# Hadron Spectroscopy at LHCb

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On behalf of the LHCb collaboration

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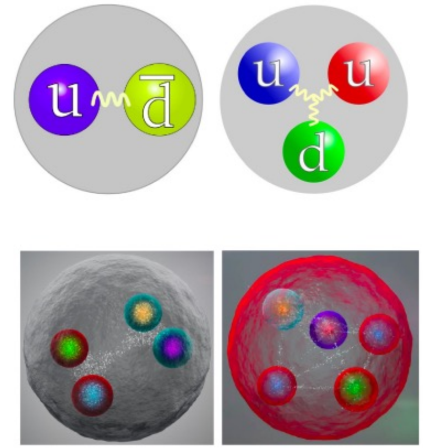
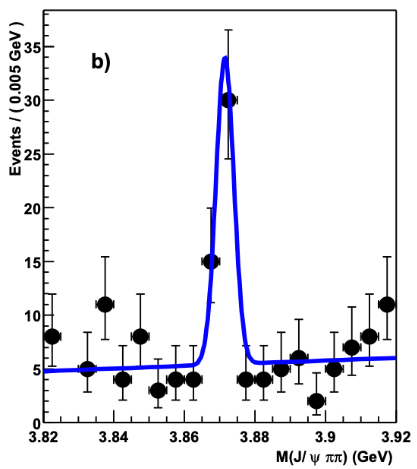
International Workshop on Hadron Structure and Spectroscopy 2023

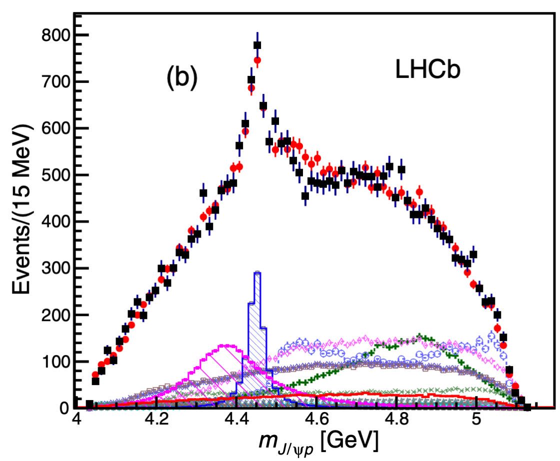
# Introduction

- QCD describing strong interaction between quarks and gluons is not well understood due to its non-perturbative nature at low energy scale
- Hadron spectroscopy allow to test the knowledge of QCD and it effective models
  - e.g. lattice QCD, diquark model, potential model …
- Exotic states provide unique probe for QCD

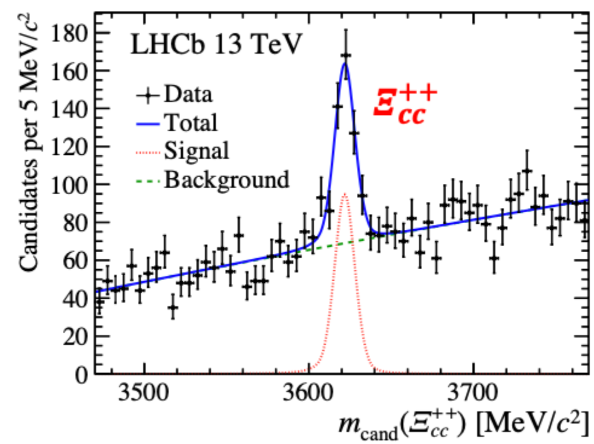



[PRL 91 (2003) 262001]



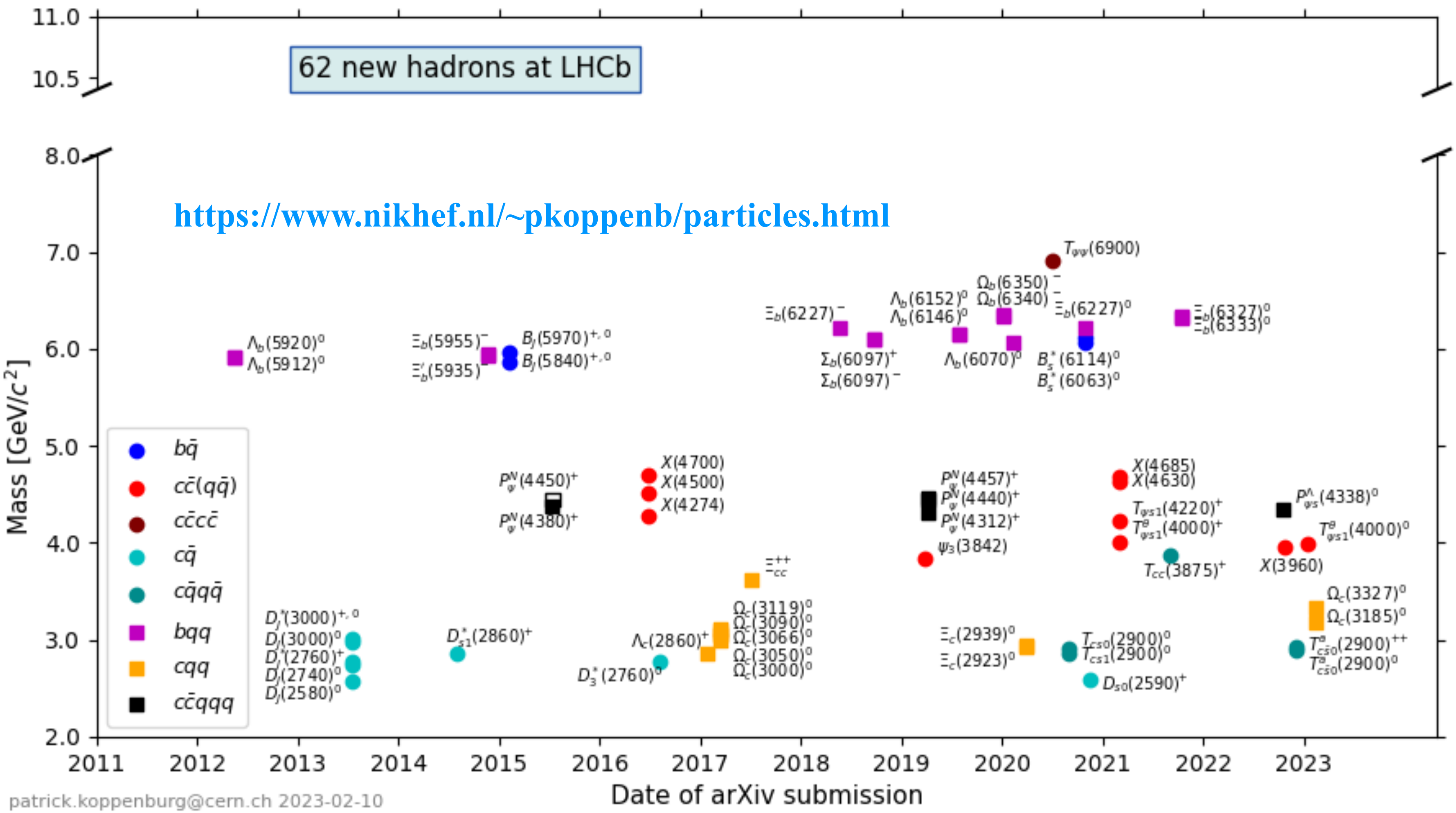

[PRL 115 (2015) 072001]




[PRL 117 (2017) 112001]

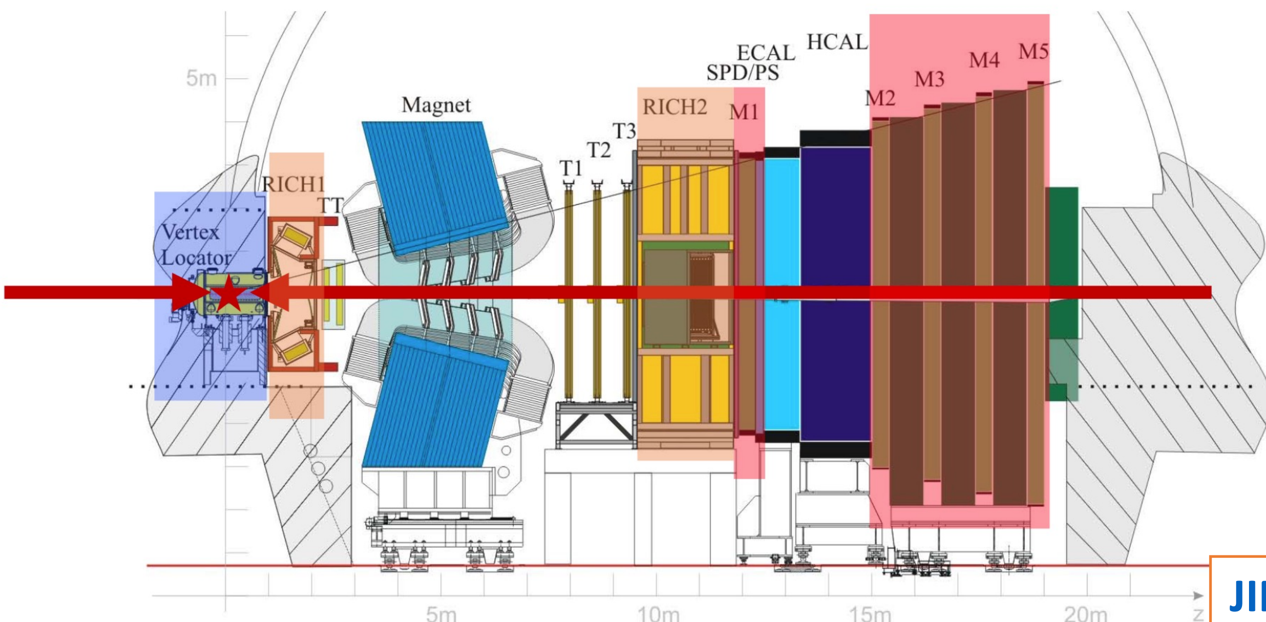
# Hadrons observed at LHCb

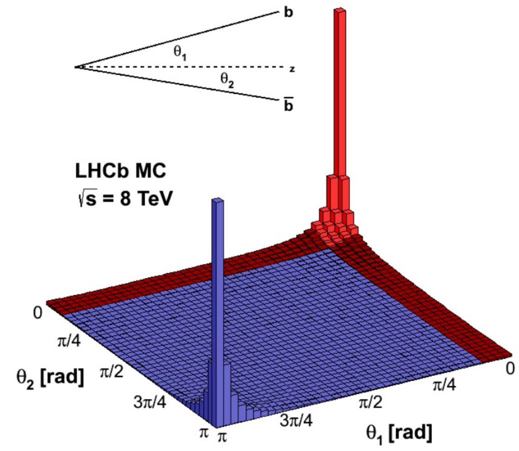
- 62 new hadrons observed at LHCb, 20+ are exotics



# The LHCb detector

- LHCb is a dedicated heavy flavor physics experiment at LHC
  - $\sim 20{,}000/\mathrm{s}\ b\bar{b}$ generated at LHCb point in Run2
  - A single-arm forward region spectrometer covering $2 < \eta < 5$




JINST 3 (2008) S08005

| | |
|---|---|
| **Vertex:** | $\sigma_{IP} = 20\ \mu m$ |
| **Time:** | $\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$ |
| **Momentum:** | $\Delta p/p = 0.4 \sim 0.6\%$ (5 – 100 GeV/$c$) |
| **Mass :** | $\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B \to J/\psi X$ (constrainted $m_{J/\psi}$) |
| **Hadron ID:** | $\varepsilon(K \to K) \sim 95\%$ mis-ID $\varepsilon(\pi \to K) \sim 5\%$ |
| **Muon ID:** | $\varepsilon(\mu \to \mu) \sim 97\%$ mis-ID $\varepsilon(\pi \to \mu) \sim 1 - 3\%$ |
| **ECAL:** | $\Delta E/E = 1 \oplus 10\%/\sqrt{E\ (\mathrm{GeV})}$ |

# Incomplete list of recent results

- Cover just a small set of very recent results since last year

LHCb Talk in IWHHS2022

## Conventional

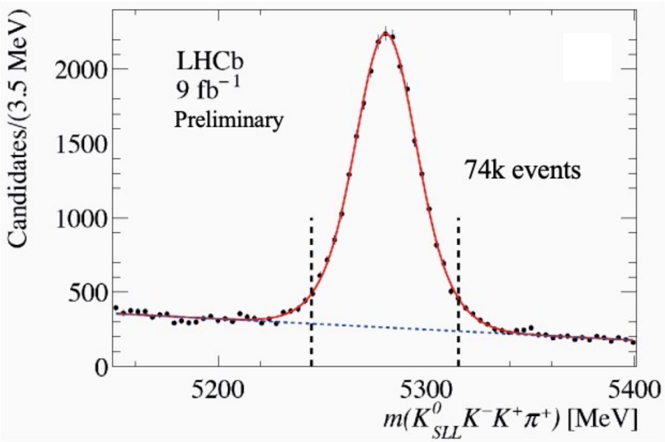
- Charmonia decaying to $K_s K\pi$ [arXiv:2304.14891]
- New excited $\Omega_c^0$ states [arXiv:2302.04733]
- New excited $\Xi_b^0$ states [LHCB-PAPER-2023-008 in preparation]
- Amplitude analysis of $D_{(s)}^+ \to \pi\pi\pi$ [arXiv:2209.09840, arXiv:2208.03300]

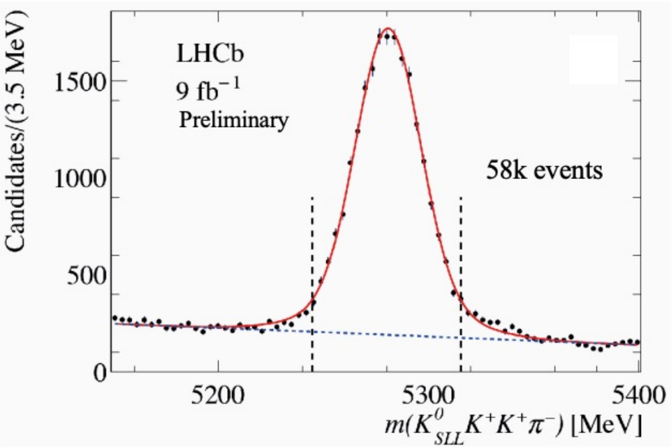
## Exotic (hadrons beyond $q\bar{q}$ and $qqq$)

- Evidence of $T_{\psi S1}^{\theta}(4000)$ [arXiv: 2301.04899]

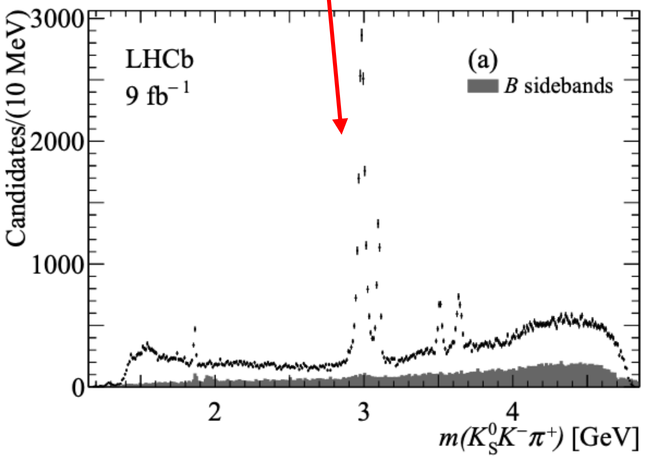
# Charmonia decaying to $K_sK\pi$ [arXiv:2304.14891]

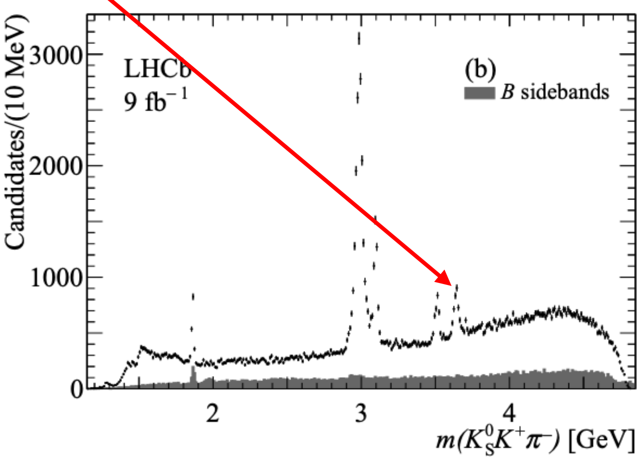
- High-statistic signals with $B^+ \to K_s^0K^+K^-\pi^+$ and $B^+ \to K_s^0K^+K^+\pi^-$
  - Two $K_s^0$ reconstruction methods (LL, DD)




- Obvious peaks of $\eta_c$, $J/\psi$, $\chi_{c1}$, $\eta_c(2S)$

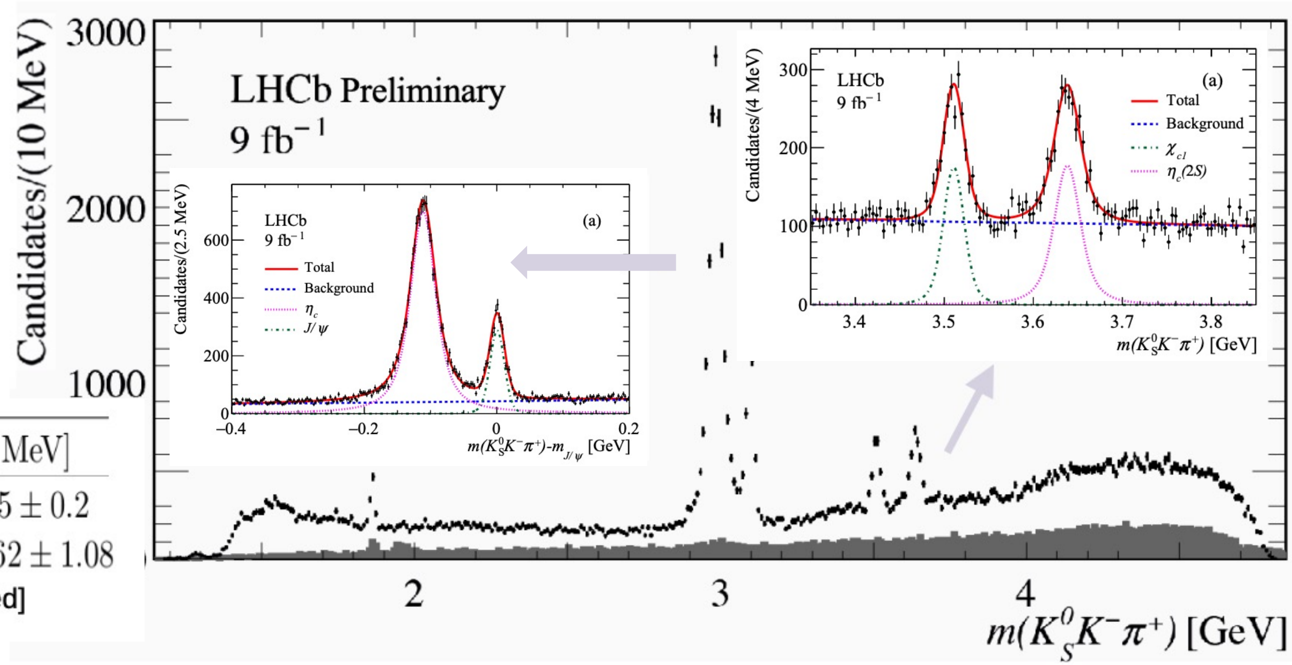


# Charmonia decaying to $K_s K\pi$

[arXiv:2304.14891]

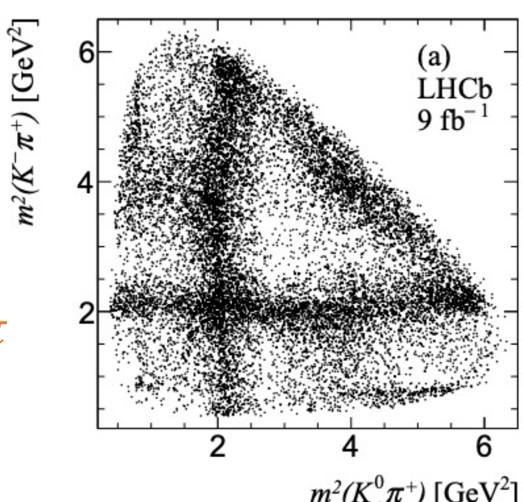
- New precision measurement of $\eta_c$, $\eta_c(2S)$

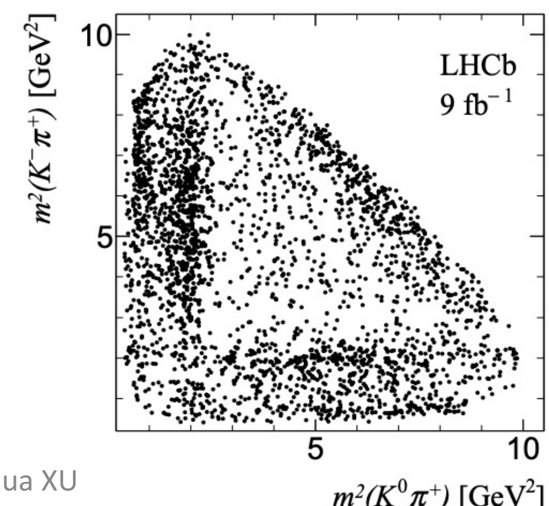



| | Mass [MeV] | Width [MeV] |
|---|---|---|
| $\eta_c$ | $2985.01 \pm 0.17 \pm 0.89$ | $29.7 \pm 0.5 \pm 0.2$ |
| $\eta_c(2S)$ | $3637.90 \pm 0.54 \pm 1.40$ | $10.77 \pm 1.62 \pm 1.08$ |
| $\chi_{c1}$ | $3509.84 \pm 0.69 \pm 0.64$ | [fixed] |

- Dalitz analyses of $\eta_c$, $\eta_c(2S)$ decays provide information on kaon spectroscopy

$\eta_c \to K^0_S K\pi$

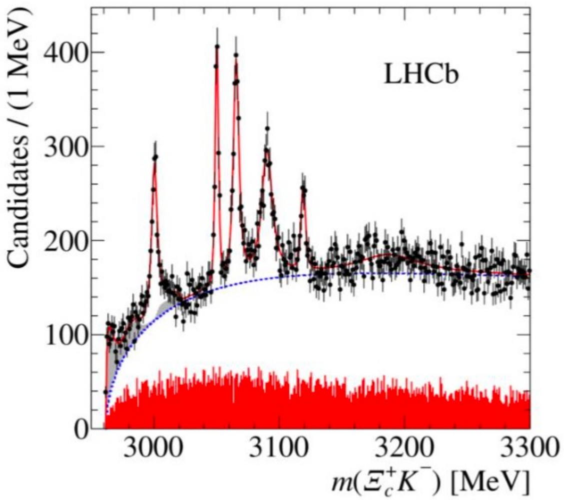



$\eta_c(2S) \to K^0_S K\pi$

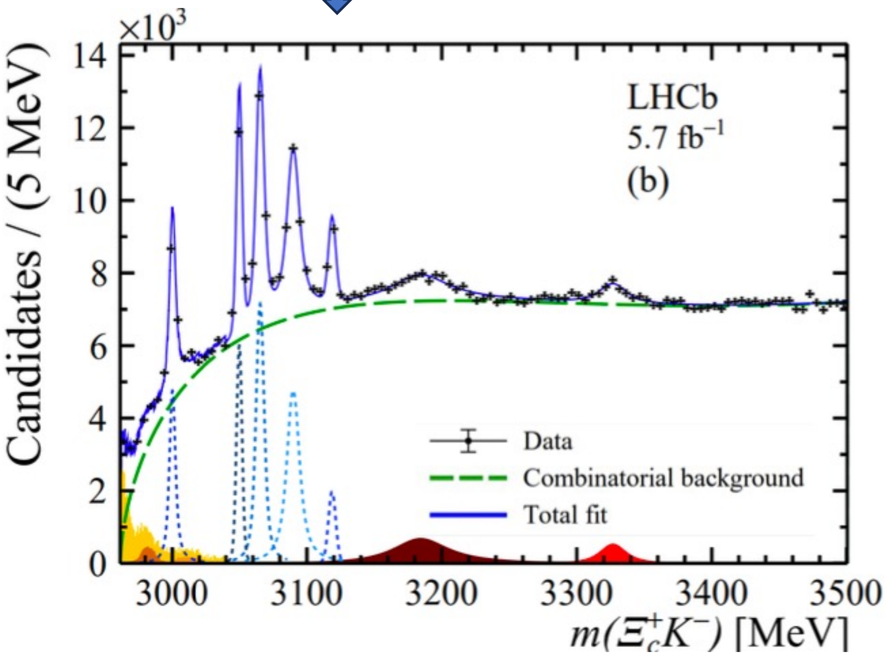
# New excited $\Omega_c^0$ states

- $\Xi_c^+ K^-$ in 2017, five excited $\Omega_c^0$ observed; updated with Run1+2 dataset




[PHYS. REV. LETT. 118(2017) 182001]

[arXiv:2302.04733]

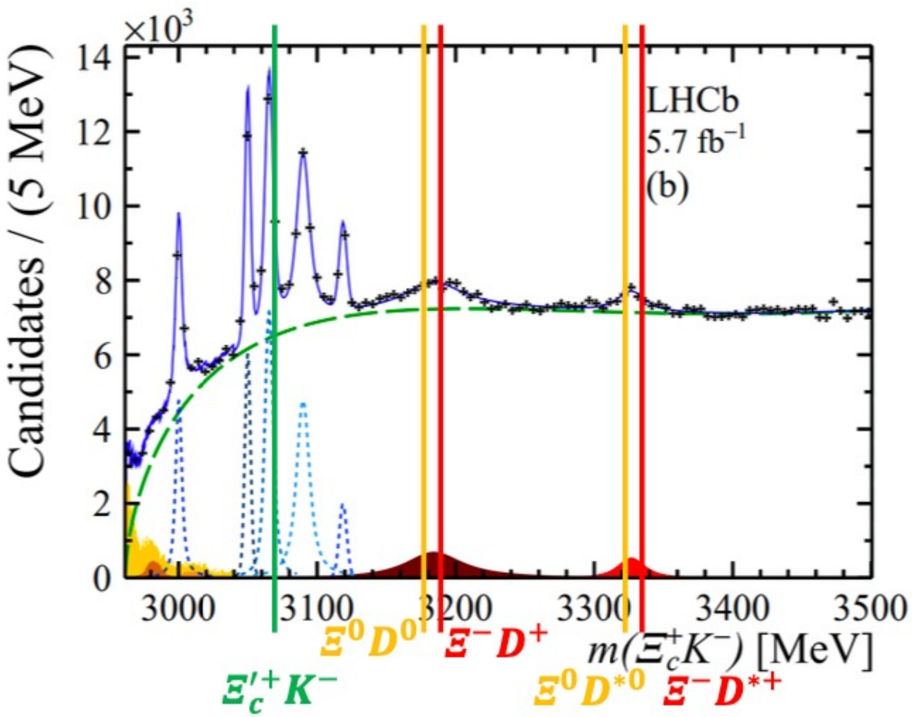


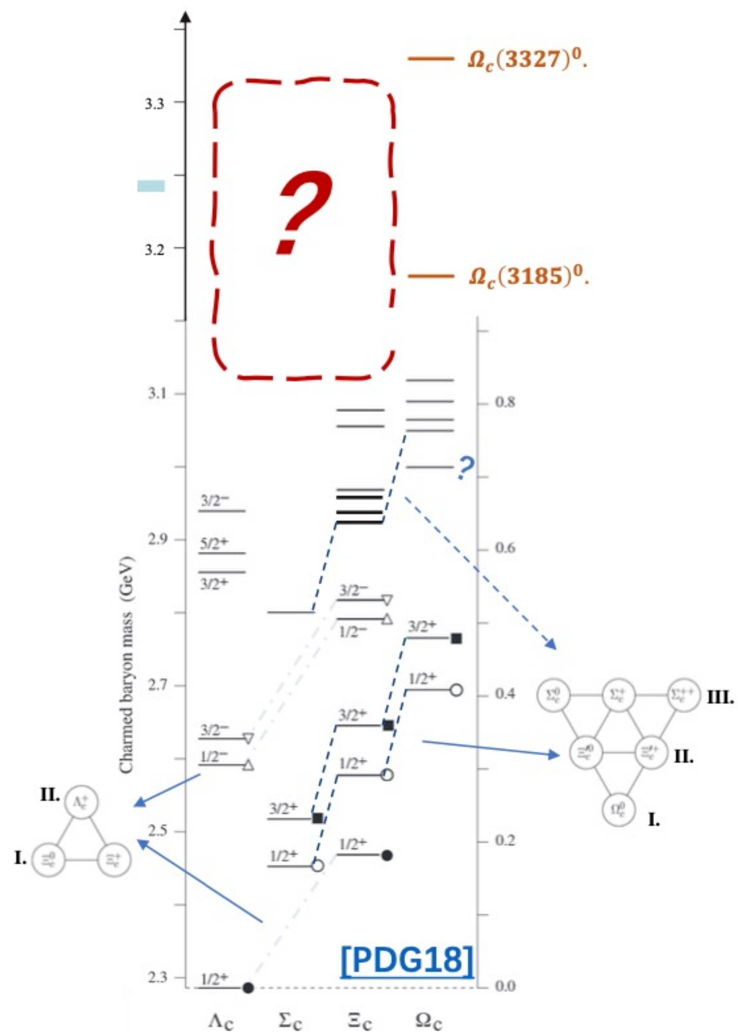

- New states: $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$
- All previous states confirmed

# New excited $\Omega_c^0$ states

[arXiv:2302.04733]

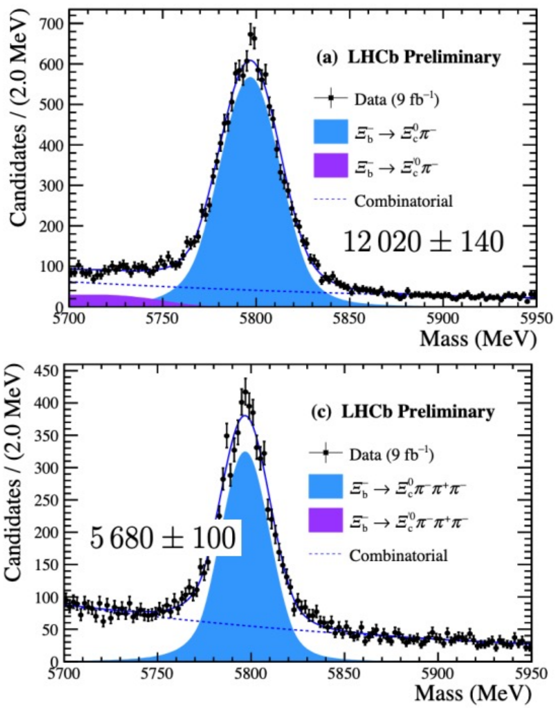
- $\Omega_c(3185)^0$ and $\Omega_c(3327)^0$ near $\Xi^0 D^{*0}$ and $\Xi_c^+ K^-$ thresholds



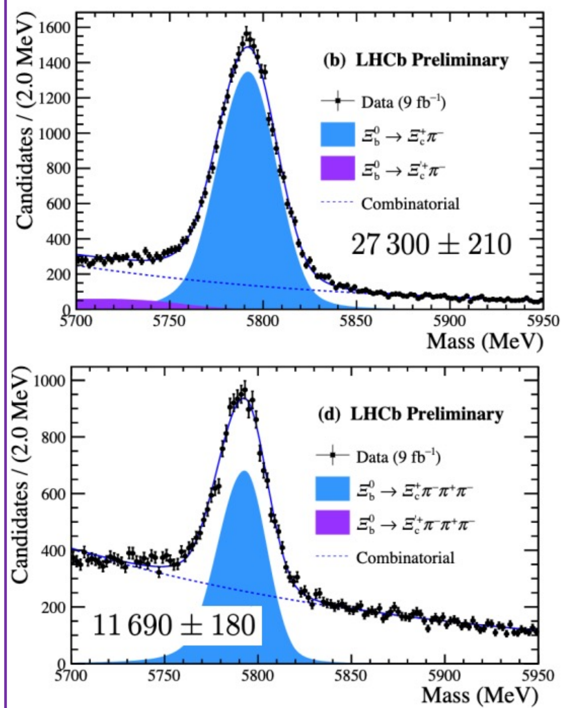



# New baryons in $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$ [LHCb-PAPER-2023-008]

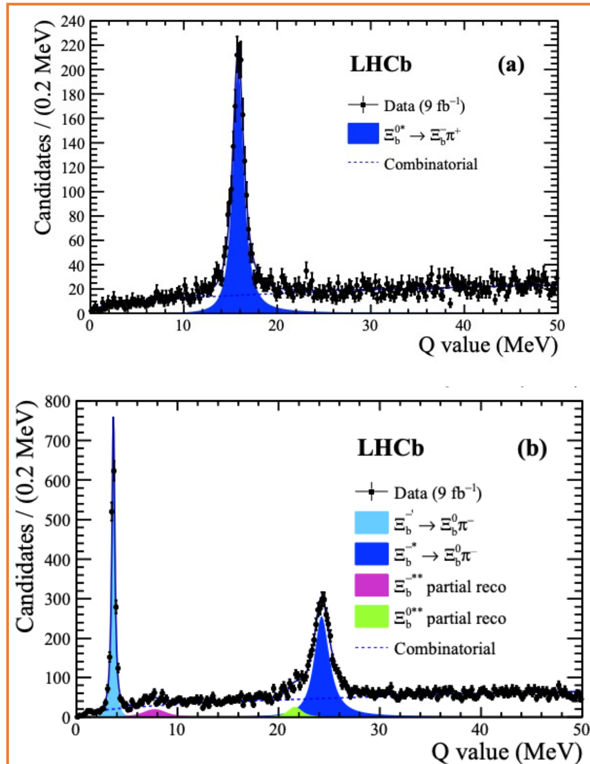
- First investigation in LHCb of the final states $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$




$\Xi_b^-$



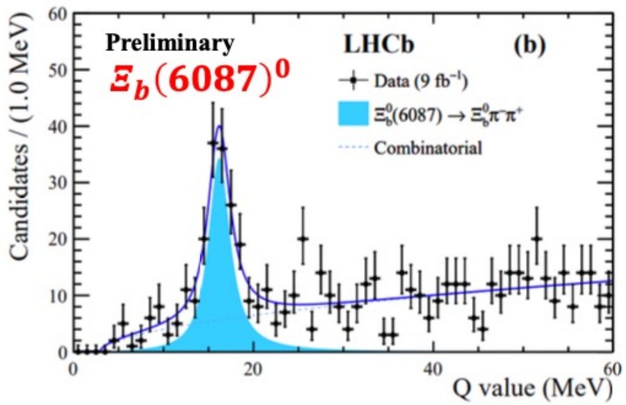

$\Xi_b^0$

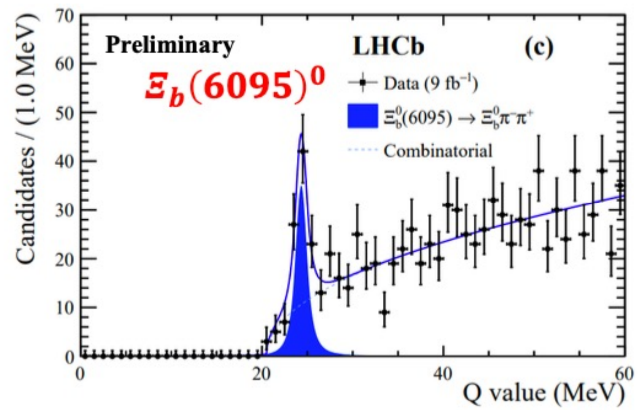


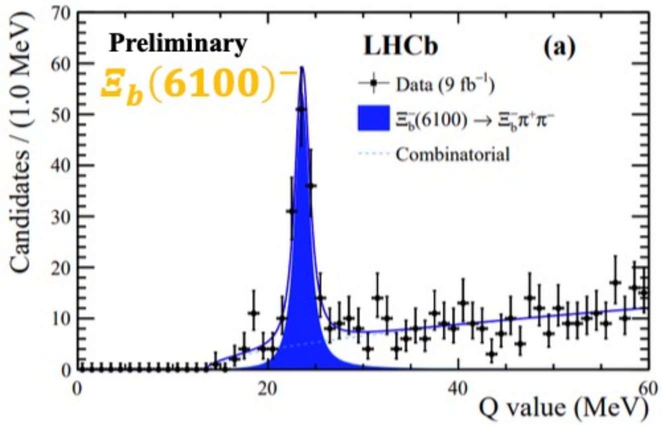

$\Xi_b^{0*}$, $\Xi_b^{-\prime}$ and $\Xi_b^{-*}$

- Charged and neutral $\Xi_b$ states reconstructed
- $\Xi_b^{0*}$, $\Xi_b^{-\prime}$ and $\Xi_b^{-*}$ reconstructed from $\Xi_b^-\pi^+$ or $\Xi_b^0\pi^-$

# New baryons in $\Xi_b^-\pi^+\pi^-$ and $\Xi_b^0\pi^+\pi^-$ [LHCb-PAPER-2023-008]




| | Value [MeV] | |
|---|---|---|
| $Q_0$ $(\Xi_b^-(6100))$ | $23.60 \pm 0.11 \pm 0.02$ | |
| $\Gamma$ $(\Xi_b^-(6100))$ | $0.94 \pm 0.30 \pm 0.08$ | |
| $m_0$ $(\Xi_b^-(6100))$ | $6099.74 \pm 0.11 \pm 0.02$ | $\pm 0.6$ $(\Xi_b^-)$ |
| $Q_0$ $(\Xi_b^0(6087))$ | $16.20 \pm 0.20 \pm 0.06$ | |
| $\Gamma$ $(\Xi_b^0(6087))$ | $2.43 \pm 0.51 \pm 0.10$ | |
| $m_0$ $(\Xi_b^0(6087))$ | $6087.24 \pm 0.20 \pm 0.06$ | $\pm 0.5$ $(\Xi_b^0)$ |
| $Q_0$ $(\Xi_b^0(6095))$ | $24.32 \pm 0.15 \pm 0.03$ | |
| $\Gamma$ $(\Xi_b^0(6095))$ | $0.50 \pm 0.33 \pm 0.11$ | |
| $m_0$ $(\Xi_b^0(6095))$ | $6095.36 \pm 0.15 \pm 0.03$ | $\pm 0.5$ $(\Xi_b^0)$ |

Confirmation

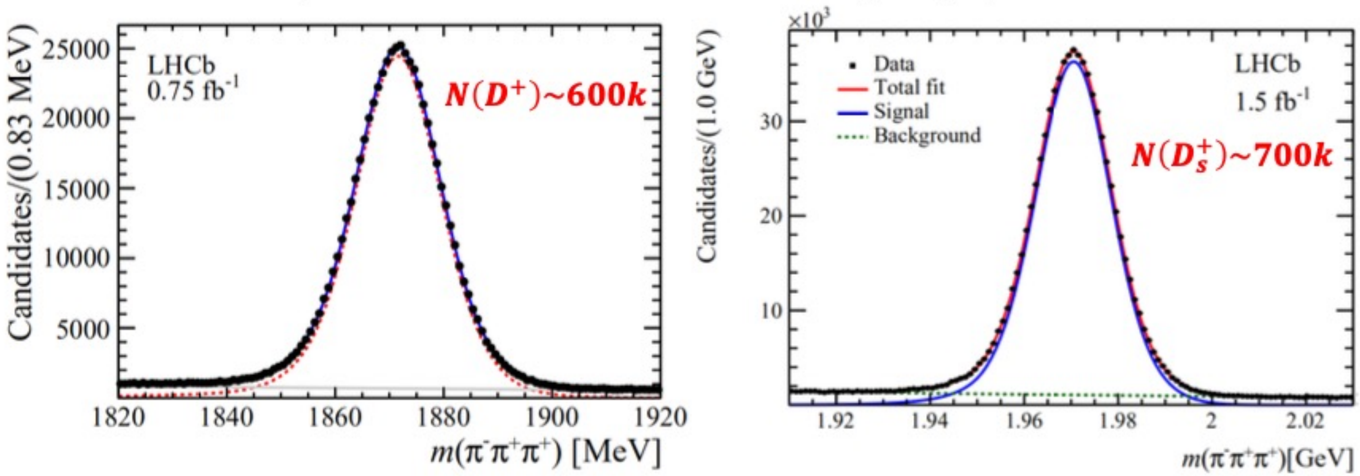
1st Observ

- Observation of two new excited baryons: $\Xi_b(6087)^0$, $\Xi_b(6095)^0$
- $\Xi_b(6100)^-$ is confirmed

# Amplitude analysis of $D^+_{(s)} \to \pi\pi\pi$

**[arXiv:2209.09840, arXiv:2208.03300]**

➢ 2012 $pp$ dataset used; promptly produced $D$ mesons




➢ Methodology for amplitude construction:

- S-wave: Quasi-Model Independent approach (**QMIPWA**)

$$\mathcal{A}_S(s_{12}, s_{13}) = \mathcal{A}_S(s_{12}) + \mathcal{A}_S(s_{13}) \qquad \mathcal{A}_S^k(s_{\pi^+\pi^-}) = c_k e^{i\phi_k}$$

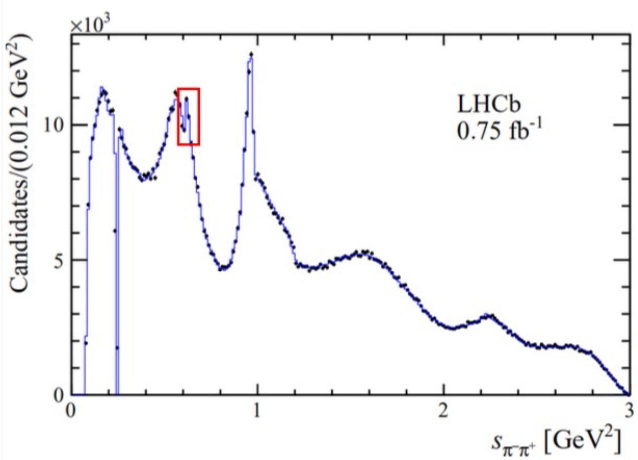
  - $c_k, \phi_k$: Generic functions determined by fit to data

- Isobar model for spin-1, spin-2 components

# Amplitude analysis of $D^+_{(s)} \to \pi\pi\pi$

[arXiv:2209.09840, arXiv:2208.03300]

➢ $D^+ \to \pi\pi\pi$

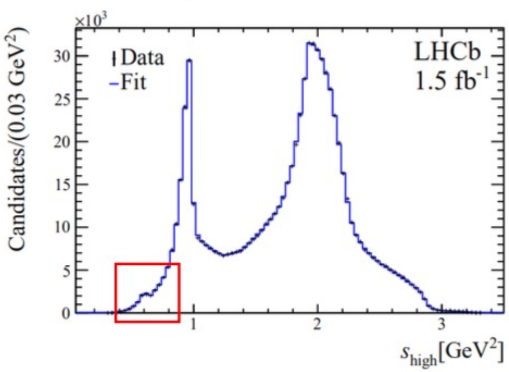


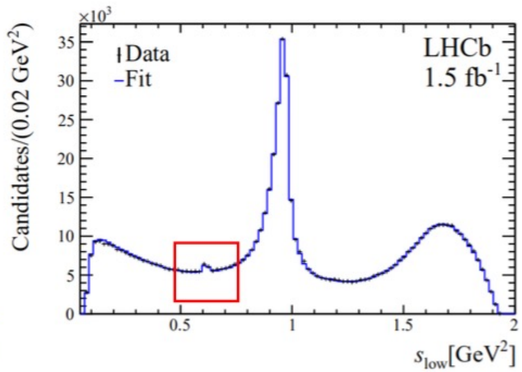

| Component | Magnitude | Phase [°] | Fit fraction [%] |
|---|---|---|---|
| $\rho(770)^0\pi^+$ | 1 [fixed] | 0 [fixed] | $26.0 \pm 0.3 \pm 1.6 \pm 0.3$ |
| $\omega(782)\pi^+$ | $(1.68 \pm 0.06 \pm 0.15 \pm 0.02) \times 10^{-2}$ | $-103.3 \pm 2.1 \pm 2.6 \pm 0.4$ | $0.103 \pm 0.008 \pm 0.014 \pm 0.002$ |
| $\rho(1450)^0\pi^+$ | $2.66 \pm 0.07 \pm 0.24 \pm 0.22$ | $47.0 \pm 1.5 \pm 5.5 \pm 4.1$ | $5.4 \pm 0.4 \pm 1.3 \pm 0.8$ |
| $\rho(1700)^0\pi^+$ | $7.41 \pm 0.18 \pm 0.47 \pm 0.71$ | $-65.7 \pm 1.5 \pm 3.8 \pm 4.6$ | $5.7 \pm 0.5 \pm 1.0 \pm 1.0$ |
| $f_2(1270)\pi^+$ | $2.16 \pm 0.02 \pm 0.10 \pm 0.02$ | $-100.9 \pm 0.7 \pm 2.0 \pm 0.4$ | $13.8 \pm 0.2 \pm 0.4 \pm 0.2$ |
| S-wave | | | $61.8 \pm 0.5 \pm 0.6 \pm 0.5$ |
| $\sum_i \mathrm{FF}_i$ | | | 112.8 |
| $\chi^2$/ndof (range) | [1.47 - 1.78] | | $-2\log\mathcal{L} = 805622$ |

**Dominated by S-wave**, followed by $\rho(770)^0\pi^+$ and $f_2(1270)^0\pi^+$

**Contribution from $(\omega(782) \to \pi^+\pi^-)\pi^+$ observed for the first time**

➢ $D_s^+ \to \pi\pi\pi$




| Resonance | Magnitude | Phase [°] | Fit fraction (FF) [%] |
|---|---|---|---|
| S-wave | | | $84.97 \pm 0.14$ |
| $\rho(770)^0$ | $0.1201 \pm 0.0030$ | $79.4 \pm 1.8$ | $1.038 \pm 0.054$ |
| $\omega(782)$ | $0.04001 \pm 0.00090$ | $-109.9 \pm 1.7$ | $0.360 \pm 0.016$ |
| $\rho(1450)^0$ | $1.277 \pm 0.026$ | $-115.2 \pm 2.6$ | $3.86 \pm 0.15$ |
| $\rho(1700)^0$ | $0.873 \pm 0.061$ | $-60.9 \pm 6.1$ | $0.365 \pm 0.050$ |
| combined | – | – | $6.14 \pm 0.27$ |
| $f_2(1270)$ | 1 (fixed) | 0 (fixed) | $13.69 \pm 0.14$ |
| $f_2'(1525)$ | $0.1098 \pm 0.0069$ | $178.1 \pm 4.2$ | $0.0455 \pm 0.0070$ |
| sum of fit fractions | | | 104.3 |
| $\chi^2$/ndof (range) | $[1.45 - 1.57]$ | | |

**Dominated by S-wave**, followed by spin-2 resonances

**Contribution from $(\omega(782) \to \pi^+\pi^-)\pi^+$observed for the first time**

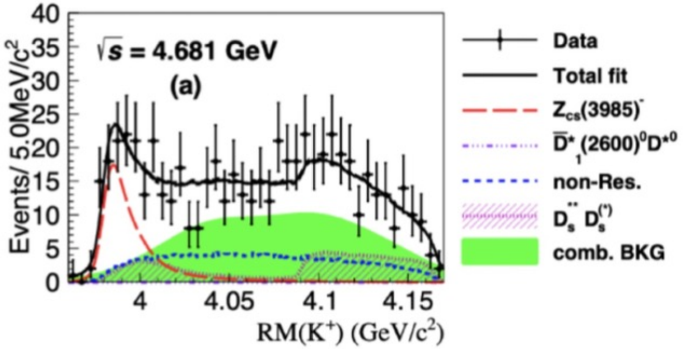
# Evidence of $T^{\theta}_{\psi S1}(4000)^0$

[arXiv: 2301.04899]

- $T^{\theta}_{\psi S1}{}^{+}$ observed at BESIII and LHCb

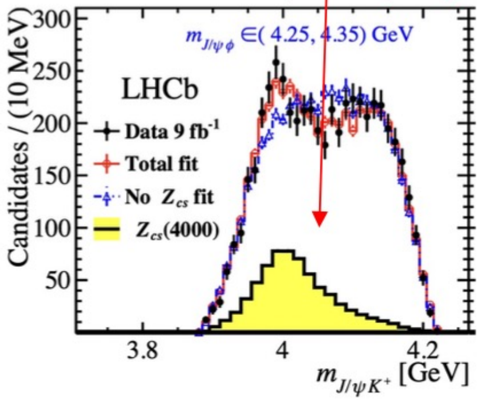
$T^{\theta}_{\psi s1}(3985)^+$ in $D_s^- D^{*0} + D^0 D_s^{*-}$ by BESIII

PRL 126 (2021) 102201

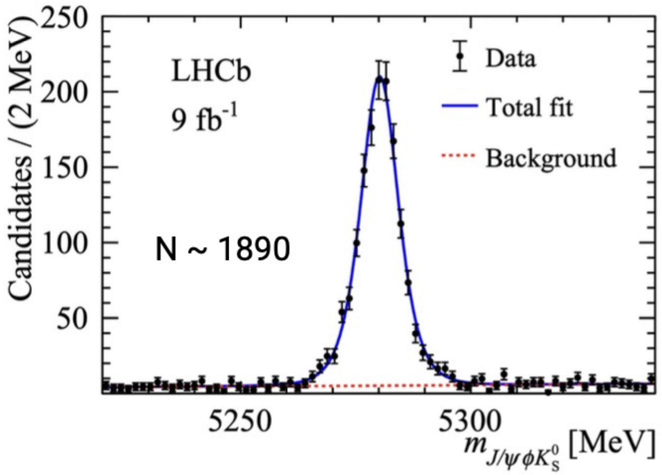


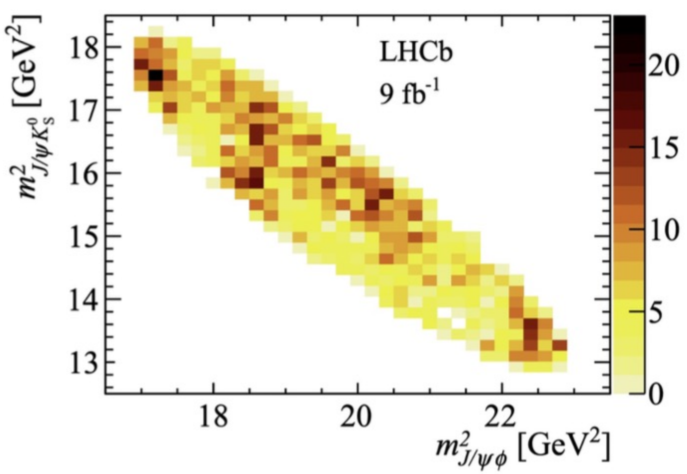

$T^{\theta}_{\psi s1}(4220)^+$ & $T^{\theta}_{\psi s1}(4000)^+$ state by LHCb

PRL 127, 082001 (2021)




- Search for $T^{\theta}_{\psi S1}$ in $B^0 \to J/\psi\phi K^0$

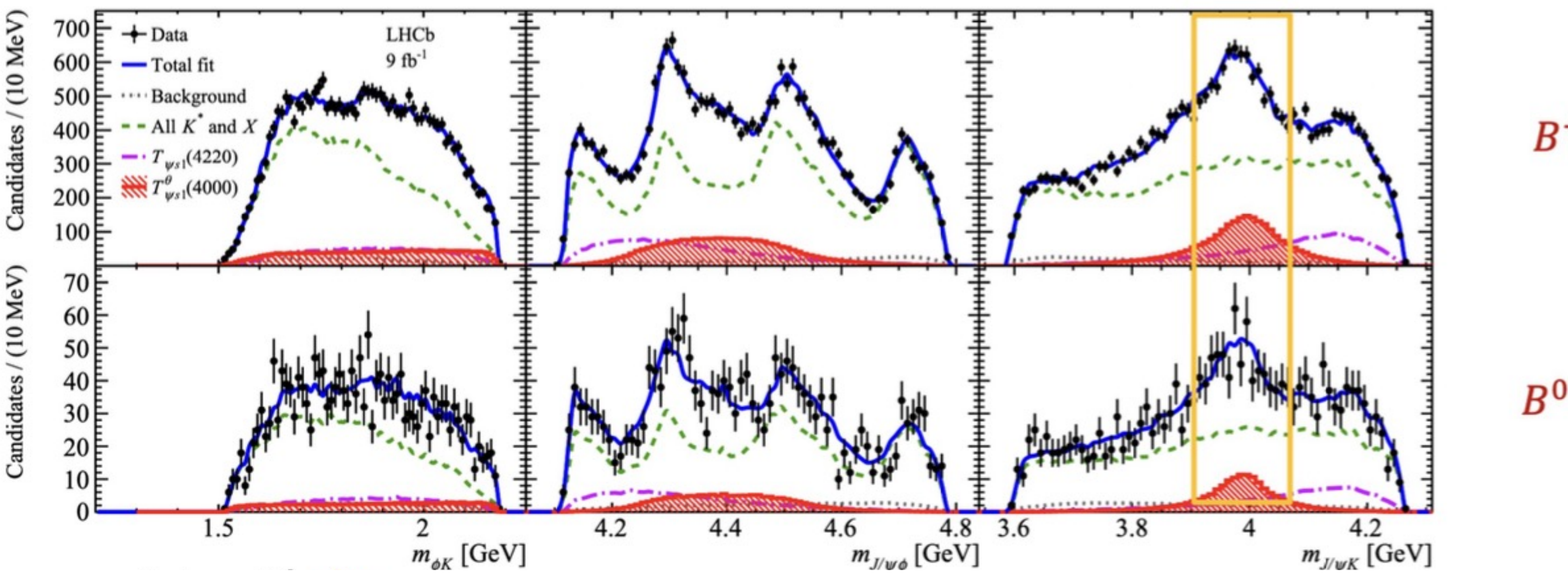


# Evidence of $T^{\theta}_{\psi s1}(4000)$

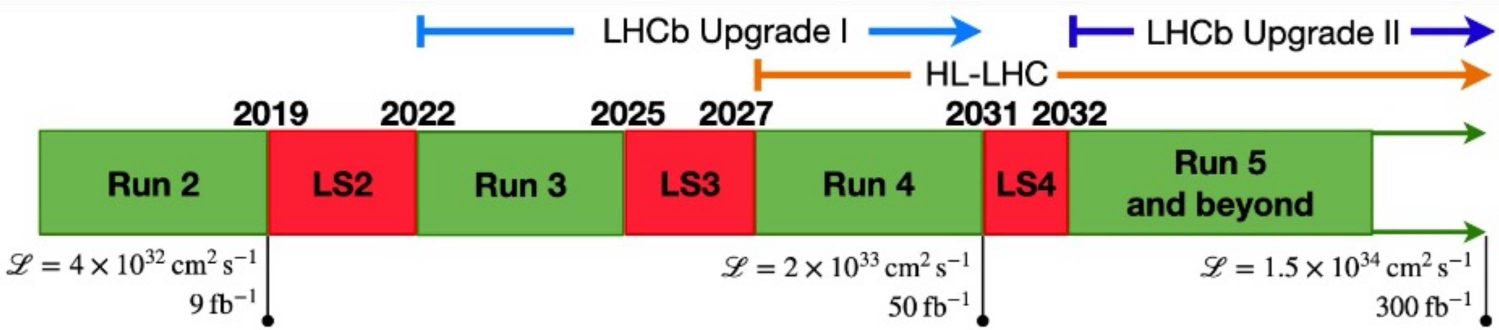
[arXiv: 2301.04899]

- Joint fit with $B^+$ and $B^0$ channels




- Joint Evidence for new tetraquark state with $4\sigma$

# Summary and Prospects




- **Some recent interesting results presented:**
  - Charmonia decaying to $K_s K\pi$
  - New excited $\Omega_c^0, \Xi_b^0$ states
  - Amplitude analysis of $D_{(s)}^{+} \to \pi\pi\pi$
  - Evidence of $T_{\psi s1}^{\theta}(4000)^0$
- **Larger statistics in Run 3 boosts hadron spectroscopy studies:**
  - Search for more conventional excited states
  - The evidence of hadrons to be confirmed
  - To confirm the observed multiquark states in other channel, e.g.: $P_c^+$ in $\Lambda_b^0 \to J/\psi p\pi$
  - Study $J^P$ and other properties of multiquark states
  - ……

# Backup

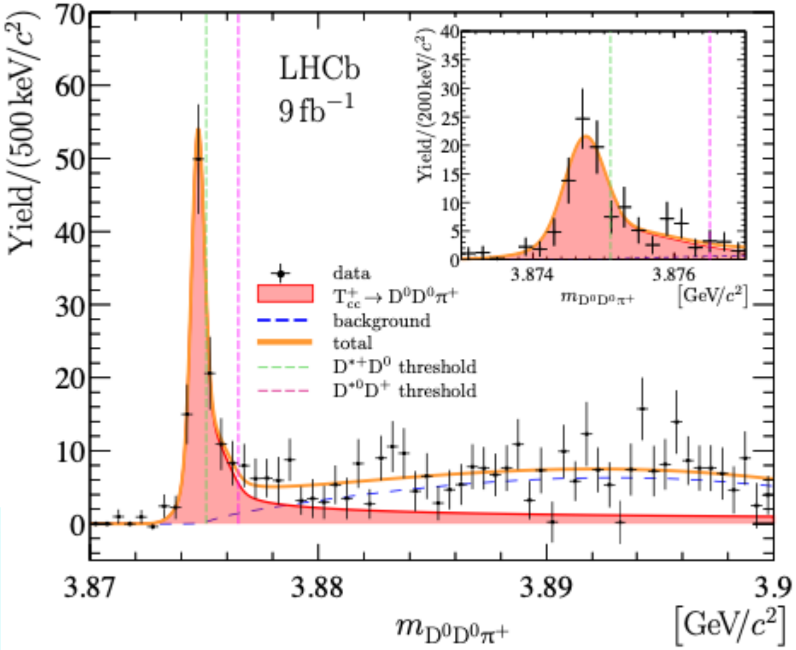
Thanks for your attention

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

[arXiv: 2019. 01038]
[arXiv: 2019. 01056]

- First observation of same-sign doubly charmed tetraquark $T_{cc}^{+}$
- Very narrow state in $D^0D^0\pi^+$ mass spectrum
- Manifestly exotic with quark content $cc\bar{u}\bar{d}$
- Mass ~ 3875 MeV, very close to the $D^{*+}D^0$ threshold

$$\delta m_{\rm BW} = -273 \pm 61({\rm stat}) \pm 5({\rm syst})^{+11}_{-14}({\rm model})\ {\rm keV}$$
$$\Gamma = 410 \pm 65({\rm stat}) \pm 43({\rm syst})^{+18}_{-38}({\rm model})\ {\rm keV}$$

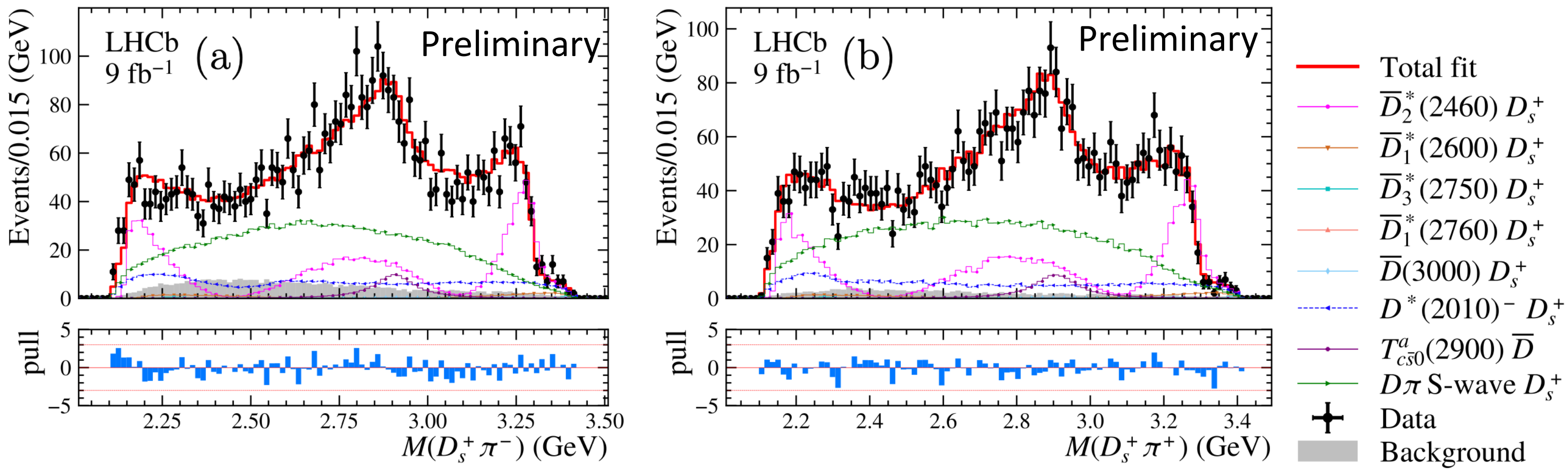



- Consistent with isoscalar $J^P = 1^+$
- No hint of possible $T^0$, $T^{++}$ isospin partners

# Dalitz fit with $T^{a}_{c\bar{s}0}(2900)^{0/++}$

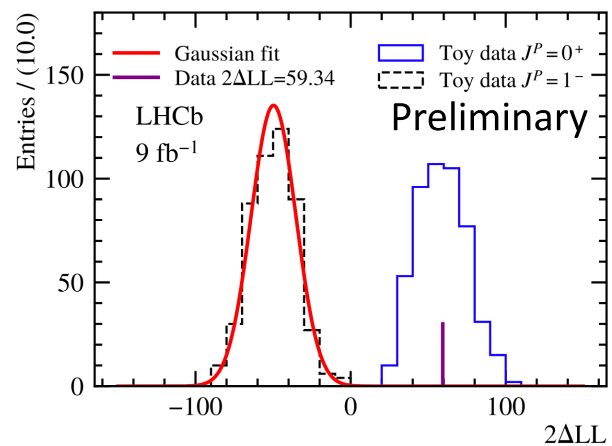
[LHCb-PAPER-2022-026]

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



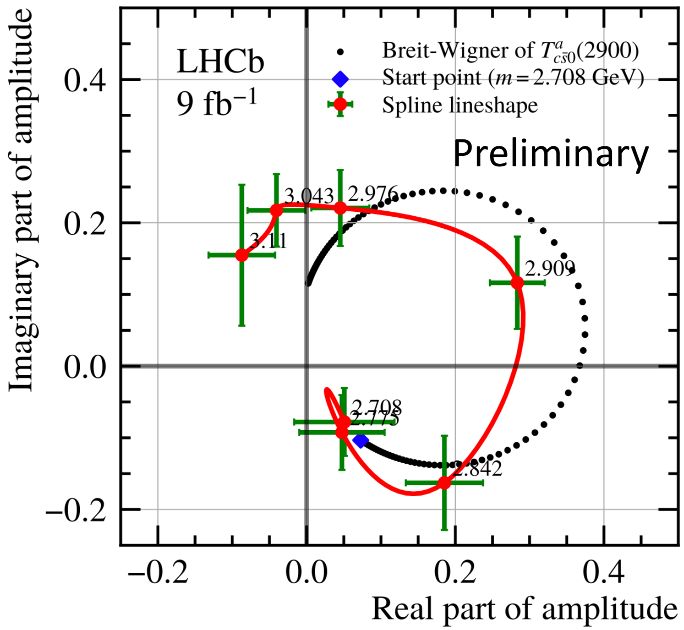

- The fit greatly improved;
- Significance of $T^{a}_{c\bar{s}0}(2900)^{0/++}$ >9$\sigma$
- Strong preference for $J^P$ as $0^+$ (>7$\sigma$)
- Mass and width are measured

$$M = 2.908 \pm 0.011 \pm 0.020\,\text{GeV and}$$
$$\Gamma = 0.136 \pm 0.023 \pm 0.011\,\text{GeV},$$



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

[LHCb-PAPER-2022-026]

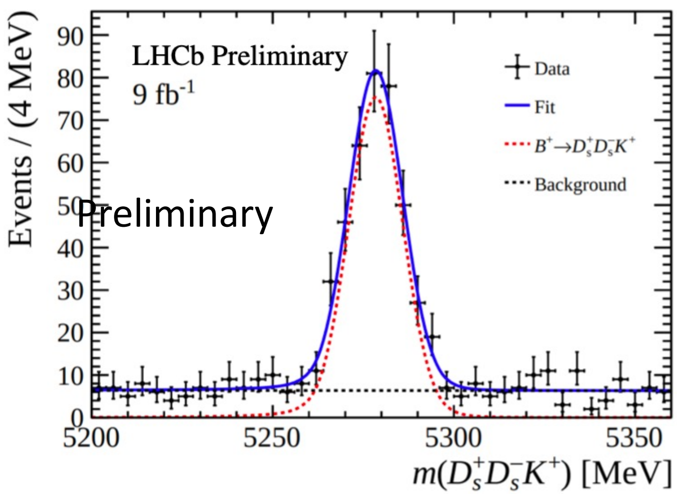



- The fit using seven spline points to describe $T^{a}_{c\bar{s}0}(2900)^{0/++}$ lineshape;
- Consistent with Breit-Wigner lineshape, further supports the resonant character

# $B^+ \to D_s^+ D_s^- K^+$ at LHCb

[LHCb-PAPER-2022-018, LHCb-PAPER-2022-019]

- Motivation:
  - $B^+ \to D_s^+ D_s^- K^+$ has not been observed previously
  - $\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)$ allows to estimate partial width of $X$ near threshold [arXiv: 1602.08421]
  - Also search for other exotics
- Signal reconstruction using LHCb Run 1+2 dataset;
  - $B^+$ yield ~360 candidates with 84.4% purity

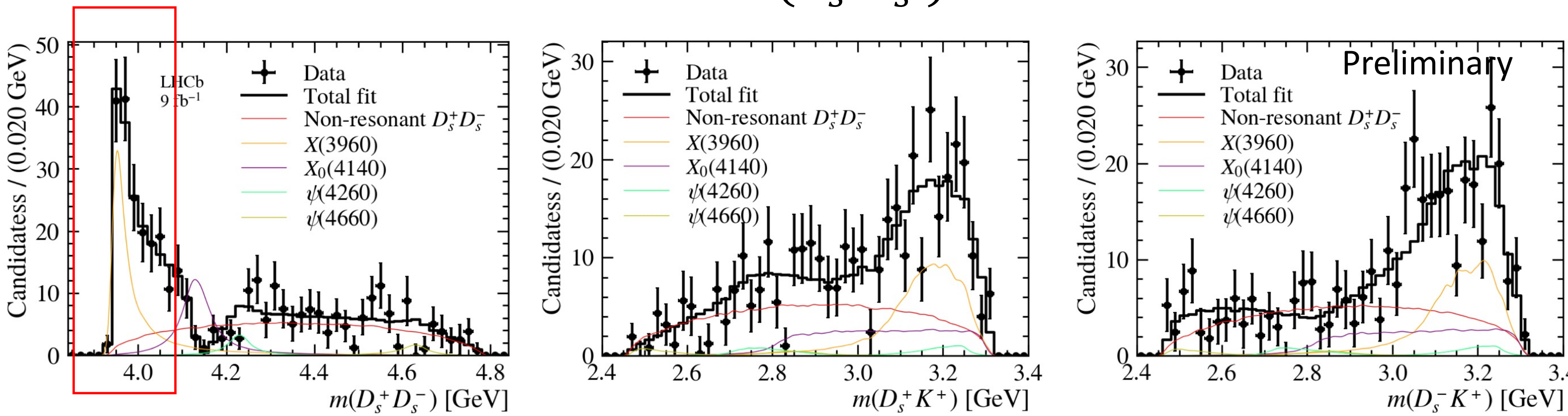



- Dalitz plot analysis to understand the resonance structure

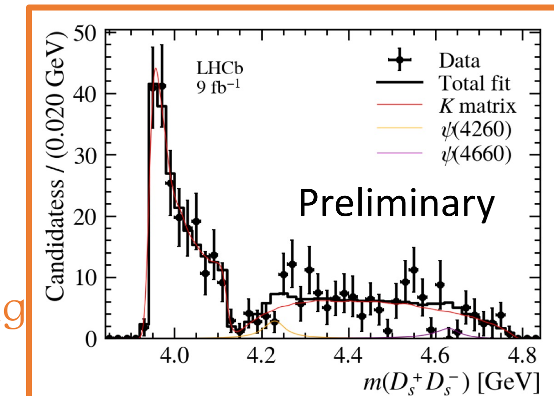
# Dalitz analysis

[LHCb-PAPER-2022-018, LHCb-PAPER-2022-019]

- Near-threshold enhancement in $m(D_s^+ D_s^-)$




- Baseline model well describes data
  - $0^{++}$: $X(3960)$, $X(4140)$ and NR; $1^{--}$: $\psi(4260)$ and $\psi(4660)$
- $X(3960)$:
  - Significance $> 12\sigma$
  - $J^{PC} = 0^{++}$ preferred over $1^{--}$ and $2^{++}$ ($> 9\sigma$)
- $X(4140)$:
  - $J^{PC} = 0^{++}$ preferred over $1^{--}$ and $2^{++}$ ($> 3\sigma$)
  - The dip can also described by $J/\psi \to D_s^+ D_s^-$ scattering



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

[LHCb-PAPER-2022-018, LHCb-PAPER-2022-019]

| | $M$ [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 particles?
  - Latest Lattice QCD shows the enhancement near the threshold of $D_s^+ D_s^-$ due to the presence of $X(3930)$ [arXiv: 2207.08490]

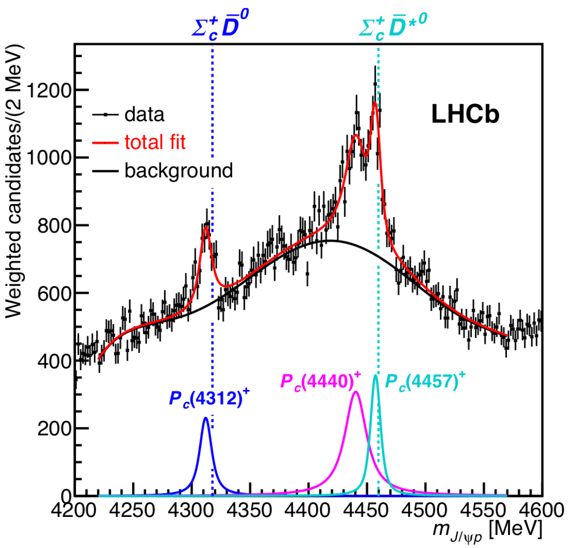
$$\frac{\Gamma(X \to D^+D^-)}{\Gamma(X \to D_s^+D_s^-)} = \frac{\mathcal{B}(B^+ \to D^+D^-K^+) \times \mathcal{FF}^X_{B^+ \to D^+D^-K^+}}{\mathcal{B}(B^+ \to D_s^+D_s^-K^+) \times \mathcal{FF}^X_{B^+ \to D_s^+D_s^-K^+}} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$$

  - $X$ has an exotic nature: creation of $s\bar{s}$ from vacuum is suppressed wrt. $u\bar{u}$ and $d\bar{d}$; $X \to D_s^+ D_s^-$ has smaller phase-space than $X \to D^+D^-$

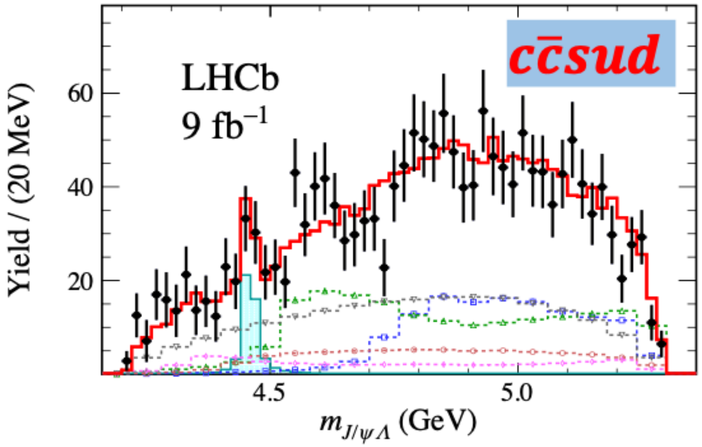
- Different particles?
  - No obvious candidate within conventional multiplets for them; likely to be exotic

# Motivation of searching for $P_{\psi s}^{\Lambda}$ in $B^- \to J/\psi\Lambda\bar{p}$

- Pentaquark seen at LHCb often noted to be close to charm-hadron threshold




$P_{\psi}^{\mathrm{N}}$ **in** $\Lambda_b^0 \to J/\psi pK$ [PRL 122 (2019) 222001]




Evidence of $P_{\psi s}^{\Lambda}$ **in** $\Xi_b^- \to J/\psi\Lambda K^-$ [Sci.Bull.66(2021) 1278]

- $B^- \to J/\psi\Lambda\bar{p}$ allows to search near threshold of $\Xi_c D^-$, $\Lambda_c^+ D_s^-$ and $\Lambda_c^+ D^0$
- $P_{\psi s}^{\Lambda}$ predicted in hadronic molecules model

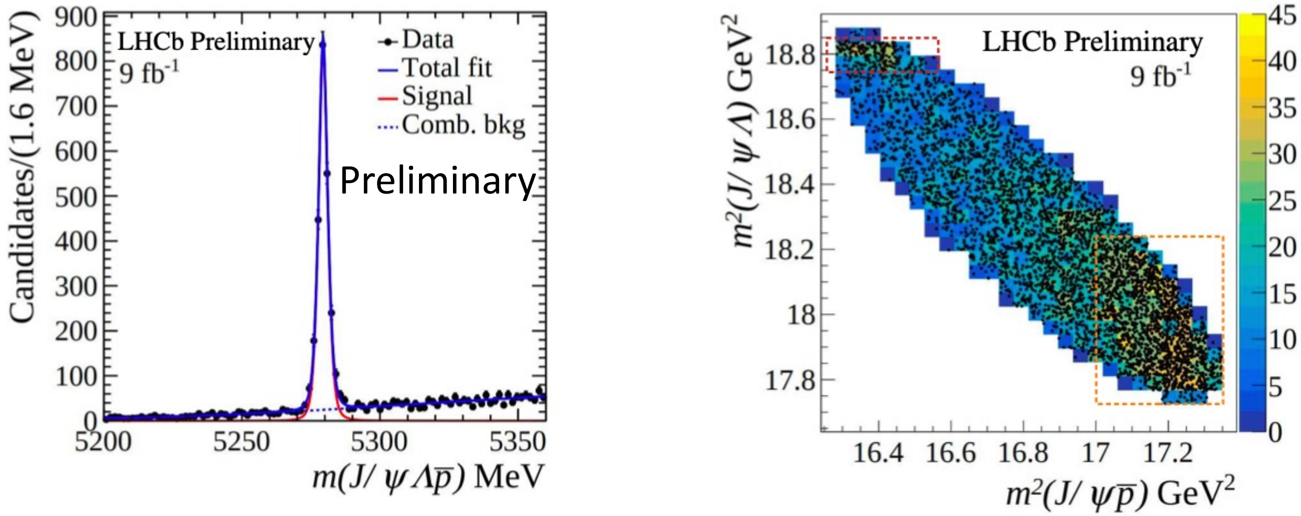
[Progr.Phys.41(2021) 65-93]

# $B^- \to J/\psi\Lambda\bar{p}$ signals

[LHCb-PAPER-2022-031]

- $B^-$ yield ~4617 with 93% purity using Run 1+2 data
- Most precise measurement of $B^-$ mass:

$$m_{B^+} = 5279.44 \pm 0.05(stat.) \pm 0.07(syst.)\ \mathrm{MeV}/c^2$$

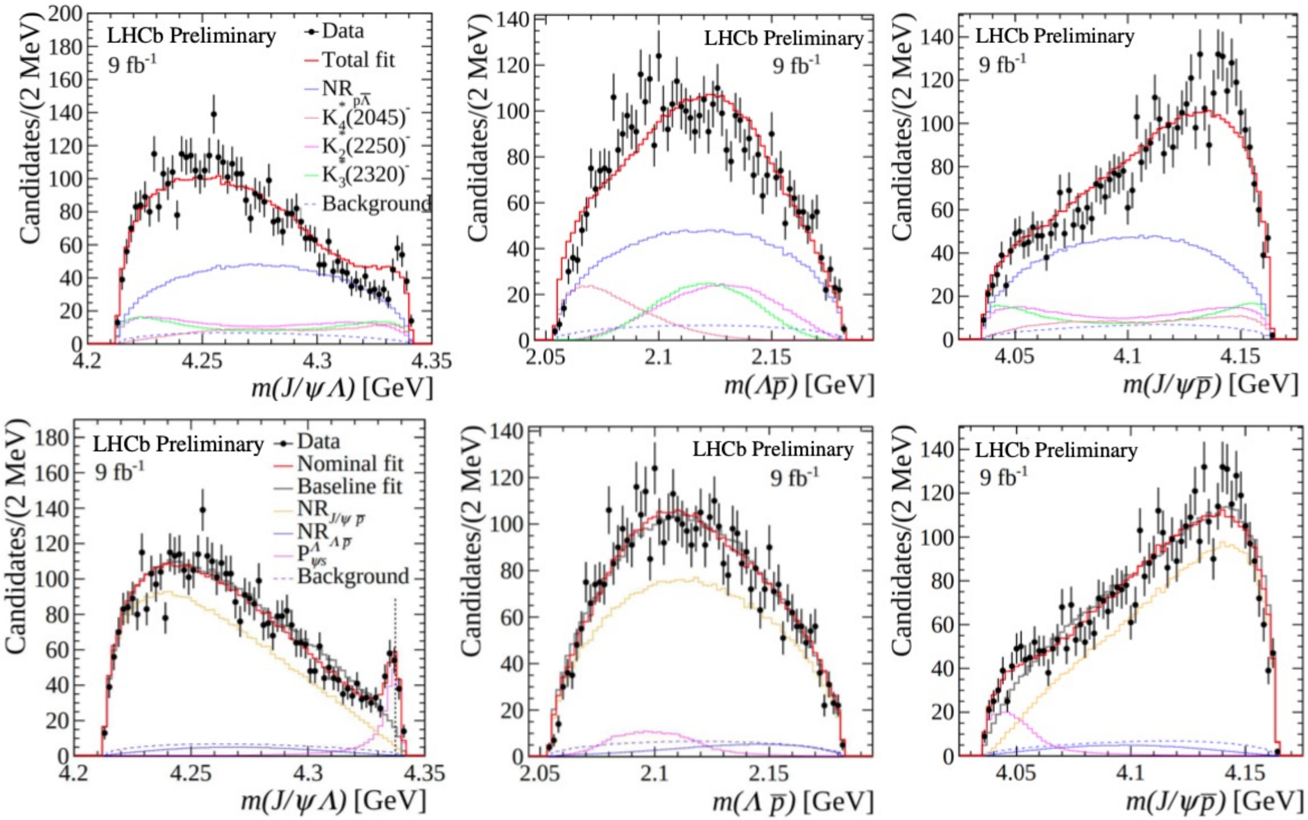



- Narrow structure in $J/\psi\Lambda$; broad structure in $J/\psi\bar{p}$
- Dalitz analysis needed to determine its resonance structure

# Dalitz fit



- $K^*$ model: $K^*_{2,3,4}$ and NR($\Lambda\bar{p}$)
- Nominal model: NR($\Lambda\bar{p}$), NR($J/\psi\bar{p}$) and $P^{\Lambda}_{\psi s}$




$K^*$ model

Nominal model

- $K^*$ model cannot describe data well
- $P^{\Lambda}_{\psi s}$ improve the fit NNL significantly

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

[LHCb-PAPER-2022-031]

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

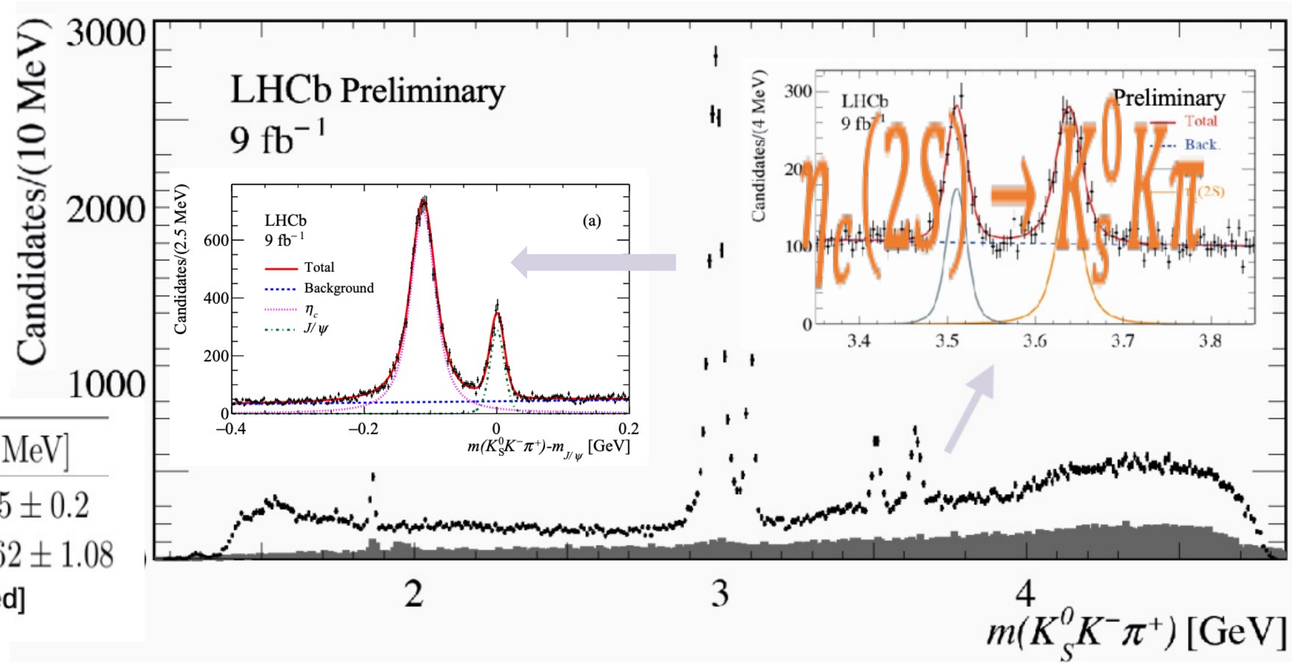
$$M(P_{\psi s}^{\Lambda}) = 4338.2 \pm 0.7 \pm 0.4 \text{ MeV}$$
$$\Gamma(P_{\psi s}^{\Lambda}) = 7.0 \pm 1.2 \pm 1.3 \text{ MeV}$$

- 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

# Charmonia decaying to $K_s K\pi$

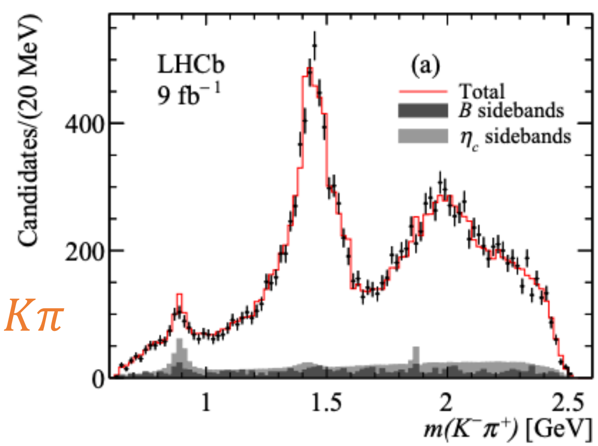
[arXiv:2304.14891]

- New precision measurement of $\eta_c$, $\eta_c(2S)$

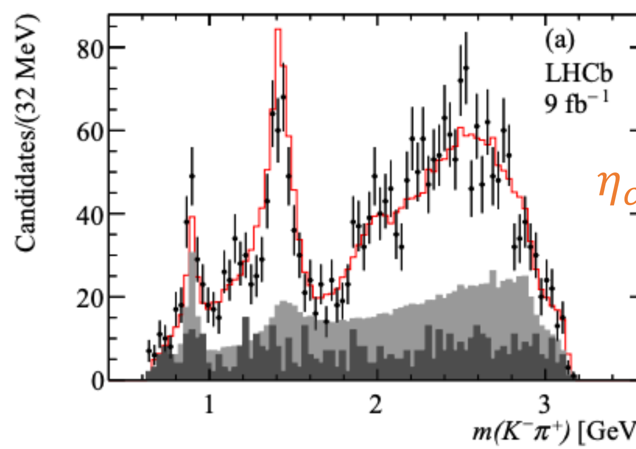



| | Mass [MeV] | Width [MeV] |
|---|---|---|
| $\eta_c$ | $2985.01 \pm 0.17 \pm 0.89$ | $29.7 \pm 0.5 \pm 0.2$ |
| $\eta_c(2S)$ | $3637.90 \pm 0.54 \pm 1.40$ | $10.77 \pm 1.62 \pm 1.08$ |
| $\chi_{c1}$ | $3509.84 \pm 0.69 \pm 0.64$ | [fixed] |

- Dalitz analyses of $\eta_c$, $\eta_c(2S)$ decays provide information on kaon spectroscopy




$\eta_c \to K^0_S K\pi$




$\eta_c(2S) \to K^0_S K\pi$