# 重味奇特态实验综述

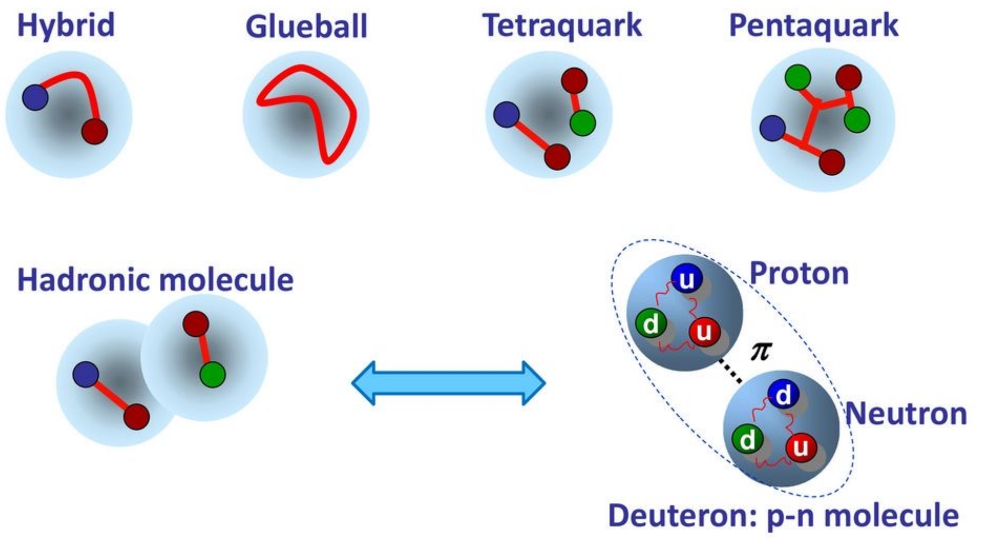
安刘攀

北京大学

强子谱和强子结构研讨会, 2023.08.29 @ 国科大雁栖湖校区

# Exotic hadrons

- The existence of exotic hadrons was already predicted since the establishment of quark model by M. Gell-Mann and G. Zweig in 1964
- Different compositions and binding schemes: $q\bar{q}g$ hybrid, glueball, compact multiquark state, molecular state …

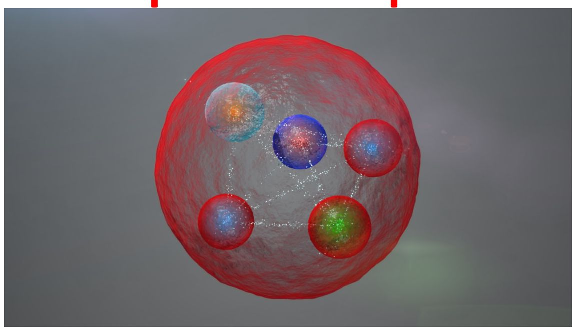



- Study of exotic hadrons can
  - ✓ provide new insights into internal structure and dynamics of hadrons
  - ✓ act as a unique probe to non-perturbative behavior of QCD

# Theoretical scenarios

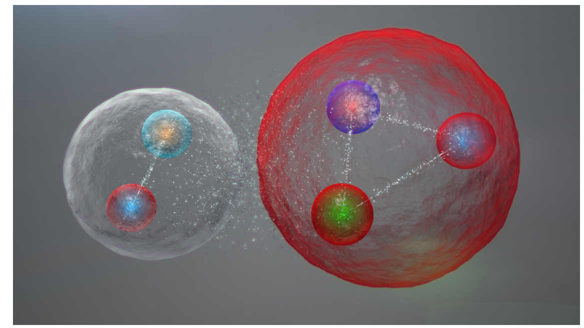
- Since the ***discovery of*** $\boldsymbol{\chi_{c1}(3872)}$ by BELLE in 2003, there is an explosion of discoveries of candidates for heavy tetra- and penta-quark states
- Two main players for multiquark state modelling:

**Compact multiquark**



(Di-)quarks bound via color forces
- Typical size $\mathcal{O}(\mathbf{1\ fm})$
- Mass proximity to threshold **accidental**
- $SU(3)_{flavor}$ multiplets from combinations of **(di-)quarks**
- No (strong) hierarchy of couplings

**Hadron molecule**

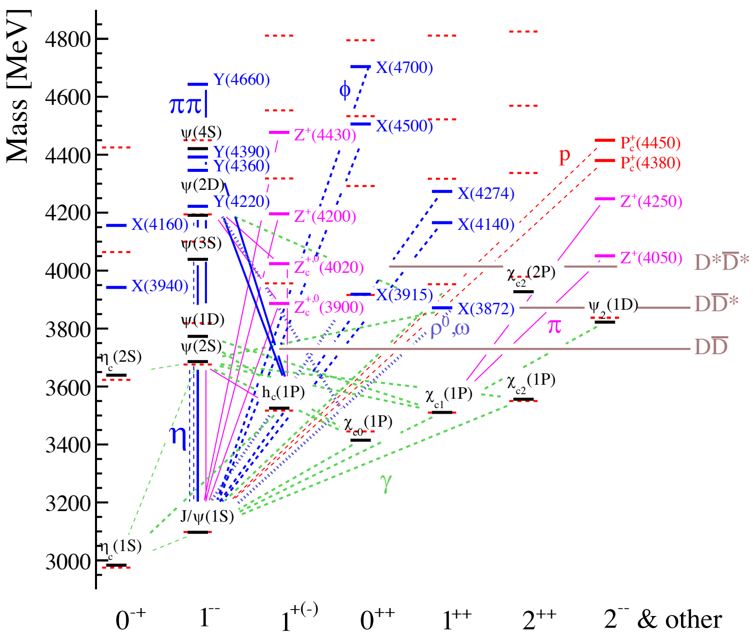


Hadrons bound via mesonic exchange
- Typical size $> \mathbf{1\ fm}$
- Mass proximity to threshold **natural**
- $SU(3)_{flavor}$ multiplets from combinations of **component hadrons**
- Fall-apart decay **dominant**

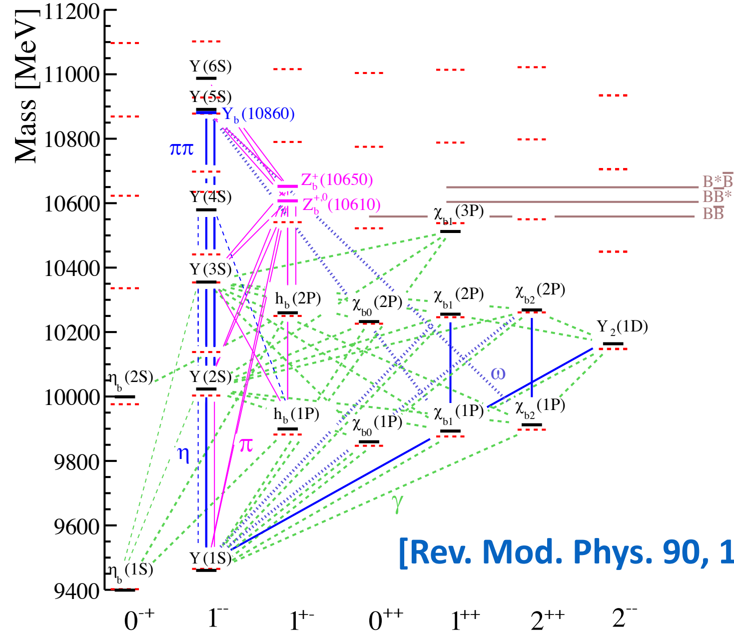
- Other possible scenarios: hadro-quarkonium, hybrid …
- ***Experimental discoveries*** help drive the development of multiquark studies

# Experimental observations

**Charmonium ($c\bar{c}$)-like spectrum**




**Bottomonium ($b\bar{b}$)-like spectrum**




**[Rev. Mod. Phys. 90, 15003 (2018)]**

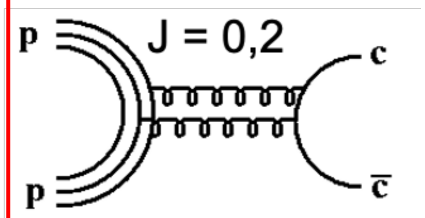
✓$Q\bar{Q}q\bar{q}$
- $Z$: $I = 1$
- $Y$: $J^{PC} = 1^{--}$
- $X$: Others

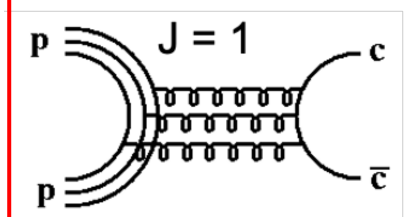
✓$Q\bar{Q}qqq$: $P_c^+, P_{cs}^0$

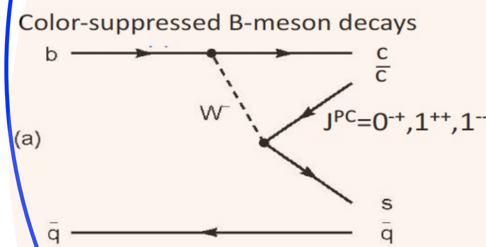
✓Open-flavor: $T_{cc}^+, T_{cs}^0, T_{c\bar{s}}$

# Major players

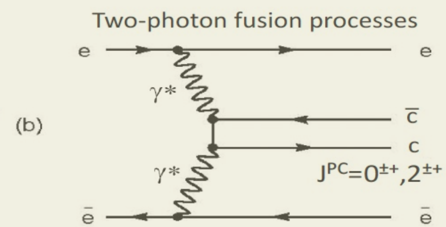
## $pp$ collider

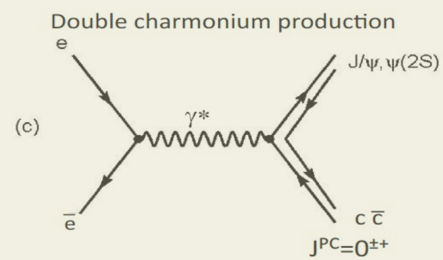


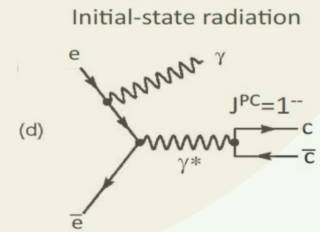



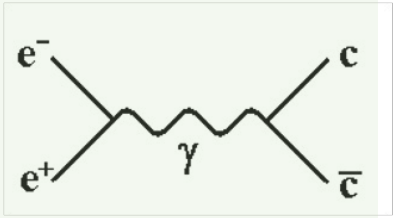




## $e^+e^-$ collider



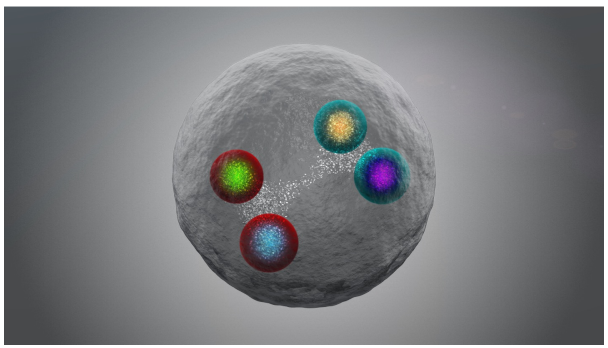



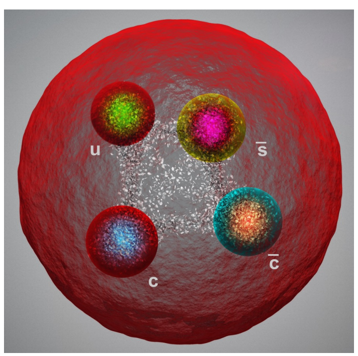



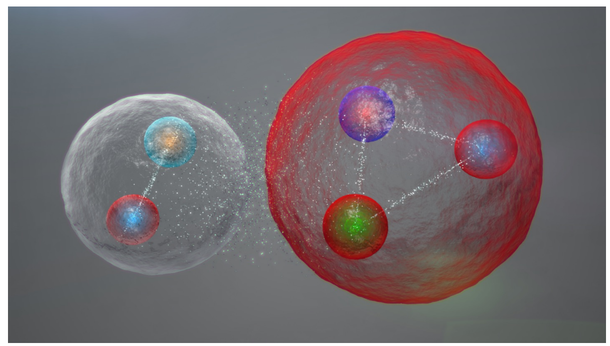
# Exotic hadron measurements

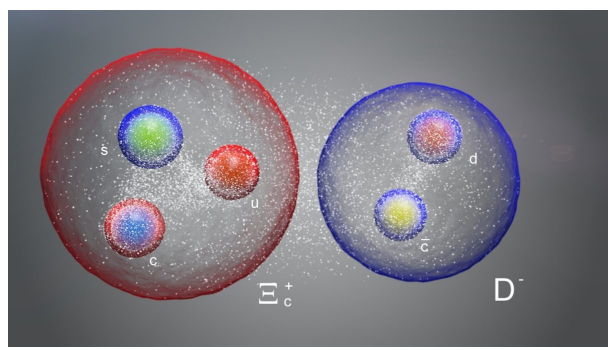
- ❑ Quarkonium-like tetraquark



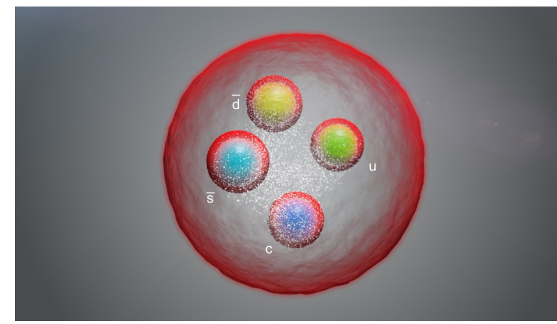


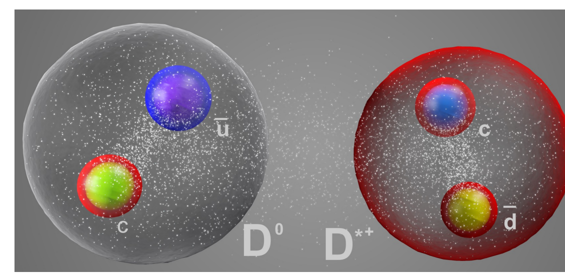

- ❑ Quarkonium-like pentaquark






- ❑ Open-charm tetraquark

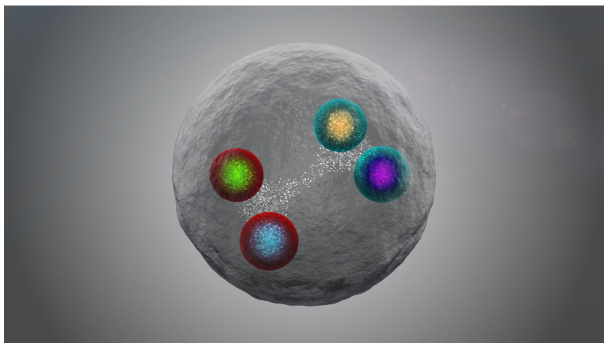


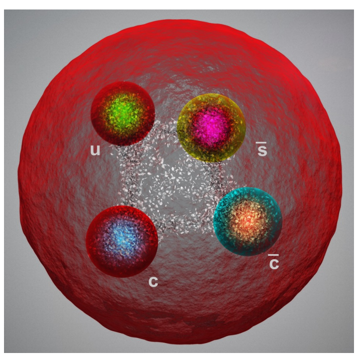




Disclaimer:
not able to cover all results

# Exotic hadron measurements

❑ Quarkonium-like tetraquark






❑ Quarkonium-like pentaquark





❑ Open-charm tetraquark



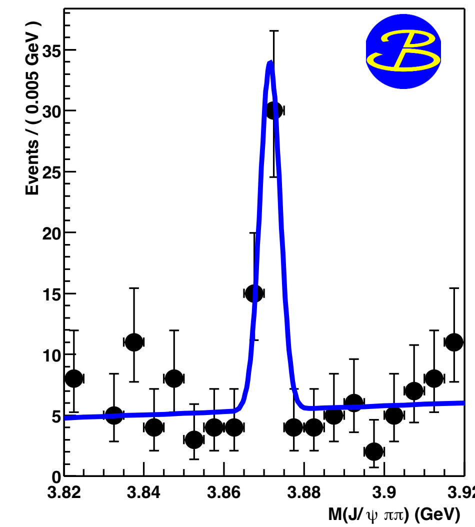


Disclaimer:
not able to cover all results

# $\chi_{c1}(3872)$ (or $X(3872)$)

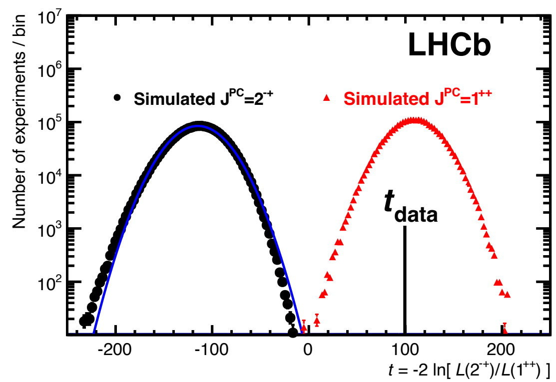
- $\chi_{c1}(3872)$ is the first observed charmonium-like exotic hadron with most abundant experimental information
  - ✓Firstly observed in $B^{\pm} \to K^{\pm}\chi_{c1}(3872)$ with $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$ by Belle

[PRL 91 (2003) 262001]

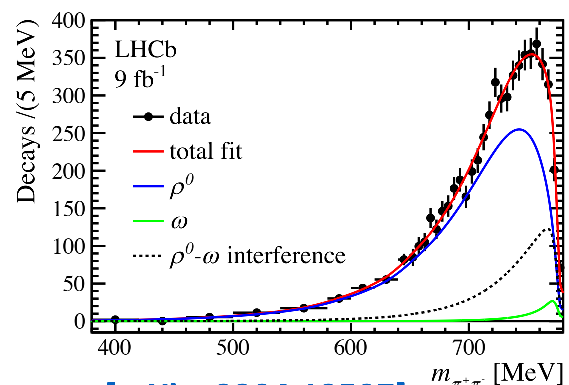



  - ✓Confirmed by other experiments in several decay modes: $J/\psi\pi^+\pi^-\pi^0$ $(J/\psi\omega)$, $D^0\overline{D}^0\pi^0$, $D^0\overline{D}^{*0}$, $J/\psi\gamma$, $\psi(2S)\gamma$, $\chi_{c1}(1P)\pi^0$
  - ✓$M_{\rm BW} = 3871.64 \pm 0.06\ {\rm MeV}/c^2$; $\Gamma_{\rm BW} = 1.19 \pm 0.19\ {\rm MeV}/c^2$
  - ✓$J^{PC} = 1^{++}$

[PRL 110 (2013) 222001]



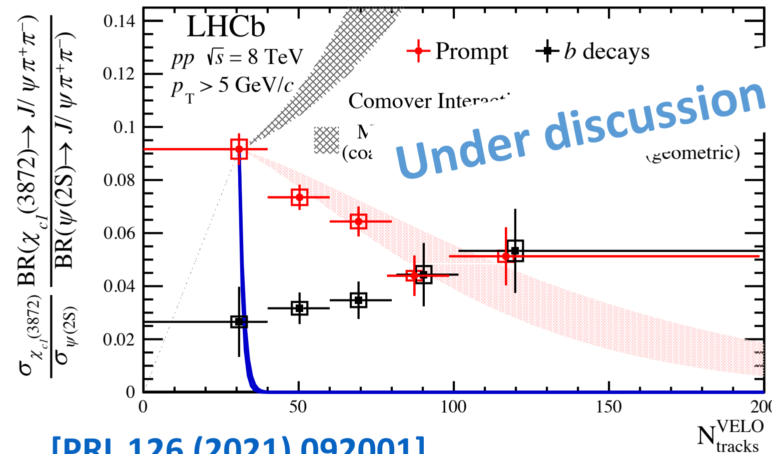

- Intriguing properties:
  - ✓Measured mass below prediction for $\chi_{c1}(2^3P_1)$
  - ✓Mass extremely close to $D^0\overline{D}^{*0}$ threshold $3871.70 \pm 0.11\ {\rm MeV}/c^2$
  - ✓$\chi_{c1}(3872) \to J/\psi\rho$ is isospin violating




[arXiv: 2204.12597]

# Nature of $\chi_{c1}(3872)$ (I)

- No consensus: conventional $\chi_{c1}(2^3P_1)$, $D^0\overline{D}^{*0}$ molecular state, tetraquark, $c\bar{c}g$ hybrid, vector glueball, or mixed?
- Experimental study
  - ✓ **Production in collisions and in weak decays**
    - Multiplicity-dependent modification of $\chi_{c1}(3872)$ production in $pp$ collisions



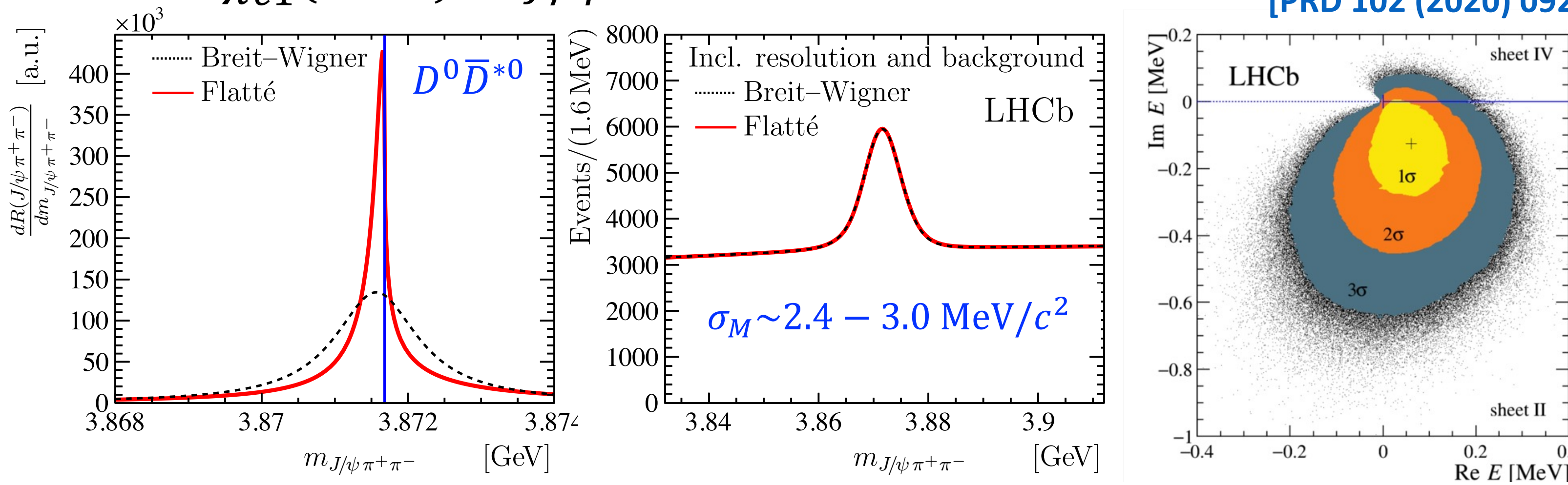

[PRL 126 (2021) 092001]

    - $\frac{\mathcal{B}(B^0\to\chi_{c1}(3872)K^0)}{\mathcal{B}(B^+\to\chi_{c1}(3872)K^+)}$ and $\frac{\mathcal{B}(B_s^0\to\chi_{c1}(3872)\phi)}{\mathcal{B}(B^+\to\chi_{c1}(3872)K^+)}$ almost half that of $\psi(2S)$, suggesting not a pure charmonium [PR D84 (2011) 052004] [PRL 125 (2020) 152001]
  - ✓ **Decays**
    - $\mathcal{B}(\chi_{c1}(3872) \to D^0\overline{D}^{*0}) > 30\%$
    - Discovery of $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-\pi^0$ is consistent with the prediction of molecular nature [arXiv: hep-ph/0410284]
    - $\mathcal{B}(\chi_{c1}(3872) \to \psi(2S)\gamma)/\mathcal{B}(\chi_{c1}(3872) \to J/\psi\gamma)$~5.6

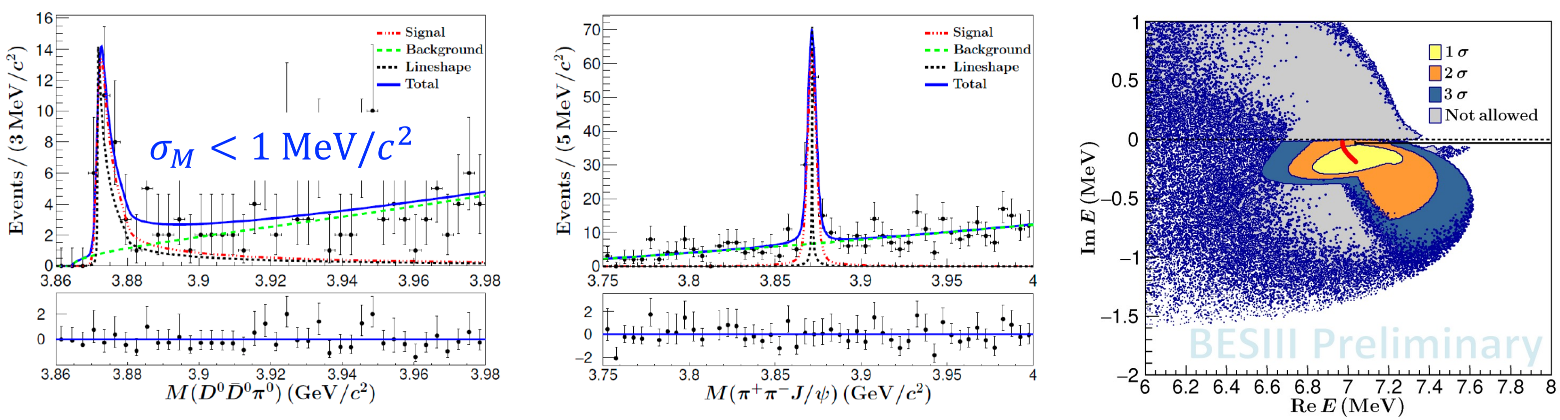
# Nature of $\chi_{c1}(3872)$ (II)

- Experimental study
  - ✓**Lineshape:** Flatté lineshape accounts for the opening up of $D^0\bar{D}^{*0}$ threshold
    - LHCb: $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$

[PRD 102 (2020) 092005]



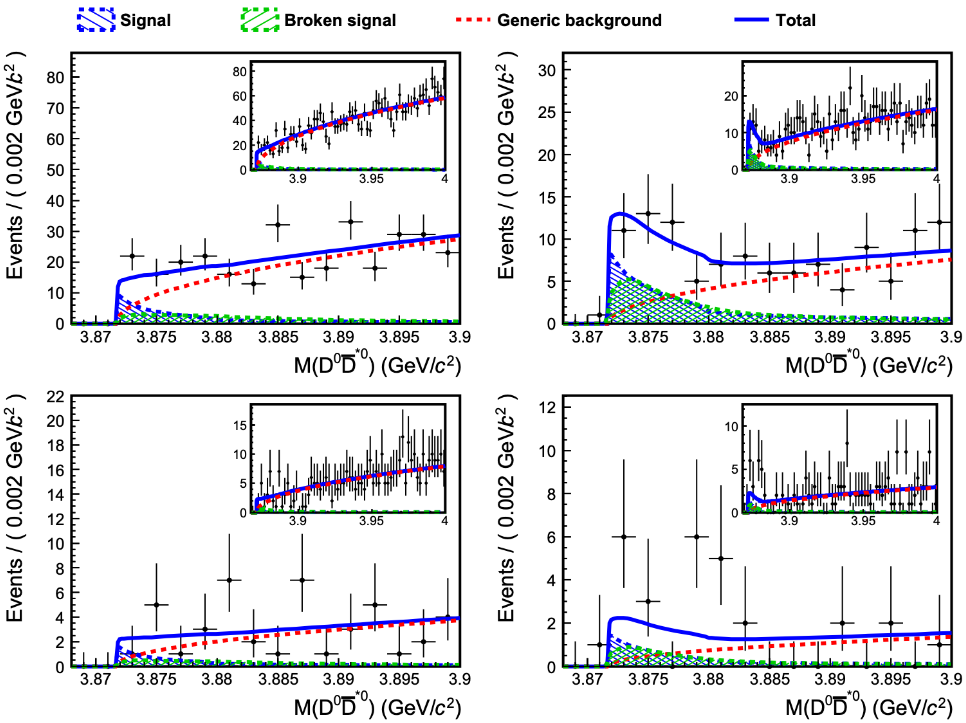

- BESIII (preliminary): $\chi_{c1}(3872) \to J/\psi\pi^+\pi^- \& D^0\bar{D}^0\pi^0$



# Nature of $\chi_{c1}(3872)$ (II)

- Experimental study
  - ✓**Lineshape:** Flatté lineshape accounts for the opening up of $D^0\bar{D}^{*0}$ threshold
    - BELLE: $\chi_{c1}(3872) \to D^0\bar{D}^{*0}(\to \bar{D}^0\gamma/\pi^0)$

[PRD 107, 112011 (2023)]




✓ Good consistency across experiments

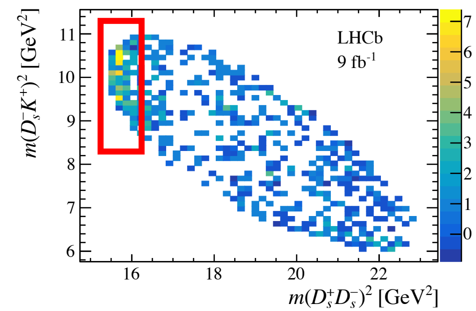
| | LHCb | Belle | BESIII |
|---|---|---|---|
| g | $0.108 \pm 0.003^{+0.005}_{-0.006}$ | $0.29^{+2.69}_{-0.15}$ | $0.16 \pm 0.10^{+1.12}_{-0.11}$ |
| $Re[E_I]$ [MeV] | 7.10 | 7.12 | $7.04 \pm 0.15^{+0.07}_{-0.08}$ |
| $Im[E_I]$ [MeV] | -0.13 | -0.12 | $-0.19 \pm 0.08^{+0.14}_{-0.19}$ |
| $Re[k^+]$ [MeV] | $-13.9$ | $-15.3$ | $-12.6 \pm 5.5^{+6.6}_{-6.2}$ |
| $Im[k^+]$ [MeV] | 8.8 | 7.7 | $12.3 \pm 6.8^{+6.0}_{-6.4}$ |
| $a$ (fm) | $-27.1$ | $-31.2$ | $-16.5^{+7.0}_{-27.6}{}^{+5.6}_{-27.7}$ |
| $r_e$ (fm) | -5.3 | $-3.0^{+1.3}_{-1.5}$ | $-4.1^{+0.9}_{-3.3}{}^{+2.8}_{-4.4}$ |
| $\bar{Z}_A$ | 0.15 (0.33) | $0.08^{+0.04}_{-0.03}$ | $0.18^{+0.06}_{-0.17}{}^{+0.19}_{-0.16}$ |

[by Junli Ma]

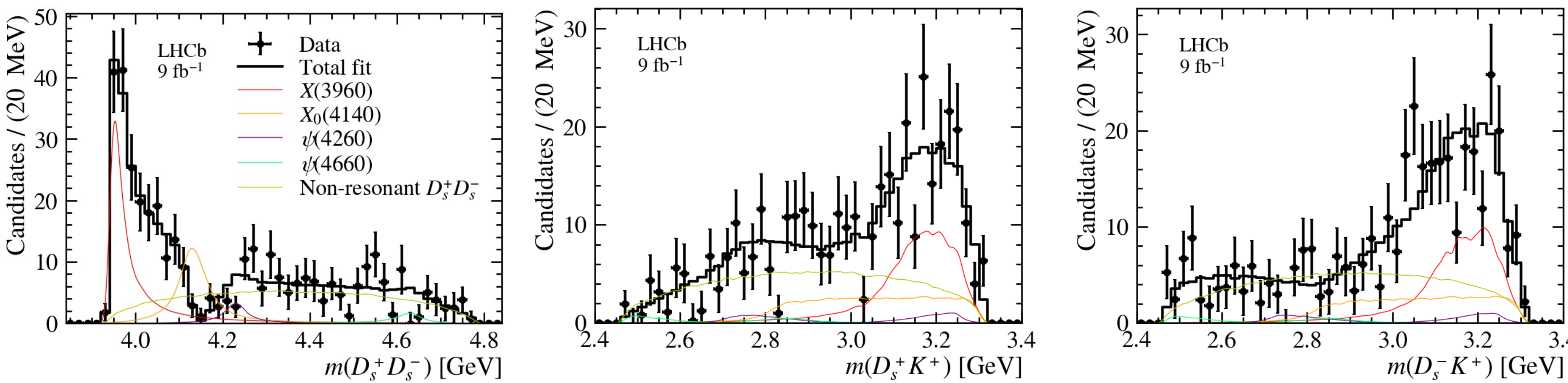
- $a$: scattering length
- $r_e$: effective range
- $\bar{Z}_A$: Weinberg's compositeness;
  $\bar{Z}_A = 1$: pure elementary (compact)
  $\bar{Z}_A = 0$: pure bound (molecular)

# $X(3960)$ in $B^+ \to D_s^+ D_s^- K^+$

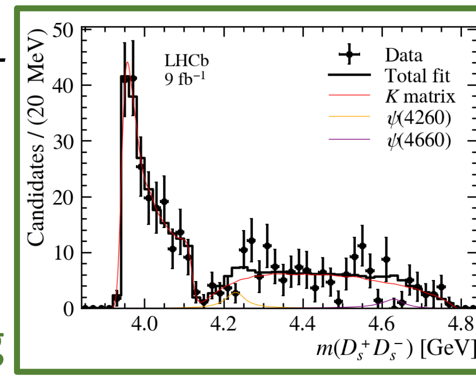
[arXiv: 2211.05034]
[arXiv: 2210.15153]




- New exotic $X$ states needed to describe data
  - ✓$0^{++}$: $X(3960)$ $(14.3\sigma)$, $X_0(4140)$ $(3.9\sigma)$, Non-resonant
  - ✓$1^{--}$: $\psi(4260), \psi(4660)$




- $X(3960)$: threshold enhancement
  - ✓$J^{PC} = 0^{++}$ preferred over $1^{--}$ and $2^{++}$ by $9.3\sigma$ and $12.3\sigma$
- $X_0(4140)$: dip at ~4.14 GeV via interference
  - ✓ $J^{PC} = 0^{++}$ preferred over $1^{--}$ and $2^{++}$ by $3.5\sigma$ and $4.2\sigma$
  - ✓the dip can also be described by $J/\psi\phi \to D_s^+ D_s^-$ scattering



# $X(3960)$ and $\chi_{c0}(3930)$

[arXiv: 2211.05034]
[arXiv: 2210.15153]

| | $M$ [MeV] | $\Gamma$ [MeV] | $J^{PC}$ |
|---|---|---|---|
| $X(3960)$ | $3955 \pm 6 \pm 12$ | $48 \pm 17 \pm 10$ | $0^{++}$ |
| $\chi_{c0}(3930)$ | $3924 \pm 2$ | $17 \pm 5$ | |

- Same particle?

$\mathcal{FF}$: Fit fraction

$$\frac{\Gamma(X \to D^+D^-)}{\Gamma(X \to D_s^+D_s^-)} = \frac{\mathcal{B}(B^+ \to D^+D^-K^+)\times\mathcal{FF}^X_{B^+\to D^+D^-K^+}}{\mathcal{B}(B^+ \to D_s^+D_s^-K^+)\times\mathcal{FF}^X_{B^+\to D_s^+D_s^-K^+}} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$$

✓Creation of $s\bar{s}$ from vacuum is suppressed wrt $u\bar{u}$ or $d\bar{d}$

✓$X \to D_s^+D_s^-$ has smaller phase-space factor than $X \to D^+D^-$

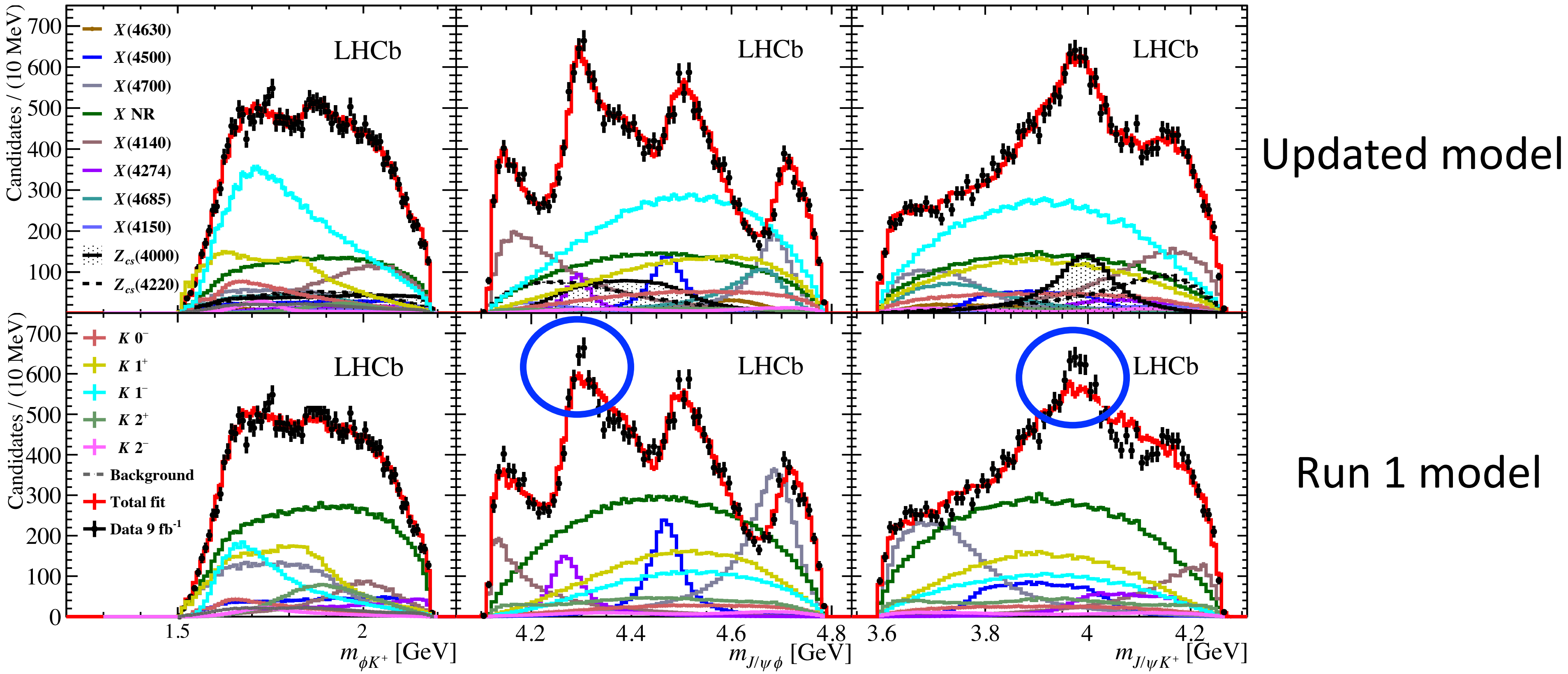
$\Rightarrow$ $X$ has an exotic nature! Candidate for $c\bar{c}s\bar{s}$

- Different particles?

✓No obvious candidate within conventional charmonium multiplets for them; likely to be exotic

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

[PRL 127 (2021) 082001]




$Z_{cs}^+ \to T_{\psi s1}^{\theta}(4000)^+$

➢New states included in updated model:

- ✓$1^+$ $Z_{cs}^+$ and $1^+$ $X$ produce the largest improvements
- ✓Additional $Z_{cs}^+$ (either $1^+$ or $1^-$)
- ✓Two $X$ with $1^-$ and $2^-$

# Amplitude fit result

[PRL 127 (2021) 082001]

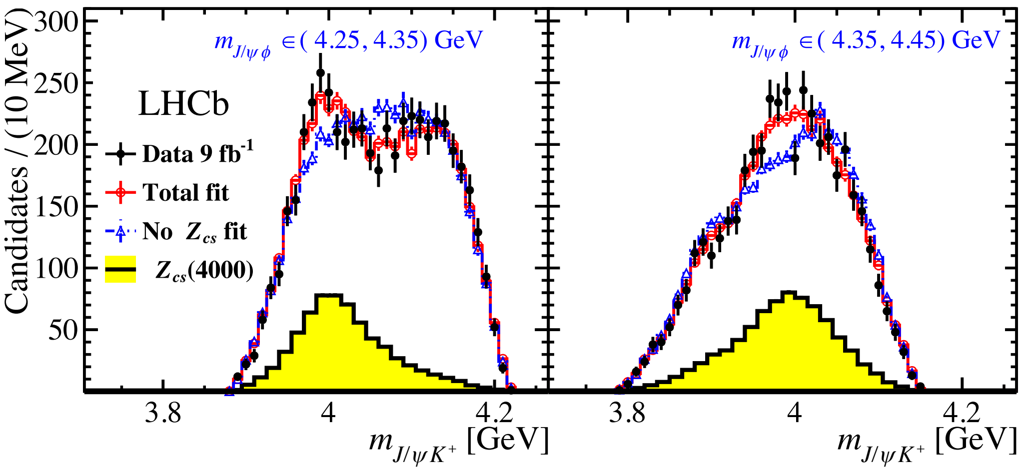
| Contribution | Significance [$\times\sigma$] | $M_0$ [MeV] | $\Gamma_0$ [MeV] | FF [%] |
|---|---|---|---|---|
| $X(2^-)$ | | | | |
| $X(4150)$ | 4.8 (8.7) | $4146 \pm 18 \pm 33$ | $135 \pm 28\,^{+\,59}_{-\,30}$ | $2.0 \pm 0.5\,^{+\,0.8}_{-\,1.0}$ |
| $X(1^-)$ | | | | |
| $X(4630)$ | 5.5 (5.7) | $4626 \pm 16\,^{+\,18}_{-\,110}$ | $174 \pm 27\,^{+\,134}_{-\,73}$ | $2.6 \pm 0.5\,^{+\,2.9}_{-\,1.5}$ |
| All $X(0^+)$ | | | | $20 \pm 5\,^{+\,14}_{-\,7}$ |
| $X(4500)$ | 20 (20) | $4474 \pm 3 \pm 3$ | $77 \pm 6\,^{+\,10}_{-\,8}$ | $5.6 \pm 0.7\,^{+\,2.4}_{-\,0.6}$ |
| $X(4700)$ | 17 (18) | $4694 \pm 4\,^{+\,16}_{-\,3}$ | $87 \pm 8\,^{+\,16}_{-\,6}$ | $8.9 \pm 1.2\,^{+\,4.9}_{-\,1.4}$ |
| $\mathrm{NR}_{J/\psi\phi}$ | 4.8 (5.7) | | | $28 \pm 8\,^{+\,19}_{-\,11}$ |
| All $X(1^+)$ | | | | $26 \pm 3\,^{+\,8}_{-\,10}$ |
| $X(4140)$ | 13 (16) | $4118 \pm 11\,^{+\,19}_{-\,36}$ | $162 \pm 21\,^{+\,24}_{-\,49}$ | $17 \pm 3\,^{+\,19}_{-\,6}$ |
| $X(4274)$ | 18 (18) | $4294 \pm 4\,^{+\,3}_{-\,6}$ | $53 \pm 5 \pm 5$ | $2.8 \pm 0.5\,^{+\,0.8}_{-\,0.4}$ |
| $X(4685)$ | 15 (15) | $4684 \pm 7\,^{+\,13}_{-\,16}$ | $126 \pm 15\,^{+\,37}_{-\,41}$ | $7.2 \pm 1.0\,^{+\,4.0}_{-\,2.0}$ |
| All $Z_{cs}(1^+)$ | | | | $25 \pm 5\,^{+\,11}_{-\,12}$ |
| $Z_{cs}(4000)$ | 15 (16) | $4003 \pm 6\,^{+\,4}_{-\,14}$ | $131 \pm 15 \pm 26$ | $9.4 \pm 2.1 \pm 3.4$ |
| $Z_{cs}(4220)$ | 5.9 (8.4) | $4216 \pm 24\,^{+\,43}_{-\,30}$ | $233 \pm 52\,^{+\,97}_{-\,73}$ | $10 \pm 4\,^{+\,10}_{-\,7}$ |

- $J^P$ assignments:
  - ✓ $J^P$ for previously reported four $X$ states confirmed
  - ✓ $Z_{cs}(4000)$ $J^P = 1^+$ and $X(4685)$ $J^P = 1^+$ firmly determined
  - ✓ $X(4150)$: $2^-$ preferred by $4\sigma$; $X(4630)$: $1^-$ over $2^-$ at $3\sigma$
  - ✓ $Z_{cs}(4220)$ could be $1^+$ or $1^-$

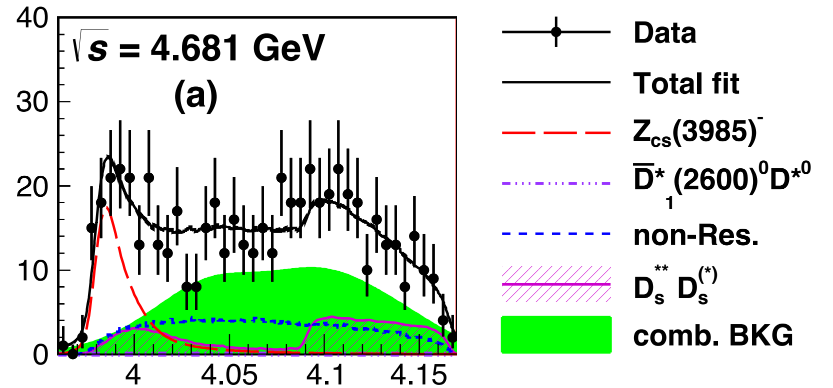
# $Z_{cs}^{+}$ at LHCb vs BESIII

- BESIII observed a $Z_{cs}^{-}$ structure in $K^{+}$ recoil-mass spectra in $e^{+}e^{-} \rightarrow K^{+}(D_s^{-}D^{*0} + D_s^{*-}D^{0})$

[PRL 127 (2021) 082001]




[PRL 126 (2021) 102001]




$M(Z_{cs}(4000)^{+}) = 4003 \pm 6^{+4}_{-14}$ MeV

$\Gamma(Z_{cs}(4000)^{+}) = 131 \pm 15 \pm 26$ MeV

$M(Z_{cs}(3985)^{-}) = 3985.2^{+2.1}_{-2.0} \pm 1.7$ MeV

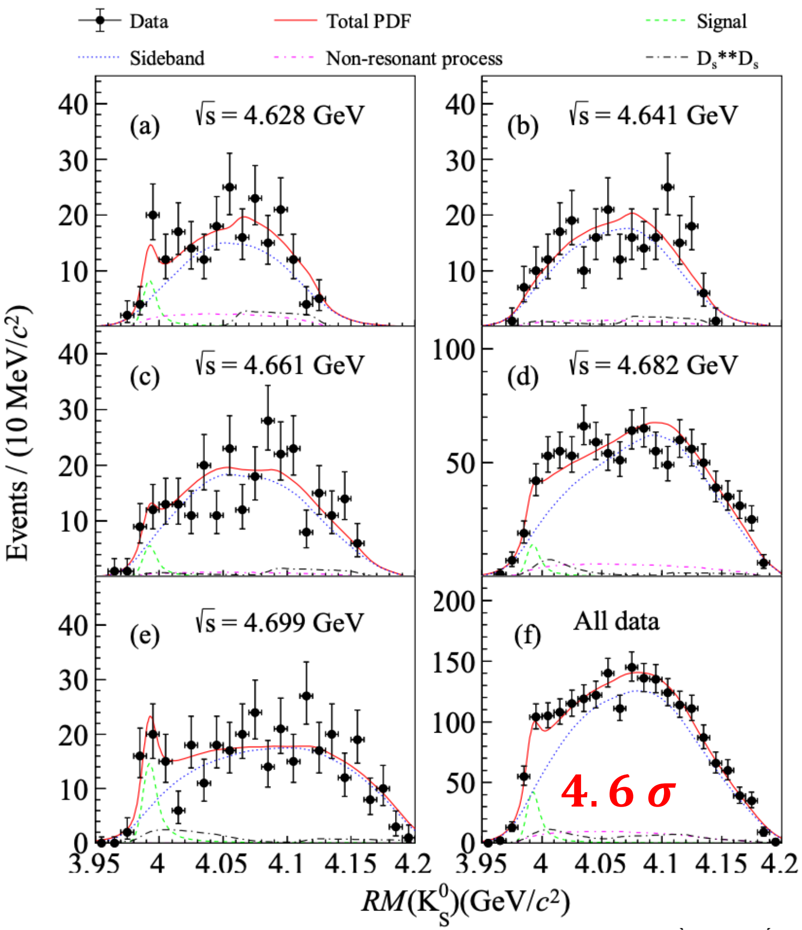
$\Gamma(Z_{cs}(3985)^{-}) = 13.8^{+8.1}_{-5.2} \pm 4.9$ MeV

- Same state or not?

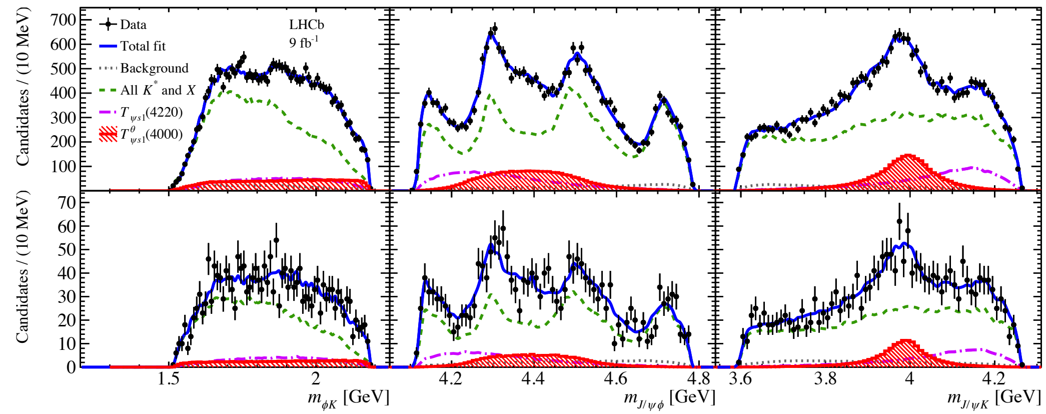
# Evidence of neutral $Z_{cs}^0$

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

➢LHCb: $B^0 \to J/\psi\phi K_S^0$




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




✓ significance is 4 $\sigma$ (5.4 $\sigma$ under isospin symmetry assumption)

$Z_{cs}^+ \to T_{\psi s1}^{\theta}(4000)^+$

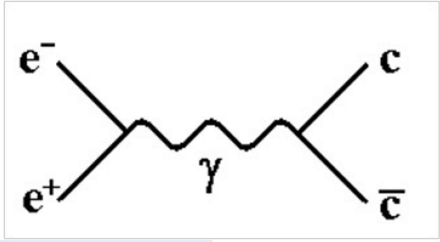
$$M(T_{\psi s1}^{\theta}(4000)^0) = 3991\,^{+12}_{-10}\,^{+9}_{-17}\ \text{MeV}$$
$$\Gamma(T_{\psi s1}^{\theta}(4000)^0) = 105\,^{+29}_{-25}\,^{+17}_{-23}\ \text{MeV}$$

$$\Delta M = -12\,^{+11}_{-10}\,^{+6}_{-4}\ \text{MeV}$$

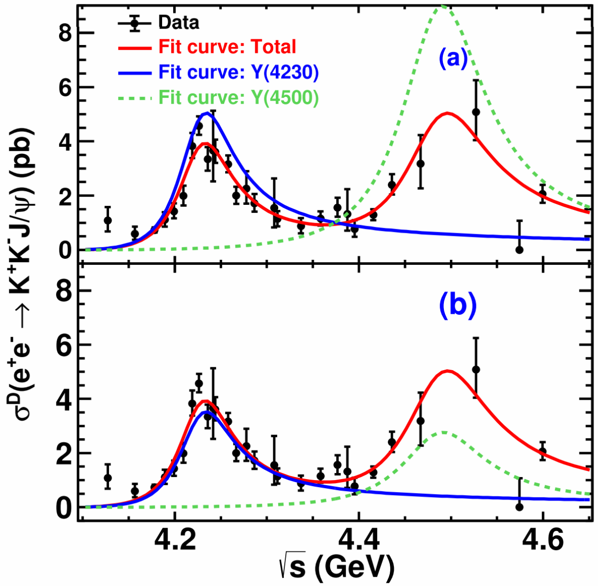
[arXiv: 2301.04899]

[PRL 129 (2022) 112003]

# $Y$ states at BESIII (I)




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



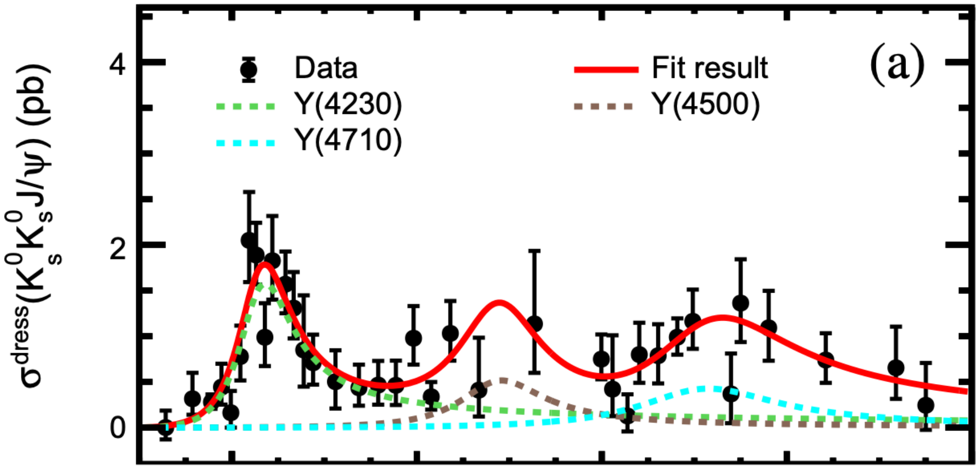

✓First observation of $Y(4230) \to J/\psi K^+K^-$

✓First observation of $Y(4500)$

| | Parameters | Solution I | Solution II |
|---|---|---|---|
| | $M$/MeV | 4225.3 ± 2.3 ± 21.5 | |
| $Y(4230)$ **29 σ** | $\Gamma_{tot}$/MeV | 72.9 ± 6.1 ± 30.8 | |
| | $\Gamma_{ee}\mathcal{B}$/eV | 0.42 ± 0.04 ± 0.15 | 0.29 ± 0.02 ± 0.10 |
| | $M$/MeV | 4484.7 ± 13.3 ± 24.1 | |
| $Y(4500)$ **8 σ** | $\Gamma_{tot}$/MeV | 111.1 ± 30.1 ± 15.2 | |
| | $\Gamma_{ee}\mathcal{B}$/eV | 1.35 ± 0.14 ± 0.07 | 0.41 ± 0.08 ± 0.13 |
| Phase angle | $\varphi$/rad | 1.72 ± 0.09 ± 0.52 | 5.49 ± 0.35 ± 0.58 |

[CPC 46, 111002 (2022)]

## $e^+e^- \to J/\psi K_S^0 K_S^0$




✓First observation (**26 σ**) of $Y(4230) \to J/\psi K_S^0 K_S^0$

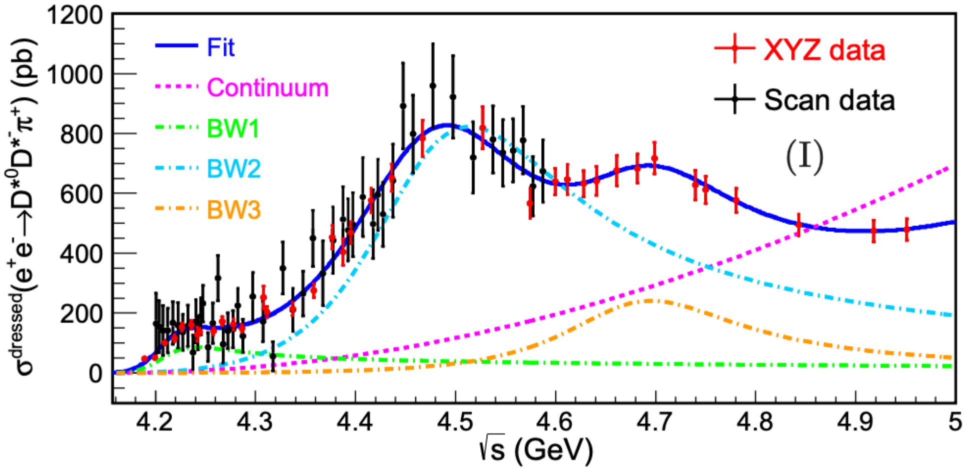
✓Strong evidence (**4.2 σ**) for $Y(4710)$ ($\psi(5S)$?); waiting for update from $e^+e^- \to J/\psi K^+K^-$

| | Mass (MeV) | Width (MeV) |
|---|---|---|
| $Y(4230)$ | $4226.9 \pm 6.6 \pm 22.0$ | $71.7 \pm 16.2 \pm 32.8$ |
| $Y(4710)$ | $4704.0 \pm 52.3 \pm 69.5$ | $183.2 \pm 114.0 \pm 96.1$ |

[PRD 107, 092005 (2023)]

# $Y$ states at BESIII (II)

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

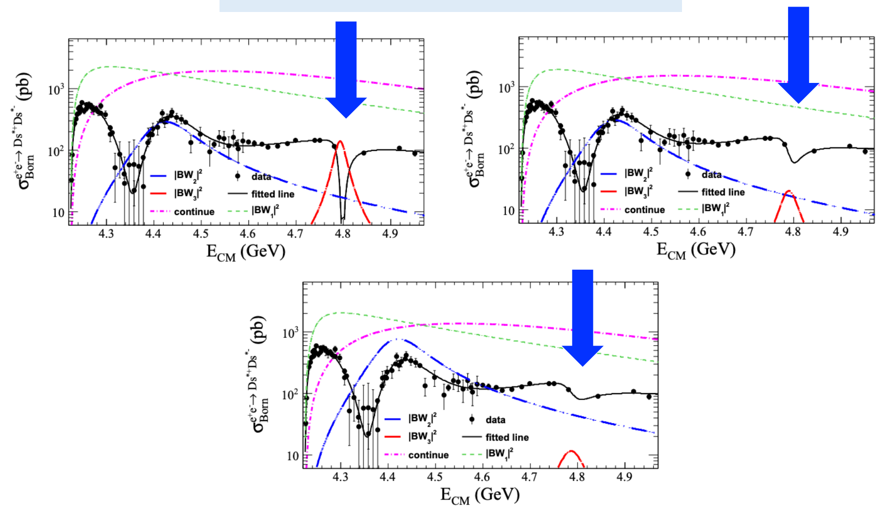



| | Mass (MeV) | Width (MeV) | |
|---|---|---|---|
| BW1 | $4210 \pm 5 \pm 6$ | $82 \pm 18 \pm 9$ | $Y(4230)$ |
| BW2 | $4469 \pm 26 \pm 4$ | $246 \pm 37 \pm 9$ | $Y(4500)$ |
| BW3 | $4675 \pm 30 \pm 4$ | $218 \pm 73 \pm 9$ | $Y(4660)$ |

✓First observation of these structures in $D^{*0}D^{*-}\pi^+$

[PRL 130, 121901 (2023)]

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




| | Result 1 | Result 2 | Result 3 |
|---|---|---|---|
| $M_1$ (MeV/$c^2$) | 4186.5±9.0 | 4193.8±7.5 | 4195.3±7.5 |
| $\Gamma_1$ (MeV) | 55±17 | 61.2±9.0 | 61.8±9.0 |
| $M_2$ (MeV/$c^2$) | 4414.5±3.2 | 4412.8±3.2 | 4411.0±3.2 |
| $\Gamma_2$ (MeV) | 122.6±7.0 | 120.3±7.0 | 120.0±7.0 |
| $M_3$ (MeV/$c^2$) | 4793.3±7.5 | 4789.8±9.0 | 4786±10 |
| $\Gamma_3$ (MeV) | 27.1±7.0 | 41±39 | 60±35 |

✓BW1: $\psi(4160)$ or $Y(4230)$?

✓BW2: $\psi(4415)$?

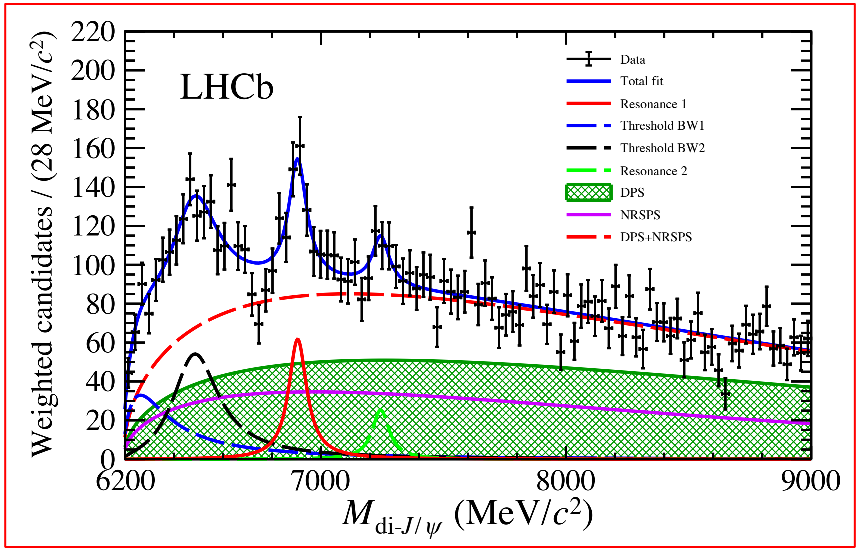
✓BW3: necessary to describe structure at ~4.79 GeV (6.1 $\sigma$)

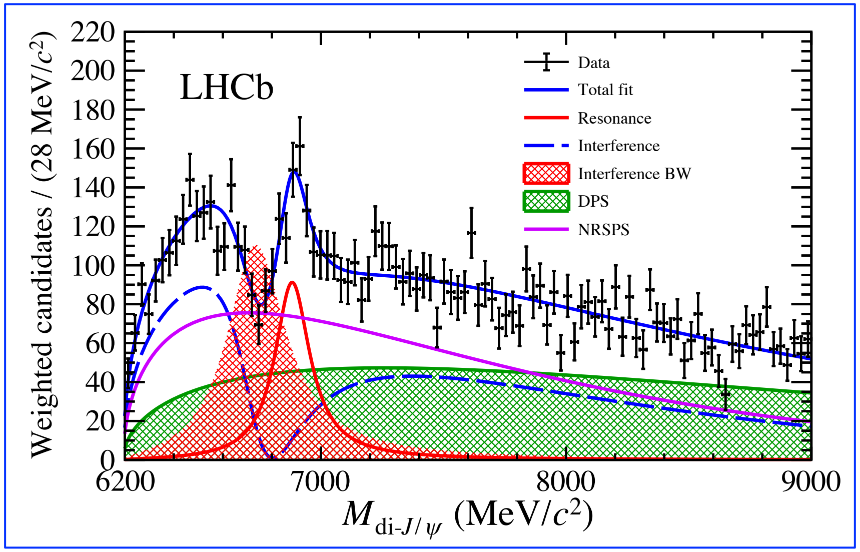
[arXiv: 2305.10789]

# $\psi$-pair structures at LHCb

**[Science Bulletin 65 (2020) 1983]**

- $X(6900)$ observed by LHCb, matching the lineshape of a $T_{cc\bar{c}\bar{c}}$ resonance; a broader structure close to the threshold is also found
- Two possible interpretations:



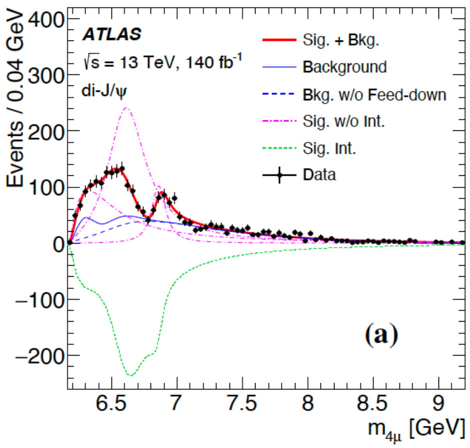

$M(X(6900)) = 6905 \pm 11 \pm 7\ \text{MeV}/c^2$
$\Gamma(X(6900)) = 80 \pm 19 \pm 33\ \text{MeV}/c^2$

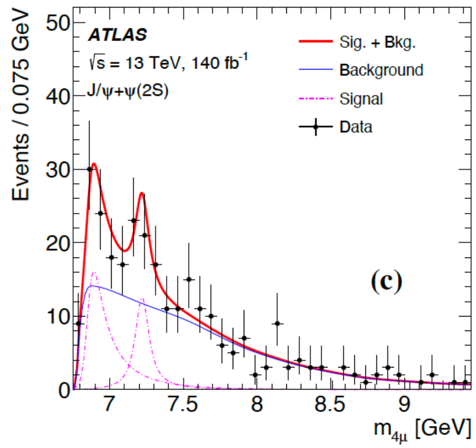
$M(X(6900)) = 6886 \pm 11 \pm 11\ \text{MeV}/c^2$
$\Gamma(X(6900)) = 168 \pm 33 \pm 69\ \text{MeV}/c^2$

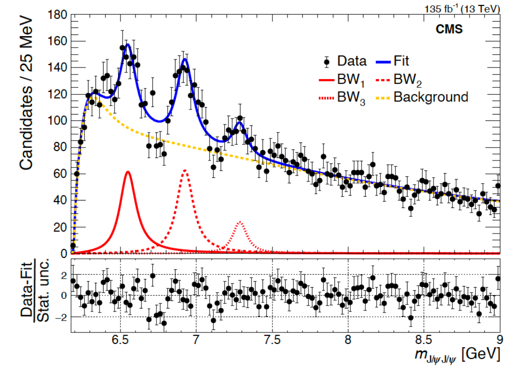
- Other possibilities: feeddown contribution, e.g. $T_{cc\bar{c}\bar{c}} \to \chi_c(\to J/\psi\gamma) + J/\psi$; near-threshold kinematic rescattering effects

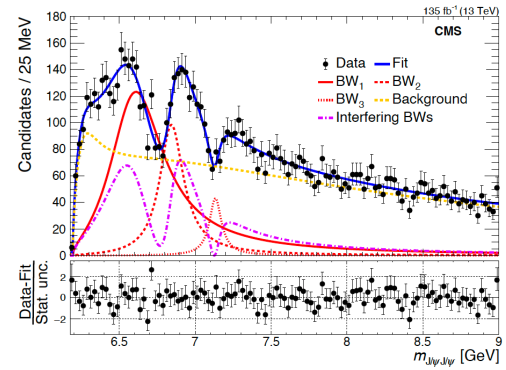
# $\psi$-pair structures at CMS and ATLAS

➢ $X(6900)$ confirmed by CMS and ATLAS




| di-$J/\psi$ | model A | model B |
|---|---|---|
| $m_0$ | $6.41 \pm 0.08^{+0.08}_{-0.03}$ | $6.65 \pm 0.02^{+0.03}_{-0.02}$ |
| $\Gamma_0$ | $0.59 \pm 0.35^{+0.12}_{-0.20}$ | $0.44 \pm 0.05^{+0.06}_{-0.05}$ |
| $m_1$ | $6.63 \pm 0.05^{+0.08}_{-0.01}$ | — |
| $\Gamma_1$ | $0.35 \pm 0.11^{+0.11}_{-0.04}$ | |
| $m_2$ | $6.86 \pm 0.03^{+0.01}_{-0.02}$ | $6.91 \pm 0.01 \pm 0.01$ |
| $\Gamma_2$ | $0.11 \pm 0.05^{+0.02}_{-0.01}$ | $0.15 \pm 0.03 \pm 0.01$ |
| $\Delta s/s$ | $\pm 5.1\%^{+8.1\%}_{-8.9\%}$ | — |
| $J/\psi$+$\psi(2S)$ | model $\alpha$ | model $\beta$ |
| $m_3$ or $m$ | $7.22 \pm 0.03^{+0.01}_{-0.03}$ | $6.96 \pm 0.05 \pm 0.03$ |
| $\Gamma_3$ or $\Gamma$ | $0.09 \pm 0.06^{+0.06}_{-0.03}$ | $0.51 \pm 0.17^{+0.11}_{-0.10}$ |
| $\Delta s/s$ | $\pm 21\% \pm 14\%$ | $\pm 20\% \pm 12\%$ |

[arXiv: 2304.08962]

[arXiv: 2306.07164]

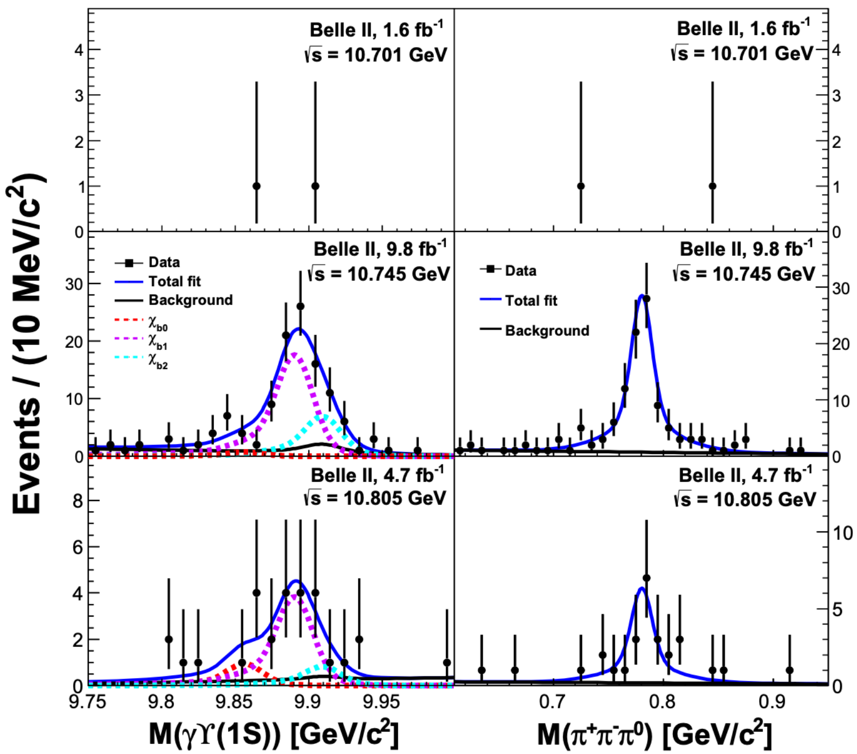
**$4.1\,\sigma$**

| | | $BW_1$ | $BW_2$ | $BW_3$ |
|---|---|---|---|---|
| No-interference | $m$ [MeV] | $6552 \pm 10 \pm 12$ | $6927 \pm 9 \pm 4$ | $7287^{+20}_{-18} \pm 5$ |
| | $\Gamma$ [MeV] | $124^{+32}_{-26} \pm 33$ | $122^{+24}_{-21} \pm 18$ | $95^{+59}_{-40} \pm 19$ |
| | $N$ | $470^{+120}_{-110}$ | $492^{+78}_{-73}$ | $156^{+64}_{-51}$ |
| Interference | $m$ [MeV] | $6638^{+43+16}_{-38-31}$ | $6847^{+44+48}_{-28-20}$ | $7134^{+48+41}_{-25-15}$ |
| | $\Gamma$ [MeV] | $440^{+230+110}_{-200-240}$ | $191^{+66+25}_{-49-17}$ | $97^{+40+29}_{-29-26}$ |

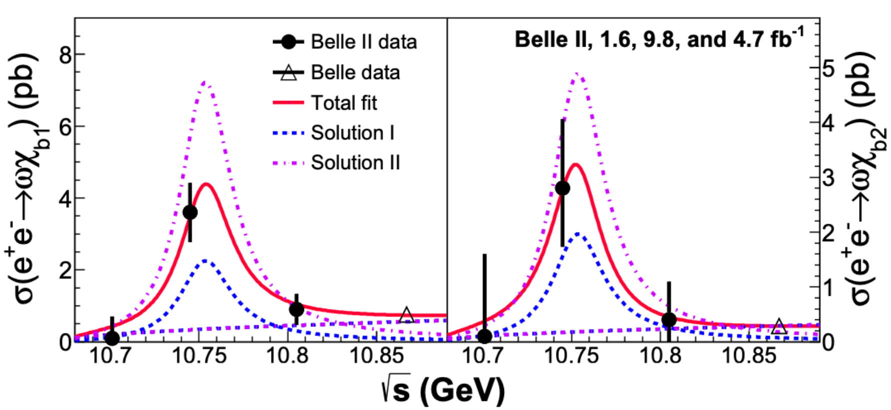
**$> 5\,\sigma$**

# Observation of $\Upsilon(10753) \to \omega\chi_{bJ}$

[PRL 130, 091902 (2023)]




| Channel | $\sqrt{s}$ (GeV) | $N^{\mathrm{sig}}$ |
|---|---|---|
| $e^+e^- \to \omega\chi_{b0}$ | 10.701 | $0.0^{+1.1}_{-0.0}$ |
| $e^+e^- \to \omega\chi_{b1}$ | | $0.0^{+2.1}_{-0.0}$ |
| $e^+e^- \to \omega\chi_{b2}$ | | $0.1^{+2.2}_{-0.1}$ |
| $e^+e^- \to \omega\chi_{b0}$ | 10.745 | $3.0^{+5.5}_{-4.7}$ |
| $e^+e^- \to \omega\chi_{b1}$ | | $68.9^{+13.7}_{-13.5}$ |
| $e^+e^- \to \omega\chi_{b2}$ | | $27.6^{+11.6}_{-10.0}$ |
| $e^+e^- \to \omega\chi_{b0}$ | 10.805 | $3.6^{+3.8}_{-3.1}$ |
| $e^+e^- \to \omega\chi_{b1}$ | | $15.0^{+6.8}_{-6.2}$ |
| $e^+e^- \to \omega\chi_{b2}$ | | $3.3^{+5.3}_{-3.8}$ |




- ➢ $\sigma_B(e^+e^- \to \omega\chi_{b1})/\sigma_B(e^+e^- \to \omega\chi_{b2}) = 1.3 \pm 0.6$ at $\sqrt{s} = 10.745$ GeV
- ✓ Contradicts expectation of pure D-wave of 15
- ✓ 1.8 $\sigma$ difference to S-D mixture of 0.2
- ➢ $\Upsilon(10753) \to \omega\chi_{bJ}$ & $\Upsilon(10860) \to \Upsilon(nS)\pi\pi$ are different states

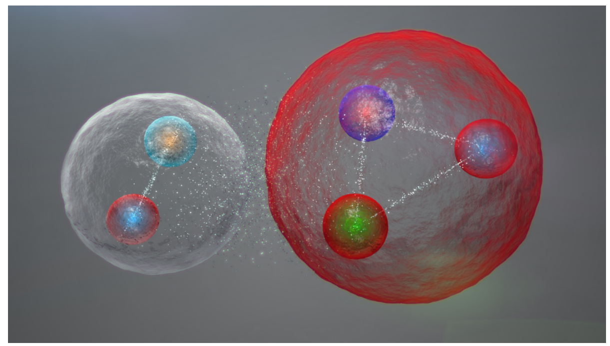
# Exotic hadron measurements

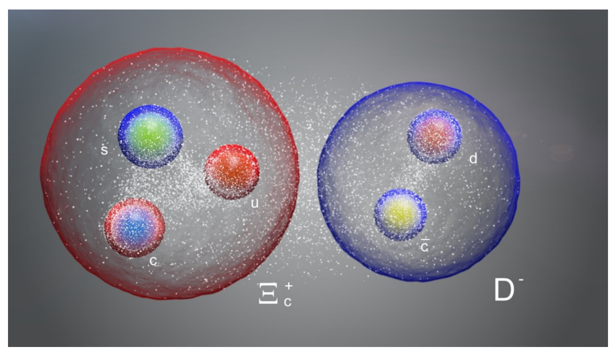
❑ Quarkonium-like tetraquark





❑ Quarkonium-like pentaquark






❑ Open-charm tetraquark



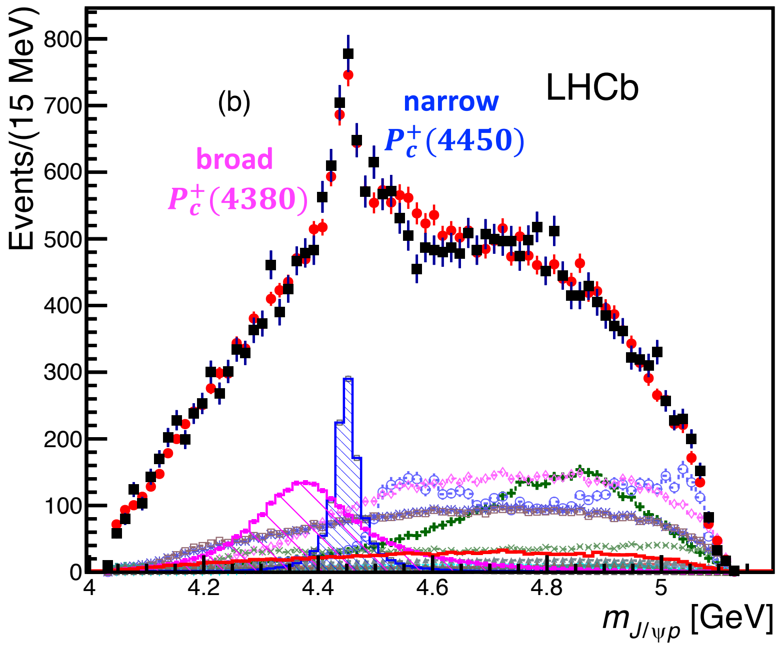



Disclaimer:
not able to cover all results

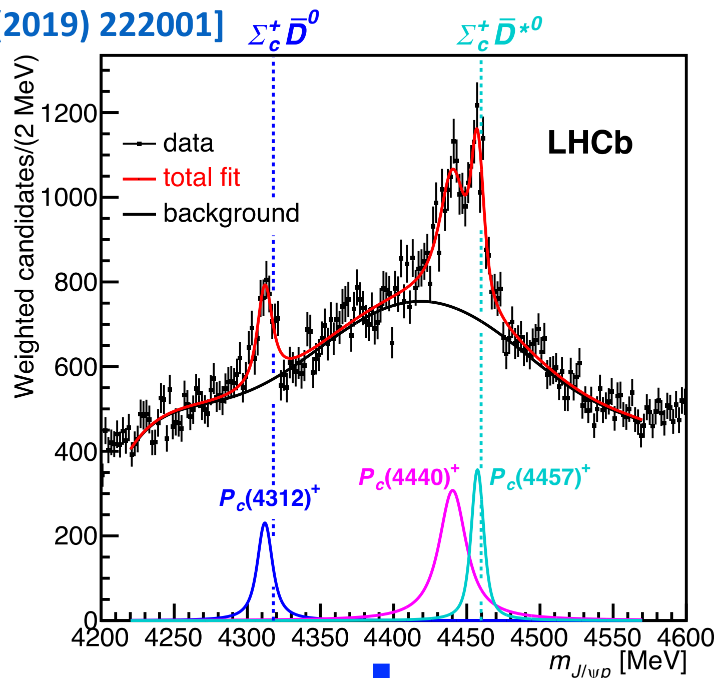
# Observation of $P_c^+$ in $\Lambda_b^0 \to J/\psi K^- p$

- ➢ $P_c^+(c\bar{c}uud)$ states were first observed in $\Lambda_b^0 \to J/\psi K^- p$ using LHCb Run1 data
- ➢ Later, the $\Lambda_b^0 \to J/\psi K^- p$ study was updated using Run 1 + Run 2 data
  - ✓ A new narrow $P_c^+(4312)$ observed with significance of 7.3 $\sigma$
  - ✓ The $P_c^+(4450)$ structure is resolved into two peaks, $P_c^+(4440)$ and $P_c^+(4457)$

[PRL 115 (2015) 072001]




[PRL 122 (2019) 222001]

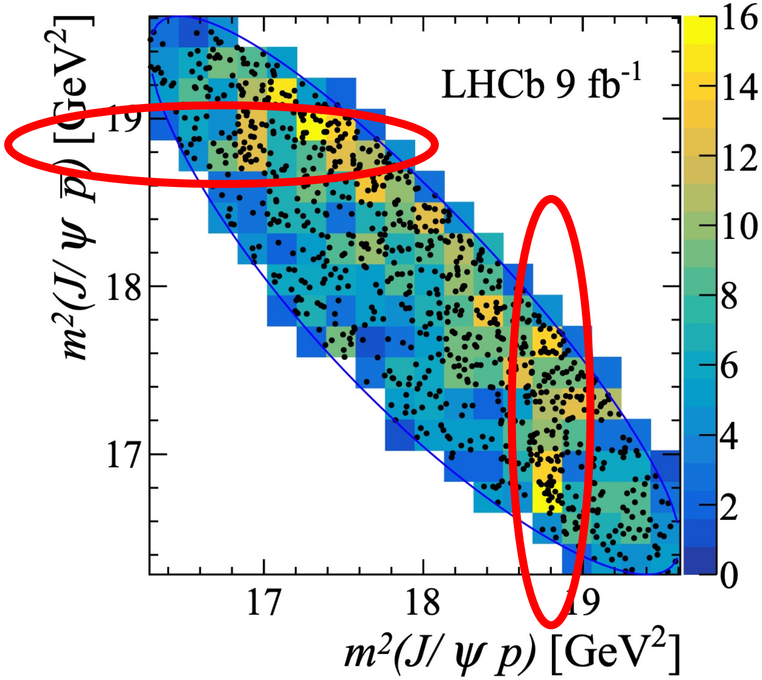



Proximity of $\Sigma_c^+ \bar{D}^0$ and $\Sigma_c^+ \bar{D}^{*0}$ thresholds to the peaks suggests they play an important role in the dynamics

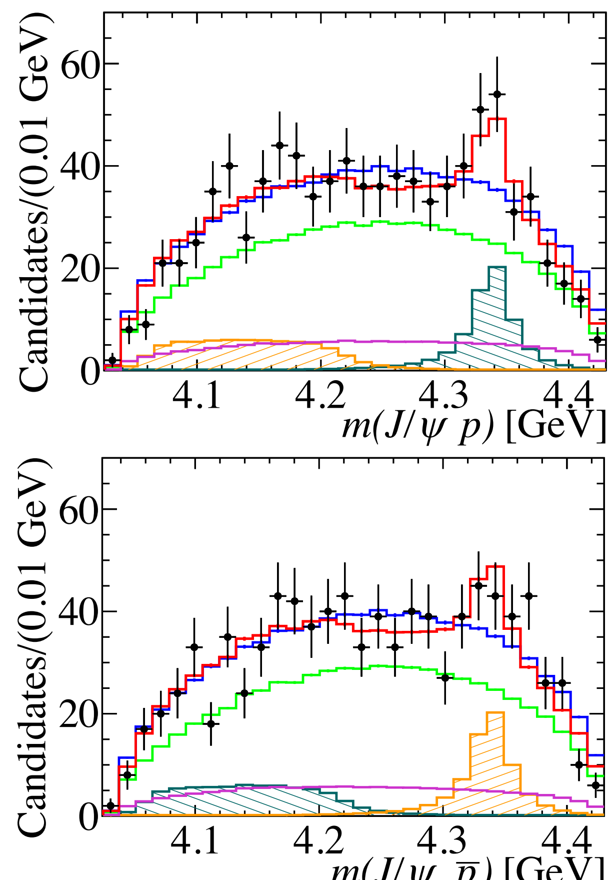
# $P_c$ search in $B_s^0 \to J/\psi p\bar{p}$

[PRL 128 (2022) 062001]

- ➢Dataset: Full Run1+Run2 LHCb data corresponding to 9 $\mathrm{fb}^{-1}$
- ➢The $B_s^0$ sample is flavor untagged, assuming CP symmetry




✓ Add Breit-Wigner shaped $P_c^+$ and $P_c^-$ with floating and identical $M$, $\Gamma$ and couplings




Hints of horizontal and vertical bands in $(18.8 - 19.0)\ \mathrm{GeV}^2$

⇒4D $(m_{p\bar{p}}, \theta_p, \theta_\mu, \phi)$ amplitude analysis

# $B_s^0 \to J/\psi p\bar{p}$ - evidence of new $P_c$

[PRL 128 (2022) 062001]

- Significance of the $P_c$ estimated with look-elsewhere effect considered
  - ✓The best $J^P$ hypothesis is $1/2^+$ for $P_c^+ \Rightarrow 3.7\sigma$
  - ✓For different $J^P$ hypotheses in $1/2^\pm, 3/2^\pm \Rightarrow 3.1 - 3.7\sigma$
  - ✓None of the $J^P$ hypotheses can be excluded at 95%

- The $P_c$ state is measured to have

$$M_{P_c} = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})\ \text{MeV}$$
$$\Gamma_{P_c} = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})\ \text{MeV}$$

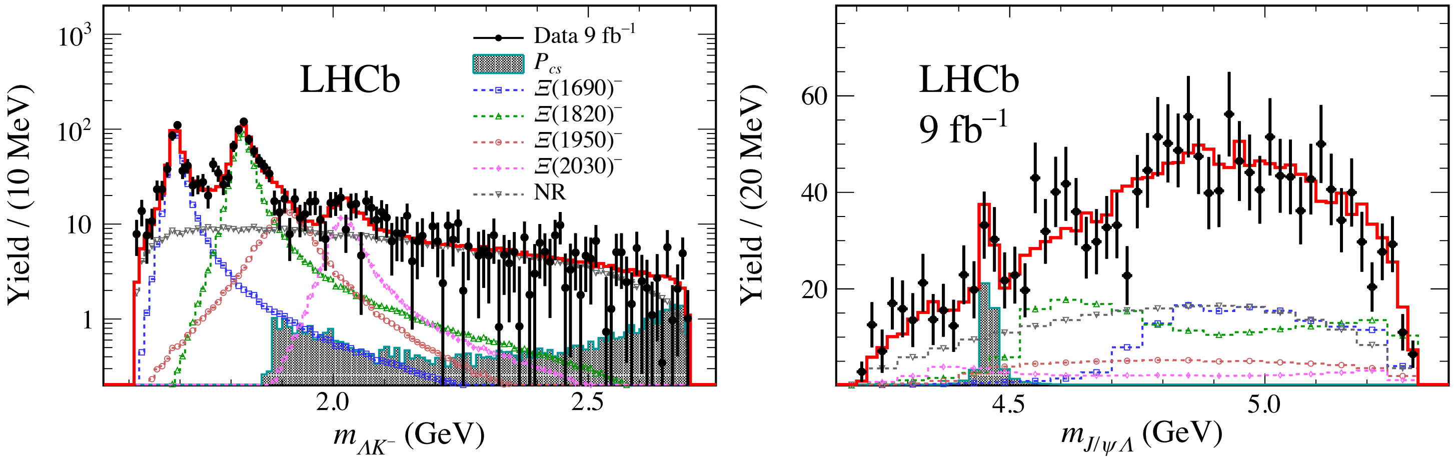
  - ✓Its mass and width are distinct from previous $P_c$ states
  - ✓It peaks $\sim 10$ MeV below the $\chi_{c0}(1\text{P})p$ threshold

- No evidence of
  - ✓$P_c(4312)$ and $P_c(4440)$ observed in $\Lambda_b^0 \to J/\psi K^- p$
  - ✓Glueball candidate $f_{\text{J}}(2230)$

# Evidence of $P_{cs}^0$ in $\Xi_b^- \to J/\psi \Lambda K^-$

[Science Bulletin 66 (2021) 1278]

- ➢$P_{cs}^0$ $(c\bar{c}sud)$, strange partner of $P_c^+$, is searched for in $\Xi_b^- \to J/\psi \Lambda K^-$
- ➢Dataset: Full Run1+Run2 LHCb data corresponding to 9 $\text{fb}^{-1}$
- ➢Six-dimensional amplitude fit performed




$P_{cs}^0$ significance: $3.1\sigma$

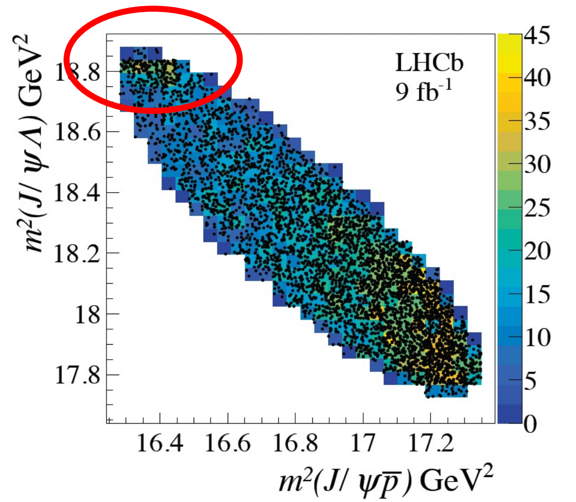
$$m(P_{cs}^0) = 4458.8 \pm 2.9^{+4.7}_{-1.1}\ \text{MeV}, \Gamma(P_{cs}^0) = 17.3 \pm 6.5^{+8.0}_{-5.7}\ \text{MeV}$$

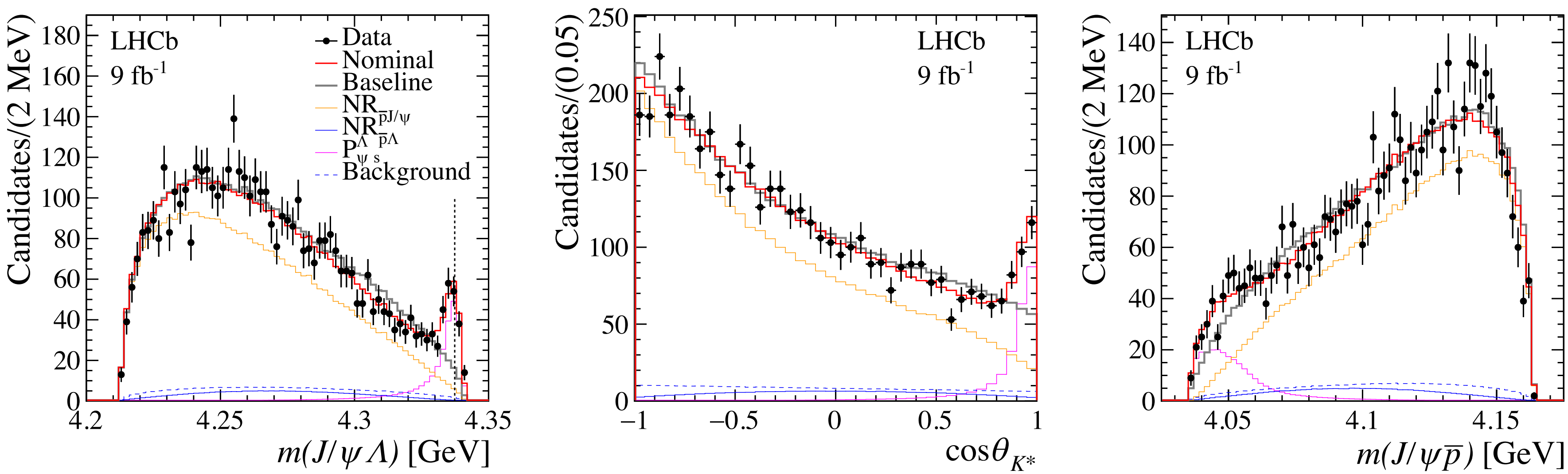
- ✓Mass ~19 MeV below of $\Xi_c^0 \overline{D}^{*0}$ threshold
- ✓The data cannot confirm or refute the two-peak hypothesis
- ✓$J^P$ determination needs more data

# Amplitude analysis of $B^- \to J/\psi \Lambda \bar{p}$

[arXiv: 2210.10346]

- Amplitude contributions
  - ✓ $\Lambda\bar{p}$: $\bar{K}_4^*(2045), \bar{K}_2^*(2250), \bar{K}_3^*(2320)$ and $J^P = 1^-$ non-resonant (NP) component ($\bar{K}^*$-only model cannot describe data)
  - ✓ $J/\psi\bar{p}$: $J^P = 1/2^-$ NR component (preferred over resonant lineshape)
  - ✓ $J/\psi\Lambda$: $\boldsymbol{P_{\psi s}^{\Lambda}}$



# Observation of $P_{\psi s}^{\Lambda} \to J/\psi\Lambda$

[arXiv: 2210.10346]

- $P_{\psi s}^{\Lambda}$ observed with significance $> 10\sigma$
- $J = 1/2$ is established
- $P = -1$ preferred; $J^P = 1/2^+$ excluded at 90% CL

$$M\left(P_{\psi s}^{\Lambda}\right) = 4338.2 \pm 0.7 \pm 0.4\ \mathrm{MeV}$$
$$\Gamma\left(P_{\psi s}^{\Lambda}\right) = 7.0 \pm 1.2 \pm 1.3\ \mathrm{MeV}$$

- Key properties
  - ✓ First observation of pentaquark with strange quark content $c\bar{c}uds$
  - ✓ Narrow
  - ✓ Close to $\Xi_c^+ D^-$ threshold and in S-wave

- The most precise single measurement of $B^-$ mass

$$M(B^-) = 5279.44 \pm 0.05 \pm 0.07\ \mathrm{MeV}$$

# Exotic hadron measurements

❑ Quarkonium-like tetraquark



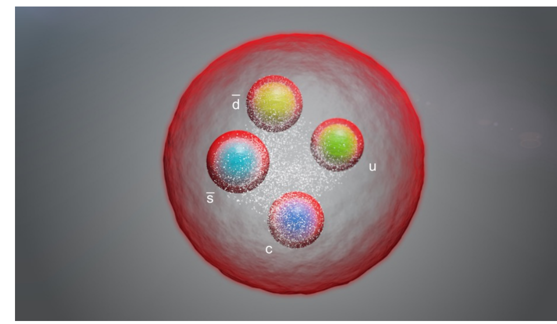


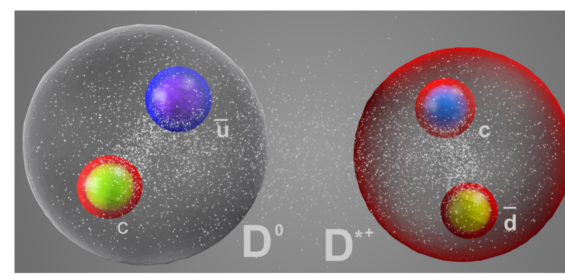

❑ Quarkonium-like pentaquark






❑ Open-charm tetraquark



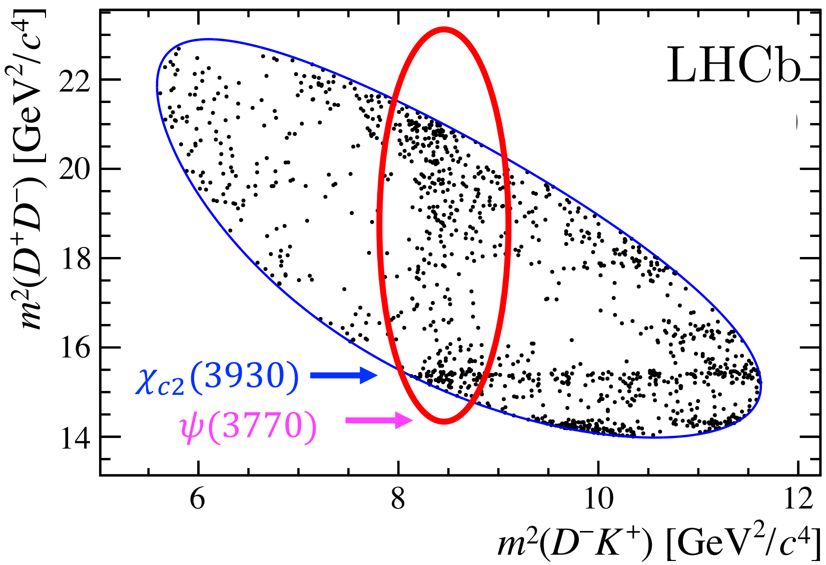



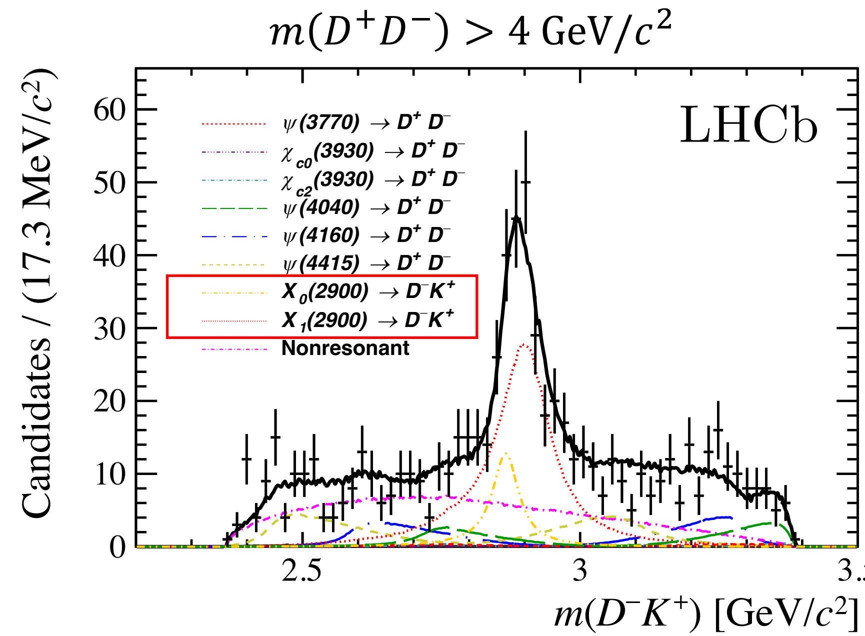

Disclaimer:
not able to cover all results

# $T_{cs}$ in $B^+ \to D^+ D^- K^+$

[PRL 125 (2020) 242001]
[PR D102 (2020) 112003]

- Resonant structures observed in the $D^- K^+$ system from an amplitude analysis of the $B^+ \to D^+ D^- K^+$ decay




$$X_0(2900): \quad M = 2.866 \pm 0.007 \pm 0.002\,\mathrm{GeV}/c^2, \quad \Gamma = 57 \pm 12 \pm 4\,\mathrm{MeV}$$
$$X_1(2900): \quad M = 2.904 \pm 0.005 \pm 0.001\,\mathrm{GeV}/c^2, \quad \Gamma = 110 \pm 11 \pm 4\,\mathrm{MeV}$$

- First discovery of open-charm tetraquarks with four different flavors $[cs\bar{u}\bar{d}]$!
- The observation motivates study of $B \to \bar{D} D_s \pi$

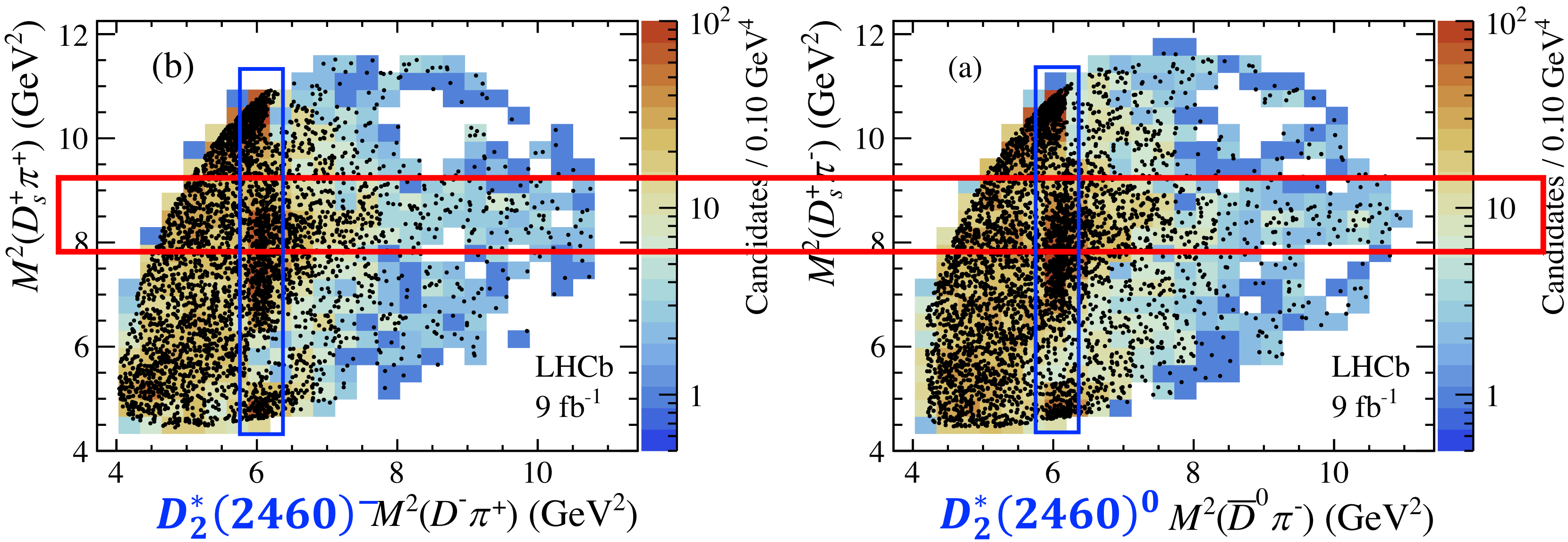
# Study of $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$

[arXiv: 2212.02716]

- Full 9 $fb^{-1}$ Run1+Run2 LHCb data

$\Rightarrow$ 4420 $B^0 \to \overline{D}^0 D_s^+ \pi^-$ candidates with signal purity of 90.7%

3940 $B^+ \to D^- D_s^+ \pi^+$ candidates with signal purity of 95.2%



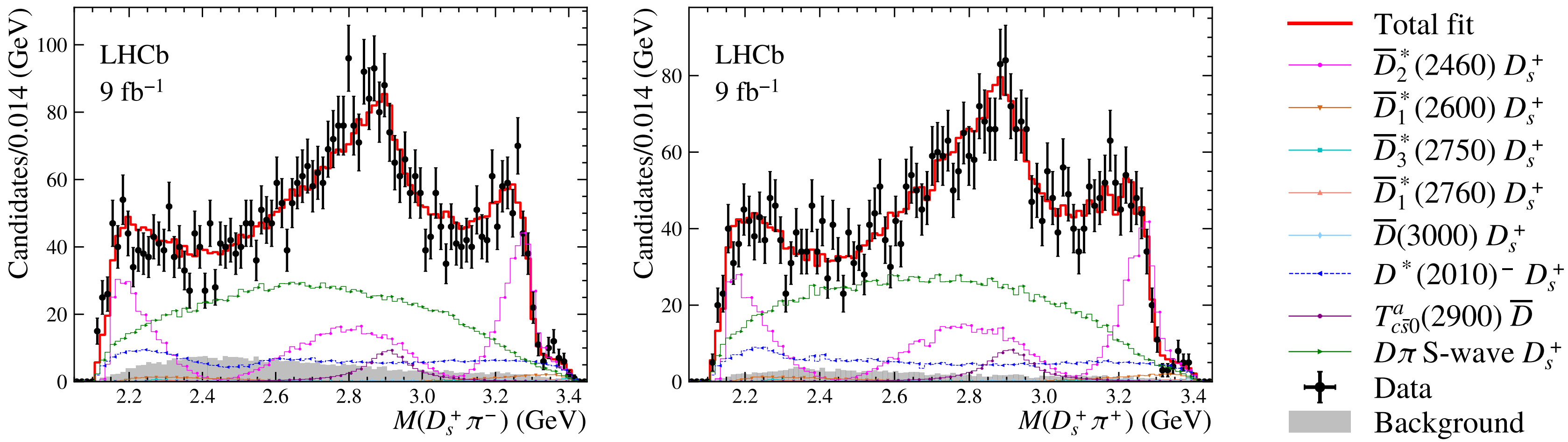

✓ Faint horizontal band at $M^2(D_s^+\pi) \approx 8.5\ \mathrm{GeV}^2$ indicating $T_{c\bar{s}}$ candidates

$\Rightarrow$ Joint amplitude analysis where amplitudes of the two decays are related through isospin symmetry

# Observation of $T^{a}_{c\bar{s}0}(2900)^{0/++}$

[arXiv: 2212.02716]

- Fit with two $D_s^+\pi$ states sharing resonance parameters




- $T^{a}_{c\bar{s}0}(2900)^{0} \to D_s^+\pi^-$ & $T^{a}_{c\bar{s}0}(2900)^{++} \to D_s^+\pi^+$ significance $> 9\sigma$
  - ✓A second $1^-$ $D_s^+\pi$ state yields significance of only $1.3\sigma$
  - ✓Additional $D\pi, D_s^+\pi, DD_s^+$ resonances disfavored
- $J^P = 0^+$ favored over other spin-parity by more than $7.5\sigma$

$$M = 2.908 \pm 0.011 \pm 0.020\ \text{GeV}$$

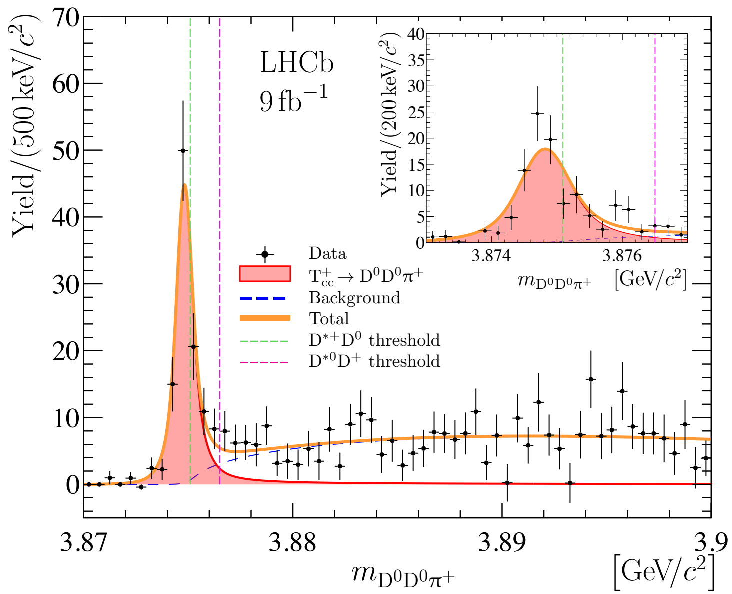
$$\Gamma = 0.136 \pm 0.023 \pm 0.011\ \text{GeV}$$

- Flavor partner of $T_{cs0}(2900)$? Multiplets to be revealed in the future.

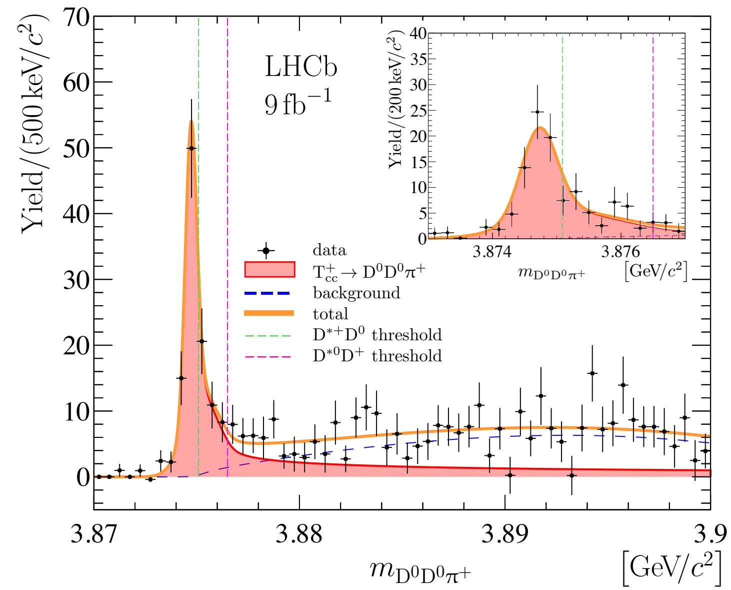
# Observation of $T_{cc}^{+}$ in $D^0D^0\pi^+$

- Dataset: Full Run1+Run2 LHCb data corresponding to 9 $\mathrm{fb}^{-1}$
- Prompt $D^0D^0\pi^+$ candidates selected;
  Non-$D^0$ background subtracted according to $(m_{K_1^-\pi_1^+}, m_{K_2^-\pi_2^+})$ fit

✓ Simple Breit-Wigner




✓ Unitarized 3-body Breit-Wigner

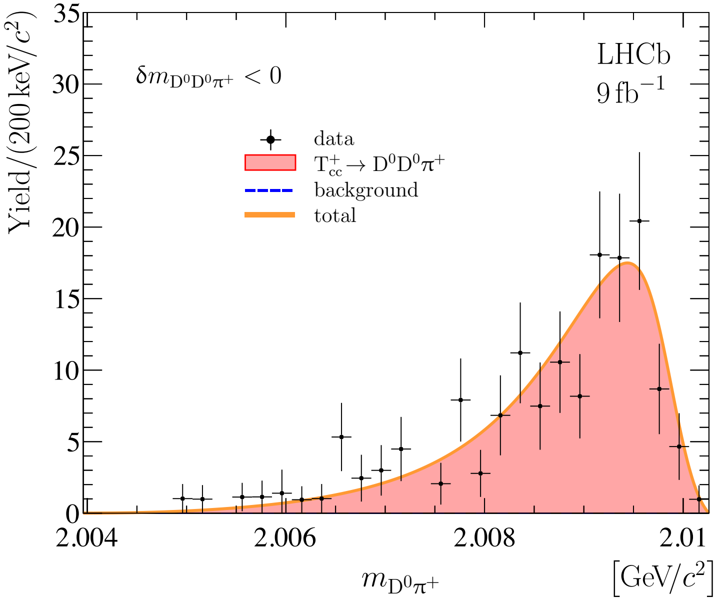


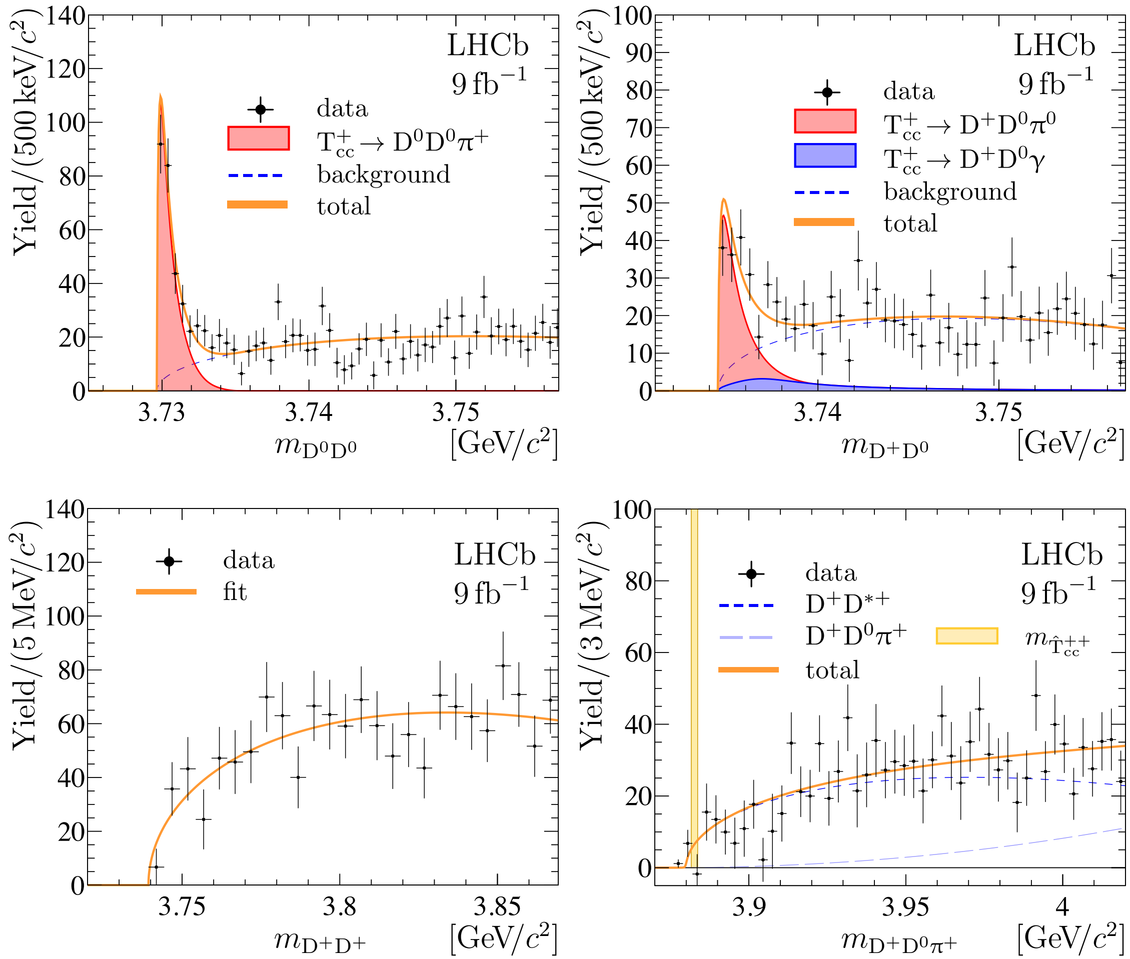

| | $\delta\mathfrak{m}$ $[\mathrm{keV}/c^2]$ | $\mathfrak{w}$ $[\mathrm{keV}/c^2]$ |
|---|---|---|
| $\mathfrak{F}^{\mathrm{BW}}$ | $-279 \pm 59$ | $409 \pm 163$ |
| $\mathfrak{F}^{\mathrm{U}}$ | $-361 \pm 40$ | $47.8 \pm 1.9$ |

[arXiv: 2109.01038] (Nature Physics)
[arXiv: 2109.01056] (Nature Communications)

# Study of $T_{cc}^{+}$ in $D^0D^0\pi^+$

[arXiv: 2109.01038] (Nature Physics)
[arXiv: 2109.01056] (Nature Communications)

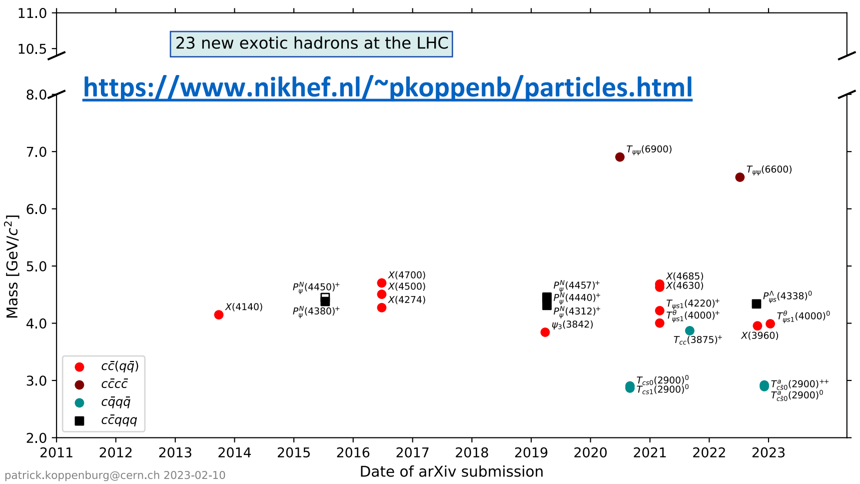


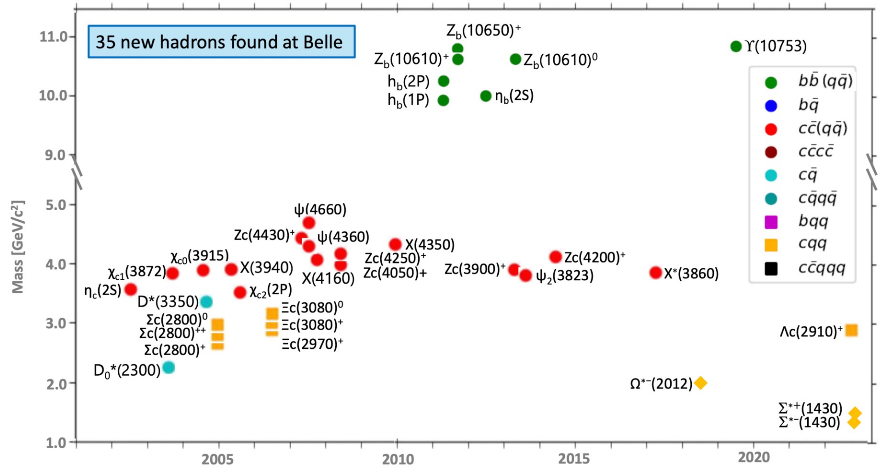



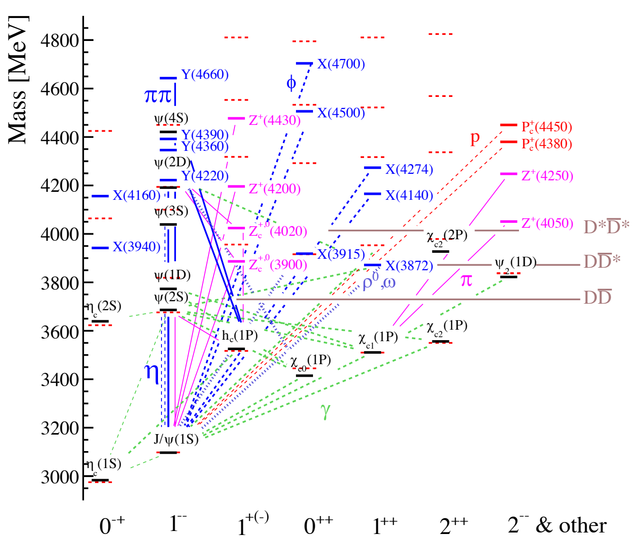

- ➢ $T_{cc}^{+}$ decay via offshell $D^*$ to $D^0D^0\pi^+$
- ➢ Results in agreement with expectations for isoscalar $T_{cc}^{+}$ with $J^P = 1^+$

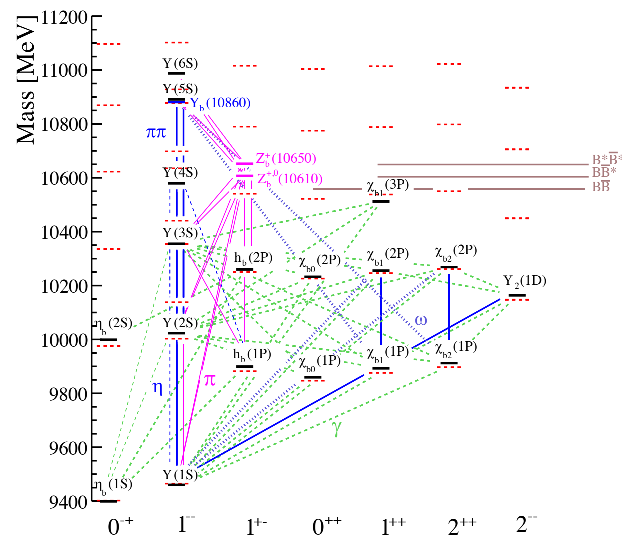
# Summary and prospects

➢A new “particle zoo”



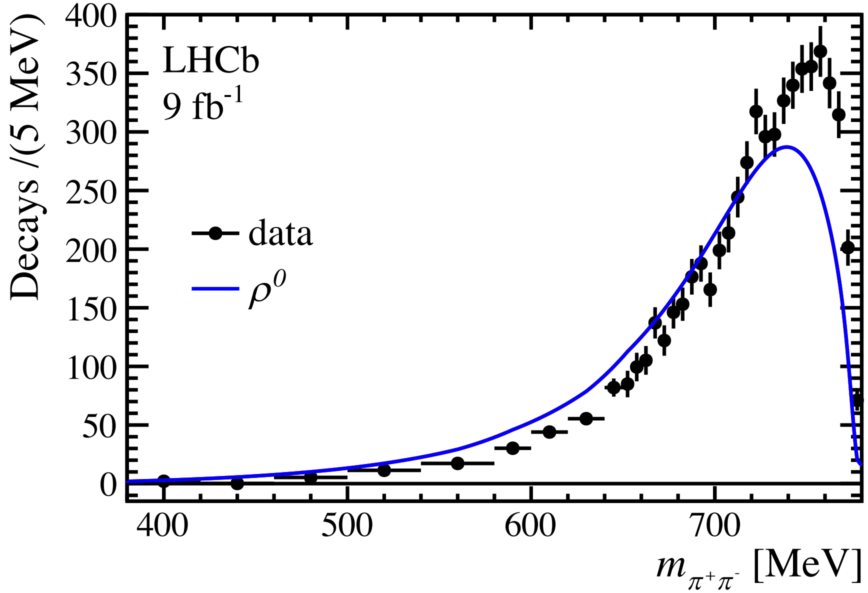

[Rev. Mod. Phys. 90, 15003 (2018)]

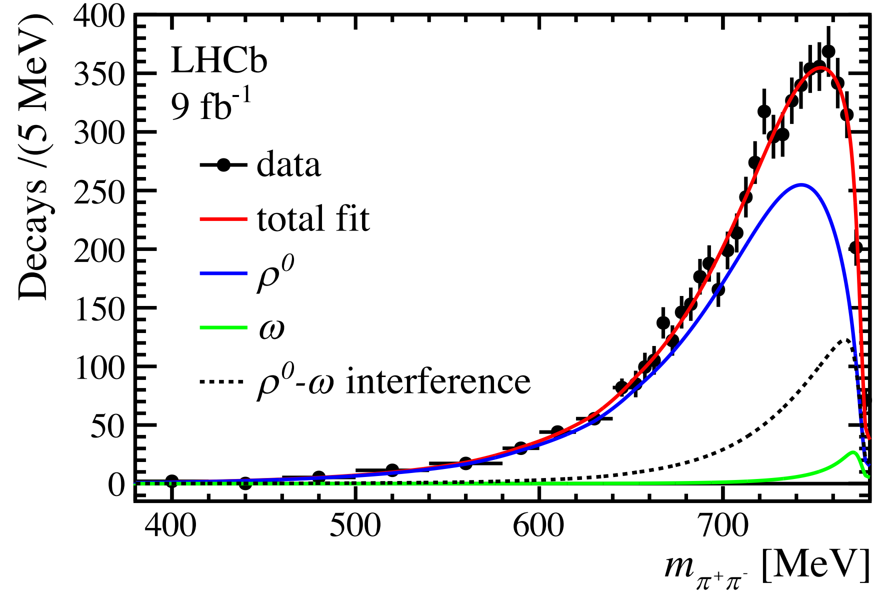
# Back up

# $\omega$ contribution to $\chi_{c1}(3872) \rightarrow J/\psi\pi^+\pi^-$

- $\chi_{c1}(3872) \rightarrow J/\psi\rho^0$ is isospin violating; **[arXiv: 2204.12597]**
  quantifying the isospin violation is important to understand its nature

- Full 9 $\text{fb}^{-1}$ Run1+Run2 LHCb data
  $\Rightarrow 6788 \pm 117$ $B^+ \rightarrow \chi_{c1}(3872)(\rightarrow J/\psi\pi^+\pi^-)K^+$ signal candidates




- Total $\omega$ contribution: $(21.4 \pm 2.3 \pm 2.0)\%$
  Excluding interference: $(1.9 \pm 0.4 \pm 0.3)\%$

- $\rho^0$ contribution an order of magnitude too large for pure charmonium