



# Excited charm hadron spectroscopy at LHCb

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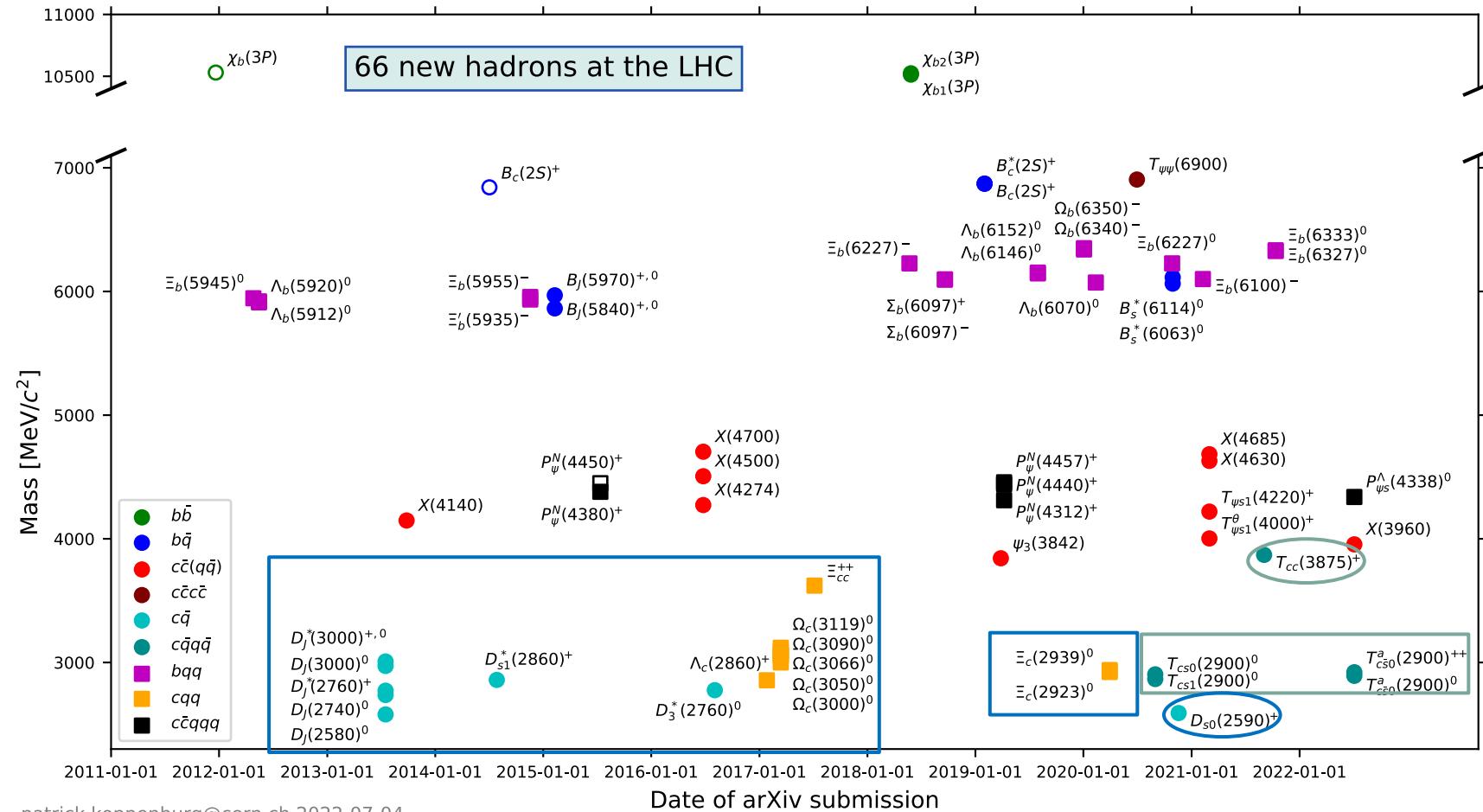
(On behalf of the LHCb collaboration)



9 July 2022

# Hadron spectroscopy @LHC

- 66 new hadrons at LHC, of which 59 from LHCb



- 22 open charm hadrons
  - 17 conventional states
    - Testing ground for potential models and lattice-QCD calculations
  - 5 exotic hadrons
    - Inner structure of great interest
  - Exciting news!
    - $c\bar{s}u\bar{d}$  and  $c\bar{s}\bar{u}d$  tetraquarks
    - $T_{c\bar{s}0}^a(2900)^{++/0}$

This talk focuses on recent results of conventional charm resonances

# Charm spectroscopy in exclusive b-hadron decays



- Many newly observed channels have the potential for charm spectroscopy
  - $\Lambda_b^0 \rightarrow D^0 p K^-$ ,  $\Lambda_b^0 \rightarrow D^{(*)+} p \pi^- \pi^-$
  - $B_{(s)}^0 \rightarrow \bar{D}^{*0} K^+ \pi^-$ ,  $B^+ \rightarrow D_s^+ D_s^- K^+$ ,  $B^{+/0} \rightarrow \bar{D}^{-/0} D_s^+ \pi^{+/-}$  See [Sophie's](#) and [Ruiting's](#) talks
  - Intermediate charm resonances to be investigated in future
- Topics in this talk:
  - $D_{s0}(2590)^+ \rightarrow D^+ K^+ \pi^-$  in  $B^0 \rightarrow D^- D^+ K^+ \pi^-$  [Phys. Rev. Lett. 126 \(2021\) 122002](#)
  - $\Omega_c^{**0} \rightarrow \Xi_c^+ K^-$  in  $\Omega_b^- \rightarrow \Xi_c^+ K^- \pi^-$  [Phys. Rev. D 104 \(2021\) L091102](#)

# LHCb detector

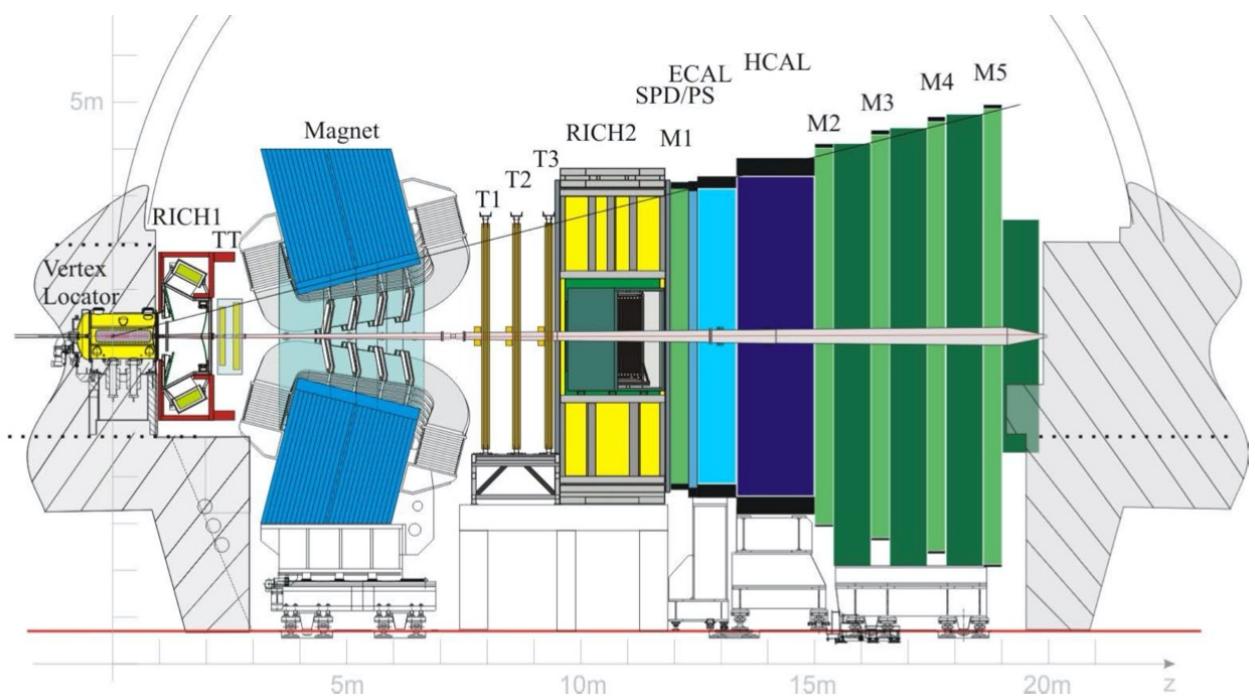
JINST 3 (2008) S08005, Int.J.Mod.Phys. A30 (2015) 1530022



- **LHCb detector:** Single arm and forward design:  $2 < \eta < 5$

- Powerful particle-ID
  - $\epsilon(K \rightarrow K) \sim 95\%$  mis-ID  $\epsilon(\pi \rightarrow K) \sim 5$
- High momentum resolution
  - $\Delta p/p = 0.4 \sim 0.6\% (5 - 100\text{GeV}/c)$
- High mass resolution
  - $\sigma_m \sim 10\text{MeV}$  for  $B \rightarrow D\bar{D}K$  ( $m_D$  constrained)
- High vertex resolution
  - $\sigma_{IP} = 20\mu\text{m}$

- ✓ Large sample of  $b$  hadrons
  - ✓ Excellent performance to reconstruct exclusive  $b$ -hadron decays
- > Enable the detailed investigation of intermediate charm resonances

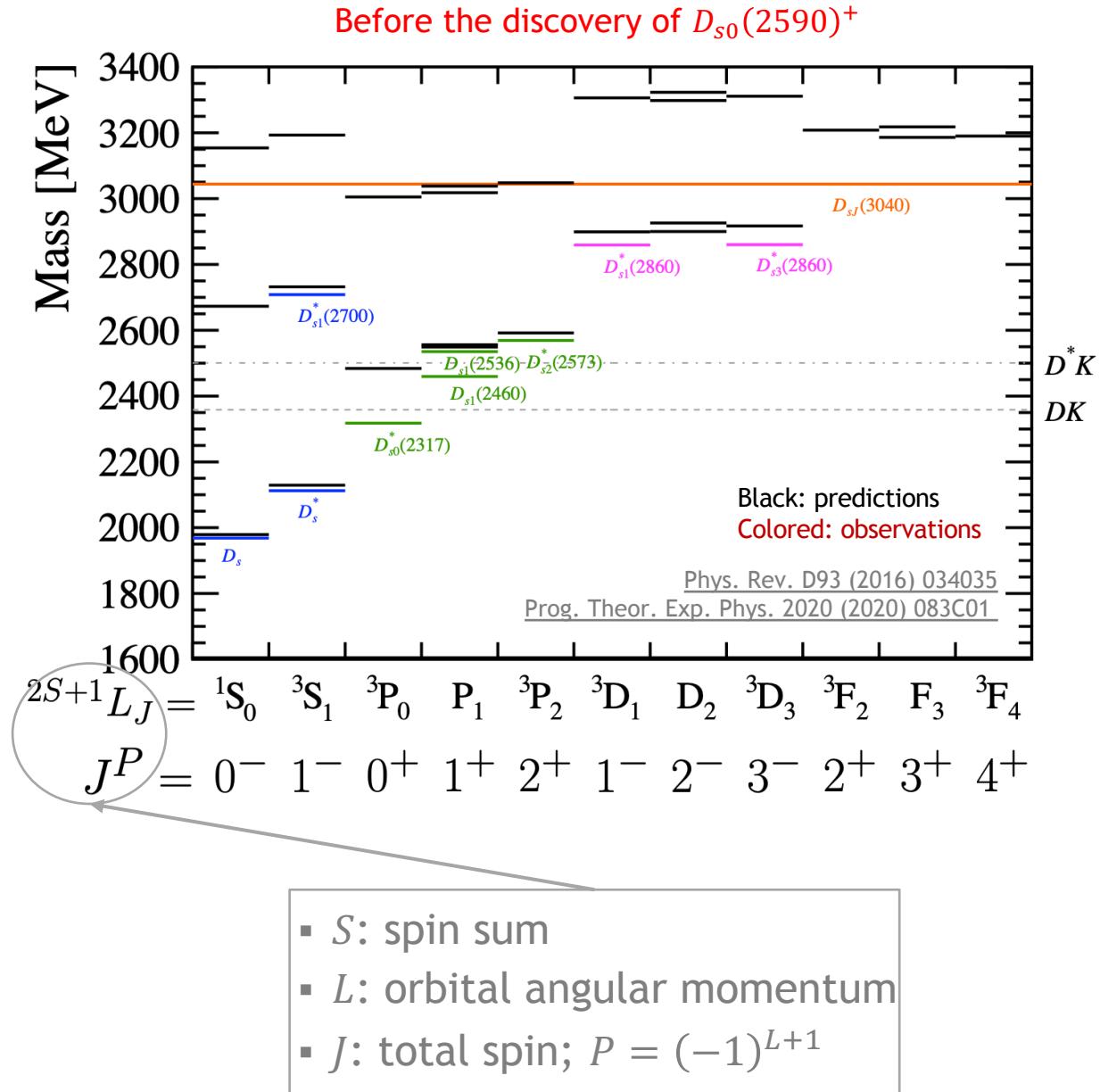


# Observation of $D_{s0}(2590)^+$ in $B^0 \rightarrow D^- D^+ K^+ \pi^-$

Phys. Rev. Lett. 126 (2021) 122002



# Previous story about $D_s^+$ spectroscopy



- 10 mesons observed

- $D_{sJ}(3040)$ :  $J^P$  undetermined
- $D_{s0}^*(2317)$  &  $D_{s1}(2460)$  puzzle:
  - Mass far below prediction
  - Inner structure unclear
    - $c\bar{s}q\bar{q}$  tetraquark?
    - $DK/D^*K$  molecular?

Eur. Phys. J. C, 2017, 77(3)

- Six states undiscovered below 3.1 GeV

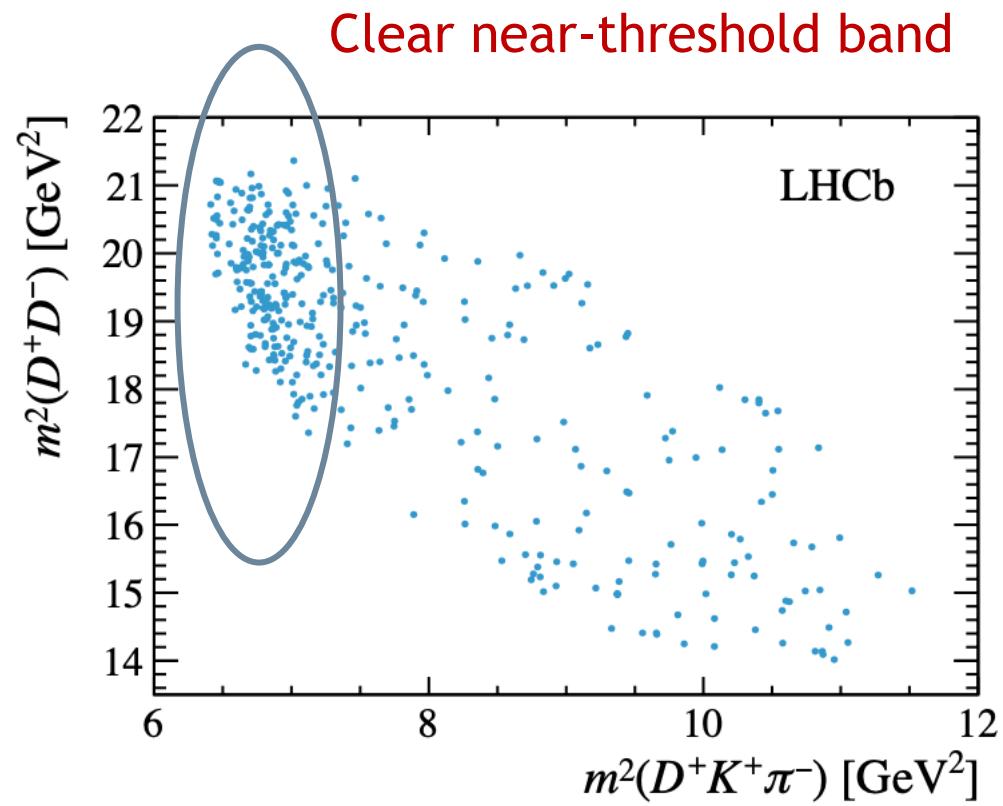
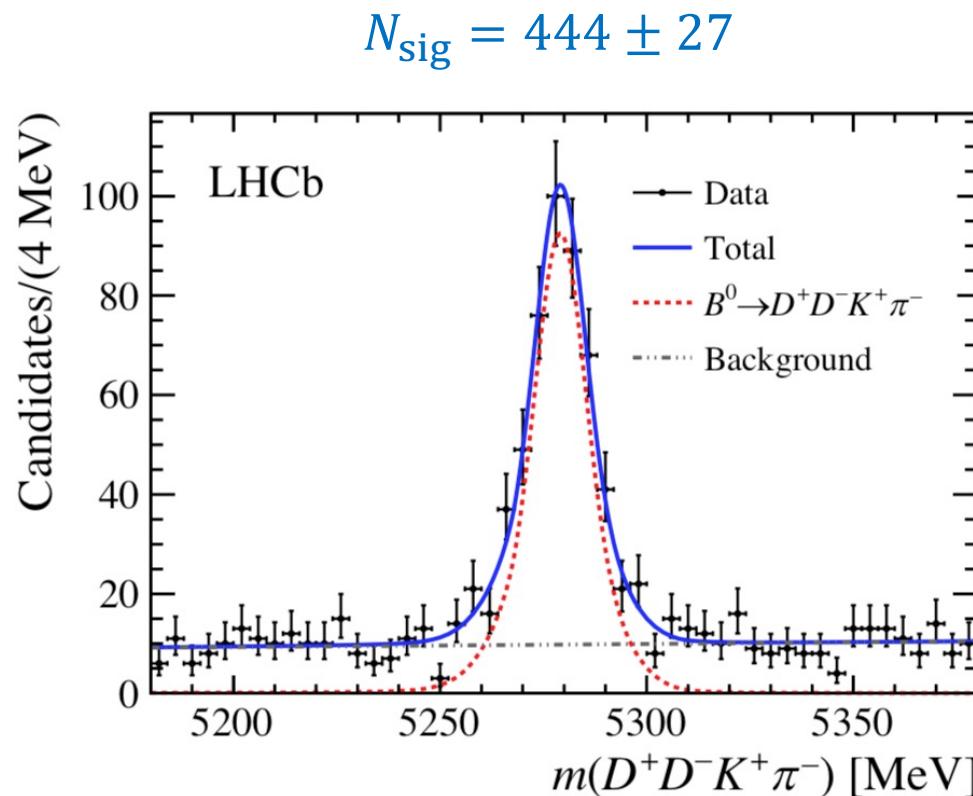
- $2^1S_0$ : ~2.6 GeV
- $1^1D_2, 1^3D_2$ : ~2.86 GeV
- $2^3P_0, 2^1P_1, 2^3P_2$ : ~3 GeV
- Can be searched for in  $D^+K^+\pi^-$  system
  - Three-body system was rarely touched before
  - $K^*(892)^0 \rightarrow K^+\pi^-$ :  $m(D_s^+) > 2.76$  GeV;  $J^P \neq 0^+$
  - $K^+\pi^-$  S-wave:  $m(D_s^+) > 2.53$  GeV;  $J^P = 0^-, 1^+, 2^-, \dots$

# $B^0 \rightarrow D^- D^+ K^+ \pi^-$ dataset

Phys. Rev. Lett. 126 (2021) 122002



- $\mathcal{L} = 5.4 \text{ fb}^{-1}$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $m(K^+ \pi^-) < 0.75 \text{ GeV}$ 
  - To avoid the interference of messy structures at higher mass



# Amplitude analysis

- Helicity formalism

- Components:

- $D^+K^+\pi^-$ :  $1^+ D_{s1}(2536)^+$ ;  $0^- \text{NR}_{D^+K^+\pi^-}$ ;  
a new  $D_s^+$  ( $J^P = 0^-, 1^+, 2^-, \dots$ )
- $K^+\pi^-$ : S-wave, modelled by  $K_0^*(700)^0$

- Properties of the new  $D_s^+$ :

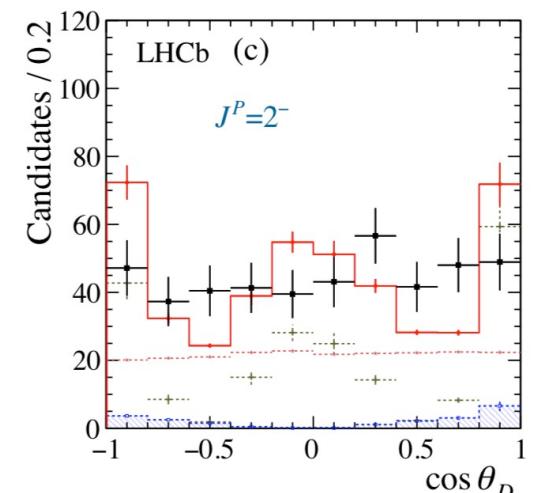
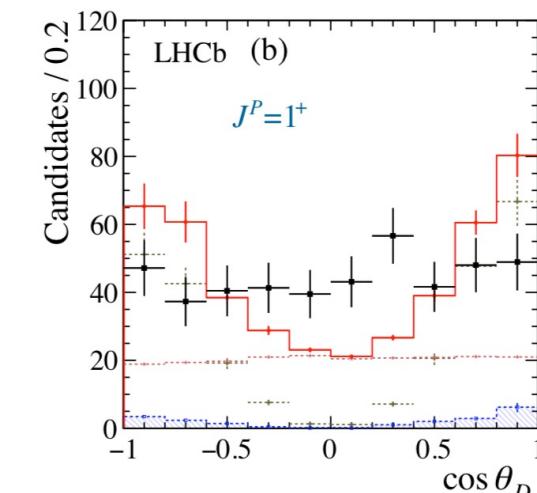
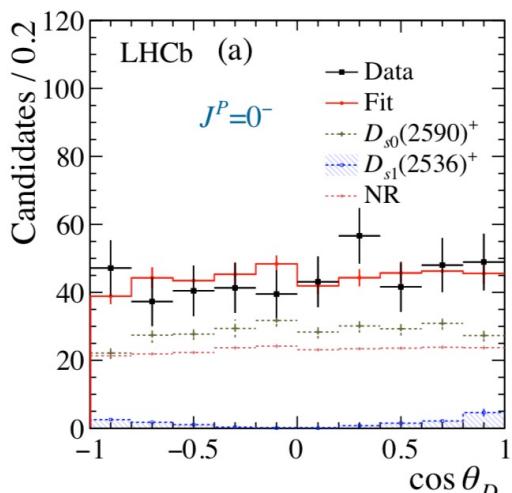
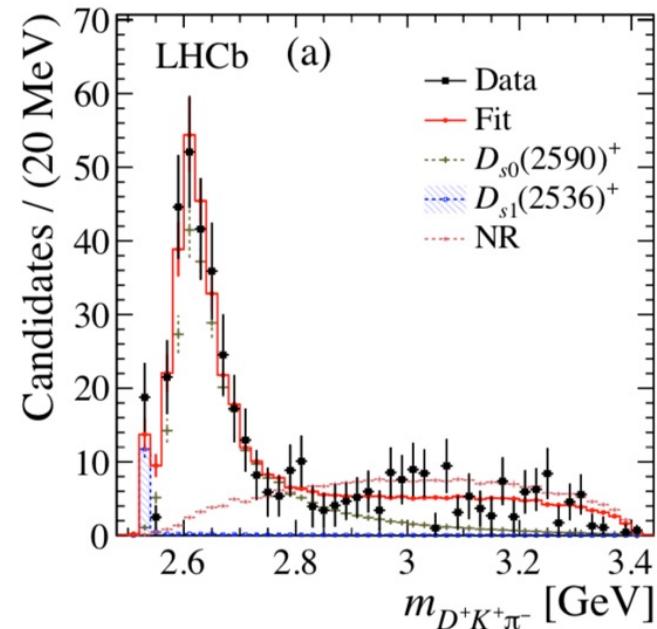
- $> 10\sigma$
- $J^P = 0^-$   
( $1^+$  &  $2^-$  rejected by  $> 10\sigma$ )

- Pole parameters:

- $m_R = 2591 \pm 6 \pm 7 \text{ MeV}$
- $\Gamma_R = 89 \pm 16 \pm 12 \text{ MeV}$

$D_{s0}(2590)^+$

Phys. Rev. Lett. 126 (2021) 122002



# $D_{s0}(2590)^+$ in $D_s^+$ spectroscopy

Phys. Rev. Lett. 126 (2021) 122002

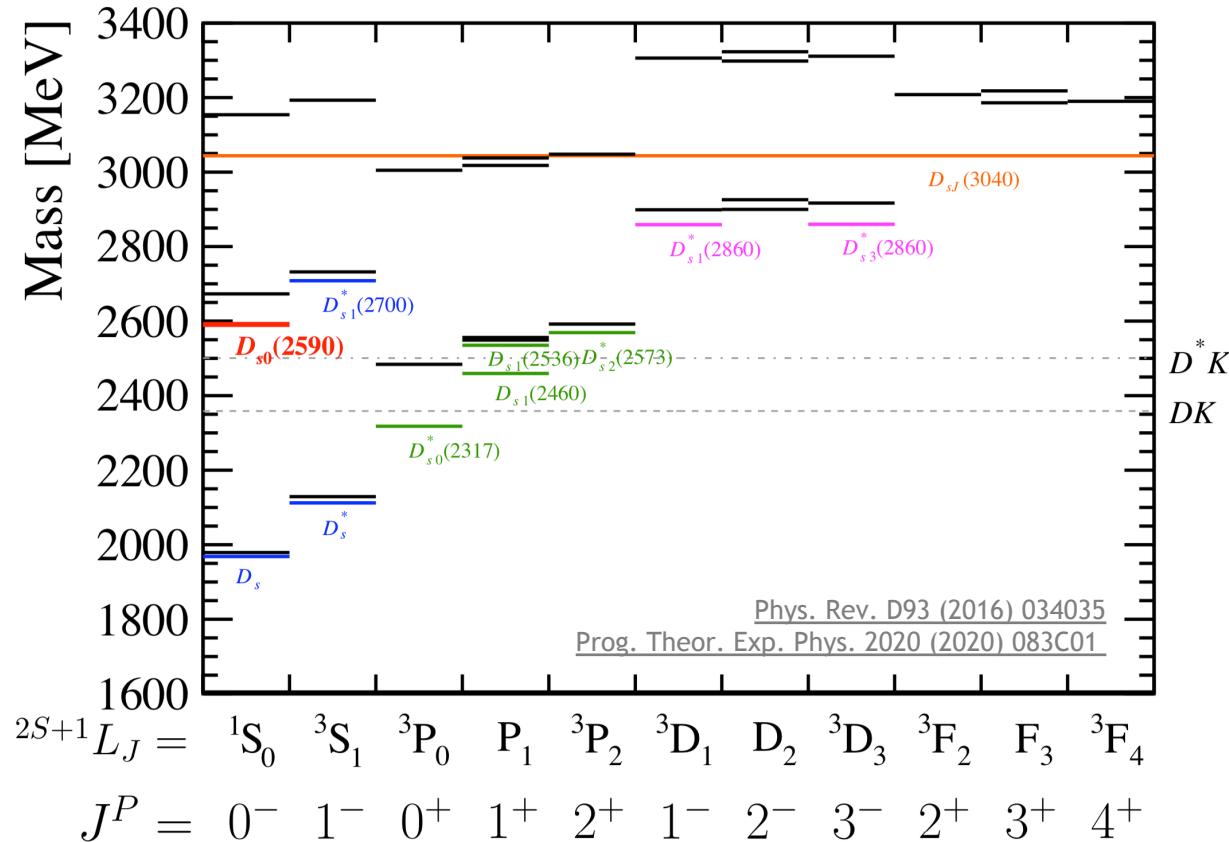


A strong candidate for  $D_s(2^1S_0)^+$ , the radial excitation of the ground-state  $D_s^+$  meson

Large discrepancy is seen in the  $D_{s0}(2590)^+$  mass and the prediction

->  
Trigger the theoretical studies to interpret its nature  
[arXiv:2204.02649](https://arxiv.org/abs/2204.02649)

- ✓ Coupled channel effect?
  - ✓  $D^*K$ ,  $D_s^{(*)}\omega$ ,  $D_s^{(*)}\eta$



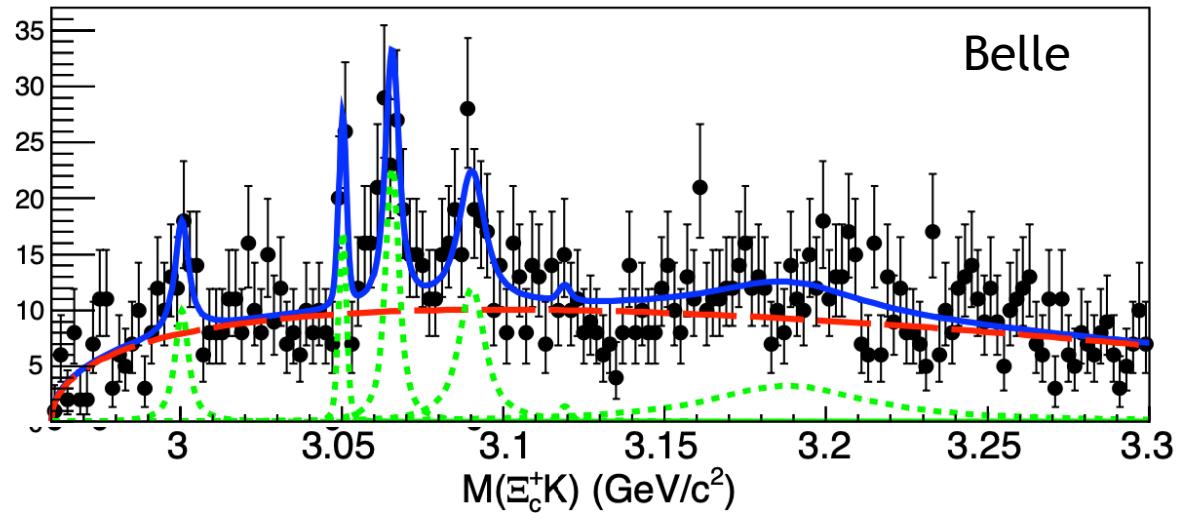
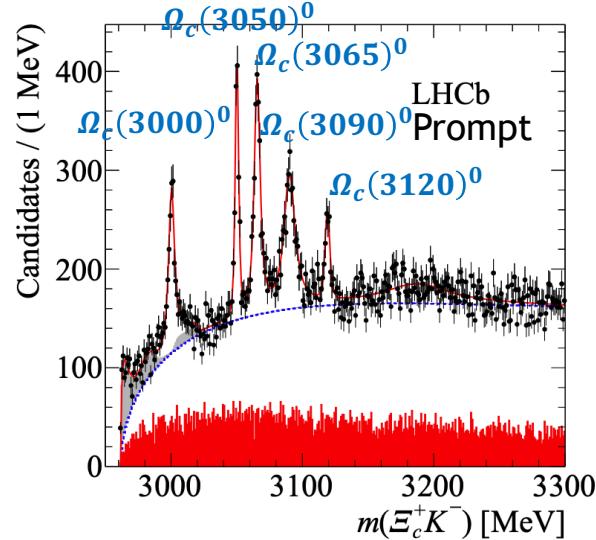
# Observation of $\Omega_c^{**0}$ baryons in $\Omega_b^- \rightarrow \Xi_c^+ K^- \pi^-$ decays

Phys. Rev. D 104 (2021) L091102



# Previous story about $\Omega_c^{**0}$

- Only ground-state  $\frac{1}{2}^+$   $\Omega_c^0$  and  $\frac{3}{2}^+$   $\Omega_c(2700)^0$  observed before 2017 [PDG2020](#)
- Five new  $\Omega_c^{**0}$  observed in prompt  $\Xi_c^+ K^-$  by LHCb in 2017 [Phys. Rev. Lett. 118 \(2017\) 18, 182001](#)
  - Four confirmed by Belle in 2018 [Phys. Rev. D97 \(2018\) 051102](#)



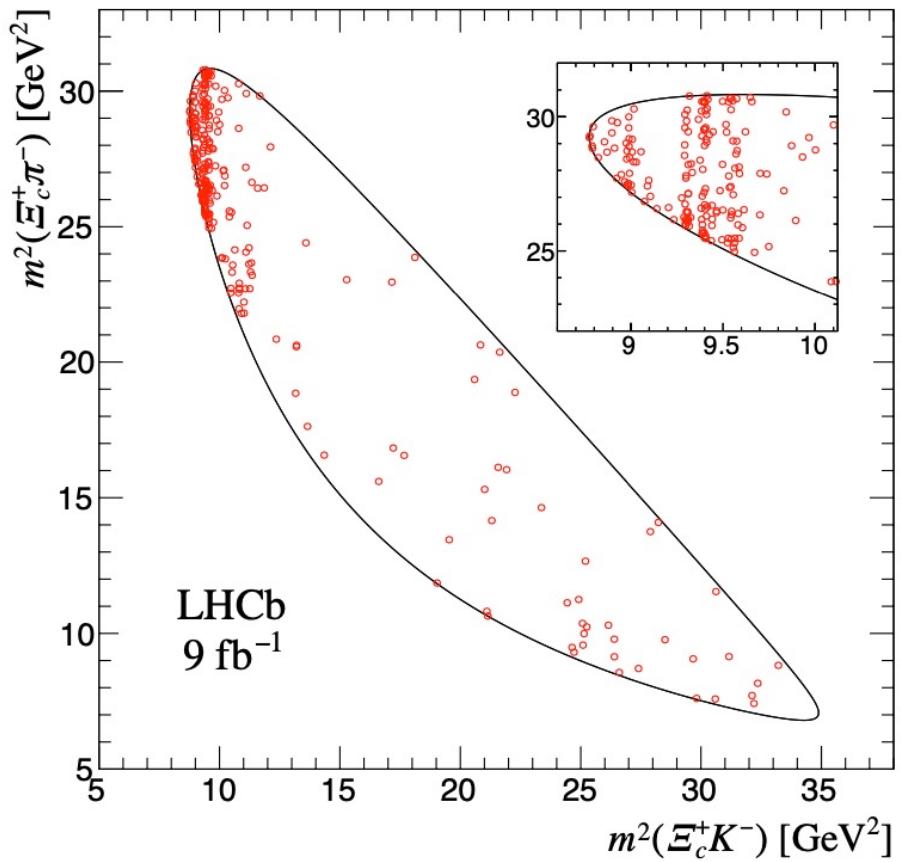
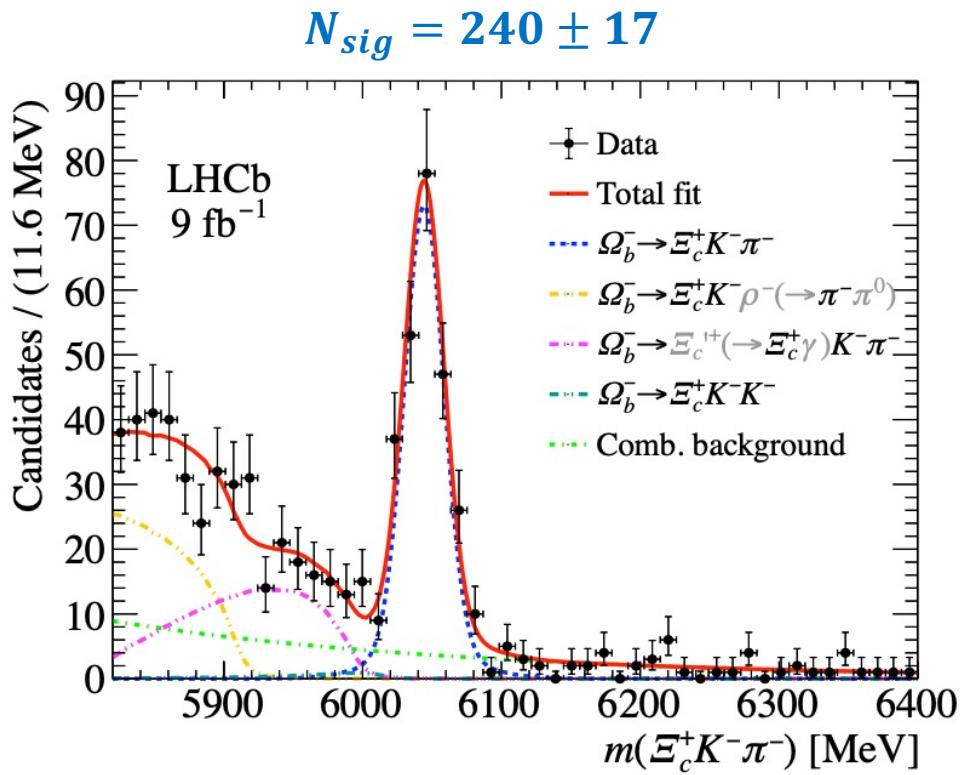
- Spin-parity undetermined
  - Could be measured in exclusive  $b$ -hadron decays  
-> additional information to help classify the new  $\Omega_c^{**0}$  in quark model

# First observation of $\Omega_b^- \rightarrow \Xi_c^+ K^- \pi^-$

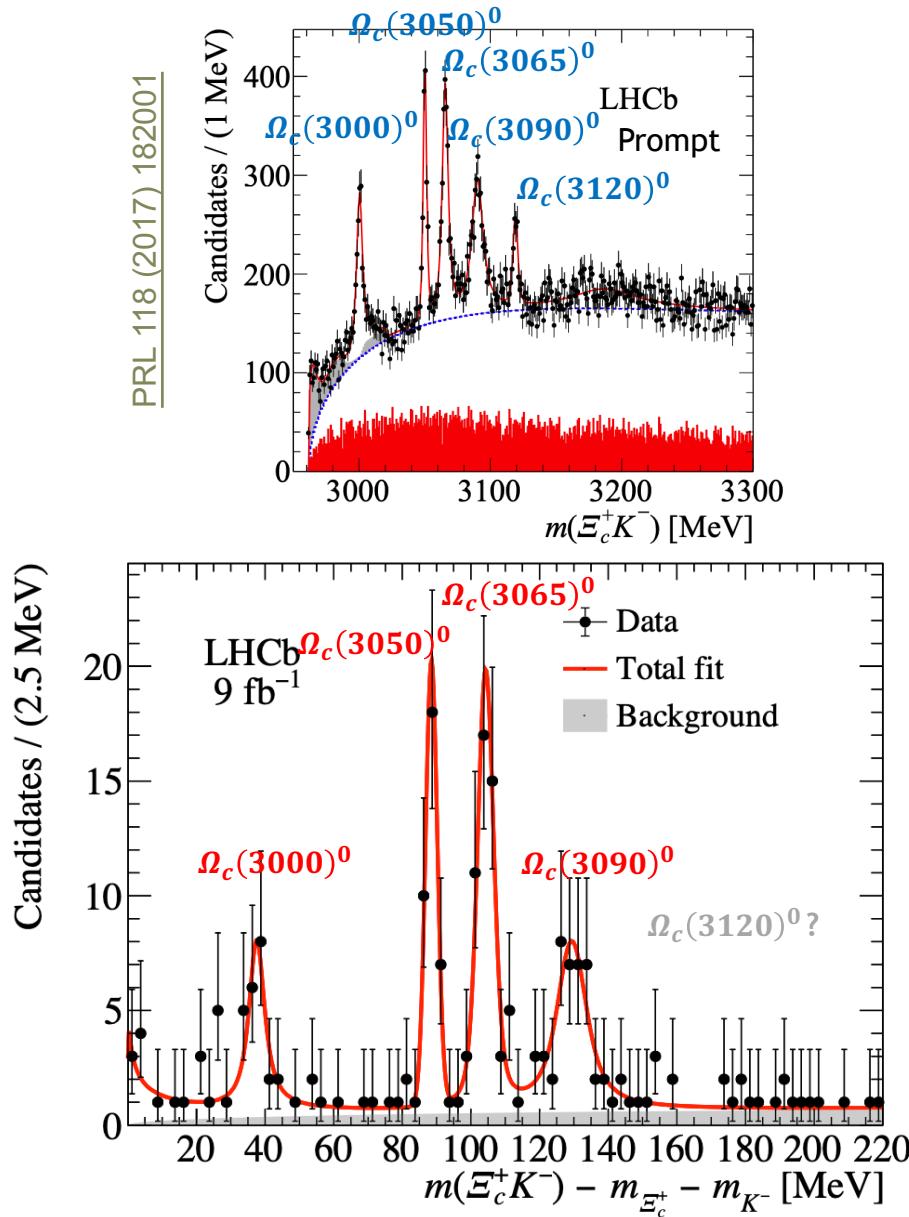
Phys. Rev. D 104 (2021) L091102



- $\mathcal{L} = 9 \text{ fb}^{-1}$
- $\Xi_c^+ \rightarrow p K^- \pi^+$



$$\Omega_c^{**0} \rightarrow \Xi_c^+ K^-$$



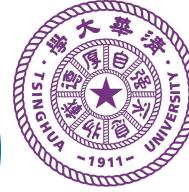
- **Re-observation:**  $\Omega_c(3000)^0$ ,  $\Omega_c(3050)^0$ ,  $\Omega_c(3065)^0$ ,  $\Omega_c(3090)^0$   
( $\Omega_c(3120)^0$  unobserved)
- **Interpretation of the threshold structure**
  - Prompt: feed down of partially reconstructed higher  $\Omega_c^{**0}$
  - $\Omega_b^-$  decay: new structures
    - partially reconstructed higher  $\Omega_c^{**0}$  is not possible as it will shift the  $\Omega_b^-$  mass away from its known value
- **Unbinned fit**
  - All resonances modelled by *S*-wave relativistic BW function
  - Significance of four states  $>6\sigma$
  - Near-threshold structure  $\sim 4.3\sigma$
  - Mass and width of each state are measured
    - Consistent with the results in the prompt study  
(Details seen in backup)

# Spin tests

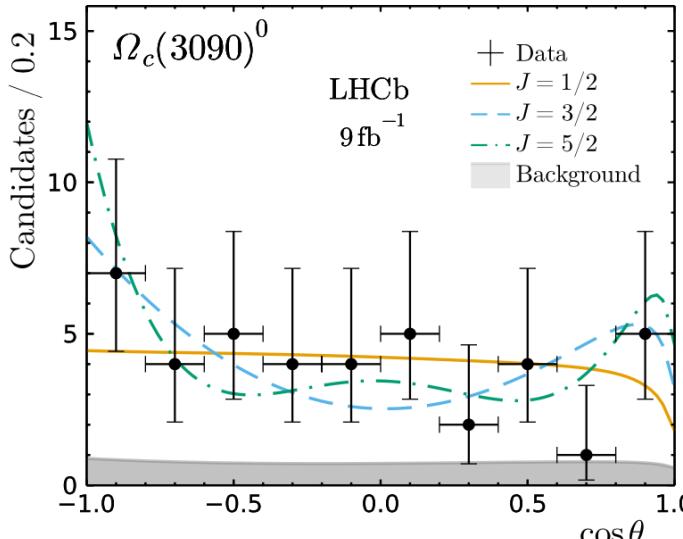
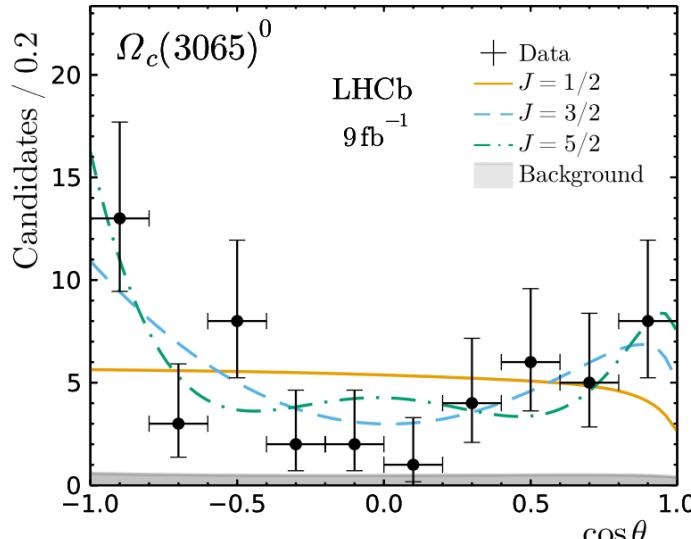
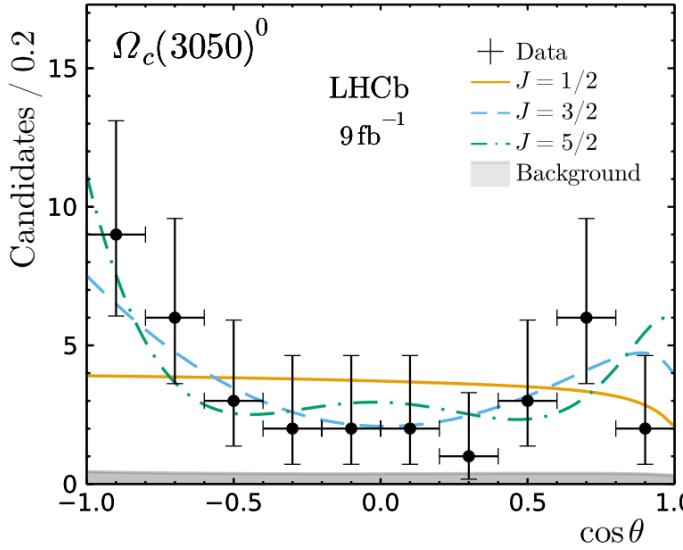
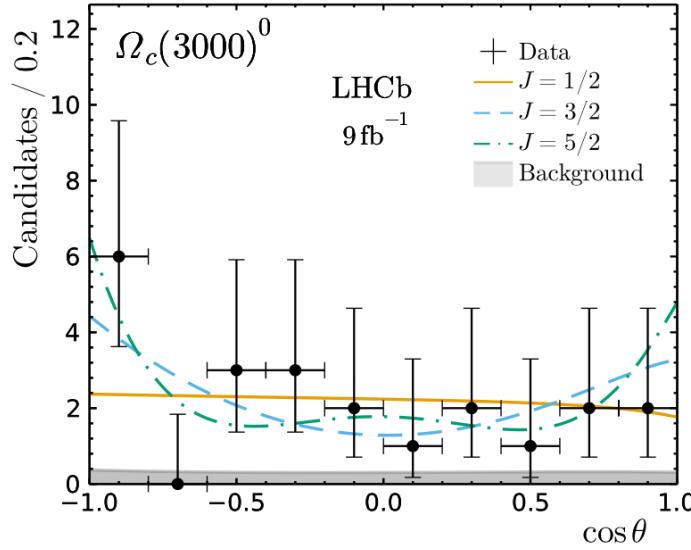
Helicity angle

$$I_J(\cos\theta) = \frac{(2J+1)}{2} \left( |d_{1/2,-1/2}^J(\cos\theta)|^2 + |d_{1/2,+1/2}^J(\cos\theta)|^2 \right)$$

[Phys. Rev. D 104 \(2021\) L091102](#)



LHCb  
LHCb



- $\Omega_c(3050)^0 \quad J \neq \frac{1}{2}: 2.2\sigma$

- $\Omega_c(3065)^0 \quad J \neq \frac{1}{2}: 3.6\sigma$

- A combined spin hypothesis of the four states:

- $(\frac{1}{2}, \frac{1}{2}, \frac{3}{2}, \frac{3}{2})$  rejected by  $3.5\sigma$

[Phys. Rev. Lett. 119, 042001](#)

[Phys. Rev. D 95, 114012](#)

[Eur. Phys. J. C 77 \(2017\) 325](#)



A grayscale photograph of a classical building facade with multiple columns and architectural details.

## Summary and prospects



# Summary and prospects

- Exclusive  $b$ -hadron decays: ideal platform for studies of charm hadron spectroscopy
  - Observation of  $D_{s0}(2590)^+$  in  $B^0 \rightarrow D^- D^+ K^+ \pi^-$  [Phys. Rev. Lett. 126 \(2021\) 122002](#)
    - $J^P = 0^-$ ; candidate for  $D_s(2^1S_0)$
  - Re-observation of four  $\Omega_c^{**0}$  in  $\Omega_b^- \rightarrow \Xi_c^+ K^- \pi^-$  [Phys. Rev. D 104 \(2021\) L091102](#)
    - $\Omega_c(3000)^0, \Omega_c(3050)^0, \Omega_c(3065)^0, \Omega_c(3090)^0$
    - Spin test:
      - $\Omega_c(3065)^0 \quad J \neq \frac{1}{2}: 3.6\sigma; \quad (\frac{1}{2}, \frac{1}{2}, \frac{3}{2}, \frac{3}{2})$  rejected by  $3.5\sigma$
- LHCb upgrades: [arXiv:1808.08865](#)
  - 7 $\times$  data by 2030 (14 $\times$  hadronic events)
  - Spin-parity determination using amplitude analysis
    - $\Omega_b^- \rightarrow \Xi_c^+ K^- \pi^-$
  - Search for new decay patterns of excited charm hadrons
    - $D_{s0}(2590)^+ \rightarrow D^* K; \Omega_c^{**0} \rightarrow \Xi_c^0 K^- \pi^+$
  - New resonances expected

LHC			LH-LHC	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2022-24)	Run 4 (2027-30)	Run 5+ (2031+)
$3 \text{ fb}^{-1}$	$6 \text{ fb}^{-1}$	$23 \text{ fb}^{-1}$	$46 \text{ fb}^{-1}$	$> 300 \text{ fb}^{-1} (?)$

Upgrade I      Upgrade Ib      Upgrade II

*Thank you for listening!*



# Backup slides



# Why studying charm hadron spectroscopy?



- Unique platform for understanding of low-energy QCD
  - Theoretical calculations generally easier than those for light hadrons
    - $m_c > \Lambda_{\text{QCD}}$ : Heavy quark effective theory + phenomenological models
  - More experimental results than those for beauty hadrons
    - Larger production cross section
      - More states observed in experiment
      - More precision measurements of properties
    - Production in beauty hadron decays
      - Determination of spin-parity from angular/amplitude analysis

# Amplitude construction

- Using Helicity formalism

  - Decay chain:  $B^0 \rightarrow D^- D_{sk}^+, D_{sk}^+ \rightarrow D^+ K^{*0}, K^{*0} \rightarrow K^+ \pi^-$

- Intermediate resonances:

  - $K^+ \pi^-$ : S-wave because  $m(K^+ \pi^-) < 0.75$  GeV

    - Modeled by  $J^P = 0^+ K^*(700)^0$

  - $D^+ K^+ \pi^-$ :  $0^- + 0^+ \rightarrow 0^-, 1^+, 2^-, \dots$

      - A non-resonant (NR) term with  $J^P = 0^-$

      - $J^P = 1^+ D_{s1}(2536)^+$

      - A new  $D_{sJ}^+$  state (three spin-parity tested:  $J^P = 0^-, 1^+, 2^-$ )

- Matrix element

Helicity coupling	Wigner d-matrix	Momentum barrier factors for $B^0$ and $D_{sk}$ decays
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$$\mathcal{M} = \sum_k \mathcal{H}^{D_{sk}} d_{0,0}^{J_{D_{sk}}}(\theta_{D_s}) p^{L_{B^0}} F_{L_{B^0}}(pd) q^{L_{D_{sk}}} F_{L_{D_{sk}}}(qd)$$

$\text{BW}(m_{K^+ \pi^-}) \text{BW}_{D_{sk}}(m_{D^+ K^+ \pi^-})$ ,

Mass lineshapes

  - $\theta_{D_s}$ : angle between  $D^+$  and  $D^-$  momenta in the  $D_{sk}^+$  rest frame

  - $p, q$ : center-of-mass momentum of  $D^- D_{sk}^+$  and  $D^+ K^{*0}$

  - $d = 3 \text{ GeV}^{-1} \sim (0.6 \text{ fm})$ : effective radius of the particle

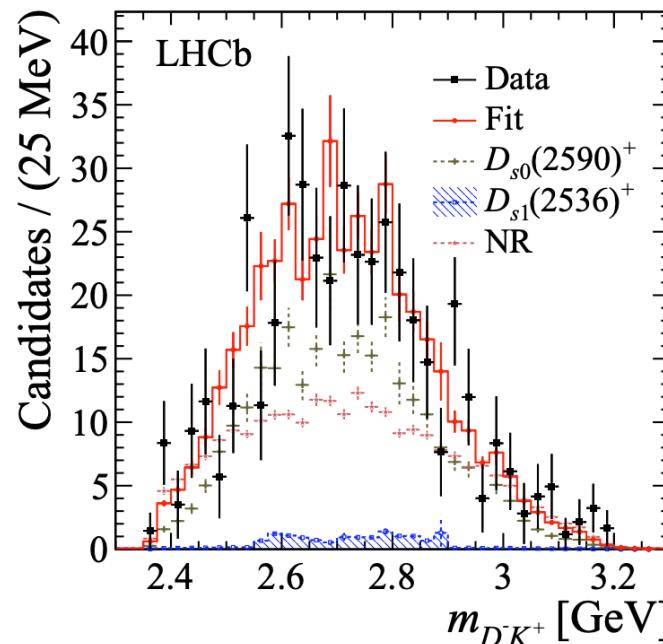
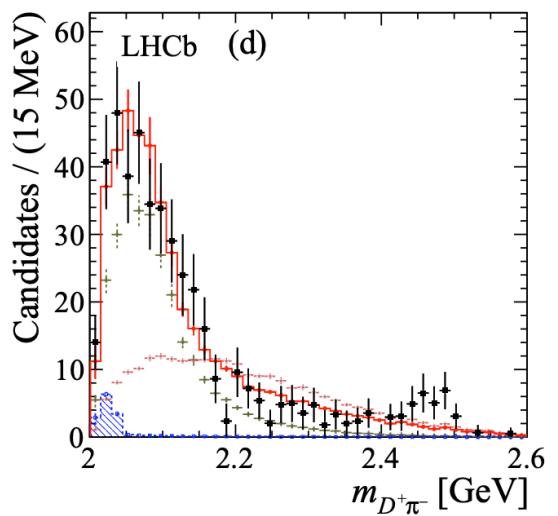
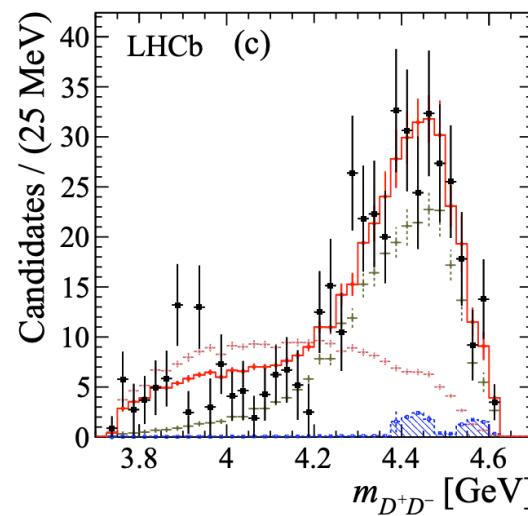
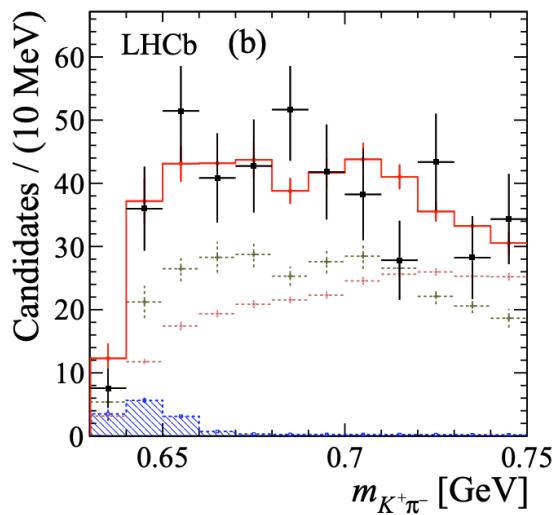
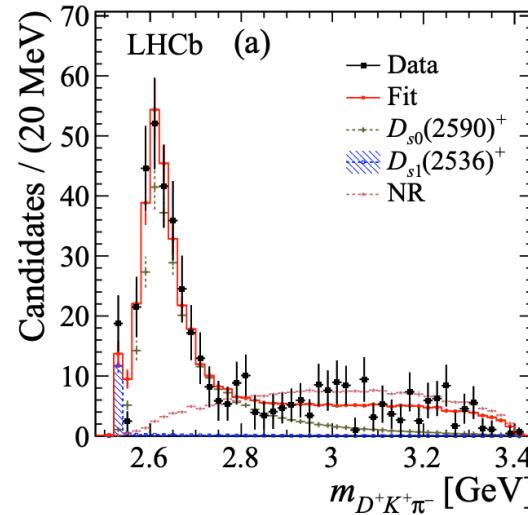
# $D_{s0}(2590)^+$ BW and pole parameters



- BW parameters vary a lot with the change of  $r$ 
  - But similar mass lineshapes and pole mass&width
- BW parameters generally do not have strict physical meaning
  - Depending on decay processes and the lineshape parameterizations
- Pole mass and width are physical quantities
  - Independent of decay processes and parameterizations

Peak position and  
FWHM

# Other mass projections



# $D_{s0}(2590)^+$ fit fractions

Phys. Rev. Lett. 126 (2021) 122002



Fit fraction ( $\times 10^{-2}$ )					
$D_{s0}(2590)^+$	63	$\pm$	9	(stat)	$\pm$ 9 (syst)
$D_{s1}(2536)^+$	3.9	$\pm$	1.4	(stat)	$\pm$ 0.8 (syst)
NR	51	$\pm$	11	(stat)	$\pm$ 19 (syst)
$D_{s0}^+ - \text{NR}$	-18	$\pm$	18	(stat)	$\pm$ 24 (syst)
$D_{s1}^+ / D_{s0}^+$	6.1	$\pm$	2.4	(stat)	$\pm$ 1.4 (syst)

# $D_{s0}(2590)^+$ systematic uncertainties

Source	$m_R$ [MeV]	$\Gamma_R$ [MeV]	Fit fraction ( $\times 10^{-2}$ )				
			$D_{s0}^+$	$D_{s1}^+$	NR	$D_{s0}^+ - \text{NR}$	$D_{s1}^+ / D_{s0}^+$
$D_{s0}(2590)^+$ width model	6.1	8.0	4.7	0.0	15.0	19.6	0.5
$D_{s1}(2536)^+$ mass shape	0.3	4.3	2.3	0.6	3.5	5.3	1.1
$K^+\pi^-$ mass shape	2.7	2.6	3.0	0.2	1.2	4.4	0.1
Blatt-Weisskopf factor	0.7	3.4	2.8	0.3	1.3	3.0	0.2
Including $c\bar{c}$ resonances	1.1	5.4	2.7	0.1	6.3	10.0	0.4
$D^+\pi^-$ resonance veto	2.4	2.1	4.6	0.3	9.4	4.6	0.2
Simulation correction	0.2	1.1	0.3	0.1	0.7	0.8	0.2
Momentum calibration	0.5	0.4	1.3	0.0	1.4	2.5	0.2
Total	7.2	11.7	8.6	0.8	19.3	23.9	1.4

# $\Omega_c^{**0}$ properties

$\Omega_c(3000)^0$	Significance	$6.2\sigma$
	$\Delta M$	$37.6 \pm 0.9 \pm 0.9$ MeV
	$m$	$2999.2 \pm 0.9 \pm 0.9^{+0.19}_{-0.22}$ MeV
	$\Gamma$	$4.8 \pm 2.1 \pm 2.5$ MeV
	$\mathcal{P}$	$0.11 \pm 0.02 \pm 0.04$
$\Omega_c(3050)^0$	$J$ rejection	$0.5\sigma (J=1/2), 0.8\sigma (J=3/2), 0.4\sigma (J=5/2)$
	Significance	$9.9\sigma$
	$\Delta M$	$88.5 \pm 0.3 \pm 0.2$ MeV
	$m$	$3050.1 \pm 0.3 \pm 0.2^{+0.19}_{-0.22}$ MeV
	$\Gamma$	$< 1.6$ MeV, 95% CL
$\Omega_c(3065)^0$	$\mathcal{P}$	$0.15 \pm 0.02 \pm 0.02$
	$J$ rejection	$2.2\sigma (J=1/2), 0.1\sigma (J=3/2), 1.2\sigma (J=5/2)$
	Significance	$11.9\sigma$
	$\Delta M$	$104.3 \pm 0.4 \pm 0.4$ MeV
	$m$	$3065.9 \pm 0.4 \pm 0.4^{+0.19}_{-0.22}$ MeV
$\Omega_c(3090)^0$	$\Gamma$	$1.7 \pm 1.0 \pm 0.5$ MeV
	$\mathcal{P}$	$0.23 \pm 0.02 \pm 0.02$
	$J$ rejection	$3.6\sigma (J=1/2), 0.6\sigma (J=3/2), 1.2\sigma (J=5/2)$
	Significance	$7.8\sigma$
	$\Delta M$	$129.4 \pm 1.1 \pm 1.0$ MeV
$\Omega_c(3120)^0$	$m$	$3091.0 \pm 1.1 \pm 1.0^{+0.19}_{-0.22}$ MeV
	$\Gamma$	$7.4 \pm 3.1 \pm 2.8$ MeV
	$\mathcal{P}$	$0.19 \pm 0.02 \pm 0.04$
	$J$ rejection	$0.3\sigma (J=1/2), 0.8\sigma (J=3/2), 0.5\sigma (J=5/2)$
	$\mathcal{P}$	$< 0.03$ , 95% CL

$$\mathcal{P}_{\Omega_c^{**0}} \equiv \frac{\mathcal{B}(\Omega_b^- \rightarrow \Omega_c^{**0} \pi^-) \mathcal{B}(\Omega_c^{**0} \rightarrow \Xi_c^+ K^-)}{\mathcal{B}(\Omega_b^- \rightarrow \Xi_c^+ K^- \pi^-)}$$

Mass and width consistent with the previous results [PRL 118 (2017) 182001]

$J$  rejection discussed in next slide

$$D_J(\cos \theta) \equiv f_s I_J(\cos \theta) \epsilon(\cos \theta) + f_b B_1(\cos \theta) + (1 - f_s - f_b) B_2(\cos \theta) \epsilon(\cos \theta)$$

$$t_{H_J|H_{J'}} = \frac{1}{N} \sum_{i=1}^N \log [D_{H_J}(\cos \theta_i)/D_{H_{J'}}(\cos \theta_i)]$$

# $\Omega_c^{**0}$ systematic uncertainties

Phys. Rev. D 104 (2021) L091102



Source	$\Omega_c(3000)^0$		$\Omega_c(3050)^0$		$\Omega_c(3065)^0$		$\Omega_c(3090)^0$	
	$m$ [MeV]	$\Gamma$ [MeV]						
Alternative $\Omega_b^-$ fit	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
$\Xi_c^+$ Dalitz weights	0.02	1.1	0.10	0.14	0.2	0.32	1.2	
Momentum calibration	0.01	—	0.03	0.03	—	0.04	—	
PID efficiency	0.56	0.1	0.05	0.14	0.2	0.73	2.1	
$\Omega_b^-$ kinematics	0.13	0.7	0.10	0.21	0.2	0.42	0.9	
Alternative $\Xi_c^+ K^-$ fit	0.70	2.1	0.10	0.28	0.4	0.39	0.9	
Efficiency map	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Background in $\Xi_c^+ K^-$	0.02	0.1	< 0.01	< 0.01	0.04	< 0.01	0.2	
Total	0.9	2.5	0.2	0.4	0.5	1.0	2.8	