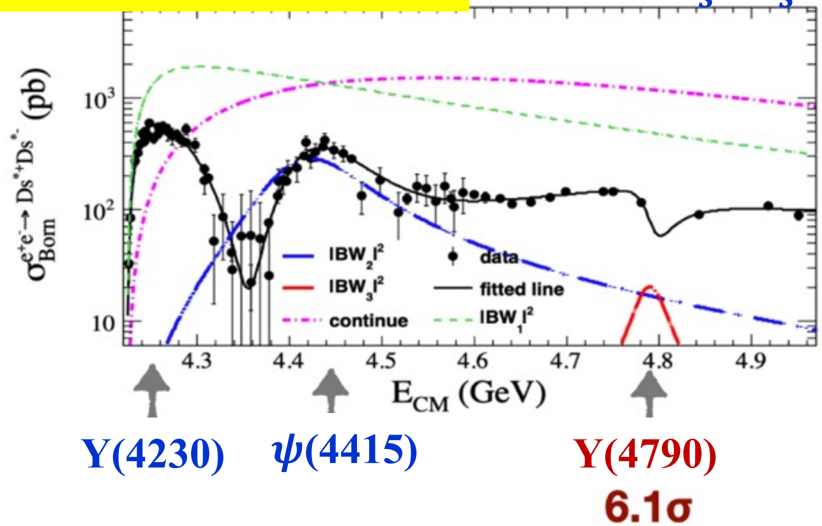
CPC 46, 111002 (2022)
PRL131, 211902 (2023)

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



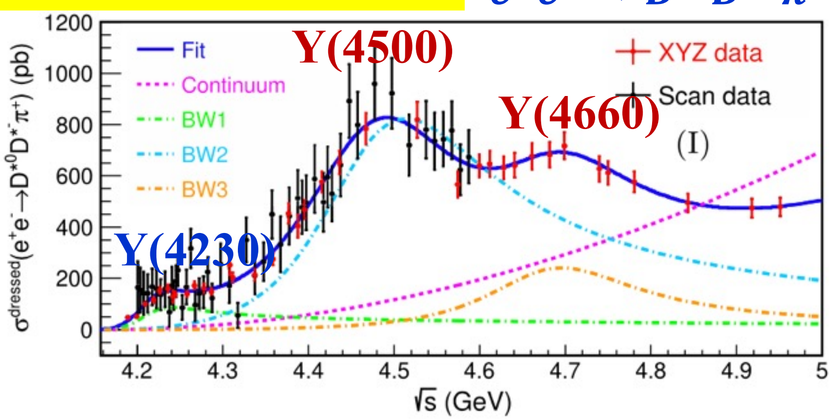

PRL131, 151903 (2023)

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



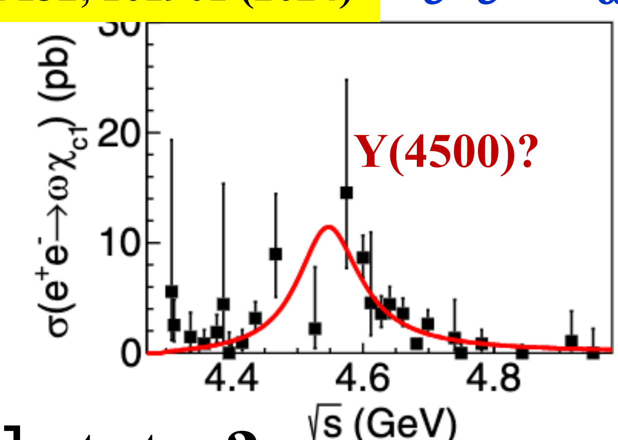

PRL130, 121901 (2023)

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




PRL 132, 161901 (2024)

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

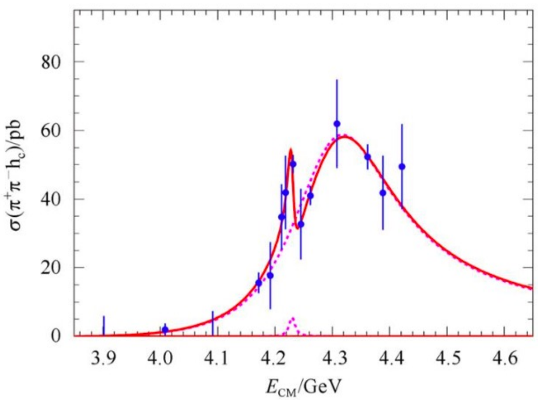



**Are they $[c\bar{c}s\bar{s}]$ states?**

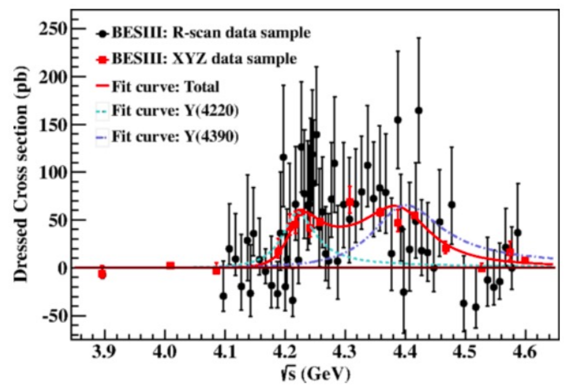
# Improved measurement of $\sigma(e^+e^- \to \pi^+\pi^- h_c)$

**PRL135, 071901 (2025)**

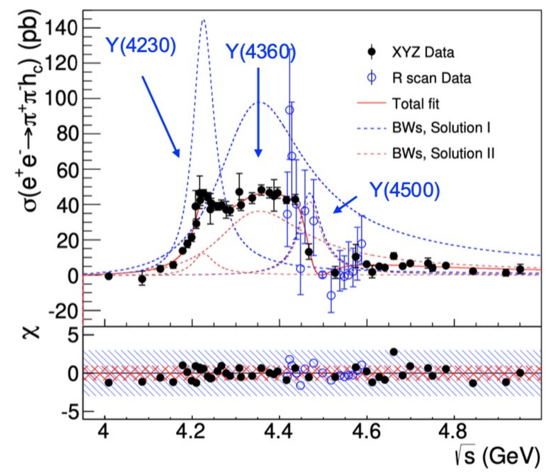
- Initially observed by CLEO-c at √s=4.17 GeV [PRL107, 041803 (2011)]
- Cross sections of $e^+e^- \to \pi^+\pi^- h_c$ obtained by BESIII at 3.9-4.6 GeV, found two structures [PRL118, 092002 (2017)]
- New data collected by BESIII between 4.18-4.95 GeV (27 data samples)




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




PRL118, 092002 (2017) - BESIII




PRL135, 071901 (2025)

Y(4230) Y(4360)

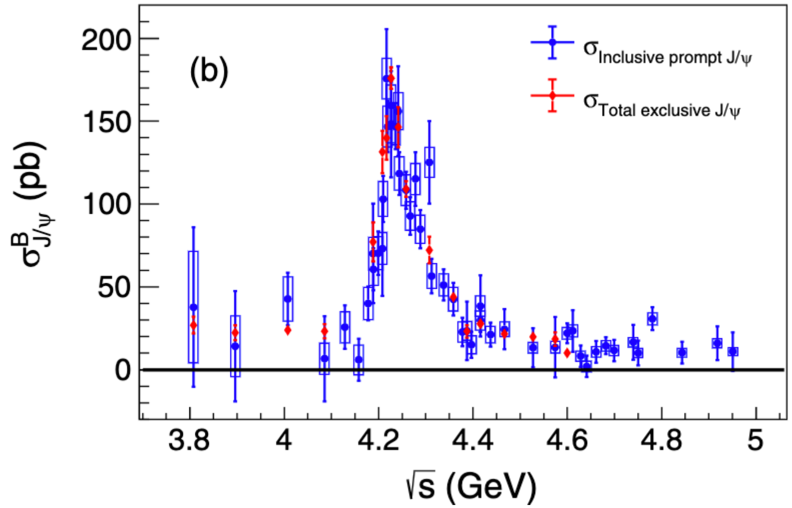
| Parameter | $R_1$ | $R_2$ | $R_3$ |
|---|---|---|---|
| $M$ (MeV/c$^2$) | $4223.6^{+3.6+2.6}_{-3.7-2.9}$ | $4327.4^{+20.1+10.7}_{-18.8-9.3}$ | $4467.4^{+7.2+3.2}_{-5.4-2.7}$ |
| $\Gamma$ (MeV) | $58.5^{+10.8+6.7}_{-11.4-6.5}$ | $244.1^{+34.0+24.2}_{-27.1-18.3}$ | $62.8^{+19.2+9.9}_{-14.4-7.0}$ |

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

>5σ
Y(4500)

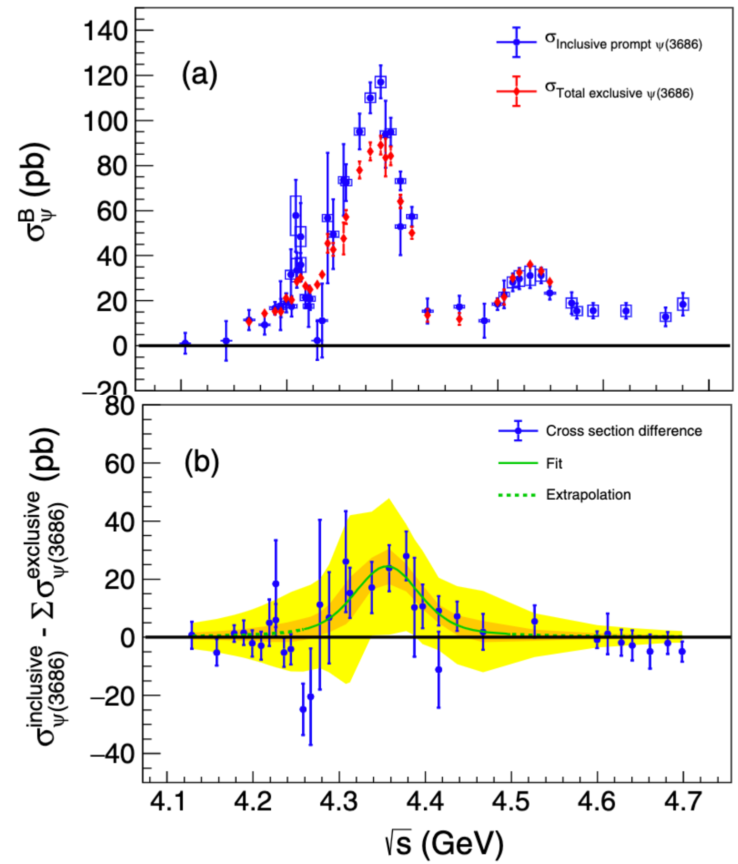
# Inclusive and exclusive $J/\psi$ and $\psi(3686)$ production

**PRD111, 052007 (2025)**




no evidence of hidden decays involving the J/ψ meson

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



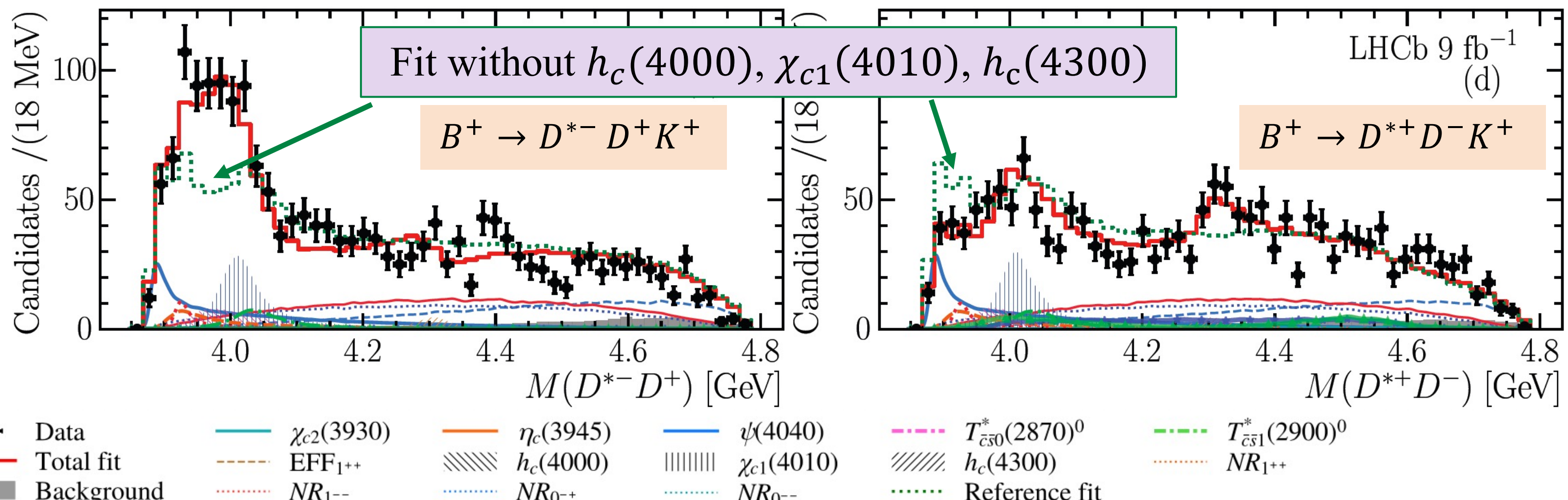

- Missing exclusive processes around the Y(4360) region
- Excess ~ 23% of the $Y(4360)_{\text{prompt}}$ inclusive cross section

# 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 $R \to D^{*-}D^+$:**

$C$-even: $\mathcal{A}_R(D^{*+}D^-) = \mathcal{A}_R(D^{*-}D^+)$ $C$-odd: $\mathcal{A}_R(D^{*+}D^-) = -\mathcal{A}_R(D^{*-}D^+)$



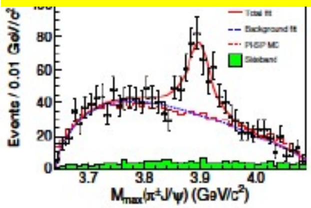

| This work | | Known states [6] | | $c\bar{c}$ prediction [34] | |
|---|---|---|---|---|---|
| $\eta_c(3945)$ | $J^{PC} = 0^{-+}$ | $X(3940)$ [9, 10] | $J^{PC} = ?^{??}$ | $\eta_c(3S)$ | $J^{PC} = 0^{-+}$ |
| $m_0 = 3945^{+28\,+37}_{-17\,-28}$ | $\Gamma_0 = 130^{+92\,+101}_{-49\,-70}$ | $m_0 = 3942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

# The Zc(s) Family at BESIII

## Zc(3900)$^+$

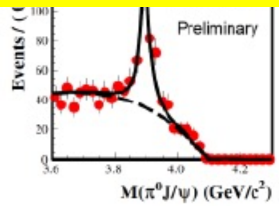
PRL 110, 252001 (2013)



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

## Zc(3900)$^0$

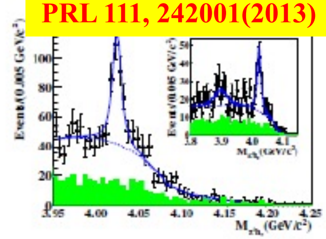
PRL 115, 112003 (2015)



$e^+e^- \to \pi^0\pi^0J/\psi$

## Zc(4020)$^+$

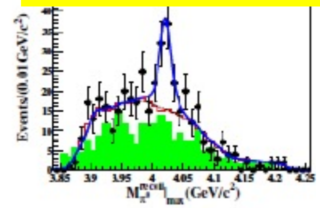
PRL 111, 242001(2013)



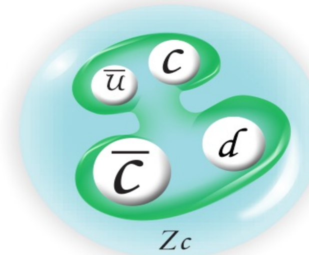
$e^+e^- \to \pi^-\pi^+h_c$

## Zc(4020)$^0$

PRL113,212002 (2014)

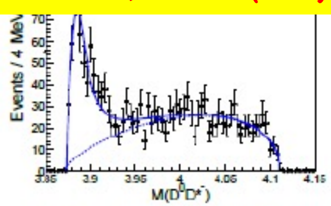


$e^+e^- \to \pi^0\pi^0h_c$



## Zc(3885)$^+$

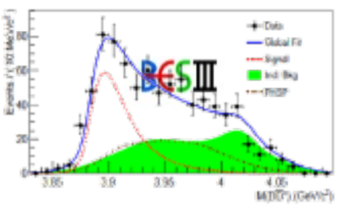
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



$e^+e^- \to \pi^-(D\bar{D}^*)^+$

## Zc(3885)$^0$

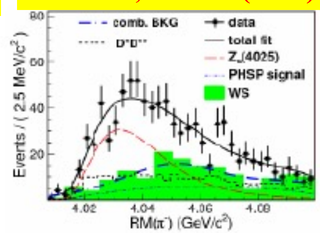
PRL 115, 222002 (2015)



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

## Zc(4025)$^+$

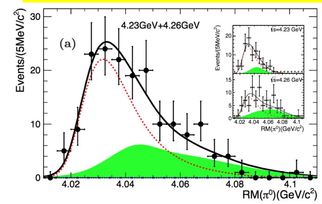
PRL 112, 132001 (2014)



$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

## Zc(4025)$^0$

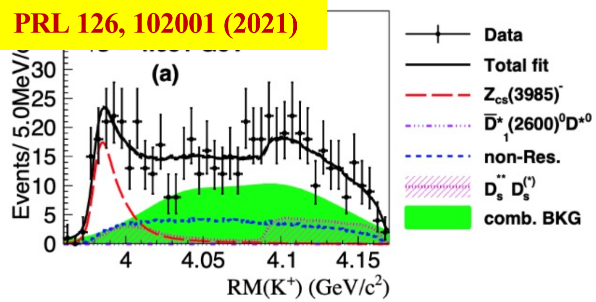
PRL115, 182002 (2015)



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

## $Z_{cs}(3985)^-$

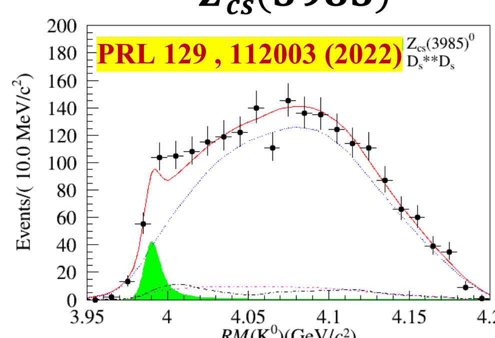
PRL 126, 102001 (2021)



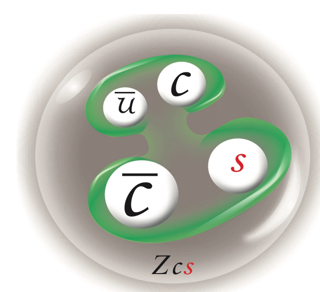
$e^+e^- \to K^+(D^{*0}D_s^- + D^0D_s^{*-})$

## $Z_{cs}(3985)^0$

PRL 129 , 112003 (2022)



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



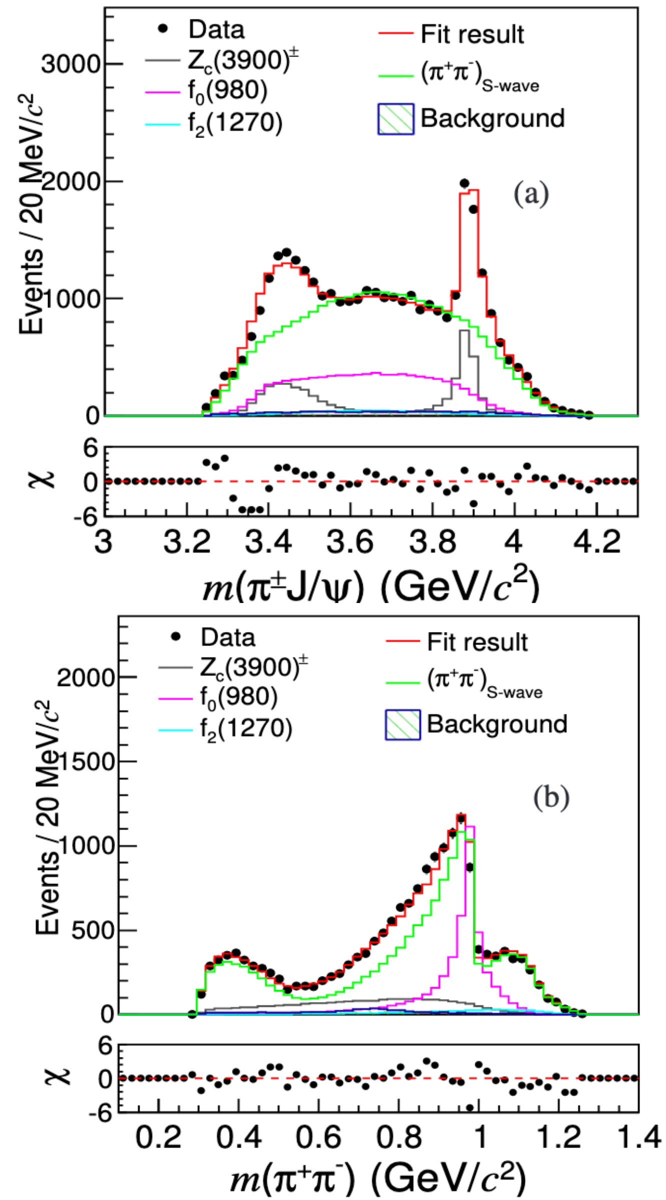
# Joint PWA of $e^+e^- \to \pi^+\pi^- J/\psi$

arXiv:2505.13222

- Based on 12.0 $fb^{-1}$ of $e^+e^-$ collision data between 4.1271 and 4.3583 GeV
- $Z_c(3900)$: BW model with constant width
- $f_0(980)$ seen at all energy points

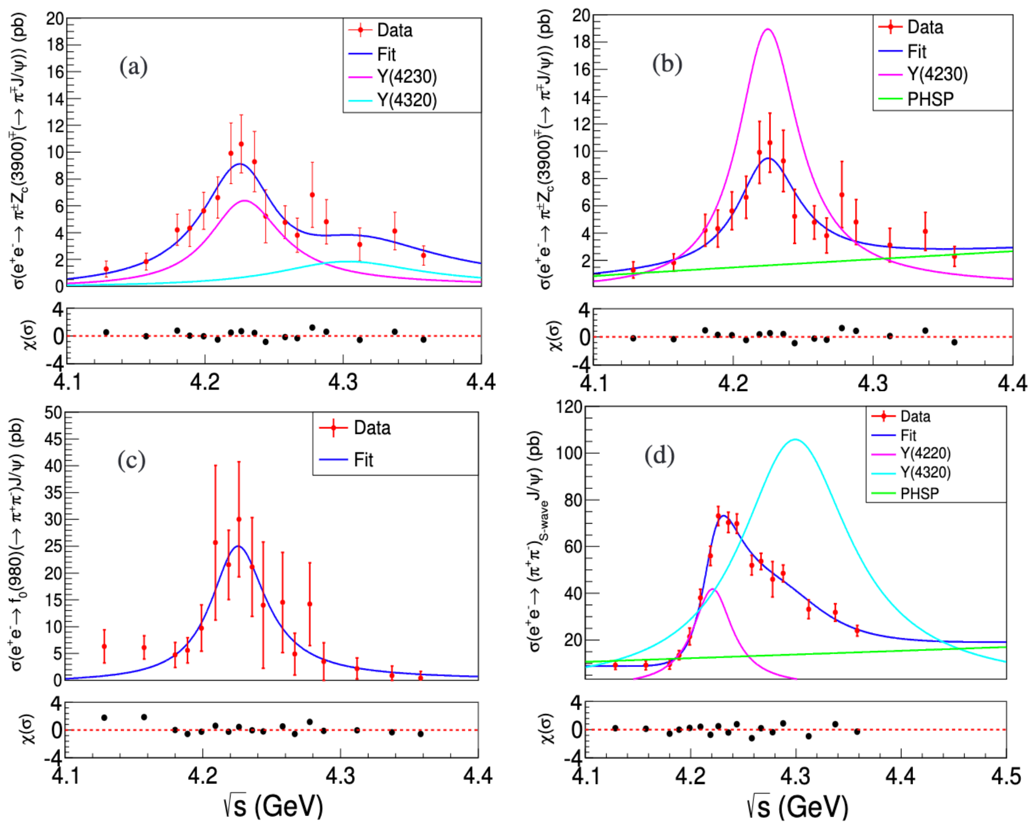
| Sample | $M$ (MeV/$c^2$) | $\Gamma$ (MeV) |
|---|---|---|
| 4.1567 – 4.1989 | 3883.5 ± 1.6 | 38.6 ± 3.6 |
| 4.2091 – 4.2357 | 3884.0 ± 1.0 | 37.8 ± 1.6 |
| 4.2438 – 4.2776 | 3884.9 ± 1.8 | 34.2 ± 3.3 |
| 4.2866 – 4.3583 | 3890.0 ± 2.3 | 36.1 ± 4.2 |
| Average | 3884.6 ± 0.7 ± 3.3 | 37.2 ± 1.3 ± 6.6 |

| State | Mass (MeV/c²) | Width (MeV) | Decay | Process |
|---|---|---|---|---|
| $Z_c(3885)^\pm$ | 3883.9±1.5±4.2 Single D tag | 24.8±3.3±11.0 Single D tag | $(D\bar{D}^*)^\pm$ | $e^+e^- \to (D\bar{D}^*)^\pm\pi^\mp$ |
| | 3881.7±1.6±2.1 Double D tag | 26.6±2.0±2.3 Double D tag | $(D\bar{D}^*)^\pm$ | $e^+e^- \to (D\bar{D}^*)^\pm\pi^\mp$ |
| $Z_c(3885)^0$ | $3885.7^{+4.3}_{-5.7}$±8.4 | $35^{+11}_{-12}$±15 | $(D\bar{D}^*)^0$ | $e^+e^- \to (D\bar{D}^*)^0\pi^0$ |



# BESIII Cross sections of $e^+e^- \to \pi^+ Z_c(3900)^-$

arXiv:2505.13222



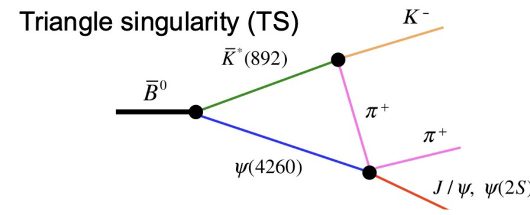

| Process | $Y(4220)$ | | $Y(4320)$ |
|---|---|---|---|
| | $M$ (MeV/$c^2$) | $\Gamma$ (MeV) | Significance |
| $\pi^\pm Z_c(3900)^\mp$ (model I) | $4227.0 \pm 7.0 \pm 6.1$ | $64.4 \pm 17.2 \pm 22.3$ | $2.1\sigma$ |
| $\pi^\pm Z_c(3900)^\mp$ (model II) | $4223.5 \pm 6.6 \pm 0.6$ | $52.8 \pm 20.2 \pm 0.3$ | $1.9\sigma$ |
| $f_0(980)J/\psi$ (model III) | $4224.6 \pm 4.5 \pm 0.6$ | $46.4 \pm 8.0 \pm 0.2$ | $0.3\sigma$ |
| $(\pi^+\pi^-)_{\text{S-wave}}J/\psi$ (model IV) | $4220.6 \pm 3.2 \pm 12.7$ | $45.4 \pm 5.8 \pm 6.3$ | $12.2\sigma$ |
| $Y(4220)^{\text{ave}}$ | $4225.8 \pm 4.2 \pm 3.1$ | $55.3 \pm 9.5 \pm 11.1$ | |

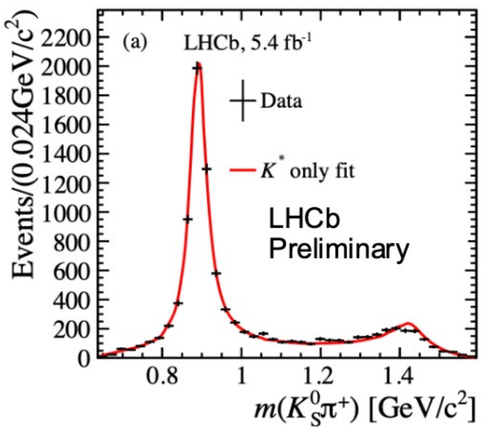
# Amplitude analysis of $B^+ \to K_S^0 \pi^+ \psi(2S)$

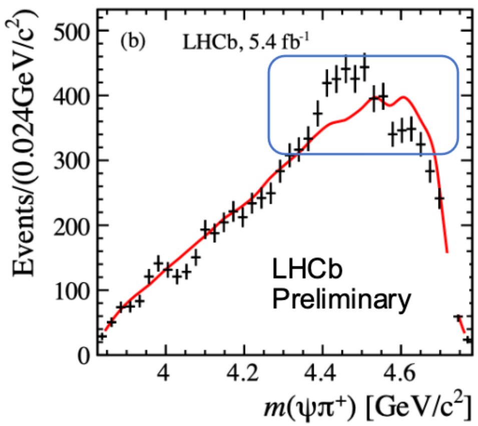
**LHCb-PAPER-2025-039 in preparation**

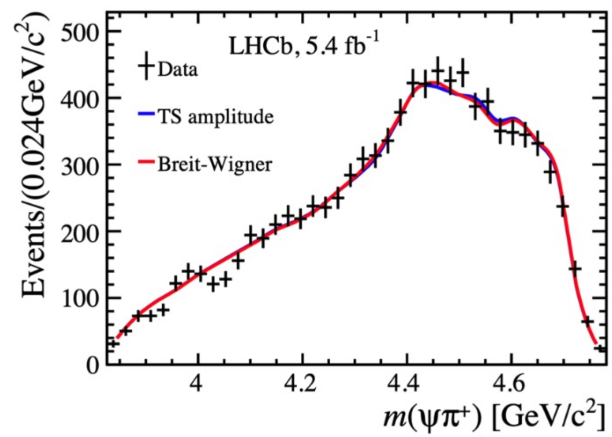
- About $T_{c\bar{c}1}(4430)^+$
  - Discovered by Belle in 2007 in $B^{+,0} \to K^{0,-}\pi^+\psi(2S)$ PRL 100 (2008) 142001
  - Confirmed by LHCb $J^P = 1^+$ in $B^0$ decays. PRL12 (2014) 22, 222002

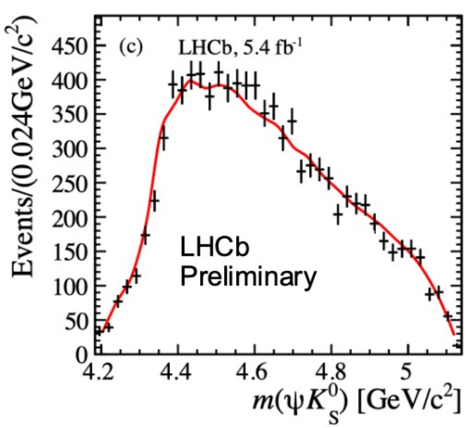
4-dimensional amplitude analysis based on RUN 2 data



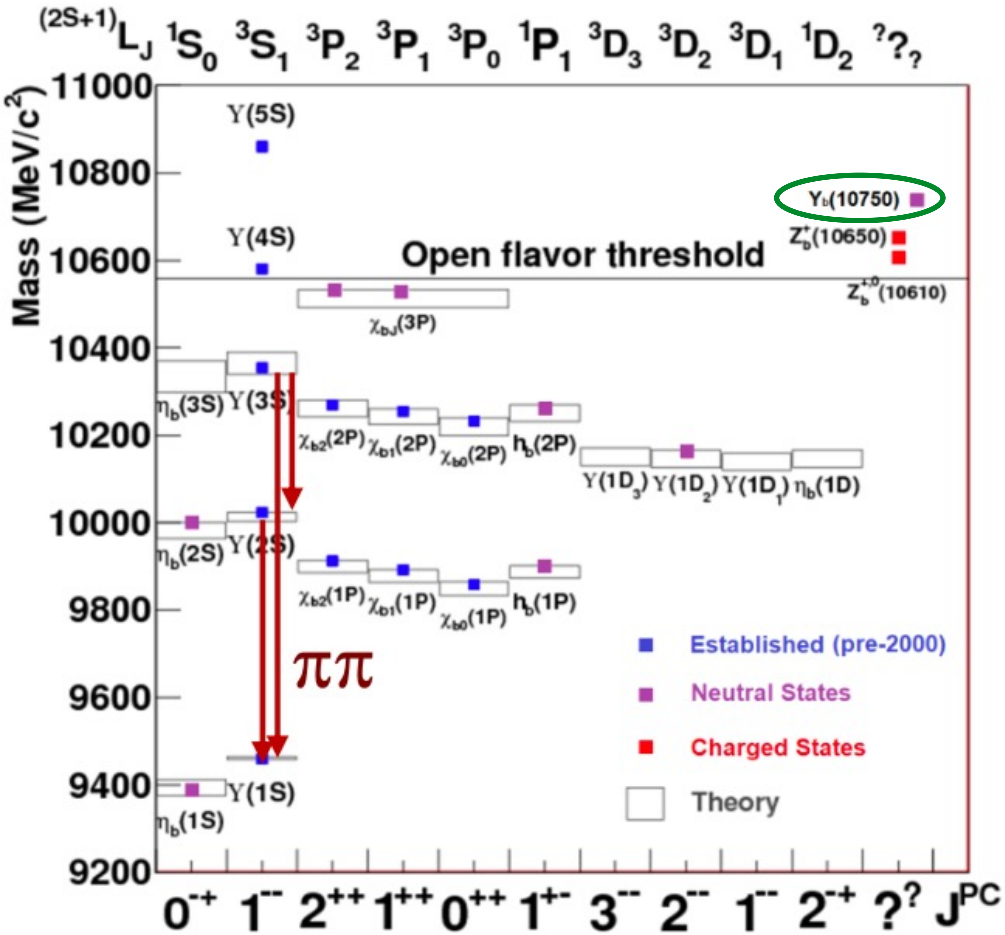

K* states alone cannot describe the $\psi(2S)\pi^+$ enhancement around 4.4 GeV in data

model with a rel. BW state

| $m(\mathrm{GeV}/c^2)$ | $\Gamma(\mathrm{GeV})$ |
|---|---|
| $4.452 \pm 0.016^{+0.023}_{-0.033}$ | $0.174 \pm 0.019^{+0.075}_{-0.020}$ |

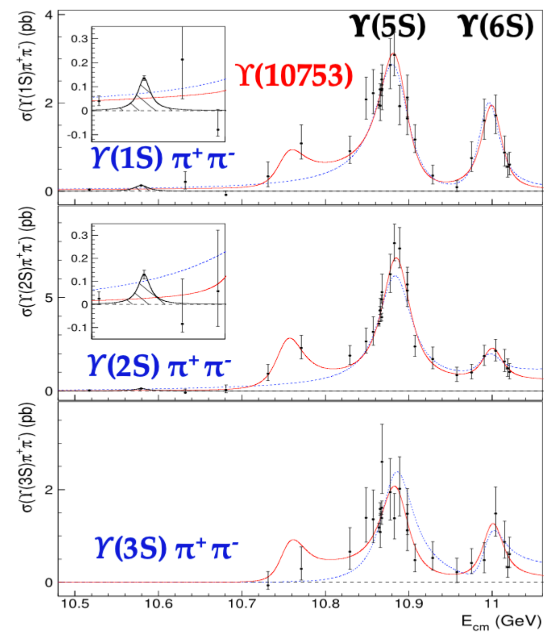
- $J^P = 1^+$ is determined unambiguously
- consistent with previous measurements

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




Belle, JHEP10, 220 (2019)

**$e^+e^- \rightarrow \Upsilon(nS)\,\pi^+\pi^-$ cross sections**

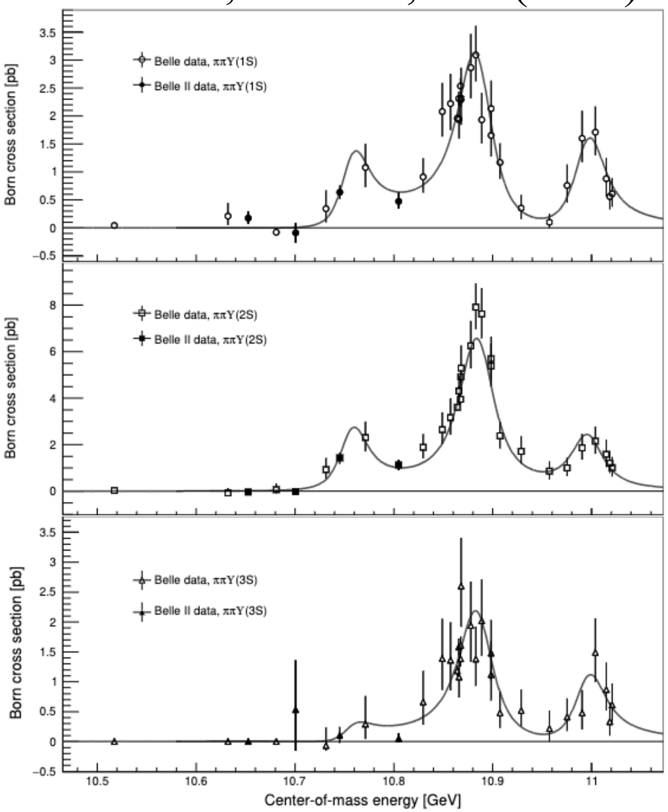



$\Upsilon(10753)$ property has Very high partial widths of hadronic transitions

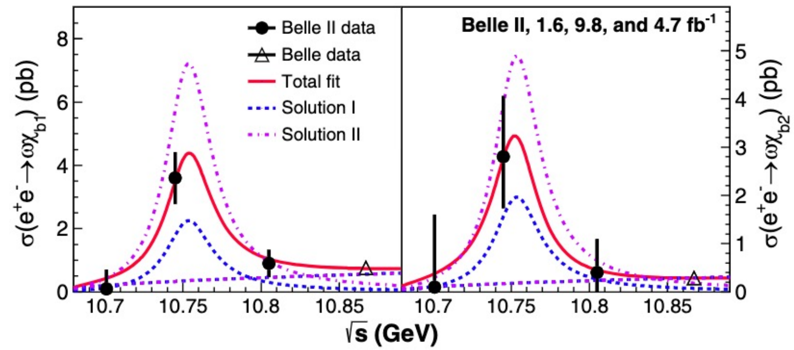
- D-wave state with S-D mixing enhanced due to hadron loops
- exotic state: hybrid, tetraquark

# Further investigation on the $\Upsilon(10753)$

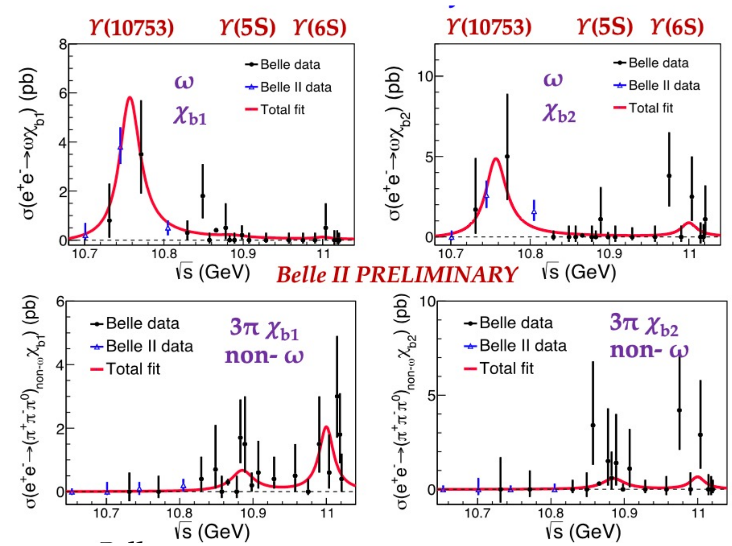
Belle II, JHEP07, 116 (2024)




Belle II, PRL130, 091902 (2023)




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




**Excellent confirmation**

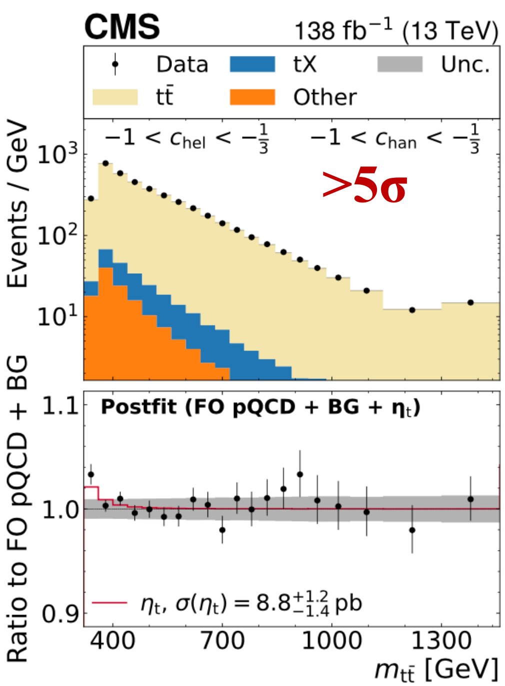
- $M = (10756.6 \pm 2.7 \pm 0.9)\ \mathrm{MeV}/c^2$
- $\Gamma = (29.0 \pm 8.8 \pm 1.2)\ \mathrm{MeV}$

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

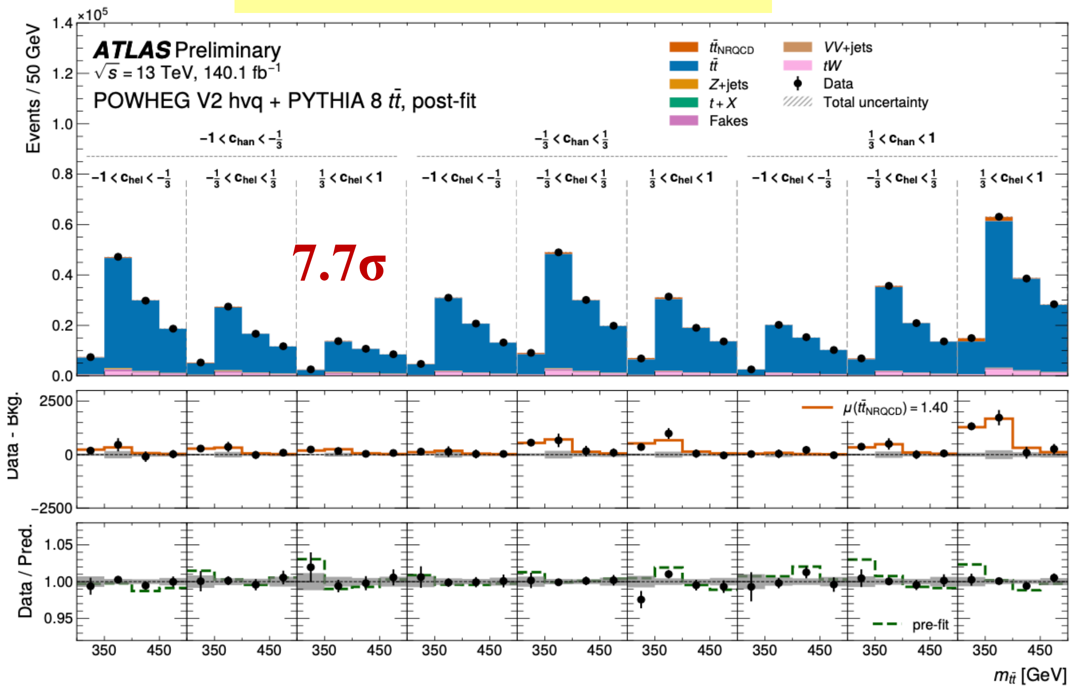
# Toponium [$t\bar{t}$] state?

- $t\bar{t}$ 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 $^1S_0^{[1]}$ $\eta_t$
- 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 $\eta_t$**

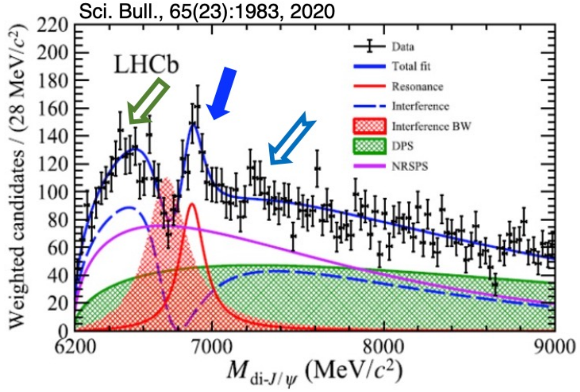
# Study on fully heavy tetraquark state

- 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

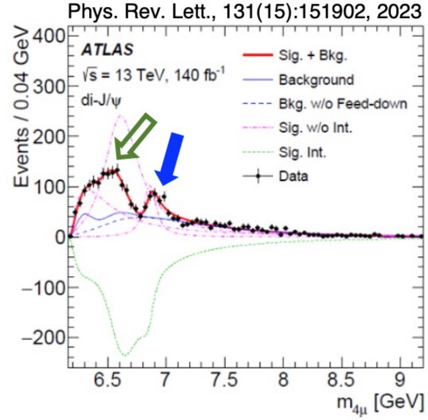
**[LHCb, JHEP 10, 086 (2018); CMS, PLB808, 135578(2020)]**

- $T_{cc\bar{c}\bar{c}}$ 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 $J/\psi$+$J/\psi$ final states **[LHCb, Sci. Bull. 23, 1983 (2020)]**

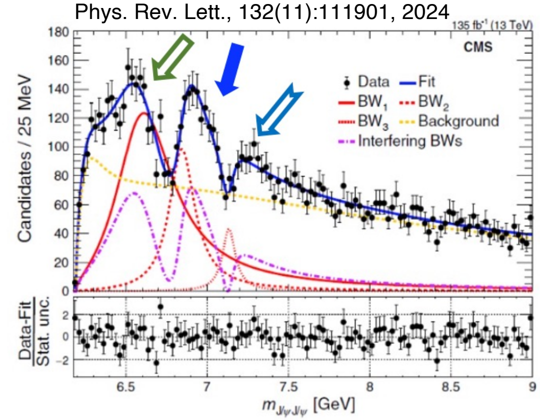
Sci. Bull., 65(23):1983, 2020




Phys. Rev. Lett., 131(15):151902, 2023



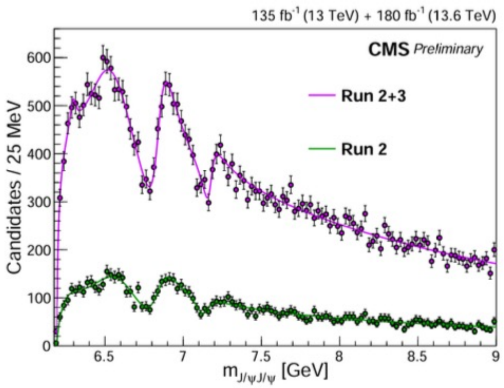

Phys. Rev. Lett., 132(11):111901, 2024

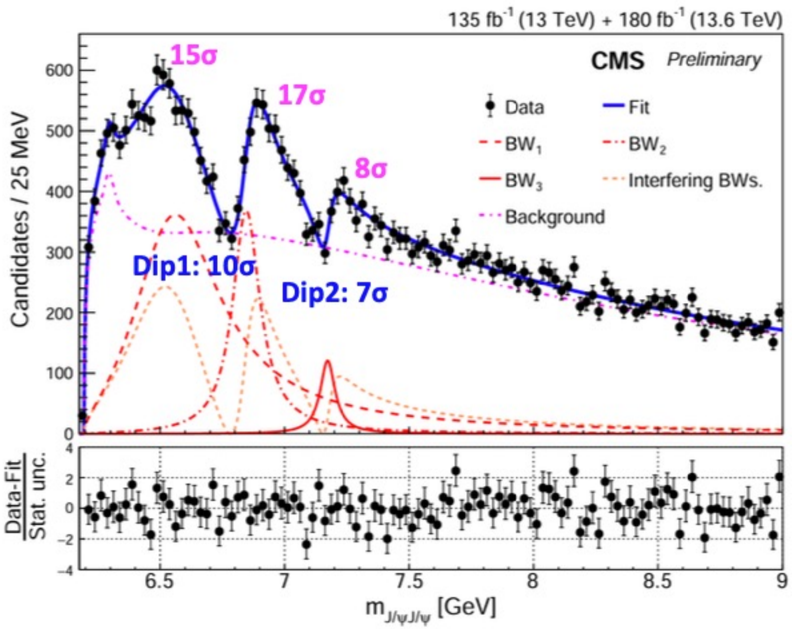



- ATLAS and CMS both confirmed the X(6900) state in $J/\psi$+$J/\psi$ final states
- CMS observed a new structure X(6600) and find an evidence of the X(7100)
- LHCb, ATLAS and CMS all see a broad enhancement at the low mass region

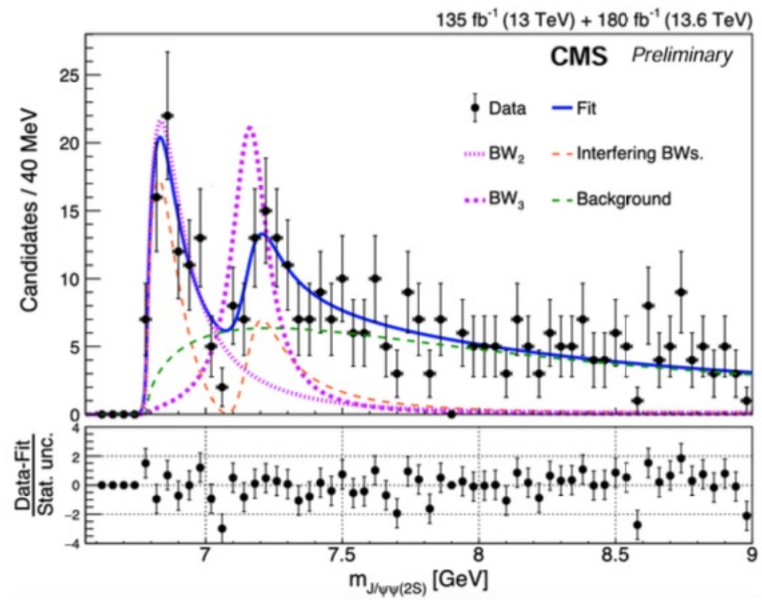
# Fully charmed tetraquark [$cc\bar{c}\bar{c}$] with run 2+3 data

**BPH-24-003**




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



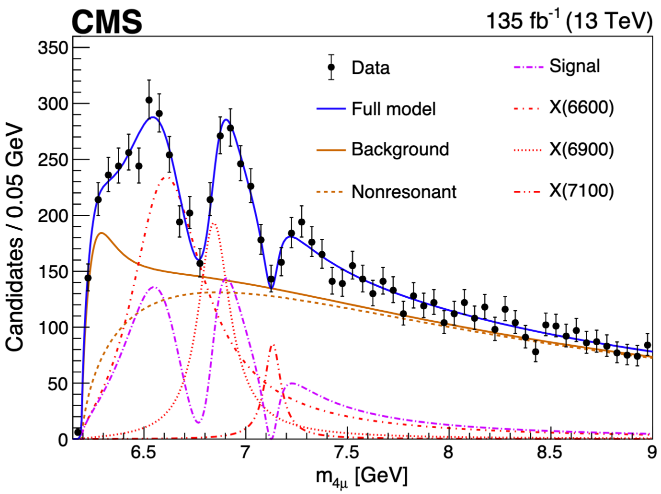

- **All states and dips are above 5σ**
- **Interferences are necessary**

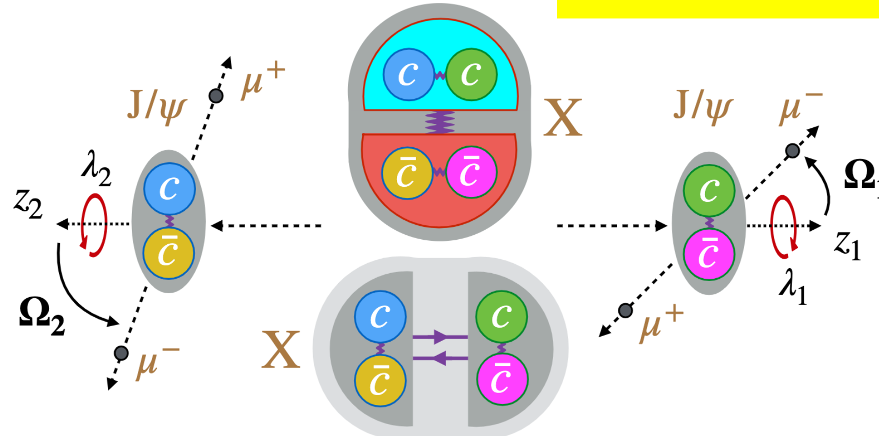
➢ Significance of **X(6900) = 7.9σ**

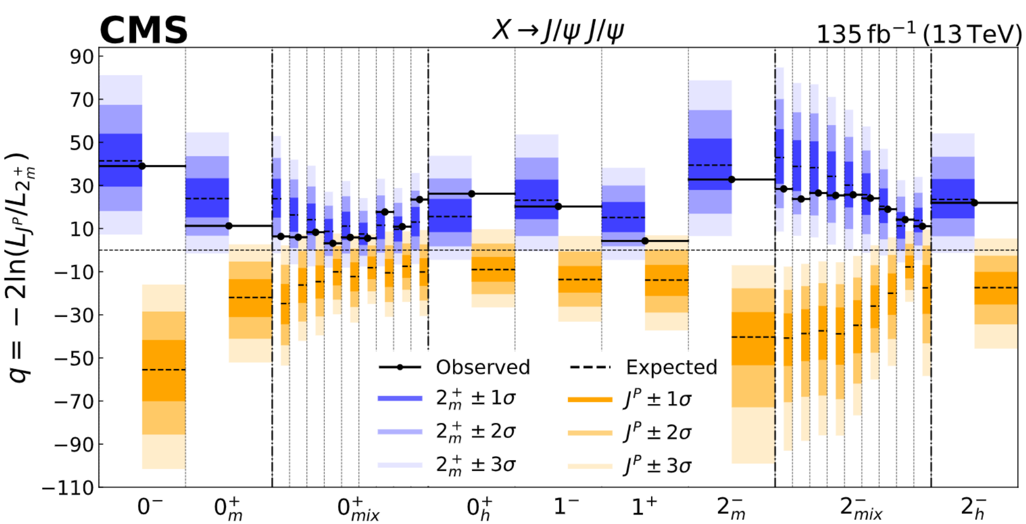
➢ Significance of **X(7100) = 4.0σ**

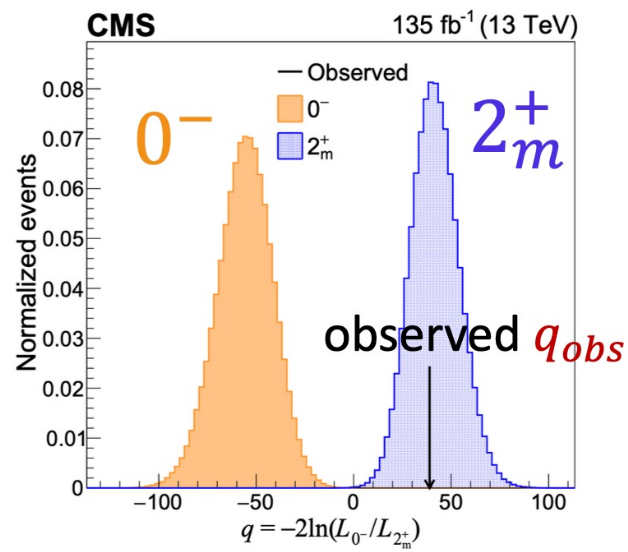
# Spin analysis of X[$cc\bar{c}\bar{c}$] states

arXiv:2506.07944



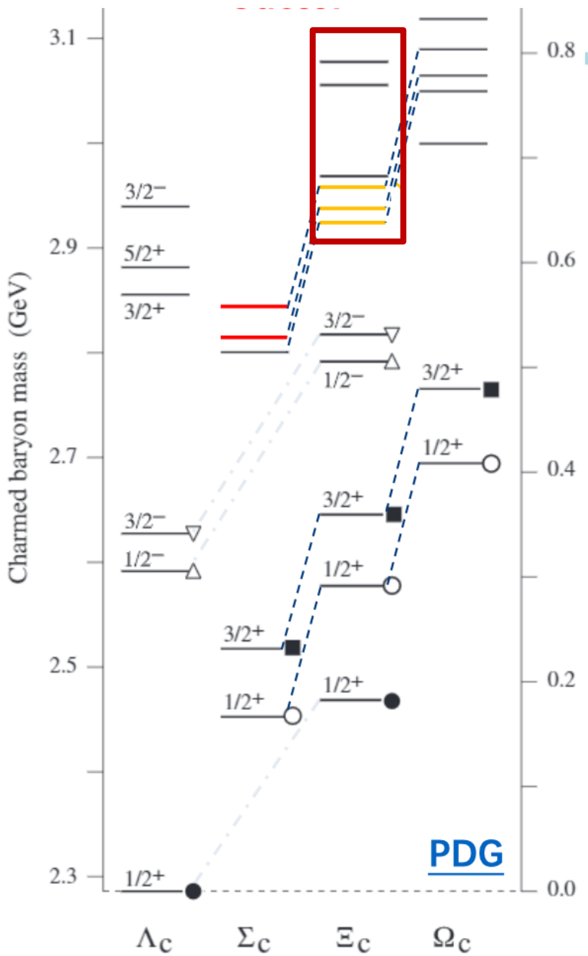




$J^{PC} = 2^{++}$ interpretation is preferred for the fully charmed tetraquark states $X(6600)$, $X(6900)$, and $X(7100)$.

# Heavy baryons

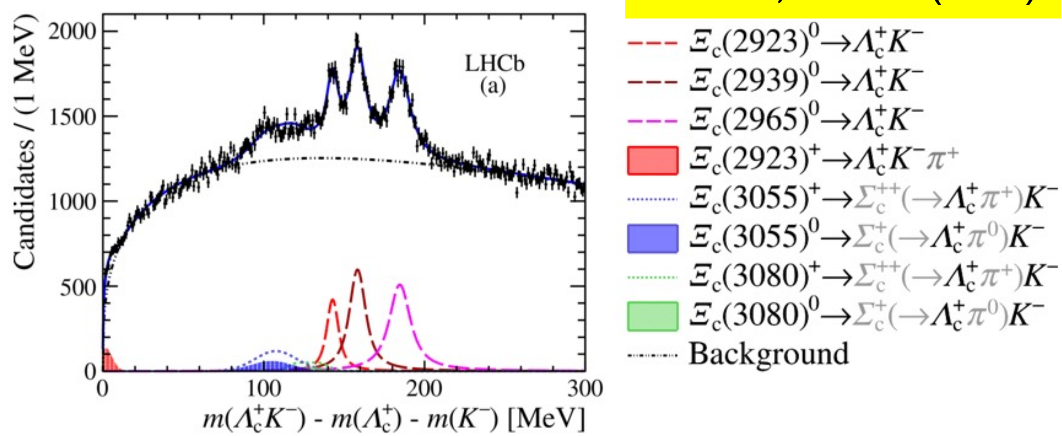
# Observation of new Ξc baryons




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

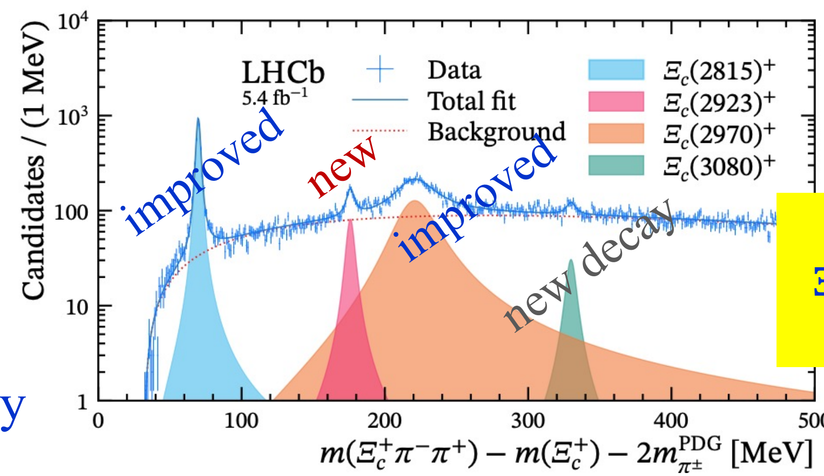
- Three excited $\Xi_c^0$ are observed in decaying into $\Lambda_c^+ K^-$

PRL124, 222001 (2020)




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

arXiv:2502.18987

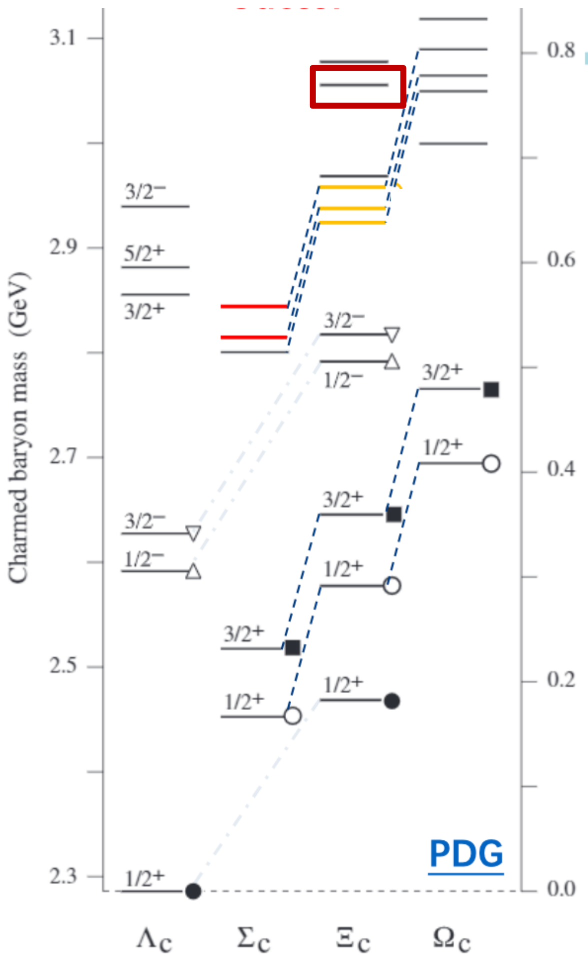



wider width of $\Xi_c(2970)^+$ than $\Xi_c(2965)^0$

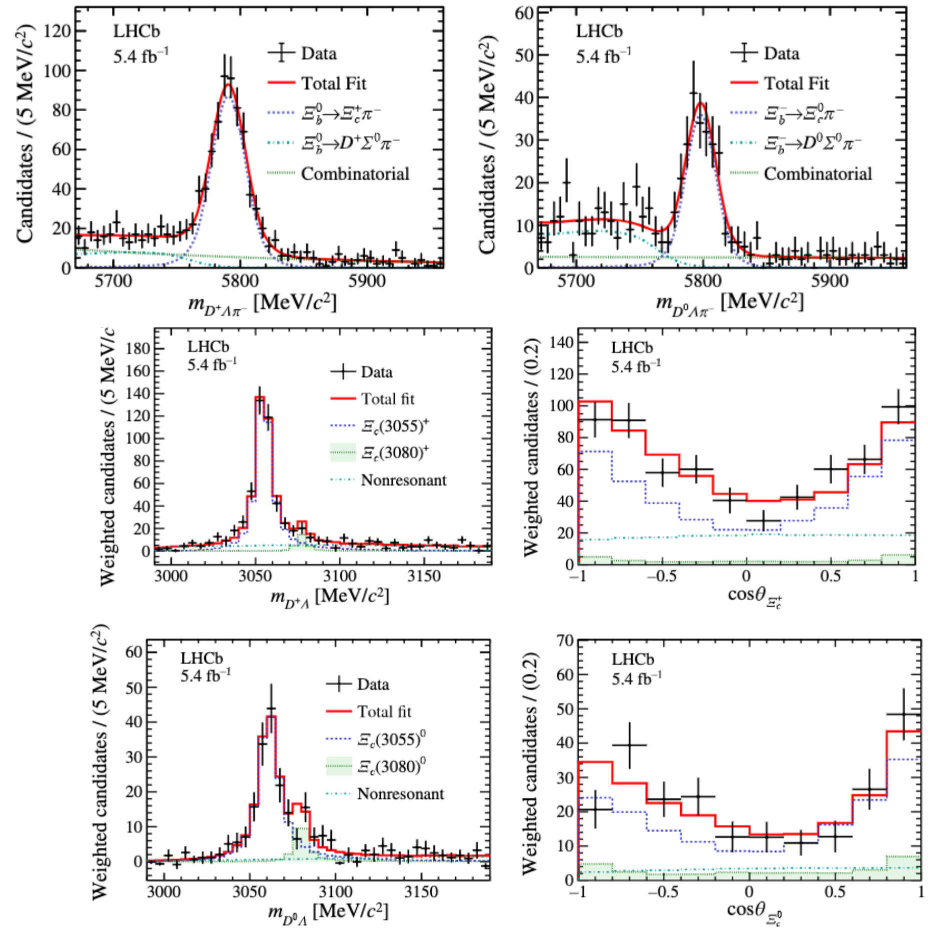
# Spin-parity of the $\Xi_c(3055)$

Amplitude analysis of the cascade weak decay of

$\Xi_b^{0(-)} \rightarrow \Xi_c(3055)^{+(0)}(\rightarrow D^{+(0)}\Lambda)\pi^-$ 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)σ for charged (neutral) $\Xi_c(3055)$

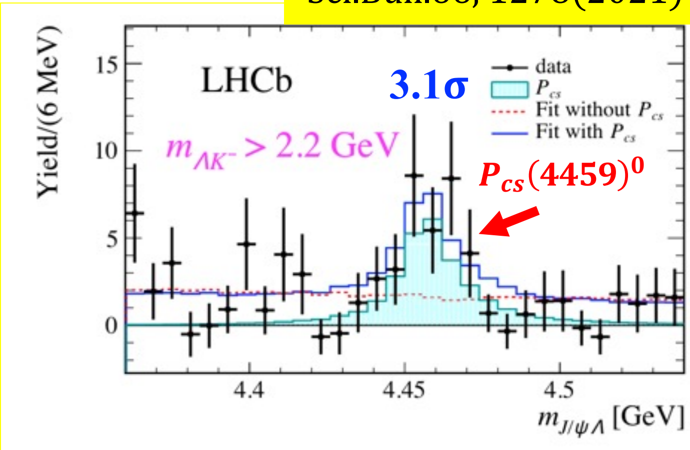
# Observation of the hidden-charm strange pentaquark [$c\bar{c}uds$]

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

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

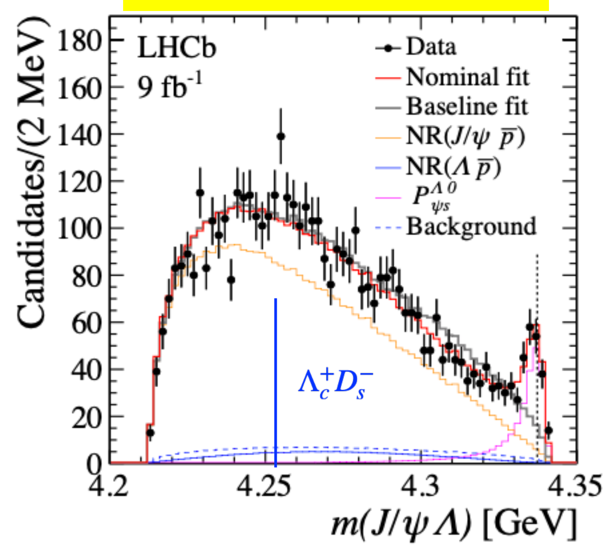
Sci.Bull.66, 1278(2021)




- $P_{c\bar{c}s}(4338)^0 \to J/\psi\Lambda$ observed in $B^- \to J/\psi\Lambda\bar{p}$ (>10$\sigma$)
- $J^P = \frac{1}{2}^-$ preferred and close to $\Xi_c^+ D^-$ threshold
  - ➢ 0.8 MeV above $\Xi_c^+ D^-$;
  - ➢ 2.9 MeV above $\Xi_c^0 \bar{D}^0$

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

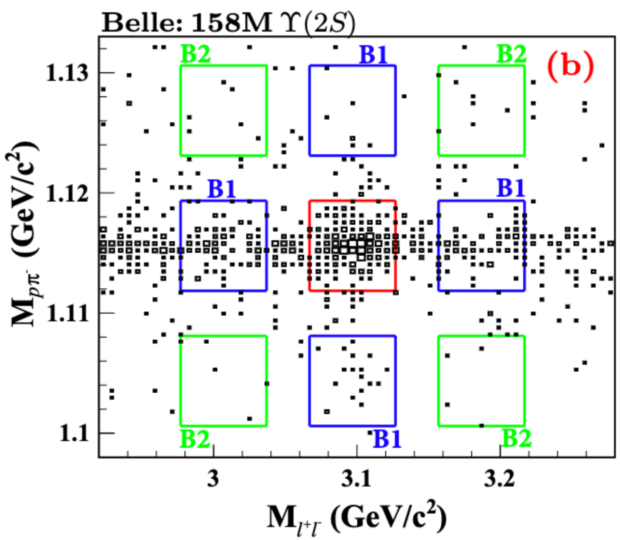
PRL131, 031901(2023)

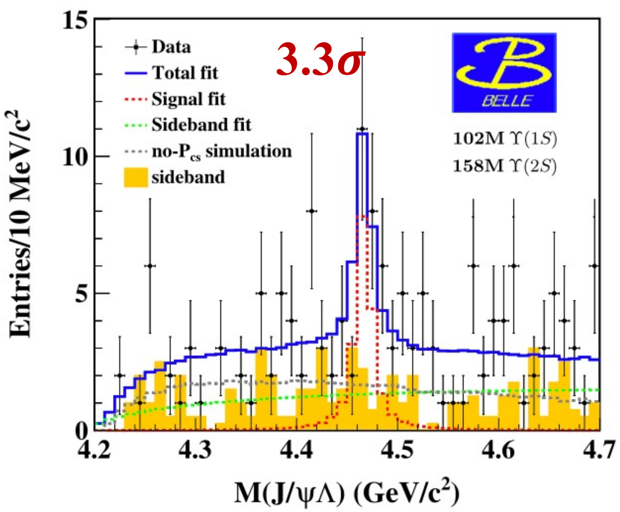


# Evidence for $\Upsilon(1S,2S) \to P_{c\bar{c}s}(4459)^0 X$

PRL135, 041901(2025)

**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: $22 \pm 13 \pm 3$ 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 $\eta_t$?
  - advances in fully charmed tetraquark: $X(6600)$, $X(6900)$ and $X(7100)$ $[c\bar{c}c\bar{c}]$
- 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.

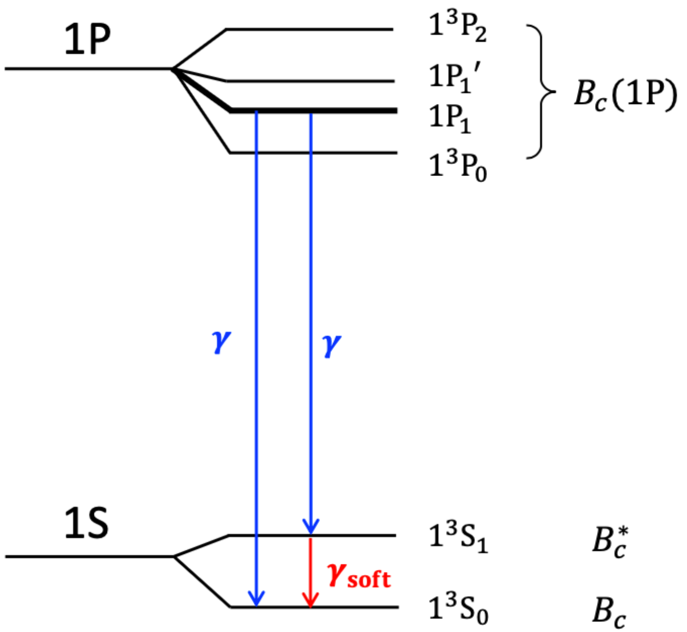
# Thank you!

# 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 | $B_c^{*+}(\to B_c^+\gamma)\gamma$ | $B_c^+\gamma$<br>$B_c^{*+}(\to B_c^+\gamma)\gamma$ | $B_c^+\gamma$<br>$B_c^{*+}(\to B_c^+\gamma)\gamma$ | $B_c^{*+}(\to B_c^+\gamma)\gamma$ |
| #peaks | 1 | 2 | 2 | 1 |



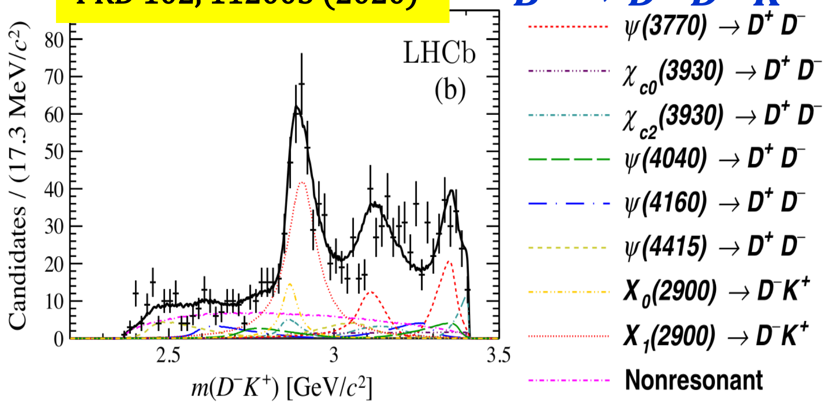

◎ *The value $\delta M = M(B_c^*) - M(B_c)$ is unknown since $B_c^*$ has not been observed yet*

# 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)]

PRD 102, 112003 (2020)

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



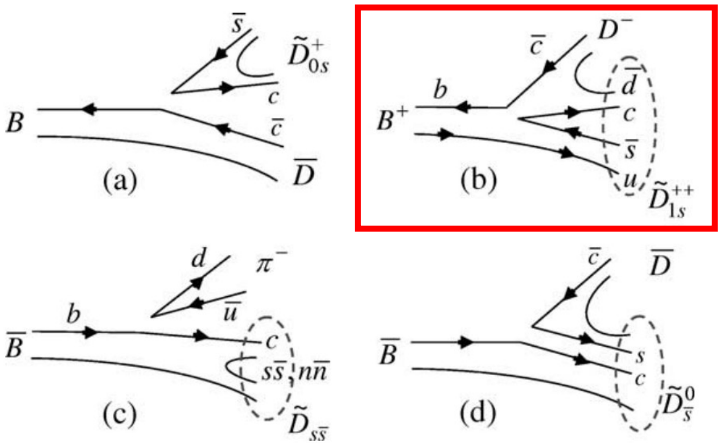



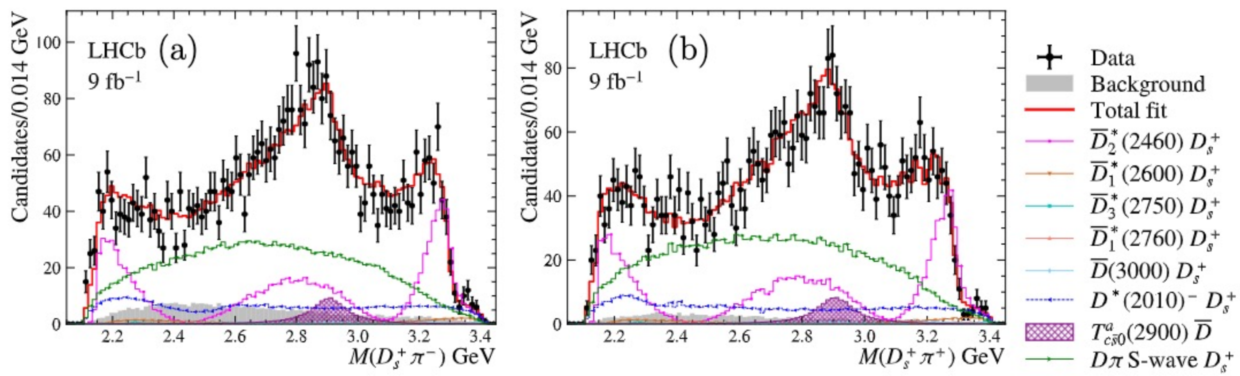

Fig. 2. Diagrams for (a) $B \to \bar{D}\tilde{D}_{0s}^+$, (b) $B^+ \to D^-\tilde{D}_{1s}^{++}$ ($B \to \bar{D}\tilde{D}_{Is}$), (c) $\bar{B} \to \pi^-\tilde{D}_{s\bar{s}}, \pi^-\tilde{D}$, (d) $\bar{B} \to \bar{D}\tilde{D}_{\bar{s}}^0$.

# 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 $\sigma$**)
  $T^a_{c\bar{s}0}(2900)$ > **9 $\sigma$**



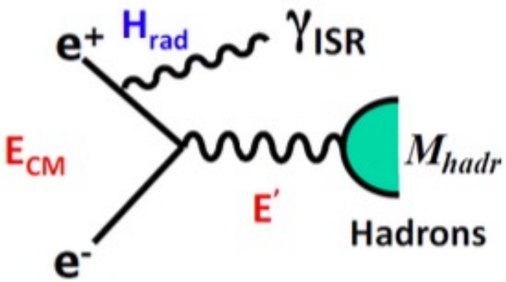

| | Mass (GeV) | Width (GeV) | $J^P$ |
|---|---|---|---|
| $T^*_{c\bar{s}0}(2900)^0$ & $T^*_{c\bar{s}0}(2900)^{++}$ | $2.908 \pm 0.011 \pm 0.020$ | $0.136 \pm 0.023 \pm 0.020$ | $0^+$ |
| $X_0(2900)/T^*_{cs0}(2870)$ | $2.866 \pm 0.007 \pm 0.002$ | $0.057 \pm 0.012 \pm 0.004$ | $0^+$ |
| $X_1(2900)/T^*_{cs1}(2900)$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

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

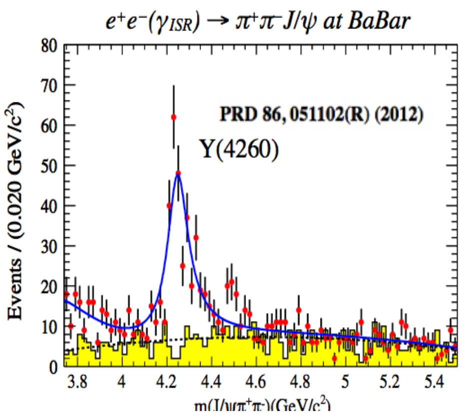
*See parallel talk by Raul Rabadan*

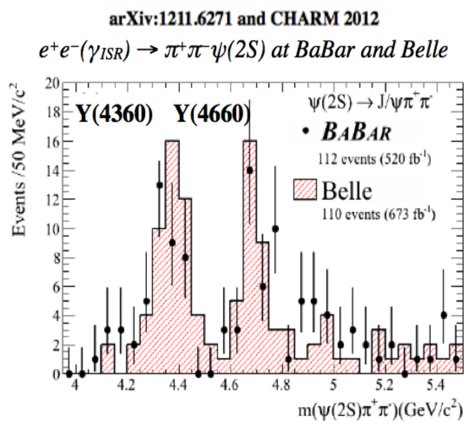
- no isospin relation: $[c\bar{s}u\bar{d}]$ v.s. $[cs\bar{u}\bar{d}]$
- U-spin relation: $[c\bar{s}\bar{u}d]$ v.s. $[c\bar{d}\bar{u}s]$
- $T^a_{c\bar{s}0}(2900)$ mass and width larger than $T_{cs0}(2900)$

# The Y states



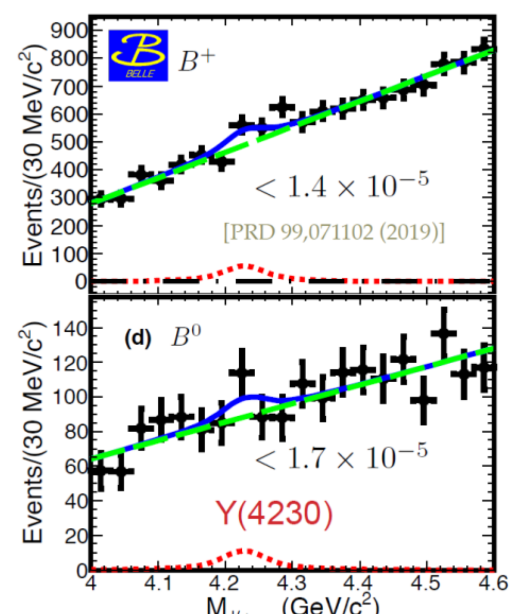

**Y states**: charmonium-like states with $J^{PC}=1^{--}$;
Observed in direct e+e- annihilation or initial state radiation (ISR).



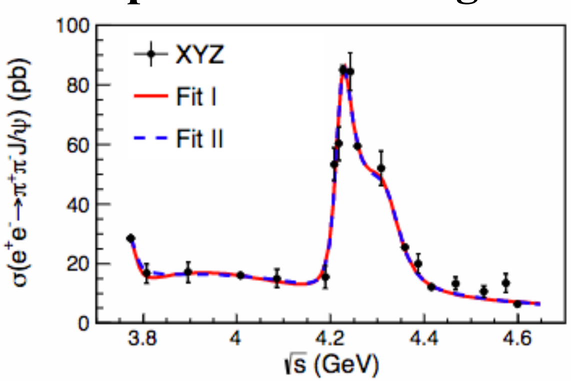




- **While not seen yet in B decays**

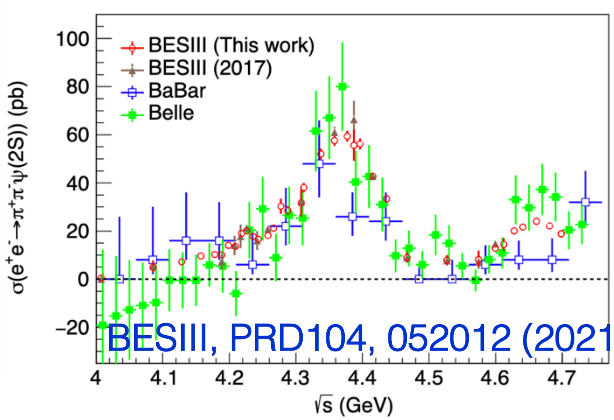
$$B^{\pm,0} \to K^{\pm,0}\pi^+\pi^- J/\psi$$




- **Improved knowledges from BESIII**



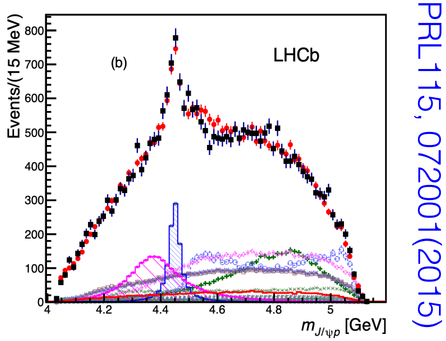

BESIII, PRL118, 092001 (2017)



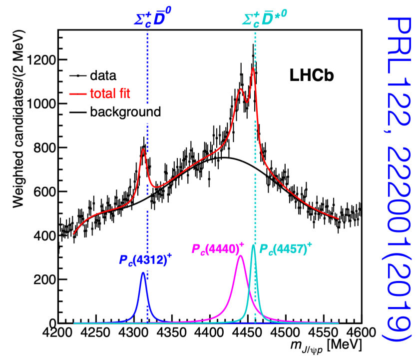

BESIII, PRD104, 052012 (2021)

# Pentaquark states at LHCb

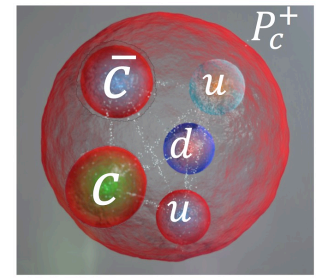
- **Observation of [$c\bar{c}uud$] pentaquarks:** $P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ in $\Lambda_b^0 \to J/\psi p K^-$ decays; near thresholds of $\Sigma_c^+\overline{D}^0$, $\Sigma_c^+\overline{D}^{*0}$, $J^P$ not determined



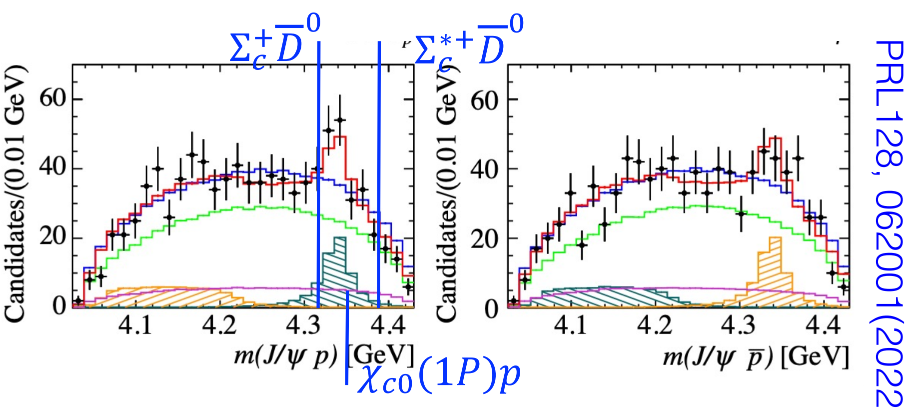

PRL115, 072001(2015)




PRL122, 222001(2019)

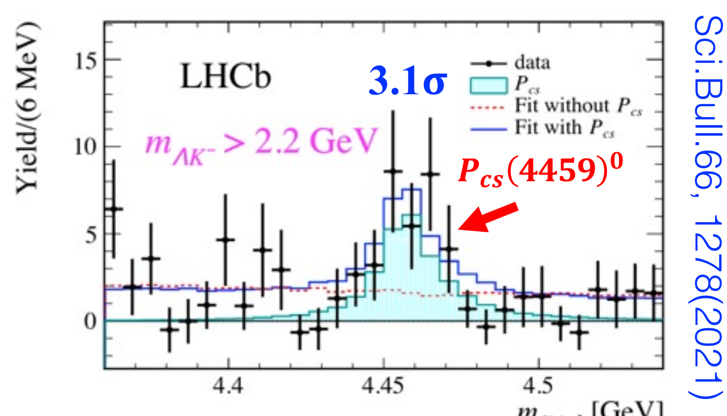



- **Evidence of [$c\bar{c}uud$] pentaquark:** $P_{c\bar{c}}(4337)^+$ in $B_s^0 \to J/\psi p\bar{p}$ decays




PRL128, 062001(2022)

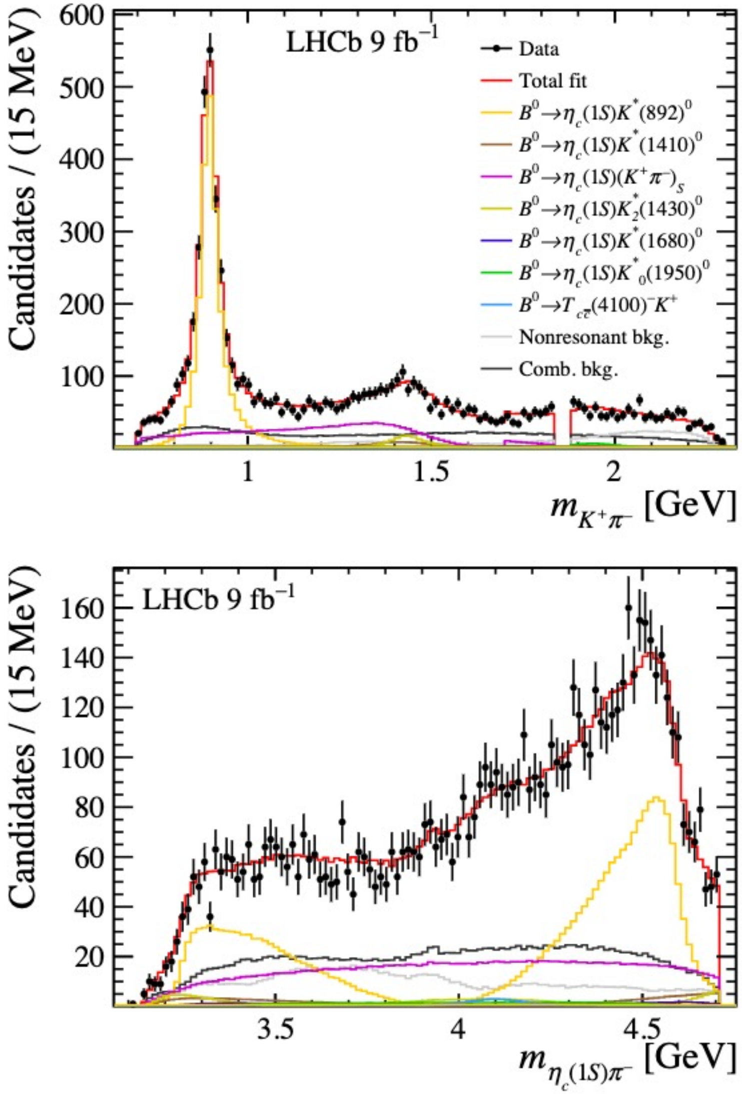
- **Evidence for [$c\bar{c}uds$] pentaquark candidate with strangeness:** $P_{c\bar{c}s}(4459)^0$ in $\Xi_b^- \to J/\psi\Lambda K^-$ decays, near threshold of $\Xi_c^0\overline{D}^{*0}$

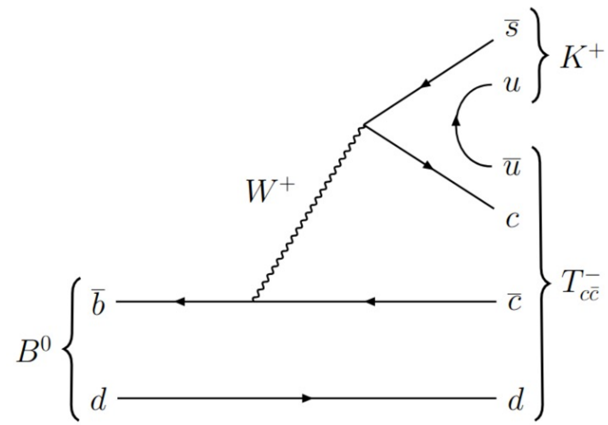



Sci.Bull.66, 1278(2021)

# Amplitude analysis of $B^0 \to K^+\pi^-\eta_c$

arXiv:2505.13222

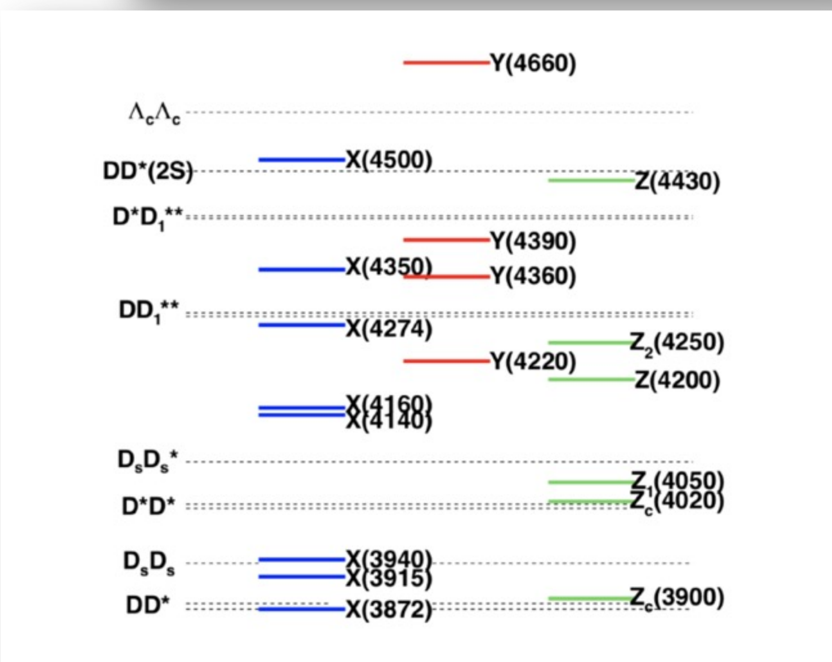


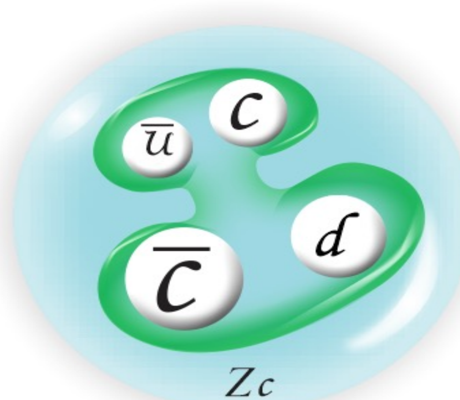



# The Zc states [$c\bar{c}u\bar{d}$]

from S. L. Olsen, arXiv:1511.01589, arXiv:1812.10947

| | | | | | |
|---|---|---|---|---|---|
| $Z_c^+(3900)$ | $3890 \pm 3$ | $33 \pm 10$ | $1^{+-}$ | $Y(4260) \to \pi^- + (J/\psi\,\pi^+)$ | BESIII [49], Belle [50] |
| | | | | $Y(4260) \to \pi^- + (D\bar{D}^*)^+$ | BESIII [69] |
| $Z_c^+(4020)$ | $4024 \pm 2$ | $10 \pm 3$ | $1(?)^{+(?)-}$ | $Y(4260) \to \pi^- + (h_c\,\pi^+)$ | BESIII [51] |
| | | | | $Y(4260) \to \pi^- + (D^*\bar{D}^*)^+$ | BESIII [52] |
| $Z_1^+(4050)$ | $4051^{+24}_{-43}$ | $82^{+51}_{-55}$ | $??^+$ | $B \to K + (\chi_{c1}\,\pi^+)$ | Belle [53], BaBar [66] |
| $Z^+(4200)$ | $4196^{+35}_{-32}$ | $370^{+99}_{-149}$ | $1^{+-}$ | $B \to K + (J/\psi\,\pi^+)$ | Belle [62] |
| $Z_2^+(4250)$ | $4248^{+185}_{-45}$ | $177^{+321}_{-72}$ | $??^+$ | $B \to K + (\chi_{c1}\,\pi^+)$ | Belle [53], BaBar [66] |
| $Z^+(4430)$ | $4477 \pm 20$ | $181 \pm 31$ | $1^{+-}$ | $B \to K + (\psi'\,\pi^+)$ | Belle [54, 56, 57], LHCb [58] |
| | | | | $B \to K + (J\psi\,\pi^+)$ | Belle [62] |




Most of them are close to the mass thresholds of charmed meson pairs