

# Recent results on hadron spectroscopy and exotic states at LHCb



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On behalf of the LHCb collaboration

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# Content

- LHCb: discovery machine for spectroscopy
- Conventional meson spectroscopy
  - $B_c(1P)$  in  $B_c\gamma$
  - $D_{s1}(2933)^+$  in  $B^0 \rightarrow D^+D^-K^-\pi^+$
- Charmonium-like exotic states
  - Observation of  $\chi_{c1}(3872) \rightarrow J/\psi\mu^+\mu^-$
  - $T_{c\bar{c}1}(4430)^+$  in  $B^+ \rightarrow \psi(2S)K_S^0\pi^+$
  - Amplitude analysis of  $B^0 \rightarrow \eta_c K^+\pi^-$
- Charmed baryons
  - $\Sigma_c^{**}$  in  $B^- \rightarrow \Lambda_c^+\bar{p}\pi^-$
  - Observation of Doubly charmed baryon results ( $\Xi_{cc}^+$ ,  $\Omega_{cc}^+$ )
- Summary & prospects

# Introduction

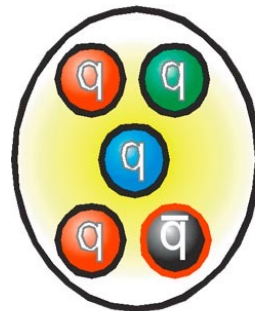
- QCD describing strong interaction between quarks and gluons is not well understood due to its non-perturbative nature at low energy scale
- Hadron spectroscopy provides opportunities to test QCD and its effective models
  - e.g. lattice QCD, diquark model, potential model ...
- Exotic hadrons provide unique probe to QCD
  - Predicted in quark model
  - Recent results show strong evidence for their existence



mesonic molecule



tetraquark



pentaquark



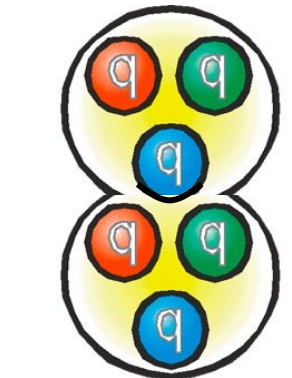
hybrid



meson



baryon

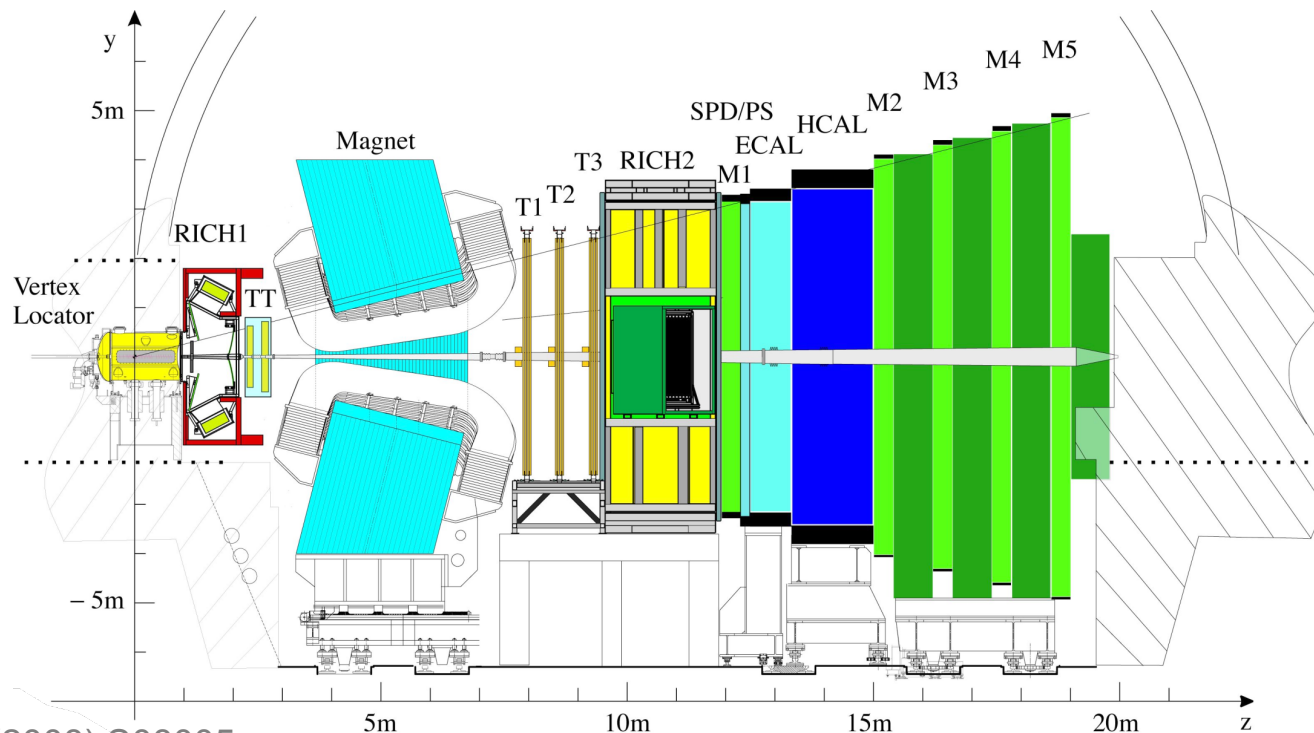


e.g. deuteron

STANDARD

# The LHCb Experiment

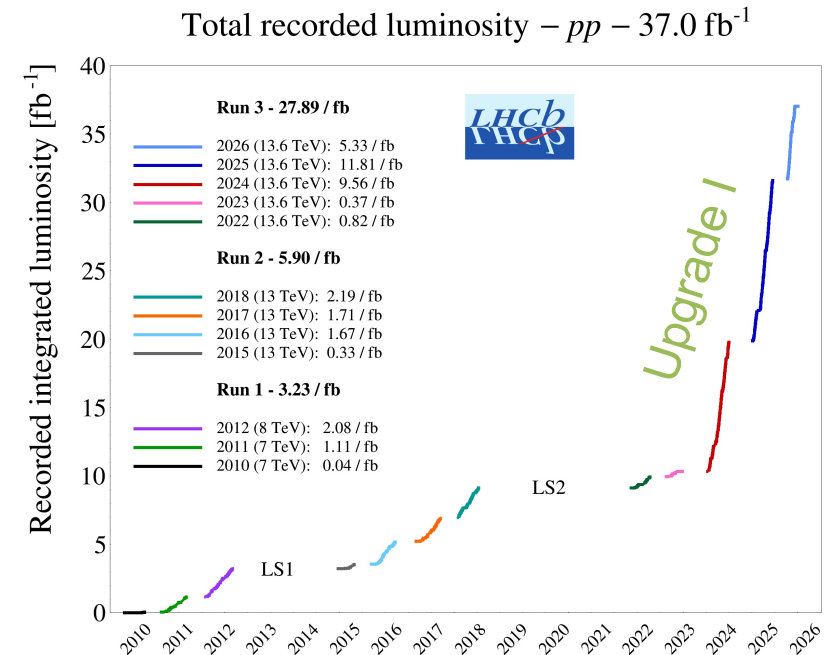
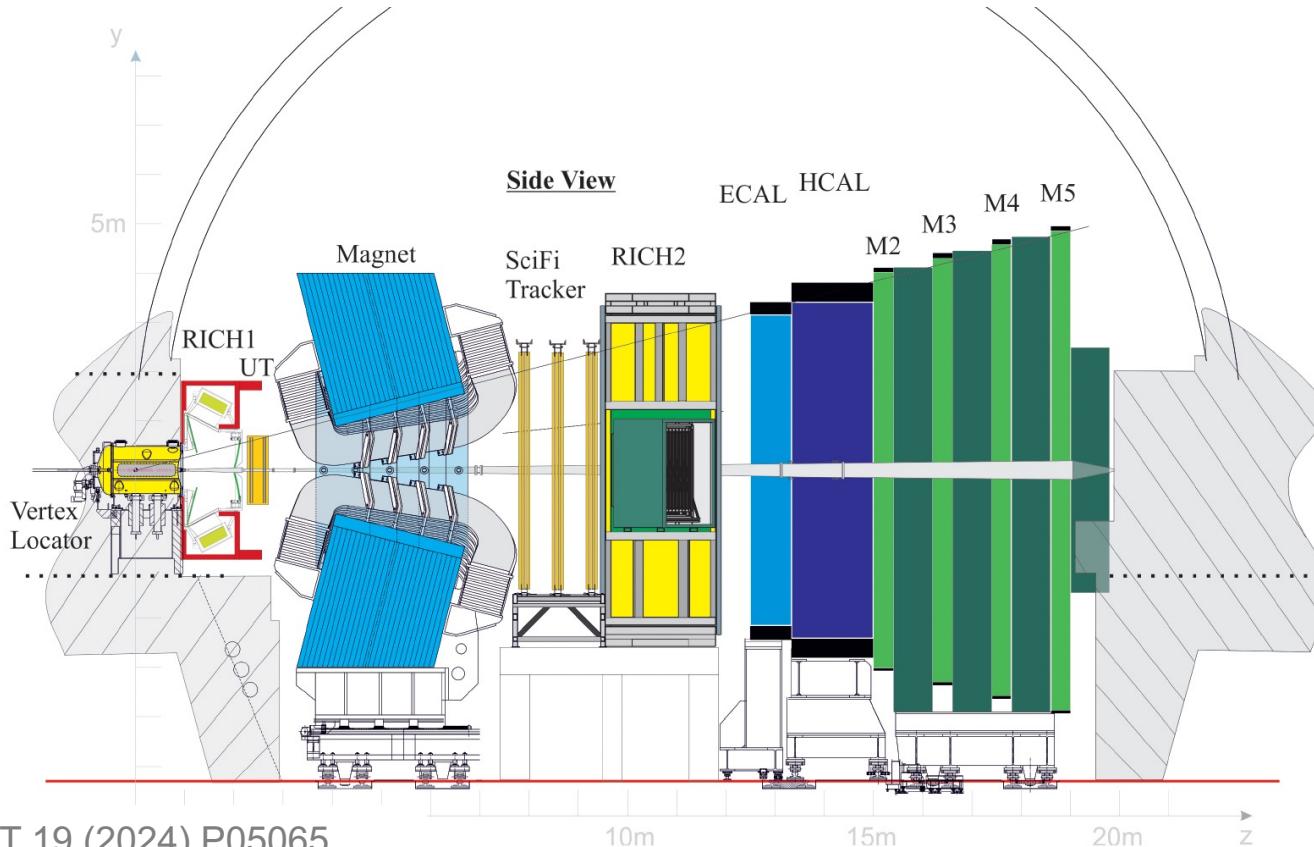
- LHCb is a dedicated flavour physics experiment at the LHC
  - Larger  $b$  and  $c$  production rate
  - Access to all  $b$ -hadrons:  $B^+$ ,  $B^0$ ,  $B_S^0$ ,  $B_c^+$ ,  $b$ -baryons



Vertex res.	$\sigma_{IP} = 20 \mu\text{m}$
Time res.	$\sigma_{\tau} = 45 \text{ fs}$ for $B_S^0 \rightarrow J/\psi\phi$ or $D_S^+\pi^-$
Momentum res.	$\Delta p/p = 0.4 \sim 0.6\%$ (5 - 100 GeV/c)
Mass	$\sigma_m = 8 \text{ MeV}/c^2$ for $B \rightarrow J/\psi X$
Hadron ID	$\varepsilon(K \rightarrow K) \sim 95\%$ mis-ID $\varepsilon(\pi \rightarrow K) \sim 5\%$
Muon ID	$\varepsilon(\mu \rightarrow \mu) \sim 97\%$ mis-ID $\varepsilon(\pi \rightarrow \mu) \sim 1 - 3\%$
ECAL res.	$\Delta E/E = 1\% \oplus 10\%/\sqrt{E} \text{ (GeV)}$

# LHCb detector ... upgraded!

- Five-fold increase in luminosity, more in yield!
  - $\sim 9 \text{ fb}^{-1}$  in Run 1+2  $\rightarrow 37 \text{ fb}^{-1}$  including Run 3!

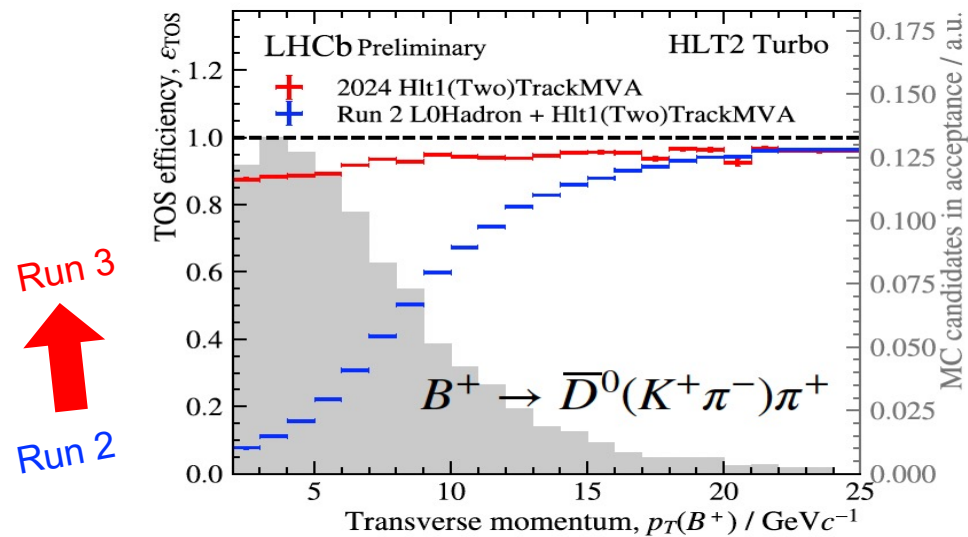


$$4.0 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} (\times 5)$$

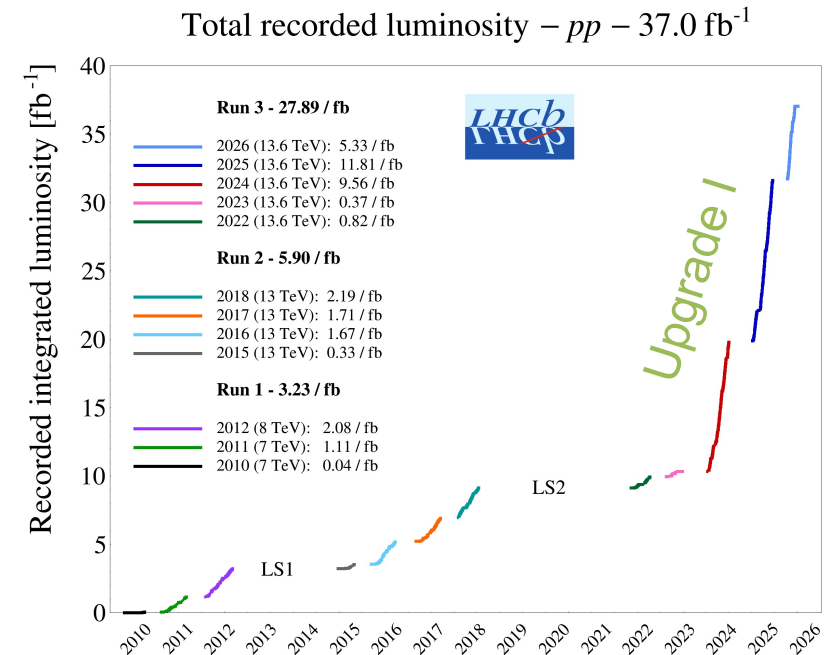
$$\rightarrow 2.0 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$$

# LHCb detector ... upgraded!

- Five-fold increase in luminosity, more in yield!
  - $\sim 9 \text{ fb}^{-1}$  in Run 1+2  $\rightarrow 37 \text{ fb}^{-1}$  including Run 3
  - Removal of hardware trigger  $\rightarrow$  yield  $\times 2\sim 4$  for hadronic final states



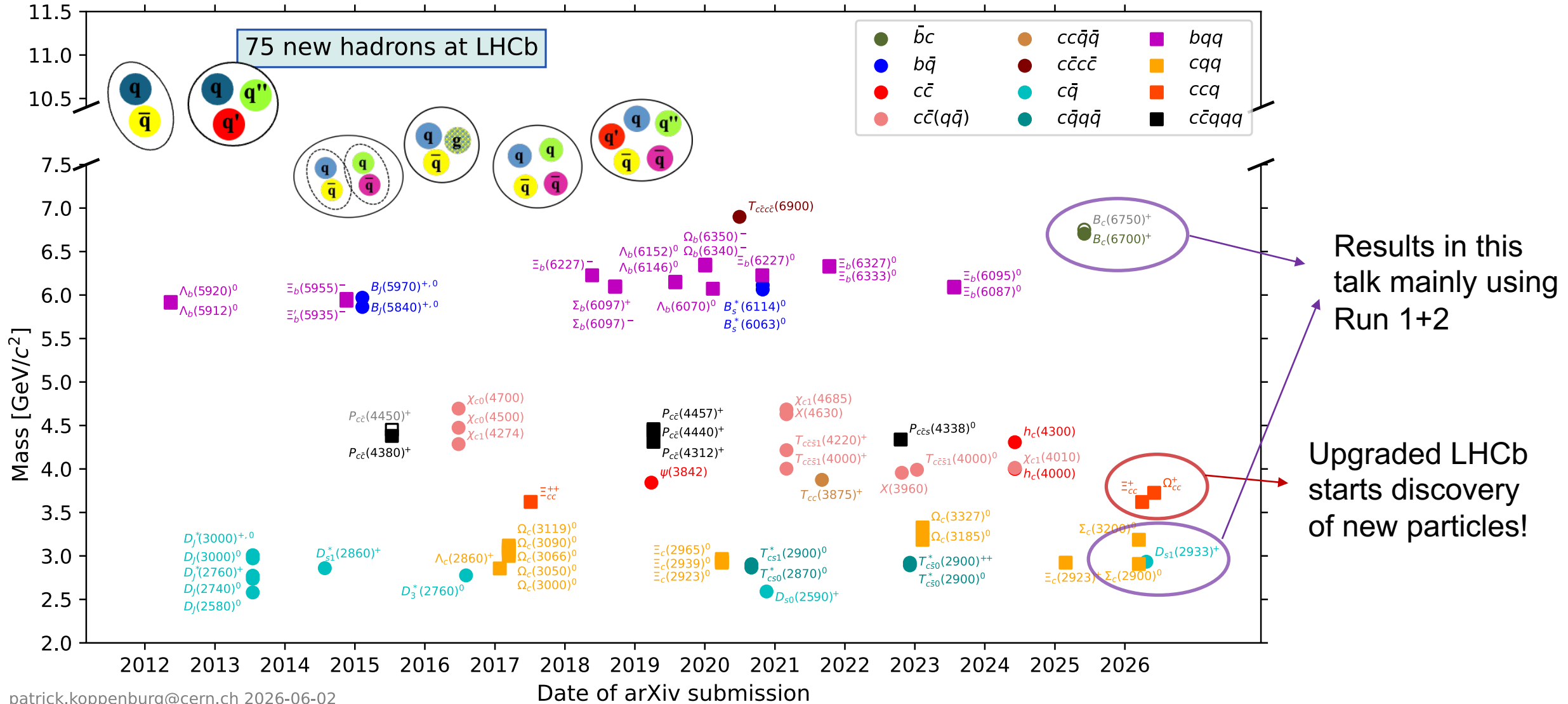
LHCb-Figure-2024-030



$$4.0 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} (\times 5)$$

$$\rightarrow 2.0 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$$

# Ideal laboratory for discovery <https://www.nikhef.nl/~pkoppenb/particles.html>



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# Conventional meson spectroscopy

# Orbitally excited $B_c^+$ states

- $B_c^+$  spectroscopy is rich, but only few excited states have been observed

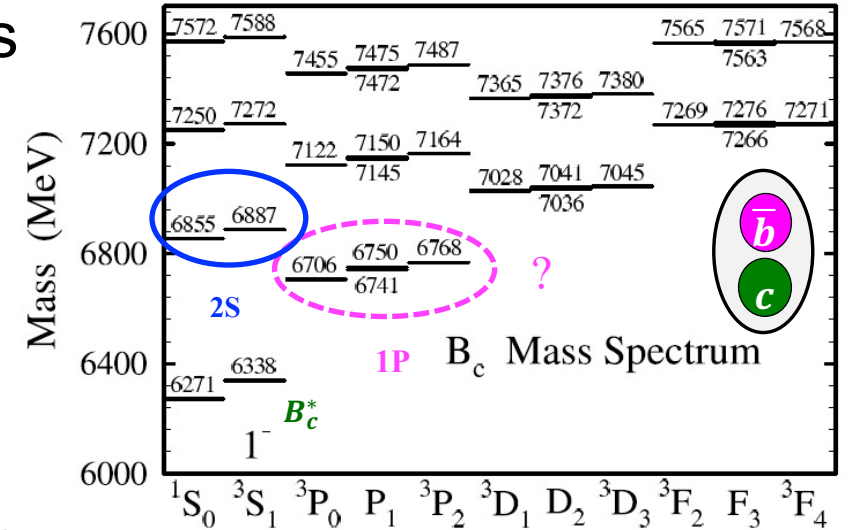
- $B_c(2S)^+$  have been discovered (ATLAS, CMS & LHCb)
- ATLAS recently observed  $B_c^{*+}$

- Search for  $B_c(1P)^+$  states in  $B_c^+ \gamma$  mass spectrum using run1+2 data

- using  $B_c^+ \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) \pi^+$  decay and calorimeter photon
- There are **four**  $B_c(1P)^+$  states, but **six** possible peaks

→  $B_c^+ \gamma$ : fully reconstructed peak

→  $B_c^{*+} (\rightarrow B_c^+ \chi) \gamma$ : partially reconstructed peak, mass shifted downwards by  $\delta M = M(B_c^{*+}) - M(B_c^+)$



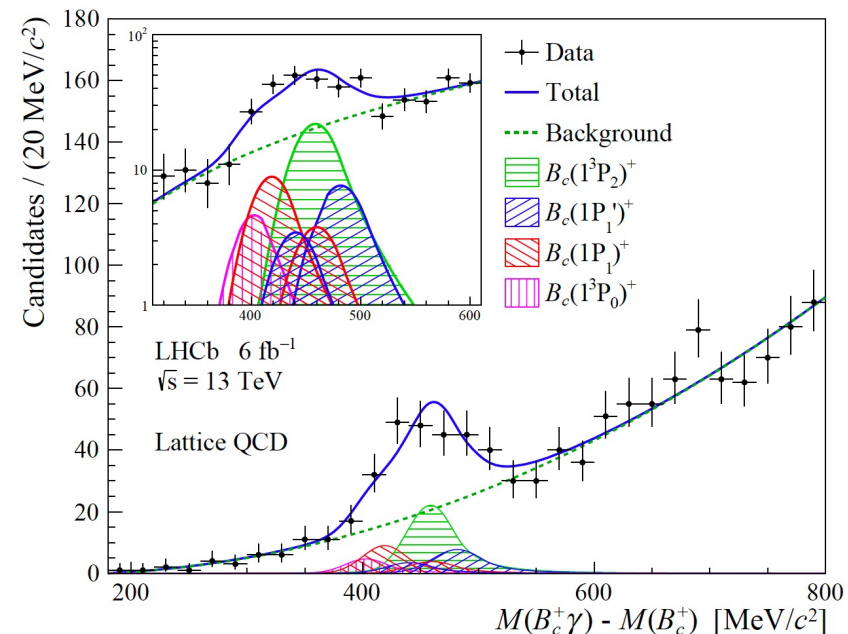
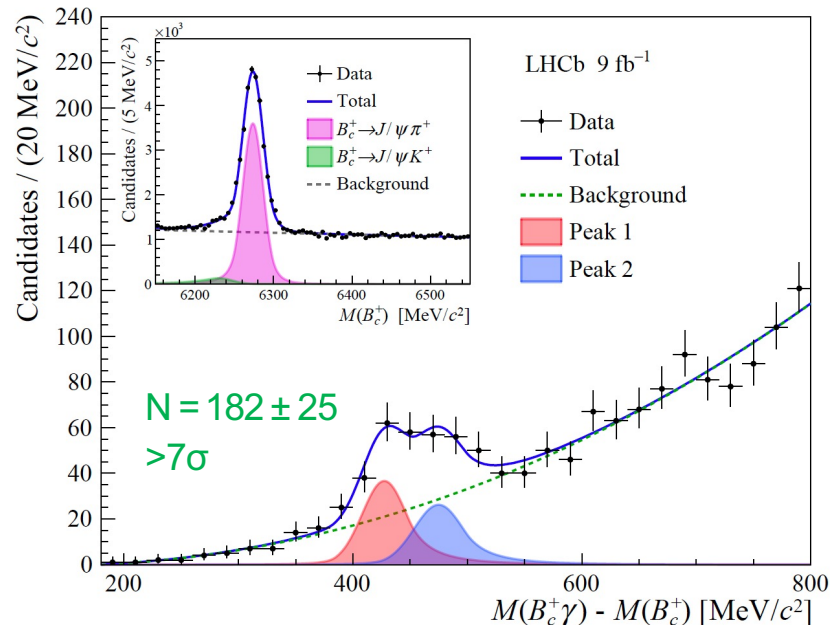
States	$1^3P_0$	$1P_1$	$1P'_1$	$1^3P_2$
Decays	$B_c^{*+} (\rightarrow B_c^+ \gamma) \gamma$	$B_c^+ \gamma$	$B_c^+ \gamma$	$B_c^{*+} (\rightarrow B_c^+ \gamma) \gamma$
#peaks	1	2	2	1

# Orbitally excited $B_c^+$ states

[PRL 135 (2005) 231902]

[PRD 112 (2025) 112003]

- A wide peaking structure is observed within the predicted mass range
  - Good fit with **two peaks**, with free masses & widths dictated by resolution
  - $M_1 = 6704.8 \pm 5.5 \pm 2.8 \pm 0.3 \text{ MeV}/c^2$
  - $M_2 = 6752.4 \pm 9.5 \pm 3.1 \pm 0.3 \text{ MeV}/c^2$
- Fit data with inputs from various theory predictions
  - Measure relative production cross-section of  $B_c(1P)$  states compared to ground-state:
  - $R = 0.20 \pm 0.03 \pm 0.02 \pm 0.03$  ( $p_T < 20 \text{ GeV}/c$  and  $2 < \eta < 4.5$ )

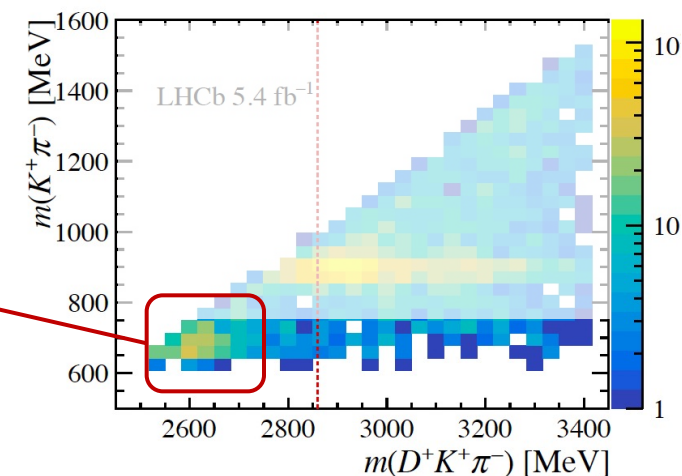
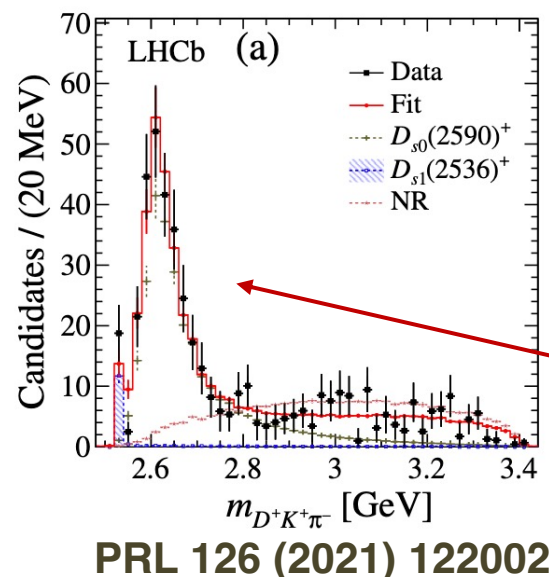
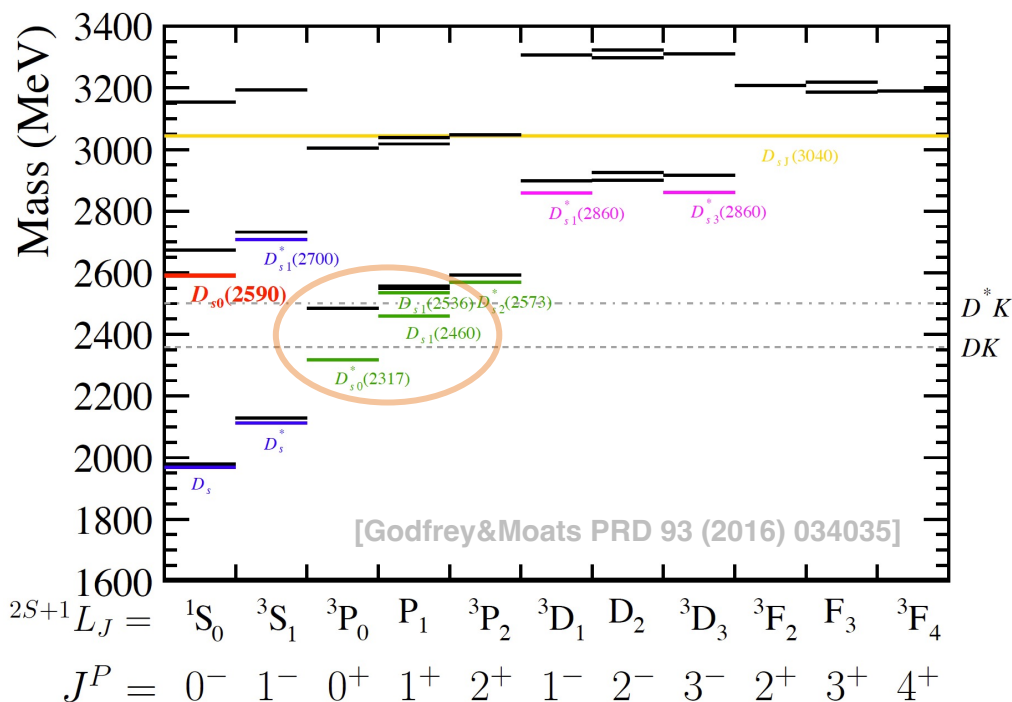


The 1<sup>st</sup> observation of two orbitally excited  $B_c^+$  states

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

[arXiv:2604.21257]

- Longstanding puzzle of  $D_{s0}^*(2317)^+$  and its spin partner  $D_{s1}(2460)^+$ 
  - 100MeV below quark model expectation for P-wave  $D_s$ : tetraquark?
- Studies in  $B^0 \rightarrow D^+ D^- K^+ \pi^-$  allows search for  $D_s$  resonances in  $D^+ K^+ \pi^-$ 
  - Previous LHCb amplitude analysis in partial phase space  $m(K^+ \pi^-) < 750$  MeV
  - Discrepancy continues with discovery of  $D_{s0}(2590)^+$



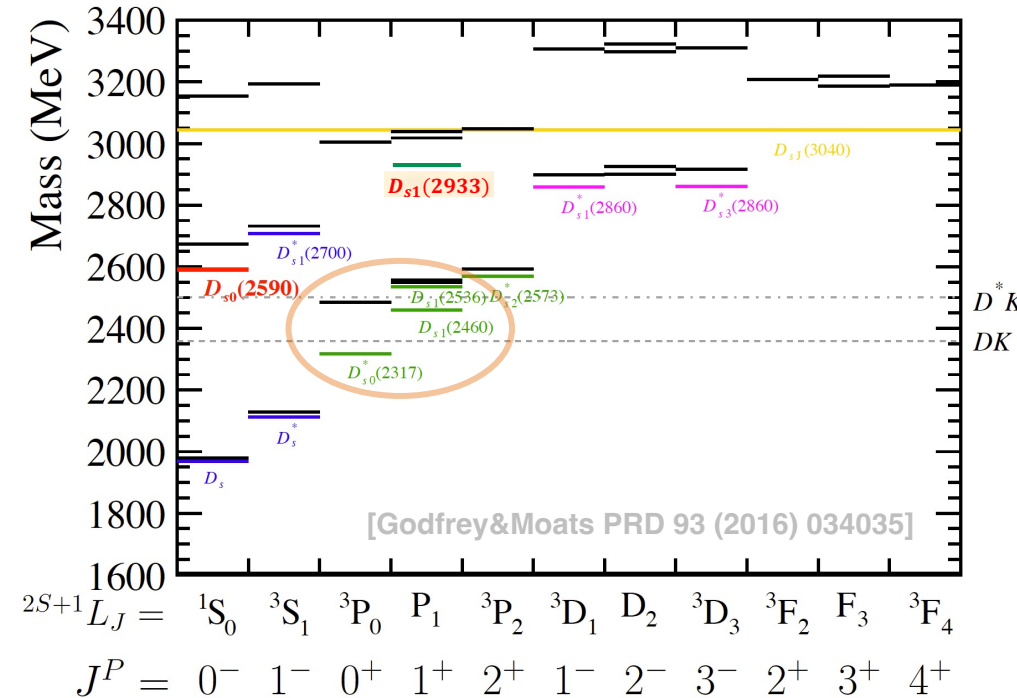
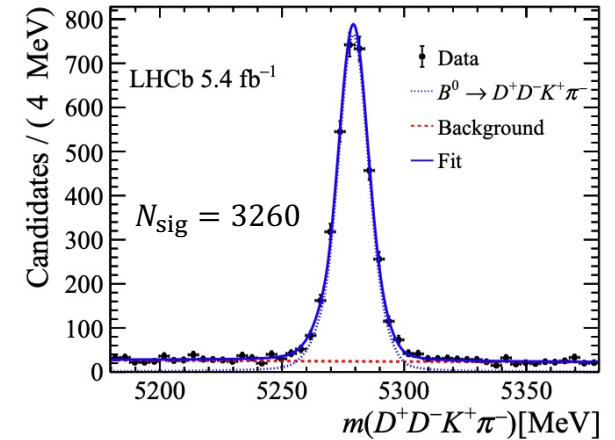
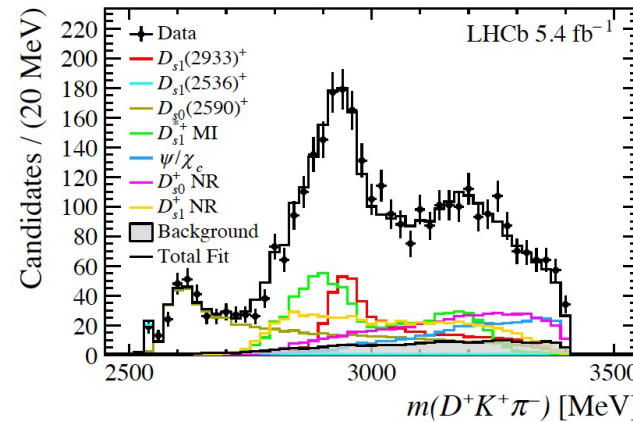
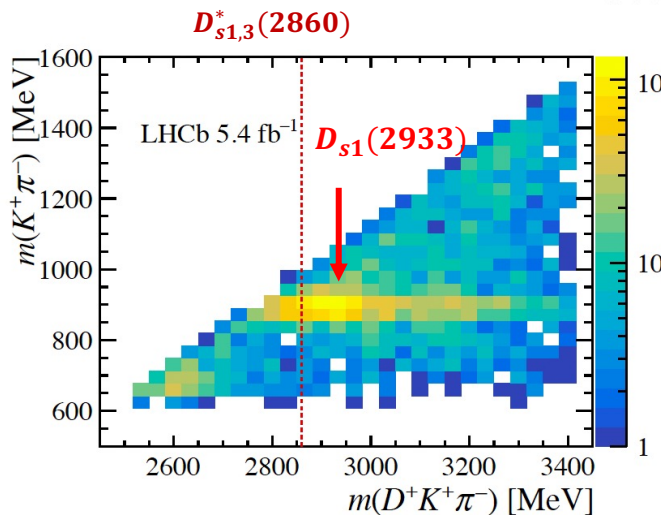
# $D_{s1}(2933)^+$ in $B^0 \rightarrow D^+ D^- K^+ \pi^-$

[arXiv:2604.21257]

- Amplitude analysis in full phase space
- $D_{s0}(2590)^+$  confirmed
- A new state  $D_{s1}(2933)^+$  observed ( $>10\sigma$ )
  - $J^P = 1^+$  determined with  $> 5\sigma$
  - 1<sup>st</sup> observation of a radial excitation of P-wave  $D_s^+$  states
  - Mass still lower than potential model predictions

$$m_0 = 2933_{-5}^{+6} (\text{stat})_{-3}^{+4} (\text{syst}) \text{ MeV},$$

$$\Gamma_0 = 72_{-12}^{+18} (\text{stat})_{-10}^{+7} (\text{syst}) \text{ MeV},$$



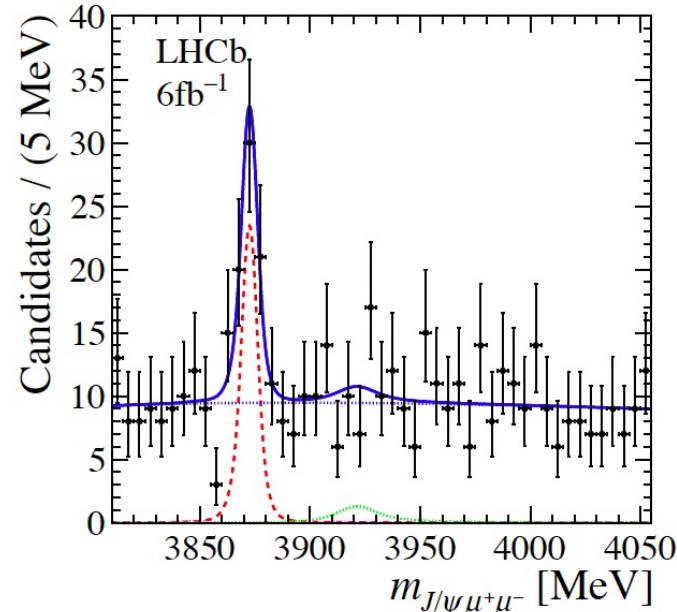
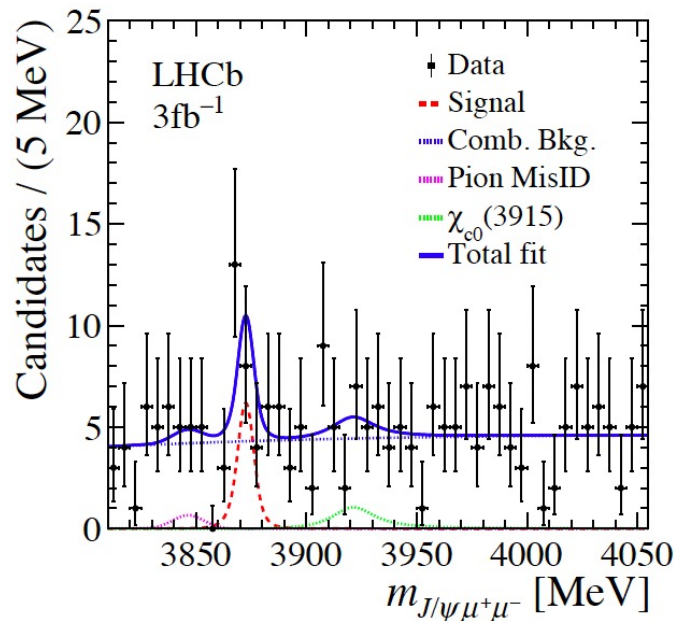
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# Charmonium(like) states

# Muon Dalitz decays $\chi_{c1}(3872) \rightarrow J/\psi \mu^+ \mu^-$

[PRD 113 (2026) 072019]

- $\chi_{c1}(3872)/X(3872)$  as well known, is the first hidden-charm exotic state
  - Extensive experimental studies, yet nature still disputed:  
compact tetraquark?  $D^*D$ bar molecule? or a mixture with charmonium? ...
- First observation of  $\chi_{c1}(3872) \rightarrow J/\psi \mu^+ \mu^-$  using LHCb Run 1+2 data
  - BR adds input to understand its nature



$$\frac{\mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi \mu^+ \mu^-)}{\mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-)}$$

$$= (1.68 \pm 0.32 \pm 0.05) \times 10^{-3},$$

Consistent with theoretical prediction as  $\chi_{c1}(2P)$  [arXiv:2512.17672]

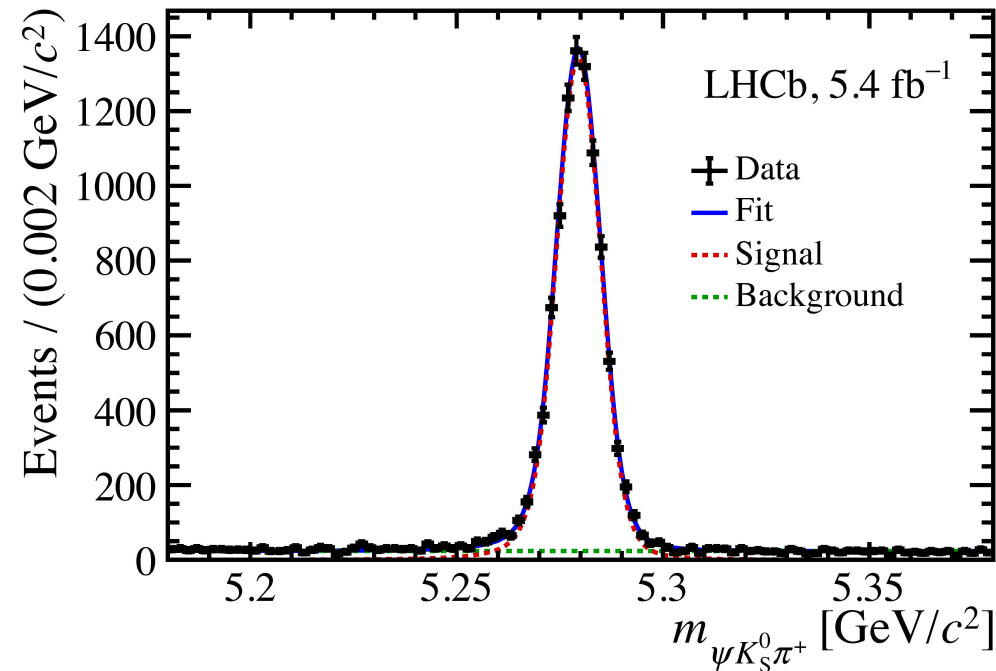
The vector  $\rho^0$  &  $\omega \rightarrow \mu^+ \mu^-$  contribution at level of 1/10 calculated using  $\mathcal{B}(\rho^0/\omega \rightarrow \mu^+ \mu^-) \sim 0.05 \times 10^{-3}$

# $T_{c\bar{c}1}(4430)^+$ in $B^+ \rightarrow \psi(2S)K_S^0\pi^+$

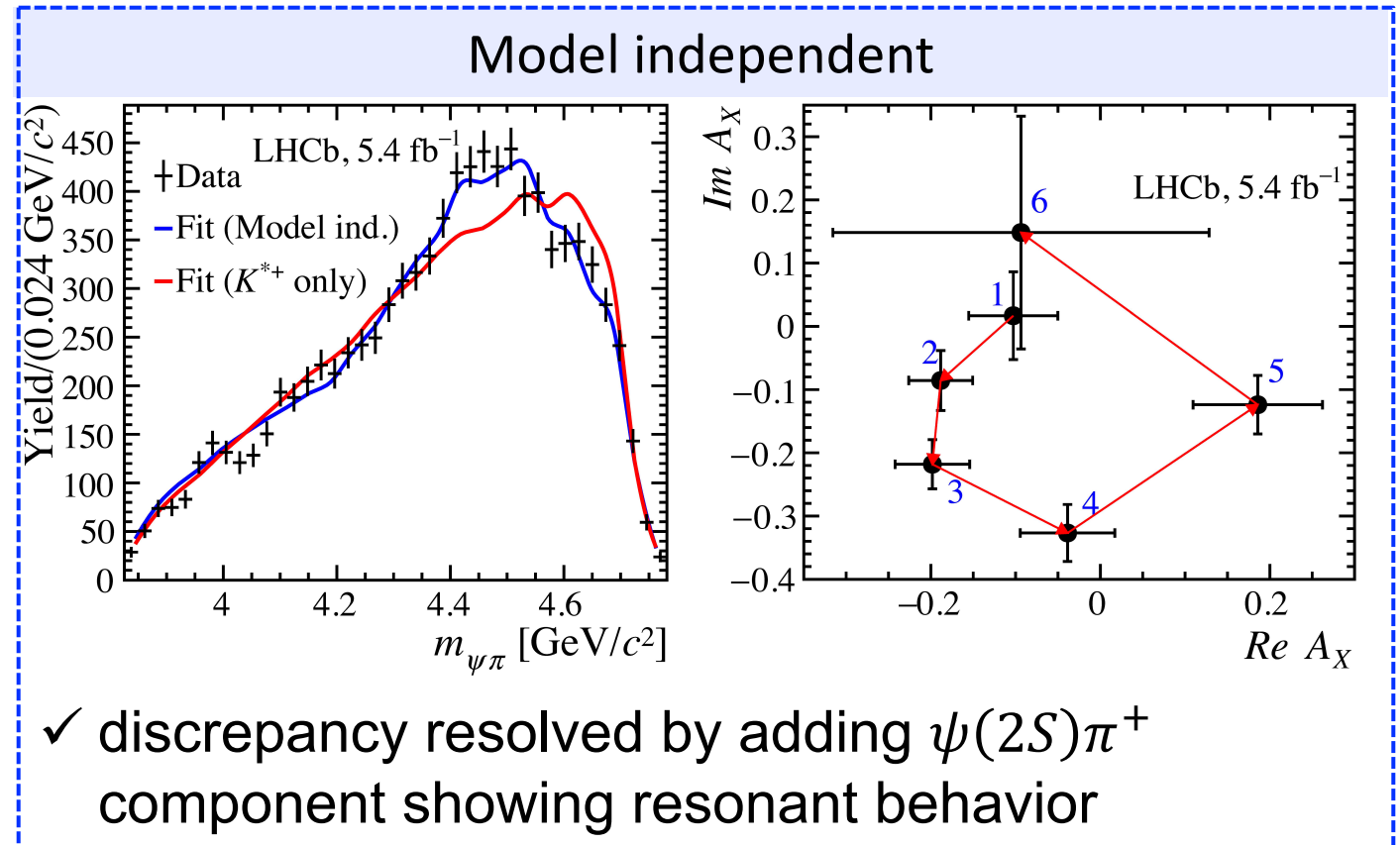
[PRD 113 (2026) L071101]

- First four-dimensional amplitude analysis of  $B^+ \rightarrow \psi(2S)K_S^0\pi^+$  is performed using  $5.4 \text{ fb}^{-1}$  Run2 data
  - related via isospin symmetry to  $\bar{B}^0 \rightarrow \psi(2S)K^-\pi^+$  where the first charged charmonium-like state  $T_{c\bar{c}1}(4430)^+(Z_c(4430)^+, J^P = 1^+)$  was seen

[PRL 100 (2008) 142001] [PRL 112 (2014) 222002]



$N = 9600 \pm 100$



# $T_{c\bar{c}1}(4430)^+$ in $B^+ \rightarrow \psi(2S)K_S^0\pi^+$

[PRD 113 (2026) L071101]

Model dependent

## ✓ Breit Wigner:

$$M = 4.452 \pm 0.016_{-0.033}^{+0.055} \text{ GeV}$$

$$\Gamma = 0.174 \pm 0.019_{-0.020}^{+0.083} \text{ GeV}$$

$$f = (3.7 \pm 0.6_{-0.7}^{+4.0})\%$$

$$J^P = 1^+$$

consistent with  $T_{c\bar{c}1}(4430)^+$

## ◆ Molecular scenario

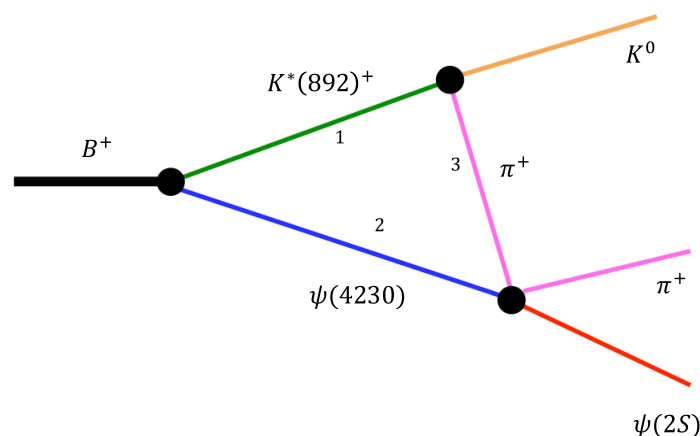
Flatté model to take into account opening of  $\bar{D}_1^*(2600)^0 D^+$

$$F = \frac{1}{m_f^2 - m^2 - i(\rho_1 g_1^2 + \rho_2 g_2^2)}$$

$g_1$ : coupling to  $\psi(2S)\pi^+$   
 $g_2$ : coupling to  $\bar{D}_1^*(2600)^0 D^+$

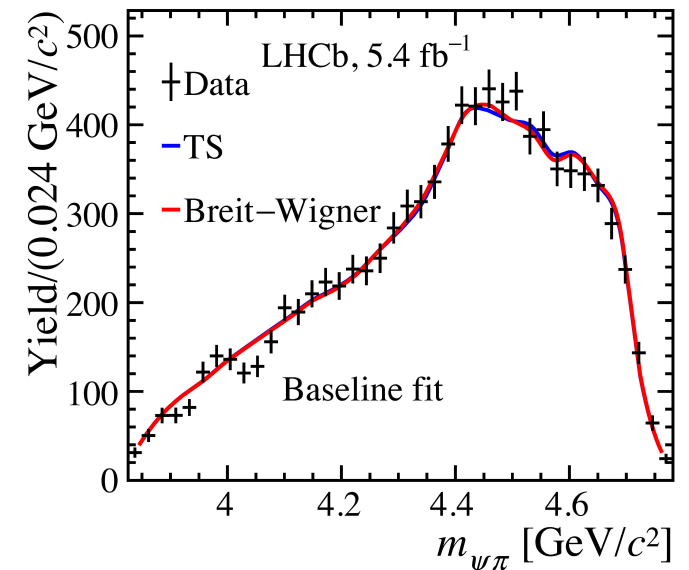
$$g_2 = 0.00 \pm 1.78 \pm 2.81 \text{ GeV}/c^2, \left| \frac{g_2}{g_1} \right| < 6.8 \text{ @ 95\% CL}$$

## ◆ Triangle singularity mechanism



✓ Amplitude obtained through integration over the triangle diagram, leaving no free parameter other than an overall complex coupling

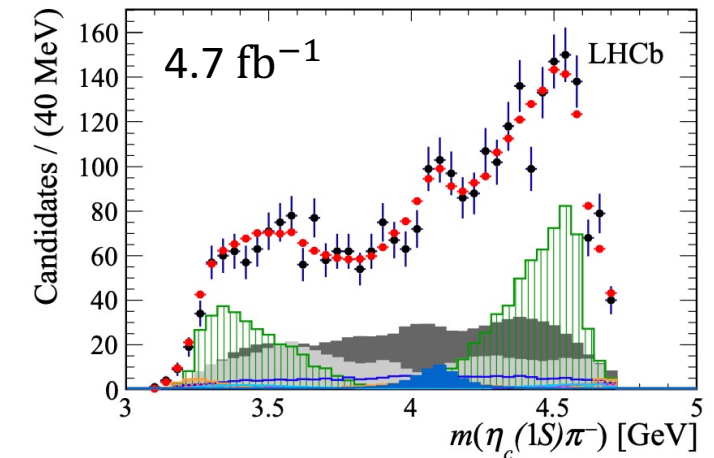
✓ A reasonable description is achieved



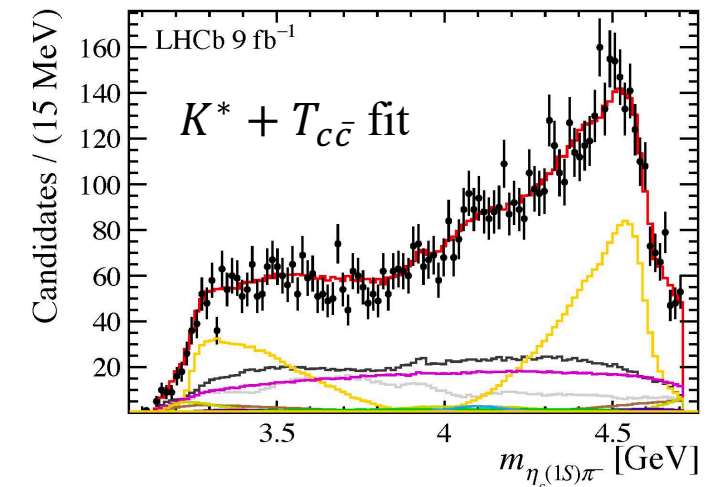
# Amplitude analysis of $B^0 \rightarrow \eta_c K^+ \pi^-$

- An evidence of  $T_{c\bar{c}}(4100)^- \rightarrow \eta_c \pi^-$  was reported by LHCb with  $4.7 \text{ fb}^{-1}$  data ( $3.4\sigma$ )
- Update with full  $9 \text{ fb}^{-1}$  data
- 5000 signal yields (  $\sim 2.5$  of previous publication)
- Amplitude results:
  - $3.6\sigma$  ( $2.5\sigma$ ) significance without (with) systematic uncertainties
  - $J^P = 0^+$  disfavoured by  $3.2\sigma$  compared to  $1^-$  (stat. only)
  - $m(T_{c\bar{c}}) = 4106 \pm 23 \text{ MeV}$
  - $\Gamma(T_{c\bar{c}}) = 514 \pm 166 \text{ MeV}$
- **$T_{c\bar{c}}(4100)^-$  is not confirmed**

[Eur. Phys. J. C78 (2018) 1019]



[Eur. Phys. J. C86 (2026) 537]

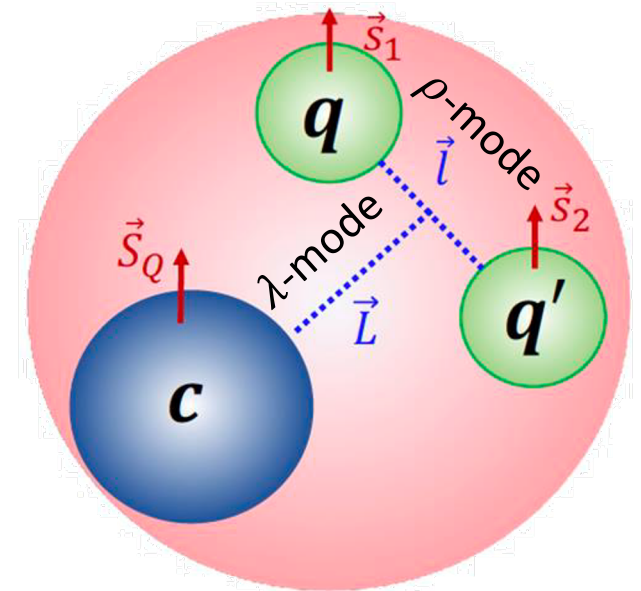
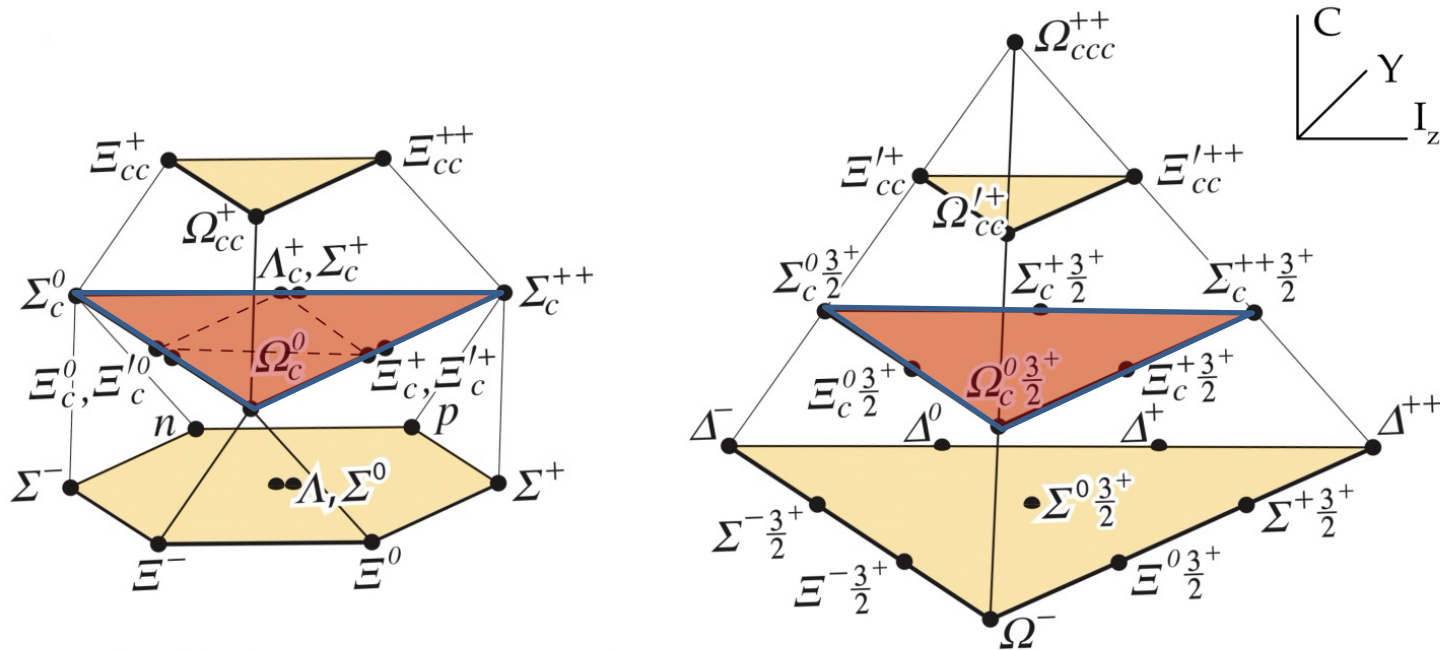


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# Single/Doubly charmed baryons

# Charm baryon spectrum

- Nice platform for nonperturbative QCD
  - Heavy + light diquark
  - $\lambda + \rho$  mode excitation



# $\Sigma_c^{**}$ in $B^- \rightarrow \Lambda_c^+ \bar{p} \pi^-$

[LHCb-PAPER-2026-001 in preparation]

- $\Sigma_c^0(cdd)$  experimental status limited

- $\Sigma_c(2455)^0, \Sigma_c(2520)^0$  well established
- Mass of  $\Sigma_c(2800)^0$  in tension

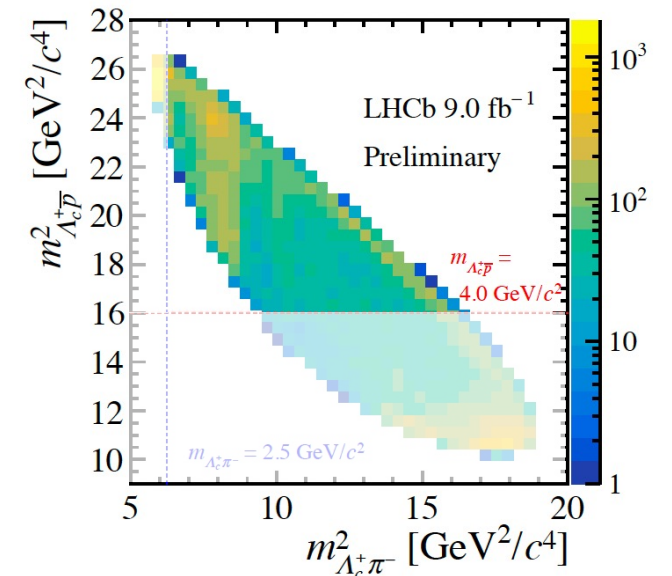
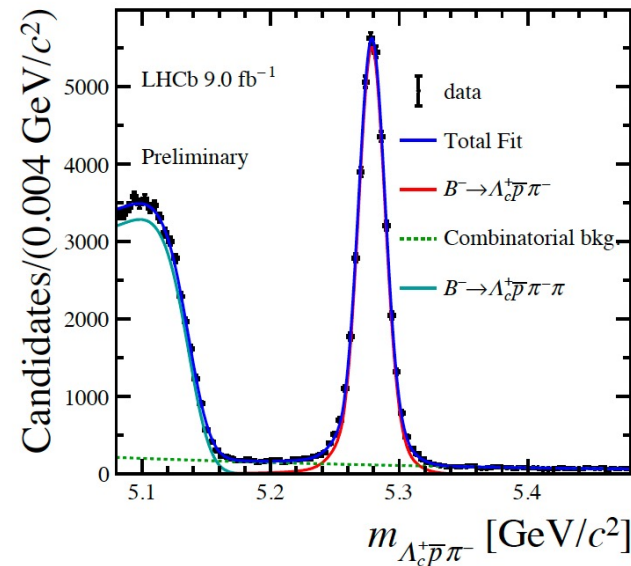
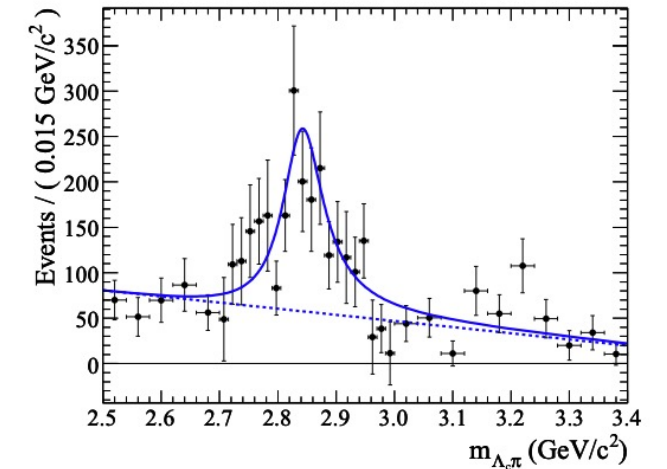
BaBar:  $2846 \pm 8 \pm 10$  MeV PRD 78 (2008) 112003

Belle:  $2801.9_{-3.1-6.0}^{+3.2+2.1}$  MeV PRL 94 (2005) 122002

- Babar used the same final state, observed peak at 2846 MeV

- LHCb performed amplitude analysis in search for excited  $\Sigma_c^{**0} \rightarrow \Lambda_c^+ \pi^-$

- $\Sigma_c(2455)^0$  studied separately
- Region with threshold enhancement vetoed
- Resonance includes  $\Sigma_c \rightarrow \Lambda_c^+ \pi^-$  and  $\bar{\Delta}^{--} \rightarrow \bar{p} \pi^-$  excitations



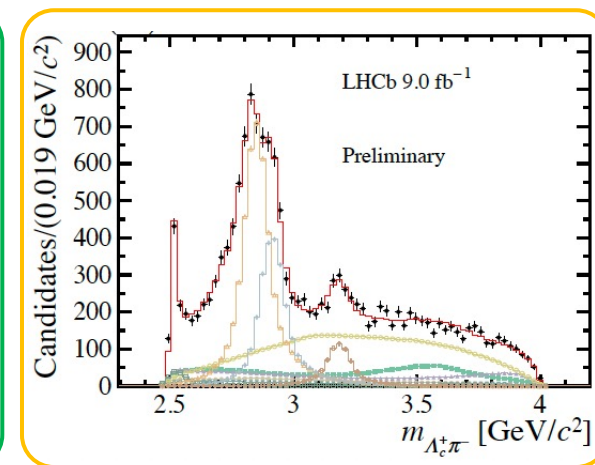
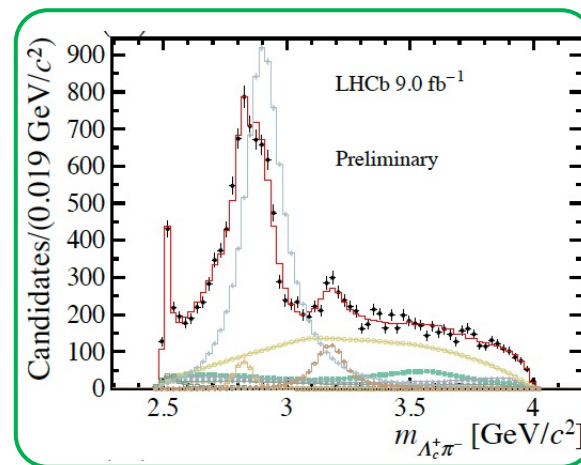
# $\Sigma_c^{**}$ in $B^- \rightarrow \Lambda_c^+ \bar{p} \pi^-$

- A new peak seen at 3200 MeV
- Large statistics show the 2846 peak is overlap of two resonances,  $\Sigma_c(2800)^0$  and  $\Sigma_c(2900)^0$  but two fit solutions called group A and B
- Observation of new states:  $\Sigma_c(2900)^0$  and  $\Sigma_c(3200)^0$ 
  - $\Sigma_c(2800)^0$  at BaBar resolved into  $\Sigma_c(2800)^0$  and  $\Sigma_c(2900)^0$
  - $\Sigma_c(2800)^0$  from Group A consistent with Belle, Group B not

$$\mathcal{R}(\Sigma_c^{**0}) \equiv \frac{\text{FF}[B^- \rightarrow \Sigma_c^{**0}(\rightarrow \Lambda_c^+ \pi^-)\bar{p}]}{\text{FF}[B^- \rightarrow \Sigma_c(2455)^0(\rightarrow \Lambda_c^+ \pi^-)\bar{p}]}$$

## ■ Possible interpretation:

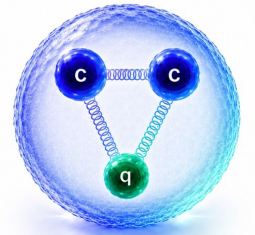
- |                                 |           |           |
|---------------------------------|-----------|-----------|
|                                 | $J^P$ (A) | $J^P$ (B) |
| □ $\Sigma_c(2800)^0$ : 1P or 2S | $(3/2)^+$ | $(1/2)^-$ |
| □ $\Sigma_c(2900)^0$ : 2S or 1P | $(1/2)^-$ | $(3/2)^+$ |
| □ $\Sigma_c(3200)^0$ : 2P or 3S | $(3/2)^-$ | $(3/2)^-$ |



Parameter	Group A	Group B
$m_{\Sigma_c(2800)^0}$ [GeV/c <sup>2</sup> ]	$2.8192 \pm 0.0060 \pm 0.0020$	$2.8483 \pm 0.0037 \pm 0.0055$
$\Gamma_{\Sigma_c(2800)^0}$ [GeV]	$0.0326 \pm 0.0068 \pm 0.0080$	$0.0990 \pm 0.0072 \pm 0.0209$
$m_{\Sigma_c(2900)^0}$ [GeV/c <sup>2</sup> ]	$2.9077 \pm 0.0048 \pm 0.0087$	$2.9143 \pm 0.0032 \pm 0.0081$
$\Gamma_{\Sigma_c(2900)^0}$ [GeV]	$0.1754 \pm 0.0082 \pm 0.0225$	$0.0921 \pm 0.0061 \pm 0.0234$
$m_{\Sigma_c(3200)^0}$ [GeV/c <sup>2</sup> ]	$3.1859 \pm 0.0059 \pm 0.0144$	$3.1898 \pm 0.0054 \pm 0.0107$
$\Gamma_{\Sigma_c(3200)^0}$ [GeV]	$0.1331 \pm 0.0176 \pm 0.0267$	$0.1001 \pm 0.0154 \pm 0.0323$
$\mathcal{R}(\Sigma_c(2800)^0)$	$0.09 \pm 0.02 \pm 0.05$	$0.86 \pm 0.07 \pm 0.42$
$\mathcal{R}(\Sigma_c(2900)^0)$	$1.68 \pm 0.07 \pm 0.29$	$0.50 \pm 0.04 \pm 0.19$
$\mathcal{R}(\Sigma_c(3200)^0)$	$0.21 \pm 0.03 \pm 0.05$	$0.17 \pm 0.03 \pm 0.05$
$\mathcal{R}(\Sigma_c(2520)^0)$	$0.09 \pm 0.01 \pm 0.02$	$0.11 \pm 0.01 \pm 0.03$
$\mathcal{R}((\Lambda_c^+ \pi^-)_{\text{NRS-wave}})$	$2.19 \pm 0.14 \pm 0.22$	$2.23 \pm 0.11 \pm 0.30$

# Doubly charmed baryons

- From the  $SU(4)_f$  multiplets, three weakly decaying doubly charmed baryons are expected
  - $\Xi_{cc}^{++}(ccu)$   $\Xi_{cc}^+(ccd)$   $\Omega_{cc}^+(ccs)$
  - Their properties are extensively studied by theorists since 1970s



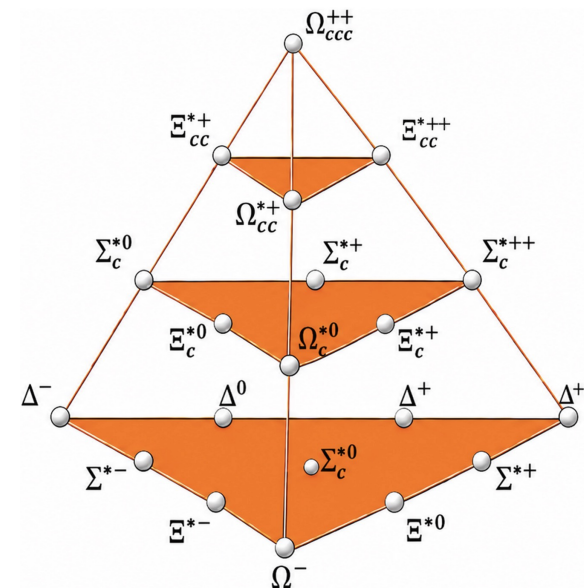
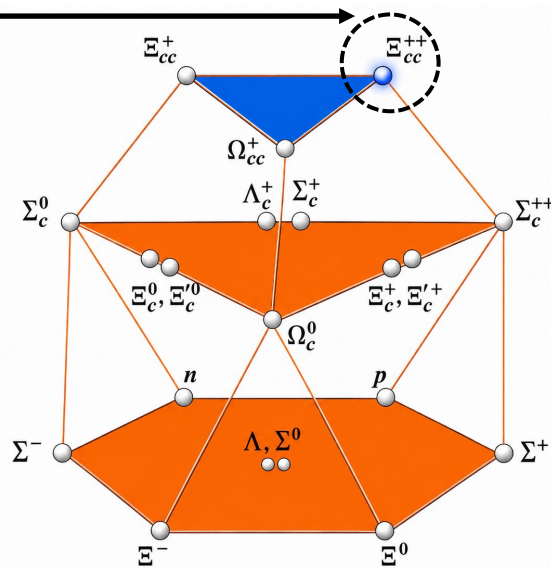
[JHEP 07 (2003) 061]

Mass	$m(\Xi_{cc}^{++}) \sim m(\Xi_{cc}^+) \sim m(\Omega_{cc}^+) - 100 \text{ MeV}$
Lifetime	$\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^+) \sim 150 \text{ fs} > \tau(\Xi_{cc}^+)$
Production	$\sigma(\Xi_{cc}^{++}) \sim \sigma(\Xi_{cc}^+) \sim 3 \cdot \sigma(\Omega_{cc}^+)$ and $\sigma(H_{cc})/\sigma(H_c) \sim \mathcal{O}(10^{-4})$

[PRD 102 (2020) 054513]

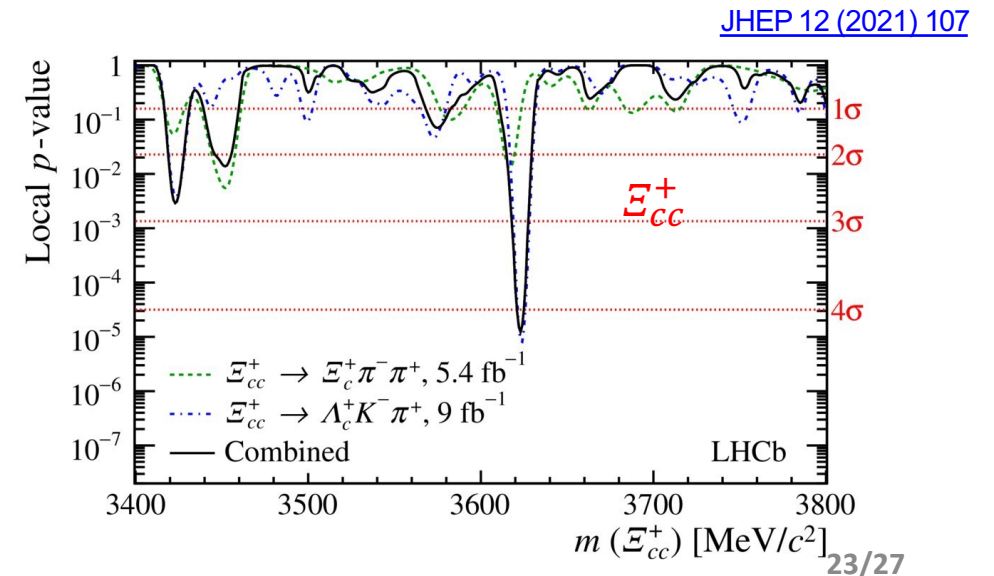
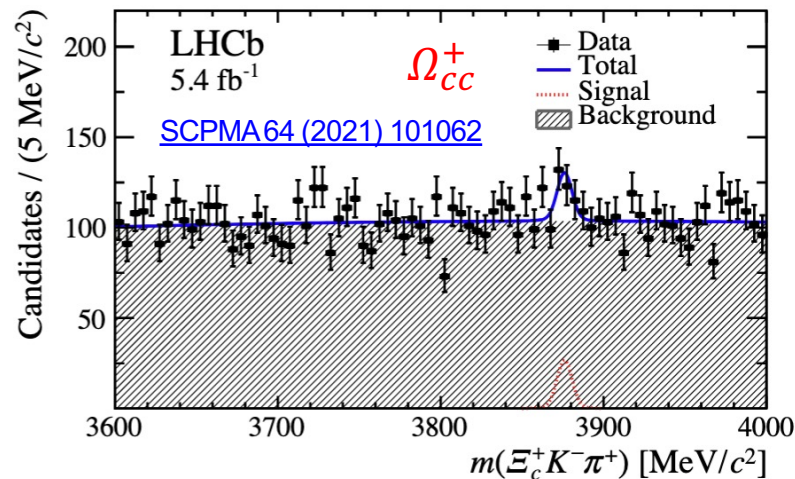
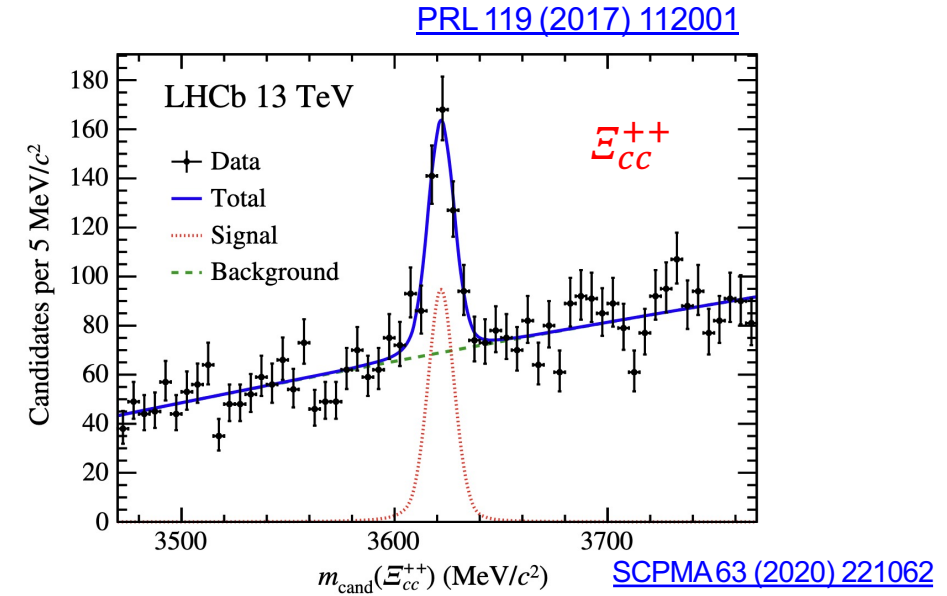
[PRD 83 (2020) 034026]

LHCb Run 1+2 established the  $\Xi_{cc}^{++}$  baryon successfully, while searches for  $\Xi_{cc}^+$  and  $\Omega_{cc}^+$  remained inconclusive...



# Experimental status before LHCb Run 3

- [SELEX] First experimental claim on  $\Xi_{cc}^+$  and  $\Xi_{cc}^{++}$ 
  - $m(\Xi_{cc}^+/\Xi_{cc}^{++}) = 3520/3460$  MeV,  $\tau(\Xi_{cc}^+) < 33$  fs at 90% CL
  - Not confirmed by other experiments
- [LHCb] Observation of the  $\Xi_{cc}^{++}$ 
  - $\Xi_{cc}^{++}$  first observed in  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$  and confirmed in  $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^+$
  - $m(\Xi_{cc}^{++}) = 3622$  MeV and  $\tau(\Xi_{cc}^{++}) = 256$  fs
- [LHCb] Searched for  $\Xi_{cc}^+$  in  $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+ / \Xi_c^+ \pi^- \pi^+$  and  $\Omega_{cc}^+$  in  $\Omega_{cc}^+ \rightarrow \Xi_c^+ K^- \pi^+$ 
  - No significant signal is observed



# Observation of $\Xi_{cc}^+$

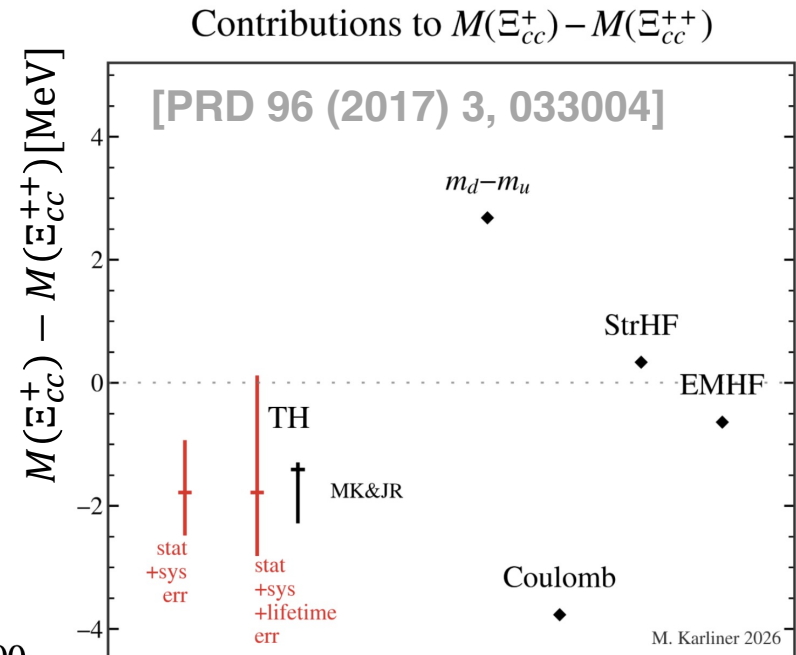
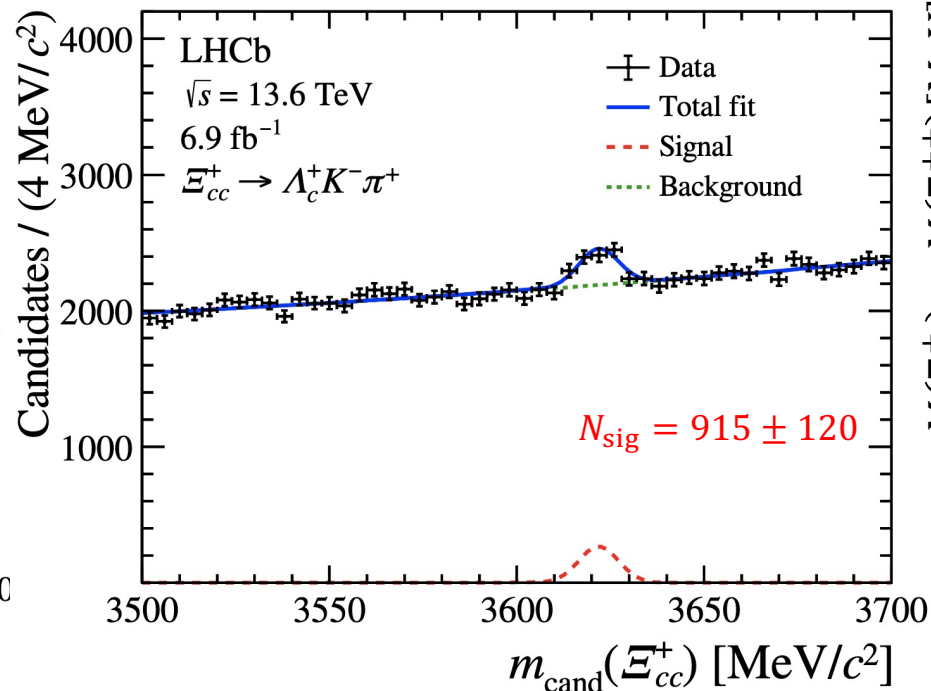
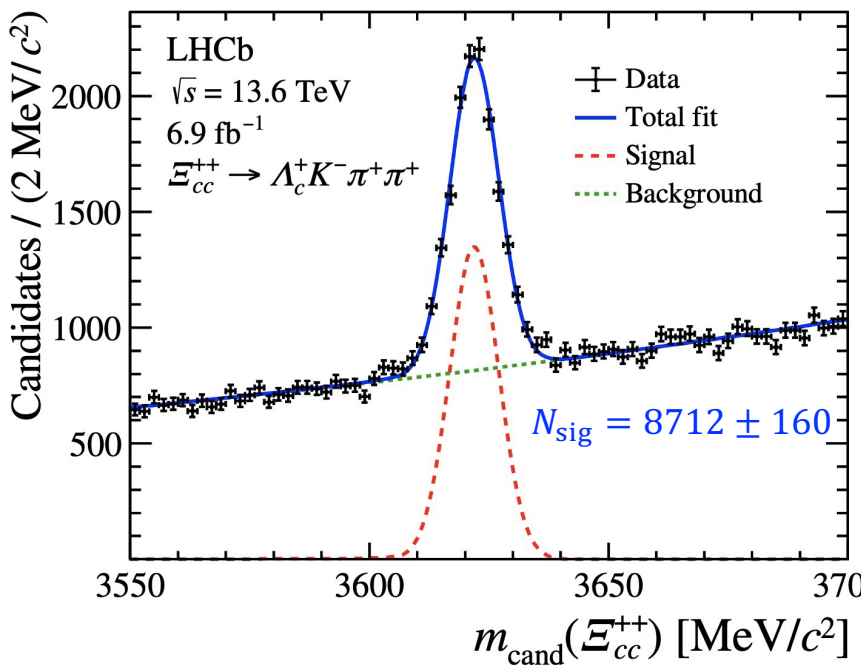
[arXiv: 2603.28456]

- $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$  decay mode is used with LHCb 2024 data ( $6.9 \text{ fb}^{-1}$ )
  - A clear peak observed with local significance  $> 7\sigma$ , consistent with LHCb previous searches

$$m(\Xi_{cc}^+) = 3619.97 \pm 0.83 \text{ (stat)} \pm 0.26 \text{ (syst)} \pm_{-1.30}^{+1.90}(\tau) \text{ MeV}/c^2$$

$$m(\Xi_{cc}^+) - m(\Xi_{cc}^{++}) = -1.77 \pm 0.84 \text{ (stat)} \pm 0.15 \text{ (syst)} \pm_{-1.30}^{+1.90}(\tau) \text{ MeV}/c^2$$

- $\Xi_{cc}^{++}$  yield per  $\text{fb}^{-1} = 1262$  (285) at 2024 (Run2) data  $\Rightarrow$  improved by a factor of 4



# Observation of $\Omega_{cc}^+$

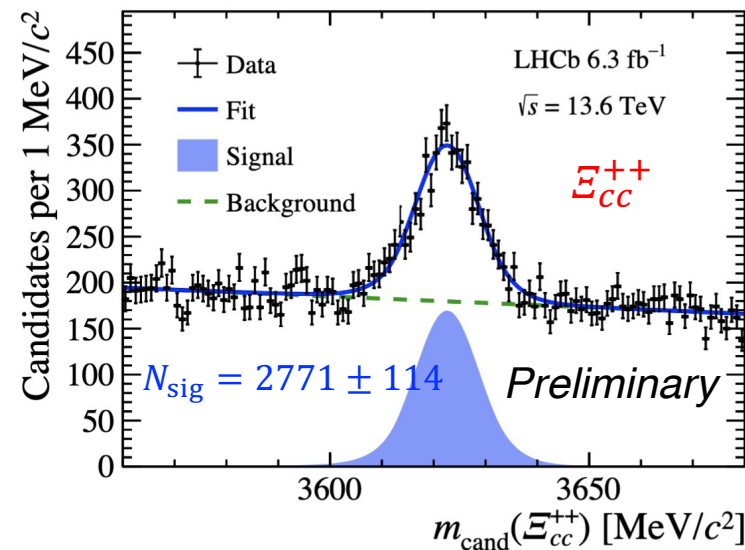
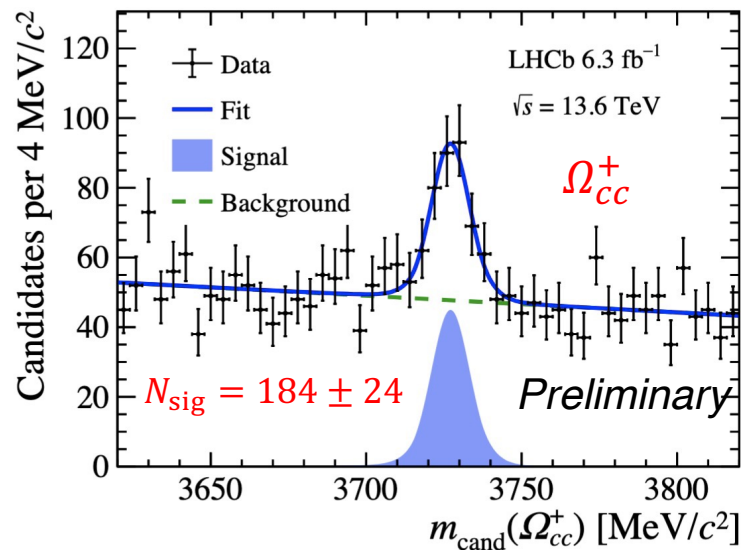
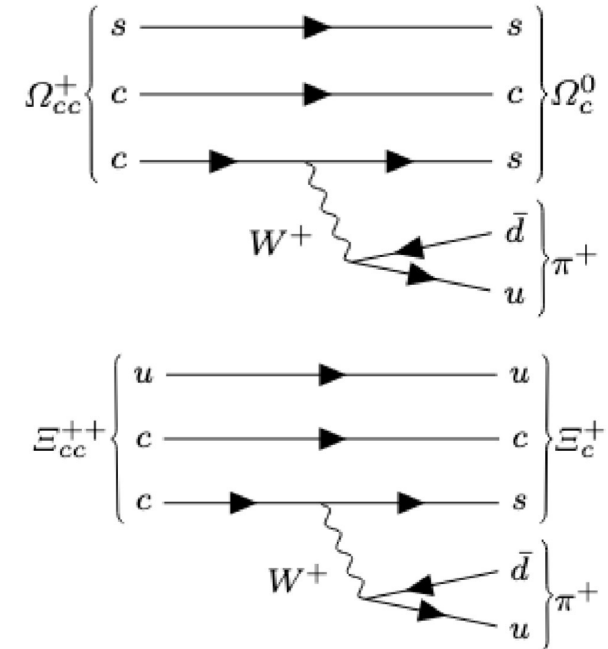
[LHCb-PAPER-2026-022, in prep.]

- $\Omega_{cc}^+ \rightarrow \Omega_c^0 \pi^+, \Omega_c^0 \rightarrow p K^- K^- \pi^+$  decay is used with 2024 ( $6.3 \text{ fb}^{-1}$ ) data
- $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+, \Xi_c^+ \rightarrow p K^- \pi^+$  decay as control mode
- A clear peak observed with global significance  $8.7\sigma$

$$m(\Omega_{cc}^+) = 3725.9 \pm 1.0 \text{ (stat)} \pm 0.2 \text{ (syst)} \pm 0.4(\tau) \pm 0.6 \text{ (ext)} \text{ MeV}/c^2$$

$$m(\Omega_{cc}^+) - m(\Xi_{cc}^{++}) = 104.3 \pm 1.0 \text{ (stat)} \pm 0.2 \text{ (syst)} \pm 0.4(\tau) \pm 0.5 \text{ (ext)} \text{ MeV}/c^2$$

- The peak remains significant after a tight requirement on the decay time  $t > 170 \text{ fs}$ , indicating **weakly-decaying nature**



Precise measurements of the lifetime and production are underway with the full LHCb Run 3 data



# Prospects

## Run 3 data: a very rich dataset

- 37 fb<sup>-1</sup> obtained by LS3 — ~4× Run 1+2 luminosity
- Software trigger → ×2–4 efficiency for hadronic final states

## More to come

- lifetime and production measurements of  $\Xi_{cc}^+$  and  $\Omega_{cc}^+$  with full Run 3 sample underway
- Several analyses still in progress (excited  $\Lambda_c/\Sigma_c$ , ...)
- More decay modes and amplitude analyses of exotic states

## Run 4 & Upgrade II

- 300 fb<sup>-1</sup> target → order-of-magnitude leap in statistics
- Open doors to: excited doubly heavy baryons ( $\Xi_{cc}^*$ ,  $\Omega_{cc}^*$ )
- doubly bottom hadrons, full spectroscopy of exotic multiplets

Stay tuned — the best is yet to come!